Black Hole Production at the LHC::
A Review of the Risks

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Draft for Discussion

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Abstract

This report reviews the potential risks associated with black hole production at the LHC. In TeV-scale gravity scenarios, the creation of black holes is expected from LHC collisions. Significant uncertainties remain about whether such black holes would radiate, and if so, how quickly. It is also not known whether such black holes would be charged, or whether they must all be neutral. The different possible scenarios are associated with different risk profiles, but in almost all cases there are considerable potential risks associated with producing black holes at an Earth-bound collider. Even under the favourable assumption that black holes rapidly radiate, no bound has been established on the potentially catastrophic environmental effects of the remnants which could be left at the end of the initial radiative phase. Similarly, no bound has been shown for the possible effects of charged stable black holes with masses greater than 7 TeV. In the case of neutral stable black holes, calculations published by CERN predict the premature destruction of the Earth in several cases. Attempts to rule out these risks based on the existence of specific massive and ultramassive white dwarfs are limited by significant uncertainties in the available data and the proposed accretion model. Bounds based on the existence of neutron stars are even weaker, since their powerful magnetic fields protect them from the direct effects of ultrahigh-energy cosmic rays, and the alternative constructions proposed by CERN are limited by the lack of sufficient evidence to justify those arguments. The only significant safety factor would be if TeV-scale gravity is not realized and black holes are not produced at the LHC.

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Contents

1 Introduction

This paper is an attempt to review the risks of black hole production at the Large Hadron Collider (LHC).[1] For the most part, it is a summary and critique of the paper, "Astrophysical implications of hypothetical stable TeV-scale black holes" prepared on behalf of CERN (the European Organization for Nuclear Research) by Professor Steven Giddings of the University of California, Santa Barbara, and Dr. Michelangelo Mangano of CERN's Theory Department.

The principal sources it is based on are:

- "Astrophysical implications of hypothetical stable TeV-scale black holes" by Giddings and Mangano [GM ↗][2]
- "Review of the Safety of LHC Collisions" by CERN's LHC Safety Assessment Group (LSAG) [LSAG ↗][3]
- "SPC Report on LSAG Documents" by CERN's Scientific Policy Committee [SPC ↗]
- "Study of potentially dangerous events during heavy-ion collisions at the LHC" by CERN's LHC Safety Study Group [LSSG ↗]

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[1] The hyperlinks in this paper are coded as follows:

- Green links are intended to help members of the public who may not be familiar with some of the terms used or people cited in this paper. Generally, they link to entries in wikipedia or to other suitable sites, if available. (These links should not, however, be taken as a citation or endorsement of whatever content may be on those sites.)
- Red links are internal links to footnotes, other parts of this paper, or bibliographical entries at the end of this paper. (Readers using these links may wish to enable the "previous view" button on the Acrobat Reader toolbar: Tools → Customize Toolbars → Page Navigation Toolbar → Previous View)
- Blue links are external links to the documents cited in this paper. Whenever possible, links are given to freely accessible versions of these documents (e.g. arXiv preprints, ADS scans). Many of these links are to specific pages, equations, tables, or figures of pdf files, although whether they arrive at the right place may depend on the browser used and the browser's or computer's settings. (Firefox usually works, Internet Explorer usually doesn't . . .)

[2] As it is referenced repeatedly in this document, the Giddings/Mangano paper is cited simply as "GM". This reference is for the version of this paper posted online on 20 June 2008. A slightly revised version, [GMv2 ↗], was posted on arXiv 23 September 2008. This document primarily cites the first version of the paper for the following reasons: substantial parts of this document were already written based on the first version, the changes between the two versions appear to be relatively minor (mostly typographical corrections), and the first version was presented by CERN as sufficient grounds to justify the commencement of high-energy collisions at the LHC [CERN08a ↗]. Nevertheless, for a number of points the second version has been checked for any significant changes, and in cases where citing the updated version better reflects the intent of the authors, this has been done.

[3] Following the abbreviated style used for the "GM" paper, this report and the other key safety documents published by CERN are cited simply as "LSAG", "SPC", and "LSSG", after the names of the committees responsible for them.

- References cited by the Giddings/Mangano Paper and the LSAG Report [GM pp. 88–96] [LSAG pp. 14–15]
- Other relevant scientific articles published in the mainstream physics literature
- Public statements by the authors of the above documents

The focus of this paper is on whether a bound can be shown for potentially catastrophic effects resulting from black hole production at the LHC. It does not look for a proof of complete safety, in the belief that a strict proof may not be possible, and that an acceptable bound on the risks must be shown before a proof of safety could be considered.

The paper focuses primarily on the risk of one or more black holes destroying the Earth, the Moon, or the Sun, and the risk that the energy generated by accreting black holes could disturb the internal heat balance of the Earth or increase the radiation from the Sun.

This paper does not assess the other possible risks which may be associated with LHC collisions, such as the production of magnetic monopoles or metastable strangelets, or the initiation of a vacuum transition. Nor does it consider the risks related to the production of either gravitational black holes or the strong force equivalent of such objects in heavy ion collisions (cf. [Nas05 ↗] [Nas06 ↗] [Nas07 ↗] [Gub07 ↗]).

Furthermore, in line with the GM paper, the calculations and analysis of this paper do not consider the risks associated with the increased luminosity planned for the "Super Large Hadron Collider" (SLHC) or the increased energies planned for the "Very Large Hadron Collider" (VLHC).

The contents of this paper are organized as follows:

After this introduction is a section describing some of the general issues related to the data, assumptions and presentation of the Giddings/Mangano paper [GM ↗].

The third section covers some of the key issues related to the flux of ultrahigh-energy cosmic rays that is used as the primary basis for astrophysical arguments about the safety of high-energy collisions.

The fourth section reviews the question of whether it is possible for high energy collisions to produce black holes, and if so, what are the factors which could affect the number produced, and how many would be expected at the LHC or in cosmic ray collisions.

The fifth section examines whether Hawking radiation or other forms of black hole radiation exist, and if so, how quickly black holes would radiate, and what their final state would be.

The sixth section reviews the arguments given to support the claim that stable black holes would preserve any initial or acquired charge.

The seventh section summarizes and comments on the findings of the GM paper on the production of black holes by cosmic ray collisions with various astronomical objects (including the Earth, the Moon, the Sun, white dwarfs, and neutron stars) and the subsequent trapping of such black holes within those objects. The paper's analysis of the trapping of LHC-produced black holes within the Earth, the Moon and the Sun is also reviewed.

The eighth section critiques the GM paper's accretion models for black holes in the Earth, the Moon, the Sun, white dwarfs, and neutron stars.

The ninth section presents a baseline assessment of the possible risks associated with black hole production at the LHC based largely on the GM paper's accretion models, but indepenent of its proposed astrophysical safety arguments.

The tenth section examines the astrophysical arguments offered as proof of the safety or non-existence of TeV-scale black holes.

The eleventh section reassesses the concluding statements of the GM paper.

The conclusions of this paper are presented in the final section.

There are a couple important caveats about this paper:

The first is that the present version is only a partial draft and is still far from complete. In particular, sections 7, 8, and 10 focus primarily on the case of neutral stable black holes, and the remaining scenarios have been treated very briefly (if at all). Section 9 and several subsections in other parts of the paper are presently under revision and have not been included in this draft. Under normal circumstances, a few more months would be spent completing this paper and substantially revising it. There would likely be legitimate complaints, however, if the public was not informed of the issues identified in this present draft until after CERN had already conducted several months of high-energy collisions.

The second caveat is that the author of this draft, Alam Rahman, is not a physicist, so it focuses on very basic problems with the evidence and arguments presented thus far. If these points are valid, it is likely that there are many more advanced criticisms of the safety arguments which are well beyond his expertise. Despite its length, this paper should be considered a very limited critique of this issue.[4]

[4] Corrections or criticisms of this paper are welcome and can be posted anywhere online or sent to "feedback@LHCSafetyReview.org".

2 General Issues

This section reviews a number of the "cross-cutting" issues that relate to the GM paper as a whole or to several different parts of it. The issues considered here are:

- Quantification of risk
- Theory versus evidence
- Standards for evidence
- Limitations of the available data
- Confidence statements
- Statistical and systematic uncertainties
- Conservative assumptions
- Safety margins
- Solar time limit

These issues are described in further detail below:

Quantification of Risk - One of the major limitations of the GM paper and the other LSAG documents is the lack of any attempt to quantify the risks being assessed. The GM paper concludes that "...there is no risk of any significance whatsoever from such black holes." [GM p. 53, hyperlink added], but at no point does it calculate that risk, or define what the authors consider to be "of any significance". The most valuable input that professional physicists can give to a public review of catastrophic risks associated with LHC collisions is a transparent, quantitative assessment of those risks. This has not been done thus far.[5]

Theory vs Evidence - While the GM paper's arguments are presented as empirical proof that black holes are safe, their basic content is almost entirely theoretical. From the production cross-section of TeV-scale black holes, to the energy losses of charged black holes, to the stopping power of white dwarfs, to the accretion of black holes within the Earth and other astrophysical bodies, almost the entire argument is based on untested theory. The SPC's report to CERN's Governing Council describes the GM paper as "relying only on solid experimental facts and firmly established theory" [SPC p. 1], but the only experimental facts that the GM paper relies on are the following:

- The limits established thus far for extra dimensions [GM p. 11, citing Yao06 ↗ (large file)]

[5]This paper is also guilty of making only a very limited attempt to quantify the various risks. The reason for this is the belief that such assessments, which typically involve a certain degree of subjectivity, should first be attempted by experts in the field. However, if such estimates are not forthcoming in the foreseeable future, an amateur attempt at such calculations could be made.

- The parton distribution functions from lower-energy experiments [GM pp. 39–40, 70, 76, 78 citing Pum02 ↗]
- The stopping power of muons moving through matter [GM p. 9, citing Yao06 ↗ (large file), GMS01 ↗]
- The cross-section of 4-dimensional Rutherford scattering [GM p. 65]
- The approximate dipole force found when separating an ion in a crystal from the electron cloud of the bonding orbitals [GM p. 18]
- The Debye temperature for typical materials forming the Earth's interior [GM p. 18]
- The speed of sound in iron at densities of 12 gm/cm^3 [GM p. 24, citing [BM86 ↗], [Fiq01 ↗]]
- Experimental verification of special relativity at lower energies [LSAG reference 6][6, 7]

The paper also makes use of some basic astronomical facts, such as the radius and mass of the Earth and the Sun, and on observations of distant white dwarfs and neutron stars. The most important astronomical data that the paper depends on, however, are present-day observations of ultrahigh-energy cosmic rays, but there is still a great deal of uncertainty about how to interpret such data—an issue described in further detail in section 3.

Standards for Evidence - Neither the GM paper nor CERN set out a clear standard for the evidence used to justify the safety of LHC collisions. The GM paper, for example, cites "private communication" for a number of the "facts" it uses [GM pp. 36, 42, 66, 86, references 46, 47, 56, 86, 116], most of which are essential for its astrophysical argument. The lack of transparency and objectivity are of particular concern when most of these references are for private communications with two of Professor Giddings' colleagues at UC-Santa Barbara who were assisting him with the paper.[8]

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[6] The GM paper also briefly mentions analogue models of gravity [GM p. 7 ↗], which are, indeed, based on an extensive programme of experimentation. Such models can only be seen, however, as a possible source of ideas or inspiration for theorizing about gravitational black holes, and not as direct experimental evidence about their behaviour. Moreover, the GM paper does not rely on these models for its argument, and, in fact, ignores the lessons from these models about when standard predictions would be expected to fail. The review article on analogue gravity cited by the GM paper emphasizes the following point:

> When one thinks about emergent gravitational features in condensed matter systems, one immediately realises that these features only appear in the low-energy regime of the analogue systems. When the systems are probed at high energies (short length scales) the effective geometrical description of the analogue models break down, as one starts to be aware that the systems are actually composed of discrete pieces (atoms and molecules). This scenario is quite similar to what one expects to happen with our geometrical description of the Universe, when explored with microscopic detail at the Planck scale. [BLV05 p. 59 ↗, hyperlinks added]

[7] This is an attempt at a complete list of the "experimental facts" that the GM paper is built upon, but other experimental facts which are implicit in some of the derivations may have been missed, so suggested additions are welcomed.

[8] Affiliations are noted from [UCSBP:fac ↗] and [Bild09 ↗]. The assistance of Shen and Bildsten is acknowledged in the GM paper [GM p. 53 ↗] and the role of Professor Bildsten is described further in an online posting

This kind of free-wheeling standard is very different from the approach taken, for example, by the Intergovernment Panel on Climate Change (IPCC). While giving clear preference to peer-reviewed documents, the IPCC has adopted a formal procedure for using non-published/non-peer-reviewed sources in its reports [IPCC99 Annex 2, pp. 14–15]. Such sources must first be critically assessed by the author citing them, and then thoroughly vetted by an independent team for their quality and reliability. The sources must also be fully documented and made available to independent reviewers who request them. Finally, the reference to the source must state how the material can be accessed.[9] It does not appear as if any formal standards have been adopted for the evidence used in the GM paper.

Limitations of the Available Data - An essential element of any formal risk assessment is a review of what's known, what's unknown, and what needs to be known. The GM paper acknowledges significant current limitations in both theory (in the case of black hole radiation) and data (in the case of the cosmic ray flux). It does not propose, however, any short-term or medium-term plan of action to address these and other gaps before the start of the LHC. Instead it presents whatever information the authors have as "the best-available scientific knowledge" [GM abstract and p. 53], without addressing the question of why we should make do with whatever happens to be available instead of waiting until we have what is needed.

Confidence Statements - The GM paper contains quite a number of "confidence statements", which try to reassure readers that the scenario the authors favour is the most likely one. A few examples included:

> Most workers consider this to be an exceedingly improbable, if not impossible, scenario [GM p. 52].
>
> In the unlikely event that our understanding of the horizon misses some critical element forbidding black hole decay. . . [GM p. 9]
>
> Moreover, decay of observed neutron stars would also have been catalyzed, unless both of two unlikely possibilities are realized. . . [GM p. 53]
>
> Thus, while not all scenarios are definitively eliminated by such a bound, it appears likely that these bounds will be strengthened with future data on composition [GM p. 47].
>
> These bounds appear quite challenging to avoid [GM p. 50].

Generally, these statements do not add any new scientific evidence, but simply convey the authors' confidence in their beliefs. To make such statements more useful and concrete, the authors could

[rite08 ↗].

[9] For only one of the 5 examples cited above does the GM paper give information on how the relevant information can be accessed. In that case [GM p. 36, reference 46 ↗], the reference gives a website with the Fortran 95 codes used for calculating the density profile of white dwarfs.

consider attaching numerical probabilities to such comments (for example, saying something like, "we estimate a 5-10% chance that both of these two unlikely possibilities are realized"). Such probabilities would still be subjective, but they could be cross-checked with the available scientific literature and with other experts in the field. These numbers would also be very helpful for trying to calculate the total risk based on the probability of each step.[10]

Statistical and Systematic Uncertainties - It is quite surprising to see a physics paper in which almost all the data has been stripped of any statistical uncertainty or systematic uncertainty. In only three cases does the GM paper present any such uncertainty. In the case of white dwarfs it notes a systematic uncertainty of the order of 10% in the theoretical calculations of integrated column densities [GM p. 36, citing private communication]. For the case of parton distribution functions applied to high energy collisions, it claims that most of the black hole production occurs within a range of momentum fractions which are accurate to better than 10% [GM p. 76, citing Pum02 ↗], although it does not incorporate the effects of this uncertainty into its production estimates. In the case of cosmic ray data from the Pierre Augur Observatory (PAO) it acknowledges a ± 20% resolution in its energy measurements [GM p. 40, 74, citing Yam07 ↗, Rid07 ↗]. The authors present as "a further robustness check" a table in which the true energies are assumed to be 16.7% less than the reported experimental values [GM p. 74, table 6], whereas such considerations should be an integral part of any risk analysis. Their data shows that even this modest correction would lead to a 40% to 55% reduction in all of their estimates based on cosmic ray data.[11]

Conservative Assumptions - The GM paper claims that its analysis is "conservative". Indeed, the paper uses the term over 40 times to describe its assumptions and calculations, so a reader may naturally get the impression that the paper is conservative. Whether this is actually the case is not as clear. In some cases the conservative assumptions are made to facilitate a calculation, but the ultimate effect is insignificant. For example, when estimating the subnuclear accretion rate in neutron stars, the authors stress that they are making conservative assumptions by underestimating the rate of accretion, but even with those assumptions they find that the timescales

[10] If the authors prefer not to give such numerical estimates, they could at least indicate whether their paper is using words in their ordinary or high-pressure form. Birch explains the conversion in his paper on the Earth's interior [Birch52 p. 234, footnote * ↗]:

> *Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth; a few examples of equivalents follow:

High-pressure form:	*Ordinary meaning*:
certain	dubious
undoubtedly	perhaps
positive proof	vague suggestion
unanswerable argument	trivial objection
pure iron	uncertain mixture of all the elements

[11] Calculations are based on tables 4, 5, and 6 of the GM paper [GM pp. 73, 74, tables 4, 5, 6 ↗]. (Due to technical limitations, direct links do not seem to work from footnotes in this paper to specific pages, tables or figures in external pdf documents.)

would range from "a fraction of a second to at most few weeks" [GM p. 49]. Thus, even if their estimate was not conservative and their calculated rate for this phase was quicker, it would have no significant effect on the whole argument (for the dimensions they consider). In other cases, such as the composition of cosmic rays, when a conservative assumption would have a significant effect on their argument, they argue strenuously against adopting such an assumption [GM pp. 46–47], and eventually try to repackage as a "safety factor" the "unlikely possibility" that the conservative assumption is valid [GM p. 53]. To more objectively determine how conservative the paper is one can compare the upper bound of estimates with the corresponding lower bound. Unfortunately, the paper does not provide such information. Although it claims to "...establish upper and lower limits to the rate at which accretion can take place..." [GM p. 4], what it does instead is calculate a theoretical upper limit for the rate of accretion within the Earth, but no lower limit, and a lower limit for the accretion in dense stars, but no upper limit. Thus, the degree to which their calculations are actually conservative remains unclear.

Safety Margins - Perhaps even more important than conservative assumptions for specific calculations is the adoption of acceptable safety margins for what the GM paper tries to show. There are a few different areas for which safety margins are needed. The most critical one would be the minimum mass of a black hole which CERN claims is safe. Thus, even though the centre-of-mass energies of the LHC are limited to 14 TeV, a reasonable expectation is that CERN shows that even higher mass black holes are safe. This safety margin is a standard way of acknowledging uncertainties in theory and data and making sure that there is plenty of room if something goes wrong. Given the scope of what is at stake, most people would expect the collision energies to be kept far below whatever safety limit can be shown, perhaps at least 1,000 times less than the theoretical maximum. In the GM paper, no such margin has been adopted. By the authors own data, the heaviest neutral stable black hole that could be stopped by the heaviest white dwarfs they consider is one with a mass of 30 TeV if there are 5 dimensions, 20 TeV if there are 6 dimensions, and 16 TeV if there are 7 dimensions. These correspond to safety factors of 2.14, 1.43, and 1.14 for the respective dimensions. Some of the other important safety margins, such as the minimum mass of a white dwarf and the possibility of multiple black holes are discussed later in this paper. Another key safety margin, the expected lifespan of the Earth, is discussed below.

Solar Time Limit - While some people may feel that black hole production is fine, as long as nothing happens until long after they're dead, CERN does recognize that no matter how great the potential contribution of the LHC to our understanding of physics, it cannot justify the premature destruction of the planet. The analysis of the GM paper is consequently based on the requirement that nothing untoward happens to the Earth before it is consumed by the Sun. It does not, however, choose to incorporate an explicit safety margin for this criterion. A natural expectation would be a target of, say, a hundred times longer than the anticipated time limit, but the authors consider only their exact estimate of the Earth's future lifespan. They assume a five billion[12] year range [GM p. 52], which is just below their estimate of 6.4 billion years for the

[12] In this paper, 1 billion means 1,000,000,000, and 1 trillion means 1,000,000,000,000.

destruction of the Earth through a 3 TeV mass black hole in a 7-dimensional scenario [GM p. 26]. On the other hand, an article published the month before the GM paper gives an estimated time of 7.59 ± 0.05 gigayears (Gyr) before the Earth is engulfed by the Sun [SS08 arXiv p. 7]. Even this prediction is not a certainty, as the authors of that paper note that if three of their parameters were at one edge of their uncertainty range, the Earth would not be engulfed at all [12 arXiv p. 7].[13] Moreover, they report that even by their standard calculations, an increase of only 8% in the Earth's angular momentum would prevent such a fate [SS08 arXiv p. 8]. Despite CERN's claim that nothing can be done to protect future life on Earth [CERN07 ↗],[14] there is already a published proposal for how the Earth could be moved to safety [KLA01 arXiv ↗], although not without its own attendant risks [KLA01 arXiv p. 20]. Such efforts would be in vain, however, if there is a black hole accreting the planet.

[13]▷ ADD NOTE on metallicity for solar time estimates

[14]The specific statement on CERN's website is, "The size of their potential macroscopic effects is defined by the rate at which they can accrete matter. If they accrete very slowly, then they have no time to absorb significant parts of the Earth during the 5 billion years that we have left before the Sun explodes anyway, and life on Earth will be impossible (and this is not something we can do anything about!)." [CERN07 ↗] (One of the ironies of this issue is that while CERN characterizes its critics as prophets of doom, its own safety argument relies on the conviction that the Earth itself is doomed.)

3 Cosmic Rays

This section reviews some of the issues related to cosmic rays which affect a number of the astrophysical arguments presented in the GM paper. The issues considered are the following:

- Proton-dominated flux
- Implications of a 10% proton flux
- Counting of iron cosmic rays
- Exclusion of ultraheavy nuclei
- Other possible components of the flux
- Variations in the flux over time
- Spatial variations in the flux
- Direct measurements of cosmic rays

These issues are described in further detail below:

Proton-Dominated Flux - The composition of the cosmic ray flux is a major source of uncertainty. Astrophysicists still do not know whether it is dominated by protons or by heavier elements such as iron, or whether it has some other mixed composition. Given this uncertainty, the GM paper considers in most cases the possibility of a 100% proton flux and a 100% iron flux, however, in at least one crucial case, it presents only the data for a 100% proton flux [GM p. 46, table 3]. The authors argue that there is "mounting experimental evidence" that cosmic ray primaries are dominantly protons and not heavy nuclei [GM p. 5], but the actual situation is just the opposite. The LSAG report, but not the GM paper, cites a journal article published in January 2008 by the Spokesperson Emeritus of the Pierre Augur Observatory in which he clearly states that,

> From measurements of the variation of the depth of shower maximum with energy, there are indications-if models of high-energy interactions are correct-that the mass composition is not proton dominated at the highest energies. [Wat08b abstract]

The trend towards a heavy nuclei dominance is clearly visible in figure 1 [Wat08b p. 222, figure 1] of that paper. Whatever the final result may be is still anyone's guess, but it is misleading to suggest that proton dominance is a foregone conclusion.

Implications of a 10% Proton Flux - As a compromise solution to the uncertainty in the composition of the cosmic ray flux, the GM paper suggests that one can assume a 10% flux of protons as a conservative benchmark [GM pp. 46–47, 73–74, 87]. This sounds quite reasonable since hydrogen is the most common element in the universe, so one might expect it to represent at least 10% of the cosmic rays. What may not be clear to readers, however, is that the authors are suggesting that protons account for 10% of the cosmic rays at any given level of total cosmic ray energy. Thus, even at the highest energies, there would be cosmic rays consisting of a single proton which have as much energy as the combined total of all 56 protons and neutrons of the most energetic iron nuclei cosmic rays. This still might be possible, depending on what the actual source of such cosmic rays are and how they are accelerated, but this is a fundamental question in astrophysics that remains unresolved. Likely scenarios would have cosmic rays accelerated in proportion to their charge, which would typically result in protons with $1/26^{th}$ of the total energy of the corresponding iron nuclei. It is instructive to consider what the GM paper's 10% proposal implies for the composition of cosmic rays at a given energy level per nucleon (i.e. the total energy of a cosmic ray divided by the number of protons or neutrons it contains). The paper's data suggests that the 10% proposal results in a 30-fold increase in the rate of black hole production [GM p. 87]. This implies, given the paper's counting of cosmic rays (see the point below), that for every iron cosmic ray of a certain energy per nucleon, there would be over 1600 hundred proton-only cosmic rays with the same energy per nucleon. Through this lens, the authors' 10% suggestion can be seen as proposing a 99.9% proton composition.[15, 16]

Counting of Iron Cosmic Rays - The LSAG report and the GM paper have chosen to count each and every nucleon in an iron nucleus as the equivalent of an independent proton cosmic ray with the same initial energy per nucleon. More specifically, their calculations are based on multiplying the flux of a given element by its atomic number [GM p. 72, eq. E.6] [LSAG reference 6]. While it is true that a number of the nucleons can be expected to undergo their own high-energy collisions, it is a rather optimistic maximum to assume that this will occur, without any energy

[15] This potential confusion is underlined by Professor Ellis' "The LHC is safe" presentation. In addressing the question of the composition of ultrahigh-energy cosmic rays he states:

> . . . and in fact, uh, uh, even if you made iron, uh, at the source of the cosmic rays, in their propagation through the universe they would make collisions and they would produce protons, and so it's in fact difficult, impossible to believe that less than 10% of the ultrahigh-energy cosmic rays are not protons. So this justifies, I believe, the estimates, uh, that I gave on the previous slide. [Ellis08 18:18–18:45 ↗]

While Professor Ellis does not explicitly state what percentage of the original iron nucleons would be broken off into protons, the clear message is that one can assume at least 10% (but he does not go further and claim that the vast majority of these iron cosmic rays are expected to be broken down into protons). If his message to his colleagues at CERN and to the wider public was that one should accept the cosmic ray assumption requested in the GM paper since at least 10% (by number) of the final cosmic rays from an initial injection of iron cosmic rays would be single protons, then he is not correctly presenting the GM paper's request. If it were just the case of a 10% iron-to-proton spallation rate, then, using the cosmic ray power law adopted by LSAG [LSAG p. 4, endnote 6 ↗], this would result in protons being only about 0.003% of the cosmic rays at a given level of total cosmic ray energy—far less than the 10% requested. It is not clear if Professor Ellis genuinely misunderstood this issue, or has deliberately misrepresented it, but in either case, it calls into question CERN's capacity to accurately analyze and responsibly manage the risks associated with the LHC.

[16] It may further be noted that while the paper speaks of, "a significative proton fraction, of the order of at least 10%, and higher at super-GZK energies" [GM p. 74 ↗, hyperlink added], the direct measurements of the composition of cosmic rays (based on records from balloon experiments instead of just observations of air showers) shows that the estimated proton component has already dropped to 16 ± 5% for cosmic rays with energies of 500 TeV [Tak98 abstract ↗]. A cosmic ray proton requires an energy of about 100,000 TeV for its collision in the atmosphere to be comparable to an LHC collision.

loss, for every single proton and neutron of every single iron cosmic ray. CERN should provide a more realistic estimate of the actual number, which may vary with the energy of the nuclei and the kinematics of the collision.[17]

Exclusion of Ultraheavy Nuclei - While the GM paper describes the possibility of a 100% iron flux as a "totally extreme case" [GM p. 40], "the most pessimistic scenario" [GM p. 74], and the "most conservative" case [GM p. 87], it is ignoring the presence of ultraheavy nuclei in the cosmic ray flux. An earlier safety report prepared by CERN in response to concerns about Brookhaven's Relativistic Heavy Ion Collider (RHIC) depends entirely on nuclei much heavier than iron in the cosmic ray flux. That reports states that lead (with a mass about 3.7 times that of iron) is relatively abundant in cosmic rays [DDH99 arXiv p. 3]. It notes that the ratio of lead-like nuclei to iron nuclei has been measured to be 0.003% at lower energies. The report further argues that it would be safe to adopt this value for the higher energy of RHIC collisions since the relative abundance of the heavier elements increases with energy as they are more efficiently accelerated and confined [DDH99 arXiv p. 5]. Similar estimates are also made in the safety report from Brookhaven itself [JBSW00 arXiv 8, footnote 2]. This may seem like a minor issue (since the iron cosmic rays would still far outnumber those of heavier elements), but in some cases the GM paper's argument involves black hole production by cosmic rays of the very highest energies [GM p. 75, table 7, figure 6]. The use of this portion of the ultrahigh-energy cosmic ray flux leads to the question of whether those cosmic rays are actually iron nuclei or ultraheavy nuclei. If ultraheavy elements are injected into the cosmic ray flux in the same way as iron, then a natural expectation is that at about 30% of the absolute maximum cosmic ray energies, the presence of iron nuclei would peter out, and the remaining cosmic rays would be heavier nuclei with the same energy per proton as the most energetic iron cosmic rays, but with a higher total energy due to their greater mass. Since their energy per nucleon would be less than that assumed by the GM paper for its 100% iron case, they would be much less effective at producing heavier black holes (judging from figure 6 of the GM paper [GM p. 75, figure 6]), and the estimated cosmic ray black hole production rates would have to be further reduced from the paper's "most conservative" case.

Other Possible Components of the Flux - Aside from the possibility of a flux of ultrahigh-energy neutrinos, the GM paper assumes that the ultrahigh-energy cosmic ray flux is composed entirely of nucleons. It should be noted, however, that physicists have proposed a number of other possible components of the flux. These possibilities include: strangelets, nuclearites (much larger lumps of strange quark matter) [GP05 pp. 7–9], magnetic monopoles [▷ ADDCITE], Q-balls

[17] A closely related issue which CERN may wish to clarify for both proton and iron cosmic rays is whether the GM paper's estimates have taken into account energy losses from interactions prior to a nucleon's first inelastic collision. The following observation should be noted for cosmic rays striking the Earth's atmosphere:

> In order to probe short distance physics at distances r, it is necessary to have a momentum transfer $\sim r^{-1}$; but the vast majority of nucleon-nucleon interactions only involve ~GeV momentum transfers. In fact, cosmic rays lose energy in the atmosphere not through diffractive QCD scattering but by creating electromagnetic showers, where the effective momentum transfer per interaction is still smaller. [▷ arXiv 9807344 p. 18 ↗]

[GP05 p. 8], dark matter, and high-energy photons[18]. A more careful safety argument based on the cosmic ray flux would need to consider these possible components and what effects they would have on the estimated rate of black hole production.

Variations in the Flux Over Time - Both the LSAG report and the GM paper have assumed that the ultrahigh-energy cosmic ray flux measured over the last 20-30 years represents the average level for the 4.5 billion years of the Earth's existence. On the other hand, a paper published by CERN just three months before the LSAG report states that "...there *is* clear evidence for long-term variability of cosmic rays" [Kirk08CERN p. 2, italics in the orginal text]. The focus of that paper was on galactic cosmic rays, but one might reasonably expect the variability of cosmic rays to increase with their energy. The potential variability is even greater when one considers proposals that ultrahigh-energy cosmic rays may come from a very limited number of sources. For example, an article cited by the GM paper notes:

> It is not impossible that all cosmic rays are produced by the active galaxy M87, or by a nearby gamma ray burst which exploded a few hundred years ago. [HH02 arXiv p. 11, hyperlinks added]

A more recent paper, posted on arXiv two months before the LSAG report and co-authored by one of the LSAG members, suggests that the nearby radio galaxy Centaurus A could be a dominant source of ultrahigh-energy cosmic rays [GTTT08 pp. 6–8]. If this is the case, then it would be essential to know how long Centaurus A has been in its current active state. Without that information, one cannot have much confidence in CERN's estimates of historic black hole production rates.

Spatial Variations in the Flux - In addition to the variation of ultrahigh-energy cosmic rays over time, there is also the possibility of their variation over space. To the extent that the distribution of ultrahigh-energy cosmic rays is not homogeneous, any estimate of the black hole production rate from cosmic ray collisions would need to include an appropriate allowance for such variability.

Direct Measurements of Ultrahigh-Energy Cosmic Rays - Given CERN's reliance on astrophysical safety arguments based on ultrahigh-energy cosmic rays, it is rather disconcerting that thus far there have been no direct measurements of any cosmic rays with energies comparable to LHC collisions. As noted in the earlier CERN safety report for Brookhaven's Relativistic Heavy Ion Collider, the composition of cosmic rays has only been measured directly up to ~ 100 TeV [DDH99 arXiv p. 3]. Other papers report direct measurements up to 1000 TeV [e.g. Tak98 abstract ↗], but cosmic rays must have an energy of about 100,000 TeV for single protons, and about 5,600,000 TeV for iron nuclei, if the energy of their collisions are to match that of the LHC. When the LSAG report speaks of high energy "cosmic rays collisions that are observed regularly on Earth" [LSAG p. 2], it is not referring to the distinctive tracks that lower energy cosmic rays have left in bubble chambers or on emulsion plates. What it and the GM paper are referring

[18] For 95% confidence bounds on the photon component of ultrahigh-energy cosmic rays, see [▷ arXiv 0606619 ↗] [▷ arXiv 0712.1147 ↗] [▷ ADDCITE Astroparticle Physics 31 (2009) 399-406]

to are "extensive air showers" caused by incoming cosmic rays colliding with particles in the Earth's upper atmosphere. These collisions result in many flashes of light, which are recorded by instruments on the ground, and a shower of energetic muons, which can be detected in specially designed arrays of water tanks. Astrophysicists analyze where the shower began, what direction it travelled, how deeply it penetrated into the atmosphere, what total energy it released, etc., and then try to guess what the cosmic ray was. Typically they are assumed to be either protons or other heavier elements, but for collisions at energies equal to or exceeding the LHC, these guesses are based on untested models of particle interactions. If the interactions are found to be different from what is presently expected, it would be a fascinating discovery by the astrophysics community [HH02 arXiv p. 6], but it might nullify most of the safety arguments presented in the GM paper. Moreover, as noted earlier, ultrahigh-energy cosmic rays could well be caused by different objects entirely.

To a large extent, the current uncertainties about ultrahigh-energy cosmic rays are the result of CERN's poor planning and misplaced priorities. Article II, paragraph 2 of the "Convention for the Establishment of a European Organization for Nuclear Research" which created CERN called for the organization to be involved in and sponsor international co-operation in the field of cosmic rays [CERN:Conv Article II]. Instead CERN has chosen to focus almost all its efforts on building larger and larger particle colliders. Now, when critical details about cosmic rays are needed to assess the safety of CERN's latest collider, that essential information is missing. Over the next few years, with much more data from PAO, OWL/Airwatch, JEM-EUSO, AMS-02, and other detectors, we can hope to better understand the cosmic ray physics of our universe, but until then we simply do not know enough to say that cosmic ray collisions prove that the LHC programme will be safe.

4 Black Hole Production in High Energy Collisions

This section reviews whether it is possible for the LHC or ultrahigh-energy cosmic rays to produce black holes, and if so, how many might be produced.

4.1 Scenarios for Black Hole Production

The possibility of the LHC producing black holes depends on the behaviour of gravity at the microscopic level. The force of gravity has been tested on scales ranging from the cosmological down to that of our everyday experience, but below approximately 37 microns, the inverse square law that is believed to govern the force of gravity remains untested.[19]

In the past, physicists have simply assumed that gravity continued to obey the inverse square law all the way down to the Planck scale (10^{-35}m), but this involved extrapolating across 30 orders of magnitude without any data or evidence. In 1998, a revolutionary proposal by Arkani-Hamed, Dimopoulos and Dvali [ADD98 ↗] [see also AADD98 ↗] suggested that gravity could become much stronger much sooner than physicists had previously expected. They presented a coherent proposal in which the hierarchy problem (the enormous difference in scale between the force of gravity and other fundamental forces) was solved through the assumption that the 3+1 dimensional world we see and feel is embedded in a higher-dimensional universe throughout which gravity, but not the other forces, can have an effect. The spread of gravity over a larger volume dilutes its effect, but when one approaches the distance scale of the extra dimensions (which are small compared to our everyday life, but very large compared to the original Planck scale) the force of gravity becomes much stronger.

The following year, Randall and Sundrum [RS99 ↗], published an alternative proposal in which the extra dimensions are not necessarily "flat", as in the initial model, but could be "warped", with an increased force of gravity within the warped extra-dimensional volume. An important consequence of this proposal was that having just 1 extra dimension could be possible, whereas in the earlier model at least 2 extra dimensions were needed for the results to be consistent with observations.

The GM paper focuses on these two scenarios, the "unwarped" extra-dimensions proposed by Arkani-Hamed, Dimopoulos and Dvali, and the "warped" extra-dimensions of Randall and Sundrum. This review will similarly be focused on those two scenarios, although it should be noted that there are numerous theories of gravity published in the mainstream scientific literature.[20] A proper assessment should systematically review all of them to determine their potential safety implications for the LHC.

[19] More specifically, 95% confidence is reported for the inverse square law down to 37 microns in the case of 2 extra dimensions, and 44 microns in the case of 1 extra dimension [Ams08 pp. 1274–1275 ↗ (large file)]

[20] For example, over 50 abstracts were submitted to the session on "Alternative Theories of Gravity" at the most recent GRG conference [Esp08 abstract]

If it is the case that our world is embedded in a warped or unwarped higher-dimensional space, then the question of whether black holes can be produced at the LHC largely depends on the sizes of the extra dimensions and the corresponding energy level. A major part of the original motivation for both theories was as a way to solve the hierarchy problem, and thus one would expect gravity to become much stronger at the TeV energies that the LHC is designed to explore. On the other hand, neither model sets an upper limit on the energy required before stronger gravity is felt, so it is possible that higher-dimensional gravity could exists, but its effects still not seen at the LHC.

From a risk assessment point of view, one of the most basic questions is, what is the chance that gravity will be strong enough for black holes to be produced at that LHC? There will necessarily be a large degree of subjectivity in trying to make any such estimate—the very fact that it is a question which physicists hope to answer at the LHC illustrates the uncertainty of this issue. Nevertheless, some attempt at quantifying the issue beforehand is useful so that the scale of any possible risk can be considered and discussed.

One attempt to do so was undertaken by Professor Giddings a few years ago. He polled about 10 of his fellow physics theorists to see what odds they would assign to various possibilities for physics at the LHC. The response he received was a 0-25% range of odds for gravity becoming strong at the TeV scale [Gid01 p. 8]. The poll was intended as an amusing exercise but unfortunately there does not appear to have been any more systematic attempt to answer this question since then.[21] The question has not been addressed in documents from CERN, beyond the excitement expressed by its scientists about the possibility of this happening [▷ ADDCITE]. Until a carefully derived estimate is provided by CERN, an interim estimate of 1% could be used for the purpose of discussions. In this paper, the working assumption is that there is perhaps a 1% chance that black holes could be produced at the LHC.

It should be noted that the option does exist for determining the behaviour of gravity at the TeV scale even without the LHC. In a paper published in *Physical Review Letters* in 2002, Professors Feng and Shapere described how the analysis of cosmic rays could reveal if gravity becomes stronger at the LHC's energy level [FS01 arXiv ↗] (see also [AFGS02 arXiv ↗] [FKRT03 arXiv ↗] [DRS03 arXiv ↗]).[22] The proposal was subsequently endorsed by Professor Frank Wilczek, a co-author of the report reviewing disaster scenarios for the Relativistic Heavy Ion Collider (RHIC) [JBSW00 arXiv ↗] and, from 2002 until 2007, a member of CERN's Scientific Policy Committee [CERN08c ↗ (old link)]. He notes that:

> Feng and Shapere have demonstrated, I think quite convincingly, how study of high-energy cosmic ray showers can be an effective way of disproving—or, heaven help us, establishing—the hypothesis [Mink02 ↗].

[21] If anyone is aware of any such attempt, kindly convey the results to LHCSafetyReview.org, or post them online.

[22] It should be noted, however, that these proposals usually involve the production of black holes by ultrahigh-energy neutrinos, and, as noted later in this paper, such neutrinos have not yet been observed.

4.2 Black Hole Production Rates

If it is possible to produce black holes at the LHC or in cosmic ray collisions, the next question is how many would be produced.

The first attempts to calculate production rates for the LHC were made in two papers prepared by independent teams of researchers and published in June 2001. Both reached the conclusion that it might be possible for the LHC to produce black holes at a rate of about one every second [GT02 arXiv p. 12] [DL01 arXiv abstract].

The exact rates would depend on the specific level of TeV-scale gravity, the number of extra dimensions, and the mass of the black holes being produced. The paper on "High energy colliders as black hole factories" by Professors Giddings and Thomas hypothesized that if the fundamental scale of gravity was 1 TeV, and the total number of dimensions was 10, then the cross-section for the production of black holes more massive than 5 TeV would be 240,000 femtobarns (fb) [GT02 arXiv pp. 12, 13, table 1]. With an anticipated integrated luminosity for the LHC of 1000 fb^{-1}, this would result in the production of about 240,000,000 black holes with masses greater than 5 TeV.

The paper on "Black holes at the LHC" by Professors Dimopoulos and Landsberg estimated that the total production cross-section at the LHC for black holes with masses above the higher-dimensional Planck mass (M_D)[23] ranges from 500,000 fb for $M_D = 2$ TeV in 11 dimensions, and 120 fb for $M_D = 6$ TeV in 7 dimensions [DL01 arXiv p. 1]. These rates would correspond to a total production of 500,000,000 black holes over the lifetime of the LHC for the first case, and 120,000 black holes for the second. The authors note that there is only a weak dependence of the production cross-section on the number of extra dimensions [DL01 arXiv p. 2, figure 1].

In a subsequent paper, Professor Landsberg estimates that if $M_D = 1$ TeV, then the cross-section for the production of black holes with masses greater than 1 TeV would be 15,000,000 fb [Land06 arXiv p. 12], implying a total production at the LHC of 15,000,000,000. He notes that this estimate varies by ~ 10% if the total number of dimensions varies between 6 and 11 [Land06 arXiv p. 12].

The GM paper presents its estimates for black hole production at the LHC as the graph of figure 4 in Appendix E [GM p. 71, figure 4]. The estimates range from ~ 100,000,000 black holes with masses greater than 4 TeV if $M_D = 1.33$ TeV and black hole-producing collisions are perfectly inelastic, down to only 1 black hole with a mass greater than 6 TeV if $M_D = 2$ TeV and only half of the energy of collisions can be converted into the mass of newly formed black holes. These estimates and their presentation are examined in more detail in section 7.1.11.

For the production of black holes by cosmic rays, the GM paper estimates that if the cosmic ray flux is composed entirely of protons, then a white dwarf with a radius of 5400 km would have 21,000,000 black holes with masses greater than 7 TeV produced on its surface every million years if $M_D = 2.33$ TeV and there is only 1 extra dimension [GM p. 40, table 2]. For a cosmic ray flux composed entirely of iron nuclei, the corresponding estimate is 72,000 black holes every

[23] The two papers use slightly different conventions to normalize M_D. A conversion between the two conventions is given in Appendix A of the Giddings and Thomas paper [GT02 arXiv pp. 26–27 ↗]

million years. For both these estimates, the GM paper assumes that half of the energy of cosmic ray collisions (or, more precisely, half the energy of the partons involved in the collisions) can be used to form black holes. A few of the factors which can affect the number of black holes produced by cosmic rays are reviewed below in section 4.2.6. The specific estimates for white dwarfs are considered again more carefully in section 7.1.4.

For the production of black holes by cosmic rays impinging on neutron stars, the GM paper gives estimates ranging from 110,000 down to only 8 every million years, depending on the minimum mass of the black holes and the number of extra dimensions [GM p. 46, tables 3, 9]. The meaning of these neutron star estimates is examined more critically in section 7.1.7.

While the above estimates give a general idea of the possible black hole production rates at the LHC and in cosmic ray collisions, there are a number of factors which could significantly increase or decrease these rates, and those factors are discussed further below in sections 4.2.3, 4.2.4, and 4.2.5. The two immediately following sections address the fundamental questions of what the minimum mass of a black hole can be for a given value of M_D, and how much of a collision's energy can be converted into the mass of a black hole.

4.2.1 Minimum Mass of Black Holes

The black hole production estimates of the GM paper are based on the assumption that the mass of any black hole must be at least three times the value of the higher-dimensional Planck mass [GM p. 70]. The GM paper justifies this assumption by noting that several criteria for the minimum mass of a black hole were discussed in the earlier paper by Giddings and Thomas [GT02 arXiv ↗], and that one particularly useful criterion is that the entropy of the black hole be large, so that a thermal approximation begins to make sense [GM p. 70]. The paper then provides a formula for the entropy of a non-rotating black hole and notes that if a black hole has a mass of 5 M_D, then for the representative cases of $D = 6$ and $D = 10$, its entropy reaches a plausible threshold for assuming semiclassical behaviour. The paper further argues that for a given mass of a black hole, the production rate decreases with increasing values of M_D, so to be conservative in estimating the cosmic ray production rates it allows the value of M_D to be as high as a third of the black hole's mass [GM p. 70]. The same criterion that $M \geq 3M_D$ is also applied for calculating the production rates at the LHC [GM pp. 71, 83 figures 4, 12], an issue discussed further in section 7.1.11.

What the GM paper does not attempt to explain, however, is why semiclassical behaviour is relevant when counting the number of black holes that are created. If one assumes that Hawking radiation exists, this criterion could be very important for detecting the presence of black holes produced at a collider and learning more about fundamental physics from the particles such black holes may emit. However, the primary focus of the GM paper is on the cases of stable black holes which do not exhibit Hawking radiation, or any other form of direct radiation. Thus, in those cases, the requirement of semiclassical behaviour is entirely irrelevant.

Moreover, even if black hole radiation exists, the behaviour of a black hole is a separate issue from whether it is actually produced. For example, the article "Black Holes from Cosmic Rays", which is cited by the GM paper [GM p. 78, reference 94], suggests that at a collider, a cut-off of $5M_D$ or higher may be necessary to distinguish between black hole events and other particle production [AFGS02 arXiv p. 8]. On the other hand, for black holes created by cosmic rays striking the Earth's atmosphere, the article assumes that the background compared to colliders would be almost nonexistent, and calculates production rates based simply on the requirement that the mass of black holes be at least M_D. From this it should be clear that the $5M_D$ or $3M_D$ restriction in the case of colliders is solely for the purpose of detecting and studying black holes, and not for determining the total number that would be created.

Estimates of the number of black holes with masses as low as M_D have, in fact, been given in one of the very first papers on black hole production at the LHC and should be considered common knowledge within the high-energy physics community. The initial paper by Dimopoulos and Landsberg contains a hard-to-miss graph with estimates of the number of black holes with masses between 1 and 1.5 TeV if M_D = 1 TeV, between 3 and 3.5 TeV if M_D = 3 TeV, and so on [DL01 arXiv p. 3, figure 2]. The very first citation of this paper was by Professors Giddings and Thomas [GT02 arXiv p. 29, reference 33]; this paper was also cited again more recently by the GM paper [GM p. 89, reference 6]; and in between it was cited by over 500 physics papers [SPIRES:DL01 ↗]. Given this level of exposure, one might reasonably expect that a good number of physicists would have criticized the higher minimum mass criterion adopted in the GM paper.

Thus far, it seems the only qualified physicist to publicly raise this issue is Dr. Rainer Plaga in his article on the catastrophic risks associated with black hole production at the LHC.[24] In the first version of his paper, posted on 10 August 2008, Plaga states the following:

> Thereby G & M introduce the assumption that mBHs in general have a minimal mass M_{min} that exceeds the new Planck scale by at least a factor 3. This constraint is motivated by the fact that the thermodynamical, semiclassical treatment of mBHs in their "scenario 1" is expected to be reliable within this mass range. This is certainly a most reasonable argument for all purposes of pure research, e.g. when predicting collider signatures etc.. However, it does not mean that mBHs below M_{min} cannot be produced. It rather means that we are presently unable to reliably predict the behaviour of such mBHs[8]. [Pla08v1 pp. 7, hyperlinks added]

On 29 August 2008 Giddings and Mangano posted on the arXiv e-print server a response to some of the points raised in Plaga's paper, but their response mentions nothing about the issue of a black hole's minimum mass [GMreply08 ↗].

On 26 September 2008 Plaga posted a revised version of his article which addressed the other comments of Giddings and Mangano and further stressed that the minimum mass issue discussed in section 5 of his paper had been ignored:

[24] If other public comments have been made by physicists on this specific issue, they will be duly acknowledged in future drafts of this paper.

> Finally G & M's comment did not address section 5 of the present manuscript in which I argue that their exclusion of dangerous mBHs is not completely definite for a general, simple reason, completely independent of the above arguments. [Pla08v2 p. 11]

Plaga did not appear to have received any further comment from CERN about this issue, so on 9 August 2009 he again reminded CERN that his criticism of the GM paper's minimum mass criterion has not be addressed [Pla08v3 p. 13].

In light of the arguments detailed above, and the absence of any response from CERN, this paper adopts the general assumption that the only restriction on the mass of a black hole is that it be no less than about M_D (while bearing in mind that there may be slightly different conventions for the definition of M_D). This results in a couple significant changes in the analysis of TeV-scale black hole production at the LHC or in cosmic ray collisions.

Firstly, the production of black holes with masses below 3 TeV needs to be considered. For the case of $M_D = 1$ TeV the GM paper only considers black holes with masses of at least 3 TeV, and in the case of $M_D = 2$ TeV it only considers black holes of at least 6 TeV. With the assumption adopted in this paper, black holes as light as 1 TeV must be considered if $M_D = 1$ TeV, and black holes of mass 2 Tev must similarly be considered if $M_D = 2$ TeV.

Secondly, the value of M_D is allowed to range up to 14 TeV. In the GM paper the maximum value considered for M_D is 4.67 TeV (i.e. one third of 14 TeV). The implications of this change are significant and are discussed further in section 7.1.4 on the trapping of black holes in white dwarfs and in sections 8.1.4 and 8.1.5 on the accretion of black holes within white dwarfs and neutron stars.

The GM paper notes that the production rates for black holes of a given mass decrease with increasing values of M_D [GM p. 70], but it may be more appropriate to simply index black hole production rates by values of M_D (i.e. estimate the total number of black holes produced for a given value of M_D). Using this approach the number of black holes associated with, say $M_D = 1$ TeV, would be much greater than that estimated in the GM paper, since its estimate was restricted to black holes with masses of at least 3 TeV. The same adjustment would apply for values of $M_D \leq 4.67$ TeV. Above that value, however, the GM paper includes no estimate for black hole production rates. Since the total black hole production rates for, say, $M_D = 12$ TeV should be less than the estimated production rates of black holes with masses ≥ 12 TeV if $M_D = 4$ TeV [cf. GM p. 70], the estimates of the GM paper for black holes of or above a given mass can be taken as an upper bound (if they are correct) for the total black hole production above the same value of M_D. However, the difference between this upper bound and the true numbers is expected to be quite large, so this can only be used as a very rough indicator.[25]

[25] The following examples may help clarify how the black hole production rates increase or decrease as a result of removing the $M_{min} = 3M_D$ restriction. For a value of $M_D = 1$ TeV the GM paper gives an estimate for black holes with masses ≥ 3 TeV, and for a value of $M_D = 3$ TeV its estimate is for black holes with masses ≥ 9 TeV. If we instead assume that $M_{min} = M_D$, then the black hole estimate for $M_D = 1$ TeV would be significantly higher

§ Subplanckian Black Holes

While the remainder of this paper adopts the assumption that $M_{min} = M_D$, it should be noted that it may be possible for black holes to be created with masses below M_D.

The first such scenario is more of a technicality based on the definition of M_D. In a recent review article on quantum black holes at the LHC, Professor Douglas Gingrich, a team leader in the ATLAS experiment [ATLAS-Can09 ↗], notes that using the more intuitive Dimopoulos-Landsberg definition of the Planck scale, the minimum mass for black holes is always above the fundamental Planck scale, but using the definition adopted by the Particle Data Group (PDG), the minimum mass is below M_D [Ging09 pp. 6–7]. (The GM paper states that it uses the conventions of the "Extra dimensions" minireview by LSAG member G.F. Giudice and J.D. Wells in the 2006 edition of the PDG's "Review of Particle Physics" [GM p. 11, footnote 7, citing Yao06 ↗ (large file)].) As a specific example, Gingrich states that accelerator experiments have set limits on M_D of $\gtrsim 1$ TeV and notes that, in theory, quantum black holes would be required to have a mass above only about 0.5 TeV [Ging09 p. 7].

A scenario in which truly subplanckian black holes could be produced was described in 2006 by Professor Landsberg, based on an earlier article by Dvali, Gabadadze, Kolanovic, and Nitti [DGKN02 arXiv ↗]. In his review article "Black holes at future colliders and beyond", he relates the following possibility:

> An interesting topic in black hole phenomenology, which has not been studied in much detail yet, is the possibility that a black hole, once produced, moves away into the bulk space. Normally it does not happen as the black holes produced in collisions at the LHC or in cosmic ray interactions are likely to have charge, colour, or lepton/baryon number hair that would keep them on the brane. However, a possibility of that kind is allowed in the case when the strength of gravity in the bulk and on the brane is very different. This is the case, e.g. in the scenario with large extra dimensions with an additional brane term [70], or in the case of infinite-volume extra dimensions [71].
>
> In these models, a particle produced in a subplanckian collision, e.g. a graviton, could move away in the bulk, where it becomes a black hole due to much lower effective Planck scale in extra dimensions. Since the Planck scale in the bulk is very low, e.g. ~ 0.01 eV in the infinite-volume scenario [71], the newly-formed black hole is very cold and therefore essentially stable. Furthermore, it generally does not move far away from the brane due to gravitational attraction to it, and can further accrete mass from relic energy density in the bulk and from other particles produced in the

(since it would now include black holes with masses between 1 and 3 TeV). The estimate for $M_D = 3$ TeV would also be higher (since it would include black holes with masses between 3 and 9 TeV), but it would be lower than the $M_{min} = 3$ TeV (i.e. $M_D = 1$ TeV) estimate in the GM paper (since the production rate would decrease if M_D is increased from 1 TeV to 3 TeV). For a value of $M_D = 9$ TeV, there is no corresponding estimate in the GM paper, but it would be less than the $M_{min} = 9$ TeV estimate (since the value of M_D would have increased from 3 TeV to 9 TeV).

subsequent collisions. Once the mass of the black hole reaches the mass of the order of the apparent Planck scale, $M_{Pl} \sim 10^{19}$ GeV, the event horizon of the bulk black hole grows so large that it touches the brane, and the black hole immediately evaporates on the brane into ~ 10 particles with the energy ~ 10^{18} GeV each. (The energy released in such an event is similar to that in an explosion of a large, few hundred pound conventional bomb!) If such black holes are copiously produced by a remote cosmic accelerator of a reasonable energy, they could act as a source of the highest energy cosmic rays that are emitted in the process of decay and deceleration of the super-energetic black hole remnants.

Even if the mass of the black hole in the bulk is small, it has certain probability to reenter our brane. In this case, since the event horizon cannot be destroyed, once it has been formed, such a subplanckian object would likely to act as a black hole on the brane and evaporate similarly to a transplanckian black hole discussed above.
[Land06 arXiv p. 27, hyperlinks added]
Reference [70]: DGKN01 arXiv ↗
Reference [71]: DGKN02 arXiv ↗

The safety implications of producing subplanckian black holes at the LHC or at other particle colliders have not yet been addressed.

4.2.2 Inelasticity of Collisions

One of the key uncertainties in estimating black hole production rates is guessing what portion of a collision's energy can go into the formation of a black hole. There is, of course, no experimental data on the inelasticity of black hole-producing collisions. One must rely instead on theoretical predictions, but even these are subject to considerable debate.

The GM paper cites a recent article by Professor Giddings which adopts the assumption that the inelasticity parameter, y, is of the order 0.6–0.7 [GM p. 69, citing Gid07 ↗]. In that article, Giddings notes that a significantly higher value for the inelasticity had been used in the initial black hole production estimates by Giddings and Thomas [Gid07 arXiv pp. 6–7, citing GT02 ↗], but that more recent estimates of the inelasticity would reduce the black hole production rates to 1 black hole every minute if $y = 0.7$, and 1 black hole every 10 minutes if $y = 0.6$ [Gid07 arXiv pp. 6], compared to the original estimates of 1 black hole every second [GT02 arXiv p. 12]. The GM paper states that the more recent estimate from Giddings is based on an article by Yoshino and Rychkov [GM p. 69, citing YR05 ↗], however, the relevant figure in that article only claims to present rigorous and non-rigorous lower bounds on the mass of black holes formed in collisions [YR05 p. 19, figure 10]. Moreover, the conclusion of that article further stresses that its estimates are only upper bounds on the amount of emitted gravitational radiation, and suggests that the real amount is likely to be smaller than the paper's estimates "by a factor of a few" [YR05 p. 23] (i.e. more energy would be available for the black hole's mass). To illustrate the potential size of the difference they cite the earlier work in 4 dimensions of D'Eath and Payne, which calculated an energy loss of 16% compared with a rigorous upper bound on the gravitational losses of 29% [YR05 p. 23, citing

D'EP92 ↗],[26] and suggest that it would be natural to expect comparable reductions in the radiation to occur in all dimensions [YR05 p. 23]. The article takes notes of another paper which predicts highly suppressed gravitational wave emissions in higher dimensions (up to 0.001% in $D = 10$), which they consider unlikely [YR05 p. 23, citing CDL03 arXiv ↗], and yet another approach which results in radiation losses of 8% in $D = 10$, which they consider closer to their own estimates [YR05 p. 23, citing CL02 arXiv ↗, BCG04 arXiv ↗]. The Yoshino/Rychkov article concludes its comparisons with the following observation:

> We point out that all these works have problems such as ignoring the nonlinearity of the system, or the setup is too far from the realistic one. Analysis without approximations remains an important open problem. [YR05 p. 23]

Aside from these problems with semiclassical calculations of the inelasticity, an important matter for the LHC is the inelasticity of collisions producing black holes with masses closer to the M_D minimum, when quantum gravitational effects can be much more important. The GM paper does not specifically address the question of the inelasticity of collisions producing black holes within this range [GM ↗]. The article by Meade and Randall cited by the GM paper stresses that it is not obvious how classical calculations should be modified for energies approaching the higher-dimensional Planck scale [MR07 10]. (See further comments below on the production rates of black holes in this range.)

Another factor which can affect the inelasticity coefficient is the angular momentum of the newly formed black hole, since rotating black holes are expected to lose more energy in gravitational waves than non-rotating black holes of equal mass [BCG04 arXiv p. 8]. Also, deviations from spherical symmetry can increase the energy losses, which Berti, Cavaglià, and Gualtieri note could be particularly relevant when the compactified space is asymmetric, and some of the extra dimensions have size of order of the fundamental gravitational scale. They stress that it would be extremely important to quantify these differences [BCG04 arXiv p. 8].

It should also be noted that the inelasticity coefficient depends on the impact parameter of a collision, and generally decreases as the impact parameter increases (cf. [MR07 p. 10 3] [YR05 p. 19, figure 10]). The GM paper simply assumes that the inelasticity is constant out to an impact parameter of half the Schwarzschild radius, and 0 beyond that point [GM p. 39]. Taking into account this factor would add to the variability in the inelasticity of collisions [cf. GT02 arXiv p. 9].

To address some of these issues, the GM paper adopts a range of $0.5 \leq y \leq 1$ for the inelasticity coefficient [GM pp. 39–40]. This seems like a reasonable range, although the paper only describes the value of $y = 0.5$ as a "lower than expected value", and one can see in the graphs of the Yoshino/Rychkov article their lower bounds for black hole masses have already dropped below 0.5 at impact parameters of 0.43 for $D = 10$ and 0.38 for $D = 11$ [YR05 p. 19, figure 10]; to account for other possible factors, it might have been prudent to consider even lower values for

[26] The article does include a footnote, however, which notes that the estimate by D'Eath and Payne did not take into account additional gravitational radiation from the centre of the system, which could not be evaluated by their method [YR05 p. 23, footnote 7 ↗, citing D'EP92 ↗].

the inelasticity. At the other end of the spectrum, the value of $y = 1$ is acknowledged in the GM paper to be "an unrealistic extreme" [GM p. 39], although the paper does note that the value of y is subject to quantum fluctuations, so in the absence of a confirmed upper bound on y, this would seem to be an appropriate upper limit for the purposes of the paper.

The main problem, though, is not with the range of $0.5 \leq y \leq 1$, but with how the GM paper decides to pick out values of y within this range. For a paper that claims to have a policy of adopting "conservative or 'worst case' assumptions" for every uncertainty [GM p. 5], one might expect that the paper would have chosen the lowest possible inelasticity for its cosmic ray calculations, and the highest possible inelasticity for black hole production at the LHC. This has not been done in the published version of the GM paper. It appears that earlier drafts of the GM paper consistently adopted a value of 0.5 for the inelasticity of cosmic ray collisions. The earlier drafts stated:

> To be conservative in bounding rates, we take an inelasticity factor $y = 0.5$, meaning that only 50% of the energy available in a given partonic collision will end up trapped in the black hole. [GM.ltx lines 3662–3664 ↗]

In the public version of the paper this assumption was applied to all the calculations for ultrahigh-energy neutrinos [GM pp. 47, 79, 80, table 10, figure 10], but for black hole production by proton or iron cosmic rays, the paper uses values for heavier black holes that range all the way up to $y = 1$. It presents this change as follows:

> In making the estimates of cosmic-ray production rates we shall conservatively choose the value of y corresponding to the smallest possible inelasticity compatible with production of a given mass value at the LHC, namely $y = M_{min} = 14$ TeV. [GM p. 39]

With this assumption, the inelasticity for the production of 10 TeV black holes is 0.71, of 12 TeV black holes is 0.86, and of 14 TeV black holes is 1. The paper does still include some alternative data based on the conservative $y = 0.5$ assumption in appendix E.2 (primarily [GM p. 75, table 7, figure 6], but see also the last column of table 8 [GM p. 76, table 8], and the dashed lines of figure 9 [GM p. 78, figure 9], however the only mention of this assumption in the main text is a single sentence at the end of the production rate analysis for white dwarfs [GM p. 40]. The data tables for white dwarfs and neutron stars highlighted in the main text are both based on the assumption that y can range up to 1 for heavier black holes [GM pp. 40, 46, tables 2, 3]. At no point does the GM paper remind readers of the fact that its cosmic ray production estimates for 14 TeV black holes are not only not conservative, but they are based on an inelasticity assumption which the paper itself describes as "an unrealistic extreme" [GM p. 39].

The GM paper justifies this assumption on the grounds that it is simply selecting the lowest value of y that is needed for black hole production to be possible at the LHC. If this is to be the basis for determining the inelasticity of cosmic ray collisions, then an appropriate approach would be to consider distributions of y which have a non-zero probability for values which would make LHC production possible. For example, for the production of 12 TeV minimum mass black holes, one could consider a distribution with a median of $y = 0.6$, but with a tail end that extends up to

$y = 0.95$ (due to variability in the dynamics of collisions, quantum fluctuations, etc.). In this case it would be possible for black holes to be produced at the LHC (depending on the momentum distribution of partons), but the cosmic ray production rates would be significantly lower than those given in the GM paper. More generally, if a maximum acceptable probability for black hole production at the LHC is given, then one could consider a wide variety of possible distributions in the value of y which would result in an unacceptable risk of black hole production, and then calculate the corresponding cosmic ray production rates for each case. What the GM paper does, however, is take the value of y needed for possible LHC production, and then apply it to every single cosmic ray collision. This results in highly inflated estimates for the production of heavier black holes by hadronic cosmic rays.

Moreover, despite arguing that its cosmic ray assumptions are only matching those needed for the LHC, the GM paper does not even apply those assumptions consistently for the LHC. The paper's calculations for black hole production at the LHC does include a graph of rates based on the assumption that $y = 1$ [GM p. 71, figure 4], but the more important issue is the number of trapped black holes, and for those estimates it does not include a graph for any value of y greater than 0.7 [GM p. 83, figure 12].[27]

4.2.3 Enhancement of Black Hole Production

A few factors could potentially increase the black hole production rates from those given in the GM paper. They include the following:

Collisions at Larger Impact Parameters - The GM paper assumes that black holes can only be produced in collisions with an impact parameter of less than half the Schwarzschild radius [GM p. 39]. Part of the motivation for this restriction is that the inelasticity drops off for larger impact parameters, so there may effectively be no black hole production past a certain point. While this assumption may be reasonably conservative for cosmic ray calculations, the paper also applies it to the LHC [GM p. 69], which could lead to an underestimate of the black hole production rates there. Even though the specific cut-off was justified by the comment that the inelasticity dies off beyond impact parameters of about half the Schwarzschild radius of the collision energy [GM p. 69], the source it cites shows the lower bound for the inelasticity coefficient staying above 0.5 until an impact parameter of 0.78 for $D = 5$ and 0.67 for $D = 6$ [YR05 p. 19, figure 10].[28]

Gravitational Infall - Section 7.1.4 of this paper reviews the GM paper's theory for the trapping of neutral stable black holes in white dwarfs and criticizes its dependence on a capture radius

[27] One may guess that the reason for this is that with an increased inelasticity the black hole may have less kinetic energy and would be more easily trapped.

[28] Since the production cross-section is based on the square of the impact parameter, using these values instead of an impact parameter limit of 0.5 would result in a 143% increase in the production rates for $D = 5$ and an 80% increase for $D = 6$. Note, however, that the distance used to normalize the impact parameter is similar to, but not the exact same as, the Schwarzschild radius [YR05 p. 6 ↗].

which is significantly larger than the black hole's Schwarzschild radius. The main objection to this expanded radius is that in the absence of a quantum theory of gravity, it is difficult to be confident about the gravitational interactions of individual particles passing just outside the Schwarzschild radius. However, if the GM paper's theoretical model turns out to be correct, it may also be necessary to increase the black hole production cross-section to take gravitational infall into account. This possibility is discussed in an article on black holes from cosmic rays cited by the GM paper which reports that this effect would enhance the cross-section by a factor of 6.75 in 4 dimensions and a factor of 4 in 5 dimensions[29, 30] [AFGS02 arXiv pp. 10–11] [cf. GM.ltx lines 3444–3448 ↗]. This process has also been described in an article published around the same time by Professor Solodukhin [Sol02 arXiv pp. 3–7].

Initial State Attraction - The calculation of the black hole production cross-section in the initial paper by Dimopoulos and Landsberg includes an endnote which observes that the production cross-section is somewhat enhanced by initial state attraction [DL01 arXiv p. 1, endnote 6, citing EHM00 arXiv ↗].[31]

4.2.4 Suppression of Black Hole Production

This section reviews the possibility that the general rate of black hole production could be lower than that predicted in the GM paper. At first it may seem like any reduction in the number or probability of black hole production would decrease the risks associated with the LHC, since fewer black holes could be trapped in the Earth or in other nearby objects. Moreover, if the expected number of trapped black holes from the LHC is less than 1, any reduction in the production rate would directly decrease the chance of any black hole being trapped at all.

On the other hand, if safety assurances are based on astrophysical arguments which require certain minimum rates of black hole production, then reductions in the general black hole rate could threaten the reliability of those arguments. Such general reductions would also reduce the production rate at the LHC, but if the astrophysical arguments become invalid before the probability of black hole production at the LHC becomes exceedingly low, then the overall risk associated with the LHC may be considered unacceptably high. With this in mind, the issue of suppression of black hole production should be recognized as a crucial issue for assessing the safety of the LHC.

A number of factors which could reduce the black hole production rate have been discussed in the mainstream scientific literature. They include the following:

[29] The article also reports an enhancement of the cross-section by 87% in 7 dimensions, but that calculation could not be verified for this draft.

[30] The article notes, however, that this estimate should be modified for a rotating black hole [AFGS02 arXiv p. 11, footnote 1 ↗]

[31] This factor has not been sufficiently researched for this draft, and is simply mentioned here for reference.

Minimal Length Effects - In an article published in *Physics Letters B* in 2004, Hossenfelder summarizes earlier discussions on the existence of a minimal length scale and calculates production rates for TeV-scale black holes which take into account its effects. Hossenfelder notes that the concept of a minimal length scale is a general feature which appears not only within a string theory framework, but also arises from other approaches, such as non-commutative geometries, quantum loop gravity, and non-perturbative implications of T-duality [Hoss04 arXiv p. 2]. For TeV-scale black holes, the higher-dimensional Planck's mass is not only a natural range for the start of black hole production, but it would also be expected to define a minimal length which limits the possible resolution of spacetime [Hoss04 arXiv p. 1]. As a sample calculation, she presents estimated black hole production rates at the LHC for the case of $D = 8$ and $M_D = 1$ TeV. Hossenfelder reports an exponential suppression of the black hole cross-section and a decrease in the expected number of black holes by a factor of ≈ 5 [Hoss04 arXiv p. 5]. (This estimate is based on the assumption that $M_{min} = M_D$, which, as discussed earlier, is also adopted in this paper; however, should one assume that $M_{min} = 3M_D$, as is done in the GM paper [GM p. 70], the cross-section would be reduced by a factor of at least 1,000 [cf. Hoss04 arXiv p. 4, figure 1].)

Electric Charge Effects - The effects of the electric charge of partons have generally been neglected in analyses of black hole production at the LHC and in cosmic ray collisions [YM06 arXiv p. 3] [Ging06 arXiv p. 2]. The GM paper itself simply considers colliding partons as small points of mass, and ignores the effects that their other properties may have on production rates [GM pp. 29, 69–70, 72]. An initial attempt at incorporating the effects of electric charges on black hole production was undertaken by Yoshino and Mann and published in 2006 in *Physical Review D*. They found that the Coulomb field is repulsive, regardless of the sign of the charge, and tends to obstruct black hole formation [YM06 arXiv pp. 15–16]. They note that charge effects had previously been presumed to be small, based on the argument by Giddings and Thomas that the effects would be proportional to the fine structure constant, α [YM06 arXiv p. 19, citing GT02 ↗], but they explain that the charge effects can be quite large since the electromagnetic energy-momentum tensor is proportional to $\gamma\alpha$, and γ is much larger than $1/\alpha$ for ultrarelativistic charges [YM06 arXiv p. 19]. Yoshino and Mann predict that if quantum electrodynamical (QED) effects are small, black hole production at LHC energies would only occur when a quark and its antiquark collide, or possibly when two gluons collide (however, see further comments below) [YM06 arXiv p. 20]. They acknowledge, however, that QED effects could play an important role [YM06 arXiv pp. 4, 21], and simply admit that it is not obvious whether QED effects weaken or further strengthen the repulsive effect that they had found [YM06 arXiv p. 21].

Color Charge Effects - The article by Yoshino and Mann does not explicitly analyze the effects of color charges on black hole production, but it does note that if color charge has an effect analogous to that which they had found for electric charge, then black hole production would similarly be suppressed in gluon collisions [YM06 arXiv p. 20, footnote 5]. The GM paper ignores the possible effects of color charge on black hole formation [GM pp. 29, 69–70, 72].

Parton Spin Effects - The Yoshino and Mann article further notes that black hole production estimates should also take into account the spin of incoming particles [YM06 arXiv pp. 20– 21]. They suggest that the recently proposed "gyraton" model could be used to do so [YM06 arXiv p. 21, citing ▷ arXiv 0504027 ↗, arXiv 0506001 ↗, arXiv 0512124 ↗]. As an initial assessment, they observe that the gravitational field is also repulsive around the center of gyratons, so they would expect a similar inhibition of black hole formation in gyraton collisions [YM06 arXiv p. 21].

Standard Model Particles in the Bulk - The GM paper states that in extra-dimensional models the standard model fields are typically taken to lie on a brane spanning the 3+1 dimensions we are familiar with [GM p. 11]. While this may be the usual assumption, it is by no means the only possible scenario (as the GM paper itself notes in the case of hypothetical black hole production by ultrahigh-energy neutrinos [GM p. 47, citing SSD06 ↗]). A number of scenarios have been proposed in which standard model particles are free to propagate within a "thick" brane, or some of the particles are assigned to specific sub-branes [▷ arXiv 9903417v1 ↗] [▷ arXiv 9909411v1 ↗].

For such scenarios with unwarped extra dimensions, the black hole production rates have been calculated in an article by Dai, Starkman and Stojkovic. They report that in a thick brane scenario in which the standard model particles have a uniform distribution along the extra dimension, the production rates decrease as a function of the brane's thickness [DSS06 arXiv p. 7]. For a case in which the value of M_D = 1 Tev, the production rates have decreased by more than a factor of 10 when the thickness of the brane is greater than 10 TeV^{-1}, and continue to decrease as the thickness increases. For higher values of M_D, the suppression rates are even greater [DSS06 arXiv p. 8, figure 4].

For scenarios with unwarped extra dimensions in which some of the particles are restricted to specific sub-branes, the reduction in the production rates depends on the extra-dimensional profile of quark wave functions. For the extreme case in which the wave function is modelled by a Dirac delta function, the suppression for a brane of thickness 10 TeV^{-1} ranges from a factor of about 2 to 6, depending on the value of M_D [DSS06 arXiv p. 6, figure 2]. As the thickness of the brane increases, the suppression approaches the limiting case in which black holes are produced primarily by collisions of particles within the same sub-brane [DSS06 arXiv p. 7]. If the quark wave functions are assumed to have a Gaussian distribution, then in a brane of thickness 100 TeV^{-1}, the suppression ranges from a factor of about 6 to 16 [DSS06 arXiv p. 7, figure 3]. As the thickness of the brane increases, the suppression similarly approaches the limiting case of production primarily by collisions within the same sub-brane [DSS06 arXiv p. 7].

The reduction of black hole production in scenarios with a warped extra dimension has been analyzed by Dr. Thomas Rizzo at the SLAC National Accelerator Laboratory (SLAC). He reports suppression factors ranging from 60 to 500, depending on the mass of the black holes and the location assigned to different fermions [Riz07 arXiv p. 11]. Of particular note is the reduction by several orders of magnitude of the quark production of black holes in scenarios in which fermions are located further away from the TeV brane [Riz07 arXiv p. 6, figure 1] [cf. GM p. 4, LSAG p. 8].

Voloshin Suppression - One of the earlier critics of the standard approach to calculating black hole production rates is Professor Mikhail Voloshin, who argued that the production of heavier black holes would be exponentially suppressed. In his first paper he states:

> By no means it would be justifiable to conclude, as claimed in the literature [10,11], that the production cross section is given by the geometric area of the horizon. The latter conclusion is based on applying the picture of classical collapse to an essentially quantum initial state of few particles, which, as argued in Section 2, does not include the effects of the initial state radiation becoming catastrophic at $GE^2 \gg 1$. Thus attempts at describing classically the production of large black holes by few initial particles as a collapse of "tiny but energetic" lumps of classical field appear to be of little relevance for a description of the actual process. [Vol01 pp. 141–142 ↗]
> Reference 10: GT02 arXiv ↗
> Reference 11: DL01 arXiv ↗

Professor Voloshin followed-up his first paper with a second article putting forth additional arguments [Vol02 ↗], however, he subsequently acknowledged an error in one of the important points of the second article [Vol05 ↗]. His arguments have been given due regard within the physics community, however, at present the consensus seems to be that the suppression he predicted would not occur. Professor Landsberg summarizes the situation as follows:

> Soon after the original calculations [25, 26] have appeared, it has been suggested [29] that the geometrical cross section is in fact exponentially suppressed, based on the Gibbons-Hawking action [30] argument. Detailed subsequent studies performed in simple string theory models [27], using full general relativity calculations [31], or a path integral approach [32] did not confirm this finding and proved that the geometrical cross section is modified only by a numeric factor of order one. A flaw in the Gibbons-Hawking action argument of [29] was further found in [33]: the use of this action implies that the black hole has been already formed, so describing the evolution of the two colliding particles before they cross the event horizon and form the black hole via Gibbons-Hawking action is not justified. By now there is a broad agreement that the production cross section is not significantly suppressed compared to a simple geometrical approximation, which we will consequently use through this review. [Land06 arXiv pp. 10–11]
> References: [Land06 arXiv pp. 29]

Aside from these criticisms, it should be noted that Voloshin's arguments primarily focus on the production of heavier black holes. These arguments might be of concern if $M_{min} \geq 3M_D$, as is assumed in the GM paper [GM p. 70], however, as noted earlier, if one is concerned simply about the production of black holes, as opposed to their immediate observation, then a criterion of $M_{min} = M_D$ is a more appropriate measure. In that case, the arguments of Professor Voloshin are not as important.

4.2.5 Other Factors Affecting Black Hole Production

There are also other factors which could affect black hole production rates, but for which it is premature to predict whether they would cause a significant increase or decrease. Those factors include:

Quantum Gravitational Corrections and "Stringy" Effects - The limitations of a semi-classical approach for black holes with masses close to M_D have been noted in most articles estimating black hole production rates. A sampling of published comments is given below:

> As M_{BH} approaches M_P , the BHs become "stringy" and their properties complex. This raises an obstacle to calculating the production and decay of light BHs, those most directly accessible to the LHC, where the center-of-mass (c.o.m.) energy of colliding beams is comparable to the Planck mass. In what follows, we will ignore this obstacle and estimate the properties of light BHs by simple semiclassical arguments, strictly valid for $M_{BH} \gg M_P$. We expect that this will be an adequate approximation, since the important experimental signatures rely on two simple qualitative properties: (i) the absence of small couplings and (ii) the "democratic" (flavor independent) nature of BH decays, both of which may survive as average properties of the light descendants of black holes. Nevertheless, because of the unknown stringy corrections, our results are approximate estimates. [DL01 arXiv p. 1, hyperlinks added]
>
> . . .
>
> While a quantitative understanding black holes with masses of order the Planck scale is quite difficult, for masses well above this scale black holes exhibit many features well described by semi-classical physics. . . .
>
> In order to discuss black hole production and evaporation in the laboratory we therefore consider black holes with masses $M \gtrsim (\text{few})M_p$ where features of the semi-classical analysis are expected to begin to be valid. [GT02 arXiv p. 5]
>
> . . .
>
> The approximate geometric subprocess cross section expression is claimed to hold by both GT and DL when the ratio M_{BH}/M_* is "large", *i.e.*, when the system can be treated semi-classically and quantum gravitational effects are small; one may debate just what "large" really means, but it most likely means "at least a few". Certainly when M_{BH}/M_* is near unity one might expect curvature and stringy effects to become important and even the finite extent of the incoming partons associated with this stringy-ness would need to be considered. Clearly caution must be applied when $M_{BH} \simeq M_*$ in interpreting cross sections evaluated in this parameter space region. [Riz02 arXiv pp. 3–4]
>
> . . .
>
> To trust the semiclassical approximation, the typical energy of the process has to be much larger than M_D. Given the present constraints on extra-dimensional gravity, it is clear that the maximum energy available at the LHC allows, at best, to only marginally access the transplanckian region. If gravitational scattering and black-hole production are observed at the LHC, it is likely that significant quantum-gravity (or string-theory) corrections will affect the semiclassical calculations or estimates. In the context of string theory, it is possible that the production of string-balls [27]

> dominates over black holes. [Yao06 p. 1167 ↗ (large file), hyperlinks added][32]
> Reference 27: ▷ arXiv 0108060 ↗

For calculating black hole production rates with $M_{min} = M_D$, it is clear that quantum gravitational corrections and "stringy" effects must be taken into account. However, even for estimating the total number of black holes with masses $\geq 3 - 5M_D$, as suggested in the GM paper [GM p. 70], these factors could still be quite important and may significantly change the expected numbers.

Uncertainties in the Momentum Distribution of Partons - The black hole production calculations of the GM paper depend on estimates of the distribution of a nucleon's momentum among its various partons [GM pp. 39–40, 70, 76, 78, figure 9]. There are, however, no experimentally validated parton distribution functions (PDFs) for LHC energies. The GM paper asserts that "the bulk of the production is always obtained for $x \lesssim 0.6$, namely the region where the knowledge of the PDFs is accurate to better than 10%" [GM p. 76, citing Pum02 ↗]. It is not clear, however, what the basis is for the GM paper's claim about the reliability of the PDFs it uses. The source it cites includes 3 graphs for the uncertainty in the distribution functions of up quarks, down quarks, and gluons at an energy of approximately 0.0032 TeV. These graphs show that at the value of $x = 0.6$, the uncertainty is approximately ±8% for up quarks and +37/-23% for down quarks [Pum02 arXiv p. 15, figure 9], and at least +100/-50% for gluons [Pum02 arXiv p. 16, figure 10]. This uncertainty range is determined by the authors' "tolerance parameter", T [Pum02 arXiv pp. 33–36]. They emphasize, however, that it is only a partial measure of the uncertainties in their parton distribution functions; their paper includes the following warning:

> As already noted, the estimated tolerance of $T = 10$ contains experimental uncertainties only. Uncertainties of theoretical or phenomenological origin are not included because they are difficult to quantify. They might be significant. For instance, we have seen throughout this paper that the parametrization of nonperturbative PDF's has a big influence on the results. Therefore in physical applications the criterion $T = 10$ must be used with awareness of its limitations. [Pum02 arXiv p. 36]

Furthermore, the GM paper only claims that the PDFs are reliable in the range below $x \sim 0.6$ [GM p. 76], which, if true, could be used to establish a lower bound on the number of black holes produced in cosmic ray collisions. The paper also makes claims about an upper bound on the production of black holes in LHC collisions [GM pp. 71, 83, figures 4, 12], but for heavier black holes these claims involve PDFs in the range above $x \sim 0.6$, yet the paper makes no mention about the uncertainty of PDFs in this range.

4.2.6 Factors Affecting Black Hole Production Rates from Cosmic Rays

The previous sections reviewed several factors which could affect the general black hole production rates, and which would be expected to apply equally to both LHC and cosmic ray collisions. There

[32] The issue of "string-balls" is not addressed in the LSAG report or in the GM paper, and has not been reviewed in the current draft of this paper [▷ ADDCITE cf. Symmetry Breaking 13 Feb 2010 ↗].

are, however, a number of factors which could reduce the cosmic ray rates while leaving the LHC rates unaffected. A few of the more general factors are summarized below, while factors which are specific to certain constructions and scenarios are discussed in the relevant parts of section 7.

A number of issues related to the composition and flux of cosmic rays were discussed earlier in section 3. The ways in which uncertainties about cosmic rays could reduce the cosmic ray black hole production rates include the following:

- As noted in the GM paper, an iron-dominated cosmic ray flux would produce far fewer black holes than a flux dominated by single protons [GM pp. 40, 46, 73, 74, 75, 77, tables 2, 3, 4, 5, 6, 7, figures 5, 6, 8].
- The GM paper's estimate of black hole production by iron nuclei may be reduced if not every single nucleon in every iron nuclei experiences an inelastic collision at its initial energy level.
- The production estimates for either a proton or iron-dominated cosmic ray flux could be reduced by elastic collisions or interactions occurring before a nucleon's inelastic collision.
- Errors in the modelling of hadronic collisions could imply a reduced value of the true energies of incoming cosmic rays [Wat08a.ppt 38] [Wat08b pp. 222–223].
- The effects of "new physics" in ultrahigh-energy collisions could similarly imply a reduction in the true energies of cosmic rays [HH02 arXiv p. 6].
- The inclusion of ultraheavy nuclei in an iron-dominated flux would reduce the energy per nucleon and the production efficiency of the highest energy cosmic rays.
- The inclusion of strangelets or nuclearites in the flux would significantly reduce the energy per parton in the collisions of such cosmic rays.
- The inclusion of ultrahigh-energy photons in the cosmic ray flux would result in a component with a black hole production rate which could be much lower than that of nucleons.
- The inclusion of other forms of matter (magnetic monopoles [▷ ADDCITE], Q-balls [GP05 p. 8], dark matter, etc.) would similarly introduce a component of the flux with an unknown black hole production rate which cannot be compared to the LHC's rate.
- As noted in the GM paper, limitations in the energy resolution of the Pierre Auger Observatory leave open the possibility of significantly lower values for the true energies of ultrahigh-energy cosmic rays [GM p. 74, table 6].
- Statistical uncertainties in measurements of the cosmic ray flux at different energies [Wat08b p. 224] could imply a significant difference between the assumed cosmic ray flux and the true cosmic ray flux presently striking the Earth.
- Possible North/South hemispheric differences in the ultrahigh-energy cosmic ray flux [Wat08a.ppt 48] could affect the expected rates for the overall ultrahigh-energy flux.[33]

[33] It should be noted that Watson considers this to be an unlikely explanation of differences in the observed cosmic

- Variations in the cosmic ray flux over time could imply that the flux of ultrahigh-energy cosmic rays measured over the past couple of decades is not representative of the average rate over the past few billion years.
- Temporal variations in the ultrahigh-energy cosmic ray flux could also imply that the exposure of an astronomical object over a specific period of time (for example, the exposure of a given white dwarf over a 10–20 million year period), may significantly differ from the average rate over billions of years.
- Spatial variations in the cosmic ray flux might also lead to differences between the expected exposure of an astronomical object and its true exposure.

Aside from these issues, it should be noted that some of the points raised in the previous sections on the general black hole production rate may be affected by the energy level of collisions. The LSAG report includes a comparison of the estimated number of cosmic ray collisions experienced by the Earth and the Sun with energies equal to or greater than that of the LHC (assuming a 100% proton cosmic ray flux in the main text [LSAG p. 4], and providing a formula for heavier elements in an endnote [LSAG p. 15, endnote 6]). While it is a useful comparison, the argument put forth in the GM paper, depends not on cosmic rays with energies similar to that of the LHC, but on cosmic rays with much higher energies.

Taking a look at figure 5 of the GM paper, one can see that for protons the vast majority of black hole-producing cosmic rays have energies 10 times higher than that required to match the LHC [GM p. 73, figure 5], even though they would only represent about 1% of the cosmic rays counted by the LSAG report.[34] For a pure iron flux, the GM paper's argument depends on cosmic rays whose total energy is 100 times greater than the 10^{17} eV benchmark given in the LSAG report [GM p. 73, figure 5] [LSAG p. 4].[35]

Figure 5 is itself based on the very optimistic assumption that for 14 TeV minimum mass black holes, every black-hole producing collision has an inelasticity coefficient of $y = 1$. Using a more conservative assumption of $y = 0.5$, figure 6 shows that most of the black hole production for a pure proton flux is caused by cosmic rays with energies between $10^{18.4}$ eV and 10^{20} eV [GM p. 75, figure 6].[36] The energies are even greater in the case of a pure iron flux, and almost all the

ray flux.

[34] This estimate assumes that the integral cosmic ray flux is falling as $1/E^2$ within this energy range [cf. LSAG p. 15, endnote 6 ↗]

[35] One may note, however, that while not stated explicitly, endnote 6 of the LSAG report implies that for a pure iron flux, only cosmic rays with energies $\gtrsim 56 \times 10^{17}$ would be included in the corresponding count [LSAG p. 15, endnote 6 ↗].

[36] For the discussion of cosmic rays in the main text of the GM paper the authors speak of confining themselves to the part of the spectrum below the GZK cutoff (i.e. $\lesssim 5 \times 10^{19}$ eV) [GM p. 28 ↗], but in appendix E.2 the authors instead explain that they "allow E_{max} to extend *only up to* the largest value for which data exist, namely $E_{max} = 2 \times 10^{20}$ eV" [GM p. 72 ↗, italics added for irony]. It is on this maximum possible energy range that the specific black hole production rates in the GM paper are based, including the data of tables 2 and 3 in the main text [GM pp. 40, 46, tables 2, 3 ↗].

black hole production predicted by the GM paper would be caused by cosmic rays with energies between $10^{19.8}$ eV and $10^{20.4}$ eV [GM p. 75, figure 6].

For collision energies above that of the LHC (i.e. those caused by proton cosmic rays with energies greater than ~ 10^{17} eV, or iron cosmic rays with energies greater than ~ $10^{18.75}$ eV), the following factors could further reduce the cosmic ray production rates:

- The minimum length effects discussed earlier may restrict the otherwise expected increase in black hole production efficiency at higher energies.
- The parton distribution functions (PDFs) may be modified at higher energies, leading to further uncertainty in the production rates (beyond the uncertainties in the PDFs discussed earlier).[37]
- As an offshoot of any changes in the PDFs, the proportion of black holes hypothetically produced in collisions of charged partons might change, and thus the suppression caused by the electric charge effects discussed earlier might be different from that of the LHC. Similarly, the suppression due to color charge effects discussed earlier might also be different from the LHC.

Beyond these factors, the possibility of a more fundamental difference between LHC and cosmic ray collisions is considered below.

§ Validity of Special Relativity

TEXT UNDER REVISION

4.3 Detection of Black Hole Production

TEXT UNDER REVISION

[37] Such changes could increase or decrease the production rates, but for a risk assessment the focus would be on a possible net decrease.

5 Black Hole Radiation

This section reviews the question of whether black holes produced in high-energy collisions would directly emit any radiation, and if so, how rapid the rate of radiation would be, and what would be left at the end of the process.

5.1 Existence of Black Hole Radiation

One of the central questions in the public debate about the safety of potential black hole production at the LHC is whether small black holes will accrete matter or decay through Hawking Radiation. What the GM paper makes clear is that its authors do not expect that black hole radiation, as originally derived by Professor Stephen Hawking [Haw75 ↗], will occur.

The GM paper begins by citing a journal article by Unruh and Schützhold which states:

> Addressing the question of whether the Hawking effect depends on degrees of freedom at ultrahigh (e.g., Planckian) energies/momenta, we propose three rather general conditions on these degrees of freedom under which the Hawking effect is reproduced to lowest order. As a generalization of Corley's results, we present a rather general model based on non-linear dispersion relations satisfying these conditions together with a derivation of the Hawking effect for that model. However, we also demonstrate counter-examples, which do not appear to be unphysical or artificial, displaying strong deviations from Hawking's result. Therefore, whether real black holes emit Hawking radiation remains an open question and could give non-trivial information about Planckian physics. [US04 arXiv abstract]

In a recent talk, cited by the GM paper, Professor Unruh puts the issue more bluntly:

> The derivation by Hawking is nonsense, in that it uses features of the theory in regimes where we know the theory is wrong. [Unr07 ↗]

The GM paper also refers to a recent review of analogue models of gravity which states:

> Most of the work on the trans-Planckian problem in the nineties focussed on studying the effect on Hawking radiation due to such modifications of the dispersion relations at high energies in the case of acoustic analogues [185, 186, 377, 378, 88], and the question of whether such phenomenology could be applied to the case of real black holes (see e.g., [50, 188, 88, 299]).[24] In all the aforementioned works Hawking radiation can be recovered under some suitable assumptions, as long as neither the black hole temperature nor the frequency at which the spectrum is considered are too close to the scale of microphysics K. However, the applicability of these assumptions to the real case of black hole evaporation is an open question. Also, in the case of the analogue models the mechanism by which the Hawking radiation is recovered is not always the same. [BLV05 p. 63, hyperlinks added]

> Footnote 24: However see also [318, 322] for a radically different alternative approach based on the idea of "superoscillations" where ultrahigh frequency modes near the horizon can be mimicked (to arbitrary accuracy) by the exponential tail of an exponentially large amplitude mostly hidden behind the horizon. References: [BLV05 pp. 84, 87, 95, 104, 105, 109]

The GM paper itself says that:

> While Hawking's result has become nearly universally accepted, it is certainly true that elements of the original derivation of black hole radiance rely on assumptions that are apparently not valid. Notable among these is the use of modes of ultra-planckian frequencies at intermediate steps in the derivation. This naturally raises the question of the robustness of the result. [GM p. 7]

In defence of Hawking radiation, the authors cite a review article by Nobel laureate and CERN SPC member Professor Gerardus 't Hooft, even though this paper states:

> Caution however is called for. We must underline that here we are dealing with a purely theoretical prediction which, whether we like it or not, is based on assumptions that cannot all be verified directly, plausible as they may seem. Black holes emitting quantum radiation have never been observed experimentally, and indeed it is conceivable that either Quantum Mechanics or General Relativity, or both, might break down precisely at the horizon, regardless how large the horizon is. ['tH96 arXiv pp. 18–19, hyperlinks added][38]

What the report instead asserts is the authors' confidence that even if Professor Hawking's original derivation is invalid, the general idea is correct. Thus it notes:

> Belief in the robustness of Hawking's prediction of nearly thermal evaporation has been boosted by arguments for the result which have now been produced from several different directions. These derivations have the virtue of either facing head-on the issue of the transplanckian modes, or being independent of them, and the basic effect has survived a number of important consistency checks. [GM p. 7]

They further cite Unruh's conclusion that:

> Analog models of gravity have given us a clue that despite the shaky derivation, the effect is almost certainly right. [Unr07 ↗]

[38] It should be noted that these comments by Professor 't Hooft were made prior to the proposal of large extra dimensions and were intended for the standard 4-dimensional scenario in which Planck's mass is several orders of magnitude larger than the 14 TeV maximum of the LHC. In such a scenario it would not be possible for the LHC to create even microscopic black holes.

Both the GM paper and the LSAG report argue that on basic quantum mechanical grounds, some form of radiation should be expected [GM pp. 4, 8] [LSAG pp. 7–8]. The LSAG report further emphasizes that quantum mechanics is "a cornerstone of the laws of Nature" [LSAG p. 8]. However, Professor Giddings has elsewhere noted that the existence of black holes "suggests that a revision of the fundamental underpinnings of physics may be necessary." [Gid95 p. 1] In a paper presented in 2007 he states:

> ... even if black hole production is not experimentally accessible, it is an extremely important theoretical problem, as it forces confrontation with our most profound theoretical issues. Notable among these is the black hole information paradox.[5] The basic statement of this paradox is that consideration of the fate of quantum information in the context of evaporating black holes apparently forces us to abandon a cherished principle of physics. The possibilities include abandoning unitary quantum-mechanical evolution, as originally suggested by Hawking[43], with the apparent consequent disastrous abandonment of energy conservation[44]; abandoning stability, as implied by a black hole remnant scenario, or abandoning macroscopic locality, in order that information can escape a black hole in Hawking radiation. [Gid07 arXiv p. 8, hyperlinks added]
> Reference 43: Haw76 ↗
> Reference 44: ▹ ADDCITE BSP84

The GM paper asserts that such problems can be solved in stating:

> Many workers feel that the resolution will be that there are subtle corrections to Hawking's thermal spectrum, that lead to unitary evolution. Thus while very few question that black holes Hawking evaporate, it is clear that there are detailed aspects of the evaporation process that we do not understand. [GM p. 8, hyperlinks added]

What is missing, however, from the GM paper and other CERN documents is a clear statement about exactly what those "subtle corrections" are, and when the aspects of the evaporation process that we do not understand will be understood. It should be stressed that these issues are not a question of whether there is any experimental verification of black hole radiation—there is none—but a more basic question of whether there is a complete and consistent theory to begin with. The text of the GM paper and the references it cites make it quite clear that no such theory presently exists.

5.2 Black Hole Radiation and Extra Dimensions

One of the strongest arguments that CERN makes in support of the safety of possible black hole production at the LHC is that the very theories which predict black hole creation also predict their immediate disintegration. The official summary of the LSAG report states the following:

> According to the well-established properties of gravity, described by Einstein's relativity, it is impossible for microscopic black holes to be produced at the LHC. There are, however, some speculative theories that predict the production of such particles at the LHC. All these theories predict that these particles would disintegrate immediately. [LSAGSum p. 1, hyperlinks added]

As this statement is from a summary document it does not include references, so it is not immediately clear which "speculative theories" CERN is referring to. A review of the key papers is summarized below:

- The initial paper establishing the theory of large unwarped extra dimensions does not mention Hawking radiation or black hole disintegration [ADD98 arXiv ↗].
- The abstract of the second paper on large unwarped extra dimensions does state the following:

  > This scenario raises the exciting possibility that the LHC and NLC will experimentally study both ordinary aspects of string physics such as the production of narrow Regge-excitations of all standard model particles, as well more exotic phenomena involving strong gravity such as the production of black holes. [AADD98 arXiv abstract, hyperlinks added][39]

  The text of this paper notes that graviton emission will be very important at energies above the type I string scale and describes such emission as analogous to Hawking radiation from an excited brane [AADD98 arXiv p. 6], but the paper makes no attempt to argue that either Hawking radiation itself or black hole disintegration are a necessary consequence of higher-dimensional black hole production [AADD98 arXiv ↗].
- The first paper describing the theory of a warped extra dimension makes no reference to Hawking radiation or black hole disintegration [RS99 arXiv ↗].
- The second key paper on warped extra dimensions by the same authors also makes no reference to Hawking radiation or black hole disintegration [▷ arXiv 9906064 ↗]

[39] This paper was posted on arXiv on 24 April 1998 [AADD98 arXiv ↗]. That date can be considered the point at which whatever risk allowance CERN did or did not make for the production of black holes at the LHC through an unknown mechanism should have been revised to take into account a specific scenario of black hole production, along with any other possible unknown mechanisms [cf. LSAG p. 3 ↗]. It may also be noted that this paper had been cited in almost 500 other physics articles by October 2000 [▷ ADDCITE SPIRES] when *Reviews of Modern Physics* published the "Review of speculative "disaster scenarios" at RHIC", which assured the public that the production of black holes at higher energy accelerators would be a "pipe dream" [JBSW00 p. 1130 ↗]. This report is presented on CERN's website page about the safety of the LHC as "the specialist report published in the United States" [CERN08b ↗].

- The first two papers to calculate the rate of black hole production at the LHC both refer repeatedly to Hawking radiation, but neither of them asserts that the higher-dimensional creation of black holes necessarily implies their immediate disintegration [GT02 arXiv ↗] [DL01 arXiv ↗]. In fact, both papers suggest that observations at the LHC could provide an opportunity to *test* the details of Hawking radiation [GT02 arXiv pp. 23, 25] [DL01 arXiv abstract].

Turning to the full LSAG report to find the basis for the claim of immediate black hole disintegration, one sees that after summarizing the arguments for Hawking radiation and the quantum mechanical instability of non-pair produced black holes, the report notes:

> Both this and the existence of Hawking radiation are *valid* in the extra-dimensional scenarios used to suggest the possible production of microscopic black holes. [LSAG p. 7, italics added]

This statement is logically very different from that of the LSAG summary. Aside from ignoring the case of stable pair-produced black holes, the LSAG summary has taken the statement that the arguments for Hawking radiation and quantum mechanical instability are still *valid* for extra-dimensional scenarios, and converted it into a claim that extra dimensional scenarios *predict* the immediate disintegration of black holes.

The GM paper itself provides even less of a basis to believe in the immediate disintegration of higher-dimensional black holes. Several of its statements or sources which raise questions about Hawking radiation were noted in the previous section, and further issues related to the rate of black hole radiation are discussed in the next section. As part of its summary of efforts to rescue Hawking radiation, the GM paper reports the following:

> One early approach relying on the trace anomaly and avoiding explicit reference to transplanckian modes was pioneered by Christensen and Fulling [13]. In this approach, the stress tensor describing the Hawking radiation is found by combining the known trace anomaly in two dimensions, and the constraint that the stress tensor be conserved. This approach has been used to give explicit models of evaporating black holes [14], and has also recently been generalized to higher dimensions in [15] and a number of followup works. [GM p. 7, hyperlinks added]
> Reference 13: CF77 ↗
> Reference 14: CGHS92 arXiv ↗
> Reference 15: RW05 arXiv ↗

For the present discussion, the key point is the last phrase. If Hawking radiation or black hole disintegration followed automatically from extra dimensional scenarios, then efforts to extend models of evaporating black holes to higher dimensions would be irrelevant.[40] As implied by the GM paper and reinforced by the findings of this section, such efforts are indeed relevant, since there does not appear to be any basis for CERN's claim that all theories which predict the creation of black holes at the LHC also predict their immediate disintegration.

[40] The extension of 2-dimensional models to 3 or 4 dimensions is of general academic interest, but the focus of the GM paper is on scenarios with more than 4 dimensions, so it is assumed that the intended message was that these models have been generalized to scenarios with $D > 4$.

5.3 Rate of Black Hole Radiation

The discussion of section 5.1 notes the lack of a complete and consistent theory for black hole radiation, but one may nevertheless ask whether microscopic black hole radiation is guaranteed to be very rapid. The Giddings/Mangano paper touches briefly on this issue, but it is not clear what conclusions can be drawn. The report states:

> Thus by basic quantum principles such a heavy black hole should decay into light, ordinary matter, and the only question is the time scale. Since such a black hole can have mass at most around ten times the higher-dimensional Planck mass, $M_D \sim 1$ TeV, the only relevant dimensionful parameter is the corresponding time scale, $t_D \sim 1/M_D \sim 10^{-27}s$, and there are no other small dimensionless parameters to suppress decay. Thus, on very general grounds such black holes are expected to be extremely short-lived, as is indeed predicted by the more detailed calculations of Hawking and successors. [GM p. 8, hyperlink added]

Professor Giddings makes a similar point in an earlier paper on the black hole information paradox, but then reaches a very different conclusion:

> Basic quantum principles imply that such formation/evaporation should be taking place all the time in virtual processes, as illustrated in fig. 2. The amplitude for these processes should approach unity as the size of the loop approaches the Planck scale-there is no small dimensionless number to suppress it. According to (6), we would therefore expect Planck size energy violations with planckian characteristic time scale. This would give the world the appearance of a thermal bath at the Planck temperature, in clear contradiction with experiment. *And that suggests we explore alternatives to Hawking's picture*. [Gid95 p. 3, italics added]

The solution he considers is the following:

> Again, in accordance with uncertainty principle arguments, the only way to radiate a large amount of information with a small amount of available energy is to do it very slowly, for example by emitting extremely soft photons. An estimate [7,8] of the time required is
>
> $$t \sim \left(\frac{M_0}{M_{p\ell}}\right)^4 t_{p\ell},$$
>
> which exceeds the age of the universe for black holes with initial masses comparable to that of an average building.[41] Therefore this scenario implies long-lived remnants.
> [Gid95 pp. 4–5, hyperlink added, footnote added]
> Reference 7: ▹ ADDCITE CW87
> Reference 8: ▹ arXiv 9209058 ↗

[41] This analysis was for a regular 4-dimensional black hole, not a higher-dimensional TeV-scale black hole.

Aside from this specific proposal, Professor Giddings has noted elsewhere that Hawking radiation would not apply to black holes with very low masses. At a conference held in 2001 on the future of particle physics (Snowmass 2001), he explained:

> Once the black hole reaches a mass $M \sim M_p$, Hawking's calculations fail. We call this phase the *Planck phase*. [Gid01 p. 6]

Since the vast majority of black holes produced at the LHC would be expected to have masses ~Planck's mass, his statement implies that Hawking's calculations would fail for the very black holes that are of concern.

In light of the GM paper's admission that "subtle corrections" may be needed to Hawking's thermal spectrum [GM p. 8], the proposal that black holes could slowly radiate extremely soft photons [Gid95 pp. 4–5], and the expectation that the particle emission rate would change during the Planck phase [Gid01 p. 6], there is evidently a great deal of uncertainty about exactly how fast black hole radiation would actually be.[42] Given this uncertainty, it will be necessary for this paper to consider a wide range in the possible rates of black hole radiation. The different possible rates are grouped into the following 4 distinct categories:

No direct black hole radiation - In this scenario, black holes emit no direct radiation. In line with the original view of black holes [Haw75 abstract], prior to Hawking's hypothesis, the mass of a black hole would monotonically increase, with no matter or radiation escaping once it has crossed the event horizon. In this paper this scenario is referred to as "stable black holes".

Black hole growth not bounded by radiation - In this category, black holes may emit some radiation, but the rate would not be sufficient to set a bound on the maximum possible mass of an accreting black hole. This category covers a very wide range in the possible rate of radiation, from the case of completely negligible radiation, up to a scenario in which the radiation rate is fast enough to significantly slow, but not completely stop, a black hole's net growth rate. In these scenarios, black holes can also be considered "stable", but to distinguish this category from the case of absolutely no direct radiation, it is referred to in this paper as "slowly radiating black holes".

Black hole growth up to an equilibrium mass - For scenarios in which the rate of direct radiation is slow for masses near Planck's mass, but becomes extremely fast at higher masses [cf. Hoss06 arXiv p. 9, 22, figures 3, 9], it is natural to expect black holes to have an equilibrium mass at which the rate of accretion balances the rate of radiation. However, until the theoretical questions associated with black hole radiation are resolved, it is difficult to predict what that mass might be. Thus, again it is necessary for this paper to consider a wide range of possibilities, from an equilibrium mass close to Planck's mass, up to an equilibrium mass approaching that of the black hole's host object. In this paper, these possible scenarios are grouped into the category "equilibrium mass radiating black holes".

Rapid direct black hole radiation - In this category, black holes radiate extremely rapidly (even during the Planck phase) and would be expected to monotonically decrease in size down to the

[42]▷ ADD NOTE on other studies suggesting slower radiation, e.g. Casadio and Harms

higher-dimensional Planck's mass. At that point, it is not clear what would happen to them. Would they remain at roughly that size, or would their event horizon somehow dissolve? The issue of black hole remnants is discussed further in the next section. These scenarios are described in this paper as "rapidly radiating", however, to take into account the uncertainty about the final step, they are divided into two categories: "rapidly radiating black holes" (in which stable remnants are expected), and "rapidly radiating remnantless black holes" (in which black holes which are not pair-produced with conserved quantum numbers are expected to dissolve).

While the category of "no direct black hole radiation" would apply to a scenario regardless of the location of a black hole, the following two categories, and possibly the final category of "rapid direct black hole radiation", can depend on the medium a black hole finds itself in [cf. GLL02 ↗], and even its initial velocity [cf. Hoss06 arXiv p. 30]. For example, a black hole which can only reach a certain equilibrium mass in the Earth might be able to grow without bounds in a white dwarf or neutron star. In analyzing the different scenarios, this paper has adopted the following framework:

- For section 7 on the production and trapping of black holes, the categorization of a scenario depends only on the object involved (i.e. an equilibrium mass black hole in a neutron star is just that within a neutron star).
- For section 8 on the accretion of black holes, the categorization is similarly based only on the object being accreted.
- For section 9 on the safety implications of black hole production, the same policy is followed. A consequence of this, however, is that the possible effects of equilibrium mass black holes in the Earth could, for example, be linked with those given for equilibrium mass black holes in the Moon and those for slowly radiating black holes in the Sun.
- For section 10, the initial analysis given for each category and each specific object is based on the assumption of that category applying to black holes within that object, however, the overall astrophysical implications must consistently match scenarios, so the summaries for each category are based on the application of that category to accretion within the Earth, and note the different possibilities depending on which categories apply to other objects.

One final point to note is that these categories apply only to radiation from a black hole itself. Another important issue is the radiation released by particles as they are being accreted. This is distinct from radiation directly from the black hole, and would be expected to occur in the region outside the black hole's event horizon. This process is described in Appendix B of the GM paper [GM pp. 57–65], and is discussed further in section 8 of this paper. In places where the two types of radiation might be confused, the first type is referred to as "direct radiation", while the second is called "reradiation".

5.4 Black Hole Remnants

For scenarios in which black holes radiate rapidly, one of the most important questions is what happens to them at the very end of the process. The answer to this question is still unknown.

This section looks at two distinct possibilities. The first is that all microscopic black holes evolve into long-lived or permanent black hole remnants. The second is that ordinary black holes end their lives in a final burst of Standard Model particles, but if they were created through pair production and have a conserved quantum number, they would be stable against a final decay. These two possibilities are discussed in more detail below.

5.4.1 Stable Remnants from All Microscopic Black Holes

Historically, the idea of long-lived or permanent black hole remnants has been touted as a possible solution to the black hole information paradox. If one accepts Hawking's theory that black holes emit radiation with a thermal spectrum, an unresolved puzzle is what happens to the information that was originally stuffed into the black hole.

Thermal radiation does not convey any information about the internal details of an object, so one is left with a theory that predict that black holes become smaller and smaller but with no outlet for their original information. Hawking had originally proposed that the information was truly lost [▷ ADDCITE Hawking *Phys. Rev.* **D14**10 pp. 2471–2472], even though this implies both a breakdown of quantum mechanics and a violation of conservation of energy [Gid94 arXiv pp. 22–25] [Gid95 arXiv pp. 2–3].

One possible resolution of this problem is for the information from a black hole to be transmitted in its radiation. The main objection to this proposal is that it would involve a signal travelling faster than the speed of light, which would violate the usual notions of locality and causality [Gid95 arXiv pp. 3–4].

A third possibility is for the original information to be preserved by the black hole and released only very slowly through the emission of soft photons [Gid95 pp. 4–5] This process would result in long-lived black holes remnants.

As plausible as this third option may seem, it nevertheless has its potential flaws. The first is that if one were to require that such remnants be capable of storing an infinite amount of information, this would lead to an infinite number of black holes states with masses close to Planck's mass. If one then assumes that such black holes can be treated as regular quantum mechanical objects, any process with available energy above Planck's mass would have a tiny but non-zero probability of pair-producing any given species of black hole remnant. If there are truly an infinite number of possible remnants, this could result in an infinite production rate, which would imply that the Universe is unstable to instantaneous decay into remnants [Gid95 arXiv p. 5].

A second argument against remnants being a solution to the black hole information paradox was presented by Professor Leonard Susskind in his article "Trouble for Remnants" [▷ arXiv 9501106 ↗].

Based on an earlier theory proposed by himself and John Uglum for infinitely large black holes [▷ arXiv 9401070 ↗], Professor Susskind has argued that if remnants have an infinite internal entropy (above and beyond the usual Bekenstein-Hawking entropy), then the existence of remnants in the thermal atmosphere of Rindler space would drive the renormalized gravitational constant to zero [▷ arXiv 9501106 ↗].[43]

Based on these argument, the proposal that the information from arbitrarily large black holes is stored in remnants has not been accepted as the solution to the black hole information paradox. Nevertheless, as noted by Professor Giddings, the alternative hypotheses are just as problematic [Gid94 arXiv pp. 30–31], so the proposal of an infinite variety of Planck-sized remnants remains in contention as a possible solution [Gid07 arXiv p. 8].

Even if remnants are not a solution to the black hole information paradox, there are a number of other independent reasons why a long-lived or permanent remnant would be expected after the initial phase of rapid radiation. The various reasons have been summarized by Koch, Bleicher and Hossenfelder in the *Journal of High Energy Physics* [KBH05 pp. 5– 6] and elsewhere [▷ ADDCITE *Phys. Lett.* **B566** p. 235] [Hoss06 arXiv pp. 25–29] [HKB05 ↗] [Koch07 pp. 57–58]:

- The uncertainty principle sets a lower bound on the size of a black hole's Schwarzschild radius. Specifically, a Planck-mass black hole has a Schwarschild radius which is of the order of Planck's length. The Planck length itself is the wavelength corresponding to a particle of Planck's mass. If the mass of a black hole drops below this, the result would be a mass trapped in a volume smaller than that permitted by the uncertainty principle [KBH05 p. 5].
- Corrections to the rate of radiation due to the curvature of a shrinking black hole can result in the rate decreasing towards zero and lead to thermodynamically stable black hole remnants [KBH05 p. 5].
- Other possible factors, such as axionic charge, modification of Hawking radiation due to quantum hair or magnetic monopoles, or the coupling of a dilaton field to gravity could also result in remnants [KBH05 p. 5].
- Calculation of lowest order quantum gravity effects can lead to stable remnants [Koch07 p. 58, citing ▷ arXiv 0602159 ↗]
- If the radiation from a black hole is quantized to wavelengths which fit its surface, then as the black hole decreases in size, the minimum energy for the emission of any radiation

[43] It should be noted, however, that the Susskind-Uglum theory implies that canonical quantum gravity field theory would also drive the renormalized gravitational constant to zero [▷ arXiv 9401070 p. 15 ↗]. The authors' only suggestion for solving this problem is to adopt superstring theory, and even for some superstring theories the renormalized gravitational coupling is still zero [▷ arXiv 9401070 p. 15 ↗]. The theorem also depends on the assumption of 4 space-time dimensions. When its authors tried to apply it to the 2-dimensional toy model developed by Callan, Giddings, Harvey, and Strominger [CGHS92 arXiv ↗], they report that their theorem fails, although they attribute this to 2-dimensional theories not possessing enough degrees of freedom to be viable models of 4-dimensional gravity [▷ arXiv 9401070 p. 18 ↗].

> increases. When the size of a black hole is close to Planck's mass, the minimum energy for emission would be greater than the mass of the black hole itself, so the process of radiation would be shut off [▷ ADDCITE *Phys. Lett.* **B566** p. 235–237].

These considerations strongly suggest that all black holes leave remnants, although this still cannot be taken as a certainty. On the other hand, if one wished to show that microscopic black holes do not leave remnants, then, in addition to addressing the above points, it would be important to present a clear description of the process through which a black hole's event horizon is dissolved and its mass energy released. After all, it is one thing to say that black holes radiate, it is another thing to say that they explode.

While the possibility of all black holes leaving remnants is not mentioned in the GM paper, it certainly has not been ignored by physicists preparing for the LHC. One of the most popular programmes used to model LHC-produced black holes is CHARYBDIS2. Developed under the leadership of SPC panel member Professor Bryan Webber, it includes an explicit option for modelling the final black hole state as a stable remnant [▷ arXiv 0904.0979 pp. 24–25 ↗]. Similarly, the CATFISH programme allows users to run simulations with the assumption that the final state is a minimum mass remnant [▷ arXiv 0609001 ↗] [▷ arXiv 0707.0317 ↗].[44]

One of the most enthusiastic proponents of black hole remnants is Professor Dr. Horst Stöcker, the former Honorary Editor (Editor-in-Chief) of the prestigious *Journal of Physics G*, who has gone so far as to patent the idea of using black hole remnants as a novel energy source [StöckPat ↗] [StöckPat ↗] [▷ ADDCITE Schwarze Löcher im Labor? ↗]. He has calculated that a billion black hole remnants stored in the LHC's rings could be used to convert 10 tons of ordinary matter into 10^{21} Joules of energy each year [Stöck06 p. S433 ↗] [for a slightly less detailed account, see Stöck06arXiv section 6, pp. 6–7], at an average rate of ~ 32,000 GW [cf. GM p. 28]. Professor Dr. Stöcker does not appear to have considered, however, the thermal or environmental consequences of black hole remnants which have escaped from the LHC and been trapped within the Earth, where they would continue to convert matter into gamma rays [Hoss07 ↗] or other high-energy particles.[45]

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[44] One of the other popular programmes is the BlackMax event generator. This programme incorporates a number of important factors for its simulation of black hole production and evolution, but it does not include an option for a stable remnant [▷ arXiv 0711.3012 ↗]. The authors of the programme acknowledge that in the absence of a self-consistent theory of quantum gravity, the final phase of a black hole cannot be described accurately, but the only option that their programme allows is a final burst of particles which conserves energy, momentum, and gauge quantum numbers [▷ arXiv 0711.3012 pp. 11–12 ↗]. The QBH event generator (version 1.01) also assumes that quantum black holes decay entirely without leaving a remnant [Ging09 p. 11 ↗].

[45] A paper by Koch, Bleicher, and Stöcker [KBS08v2 arXiv ↗] has been cited by CERN as an independent assessment of the safety of black hole scenarios at the LHC. CERN's website quotes the paper's concluding statement that:

> We discussed the logically possible black hole evolution paths. Then we discussed every single outcome of those paths and showed that none of the physically sensible paths can lead to a black hole disaster at the LHC. [CERN08b ↗, citing KBS08v1 arXiv p. 7 ↗]

For the scenario most favoured by CERN in which all black holes radiate very rapidly, the Koch/Bleicher/Stöcker paper only states that, "From this estimate it is clear that such mini black holes that are produced on the earth can never grow." [KBS08v2 arXiv p. 6 hrefhttp://arxiv.org/pdf/0807.3349v2↗], which, given the authors'

The possible catastrophic risks associated with black hole remnants are (to be) discussed further in sections 9.4 and 9.9 on the safety implications of neutral or charged rapidly radiating black holes.[46]

5.4.2 Stable Remnants from Pair-Produced Black Holes with Conserved Quantum Numbers

While the above section identified a number of reasons why Planck-sized remnants may be expected from all rapidly radiating black holes, this issue cannot be considered as resolved, and other possibilities should be considered. One of the most common assumptions is that black holes typically end their lives in a burst of Standard Model particles. Even if this is the usual case, an important exception is pair-produced black holes with conserved quantum numbers.

The stability of pair-produced black holes is acknowledged in the earlier report by the LHC Safety Study Group (LSSG). The report notes the following:

> Even this bound is weaker than is necessary because black holes decay (unless they carry a conserved quantum number Q, in which case extremal black holes with mass $M = Q$ are stable — see below for a discussion of this case). [LSSG p. 10]
> . . .

previous statements, clearly leaves open the possibility of these black holes persisting as stable, but non-growing, remnants. The remnants would not be able to significantly increase their size, but they would continually accrete matter and emit radiation. Their independent safety assessment includes no analysis of the thermal risks or other environmental effects of black hole remnants trapped in the Earth.

[46]As the text of those sections is still under revision, a few important points are noted here. When only a small change in the Earth's internal heat balance could have a potentially disastrous effect on the planet, the possibility of remnants producing almost as much energy as the Earth generates each year raises a rather large red flag for the idea of creating billions of microscopic black holes at the LHC. On the other hand, the estimate given by Professor Dr. Stöcker applies specifically to a billion black holes trapped at the LHC and being used in a way which may maximize the column density they cover each second. Presumably, the energy production rate of remnants "in the wild" would be much less, although this assumption should be checked. But, even if their energy production rate per remnant is much lower, a proportionate increase in their total numbers would result in the same output. If the LHC's operation does not produce enough remnants to pose a threat, the subsequent operation of the Super Large Hadron Collider (SLHC) could significantly increase their expected numbers, and the long-term plan to build a Very Large Hadron Collider (VLHC) could boost their numbers by several orders of magnitude. Professors Giddings and Thomas have estimated that with a centre-of-mass energy of 100 TeV and an integrated luminosity of 100 fb^{-1} per year, the VLHC would, if $M_D = 1$ TeV and $D = 10$, produce black holes of average initial mass of roughly 10 TeV at a rate of ~ 1,000 per second [GT02 arXiv p. 12 ↗]. Another key issue is how long these remnants would last. From the discussion of this section it seems they would last a very long-time, if not forever. However, one possible way for their total numbers to decrease over time is through mergers. If, for example, a positively charged black hole remnant merged with a negatively charged remnant, all that would be left, after a brief period of radiation, would be a single neutral remnant [HKB05 p. 5 ↗]. Mergers could be arranged for charged remnants trapped in the LHC's rings, but within the Earth the rate may be very low for charged remnant mergers, and even lower for neutral remnant mergers. It may be that their numbers within the planet would only be reduced if their interactions give them enough momentum to leave the Earth and be spread across the Solar System and more distant space.

> One might worry that the discussion presented above fails for the case of a new conserved quantum number Q stabilizing the black hole. However, this is not the case because only extremal black holes are stable; others will rapidly decay to extremal black holes in the manner just discussed. Extremal black holes have $M = Q$ and so can only grow provided there is the source of the absolutely conserved quantum number Q. We know that normal matter does not possess such a quantum number and so there is no source of matter capable of causing the extremal black hole to grow, even if the LHC energy is capable of producing the new charge and thus a new stable form of matter. [LSSG pp. 12–13, hyperlinks added]

The LSAG report also acknowledges the possibility of such stable remnants:

> The case of pair production of black holes carrying new and opposite conserved quantum numbers leads to similar conclusions: only their ground state is guaranteed to be stable, and any further accretion of normal matter in the form of quarks, gluons or leptons would immediately be radiated away. [LSAG p. 7, hyperlinks added]

An important question which is not answered in either the LSSG report or the LSAG report is what percentage of microscopic black holes would be pair-produced. Admittedly, this may not be easy to estimate, since it may require a working theory of quantum gravity and a resolution of several other fundamental questions of physics.

The GM paper does not address this issue at all. Even though it focuses exclusively on stable TeV-scale black holes, and even though Professor Giddings has previously co-authored an article on the pair-production of extremal black holes [▷ arXiv 9312172v2 ↗], the GM paper makes no mention whatsoever of pair-produced black holes.

The possible safety implication of such black holes are (to be) discussed further in sections 9.5 and 9.10.

6 Charge Retention of Black Holes

TEXT UNDER REVISION

6.1 Charge Retention of Stable Black Holes

6.2 Charge Retention of Radiating Black Holes

7 Production and Trapping of Black Holes

This section reviews the possibility of black holes being produced in cosmic ray collisions and subsequently being trapped in the Earth, the Moon, or the Sun, or in white dwarfs or neutron stars. It also assesses the possibility of black holes being produced at the LHC and then being trapped in the Earth, the Moon, or the Sun.

The case of neutral stable black holes is examined in depth, and the case of charged stable black holes is also carefully reviewed. The trapping of neutral or charged radiating black holes has not been addressed in the GM paper [GM ↗], and the analysis in this paper focuses mainly on how these cases may or may not differ from that of stable black holes.

7.1 Production and Trapping of Neutral Stable Black Holes

This section reviews the possible production and trapping of neutral stable black holes on various astronomical objects. This case is the main focus of the GM paper, and is reviewed in some detail here. It will also serve as a reference point for the other cases of neutral radiating black holes (sections 7.2, 7.3, 7.4, and 7.5).

7.1.1 Cosmic Ray Production and Trapping in the Earth

§ Production in Cosmic Rays Collisions with the Earth

The production of black holes in cosmic ray collisions with the Earth may be possible, subject to the various factors outlined in section 4. The specific details of possible production are not examined further here in light of the discussion on trapping below.

§ Trapping in the Earth after Cosmic Ray Production

The GM paper examines the process through which gravitational scattering and the absorption of other particles can slow down neutral stable black holes and concludes that:

> In view of the value for Earth $d_0(E) \approx 3\times10^{11}$ cm, these mechanisms cannot efficiently slow down neutral CR-produced black holes in Earth, or in other bodies such as planets and ordinary stars[14]. [GM p. 33]

The importance of this finding is discussed further in section 10.1.1.

7.1.2 Cosmic Ray Production and Trapping in the Moon

§ Production in Cosmic Rays Collisions with the Moon

The GM paper does not review the possibility of cosmic rays producing black holes in collisions with the Moon, however, the situation may be similar to that of the Earth (with a reduction due to the Moon's smaller surface area). The key issue, though, is the trapping of such black holes, as noted below.

§ Trapping in the Moon after Cosmic Ray Production

The GM paper's finding that neutral stable black holes cannot be trapped by the Earth or other bodies such as planets and ordinary stars [GM p. 33] also applies to the Moon, which the GM paper describes as having "limited stopping power" [GM p. 84]. Thus, no neutral stable black holes are expected to have been trapped by the Moon.

7.1.3 Cosmic Ray Production and Trapping in the Sun

§ Production in Cosmic Rays Collisions with the Sun

The production of black holes in cosmic ray collisions with the Sun may be similar to the case of the Earth described above, but with a significant increase in the number due to the size of the Sun. The LSAG report notes that the effective surface area of the Sun is about 10,000 times that of the Earth [LSAG p. 4], so the number of black holes produced in the Sun's history should be roughly 10,000 times that of the Earth. The issue of trapping, however, is discussed below.

§ Trapping in the Sun after Cosmic Ray Production

As noted in the case of the Earth, the GM paper states:

> In view of the value for Earth $d_0(E) \approx 3\times10^{11}$ cm, these mechanisms cannot efficiently slow down neutral CR-produced black holes in Earth, or in other bodies such as planets and ordinary stars[14]. [GM p. 33]

The footnote for this quote further adds that:

> As a consequence of this, neutral black holes produced during head-on collisions of cosmic rays within the galaxy will freely escape the galaxy, not being trapped by either collisions with the interstellar medium and stars, or by the galactic magnetic field. [GM p. 33, hyperlinks added]

The Sun is considered an ordinary star and thus is not expected to have ever trapped any neutral stable black hole produced by cosmic rays.

The significance of this finding is discussed further in section 10.1.3

7.1.4 Cosmic Ray Production and Trapping in White Dwarfs

§ Production in Cosmic Rays Collisions with White Dwarfs

As the discussion further below finds that in some scenarios, a few white dwarfs may be able to trap neutral stable black holes, the question of their cosmic ray production rates becomes important, so it is reviewed more closely here.

The GM paper presents its estimates of black hole production rates in table 2, which includes figures for both a 100% proton and 100% iron cosmic ray flux [GM p. 40 2]. The figures are limited to the cases of 5, 6, or 7 dimensions, since these are the cases for which a white dwarf astrophysical argument is given. Table 2 indicates that the number of 7 TeV black holes produced is between 21,000,000 and 67,000,000 every million years for a 100% proton flux, and between 72,000 and 260,000 for a 100% iron flux. For the production of a 14 TeV black hole, the corresponding numbers are 2,300,000 to 10,000,000 every million years for a 100% proton flux, and 7,300 to 38,000 for a 100% iron flux.

Before reviewing the different factors which can affect the production numbers, a couple points should be noted. The first is that these are simply rates for the cosmic ray-production of black holes on the surface of a white dwarf, and not the rates for black holes being trapped within a white dwarf. Those rates are discussed further below.

A second point to note is that the assumption of a 100% proton flux is unrealistic and, by the GM paper's own admission, inconsistent with the available data [GM pp. 73–74]. On the other hand, the assumption of 100% iron can also be considered unrealistic, or, as the GM paper describes, "the totally extreme case" [GM p. 40]. It would be a mistake, however, to simply assume that the real situation lies somewhere roughly in the middle. The GM paper's supposedly conservative proposal of a 10% proton flux (for a given level of total cosmic ray energy) was critiqued in section 3 as simply being a way of packaging a scenario which is still very much proton-dominated. The assumption of a 100% composition of any single element is obviously an extreme case, but it is not clear if the true black hole production rates are significantly different from one of the extreme scenarios.

A more realistic guess about the hadronic component of cosmic rays would ultimately be based on assumptions about the proportion of different elements among whatever is being accelerated to produce cosmic rays. Instead of assuming 100% protons, or 100% iron, one could, for example, assume 50% protons and 50% other heavier elements, or 50% iron and 50% other lighter elements. This is, however, where an important assymmetry in the situation for proton and iron comes into play. For a proton-based injection, if other heavier elements are added and accelerated to the same energy per charged nucleon (i.e. per proton), then these other elements will begin to dominate the composition for a given level of total cosmic ray energies, since the (integral) cosmic ray spectrum is dropping off as the square of the total energy [cf. LSAG p. 4, endnote 6, for the differential spectrum]. For iron, on the other hand, the addition of other lighter elements at injection would have much less of an effect on the composition of cosmic rays at a given total energy level, since those other elements would result in cosmic rays which have lower total energies, and which would be overshadowed by more numerous iron nuclei with lower energy levels per proton but equal total cosmic ray energies. Visually, one can picture changes in the composition of a proton-dominated injection resulting in a very wide spread in the rate of cosmic ray-induced black hole production, whereas changes in the composition of an iron-dominated injection would result in production rates which would still be clustered near the 100% iron extreme.

As the purpose of both this paper and the GM paper is to assess the risks associated with black hole production at the LHC, it is not actually necessary to make a final choice between the cases of a 100% proton or 100% iron flux, or to settle on a compromise between the two. A standard approach for a risk assessment would be to treat these cases separately, and simply assign a probability for each of them. Such an approach would likely result in a more significant risk being associated with the iron-dominated case, so that will be the primary focus of the remainder of this section (even though risks may still be associated with the proton-dominated case). Based on the discussion in the previous paragraph, the case of 100% iron is viewed in this paper simply as a reference point for the iron-dominated case, whose true black hole production rates should be slightly higher. It is not considered, however, a "totally extreme case" in the sense of being overly conservative or numerically unrealistic.

Aside from the above points, there are a number of other factors which can affect the cosmic ray-induced black hole production rate. They are reviewed briefly below:

General Factors Affecting the Cosmic Ray Flux - As outlined in section 4.2.6, factors such as errors in the measurement of the cosmic ray flux, problems with the hadronic models used to interpret cosmic ray events, possible non-hadronic components of the ultrahigh-energy flux, and historical variations in the flux could all have a significant effect on the expected black hole production rates. Of these various factors, the GM paper only considers the effects of a possible overestimate of cosmic ray energies due to the official energy resolution of measurements from the Pierre Augur Observatory (PAO) [GM pp. 40, 74], and only considers this in a separate, sample calculation [GM p. 74, table 6], which, as noted in section 2, found a 40% to 55% reduction in the estimated production rates. The other black hole production numbers given in the GM paper for white dwarfs do not include the effects of this possible error in the cosmic ray data [GM pp. 40, 73, 74, 75, tables 2, 4, 5, 7, figure 6]. Both the question of measurement errors and the other possible factors affecting the cosmic ray flux can be seen as assuming even greater importance when analyzing the production of black holes from iron cosmic rays with energies above 10^{19} eV [GM pp. 73, 75, figures 5, 6]

Effects of Magnetic Fields on Ultrahigh-Energy Cosmic Rays - Assuming a given cosmic ray flux, the GM paper does analyze the effects that magnetic fields could have on cosmic rays actually reaching a white dwarf and producing black holes. The two effects it considers are the deflection of cosmic rays away from an object, and the reduction of cosmic ray energies due to synchrotron radiation [GM pp. 38–39, 84–85]. For the first effect, the GM paper finds that for cosmic rays with energies in the range of 10^{18} or more and a white dwarf's magnetic field of 1,000,000 Gauss (1 MG), the deflections would be relatively small (and even smaller for weaker magnetic fields). For the second effect, the GM paper finds that it is, indeed, important, and for this reason states that in order to avoid significant magnetic screening it must consider white dwarfs with magnetic fields $B_p \lesssim$ few$\times$ 100,000 Gauss [GM p. 39].[47] It is not clear from the text, however, if the given black hole production rates take into account the reductions due to possible deflections of cosmic rays which might otherwise strike almost parallel to the surface of the white dwarf, or the reductions due to synchrotron radiation energy losses. The GM paper cites WD0652–563 as one of its examples to prove the safety of black holes, and lists the magnetic field strength of this white dwarf as $B_p < 270{,}000$ Gauss [GM p. 45]. Applying the paper's equation for synchrotron radiation losses for cosmic rays [GM p. 39, eq. 6.4], assuming a radius of 5000 km, and using 270,000 Gauss as a reference value, the maximum possible energy would be about 4.94 $\times 10^{19}$ eV (for $\theta = \pi/2$) for a proton cosmic ray striking such a white dwarf, and about 1.06 $\times 10^2 1$ eV for an iron cosmic ray (after multiplying by $(A/Z)^4$ [GM p. 85, eq. G.6]). This would not be a signficant restriction for iron cosmic rays, but looking at figure 5 (right graph) [GM p. 73, figure 5] and figure 6 [GM p. 75, figure 6], one can readily see that for the proton component of the flux this restriction would cut off a noticeable portion of black hole production from the most energetic cosmic rays, and would likely also reduce production from cosmic rays with initial energies just below that limit. (Both of these factors may involve relatively modest reductions in the total black hole production rates, but the issue of deflection is revisited below in the discussion on trapping, for which its impact may be more significant.)

Variations in Surface Areas - All of the GM paper's calculations of the black hole production rate for white dwarfs are based on the assumption of a 5400 km radius [GM pp. 40, 73, 74, 75, tables 2, 4, 5, 6, 7]. While this is a reasonable (but not conservative) value for a white dwarf with a mass of 1.0 $M_\odot$, it may not be appropriate for the heavier white dwarfs cited by the paper. The radii of white dwarfs are inversely proportionate to their masses, and begin to drop off rapidly as they approach the Chandrasekhar limit [▷ ADDCITE]. The first three candidate white dwarfs cited by the GM paper (WD0346-011, WD1022-301, and WD1724-359 [GM pp. 44–45] have estimated masses equal to or greater than 1.20 $M_\odot$, so their radii may be expected to be significantly less than 5400 km. The corresponding reductions in the black hole production rate would be proportionate to the square of the relative reductions in their radii. A further issue is that some white dwarfs have been found to have unexpectedly small radii when compared with standard predictions [PSHT98 p. 764, figure 2]. This finding underlines the need to have estimated production rates for individual white dwarfs based on verified observations of their actual radii.

Artificial Restrictions on the Minimum Mass of Black Holes - As noted in section 4.2.1, the GM paper artificially sets what it claims to be a conservative criterion that black holes must have masses at least three times greater than the value of M_D [GM pp. 39-40, 70].[48] This criterion

[47] The text does mention that bounds from white dwarfs with larger magnetic fields are still achievable through cosmic rays striking at angles closer to the magnetic poles, but it says that this leads to a reduction of rates for acceptable cosmic rays [GM p. 39 ↗], and it does not provide any specific production rates or attempt to make an astrophysical argument based on cosmic rays directly striking such stars. For these reasons, only the case of white dwarfs with weaker magnetic fields is considered in this paper for the safety argument based on direct cosmic ray production of black holes.

[48] The GM papers argues that this criterion is conservative compared to the benchmark of $M_{min} = 5M_D$ used in

was originally based on the size required for the hypothesized radiation of a black hole to be observable, but it does not reflect the true rate of black hole production, and it is not relevant for the case of neutral stable black holes. Adopting instead the assumption that masses of M_D are sufficient for black hole production, the estimated black hole production rates from the GM paper would need to be significantly revised. When considering the rates for a given value of M_D the total production rates would actually be much higher, since lighter black holes could be produced and they would be much more numerous than the black holes counted by the GM paper [cf. DL01 arXiv p. 3, figure 2]. On the other hand, under this new assumption it would be more appropriate to index the production rates for black holes of a given mass by the same value for M_D. If the rates are presented this way, they would show a very significant decrease. For example, when considering the production rates for 3 TeV black holes, the graph published by Dimopoulos and Landsberg indicates that the number of black holes (detected through the electron or photon decay channels) would be about 13 times lower for $M_D = 3$ TeV compared to $M_D = 1$ TeV when $D = 6$, and about 31 times lower when $D = 11$[49] [DL01 arXiv p. 3, figure 2]. Moreover, these figures are based on semiclassical arguments which are strictly valid only for $M_{BH} \gg M_D$ [DL01 arXiv p. 1]. The true rates, when the effects of quantum gravity are included [cf. GT02 arXiv p. 7], could be very different indeed!

Unrealistic Assumptions for the Inelasticity of Collisions - One of the key uncertainties for black hole production through cosmic ray collisions or at the LHC is the value of the inelasticity, y, for the collisions. If the value of y is close to one, more energy from a collision can be used to create a black hole, and thus cosmic rays of lower energies would be sufficient for black hole production. On the other hand, if the value of y is lower, then the less frequent cosmic rays of higher energies would be required to produce black holes. For the purpose of developing a conservative estimate of the cosmic ray production rate, a natural expectation is that the lowest conceivable value of y would be adopted. As noted earlier, for the production of heavier black holes (with masses greater than 7 TeV), it appears that an earlier draft of the GM paper consistently adopted a value of 0.5 for y [GM.ltx lines 3662–3664 ↗]–a value which is not a worst case (the GM paper only describes $y = 0.5$ as a "lower than expected value" and does not claim that it is a lower bound [GM p. 39]), but it is a value which can at least be considered reasonably conservative. Regrettably, the final draft of the GM paper abandoned this approach and instead adopted the assumption that y was equal to $M_{min}/14$ TeV [GM pp. 40, 73, 74, tables 2, 4, 5, 6]. Thus, in this case the GM paper is assuming that for the production of 14 TeV black holes from cosmic rays, the value of y would be 1–a value which the GM paper itself describes as "an unrealistic extreme" [GM p. 39]. Clearly this is not a conservative assumption. The GM paper justifies this assumption with the argument that the same value of y would be needed for black holes of that mass to be produced at the LHC [GM p. 39], but it fails to inform readers that all the estimated black hole production rates based on this assumption [GM pp. 40, 73, 74, tables 2, 4, 5, 6]

the Giddings and Thomas paper [GT02 arXiv p. 8 ↗]

[49] The case of $D = 11$ is not directly relevant to the white dwarf astrophysical argument, which only applies to the cases of $D = 5$, 6, or 7. It has been mentioned here simply because it is the only other case included in the graph and it gives readers an idea of the dependence of this result on the value of D.

are extremely optimistic.[50] (In fact, it appears that it may have taken steps to downplay this fact, as an earlier draft of table 8, for example, shows explicitly the value of y adopted for each value of M_{min} [GM.ltx lines 3965, 3967, 3969, 3971, 3973, 3979, 3981, 3983, 3985, 3987 ↗], but in the final version this has been replaced in all but the final column with the statement that $y = M_{min}/14$ TeV [GM p. 76, table 8].) For white dwarfs, the vestiges of the conservative approach left in the final draft are table 7 [GM p. 75, table 7], figure 6 [GM p. 75, figure 6], figure 9 [GM p. 78, figure 9], and the last column of table 8 [GM p. 76, table 8], which are included for reference in Appendix E.2 [GM pp. 72–78] but are not incorporated in the cosmic ray production rates highlighted in the main text [GM p. 40, table 2], and are only mentioned in a final remark at the end of section 6.2 [GM p. 40].[51] The effects of returning to a conservative assumption are quite dramatic. For the case of a 100% proton flux, the estimated black hole production rates are reduced by factors ranging from 8.2 in 5 dimensions up to 11.0 in 7 dimension. For a 100% iron flux, the reduction factors are even greater: 209 in 5 dimensions, 263 in 6 dimensions, and 281 in 7 dimensions [GM pp. 40, 75, tables 2, 7]. Moreover, for the case of a 100% iron flux, no black holes whatsoever would be expected from cosmic rays with energies less than an order of magnitude below the most energetic cosmic ray ever observed [GM p. 75, figure 6].

Dependability of Special Relativity - As explained in section 4.2.6, any cosmic ray argument for the safety of LHC collisions involves applying the theory of special relativity to a collision with a highly relativistic centre-of-mass. While it seems unlikely that there would be significant deviations from special relativity for cosmic rays with energies of about 10^{17} eV, the same cannot be said for cosmic rays with energies close to 10^{20} eV. The highest observed energies for cosmic rays is approximately 3×10^{20} eV [LSAG p. 5, figure 1], so this is a region close to the limits of recorded physics. It is also well above the region for which special relativity has been experimentally tested [cf. LSAG p. 4, endnote 4]. In this situation, it is not unreasonable to wonder whether special relativity still holds for such energies, or whether that level marks the start of "new physics" [HH02 arXiv p. 6]. Unfortunately, most of the anticipated production of black holes by iron cosmic rays involve energies of around 10^{20} eV [GM pp. 73, 75, figures 5, 6], so if there is a significant deviation from special relativity in this region, the safety argument for an iron-dominated cosmic may no longer apply.

FURTHER TEXT PENDING

[50] Unlike the case of the LHC, the possibility of $y = 1$ is not strictly necessary for cosmic ray production of 14 TeV black holes, since there are cosmic rays which collide with centre-of-mass energies greater than 14 TeV. The only purpose behind adopting the value of $y = 1$ for cosmic ray collisions is to increase the predicted black hole production rates.

[51] As mentioned earlier, one may note that the GM paper's black hole production rates for hypothetical ultrahigh-energy neutrino cosmic rays are based solely on the conservative assumption of $y = 0.5$ [GM pp. 47, 79, 80, table 10, figure 10 ↗]

§ Trapping in White Dwarfs after Cosmic Ray Production

TEXT UNDER REVISION

§ Candidate White Dwarfs for Production and Trapping of Black Holes

The GM paper identifies 8 specific massive or ultramassive white dwarfs which it claims currently have a high enough mass and a low enough magnetic field to trap neutral TeV black holes produced by cosmic rays striking their surface. These "candidate white dwarfs"[52] are summarized in the following table:

Table 1: **Candidate White Dwarfs**

[GM p. 44-45]

No	ID	Mass (est.)	Magnetic Field (est.)	Age (est.)
1	WD0346–011	1.25 $M_\odot$	< 120,000 G	~100 Myr
2	WD1022–301	1.2 $M_\odot$	< 120,000 G	$\gtrsim$100 Myr
3	WD1724–359	1.2 $M_\odot$	< 120,000 G	~150 Myr
4	WD2159–754	1.17 $M_\odot$	< 30,000 G	~2,500 Myr
5	WD0652–563	1.16 $M_\odot$	< 270,000 G	~100 Myr
6	WD1236–495	1.1 $M_\odot$	< 30,000 G	$\gtrsim$1,000 Myr
7	WD2246+223	0.97 $M_\odot$	1,500 ± 13,800 G	~1,500 Myr
8	WD2359–434	0.98 $M_\odot$	3,000 G	~1,500 Myr

These specific candidates are reviewed more carefully in section 10.1.4 on the astrophysical implications of white dwarfs exposed to high energy cosmic rays.

[52] The term "candidate white dwarfs" is used in this paper to mean those white dwarfs which may be suitable for the astrophysical safety argument put forth in the GM paper. It does not mean "white dwarf candidate" in the traditional astronomical sense of a stellar object which is suspected, but not confirmed, to be a white dwarf.

7.1.5 Production in Cosmic Ray Collisions with the Interstellar Medium and Subsequent Trapping in White Dwarfs

To circumvent the restrictions caused by the magnetic fields of white dwarfs, the GM paper presents another construction in its attempt to make an astrophysical argument for the safety of TeV-scale black holes. In this scenario, ultrahigh-energy cosmic rays strike particles in the interstellar medium (ISM) and produce neutral black holes which can then be trapped by white dwarfs, regardless of their magnetic fields. The details of the production and trapping of these black holes are reviewed below.

(The case black holes produced in the ISM and being trapped in neutron stars is discussed in section 7.1.9)

§ Production in Cosmic Ray Collisions with the Interstellar Medium

TEXT UNDER REVISION

§ Trapping in White Dwarfs after Production in Cosmic Ray Collisions with the Interstellar Medium

TEXT UNDER REVISION

§ Additional Candidate White Dwarf for Black Hole Trapping after Production in Cosmic Ray Collisions with the Interstellar Medium

The possibility of production of black holes in the interstellar medium adds less than 0.014% [GM p. 87] to the expected black hole production rates for the 8 candidate white dwarfs identified in section 7.1.4, but for those few ISM-produced black holes, uncertainties in the present or past magnetic fields of those white dwarfs would not be a factor.

The main purpose of this construction, however, is the inclusion of white dwarfs with strong magnetic fields as possible candidates for demonstrating the safety of black hole production. The paper cites a single massive white dwarf, Sirius-B, as an additional candidate [GM p. 87]. Its details are summarized in the following table:

Table 2: **Additional Candidate White Dwarfs from ISM Production**

No	Name	Mass (est.)	Magnetic Field (est.)	Age (est.)
1	Sirius-B	1 $M_\odot$	not applicable	~120 Myr

7.1.6 Production in Cosmic Ray Collisions with Dark Matter and Trapping in White Dwarfs

A final possibility mentioned at the end of the introduction [GM p. 6] and described in the last paragraph of the Appendix [GM p. 87] is that cosmic rays could strike massive weakly-interacting dark matter and thus produce neutral TeV-scale black holes. The GM paper predicts that the expected densities could be sufficient to generate large numbers of black holes which could be absorbed by white dwarfs. The paper further notes that the lower velocities expected for black holes produced on such heavy targets could facilitate their capture by lighter white dwarfs, and extend the stopping potential of white dwarfs to black holes significantly heavier than those within the range of the LHC.

The paper does note, however, that "...lack of direct experimental evidence for it makes it insufficient today for our purposes..." [GM p. 87], which is the authors' way of admitting that they do not even know whether massive weakly-interacting dark matter actually exists.

It may be noted that microscopic black holes have themselves been suggested as a possible component of the dark matter in the Universe. This possibility was proposed in a paper from CERN's Theory Department for scenarios with extra dimensions and TeV-scale gravity [ADMR98 arXiv ↗]. As these are the underlying assumptions of the GM paper, it further highlights the need to determine what dark matter actually is before giving serious consideration to a safety argument based on its properties.

7.1.7 Cosmic Ray Production and Trapping in Neutron Stars

As the astrophysical argument for white dwarfs is limited to the cases of 5, 6 or 7 dimensions, the GM paper turns to neutron stars to provide a bound on the risk of black holes should there be 8 or more dimensions [GM p. 38].

§ Production in Cosmic Ray Collisions with Neutron Stars

The production of black holes by cosmic rays striking neutron stars is referred to in the abstract of the GM paper, which states:

> We argue that cases with such effect at shorter times than the solar lifetime are ruled out, since in these scenarios black holes produced by cosmic rays impinging on much denser white dwarfs and neutron stars would then catalyze their decay on timescales incompatible with their known lifetimes. [GM abstract]

It is mentioned again in the conclusion of the GM paper which refers to the "significant production rates on neutron stars when $D \geq 8$" [GM p. 52].

The main LSAG report similarly states:

> In fact, ultra-high-energy cosmic rays hitting dense stars such as white dwarfs and neutron stars would have produced black holes copiously during their lifetimes. [LSAG p. 9, hyperlink added]

The details of this production and its implications are reviewed further in the introductory part of section 8.1 of the GM paper [GM p. 45]. The paper notes that neutron stars are very common in the Universe and provide robust examples of long-lived objects in other galaxies. Neutron stars are extremely dense objects, and the authors suggest that the introduction of a microscopic black hole into a neutron star would rapidly catalyze its decay into a macroscopic black hole. The paper does note, however, that neutron stars have strong magnetic fields which limit the maximum energy of proton and iron cosmic rays impinging perpendicular to the magnetic field axis. This limit can be avoided for cosmic rays incident near the magnetic poles, but this reduces the acceptable flux by a factor of 10^{-3} which, the authors note, considerably weaken the resulting bounds [GM p. 45].

The production rates per million years are summarized in table 3, which has the following title:

> *Summary of black hole production rates, per million years, induced by proton cosmic rays impinging on a $R = 10$ km neutron star. $M_D = M_{min}/3$ and $y = M_{min}/14$ TeV.* [GM p. 46, 3]

The table shows the estimated number of black holes produced of masses 7, 10, 12, and 14 TeV for the cases of 8, 9, 10, and 11 dimensions. These numbers range from a low of 54 to a high of 633 black holes per million years. The weakening of the bounds is clear when compared to the rates for white dwarfs shown in table 2, which range from 7,300 up to 67,000,000 per million years [GM p. 40, 2]. Nevertheless, even the lowest figure of 54 would imply approximately 5,400 black holes being produced over 100 million years, which should easily be enough to conclude that a black hole must have been produced on any neutron star of that age.

The data in the table seem to be at odds, however, with the conclusion of Appendix G [GM pp. 84–85], which, after analyzing the effects of magnetic fields on the black hole production rate, clearly states:

> These numbers are too small to allow sufficient rate for all cases, and specifically those at the highest black hole masses. [GM p. 85]

The numbers in table 3 would seem to be sufficient, even in the case of the highest black hole masses. The following convoluted clarification is given in the text:

> In order to compute the actual production rate on the neutron star, we use the uncorrected rates of Appendix E, times the number of years of *FCE*. A survey of known classes of binary systems (see Appendix H.1) reliably yields FCE's in the 2 Myr range, resulting from systems with a 1 Gyr lifespan. The neutron star production rates are exhibited in table 9 and in fig. 8 of Appendix E.2. A summary of that table, focusing on the most interesting cases of $D \geq 8$, is shown here in table 3. [GM p. 46]

Appendix E contains 7 tables and 9 figures [GM pp. 69–79], so it may not be immediately clear which rates are "uncorrected", but the following sentences refer to table 9 [GM p. 77, table 9]. Table 9 itself does not mention anything about its data being "uncorrected", but the text on the previous page includes the sentence:

> The production rates on a neutron star (neglecting the magnetic screening) can be obtained from the white dwarf's ones by rescaling by the surface area. Assuming a 10 km radius, the proton rates in Table 4 are reduced by a factor of 3.4×10^{-6}, leading to the numbers in Table 9. [GM p. 76]

Thus, with a bit of digging it becomes clear that "uncorrected" means neglecting the powerful magnetic screening of neutron stars. At this point it also becomes clear that the figures in table 3 have no relationship with the actual number of black holes produced by cosmic rays impinging on a $R = 10$ km neutron star. In order to arrive at those numbers one must also divide the figures in table 3 by the factor of 10^{-3} mentioned in the text [GM pp. 45, 85] to take into account a neutron star's very limited acceptance of ultrahigh-energy cosmic rays.

Given the comments in the abstract and conclusion of the GM paper about cosmic rays producing black holes on neutron stars [GM abstract, p. 52], and the claim in the LSAG report that cosmic rays hitting neutron stars "would have produced black holes copiously during their lifetimes" [LSAG p. 9], one may be left with the suspicion that the authors and CERN were deliberately trying to obscure the finding that an insufficient number of black holes would be produced by cosmic rays striking neutron stars [GM p. 85]. While obscuring inconvenient truths may be part and parcel of a spin doctor's trade, it would mark a new low for a prestigious scientific institution like CERN to knowingly publish a table in a peer-reviewed journal with data that has been inflated by at least three orders of magnitude [GMPhysD p. 23, table III ↗].[53]

One may give CERN the benefit of the doubt and assume that it was just a case of a poorly worded title, since the text clarifies that table 3 relates to the production of black holes in binary systems. Even in this case, the table is still extremely misleading since it claims to be the rate of black hole production "per million years", which readers will naturally assume to actually mean "per million years".[54] The explanation in the text about table 3 [GM p. 46] facilitates this interpretation since if one were to read it without carefully cross-checking every detail with the appendix, the impression would be that some uncorrected rates in Appendix E must be multiplied by the number of years of "FCE" (full-coverage equivalent–explained further below), which are confirmed to be in the 2 million year range, resulting in the production rates in table 9 and figure 8, which are then summarized in table 3. Table 3 [GM p. 46, 3] mentions nothing about being the rates being per million years of "FCE", and neither do table 9 [GM p. 77, table 9] or figure 8 [GM p. 77, table 8]. To arrive at the rates per real million years one would have to multiply by the fraction of the sky covered by the neutron star's companion.[55] This fraction would vary depending on the size of the companion and its distance from the neutron star. Appendix H.1 gives a range from 0.002 up to 0.06 [GM p. 86], which implies that the rates in table 3 are actually the number of black holes expected during a time period ranging from 500 million years down to about 17 million years. A careful reader may realize that this is implied in the paper's brief description of a system with 2 million years of FCE [GM p. 46], but this does not change the fact that table 3 mentions nothing about FCE, leaving many readers with the impression that the rates are per real million years.[56]

Aside from the issue of misleading data given in table 3, there are a number of other factors which could lead to a further reduction in the neutron star black hole production rates. Since the GM paper acknowledges that their black hole production rates for cosmic rays directly striking neutron stars "are too small to allow sufficient rate for all cases, and specifically those at the

[53] The phrase "at least three orders of magnitude" has been used since the suppression factor of order 10^{-3} given in the GM paper applies only to neutron stars with the weakest magnetic fields ever observed [GM p. 85 ↗]. Neutron stars with stronger magnetic fields would have even lower rates of direct black hole production. Moreover, other reduction factors are described further below.

[54] For comparison, the immediately previous table is entitled:

> *Black hole production rates, per million years, induced by cosmic rays impinging on a* $R = 5400$ *km white dwarf.* N_p *refers to the case of 100% proton composition,* N_{Fe} *refers to 100% Fe.* $M_D = M_{min}/3$ *and* $y = M_{min}/14$ *TeV.* [GM p. 40, table 2 ↗]

In that case the rates "per million years" really means "per million years".

[55] The GM paper states that the actual production rate is calculated by multiplying "uncorrected rates" by the number of years of FCE. This calculation gives the total integrated black hole exposure over the lifetime of the object–not the time-based production rate. The production rate could be calculated by dividing by the object's estimated age.

[56] For those who may still be inclined to write this off as a simple misunderstanding, one can further ask why the only tabular data for neutron stars presented in the main text are "uncorrected rates", whose sole purpose should be to serve as a starting point for calculating the true black hole production rates.

highest black hole masses" [GM p. 85],[57] these factors are only briefly listed below. In the next section on neutron stars in binary systems, for which the GM paper claims that there are sufficient production rates for an astrophysical argument, these factors and their quantitative consequences are examined more closely.

▷ ADD SUMMARY of factors

§ Trapping in Neutron Stars after Cosmic Ray Production

The trapping of black holes in neutron stars is a much more straightforward issue. The GM paper states that:

> On the other hand, for a neutron star with densities surpassing 10^{14}gr/cm^3, one has $d_0(NS) \lesssim 0.01\,\text{cm}$. Thus neutron stars can promptly slow down such black holes, and then quickly bring them to below the escape velocity, which for a neutron star is close to $v \sim 1$. [GM p. 33]

The exact distance may vary depending on the number of dimensions, but it would seem reasonable to conclude that a neutron star could trap practically any black hole that reaches it.

§ Candidate Neutron Stars for Production and Trapping of Black Holes

In line with the admission in Appendix G [GM pp. 84–85] that neutron stars are effectively shielded by their magnetic fields, the paper provides no example of a neutron star which the authors claim should have been destroyed by cosmic rays directly striking its surface and producing black holes.

A possible example of a neutron star in a binary system which theoretically could have been affected by black holes produced on its companion is examined in the next section.

[57] The phrasing of this statement leaves open the possibility that the production rates may be sufficient for some cases, including especially those of the lowest black hole masses. The GM paper does not, however, specify which cases it believes have an acceptable production rate, and it does not claim to have an argument involving cosmic rays directly striking neutron stars for any specific black hole mass or number of dimensions. If such a claim is made in the future, the quantitative implications of the various reduction factors could also be considered.

7.1.8 Production in Cosmic Ray Collisions with Binary Companions and Subsequent Trapping in Neutron Stars

This section reviews an alternative construction of the neutron star argument in which black holes are first produced by cosmic rays striking the companion of a neutron star, and, after passing through the companion, are trapped by the neutron star. Since the black hole is assumed to be neutral, it would not be deflected by the neutron star's magnetic field during its transit from the binary companion to the neutron star.

§ Production in Cosmic Ray Collisions with Binary Companions of Neutron Stars

In TeV-gravity scenarios, one may generally expect that black holes could be produced by cosmic rays striking the companions of neutron stars. Some of the exceptions, however, include the following:

- Black hole companions of neutron stars would not be a useful target.
- Neutron star companions of other neutron stars would also not be useful because their magnetic fields would deflect or reduce the energy of cosmic rays.
- White dwarfs with magnetic fields greater than a few hundred thousand Gauss would not be useful targets because their magnetic fields would have a similar effect on the energy of cosmic rays.

Five classes of neutron star binary systems with potentially acceptable companions and configurations are suggested by the GM paper. They are the following:

- Massive X-ray binaries, with a donor star at least 5 times more massive than the Sun
- Neutron stars accreting from a solar mass red giant companion
- Traditional low-mass X-ray binaries, with a donor star less massive than the Sun
- Neutron stars with brown dwarf companions
- Ultracompact binaries, with a helium white dwarf donor star

These specific classes are considered in more detail further below.

The approach taken in the GM paper is to define the "full-coverage equivalent" (FCE) of a neutron star's companion as the sum over time of the percentage of the neutron star's sky covered by the companion [GM p. 46, eq. 8.1] . Using this construction, the paper estimates that some binary systems could, over the course of a billion years, result in the neutron star receiving the equivalent of 2 million years worth of the direct cosmic ray exposure it would experience if it had no magnetic field [GM p. 46]. Other systems could potentially lead to 5 or 6 million years of full-coverage equivalent. One of the scenarios involving accretion from a red giant could theoretically result in 30 million years of full-coverage equivalent [GM p. 86]. These possibilities are also considered further further below.

The principal challenge for this construction is ensuring a sufficient rate of expected black hole production. Considering just the reduction in surface area when shrinking down from a white dwarf with a radius of 5400 km to a neutron star of radius 10 km, the expected flux would be multiplied by a factor of 0.0000034 [GM p. 76], which imposes very tight limits on the expected number of black holes.

In addition to this primary issue, there are also a number of other factors which can reduce the expected black hole production rate. These factors were briefly listed in the previous section, but they are examined in more detail here.

Unrealistic Assumptions for the Inelasticity of Collisions - For the case of 14 TeV black holes, the rates given in table 3 of the GM paper [GM p. 46, table 3] are based on the assumption that $y = 1$, even though the paper describes this value as "an unrealistic extreme" [GM p. 39]. If a more conservative value of $y = 0.5$ is used, the rates of table 3 would be significantly reduced.[58] Based on the trends from 14 TeV black holes in 5-7 dimensions [GM pp. 73, 75, tables 4, 7], this reduction would be at least a factor of 10, but the GM paper does not include the data required to calculate this more precisely. For the case of white dwarfs this issue is downplayed, but nonetheless, the relevant data is given in tables 7 and 8 and figure 6 [GM pp. 75, 76, tables 7, 8, figure 6], and the analysis of black hole production in the main text concludes with a calculation assuming $y = 0.5$ [GM p. 40]. For neutrinos striking neutron stars, all the calculations are based on the assumption of $y = 0.5$ [GM pp. 47, 79, table 10]. For hadronic cosmic rays striking neutron stars or their companions, there is no tabular data and no mention in the text of production rates with the assumption that $y = 0.5$. One may note that for the example of a 2 Myr FCE system given in the main text [GM p. 46], if $D = 8$ and $y = 0.5$, a 10% proton flux would produce only 1 black hole in a billion years.[59]

Assumption of a 100% Proton Flux - The rates given in table 3 are based on the assumption of a 100% proton flux–an assumption which the GM paper itself admits is inconsistent with the available data [GM pp. 73–74]. The title of the table states that the data is black hole production "induced by proton cosmic rays", but that does not clearly express the assumption of a 100% proton composition, since the assumption of a 10% proton composition would still result in the vast majority of black holes being "induced by proton cosmic rays". In several other parts of the paper the assumed composition of the flux, whether 100% proton or 100% iron, is explicitly stated in the description of tables or figures [GM pp. 40, 73, 74, 75, 76, 77, tables 2, 6, 7, 8, figures 5, 6, 8]. The only cases in which it is ambiguous in a table or figure's description is for table 4 [GM p. 73, table 4], table 9 [GM p. 77, table 9] (which is based on table 4), and table 3 [GM p. 46, table 3]

[58] As described earlier, it would still be possible for heavier black holes to be produced at the LHC if the value of y had a probability distribution with, say, a median value of $y = 0.6$, but a tail end that extended close to 1 (although falling parton distribution functions would further reduce the probability of such events).

[59] This calculation is based on the assumption that for $D = 8$, approximately 10.8 black holes would be produced by a 10% proton flux over the course of a billion years if $y = 1$, and this rate would be reduced by a factor of at least 10 when adopting the assumption of $y = 0.5$. This calculation does not take into account other factors which could further reduce the production rate.

(which is based on table 9).[60] The GM paper's sample calculation involving the assumption of a 10% proton flux, does, however, take into account the reduced production rate.

No Tabular Data for an Iron-Dominated Flux - For its analysis of black hole production on white dwarfs, the GM paper includes tabular data for both a 100% proton flux and a 100% iron flux [GM p. 40, table 2]. For the case of hadronic cosmic rays striking neutron stars or neutron star companions, the corresponding table includes only the data for a 100% proton flux [GM p. 46, table 3]. The text asserts that for certain types of binary systems, the assumption of a 10% proton flux would result in sufficient black hole production to initiate accretion, but for an iron-dominated flux it simply states that "a greater dominance of heavy elements reduces the range of such bounds", and then argues in favour of a predominantly light composition of cosmic rays [GM pp. 46–47]. The appendix similarly includes a table with production rates for a 100% proton flux [GM p. 77, table 9], but no corresponding table for a 100% iron flux. Information about the iron-dominated case can only be found by examining the two lower curves in figure 8 [GM p. 77, figure 8]. Since CERN has presumably calculated the specific rates for a 100% iron flux, the only apparent reason why a table has not been included is to downplay a scenario it would prefer to avoid. The paper does recognize this issue in the conclusion of its neutron star section [GM p. 50], and in the final conclusion of the paper [GM p. 53], although not in its summary of the case of $D \geq 8$ [GM p. 52].

The problem is that without providing specific numbers, readers may not realize how serious this issue is. The graph of figure 8 suggests a rate of only 0.2 per million years of FCE for 14 TeV minimum mass black holes in 8 dimensions.[61] This would in turn imply that about 64% of neutron stars in binary system with 2 million years of FCE over the course of a billion years would not encounter a single black hole.[62] In the case of 5 million years of FCE, about 33% of neutron stars would not be exposed to any black holes, and for 6 millions years of FCE, 26% of neutron stars would be black hole-free.[63] Only in the case of 30 million years of FCE could one be reasonably confident that the neutron star had met a black hole, since the chance of it not meeting any would be about 0.12%. However, even these rates are overly optimistic since they are based on the assumption that every collision producing a 14 TeV black hole is perfectly inelastic (i.e. $y = 1$) [GM p. 46, table 3]. For a more conservative assumption of $y = 0.5$, a billion-year binary

[60] The possibility for confusion is demonstrated in the final section on production of black holes in the interstellar medium, in which the paper refers readers to table 4 for a 10% proton composition, even though its data is for a 100% proton composition [GM p. 87 ↗].

[61] For consistency, the following calculations follows the GM paper's definition of "minimum mass", although as noted earlier, this does not seem to be a justifiable restriction.

[62] The percentage of neutron stars not encountering a single black hole might actually be a bit higher, since the rate of 0.2 black holes per million years of FCE probably includes the contribution from neutron stars encountering more than one black hole.

[63] As explained in more detail in section 10.1.7, the GM paper's argument is not that no neutron stars have been destroyed by TeV-scale black holes, but that any given neutron star in a binary system with sufficient parameters must have been destroyed if such black holes were dangerous for them. For this type of argument even a 74% exposure/destruction rate is not very useful, since one requires almost 100% certainty that a given neutron star would have been destroyed.

system with 2 million years of FCE [GM p. 46] would have less than a 0.0015% chance of ever encountering a 14 TeV minimum mass black hole (corresponding to a statistical rate of about 1 such black hole every 700 billion years). Even a system with 30 million years of FCE would only have about a 2% chance of ever encountering such a black hole.[64]

Surface Area Uncertainty - The black hole production figures for neutron stars all assume a radius of 10 km [GM pp. 46, 77, tables 3, 9, figure 8], resulting in a surface area of approximately 1257 km^2. While this may be a reasonable average value assuming the standard interpretation of neutron stars, it does not take into account any individual differences for neutron stars, or the possibility that what we think of as neutron stars are composed partly or entirely of stable quark matter. These issues are discussed further in section 8.1.5, but for assessing the reliability of the GM paper's neutron star production rates, one may note that if the real radius of a given "neutron star" is a certain fraction of 10 km, then the paper's production rates should be multiplied by the square of that fraction. For example, if the real radius if a neutron star is 5 km, then the black hole production rates would be 25% of the given estimates.

General Factors Affecting the Cosmic Ray Flux

▷ ADD SUMMARY

FURTHER TEXT PENDING

§ Trapping in Neutron Stars after Production in Cosmic Ray Collisions with Binary Companions

As discussed in section 7.1.7, if a black hole could reach a neutron star, it would almost certainly be trapped.

§ Classes of Binary Systems for Possible Candidates

This section reviews the specific classes cited in the GM paper [GM p. 86] which may be suitable for testing the hypothesis that a given neutron star with sufficient FCE exposure would almost certainly have been destroyed in certain neutral stable black hole scenarios.

In assessing the proposed classes, it should first be noted that the authors have completely abandoned their pledge to make "conservative" or "worst case" assumptions [GM p. 5]. The authors begin their analysis by stating that they would like to understand the range of possible full coverage equivalent values for different neutron star binary systems. They further reassure readers that these systems are well-studied and modeled, and deviations from the values they give

[64] These estimates are based on the previous rate of 0.2 per Myr of FCE divided by 280. The reduction in rates between those of table 5 [GM p. 74, table 5 ↗] and table 7 [GM p. 75, table 7 ↗] for $D = 7$ and $M_{min} = 14$ TeV is a factor of 281. This factor is greater than those for $D = 5$ and $D = 6$, so it is assumed that for $D = 8$ the reduction factor is at least 280.

would require substantial revisions of the theoretical description of the formation and evolution of these systems [GM p. 85]. In reality, the FCE numbers they derive are the absolute maximum possible values for each class [GM p. 86]. Their specific assumptions and calculations are reviewed below.

Massive X-ray Binaries - For these systems, involving donor stars with masses between 5 $M_\odot$ and 50 $M_\odot$, the greatest FCE value will occur when the donor star just underfills its Roche lobe, and the neutron star is only accreting matter from the donor's stellar wind instead of its Roche lobe overflow. In this case, the companion lives out its normal lifespan instead of experiencing an accelerated demise due to accretion by the neutron star. More massive donor stars cover a slightly greater portion of the neutron star's sky, but their lifetimes are much shorter, so their cumulative FCE is less than that of a 5 solar mass donor. The maximum possible FCE for a massive X-ray binary occurs when a neutron star of mass no greater than 1.4 $M_\odot$ is paired with a 5 $M_\odot$ star that is just completing its natural life, always having just underfilled its Roche lobe and never having lost mass through Roche lobe overflow. At that point, according to the authors' calculations, the neutron star will have accumulated approximately 5 million years of FCE [GM p. 86]. Thus, the FCE range for massive X-ray binaries is from 0—as for all X-ray binaries at the start of their conjugal lives—up to a maximum of approximately 5 million years.

Neutron Stars with Solar Mass Red Giant Companions - Neutron stars accreting from solar mass red giants have about 3% of their total sky covered by the donor star when Roche-lobe filling mass transfer is occurring. The paper does not specify what the typical time period for this transfer is, but does mention that if the donor starts Roche-lobe filling at orbital periods of less than 10 days, this mass transfer can last for a billion years. In such cases the FCE values will range from 0, for new binary systems, all the way up to 30 million years at the end of mass transfer.

Traditional Low-Mass X-ray Binaries - The paper describes traditional low-mass X-ray binaries with donor stars of mass less than the Sun as the "best examples", but gives no estimate of the FCE values for such systems that do not involve brown dwarfs. The paper notes that such systems have lifetimes ranging from 100 million to 1 billion years, depending on the rate of mass transfer.

Neutron Stars with Brown Dwarf Companions - A sub-class of traditional low-mass X-ray binaries cited by the paper are systems in which the donor star's mass is approximately 0.05 $M_\odot$, and the donor is believed to be a brown dwarf. The paper notes that mass transfer rates of $10^{-11} M_\odot$ per year would result in the mass transfer lasting for over a billion years, which would give (over) 6 million years of FCE. Thus, such systems could have FCE values ranging from 0, for those at the start of their lives, up to 6 million (or more).

Ultracompact Binaries with a Helium White Dwarf Donor - For ultracompact binaries in which the donor has a mass about 0.01 $M_\odot$, the paper notes that the highest FCE values will occur for systems at the longest orbital period of 40 minutes, resulting in a lifetime of 1 billion years and an FCE total of 2 million years. Thus, the FCE range for such systems is 0 up to 2 million years.

§ Possible Candidate Binary System

From the five different classes of binary systems described above, the paper identifies one specific candidate system for its astrophysical argument [GM p. 86]. The details of this system are summarized in the table below:

Table 3: **Candidate Neutron Star in a Binary System**

No	ID	Donor	Donor Mass (est.)	Donor Solid Angle (f)	Donor Age (est.)	FCE (est.)
1	SAX J1808.4–3658	Brown dwarf	0.05 $M_{\odot}$	0.006	not given	not given

This specific candidate system is examined more closely in section 10.1.8.

7.1.9 Production in Cosmic Ray Collisions with the Interstellar Medium and Subsequent Trapping in Neutron Stars

As a diffuse equivalent of the binary system construction, the GM paper considers the possibility of cosmic rays striking particles in the interstellar medium and producing neutral black holes which can then be trapped by neutron stars or white dwarfs with strong magnetic fields.

(The case of white dwarfs was reviewed in section 7.1.5)

§ Production in Cosmic Ray Collisions with the Interstellar Medium

As noted earlier, the GM paper models stars in the galactic disk as embedded in a disk of interstellar medium with a height of 600 light years and a radius of 36,000 light years. Within this disk the density of the interstellar medium is about 1 proton/cm^3. The paper calculates that the probability of a cosmic ray interacting with the interstellar medium on its path towards a star is about 0.014% [GM p. 87].

The paper then notes that:

> The number of black holes is obtained by applying this reduction factor to the rates calculated for the production of black holes via cosmic rays directly hitting a star. This suppression is too large to give acceptable rates on neutron stars. [GM p. 87]

Thus, by the authors' calculations, this construction is not relevant for neutron stars.

Other possible factors reducing the black hole production rate will be the same as those listed in section 7.1.7.

§ Trapping in Neutron Stars after Production in Cosmic Ray Collisions with the Interstellar Medium

As noted earlier for the other constructions involving neutron stars, if a black hole could reach a neutron star, it would almost certainly be trapped.

7.1.10 Production in Ultrahigh-Energy Neutrino Collisions and Trapping in Neutron Stars

As another approach to avoid the magnetic screening of neutron stars, the GM paper presents a scenario in which ultrahigh-energy neutrinos strike neutron stars and produce black holes. As neutrinos have no charge, they would be unaffected by the neutron star's magnetic field.

§ Production in Ultrahigh-Energy Neutrino Collisions with Neutron Stars

The paper estimates rates ranging from 4,500 up to 62,000 black holes of minimum mass 14 TeV produced every million years by neutrinos striking neutron stars [GM p. 79, table 10]. The authors stress that these rates are based on very conservative assumptions, and do not include the contribution from neutrinos originating directly at cosmic ray sources.

On the hand, the authors note that there are theoretical uncertainties about whether the production of neutrinos through the interaction of primary cosmic rays with the cosmic microwave background photons could be suppressed in models with extra dimensions. The paper states, however, that these suggestions do not appear relevant to the scenarios for which it requires bounds [GM p. 47].

The paper also notes that there are proposals in which neutrino cosmic rays do not produce black holes in the same way that protons or iron cosmic rays would be expected to. The authors say these models are not compelling, but admit a small possibility that this could be a factor [GM p. 47].[65] In general, however, it would seem that a degree of uncertainty will always be inherent in trying to demonstrate the safety of colliding charged hadrons by pointing to collisions caused by neutral leptons.

The largest uncertainty, though, is with the flux of ultrahigh-energy cosmic ray neutrinos. The paper admits the lack of experimental evidence, but appears quite confident about such neutrinos, pointing out that:

> . . . any modeling of cosmic ray production and evolution predicts their presence, with rates that are consistent with the current non-observation. [GM p. 78]

A more critical response is to ask why the paper is even considering an empirical safety argument based on a flux that has never been observed. Such an argument should, at best, be left as a footnote, to be picked up again if and when ultrahigh-energy neutrinos are actually observed.

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[65] The GM paper does not quantify this possibility. Its exact statement is the following:

> While these models are not compelling, they would seem to raise a small possibility that neutrino cosmic rays would not produce black holes the same way that nucleons do. [GM p. 47 ↗]

If one assumes that a model is compelling when there is at least 90% confidence that it is correct, then the first statement is that there is less than a 90% chance that the model is correct and neutrino cosmic rays do not produce black holes in the same way as nucleons. The paper does not specify how much less than 90% its authors consider "a small possibility".

7.1.11 LHC Production and Trapping in the Earth

TEXT UNDER REVISION

§ Production in LHC Collisions

§ Trapping in the Earth after LHC Production

7.1.12 LHC Production and Trapping in the Moon

TEXT UNDER REVISION

§ Production in LHC Collisions

§ Trapping in the Moon after LHC Production

7.1.13 LHC Production and Trapping in the Sun

TEXT UNDER REVISION

§ Production in LHC Collisions

§ Trapping in the Sun after LHC Production

7.1.14 Summary of Production and Trapping of Neutral Stable Black Holes

If neutral stable black holes can be produced in collisions at LHC energies, their expected production and trapping in various astronomical bodies can be summarized as follows:

Earth (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Moon (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Sun (from cosmic rays)

- Black holes may be produced, but none will be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $< 1.0\,M_\odot$, then black holes may be produced, but they may not be trapped.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\approx 1.0\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to ~ 12 TeV in 5 dimensions, up to ~ 7 TeV in 6 dimensions, and up to ~ 6 TeV in 7 dimensions).
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\approx 1.1\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to ~ 15 TeV in 5 dimensions, up to ~ 8 TeV in 6 dimensions, and up to ~ 7 TeV in 7 dimensions).
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\approx 1.2\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to ~ 18 TeV in 5 dimensions, up to ~ 10 TeV in 6 dimensions, and up to ~ 8 TeV in 7 dimensions).

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM, but their trapping in white dwarfs would not be affected by magnetic fields.
- If a white dwarf has a mass $< 1.0\,M_\odot$, then ISM-produced black holes may not be trapped.
- If a white dwarf has a mass $\approx 1.0\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to ~ 12 TeV in 5 dimensions, up to ~ 7 TeV in 6 dimensions, and up to ~ 6 TeV in 7 dimensions.

- If a white dwarf has a mass $\approx 1.1\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to ~ 15 TeV in 5 dimensions, up to ~ 8 TeV in 6 dimensions, and up to ~ 7 TeV in 7 dimensions.
- If a white dwarf has a mass $\approx 1.2\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to ~ 18 TeV in 5 dimensions, up to ~ 10 TeV in 6 dimensions, and up to ~ 8 TeV in 7 dimensions.

White Dwarfs (after dark matter production)

- The nature of dark matter is too uncertain to predict black hole production.

Neutron Stars (from cosmic rays)

- The magnetic fields of all known neutron stars are too strong to permit significant production of black holes from direct cosmic ray collisions.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields, and subsequently trapped in the neutron star.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.

Neutron Stars (after ISM production)

- An insufficient number of black holes would be produced in the ISM for a neutron star argument.

Neutron Stars (from ultrahigh-energy neutrinos)

- There is presently no empirical evidence for a flux of ultrahigh-energy neutrinos.
- If a flux does exist, black hole production in neutrino-hadron collisions may be significantly different from black hole production in hadron-hadron collisions.
- If a significant flux of ultrahigh-energy neutrinos does exist, and if collisions of neutrinos with hadrons has a sufficiently high cross-section for black hole production, then black holes could be trapped in neutron stars.

Neutron Stars (after dark matter production)

- The nature of dark matter is too uncertain to predict black hole production.

Earth (after LHC production)

- A significant number of black holes may be produced and trapped in the Earth, with the expected number dependent on the value of M_D and the number of extra dimensions.

Moon (after LHC production)

- A significant number of black holes may be produced and some may be trapped in the Moon, with the expected number dependent on the value of M_D and the number of extra dimensions.

Sun (after LHC production)

- A significant number of black holes may be produced and some may be trapped in the Sun, with the expected number dependent on the value of M_D and the number of extra dimensions.

7.2 Production and Trapping of Neutral Slowly Radiating Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Moon (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Sun (from cosmic rays)

- Black holes may be produced, but none will be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $< 1.0\,M_\odot$, then black holes may be produced, but they may not be trapped.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\approx 1.0\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to $\sim$ 12 TeV in 5 dimensions, up to $\sim$ 7 TeV in 6 dimensions, and up to $\sim$ 6 TeV in 7 dimensions).
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\approx 1.1\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to $\sim$ 15 TeV in 5 dimensions, up to $\sim$ 8 TeV in 6 dimensions, and up to $\sim$ 7 TeV in 7 dimensions).
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\approx 1.2\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to $\sim$ 18 TeV in 5 dimensions, up to $\sim$ 10 TeV in 6 dimensions, and up to $\sim$ 8 TeV in 7 dimensions).

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM, but their trapping in white dwarfs would not be affected by magnetic fields.
- If a white dwarf has a mass $< 1.0\,M_\odot$, then ISM-produced black holes may not be trapped.
- If a white dwarf has a mass $\approx 1.0\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to $\sim$ 12 TeV in 5 dimensions, up to $\sim$ 7 TeV in 6 dimensions, and up to $\sim$ 6 TeV in 7 dimensions.
- If a white dwarf has a mass $\approx 1.1\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to $\sim$ 15 TeV in 5 dimensions, up to $\sim$ 8 TeV in 6 dimensions, and up to $\sim$ 7 TeV in 7 dimensions.

- If a white dwarf has a mass $\approx 1.2\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to ~ 18 TeV in 5 dimensions, up to ~ 10 TeV in 6 dimensions, and up to ~ 8 TeV in 7 dimensions.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields, and subsequently trapped in the neutron star.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.

Earth (after LHC production)

- A significant number of black holes may be produced and trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, and the rate of radiation.

Moon (after LHC production)

- A significant number of black holes may be produced and some may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, and the rate of radiation.

Sun (after LHC production)

- A significant number of black holes may be produced and some may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, and the rate of radiation.

7.3 Production and Trapping of Neutral Equilibrium Mass Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Moon (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Sun (from cosmic rays)

- Black holes may be produced, but none will be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $< 1.0\,M_\odot$, then black holes may be produced, but they may or may not be trapped, depending on the value of M_D, the number of dimensions, the white dwarf's maximum column density, and the rate of reradiation.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\gtrsim 1.0\,M_\odot$, then black holes may be produced, and some may be trapped, depending on the value of M_D and the number of dimensions (up to at least ~ 12 TeV in 5 dimensions, and up to masses in 6 or 7 dimensions which depend on the white dwarf's maximum column density and the rate of radiation).

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM, but their trapping in white dwarfs would not be affected by magnetic fields.
- If a white dwarf has a mass $< 1.0\,M_\odot$, then ISM-produced black holes may or may not be trapped, depending on the value of M_D, the number of dimensions, the white dwarf's maximum column density, and the rate of reradiation.
- If a white dwarf has a mass $\gtrsim 1.0\,M_\odot$, then it could trap ISM-produced black holes for values of M_D up to at least ~ 12 TeV in 5 dimensions, and up to masses in 6 or 7 dimensions which depend on the white dwarf's maximum column density and the rate of radiation.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields, and subsequently trapped in the neutron star.

- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.

Earth (after LHC production)

- A significant number of black holes may be produced and trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, and the rate of radiation.

Moon (after LHC production)

- A significant number of black holes may be produced and some may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, and the rate of radiation.

Sun (after LHC production)

- A significant number of black holes may be produced and some may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, and the rate of radiation.

7.4 Production and Trapping of Neutral Rapidly Radiating Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Moon (from cosmic rays)

- Black holes may be produced, but none will be trapped.

Sun (from cosmic rays)

- Black holes may be produced, but none will be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $< 1.0\,M_\odot$, then black holes may be produced, and black hole remnants may or may not be trapped, depending on the value of M_D, the number of dimensions, and the white dwarf's maximum column density.
- If a white dwarf's magnetic field is $\lesssim$ few $\times 10^5\,G$, and it has a mass $\gtrsim 1.0\,M_\odot$, then black holes may be produced, and black hole remnants may be trapped, depending on the value of M_D and the number of dimensions (up to at least ~ 12 TeV in 5 dimensions, and up to masses in 6 or 7 dimensions which depend on the white dwarf's maximum column density).

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM, but trapping their remnants in white dwarfs would not be affected by magnetic fields.
- If a white dwarf has a mass $< 1.0\,M_\odot$, then ISM-black hole remnants may or may not be trapped, depending on the value of M_D, the number of dimensions, and the white dwarf's maximum column density.
- If a white dwarf has a mass $\gtrsim 1.0\,M_\odot$, then it could trap ISM-black hole remnants for values of M_D up to at least ~ 12 TeV in 5 dimensions, and up to masses in 6 or 7 dimensions which depend on the white dwarf's maximum column density.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields, and their remnants subsequently trapped in the neutron star.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.

Earth (after LHC production)

- A significant number of black holes may be produced and their remnants trapped in the Earth, with the expected number dependent on the value of M_D and the number of extra dimensions.

Moon (after LHC production)

- A significant number of black holes may be produced and some of their remnants may be trapped in the Moon, with the expected number dependent on the value of M_D and the number of extra dimensions.

Sun (after LHC production)

- A significant number of black holes may be produced and some or their remnants may be trapped in the Sun, with the expected number dependent on the value of M_D and the number of extra dimensions.

7.5 Production and Trapping of Neutral Rapidly Radiating Remnantless Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Pair-produced black holes may be created, but their remnants would not be trapped.

Moon (from cosmic rays)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Pair-produced black holes may be created, but their remnants would not be trapped.

Sun (from cosmic rays)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Pair-produced black holes may be created, but their remnants would not be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times\ 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\ 10^5\,G$, and it has a mass $< 1.0\,M_\odot$, then black holes may be produced; independently-produced black holes would decay while the remnants of pair-produced black holes may or may not be trapped, depending on their mass and the white dwarf's maximum column density.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\ 10^5\,G$, and it has a mass $\gtrsim 1.0\,M_\odot$, then black holes may be produced; independently-produced black holes would decay while the remnants of pair-produced black holes may be trapped, depending on the value of M_D and the number of dimensions (up to at least $\sim$ 12 TeV in 5 dimensions, and up to masses in 6 or 7 dimensions which depend on the white dwarf's maximum column density).

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM, but the trapping of the remnants of pair-produced black holes would not be affected by a white dwarf's magnetic field.
- If a white dwarf has a mass $< 1.0\,M_\odot$, then remnants of pair-produced ISM-black holes may or may not be trapped, depending on the value of M_D, the number of dimensions, and the white dwarf's maximum column density.
- If a white dwarf has a mass $\gtrsim 1.0\,M_\odot$, then it could trap the remnants of pair-produced ISM-black holes for values of M_D up to at least $\sim$ 12 TeV in 5 dimensions, and up to masses in 6 or 7 dimensions which depend on the white dwarf's maximum column density.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields, and their remnants subsequently trapped in the neutron star.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.

Earth (after LHC production)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Pair-produced black holes may be created and their remnants trapped in the Earth, with the expected number dependent on the value of M_D and the number of extra dimensions.

Moon (after LHC production)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Pair-produced black holes may be created and some of their remnants may be trapped in the Moon, with the expected number dependent on the value of M_D and the number of extra dimensions.

Sun (after LHC production)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Pair-produced black holes may be created and some of their remnants may be trapped in the Sun, with the expected number dependent on the value of M_D and the number of extra dimensions.

7.6 Production and Trapping of Charged Stable Black Holes

7.6.1 Cosmic Ray Production and Trapping in the Earth

§ Production in Cosmic Rays Collisions with the Earth

TEXT UNDER REVISION

§ Trapping in the Earth after Cosmic Ray Production

The possibility that charged cosmic ray-produced black holes could be trapped in the Earth is a key difference between this scenario and that of neutral stable black holes, for which the GM paper found that no cosmic ray-produced black hole could be trapped in either the Earth or the Sun [GM p. 33].

Both the LSAG report and the GM paper are clear in their conclusion that charged black holes can be trapped in the Earth or the Sun. Without distinguishing the separate scenarios of charged or neutral black holes, the LSAG report states in its summary that:

> If some microscopic black holes were stable, those produced by cosmic rays would be stopped inside the Earth or other astronomical bodies. [LSAG p. 1]

Within the text of the LSAG report, it is noted that:

> Most black holes produced at the LHC or in cosmic-ray collisions would have an electric charge, since they would originate from the collisions of charged quarks. A charged object interacts with matter in an experimentally well-understood way. A direct consequence of this is that charged and stable black holes produced by the interactions of cosmic rays with the Earth or the Sun would be slowed down and ultimately stopped by their electromagnetic interactions inside these bodies, in spite of their initial high velocities. [LSAG p. 8]

The introduction of the GM paper similarly states:

> We argue here that charged black holes will loose enough energy to stop when traversing the Earth or the Sun, via standard electromagnetic processes. [GM p. 4]

Before reviewing the details of the GM paper's analysis and calculations, it may be helpful to put the question of trapping of charged stable black holes into perspective. Physicists do not, in general, expect cosmic ray-produced black holes to be stable and trapped in the Earth. Rather, they expect such black holes to first lose their charge, and then radiate their energy above the higher-dimensional Planck's mass [Gid07 arXiv pp. 3–5]. The question of having charged, non-extremal black holes[66] only arises when CERN makes the argument that if critics assume that Hawking radiation doesn't exist, then probably the Schwinger mechanism, which would otherwise

[66] The issue of charged black hole remnants is discussed further in section 7.9

be expected to rapidly neutralize black holes, doesn't exist either [GM p. 4] [LSAG p. 8]. The GM paper recognizes, however, that there are possible boundary conditions which would prevent Hawking radiation but still permit Schwinger discharge.[67] For this scenario of charged stable black holes, it is nevertheless assumed that neither Hawking radiation nor any other form of black hole radiation exists, and the Schwinger mechanism also does not exist.

It is one thing to argue that if black hole radiation does not exist, then neither does the Schwinger mechanism; it is another thing to claims that if black hole radiation does not exist, then neither does the Schwinger mechanism, *and* whatever charged black holes are produced must have the same electromagnetic interactions as a muon. Even if it is assumed that the Schwinger mechanism does not exist, a detailed theoretical argument would be needed if any claims are to be made about the electromagnetic interactions of black holes in such a scenario. The GM paper's entire theoretical treatment of those interactions are the following three sentences, stated almost like an article of faith:

> Passage of a high-energy charged particle through matter leads to well-understood energy loss [26,27]. This is due to long-range electromagnetic effects, that have nothing to do with the microphysics associated to the particle itself. Therefore, a muon, or a black hole with the electric charge and the mass of a muon, would be subject to the same energy loss through radiative processes as they move through matter. [GM p. 9]

After these three sentences, the rest of the GM paper's analysis is simply a calculation of what the stopping distance in the Earth or the Sun would be for an extraordinarily heavy muon.

The first element of the GM paper's "analysis", is that energy losses during the passage of a high-energy charged particle are "well-understood". The LSAG report similarly states that, "A charged object interacts with matter in an experimentally well-understood way." [LSAG p. 8] Reading through the two references given in the GM paper, one can readily see that the movement of charged particles in matter has been subject to a great deal of experimental research. On the other hand, it is also clear that it is an area which requires such extensive research. The primary reference for the GM paper, "Muon Stopping Power and Range Tables 10 MeV–100 TeV", includes an instructive graph showing the stopping power of positive muons for a 12 orders of magnitude range of energy [GMS01 p. 187, figure 1 (top) ↗] [reprinted in Ams08 p. 258, figure 27.1 ↗ (large file)]. What the graph shows is that the muon's stopping power is not a simple curve based on a simple equation, but has been found to go through at least four different phases, with significant qualitative and quantitative differences between them. The article further describes in detail a number of the different factors which must to be taken into account when calculating a muon's stopping power [GMS01 pp. 186–200, 204–206 ↗]. The bulk of the article, however, is over 100 separate tables for the stopping power of muons in different elements, compounds, mixtures and biological materials [GMS01 pp. 211–337 ↗]. The article also includes suggested guidelines for

[67] The paper describes these conditions as "rather artificial", but otherwise does not provide any substantive argument against them. Nor does the paper give a subjective estimate of the probability associated with those boundary conditions.

how stopping power can be calculated for other unlisted compounds and mixtures, however it emphasizes that those calculations should be superseded by experimental numbers when available [GMS01 Appendix A, pp. 203–204 ↗]. The article includes tables specifically for pure iron [GMS01 p. 245, table I-35 ↗] and for the overburden of the Cayuga Rock Salt Mine that has become known as "standard rock" [GMS01 pp. 203, 328, table IV-6 ↗], but it does not include any tables which match the composition and temperatures of the Earth's inner core, outer core, or mantle.

Whether the energy losses of a charged particle can be considered "well-understood" is debatable. The "Review of Particle Physics" cited by the GM paper notes that at the lower energy range, for values of β between 0.01 and 0.05, there is no satisfactory theory, and physicists rely on phenomenological fits developed by Anderson and Ziegler [Yao06 p. 260 ↗ (large file)]. At the higher energy range, one may note that in just the 5 years between the submission of the muon stopping power tables [GMS01 ↗] and the preparation of the chapter on stopping power for the 2006 "Review of Particle Physics", "it has become likely that post-Born corrections to the direct pair production cross section should be made" [Yao06 p. 269, reference 1 ↗ (large file)]. These corrections are relatively minor (e.g. less than 1% for iron), however, this example illustrates that our theoretical understanding of the energy losses of charged particles is still incomplete. The LSAG report describes a charged object's interactions as "experimentally well-understood" [LSAG p. 8], but an experimentally-based understanding cannot usually be extended far beyond the data that supports it. As there presently is absolutely no experimental data on the energy losses from the interaction of charged TeV-scale black holes with ordinary matter, there is no reliable basis for predicting their stopping power.

The limited scope for generalizing the stopping power of muons is clear from the muon stopping power article cited by the GM paper. One of the very first points it makes is the following:

> The radiative loss formulae given in this paper apply only to spin-1/2 pointlike heavy particles, where "heavy" means "much more massive than an electron." Insofar as we know, the solution for spin-0 particles has never been published. [GMS01 p. 185, footnote 1 ↗]

Thus, unless the GM paper is contending that TeV-scale black holes are really just a type of spin-1/2 pointlike heavy particle, its calculations for the stopping power of charged black holes are based on formulae pulled from a source which explicitly says the formulae do not apply.[68]

Looking more closely at the details of the stopping process, it becomes even more implausible to simply consider charged black holes as very heavy muons. As noted above, the GM paper asserts that the energy loss would be "...due to long-range electromagnetic effects, that have nothing to do with the microphysics associated to the particle itself." [GM p. 9] On the other hand, the specific

[68] For its section on radiative losses, the stopping power article ventures that, "The results below probably apply fairly well to charged pion radiative energy losses, although to the best of our knowledge radiative losses by spin-0 particles have not been treated." [GMS01 p. 193 ↗] The GM paper, on the other hand, blithely claims that its stopping power calculations based on the muon tables apply to any imaginable elementary charged particle that could be produced at the LHC [GM p. 10 ↗].

process involved in stopping a muon bears little resemblance to what one might expect from a charged stable black hole. For example, the stopping power article explains that a component of the energy losses involves, "Photon emission by the muon before and after photon exchange with the electron, and emission by the electron before and after photon exchange." [GMS01 p. 191 ↗] Given that this scenario assumes neither black hole radiation, nor the Schwinger mechanism, CERN may wish to explain how a stable charged black hole could emit the photons necessary for these and other electromagnetic processes.[69]

More generally, one would reasonably expect an analysis of this issue to consider all the possible differences between a charged stable black hole and a muon, and then check if they could result in any differences in the stopping power.[70] One of the most significant differences is the powerful effect that a black hole's gravitational field will have in the vicinity of its event horizon. Any process of energy loss which involves an effect across the event horizon should be carefully scrutinized to see if it would really apply to a TeV-scale black hole. Another difference is that black holes can trap other particles. Part of the energy loss for charged particles is from Coulomb scattering by other charged particles [Yao06 p. 262 ↗ (large file)].[71] Since black holes could capture some of those particles instead of being scattered, its rate of energy loss may be reduced.[72] Considering these and other possible factors, determining the stopping power of a charged stable TeV-scale black hole should be based on a first principles analysis of its properties and interactions, and not simply the assumption that it acts like a muon.

Beyond the belief that the stopping of a charged black hole is basically the same as a muon, the GM paper goes further and asserts that the stopping distance will be exactly that of a muon rescaled to a TeV-scale black hole's mass. Even if the question was simply calculating the stopping distance of an unnaturally heavy muon, it would be risky to assume that the adjustment would be just a matter of multiplying by the new mass. A 1 TeV-black hole has a mass that is about 9464 times greater than that of a muon, and four orders of magnitude is a rather long leap to make into the unknown. (The situation would not be quite so bad if the GM paper had, for example, cited the stopping power of high-energy tauons, which have masses about 17 times greater than that of muons, although they would still be 563 times less massive than a 1 TeV black hole.)

This issue is one that should have been addressed in the GM paper. The edition of the "Review of Particle Physics" cited by the GM paper explicitly states that for radiative processes, "There is no simple scaling with particle mass, but for protons the "critical energy" is much, much higher." [Yao06 p. 267 ↗ (large file)] [cf. Ams08 p. 277 ↗ (large file)] Radiative processes are the main factor which increases the rate of energy losses from a level of about 11 MeV/cm for γ ~ 1,000

[69] For Professor Giddings' explanation of the relationship between a black hole's charge and the Schwinger mechanism, please see [Gid94 arXiv p. 30 ↗].

[70] It is interesting to note that even positive and negative muons do not have the same stopping power [GMS01 p. 192 ↗].

[71] "Coulomb scattering" is used here in its original sense–not as the gravitational analogue of coulomb scattering discussed in the GM paper [GM p. 29 ↗].

[72] This factor may not be very significant if other sources of energy losses for a TeV-scale black hole exist, but if they do not, then its relative importance would increase.

up to about 60 MeV/cm for $\gamma \sim 10{,}000$ (rates as per the GM paper [GM p. 9]). The "critical energy" is defined in this case as the energy at which the radiative and ionization losses are equal [Yao06 p. 268 ↗ (large file)], so if this energy is much, much higher than one would expect from a simple mass scaling, it implies a delay in the increase in the radiative losses (since ionization losses are assumed to increase very slowly). If the increase in radiative losses is delayed for a proton, with a mass of just under 0.001 TeV, one could hardly expect that a black hole, with a mass of 1 TeV or more, would not also be affected.

Even if one does assume that a charged stable black hole will behave exactly as a very heavy muon, the GM paper's calculation of its stopping distance gives rise to a number of serious questions. These issues are outlined below:

Absence of Any Safety Margin - The GM paper's estimate of a charged black hole's stopping distance is surprisingly similar to the diameter of the Earth. The paper in fact finds that for cosmic ray-produced black holes with masses of the order of 14 TeV, even if they pass through the full length of the Earth they would not be trapped [GM pp. 9–10]. Only if they have a mass of the order of 7 TeV does the GM paper claim that they could be trapped [GM p. 10]. As this would be the maximum theoretical mass for the stopping of a cosmic ray-produced black hole, a standard practice for any safety analysis would be to include an explicit safety factor to provide some kind of cushion if anything goes wrong. In this case, the paper has simply assumed that the 7 TeV range should be accepted as is. It should also be noted that at no point does the GM paper claim to have made conservative assumptions in the estimate of a charged black hole's stopping power.

Dependence on Unpublished Calculations - The GM paper does not actually present any explicit calculations to justify its claim that charged black hole with masses of the order of 7 TeV could be trapped. After presenting calculations showing that a 14 TeV black hole would not be trapped, the paper simply says,

> The stopping distance grows with M, and a more careful estimate shows the Earth provides enough stopping power for black holes with unit electric charge up to a mass of the order of 7 TeV. [GM p. 10]

The paper does not give the details of its calculations, or even indicate what the differences are between the published calculations and the unpublished "more careful estimate".[73]

Vague Statement of the Mass Limit for Stopping in the Earth - For charged black holes with masses above 7 TeV the GM paper argues that they would be trapped in the Sun, and the continued health of the Sun implies their safety [GM p. 10]. For a risk analysis, however, there is a world of difference between the safety implications of finding that charged black holes would have

[73] If this was an acceptable standard for a scientific publication, one wonders why CERN bothered commissioning a detailed paper on the risks of TeV-scale black holes, when it could have simply said "We have considered this issue carefully and find that black hole production is safe", and leave the scientific community and the general public to dutifully accept its pronouncement.

been trapped in the Earth compared to the implications of finding that they could not be trapped in the Earth but would have been trapped in the Sun. The GM paper does not clearly indicate where the cut-off is between these two cases, since it only states that the Earth's stopping power is enough for a singly charged black holes with a mass "of the order of 7 TeV" [GM p. 10]. With this phrasing a reader cannot tell if the mass limit for stopping in the Earth runs as high as, say, 9 TeV, or as low as 3 or 4 TeV. For simplicity this paper refers to 7 TeV as the mass limit, but the uncertainty about the exact figure remains unresolved.

Calculation of the Distance for Slowing Down to $\gamma = 1000$ - The GM paper notes that pair production, bremstrahlung and nuclear dissociation appear above $\gamma \sim 1000$ and grow approximately linearly with γ [GM p. 9]. This leads to an increase in the energy losses from about 11 MeV/cm below $\gamma = 1{,}000$ to the paper's estimate of 60 MeV/cm at $\gamma \sim 10{,}000$. The paper then states that, "...the distance scale necessary to slow down from the production energy $E \sim M^2/m_p$ to $\gamma \sim 10^3$ is thus of order $M/(6\text{ keV})$ cm..." [GM p. 9] It is not clear if the authors intended for their formula to apply for the slow down specifically from $E \sim M^2/m_p$, or more generally for the slow down from $\gamma = 10{,}000$. If their intent was to calculate the distance from $E = M^2/m_p$ to $\gamma = 1{,}000$, then their formula should involve an additional function of M (i.e. their stated formula would be an overestimate for lower black hole masses, and an underestimate for higher masses). (Whether this would be a reasonable initial energy for a cosmic ray-produced black hole is reviewed below.) If the intent was to calculate the slow down from $\gamma = 10{,}000$ to $\gamma = 1{,}000$, the formula would likely underestimate the distance.[74] The formula would then imply that the average energy loss is of order 54 MeV/cm, which is much closer to the highest rate during the slow down than the average rate. If one were to simply assume that the energy loss rate was linear between 11 MeV/cm for $\gamma = 1{,}000$ and 60 MeV for $\gamma = 10{,}000$, then the average would be only about 29 MeV/cm. This would imply a stopping distance for this phase that is about 85% longer than that suggested by the GM paper's formula.[75]

Stopping Only the Slowest Cosmic Ray-Produced Black Holes - As noted above, the GM

[74] For reference, for all black holes with masses greater than 9.4 TeV, a production energy of $E = M^2/m_p$ implies that γ is greater than 10,000.

[75] The GM paper only claims that the energy loss is of order 11 MeV/cm for γ up to $\sim$ 1,000, so it could be slightly higher than 11 MeV/cm for $\gamma = 1{,}000$. Using a value of 2.82 MeV cm^2/g for $\gamma = 1{,}000$ (interpolating from the closest values in the tables for pure iron [GMS01 p. 245, table I-35 ↗] and "standard rock [GMS01 p. 328, table IV-6 ↗] and taking the largest of the two values), and assuming 5.5 g/cm^3 as the average density of the Earth, then the energy loss rate for $\gamma = 1{,}000$ would be about 15.5 MeV/cm. If one assumes a linear increase up to 60 MeV for $\gamma = 10{,}000$, then the average energy loss rate would be about 33 MeV/cm, implying a stopping distance that is about 64% longer than that of the GM paper's formula. One may also note that if the emphasis is on determining the maximum possible stopping power, a black hole passing through the exact centre of the Earth would experience a greater column density than that calculated using the average density of the Earth (since it would have a higher than average portion of its path through the Earth's core). This may not change the average stopping distance for a cosmic ray-produced black hole, but it would increase the maximum possible mass that could be stopped. These calculations and considerations highlight the need for the authors of the GM paper to publish the details of their "more careful estimate" for the stopping power of charged black holes.

paper refers to a production energy of order M^2/m_p, but it is not clear if its stopping estimates are based on that value, or an initial γ of 10,000. If stopping estimates are based on a hypothetical initial energy of $E = M^2/m_p$, then it should first be noted that these would be among the slowest cosmic ray-produced black holes, since the typical initial energies for such black holes is about three times greater [cf. GM p. 29].[76] Moreover, it is not clear whether such a low initial energy would even be possible. The GM paper typically uses the assumption that $y = 0.5$ for its calculation of the production rates for black holes with masses up to 7 TeV [GM pp. 40, 46, 73, 74, 76, 77, 79, tables 2, 3, 4, 5, 6, 8, 9, 10]. For this value of y, by equation 5.5 [GM p. 29, eq. 5.5], the value of x_1 would have to equal 1 for γ to equal M/m_p and E to equal M^2/m_p. On the other hand, the CTEQ6M parton distribution functions cited by the GM paper [GM pp. 40, 70, 76, 78, figure 9] give a value of 0 for x approaching 1 [Pum02 arXiv p. 8, figure 1]. If instead of a production energy of M^2/m_p, the GM paper was generally considering black holes with an initial γ of 10,000, they would still be among the slower cosmic ray-produced black holes for masses greater then 4 TeV [cf. GM p. 29]. Figure 7 in the GM paper shows that for 14 TeV black holes, the bin centred on $\gamma = 10{,}000$ is the lowest in which cosmic ray black holes may be produced, and represents a very small portion of the total overall production [GM p. 76, figure 7]. Moreover, this graph appears to be based on the unrealistic assumption that $y = 1$; if $y = 0.5$, then by equation 5.5 [GM p. 29, eq. 5.5], the initial γ of any cosmic ray-produced 14 TeV black hole must be at least 14,900, and only for black holes with masses below 9.4 TeV would it even be possible for the initial γ to be less then 10,000.

The final issue for the trapping of charged black holes is determining the rate at which such black holes are trapped in the Earth. The specific trapping rate is important for a safety analysis for two distinct reasons. If it is possible for a charged black hole of a certain mass to be trapped, but the rate is so low that one cannot be reasonably certain that at least one such black hole has been trapped in the Earth, then there would no longer be an astrophysical safety argument based on the existence and state of the Earth. A claim that the production of charged stable black holes is safe would then depend on the much weaker astrophysical argument based on the existence of the Sun (assuming such black holes are trapped there) and a purely theoretical argument for their accretion in the Earth. If one can be reasonably certain that one or more charged black holes would have been trapped in the Earth, then an astrophysical safety argument would require a comparison of the cumulative number which would have already been trapped, with the additional number expected from the LHC. This would be needed in order to place empirical bounds on effects such as an increase in the Earth's internal heat generation.

The LSAG report claims that if they could be produced at the LHC, billions of cosmic ray-produced charged stable black holes would have already been trapped during the lifetime of the

[76] Black holes produced at the LHC do not face the same constraint, since the collision of partons occurs with a centre of mass that is moving relatively slowly in relation to the Earth. Their initial energies are expected to be much less than M^2/m_p [cf. GM pp. 79, 81–83 ↗].

Earth. The report's full statement is:

> Most black holes produced at the LHC or in cosmic-ray collisions would have an electric charge, since they would originate from the collisions of charged quarks. A charged object interacts with matter in an experimentally well-understood way. A direct consequence of this is that charged and stable black holes produced by the interactions of cosmic rays with the Earth or the Sun would be slowed down and ultimately stopped by their electromagnetic interactions inside these bodies, in spite of their initial high velocities. The complete lack of any macroscopic effect caused by stable black holes, which would have accumulated in the billions during the lifetime of the Earth and the Sun if the LHC could produce them, means that either they are not produced, or they are all neutral and hence none are stopped in the Earth or the Sun, or have no large-scale effects even if they are stopped. [LSAG p. 8]

The statement of the LSAG report goes well beyond what is claimed in the GM paper. Firstly, the report makes no mention of the mass limit for the trapping of charged black holes in the Earth. Secondly, it claims that charged black holes will be trapped in the Earth "in spite of their initial high velocities", which fails to note that for medium to high masses, only the slower black holes could be trapped, and only if they pass through a substantial column density of the Earth.[77] Thirdly, it ignores the GM paper's own estimates for the black hole production rates by a pure iron cosmic ray flux, which, in the case of 5 dimensions and black hole masses equal to or greater than 7 TeV, do not even predict the production, let alone trapping, of a billion black holes in the history of the Earth.[78]

The introduction of the GM paper includes a similarly misleading presentation about the stopping of charged black holes. It states:

> We argue here that charged black holes will loose enough energy to stop when traversing the Earth or the Sun, via standard electromagnetic processes. Since black holes would be typically produced by the collision of quark pairs, whether in cosmic-ray interactions or at the LHC, they would often be initially charged. To the extent that no mechanism leads to their neutralization, the cosmic-ray based argument for their being harmless is therefore robust. [GM p. 4]

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[77] For a very rough indication of variations in column density as a function of penetration angle, see the graph for a solar mass white dwarf given in figure 1 [GM p. 37, figure 1 (right) ↗]. Massive and ultramassive white dwarfs have a much steeper density profile [GM p. 37, figure 1 (left) ↗] than the Earth, but the graph does illustrate that this factor needs to be taken into account when calculating black hole trapping rates.

[78] This calculation is based on table 5 in the GM paper [GM p. 74, table 5 ↗], with an estimated age of the Earth of 4540 million years [▷ ADDCITE] and an average radius of 6,371 km [▷ ADDCITE]. These are estimates for black holes of any initial charge; some may initially be neutral and some initially electrically charged (although for the white dwarf discussion based on table 5 they are all assumed to be neutral very soon after production). These estimates do not include any possible suppression of black hole production, as reviewed in section 4.2.4.

This statement gives readers no indication that the GM paper's claim is only that lighter and slower charged black holes may be trapped in the Earth.[79]

The main text of the GM paper does not give any specific numbers for either the percentage of charged cosmic ray-produced black holes which may be trapped, or the total number which would have been trapped over the course of the Earth's lifetime [GM ↗]. Given the unresolved questions about the validity of the GM paper's trapping model, an independent calculation of these numbers has not been attempted in this paper.

Despite the criticisms expressed above of the GM paper's model for charged black hole trapping, the summary of the trapping of charged stable black holes in various astronomical bodies, and the summaries for the trapping of charged radiating black holes (sections 7.7, 7.8, 7.9, and 7.10), adopt the assumption, for the sake of following the GM paper's argument, that its trapping model is more or less correct. At the other extreme, if the charge of a black hole does not assist trapping, then the production and trapping situation would be mostly the same as the corresponding case for neutral black holes.

7.6.2 Cosmic Ray Production and Trapping in the Moon

§ Production in Cosmic Rays Collisions with the Moon

The production of charged stable black holes in cosmic ray collisions with the Moon may be similar to the situation reviewed above for collisions with the Earth, except reduced in proportion to the difference in surface area. The overall number would likely by similar to the neutral stable black hole scenario, although only a certain portion of the black holes produced would have an initial charge, or would gain or lose charge during passage through the Moon. The GM paper does not estimate what that portion might be [GM ↗].

§ Trapping in the Moon after Cosmic Ray Production

A number of problems with the basic trapping theory presented in the GM paper are review above in the discussion on trapping within the Earth.

Aside from these issues, in the case of the Moon the expected trapping power is much less than that of the Earth. The mean radius of the Moon is about 27.3% of the Earth's [NSSDC:Moon ↗], and its mean density is about 60.7% of the Earth's [NSSDC:Moon ↗], implying that the overall stopping power is only about 16.6% of the Earth's.[80] As the GM paper only vaguely refers to

[79] While introductory statements are by their very nature more succinct and sometimes less precise, if the intent was to give readers an accurate understanding of the issue, the paper could have said something like, "We argue here that some of the lighter charged black holes will loose enough energy to stop when traversing the Earth"

[80] Difference in the maximum column density based on a more accurate calculation of the average density encountered by a black hole passing through the exact centre of the Earth might change this figure somewhat. As the Moon's core is believed to be a much smaller portion of the Moon, than the Earth's core is of the Earth [▷ ADDCITE], the Moon's stopping power relative to the Earth's might be further reduced.

the Earth's stopping power being sufficient for singly charged black holes "up to a mass of the order of 7 TeV" [GM p. 10], it is not possible to calculate precisely what the correspondingly mass would be for the Moon, although a reasonable guess might be in the range of 1–3 TeV (after taking into account the reduced γ of lighter black holes).

As with the case of the Earth, the GM paper includes no specific calculation for the number of black holes which may have been trapped in the Moon [GM ↗].

▷ ADD NOTE on the Earth slowing down black holes with masses of the order of 7 TeV for trapping in the moon

7.6.3 Cosmic Ray Production and Trapping in the Sun

TEXT UNDER REVISION

7.6.4 Cosmic Ray Production and Trapping in White Dwarfs

FULL TEXT PENDING

7.6.5 Production in Cosmic Ray Collisions with the Interstellar Medium and Subsequent Trapping in White Dwarfs

FULL TEXT PENDING

7.6.6 Production in Cosmic Ray Collisions with Dark Matter and Trapping in White Dwarfs

FULL TEXT PENDING

7.6.7 Cosmic Ray Production and Trapping in Neutron Stars

FULL TEXT PENDING

7.6.8 Production in Cosmic Ray Collisions with Binary Companions and Subsequent Trapping in Neutron Stars

FULL TEXT PENDING

7.6.9 Production in Cosmic Ray Collisions with the Interstellar Medium and Subsequent Trapping in Neutron Stars

FULL TEXT PENDING

7.6.10 Production in Ultrahigh-Energy Neutrino Collisions and Trapping in Neutron Stars

FULL TEXT PENDING

7.6.11 LHC Production and Trapping in the Earth

FULL TEXT PENDING

7.6.12 LHC Production and Trapping in the Moon

FULL TEXT PENDING

7.6.13 LHC Production and Trapping in the Sun

FULL TEXT PENDING

7.6.14 Summary of Production and Trapping of Neutral Stable Black Holes

Earth (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses $\lesssim 7$ TeV may be trapped.
- Charged black holes with masses > 7 TeV are not expected to be trapped.
- Initially neutral black holes are not expected to be trapped unless they have a low mass and acquire charge during subsequent accretion.

Moon (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses significantly less than 7 TeV may be trapped.
- Charged black holes with higher masses are not expected to be trapped.
- Initially neutral black holes are not expected to be trapped unless they have a very low mass and acquire charge during subsequent accretion.

Sun (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses well in excess of 100 TeV may be trapped by the Sun's core.
- Initially neutral black holes are not expected to be trapped unless they acquire charge during subsequent accretion.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times\ 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\ 10^5\,G$, black holes may be produced and charged black hole may be trapped; initially neutral black holes may also be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the acquisition of charge during subsequent accretion.

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM.
- Charged ISM-produced black holes may be trapped in a white dwarf if they have not been deflected by the white dwarf's magnetic field.
- Initially neutral ISM-produced black holes may be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the acquisition of charge during subsequent accretion.

White Dwarfs (after dark matter production)

- The nature of dark matter is too uncertain to predict black hole production.

Neutron Stars (from cosmic rays)

- The magnetic fields of all known neutron stars are too strong to permit significant production of black holes from direct cosmic ray collisions.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.
- Charged black holes produced in collisions with binary companions would likely be deflected by the neutron star's magnetic field.
- Neutral black holes produced in collisions with binary companions could be trapped in the neutron star.

Neutron Stars (after ISM production)

- An insufficient number of black holes would be produced in the ISM for a neutron star argument.

Neutron Stars (from ultrahigh-energy neutrinos)

- There is presently no empirical evidence for a flux of ultrahigh-energy neutrinos.
- If a flux does exist, black hole production in neutrino-hadron collisions may be significantly different from black hole production in hadron-hadron collisions.
- If a significant flux of ultrahigh-energy neutrinos does exist, and if collisions of neutrinos with hadrons has a sufficiently high cross-section for black hole production, then black holes could be trapped in neutron stars.

Neutron Stars (after dark matter production)

- The nature of dark matter is too uncertain to predict black hole production.

Earth (after LHC production)

- A significant number of black holes may be produced at the LHC.
- A significant faction of the charged black holes produced at the LHC may be trapped in the Earth.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, and the acquisition of charge during subsequent accretion.

Moon (after LHC production)

- Some of the charged black holes produced at the LHC may be trapped in the Moon.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, and the acquisition of charge during subsequent accretion.

Sun (after LHC production)

- Some of the charged black holes produced at the LHC may be trapped in the Sun.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, and the acquisition of charge during subsequent accretion.

7.7 Production and Trapping of Charged Slowly Radiating Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses $\lesssim 7$ TeV may be trapped.
- Charged black holes with masses > 7 TeV are not expected to be trapped.
- Initially neutral black holes are not expected to be trapped unless they have a low mass and acquire charge during subsequent accretion.

Moon (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses significantly less than 7 TeV may be trapped.
- Charged black holes with higher masses are not expected to be trapped.
- Initially neutral black holes are not expected to be trapped unless they have a very low mass and acquire charge during subsequent accretion.

Sun (from cosmic rays)

- Black holes may be produced
- Charged black holes with masses well in excess of 100 TeV may be trapped by the Sun's core.
- Initially neutral black holes are not expected to be trapped unless they acquire charge during subsequent accretion.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times\, 10^5\, G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\, 10^5\, G$, black holes may be produced and charged black hole may be trapped; initially neutral black holes may also be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the acquisition of charge during subsequent accretion.

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM.
- Charged ISM-produced black holes may be trapped in a white dwarf if they have not been deflected by the white dwarf's magnetic field.

- Initially neutral ISM-produced black holes may be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the acquisition of charge during subsequent accretion.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.
- Charged black holes produced in collisions with binary companions would likely be deflected by the neutron star's magnetic field.
- Neutral black holes produced in collisions with binary companions could be trapped in the neutron star.

Earth (after LHC production)

- A significant number of black holes may be produced at the LHC.
- A significant faction of the charged black holes produced at the LHC may be trapped in the Earth.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, and the acquisition of charge during subsequent accretion.

Moon (after LHC production)

- Some of the charged black holes produced at the LHC may be trapped in the Moon.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, and the acquisition of charge during subsequent accretion.

Sun (after LHC production)

- Some of the charged black holes produced at the LHC may be trapped in the Sun.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, and the acquisition of charge during subsequent accretion.

7.8 Production and Trapping of Charged Equilibrium Mass Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses $\lesssim 7$ TeV may be trapped.
- Charged black holes with masses > 7 TeV may or may not be trapped, depending on the dynamics of radiation and trapping.
- Initially neutral black holes may be trapped if their mass is not too great and they acquire charge during subsequent accretion.

Moon (from cosmic rays)

- Black holes may be produced.
- Charged black holes with relatively low masses may be trapped.
- Charged black holes with higher masses may or may not be trapped, depending on the dynamics of radiation and trapping.
- Initially neutral black holes may be trapped if their mass is not too great and they acquire charge during subsequent accretion.

Sun (from cosmic rays)

- Black holes may be produced.
- Charged black holes with masses well in excess of 100 TeV may be trapped by the Sun.
- Initially neutral black holes may be trapped if they acquire charge during subsequent accretion.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times\ 10^5\,G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\ 10^5\,G$, black holes may be produced and charged black hole may be trapped; initially neutral black holes may also be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, the rate of radiation, and the acquisition of charge during subsequent accretion.

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM.
- Charged ISM-produced black holes may be trapped in a white dwarf if they have not been deflected by the white dwarf's magnetic field.

- Initially neutral ISM-produced black holes may be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, the rate of radiation, and the acquisition of charge during subsequent accretion.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.
- Charged black holes produced in collisions with binary companions would likely be deflected by the neutron star's magnetic field.
- Neutral black holes produced in collisions with binary companions could be trapped in the neutron star.

Earth (after LHC production)

- A significant number of black holes may be produced at the LHC.
- A significant faction of the charged black holes produced at the LHC may be trapped in the Earth.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, the rate of radiation, and the acquisition of charge during subsequent accretion.

Moon (after LHC production)

- Some of the charged black holes produced at the LHC may be trapped in the Moon.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, the rate of radiation, and the acquisition of charge during subsequent accretion.

Sun (after LHC production)

- Some of the charged black holes produced at the LHC may be trapped in the Sun.
- Some of the initially neutral black holes produced at the LHC may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, the rate of radiation, and the acquisition of charge during subsequent accretion.

7.9 Production and Trapping of Charged Rapidly Radiating Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Black holes may be produced.
- Charged black hole remnants with masses up to about 7 TeV (i.e. for values of M_D up to about 7 TeV) may be trapped.
- Charged black holes remnants with masses above 7 TeV may or may not be trapped, depending on the dynamics of radiation and trapping.
- Neutral black hole remnants will probably not be trapped.

Moon (from cosmic rays)

- Black holes may be produced.
- Charged black hole remnants with relatively low masses may be trapped.
- Charged black hole remnants with higher masses may or may not be trapped, depending on the dynamics of radiation and trapping.
- Neutral black hole remnants will probably not be trapped.

Sun (from cosmic rays)

- Black holes may be produced.
- Charged black hole remnants with masses well in excess of 100 TeV may be trapped by the Sun.
- Neutral black hole remnants will probably not be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times\ 10^5\ G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\ 10^5\ G$, black holes may be produced and charged black hole remnants may be trapped; neutral black hole remnants may also be trapped, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the dynamics of radiation and trapping.

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM.
- Charged remnants of ISM-produced black holes may be trapped in a white dwarf if they have not been deflected by the white dwarf's magnetic field.

- Neutral remnants of ISM-produced black holes may be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the dynamics of radiation and trapping.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.
- Charged remnants of black holes produced in collisions with binary companions would likely be deflected by the neutron star's magnetic field.
- Neutral remnants of black holes produced in collisions with binary companions could be trapped in the neutron star.

Earth (after LHC production)

- A significant number of black holes may be produced at the LHC.
- A significant faction of the charged black hole remnants produced at the LHC may be trapped in the Earth.
- Some of the neutral black hole remnants produced at the LHC may be trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, and the dynamics of radiation and trapping.

Moon (after LHC production)

- Some of the charged black hole remnants produced at the LHC may be trapped in the Moon.
- Some of the neutral black hole remnants produced at the LHC may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, and the dynamics of radiation and trapping.

Sun (after LHC production)

- Some of the charged black hole remnants produced at the LHC may be trapped in the Sun.
- Some of the neutral black hole remnants produced at the LHC may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, and the dynamics of radiation and trapping.

7.10 Production and Trapping of Charged Rapidly Radiating Remnantless Black Holes

FULL TEXT PENDING

Earth (from cosmic rays)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Charged remnants of pair-produced black holes with masses up to about 7 TeV (i.e. values of M_D up to about 7 TeV) may be trapped.
- Charged remnants of pair-produced black holes with masses above 7 TeV may or may not be trapped, depending on the dynamics of radiation and trapping.
- Neutral remnants of pair-produced black holes will probably not be trapped.

Moon (from cosmic rays)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Charged remnants of pair-produced black holes with relatively low masses may be trapped.
- Charged remnants of pair-produced black holes with higher masses may or may not be trapped, depending on the dynamics of radiation and trapping.
- Neutral remnants of pair-produced black holes will probably not be trapped.

Sun (from cosmic rays)

- Independently-produced black holes may be produced, but they would rapidly decay.
- Charged remnants of pair-produced black holes may be trapped by the Sun.
- Neutral remnants of pair-produced black holes will probably not be trapped.

White Dwarfs (from cosmic rays)

- If a white dwarf's magnetic field is greater than a few $\times\ 10^5\ G$, an insufficient number of black holes would be produced.
- If a white dwarf's magnetic field is $\lesssim$ few $\times\ 10^5\ G$, black holes may be produced; independently-produced black holes would decay while the remnants of pair-produced black holes may or may not be trapped, depending on their charge, their mass, the number of dimensions, the value of M_D, and the white dwarf's maximum column density.

White Dwarfs (after ISM production)

- A much smaller number of black holes could be produced in the ISM.
- Independently-produced ISM black holes would rapidly decay.
- Charged remnants of pair-produced ISM black holes may be trapped in a white dwarf if they have not been deflected by the white dwarf's magnetic field.

- Neutral remnants of pair-produced ISM black holes may be trapped in a white dwarf, with the details dependent on the number of dimensions, the value of M_D, the mass of the black hole, the white dwarf's maximum column density, and the dynamics of radiation and trapping.

Neutron Stars (after production on binary companions)

- For a proton-dominated cosmic ray flux, a relatively small number of black holes could be produced in cosmic ray collisions with neutron star companions with weak magnetic fields.
- For a heavy ion-dominated cosmic ray flux, an insufficient number of black holes would be produced in cosmic ray collisions with neutron star companions.
- Independently-produced black holes from cosmic ray collisions with a binary companion would rapidly decay.
- Charged remnants of pair-produced black holes from cosmic ray collisions with a binary companion would likely be deflected by the neutron star's magnetic field.
- Neutral remnants of pair-produced black holes from cosmic ray collisions with a binary companion could be trapped in the neutron star.

Earth (after LHC production)

- A significant number of black holes may be produced at the LHC.
- Independently-produced black holes may be produced, but they would rapidly decay.
- A significant fraction of the charged remnants of pair-produced black holes created at the LHC may be trapped in the Earth.
- Some of the neutral remnants of pair-produced black holes created at the LHC may be trapped in the Earth, with the expected number dependent on the value of M_D, the number of extra dimensions, and the dynamics of radiation and trapping.

Moon (after LHC production)

- A significant number of black holes may be produced at the LHC.
- Independently-produced black holes may be produced, but they would rapidly decay.
- Some of the charged remnants of pair-produced black holes created at the LHC may be trapped in the Moon.
- Some of the neutral remnants of pair-produced black holes created at the LHC may be trapped in the Moon, with the expected number dependent on the value of M_D, the number of extra dimensions, and the dynamics of radiation and trapping.

Sun (after LHC production)

- A significant number of black holes may be produced at the LHC.
- Independently-produced black holes may be produced, but they would rapidly decay.

- Some of the charged remnants of pair-produced black holes created at the LHC may be trapped in the Sun.
- Some of the neutral remnants of pair-produced black holes created at the LHC may be trapped in the Sun, with the expected number dependent on the value of M_D, the number of extra dimensions, and the dynamics of radiation and trapping.

8 Accretion of Trapped Black Holes

This section reviews the process of black hole accretion within astronomical objects. The cases of radiating black holes and charged stable black holes are briefly considered, but the main focus of this section is on the model for neutral stable black hole accretion proposed in the GM paper. The proposed model for accretion within the Earth, white dwarfs and neutron stars are reviewed in detail, while initial comments are made about accretion within the Moon and the Sun. The effects of multiple black hole accretion are also considered, along with the possibility of a limit in the rate of accretion caused by the reradiation from infalling particles.

8.1 Accretion of Neutral Stable Black Holes

8.1.1 Neutral Stable Black Hole Accretion within the Earth

Understanding the process of black hole accretion within the Earth is one of the most important questions for assessing the potential risks associated with producing slow-moving black holes on the Earth. The bounds presented in the GM paper for different phases of single black hole growth and for different dimensions with different warping are briefly summarized, following which the paper's model is more carefully reviewed. The case of multiple black hole accretion and the possibility of an Eddington limit are also considered.

§ Summary of CERN's Estimates of Single Black Hole Accretion Times

The following is a summary of accretion times[81] for a single black hole according to the GM paper:

5 Dimensions - The GM paper finds that the rate of black hole accretion in a 5-dimensional scenario could be extremely rapid. The paper estimates that for a crossover radius just within the experimental bound, a neutral stable black hole would reach a mass of 100 milligrams in about 5 milliseconds [GM p. 26].[82] After the first phase of 5-dimensional growth, the black hole would then

[81] These are the times listed in the GM paper as a lower bound–i.e. the shortest possible times for accretion. Unfortunately, they are the only times given in the paper. The paper does not present what it considers to be a "best guess" for the accretion times for neutral stable black holes, nor does it present an upper bound for the accretion times for different stages. If it did so, one could see the range in possible accretion times and judge how conservative the supposedly conservative case actually is.

[82] This finding contrasts sharply with the earlier reassurances, given by a leading physicist and apparently accepted by the physics community, that it would take an extremely long time for any black holes produced at the LHC to grow. Professor Greg Landsberg, a co-author of the first peer-reviewed paper predicting a high rate of black hole production at the LHC [DL01 arXiv ↗] and the US physics coordinator for the CMS experiment [▷ ADDCITE New Scientist ↗], had previously been reported stating the following:

> "Still, let's assume that even if Hawking is a genius, he's wrong, and that such black holes are

enter a transitional phase until its Bondi radius equals the crossover radius, R_C, followed by a phase of purely 4-dimensional growth until it destroys the Earth. The paper estimates that both these phases would be considerably longer, but still very short in geological terms. The paper acknowledges that the precise nature of the transitional phase is "not completely understood" [GM p. 26], but nevertheless calculates that the time involved is approximately 300,000 years. Similarly, it estimates that the subsequent phase of 4-dimensional growth would also require about 300,000 years [GM p. 26, eq. 4.52].

The paper argues against an Eddington limit for black hole growth within the Earth [GM pp. 61–62], though it should be noted that an Eddington limit would add to the estimated time for the destruction of the planet. The amount of time involved is discussed further below, but it would not appear to be enough to protect the world from premature destruction.

For scenarios in which the crossover radius is further below the experimental bound, the initial 5-dimensional phase would be even faster (albeit to reach a smaller mass), but the warped phase and the final 4-dimensional phase would take longer. In particular, the GM paper estimates that if the crossover radius is less than about 200 Å (i.e. about 10,000 times smaller than the experimental bound), the time involved for the final growth stage would be in excess of 3 billion years [GM p. 26]. It further states that the warped phase should also yield a similar time scale, but does not give an exact estimate [GM p. 26].

(It is not actually clear whether, even assuming that the GM paper's accretion predictions are correct, the benchmark of 200 Å would be sufficient to prevent the premature destruction of the Earth. The paper repeatedly refers to the "Sun's natural lifetime" [GM abstract, cf. pp. 28, 52], suggests that 6 billion years would be longer than the Sun's lifetime [GM p. 28], and in its conclusion speaks of the natural life of the solar system being "in the five billion year range" [GM p. 52]. It does not, however, give any reference with a specific prediction for the Earth's demise.

> more stable," Landsberg said. Nearly all of the black holes will be traveling fast enough from the accelerator to escape Earth's gravity. "Even if you produced 10 million black holes a year, only 10 would basically get trapped, orbiting around its center," Landsberg said.
>
> However, such trapped black holes are so tiny, they could pass through a block of iron the distance from the Earth to the Moon and not hit anything. They would each take about 100 hours to gobble up one proton.
>
> At that rate, even if one did not take into account the fact that each black hole would slow down every time it gobbled up a proton, and thus suck down matter at an even slower rate, "about 100 protons would be destroyed every year by such a black hole, so it would take much more than the age of universe to destroy even one milligram of Earth material," Landsberg concluded. "It's quite hard to destroy the Earth." [Choi06 ↗]

According to the main text of the GM paper this analysis is incorrect, since even microscopic black holes are capable of extremely fast growth. It should be noted, though, that Professor Landsberg's estimate was originally intended for scenarios with two or more unwarped extra dimensions, and not scenarios with a single warped extra dimension and much faster black hole accretion [▷ ADDCITE GL letter 25 Feb 2010] (The calculations of the GM paper also show that the probability of a neutral stable LHC black hole being trapped could be between 24 to 1400 times greater than the 1 in a million rate used for this estimate, and may be even higher for black holes with masses below 4 TeV [GM p. 83, table 12 ↗].)

A recent study examining this issue concluded that the Earth would not be destroyed by the Sun for another 7.59 ± 0.05 billion years [SS08 arXiv p. 7] (and, as noted earlier, it is still not certain that the Earth's fate is sealed). Assuming that single black hole accretion in a 5-dimensional scenario with a crossover radius of 200 Å would take approximately 6 billion years (the paper does not give an exact prediction), this would still result in shortening the Earth's life by about 1.5 billion years. A crossover radius somewhat less than 200 Å may be required for the GM paper's accretion models not to predict the premature destruction of the Earth.)

6 Dimensions - For the case of 6 dimensions, there are 4 different scenarios to consider: 2 unwarped extra dimensions of identical radii, 2 unwarped extra dimension with different radii, 2 warped extra dimensions with identical warping, and 2 warped extra dimensions with different warping.

- **Identical Unwarped Extra Dimensions** - For the scenario with 2 unwarped extra dimensions of identical radii, the GM paper breaks its analysis into 5 different phases. The first phase is subnuclear growth, from the black hole's initial formation until it has a capture radius the size of a nucleon. The second phase is from a capture radius the size of a nucleon to a capture radius the size of an atom (1 Å). The third phase is a period of "macroscopic" 6-dimensional growth until the Bondi radius reaches R_D. The fourth phase is the transition phase as the Bondi radius grows from R_D to R_C. The fifth phase is the growth of the black hole from a Bondi radius of R_C until the destruction of the planet. The GM paper argues against an Eddington-limited phase [GM pp. 61–62], which would otherwise be a sixth phase and increase the total accretion time.

  The GM paper estimates that the first phase is very quick and thus does not include it in the total accretion times [GM p. 19].[83]

  The GM similarly reports that the second phase of growth, up to a capture radius the size of an atom, would also be quite short and is therefore regarded as negligible [GM p. 20]. Based on the equation provided in the paper [GM p. 20, eq. 4.23], the estimated time would range from about 75 minutes in the case of $M_D = 1$ TeV up to about 5.5 years in the case of $M_D = 14$ TeV.[84]

  The times for the third phase, up to a Bondi radius of R_D, is given by equation 4.46 in the GM paper [GM p. 25, eq. 4.46]. The estimated time for this phase would be almost 12,000 years for $M_D = 1$ TeV, and 2.3 million years for $M_D = 14$ TeV.

  The fourth phase, the transition from R_D to R_C, is given by equation 4.49$_{\text{(with subscript 6)}}$

[83]While the GM paper says that this growth phase is "nearly negligible" [GM p. 19 ↗], it is not clear whether it even exists for the case of 6 unwarped dimensions (i.e. whether, for a value of $M_D \leq 14$ TeV, the initial capture radius for a black hole trapped within the Earth could be less than 1 fm.)

[84]The GM paper only considers values of $M_D < 4.7$ TeV, since it argues that the minimum mass of a black hole is about three times the value of M_D. Since that argument has been rejected in this paper, values of M_D up to and including 14 TeV are considered. Generally, the total accretion times are greater for higher values of M_D.

[GM p. 25, eq. 4.49]. The estimated time would be about 21,000 years for $M_D = 1$ TeV and about 4.1 million years for $M_D = 14$ TeV.

The fifth and final phase, black hole growth until the destruction of the planet, is given again by equation 4.49$_{\text{(with subscript 4)}}$ [GM p. 25, eq. 4.49]. The estimated time would be about 24,000 years for $M_D = 1$ TeV and about 4.8 million years for $M_D = 14$ TeV.

While the times involved in this scenario are not short enough to threaten the current inhabitants of the planet and their immediate descendants, they are still far too short to be considered morally acceptable by any reasonable standard.

- **Non-Identical Unwarped Extra Dimensions** - The GM paper does not consider the second scenario with 2 unwarped extra dimensions of unequal radii. An independent calculation for this scenario has not been attempted in this paper, but generally, the times may be expected to be somewhat shorter due to an extension of the period of extra-dimensional growth.

- **Identically Warped Extra Dimensions** - The third scenario is addressed in the GM paper with the general bounds placed on the times involved in warped evolution. The GM paper reports that for values of R_C significantly larger than 200 Å, single black hole accretion could cause the premature destruction of the Earth [GM p. 26]. On the other hand, it contends that the Earth would be safe from a single black hole for values of $R_C \lesssim 200$ Å[GM p. 26] (although as noted above, it is not clear whether this particular value would be sufficient to prevent the Earth's premature destruction).

- **Non-Identically Warped Extra Dimensions** - The GM paper does not explicitly address the fourth scenario, that of 2 extra-dimensions with non-identical warping, although one may assume that the 200 Å criterion provides a useful indication of the approximate accretion times involved.

7 Dimensions - For the case of 7 dimensions, 4 different scenarios also need to be considered, viz.: 3 unwarped extra dimensions of identical radii, 3 unwarped extra dimension with non-identical radii, 3 warped extra dimensions with identical warping, and 3 warped extra dimensions with non-identical warping.

- **Identical Unwarped Extra Dimensions** - This scenario is qualitatively similar to the scenario discussed above of 6 dimensions with identical unwarped extra dimensions, and the GM paper analyzes these scenarios together. The only significant difference between the two scenarios is that the GM paper estimates that accretion would take significantly longer in the 7-dimensional case. The process of accretion can be analyzed by looking at the same five phases that applied to the 6-dimensional scenario.

  The first phase, up to a capture radius of a nucleon is reported to be very quick [GM p. 19]. The time involved is considered negligible in the GM paper, although, as with the

6-dimensional case, it is not clear whether it even exists within the Earth for values of M_D below 14 TeV.

The second phase, up to a capture radius of an atom, is similarly modelled based on the competition between the gravitational pull of the black hole and the electromagnetic resistance to movement of an atom's inner ion. The times involved are substantially longer than the corresponding scenario in 6 dimensions. They also vary significantly depending on the value of M_D. Based on equation 4.24 in the GM paper [GM p. 20, eq. 4.24], the accretion times would be about 10,000 years for $M_D = 1$ TeV, 22 million years for $M_D = 4.7$ TeV, and 5.1 billion years for $M_D = 14$ TeV.

At the start of the third phase, Bondi accretion from a Bondi radius of ≈ 1 Å up to R_D, the mass of the black hole is estimated to be on the order of 10 kg [GM p. 25].[85] The times required for the third phase are given by equation 4.47 [GM p. 25, eq. 4.47]. The accretion times would be about 215 million years for $M_D = 1$ TeV, 2.8 billion years for $M_D = 4.7$ TeV, and 17.5 billion years for $M_D = 14$ TeV.

The fourth phase, Bondi accretion from R_D to R_C, is addressed by equation $4.50_{\text{with subscript 7}}$ [GM p. 25, eq. 4.50], with resulting times of about 3.2 billion years for $M_D = 1$ TeV, 42 billion years for $M_D = 4.7$ TeV, and 260 billion years for $M_D = 14$ TeV.

The final phase, Bondi accretion from R_C until the destruction of the planet, is also addressed by equation $4.50_{\text{with subscript 4}}$ [GM p. 25, eq. 4.50], with times that are the same as those for the fourth phase. The GM paper gives combined times of 6.4, 20, 40, 65, and 94 billion years for values of $M_D = 1$, 2, 3, 4, or 5 TeV respectively [GM p. 26].

As in the case of 6 dimensions, the GM paper argues against an Eddington-limited phase [GM pp. 61–62], which could otherwise slow down the final stages of Bondi accretion.

(As per the estimates of the GM paper, the estimated lower bounds on the accretion times within the Earth involve many billions of years for higher values of M_D, however it should be noted that for the case of $M_D = 1$ TeV, the lower bound on the accretion time may be less than the Earth's expected lifespan. The GM paper states that the combined time scale is 6.4 billion years for $M_D = 1$ TeV, although this total may not have included the time involved in the third phase. Using an estimate of 6.62 billion years for the total time involved in single black hole accretion, it is still almost a billion years shorter than a recently published estimate of 7.59 ± 0.05 billion years before the Earth's natural demise [SS08 arXiv p. 7].)

- **Non-Identical Unwarped Extra Dimensions** - The GM paper does not explicitly address the second scenario in which the radii of the extra dimensions are not all the same. This

[85] The paper does not state what the value of M_D is for this mass estimate. When compared to the mass of a black hole in 7 dimensions with $M_D = 1$ TeV, the mass of a black hole with the same Bondi radius would be about 2300 times greater for $M_D = 4.7$ TeV and over 500,000 times greater for $M_D = 14$ TeV [cf. GM pp. 12, 22 eqs. 3.16, 4.32 ↗]. If the estimate of 10 kg was for a black hole with $M_D = 1$ TeV, then the masses would be on the order of 20 tons for $M_D = 4.7$ TeV and 5000 tons for $M_D = 14$ TeV.

is an important case since an extended period of higher-dimensional growth could lead to much shorter accretion times (including for values of M_D up to 14 TeV). An independent analysis of this case has not been attempted in this paper.

- **Identically Warped Extra Dimensions** - The general criterion that the GM paper adopts for warped scenarios is that if the value of the crossover radius is significantly larger than 200 Å, the Earth could be prematurely destroyed [GM p. 26]. On the other hand, the paper also claims that a crossover radius below 200 Å implies a safe time scale for accretion (although, as noted earlier, it is not clear if an even smaller radius is required).[86]

- **Non-Identically Warped Extra Dimensions** - The GM paper does not explicitly address the scenario of non-identical warping, but the 200 Å criterion may help determine which cases might involve significant risks.

8 to 11 Dimensions - The cases of 8, 9, 10, or 11 dimensions require an analysis of the 4 different types of scenarios identified for the cases of 6 or 7 dimensions.

- **Identical Unwarped Extra Dimensions** - Black hole accretion in 8 to 11 unwarped dimensions is broken down into 5 distinct phases in the GM paper. These phases differ, however, from those of 6 or 7 unwarped dimensions since the crossover to 4-dimensional growth is expected to occur at a radius of less than 1 Å. Thus, the five phase are: subnuclear growth up to a capture radius the size of a nucleon, subatomic growth up to a capture radius of R_D, transitional subatomic growth from a capture radius of R_D up to R_C, initial 4-dimensional subatomic growth from a capture radius of R_C up to ≈ 1 Å, and final 4-dimensional growth from a Bondi radius of ≈ 1 Å until the destruction of the world.

  For the first phase, the GM paper's equation indicates that the initial electromagnetic capture radius is already about a third of the radius of a nucleon for the case of 11 dimensions [GM p. 19, eq. 4.18], and is even larger for fewer dimensions. Based on this, the paper concludes that the time involved in the subnuclear growth phase is nearly negligible [GM p. 19].[87]

  The times for the second phase, up to a capture radius of R_D, are given in the GM paper by equations 4.25 to 4.28 [GM p. 21, eqs. 4.25, 4.26, 4.27, 4.28]. For a value of $M_D = 1$ TeV the times are approximately 5.4 million years for 8 dimensions, 20,000 years for 9 dimensions, 220 years for 10 dimensions, and 4.8 years for 11 dimensions. For a value of $M_D = 14$ TeV the times are approximately 103,000 years for 8 dimensions, 500 years for 9 dimensions, 7

[86] While not mentioned specifically in the paper, the earlier phases of 7-dimensional growth could add to the total accretion times (and thus increase the theoretically safe crossover radius), however, the ratio between the values of R_C and R_D can be much greater in warped scenarios, so this might significantly reduce the time allocated for those phases.

[87] The paper does not provide specific figures for the other dimensions, and it is not clear whether there even is a subnuclear phase for lower values of M_D in the cases of 8 or 9 dimensions.

years for 10 dimensions, and about 2 months for 11 dimensions. (The accretion times for this phase decrease with increasing dimensions simply because the value of R_D is decreasing [GM p. 12, eqs. 3.10, 3.11, 3.12, 3.13], so the black hole does not have to become as large. Similarly, the times decrease for increasing values of M_D since higher values of M_D result in lower values of R_D [GM p. 12, eq. 3.14].)

The third phase, from a capture radius of R_D up to R_C, and the fourth phase, from a capture radius of R_C up to 1 Å, are addressed in the GM paper with a single bound, given by equation 4.30 [GM p. 21, eq. 4.30]. The reason only a single bound is used is because according to the GM paper's model for subatomic accretion, the electromagnetic capture radius only increases as the (D-1)th root of the black hole's mass, so even during a phase of 4-dimensional growth, the accretion times are governed by the upper limit of the black hole's mass. The times for 8 to 11 dimensions are assumed to be roughly the same,[88] since the GM paper's treatment of the transition to 4-dimensional subatomic growth assumes that once a black hole has a capture radius larger than R_C, its mass must be exactly the same as if extra-dimensional gravity never existed [GM pp. 13, 19, 20, 21, 22, eq. 4.22]. The paper calculates a "flux distance" that a black hole must cover to accrete a certain mass [GM p. 21, eq. 4.29], and asserts that a microscopic black hole accreting within the Earth would experience a flux bounded by to the Earth's escape velocity [GM p. 21] of approximately 11 km/s [GM p. 88, eq. I.13]. Based on this assumption, the paper estimates that the subatomic accretion time for a single black hole would be on the order of 300 billion years [GM p. 21, eq. 4.30]

For the fifth phase, Bondi accretion from a radius of ≈ 1 Å until the destruction of the world, the published version of the GM paper does not include an explicit estimate. An earlier draft of the paper included an equation for this time [GM.ltx lines 1297–1304 ↗], which, when combined with a value of $\lambda_4 = 4$ [GM p. 25], results in a total time for this phase of ~ 600 billion years. In the final draft, however, this equation was "commented out" and replaced with an estimate of the time required for the black hole's Bondi radius to double from ≈ 1 Å to ≈ 2 Å [GM.ltx lines 1305–1313 ↗]. The paper does not explicitly state how much this is of the total accretion time and many readers may simply assume that this is the black hole's doubling time, although from the paper's equation for 4-dimensional Bondi growth [GM p. 24, eq. 4.41] one can see that the phase from 1 Å to 2 Å would be just over half of the Bondi accretion time before the destruction of the Earth.

The GM paper argues against a final Eddington-limited phase of black hole accretion [GM pp. 61–62], however, as discussed below, even if there was one, its contribution to the total accretion time would be relatively minor.

- **Non-Identical Unwarped Extra Dimensions** - The GM paper does not estimate the accretion rates for scenarios with non-identical unwarped extra dimensions. This is a major gap in the paper since it concludes that the accretion times for $D \geq 8$ are long compared to

[88] A possible exception due to uncertainties in the value of R_C in the case of 8 dimensions is mentioned in the GM paper [GM pp. 21-22 ↗] and discussed further below.

the natural lifetime of the Sun [GM pp. 27–28], even though this is not necessarily the case if the extra dimensions have different radii. For example, if one of the extra dimensions has a radius significantly greater than 200 Å, it might be possible for the accretion rate of a single black hole to be fast enough to prematurely destroy the planet.

- **Identically Warped Extra Dimensions** - The accretion times for identically warped extra dimensions would likely be covered by the 200 Å criterion given in the GM paper [GM p. 26], and may be expected to be sufficiently long in this scenario.

- **Non-Identically Warped Extra Dimensions** - Accretion times for non-identically warped extra dimensions could potentially be much faster due to the delay in the start of the period of 4-dimensional growth. As with the case of non-identical unwarped dimensions, if the warping of at least one of the extra dimensions is significantly greater than 200 Å, the accretion rate of a single black hole could be fast enough to prematurely destroy the Earth.

12 or More Dimensions - The four different scenarios for $D \geq 12$ are reviewed below:

- **Identical Unwarped Extra Dimensions** - While the GM paper occasionally addresses the case of $D \geq 12$ implicitly (e.g. through references to $D \geq 8$ [GM pp. 19–20, 20–22, 23–25, 27–28, 50–51, 52, 56, 59, 64]) and explicitly (by referring to higher dimensions after providing an equation for $D = 11$ [GM p. 21]), its coverage is spotty and there are a couple important gaps.

  The first phase of accretion, the growth from black hole formation until a capture radius the size of a nucleon, has been treated as negligible in the GM paper. This may be true for $D \leq 11$ [GM p. 19], but it is not clear if the same can be said for $D \geq 12$. In the case of 13 or more dimensions with unwarped dimensions of identical radii, the value of R_D is less than a nucleon [GM p. 12, eq. 3.7], so the transition to 4-dimensional growth must begin during this phase; for the case of 15 or more dimensions, the transition must also be completed during the subnuclear phase [GM p. 13, eq. 3.22]. Since the GM paper's modelling of the transition to 4-dimensional growth requires the black hole to acquire the mass equivalent to a non-extradimensional scenario, this would involve a very significant increase in mass before its capture radius reaches even a fermi. Insofar as the GM paper's accretion model is correct, this suggests that the accretion times could be very long for this phase.

  The subsequent growth of the black hole to a capture radius of 1 Å may also be bounded by equation 4.29 [GM p. 21, eq. 4.29], implying accretion times on the order of 300 billion years if one assumes that the rate of flux is approximately 11 km/s [GM p. 21].

  The final phase of accretion, from a Bondi radius of ≈ 1 Å until the destruction of the planet, would involve 4-dimensional accretion and may be expected to be similar to the times estimated for $8 \leq D \leq 11$. Based on the equation in an earlier draft of the GM paper [GM.ltx lines 1297–1304 ↗], and a value of $\lambda_4 = 4$ [GM p. 25], the accretion time would be ~ 600 billion years.

As noted for the other cases, the GM paper argues against an Eddington-limit [GM pp. 61–62], which would otherwise slow down the final phase of accretion.

- **Non-Identical Unwarped Extra Dimensions** - The possibility of unequal unwarped extra dimensions is not explicitly addressed in the GM paper. As with the case of $8 \le D \le 11$, scenarios for $D \ge 12$ in which at least one of the extra dimensions has a radius significantly larger than 200 Å could result in accretion times which are shorter than the Earth's natural lifetime.

- **Identically Warped Extra Dimensions** - As with the case of $8 \le D \le 11$, the accretion times for identically warped extra dimensions would likely be covered by the 200 Å criterion given in the GM paper [GM p. 26], and may be expected to be sufficiently long.

- **Non-Identically Warped Extra Dimensions** - The scenario of non-identically warped extra dimensions presents the possibility that at least one of the extra dimensions may have a warping which leads to the value of R_C being significantly greater than 200 Å. If this should be the case, the expected accretion time for a single black hole could be shorter than the Earth's nature lifetime.

Eddington-Limited Growth - The GM paper presents an argument against the possibility of an Eddington limit for the Earth [GM pp. 61–62], which is reviewed more carefully later in this section.

Nevertheless, the GM paper does give a general equation for the e-fold time for Eddington-limited growth, viz. $t_{Edd} \approx 2.3\eta \times 10^8$yr [GM p. 27]. The paper includes no estimate, however, for the value of η (the efficiency parameter of reradiation), although it does claim that spherical accretion onto a black hole is inefficient at producing a large luminosity [GM p. 27], and suggests, in the case of white dwarfs, that $\eta = .01$ is a relatively large value [GM p. 65]. For a value of $\eta = .01$, the e-fold time for Eddington-limited growth would be only 2.3 million years, and the time would be proportionately shorter for smaller values of η.

To establish a bound on the possible effects of an Eddington-limited phase on the total black hole accretion time, one may note that there are just under 64 e-fold increases in mass when going from 1 gram to the mass of the Earth. For the case of $\eta = .01$ this would involve a total time of about 147 million years (for a value of $\eta = .001$, the time would be 10 times shorter, or 14.7 million years; for a value of $\eta = .1$, the time would be 10 times longer, or about 1.47 billion years). These values are an upper bound for the additional time until the destruction of the Earth since one would generally not expect a black hole to accrete the full mass of the Earth. Well before that stage one may expect the Earth to implode due to black hole compaction of its interior, or explode due to the energy release from reradiation.

If, hypothetically, one were to consider the time required for Eddington-limited growth from the mass of 1 TeV up to the mass of the Earth, the above time estimates should be increased by about 75%. Specifically, the combined times would be about 25.7 million years for $\eta = .001$, 257 million years for $\eta = .01$, and 2.57 billion years for $\eta = .1$. While these times are not negligible (for the case of $\eta = .1$), they are still not expected to be enough to make the difference between whether the Earth is or is not prematurely destroyed.

§ Critical Review of Single Black Hole Accretion in the Earth

The model of single black hole accretion presented in the GM paper is critically reviewed in the remainder of this section. Some of the more general concerns are described first, followed by specific notes on the different phases of growth from the subnuclear stage until the destruction of the planet.

▼ General Concerns

Purely Theoretical Treatment - One of the essential elements that distinguishes science from other fields of human thought, such as philosophy or religion, is its emphasis on the empirical confirmation of hypotheses. Modern society has come to respect and appreciate science in large part because scientists are expected to subject their theories to rigorous testing against reality, and until such testing is done, their theories are no more than interesting speculations. In this case, CERN tries to assure the world community that, on the basis of purely theoretical and untested calculations, the accretion of a microscopic black hole is completely safe in scenarios with 8 or more dimensions or a cross-over radius of less than 200 Å. In the absence of empirical confirmation of the GM paper's accretion model, the confidence CERN expresses in its conclusions has no genuine scientific basis. Indeed, the sprinkling of equations throughout the GM paper appears to be the only thing that distinguishes it from a theological treatise.

Conservative Claims - As noted in section 3, the GM paper repeatedly claims that its analysis is "conservative". In the specific case of accretion, the paper claims to "...establish upper and lower limits to the rate at which accretion can take place ..." [GM p. 4], but it only calculates an upper limit for the rate of accretion in the Earth and not a lower limit, so how conservative the paper's estimates actually are cannot be objectively assessed. While some assumptions in the paper are conservative, there are also many factors that are completely ignored, so the claim that the paper's estimates are the "fastest possible growth in Earth" [GM p. 5] is untenable. A number of these factors are described in further detail below.

Absence of Reradiation - The GM paper does consider the possibility that reradiation could cause an Eddington limit of the rate of accretion within the Earth, but aside from this case, it completely ignores the effects of reradiation or other forms of radiative transport during the accretion process. The paper justifies this by asserting that if reradiation is present it can lower the black hole growth rate [GM p. 15]. Since the estimate for the Earth is supposed to be an upper bound on the black hole growth rate, it would seem to be reasonable and conservative to ignore this factor. On the other hand, the appendix notes that:

> For example, in the case of accretion on Earth, such radiant energy could melt the material surrounding the black hole, and thus has potential to increase the accretion rate. [GM p. 57]

The paper then claims to have accounted for this example, since it has supposedly already assumed that accretion within the Earth is of a liquid,[89] however, it does not make any effort to demonstrate a general rule that reradiation cannot increase the rate of accretion through other processes. Without such a finding, the estimated accretion rates for the Earth cannot be considered an upper bound, or even conservative.

Contribution from Bulk Particles - Even though the basic assumption of the GM paper is a higher-dimensional brane-world scenario, no consideration is given to the possible contribution that gravitons or other hypothetical particles in the bulk could make to the growth of black holes. The calculations in the paper only consider black hole growth from the consumption of particles in the brane. If there is any additional contribution from particles in the bulk, then the asserted upper bound for black hole growth within the Earth would likely be an underestimate.

Movement of Black Holes Off the Brane - A related question that is unaddressed in the GM paper is whether black holes can move off the brane and accrete while centred in the bulk. (This possibility was mentioned earlier in this paper in the discussion of subplanckian black holes.) In such a scenario, the key question is whether the black hole growth rate would be faster in the bulk (or even in other branes!) but this is not considered in the GM paper. A first guess could be that growth in the bulk would be less rapid than in our brane, but it may be difficult to resolve this theoretical question with the degree of confidence that this issue demands. The effects that other nearby branes could have on black hole growth is even more uncertain.

General Forms of the Potential - The GM paper does acknowledge the possibility of more general forms of the potential in an extra-dimensional scenario but the authors are content to restrict their analysis to what they call "a very wide class of potentials that become strong at the TeV scale." [GM p. 15] While their analysis may indeed cover "a very wide class", for the purpose of a risk assessment, it is necessary to consider all possible scenarios, or at least to set a bound on the probability of scenarios that are not covered. This has not been done in the paper.

Non-Identical Extra Dimensions - The radii associated with extra-dimensions need not be identical. Indeed, Professor Giddings has previously argued in favour of producing larger and larger black holes for the purpose of mapping out the sizes of the different radii. He presents the following plan:

> Black hole production therefore represents the end of short distance physics. Fortunately, it is not the end of high energy physics. As we go to higher energies, the black holes that we make get larger and extend further into the extra dimensions. At some point they get large enough to run into other features of the extra dimensions. For example, they might encounter the finite radius of one of the dimensions, or finite curvature radii, or bump into other branes in the extra dimensions. As the black holes become large enough to detect these features, their cross-sections, decay rates, and decay spectra change. For example, once a black hole has a radius larger than

[89] See further comments about this below in the section on microscopic accretion

> that of one of the extra dimensions, or larger than a curvature radius in the extra dimensions, the effective dimension in the production cross-section (17) changes. By measuring kinks in the cross-section at larger energies, one can explore the extra dimensions. So high energy experiments will be used to study the geography of the extra dimensions. [Gid01 p. 8][90]

Given the importance Professor Giddings attaches to such details, it is surprising that the paper he co-authored seems to ignore the scenarios with non-identical radii. The paper does begin its analysis of black hole growth above a fermi in the case of 8 or more dimensions by stating:

> For concreteness, let us first neglect warping and assume that all radii are the same so that this is a transition to the four-dimensional regime. [GM p. 21]

However, the paper does not subsequently address the case of the radii not all being the same. Giving the authors the benefit of the doubt, one could say that it is implicitly covered by the initial phrase of the section on warped evolution, which states:

> In order to parameterize more general evolutions, we consider the case of a warped scenario, as described in section 3.2.3. [GM p. 26]

The text does not, however, make an explicit parameterization between the warped scenario and more general evolutions. Moreover, in the summary of black hole growth on Earth, the paper reports that the growth times for 8 or more dimensions are bounded below by many-billion-year time scales [GM pp. 27–28], which applies only to the case of identical extra-dimensions. As noted above in the summary of CERN's accretion estimates, no such bound has been shown in the paper should any of the extra dimensions have a relatively large radius. The case of identical extra-dimensions—the only case explicitly considered in the paper—is the one expected to maximize the period of 4-dimensional growth and thereby maximize the black hole accretion time.

Contribution from Dark Energy - The GM paper ignores the question of dark energy and its potential effect on the growth rate of black holes in the Earth. The nature of dark energy is still very much unknown and it may be difficult to predict the effects that dark energy could have within the vicinity of microscopic black holes, and whether it could directly contribute to the black hole growth rate.

Numerical Simulations - While not absolutely essential, an extremely valuable tool in the analysis of the expected behaviour of accreting black holes is the construction of numerical simulations using high-speed computers. With the steady increase in computing power over the last few years, physicists studying astronomical black holes have come to rely more and more on computer simulations to better understand their basic behaviour. Such simulations permit the consideration of more complicated models that cannot be solved through current analytical techniques. Often these simulations reveal unexpected dynamics of accreting black hole and help theorists better understand some of the complexities of realistic accretion. CERN has thus far not presented any numerical simulation of the accretion behaviour of the black holes it may produce in LHC collisions.

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[90] See also [GT02 ↗]

▼ Subnuclear Accretion

The time from the initial formation of a TeV-scale black hole until its electromagnetic capture radius has grown to the size of a nucleon is found to be negligible in the GM paper, so any errors in the paper's modelling of this phase are relatively unimportant for critiquing the paper's overall bounds on black hole growth times. The basic model for growth during this phase is based, however, on the electromagnetic capture radius, so many of the points described below for subatomic accretion would also apply to this phase.

One important point to note, however, is that the introduction of the GM paper misleads readers about the accretion rate during this phase. The introduction describes the evolution of neutral stable black holes trapped in the Earth and dense objects [GM p. 4] as follows:

> Such black holes are very small, and their accretion power, if limited to absorbing particles that have impact parameters of the order of the Schwarzschild radius, is typically insufficient to cause macroscopic growth. [GM p. 5]

What the introduction does not mention is that the authors do not at all expect that a black hole trapped in the Earth would be limited to absorbing particles that are close to its Schwarzschild radius. The paper's own calculations show that immediately after formation, a minimum-mass Earth-bound black hole in an 11-dimensional scenario would have a capture radius that is about a third the size of a nucleon [GM p. 19, eq. 4.18]–and this radius would be even larger in cases of fewer dimensions [GM p. 19]. This capture radius would be about 500 times larger than the Schwarzschild radius of a black hole in 11 dimensions [GM p. 12, eq. 3.16], and the capture rate would be about 250,000 times faster [GM p. 19, eq. 4.19].

A capture radius of the order of the Schwarzschild radius would only apply to relativistic black holes formed through cosmic ray collisions with the Earth's atmosphere. Only those black holes would have such a small capture radius, and, as clearly stated in the main text of the GM paper, they would be expected to pass harmlessly through the Earth [GM p. 33], and not be trapped at all.

▼ Subatomic Accretion

Before describing specific problems with the model for subatomic growth put forth in the GM paper, a few words should be said about the authors' characterization of their estimates as "Subatomic growth laws" [GM p. 19]. Neither the scientific community nor the general public usually describes any new bit of scientific speculation as a physical "law". While different authors may differ on the details, a "law" can generally be described as follows:

> A physical law or scientific law is a scientific generalization based on empirical observations of physical behavior (i.e. the law of nature [1]). Laws of nature are observable. Scientific laws are empirical, describing the observable laws. Empirical laws are typically conclusions based on repeated scientific experiments and simple observations, over many years, and which have become accepted universally within the scientific community. [Wiki:PhysLaw ↗]

More succinctly, a physical law can be defined as:

> A well-established, observed physical characteristic or behavior of nature. [Wikt:Law ↗]

Some of the specific attributes associated with physical laws include the following:

> True, at least within their regime of validity. By definition, there have never been repeatable contradicting observations.
>
> Universal. They appear to apply everywhere in the universe. (Davies, 1992:82)
>
> Simple. They are typically expressed in terms of a single mathematical equation. (Davies)
>
> Absolute. Nothing in the universe appears to affect them. (Davies, 1992:82)
>
> Stable. Unchanged since first discovered (although they may have been shown to be approximations of more accurate laws-see "Laws as approximations" below),
>
> Omnipotent. Everything in the universe apparently must comply with them (according to observations). (Davies, 1992:83) [Wiki:PhysLaw ↗]

While one could facetiously note that the GM paper's "growth laws" have never been contradicted by any observations, the more serious problem is that they are not based on any observations. An unfortunate—but likely intentional—result of the authors' characterization of their speculations as laws is that unsuspecting readers may actually take the term seriously and assume that there is some observed basis for their equations, and that they are a well-established characterization of the growth of microscopic black holes within the Earth. Clearly, the authors' speculations are not a "law", and, as the following text describes, they are not even a reasonable first guess of what the growth rate of black holes could be.

Flux from Thermal Velocity - The flux of matter is a critical element in the GM paper's calculation of the rate of black hole growth. For the case of subatomic accretion within the Earth the paper focuses exclusively on the flux of matter caused by the velocity of the black hole. The paper states:

> The flux can arise either from the motion of the black hole relative to the body, or from the motion of the constituents of the body relative to the black hole. In the case where the dominant effect is the velocity v of the black hole, we have
>
> $$F = \rho v$$
>
> where ρ is the mass density near the capture radius. [GM p. 15]

On the other hand, for accretion within a white dwarf, the GM paper uses an estimate of the thermal velocity to set a lower bound on the flux [GM p. 41]. For the case of the Earth, even if the velocity of the black hole is the dominant factor determining the flux, any reasonable effort to set a bound on the growth of a black hole would look not just at the dominant factor, but also any other possible factors. Thus, one would expect the subatomic accretion model to include an estimate of the contribution to the flux from the thermal velocity of matter within the Earth, or at least set a bound on its possible contribution.

Moreover, the paper has not demonstrated that in the later stages of subatomic growth, the contribution from the thermal velocity of particles is not the dominant factor determining the flux of matter towards the black hole. This is particularly a concern should the black hole be relatively stationary while its reradiation dramatically increases the temperature of its local environment. While the precise dynamics of such a situation need to be more carefully determined, if the subatomic growth of a microscopic black hole could be accelerated by such thermal effects, the accretion time estimates given in the GM paper would be essentially meaningless.

Electron–Ion Attractions - As noted in section 8.6 on charged stable black hole accretion, the GM paper suggests that the accretion of ions might result in the accumulation of positive charge which would create a force of repulsion acting against the accretion of other ions. The paper does note that, "A positively-charged black hole will also have an enhanced absorption rate for electrons, which works toward neutralization." [GM p. 18] Despite this acknowledgement, the paper then simply asserts that, "So, while charge effects could possibly somewhat slow the absorption rate, we will make the conservative assumption that they don't, and that sufficient neutralization is automatic." [GM p. 18] It is very much possible that charge effects (including those within the capture radius but outside the black hole horizon) could slow the absorption rate, but the paper presents no evidence or argument to show that such effects could not have the opposite result and accelerate the accretion rate. The paper simply uses the casual wording, "...which works toward neutralization" to leave readers with the impression that a black hole with multiple positive charges will take a while to attract electrons, even though a more realistic expectation is that it would be a very rapid process. The paper makes no attempt to calculate or set bounds on the time for neutralization. It is not unreasonable to wonder whether the oscillations in the charge of the black hole, superimposed on the process of gravitational attraction, could not, in fact, significantly accelerate the overall accretion of matter.

Effect on Outer Electron Cloud - The basic accretion model proposed in the GM paper is essentially that of a spring, with the nucleus and inner electrons being pulled by the black hole while the outer electrons are held rigidly in place and exert powerful electromagnetic resistance to the movement of the nucleus [GM p. 16-19]. The paper begins by stating that, "...we will largely neglect separate capture of electrons since their capture rates are much smaller due to their smaller masses and higher velocities." [GM p. 16], but no realistic treatment of accretion can ignore the effect that a black hole has on electrons. It may be true that the direct contribution of electrons to the growth of the black hole's mass is small, but the entire model for this phase is based on a competition between the electromagnetic force of the outer electron cloud and the gravitational force of the black hole, so a very basic question is what effect the black hole has on the outer electron cloud. The effect may be relatively insignificant when the black hole is very small, but by the time the black hole's electromagnetic capture radius is in the range between 0.1 Å and 1 Å, the effect could be extremely important. This is the range that the GM paper predicts will take the lion's share of the subatomic accretion time, so an accurate model of black hole growth at this size is essential.

When a black hole has enough power to pull a nucleus/ion a distance of 0.1 Å away from the centre of a hypothetically fixed outer electron cloud, it is unreasonable to claim that, in a more realistic treatment, it could not have any effect on the outer electrons. If the black hole is able to pull the centre of the outer electron cloud towards it, then this effect could be (roughly) added to the black hole's pull on the nucleus/ion, thereby increasing the effective electromagnetic capture radius and accelerating the accretion rate.

As the electromagnetic capture radius grows larger, the scope of analysis should also grow to focus on the weaker links in the chain resisting the black hole's gravitational pull. Thus, beyond the effect on the outer electron cloud, one would also need to consider the black hole's effect on nearby particles. As these may be interacting with the outer electrons, any attraction that the black hole exerts on them could also affect the centre of the outer electron cloud and may similarly be (roughly) added to the electromagnetic capture radius.

Distribution of the Electron Cloud - The GM paper states in its derivation of the electromagnetic capture radius that it assumes the electron charge to be uniformly distributed in the atomic volume [GM p. 17]. On the other hand, the paper also notes that the inner electrons are strongly bound to the nucleus and move with it [GM p. 17, footnote 9]. Since these electrons are more concentrated closer to the nucleus, this would imply that the remaining electrons are less concentrated in that region. The derivation of the electromagnetic capture radius is based on a charge that is reduced to account for the movement of the inner electrons, but it assumes the same distribution associated with the entire cloud. A more accurate model would instead by based solely on the distribution of the outer electrons. Taking into account this difference could significantly reduce the resistance to gravitational attraction experienced during the earlier stages of accretion, and thus speed up that part of the process.[91]

Ionization by Reradiation - In addition to the effect that the gravitational attraction of the black hole has on the outer electron cloud, another possible effect could be ionization caused by reradiation. If reradiation from the particles that are already in the process of being accreted can cause the removal of electrons from an atom, it could possibly reduce the electromagnetic force on the nucleus and reduce the gravitational force required to move the nucleus/ion a given distance. (The details of this process would need to be more carefully considered, since the force of radiation on electrons and their outgoing pull on protons is an effect that can slow the rate of accretion, and even lead to an Eddington limit. In this case, a factor to consider is the timing of the force from outgoing electrons in relation to the timing of the black hole's approach to the nucleus.)

Subatomic Accretion of a Liquid - Despite the GM paper's claim that it had treated the problem as accretion from a fluid [GM p. 57], the subatomic model is, in fact, based on the

[91] Ideally, the precise details of accretion and the distribution of electrons would be checked with a computer simulation of subatomic accretion that accounted for this and other factors. One important detail that could be checked through a computer simulation is the effects that the presence of a microscopic black hole passing through an atom has on the distribution of the atom's outer electrons. The results of the revised distribution could then be fed back into the model for a more accurate estimate of the electromagnetic capture radius.

accretion of ions within a crystal [GM p. 18]. The closest the paper comes to dealing with the case of subatomic accretion within a liquid is its note that the semi-solid or semi-fluid layers of the Earth have characteristic values of K/m that are similar to those of solids [GM p. 18]. The paper does note that the Earth has "crystalline, semisolid, and liquid phases at various depths." [GM p. 22, hyperlinks added], but at no point does it explicitly calculate what the electromagnetic capture radius of a black hole is when accreting fully liquid matter.

Criterion for the Electromagnetic Capture Radius - The GM paper asserts that a black hole can have an electromagnetic capture radius of distance b if and only if the gravitational force of the black hole is greater than the restoring force on the inner ion at every point from its original rest position until the centre of the black hole [GM p. 17]. This criterion may be too strict. Even if the restoring force is greater than the gravitational attraction of the black hole for a brief stage in the journey of the ion, as long as the momentum acquired by the ion is sufficient to carry it through this barrier it could still be accreted. More specifically, instead of demanding that gravitational attraction be greater than the restoring force at every point, one should require that the integral of the net force over the distance travelled by the ion always be positive towards the black hole. (A more complete treatment might even consider the possibility of quantum tunnelling towards or away from the black hole through a potential barrier. On the other hand, a proper treatment would also need to look at the dynamics of the capture process and changes in the net force on the ion being accreted as the black hole moves away from its point of closest approach to the centre of the outer electron cloud.)

Attraction from an Approaching Black Hole - In addition to the effects that a black hole may have while inside an atom, one should also consider the effects it has while approaching the atom. The GM paper implicitly treats the impact parameter of the black hole with respect to a given nucleus as a randomly determined initial condition and focuses only on whether the black hole can overcome the restoring force on the inner ion while it passes through the atom. Another factor not considered in the paper's derivation is the overall attraction the black hole will have on the whole atom (and the neighbouring particles) while it approaches the atom. The electromagnetic capture radius should be calculated as a combination of both the black hole's power to capture an inner ion while inside the atom, and its power to draw the centre of an atom closer to its trajectory as it approaches the atom. When the (previously calculated) electromagnetic capture radius of a black hole is close to 1 Å this effect could significantly increase the effective capture radius and accelerate the rate of accretion.

Limited Range of the Force Equation - The GM paper mentions no limit on the range of validity for its calculation of the electromagnetic capture radius. The derivation for the electromagnetic restoring force acting on the inner ion appears to parameterize the portion of the charge of the outer electron cloud which affects the inner ion with the term d^3/a^3 [GM p. 17, eq. 4.6]. (This is not stated explicitly in the text, but it seems to be a reasonable explanation of that term.) As such, a natural limit for the equation is $d \leq a$. Once $d = a$, the restoring force will be based on the full charge of the outer electron cloud. With this interpretation, there does not seem to be any scope for increasing the effective charge beyond this limit, and the force exerted by this charge will simply drop off as the square of the distance from the centre of the outer electron cloud. If, on the other hand, the equations are presumed to apply unchanged for distances greater than 1 Å, then, supposedly, the force being exerted by the outer electron cloud on the (formerly) inner ion once it reaches a distance of 10 Å is 10 times greater than the force exerted at a distance of 1 Å due to a 1000-fold increase in the d^3/a^3 term and a 100-fold reduction from the $1/d^2$ term. This model does not seem to have a reasonable physical basis, and unless it can be justified, there is effectively no formula presented in the GM paper for electromagnetic capture radii greater than 1 Å. The significance of this issue is discussed further below.

▹ ADD NOTE on assumptions for the average density and black hole velocity within the Earth [GM pp. 19–20]. Compare with values for an LHC black hole trapped by the Earth's core (combined inner and outer core).

▼ Transition to Macroscopic Accretion

This phase of the accretion process merits special attention since in scenarios with 8 or more dimensions CERN's claim that neutral stable black hole production is safe rests almost entirely on the belief that accretion will be extremely slow when the electromagnetic capture radius or the Bondi radius of the black hole is within a couple orders of magnitude of 1 Å. This argument can be described as the "speed bump" theory of black hole safety. The doubling time of a black hole is relatively short in geological terms as it grows from its initial size until it has a capture radius of about 0.01 Å. The subsequent growth is said to be extremely slow up to a capture radius of 1 Å [GM p. 21]. Thereafter, growth is modelled as Bondi accretion and the GM paper asserts that the time required for the Bondi radius to double from approximately 1 Å to 2 Å is on the order of 300 billion years [GM pp. 24–25].[92] Slow growth during this phase is also essential for the safety argument in the case of 5, 6, or 7 dimensions if the extra dimensions are warped with a crossover radius of less than 0.01 Å. Whether the growth actually is that slow is a question considered below.

Interdependence of Growth Models - The conclusion of the GM paper claims to have presented two different arguments for why black hole growth times will be exceedingly long if the crossover to four-dimensional growth occurs at less than 1 Å. The paper states:

> In this case we have argued that this evolution occurs on times longer than the expected natural solar lifetime, in two different ways: via a microscopic argument, and via a macroscopic, hydrodynamic argument. [GM p. 50, hyperlink added]

[92]As mentioned earlier, the paper may have left it for the reader to assume that this is in general the doubling time as the black hole continues its growth, but it is not. The growth during this phase is constantly accelerating and by the GM paper's equation [GM p. 24, eq. 4.41 ↗], it will take half as long for the black hole to grow from 2 Å to 4 Å and then half of that time to grow from 4 Å to 8 Å, and so on. The time required for the Bondi radius to grow from 1 Å to 2 Å is not the doubling time in the sense of exponential growth, but rather slightly more than half the time until the destruction of the Earth (assuming continued Bondi growth). It may be noted that, according to the paper's model, 25% of the time needed for growth from 1 Å until planetary destruction is taken up by growth from 1 Å to just 1.34 Å.

The two arguments are, indeed, different, but they are also interdependent. Instead of offering two theoretical layers of protection against rapid black hole growth, the situation presents two different ways in which black hole growth could be fast enough to threaten the planet. This would not be the case if the longest time for microscopic growth occurred well below 1 Å and the longest time for macroscopic growth occurred well above 1 Å. In that case, the two arguments could be seen as offering two independent assurances of safety. The problem is that the most time-consuming period for both growth models occurs at the very same juncture. The GM paper conservatively assumes that the growth of the black hole is governed by the fastest of the models [GM p. 23], but if either of the models significantly underestimates the speed of accretion, then not only would this reduce the time presently allotted to that model, but it could also shift the transition point so that it cuts into what would be the most time-consuming part of the other growth model.

For example, if, as argued in the previous subsection, the electromagnetic capture radius has been underestimated and the growth during that phase is significantly faster, let us suppose that this model of growth is faster than Bondi growth until the Bondi radius is a size of 5 Å. In this case, the growth up to an electromagnetic capture radius of 1 Å is significantly faster, the phase from a Bondi radius of 1 Å to 5 Å is now covered by faster electromagnetic accretion, with the time reduced accordingly, and the remaining period of Bondi growth is only 20% of what it was before. Conversely, should the process of Bondi growth be faster than expected, it could be the dominant model even before the electromagnetic capture radius reaches 1 Å, and thus replace the slowest phase of electromagnetic growth.[93]

Absence of Electromagnetic Capture Model - As noted above, the derivation for the electromagnetic capture radius is limited to the internuclear separation distance, *a*, in atomic matter, which corresponds to about 1 Å for material within the Earth. For greater distances, the GM paper presents no plausible model for accretion based on the electromagnetic capture radius. Since the paper claims to adopt the fastest of Bondi accretion or electromagnetic capture at this stage, it is impossible to decide which is faster when the rate of one model is unknown. After passing the value of *a*, one may expect the electromagnetic restoring force to simply drop off as the square of the distance, which would greatly facilitate the capture of particles and radically change the growth equation of the black hole.

Transition Criteria for 7 Dimensions - The GM paper ends its section on the matching of microscopic and macroscopic regimes with the conclusion that:

> The subatomic growth is faster when $M < M_{a,D}$, while Bondi's growth is faster when $M > M_{a,D}$. This means that for the purpose of being conservative, it is justified to use the former accretion model below $M_{a,D}$, and the latter above $M_{a,D}$. [GM p. 23]

[93] It should be noted, however, that a reasonable argument could be made that the sharp cut-off between electromagnetic capture and Bondi accretion is an artefact of the GM paper's presentation of two distinct accretion models, and what is really needed is a single model that combines all aspects of accretion at every stage of growth.

In the case of 7 dimensions, when the black hole's mass is equal to $M_{a,D}$ its Bondi radius is equal to a, or approximately 1 Å [GM p. 23, eq. 4.36]. At that point, the subatomic growth rate is equal to approximately 3.10 $\chi^{1/3}\,\pi\,\rho\,v_{EM}\,a^2$ [GM p. 23, eq. 4.37], while the Bondi accretion rate is $4\,\pi\,\rho\,c_s\,a^2$ [GM p. 23, eq. 4.38]. The GM paper notes that v_{EM} has a value similar to c_s inside the Earth [GM p. 23]. χ is said to be a constant of order 1 [GM p. 18], but no specific value is given for it, and no bound is shown for its possible values. In this case, if $v_{EM} = c_s$, then unless the value of χ is less than 2.15, the growth rate based on electromagnetic capture would be faster than that of Bondi accretion. If the value of v_{EM} is greater than c_s, then the bound on the value if χ would be even stricter.[94] As noted above, the GM paper's model for electromagnetic capture is no longer valid above a distance of a, so if that model of accretion is indeed faster than Bondi accretion, it is unclear how long it would continue to be so. A careful review of these factors is needed to determine the effect they could have on the GM paper's tentative claims of a safe accretion time in 7 dimensions [GM pp. 25–26].

Transition Criteria if $R_C < 0.25$ Å - Should the crossover to 4-dimensional growth occur at less than 0.25 Å (the scenarios with 9 or more unwarped dimensions, and warped scenarios of 5 or more dimensions with a crossover radius less than 0.25 Å), a bound is also needed on the value of χ to determine which model of accretion is faster when the black hole's mass equals $M_{a,D}$. For that mass the electromagnetic capture rate is approximately $2.25\,\chi^{2/3}\,\pi\rho\,?_{EM}\,a^2$ [GM p. 23, eq. 4.37], while the Bondi accretion rate is $0.25\,\pi\,\rho\,c_s\,a^2$ [GM p. 23, eq. 4.38]. In this case, if $v_{EM} = c_s$, then unless the value of χ is less than approximately 0.037, the growth rate based on electromagnetic capture would be faster than that of Bondi accretion. Since the value of χ is supposed to be a constant of order 1 [GM p. 18], it would suggest that the electromagnetic capture rate is indeed faster (unless the flux of matter to the black hole is sufficiently slow). As the equation for the electromagnetic capture growth rate is not valid beyond approximately 1 Å, it is not possible to say how long this situation would continue.

If, hypothetically, one were to apply equation 4.37 [GM p. 23, eq. 4.37] in this range, then if $\chi = 1$ and $v_{EM} = c_s$, the mass of the black hole would need to increase by a factor of approximately 5.20 in order for the Bondi accretion rate to equal the electromagnetic capture rate [GM p. 23, eqs. 4.37, 4.38]. At that point the Bondi radius would be approximately 1.30 Å [GM p. 23, eq. 4.36]. This would imply that the time allotted to Bondi accretion is reduced by approximately 23% [GM p. 24, eq. 4.41] (although the net time difference would depend on how much faster the electromagnetic capture rate is).[95]

Two important points should be noted. The first is that whether the Bondi accretion rate can actually catch up with the electromagnetic capture rate depends on the exponents associated with the growth rates (an exponent of 2 for Bondi accretion and an exponent of 2/3 for electromagnetic

[94] The paper does mention that its estimates for the transition mass are only valid up to an overall factor of order 1 [GM p. 23 ↗], but this detail is omitted in its concluding sentences, and no effort is made in the paper to analyze the potential significance of this unknown factor.

[95] This point may also apply to the case of 8 unwarped dimensions, but due to the timing of the crossover the situation is less clear-cut.

capture in four-dimensions). The exponent for the electromagnetic capture in turn depends on the effective source of the charge increasing as the cube of distance [GM p. 17, eq. 4.6]. As described above, this may not be valid for electromagnetic capture radii greater than 1 Å, so if and when the Bondi accretion rate would catch up to the electromagnetic capture rate remains an open question.

The second point is that, using the given equations [GM p. 23, eqs. 4.37, 4.38], the estimated transition point depends on the precise value of χ and the ratio of v_{EM}/c_s. In the absence of any specific value for χ, it is not possible say where the transition point is. As noted earlier, roughly half of the total time for Bondi growth occurs between 1 Å and 2 Å so the precise value of χ could have a significant effect on the overall accretion time estimate.

Crossover Radius for 8 Dimensions - The GM paper notes that:

> In the case of $D = 8$, R_C is close to 1 Å. One may therefore fear that, should the effective R_C be an underestimate by a factor of 2–3, there will be no room for this phase of evolution. [GM p. 21]

The paper reports that for $M_D = 1$ TeV, no warping, and extra dimensions with identical radii, the value of R_D for $D = 8$ will be 0.097 Å [GM p. 12, eq. 3.10]. Using the equation given in the paper, the crossover radius in this case will be 5.60 times larger, occurring at a distance of 0.54 Å [GM p. 13, eq. 3.22]. Should the effective R_C be an underestimate by a factor of 2–3, the crossover radius will instead occur between 1.08 Å and 1.62 Å. The paper argues that a lower bound can be set based on the e-fold time for R_{EM} to reach a distance of approximately 1 Å, although the paper does not explicitly calculate any such bound.

It is not immediately clear what that bound will be, and, more generally, whether the black hole growth time to a capture radius of 1 Å will be long or short by geological standards. By the equations provide in the paper, the time required to reach 0.097 Å in 8 unwarped dimensions is only about 5.4 million years (assuming $M_D = 1$ TeV, $\chi = 1$, and $T_D = 400$ K) [GM p. 21, eq. 4.25]. A lower bound for the evolution from that size up to 1 Å can only be given if there is a lower bound on the mass of the black hole when its capture radius equals 1 Å. Unfortunately, in the "underestimate scenario" this would fall within the transition zone to 4-dimensional growth and the GM paper provides no estimate for what the minimum mass must be at different points during the transition. If the underestimate is by a factor of 2, the transition will be complete by 1.08 Å, so one might expect that the mass will be close to the matching 4-dimensional value. If the underestimate is by a factor of 3, there would still be room for significant growth in the mass before reaching the crossover radius, so it is more difficult to set a lower bound on the black hole's mass at 1 Å. The other essential component is the time required to reach a given mass. For this, the paper waves towards equation 4.20 [GM pp. 21–22, citing p. 19, eq. 4.20], however, it is not at all clear how this equation should be applied during a transition phase in the dimensionality of the growth. The term $(M_D/M_0)^3$ will reach the value of $(M_4/M_0)^3$ once the transition to 4-dimensional growth is complete, but what should the value be at different stages of the transition? The exponent governing the relationship between distance travelled and mass will also change from 5/7 to 1/3 in the shift from 8-dimensional to 4-dimensional growth. Similarly the value of β_D will change, as well as its exponent, resulting in a reduction by a factor of 3.87×10^{29} (assuming $\chi = 1$ and $T_D = 400$ K) [GM p. 19, eqs. 4.17, 4.20]. These different factors are no doubt interrelated, but their specific relationship is not necessarily straightforward as part of it is related to matching force laws, and part is related to the geometry of the shift to a growth model in which the extra-dimensions are saturated. Ultimately, what is missing is a proper treatment of the black hole's growth during the crossover period, and without that analysis one cannot assume that there is a comfortable bound on the subatomic growth rate in this case.

More generally, this case raises the question of how much confidence can be placed in the stated estimates of the crossover radius. For the case of 8 or more unwarped dimensions, the estimate of the crossover radius is an essential element of the safety argument. (For the case of warped dimensions, the time estimates are parameterized by the crossover radius, so its importance is shown explicitly.) The assumption that the crossover radius is relatively close to the value of R_D means that a black hole must increase its mass by several orders of magnitude while its capture radius remains comparatively small. If, hypothetically, the mass of a higher-dimensional black hole did not have to increase to levels comparable with 4-dimensional accretion until the electromagnetic capture radius or the Bondi accretion radius were much larger than 1 Å (but still within the bounds of experimental limits), then the growth rates would be much quicker at the subatomic and atomic levels, since much less matter would need to be accreted for an e-fold increase in the black holes mass. This in turn could nullify any safety assurances based on exceedingly slow (proportional) growth during those stages.

Most of the GM paper presents the value of the crossover radius for unwarped extra dimensions as a mathematical certainty determined by equation 3.22 [GM p. 13]. The authors' implicit acknowledgement that it is possible for this value to be an underestimate [GM p. 21] calls for a full clarification of this point. The paper makes no mention of exactly what the criteria or conditions are under which the crossover radius would be larger than the previously expected value. Moreover, it does not indicate any specific bound on the factor by which the radius was underestimated. As an example, the paper considers a factor of 2-3, but it does not even attempt to show that the factor could not be larger, or even much larger, than this. Any change in the crossover radius has significant ramifications for the overall accretion time estimate, so unless the authors can conclusively show that the crossover radius cannot differ from the calculated value, it may be necessary to also parameterize the accretion time estimates for unwarped dimensions with different possible values for the crossover radius.

▼ Macroscopic Accretion

Once the capture radius of a black hole exceeds 1 Å, the focus of the GM paper is on the process of Bondi accretion. For the cases of 7 or more unwarped dimensions and warped scenarios with a crossover radius less than 200 Å, the GM paper asserts that Bondi accretion by a microscopic black hole within the Earth will take billions of years. As with the other stages of black hole accretion, this claim is not based on any empirical evidence, but just the confidence the authors have in their theoretical calculations.

The following text reviews the theoretical validity of the GM paper's argument and identifies a number of areas of concern. They include the following:

Extremely Oversimplified Treatment - In the process of studying astrophysical black holes, physicists often adopt a number of simplifications to facilitate calculations and analysis. Over the years, as ideas are further developed, physicists have progressively removed several of the simplifications and have attempted to deal with more realistic models of black hole accretion. In this case, when the issue at hand is the continued physical existence of the planet, a natural expectation is that any theoretical analysis of the problem would be the most complete and realistic possible. The analysis would be expected to easily match or exceed the rigor and complexity of any existing accretion model. Instead, the GM paper has presented the exact opposite; its treatment of black hole accretion within the Earth is the most simplistic possible. Overlooking half a century of theoretical advances in the study of black hole accretion, its model is not much different than what might have been written on the basis of Bondi's 1952 paper [Bon52 ↗] and a glance at Begelman's 1978 paper [Beg78 ↗].[96] The insufficiency of the paper's analysis and the importance of a realistic treatment of the problem are described in further detail below.

Implications of a "Canonical Framework" - The introduction of the GM paper describes Bondi accretion as "the canonical framework to deal with the flow of matter into a black hole" [GM p. 6]. This may be a correct statement, but it is likely to be misinterpreted by most readers. Bondi accretion is a "canonical framework" but not in the sense that the Bondi accretion rate of a black hole is universally accepted as the most accurate possible estimate of the true accretion rate. Rather, the Bondi accretion rate is just an easy-to-calculate reference value against which more accurate estimates of black hole accretion rates can be compared; typically, an analysis of black hole accretion will be presented as a ratio of the Bondi accretion rate (for examples among the articles cited by the GM paper of the Bondi rate being used as a reference value, see [Bon52 pp. 203–204] [Beg78 abstract, pp. 56, 59, 60, 66] [FKR02 p. 319 ↗]; for examples among the more recent astrophysical literature, see [▷ ▷ ▷ ADDCITE e.g. arXiv 0809.2404 abstract ↗]). With this "canonical framework" it is easy for physicist to compare theoretical accretion rates, even if they differ from the Bondi rate by a few orders of magnitude.

Importance of Details of the Accretion Process - Given the public's realization that many details about microscopic black holes are still unknown, the GM paper tries to argue that these details are irrelevant. The paper claims that, "At large distances the physical processes become independent of the short-distance properties of the black hole, which only acts through its attractive potential, and as a mass sink." [GM p. 5] and that ". . . many features of the accretion process only depend on the long range potential . . . " [GM p. 15]. It may be true that detailed knowledge about the physics inside a black hole [GM p. 5] are unimportant, but the paper itself demonstrates that the physics in the immediate vicinity of a black hole are an essential part of any analysis.

[96] The paper also refers to the Frank, King, and Raine text [FKR02 ↗] which provides an updated review of the field, but the contents of that book are not reflected in the analysis of the GM paper. The paper also cites the 1983 textbook by Shapiro and Teukolsky [ST83 ↗] to support its claim that relativistic effects are relatively unimportant.

Determining the possible effects of reradiation are necessary for any estimate of a black hole's accretion rate and the paper's treatment of this issue (within different objects) depends on details such as: gray body factors associated with the black hole [GM p. 57], the radial density dependence within the sonic horizon of a black hole [GM p. 58, citing eq. A.21], the frequency of the radiation emitted during accretion [GM p. 59], the optical thickness from the crossover radius to the sonic radius [GM p. 62], the possible existence of a trapping radius for photons [GM p. 62], etc. Even the very assumption of spherically-symmetric accretion is itself a detail about the accretion process which shows that it is not just the long range factors which determine the accretion rate. Based on these considerations, it is clear that this case is not just an application of well-understood macroscopic physics.

Standard Range for Bondi Accretion - To put the GM paper's analysis into perspective, it is useful to compare the typical situations in which Bondi accretion is applied with the case of microscopic black holes within the Earth. Scientists usually take care to point out what the valid range is for any theory or equation. No such effort has been made in this case. Instead, the paper makes the general comment that accretion under the conditions it has assumed was developed by Bondi, Hoyle and Lyttleton [GM p. 22].[97] It may be noted, however, that:

- ▷ ADD NOTE on distance scales for astronomical Bondi accretion
- ▷ ADD NOTE on densities for astronomical Bondi accretion
- ▷ ADD NOTE on pressures for astronomical Bondi accretion
- ▷ ADD NOTE on elemental abundances for astronomical Bondi accretion

It may be further noted that the authors have cited no references in the scientific literature for Bondi accretion within the Earth–the entire analysis is their own construction for the sake of a safety argument.

Nano-Scale Hydrodynamics - The GM paper speaks of "well-tested physical laws" [GM abstract], "well-established macroscopic properties of matter" [GM p. 5], and "the general laws of hydrodynamics" [GM p. 22], but it fails to recognize that these laws are being applied on a scale smaller than a nanometer. Ninety percent of the "macroscopic" accretion is expected to occur when the Bondi radius of the black hole is less than a nanometer, and fully half of the macroscopic accretion takes place when the Bondi radius is between 0.1 and 0.2 nanometers. The paper cites no references that have verified the "general laws of hydrodynamics" on this scale, so it would seem that the "macroscopic properties" that the paper depends on are just as uncertain as the properties of a microscopic black hole

Extra-Dimensional Hydrodynamics - The GM paper's analysis also depends on the hydrodynamics of atomic matter within a brane embedded in higher-dimensional space. Hydrodynamics

[97] This statement in the paper may be justified by the claim that it was just a reference to the hydrodynamic assumptions and not the specific conditions within the Earth, but the paper makes no effort to point out this distinction.

have not been tested in a scenario in which the gravitational potential is altered by the geometry of higher dimensions.

Validity of Macroscopic Treatment - The GM paper begins its treatment of "macroscopic accretion" within the Earth at the scale of about 1 Å. The paper states that:

> When the Bondi radius exceeds the internuclear separation *a* in atomic matter, or r_N in nuclear matter, accretion transitions to that of a continuous medium. [GM p. 58]

While it may be fair to say that accretion *begins* its transition at that scale, no indication is given as to when that transition is complete, or at least when the scale is sufficiently large for the macroscopic assumptions associated with Bondi accretion to be valid. The radius of a single atom is only about 1 Å, so until the Bondi radius is much, much larger than that, one cannot depend on the validity of statistical, macroscopic concepts. A minimum expectation would be a scale of about 1000 Å, although even that may be too small. More realistically, a scale of about 1,000,000 Å may be required before one can speak of such things as a "sonic radius", or an "equation of state" within the Bondi radius. Even if one were to assume that the model of Bondi accretion becomes valid at the scale of just 1000 Å, this would still leave the question of the speed of accretion between 1 Å and 1000 Å. As noted earlier, the vast majority of the time estimate for 4-dimensional Bondi accretion occurs close to the scale of 1 Å. By the time the Bondi radius reaches a size of 1000 Å there would be just 0.1% of the total Bondi accretion time [GM p. 24, eq. 4.41] left before the destruction of the world.[98]

What is needed for this "pre-macroscopic" phase is a detailed kinetic treatment of the accretion process in which the motions and interactions of individual particles are modelled. This may be difficult to treat analytically, so a numerical simulation of the process may be the only realistic option for modelling this phase. There is an critical need for such an effort, since otherwise there is no valid model governing what is supposed to be the most time-consuming phase of Bondi accretion. As noted in the previous subsection, there is also the risk that if this phase is faster than currently expected, it could dominate part of the subatomic phase and reduce those times as well.

Assumption of Steady Accretion - The GM paper adopts the assumption that matter will flow steadily into a black hole [GM p. 54]. Unfortunately, the paper makes no effort to either analyze the case of non-steady accretion, or demonstrate why the accretion must be steady. The assumption of the steady flow of matter is often adopted to simplify the analysis of accretion, but it is by no means certain that it represents the actual process of accretion. Indeed, Bondi himself concluded his 1952 paper with the advice:

> Further progress in this field will probably require the consideration of non-steady states. [Bon52 p. 204]

[98] This calculation does not apply if the crossover radius is greater than 1 Å. The overall accretion times are much shorter in those cases, but the exact percentage from the phase between 1 Å and 1000 Å would need to be recalculated.

This has been ignored in the GM paper.

Effects of the Black Hole's Motion - During the Bondi accretion phase—in contrast to the subatomic phase—the GM paper assumes accretion by a stationary black hole. This was one of the assumptions adopted in the 1952 Bondi paper, however, it was done so only with the intent of analyzing a limiting case. That paper explains that previous works had considered the case of an accreting object moving in a medium of negligible pressure, so it focuses instead on the case of a stationary object accreting within a medium with a non-negligible pressure. It states:

> In all this work pressure effects were neglected, the argument being that any heat generated would be radiated away rapidly, so that the temperature of the gas was always very low. Considerable mathematical simplification is introduced by this assumption, and it was shown that it was likely to be satisfied in most cases of astrophysical interest (**3**). The mathematical difficulties of the more general problem, in which both dynamical and pressure effects are considered, seem insuperable at present. However, the extreme case of negligible dynamical effects is again far simpler, and will be discussed in this paper. It may reasonably be expected that the case discussed here together with the case discussed previously bracket the complete problem. [Bon52 p. 195]

Despite the advances in mathematical techniques and computing power in the half-century since the Bondi paper, the GM paper makes no attempt to directly address the general problem in which dynamical and pressure effects are considered. Moreover, it makes no attempt to reconcile how this more realistic case is bracketed by that of earlier works and the Bondi case.[99]

Assumption of a Non-Rotating Black Hole - In a footnote to a marginally related point, the GM paper presents the following argument for why a black hole accreting within the Earth can be treated as non-rotating:

[99] The GM paper describes its assumptions as follows:

> Since our aim is to be conservative and consider the fastest conceivable evolution, we shall neglect the slow down due to cohesion forces, and treat the inside of the Earth as a non-viscous fluid, free to fall into the black hole, subject only to the general laws of hydrodynamics, such as the continuity equation and energy conservation. The compressibility of the medium, which limits the amount of matter that can be funnelled towards the black hole, is accounted for by macroscopic hydrodynamic properties of the medium, such as its sound speed.
>
> The description of accretion under these conditions was developed by Bondi, Hoyle and Lyttleton [33]. We review the derivation of the resulting evolution equation and extend it to incorporate the *D*-dimensional force law in Appendix A. . . [GM p. 22 ↗] References [33]: HL39a ↗ HL40a ↗ HL40b ↗ BH44 ↗ Bon52 ↗

Even though the GM paper cites the works of Hoyle and Lyttleton and a subsequent paper by Bondi and Hoyle, it uses only the 1952 paper by Bondi as the basis for its calculations. This might be justified for accretion within the Earth through the argument that the Bondi case would be the faster rate and thus would give a lower bound on the accretion time (although this would need to be carefully checked when the other assumptions of the Bondi case are removed). It would not be justified, however, in the cases of white dwarfs and neutron stars, which are considered below in sections 8.1.4 and 8.1.5.

> [8]They also may have significant initial angular momentum. However, as they absorb matter, with negligible average angular momentum, they become increasingly well-approximated as non-spinning black holes. [GM p. 16, footnote 8]

The paper does not consider the case of a rotating black hole, so its entire argument for macroscopic accretion depends on this assumption being true. The argument given, however, is insufficient to justify ignoring the black hole's angular momentum. It may be true that the black hole's angular velocity becomes smaller and smaller as it accretes matter, but it would not be exactly zero. What needs to be shown is that the black hole's angular velocity or angular momentum is sufficiently small for the assumptions associated with the paper's Bondi accretion model to be valid. Instead of showing this, the paper simply asserts that black holes become "well-approximated as non-spinning black holes", and hopes for the best.

Whether the angular momentum of a black hole in the Earth actually does become negligible is an open question. Among other factors, the rate of rotation of the Earth's inner core is believed to be different from the rest of the planet [▷ ADDCITE]. If a black hole accretes a significant amount of matter outside the inner core, the dynamics from this difference may mean that its angular momentum is non-negligible when it arrives in the inner core. Furthermore, as the black hole grows it would be expected to eventually reach the very centre of the Earth, so one must also know what the rate of rotation is there.

As with the point above, it may be the case that accretion is faster into a non-rotating black hole, but in that case, the estimates for white dwarfs and neutron stars would need to be reconsidered.

Assumption of Perfectly Spherical Accretion - Closely related to the assumptions of a non-moving and non-rotating rotating black hole is the assumption that its accretion will be perfectly spherical. The GM paper assumes that accretion during the macroscopic phase is spherically symmetric [GM p. 54] and fails to even consider the more realistic scenario in which accretion is not spherically symmetric. Thus, the safety argument presented in the GM paper for this phase is only applicable should this assumption be true—there is no argument if it is not.

Firstly, one may note that accretion would not be spherically symmetry if the black hole has a non-zero angular velocity, as that velocity would define an axis of rotation which would almost certainly break the spherical symmetry of accretion (since accretion along either pole of the axis would likely be different from accretion along a line through the black hole's equator).

Secondly, it does seem absurd to assume spherical accretion when the Bondi radius of the black hole is the size of an atom. In line with the note above on the validity of a macroscopic treatment, a Bondi radius of 1,000 Å or 1,000,000 Å would be a more reasonable starting point before speaking of spherical accretion. Until that stage, one should consider the orbital angular momentum of particles on an individual basis (through a numerical simulation) as they spiral towards the black hole.

Thirdly, even when the Bondi radius sufficiently large that one can parameterize microscopic motion deviating from the overall radial macroscopic flow by the temperature of the medium [GM p. 58], the ratio of such "lateral motion" to the radial flow should be checked to ensure that lateral motion is not significant enough to disrupt the predicted flow of matter into such a small object.

Fourthly, one would also need to demonstrate during larger scale accretion that there are no effective "holes" in the spherically accreting shells that could change the dynamics of the accretion process.

Fifthly, one must show how perfectly spherical accretion near the centre of the Earth can be sustained when external factors such as magnetic fields and seismic shocks are not expected to be spherically symmetric. (These and other factors associated with a more realistic accretion model are discussed further below.)

Finally, if it can be shown that spherical accretion is generally expected, one must further show that it is stable against random perturbations, or that the effects of random perturbations on the total accretion time estimates would be bounded within a certain limit.

The LSAG report reassures the public that, "...conventional astrophysics can explain all the astrophysical black holes detected." [LSAG p. 4], so one may reasonably ask CERN whether any astrophysicist believes that any of these black holes are accreting spherically symmetrically?

For the case of the Earth, one could try to argue that spherically symmetric accretion represents the fastest rate, and thus serves the purpose of a lower bound on the accretion time. This is not an entirely straightforward argument as one would need to show that there is no possible non-spherically symmetric mechanism which could produce a faster accretion rate. The issue would also need to be reconsidered for the supposedly slowest possible rates for white dwarf and neutron star accretion [GM p. 5].

Accretion in a Non-Gas - The model of Bondi accretion is based on the assumption that the medium is a gas in which the only interaction is the random collision of particles. In the case of the Earth, the medium is solid, semi-solid, or liquid [GM p. 22]. The GM paper would need to convincingly show that the equations derived for Bondi accretion are unaffected by this difference.

Electron-Ion Attractions - As with the model for subatomic accretion, the GM paper does not consider the effects that the attraction between electrons and ions may have on the rate of accretion. On the other hand, it also ignores the force of repulsion between similarly charged particles. One cannot simply assume that these two factors balance out. The possible effects of electromagnetic interactions among the accreting particles may be further clarified through a careful theoretical analysis, and, preferably, a computer simulation of the process, although a large degree of uncertainty will likely remain about this factor in the absence of any empirical evidence.

Assumption of a Single Temperature - The paper assumes a single temperature for the medium without bothering to model the interactions between the accreting nuclei and electrons to determine whether they are sufficiently rapid to maintain a single temperature at all radii. In many astrophysical cases the accreting medium is better described as having two distinct temperatures for the protons and electrons [▷ ADDCITE].

Distribution of Particle Velocities - For a given temperature and type of particle, the paper does not consider what the distribution is of the velocities of the particles. In particular, it fails to examine whether an excess number of unusually fast or slow particles could have an effect on the overall accretion process.

Assumption of Adiabatic Evolution - The GM paper assumes that Bondi accretion within the Earth follows an adiabatic evolution with a constant adiabatic index of $\Gamma = 5/3$ [GM pp. 25, 54]. The paper does not consider the case of non-adiabatic accretion. The original Bondi paper also adopts the assumption of adiabatic evolution, but it notes at the end that:

> The limitations due to pressure have probably been somewhat overestimated in this work. For if the cloud is able to radiate away some of the heat of compression then the adiabatic law will not apply, the pressure near the star will be diminished, and the accretion rate somewhat increased. [Bon52 p. 203]

The 1978 Begelman paper undertakes a more detailed analysis of the effects of radiation and reports that:

> The actual accretion rate depends on the optical depth τ_{B} of a column of unperturbed gas spanning the Bondi radius, $r_{\mathrm{B}} = GM/c_{\infty}^2$. If $\tau_{\mathrm{B}} > (\sqrt{2}/3)(c/c_{\infty})$, then the flow is adiabatic, and $\dot{M} = \dot{M}_{\mathrm{B}}$. For a somewhat smaller τ_{B}, diffusion is efficient enough for the radiation to leak out of the gas as it moves towards the trans-sonic point. As a result, the sound speed *decreases* inwards in the subsonic region, while the density must increase steeply to maintain pressure balance. $\dot{M}$ may then exceed $\dot{M}_{\mathrm{B}}$ by a factor of up to $(\sqrt{2}/3)(c/\tau_{\mathrm{B}} c_{\infty})$, although this effect can be limited by thermal pressure. [Beg78 abstract]

The GM paper fails to take into account the impact that this effect could have on its accretion estimates for the Earth.

Specific Value for the Adiabatic Index
▹ ADD NOTE on selection of $\Gamma = 5/3$ for the adiabatic index. The GM paper gives no specific reference to justify its selection of $\Gamma = 5/3$ to represent accretion in the centre of the Earth; it states only:

> As shown in Appendix A, the value of λ_4 is in the range 4–18; for $\Gamma = 5/3$ (namely the adiabatic index of a non-relativistic electron gas), $\lambda_4 = 4$. [GM p. 25]

▹ Compare with other possible values for Γ. Note that if $\Gamma = 1.4$, the 4-dimensional phase of Bondi accretion would be 2.5 times faster [GM p. 56, eq. A.20]

Neglect of Seismic Effects - The earth is subject to intermittent seismic activity of various levels of intensity. As suggested above, seismic activity might be expected to disrupt the process of spherically symmetric accretion. More generally, however, one would want to see an account for what contribution seismic activity over a billion year time frame could have on the overall accretion rate. If a bound can be set on its contribution, then that should be shown explicitly. No mention of this factor is included in the GM paper.

In addition to the above points, there are a number of other considerations which are very basic expectations of any modern treatment of black hole accretion. They are listed below, but in this draft no attempt has been made to claim that a given factor must increase or decrease the accretion rate. Such issues are not always straightforward to resolve, since such general statements imply that under no possible circumstances could that factor have the opposite net effect on the accretion rate. It may be noted, though, that a factor which in general decreases the accretion rate would help improve the expected safety times for the Earth, but would also increase the accretion times in white dwarfs and neutron stars, which could further constrain the GM paper's astrophysical argument. The factors include the following:

Magnetic Fields - The GM paper neglects the effects that magnetic fields can have on the process of accretion. The effects of magnetic fields are a standard element of modern accretion models, so it is unclear why this factor was completely ignored in the text. Even the 1978 Begelman article cited by the GM paper explicitly notes that the presence of a tangled magnetic field can affect the accretion rate [Beg78 p. 60].

Turbulence - The effects of turbulence are similarly ignored, despite being a standard concern for accretion models and being explicitly mentioned in the 1978 Begelman article [Beg78 p. 60]. It is worth noting the results from a more recent investigation which finds that:

> ...the mean accretion rate in supersonically turbulent gas can be substantially enhanced above the value that would be predicted by a naive application of the Bondi-Hoyle formula. [KMK05 arXiv abstract]

and warns astrophysicists that:

> ...there are likely to be significant errors in results that assume that accretion from turbulent media occurs at the unmodified Bondi-Hoyle rate... [KMK05 arXiv abstract]

Viscosity - The GM paper does acknowledge the issue of viscosity, but then simply assumes that whatever is at the centre of the Earth will behave like a perfect fluid [GM p. 58]. The paper provides the following justification for this assumption:

> Since our aim is to be conservative and consider the fastest conceivable evolution, we shall neglect the slow down due to cohesion forces, and treat the inside of the Earth as a non-viscous fluid, free to fall into the black hole, subject only to the general laws of hydrodynamics, such as the continuity equation and energy conservation. [GM p. 22]

If the paper's analysis did take into account the effects of the orbital angular momentum of the accreting particles, the claim that a non-viscous fluid has the fastest conceivable accretion rate would not be justified. For more realistic accretion models, a central concern is how accreting matters loses enough angular momentum to finally fall into a black hole. Viscosity is often the principal mechanism to mediate the loss of angular momentum and thus facilitate accretion.

Homogeneous Medium - The GM paper assumes a purely homogeneous medium, with no variations in composition, phase of matter, pre-accretion density, pre-accretion temperature, etc. A more responsible treatment of the accretion question would attempt to set a bound on the possible effects of such variations.

Geometry of Accretion - The GM paper assumes the simplest possible geometry of accretion, imagining only the spherical compression of matter into a black hole. The paper does not even mention any of the basic formations found in many accretion models, such as funnels, shocks, and outflows (such as winds and jets).

Relativistic Corrections - The GM paper does acknowledge the issue of relativistic corrections to its accretion model, but simply states that "relativistic corrections, which are typically small, are described for example in [59]." [GM p. 54, citing ST83 ↗] This treatment of the issue is wholly inadequate. Instead of simply assuring people that the effects are "typically small", CERN needs to set a quantitative bound on the effects of these corrections on their accretion time estimates (bounds which, ideally, should also cover the "atypical" cases).[100]

▼ Post-Bondi Accretion

TEXT PENDING

§ Eddington Limit in the Earth

TEXT UNDER REVISION

§ Multiple Black Hole Accretion in the Earth

The accretion rate of multiple black holes within the Earth is a key question in determining the potential risks associated with black hole production at the LHC. In scenarios with a minimum black hole mass above 7 TeV, the GM paper argues in Appendix F that the expected number of trapped black holes is less than 1 [GM p. 83]. On the other hand, for a minimum mass of 4 TeV or less, the paper's own calculations predicts that if such black holes exist, then hundreds or even thousands of black holes would be produced during the operation of the LHC and trapped in the Earth [GM p. 83, figure 12].

[100] The text of ST83 has not been reviewed in time for this present draft; further comments on this issue may be made in the future.

This section does not present a critique of the GM paper's model of multiple black hole accretion since no model is presented in the paper. At the start of its analysis of black hole accretion within the Earth, the paper states:

> "For present purposes, we will simply make the most conservative assumption that *some* of these black holes do become gravitationally bound to Earth." [GM p. 16, italics added]

Readers might naturally expect that if the paper is assuming that some black holes are trapped in the Earth then it would be analyzing the case of at least a few accreting black holes, but the remainder of the paper's accretion section [GM pp. 16–28] is based on the assumption of just a single black hole growing inside the Earth.

The issue is revived at the beginning of Appendix F, with the statement:

> In this Appendix we estimate the number of LHC-produced black holes that could in these hypothetical scenarios become gravitationally trapped by the Earth. This in particular addresses questions about whether there could be multi-black hole effects. [GM p. 79]

Appendix F does not, however, analyze what the "multi-black hole effects" could be. Instead it argues that there could not be multiple black holes to cause such effects. The paper simply states.

> We notice that mass values where the build up of multiple black holes could significantly exceed the value one are firmly excluded for $8 \leq D \leq 11$ by the neutron stars, and for $D \leq 7$ by the white dwarfs. [GM p. 83]

The extent to which these cases are "firmly excluded" is examined further in section 10.1.

This section does not attempt a detailed independent analysis of the question of multiple black hole accretion, but given the importance of this issue, a few comments are in order. The starting point for any analysis of multiple black hole accretion is a model for the accretion of a single black hole. The GM paper does present a single black hole accretion model, however, as described in the text above, there are numerous problems with that model, so it is not possible to depend on it as basis to construct a multiple black hole accretion model. Given this situation, the remainder of this section presents only a broad outline of the issue, although as a specific reference point it refers to the single black hole model of the GM paper.

In general, the issue of multiple black hole accretion involves three key aspects:

- The effect that the presence of other black holes has on single black hole accretion rates
- The contribution that multiple black holes make to the total energy generated within their host object
- The effect that the merger of black holes has on the total time required to destroy the host object

There may be a number of different ways that the presence of other black holes can affect the accretion process and times of a black hole. In the case of the Earth, perhaps the most important could be the effect that multiple black holes would have on the temperature of the accreting medium. The centre of the Earth is believed to be a relatively cool (compared to the Sun and white dwarfs) 5700 ± 500 K [SSC02 arXiv p. 16]. With the presence of a number of black holes accreting matter and causing reradiation, the temperature at the very centre of the core could increase dramatically. The time estimates for subatomic accretion within white dwarfs depends on the assumption of a minimal thermal velocity of about 0.0003 c [GM p. 41] due to their high core temperature. The model for accretion within the Earth depends instead on the velocity of motion of the black hole and results in an accretion time estimate on the order of hundreds of billions of years [GM p. 21]. If a higher thermal velocity results in a significantly higher effective flux of matter towards a black hole, this time estimate would need to be completely revised and any safety factor associated with it could easily vanish.

As noted earlier, even in the absence of other black holes, the process of 'thermal acceleration" could affect single black hole accretion times. In the case of a solitary black hole, however, the process is more complicated since reradiation would also produce a force countering the gravitational pull of the black hole, so the precise balance of factors would need to be considered. For the case of a cluster of black holes, the radiant energy from other black holes could increase a given black hole's accretion rate without exerting a force away from that black hole.

For both a single black hole and multiple black holes, this factor may only be expected to play a role when the black hole or black holes have settled down to a sufficiently confined volume. In the case of 8 or more dimensions, the GM paper estimates that by the time a black hole has a Bondi radius of ~ 1 Å, its mass would be on the order of 10^{11} gr [GM p. 24], having grown in mass by ~ 31 orders of magnitude from its original creation at the LHC. One may expect that well before that time a black hole would have sunk to pretty close to the exact centre of the planet, but how close is "close" would need to be more carefully calculated to determine how concentrated the effect of black hole reradiation is, and what the consequent increase in the local temperature would be.

In the case of 6 or 7 unwarped dimensions, the mass of a black hole would be much less when it has a Bondi radius of 1 Å, with the GM paper estimating a mass of 10^4 gr in the case of 7 dimensions, and much less in the case of 6 dimensions [GM p. 25]. Even still, a mass of 10^4 gr is ~ 24 orders of magnitude greater than a TeV-scale black hole's original size, so it could well be localized enough at that stage to cause significant heating of its immediate environment. Moreover, even if it doesn't settle down until its mass is much larger, the main issue is whether any thermal acceleration would affect the slowest phase of accretion, which, in the case of 6 or 7 unwarped dimensions, occurs at a higher mass.

For the case of 5, 6 or 7 dimensions with warping, the mass of a black hole at a given stage would depend largely on the value of the crossover radius, R_C, so both the mass and the expected localization could be parameterized by this variable.

Another effect of the presence of multiple black holes is the disruption of any spherical symmetry.

While the previous section did describe how the assumption of spherical symmetry for the accretion of a single black hole was rather dubious, the assumption would be even more questionable for multiple black hole accretion. Once black holes are sufficiently localized, their gravitational fields and reradiation could easily alter the accretion patterns of other black holes and would effectively rule out the possibility of spherical symmetry. The GM paper does not present any model for non-spherically symmetric accretion, so there is essentially no prediction for accretion times in such a situation.

The second major consideration with multiple black hole accretion is the collective contribution that an ensemble of black holes would have on the total additional energy generated within a host object. The GM paper does briefly consider the thermal impact of black hole accretion, but it considers only the case of a single black hole within the Earth [GM p. 28], even though, as noted above, there are scenarios in which hundreds or thousands of black holes would be trapped [GM p. 83, figure 12]. (In contrast, for its analysis of black hole heating of white dwarfs, the paper emphasizes the effect that a large number of trapped black holes would have on white dwarf cooling [GM p. 65].) In the case of black holes produced at the LHC, they would all be created within a relatively short time period, so the heating effect of multiple black holes can roughly be seen as the effect of a single black hole (adjusted for the presence of other black holes, as described above), multiplied by the number of black holes trapped in the Earth. A more detailed analysis might consider the effects that differing initial conditions (mass and velocity) might have on the subsequent evolution of a black hole, but the above guideline should be a useful reference point. The question of what is a tolerable level of energy production from man-made black holes is discussed further in section 9.

The third major consideration is how the merger of multiple black holes would affect the time required for a black hole to destroy the Earth. We consider here the case of N black holes produced at roughly the same time, as may be expected from production at the LHC. (The case of black holes produced over an extended geological time period is analyzed in the corresponding section for white dwarfs.) In the case of the Earth, if the LHC were to, hypothetically, produce a thousand trapped black holes, a common expectation might be that the total accretion time would be a thousand times faster, but that would not necessarily be the case. The effect that N black holes would have on the total accretion time depends on the nature of the black hole's growth. In the simplest case of exponential growth, the effect of a thousand black holes merging together is simply to save a time period equal to three orders of magnitude of growth. The exact stage at which the black holes merge is not an important factor since the growth rate per unit mass is, by assumption, constant throughout the process. A black hole starting from a mass of 14 TeV would need to grow by ~ 47 orders of magnitude to reach the mass of the Earth [GM p. 88]. (As noted earlier, a mass a few orders of magnitude smaller than that should be enough to structurally destroy the planet, but the GM paper does not include an estimate of what that mass would be. For the time being, let us assume that about 42 orders of magnitude covers the growth of a black hole from initial formation until planetary destruction.) In such a scenario, the impact of a thousand black holes saving three orders of magnitude of growth is to reduce the total accretion time by about 7%, which is not that big a difference.

In the general case, however, the impact of multiple black holes can be quite different. The GM paper's model for single black hole accretion involves different phases with qualitatively different growth rates. The paper predicts that the subatomic phase begins with a relatively fast doubling time, but the growth is slower than exponential so the doubling time is much longer by the time a black hole attains an electromagnetic capture radius of ~ 1Å [GM pp. 19–22]. Once the Bondi phase begins, the growth rate is predicted to be slower than exponential for $D > 5$ [GM p. 24, eq. 4.39], exponential for $D = 5$ [GM p. 24, eq. 4.40], and faster than exponential[101] for $D = 4$ [GM p. 24, eq. 4.41]. During any Eddington limited stage, the growth rate would be expected to be exponential, with the doubling time given by equation 4.55 [GM p. 27, eq. 4.55]. In this more complex scenario, the question of when black holes merge assumes prime importance. If a thousand black holes merge during a phase in which the doubling times are shorter than average, then the net effect of these additional black holes would be less than the 7% reduction described in the previous paragraph.

On the other hand, if the black holes merge during a particularly slow period, the effect on the total accretion times could be much more dramatic. The GM paper predicts that in the case of 8 or more unwarped dimensions, the time required for a black hole to double in mass and increase its Bondi radius from 1 Å to 2 Å is on the order of 300 billion years [GM pp. 24–25, eq. 4.45]. This is roughly half of the total time remaining before the black hole would destroy the planet [GM p. 23, eq. 4.41], but it would disappear if two black holes merge once they both reach a Bondi radius of 1 Å. If a thousand black holes are produced at the LHC and merge once they have a Bondi radius of 1 Å this would reduce the total time for the Bondi accretion phase to just 0.1% of the GM paper's estimate for a single black hole [GM p. 23, eq. 4.41].

The GM paper also predicts an extremely long time period for the final phase of subatomic growth, but this can also be affected by the merger of multiple black holes. For the case of 9 or more unwarped dimensions the merger of 1000 black holes with an electromagnetic capture radius of 0.1 Å would reduce by about 90% the total time estimated for 4-dimensional growth to a capture radius of 1 Å.[102] The merger of a thousand black holes would likely have the great effect on the total accretion time if it occurs near the last stages of subatomic accretion, thereby covering the slowest part of that growth and the initial phases of Bondi accretion.[103]

When black holes would actually be expected to merge is an unresolved question. The slowest periods of growth present the longest time window for mergers, but the key issues are how close together black holes are expected to be during that phase, and whether the dynamics of black hole interactions promote or prevent mergers at that point. What is clear, however, is that the possible production of multiple trapped black holes and their merger during the accretion process

[101] "Faster than exponential" means simply that the doubling time decreases with time. How fast or slow it is in absolute terms depends on the initial doubling time.

[102] The case of 8 dimensions is not included in this example since its 4-dimensional growth is only expected to begin after its electromagnetic capture radius reaches a size of about 0.5 Å.

[103] A more complete analysis, however, should take into account the effects that accreting black holes have on each other, and determining the minimum accretion time would be based on both black hole interactions and the timing of mergers.

is a critical issue for determining the planetary risks associated with the LHC's experimental programme.

8.1.2 Neutral Stable Black Hole Accretion within the Moon

§ Single Black Hole Accretion in the Moon

The process of accretion of a black hole within the Moon may be expected to be comparable to that of the Earth. There are, however, a few differences which could affect the accretion times. They include the following:

Flux During Subatomic Accretion - The escape velocity of the moon is less than the Earth's, so a bound on the growth rate during the subatomic phase could be reduced in proportion to this factor if the velocity of the black hole is the dominant cause of the flux of matter into the black hole. If the flux of matter is primarily determined by the thermal velocity of the accretion environment, it may also be lower during the initial stages in the moon when compared to the Earth [▷ ADDCITE]. On the other hand, if the effective thermal velocity is largely determined by the energy released by reradiation, there may not be a significant difference.

Composition of the Core of the Moon - Differences in the composition of the core of the Moon compared to the core of the Earth could result in different rates of accretion if those differences affect the expected size of a black holes' electromagnetic capture radius.

Compressibility During the Bondi Phase - The GM paper notes that more highly compressible matter results in a higher accretion rate, so insofar as the Moon is more compressible than the Earth, this could contribute to a faster Bondi accretion rate. A more specific estimate should be made, however, based on the density and the speed of sound in different parts of the Moon.

Smaller Mass of the Moon - The smaller mass of the Moon compared to the Earth would imply that for the same rate of accretion, the Moon would be destroyed before the Earth. If Bondi accretion continues until the complete destruction of both host objects, the difference may not be very much, since the final phase of Bondi accretion is very rapid. If the final accretion phase is governed by an Eddington limit, the difference in time might be slightly larger (essentially a few e-fold times [cf. GM p. 27]).

§ Eddington Limit in the Moon

TEXT PENDING

§ Multiple Black Hole Accretion in the Moon

The GM paper does not consider the case of multiple black holes within the Moon.

The issue of black hole accretion within the Moon may be expected to be similar to that of the Earth. As with the Earth, two key questions are what effect black holes would have on each other's growth, and how the merger of two or more black holes would affect the overall accretion times. Multiple black holes would also be expected to have an increased impact on the internal heat energy of the Moon, however, this should not be a significant issue for life on Earth.

One important difference between the case of the Earth and the Moon is the total number of black holes. In both cases, black holes produced by the LHC would be roughly the same age, but the absolute number would be expected to be much greater in the Earth than in the Moon. In scenarios in which the merger of multiple black holes does not significantly affect the overall accretion times, this difference may not be important, but in some scenarios it could be a crucial factor. As discussed above in the section on multiple black hole accretion within the Earth, if, hypothetically, a thousand black holes were trapped in the Earth and merged when they reached a Bondi radius of 1 Å, the remaining Bondi accretion time would be reduced by 99.9%. On the other hand, if, hypothetically, only ten black holes were trapped in the Moon and similarly merged when they reached a Bondi radius of 1 Å, the remaining Bondi accretion time would be reduced by only 90%. There are other potential differences between the two cases (for example, the time needed to reach a Bondi radius of 1 Å could be very different), but it does show that the issue of multiple black holes could determine whether the greatest risk comes from black holes in the Earth or in the Moon.

8.1.3 Neutral Stable Black Hole Accretion within the Sun

§ Single Black Hole Accretion in the Sun

Black hole accretion within the Sun may be expected to be qualitatively different from accretion within the Earth. To review this important case, the GM paper's treatment of it is cited, followed by a critique of the paper's analysis and further notes on the crucial differences between accretion within the Earth and the Sun.

The GM paper's entire text on accretion within the Sun is the following sentence:

> We also note that the parameter controlling macroscopic accretion, $d_0 c_s$, is for the Sun approximately four times its value on Earth (with ρ = 150 gr/cm^3 and c_s = 500 km/s), implying accretion time scales that are four times longer. [GM p. 84]

Most of the criticisms described earlier of the GM paper's treatment of black hole accretion within the Earth are indirectly applicable here, since accretion time scales within the Sun are presented simply as a multiple of those of the Earth.

However, the "four times longer" argument is itself deeply flawed. While $d_0 c_s$ is one of the parameters controlling macroscopic accretion, a simple glance at the GM paper's equations show that it is not the only parameter involved [GM p. 24] [cf. the Earth/white dwarf accretion ratio: GM p. 44, equation 7.14]. Another parameter that can vary depending on the accretion environment is the value of λ_D. This coefficient depends on the number of dimensions and on the polytropic index Γ. The GM paper does not indicate what polytropic index should be used for the calculation of accretion time scales within the Sun. A value of $\Gamma = 5/3$ had been used for the Earth, and $\Gamma = 4/3$ for white dwarfs, with the result that the times for 4-dimensional accretion (the most time-consuming phase) were divided by 4 for the Earth and 11.31 for white dwarfs. Any differences between the values of λ_D for the Earth and the Sun would need to be taken into account if one wished to present a ratio of their Bondi accretion times.

An even more serious problem, though, is that the paper tries to pass off a ratio of Bondi accretion times as the ratio of total accretion times. The paper makes no mention at all of the subatomic accretion phase. The process of subatomic accretion within the Sun may be expected to be completely different from that of the Earth. In the case of the Earth, the basic model presented in the GM paper is one in which the gravitational pull of a moving black hole captures the inner ion of an atom if it is able to overcome the electromagnetic restoring force of the atom's outer electron cloud. Within the Sun, the accreting medium is primarily an electron-proton plasma, albeit with a higher concentration of helium in the core. An entirely different model of subatomic accretion would be needed in this case, although a reasonable guess is that it would be much, much quicker, since there would no longer be an outer electron cloud to resist the black hole's pull.

In addition to this expected increase in a black hole's electromagnetic capture radius for a given mass, the other parameters governing this phase of accretion [GM p. 19, eq. 4.19], namely the density of the medium and the flux (dominated by either the escape velocity or the thermal velocity), are much higher in the Sun's core than in the Earth. The increases in these parameters proportionately decreases the subatomic accretion time.

The effect of accelerating this phase on the overall accretion time was stressed earlier in the review of the transition from subatomic to macroscopic accretion within the Earth. There it was noted that the most time-consuming part of both types of accretion overlap, and the acceleration of either type could shift the expected transition point, and reduce the time allotted for the other type of accretion. Thus, in the case of the Sun, even if the process of Bondi accretion is slower than in the Earth, a significant acceleration of subatomic accretion could mean that it cuts into the Bondi phase and greatly reduces its contribution to the total accretion time.

Some of the other factors which are important for analyzing accretion within the Sun include the following:

Nuclear Fusion - The potential for nuclear burning is much greater for accretion processes within the Sun when compared to the Earth. Within the core of the Sun the dominant elements are hydrogen and helium, which are prime candidates for fusion processes. In contrast, the core of the Earth is primarily iron, and has very limited potential for (energy-releasing) fusion.[104] If fusion does occur, it could add to the reradiation from the black hole which would most likely slow down accretion, although it could have other indirect effects. It should be noted that counteracting any fusion process is the tendancy of smaller black holes to rip apart nuclei, and even nucleons themselves, so the question of nuclear fusion would need to be examined through a more careful model to determine if and when it could have an effect.

Rotation of the Core - The core of the Sun is believed to be rotating at a faster rate than the rest of radiative zone [▷ ADDCITE García 2007], so, as in the case described earlier for the Earth, there is an increased likelihood that a given black hole does not have an effectively zero angular velocity.

Effects of Pressure Regulation - The Sun's internal system for regulating the pressure within its core could have an effect on some of the parameters relevant for accretion, including the density and sound speed in the core. It is likely, however, that a black hole would have to be rather large for this to be a factor, and the effect on the total accretion times may not be very significant.

§ Eddington Limit in the Sun

TEXT PENDING

[104] For an alternative model of the innermost core, see the georeactor scenario described in section 9.1

§ Multiple Black Hole Accretion in the Sun

The GM paper does not consider the case of multiple black holes within the Sun.

The three general issues related to multiple black holes that were discussed earlier in the case of the Earth would also apply to multiple black holes within the Sun, although their relative importance may be different.

The presence of other black holes may be expected to affect a given black hole's accretion, but the impact may or may not be as great as that within the Earth. In both cases the proximity of other black holes would effectively rule out the assumption of spherical symmetry, leading to the absence of any macroscopic accretion model. In the case of the Earth, the energy output from other black holes could potential cause a thermal acceleration of the accretion process if multiple black holes are contained in a relatively small space. A similar process might be expected in the Sun, but the temperature of the Sun's core is about 2760 times greater than the Earth's [NSSDC:Sun ↗] [SSC02 arXiv p. 16], so the relative importance of this factor may not be as great.

Multiple black holes may in general be expected to increase the total radiative output of the Sun, although the size of this effect would need to be determined. If the effect that black holes have on the Sun's output is moderated or magnified by the Sun's internal regulatory mechanisms, a detailed model would be needed to estimate the impact that an increase in the number of black holes would have. (This issue is considered further in section 9.)

The impact that the merger of multiple black holes would have on the total accretion time is, as in the case of the Earth, dependent on precisely when such mergers would occur. The impact would be relatively insignificant if mergers occurred during one of the quicker phases, but potentially very important if they happened during one of the slower periods. The absolute number of black holes available for such mergers should be much less than in the case of the Earth, as far fewer LHC-produced black holes are expected to be trapped in the Sun. This would in turn limit the potential reduction in the total accretion time due to mergers.

The accretion environment within the Sun is also chemically and physically very different from the Earth's core, so the effect that these differences could have on the dynamics leading to or preventing mergers should also be examined further.

8.1.4 Neutral Stable Black Hole Accretion within White Dwarfs

The GM paper's predictions of the times required for black hole accretion within white dwarfs is an essential component of its astrophysical argument. This section reviews the paper's analysis of the process and its time estimates. A more detailed analysis is given of single black hole accretion within a white dwarf, followed by a few notes about the accretion process of multiple black holes. Any possible astrophysical implications stemming from the existence and state of white dwarfs is considered later in section 10.1.4.

§ Summary of CERN's Estimates of Single Black Hole Accretion Times

TEXT PENDING

5 Dimensions

6 Dimensions

- **Identical Unwarped Extra Dimensions**
- **Non-Identical Unwarped Extra Dimensions**
- **Identically Warped Extra Dimensions**
- **Non-Identically Warped Extra Dimensions**

7 Dimensions

- **Identical Unwarped Extra Dimensions**
- **Non-Identical Unwarped Extra Dimensions**
- **Identically Warped Extra Dimensions**
- **Non-Identically Warped Extra Dimensions**

Eddington-Limited Growth

§ Critical Review of Single Black Hole Accretion in White Dwarfs

A critique of the theory of black hole accretion within white dwarfs is provided below. Some of the more general concerns are mentioned first, followed by a review of the different phase of the accretion process. Problems with the assumptions and the analysis are noted first, followed by a few comments on the data used for the paper's calculations, and the paper's presentation of the estimated accretion times. Many of the points in this section are the same as those described earlier for accretion within the Earth, so they are mentioned only very briefly here.

▼ General Concerns

Purely Theoretical Treatment - The GM paper's analysis of black hole accretion in white dwarfs is a purely theoretical treatment with no empirical basis whatsoever.

Limited Understanding of White Dwarfs - The GM paper expresses a very high level of confidence in our general understanding of white dwarfs. CERN's Scientific Policy Committee similarly speaks of irrefutable observational data on compact stars interpreted using firmly established theory [SPC p. 4], but how well established is that theory? The authors of the article cited by the GM paper on "The Age and Colors of Massive White Dwarfs", claim that their publication is, to their knowledge, the first attempt to compute the evolution of massive white dwarfs with a realistic equation of state [Alt07 arXiv p. 8]. This "first attempt" was published in 2007. A more honest assessment would describe our understanding of white dwarfs, and in particular massive and ultramassive white dwarfs, as an active area of scientific research, with much still to be discovered [cf. FBB01 pp. 433–434].

Conservative Claims - The GM paper's time estimates for white dwarf accretion are presented as an upper bound, but neither a "best estimate" nor a lower bound is given, based on which one could quantitatively assess how conservative the paper's estimates are. Some assumptions adopted in the paper are conservative, but others are not. Moreover, a number of factors have also been ignored which could have a significant effect on the accretion times.

Sensitivity to Slowdown at any Stage - The GM paper's analysis for the Earth shows that a slowdown at any stage of the accretion process could greatly increase the estimated times. In the case of the Earth, an assurance of safety was offered based on the prediction of a "speed bump" around a capture radius of about 1 Å. For the case of white dwarfs, the paper needs to conclusively demonstrate that there cannot be any such slowdown at any stage in the accretion process for any known or unknown reason.

Absence of Reradiation - Accounting for the effects of reradiation is essential for establishing an upper bound on accretion times within white dwarfs. The GM paper's discussion on "Accretion basics" begins by trying to suggest that it is possible—or even expected—that reradiation does not occur. The text states:

> This formula neglects reradiation of incident energy, which is discussed in Appendix B, and, if present, can lower the growth rate. [GM p. 15]

From a risk analysis point of view, the expectation that reradiation may not exist, as implied by the phrase "if present", provides an important layer of protection for the paper's accretion analysis. Reradiation could affect the accretion times, so if it does not even exist, there is no question of it having an effect, and the paper's subsequent analysis of an Eddington limit is simply a back-up argument for a less likely scenario.[105] There is, however, no justification for

[105] The phrase "if present" does not explicitly quantify the likelihood of reradiation, however, under normal circumstances such a phrasing would be reserved for a scenario which is not the default expectation.

suggesting that reradiation does not exist. One can consider the possibility of reradiation being trapped, but that would be limited to within a certain radius. Beyond that radius there would still be reradiation, unless CERN can show how particles could accelerate towards a black hole without producing any radiation whatsoever.

The paper then throws in another fictitious argument against reradiation having any effect with the suggestion that a minimum level of radiation is required. It states:

> ...we also briefly discuss, and argue against, the presence of an Eddington limit, which would be relevant if emitted radiation were sufficient to slow accretion. [GM p. 16]

The implication of the phrase "if emitted radiation were sufficient to slow accretion" is that reradiation below a certain level would have no effect on the accretion rate. This is not justified since any level of reradiation may, in general, slow the infall of matter into a black hole (although, as noted earlier in the case of the Earth, one also needs to check for the possible indirect effect that reradiation may have in accelerating accretion). The question is not whether emitted radiation is sufficient to slow accretion, but rather how significant its effect would be on the accretion times.[106]

Later, the paper tries to present its arguments against an Eddington limit in a way that encourages readers to think that the short accretion time scales it predicts are unmodified. The paper states:

> From this analysis we conclude that Bondi accretion time scales for the unwarped $D = 6, 7$ scenarios are quite short, especially as compared to known white dwarf lifetimes that exceed 1 Gyr. We have argued in Appendix B that these are not modified by an Eddington limit, at least until accretion macroscopically disrupts the star. [GM p. 43]

Insofar as the paper's arguments against an Eddington limit are valid, the authors can claim that the time scales are not modified by an Eddington limit per se; but the real question is whether the time scales are modified by any of the radiation emitted during the accretion process. It would seem that by focusing on the Eddington limit issue, the authors may have been hoping that readers forget about the broader issue of the effects of reradiation. (The question of an Eddington limit in white dwarfs is examined more critically in section 8.1.4 of this paper.)

The paper finally does address the effects of radiation on accretion rates in Appendix B.3 where it defines a modified Euler equation and modified Bernoulli equation to take into account the force exerted by reradiation [GM p. 63, eqs. B.21, B.22]. These equations are then used to calculate an

[106] The paper's phrasing would also lead some readers to logically conclude that the absence of an Eddington limit implies that radiation cannot slow accretion. The confusion is facilitated by the ambiguous term "relevant". If a reader accepts the paper's arguments against the existence of an Eddington limit, as well as its characterization of the relationship between an Eddington limit and radiation slowing accretion, then the reader would have to think that an Eddington limit is relevant, despite its non-existence, in order for radiation to possibly slow accretion.

Eddington limit, but what the authors needed to do was recalculate all their previous accretion estimates based on the corrected equations. Until they do so, there are essentially no valid estimates for the accretion times of a black hole in a white dwarf.

Other Forms of Dissipation - The GM paper focuses almost exclusively on the possible effects of electromagnetic radiation. It does acknowledge the existence of other forms of dissipation, but then proceeds to ignore them. The paper states:

> From these considerations we conclude that there are good reasons to rule out important radiation effects that could produce an Eddington limit for accretion within a white dwarf, although one cannot state for certain that some form of dissipation would not play such a role. [GM p. 61]

For a risk analysis there is not much point in simply acknowledging the potential role of other factors without attempting to set a bound on their potential effects. In this case, failing to do so means that the report cannot make any conclusion about the possibility of an Eddington limit.

The statement cited above is specifically for an Eddington limit, but the issue of other forms of dissipation (such as that caused by magnetic fields) applies more generally to the question of what forces could modify a black hole's accretion rate. This is not addressed in the paper and no modification of the accretion equations have been made to take other forces into account.

Contribution from Bulk Particles - The GM paper does not consider the effects that particles from the bulk could have on black hole accretion. A first expectation is that they would increase the accretion rate, but the question needs to be examined more carefully.

Movement of Black Holes off the Brane - The possibility of black holes moving off the brane is a more serious issue for the GM paper's argument. No estimate is given for the accretion time of a black hole that has moved off our brane. If a significant fraction of cosmic ray-produced black holes can move into the bulk, where their accretion rates are unknown, this effect would be similar to a suppression of the black hole production rate. Unless CERN can show that a sufficient minimum percentage must stay on the brane and continue accreting there, there is effectively no astrophysical argument involving white dwarfs.[107]

General Forms of the Potential - The GM paper only covers what it describes as "a very wide class of potentials that become strong at the TeV scale." [GM p. 15] It does not attempt to cover

[107] As discussed earlier, the movement of black holes off the brane would also affect the accretion rates within the Earth, however, the requirements of a safety argument for the Earth are very different from those of an astrophysical counterargument involving white dwarfs. For example, if the movement of black holes off the brane delay their expected accretion times by a couple hundred million years, this would have serious implications for the white dwarf argument (for a review of various issues related to this argument, see section 10.1.4), but this would not have a significant effect on whether the Earth is prematurely destroyed. Similarly, if the movement of black holes off the brane changes the rate of heating caused by black hole accretion, the tolerance of the Earth is very different from that of white dwarfs (for further comments, see section 9). Moreover, the possibility of a catastrophic risk for the Earth is fundamentally different from requiring the assured destruction of white dwarfs.

all possible forms of the gravitational potential, or set a bound on the probability of less likely forms of the potential.

Accretion Times for $M_D > 4.7$ TeV - As noted earlier, for the trapping of black holes in white dwarfs, the GM paper's limits its argument to values of $M_D \not> 4.7$ TeV, based on the unjustified assumption that the LHC cannot produce black holes if M_D is greater than this value. Similarly, for the accretion of black holes within white dwarfs, the conclusions at the end of the section on accretion in 6 or 7 unwarped dimensions are based on the assumption of 4.7 TeV as the maximum value of M_D that would be of concern for the LHC. [GM p. 43] Consequently, the stated bounds on the accretion times for white dwarfs do not apply if the value of M_D is greater than 4.7 TeV. ▷ ADD NOTE on the specific accretion times for $M_D = 14$ TeV.

Accretion Times in Crystallized White Dwarfs - An important question that the GM paper leaves unresolved is what the process of black hole accretion would be in a white dwarf with a core that has begun to crystallize. The paper suggests that it does not have to consider this issue since white dwarfs crystallize later, at time scales of about a billion years [GM p. 33], or about 600 million years [GM p. 41], or about a billion years [GM p. 44]. As the paper repeatedly refers to white dwarfs having ages of a billion years or more [GM pp. 5, 43, 44, 51, 52, 87] it seems reasonable to ask what would actually happen if one of those white dwarfs were to trap a black hole now. The issue is especially important for the Bondi accretion phase as the paper notes that the compressibility of the medium counteracts the flow of matter into a black hole [GM p. 22], and more highly compressible matter results in a higher accretion rate [GM p. 54]. This would suggest that the accretion rate within white dwarfs with a crystallized core could be much slower than the liquid phase estimates that the paper provides. It should also be noted that the time scales for crystallization of massive and ultramassive white dwarfs is much shorter than that for regular white dwarfs, an issue described further in section 10.1.4.

Possibility of "Strange Dwarfs" - While this issue is more of a concern for neutron stars, it should be noted that one unresolved aspect of white dwarfs is whether they can have a core composed of strange matter. In his review of the physics and astrophysics of strange quark matter, LSSG member Jes Madsen noted:

> As emphasized by Glendenning, Kettner and Weber [72, 73], the existence of crusts not only changes the mass-radius relation for strange stars, but also opens a rich plethora of new stellar configurations. In particular, one may have a sequence of "strange dwarfs", much like white dwarfs except for an SQM core. At present there is no well-studied model for formation of such strange dwarfs. [Mad98 arXiv p. 26, hyperlinks added]

If a given white dwarf has a strange matter core, it would be necessary to have a distinct accretion model for it. A first guess would be that its accretion rate would be much faster, given its higher core density, but a more careful analysis would need to consider other possible factors, including the effects of color-flavor locking [cf. LSSG p. 3]. Changes to the estimated ages of such white dwarfs are also discussed further below.

Contribution from Dark Energy - The possible contribution of dark energy to white dwarf accretion is not considered in the paper. It is not known whether dark energy would increase or decrease the expected accretion rates.

Numerical Simulations - The GM paper does not use any numerical simulations as a cross-check or supplement to its analytical treatment.

▼ Subnuclear Accretion

(Chromo-)Electrostatic Effects - For the analysis of subatomic accretion in the Earth, the GM paper includes the following footnote:

> [10]In particular, (chromo-)electrostatic effects apparently slow accretion early in this phase. [GM p. 18]

These effects were ignored in the case of the Earth, which would be justified if one could guarantee that their only possible impact would be to slow accretion. On the other hand, since the accretion time estimates for white dwarfs are intended to be an upper bound, and since the paper explicitly states that (chromo-)electrostatic effects are expected to slow accretion, one would naturally expect these effects to be incorporated into the analysis for white dwarfs. Unfortunately, there is no mention of such effects in the paper's accretion model for white dwarfs. One may argue that since they have been ignored in the case of the Earth, they should, for balance, also be ignored in the case of white dwarfs, but a more sensible approach would be to include these factors in both cases.

Absence of Equations - The GM paper concludes that both the subnuclear phase, and a brief phase for $D = 5$ in which the growth is limited by the velocity capture radius, are governed by very short time scales [GM p. 41]. The paper does not, however, provide any equations to back-up their statement and to permit independent verification of their claims. The main benefit of having a detailed scientific paper reviewing this issue is to make the full argument transparent so that it can be scrutinized by the scientific community and the general public. The equations and calculations should be published by CERN so they can be more carefully examined, especially in this case since by the paper's own analysis the subnuclear phase has a mix of electromagnetic capture-dominated accretion, and velocity capture-dominated accretion [GM p. 41]. It would also be interesting to compare the accretion times for white dwarfs with the accretion times for the Earth during this stage.

Velocity Dominated Capture in Hotter White Dwarfs - The GM paper reports that for temperatures greater than or approximately equal to about 10^7 K, the thermal velocity will be of size greater than or approximately equal to 0.0003 c [GM p. 41]. A higher thermal velocity increases the effective flux towards the black hole, but it also reduces the size of the velocity capture radius by the same factor, and the capture radius is then squared to give the capture cross-section. A reduction in the velocity capture radius would also mean that it is the dominant factor for a longer period (both starting at a smaller radius, and, by equation 7.2, extending to a larger radius [GM p. 41, eq. 7.2]). Thus, an upper bound on the accretion times for this phase should also consider the maximum possible thermal velocity within the paper's candidate white dwarfs. In doing so, it would also be advisable to take into account the heating effects of reradiation during this stage.

▼ Subatomic Accretion

(Chromo-)Electrostatic Effects - As noted above for subnuclear accretion, (chromo-)electrostatic effects have been ignored, despite the paper itself noting that they apparently slow accretion.

Calculation of K - The GM paper gives an estimate of the value of K/mM_0^2, however, it provides few details on how the figure was arrived at [GM p. 41, eq. 7.1]. As such, it leaves a number of questions unanswered about which factors were or were not taken into account when calculating K. Those questions include:

- The calculation of K for the Earth assumed that the inner electrons moved along with the nucleus (thereby reducing the effective charge). What assumptions were made in this case to model the behaviour of degenerate electrons?
- The given estimate for the value of K/mM_0^2 applies to white dwarf cores of what composition?
- The estimate seems to be based on an assumed density of about 10^7gr/cm^3, however, figure 1 of the GM paper [GM p. 37, figure 1] indicates that 1 $M_\odot$ white dwarfs have a central core density in excess of 3×10^7gr/cm^3, and 1.1 $M_\odot$ white dwarfs have a corresponding density above 6×10^7gr/cm^3. The first three candidate white dwarfs [GM pp. 44–45] have masses equal to or greater than 1.2 $M_\odot$, so their central core density would be expected to be even higher still. To what extent does the estimated value of K apply to these cases?[108]

Capturing of Full Nucleus - For the purposes of a conservative lower bound on the accretion time estimates, the GM paper assumed that all of the mass of a nucleus is absorbed [GM p. 18]. For a conservative upper bound on the accretion time, the opposite assumption should be adopted, viz. that the least possible portion of a nucleus' mass is captured in any encounter. It seems, however, that the paper has assumed that for accretion within white dwarfs the entire mass of a nucleus is captured.[109]

Accretion Dynamics - Beyond the initial criterion of the black hole's gravitational pull overcoming the restoring force on a nucleus, for a dense environment such as the core of a white

[108] On the other hand, the "characteristic distance" for these cases would be a number divided by the density, which might be expected to counterbalance changes in the value of K.

[109] One may argue that the accretion process will be substantially the same in both cases, so it is unrealistic to assume one process for the Earth and an entirely different one for white dwarfs. The two accretion environments are extremely different, so it might not be so surprising to find that the processes are different, but if they are assumed to be the same, then one should consider all the possible scenarios (e.g. full nucleus capture, partial nucleus capture, minimal capture, etc.), and apply them equally to both cases.

dwarf one should check whether any of the interactions of particles within the electromagnetic capture radius (but outside the black hole's event horizon) could impede the capture of particles. Given the relatively high speed of the particles being accreted, the precise manner through which they lose orbital angular momentum and finally fall into the black hole also needs to be clearly described.

Effects of Fermi Blocking - The paper considers the effects of Fermi blocking when analysing the possibility of an Eddington limit [GM p. 60], but it does not appear to have considered the effects that Fermi blocking would have on the accretion process itself. This should be considered a minimal requirement for any model of accretion within a white dwarf.

Nuclear Burning - In astrophysical cases, the accretion disks of black holes have been hypothesized as a site for nuclear fusion [▷ ADDCITE]. In this case, depending on the specific elements, nuclei being accreted could also undergo fusion.[110] If fusion does occur, it could add to the radiation emitted from the vicinity of the black hole and affect the rate of accretion. This possibility should be more carefully examined and a bound set on its possible effect on the accretion times.

Quantum Tunnelling - A more complete treatment of the accretion process during this phase would also look at any quantum tunnelling into or out of the electromagnetic capture radius.

Other Factors and Unknowns - The GM paper does not consider any other factors documented in the scientific literature which might affect the subatomic accretion process. Similarly, it does not make any allowance for "unknown unknowns" during this stage of accretion.

▼ Transition to Macroscopic Accretion

Criterion for Transition - In order to determine a conservative lower bound for the accretion times within the Earth, the GM paper adopted a policy of using the electromagnetic capture model when it was fastest, and the Bondi accretion model when it was fastest [GM p. 23]. As the estimates for white dwarfs are presented as an upper bound on the accretion times, one might expect that the paper would adopt the opposite policy of using the slowest of either model (provided the model is in its range of validity). Instead, it appears that the paper has simply followed the previous policy of using the fastest of either model. In this case, it has used the electromagnetic capture model below a_{WD}, and the Bondi accretion model above a_{WD} [GM pp. 41–44].

One of the potential benefits, if the paper had adopted a conservative approach of using the slowest of either model (within a reasonable range), is that if either of the models were to be shown to be slower than predicted during any part of the transitional phase, there would still be the back-up of the other accretion model. With that back-up, one could argue that the accretion

[110] In the case of the Earth, the accretion of iron would not be expected to result in any fusion, although this possibility for lighter elements could be examined.

times wouldn't necessarily be longer than predicted. With the paper's treatment, however, there is no back-up option; instead there are at least two ways in which the supposed upper bound could fail. Any increase in the expected accretion time during either the electromagnetic capture phase or the Bondi accretion phase would result in a direct increase in the overall white dwarf accretion times. (The only limit to this increase would be if the increased time for the model assumed during a given phase were to be so great that it would be even slower than what was previously considered the slower model for that phase.)

Transition at 0.01 Å - The transition to Bondi growth is assumed in the GM paper to occur once the electromagnetic capture radius is greater than 0.01 Å, corresponding to the internuclear separation distance within white dwarfs with a core density of approximately 10^7gr/cm^3 [GM pp. 41–42]. Bondi accretion at this scale is discussed further below. Here it is simply noted that in absolute terms this distance scale is 100 times smaller than the transition point used for the case of the Earth. If the Bondi accretion model cannot be applied at this scale and the transition instead occurs at 1 Å, then the estimated times for the electromagnetic capture phase would be significantly longer. In the case of 5-dimensional warped growth, if the crossover radius is greater than 20 Å, then according to the GM paper's equations, the accretion time to 1Å is 10,000 times longer than the accretion time to 0.01 Å [based on GM p. 19, eq. 4.22]. For the case of 6 dimensions the times would be 1,000,000 longer, and for 7 dimensions it would be 100,000,000 times longer. However, as with the case discussed earlier for the Earth, it is not clear if the electromagnetic capture equations can be used for distances greater than the typical internuclear separation scale. In such a situation, there would then be no valid model to cover black hole accretion in a white dwarf between a capture radius of 0.01 Å and a Bondi radius of 1 Å.

▼ Macroscopic Accretion

Extremely Oversimplified Treatment - As in the case of the Earth, the GM paper's treatment of macroscopic accretion is the most simplistic possible. For the cases of 6 or 7 unwarped dimensions and warped scenarios with a crossover radius greater than 200 Å, the reliability of the paper's model for accretion within a white dwarf can be considered even more important than its model for accretion within the Earth. It is on the basis of this model and its possible astrophysical implications that the GM paper declares that there are no grounds for concern over the scenarios in which its accretion model for the Earth predicts its premature destruction. One might normally expect an extremely detailed and rigorous model for black hole growth within white dwarfs, but instead the paper brushes aside almost all complexities, and assumes that black holes grow according to its simplified equations.

Importance of Details of the Accretion Process - The GM paper claims that we can reliably predict the behaviour of microscopic black holes since the physical processes at large distances become independent of the short-distance properties of the black holes [GM p. 5]. This claim is contradicted by some of the very assumptions adopted in the paper, as described earlier in the section on Bondi accretion within the Earth. Moreover, in the case of white dwarfs, one may further ask how well we really understand the physical properties of a medium so radically different from our own.

Implications of a "Canonical Framework" - The GM paper presents Bondi accretion as "the canonical framework to deal with the flow of matter into a black hole" [GM p. 6], but, as noted earlier, it should be clearly understood that it is only a framework that provides a reference value which can be compared with more realistic estimates. Such estimates can differ from the Bondi accretion rate by orders of magnitude [▷ ADDCITE]. Whether it can even be considered the canonical framework for black accretion within white dwarfs is itself debatable—the paper cites no references that have modelled the growth of black holes in white dwarfs through Bondi accretion.

Standard Range for Bondi Accretion - In line with comments expressed in the critique for the Earth, it should be noted that:

- ▷ ADD NOTE on distance scales for astronomical Bondi accretion
- ▷ ADD NOTE on densities for astronomical Bondi accretion
- ▷ ADD NOTE on pressures for astronomical Bondi accretion
- ▷ ADD NOTE on elemental abundances for astronomical Bondi accretion
- ▷ ADD NOTE on form of matter for astronomical Bondi accretion

Adoption of the Earth's Equations - The accretion times for white dwarfs are estimated using the equations developed for the Earth [GM pp. 42–43]. The paper uses parameter relevant for white dwarfs and does adopt a conservative value for the Bondi radius during the transition to 4-dimensional growth, but the model for growth is essentially the same as that for the Earth. The problem with this approach is that the Earth's equations were designed to give a lower bound on the accretion times. Thus, assumptions such as steady accretion, spherical accretion, no reradiation, etc. were integrated into the accretion model and are reflected in the equations. If one intends to develop an upper bound for accretion times, as is promised in the case of white dwarfs, then one has to return to the basic assumptions of the model, select the options leading to the slowest possible growth, and then reconstruct the equations. Some of the inappropriate assumptions underlying the equations are described further below.

Pico-Scale Hydrodynamics - The model of Bondi accretion within the Earth was criticized earlier for depending on the hydrodynamic properties of matter on a nanometer scale. In the case of white dwarfs, the accretion model depends on hydrodynamic equations on a picometer-scale—a thousand times smaller than the nanoscale.

Extra-Dimensional Hydrodynamics - The analysis also depends on the untested hydrodynamics of atomic matter within a brane embedded in higher-dimensional space.

Validity of Macroscopic Treatment - The Bondi accretion model depends on a number of statistical, macroscopic properties, but the GM paper makes no effort to determine when such a treatment is valid. In the case of the Earth, an increase in the scale by a factor of 1,000 or 1,000,000 was suggested as a more reasonable range to begin using a macroscopic approach. In the present treatment, the paper depends on a macroscopic model when the purported Bondi radius is the size of only a single internuclear separation.

Assumption of Steady Accretion - The paper assumes that matter will flow steadily into a black hole [GM p. 54] and fails to consider the case of unsteady and irregular accretion. This is of particular concern if the argument for assuming steady accretion within the Earth was that it was probably the fastest form of accretion.

Effects of the Black Hole's Motion - The GM paper assumes that during the Bondi phase the position of the black hole will be stationary with respect to the medium. This is an uncertain assumption, as the black hole will have acquired a good deal of potential energy from the matter it has accreted within the white dwarf, which could result in a non-negligible velocity even when the mass of the black hole has grown considerably. The case of a stationary accreting object was intended only to represent a limiting case [Bon52 p. 195] (and not the slowest limit). A more credible model for accretion within white dwarfs should incorporate the effects that the black hole's motion would have on the accretion rate.

Assumption of a Non-Rotating Black Hole - The GM paper assumes that the accreting black hole will not be rotating, but it fails to prove that this will be the case. The black hole is expected to have an angular velocity upon formation which should be significantly reduced as its mass increases, but it is not expected to become exactly zero. The paper states that TeV-scale black holes "...become increasingly well-approximated as non-spinning black holes" [GM p. 16, footnote 8], however it fails to define what level of angular velocity is low enough for an accretion model based on zero angular velocity to apply. The GM paper needs to demonstrate a bound on the effects that even a slight angular velocity could have on its accretion time estimates.

Assumption of Perfectly Spherical Accretion - As noted earlier in the case of the Earth, the GM paper assumes that the macroscopic accretion of a black hole will be spherically symmetric [GM pp. 27, 54–56, 58–65], even though that is a very unrealistic assumption. Moreover, if it can be shown that spherical symmetry produces the fastest possible accretion rates under all conditions, then that assumption would be justified for the Earth, but it clearly would not be appropriate for determining the slowest possible accretion rates within a white dwarf.

Fermi Blocking - The GM paper's model for accretion within a white dwarf does not appear to take into account the effects of Fermi blocking.

Nuclear Burning - The possible effects of nuclear fusion of the accreting nuclei are not incorporated into the GM paper's model of accretion within white dwarfs. The release of energy from fusion may affect the accretion rate.

Assumption of Single Temperature - The paper assumes a single temperature for the medium without bothering to model the interactions between the accreting nuclei and electrons.

Neglect of Seismic Effects - White dwarfs are known to experience significant seismic activity [▷ ADDCITE], so the possible effects of such activity on the accretion rate should be taken into account. The net effect could well be an increase in the average rate of accretion, however, seismic activity may also interfere with established accretion flows.

As noted in the case of the Earth, there are also a number of other considerations which are very basic expectations of any modern treatment of black hole accretion. They include the following

Magnetic Fields - The effects of magnetic fields have not been taken into account in the GM paper's model.

Turbulence - The effects of turbulence have been ignored.

Viscosity - The GM paper justifies the assumption that matter inside the Earth can be modelled as a non-viscous fluid on the grounds that it is trying to determine the fastest possible rate of accretion [GM p. 22]. For white dwarfs it still assumes that there will be no viscosity, even though its estimates are intended to represent the slowest possible rate of accretion.

Homogeneous Medium - The GM paper assumes a purely homogeneous medium, with no variations in composition, phase of matter, pre-accretion density, pre-accretion temperature, etc.

Geometry of Accretion - The GM paper does not consider any of the basic formations found in many accretion models, such as funnels, shocks, and outflows (such as winds and jets). The effects are a particular concern for white dwarf accretion given the very high orbital angular momentum of the accreting particles.

Relativistic Corrections - The GM paper does not set a bound on the effects that relativistic corrections could have on its accretion time estimates, and simply applies its non-relativistic model to massive and ultramassive white dwarfs. In contrast, one may note that when white dwarf researchers Xu and Van Horn attempted to calculate the possible effects of Fe/C phase separation on the evolution of white dwarfs, they clearly state:

> Note that our equation of state, like that of Salpeter & Zapolsky, is nonrelativistic. This limits the applicability of our calculations to cases with $\rho \lesssim 10^6 gcm^{-3}$, corresponding to white dwarfs with $M \lesssim 0.6 M_\odot$. [▷ ADDCITE Xu and Van Horn p. 664]

The GM paper estimates central core densities ranging from over $30 \times 10^6 g/cm^{-3}$ up to almost $70 \times 10^6 g/cm^{-3}$ for the white dwarfs it considers [GM p. 37, figure 1], and yet it still applies its non-relativistic model without any corrections for either the ambient environment or the increasingly relativistic accretion zone.

Reliability of the Sound Speed Estimate - The GM paper notes that the evolution time scales for white dwarfs are determined by their density and sound speed [GM p. 42], however it cites no published literature to support the value that it uses for the sound speed in the centre of massive and ultramassive white dwarfs. For this crucial parameter the paper simply relies on private communication with one of Professor Giddings' colleagues at UC Santa Barbara. [GM p. 42, citing reference [56]] As with most other estimates in the paper, no error range is given for this figure.

Other Factors and Unknowns - The paper does not consider any other possible factors or any "unknown unknowns" that might affect the Bondi accretion phase within white dwarfs. Any factor which can delay the process of accretion has the potential to negate the paper's astrophysical safety argument.

Description of Accretion Times in 7 Dimensions - The conclusion of section 7.2 of the GM paper reports that the accretion time scales for 6 or 7 unwarped dimensions are "quite short" [GM p. 43]. This may be the case for 6 unwarped dimensions, but it is not true for 7 dimensions. In the case of 7 dimensions, the time scales run as high as 80 million years for $M_D = 4.7$ TeV [GM p. 43] (and even higher for $M_D = 14$ TeV). Such times cannot be characterized as "quite short".[111]

Accretion Times in Higher Mass White Dwarfs - In trying to put a positive spin on the 80 million year estimate for accretion within a white dwarf (if $M_D = 4.7$ TeV and $D = 7$), the paper tries to argue that the time would be reduced in more massive white dwarfs. It states:

> We also notice that if we consider the case of more massive and thus denser white dwarfs, the timescales are reduced. For example, the central densities of white dwarfs of mass $M = 1.1\ M_\odot$ and $M = 1.2\ M_\odot$ are 2 and 4 times, respectively, larger than for $M = M_\odot$ [56], leading to accordingly shorter evolution times. [GM p. 43]

The phrasing of the paper clearly implies that the accretion times in this case would be 40 million years for white dwarfs with a mass equal to 1.1 $M_\odot$, and 20 million years for white dwarfs with a mass of 1.2 $M_\odot$. In complete contrast, for the Earth the paper presents a linear relationship between sound speed and density and thereby concludes that the value of $d_0 c_s$, which the paper describes as the parameter controlling macroscopic accretion [GM p. 84], is density independent [GM p. 24]. While it may be premature to assert that Birch's law must apply within the core of white dwarfs, it is disingenuous to suggest that the accretion times will be shortened in proportion to an increase in a white dwarf's density, without taking into account any commensurate change in its sound speed.

[111] One might argue that the paper says "especially as compared to known white dwarf lifetimes that exceed 1 Gyr" [GM p. 43 ↗], however, the authors had chosen not to make their claim conditional on this case, which they could have by instead writing, "if compared to ...". Moreover, as discussed later, the candidate white dwarfs with lifetimes in excess of 1 Gyr are irrelevant for the safety argument since they are expected to have crystallized cores.

Transition Phase for 6 and 7 Unwarped Dimensions - The transition phase from higher-dimensional growth to 4-dimensional growth is a difficult part to model as there is a great deal of uncertainty about the nature of the transition. The paper does adopt the conservative assumption that the Bondi radius is a constant value of R_D until the black hole reaches a mass corresponding to a Bondi radius of R_C [GM p. 42]. The paper claims that its assumption of 4-dimensional growth during this phase is conservative, but it does not appear to be significant since the paper is already assuming a constant Bondi radius.[112] What is not conservative, however, is the choice of $1/\lambda_4$ instead of $1/\lambda_D$ as a parameter governing transition accretion times [GM pp. 42, 43, eqs. 7.8, 7.11]. As the paper assumes a value of $\Gamma = 4/3$ for white dwarfs, the value of λ_4 is 11.31 while the value of λ_6 is 4.70 and the value of λ_7 is 4.00 [GM p. 56, eq. A.20]. This means that their decision to use λ_4 leads to accretion times which are 2.41 times faster than if they had used λ_6 during the transition, and 2.83 times faster than if they had used λ_7.

Transition Phase for Warped Extra Dimensions - The GM paper's treatment of the transition phase for warped scenarios is even more questionable. The paper again assumes that the transition is governed by the parameter $1/\lambda_4$ [GM p. 43, eq. 7.13], even though the value of λ_4 is greater than λ_D for all $D > 4$ if $\Gamma = 4/3$ [GM p. 56, eq. A.20]. In the case of $D = 5$, this assumption leads to accretion times which are 1.79 times faster than if the paper had used $1/\lambda_5$ instead. Moreover, the paper derives its baseline estimate by assuming that the Bondi radius is at the maximum value of R_C from the very start of the transition phase [GM p. 43, eq. 7.13]. It then ridicules the idea of using the conservative value of R_D for the transition phase [GM pp. 43–44], even though it had more calmly adopted this very assumption for the case of 6 or 7 unwarped dimensions [GM p. 42]. Neither assumption can be considered "realistic" since both of them represent limiting cases; a constant value of R_C gives a lower bound on the accretion times while a constant value of R_D gives an upper bound. Insofar as the paper is trying to establish an upper bound for the accretion times, it does not really have an option but to use the assumption of a constant Bondi radius of R_D during the transition phase.[113]

Using the parameter $1/\lambda_4$ and the assumption of a constant Bondi radius of R_D, the paper implicitly recognizes that if the crossover radius is equal to 15 Å, the upper bound on accretion times would not be less than a billion years [GM p. 44]. As a fall-back position, the paper notes that for crossover radii greater than or equal to approximately 30 Å, the accretion times would be

[112] Moreover, whether or not it is conservative is not entirely clear. The authors may clarify this issue by reporting what value they would be assuming for the starting mass of the black hole for D-dimensional growth compared to 4-dimensional growth. In any case, the difference may not be significant since the time is largely governed by the final mass of the black hole at R_C.

[113] If the paper could demonstrate a minimum value for the Bondi radius at different points during the transition this could be an approach to reduce the value of the upper bound, but it may be difficult to do so if the aim is to cover all possible warped scenarios. Another possible approach could be to parameterize the total expected accretion times by the average Bondi radius during the transition phase.

less than a billion years [GM p. 44].[114, 115] These time scales are described as being "in the range constrained by experimental bounds" [GM p. 44], however, white dwarfs with estimated ages of a billion years or more are expected to have a crystallized core [GM pp. 33, 41, 44] and thus would likely have a much slower rate of accretion. Of the four non-crystallized white dwarfs that the paper identifies, three have reported ages of 100 million years, and one is said to have an age of 150 million years.[116] In order to have an upper bound on accretion times of no more than 100 million years, the crossover radius would need to be $\gtrsim$ 126 Å(when using the parameter $1/\lambda_4$), or $\gtrsim$ 227 Å (for the more conservative parameter $1/\lambda_5$).

▼ Post-Bondi Macroscopic Accretion

Final Stages of Growth in Unwarped Scenarios - The GM paper concludes its analysis of Bondi accretion in 6 or 7 unwarped dimensions by stating:

> We note, parenthetically, that in the true macroscopic regime, when the black hole starts to exert large-scale effects on its host body, the evolution may well not be Bondi, but in any case would disrupt the object in question. [GM p. 43]

On the other hand, we may note, parenthetically, that in the absence of any estimate of the time involved before the large-scale effects of an accreting black hole can be conclusively identified, there is effectively no bound on the accretion time estimates, and consequently no astrophysical safety argument based on the existence or observable properties of any white dwarf. No estimate is given in the paper of the times required for post-Bondi evolution, although a generic formula for the specific case of 4-dimensional Eddington-limited growth is included in Appendix B.3 [GM p. 64, eq. B.28] The times involved for Eddington growth are discussed further in section 8.1.4.

The GM paper's statement is also unclear about whether disruption of a white dwarf can only occur at the start of (or possibly before) the post-Bondi phase, or whether the post-Bondi phase could start before a white dwarf is disrupted. (In the case of neutron stars, the paper does explicitly claim, albeit without much justification, that the "... evolution is described as Bondi until the black hole reaches a scale where it disrupts the star." [GM p. 49]) If there is a "post-Bondi pre-disruption phase" for white dwarfs, then any additional time it involves must be added to the total "unobservable" accretion times.

[114] These time scales are very different from the claim in the conclusion of the GM paper that for $D = 5$ the production of black holes by cosmic rays "... would make it impossible for any white dwarf with a mass of the order of one solar masses to have survived longer than few thousand years ..." [GM p. 51 ↗]. It should be noted, however, that this claim is only for the case of the maximum allowed crossover radius. For all other permitted values of R_C, the conclusion more vaguely states that, "Scenarios with increased warping have correspondingly lower R_C and longer accretion times." [GM p. 51 ↗]

[115] It should also be noted that even this larger estimate depends on the paper's estimate for the reduction in the approximate maximum for the ratio of R_C/R_D being correct when R_C is greater or equal to approximately 15 Å [GM p. 43 ↗]. If, to be conservative, the general limit on the R_C/R_D ratio [GM p. 26 ↗] is applied, the bound for the accretion times would be about 25 times longer.

[116] For further comments on the ages, please see section 10.1.4

Final Stages of Growth in Warped Scenarios - In its section on black hole accretion in warped scenarios, the paper presents estimates of the minimum crossover radius for which accretion times can be expected to be less than a billion years [GM pp. 43–44]. These estimates leave no allowance for the time involved in growth that may not be Bondi, whether it be Eddington-limited or whether it differs from Bondi growth in other ways. Any increase in the accretion times resulting from a slower growth model can in turn be expected to increase the crossover radius required for black hole accretion to be complete (or identifiable) within a given time limit.

Definition of Disruption - Despite repeated references to disruption [GM pp. 43, 49, 51, 64] , and accretion time estimates which only apply up to the period of macroscopic disruption [GM p. 43], the GM paper offers no clear definition or restriction of what constitutes disruption of a host object. The only specific example it gives is the effect that numerous Eddington-limited black holes may have on the cooling rate of white dwarfs [GM pp. 64–65]. Since other forms of macroscopic disruption are also possible, this makes it very difficult to determine when the "non-disruptive" phase of black hole accretion is considered over (and how large a black hole would be at that point). The challenge of confirming the absence of macroscopic disruptions is discussed further in section 10.1.4.

§ Eddington Limit in White Dwarfs

TEXT UNDER REVISION

§ Relationship between Eddington Limits in the Earth and White Dwarfs

TEXT UNDER REVISION

§ Multiple Black Hole Accretion in White Dwarfs

Unlike its coverage of the Earth, the Moon and the Sun, the GM paper not only considers the case of multiple black holes accreting within white dwarfs, but makes this scenario a crucial element of its astrophysical argument. The GM paper concludes its analysis of macroscopic accretion in white dwarfs with the following statement:

> Moreover, as discussed in Appendix B, radiation of an ensemble of black holes at Eddington fluxes would interfere with white dwarf cooling, providing an independent argument against this possibility. [GM p. 43]

Appendix B makes the following more detailed argument:

> Typical cooling rates are in the range $10^{-1} - 10^{-3} L_\odot$, where the solar luminosity is $L_\odot = 4 \times 10^{33} erg/s$. As an example, we find that the Eddington output of N black holes of Bondi radii R_B would exceed $10^{-2} L_\odot$ for
>
> $$NR_B/\text{cm} \gtrsim 60 \ .$$

> Given the large numbers of black holes that would be produced, on relatively short time scales one would find a buildup of black holes that have a major impact on cooling, even for a relatively large value like $\eta = .01$. [GM p. 65]

This argument is examined further in section 10.1.4, although a couple aspects of it are discussed below.

In general, the effects that multiple black holes could have when compared with the accretion of a solitary black hole can be grouped into the three main issues identified for the case of the Earth. Those issues were:

- The effect that the presence of other black holes has on single black hole accretion rates
- The contribution that multiple black holes make to the total energy generated within their host object
- The effect that the merger of black holes has on the total time required to destroy the host object

For clarity, the second point can be subdivided into the energy production of multiple distinct black holes and the energy production of a single black hole formed by the merger of smaller black holes. For the white dwarf astrophysical argument, it may also be appropriate to expand the final point to consider both the time required to destroy a host object, and the (shorter) time required for the effects of a black hole to be discernible.

As in the case of other host objects, the presence of multiple black holes concentrated within a white dwarf may be expected to alter the accretion patterns of individual black holes. As noted earlier, the assumption of spherically symmetric accretion would become even more untenable. As the GM paper presents no model for non-spherically symmetric accretion within white dwarfs, this would effectively end this particular astrophysical argument. (In the case of the Earth, the heating caused by multiple black holes was identified as a factor which could possibly accelerate the rate of single black hole accretion. A similar process could take place within white dwarfs, but as in the case of the Sun, the temperature in the core of white dwarfs is already quite high, so this effect may not be as pronounced.)

The effect that multiple black holes would have on the energy generation within a white dwarf is a point that the GM paper identifies and argues would interfere with white dwarf cooling. The presence of numerous black holes within a white dwarf would naturally be expected to increase the total black hole energy production, but this effect should be more carefully quantified. One importance difference between the case of the Earth and white dwarfs is the distribution of the ages of black holes. For the Earth, neutral stable black holes would only be produced during the decade or so of the LHC's operation, and thus would all be essentially of the same geological age (although differences in their initial conditions might cause a spread in their masses at different stages). For the case of white dwarfs, trapped black holes are hypothesized to be naturally produced and thus their ages would be spread out over the time period in which the host white dwarf has had a low enough magnetic field and high enough column densities to capture cosmic ray-produced black holes. The GM paper makes its argument based on the expected energy production of N black holes with the same Bondi radius R_B [GM p. 65], but, in general, one would expect the Bondi radii of black holes within a white dwarf to range over many orders of magnitude. If there are $N^{\star}$ black holes in a white dwarf, then those with roughly the same Bondi radius R_B would represent only a small subset of the total number.

In the case of the Sun, the possible effects of internal regulatory mechanisms meant that it would be difficult to predict the net effect of multiple trapped black holes. The possibility of such regulatory mechanisms would seem to be less likely in the case of white dwarfs. For the Sun, the primary factor is the regulation of its fusion energy production. White dwarfs, on the other hand, are normally in a cooling state, without the production of additional energy, which might otherwise confound the question of the net effect of multiple black holes. Thus, the heating effect of multiple distinct black holes is, after taking into account the interaction of black holes, most likely proportionate to the number of black holes of significant size (although this cannot be stated with certainty).

An important question is how the merger of multiple black holes would affect the total black hole energy production. In general, this process can be viewed as the merger of black holes causing a jump to a later point in their evolution (discussed further below). The energy output of the merged black holes should be whatever is expected from a black hole with the combined mass. Two points, however, should be noted. The first is that if the process of mergers is relatively complete (i.e. covering all but the smallest black holes in the neighbourhood of the amalgamated black hole), then the energy output and future evolution of the new black hole will revert to the case of solitary black hole accretion, and the effects that black holes have on each other's growth would effectively be over.

The second is that the energy output of a black hole is not necessarily proportionate to its mass. This is an important distinction between the energy effects of multiple black holes that remain separate and black holes that merge. The relationship between energy output and mass depends on both the number of dimensions and the phase of black hole growth. For growth based on an electromagnetic capture radius, the energy output is proportionate to $M^{2/(D-1)}$ [GM pp. 15, 17, 57, eqs. 4.1, 4.10, B.1][117] so the output per unit mass decreases as the black hole increases in size, with this effect being especially pronounced in the case of higher dimensions. For Bondi accretion, the reradiation per unit mass would be expected to decrease with an increase in mass for the case of $D \geq 6$, remain constant for the $D = 5$, and increase in proportion to the relative change in mass for $D = 4$ [GM pp. 22, 23, 57, eqs. 4.31, 4.36, B.1]. For the Eddington evolution of a black hole, the energy output is proportionate to the Bondi radius [GM pp. 57, 64, eqs. B.1, B.25], so the reradiation per unit mass would decrease with increases in mass for $D = 5$ while remaining constant for $D = 4$ [GM p. 23, eq. 4.36]. (Thus, if multiple black holes merge during the 4-dimensional Eddington-limited phase the only difference in their energy output would be due to the end of interactions in the media between those black holes.)

[117] As was done in the case of the Earth, in this section we have set aside the numerous criticisms of the treatment of single black hole accretion presented in the GM paper, and are simply using the paper's model as a convenient illustration. It should be noted, though, that the relationship between mass, reradiation, and dimensions could change if the calculation of the electromagnetic capture radius above a_{WD} is altered.

The effect that the merger of black holes could have on the total accretion times within white dwarfs can be analyzed in the same way as the case of the Earth. If, hypothetically, the growth of black holes is simply exponentially, then the effect of multiple black holes would be to save the time associated with the equivalent exponential growth, which may not be that much. In this case, however, instead of the jump in mass being proportionate to the total number of black holes, it would most likely be proportionate to the number and relative sizes of the larger black holes. In the more general case, the time savings would be much greater if the mergers occur during a particularly slow period, and would be much less if they occur during a relatively fast phase. It should be noted that the timing of mergers, and even the timing of when black holes have significant interactions, could well be very different in white dwarfs than in the Earth. The differences in the density of the media and the velocities of trapped black holes could affect the likelihood of mergers during different phases. In both cases, the question of the timing of mergers and interactions merits further examination.[118]

§ General Relationship Between Earth and White Dwarf Accretion Times

The conclusion of the GM paper makes the following argument:

> We then studied accretion, showing that accreting black holes will disrupt such objects on time scales short as compared to their observed lifetimes. In particular, we found a general relationship (7.15) between accretion times for Earth and for white dwarfs, which, when combined with white dwarf ages exceeding 10^9 years, provides a very strong constraint. Thus, the implication of these arguments is that such scenarios, where Earth would be disrupted on time scales short as compared to its natural lifetime, are ruled out. [GM p. 51]

While the conclusion claims that the paper had found a "general relationship" between accretion times for the Earth and for white dwarfs, this is not supported by the actual text, which only touches on this issue in two sentences at the end of section 7.3 [GM p. 44], and a third summary sentence near the end of section 7.4 [GM p. 45]. The problems with this claim include the following:

No Comparison of Subnuclear Growth - The GM paper includes no comparison of the accretion rates of the Earth and white dwarfs during the subnuclear phase.

No Accounting for Velocity-Limited Growth - Growth in white dwarfs can be limited during part of the subnuclear and supernuclear phase by the velocity of the particles to be accreted [GM p. 41]. This limit is not expected to affect the growth of a black hole within the Earth [GM p. 18].

No Comparison of Subatomic Growth - The GM paper includes no comparison of rates during the subatomic phase of accretion within the Earth and white dwarfs.

No Comparison of Higher-Dimensional Bondi Growth - The GM paper only includes a comparison between the Earth and white dwarfs during the 4-dimensional phase of Bondi accretion.

[118] This general issue has also been noted by Plaga [Pla08v1 p. 6, footnote 7 ↗].

Due to changes in the value of λ_D (assuming $\Gamma = 5/3$ for the Earth and 4/3 for white dwarfs [GM p. 44]), the ratio of Earth to white dwarf accretion times during higher-dimensional Bondi growth would be between about 2.7 and 2.8 times less [GM p. 24, eq. 4.43] [GM p. 42] [GM p. 56, eq. A.20].

No Comparison During Transition from Higher-Dimensional to 4-Dimensional Bondi Growth - The effects of changes in the value of λ_D similarly apply during the transition to 4-dimensional Bondi growth. This change could reduce the ratio of Earth to white dwarf accretion times by a factor of up to 2.7 or 2.8. (It may also be noted that if one were to compare the fastest possible growth within the Earth to the slowest possible growth within white dwarfs during this phase, the ratio of accretion times would be further reduced by a factor of about 30 for 5, 6, or 7 unwarped dimensions, and a factor on the order of 400 for warped scenarios with R_C greater than or equal to about 15 Å.[119])

Comparison Invalid for $R_C < 1$ Å - For value of R_C less than about 1 Å, the ratio of Earth and white dwarf accretion times presented in the GM paper [GM p. 44, eq. 7.15] does not apply. The paper argues that for accretion within the Earth (but not in white dwarfs), its model of electromagnetic capture would be faster than Bondi accretion until the black hole's Bondi radius is about 1 Å [GM p. 23]. Any comparison of accretion rates in the range from 0.01 Å (where Bondi accretion in white dwarfs theoretically begins [GM p. 42]) to about 1 Å should compare the electromagnetic capture times in the Earth with Bondi accretion times within white dwarfs. (See, however, the note below on the validity of capture-radii based comparisons.)

Comparison Dependent on a Simplistic Model - The overly simplistic and unrealistic models for black hole accretion that the paper presents for both the Earth and white dwarfs has been critiqued above. It should be noted that the proposed ratio of accretion times [GM p. 44, eq. 7.15] can only be considered valid if the accretion models it depends on are valid. In more realistic models the ratio of $d_0 c_s$ may still play an important role, but there would likely be several other variables that could significantly affect the estimated accretion times. The ratio also depends on the validity of a macroscopic treatment of the accretion process.

Comparison of Accretion Times for Black Holes of Different Masses - The GM paper chooses to compare black hole accretion times on the basis of Bondi radii instead of black hole masses. For a given Bondi radius, a black hole accreting within a white dwarf is much more massive than a black hole with the same Bondi radius accreting within the Earth. At the stage when the Bondi radii and the Schwarzschild radii are all in the 4-dimensional regime, the mass of a black hole in a white dwarf is approximately 180,000 times more massive than a black hole with the same Bondi radius accreting in the Earth.[120] If one were to compare fully 4-dimensional

[119] The factor of about 30 is the square of the ratio of R_C/R_D for 5, 6, and 7 dimensions [GM p. 13, eq. 3.22 ↗]. The factor of 400 is used in the GM paper as the square of the ratio of R_C/R_D for warped scenarios with a crossover radius greater than or equal to about 15 Å [GM pp. 43–44 ↗].

[120] This estimate was calculated based on an approximate value of $0.0000327c$ for c_s in the core of the Earth [GM pp. 19, 24 ↗], a value of $0.014c$ for c_s in white dwarfs [GM p. 42 ↗], equation 4.32 [GM p. 22, eq. 4.32 ↗] with $D = 4$, and equation 3.16 [GM p. 12, eq. 3.16 ↗] with $D = 4$.

accretion times for black holes in the Earth and in white dwarfs with the same mass, then the accretion times in the Earth would be almost 10 times quicker.[121] (For the cases where only the Bondi radius of a black hole in a white dwarf is greater than or equal to R_C, a similar statement may be made, but the calculations are more complex since the distance from the black hole's horizon to its Bondi radius includes a transition from higher dimensions to 4 dimensions, for which no equations are given [GM p. 55].)

No Comparison of the Post-Bondi Phase - The GM paper includes no comparison of Earth and white dwarf accretion times during the post-Bondi phase. The paper does provide an estimate for the e-fold time (as a function of the efficiency parameter η) during 4-dimensional Eddington-limited growth within the Earth [GM p. 27], but it does not provide a specific estimate for such growth in white dwarfs. The general equation for the Eddington-limited e-fold time seems to be the same in both cases [GM p. 27, eq. 4.55] [GM p. 64, eq. B.28], provided that the value of σ (the scattering cross-section for infalling particles [GM p. 63]) and the value of η (the portion of energy reradiated [GM p. 57]) are the same.[122] To compare the total time for the post-Bondi phases in the Earth and white dwarfs one would also need to know when such growth starts and ends. The GM paper does not clearly specify a start time for either case, however, it can be noted that the Eddington radius defined in the paper [GM p. 64, eq. B.27] is about 19,000 times smaller for white dwarfs than for the Earth,[123] implying that 4-dimensional Eddington-limited growth starts at a much smaller Bondi radius in white dwarfs (albeit at a black hole mass that would be almost ten times larger than the corresponding mass in the Earth). The end of the post-Bondi phase is discussed in the next point.

No Accounting for Differences in Masses - The GM paper makes no mention of the differences between the mass of the Earth and white dwarfs in its comparison of accretion times. As a reference point, one may note that a solar mass white dwarf has a mass about 333,000 times greater than the Earth's [NSSDC:Sun ↗]. A more appropriate indicator to use for a comparison could instead be the mass of a black hole which would be sufficient to destroy the object—the ratio of these masses may be different from the ratio of total masses due to differences in the structure of the Earth and white dwarfs, although the ratio may be in the same rough ballpark.[124] Using the ratio of 333,000, one may first note that it may not result in that much of a difference in the total times for Bondi-only growth, since equation 4.41 implies that accretion times are very

[121] This was calculated from the previous ratio of approximately 19,000 [GM p. 44, eq. 7.15 ↗] divided by a factor of about 180,000 to account for the change in mass. The change in Bondi accretion times in 4 dimensions as a function of black hole mass is given from equation 4.41 [GM p. 24, eq. 4.41 ↗].

[122] Any differences in the values of either of these two parameters would cause a proportionate difference in the e-folding times.

[123] The dependence of the Eddington radius on $c_s(\infty)/\lambda_D \, \rho$ is the same as that for the Bondi accretion times. The ratio of Bondi accretion times were given in equations 7.14 and 7.15 [GM p. 44, eqs. 7.14, 7.15 ↗], and the inverse relationship between d_0 and ρ is given in equation 4.21 [GM p. 19, eq. 4.21 ↗]

[124] An even more relevant criterion for the purpose of a safety review is the ratio of the mass of a black hole which is sufficient to harm life on Earth to the mass of a black hole in a white dwarf which could be identified through present-day astronomical observations. This criterion is discussed further in section 10.1.4.

much dominated by the starting phase, not the explosive end. Moreover, it can also be noted from the discussion above that a black hole in a white dwarf with a mass 333,000 times greater than a black hole within the Earth will have a Bondi radius that is only about 1.8 times larger. On the other hand, the time for Eddington-limited growth is very much affected by the final mass. To increase a black hole's mass by a factor of 333,000 would require about 12.7 e-folds. After accounting for the potentially higher initial mass of the black hole in a white dwarf at the start of Eddington-limited growth, the figure would then be about 10.5 e-folds. The time for a single e-fold within a white dwarf is not given explicitly in the paper, but the times for the Earth are given (as a function of the efficiency parameter η) [GM p. 27], and they may be similar for white dwarfs. For values of $\eta = 0.001, 0.01, \text{or} 0.1$, this would lead to an additional time for 10.5 e-folds of about 2.4 million years, 24 million years, or 240 million years, respectively. (These additional times would apply for all white dwarf accretion scenarios in which the Eddington radius is greater than R_C. For cases in which the Eddington radius is less than R_C, the additional times would be a combination of the 4-dimensional e-folding times with the higher-dimensional and transitional e-folding times.)

Clarification on the Accretion Times for Primordial Black Holes - Given the GM paper's claim to have found a "general relationship" for accretion times within the Earth and accretion times in white dwarfs [GM p. 51, citing eq. 7.15], it may wish to further clarify its estimate of accretion times for primordial black holes. The paper estimates that a primordial black hole with a mass of 10^{15} gr would take about 47 million years to destroy the Earth [GM p. 25], while a black hole of the same starting mass would require about 1,800 million years to destroy a white dwarf [GM p. 45]

Non-Applicability to Crystallized White Dwarfs - The ratio of accretion times given in the GM paper [GM p. 51, citing eq. 7.15] is the ratio of Bondi accretion times for the Earth with Bondi accretion times for non-crystallized white dwarfs. The GM paper presents no model or analysis of black hole accretion in crystallized white dwarfs.

Non-Applicability to Multiple Black Hole Accretion - The ratio presented in the GM paper [GM p. 44, eq. 7.15] applies only to single black hole accretion. No effort is made in the GM paper to determine what effect multiple black holes would have on the accretion times in the Earth and in white dwarfs (and thus what the ratio of accretion times of, say, 10 identical black holes in the Earth would be compared to 10 identical black holes in a white dwarf). The effects of multiple black hole accretion in the Earth may be different from their effects in white dwarfs for a number of reasons, including, for example, the difference in the initial temperatures of the media, so one cannot simply assume that the accretion ratio will remain unchanged. Moreover, the paper does not even attempt to estimate the number of black holes accreting within the Earth which would be sufficient to match the rate of a single black hole, or the expected ensemble of black holes, accreting within a white dwarf.[125]

[125] Matching the accretion rate may be an unnecessarily strict criteria. A more appropriate question would be what number of black holes within the Earth would be sufficient for the ratio of their collective accretion rate

Non-Invariance Under "Error Transformations" - The claim of a "general relationship" [GM p. 51] is sufficiently vague that readers may have the impression that even if there are problems with the accretion models of the GM paper, the errors would apply equally to the Earth and white dwarfs, so the ratio of accretion rates and the general astrophysical argument based on the existence of white dwarfs would be preserved. There are, however, very significant differences between the accretion environments within the Earth and white dwarfs, so it is entirely possible for the accretion rate of one to be affected while the other remains relatively unchanged. Some of the key differences between the two environments and accretion models include:

- Differences in the fundamental nature of the matter (regular atomic matter in the Earth compared to a degenerate electron plasma in white dwarfs)
- Differences in composition (the core of the Earth likely being composed mainly of iron, unlike the carbon, oxygen, or neon cores of massive and ultramassive white dwarfs)[126]
- Differences in densities (white dwarfs being about a million times more dense than the Earth)
- Differences in pre-accretion temperatures (temperatures in the Earth's inner core being about 5700 ±500 K [SSC02 arXiv p. 16], compared to temperatures in the range of 10,000,000 to 100,000,000 K in young white dwarfs [GM p. 59]
- Differences in the scales for the start of Bondi accretion (starting, according to the GM paper, at 1 Å within the Earth [GM p. 23] and at 0.01 Å within white dwarfs [GM p. 42])

Beyond the question of whether there is a relationship in the accretion times between the Earth and white dwarfs, the key issue is what the safety implications would be of any possible relationship. This issue is examined further in section 10.1.4.

compared to the expected white dwarf accretion rate to be low enough to preclude any astrophysical safety argument.

[126] It may be noted, however, that an iron core has been proposed to explain the smaller than expected radii of some white dwarfs [▷ ADDCITE]. On the other hand, an alternative ultra-heavy composition has been proposed for the very centre of the Earth [▷ ADDCITE]

8.1.5 Neutral Stable Black Hole Accretion within Neutron Stars

This section reviews the model presented in the GM paper for black hole accretion within neutron stars. As in the previous sections, the initial focus is on the case of single black hole accretion, followed by comments about multiple black holes. The astrophysical argument is reviewed later in sections 10.1.7, 10.1.8, 10.1.9, and 10.1.10.

§ Summary of CERN's Estimates of Single Black Hole Accretion Times

TEXT PENDING

5 Dimensions

6 Dimensions

- **Identical Unwarped Extra Dimensions**
- **Non-Identical Unwarped Extra Dimensions**
- **Identically Warped Extra Dimensions**
- **Non-Identically Warped Extra Dimensions**

7 Dimensions

- **Identical Unwarped Extra Dimensions**
- **Non-Identical Unwarped Extra Dimensions**
- **Identically Warped Extra Dimensions**
- **Non-Identically Warped Extra Dimensions**

8 to 11 Dimensions

- **Identical Unwarped Extra Dimensions**
- **Non-Identical Unwarped Extra Dimensions**
- **Identically Warped Extra Dimensions**
- **Non-Identically Warped Extra Dimensions**

12 or More Dimensions

- **Identical Unwarped Extra Dimensions**
- **Non-Identical Unwarped Extra Dimensions**

- **Identically Warped Extra Dimensions**
- **Non-Identically Warped Extra Dimensions**

Eddington-Limited Growth

§ Critical Review of Single Black Hole Accretion in Neutron Stars

The GM paper's theory of single black hole accretion within neutron stars is reviewed below. General criticisms are mentioned first, followed by an examination of the different phases of black hole growth. Many of the points have already been described in the earlier discussions on accretion in the Earth and in white dwarfs, so they are mentioned only very briefly here.

▼ General Concerns

Purely Theoretical Treatment - The GM paper's general analysis of black hole accretion in neutron stars is a purely theoretical treatment and has no empirical basis.

Conservative Claims - The time estimates for neutron star accretion are presented as an upper bound, but a number of factors have been ignored which could have a significant effect on the accretion rate. Several of those factors are mentioned in the points below.

Sensitivity to Slowdown at any Stage - A significant delay for any reason during any of the stages of a black hole's growth within a neutron star could increase the total accretion time and invalidate a safety argument based on the existence of neutron stars. The GM paper needs to show that it would be impossible for any such slowdown to occur.

Absence of Reradiation - As in its treatment for the Earth and white dwarfs, the GM paper ignores the effects of reradiation in its model of accretion within neutron stars. Until those effects are incorporated, the paper's accretion time estimates do not have any theoretical validity.

Other Forms of Dissipation - Beyond its references to photons and light particles [GM p. 63], the GM paper ignores the effects that other forms of dissipation may have on the accretion process [cf. GM p. 61].

Contribution from Bulk Particles - The GM paper does not consider the effects that particles from the bulk could have on black hole accretion within neutron stars.

Movement of Black Holes Off the Brane - The GM paper includes no estimate for the accretion rate of black holes which have moved off the brane from within a neutron star.

General Forms of the Potential - The GM paper does not attempt to cover all possible forms of the gravitational potential, or set a bound on the probability of less likely forms of the potential [cf. GM p. 15].

Accretion Times for $M_D > 4.7$ TeV - The GM paper's estimates for the total accretion times within neutron stars are limited to values of $M_D \ngtr 4.7$ TeV.
▹ ADD NOTE on the specific accretion times for $M_D = 14$ TeV.

Restriction to D ≤ 11 - The conclusion of the GM paper reports an upper bound for accretion times within neutron stars in the case of $D \geq 8$ [GM p. 52]. The paper does not, however, present accretion time estimates for the cases of $D \geq 12$, including especially during the subnuclear phase of accretion [GM p. 49] (an issue discussed further below). As a result of this omission, the accretion time bounds for neutron stars are only relevant for scenarios with $D \leq 11$.

Restriction to $R_D \geq$ 1 Å - Determining whether there is an Eddington limit is an essential part of any overall accretion time estimate, but when analyzing this issue, the GM paper claims to only be seeking a bound for the cases with R_D greater than or approximately equal to 1 Å. The paper states:

> Thus in all cases where we seek a bound (namely, if $R_D \gtrsim 1$ Å), we are in a situation analogous to that of the second and third regimes for a white dwarf, but with an even higher opacity. [GM p. 62]

This statement is somewhat surprising since the paper highlights its black hole production estimates for neutron stars for the cases of $8 \leq D \leq 11$ [GM p. 46, table 3] and emphasizes the importance of neutron stars for its astrophysical argument when $D \geq 8$. It states:

> As shown in table 1, the column densities required to stop the heaviest black holes for $D \geq 8$ exceed the stopping power of even the most massive white dwarfs, and therefore we shall only state empirical constraints on such scenarios when discussing the neutron stars case. [GM p. 38, hyperlink added]

The paper notes elsewhere, however, that $R_D < a$ (≈ 1 Å) for $D \geq 8$ [GM p. 23] (for extra dimensions of identical radii). Thus, the first statement cited above implies that despite the impression given elsewhere in the text, the GM paper is not attempting to show an empirical bound for the cases of $D \geq 8$.

Unknown Nature of Neutron Stars - A more fundamental issues is that we simply do not know what a "neutron star" actually is. The previous CERN safety report openly acknowledged that we do not know if neutron stars are actually composed of neutrons, or if they are instead composed of strange quark matter or some other form of matter. In the context of reviewing the question of strangelets, the LSSG report summarized the issue as follows:

> Since absolute stability of strange quark matter inevitably leads to the conclusion that all pulsars (and in general all compact objects normally believed to be neutron stars) are strange stars rather than neutron stars, proving that some compact object is a neutron star rather than a quark star would rule out the hypothesis of absolutely stable strange quark matter.

> Strange stars with masses significantly below 1 solar mass are mainly confined by the strong interactions, with gravity playing a less important role. However, for the compact object masses typically created in supernova explosions ($M \approx 1.4 M_{\odot}$), gravity is dominant for strange stars as well as neutron stars and the global stellar properties are not very different. In spite of several tentative 'proofs' and 'disproofs' of the existence of strange stars in the literature, the present situation is inconclusive. Possible ways of distinguishing between them in the future involve detailed comparisons of pulsar or X-ray binary radii and masses; the glitch phenomenon (sudden speed-up in pulsar rotation, for a long time thought to be very difficult to reconcile with strange stars, but apparently explainable with CFL); stellar neutrino cooling; the behaviour of r-mode instabilities; or the evolution of the braking index, which describes the time evolution of pulsar spin-down, and which has been suggested to show a very specific signature if a quark–hadron separation front moves as a pulsar spins down. This can only happen if quark matter is metastable rather than absolutely stable, and might therefore disprove the stability hypothesis if observed (though other phase transitions might mimic the signature).
>
> While some of the signatures mentioned are promising in principle, the situation has been significantly complicated by the concept of CFL, which permits a much richer internal structure in strange stars than hitherto believed. At present there is no clearcut evidence for or against the existence of strange stars, and therefore for or against strange quark matter stability. [LSSG p. 5, hyperlinks added]

The basic nature of neutron stars is still very much an unresolved issue in cosmology. A more recent report, written by a co-author of the LSSG report and cited by the LSAG report, states:

> *If* it is possible to prove that some neutron stars are indeed neutron stars rather than strange stars, the sensitivity of the astrophysical detectors rules out quark nuggets as dark matter for $A < 10^{34-38}$. And it questions the whole idea of stable strange quark matter, since it is impossible to avoid polluting the interstellar medium with nuggets from strange star collisions or supernova explosions at fluxes many orders of magnitude above the limit measurable in this way.
>
> *If* on the other hand strange quark matter is stable, then all neutron stars are likely to be strange stars, again because some pollution can not be avoided. [Mad06 p. 4]

▷ ADD NOTE on quark hypernovae

The two basic questions about the nature of neutron stars are whether there is quark matter at the centre of "neutron stars", and whether such stars are composed exclusively of quark matter (and are not even covered by a crust of neutrons). The GM paper considers only the case of a pure neutron star, and thus any conclusion it reaches is restricted by the caveat that it applies only if not all neutron stars are quark stars, and then, more specifically, if the neutron star that it cites is not, in fact, a quark star.

Yet another possibility that has been suggested in the scientific literature is that neutron stars have a Bose–Einstein condensate core [cf. LBD99 arXiv p. 2] [▷ ADDCITE].

These possibilities do not in any way mean that such stars would be protected from black hole accretion—indeed, the rate of accretion could well be faster within a strange star. Nevertheless, a compelling argument has to be presented that black hole accretion will be sufficiently rapid in a regular strange star, in a color-flavor locked (CFL) quark star, or in any other possible collection of matter that could pass for a neutron star.

Contribution from Dark Energy - The possible contribution of dark energy to neutron star accretion is not considered in the GM paper.

Numerical Simulations - The GM paper does not use any numerical simulations as a cross-check or supplement to its analytical treatment.

▼ Penetration Phase

While the GM paper presents its discussion on the penetration of a black hole through the crust of a neutron star as a way to simplify the analysis of accretion, it does not say what would happen if a black hole is unable to reach the inner region of a neutron star [GM p. 47–48]. Due to this gap, the neutron star argument applies only if a black hole does indeed reach the inner region. It certainly is a reasonable expectation that an accreting black hole would eventually find its way through a neutron star's crust, but after reviewing the argument presented in the GM paper, a number of questions still remain. They include the following:

Effects of the Density Gradient - In the span of a single kilometre, the density of a neutron star's (hypothetical) crust increases by 5 orders of magnitude [GM p. 48]. The analysis of the GM paper assumes that there is no net upwards or downwards momentum of the matter that the black hole accretes [GM p. 48], however, given that the black hole is more likely to have a collision with a particle from below it than above it, one should check if this results in a net upwards force on the black hole. If this results in the black hole spending more of its time in the less dense regions of the crust, it would increase the time associated with this phase.

Thermal Velocity of the Medium - In calculating the distance travelled by a black hole after each encounter with a particle, the GM paper appears to ignore the thermal velocity of the medium, and assumes that the black hole will be free-falling into more-or-less stationary particles [GM p. 48]. The paper does not give an estimate of the thermal velocity in different segments of the crust, although for the core of the neutron star it does report that asymptotic interior temperatures are expected to be in the range of 10,000 to 100,000 eV [GM pp. 62–63], or about $100,000,000$ to $1,000,000,000$ K. The motion of particles in the crust could significantly shorten the distance between each encounter and reduce the average downwards velocity of the black hole. (Since the black hole is assumed to be accelerating downwards, more frequent collisions would reduce the average velocity.)

Penetration in a Quark Star - As noted above, it is not known whether "neutron stars" are actually composed of neutrons or quark matter. If they are composed of quark matter, it is also not known whether they do or do not have a crust. An important question that is not addressed in the GM paper is what the capacity of a black hole would be to penetrate quark matter. The extreme density of such matter raises the possibility that a black hole would begin accreting rapidly while still relatively close to the surface of a quark star. The astrophysical implications of such a scenario would need to be examined separately.

▼ Subnuclear Accretion

(Chromo-)Electrostatic Effects - The GM paper notes in its analysis of accretion in the Earth that, "(chromo-)electrostatic effects apparently slow accretion early in this phase." [GM p. 18, hyperlinks added] The paper does not consider these effects in its estimates of the time required for subnuclear accretion in neutron stars.

Effect of Accretion on Nucleons - The paper's analysis of a black hole's travel through the crust describes how a black hole can capture a parton of a nucleon and then could remain bound to the nucleon until it absorbs the remaining partons [GM p. 48]. One may ask, however, what effect the capture of a parton would have on the integrity of the nucleon itself. If the capture of a parton could cause the break up of a nucleon, then a very significant amount of energy would be released into the surrounding environment. For the nuclei-like densities in the inner region of a neutron star, one should check if the force exerted by the release of this energy would reduce the effective density in the black hole's path and thereby its mass accretion rate.

Possible Effects of a Second Strong Force - One of the main justifications that CERN presents for its "Super-LHC" programme to increase the intensity of the LHC is to determine whether there is a second strong force [SPC08b p. 2]. The GM paper [GM ↗] and the LSAG report [LSAG ↗] make no mention of the possibility of a second strong force, and no allowance is made for it in the GM paper's model of subnuclear growth in neutron stars.

Absence of Accretion Time Estimates for 5 Dimensions - The GM paper reports that the growth times for $6 \leq D \leq 11$ dimensions range from a fraction of a second to at most a few weeks [GM p. 49]. The paper says nothing, however, about the case of 5 dimensions. From the examples of 5-dimensional growth in the Earth and white dwarfs one might expect that the accretion time would be very rapid, however this should be addressed directly by CERN. (The equation that the paper uses to estimate the accretion time [GM p. 49, eq. 8.11] has a coefficient that is divided by $(D-5)$, so it cannot be applied to this case.)

Absence of Accretion Time Estimates for 12 or More Dimensions - The GM paper leaves readers with the impression that the subnuclear phase is very short, but, as noted above, it only reports the times for $6 \leq D \leq 11$ dimensions. The equation it uses [GM p. 49, eq. 8.11] can be applied to higher dimensions, and one may note that growth times are proportionate to $r_N M_0$ raised to the $(D-5)^{\text{th}}$ power. Thus, with each additional dimension the time required to reach different sub-nuclear sizes (less than R_D) increases by a factor of approximately 500 (i.e. ~ 5000 divided by a factor ~ 10 due to changes in k_D [GM p. 12, eq. 3.17]). It should also be noted that the times are also proportionate to the $(D-2)^{\text{th}}$ power of (M_D/M_0), implying significantly higher times in the case of $M_D = 14$ TeV.

▼ Transition to Macroscopic Accretion

Criterion for Transition - As described earlier in the section on white dwarfs, a conservative approach for developing an upper bound on the accretion times would be to assume the slowest of the two accretion models during the transition phase. The GM paper does not adopt this approach, and simply switches to Bondi accretion once the capture radius reaches the size of a nucleon.

Transition at 0.00001 Å - The GM paper assumes that Bondi accretion starts at a radius of about 0.00001 Å (1 fm), which is 100,000 smaller than the case of the Earth, and even 1,000 times smaller than it assumes for white dwarfs. If Bondi accretion cannot be applied until the black hole is larger, the accretion times could be significantly longer. (See below for further notes on the applicability of Bondi accretion on this scale.)

▼ Macroscopic Accretion

Extremely Oversimplified Treatment - As in the cases of the Earth and white dwarfs, the GM paper's treatment of accretion within neutron stars is the most simplistic possible. Given the importance that the paper attaches to neutron stars, one would instead have expected the most complete and rigorous treatment possible.

Importance of Details of the Accretion Process - The GM paper's assertion that we can do not need to know the short-distance properties of black holes [GM p. 5] is contradicted in this case by its dependence on these factors for its analysis of an Eddington limit in neutron stars [GM pp. 62–63]. Moreover, it is doubtful that anyone can seriously claim that "classical or quantum dynamics are well-tested" [GM p. 5] within the core of a neutron star.

Argument for the Applicability of Bondi Accretion - The argument given in the GM paper to justify applying the theory of Bondi accretion to the macroscopic phase within a neutron star is wholly insufficient. The paper states:

> When the black hole enters the regime $R \gtrsim r_N$, the absorption becomes macroscopic – the black hole is capable of absorbing multiple nuclei, and its gravitational range exceeds mean free paths. As Appendix B describes, an Eddington limit would be even more problematic for a neutron star, given its high density and opacity, and so evolution is described as Bondi until the black hole reaches a scale where it disrupts the star. [GM p. 49]

The issue of Eddington-limited growth within a neutron star is discussed further below, however, one cannot simply assume that if an Eddington limit does not occur, then the accretion process must automatically be described as Bondi. A number of other criteria, detailed in the points below, must be met for Bondi accretion to occur.

Implications of a "Canonical Framework" - As noted earlier, Bondi accretion can be understood as a canonical framework for black hole accretion [GM p. 6] only in the sense of providing an easy to calculate reference value against which other more realistic estimates can be compared.

Standard Range for Bondi Accretion - In line with previous comments for the Earth and white dwarfs, it should be noted that:

- ▹ ADD NOTE on distance scales for astronomical Bondi accretion
- ▹ ADD NOTE on densities for astronomical Bondi accretion
- ▹ ADD NOTE on pressures for astronomical Bondi accretion
- ▹ ADD NOTE on elemental abundances for astronomical Bondi accretion
- ▹ ADD NOTE on form of matter for astronomical Bondi accretion

Adoption of the Earth Equations - As with the situation described earlier for the case of white dwarfs, the adoption of equations developed for the fastest possible accretion times within the Earth [GM pp. 49–50, citing eqs. 4.43, 4.48] are not an appropriate basis for determining the slowest possible accretion times within a neutron star. The equations are based on a number of assumptions which may (or may not) be justified for a lower bound, but which would clearly not be acceptable for an upper bound. Several of these assumptions are reviewed further below.

Femto-Scale Hydrodynamics - The model of Bondi accretion for the Earth was criticized earlier for depending on nano-scale hydrodynamics. The model for white dwarfs was also criticized above for depending on pico-scale hydrodynamics. In this case, the scale is yet another 3 orders of magnitude smaller, with femto-scale hydrodynamics. It would take a great deal of faith to depend on regular hydrodynamic equations applying unchanged on this scale.

Extra-Dimensional Hydrodynamics - The accretion model also depends on the untested hydrodynamics of nuclear matter within a brane embedded in higher-dimensional space.

Validity of Macroscopic Treatment - As with its model of white dwarf accretion, the GM paper adopts a statistical, macroscopic treatment from a Bondi radius equal to just a single unit (in this case a nucleon's radius). A more reasonable approach would be to use a statistical approach only after the scale has grown to the size 1,000 or 1,000,000 times larger.

Assumption of Steady Accretion - The paper fails to consider the possibility of accretion within a neutron star being unsteady and irregular. The average rate of unsteady accretion could be significantly different from that expected for steady accretion.

Effects of the Black Hole's Motion - The model adopted in the paper assumes a perfectly stationary black hole and does not consider the effect that a black hole's movement may have on the rate of accretion.

Assumption of a Non-Rotating Black Hole - The GM paper presents an accretion model for a non-spinning black hole but fails to show that the black hole's angular velocity is exactly zero with respect to the medium, or that its angular velocity is sufficiently low for the effects of that velocity on the accretion time to be within a certain bound.

Assumption of Perfectly Spherical Accretion - The GM paper assumes, unrealistically, that black hole accretion within a neutron star will be perfectly spherical. It presents no model for non-spherical accretion.

(Chromo-)Electrostatic Effects - As with its model of subnuclear accretion, the GM paper's treatment of early Bondi accretion in neutron stars ignores possible (chromo-)electrostatic effects, which the paper itself suggests can slow accretion [GM p. 18].

▷ ADD NOTE on the value of Γ within neutron stars and the compressibility of nuclear matter

Neglect of Seismic Effects - The GM paper does not consider the effects that seismic activity in neutron stars could have on the rate of black hole accretion.

Possible Effects of a Second Strong Force - As noted above, the possibility of a second strong force is an area of active scientific investigation [SPC08b p. 2]. No allowance for the existence of such a force has been included in the paper's treatment of the early stages of Bondi accretion in a neutron star.

As noted in the case of the Earth and white dwarfs, there are also a number of other considerations which are very basic expectations of any modern treatment of black hole accretion. They include the following

Magnetic Fields - Neglecting the effects of magnetic fields is a major oversight in the GM paper's model of accretion within the Earth and white dwarfs; neglecting the effects of magnetic fields for accretion within a neutron star can only be described as absurd. The magnetic fields within neutron stars are among the most powerful in the universe, and if there is any place where magnetic fields would have an effect on accretion, it would be within neutron stars. Yet the GM paper simply assumes that they would have no effect.

Turbulence - The effects of turbulence are ignored in the accretion model.

Viscosity - The effects of viscosity are similarly ignored.

Homogeneous Medium - The paper assumes a medium with no variations in pre-accretion density, temperature, etc.

Geometry of Accretion - The GM paper does not consider the possible formation of funnels, shocks, or outflows in its accretion model.

Relativistic Corrections - The GM paper states the following with respect to relativistic corrections for black hole accretion within a neutron star:

> Accretion from within a neutron star approaches the relativistic regime; relativistic corrections, which are typically small, are described for example in [59]. [GM p. 54]

The paper makes no attempt, however, to quantify these effects or set a bound on the impact they could have on the total accretion times.

Other Factors and Unknowns - The paper does not consider any other possible factors or any "unknown unknowns" that might affect the Bondi accretion phase within neutron stars.

Transition Phase for Warped Extra Dimensions - For scenarios with warped extra dimensions, the GM paper assumes that black holes in neutron stars grow according to the equation used in its baseline estimate for white dwarfs [GM p. 43, eq. 7.13]. As described previously, this equation is based on the completely unrealistic assumption that from the very start of the transition period the black hole is accreting matter with a capture radius of R_C (i.e. the capture radius corresponding to the final stage of the transition). In the case of white dwarfs the paper at least acknowledges it previous assumption of a capture radius of R_D (the capture radius corresponding to the initial stage of the transition), with an estimated accretion time that is 400 times longer [GM pp. 43–44]. In its discussion for neutron stars, however, the paper makes no mention of this more conservative treatment. The paper only gives a estimate, using its unrealistic capture radius assumption, for warped scenarios with $R_C \geq 5$ Å [GM p. 50]. It may be noted that if $R_C \leq 5$ fm (0.00005 Å), then with a conservative value for the capture radius, the transition phase would take ~ 800 million years.[127]

▼ Post-Bondi Macroscopic Accretion

The GM paper addresses the post-Bondi phase of accretion in a neutron star with the following statement:

[127] This calculation is based on the estimate of approximately 20 years provided in the text [GM p. 50 ↗], the factor of 400 based on the assumed capture cross-section [GM p. 44 ↗], and a factor of 100,000 to scale down from 5 Å to 5 fm [GM p. 43, eq. 7.13 ↗] The factor of 400 for the capture cross-section is likely an underestimate for the case of $R_C \leq 5$ fm since it was calculated for the case of $R_C \gtrsim 15$ Å. The maximum value for R_C/R_D increases as R_D decreases, and in the limit of $R_D = M_D^{-1}$ the value of this factor would be 10,000 [GM p. 26 ↗].

> As Appendix B describes, an Eddington limit would be even more problematic for a neutron star, given its high density and opacity, and so evolution is described as Bondi until the black hole reaches a scale where it disrupts the star. [GM p. 49]

The problems with this treatment include the following:

Absence of Estimates - The paper provides no estimate of the time involved in the post-Bondi evolution of a black hole within a neutron stars. Without that information, there is no specific estimate of the time required for a black hole to destroy a neutron star, since the given estimates apply only up to the point at which there is some form of disruption of the star.

Post-Bondi Pre-Disruption Phase - The paper claims that the accretion will be Bondi until the black hole is large enough to disrupt the star, but fails to show why the post-Bondi phase cannot begin before such a point.

Definition of Disruption - The paper provides no definition of what it means to "disrupt" a neutron star. In the case of white dwarfs, the paper gives the example of disruption of cooling, and compares the Eddington output of accreting black holes with the expected cooling rates of white dwarfs [GM pp. 64–65]. No such examples or indicators of disruption are given for the case of neutron stars.

▼ Summary of Accretion

A final note on the GM paper's presentation is a criticism of the way that the paper leaves readers with the impression that black hole accretion in neutron stars must be a rapid process. The section on neutron stars begins with the following explanation:

> Neutron stars are very common in the Universe, and in fact provide robust examples of long-lived objects in other galaxies. They also represent the highest known densities of matter that have not undergone gravitational collapse to a black hole. Since they are particularly close to densities beyond which black holes are expected to form, one might expect that introduction of a microscopic stable black hole into a neutron star would rapidly catalyze its decay into a macroscopic black hole. [GM p. 45]

The subsection on accretion similarly begins:

> Due to the immense pressures inside a neutron star, one expects introduction of even a microscopic black hole to rapidly catalyze its decay. [GM p. 47]

From these initial statements readers would likely get the impression that, given their densities and pressures, neutrons stars are poised on the verge of collapsing into a black hole. Only later, in the middle of one of its last paragraphs, does the paper clarify that "rapid" really means "rapid compared to a billion years". It states:

> Once it reaches the core, the accretion times are very rapid compared to the neutron star's lifetime, $O(\text{Gyr})$. [GM p. 50]

Even this statement is not fully justified, as the paper does not qualify it with restrictions on the crossover radius to 4-dimensional growth. As noted above, if the crossover occurs at 5 fm, and some conservative assumptions are made, then the accretion time would be ~ 800 million years; for a crossover radius of 4 fm, the time would be ~ 1 billion years.

Even if one accepts the GM paper's basic accretion model, the accretion times for neutron stars still depend on the details of the extra-dimensional scenario. In some cases they could be extremely fast, but in others they could be extremely slow.

§ Eddington Limit in Neutron Stars

TEXT UNDER REVISION

§ Multiple Black Hole Accretion in Neutron Stars

The possible effects of multiple black holes were discussed in some detail for the cases of the Earth and white dwarfs. The effects of multiple black holes in neutron stars may share a number of similarities with these cases, but a few key differences should be mentioned.

As noted earlier in the white dwarf section, the differences in the accretion environment between the Earth and white dwarfs might be sufficient for there to be significant differences in determining the time when black holes come close enough to affect each other or to merge together. This issue is even more important for the case of neutron stars due to their extreme density. The GM paper's analysis of the penetration of black holes into the core of neutron stars showed that their velocity could become extremely slow [GM p. 48].[128] When, or how, a black hole could reach the very centre of a neutron star was not addressed. This might make it difficult for black holes that were initially trapped in different parts of a neutron star to ultimately reach each other. On the other hand, if those black holes do meet, their low velocity might increase the effects they have on each other, and possibly increase the chances of a merger.

Multiple black holes within neutron stars might also be expected to increase the internal heat energy of their host. The GM paper does not, however, present an astrophysical argument based on the heating of neutron stars, so this effect is not a critical issue at this stage.

A final point is that, except for the speculative case of high-energy neutrinos, the number of black holes that the GM paper predicts would be trapped in a neutron star is extremely low [GM pp. 46, 85, 87]. The likelihood of multiple black holes existing in a neutron star is correspondingly much lower. Even if more than one black hole is trapped in a neutron star, the expected gap in the ages of those black holes would imply that the multiple black hole effects discussed in the case of the Earth and white dwarfs would probably not be of much significance.

[128] The GM paper does say that the black hole should rapidly penetrate the crust, but it does not attempt to quantify this description. It may be noted that, as per the analysis of the GM paper, the black hole's drift velocity is proportionate to its capture radius [GM p. 48, eq. 8.7 ↗] and thus would become extremely slow as the black hole becomes larger and larger in size. Whether this can be considered slow over a million year time frame would depend on the growth rate of the black hole and the effects of reradiation.

8.2 Accretion of Neutral Slowly Radiating Black Holes

TEXT UNDER REVISION

8.3 Accretion of Neutral Equilibrium Mass Radiating Black Holes

TEXT UNDER REVISION

8.4 Accretion of Neutral Rapidly Radiating Black Holes

TEXT UNDER REVISION

8.5 Accretion of Neutral Rapidly Radiating Remnantless Black Holes

TEXT PENDING

8.6 Accretion of Charged Stable Black Holes

The possibility that hypothetically stable black holes would retain their charge is given considerable importance in the GM paper [GM pp. 4, 9–10, 52], the LSAG report [LSAG pp. 8, 9], and the public summary of the LSAG report [LSAGSum p. 2], with the implication being that if they do retain their charge, some must have already been trapped in the Earth or the Sun, and thus we can assume that they are safe. An essential component of this argument is the expected accretion model for such black holes. Unfortunately, this is missing from the GM paper.

The situation for different astrophysical objects are reviewed briefly below, along with some initial notes on the differences between the accretion of charged stable black holes and neutral ones.

8.6.1 Charged Stable Black Hole Accretion within the Earth

For the case of a charged stable black hole, the GM paper does note that:

> In the absence of other effects, this black hole would also have the charge of the nucleus. This charge may discharge through the Schwinger mechanism, or be retained, depending on assumptions. If it is retained, the next time that the black hole encounters a nucleus within R_{EM} , this charge is insufficient to prevent absorption, but with sufficient charge buildup repulsion could become an important effect. A positively-charged black hole will also have an enhanced absorption rate for electrons, which works toward neutralization. So, while charge effects could possibly somewhat slow the absorption rate, we will make the conservative assumption that they don't, and that sufficient neutralization is automatic. [GM p. 18, hyperlink added]

Beyond this brief analysis and a short footnote [GM p. 18, footnote 10], the GM paper offers no quantitative model for the accretion of charged stable black holes captured within the Earth. Such a model is essential for assessing the safety of producing such black holes at the LHC since it is needed for estimating the possible effects of such black holes over different time periods, and also for determining the relative importance of the GM paper's theory that charged black holes with masses less than ~ 7 TeV would already have been captured within the Earth. For scenarios in which the rapid destruction of the Earth by charged stable black holes is predicted, the only line of defence against such a catastrophe is the unpublished "more careful estimate" mentioned in the GM paper [GM p. 10] which finds that low mass charged black holes would have been trapped in the Earth (and thus, probably, do not exist).

It should also be noted that while the GM paper describes how the retention of charge could slow down accretion, it makes no effort to show either quantitatively or on general theoretical grounds that the retention of charge and the intermittent effects of electrostatic attraction could not accelerate the accretion process.

8.6.2 Charged Stable Black Hole Accretion within the Moon

The GM paper presents no model for the accretion of charged stable black holes within the Moon.

In general, one might expect such accretion to be similar to the case of the Earth, with suitable corrections for the modest differences in density and composition.

8.6.3 Charged Stable Black Hole Accretion within the Sun

As cosmic ray-produced black holes with initial masses above ~ 7 TeV are not expected to be trapped in the Earth, the GM paper argues instead that such black holes would be trapped in the core of the Sun [GM p. 10]. This is presented in the GM paper as sufficient grounds to declare that they are safe [GM p. 10]. What is missing, however, is any kind of model describing what would happen to charged stable black holes trapped in the Sun.

The accretion environment within the core of the Sun, being composed primarily of a a hydrogen and helium plasma, is qualitatively different from that of both the Earth and white dwarfs, and it would be difficult to define a relationship between the accretion of charged stable black holes within the Sun when compared to those other environments. Nevertheless, it would still have been useful for CERN to publish whatever analysis it may have completed of charged stable accretion within either the Earth or White Dwarfs to serve as a possible comparison. This issue is discussed further below.

8.6.4 Charged Stable Black Hole Accretion within White Dwarfs

The GM paper presents no analysis of the accretion process of charged stable black holes within white dwarfs. It still remains unclear whether CERN, or LSAG, or the GM paper's authors have developed a model for such accretion. The only information publicly available on this issue is the brief comment made by LSAG member Professor John Ellis during his presentation in August 2008 on the safety of LHC collisions. In summarizing the GM paper's astrophysical argument based on the existence of neutron stars and white dwarfs, Professor Ellis notes that the survival of neutron stars and white dwarfs could imply any of a number of changes in the logical chain related to neutral stable black hole accretion, including the possibility that stable black holes retain their charge [Ellis08 at 26:37 ↗].[129] This statement implies that Professor Ellis, and presumably LSAG,

[129] The full statement from Professor Ellis' talk is the following: "[25:49] In that case, uh, you can make appeal to, uh, other astronomical objects, in particular, neutron stars and white dwarfs. Uh, these are particularly good at stopping, uh, black holes that are produced by cosmic rays, and the accretion rate there could also be calculated, that could... The accretion rate is actually enhanced because these things are extremely dense, and, uh, the bottom line is that, those, hypothetical, neutral, low-dimensional, stable black holes would have destroyed those neutron stars and white dwarfs, but, such neutron stars and white dwarfs exist, so clearly that has not happened, and so, well you can take your bet as to whether that's because microscopic black holes don't exist, [26:37] or because they're charged, or because they're unstable, or because there are more dimensions, but, the dangerous ones do not exist."

believe that the accretion of charged stable black holes within a white dwarf would require enough time to invalidate any prediction that the white dwarfs which they have identified (and possibly other, lower mass white dwarfs) should have already been destroyed by cosmic ray-produced black holes.

Whether this is indeed the position of LSAG, or whether it was simply a random remark during an oral presentation, can be clarified by CERN publishing whatever calculations or models it may have for the accretion of charged stable black holes in white dwarfs and other astronomical objects.

8.6.5 Charged Stable Black Hole Accretion within Neutron Stars

The GM paper presents no analysis of the accretion process of charged stable black holes within neutron stars. As noted above in the section on white dwarfs, LSAG member Professor John Ellis had stated during his August 2008 presentation on the safety of LHC collisions that possible charge retention of black holes could imply the survival of neutron stars [Ellis08 at 26:37 ↗]. No further details on this issue have been published yet by CERN.

8.7 Accretion of Charged Slowly Radiating Black Holes

TEXT PENDING

8.8 Accretion of Charged Equilibrium Mass Radiating Black Holes

TEXT PENDING

8.9 Accretion of Charged Rapidly Radiating Black Holes

TEXT PENDING

8.10 Accretion of Charged Rapidly Radiating Remnantless Black Holes

TEXT PENDING

9 Safety Implications

9.1 Safety Implications of Neutral Stable Black Holes

TEXT UNDER REVISION

9.2 Safety Implications of Neutral Slowly Radiating Black Holes

TEXT UNDER REVISION

9.3 Safety Implications of Neutral Equilibrium Mass Radiating Black Holes

TEXT UNDER REVISION

9.4 Safety Implications of Neutral Rapidly Radiating Black Holes

TEXT UNDER REVISION

9.5 Safety Implications of Neutral Rapidly Radiating Remnantless Black Holes

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9.6 Safety Implications of Charged Stable Black Holes

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9.7 Safety Implications of Charged Slowly Radiating Black Holes

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9.8 Safety Implications of Charged Equilibrium Mass Radiating Black Holes

TEXT UNDER REVISION

9.9 Safety Implications of Charged Rapidly Radiating Black Holes

TEXT UNDER REVISION

9.10 Safety Implications of Charged Rapidly Radiating Remnantless Black Holes

TEXT UNDER REVISION

10 Astrophysical Implications

The previous section reviewed the risks associated with LHC collisions based solely on theoretical predictions for the production, trapping and accretion of TeV-scale black holes. This section turns to the various astrophysical arguments put forth in the GM paper or elsewhere and assesses what implications they may have for TeV-scale black holes. In cases where plausible implications or bounds can be identified, the baseline LHC risks outlined in section 9 are revised to take into account any possible restrictions.

Each of the ten black hole scenarios reviewed in section 7 are also reviewed here, and for each of these scenarios, possible arguments involving the Earth, the Moon, the Sun, white dwarfs and neutron stars are assessed. As in section 7, a more detailed treatment is given for the scenario of neutral stable black holes, as this is the primary focus of the GM paper. The scenario of charged stable black holes is also given due consideration. The remaining eight scenarios of neutral or charged radiating black holes are dealt with only briefly, and in most cases involve simply short notes on how those cases may or may not differ from the corresponding case for stable black holes.

Before proceeding to the review of the different scenarios, a general introduction is given below on the possible goals of an astrophysical argument, followed by a couple short notes on the need for a production-based astrophysical safety argument and on the importance of considering low-probability values for various parameters when assessing a catastrophic risk.

§ Possible Goals of an Astrophysical Argument

Astrophysical arguments can be a useful way of placing limits on the effects of theoretical objects, such as TeV-scale black holes, strangelets, magnetic monopoles, etc. Ideally, such arguments should be based on nearby, familiar astronomical objects such as the Earth and the Sun, and should involve few, if any, differences between the natural conditions of the astrophysical events and the conditions planned for the corresponding man-made experiment. In cases where an argument based on nearby objects cannot be constructed, one may instead turn to more distant objects, although this can often introduce a number of uncertainties. This is especially a problem when the distant objects or events are poorly understood and are of a fundamentally different character from the forms of matter that we are familiar with.[130]

There are a number of different types of bounds that could be established by an astrophysical argument. Listed from strongest to weakest, they include the following:

- Non-existence of an object (e.g. TeV-scale black holes cannot exist)

[130] As shown in the GM paper [GM pp. 47, 78–79, 80, 87 ↗], an astrophysical argument can also be constructed involving objects that are themselves purely theoretical, although such arguments can hardly be taken seriously as a guarantee of safety for the planet.

- Restrictions on the properties of an object (e.g. if TeV-scale black holes exist, they must radiate; if TeV-scale black holes exist, they must retain their charge)[131]
- Strict bounds on an object's production rate (e.g. the black hole production rate per hadronic collision at LHC energies must be less than, say, one in 10^{24})—see further description below[132]
- Bounds on the harmful effects of a certain number of the object (e.g. a million TeV-scale black holes cannot increase the internal heat of the Earth by more than, say, 0.001%)
- Bounds on the harmful effects of a single object (e.g. a single TeV-scale black hole cannot increase the internal heat of the planet by more than, say, 0.001%)
- Bounds on the annihilation risk from a certain number of the object within a certain time frame (e.g. a million TeV-scale black holes cannot destroy the Earth in less than ten billion years)[133]
- Bounds on the annihilation risk from a single object within a certain time frame (e.g. a single TeV-scale black holes cannot destroy the Earth in less than ten billion years)
- Bounds on the harmful effects on a nearby body of a certain number of the object (e.g. a million TeV-scale black holes cannot increase the heat generation of the Sun by more than a GigaWatt)[134]
- Bounds on the annihilation risk for a nearby body from a certain number of the object within a certain time frame (e.g. a million TeV-scale black holes cannot destroy the Sun in less than ten billion years)
- Bounds on the harmful effects on a distant and very different host body of a certain number of the object (e.g. the heat generation caused by a hundred TeV-scale black holes accreting within a white dwarf would be less than 0.001 $L_{\odot}$)
- Bounds on the annihilation risk for a distant and very different host body from a certain number of the object within a certain time frame (e.g. a hundred TeV-scale black holes cannot destroy a given white dwarf in less than a billion years)[135]

[131] The relative strength of this bound may depend, however, on the possibility of harmful effects even if an object has a desired property (e.g. potential harmful effects from radiating black holes or from charged black holes).

[132] Whether this is a stronger or weaker bound than the points below can be a judgement call that depends on the specific numerical probability of production and the expected harm if an object is produced.

[133] It is assumed that the previous points on the harmful effects of a type of object would implicitly include a bound on the annihilation risk (being the very worst imaginable harmful effect). This and the following point refer to a bound only on the annihilation risk, without establishing a bound on other possible effects.

[134] For this and the following point it is assumed that there is a bound on the harmful effects on a nearby body, but this bound does not directly establish a bound on the annihilation risk or other harmful effects potentially caused by one or more black holes trapped within the Earth.

[135] Astrophysical bounds established for a distant object may in some cases be used as an input towards establishing a safety bound for the Earth, however, doing so would typically involve several theoretical steps which may not

While these may be the desired endpoints of an astrophysical argument, it is often quite difficult to actually reach them. If the argument is a simple one-step path from the observation to the desired conclusion, there can be a reasonable degree of certainty in the intended result. For the arguments presented in the GM paper, however, there are quite a number of steps involved, which can significantly reduce the confidence attached to the authors' conclusions. The specific details of these arguments are examined later in this section.

§ Safety Arguments Based on an Unknown Production Rate

The numerous uncertainties associated with the rate of black hole production in hadronic collisions were reviewed earlier in section 4. In this situation, one of the fundamental challenges for an astrophysical safety argument is to recognize these uncertainties, but nevertheless construct an argument around them. A standard approach to this problem is to declare the production rate an unknown variable and then use an astrophysical argument to place a bound on that rate. This bound would in turn be used to calculate an upper limit on the possible risks for the Earth.

This approach was adopted in an early paper from CERN's Theory Department on the risk of strangelet production from heavy ion collisions, published just before the commissioning of the Relativistic Heavy Ion Collider (RHIC) [DDH99 arXiv ↗]. In that paper, the authors openly acknowledged the uncertainties associated with both the production and survival of strangelets and started their argument by defining p as the probability of making a slow strangelet in a single Au-Au collision at RHIC energies [DDH99 arXiv p. 4]. The authors then constructed an astrophysical argument and arrived at a bound on the value of p [DDH99 arXiv p. 7]. This probability was then applied to the experimental programme planned for RHIC to arrive at a bound on the catastrophic risk associated with the collider.[136]

Adopting a similar approach for TeV-scale black holes at the LHC would involve first defining p_{BH} as the probability that a black hole could be produced in a hadronic collision of a given energy, and then using different astrophysical arguments to place bounds on the value of p_{BH} in various scenarios. For the case of charged stable black holes with masses below 7 TeV, this might involve placing a bound on the production of a black hole at the LHC based on the GM paper's theory of charged black hole trapping and the survival of the Earth over billions of years. For the case of neutral stable black holes, the white dwarf argument of the GM paper could be reorganized to determine the maximum rate of black hole production, assuming the GM paper's models for trapping and accretion within white dwarfs, which would be consistent with astronomical observations.

This approach was not adopted or even mentioned in the GM paper, and it is not hard to guess

be directly related to the original bound. Thus, for clarity it is usually preferable to separate the process of verifying the initial bound (applying to, say, specific white dwarfs), from the assessment of the steps required to establish a secondary bound (applying to the Earth or other nearby objects).

[136] This very brief summary of the DDH paper should not be taken as an endorsement of it. Rather, it is intended simply to show that an earlier paper from CERN had adopted a more responsible structure for its safety argument.

why. For the case of charged stable black holes, one may note that assuming an exclusively proton composition of the cosmic ray flux, the LSAG report calculates that the number of LHC-equivalent cosmic ray which have ever struck the Earth is about a hundred times greater than that planned for the LHC [LSAG p. 4, endnote 6]. This would imply that if the risk of black hole production at the LHC is 1 in a million, there would be no more than a 10% chance that any charged black holes would have ever been produced in the Earth,[137] and, thus, at most a 10% chance that the survival of the Earth has any implications for the safety of charged stable black holes. For the remaining 90% of the scenarios, the risk would simply be bounded by the 1 in a million chance that the LHC could introduce the first such black hole to the world. Unfortunately, the idea of only a 1 in 1.11 million bound on the catastrophic risk would not be acceptable to most people.[138]

The case of neutral stable black holes is even less reassuring. For several of the astrophysical arguments presented in the GM paper, the expected rate of black hole trapping is not very high (e.g. white dwarfs exposed to an iron-dominated flux [GM p. 40], white dwarfs exposed to black holes produced in cosmic ray collisions with the interstellar medium [GM p. 87]) and the arguments could easily be wiped out through reductions in the black hole production rate by factors of about 10,000 or less. For the case of neutron stars in binary systems, even if the ultrahigh-energy cosmic ray flux is composed entirely of protons, the exposure of these neutron stars to high energy collisions would be about 3–4 orders of magnitude less than that planned for the LHC.[139] Moreover, for all these cases, if there are any reductions due to cosmic ray factors

[137] The figure of 10% is given here as a convenient upper bound. Assuming an LHC probability of 1 in a million, the expected number of cosmic ray-produced black holes would be 0.1 for a 100% proton flux. Since this figure includes the contribution from multiple black hole production, the probability of at least one black hole having been produced in the past would be less than 10%.

[138] The example of a 1 in a million risk resulting in a 1.11 million bound was chosen for illustrative purposes only; the actually bound could be even worse than this. For example, if the risk of black hole production at the LHC was 1 in 100,000, then there would be about a 37% chance that none of the cosmic ray collisions striking the Earth would have ever produced a black hole. This would imply about a 1 in 272,000 chance that the LHC would produce the first black hole. This sample calculation also does not take into account effects of a survivor's bias (i.e. we are able to conduct the LHC experiment because we are on one of the planets that was fortunate enough not to have been exposed to a charged stable black hole)—interested readers are referred to a recent article by Professors Tegmark and Bostrom for an illustration of how the issue of a survivor's bias can be incorporated into a catastrophic risk assessment [TB05 ↗], [TB05arXiv ↗].

[139] The LSAG report estimates that with a pure proton cosmic ray flux, the Earth has been exposed to ~ 100,000 times more high energy collisions than will occur at the LHC [LSAG p. 4 ↗]. The surface area of a 10 km radius neutron star is ≈406,000 times less than the Earth's [NSSDC:Earth ↗], so the expected rate of cosmic rays directed towards it is also ≈406,000 times less. Even a very optimistic scenario of 10 million years of FCE would be 454 times less than the estimated 4540 million years [▷ ADDCITE Dalrymple 2001] of direct exposure of the Earth. Combining these factors (i.e. 100,000 divided by 406,000, divided by 454) results in a total number of high energy collisions which is ≈1800 times less than the LHC's. It should be noted, however, that cosmic rays which collide with energies greater than 14 TeV may be more effective at producing black holes [cf. GM pp. 73, 75, figures 5, 6 ↗], so a comparison could also be made of the expected number of black holes (although this would bring additional uncertain elements into the analysis). The GM paper gives a graph of the number of black holes which could be produced at the LHC, but it only covers a limited range of parameters [GM p. 71, figure 4 ↗]. For $D = 11$ and $y = 0.5$, if $M_D = 4$ TeV, then the graph predicts ~

listed in section 4.2.6, the required reduction in the generic black hole production rate (applicable to both cosmic rays and the LHC) would be even less, and the consequent LHC bounds even weaker. Overall, the resulting bounds on risks from the LHC would appear to be far greater than what may be generally acceptable.

§ Risk Contribution from Low-Probability Scenarios or Parameter Values

One of the most challenging aspects of bounding a catastrophic risk below levels such as 1 in 1,000 is that it requires a calculation of the risks associated with low-probability theoretical scenarios and low-probability parameter values. If, for example, there is a theoretical scenario which has a (subjective) probability of 0.1%, and in that scenario there is no bound on the catastrophic risk, then the total bound cannot be less than 1 in 1,000. Similarly, if the value of a parameter, such as the flux of ultrahigh-energy hadronic cosmic rays, can vary over a wide range, and there is a 0.1% chance that its value could be so low that a proposed astrophysical argument would be invalidated, then a bound on the risk based on that argument cannot be stronger than 1 in 1,000.

A common mistake in the presentation of catastrophic risks from high-energy physics experiments is to adopt the most favoured theoretical scenarios, adopt the most likely values for all the variables involved in the argument (or perhaps the lower 1σ bound for some of the variables), calculate what the bound on the risk would be in that case, and then present it as the overall bound on the catastrophic risks (cf. [▷ ADDCITE Hut Rees 1983 ↗] [▷ ADDCITE Hut 1984 ↗] [▷ ADDCITE Desai Shaw 1991 ↗] [JBSW00 arXiv ↗] [LSSG ↗]). Often such numbers can be impressively low, but they would hardly reflect the true risk associated with the experiment.

A proper calculation of the total risk would involve examining the risk contribution from across the full range of theoretical possibilities and parameter values. If there are a total of n different variables (either parameter variables or theoretical issues for which there are different possibilities), then the calculation can be visualized as an n-dimensional unit cube broken up into different blocks, with the total risk being the sum of the contribution from each of those blocks (weighted by their respective volumes). The approach criticized in the previous paragraph can be seen as picking a block from the central region of the cube, estimating its corresponding bound, and then assuming that that bound applies for the entire cube. A more systematic approach would be to break each of the variables into bins of width, say, 0.001, and then calculate the risk for each

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470,000 black holes produced by the LHC, and if M_D = 6 TeV, then ~ 1 black hole would be expected. The corresponding predictions are 19,000 and 1,600 black holes after 10 million years of FCE for a neutron star [GM p. 77, table 9 ↗]. Thus, in the case of M_D = 4 TeV, ~ 25 times more black holes would be expected at the LHC than after 10 million years of FCE for a neutron star. In the corresponding case for M_D = 6 TeV, ~ 1200 more black holes would be expected for that neutron star. For higher values of M_D, the ratio would be expected to increase in favour of black hole production in neutron stars since the fixed energy limit of the LHC would make black hole production there more difficult. On the other hand, for values of M_D < 4 TeV, the ratio may be expected to increase in favour of the LHC. An exact number cannot be estimated here since the LHC graph is cut off at M_D = 4 TeV. For higher values of the inelasticity parameter y, the ratio would also increase in favour of LHC production, but a direct comparison cannot be made due to the specific choices of parameters for the neutron star table.

of these “milli-cubes”.[140] The average of the risk from all of these cubes would then be a more reliable bound on the overall risk. In most cases, the greatest contribution to the total risk would come from the regions near the faces and vertices of the unit cube.

A risk of 1 in a billion has been suggested as an intolerable level for the LHC. For example, Professor Brian Cox, a CERN collaborator, has publicly stated:

> I and all my colleagues consider our personal safety and the safety of our families to be FAR more important than the search for the Higgs particle - indeed, if the risk were even as high as 1 in a billion, or whatever people quote, then I would be campaigning with you to stop it.[141] [Cox08 ↗]

In order to set a bound below 1 in a billion, one would need to calculate the risk bound for all theoretical scenarios and parameter values which have a likelihood of 1 in a billion (or slightly less), and show that the sum of their contributions results in a total risk that is no more than 1 in a billion. Given the uncertainties inherent in theoretical physics, and the wide range of possible values for many of the variables, this would be a very challenging task indeed.

CERN itself claims an even stricter standard for its risk tolerance. CERN’s website states:

> We are talking about wanting to be absolutely certain that absolutely nothing can happen. [CERN07 ↗]

While this would be a laudable standard, the claim that there is absolute certainty that absolutely nothing can happen has absolutely no basis in reality.

[140] It should be noted that demonstrating a bound of less than 1 in 1,000 would likely require dividing the variables into even smaller bins, say of width 0.0001, so that the contribution from extreme values of different independent variables would still be less than 1 in 1,000.

[141] Professor Cox’s conditional promise to campaign against the LHC is, presumably, referring to the sum total of all possible Earth-ending risks which may be associated with the LHC. The discussion in this section refers to just a single risk (i.e. black hole production) in a single scenario (e.g. neutral stable black holes), but it does not take into account the probability of that specific scenario being realized (i.e. the preconditions required for neutral stable black hole formation). A more complete analysis would look at the risk contribution from all potentially harmful products (e.g. black holes, strangelets, magnetic monopoles, vacuum transitions, etc.). The risk specifically from black holes could be calculated by first estimating the probability of black hole production, then estimating the probability for each of the distinct scenarios (e.g. neutral stable black holes, neutral rapidly radiating black holes, charged stable black holes, etc.), and then calculating the risk for each specific scenario.

10.1 Astrophysical Implications for Neutral Stable Black Holes

The assertion that astronomical observations permits one to firmly exclude any possible risks from neutral stable black hole production at the LHC is the central thesis of the GM paper.

This section reviews this claim, beginning first with a short summary of the GM paper's findings for the Earth, the Moon, and the Sun. The astrophysical arguments involving white dwarfs are then reviewed, followed by notes on the arguments involving neutron stars. The section then concludes with a brief summary of the possible astrophysical bounds and an overview of the possible revisions to the safety assessment of section 9.1 in light of those bounds.

10.1.1 Existence and State of the Earth

As noted in section 7.1.1, the GM paper finds that a neutral stable black hole produced in a cosmic ray collision with the Earth would simply pass through the Earth without stopping [GM p. 33]. Since no such black holes are expected to be trapped in the Earth, no astrophysical bounds are implied by the continued existence or state of the Earth.

This is an important acknowledgement on the part of the authors as it sharply contrasts with earlier public statements. For example, at the Snowmass 2001 Conference, Professor Giddings stated:

> Physicists be warned: journalists regularly read our electronic archives! After [2] appeared, a journalist almost immediately asked me the question, what if Hawking's calculations are wrong, and black holes don't evaporate? Of course, we certainly believe that Hawking's calculations are correct, if not to the last detail, and furthermore on general quantum grounds black holes should decay – they are massive states with no conserved quantities to stabilize them. But further assurances are welcome.
>
> For energies accessible in the foreseeable future, an answer comes from cosmic rays, which are observed up to lab energies 10^{11} GeV. They collide with protons in the atmosphere, and therefore probe CM energies up to $\sqrt{s} \sim 400$ TeV. So if accelerators can investigate black hole production, black holes are already being produced in the atmosphere; if this weren't a safe thing to do, we wouldn't be here to talk about it. [Gid01 p. 7]
> Reference [2]: GT02 arXiv:hep-ph/0106219v1 ↗

Professor Giddings repeated this argument more recently in an interview published in 2007 in the *New York Times*:

> "There is a constant flux of ultrahigh-energy cosmic rays striking the atmosphere," Dr. Giddings said. "The same calculations that we do for the L.H.C. also predict that around 100 such black holes a year are 'organically' and apparently safely produced in the earth's atmosphere in cosmic ray collisions. So if this were dangerous, we shouldn't be here to begin with." [John01 ↗]

What the GM paper now shows is that the argument which Professor Giddings believed to be the back-up in case Hawking radiation failed was completely invalid for all neutral black holes, and even according to the GM paper's analysis [GM pp. 9–10], charged cosmic ray-produced black holes with masses greater than ~ 7 TeV would be expected to simply pass through the Earth without any significant effect.

It is thus surprising to see this argument still being trotted out in the LSAG report. The report states:

> This means [6] that Nature has already conducted the equivalent of about a hundred thousand LHC experimental programmes on Earth already - and the planet still exists. [LSAG p. 4]

This argument even features prominently in CERN's public assurances about the safety of the LHC. As part of the organization's award-winning public relations performance [ES09 ↗] in the lead-up to the LHC's injection test, CERN spokesperson Dr. James Gillies proclaimed that cosmic rays striking the Earth's atmosphere showed that the LHC is not only safe, but "absolutely safe". He is reported to have stated the following:

> "There's nothing to worry about, the LHC is absolutely safe, because we have observed nature doing the same things the LHC will do.
>
> "Protons regularly collide in the earth's upper atmosphere without creating black holes."[142] [Tel08 ↗]

This argument was also repeated by CERN's Chief Scientific Officer, Professor Dr. Jos Engelen, who stated:

> "The LHC safety review has shown that the LHC is perfectly safe...
>
> "It points out that nature has already conducted the equivalent of about a hundred-thousand LHC experimental programs on Earth – and the planet still exists." [▷ ADDCITE "Threats Won't Stop Collider" ↗]

This discrepency between the findings of the GM paper and the public statements from CERN highlights the need for policymakers and concerned members of the public to consult the original text, insofar as it can be trusted, when forming a judgement about the risks of the LHC.

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[142] Dr. Gillies' statement about proton collisions would be technically true if he meant to say that no more than a certain fraction of high-energy proton collisions might be expected to produce black holes (which would still leave a number of high-energy protons, not to mention lower-energy ones, to regularly collide in the Earth's upper atmosphere without producing black holes). It is not clear, however, if he intended this kind of weasely interpretation of his remark. If he meant to say that no black holes have ever been produced by protons colliding with the Earth, he would have no basis for that claim. If he meant to say that proton collisions with the Earth show that no "dangerous black holes" have ever been produced, he has missed the entire reason why Giddings and Mangano had to reach out to distant white dwarfs and neutron stars in order to argue that the production of neutral stable black holes would be safe.

10.1.2 Existence and State of the Moon

As noted in section 7.1.2, the Moon would not be able to trap cosmic ray-produced neutral black holes. There are thus no astrophysical bounds for neutral black holes based on the existence and state of the Moon, and no such bounds have been claimed in the GM paper [GM ↗].

10.1.3 Existence and State of the Sun

As noted in section 7.1.3, the GM paper reports that the stopping power of cosmic ray-produced neutral black holes is so low that they would be expected to pass through the Sun and other similar stars without being trapped [GM p. 33]. This finding prevents any astrophysical bound being claimed for such black holes based on the existence and state of the Sun.

This finding shows again that one of the main safety arguments of the LSAG report is invalid. The report states:

> Moreover, our Milky Way galaxy contains about 10^{11} stars with sizes similar to our Sun, and there are about 10^{11} similar galaxies in the visible Universe. Cosmic rays have been hitting all these stars at rates similar to collisions with our own Sun. This means that Nature has already completed about 10^{31} LHC experimental programmes since the beginning of the Universe. Moreover, each second, the Universe is continuing to repeat about 3×10^{13} complete LHC experiments. There is no indication that any of these previous "LHC experiments" has ever had any large-scale consequences. The stars in our galaxy and others still exist, and conventional astrophysics can explain all the astrophysical black holes detected. [LSAG p. 4, hyperlinks added]

The text of the GM paper shows that, in the case of neutral stable black holes, the real LHC experiment could result in black holes trapped in the Earth, whereas in the "10^{31} natural LHC experiments", black holes would be expected to pass harmlessly through.

A more detailed calculation could be provided by CERN, but from the trapping analysis of the GM paper it would seem that if neutral, stable TeV-scale black holes exist, then in just 10 years of the real LHC's operation, more black holes could be produced at the LHC and trapped in the Earth than have been produced on and trapped directly within stars by all the cosmic rays striking 100 billion Sun-like stars in 100 billion Milky Way-like galaxies in the billions of years since the beginning of the Universe.

10.1.4 Existence and State of White Dwarfs Exposed to High Energy Cosmic Rays

The existence and present state of a few specific white dwarfs is presented by the GM paper as proof that, in the case of 5, 6, or 7 dimensions, the production of black holes at the LHC is safe.

The argument is a complex one involving several steps and assumptions. It begins with assumptions about the hadronic component of ultrahigh-energy cosmic rays, follows with estimates of the black-hole production rate for hadronic collisions, continues with a theoretical analysis of the trapping of cosmic ray-produced black holes in massive and ultramassive white dwarfs, and concludes with a model for the accretion of such black holes in those white dwarfs. Selected astronomical data for a few white dwarfs is then offered as proof that black holes cannot be dangerous for the Earth.

A number of significant unknowns related to ultrahigh-energy cosmic rays were described in section 3. Uncertainties about the rate of black hole production in hadronic collisions were summarized in section 4. Questions about the GM paper's analysis of the trapping of neutral stable black holes in white dwarfs were noted in section 7.1.4. As well, the numerous theoretical uncertainties in the GM paper's model for neutral stable black hole accretion within white dwarfs were described in section 8.1.4.

All these steps are essential for the overall astrophysical argument. If there is an insufficient hadronic component of ultrahigh-energy cosmic rays, or if the general rate for black hole production is too low, then one may not be able to guarantee that there are enough black holes produced for a white dwarf to trap at least one in a given time frame. Similarly, if the theoretic analysis for the trapping of cosmic ray-produced black holes has underestimated the matter required to stop a black hole, one may not be able to conclude that, if black holes could be produced, they must be present within certain white dwarfs. Finally, if the model for black hole accretion underestimates the time required for a black hole to destroy or affect a white dwarf, then no conclusions can be inferred from the absence of a visible effect on a given white dwarf.

As these issues have been reviewed earlier in this paper, this section focuses instead on the astronomical aspects of the argument, including especially the criteria for "candidate" white dwarfs, the observability of the effects of accreting black holes, and the data presented on the specific white dwarfs identified in the GM paper.

In addition to its "specific" argument based on predicted accretion times and individual white dwarfs, the GM paper also presents a "general" safety argument based on a purported relationship between accretion times within white dwarfs and the Earth. This argument is reviewed at the end of this section.

A further variant on the white dwarf argument based on the production of neutral stable black holes in collisions in the interstellar medium is briefly reviewed further below in section 10.1.5.

▼ General Issues with the White Dwarf Argument

Before going into the details of the GM paper's white dwarf argument, there are a few general issues which should be noted:

Limited Dimensions - The astrophysical argument for white dwarfs applies only to the cases of 5, 6, or 7 dimensions. It has no validity for the cases of 8 or more dimensions. This point is expressed clearly in the main text of the GM paper [GM p. 38], but not that clearly in the introduction [GM pp. 4–6] or the final conclusion [GM p. 53]). The LSAG report does not make it clear at all that the white dwarf argument is restricted only to those dimensions [LSAG pp. 1, 9].

Limited Values of R_C for Warped Scenarios - For the case of warped extra dimensions, the bounds for Bondi accretion times within white dwarfs depend on both the crossover radius R_C and the nature of the transition phase (as described in section 8.1.4). Under the most favourable assumptions (i.e. using the parameter $1/\lambda_4$ and assuming $R_B = R_C$ throughout the transition), the Bondi accretion of a white dwarf could be completed in 100 million years [cf. GM p. 44] if the value of R_C is $\gtrsim 0.63$ Å[cf. GM p. 43]. In a worse case scenario (i.e. using the parameter $1/\lambda_5$ and assuming $R_B = R_D$ throughout the transition), the 100 million year time limit requires $R_C \gtrsim 227$ Å. In the very worst case scenario while still using the GM paper's general accretion model (i.e. using the parameter $1/\lambda_5$ and assuming $R_B = R_D$ throughout the transition, and using only the general limit for the ratio R_C/R_D [GM p. 26, eq. 4.51, cf. p. 43]), the 100 million year limit would require $R_C \gtrsim 5000$ Å.

Limited Planck Mass - The arguments and calculations presented in the GM paper apply only to the case of the higher-dimensional Planck mass being less than 4.67 TeV. As noted in section 7.1.4, the paper's data suggest that the most massive white dwarf cited as a candidate should be able to stop black holes if the higher-dimensional Planck mass is up to ~ 10 TeV in 6 dimensions and ~ 8 TeV in 7 dimensions. For Planck masses above these levels there does not seem to be any grounds for claiming that white dwarfs can trap black holes.

Dependence on Distant Objects - While the strength of any astrophysical argument depends on its line of reasoning and the available data, all things being equal, it is much more reassuring to have an argument based on nearby objects such as the Earth, the Moon, and the Sun. These are objects that have been studied for thousands of years and we can be confident about their general properties and parameters. When it is not possible to make an argument based on these objects and one must instead refer to exotic objects many light years away, a much greater degree of uncertainty arises.

Restricted Sub-Class of White Dwarfs - The GM paper and the LSAG report typically refer to the astrophysical argument as one based on the existence of "white dwarfs" [GM e.g. pp. 4, 5, 6, 25, 28, 39–40, 50, 51, 52, 74, 83] [LSAG summary, pp. 8, 9], but it does not actually apply to the vast majority of white dwarfs. The argument applies solely to a few white dwarfs with masses equal to or greater than the Sun's and with magnetic fields of less than a few hundred thousand Gauss [GM p. 44]. The range of acceptable values for a white dwarf's mass is rather limited since the maximum possible mass for a white dwarf is the Chandrasekhar limit of $\approx 1.4 M_\odot$. Thus the mass of any candidate white dwarf for the GM paper's argument must lie within the narrow range of 1.0 $M_\odot$ up to at most $\approx 1.4 M_\odot$.[143] In the case of 7 dimensions, the safety argument for heavier black holes is further restricted to white dwarfs with masses greater than 1.1 $M_\odot$ [GM p. 38]. The highest mass of a white dwarf cited is 1.25 $M_\odot$, so in this case the effective range for the GM paper's white dwarf argument is only 1.1 $M_\odot$ to 1.25 $M_\odot$.

Only Uncrystallized White Dwarfs - As noted in section 8.1.4, the GM paper's accretion model is only applicable to white dwarfs which have not crystallized. No calculations have been presented for the rate of accretion of crystallized white dwarfs, but it could be expected to be much longer due to their reduced compressibility. The age at which massive and ultramassive white dwarfs begin crystallizing is discussed further below.

Strong Proof Versus Weak Proof - A much stronger empirical argument would be one in which CERN shows that no white dwarf has ever been destroyed by a cosmic ray-produced black hole (or at least not in the recent, observable past). This type of strong argument is suggested in the LSAG report when it speaks of the impact of black holes in 5 or 6 dimensions being detectable in the Universe [LSAG p. 8] and more generally notes that the destruction of white dwarfs "would have been highly visible" [LSAG p. 9]. The argument of the GM paper, however, is not that such black hole-induced annihilations have never occurred or have never been detected, but rather that there exists a few massive or ultramassive white dwarfs which have not been destroyed [GM pp. 51–52]. Such a proof by counterexamples is much riskier as it depends not only on a rock-solid line of reasoning, but also on there being no other possible explanation for the exceptions (an issue discussed further below).

Accretion Prediction of Disaster Versus Astrophysical Prediction of Safety - Ideally, a safety analysis should show that there is a compelling theoretical argument that nothing could go wrong, supported by one or more empirical arguments reinforcing that conclusion. In this case, the theoretical accretion argument predicts, for a number of 5 or 6-dimensional scenarios, a total catastrophe from a trapped LHC-produced black hole, while the empirical argument based on a few white dwarfs suggests that such a catastrophe is unlikely. The GM paper contends that the astrophysical prediction overrules the theoretical prediction. Clearly, this situation is much less reassuring than if both arguments predicted safety. It also raises the standard expected from the white dwarf argument because so much more depends on it.

▼ Criteria for Possible Candidate White Dwarf

Before examining the specific white dwarfs identified in the GM paper, it may be useful to review in general what data is required for a white dwarf to be considered a reliable candidate for the astrophysical argument. After noting a couple general issues we consider below the criteria for the

[143] It is interesting to note that not that long ago, physicists believed that the maximum mass of a white dwarf was the even lower value of $\approx 1.2 M_\odot$ [▷ ADDCITE Weinberg 1972 pp. 316–317]

present state of a white dwarf, and then identify what information is needed about its historical development.

Error Estimates - As noted in section 2, one of the most basic expectations of scientific data is an estimate of the possible systemic or statistical error. For candidate white dwarfs this should include the error for the estimated current mass, the error for the estimated current magnetic field, and the error for the estimate time since the white dwarf's formation. For a situation in which a very high degree of certainy is expected, and, indeed, "absolute" certainty is claimed [Tel08 ↗] [CERN07 ↗], the error estimate forms an integral part of the argument. Errors in the estimated age, for example, are needed for explicitly calculating the probability that a given white dwarf should have been destroyed or affected by a black hole by now. As will be noted in the following subsection, the GM paper includes no error estimates for the white dwarf data it presents [GM pp. 44–45], and, in fact, has removed the error estimates that were originally attached to almost all the data it cites (cf. [SS95 ↗] [Kaw07 ↗] [NM04 ↗] [Cuad04 ↗]).

Independent Confirmation of Data - All the data presented in the GM paper were obtained during the regular process of astronomical observations. While reasonable care was likely taken during the collection of the data, one might expect that the standard of care and the attention to details and possible errors would be very different if the astronomers involved knew that the fate of the world might depend on the accuracy of their measurements. Given the importance of these data, they should be checked and rechecked by independent teams commissioned specifically for this purpose, with all their measurements, calculations, and uncertainties published online for public review.[144]

▾ Present State of Candidate White Dwarfs

For white dwarfs identified as possible candidates, there are a number of issues that need to be considered with respect to their mass, magnetic field, state of crystallization, and estimated age. They include the following:

Dependence of Mass Estimates on White Dwarf Composition - The GM paper does not explicitly address the question of the composition of its candidate white dwarfs. Its mass estimates are taken from the published literature and would generally be based on the assumption of a carbon-iron or oxygen-neon core for an ultramassive white dwarf. Such assumptions are not unreasonable guesses, but by no means can they be taken as definite determinations. A recent

[144] As an instructive example of the fallibility of published astronomical claims, interested readers are referred to the recent article by Vennes and Kawka [VK08 arXiv ↗] which reviews a number of objects identified as ultramassive white dwarfs by Silvestri *et al.* [Silv01 ↗]. Based on their re-examination of the available data they found that none of these objects were actually ultramassive white dwarfs. In all but one case they found that the objects were normal white dwarfs with masses of about 0.6 to 0.7 $M_{\odot}$. In the remaining case they found that the object wasn't even a white dwarf [VK08 arXiv p. 7 ↗]. The paper by Silvestri *et al.* itself notes that, in general, "the agreement between different mass estimates for any particular individual WD remains unacceptably poor." [Silv01 p. 507 ↗; see also p. 512, table 6]

review article by Vennes and Kawka notes that predicted masses based on the assumption of an oxygen-neon core were systematically 0.02 $M_\odot$ lower than those predicted for a carbon-oxygen core [VK08 arXiv p. 7]. This potential difference should be kept in mind, but it is not likely to significantly affect the GM paper's astrophysical argument. A far more serious issue is the possibility that certain white dwarfs have an iron core. Vennes and Kawka note a recent paper by Catalán *et al.* which suggests that an anomalously cool white dwarf in the Hyades could be explained by assuming it has an iron core [VK08 arXiv p. 2]. For this white dwarf, Catalán *et al.* report that assuming a carbon-oxygen core implies a mass of 0.67 ± 0.03, whereas assuming an iron core implies a mass of 0.46 ± 0.07 [CRIG08 arXiv p. 4, table 5]—a relative reduction of over 30% and an absolute reduction of 0.21 $M_\odot$. After taking into account any associated changes in the column densities, the change in mass resulting from the assumption of an iron core could potentially disqualify most, or even all, of the candidate white dwarfs proposed in the GM paper.

Mass Estimates of Older White Dwarfs - For older white dwarfs with an effective temperature below 12,000 K, there is a very high degree of systematic uncertainty in the estimated values of their mass. The article cited by the GM paper on the formation rate, mass and luminosity functions of DA white dwarfs explicitly excludes all white dwarfs with effective temperatures below 13,000 K out of concern that measurements of high masses might be erroneous. It states:

> Below $T_{\rm eff} \sim 13,000$ K ($\log\ T_{\rm eff} = 4.11$), the atmospheres of DA stars become convective, and there is the suspicion that the high masses inferred from spectroscopy below ~ 12,000 K are actually a measure of the presence of helium brought to the surface by the hydrogen convection zone (Bergeron et al. 1990, BSL). As in BSL, our strategy is thus to exclude all stars below 13,000 K from the following discussion. [LBH05 p. 57, hyperlinks added]
>
> Reference (Bergeron *et al.*): ▷ ADDCITE BSL90

A summary of this problem is given in the section entitled, "WHY WE DO NOT TRUST MASSES FOR $T_{\rm eff} < 12000$ K FOR DA STARS", in a paper on the mass distribution of white dwarfs by Kepler *et al.* [Kep07 pp. 1318–1319]. Such white dwarfs are typically old enough to have a crystallized core, so in addition to the GM paper's accretion model not applying to them, their masses may not even be sufficient to trap heavier black holes. As noted below, this problem applies to half of the white dwarfs candidates cited in the GM paper (viz. WD2159–754, WD1236–495, WD2246+223, and WD2359–434).

Fluctuations in Magnetic Fields - The magnetic fields of white dwarfs are also an important source of uncertainty for individual white dwarfs. The figures given in the GM paper are essentially point measurements of the magnetic fields of those white dwarfs at a specific instant in time. If one considers that the magnetic field of the Earth can be significantly reduced during periods of geomagnetic reversals or excursions, it would be reasonable to check whether the magnetic fields of the candidate white dwarfs are also subject to variability. For example, for white dwarf WD0652–563, with a magnetic field of 270,000 Gauss [GM p. 45], how do we know that its magnetic field has not been measured during a low point? If this is indeed the case, the expected rate of black hole formation through cosmic ray collisions should be reduced to reflect only those times for which the magnetic field of the white dwarf is confirmed to be sufficiently low.

Effects of Magnetic Field Geometry - Furthermore, the published magnetic field measurement at a given point in time may not even be representative of the average magnetic field or the maximum magnetic field at that time. The limitations of magnetic field measurements are described as follows in the article on white dwarfs with low magnetic fields cited by the GM paper:

> Note, however, that our investigation is based on the averaged longitudinal component of the magnetic field, meaning that the maximum magnetic field at the white dwarf surface can be stronger, depending on the field geometry (described e.g. by offset dipoles, or more complex distributions; with the underestimate being larger for a more complex magnetic distribution) and on the orientation relative to the observer. Therefore, our results for the three objects with a positive detection are lower limits, since cancellation effects are expected. [Cuad04 p. 1092]

Given these uncertainties, one wonders what level of confidence should be given to an argument that depends on measurements from the Earth of weak magnetic fields in certain white dwarfs.

Timing of Crystallization - As noted above, the GM paper's accretion model only applies to non-crystallized white dwarfs, so there is presently no astrophysical safety argument based on the existence of crystallized white dwarfs. The GM paper gives time frames of a billion years [GM p. 33], 600 million years [GM p. 41], and, again, a billion years [GM p. 44] for the crystallization of white dwarfs, but for massive and ultramassive white dwarfs crystallization is expected to occur much sooner. The article on white dwarf cosmochronology cited by the GM paper states the following:

> We note that because of their larger masses *and* smaller radii, more massive white dwarfs have larger internal densities (for comparable temperatures) and, therefore, develop a crystallized core earlier, at higher luminosities or, equivalently, higher effective temperatures. [FBB01 p. 419]

The most recent reference cited by the GM paper for the ages of white dwarfs gives an example of a 1.31 $M_{\odot}$ white dwarf which is believed to have an appreciable fraction of its core in a crystallized state after only 280 million years [Alt07 arXiv p. 7]. For white dwarfs with masses of 1.06, 1.10, 1.16, 1.20, 1.24, and 1.28 $M_{\odot}$, this reference gives the times for the onset of crystallization[145] as 321

[145] The time for the start of crystallization has been taken as the key point instead of the time required for most of the white dwarf's core to be crystallized. To affect the accretion times of a microscopic black hole all that may be required is a crystallized volume that is sufficient to contain the black hole and the region the black hole is capable of affecting through both its gravitational pull and reradiation. As a black hole in a white dwarf may be considered more or less stationary after its first phase of growth, the volume involved would be only a very small fraction of the white dwarf's core.

million, 276 million, 219 million, 155 million, 115 million, and 102 million years, respectively.[146] The article notes that the time frames for crystallization are shorter still for white dwarfs with pure helium atmospheres, with an estimated time of 257 million years for 1.10 $M_{\odot}$ white dwarfs, and 148 million years for 1.20 $M_{\odot}$ white dwarfs.[147]

If a white dwarf has an iron core, then the time required for its crystallization is extremely short. The research group responsible for the article cited above on the age and colors of massive white dwarfs had earlier analyzed the theoretical evolution of white dwarfs with iron cores and reported that the onset of crystallization occurs at a luminosity 2000 times higher for a 1 $M_{\odot}$ white dwarf with a pure iron core compared to a white dwarf of the same mass but with a carbon/oxygen core [PAB00 p. 537]. Their article does not given enough information to convert this finding to a specific age, since the estimated luminosity [PAB00 p. 534, figure 11] occurs before the "zero-age point" that the authors use for their graph of luminosity over time [PAB00 p. 537], however, from the relevant graphs [PAB00 pp. 535–536, figures. 15, 16, 17] it is clear that the time involved is much less than 100 million years.

▾ Present Age of Candidate White Dwarfs

The estimated ages of candidate white dwarfs are a crucial part of the astrophysical argument since they are needed to show that the white dwarf has been around long enough for it to trap a black hole and for the effects of that black hole to become visible. The GM paper speaks assuredly of "known lifetimes" of white dwarfs [GM abstract and pp. 43, 44]. It explains that ages are determined through white dwarf cooling and refers readers to "a textbook account" and three more references [GM p. 44, citing ST83 ↗, FBB01 ↗, LBH05 ↗, Alt07 ↗], leaving readers with the impression that this is a settled issue. The references it cites, however, indicate that there remains a great deal of uncertainty about such age estimates. Some of the key issues include:

General Uncertainty in Age Estimates - The article on white dwarf cosmochronology cited by the GM paper stresses the complexity and potential unpredictability associated with estimating the ages of white dwarfs. It states:

> It has nevertheless often been claimed that the evolution of white dwarfs, a "simple" cooling problem, is so well understood that more accurate ages naturally follow from the applications of white dwarf cosmochronology. We currently think otherwise. The

[146] The values of $\log(L/L_{\odot})$ at the onset of crystallization were -2.15, -2.03, -1.85, -1.63, -1.41, and -1.3, respectively. The first and last of these values are given explicitly in the article [Alt07 arXiv p. 4 ↗] and the values for masses in between were estimated from the graph of figure 1 [Alt07 arXiv p. 3, figure 1 ↗], after sufficiently magnifying the image. The corresponding ages for the white dwarfs were then estimated from the data tables the authors have made available on their website [Alt07.xls ↗], with a linear log-log interpolation, when needed, between the specified luminosities and ages.

[147] The values of $\log(L/L_{\odot})$ at the onset of crystallization were approximately -1.98 for 1.10 $M_{\odot}$ and -1.61 for 1.20 $M_{\odot}$, based on the graph of figure 5 [Alt07 arXiv p. 5, figure 5 ↗]. The corresponding times were estimated from figure 10 [Alt07 arXiv p. 9, figure 10 ↗]. The times for other masses could not be estimated since figure 10 includes only the cases of 1.10 $M_{\odot}$ and 1.20 $M_{\odot}$.

fact of the matter is that white dwarf physics is much more complex, and therefore more uncertain, than main-sequence and giant star physics, and one would be hard pressed to demonstrate, for example, that white dwarf cosmochronology presently gives better estimates of the ages of Galactic clusters than the turnoff point method, especially for the older systems. We caution that white dwarf evolution, supposedly bland and uneventful, may still have some surprises for us![148] [FBB01 pp. 433–434]

Recent Reduction of Age Estimates - The most recent reference cited by the GM paper, an article published in 2007 on the age and colours of massive white dwarfs, states:

> To our knowledge this is the first attempt to compute the evolution of massive white dwarfs with a realistic equation of state — which includes all the non-ideal, corrective terms, and the full temperature dependence — and reliable chemical profiles for the degenerate interior expected from the previous evolutionary history of massive white dwarf progenitors that burned carbon in semidegenerate conditions. We have examined the cooling ages, colors, and magnitudes of our sequences and find that massive white dwarfs are characterized by very rapid evolution. [Alt07 arXiv p. 8, hyperlinks added]

This statement implies that all of the other references cited by the GM paper for the ages of white dwarfs were based on an unrealistic equation of state and/or unreliable chemical profiles for the degenerate interior. Of particular concern is that this article's estimates for the ages of massive white dwarfs are significantly lower than previous estimates in the scientific literature. It gives the example of WD 1658+441 (not one of the candidate white dwarfs), which it now estimates to have an age of 280 millions years [Alt07 arXiv p. 7]. It notes that the article published in 2005 by Liebert *et al.* (the second most recent reference cited by the GM paper), estimated an age of 380 million years for the same white dwarf [Alt07 arXiv p. 7, citing LBH05 ↗]. Since the ages given in the GM paper for the non-crystallized candidate white dwarfs[149] range from only 100 million to 150 million years, the paper's astrophysical argument could easily be affected if these most recent, revised age estimates are superseded in the future by significantly lower age estimates.

[148] This quotation deals primarily with the reliability of white dwarfs for time estimates in the multi-billion year range, but the general issues it identifies are also relevant for the shorter time periods associated with the GM paper's candidate white dwarfs.

[149] This paper uses the term "non-crystallized candidate white dwarfs" to refer to WD0346–011, WD1022–301, WD1724–359, and WD0652–563, although, as noted above, whether these white dwarfs do not contain any crystallization in their core cannot be taken as a certainty. For example, the GM paper gives the age of WD1724–359 as ~ 150 million years, whereas the article it cites on the age and colors of massive white dwarfs estimates that a white dwarf of mass 1.20 $M_\odot$ should start crystallization after about 155 million years if it has a maximal hydrogen atmosphere [Alt07 arXiv p. 3, ↗] and after about 148 million years if it has a pure helium atmosphere [Alt07 arXiv p. 5, figure ↗]. Thus it may be more appropriate to describe some of these white dwarfs as "possibly, but not necessarily, crystallized candidate white dwarfs", however, for simplicity they are collectively called "non-crystallized candidate white dwarfs". The main purpose of this term is to exclude the candidate white dwarfs cited in the GM paper which have estimated ages of a billion years or more and almost certainly have started crystallizing.

Atmosphere Assumption for Maximizing Ages - The age estimates given in the 2007 article are based on what the authors calculate to be an upper limit for the amount of hydrogen in a massive white dwarf [Alt07 arXiv p. 2]. This hydrogen serves as the insulating blanket for white dwarfs, so maximizing the amount of hydrogen maximizes the time required for cooling to a given effective temperature, and thus maximizes the estimated age for a white dwarf of that temperature. The article does consider the opposite extreme of a pure helium atmosphere (i.e. no hydrogen blanket), and notes that the cooling times are significantly faster. As an example it points out that its cooling sequence for $1.28M_{\odot}$ white dwarfs with a helium atmosphere reach a luminosity of $\log(L/L_{\odot}) = -4.70$ at an age that is about 1/3 less than that associated with the maximum hydrogen case [Alt07 arXiv p. 5] (although the differences appear to be much less at higher luminosities [Alt07 arXiv p. 3, figure 1, compared with p. 5 5]). The authors have only published tables for the case of a maximal hydrogen atmosphere, and it seems that these are the estimates that the GM paper has chosen to use.

The age estimates in the 2005 article by Liebert *et al.* are similarly based on the assumption of a "thick" outer hydrogen layer [LBH05 p. 52]. The white dwarf cosmochronology article cited by the GM paper also adopts the assumption of a thick hydrogen envelope for its calculations [FBB01 pp. 416, 433, 434]. Thus, all three articles cited by the GM paper assume a thick hydrogen atmosphere, whereas a conservative age estimate would require assuming the thinnest possible hydrogen atmosphere consistent with astronomical observations.

Effects of Spectral Evolution - The article on cosmochronolgy cited by the GM paper notes that there is strong evidence that spectral evolution takes place among white dwarfs [FBB01 p. 411] but the age estimates of the candidate white dwarfs do not take this potential factor into account. Of particular concern is that, as noted below, all of the non-crystallized candidates have temperatures which fall within the "DB gap" of 30,000 – 45,000 K, so it is not possible to determine if they have always been DA white dwarfs, or simply appear that way now. If these candidates have been affected by spectral evolution, the issue would be more than one of simply assuming that they have or had a thin hydrogen or pure helium atmosphere. What would be needed is an evolutionary model that not only accurately predicts a white dwarf's atmosphere and opacity at different times, but also incorporates the processes that lead to spectral evolution as an integral part of its determination of the cooling rate. Such a model would need to cover both the time before the DB gap (i.e. above 45,000 K) and the time the white dwarf has spent within that gap. Without such a model, the ages for white dwarfs in the DB gap can at best be considered a first guess.

Effect of Core Composition - As noted earlier, the GM paper does not directly address the question of the composition of the cores of its candidate white dwarfs. The presence of heavier elements in the cores of white dwarfs results in a lower specific heat per gram [Alt07 arXiv p. 7] [FBB01 p. 412] and thus decreases their cooling times.[150] The ages cited above from the 2007 article on the ages and colours of massive white dwarfs are based on the assumption of the same

[150] The article on white dwarf cosmochronology cited by the GM paper as a reference for white dwarf ages very clearly explains that it adopted the unrealistic assumption of a pure carbon core for its models with the deliberate

oxygen-neon core composition for all the white dwarf masses considered [Alt07 arXiv p. 2]. The article itself notes that changes in the chemical profile of the white dwarfs are expected due to different masses of the progenitors, but the authors assert that these are minor and have a negligible influence on the cooling times. This statement may be true for the article's primary purpose of calculating the cooling of massive white dwarfs over billions of years, but the specific need in this case is an accurate estimate of the cooling time in just the first 100 to 150 million years. Moreover, the possibility of higher than expected concentrations of neon, or of other heavier elements such as sodium or magnesium, would need to be considered for determining lower limits on the ages of the candidate white dwarfs. In the extreme case of a pure iron core, the same research group notes that, "The cooling process at very high luminosities proceeds in a much faster way (up to a factor of ten) compared to the standard case." [PAB01 p. 36]

Accelerated Cooling Times for Strange White Dwarfs - As noted earlier, the GM paper does not present a model of accretion to cover the possibility of white dwarfs with strange matter cores, so no astrophysical argument can be based on such stars. If, in the future, CERN does present a model for black hole accretion of strange matter, it should be noted that the strange white dwarfs are expected to have "an anomalously rapid cooling rate" [▷ arXiv 0604366v1 p. 9 ↗], so their estimated ages would be much less than that of regular white dwarfs. Accretion within strange matter could be faster than that of regular degenerate matter, but there would be a much shorter time window for both trapping and accretion to occur.[151]

▷ ADD NOTE on the possible effects of axions on the cooling rate [▷ arXiv 0806.2807 ↗] [▷ arXiv 0812.3043 ↗], but note that TeV-scale black hole formation might not be possible in such a scenario [Wil04 arXiv p. 7].

Ages Estimates for Binary Mergers - The articles cited by the GM paper apply solely to white dwarfs which are the result of a unitary evolution. The GM paper cites no recent articles which model the evolution of massive or ultramassive white dwarfs that have formed through the merger of two smaller white dwarfs. As described further below, the majority of massive white dwarfs are believed to have been created through such mergers.

Other Uncertainties in Age Estimates - The above points describe some of the systematic factors which have been discussed in the scientific literature which can reduce the expected ages of white dwarfs. Given the essential role of estimated ages in the GM paper's astrophysical argument, in addition to these known factors one must consider the possibility of other, presently unknown factors which could result in an unexpectedly quick reduction of the effective temperatures of

intention of calculating upper limits for the ages of white dwarfs [FBB01 p. 417 ↗]. Just in case readers may have missed this point, the authors emphasize repeatedly throughout the article that their estimates are upper limits [FBB01 pp. 423, 424 (figure 7), and 432 ↗]. What the GM paper needs, however, are lower limits for the white dwarfs' ages.

[151] A rough indicator of whether it is or isn't helpful for a candidate white dwarf to have a strange matter core could be the ratio of strange/normal accretion times compared with the ratio of strange/normal white dwarf ages.

white dwarfs in general, massive or ultramassive white dwarfs in particular, or the candidate white dwarfs specifically. A bound on these unknown factors would need to be established in order to claim any degree of certainty in the overall astrophysical argument.

▾ Historical State of Candidate White Dwarfs

The current values of the mass, magnetic field, internal state, and age provide a convenient set of criteria to rule out white dwarfs candidates, but in order to accept a white dwarf as a potential candidate, additional information is required about its historical development.

The astrophysical argument presented in the GM paper does not claim that candidate white dwarfs are instantly destroyed after trapping a microscopic black hole. What the paper argues is that a trapped black hole would grow steadily, and eventually, after a period of possibly millions or tens of millions of years [GM pp. 43–44] [152, 153], would either destroy or interfere with the cooling of its host white dwarf. What this argument requires then, is that candidates have the appropriate parameters (i.e. high enough mass and low enough magnetic field) at the time when they are expected to have trapped at least one black hole. In the text below, meeting the mass and magnetic field requirements places a white dwarf in its "trapping window", and the time since that white dwarf was first in its trapping window is defined as its "trapping age". For the astrophysical argument to apply, the trapping age must be sufficient to include both the period of time required to be confident that at least one black hole has been trapped, and the period of time required for that black hole to have a discernible effect.

Some of the issues related to the historical state of candidate white dwarfs include the following:

Mass Accretion Over Time - While familiar objects like the Earth and the Sun may have a relatively constant mass over billions of years, the same cannot be assumed for distant white dwarfs. Many white dwarfs are members of binary systems, either with main sequence stars, or with other white dwarfs in double degenerate systems. The gravitational interactions of these objects often results in a significant transfer of mass from one body to the other. The challenge this poses to the GM paper's astrophysical argument is that insofar as one requires a certain minimum mass, say 1.0 $M_\odot$, to effectively trap black holes, it is not enough to report that a candidate white dwarfs presently possesses that mass. One must also know how long that white dwarf has had such a mass in order to estimate its trapping age. If it has been accreting mass from a binary companion, it could, for example, have increased its mass from 0.8 $M_\odot$ to 1.1$M_\odot$ over a period of time. At a mass of 0.8 $M_\odot$ it would not have been able to trap heavier black holes,

[152] The final summary of the GM paper states that in the case of $D = 5$ it would be "impossible for any white dwarf with a mass of the order of one solar masses to have survived longer than few thousand years" [GM p. 51 ↗], but this only applies to the maximum allowed crossover radius, R_C, and either ignores the possibility of post-Bondi accretion [GM p. 43 ↗], or has adopted a rather broad interpretation of what it means to have a mass "comparable to that of the star..." [GM p. 51 ↗].

[153] Adopting a conservative model for the transition to 4-dimensional growth, the GM paper only claims that the accretion times are $\lesssim 1$ billion years for warped scenarios with $R_C \gtrsim 30$ Å [GM pp. 43–44 ↗].

whereas with a mass of 1.1 $M_\odot$ it could qualify as a candidate if the GM paper's calculations are correct.

To assess a potential candidate white dwarf, one could first look at whether the object is presently accreting mass, and if so, at what rate. If there are no signs of ongoing mass accretion, one must then look for any indicators of mass transfers in the past (e.g. a binary companion that appears to have lost significant mass). If a significant mass transfer did occur in the past, it would be essential to determine when this process had transferred enough mass for the white dwarf to be able to trap cosmic ray-produced black holes. If there are no immediately obvious signs of a mass transfer in the past, it would be important, nevertheless, to set a bound on the possibility that a mass transfer had occurred but the signs have not yet been observed, or that practically no signs remain. Minimizing this bound would likely involve a fairly intensive programme of astronomical observations over several years. The GM paper itself makes no mention of previous mass transfers onto its candidate white dwarfs, and only provides estimates of the time since their original formation through the mass losses of their main sequence progenitors [GM pp. 44–45].[154]

Binary Mergers - An even greater uncertainty associated with massive and ultramassive white dwarfs is whether they were formed through the unitary evolution of a massive progenitor star or through the merger of two smaller-mass white dwarfs. The article cited by the GM paper on the formation rate, mass, and luminosity function of white dwarfs presents an initial calculation predicting that only 17.5% of massive white dwarfs are the result of single star evolution, while the remaining 82.5% are the product of binary mergers [LBH05 p. 65] (although the article also argues that the single-star fraction may be significantly higher for the hot white dwarfs in the associations of massive stars near the Galactic plane [LBH05 p. 67]). With the development of other models for the evolution of massive progenitor stars this fraction may be expected to change, however it does underline the importance of determining whether a given candidate white dwarf is the product of a binary merger, and if so, when did that merger occur. Prior to their merger, separate white dwarfs might not possess a sufficient column density to trap black holes, and only after their merger and the consolidation of a new, massive white dwarf would the column densities be enough to trap heavier black holes. For this reason, the trapping age of a candidate white dwarf that was produced through a merger should only be counted from the time of that merger.[155] The GM paper does not attempt to determine which of its candidate black holes were produced through binary mergers.

[154] If only to play the devil's advocate, one may note that if the GM paper had underestimated by 20% the mass required to trap heavier black holes in 7 dimensions, then the minimum requirement would be about 1.37 $M_\odot$. The Chandrasekhar Limit for white dwarfs is in the neighbourhood of 1.4 $M_\odot$, above which white dwarfs are expected to explode in a Type IA supernovae. A core collapse due to the limits of electron degeneracy pressure is certainly a much more plausible explanation of this phenomenon, but another, very faint possibility is that only after white dwarfs approach this mass are they capable of trapping black holes, which in turn cause their destruction. This scenario would require, however, an exceptionally fast rate of black hole accretion.

[155] In the case of a merger with a helium-core white dwarf it may be more appropriate to start counting the trapping age after the phase of helium burning [Berg91 p. 271], or more generally, after a sufficient increase in the column density of the new star.

Magnetic Field Evolution - The section on the current state of proposed candidates noted the issues of variability in the magnetic field of white dwarfs and the degree to which specific measurements are representative of a white dwarf's overall magnetic field. In addition to these factors, an issue of special concern is the secular decline of the magnetic field strength of white dwarfs over time. The source and evolution of white dwarfs' magnetic fields are still not well understood, but a leading explanation is that they are inherited from the white dwarf's progenitor star and strongly amplified through the star's contraction [Cuad04 p. 1081]. The article cited by the GM paper on the detection of weak magnetic fields in white dwarfs highlights the question of whether magnetic field strengths correlate with temperature [Cuad04 p. 1093], which would imply a decrease as the white dwarf cools.[156] As with the question of a candidate white dwarf's mass, reviewing a candidate's magnetic field must involve not only a measurement of its current state, but also an analysis of what it may have been in the past.[157]

As noted earlier, the candidate white dwarf WD0652–563, is reported in the GM paper to presently have a magnetic field strength of less than 270,000 G [GM p. 45]. This is taken to be sufficiently low to meet the criteria of "$B_p \lesssim$ few $\times 10^5$ G" [GM p. 44]. What one needs to ask is how long its magnetic field has been at its current level. How long ago was its magnetic field greater than, say, 500,000 G? Since the GM paper's accretion predictions involve times of up to 80 million years [GM p. 43], but the estimated ages of its non-crystallized candidates are only 100 to 150 million years, a particular concern is the relative age of the candidate when it is expected to have trapped a black hole. In the case of WD0652–563, this could involve an estimate of its magnetic field strength when it was only a fifth of its current age. The GM paper needed to set upper bounds on the magnetic field strength of its candidate white dwarfs at different points in the past, but the paper did not even consider the possible evolution of the magnetic fields of its proposed candidate white dwarfs.

▼ Demonstrating the Absence of Black Hole Accretion

If a white dwarf's past and present parameters are sufficient to qualify it as a candidate, the next step is to determine whether it is being affected by black hole accretion. The GM paper's astrophysical argument is based on the claim that current astronomical observations conclusively

[156] The article also notes that several authors have suggested that the frequency of magnetic white dwarfs may increase with decreasing effective temperature, luminosity and with increasing cooling age [Cuad04 p. 1093 ↗], but this is not quite the same as saying that the magnetic field of a given white dwarf increases over time. To play the devil's advocate again, one could also suggest that this may indicate a selection pressure in favour of magnetic white dwarfs, and that white dwarfs without a strong enough magnetic field run a higher risk of being destroyed by black hole accretion.

[157] Aside from the uncertainties about current masses and the possibility of changes in mass, the expectation of a steady reduction in magnetic field strength over time is one of the reasons it is not possible to claim that a now-crystallized white dwarf should have been destroyed by a black hole long before it had a chance to crystallize. In order to make such a claim one would need to set an upper bound on the strength of the magnetic field of a white dwarf in the far distant past. For the 4 crystallized candidates mentioned in the GM paper [GM p. 45 ↗], this would involve estimates of their magnetic fields at a time ranging from hundreds of million to almost 2 billion years in the past. Clearly, no credible claim can be made about a period so long ago.

demonstrate that the white dwarfs it identified are not experiencing significant black hole accretion.

The GM paper gives two criteria which must be met in order to show that a white dwarf is not being affected by accretion. The first is that it exist (i.e. has not been destroyed by black hole accretion). The second is that black hole accretion is not interfering with the white dwarf's cooling, or otherwise macroscopically disrupting the star [GM p. 43].[158]

The text below reviews a number of theoretical issues involved in verifying that a white dwarf meets these two criteria.

Criterion 1 - Non-Destruction of a White Dwarf

Showing that a white dwarf has not been destroyed is fairly straightforward. It is reasonable to assume that a constant source of light from a specific direction corresponds to a constant object which had not been destroyed at the time the light was originally emitted.

One important complication, however, is quantifying the probabilistic significance of the existence of specific white dwarfs. As noted above, the GM paper does not make the argument that no white dwarf has been destroyed by black hole accretion, and consequently makes not effort to estimate the number of massive or ultramassive white dwarfs with historically low magnetic fields which may have been destroyed through black hole accretion. The paper could claim that it is extremely unlikely for its candidate white dwarfs to have survived (the paper, in fact, goes further and speaks of contradictions with observations [GM p. 53], older white dwarfs being "ruled out" [GM p. 52], and it being "impossible" for a white dwarf to have survived [GM p. 51]), but a probabilistic analysis would require information on the total size of the population. For example, one could say that there is only a one in a million chance of an ultramassive white dwarf not being infected by a black hole, but if there were a million ultramassive white dwarfs, of which 999,999 have already been destroyed, then pointing to the sole surviving white dwarf as evidence against the existence of stable TeV-scale black holes would not be very convincing. More realistically, the maximum theoretical size of the initial population of massive and ultramassive white dwarfs is much, much less than a million times the number of visible survivors, but unless the argument is so strong that a couple orders of magnitude don't make much of a difference, a genuine attempt should be made to set an upper bound on the initial population and the number of white dwarfs which may already have been destroyed.

[158] In theory, the GM paper could have consolidated these criteria into the single criterion that a white dwarf has not being destroyed by providing revised accretion time estimates which include the period of post-Bondi evolution. There is, however, a great deal of uncertainty about how much time that phase would take. It is also not clear whether the GM paper's estimates for the ages of its non-crystallized candidates would be less than the total time involved.

Criterion 2 - Absence of Interference with White Dwarf Cooling or Other Macroscopic Disruptions

A far more difficult criterion to assess is the absence of interference with white dwarf cooling, so it is rather surprising that CERN is willing to base its safety assurances for the LHC on the claim that the cooling rates of specific white dwarfs have not been affected.

The GM paper addresses this matter briefly at the end of section 7.3 [GM p. 43] and again in more detail at the end of Appendix B.3 [GM pp. 64–65]. Its treatment, however, is far from sufficient as it fails to identify what astronomical data is needed to conclusively demonstrate non-interference with white dwarf cooling. Some of the theoretical issues associated with this criterion and the GM paper's treatment of it include the following:

Visibility from the Start of Eddington Limited Growth - The GM paper claims that black hole accretion rates "are not modified by an Eddington limit, at least until accretion macroscopically disrupts the star." [GM p. 43] What is needed to demonstrate this is an estimate of the lowest mass or accretion rate at which an Eddington limit could occur, and an estimate of the possible effects of accretion at that stage. If one could show that these effects must macroscopically disrupt a white dwarf, then the claim would be valid. The GM paper does provide an equation for calculating when an Eddington limit would be expected to occur [GM p. 64, eq. B.27], but it does not explicitly calculate that point and does not provide an estimate for the value of the coefficient η which is needed to determine that point. Thus, the paper fails to demonstrate its claim that there is no period of Eddington-limited growth prior to macroscopic disruption, and, more importantly, does not set a bound on the possible length of any such period.

The paper does include a sample calculation of how Eddington-limited growth might interfere with white dwarf cooling [GM p. 65], but it does not claim that this is the earliest point at which Eddington-limited growth could occur. Moreover, its calculation is only for a scenario of N black holes of Bondi radius R_B, and the luminosity values it gives suggest, depending on the value of N, that the effects during that stage of a single Eddington-limited black hole would not be visible.

Effect of Multiple Black Holes - As noted in the previous paragraph, the sample calculation provided in the GM paper [GM p. 65, eq. B.29] involves the assumption of N black holes of Bondi radius R_B. The paper then claims that, "Given the large numbers of black holes that would be produced, on relatively short time scales one would find a buildup of black holes that have a major impact on cooling..." [GM p. 65]. As discussed earlier in the section on multiple black hole accretion within white dwarfs, the issue is not just a simple case of assuming that the rate of production determines the number of black holes during the Eddington phase or at other stages. What is needed is, firstly, a model of the interactions between accreting black holes, and, secondly, an analysis of if and when the merger of black holes might occur. If many of the black holes have already merged prior to the Eddington phase, then the effective number of black holes at that stage could be significantly less. The GM paper addresses neither of these issues in its treatment of black hole accretion in white dwarfs.[159]

Applicability to Limited Range of η - The GM paper argues that, "...one would find a buildup of black holes that have a major impact on cooling, even for a relatively large value like $\eta = .01$", but it makes no such claim should the value of η be greater than 0.01. The paper does assert that the reradiation efficiency of spherically-symmetric accretion is quite low [GM p. 27, citing FKR02 ↗], but it does not provide a numerical model or other convincing evidence to prove its claim, and it ignores the very accretion textbook it cites which concludes that, "...the efficiency problem in spherical accretion can therefore be overcome if sufficient dissipation occurs" [FKR02 p. 243 ↗]. It should also be noted that the *Accretion Power in Astrophysics* textbook uses a value of $\eta \approx 0.1$ for the accretion of neutron stars and black holes [FKR02 p. 98 ↗]. This value is referred to by other authors as the "canonical" efficiency for radiation caused by black hole accretion [MCF08 p. 734]. Unfortunately, the GM paper does not present an astrophysical safety argument should a black hole within a white dwarf actually cause reradiation with this level of efficiency.

Identification of Non-Interference with Cooling - Perhaps the biggest challenge associated with this criterion is actually identifying when there is no interference with white dwarf cooling. The approach the GM paper suggests is rather simplistic. It states that typical cooling rates for white dwarfs are in the range of $0.1 - 0.001 L_\odot$ and then calculates the number of identical black holes multiplied by their Bondi radius which would result in an output greater than $0.01 L_\odot$ [GM p. 65].

An immediate question is why the paper chooses an output limit of $0.01 L_\odot$ when the typical range it cites is $0.1 - 0.001 L_\odot$? If the typical range goes up to $0.1 L_\odot$, a natural expectation would be to use that upper limit as a target. Better still, one can look at the estimated luminosities (assumed to be similar to cooling rates in the absence of other heating mechanisms) of the non-crystallized candidate white dwarfs. Their estimated luminosities are summarized below:

▷ ADD TABLE: WD0346–011, WD1022–301, WD1724–359, WD0652–563[160]

The lowest luminosity of these candidates is WD1724–359, with a value of approximately $0.029 L_\odot$. Even for this case, the heat from the GM paper's N black holes would be less than 35% of the luminosity, so all that could be claimed is that the cooling rate would be about 35% lower than expected.

The real problem, though, is conclusively identifying the absence of interference with cooling. The first step would be to review the theoretically expected rate for white dwarf cooling. There is presently no single, universally accepted model, so a number of published models would need

[159] One of the unfortunate ironies of the GM paper is that even though one might expect a conservative analysis to show, theoretically, that N black holes could not possibly harm the Earth, and reinforce this argument by proving that even a single black hole would destroy a white dwarf, instead the paper only argues that a single black hole would not be dangerous for the Earth since N black holes would have a visible effect on a white dwarf.

[160] Luminosities calculated from [Alt07.xls ↗] with log-log interpolation between given values.

to be considered, some of which may predict a faster rate of cooling, while other may predict a much slower rate of cooling. For a given white dwarf there will also be variations in the possible cooling rate due to uncertainties in factors such as its mass, core composition, and atmosphere. As a baseline, one could adopt the fastest possible rate of cooling, based on the different models, and the different possible parameters for the white dwarf. If the observed cooling rate matches this there would be very little scope for significant heating by accreting black holes, so one may be able to set a tight limit on the collective mass and reradiation from any possible black holes. If the observed cooling rate is between the fastest and slowest possible rates there will be some uncertainty whether the observed rate is the result of the true natural rate in the absence of black holes, or whether it is the result of black hole accretion slowing down what would otherwise be a faster cooling rate. Nonetheless, a bound could still be set on the possible reradiation from black holes by comparing the observed rate with the fastest possible rate and then asserting that the total heating from any possible black holes must be less than the difference of these two rates.[161] If the rate of cooling is slower than the slowest conceivable natural rate, then one may conclude that there is some unknown process of heating within the white dwarf, including possible reradiation from accreting black holes.

One important factor to incorporate into the theoretical framework is the possibility of natural fluctuations in the effective temperature of a white dwarf. Suppose a black hole is large enough to cause a net heating of a white dwarf, but there are also periodic fluctuations in the effective temperature of that white dwarf. At times the temperature may be observed to be increasing rather rapidly, but at other times it may appear to be declining. If observations are made during a declining phase one might incorrectly conclude that there are no black holes within that white dwarf, or otherwise set excessively strict bounds on the size of possible black holes. For this reason, the theoretical models of white dwarf cooling used for the GM paper's astrophysical argument must also include limits on the amplitude and period of possible intrinsic or extrinsic variations in the observed effective temperature of a given white dwarf.

As there will always be a degree of uncertainty associated with purely theoretical cooling models, it would be preferable to have empirically determined cooling rates based on astronomical observations. In order to determine these rates one would have to make numerous measurements of members of the reference population, in this case massive and ultramassive white dwarfs with low magnetic fields. After these rates are established, one can measure the cooling rates of the candidate white dwarfs, but then what can be concluded? If the cooling rates match the empirically determined model, does it mean that these candidates do not contain black holes, or has the effect of black hole accretion already been inadvertently incorporated into the expected cooling rates? The hypothetical scenario described in the GM paper would see numerous black holes produced in cosmic ray collisions with white dwarfs, and practically all the members of the reference population would be expected to have trapped many black holes over their lifetimes. One could look instead for a reference population which is not expected to be infected by black

[161] As there may be some extreme possibilities for the fastest possible rate, it may be preferable to assign probabilities to different theoretically possible cooling rates and then transfer these probabilities to the consequent bounds on black hole heating associated with a given observed rate.

holes (depending on the scenario), such as lighter mass white dwarfs, or massive and ultramassive white dwarfs with strong magnetic fields, but difference in mass or magnetic fields could directly cause differences in cooling rates, and could indirectly be an indication of other underlying differences which might significantly affect cooling rates. Bridging the gap would involve theoretical predictions about the differences in cooling rates for these different populations, so such an attempt at an empirical model would end up depending, to a large degree, on theoretical assumptions.

It should be noted that the above discussion applies only to non-crystallized white dwarfs. The GM paper does not present a model for accretion within crystallized white dwarfs, but if it did, it might find further difficulties in proving that such white dwarfs are not being heated by black holes. In crystallized white dwarfs, the monotonic cooling over time can be counterbalanced by the release of latent heat during the transition from a liquid to a crystallized solid [Alt07 arXiv p. 2]. Coupled with uncertainties in when crystallization begins and how quickly it proceeds, the resulting bounds on the possible reradiation from black holes within the white dwarf would be even looser than the non-crystallized case. During advanced stages of crystallization, much of the heat released during accretion may also be absorbed by parts of the core reverting back to a liquid state, so the identification of any heating effect may be further delayed.

For non-crystallized white dwarfs, once a firm theoretical framework is established for identifying interference with cooling, the next challenge is to obtain sufficiently precise astronomical measurements to detect or set limits on possible white dwarf heating. To give an idea of the level of precision required to do so, consider the case of a 100 million year old white dwarf with a mass of 1.1 $M_{\odot}$. According to the data tables of the article on the ages of colours of massive white dwarf stars, the effective temperature of the star would presently be 30,194 K, and after a million years it would be expected to cool to 30,111 K [Alt07.xls ↗].[162] The absolute value of the decrease would be 83 K, and the relative decrease would be 0.275%. If its cooling is monitored over the course of, say, the next century, then the expected absolute decrease would be about 0.0083 K, and the relative decrease would be 0.0000275%.

To put this precision into perspective, one can consider the various estimates of the effective temperature of the first candidate white dwarf, WD0346–011. Some of the published estimates of its effective temperature are: 47500 K, 34282 K, 43330 K, 46600 K, 41000 K, 42400 K, 46100 K, 43500 K, 40540 K, 43400 K, 37375 K, 43102 K, 40300 K, 43000 K, 43200 K, 42373 K,

[162] Estimates for the 100 Myr and 101 Myr marks were calculated through log-log interpolations of the values given in the 1.1 $M_{\odot}$ table [Alt07.xls ↗].

39508 K, 43170 K, and 41480 K, with associated errors ranging from ± 100 K to ± 5000 K.[163, 164] Given this level of imprecision and uncertainty, it is difficult to see what claims could seriously be made about the cooling of a given candidate white dwarf.[165]

Considering again the case of a 100 million year old 1.1 $M_{\odot}$ white dwarf, if one supposes that an ensemble of black hole within that white dwarf are emitting energy at a level 100 times higher than its natural luminosity, then instead of a cooling of 0.0083 K over the next century, one would

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[163] More specifically, the estimates are the following: 47,500 ± 2500 K (1 σ) based on X-ray, ultraviolet, and optical observations [Kahn84 p. 261, table 2]; 34,282 ± 696 K based on fitting of observed optical spectra to the predictions of theoretical model atmospheres [McM89 p. 412, table 1]; 43,330 +1380/ − 1270 K based on the *International Ultraviolet Explorer* (IUE) continua data [FBB90 p. 492, table 6]; 46,600 +4500/ − 3500 K based on optical photometric measurements [FBB90 p. 496]; 41,000 ± 1000 K (3 σ) based on 8 Å resolution data [Berg91 p. 269]; 42,400 ± 2100 K (3 σ) based on 1 Å Hβ data [Berg91 p. 269]; 46,100 ± 2200 K (3 σ) based on Lyα data [Berg91 p. 269]; 43,500 ± 1500 K as a compromised based on the previous three estimates [Berg91 p. 270] (after noting that "If the full range of uncertainties associated with each fit is considered, then the effective temperature estimates range from 40,000 K to 50,000 K." [Berg91 p. 269]; 40,540 based on the fitting of hydrogen line profiles to the predictions of atmosphere models [BSL92 p. 231, table 1], although noting that the low temperature estimate may have resulted from the reduced sensitivity of the spectroscopic technique at high effective temperatures [BSL92 p. 245]; 43,400 ± 1700 K (1σ) [Bar93 p. 21, table 2, citing Kid91]; 37,375 K (34,100 K – 39,600 K) based on spectral fitting of soft X-ray and extreme-ultraviolet data with homogeneous atmosphere models [Bar93 p. 23, table 5(a)]; 43,102 ± 1982 K (1σ external errors) [BRB95 p. 740, table 1], ≈ ± 610 K (1σ internal errors) [BRB95 p. 741, figure 5], based on fitting optical spectra to theoretical model atmospheres; 40,300 ± 100 K (internal error only), based on fitting of extreme-ultraviolet spectroscopic data to homogenous LTE (Local Thermodynamic Equilibrium) line-blanketed model atmospheres and assuming $\log g = 9$ [VBD96 p. L104]; 43,000 ± 5,000 K based on *Extreme-Ultraviolet Explorer* (*EUVE*) photometric measurements using 400 Å and 600 Å bandpasses and assuming log g = 9 [VBD96 p. L104]; 43,200 ± 500 K [VTGD97 p. 727, table 2 ↗] based on fits of Balmer line spectra to theoretical model atmospheres while assuming a pure hydrogen atmosphere [VTGD97 p. 720 ↗]; 42,373 K with a 1σ range for the formal error of 41,577 K – 43,473 K [Marsh97 p. 376, table 2], based on fitting of optical spectra data to theoretical model atmospheres and assuming the equivalent of a pure hydrogen atmosphere; 39,508 ± 464 K (internal error only) [NGS99 p. 401, table 1 ↗] based on fitting of optical and near-infrared spectra with theoretical model atmospheres, noting that the internal errors significantly underestimate the real errors [NGS99 pp. 407–410 ↗], and assuming the published value of 3950 ± 8464 K was a typographical error [cf. Dob06 arXiv p. 3, table 2 ↗]; 43,170 [Cuad04 p. 1090, table 3 ↗] ± 993 K [Cuad04 p. 1089 ↗] based on spectropolarimetric observations using FORS1 (multi-mode FOcal Reducer imager and grism Spectrograph) at the 8 m Unit Telescope 1 (UT1) of the Very Large Telescope, "Antu"; and 41,480 ± 954 K based on an independent analysis of the FORS1 spectrum detailed in [Cuad04] [Dob06 arXiv pp. 2, 3, table 2 ↗].

[164] It may be noted that the estimated ages of white dwarfs are based on their estimated effective temperatures compared with theoretical evolutionary predictions. The estimated effective temperatures are, in turn, usually based on statistical fitting of observed line spectra with the line spectra predicted by theoretical model atmospheres, while simultaneously fitting the estimated surface gravity. Considering the dependence on theoretical models at two distinct stages, and the wide range of estimated temperatures documented in this case, one wonders what basis the GM paper has for describing its candidate white dwarfs as having "known lifetimes" [GM abstract; similarly in GM pp. 43, 44 ↗].

[165] It should be noted, however, that measuring changes in a white dwarf's effective temperature when using the same equipment and methodology would not have the same variability as estimating its absolute temperature. For an example of the differences between multiple observations with the same equipment of the same stellar object, the reader is referred to table 2 of a paper by Bergeron *et al.*, which shows a mean error of 350 K. The authors describe these individual errors as "remarkably small" [▷ ADDCITE BSL 1992 p. 237].

expect an increase of about 0.82 K. Considering other uncertainties, such as variability in the interstellar medium and natural fluctuations in the white dwarf's effective temperature, detecting even this level of reradiation would seem to be a nigh impossible task.

One of the reasons identifying interference with white dwarf cooling is so difficult is that the effective temperature of a white dwarf is a function of its total heat energy. The GM paper chooses to compare the luminosity of a black hole with the expected cooling rate of the white dwarf, but the total heat energy of the white dwarf will not be noticeably affected by the luminosity of a black hole at just a single point in time. Rather, the heat contribution of the black hole over the course of many years must be significant compared to the white dwarf's total heat energy in order for it to significantly change the white dwarf's effective temperature.[166] In this case, the cumulative heating of a relatively small black hole (in astrophysical terms) must be significantly compared to the total heat energy of a white dwarf with a total mass greater than the Sun's at a temperature of tens of millions of degrees Kelvin. The enormous volume of mass which would needed to be heated by the accreting black hole implies that an extended period of time may be required for the heating effects of an Eddington-limited black hole to become externally visible .

One final point that should not even have needed mentioning is that, aside from concerns over the high level of required precision, white dwarf cooling is about the decrease in temperature of a white dwarf over time, so the most basic expectation for any claim of an effect or non-effect on white dwarf cooling is a sequence of measurements over time. Reporting a white dwarf's temperature at just a single point in time is of practically no value in this case since it gives no information about whether the temperature is increasing, decreasing, or staying the same. Astonishingly, the GM paper includes no data and cites no references whatsoever on observed changes over time in the temperature of its candidate white dwarfs. Without such data, this part of the GM paper cannot even be considered a token attempt at an argument.

Observability of Characteristic Emissions - The GM paper notes that if the growth of a black hole is Eddington-limited, "...then each black hole within the dwarf would be emitting at the characteristic Eddington luminosity $L_{Edd} \simeq 8\pi m R_B c_s^2/\sigma$." [GM pp. 64–65]. The GM paper states that, "This would *also* be evident through interference with white dwarf cooling." [GM p. 65, italics added], implying that it would be evident in some way other than its heating of a white dwarf. The GM paper describes each black hole as emitting at a "characteristic" luminosity, implying that there is something identifiable about it. However, the luminosity is simply proportionate to R_B, so unless one independently knows the mass or Bondi radius of that black hole deep within a white dwarf, there is nothing to stop it from being anything ranging from the luminosity at the start of Eddington-limited growth up to the destruction of the star.

More fundamentally, it is not clear what the authors mean by "emitting", beyond increasing the heat within a white dwarf. If they are implying that the accreting black holes are emitting a luminosity that can be observed here on Earth, they are missing the entire point of the white

[166] Extremely high levels of luminosity could potentially cause other disruptions of a white dwarf, but the indicators of those disruptions would have to be specified and searched for separately.

dwarf cooling models they cite. The basic premise of white dwarf cosmochronology is that, even though the interior of a white dwarf is believed to be nearly isothermal, it is surrounded by an opaque outer envelope [FBB01 p. 411], which slowly releases the thermal energy of a white dwarf over the course of billions of years. If white dwarfs didn't have an opaque atmosphere, they would cool extremely rapidly and become essentially invisible, except for their gravitational effects. Due to this insulating layer, very little of the luminosity "emitted" by a black hole in a white dwarf would be going anywhere any time soon.

Other Macroscopic Disruptions - As mentioned earlier, the GM paper speaks repeatedly about black hole accretion macroscopically disrupting a white dwarf, but aside from interference with white dwarf cooling, it does not specify what the other forms of macroscopic disruptions could be. This only adds to the difficulty of proving that no black holes are causing any form of macroscopic disruption of a given white dwarf.

Two possible forms of macroscopic disruption which might plausibly be caused by an accreting black hole are pulsations and other seismic activity. Demonstrating that a large[167] black hole is not present in a candidate white dwarf should thus involve showing that no pulsations or other seismic activity have occurred beyond those which must have been caused by natural processes.

Another possible form of macroscopic disruption is the establishment of convection currents or other mass flows within the host white dwarf to transfer heat away from the accreting black hole. Such flows may or may not result in noticeable seismic activity, depending on their size, speed, and configuration, and the sensitivity of our measurements. Ruling out the presence of a large black hole in a white dwarf would require proof that no internal flows have been caused by the black hole, a task which may be beyond the present-day capabilities of astronomers.

Before moving on to a review of the specific candidate white dwarfs proposed in the GM paper, a general question that should be asked is what constitutes "proof"? There are many examples in modern science in which observations differ from theoretical predictions, but what criteria will decide when those observations constitute proof of an alternative theory, and when they are considered a "paradox"? If a specific white dwarf exists and is cooling normally, contrary to the GM paper's predictions, should we simply take this as proof of the non-existence of neutral stable TeV-scale black holes, or should we search for other possible explanations. Thus far, CERN does not appear interested in trying to find other possible explanations. It has not, for example, issued a public appeal to astrophysicists to try to suggest other reasons for the existence and state of its candidate white dwarfs. Instead, CERN seems all too quick to declare that whatever evidence the GM paper presents is enough to show that black holes are not significantly affecting the candidate

[167] "Large" is used here in the sense of being at least as large as the minimum mass expected for a black hole at the time when the GM paper predicts that it would either destroy or macroscopically disrupt its host white dwarf. The GM paper does not claim that smaller black holes must be detectible.

white dwarfs, and, by extension, that LHC collisions are safe. The actual evidence presented in the GM paper is reviewed below.

▼ Review of Proposed Candidate White Dwarfs

The first part of this section critically reviews the basic parameters (mass, magnetic field, age, crystallization, etc.) of the 8 candidate white dwarfs proposed in the GM paper, and the second part examines the evidence for whether or not they are being affected by black hole accretion.

The candidate white dwarfs and the data presented about them in the GM paper [GM pp. 44–45] are the following:

No	ID	Mass (est.)	Magnetic Field (est.)	Age (est.)	Ref.
1	WD0346–011	1.25 $M_\odot$	< 120,000 G	~100 Myr	[SS95 ↗], [Kaw07 ↗]
2	WD1022–301	1.2 $M_\odot$	< 120,000 G	≳100 Myr	[Kaw07 ↗]
3	WD1724–359	1.2 $M_\odot$	< 120,000 G	~150 Myr	[Kaw07 ↗]
4	WD2159–754	1.17 $M_\odot$	< 30,000 G	~2,500 Myr	[Kaw07 ↗]
5	WD0652–563	1.16 $M_\odot$	< 270,000 G	~100 Myr	[Kaw07 ↗]
6	WD1236–495	1.1 $M_\odot$	< 30,000 G	≳1,000 Myr	[Kaw07 ↗]
7	WD2246+223	0.97 $M_\odot$	1,500 ± 13,800 G	~1,500 Myr	[SS95 ↗], [NM04 ↗]
8	WD2359–434	0.98 $M_\odot$	3,000 G	~1,500 Myr	[Cuad04 ↗], [Kaw07 ↗]

1 - Qualifications of Candidate White Dwarfs

This first part focuses largely on the three criteria set out in the GM paper, viz.:

> Several known white dwarfs satisfying our criteria of mass $M \gtrsim M_\odot$, $B_p \lesssim \text{few} \times 10^5 G$, and age $T \gtrsim 100$ Myr can be found, for example, in [62-64]. [GM p. 44]

Along with these criteria is the requirement that a candidate white dwarf not have started crystallizing. The results from vetting each candidate are summarized below:

WD0346–011 (also known as EUVE J0348–009, GD 50, GR288, KUV 898–9, REJ0348–005)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The article by Aznar Cuadrado *et al.* (cited by the GM paper for another candidate) estimates the age of this candidate to be only 59 million years [Cuad04 p. 1090, table 3].
- Another recent article specifically on this candidate estimates its age as 61 ± 6 million years (assuming a carbon-oxygen core and a thick hydrogen atmosphere), or 58 ± 6 million years (assuming a carbon-oxygen core and a thin hydrogen atmosphere) [Dob06 arXiv p. 2]. This estimate is reinforced by the authors' theoretical modelling of the candidate's ejection from the Pleiades [Dob06 arXiv p. 3].

- The effective temperature estimates listed earlier for this candidate places it in the DB gap. No age estimate has been given to address the possibility that this white dwarf has undergone spectral evolution.
- No age estimate is given for this candidate if it has a core composed of heavier than usual elements (i.e. heavier than an oxygen-neon-magnesium core), or if it has a core which contains strange quark matter.
- The level of helium found in the atmosphere of this candidate is considered "paradoxical" [VBD96 abstract] and remains unexplained [Ven99 p. 1001] [DVC02 p. 1098]. Understanding the reasons behind its helium levels would be important for both confirming estimates of its basic parameters, and understanding its evolution. If the processes leading to these helium levels are associated with a more rapid evolution, it would further reduce the estimated age of this candidate.
- This candidate is reported to have the broadest Balmer lines of the survey by Aznar Cuadrado *et al.*, and consequently the weakest limit on its magnetic field strength [Cuad04 p. 1091, see also p. 1085, figure 1].
- While this candidate is generally believed to be an ultramassive white dwarf, there is still a small degree of uncertainty about its actual mass. An earlier article by McMahan estimated its surface gravity as $\log g = 8.03 \pm 0.19$ with a corresponding mass of only $0.585 \pm 0.121 M_\odot$ [McM89 p. 416, table 2]. A couple years later Bergeron *et al.* investigated this star in further detail and estimated its surface gravity as $\log g = 9.00 \pm 0.15$ based on a comprehensive fit of Balmer lines from their 8 Å resolution data, $\log g = 9.36 \pm 0.39$ based on a fit of the 1 Å Hβ profile, and $\log g = 9.40 \pm 0.50$ based on a fit of the Lyα profile [Berg91 p. 269]. They adopted the value $\log g = 9.00 \pm 0.15$, which corresponds to a mass of $1.20 + 0.07 / - 0.08 M_\odot$ [Berg91 pp. 270, 271]. The authors considered whether the peculiar spectrum of the candidate could still be possible when assuming their estimated effective temperature, but a surface gravity of $\log g = 8.0$ (corresponding to a normal-sized white dwarf). They concluded that an unusually high surface gravity (and mass) is the most plausible explanation of the candidate's spectrum, but they could not completely rule out the possibility that it could be the result of rotational broadening or a stronger magnetic field [Berg91 pp. 270, 271]. A subsequent article by Vennes *et al.* lent support to the possibility that the candidate could be rotating very rapidly [VBD96 ↗], but a later paper by Vennes discounted this possibility [Ven99 p. 1001].
- This candidate has in the past been identified as the possible product of a binary merger [Berg91 p. 271] [VBD96 p. L106] [Segretain]. In light of observations indicating a slower rotational speed [Ven99 p. 1001, also p. 1003, figure 5a] this proposal has lost part of its appeal, but it is still considered a possible explanation for the formation of the candidate [DVC02 p. 1097].
- An article by Maxted *et al.* reporting 594 previously unpublished radial velocity measurements for 71 white dwarfs documented an extraordinary range in the radial velocity measurements of the candidate. The measurements ranged from a low of 42.2 ± 47.1

km/second to a high of 310.4 ± 46.0 [MMM00 p. 313, table 9].[168]. The range and errors for this candidate were much greater than those that the authors report for all the other white dwarfs in their paper. [MMM00 pp. 312–317, table 9] Complementing the uncertainty in spectroscopic determinations of this candidate's mass, such variability throws into question the reliability of any mass estimate based on the star's gravitational redshift. More generally, these measurements beg the question, exactly what is going on at the place called white dwarf 0346—011?

▹ ADD NOTE on even shorter time frames from some temperature estimates

▹ ADD NOTE on mass and temperature estimates for possible crystallization

WD1022–301 (EUVE J1024–303, RE J1024–302, WD1024–303J)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The GM paper's age estimate for this candidate ignores the range of possible masses and effective temperatures stated in the original source that it cites. The article by Kawka *et al.* gives the parameters $M = 1.21 \pm 0.05 M_\odot$ and $T_{\rm eff} = 34{,}700 \pm 700$ K [Kaw07 p. 505, table 2 ↗]. Using the evolutionary tracks published by Althaus *et al.*, the lower end of the mass range corresponds to an estimated age of 77 to 89 million years. At the higher end of the mass range the estimated age is 153 to 173 million years [Alt07.xls ↗].[169] For the lower age estimate of 77 million years (corresponding to a mass of 1.16 $M_\odot$ and an effective temperature of 34,000 K), one must wait another 3 million years to observe the effects of black holes in the GM paper's 80 million year accretion scenarios.[170, 171] For the higher mass estimate, the candidate would have begun crystallizing about 45 to 65 million years ago.[172] No information has been given on whether the candidate's mass was high enough and magnetic field low enough to trap black holes prior to the onset of crystallization. It should be noted that the given errors in the estimates of the candidate's mass and effective

[168] The 10 heliocentric radial velocity measurements for WD0346–011 are: 89.6 ± 35.2, 70.4 ± 43.9, 99.8 ± 55.2, 179.9 ± 54.6, 42.2 ± 47.1, 310.4 ± 46.0, 120.5 ± 43.6, 121.1 ± 43.0, 225.3 ± 48.7, and 136.0 ± 51.5 km/second [MMM00 p. 313, table 9]

[169] Values between data points in the given tables were based on log-log interpolation. Age estimates for a mass of 1.26 $M_\odot$ were based on the average of the log of the age estimates from the 1.24 $M_\odot$ and 1.28 $M_\odot$ tables–a rough approximation.

[170] The cooling tracks used are those for ultramassive white dwarfs with the maximum possible hydrogen in their atmosphere. If the candidate has less than the maximum level of hydrogen in its atmosphere, its estimated age should be further reduced.

[171] The GM paper suggests that accretion times are proportionately faster for white dwarfs with higher central densities but it ignores the effect that changes in the sound speed would have on the Bondi accretion times. For further comments about this, please see section 8.1.4

[172] The time for the onset of crystallization in a 1.26 $M_\odot$ white dwarf was taken as ~ 108 million years, based on the average of the log of the crystallization times for 1.24 $M_\odot$ and 1.28 $M_\odot$ white dwarfs.

temperature are only 1 σ statistical fitting errors and do not take into account possible systematic effects in model calculations or data acquisition and reduction procedures [Kaw07 p. 501 ↗]. If other errors were included, the age would be reduced at the lower end and the time since the start of crystallization would be increased at the higher end.[173]

- An estimated effective temperature of 34,700 ± 700 K [Kaw07 p. 505, table 2 ↗] places this white dwarf in the DB gap. No age estimate has been given to address the possibility that this star has undergone spectral evolution.
- No age estimate is given for this candidate if it has a core composed of heavier than usual elements, or if it has a core which contains strange quark matter.
- ▷ ADD NOTE on the number of studies of this WD

WD1724–359 (EUVE J1727–360, RE J1727–355)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The GM paper's age estimate for this candidate ignores the range of possible masses and effective temperatures stated in the original source that it cites. The article by Kawka *et al.* gives the parameters M $= 1.20 \pm 0.03 M_\odot$ and $T_{\text{eff}} = 32{,}000 \pm 250$ K [Kaw07 p. 505, table 2 ↗]. Using the evolutionary tracks published by Althaus *et al.*, the lower end of the mass range corresponds to an estimated age of 107 to 113 million years and the higher end of the mass range to an estimated age of 161 to 181 million years [Alt07.xls ↗].[174] For the higher mass estimate, the candidate would have begun crystallizing about 37 to 57 million years ago.[175] No information has been given on whether the candidate's mass was high enough and magnetic field low enough to trap black holes prior to the onset of crystallization. It should also be noted that the given errors in the estimates of the candidate's mass and effective temperature are only 1σ statistical fitting errors and do not take into account possible systematic effects in model calculations or data acquisition and reduction procedures [Kaw07 p. 501 ↗]. If other errors were included, the age would be further reduced at the lower end (possibly to the point where the estimated age would be insufficient to cover longer accretion scenarios), and the time since the start of crystallization would be increased at the higher end.

[173] It should also be noted that while a 1 σ error range is a convenient convention for general scientific research, it is wholly insufficient for an assessment of catastrophic risks which could affect the entire planet. CERN may wish to indicate what range of errors should be considered for such a risk assessment, while keeping in mind that insofar as a risk assessment is based on certain data, limits in the error range considered would correspond to limits in the confidence of any safety assertions. For further comments on this issue, please see section 10.

[174] Values between data points in the given tables were based on log-log interpolation. Age estimates for masses of 1.17 $M_\odot$ and 1.23 $M_\odot$ were based on linear interpolation of the log of the age estimates for the nearest masses with published tables.

[175] The time for the onset of crystallization in a 1.23 $M_\odot$ white dwarf was taken as ~ 124 million years, based on linear interpolation between the log of the crystallization times for 1.20 $M_\odot$ and 1.24 $M_\odot$ white dwarfs.

- An estimated effective temperature of 32,000 ± 250 K [Kaw07 p. 505, table 2 ↗] places this white dwarf in the DB gap. No age estimate has been given to address the possibility that this star has undergone spectral evolution.
- No age estimate is given for this candidate if it has a core composed of heavier than usual elements, or if it has a core which contains strange quark matter.

▷ ADD NOTE on other estimates for higher mass and possible crystallization (1.22)

WD2159–754 (BPM 14525, L0048–015, LFT 1679, LHS 3752, LP 48–15, LTT 8816, NLTT 52728, Wg 52)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The candidate's estimated age of ~ 2.5 Gyr [GM p. 45] implies that it began crystallizing well over a billion years ago. The GM paper's accretion time estimates do not apply to crystallized white dwarfs. No information is available on the candidate's mass or magnetic field prior to the onset of crystallization.
- The candidate's estimated temperature of 9040 ± 80 K [Kaw07 p. 505, table 2 ↗] is in the range for which mass estimates are considered unreliable [Kep07 pp. 1318–1319].
- The candidate is reported in an earlier article to have a surface gravity of 8.1 ± 0.2 [SW81 p. 275, table 1], implying the mass of a regular white dwarf—well below the mass criterion of the GM paper. This lower estimate is noted, but not refuted, in the article cited by the GM paper for this candidate's mass qualification [Kaw07 p. 507 ↗]. Uncertainty over the distance (and thus the mass) is highlighted in a second article cited by the GM paper, which based its distance estimate for the candidate on the assumption that its surface gravity was $\log g = 8.0$ [Sub08 arXiv p. 7] (compared to an estimate of $\log 8.95 \pm 0.12$ by Kawka *et al.* [Kaw07 p. 505, table 2 ↗]. This article further states that, "Trigonometric parallax measurements are underway to confirm its luminosity and hence its mass." [Sub08 arXiv p. 7, hyperlink added] The GM paper similarly states, "Parallax determinations of the absolute distance are underway to confirm the mass assignment." [GM p. 45, footnote 18] As of 14 September 2009, CERN has provided no further information on the estimated mass of this candidate. The slightly revised version of the GM paper contains the same footnote as that cited above [GMv2 p. 45, footnote 18]. A search of CERN's website uncovered no new statements about this candidate [▷ ADDCITE CERN website search]. The researchers who reported that "Trigonometric parallax measurements are underway..." [Sub08 arXiv p. 7] are also responsible for the Discovery & Evaluation of Nearby Stellar Embers (DENSE) project which is attempting to identify and accurately characterize all white dwarfs within 25 parsecs of the Sun [▷ ADDCITE DENSE ↗]. The higher mass estimate for this candidate is associated with a distance estimate of 14 parsecs, while the much lower mass estimate is associated with a distance estimate of 30.5 ± 5.3 parsecs [Sub08 arXiv p. 7]. As of 10 February 2009, this candidate has not been included in the DENSE project's attempt at a comprehensive catalogue of all white dwarfs within 25 parsecs of the Sun, even though it

should be if its mass is that assumed in the GM paper. The candidate is also not mentioned in the subsequent instalment of "The Solar Neighborhood", which identifies 20 new white dwarfs within 25 parsecs of the Sun [Sub09 arXiv http://arxiv.org/pdf/0902.0627v1↗].[176]

- The qualifying magnetic field estimates for this candidate appear to be based on just a single published article, which is itself based on just two nights of observation of the candidate in 2000. The first observation took place on 25 November 2000, during which data was collected on the candidate along with data on 5 other white dwarfs. The second observation took place a week later on 2 December 2000 when again data was collected on the candidate along with 5 other white dwarfs. [Kaw07 p. 501, table 1 ↗]

WD0652–563 (EUVE J0653–564)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The GM paper's age estimate for this candidate ignores the range of possible masses and effective temperatures stated in the original source that it cites. The article by Kawka *et al.* gives the parameters M $= 1.16 \pm 0.06 M_\odot$ and $T_{\text{eff}} = 33{,}480 \pm 620$ K [Kaw07 p. 505, table 2 ↗]. Using the evolutionary tracks published by Althaus *et al.*, the lower end of the mass range corresponds to an estimated age of 62 to 72 million years and the higher end of the mass range to an estimated age of 125 to 141 million years [Alt07.xls ↗].[177] For the lower mass estimate one must wait another 8 to 18 million years to observe the effects of black holes in the GM paper's 80 million year accretion scenarios. At the high end of the mass estimate and low end of the temperature estimate, the candidate would have begun crystallizing about 8 million years ago.[178] No information has been given on whether the candidate's mass was high enough and magnetic field low enough to trap black holes prior to the possible onset of crystallization. As noted in the cases of WD1022–301 and WD1724–359, the given errors in the estimates of the candidate's mass and effective temperature are only 1σ statistical fitting errors and do not take into account possible systematic effects in model calculations or data acquisition and reduction procedures [Kaw07 p. 501 ↗]. If other errors were included, the ages would be further reduced at the lower end, and the time since the start of crystallization would be increased at the higher end.
- An estimated effective temperature of 33,480 ± 620 K [Kaw07 p. 505, table 2 ↗] places this white dwarf in the DB gap. No age estimate has been given to address the possibility that this star has undergone spectral evolution.

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[176] The inclusion of this white dwarf in the list of potential candidates can be taken as an indication that CERN was somewhat desperate in its search for examples. Given that a mass $M \gtrsim 1.0 M_\odot$ is clearly stated in the GM paper as a qualifying criterion for candidates [GM p. 44 ↗], this white dwarf should only have been considered after its mass had been independently examined and confirmed.

[177] Values between data points in the given tables were based on log-log interpolation. Age estimates for a mass of 1.22 $M_\odot$ were based on the average of the log of the age estimates from the 1.20 $M_\odot$ and 1.24 $M_\odot$ tables.

[178] The time for the onset of crystallization in a 1.22 $M_\odot$ white dwarf was taken as ~ 134 million years, based on the average of the log of the crystallization times for 1.20 $M_\odot$ and 1.24 $M_\odot$ white dwarfs.

- No age estimate is given for this candidate if it has a core composed of heavier than usual elements, or if it has a core which contains strange quark matter.

▷ ADD NOTE on limited observations of this white dwarf

WD1236–495 (BPM37093, L0327–186, LFT 0931, LHS2594, LTT 4816, V886 Cen)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The candidate's estimated age of $\gtrsim$ 1 Gyr [GM p. 45] implies that it began crystallizing hundreds of millions of years ago. The GM paper's accretion time estimates do not apply to crystallized white dwarfs. No information is available on the candidate's mass or magnetic field prior to the onset of crystallization.
- The candidate's estimated temperature of 11,870 ± 130 K [Kaw07 p. 505, table 2 ↗] is in the range for which mass estimates are considered unreliable [Kep07 pp. 1318–1319].

WD2246+223 (EG155, G067–023, G127–058, G128–004, LHS3857, LTT18580)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The candidate's estimated age of ~ 1.5 Gyr [GM p. 45] implies that it began crystallizing hundreds of millions of years ago. The GM paper's accretion time estimates do not apply to crystallized white dwarfs. No information is available on the candidate's mass or magnetic field prior to the onset of crystallization.
- The candidate's estimated temperature of 10,330 ± 300 K [Berg 2001 p. 440, table 2] is in the range for which mass estimates are considered unreliable [Kep07 pp. 1318–1319].

WD2359–434 (BPM 45338, EG165, L0362–081, LEHPM 1–64, LP988–088, LTT 9857)

- No errors are given for the mass, magnetic field, or age estimates in the GM paper.
- No information is given on the evolution of the candidate's mass or magnetic field.
- The candidate's estimated age of ~ 1.5 Gyr [GM p. 45] implies that it began crystallizing hundreds of millions of years ago. The GM paper's accretion time estimates do not apply to crystallized white dwarfs. No information is available on the candidate's mass or magnetic field prior to the onset of crystallization.
- All three of the articles cited by the GM paper that include a mass estimate for this candidate give a value below 1.0 $M_\odot$. The three estimates are: 0.95 $M_\odot$ [Cuad04 p. 1090, table 3], 0.956 [▷ ADDCITE Isolated Massive p. 510, table 1], and 0.98 $\pm 0.04 M_\odot$ [Kaw07 p. 505, table 2 ↗]. Of these three, the GM paper presents only the highest mean value, $0.98 M_\odot$, given by Kawka

et al. [Kaw07 p. 505, table 2 ↗], even though the main reference it cites for this white dwarf gives a lower mass estimate [Cuad04 p. 1090, table 3].[179] It should also be noted that the lower $1\,\sigma$ statistical error range for the figure the GM paper does cite is a mass of only $0.94 M_{\odot}$. While the GM paper does present its mass criterion as greater than approximately $M_{\odot}$ [GM p. 44], it does not present data, such as a calculation of column densities, to justify the inclusion of candidates with masses even slightly below $1.0 M_{\odot}$. Moreover, the paper does explicitly state that, "In the case of $D = 7$, one needs stars heavier than approximately 1.1 solar masses in order to achieve stopping up to 14 TeV." [GM p. 38], so both this candidate and the previous one, WD2246+223, are only relevant for a limited range of parameters.

- An earlier article by Koester *et al.* reported a much lower mass for this candidate. Based on its surface gravity they estimated a mass of $0.41 M_{\odot}$,[180] and based on its radius they estimated a mass of $0.69 M_{\odot}$ [KSW79 p. 270, table 4].

- The candidate's estimated temperature of 8570 ± 50 K [Kaw07 p. 505, table 2 ↗] is in the range for which mass estimates are considered unreliable [Kep07 pp. 1318–1319].

- A study on the rotation of white dwarfs by Koester *et al.* reports that the observed Hα core of this candidate is much narrower and flatter than the authors' zero-rotation model predicts. The authors state, "We have no explanation in this case and can only speculate, that perhaps we see only the unshifted component of a Zeeman triplet, with the other components shifted outside the observed spectral range or smeared out due to the inhomogeneity of the field." [▷ ADDCITE Koester 1998 p. 618] This issue is also noted in the article by Aznar Cuadrado *et al.* cited by the GM paper, which calculates that a magnetic field greater than 50 kG would be needed to shift the σ components outside the spectral range observed by Koester *et al.*, but they report that no further components could be detected in their spectra or in the ESO Supernovae type Ia Progenitor surveY (SPY) spectra [Cuad04 p. 1092]. The article concludes that the reason for the flat Balmer line cores of this candidate remains a mystery, however, they suggest that it could be due to the star having a broad range of magnetic fields, since that would smear out the σ components. They note, though, that there was no indication of such a broad range in their polarization measurements [Cuad04 p. 1092]. Thus, there still remains significant uncertainty about the nature and magnitude of the magnetic fields of this candidate.

- An article by Maxted and Marsh on double degenerates among DA white dwarfs identifies this candidate as an odd star that clearly deserves further investigation [MM99 p. 127, see also figure 6].

[179] It may be noted that the candidate white dwarfs presented in the GM paper are listed in descending order according to their mass [GM pp. 44-45 ↗], except for this candidate. This suggests the possibility that an earlier draft of the paper included the mass estimate of $0.95\ M_{\odot}$ found in [Cuad04 ↗] (in which case all of the candidates would have been listed in order of mass), but the authors later picked out a higher mass estimate to put in the text without changing the order of the list. This is, however, pure speculation...

[180] This was erroneously reported as $0.91\ M_{\odot}$ by Bragaglia *et al.* [BRB95 p. 744, table 2] due to the extremely small font of the original table.

Summary of the Review of Qualifications

The results of this review can be summarized as follows:

- ✗ Four of the eight candidates (WD2159–754, WD1236–495, WD2246+223, and WD2359–434) were crystallized hundreds of millions of years ago, and no model for black hole accretion within crystallized white dwarfs was presented in the GM paper. Moreover, the temperature of these four white dwarfs are so low that their mass estimates are considered unreliable.
- ✗ All of the remaining four candidates (WD0346–011, WD1022–301, WD1724–359, and WD0652–563) have effective temperatures in the DB gap and should have age estimates which include the possibility that they have undergone spectral evolution.
- ✗ Three of the remaining four candidates have mass and temperature estimates from the source cited by the GM paper which for the higher end of the mass estimates imply they may have started crystallizing millions of years ago. More specifically, the time since the onset of crystallization would be 45 to 65 million years for WD1022–301, 37 to 57 million years for WD1724–359, and 8 million years for a low temperature estimate of WD0652–563.
- ✗ The remaining candidate (WD0346–011) has a published age estimates of ~ 60 million years, which would be too short for the GM paper's argument. It also has a number of other peculiar features which should have been further investigated before its nomination as a candidate.
- ✗ No information has been provided on the history of the mass evolution of any of the candidates, and in at least one case (WD0346–011) a candidate has features which suggest that it may have formed through the recent merger of two smaller white dwarfs.
- ✗ No variability or uncertainty in the present magnetic field has been considered for any of the candidates, even though in at least one case (WD2359–434) a broad range of magnetic fields has been proposed to explain a candidate's peculiar spectra.
- ✗ No information has been given on the past evolution of the magnetic fields of any of the candidates.

2 - Evidence for the Absence of Effects of Hypothetical Black Holes

This part reviews what evidence has been presented in the GM paper that the candidate white dwarfs are not being affected by black hole accretion. The findings are as follows:

WD0346–011 (EUVE J0348–009, GD 50, GR288, KUV 898–9, REJ0348–005)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.

- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.

WD1022–301 (EUVE J1024–303, RE J1024–302, WD1024–303J)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.
- ▷ ADD NOTE about the need to distinguish between heating from crystallization versus heating from black holes reradiation

WD1724–359 (EUVE J1727–360, RE J1727–355)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.
- ▷ ADD NOTE about the need to distinguish between heating from crystallization versus heating from black holes reradiation

WD2159–754 (BPM 14525, L0048–015, LFT 1679, LHS 3752, LP 48–15, LTT 8816, NLTT 52728, Wg 52)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.

WD0652–563 (EUVE J0653–564)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.
- ▷ ADD NOTE about the need to distinguish between heating from crystallization versus heating from black holes reradiation

WD1236–495 (BPM37093, L0327–186, LFT 0931, LHS2594, LTT 4816, V886 Cen)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.
- This candidate is a well known ZZ Ceti star [▷ ADDCITE], experiencing non-radial pulsations and significant fluctuations in its temperature. No attempt has been made to show that such macroscopic disruptions are unrelated to possible internal black hole accretion.

WD2246+223 (EG155, G067–023, G127–058, G128–004, LHS3857, LTT18580)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.

WD2359–434 (BPM 45338, EG165, L0362–081, LEHPM 1–64, LP988–088, LTT 9857)

- The astronomical data demonstrates that this candidate has not been destroyed by black hole accretion.
- No data whatsoever is given on the candidate's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.

- No evidence is presented to show that the candidate has not experienced other macroscopic disruptions.
- The article by Maxted and Marsh notes that there is some hint of variability in the Hα line of their spectra from this candidate [MM99 p. 127]. Any argument against the presence of black holes within this candidate would need to first rule out the possibility that macroscopic disruption caused by black hole accretion is one of the causes of this variability. Secondly, any bound on the possible black hole heating of the candidate would need to be based on an analysis which took into account any variability in the electromagnetic radiation from the star.

Summary of the Review of Evidence of No Effect

The results of this review can be summarized as follows:

✓ All of the eight candidates appear to still exist and therefore have not been destroyed by black hole accretion or any other causes.

✗ No evidence whatsoever is provided for any of the candidates to show that they are not presently experiencing significant heating from black hole accretion.

✗ No effort has been made for any of the candidates to show that they have not experienced other macroscopic disruptions due to black hole accretion.

§ General Relationship Between Earth and White Dwarf Accretion Times

The previous section reviewed the GM paper's "specific" astrophysical argument in which definite predictions are given for the maximum accretion times within white dwarfs and these predictions are compared with astrophysical observations.

This section briefly reviews the "general" astrophysical argument of the GM paper, which contends that there is a relationship between accretion times in the Earth and in white dwarfs, and that the long lives of certain white dwarfs implies that the Earth cannot be destroyed by black holes within a short time frame. The GM paper presents the argument as follows:

> We then studied accretion, showing that accreting black holes will disrupt such objects on time scales short as compared to their observed lifetimes. In particular, we found a general relationship (7.15) between accretion times for Earth and for white dwarfs, which, when combined with white dwarf ages exceeding 10^9 years, provides a very strong constraint. Thus, the implication of these arguments is that such scenarios, where Earth would be disrupted on time scales short as compared to its natural lifetime, are ruled out. [GM p. 51, hyperlink in original]

The claim that there is a general relationship between the physical accretion times within the Earth and white dwarfs has been critically reviewed earlier in section 8.1.4. This section focuses on whether the relationship presented in the GM paper can be used to demonstrate the safety of black hole production on the Earth. Some of the problems with the GM paper's argument include the following:

General Issues - This "general" argument shares a number of the same weaknesses as the "specific" argument, including uncertainties about the cosmic ray production rates and black hole trapping rates. Several of the other general issues reviewed above for the specific argument also apply in this case, including its applicability to a limited number of dimensions and a limited range for the value of M_D, as well as the risks inherent in a safety argument based on distant and poorly understood objects.

Restriction to Specific Candidate White Dwarfs - While the GM paper claims to have found "a general relationship (7.15) between accretion times for Earth and for white dwarfs", any possible relationship would only be relevant for white dwarfs which are able to trap black holes in the first place. This again restrict the argument to the 8 candidate white dwarfs identified in the GM paper [GM pp. 44–45] (with the possible addition of other white dwarfs which meet the mass and magnetic field criteria, but whose estimated ages are too short to qualify for the specific argument).

Non-Applicability to Crystallized White Dwarfs - As noted previously for the specific argument, the GM paper's accretion model does not apply to crystallized white dwarfs. This is also clearly the case for the general argument since the purported accretion time ratios are based solely on a portion of the Bondi accretion phase [GM p. 44, eq. 7.15], which in turn depends on hydrodynamical conditions [GM p. 54]. This limitation is particularly noteworthy, considering that the GM paper claims that the combination of the general accretion times relationship and the existence of white dwarf with ages greater than a billion years provides a very strong constraint, even though all such white dwarfs would be expected to have started crystallizing and the general relationship would not apply to them.

Non-Applicability to Multiple Black Hole Accretion in the Earth - As noted earlier, the proposed general relationship would not apply to the case of multiple black holes accreting within the Earth. Thus, any safety argument based on this relationship would only be relevant if just a single black hole is trapped from the LHC or any other future collider experiments conducted over the next few billion years.

Non-Applicability to Subnuclear Phase - As noted earlier, no general relationship has been proposed for the subnuclear phase of black hole accretion. If this phase takes longer in white dwarfs, no immediate conclusions can be drawn for the corresponding time within the Earth.

Non-Applicability to Subatomic Phase - As also noted earlier, no general relationship has been proposed for the subatomic phase of black hole accretion. No claim is made about a ratio between these times, and, in fact, the subatomic phase in white dwarfs stops at a scale 100 times smaller than that in the Earth [GM pp. 41, 42]. No claim is made either for a ratio of accretion times for the period in which accretion within the Earth is based on an electromagnetic capture radius while accretion within white dwarfs is modelled as Bondi accretion.

Non-Applicability if No Bondi Accretion - If black hole accretion within either the Earth or white dwarfs is not spherically symmetric and steady during macroscopic accretion, there would be no basis for a general relationship based on Bondi accretion rates. (Although, if it could be shown that the accretion rate is no faster than the Bondi rate in the Earth, and no slower than the Bondi rate in white dwarfs, then the Bondi-based ratio could still be a useful bound.)

Non-Applicability to Post-Bondi Phase - Even if there is a Bondi accretion phase for both the Earth and white dwarfs, the GM paper makes no claim about the purported general relationship holding during the post-Bondi phase. One likely form of post-Bondi accretion is Eddington-limited growth, and the equation given in the GM paper [GM p. 64, eq. B.28] suggests that the doubling times within both the Earth and white dwarfs would be relatively similar (more specifically, the ratio of doubling times would be the ratio of the scattering cross-section of infalling particles, σ, which may be similar, possibly multiplied by the ratio of the coefficient for reradiation, η, if there is a difference in this coefficient.)

Non-Applicability to Smaller Values of R_C - For values of $R_C < 15$ Å, the specific argument is not expected to apply, since the GM paper's bound on the white dwarf accretion times is far too long [GM p. 43]. One may instead try to apply the general argument and claim that if the accretion process takes so long, this would itself imply a safety bound on the Earth (and this is, indeed, where the GM paper first introduces its proposed ratio of accretion times [GM p. 44]) . However, for young, non-crystallized white dwarfs, the GM paper only attempts an argument against an Eddington limit for values of $R_D \gtrsim 5$ Å[GM p. 59] (i.e. values of $R_C \gtrsim 27$ Å). Thus, for these values of R_C there is no claim against an Eddington limit during even the earlier "macroscopic" stages of accretion. As noted above, the proposed general relationship does not apply to the post-Bondi phase (or even the pre-Bondi phases). The GM paper sets no limit on the (pre-disruptive) Eddington-limited growth times for these values of R_C, so there is effectively no minimum time on which to base a general relationship with the Earth.

Application to Trapping Age Only - The GM paper presents it general relationship as a ratio based on the age of white dwarfs, but, aside from its applicability only to one phase of the accretion process, the ratio can only be applied after a white dwarf has trapped a black hole. This requires first that a white dwarf have a high enough mass and low enough magnetic field to be capable of trapping a black hole. As noted above, white dwarfs can undergo significant changes in both their mass and magnetic field, so the present mass and magnetic field estimates for a white dwarf cannot be assumed to hold for an arbitrary point in the past. Thus far, no information has been given about the historical state of the candidate white dwarfs, so there is not yet any basis for any conclusions based on a general relationship. Moreover, even after a white dwarf meets the mass and magnetic field requirements, it must wait for the random probability of a black hole being created and trapped, which in turn depends on uncertain production and trapping rates.

Differences in Sensitivity to Small Additions - Since all of the non-crystallized white dwarfs cited by the GM paper have estimated ages of only 100 million to 150 million years (and possibly less), they are very sensitive to relatively small increases in the times required for the non-Bondi accretion phases. Suppose an additional 50 million years are required for the subatomic phase for both white dwarfs and the Earth (as noted above, there is no proposed general relationship for this stage), then the implications for the Earth's safety would be relatively insignificant, but the white dwarf argument would most likely be invalidated. If the increase in accretion times is 150 million years, the white dwarf argument would certainly be invalidated. This illustrates the fairly tight constraints on acceptable increases in time for the other accretion phases.

Uncertainty in Age Estimates - As reviewed above, there is a great deal of uncertainty in what the GM paper characterizes as the "known lifetimes" of white dwarfs [GM abstract, p. 43, and p. 44]. Should the true age of a candidate white dwarf be significantly shortened, this would further reduce the time available for that white dwarf to meet the mass and magnetic field criteria, trap a black hole, complete the subnuclear accretion phase, complete the subatomic accretion phase, complete the Bondi accretion phase, and complete any post-Bondi pre-disruptive accretion phase. Reductions in a white dwarf's age do not necessarily result in proportionate reductions in these different phases, so the net result may simply be a direct reduction in the lower bound on the Bondi accretion time, which is the key time frame on which the general relationship is based.

Application to Longer-than-Predicted Accretion Times - If the specific argument was based on the authors' best estimates of the accretion times within white dwarfs, then the proposed general relationship might be useful to address the cases in which the white dwarf accretion times are longer than expected. The argument presented in the GM paper, however, is based on the claim that the calculated white dwarf accretion times are, in fact, the longest possible times [GM pp. 4, 5, 43]; the paper contends that it is simply impossible for white dwarf accretion to take longer than the times it gives. Applying the general argument to such a "non-scenario" would first entail an analysis of how black hole accretion within a white dwarf could possibly take longer than its upper bound, and then, based on that analysis, a reassessment of the model for black hole accretion within the Earth. For a risk assessment, another essential step would be a reassessment of the credibility of all the bounds stated in the GM paper and endorsed by CERN.

Application to Shorter Accretion Times - The proposed general relationship of accretion times would not be applicable to time frames shorter than those given in the specific argument unless one decides to abandon the conservative framework of assuming the fastest accretion rate within the Earth, and the slowest in white dwarfs. If this is done, the general argument could, in theory, provide a helpful constraint on accretion times within the Earth, but it is plagued by the same uncertainties described above. Suppose that a white dwarf's age, or, more specifically, trapping age, is assumed to be 1 million years. If the general relationship applied then this would imply a 19 billion year accretion process within the Earth. The problem, however, is being sure that the Bondi accretion phase is a significant portion of that million year period. As noted above, that period would need to be divided into the black hole trapping phase, the subnuclear phase, the remaining subatomic phase, the Bondi phase, and any possible post-Bondi pre-disruptive phase.

If an attempt is made to argue that the Bondi phase must take at least, say, 250,000 years in a white dwarf (implying a corresponding time of 4.75 billion years within the Earth), then one would need to prove that it is simply impossible for any of the other phases to take even longer than expected and further reduce the time available for the white dwarf Bondi phase. Given the uncertainties described in section 8.1.4 about the other accretion phases, the uncertainties about the average black hole trapping rate described in section 7.1.4, and the inherently random nature of the black hole production and trapping process, it may be difficult to set any firm lower bound on the Bondi accretion phase in individual white dwarfs.

Identifying the Effects of Black Hole Accretion - The GM paper does not attempt to estimate the time involved in black hole accretion after it reaches a stage which macroscopically disrupts the host white dwarf. Instead it merely asserts that at that point the white dwarf will either be destroyed or the effects of accretion will be macroscopically visible, with interference with cooling being the only specific example given. As described earlier, this was one of the major gaps in the specific argument since the GM paper presents no data on whether white dwarfs are presently being cooling, and it may be practically impossible to observe any interference with cooling until it reaches a very advanced stage. This issue is equally problematic for the general argument, since for a given white dwarf one must first set a bound on the time involved in this macroscopically disruptive phase (as noted earlier, the general relationship does not apply to it) and then subtract it from the possible trapping age of the white dwarf. Since there is no bound whatsoever on this time, and it could potentially be quite long [cf. GM p. 27], this leaves little scope for a firm time frame on which to base a general argument. This issue is similar to the problem discussed above for low values of R_C, however, in that case the problem was the absence of a bound on a possible pre-disruptive Eddington-limited phase. In this case, which applies to all values of R_C, the problem is the lack of a bound on the subsequent phase when accretion is expected to be macroscopically disruptive. One might consider at least adding the Eddington-limited phase on a one-to-one basis (or whatever the ratio may be) to produce some kind of bound on the times for the Earth (as suggested by the GM paper's argument that if there were an Eddington limit for white dwarf accretion, one is even more likely to find one for the Earth [GM p. 43]). The benefit of doing so, however, is very limited, since the estimated ages of the candidate white dwarfs [GM pp. 44–45] are much less than the 5-8 billion year time frame needed for the Earth.[181]

[181] Moreover, in making such a comparison one may need to take into account the difference in relative tolerance to internal heating. For the Earth, a black hole heating rate of 40 TW [cf. GM p. ↗] (and potentially much less) would be devastating (for a more detailed analysis see section 9), whereas for a white dwarf, a net heating rate of 40,000,000,000,000 TW (i.e. ~ $0.1 L_{\odot}$) [NSSDC:Sun ↗] may not be noticeable after even the most careful observations (see earlier comments).

10.1.5 Existence and State of White Dwarfs Exposed to Flux of Neutral Stable Black Holes

NOTES:

▹ Argument shares many of the same weakness as the standard argument reviewed in section 10.1.4 ▹ ADD SUMMARY

▹ Primary benefit is that magnetic fields are no longer relevant. Useful for adding non-magnetic white dwarfs as possible candidates, although they would still need to have a mass equal to or greater than 1.0 $M_{\odot}$. Also useful for removing uncertainty about the present magnetic fields and the past evolution of the magnetic fields of the 8 candidate white dwarfs identified in the GM paper.

▹ Main drawback, however, is a very large reduction in the black hole production rate. As noted in section 7.1.5, the rate would be reduced to 0.014% of the direct cosmic ray rate. The rate of production assuming a 100% iron cosmic ray flux is only 1 per million years [GM p. 87], and the rate of such black holes being trapped would be even less. Given the possibilities for the suppression of hadronic cosmic rays, or the general suppression of black hole production from hadronic collisions, this argument is of very limited value.

▹ Further uncertainty related to specific location of the white dwarf and its surrounding interstellar medium in relation to possible sources of ultrahigh-energy cosmic rays. The past exposure could be different for different white dwarfs and thus should be checked for any candidate.

▼ Review of Proposed Candidate White Dwarf

The GM paper only suggests one additional candidate based on this argument, although one would expect that with a bit of effort others could be added. That candidate, Sirius-B, is reviewed below.

1 - Qualifications of Sirius-B

- No errors are given for the mass or age estimates in the GM paper.
- The mass is reported to be "exactly one solar mass" [GM p. 87], however, the latest effort to determine the mass of Sirius-B using the Hubble Space Telescope resulted in estimates of 0.84, 0.91, 1.01, and 1.05 $M_{\odot}$[182] depending on the wavelength used and the method of calculation [Bar05 p. 1140, table 5; see also p. 1141, figure 6]; for 2 of the 4 estimates the mass of Sirius-B would not be enough to assume effective trapping of black holes.

[182] More specifically, 0.841 +0.080/-0.026, 0.911 +0.084/-0.027, 1.012 ± 0.060, and 1.050 ± 0.063 $M_{\odot}$ [Bar05 p. 1140, table 5]

- Even assuming a mass of exactly 1 $M_{\odot}$, Sirius-B would not be able to trap black holes in the scenarios requiring a mass of 1.1 $M_{\odot}$.
- No information is given on the evolution of Sirius-B's mass.
- No age estimate has been given to address the possibility that Sirius-B has undergone spectral evolution.
- No age estimate is given for Sirius-B if it has a core composed of heavier than usual elements, or if it has a core which contains strange quark matter.

2 - Evidence for Absence of Effect of Hypothetical Black Holes on Sirius-B

- The astronomical data demonstrates that Sirius-B has not been destroyed by black hole accretion.
- No data whatsoever is given on Sirius-B's rate of heating or cooling. There is no basis for concluding that it is not presently being heated by black hole accretion.
- No evidence is presented to show that Sirius-B has not experienced other macroscopic disruptions.

10.1.6 Existence and State of White Dwarfs Exposed to Flux of Neutral Stable Black Holes Produced in Cosmic Ray Collisions with Dark Matter

As described in section 7.1.6, the very nature of cosmic dark matter is still a mystery. Only after the composition and properties of dark matter are better known would it be possible to claim any reasonable astrophysical bound based on the hypothetical production of black holes in cosmic ray collisions with it.

10.1.7 Existence and State of Neutron Stars Exposed to High Energy Cosmic Rays

TEXT UNDER REVISION

10.1.8 Existence and State of Neutron Stars in Binary Systems

TEXT UNDER REVISION

▷ Rejected as an astrophysical safety argument by CERN's SPC. They deemed the assumptions on cosmic ray composition too speculative at this stage. SPC's advisory states:

> A powerful argument applicable also to higher energies is formulated making reference to observed neutron stars, but this argument relies on properties of cosmic rays and neutrinos that, while highly plausible, do require confirmation, as can be expected in the coming years. [SPC p. 3][183]

[183] As CERN has objected to the use of this statement to sow doubts about the safety of the LHC, it would be appropriate to carefully examine the quotation and the claims made about it.

Shortly after the release of the GM paper, the LSAG report, and the SPC's opinion about those documents, LHC critic James Tankersley Jr. posted an online comment citing the SPC's statement that, "this argument relies on properties of cosmic rays and neutrinos that, while highly plausible, do require confirmation", and claiming that this disclaimer puts the entire LSAG report back into the category of an "open question" [Tank08a ↗].

In response, representatives of the SPC posted the following comment:

> The comment by James Tankersley contains false and misleading statements on the SPC report. The selected quote refers to the possibility of extending the complete safety proof, that has been provided for the LHC, to colliders of much higher energies that could be conceived for the distant future.
>
> The conclusions of the SPC report on the LHC are quite clear: "To summarize, we fully endorse the conclusions of the LSAG report: there is no basis for any concerns about the consequences of new particles or forms of matter that could possibly be produced at the LHC."
>
> Enrique Fernandez chair of the CERN Scientific Policy Committee
>
> Fabio Zwirner member of the CERN Scientific Policy Committee and coordinator of the SPC review panel [FZ08 ↗, hyperlinks added]

In his lecture on the safety of the LHC, Professor John Ellis, representing LSAG, states in a similar vein:

> [32:50] Perhaps a little aside here as to how careful one has to be. So I think that Steve and Michelangelo were were extremely careful and extremely conservative. The SPC committee, when it reviewed, uh, their paper said what a fantastic job they'd done, you know what a fantastic job LSAG had done, et cetera. They made the comment that if, in the future, one wanted to extend these safety arguments to future higher-energy colliders, then, you know, the data did not exist, and this phrase, this part of a sentence was then taken out of context by some of the anti-LHC bloggers and, uh, there was one of them in particular, I've seen about half a dozen different postings by him where he lifts out of context this, uh, SPC report statement, so one has to be very, very careful that whatever, uh, argumentation one provides, ahhh, even if taken out of context cannot be used against you. [Ellis08 from 32:50 to 33:53 ↗]

Interested readers are encouraged to examine the full text of the SPC's document [SPC ↗], however, the context of that particular statement can be described as follows:

On the third page of their opinion, the SPC reviews the potential risks associated with black hole production at the LHC.

The first paragraph begins by noting that for the cases considered in previous reports (i.e. the case that TeV-scale black hole radiate exactly as per the equation for Hawking radiation extended to higher dimensions

Strong Proof vs Weak Proof - As in the case of white dwarfs, the GM paper does not attempt to go for a "strong proof" by showing that no neutron star in a binary system as been affected

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and applied to masses near the higher-dimensional Planck's mass), the LSAG report confirms that there is absolutely no danger. The paragraph then looks at the case of neutral, stable, microscopic black holes and repeats the conditions described in the GM paper for such black holes to exist.

The second paragraph describes how the GM paper is "the most detailed and specialized presentation of all the scientific evidence we have on this issue", and emphasizes that the paper chooses a conservative or "worst-case" scenario at every instance where an experimental or theoretical uncertainty is encountered. It states that the GM paper uses observational data on cosmic rays and astronomical objects to exclude any danger at the LHC.

The third paragraph states that at the LHC energy, "any danger for the Earth on time scales lower than or comparable to the natural lifetime of the solar system can be ruled out on the basis of its contradiction with the observation of white dwarf stars of known mass, age and other properties." The next sentence re-emphasizes that this conclusion is entirely valid for the LHC, but notes that further work would be needed to extend it to conceivable future colliders of much higher energies. The paragraph then concludes with the key statement that the GM paper formulates a powerful argument making reference to observed neutron stars which is *also* applicable to higher energies, but this argument relies on properties of cosmic rays and neutrinos which require confirmation.

The fourth and final paragraph is the statement that, "On the basis of all these findings, we can conclude that there is no danger of whatever kind from the hypothetical production of black holes at the LHC."

The overall conclusion for the SPC's opinion similarly emphasizes that the LSAG report adds further layers of safety to the previously existing ones, "excluding any possibility that the highly hypothetical production of black holes at the LHC could create a danger of whatever kind."

As cited above, the final statement of the opinion is,

> To summarize, we fully endorse the conclusions of the LSAG report: there is no basis for any concerns about the consequences of new particles or forms of matter that could possibly be produced at the LHC. [SPC p. 4 ↗]

What should be clear from this summary is that the SPC emphatically endorses the safety of potential black hole production at the LHC. On the other hand, it is also reasonably clear that the committee did not endorse the safety argument presented in the GM paper based on a hypothetical flux of ultrahigh-energy neutrinos, or based on the production of black holes through cosmic ray collisions with the companions of neutron stars.

The statement from the SPC about these two argument is actually not very different from their presentation in the GM paper. In its conclusion, the GM paper describes it as unlikely that "the composition of ultrahigh-energy cosmic ray primaries is dominantly heavy elements", and unlikely that "ultrahigh energy cosmic ray neutrinos either are not produced, or have suppressed gravitational interactions with partons", and emphasizes that both of these unlikely possibilities would have to be realized for its neutron star argument to fail [GM p. 53 ↗]. The SPC similarly states that the properties of cosmic rays and neutrinos required for the neutron star argument are "highly plausible". The only difference is that the SPC then goes on to express its view that these properties, "require confirmation, as can be expected in the coming years." [SPC p. 3 ↗] The SPC's document makes no other reference to neutron stars, and the SPC does not appear to have issued any other public statement clarifying its opinion about the neutron star argument.

A fair summary of the situation is that the SPC says that it is fully convinced that black hole production at the LHC is safe, but it cannot presently endorse the specific neutron star argument presented in the GM paper.

It may be noted that it is entirely possible for someone so inclined to believe in the safety of black hole production without the neutron star argument, although that would involve ignoring the cases in 6 and 7 by a black hole produced on its companion. The intended argument of the GM paper is only that some neutron stars in binary systems exist with estimated ages (or rather, estimated years of FCE) which are incompatible with the paper's predictions for the production, trapping and accretion of TeV-scale black holes.

Missing Even a Weak Proof - The GM paper fails to even present a "weak proof" that collisions at LHC energies are safe. The paper focuses only on identifying classes of binary systems which could potentially result in enough years of FCE to claim that the neutron star in that system should have been destroyed by a cosmic ray-produced black hole. If the paper's predictions for the production, trapping, and accretion of such black holes are correct, these classes of binary systems could then provide an opportunity for *testing* the hypothesis that "dangerous" TeV-scale black holes do not exist. The existence of the classes themselves is meaningless, since the real question is whether within these classes specific members with sufficient years of FCE actually exist. The paper presents just a single example of a neutron star in a binary system which may meet its FCE criterion. This example, SAX J1808.4–3658, is examined more closely below. Implicitly recognizing that this single example does not constitute a proof, the GM paper then makes the following statement:

> These bounds appear quite challenging to avoid. In order to do so, one would need a significant deficit of light cosmic ray primaries, together with a heavy ($\gtrsim$ 7 TeV) minimum black hole mass *and only systems with low FCE*... [GM p. 50, italics added]

The paper thus abandons any attempt to actually prove its argument, and instead is content to assume that the evidence it requires must exist somewhere.

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dimensions which are not covered by the white dwarf argument, fully accepting the white dwarf argument for the remaining cases, and placing complete faith in the GM paper's calculation of accretion rates in 8 or more dimensions or for values of R_C less than about 200 Å. However, the SPC does seem to have overlooked the GM paper's assertion that, "mass values where the build up of multiple black holes could significantly exceed the value one are firmly excluded for $8 \leq D \leq 11$ by the neutron stars..." [GM p. 83 ↗].

In a subsequent post on his LHCFacts.org website, Tankersley asks if Fernandez and Zwirner are arguing that "the properties of cosmic rays and neutrinos prove safety from micro black holes created by the Large Hadron Collider, but are only highly probable and require confirmation with respect to micro black holes created from higher energy colliders?" [Tank08b ↗]. There does not appear to be any reply to this question from CERN or the SPC.

This interpretation does not seem valid, since, as noted earlier, the SPC document says that the neutron star argument would *also* be applicable to higher energies, implying that their reservations about the neutron star argument apply to LHC energies. Moreover, the ultrahigh-energy neutrino argument presented in the GM paper [GM pp. 78–79, appendix E.3 ↗] does not appear to be very sensitive to reasonable increases in energy above 14 TeV, so if it were applicable, it would apply to both LHC energies and somewhat higher energies. On the other hand, the binary companion argument is much more sensitive to increases in energy—as can be seen in table 9 [GM p. 77, table 9 ↗]—so despite the SPC's optimistic pronouncement for the future, the only hope for this argument is near the LHC's energy range.

Based on these considerations, this paper concludes that the neutron star–neutrino argument and the neutron star–binary companion arguments have been effectively rejected by CERN's SPC. It may be noted, however, that even if the SPC had nominally endorsed these arguments, they would have been rejected in this paper because they are simply too speculative to be considered reasonable safety arguments.

Evidence that Neutron Stars are Being Destroyed by Black Holes - Somewhat ironically, the GM paper further demonstrates that it is not attempting a "strong proof" by itself suggesting that neutron stars are presently being destroyed by black holes. The paper states the following:

> As a final note, in our framework we can estimate the lifetime of a neutron star that captures a primordial black hole of mass $O(10^{15}\text{gr})$. Our parameters yield a time of order $3 \times 10^5 yr$. We note that such processes have been proposed as the origin of some gamma ray bursts [79], with roughly comparable accretion times. The present analysis, in addition to giving the analogous accretion time scales for Earth and white dwarfs, lends further detail to such a possibility through our description via Bondi accretion, and through our arguments against an Eddington limit. [GM p. 50, hyperlinks added]
>
> Reference [79]: DKK99 ↗

The paper mentions no criteria or methodology for using astronomical observations to distinguish between a neutron star destroyed by a hypothetical primordial black hole and a neutron star destroyed by a hypothetical cosmic ray-produced black hole.

The LSAG report, despite being co-authored by Dr. Mangano, seems to have missed the GM paper's suggestion that black hole destruction of neutron stars could be the cause of highly visible gamma ray bursts. It argues the following:

> In fact, ultra-high-energy cosmic rays hitting dense stars such as white dwarfs and neutron stars would have produced black holes copiously during their lifetimes. Such black holes, even if neutral, would have been stopped by the material inside such dense stars. The rapid accretion due to the large density of these bodies, and to the strong gravitational interactions of these black holes, would have led to the destruction of white dwarfs and neutron stars on time scales that are much shorter than their observed lifetimes [2]. The final stages of their destruction would have released explosively large amounts of energy, that *would have been* highly visible. [LSAG pp. 9, italics added]
>
> Reference [2]: GM ↗

The LSAG report then switches to the "weak proof" and states that "The observation of white dwarfs and neutron stars that would have been destroyed in this way tells us that cosmic rays do not produce such black holes, and hence neither will the LHC." [LSAG pp. 9] This final statement is closer to what the GM paper is claiming, but the presentation of this argument in the LSAG report leaves readers with the impression that not only has the "weak proof" been proven, but that it is further backed up by the fact that the explosive destruction of neutron stars has not been observed.

FURTHER TEXT UNDER REVISION

10.1.9 Existence and State of Neutron Stars Exposed to Flux of Neutral Stable Black Holes Produced in Cosmic Ray Collisions with the Interstellar Medium

As noted in section 7.1.9, the GM paper reports that the expected black hole production rate from cosmic rays striking the interstellar medium is too low for the construction of an astrophysical argument based on the assumption that neutron stars of a certain age would have trapped at least one TeV-scale black hole [GM p. 87].

10.1.10 Existence and State of Neutron Stars Exposed to Flux of Ultrahigh-Energy Neutrinos

The GM paper presents an astrophysical argument that neutron stars are exposed to a flux of ultrahigh-energy neutrinos which could produce TeV-scale black holes (if such black holes exist) [GM pp. 47, 78–79, 80]. The continued presence of neutron stars on timescales which are incompatible with the black hole production estimates and the neutron star accretion estimates of the GM paper would then imply a bound on the risks associated with the LHC.

The GM paper recognizes, however, that there are fundamental weaknesses with this proposed argument. Firstly, no ultrahigh-energy neutrinos has ever been observed [GM p. 78]. Secondly, their interactions with hadronic matter may be different from that of protons [GM pp. 47, 50, 53].[184]

In light of these uncertainties, the neutrino argument has been rejected by CERN's Scientific Policy Committee. As noted in section 10.1.8, the SPC's written opinion of the LSAG documents submitted to CERN's Governing Council states:

> A powerful argument applicable also to higher energies is formulated making reference to observed neutron stars, but this argument relies on properties of cosmic rays and neutrinos that, while highly plausible, do require confirmation, as can be expected in the coming years. [SPC p. 3]

Aside from these two issues, the neutrino argument would also be subject to the uncertainties in the GM paper's neutron star accretion model described in section 8.1.5. Thus, at present, no significant astrophysical bound can be claimed based on neutron stars surviving a hypothetical bombardment by ultrahigh-energy neutrinos.

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[184] This is characterized as a "small possibility" in the GM paper but it gives no quantitative estimate for this possibility. The paper's exact statement is the following:

> While these models are not compelling, they would seem to raise a small possibility that neutrino cosmic rays would not produce black holes the same way that nucleons do. [GM p. 47 ↗]

If one assumes that a model is compelling when there is at least 90% confidence that it is correct, then the first phrase means that none of the models has a 90% or greater chance of being correct in its prediction that neutrino cosmic rays do not produce black holes in the same way as nucleons. The GM paper does not specify how much less than 90% it considers "a small possibility".

10.1.11 Summary of Astrophysical Bounds on Neutral Stable Black Holes

Earth (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Earth, there are no astrophysical bounds based on the Earth's existence.

Moon (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Moon, there are no astrophysical bounds based on the Moon's existence.

Sun (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Sun, there are no astrophysical bounds based on the Sun's existence.

White Dwarfs (from cosmic rays)

- An argument has been presented for an astrophysical bound based on the existence of specific massive and ultramassive white dwarfs, but it is subject to a number of uncertainties and unknowns.
- Another argument has been presented based on a proposed general relationship between accretion times within white dwarfs and within the Earth, but this might only apply to single black hole accretion during one phase in the accretion process, and also involves a number of uncertainties and unknowns.

White Dwarfs (after ISM production)

- An argument has been presented for an astrophysical bound based on the existence of specific massive and ultramassive white dwarfs, regardless of their present or past magnetic fields, but the expected black hole production rate is reduced by almost 4 orders of magnitude, and the argument also involves a number of other uncertainties and unknowns.

White Dwarfs (after dark matter production)

- The uncertain nature of cosmic dark matter preclude any meaningful astrophysical bound.

Neutron Stars (from cosmic rays)

- The small size of neutron stars and their powerful magnetic fields prevent a sufficient number of ultrahigh-energy cosmic rays from reaching neutron stars.

Neutron Stars (after production on binary companions)

- The extremely low rate of black hole production for an iron-dominated cosmic flux has led to the GM paper acknowledging that it would insufficient in that case.
- Even if the cosmic ray flux is not iron-dominated, the proposed astrophysical bound would not apply to a number of cases, and would be subject to a number of other uncertainties and unknowns.

Neutron Stars (after ISM production)

- The GM paper acknowledges that the hypothesized rate from ISM production would be too low for an astrophysical argument.

Neutron Stars (from ultrahigh-energy neutrinos)

- The lack of any empirical evidence for the existence of ultrahigh-energy neutrinos precludes any astrophysical bound based on their hypothesized interactions.
- Even if ultrahigh-energy neutrinos were observed, the fundamental differences between charged hadrons and neutral leptons would significantly limit any proposed astrophysical bound.

10.1.12 Safety Implications of Astrophysical Bounds on Neutral Stable Black Holes

TEXT PENDING

10.2 Astrophysical Implications for Neutral Slowly Radiating Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Neutral Slowly Radiating Black Holes

Earth (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Earth, there are no astrophysical bounds based on the Earth's existence

Moon (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Moon, there are no astrophysical bounds based on the Moon's existence

Sun (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Sun, there are no astrophysical bounds based on the Sun's existence

White Dwarfs (from cosmic rays)

- Any possible astrophysical bound based on the existence of specific massive or ultramassive white dwarfs may be similar to the case of neutral stable black holes, but with the added uncertainty of how the radiation from these black holes might affect the expected accretion times
- Compared to slowly radiating black holes within the Earth, there is less of a chance that the heat released through black hole radiation may accelerate the accretion process within white dwarfs (due to their high initial temperatures).

White Dwarfs (after ISM production)

- Any possible astrophysical bound based on the existence of specific massive or ultramassive white dwarfs may be similar to the case of neutral stable black holes produced in the interstellar medium, but with the added uncertainty of how the radiation from these black holes might affect the expected accretion times

Neutron Stars (after production on binary companions)

- Any possible astrophysical bound based on the existence of a specific neutron star binary system may be similar to the case of neutral stable black holes, but with the added uncertainty of how the radiation from these black holes might affect the expected accretion times

§ Safety Implications of Astrophysical Bounds on Neutral Slowly Radiating Black Holes

TEXT PENDING

10.3 Astrophysical Implications for Neutral Equilibrium Mass Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Neutral Equilibrium Mass Black Holes

Earth (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Earth, there are no astrophysical bounds based on the Earth's existence

Moon (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Moon, there are no astrophysical bounds based on the Moon's existence

Sun (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Sun, there are no astrophysical bounds based on the Sun's existence

White Dwarfs (from cosmic rays)

- If black holes which reach an equilibrium mass within the Earth can grow without bounds within white dwarfs, then any possible astrophysical bound may be similar to the case described in section 10.2.
- If the equilibrium mass for black holes within white dwarfs is relatively large, it may be possible, in theory, to determine whether or not they exist through extremely careful observations of specific massive or ultramassive white dwarfs over the course of several decades. Presently there is no evidence from white dwarfs which can be used to claim any astrophysical bound on equilibrium mass black holes.
- If the equilibrium mass for black holes within white dwarfs is relatively small, there would be no basis for claiming that their existence could be detected, and thus, there would be no astrophysical bound based on white dwarfs.

White Dwarfs (after ISM production)

- Any possible astrophysical bound may be similar to the case described above of cosmic rays directly striking white dwarfs, with the added benefit of considering massive or ultramassive white dwarfs regardless of the strength of their present or past magnetic field, but the expected number of black holes would only be about 0.014% of that from direct cosmic rays.

Neutron Stars (after production on binary companions)

- If black holes which reach an equilibrium mass within the Earth can grow without bounds within neutron stars, then any possible astrophysical bound may be similar to the case described in section 10.2.
- If the equilibrium mass for black holes within neutron stars is relatively large, it is not clear if the presence of such black holes could be detected. Unless their detection can be conclusively excluded, no astrophysical bounds can be claimed based on the existence of a specific neutron star in a binary system.
- If the equilibrium mass for black holes within neutron stars is relatively small, there would be no basis for claiming that their existence could be detected, and thus, there would be no astrophysical bound based on a specific neutron star in a binary system.

§ Safety Implications of Astrophysical Bounds on Neutral Equilibrium Mass Black Holes

TEXT PENDING

10.4 Astrophysical Implications for Neutral Rapidly Radiating Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Neutral Rapidly Radiating Black Holes

Earth (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Earth, there are no astrophysical bounds based on the Earth's existence

Moon (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Moon, there are no astrophysical bounds based on the Moon's existence

Sun (from cosmic rays)

- Since cosmic ray-produced neutral black holes would be expected to pass harmlessly through the Sun, there are no astrophysical bounds based on the Sun's existence

White Dwarfs (from cosmic rays)

- Rapidly radiating black holes would be expected to remain relatively small within white dwarfs, which would prevent the detection of their effects and would preclude any astrophysical bound based on white dwarfs.

White Dwarfs (after ISM production)

- Rapidly radiating black holes would be expected to remain relatively small within white dwarfs, which would prevent the detection of their effects and would preclude any astrophysical bound based on white dwarfs.

Neutron Stars (after production on binary companions)

- Rapidly radiating black holes would be expected to remain relatively small within neutron stars [GLL02 arXiv p. 2] [Hoss06 arXiv p. 30], which would prevent the detection of their effects and would preclude any astrophysical bound based on neutron stars.

§ Safety Implications of Astrophysical Bounds on Neutral Rapidly Radiating Black Holes

TEXT PENDING

10.5 Astrophysical Implications for Neutral Rapidly Radiating Remnantless Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Neutral Rapidly Radiating Remnantless Black Holes

Earth (from cosmic rays)

- Since pair-produced neutral black holes created in cosmic ray collisions would be expected to pass harmlessly through the Earth, there are no astrophysical bounds based on the Earth's existence

Moon (from cosmic rays)

- Since pair-produced neutral black holes created in cosmic ray collisions would be expected to pass harmlessly through the Moon, there are no astrophysical bounds based on the Moon's existence

Sun (from cosmic rays)

- Since pair-produced neutral black holes created in cosmic ray collisions would be expected to pass harmlessly through the Sun, there are no astrophysical bounds based on the Sun's existence

White Dwarfs (from cosmic rays)

- Pair-produced rapidly radiating black holes would be expected to remain relatively small within white dwarfs, which would prevent the detection of their effects and would preclude any astrophysical bound based on white dwarfs.

White Dwarfs (after ISM production)

- Pair-produced rapidly radiating black holes would be expected to remain relatively small within white dwarfs, which would prevent the detection of their effects and would preclude any astrophysical bound based on white dwarfs.

Neutron Stars (after production on binary companions)

- Pair-produced rapidly radiating black holes would be expected to remain relatively small within neutron stars [GLL02 arXiv p. 2] [Hoss06 arXiv p. 30], which would prevent the detection of their effects and would preclude any astrophysical bound based on neutron stars.

§ Safety Implications of Astrophysical Bounds on Neutral Rapidly Radiating Remnantless Black Holes

TEXT PENDING

10.6 Astrophysical Implications for Charged Stable Black Holes

10.6.1 Existence and State of the Earth

FULL TEXT PENDING

10.6.2 Existence and State of the Moon

FULL TEXT PENDING

10.6.3 Existence and State of the Sun

As noted in section 7.1.3, if charged stable black holes have electromagnetic interactions that are the same as muons, then the GM paper estimates that the Sun could stop such black holes with masses in excess of 100 TeV [GM p. 10]. The paper then suggests that the Sun's "continued health" allows us to immediately rule out any risk from charged TeV-scale black holes [GM p. 10]. It does not, however, even attempt to make a serious argument in support of this assertion.

What the paper avoids mentioning is whether such black holes would be expected to destroy the Sun during its natural lifetime. One may note that Stephen Hawking's 1971 paper on primordial black holes suggests the following:

> A mass of 10^{17} g of such objects could have accumulated at the centre of a star like the Sun. If such a star later became a neutron star there would be a steady accretion of matter by a central collapsed object which could eventually swallow up the whole star in about ten million years. [Haw71 abstract ↗, hyperlinks added]

Thus, according to his calculations at that time, primordial black holes could be accreting matter within the Sun during the Sun's normal lifetime but not cause its complete destruction until about ten million years after it (or a heavier star) becomes a neutron star.

The GM paper cites a more recent publication in which it is similarly claimed that a number of primordial black holes could reside in a newly born star, and only after a supernova explosion would some of these black holes, with orbits close to the collapsed core, eventually fall into the resulting neutron star and cause its destruction. [DKK99 p. 653 ↗]

The expected orbits of the primordial black holes considered by these authors and the orbits of TeV-scale black holes would be very different due to the vast difference in their initial masses, but the above references demonstrate that one cannot simply say, "See, the Sun hasn't been destroyed, so black holes must be safe!"

For the case of TeV-scale black holes one would especially need to consider whether there is an Eddington limit for the rate of accretion of any such black hole in the Sun's core. While Appendix

B of the GM paper does consider whether there is an Eddington limit for white dwarfs, the Earth, and neutron stars, it does not consider the case of the Sun or other Sun-like stars. Without this analysis it is difficult to draw any conclusions from the possibility of charged black holes being trapped in the Sun, beyond the general statement that if they are expected to be produced and trapped, then a certain number cannot destroy the Sun in less than a few billion years. Moreover, the "health" of the Sun, a body radiating 385 $\times 10^{24}$ Joules every second [NSSDC:Sun ↗], is not a useful indicator for declaring the absence of any risk for our cool and peaceful planet.

10.6.4 Existence and State of White Dwarfs Exposed to High Energy Cosmic Rays

FULL TEXT PENDING

10.6.5 Existence and State of White Dwarfs Exposed to Flux of Charged Stable Black Holes

FULL TEXT PENDING

10.6.6 Existence and State of White Dwarfs Exposed to Flux of Charged Stable Black Holes Produced in Cosmic Ray Collisions with Dark Matter

FULL TEXT PENDING

10.6.7 Existence and State of Neutron Stars Exposed to High Energy Cosmic Rays

FULL TEXT PENDING

10.6.8 Existence and State of Neutron Stars in Binary Systems

FULL TEXT PENDING

10.6.9 Existence and State of Neutron Stars Exposed to Flux of Charged Stable Black Holes Produced in Cosmic Ray Collisions with the Interstellar Medium

FULL TEXT PENDING

10.6.10 Existence and State of Neutron Stars Exposed to Flux of Ultrahigh-Energy Neutrinos

FULL TEXT PENDING

10.6.11 Summary of Astrophysical Bounds on Charged Stable Black Holes

Earth (from cosmic rays)

- The electromagnetic interactions of charged stable TeV-scale black holes are not known, so it is not possible to confidently predict whether they could be trapped in the Earth after production in cosmic ray collisions. If such black holes are not trapped in the Earth, there would be no astrophysical bounds based on the Earth's existence.
- If the electromagnetic interactions of charged stable TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses up to about 7 TeV to be trapped in the Earth after cosmic ray production. This could in turn be used to limit some of the possible planetary effects of additional black holes produced at the LHC.

Moon (from cosmic rays)

- The electromagnetic interactions of charged stable TeV-scale black holes are not known, so it is not possible to confidently predict whether they could be trapped in the Moon after production by a cosmic ray collision. If such black holes are not trapped in the Moon, there would be no astrophysical bounds based on the Moon's existence.
- If the electromagnetic interactions of charged stable TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses significantly below 7 TeV to be trapped in the Moon after cosmic ray production. This might be used to establish some bounds on the effects that lighter black holes produced at the LHC could have if trapped in the Moon.

Sun (from cosmic rays)

- The electromagnetic interactions of charged stable TeV-scale black holes are not known, so it is not possible to confidently predict whether they could be trapped in the Sun after production by a cosmic ray collision. If such black holes are not trapped in the Sun, there would be no astrophysical bounds based on the Sun's existence.
- If the electromagnetic interactions of charged stable TeV-scale black holes are roughly the same as hypothetical muons of the same mass, then it may be possible for charged black holes with masses well above 14 TeV to be trapped in the Sun after cosmic ray production. This could be used to limit some of the possible effects on the Sun of additional black holes produced at the LHC. With much greater uncertainty, it might also bound some of the effects that LHC black holes could have on the Earth.

White Dwarfs (from cosmic rays)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

White Dwarfs (after ISM production)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

White Dwarfs (after dark matter production)

- The uncertain nature of cosmic dark matter preclude any meaningful astrophysical bound.

Neutron Stars (from cosmic rays)

- The small size of neutron stars and their powerful magnetic fields prevent a sufficient number of ultrahigh-energy cosmic rays from reaching neutron stars.

Neutron Stars (after production on binary companions)

- The extremely low rate of black hole production for an iron-dominated cosmic flux has led to the GM paper acknowledging that it would insufficient in that case.
- Even if the cosmic ray flux is not iron-dominated and a sufficient number of black holes are produced, the GM paper presents no model for the accretion of charged black holes within neutron stars, so no astrophysical bound can be claimed.

Neutron Stars (after ISM production)

- The GM paper acknowledges that the hypothesized rate from ISM production would be too low for an astrophysical argument.

Neutron Stars (from ultrahigh-energy neutrinos)

- The lack of any empirical evidence for the existence of ultrahigh-energy neutrinos precludes any astrophysical bound based on their hypothesized interactions.
- Even if ultrahigh-energy neutrinos were observed, the fundamental differences between charged hadrons and neutral leptons would significantly limit any proposed astrophysical bound. Moreover, the GM paper presents no model for the accretion of charged black holes within neutron stars, so no astrophysical bound can be claimed.

10.6.12 Safety Implications of Astrophysical Bounds on Charged Stable Black Holes

TEXT PENDING

10.7 Astrophysical Implications for Charged Slowly Radiating Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Charged Slowly Radiating Black Holes

Earth (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Earth after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Earth, a reliable astrophysical bound based on the existence and state of the Earth cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses up to about 7 TeV (and possibly higher) to be trapped in the Earth after cosmic ray production. This could in turn be used to limit some of the possible planetary effects of additional black holes produced at the LHC.

Moon (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Moon after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Moon, a reliable astrophysical bound based on the existence and state of the Moon cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses somewhat below 7 TeV to be trapped in the Moon after cosmic ray production. This could in turn be used to limit some of the effects on the Moon of additional black holes produced at the LHC.

Sun (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Sun after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Sun, a reliable astrophysical bound based on the existence and state of the Sun cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are roughly the same as hypothetical muons of the same mass, then it may be possible for charged radiating black holes with masses well above 14 TeV to be trapped in the Sun after cosmic

ray production. This could be used to limit some of the possible effects on the Sun of additional black holes produced at the LHC. With much greater uncertainty, it might also bound some of the effects that LHC black holes could have on the Earth.

White Dwarfs (from cosmic rays)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

White Dwarfs (after ISM production)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

Neutron Stars (after production on binary companions)

- The extremely low rate of black hole production for an iron-dominated cosmic flux has led to the GM paper acknowledging that it would insufficient in that case.
- Even if the cosmic ray flux is not iron-dominated and a sufficient number of black holes are produced, the GM paper presents no model for the accretion of charged black holes within neutron stars, so no astrophysical bound can be claimed.

§ Safety Implications of Astrophysical Bounds on Charged Slowly Radiating Black Holes

TEXT PENDING

10.8 Astrophysical Implications for Charged Equilibrium Mass Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Charged Equilibrium Mass Black Holes

Earth (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Earth after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Earth, a reliable astrophysical bound based on the existence and state of the Earth cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses up to about 7 TeV to be trapped in the Earth after cosmic ray production. This could in turn be used to limit some of the possible planetary effects of additional black holes produced at the LHC.

Moon (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Moon after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Moon, a reliable astrophysical bound based on the existence and state of the Moon cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses somewhat below 7 TeV to be trapped in the Moon after cosmic ray production. This could in turn be used to limit some of the effects on the Moon of additional black holes produced at the LHC.

Sun (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Sun after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Sun, a reliable astrophysical bound based on the existence and state of the Sun cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are roughly the same as hypothetical muons of the same mass, then it may be possible for charged radiating black holes with masses well above 14 TeV to be trapped in the Sun after cosmic

ray production. This could be used to limit some of the possible effects on the Sun of additional black holes produced at the LHC. With much greater uncertainty, it might also bound some of the effects that LHC black holes could have on the Earth.

White Dwarfs (from cosmic rays)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

White Dwarfs (after ISM production)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

Neutron Stars (after production on binary companions)

- The extremely low rate of black hole production for an iron-dominated cosmic flux has led to the GM paper acknowledging that it would insufficient in that case.
- Even if the cosmic ray flux is not iron-dominated and a sufficient number of black holes are produced, the GM paper presents no model for the accretion of charged black holes within neutron stars, so no astrophysical bound can be claimed.

§ Safety Implications of Astrophysical Bounds on Charged Equilibrium Mass Black Holes

TEXT PENDING

10.9 Astrophysical Implications for Charged Rapidly Radiating Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Charged Rapidly Radiating Black Holes

Earth (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Earth after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Earth, a reliable astrophysical bound based on the existence and state of the Earth cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses ~ 7 TeV (and possibly higher) to be trapped in the Earth after cosmic ray production. This could in turn be used to limit some of the possible planetary effects of additional black holes produced at the LHC.

Moon (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Moon after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Moon, a reliable astrophysical bound based on the existence and state of the Moon cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged black holes with masses somewhat below 7 TeV to be trapped in the Moon after cosmic ray production. This could in turn be used to limit some of the effects on the Moon of additional black holes produced at the LHC.

Sun (from cosmic rays)

- The electromagnetic interactions of charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Sun after being producing in cosmic ray collisions. Without any certainty that cosmic ray-produced black holes would have been trapped in the Sun, a reliable astrophysical bound based on the existence and state of the Sun cannot be claimed.
- If the electromagnetic interactions of charged radiating TeV-scale black holes are roughly the same as hypothetical muons of the same mass, then it may be possible for charged radiating black holes with masses well above 14 TeV to be trapped in the Sun after cosmic

ray production. This could be used to limit some of the possible effects on the Sun of additional black holes produced at the LHC. With much greater uncertainty, it might also bound some of the effects that LHC black holes could have on the Earth.

White Dwarfs (from cosmic rays)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

White Dwarfs (after ISM production)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

Neutron Stars (after production on binary companions)

- The extremely low rate of black hole production for an iron-dominated cosmic flux has led to the GM paper acknowledging that it would insufficient in that case.
- Even if the cosmic ray flux is not iron-dominated and a sufficient number of black holes are produced, the GM paper presents no model for the accretion of charged black holes within neutron stars, so no astrophysical bound can be claimed.

§ Safety Implications of Astrophysical Bounds on Charged Rapidly Radiating Black Holes

TEXT PENDING

10.10 Astrophysical Implications for Charged Rapidly Radiating Remnantless Black Holes

FULL TEXT PENDING

§ Summary of Astrophysical Bounds on Charged Rapidly Radiating Remnantless Black Holes

Earth (from cosmic rays)

- The electromagnetic interactions of pair-produced charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Earth after being producing in cosmic ray collisions. Without any certainty that pair-produced black holes created by cosmic ray collisions would have been trapped in the Earth, a reliable astrophysical bound based on the existence and state of the Earth cannot be claimed.
- If the electromagnetic interactions of pair-produced charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged pair-produced black holes with masses ~ 7 TeV (and possibly higher) to be trapped in the Earth after cosmic ray production. This could in turn be used to limit some of the possible planetary effects of additional pair-produced black holes from the LHC.

Moon (from cosmic rays)

- The electromagnetic interactions of pair-produced charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Moon after being producing in cosmic ray collisions. Without any certainty that pair-produced black holes created by cosmic ray collisions would have been trapped in the Moon, a reliable astrophysical bound based on the existence and state of the Moon cannot be claimed.
- If the electromagnetic interactions of pair-produced charged radiating TeV-scale black holes are exactly the same as hypothetical muons of the same mass, then it may be possible for singly charged pair-produced black holes with masses ~ 7 TeV to be trapped in the Moon after cosmic ray production. This could in turn be used to limit some of the effects on the Moon of additional pair-produced black holes from the LHC.

Sun (from cosmic rays)

- The electromagnetic interactions of pair-produced charged radiating TeV-scale black holes are not known, and their gravitational interactions alone would not be sufficient to ensure that some would be trapped in the Sun after being producing in cosmic ray collisions. Without any certainty that pair-produced black holes created by cosmic ray collisions would have been trapped in the Sun, a reliable astrophysical bound based on the existence and state of the Sun cannot be claimed.

- If the electromagnetic interactions of pair-produced charged radiating TeV-scale black holes are roughly the same as hypothetical muons of the same mass, then it may be possible for charged pair-produced black holes with masses well above 14 TeV to be trapped in the Earth after cosmic ray production. This could be used to limit some of the possible effects on the Sun of additional black holes produced at the LHC. With much greater uncertainty, it might also bound some of the effects that LHC black holes could have on the Earth.

White Dwarfs (from cosmic rays)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

White Dwarfs (after ISM production)

- According to CERN representative Professor John Ellis, charged black holes would be safe for white dwarfs, so no astrophysical bounds can be claimed based on their existence.

Neutron Stars (after production on binary companions)

- The extremely low rate of total black hole production for an iron-dominated cosmic flux has led to the GM paper acknowledging that it would insufficient in that case.
- Even if the cosmic ray flux is not iron-dominated and a sufficient number of pair-produced black holes are created in cosmic ray collisions , the GM paper presents no model for the accretion of charged black holes within neutron stars, so no astrophysical bound can be claimed.

§ Safety Implications of Astrophysical Bounds on Charged Rapidly Radiating Remnantless Black Holes

TEXT PENDING

11 Conclusions of the Giddings/Mangano Paper

This section reviews the conclusions of the GM paper [GM pp. 52–53] in light of the findings of this paper. The GM paper first identifies a number of conditions which must be met for its bounds to apply, and then presents what it calls "layers of safety" which would apply to possible LHC production of TeV-scale neutral stable black holes. The conditions identified by the GM paper are reviewed in the first subsection, and the "layers of safety" are reviewed in the subsequent subsection.

11.1 Review of Pre-Conditions for the "Layers of Safety"

The GM paper describes the conditions for the application of its bounds as follows:

> We conclude by first summarizing the conditions needed for our bounds to be necessary to rule out a possible risk. In order for our bounds to have relevance, a sequence of unlikely things would have to be true. First, TeV scale gravity, with a Planck scale no higher than a few TeV, would have to be correct, so that black holes can be produced at LHC. Most workers consider this to be a fascinating possibility, but also a somewhat unlikely possibility. Second, black hole radiance, which has been deeply studied from a number of theoretical perspectives, would have to be wrong, *and* more general quantum mechanical arguments for black hole instability would have to be wrong. Most workers consider this to be an exceedingly improbable, if not impossible, scenario. Finally, one would need a mechanism to shut off the quantum effects responsible for Hawking radiation, but still leave intact either the quantum effects responsible for Schwinger discharge, or some other neutralization mechanism that acts to discharge the resulting stable black holes. It is very difficult to conceive of a consistent physical framework that provides such a mechanism. [GM p. 52, hyperlinks added]

The following sections look at each of these conditions, first examining the likelihood of the condition being met, and then considering what the possible risks would be even if the condition is not met.

11.1.1 Condition 1 - TeV-Scale Gravity

> First, TeV scale gravity, with a Planck scale no higher than a few TeV, would have to be correct, so that black holes can be produced at LHC. Most workers consider this to be a fascinating possibility, but also a somewhat unlikely possibility. [GM p. 52, hyperlink added]

The GM paper describes this precondition as a "somewhat unlikely possibility", but makes no statement about what likelihood should be assumed for the purposes of a risk assessment. As discussed in section 4.1, a survey of theoretical physicists conducted earlier by Professor Giddings resulted in estimates of 0-25%, so a working assumption of 1% has been adopted in this paper for the probability that this condition is met.

If this condition is not met, it can generally be assumed that direct formation of black holes at the LHC would not occur, however, the process of subplanckian black hole creation described earlier would remain a possibility.

If no black holes are created as a result of LHC collisions, either through direct formation or through a subplanckian mechanism, then there would, of course, be no risks associated with black holes.

This is not to say, however, that there are no other risks associated LHC collisions, such as the production of strangelets or magnetic monopoles, or the initiation of a vacuum transition.

The GM paper's conclusion also includes the following rather broad generalization:

> We also note that these bounds likely extend in case other objects are imagined that could result from high-energy collisions in the relevant energy ranges, that have weak-scale cross sections, and that could threaten the long-term stability of matter. [GM p. 52]

This claim appears to be simply an ad hoc statement for public relations purposes. The GM paper does not provide any genuine scientific justification for it, and makes no attempt at a general argument starting from the two properties (weak-scale cross-sections and threat to the long-term stability of matter) and arriving at the desired astrophysical bound. It should also be noted that in at least two stages (the trapping of charged black holes in the Earth discussed in section 7.6.1, and the trapping of neutral black holes in white dwarfs discussed in section 7.1.4), the GM paper's argument itself crucially depends on a relatively narrow range for the expected interactions of black holes and other matter, which cannot in general be assumed to apply to all other imaginable objects. Moreover, just as the astrophysical safety argument for black holes is susceptible to reductions in their production cross-section (as discussed in section 10), the production rates for other imagined objects are unknown, and there exists a fairly large range of possible production rates which would be too low for the GM paper's arguments, yet too high to be generally acceptable for a potentially catastrophic risk.

11.1.2 Condition 2a - No Black Hole Radiation

> Second, black hole radiance, which has been deeply studied from a number of theoretical perspectives, would have to be wrong... [GM p. 52]

The conclusion of the GM paper stresses that black hole radiance has been deeply studied but fails to mention that one of the main reasons it has been deeply studied is that it remains an unresolved and perplexing issue. As noted in section 5.1, Professor Giddings himself has described how one or more of the very basic tenets of physics may have to be sacrificed in order to resolve the contradictions exposed by the theory of black hole radiation [Gid07 arXiv p. 8].

In terms of empirical evidence for black hole radiation, there is none. Black holes emitting quantum radiation is a purely theoretical prediction which has never been observed experimentally ['tH96 arXiv pp. 18–19].

The GM paper does not provide any quantitative estimate of the probability that black holes do not radiate. (An independent working estimate has not been attempted in this draft either.)

Even if black holes do radiate, there still may be a number of risks associated with their production at the LHC. The foremost question is how quickly they radiate. The GM paper argues that on general quantum mechanical grounds, "such black holes are expected to be extremely short-lived" [GM p. 8]. On the other hand, the paper also notes that many workers feel that the resolution of the black hole information paradox will be "subtle corrections to Hawking's thermal spectrum" [GM p. 8], but fails to set any bounds on the effects that such corrections could have on the rate of radiation of TeV-scale black holes.

This paper considers three distinct possibilities for the rate of radiation: that it is slow enough to permit unbounded accretion within the Earth; that it is slow when the mass of a black hole is close to the higher-dimensional Planck mass, but becomes fast enough at higher masses to limit the possible growth of a single black hole; or that it is extremely fast, with the mass of a TeV-scale black hole being rapidly reduced to the higher-dimensional Planck mass. The final case is further subdivided into the case in which a stable black hole remnant is usually left, and the case in which the final stage for non-pair-produced black holes involves the destruction of the event horizon through some unspecified mechanism. For all these cases, this paper considers both the possibility of black holes retaining their charge and the possibility of them always being rapidly neutralized. As described in sections 9.2, 9.3, 9.4, 9.5, 9.7, 9.8, 9.9, and 9.10, there are potentially catastrophic risks associated with all of these scenarios.

11.1.3 Condition 2b - No Quantum Mechanical Instability of Black Holes

> . . . *and* more general quantum mechanical arguments for black hole instability would have to be wrong. Most workers consider this to be an exceedingly improbable, if not impossible, scenario. [GM p. 52]

As described in section 5.3, the GM paper presents an argument that on general quantum mechanical grounds black holes should decay into light, ordinary matter [GM p. 8]. On the other hand, in an earlier paper Professor Giddings counters this argument with the assertion that if it were true, the virtual formation/evaporation of black holes would give the world the appearance of a thermal bath at the Planck temperature, in clear contradiction with experiment [Gid95 p. 3].

Moreover, the LSSG report acknowledges the stability of extremal black holes with a conserved quantum number [LSSG pp. 10, 12–13] and the LSAG report [LSAG p. 7] admits the possibility of pair production of black holes which could then be stable against decay. (The GM paper focuses exclusively on the risks from TeV-scale black holes, yet it makes no mention of this possibility [GM p. ↗].)

As with the case of black hole radiation, the GM paper makes no attempt to quantify the possibility that the quantum mechanical argument it presents could be wrong. The paper does, however, claim that most workers consider the possibility of both black hole radiance and quantum mechanical arguments for instability being wrong, "...to be an exceedingly improbable, if not impossible, scenario." [GM p. 52] The paper does not provide any evidence that it undertook a formal survey of theoretical physicists working in this field which resulted in this scenario being classified as "exceedingly improbable, if not impossible". As such, the statement would appear to be a rhetorical flourish instead of a serious assessment of the issue.

Even if black holes do radiate and the quantum mechanical argument for black hole instability is correct, there would nevertheless appear to be potentially catastrophic risks associated with black hole production at the LHC based on the possibility of pair production of black holes with conserved quantum numbers. The risks associated with this scenario were reviewed in sections 9.5 and 9.10.

11.1.4 Condition 3 - Black Hole Neutralization

> Finally, one would need a mechanism to shut off the quantum effects responsible for Hawking radiation, but still leave intact either the quantum effects responsible for Schwinger discharge, or some other neutralization mechanism that acts to discharge the resulting stable black holes. It is very difficult to conceive of a consistent physical framework that provides such a mechanism. [GM p. 52, hyperlink added]

As discussed in section 6.1, while the GM paper claims at one point that there is "a likely contradiction in assuming that stable black holes must be neutral" [GM p. 4], it also implicitly admits that there is no contradiction by noting that, "One could parameterize such a scenario by imposing rather artificial boundary conditions at the horizon." [GM p. 9, hyperlinks added]. The paper makes no attempt to quantify the probability associated with what it characterizes as "artificial boundary conditions", and, in general, does not quantify the probability that all TeV-scale black holes could be neutralized through the Schwinger mechanism.

The paper does recognize the possibility of "some other neutralization mechanism" [GM p. 52] but does not carefully examine the dynamics of such processes, or assign a probability of them occuring. The only reference it makes to such other mechanisms is the statement that, "A positively-charged black hole will also have an enhanced absorption rate for electrons, which works toward neutralization." [GM p. 18] This statement demontrates that other mechanisms could help neutralize black holes.

Considering both these possible mechanisms, it does not appear to be so unlikely that stable TeV-scale black holes are rapidly neutralized.

Even if stable black holes do retain their charge, there may still be significant potential risks associated with their production at the LHC. The GM paper argues that charged black holes with masses less than about 7 TeV could be trapped in the Earth after produced in cosmic ray collisions [GM pp. 9–10]. As discussed in section 7.6.1, the GM paper's theory of charged black hole trapping depends on a number of dubious assumptions.

Assuming, nevertheless, that some cosmic ray-produced charged stable black holes of mass less than ~ 7 TeV have been trapped in the Earth, one can assert a bound on their potential for rapid destruction of the planet, but in order to put a bound on the possibility that LHC-produced charged stable black holes could disrupt the thermal balance of the Earth, one would need an estimate of the number of black holes hypothetically trapped so far and the number that would be trapped after the completion of the LHC's programme. As discussed in section 7.6.11, neither the GM paper nor CERN provides any such estimate.

For the case of charged stable black holes with masses greater than 7 TeV, the GM paper argues that they would have been trapped in the core of the Sun after production in cosmic ray collisions. This argument is useful for setting a bound on the possibility that the production of charged stable black holes at the LHC could result in some of them being trapped in the Sun and causing its destruction. It is of limited value, however, in demonstrating the safety of charged stable black holes trapped in the Earth. The Sun and the Earth are clearly very different astronomical objects, and if black holes trapped within the Earth were to produce even a slight fraction of the energy output of the Sun, they could make life on the planet unbearable. The GM paper fails to demonstrate any bounds on such risks.

11.2 Review of the "Layers of Safety"

The GM paper presents the following points as its "layers of safety"

1. **Only in scenarios such that the crossover scale to four-dimensional gravity is larger than about 200 Å does one have significant accretion at times short as compared to the natural lifetime of Earth. This is a-priori unlikely, due to the additional fine-tuning required to realize such a TeV-scale gravity scenario.**

2. **In these scenarios where the bound on black hole accretion time on Earth is short as compared to natural time scales, white dwarfs would likewise be accreted, on much shorter time scales, in contradiction to observation.**

3. **Unless cosmic rays have dominantly a very heavy composition, and moreover either the expected neutrino flux doesn't exist or has unusual gravitational couplings to hadronic matter, neutron star decay would likewise be catalyzed on time scales contradicting observation.** [GMv2 p. 53][185]

Each of these points are reviewed in the following sections, however, before examining them more closely, it would be useful to consider what is implied by the phrase "layer of safety". The use of

[185] The citation for the "layers of safety" is taken from the revised version of the GM paper, since it does not include an extra comma after "time scales" in the last paragraph.

this phrase in the GM paper carries the metaphorical image of a complete cover, which provides a safety argument applicable to all the possible cases within the scenario of neutral stable TeV-scale black holes. Having three layers of safety implies that there are three more-or-less independent arguments which would protect the planet from any possible disaster.

A somewhat looser interpretation of a "layer of safety" is an argument significantly restricting the cases in which there are possible risks. For example, if there is an argument which shows that in 99% of the possible cases there is no risk, and in only 1% of the cases the argument does not apply, this could be called a "layer", although it could more accurately be described as an argument which narrows down the possible risk. If there were three such layers of safety, the size for the unmanaged risk would have been progressively whittled down from 1% to 0.01% to 0.0001% (i.e. one in a million).[186]

What the GM paper presents, though, can hardly be considered "layers of safety". As described in the sections below, the various points that the paper makes would more accurately be described as safety arguments applicable to different cases within the scenario of neutral stable TeV-scale black holes. If all of these arguments were correct, they would collectively cover sizeable parts of a single layer (with a bit of overlap of safety arguments near the crossover radius of 200 Å, and the possibility of a duplicate layer for some parts based on the hypothetical ultrahigh-energy neutrino argument). The details of each argument are discussed further below, but what is clear is that as a group they are not even structured to be a triple layer of defence for the planet.

11.2.1 Layer 1 - Crossover Scale

1. **Only in scenarios such that the crossover scale to four-dimensional gravity is larger than about 200 Å does one have significant accretion at times short as compared to the natural lifetime of Earth. This is a-priori unlikely, due to the additional fine-tuning required to realize such a TeV-scale gravity scenario.** [GMv2 p. 53]

The safety value of this "layer" can be assessed by noting which cases it covers, estimating the likelihood of its criterion being met, and then reviewing the risks if the criterion is or is not met.

This layer is essentially a summary of the results from the GM paper's estimate of accretion times within the Earth. The paper includes no model or estimates whatsoever for multiple black hole accretion in the Earth, so this layer applies only to the case of single black hole accretion. If more that one black hole is produced by the LHC and trapped in the Earth, this layer would not apply.

For the case of a single black hole, there are a number of fundamental problems with the GM paper's simplified model for black hole accretion, and unless a more realistic model is presented, it is difficult to have any confidence in the predicted black hole accretion rates within the Earth. The specific problems with the model are described in further detail in section 8.1.1.

[186] This would not in itself imply that there is a one in a million chance of a catastrophe, rather, just a one in a million chance of a situation in which it is not known whether there would or would not be a catastrophe if neutral stable black holes are produced.

Assuming, nevertheless, that this layer is relevant, one can next ask what the likelihood is "that the crossover scale to four-dimensional gravity is larger than about 200 Å". The GM paper does not provide a quantitative estimate, and instead simply states that, "This is a-priori unlikely, due to the additional fine-tuning required to realize such a TeV-scale gravity scenario."

The concept of fine-tuning plays a major role in modern physics, however, the term is typically used to describe a parameter restricted to an extremely narrow, and apparently arbitrary, range of values. Just before its final summary, the GM paper describes the crossover scale criterion as follows:

> This paper has argued that in order for such a scenario to have an impact on Earth at time scales short as compared to the natural lifetime of the solar system, in the five billion year range, the configuration of extra dimensions would have to be such that gravity doesn't transition to four-dimensional behavior until around the 200 Å scale. This apparently requires additional fine-tuning, reducing the likelihood even further. [GM p. 52]

There may be some scope for interpretation of this statement. If it mean that "...gravity doesn't transition to four-dimensional behavior until around the 200 Å scale", as opposed to "gravity doesn't transition to four-dimensional behavior until *after* approximately the 200 Å scale", then it could be considered a case of fine-tuning. For example, if the possible range for the transition is, say, between 200 Å and 210 Å, then it would be a significant and arbitrary restriction on this parameter which could reasonably be taken as limiting its likelihood. The main text of the GM paper does not give any indication, however, that the transition range is restricted in this way.

The final statement says only that, "the crossover scale to four-dimensional gravity is larger than about 200 Å..."[GMv2 p. 53], which is a more accurate summary of the GM paper's findings. What this means is that the transition could occur anywhere between about 200 Åand the experimental bound of about 2,000,000 Å given in the text [GM p. 26]. This is a range of a full 4 orders of magnitude, which, in addition to cases of warped or non-identical extra-dimensions, includes the case of 6 dimensions with unwarped extra dimensions of identical radii and $M_D \gtrsim 3.6$ TeV, and possibly a case of 7 dimensions with unwarped extra dimensions of identical radii if the value of M_D is a bit below 1 TeV.

Moreover, a large part of the appeal of TeV-scale gravity scenarios is the possibility that the transition to higher-dimensional behaviour occurs in this range (cf. "The hierarchy problem and new dimensions at a millimeter" [ADD98 ↗]). Given that one of the assumptions of this scenario is TeV-scale gravity, meeting this criterion can hardly be described as "fine-tuning" in the usual sense of the term.

As noted above, the GM paper does not assign a specific numerical probability for this criterion being met. The probability that the criterion is *not* met would appear to cover a somewhat larger share of parameter space (in terms of range for the crossover and number of cases with extra dimensions of identical radii), but the difference between the two cases is not very significant for a catastrophic risk assessment.

The final step in reviewing this layer is looking at the risks if the criterion is or is not met. If the criterion is not met, then the GM paper's prediction is that the accretion of a single black hole would take longer than the time frame that the GM paper assumes is the natural lifetime of the Earth. Behind all its dressing, this is the essential point of this layer–that if the crossover occurs before 200 Å, then the GM paper's accretion model predicts a very long time for single black hole accretion. The phrasing adopted in the text is somewhat different, as it states that, "Only in scenarios such that the crossover scale to four-dimensional gravity is larger than about 200 Å does one have significant accretion at times short as compared to the natural lifetime of Earth." With this phrasing, the GM paper encourages readers to completely accept its single black hole accretion predictions as an iron-clad guarantee of the planet's safety. The weaknesses of the paper's accretion model were reviewed in section 8.1.1 of this paper.

Ironically, if one accepts the other layers presented in the conclusion, then the risk of a catastrophe could well be greater if the criterion is not met. The reason for this is that for values of R_C below approximately 15 Å, the GM paper does not present any astrophysical bound based on the existence of white dwarfs [GM pp. 43–44]. Similarly, for neutron stars, the GM paper does not attempt a complete argument for values of $R_D \lesssim 1$ Å[GM p. 62]. The GM paper does claim a general relationship between single black hole accretion within the Earth and within white dwarfs [GM p. 51, citing p. 44, eq. 7.15], however, as described in section 8.1.4, even if it were valid, it would only apply to the Bondi phase of accretion, and would not apply at all to scenarios with more than 7 dimensions. In this situation, there is almost nothing to prevent a global catastrophe if single black hole accretion is much faster in the Earth than the GM paper's estimates.

If, on the other hand, the crossover criterion is met, then the GM paper's own calculations predict that just a single trapped black hole could result in the premature destruction of the Earth. Far from supporting the GM paper's concluding statement that, "...there is no risk of any significance whatsoever from such black holes." [GM p. 53], this "layer of safety" demonstrates that there is a very serious potential risk which must be avoided at all costs. The extent to which the other two layers can rule out any catastrophe are reviewed below.

11.2.2 Layer 2 - White Dwarf Argument

2. **In these scenarios where the bound on black hole accretion time on Earth is short as compared to natural time scales, white dwarfs would likewise be accreted, on much shorter time scales, in contradiction to observation.** [GMv2 p. 53]

Given the GM paper's positive prediction of the destruction of the Earth in a number of black hole production scenarios, this "layer of safety" is of paramount importance since it is the only significant defence against disaster. One might hope that this point is rock-solid and indisputable, but, sadly, that is not the case.

First, as noted in section 10.1.4, this "layer" only applies to certain specific cases. Those cases are:

- Scenarios with 5 dimensions and a cross-over radius greater than 200 Å
- Scenarios with 6 unwarped dimensions and a value of M_D less than ~ 10 TeV
- Scenarios with 6 dimensions and warping, with a cross-over radius greater than 200 Åand a value of M_D less than ~ 10 TeV
- Scenarios with 7 unwarped dimensions and a value of M_D less than ~ 8 TeV
- Scenarios with 7 dimensions and warping, with a cross-over radius greater than 200 Åand a value of M_D less than ~ 8 TeV

This layer may also apply to some cases of unwarped but non-identical dimensions, however, the GM paper does not explicitly address such cases.

The phrasing used in the GM paper to describe this layer may give readers the impression that if black hole accretion times on Earth are short, then the destruction of white dwarfs must be even more rapid, but this is not the case. For example, if the GM paper underestimated the accretion rate in 8 dimensions and a single black hole could prematurely destroy the Earth, there is no conclusion that can be drawn from the existence of white dwarfs since the GM paper does not predict that they could trap heavier black holes in scenarios with 8 or more dimensions [GM p. 36, table 1].

For scenarios with 5, 6, or 7 dimensions, the GM paper does contend that there is a "general relationship" between accretion times within the Earth and within white dwarfs [GM p. 51, citing p. 44, eq. 7.15], however, as mentioned above, and described in more detail in section 8.1.4, if this relationship is valid, it would apply only to the case of single black hole accretion and only to the Bondi accretion phase. Since there is no relationship covering the whole accretion process, if the GM paper underestimated the total accretion times within the Earth for scenarios with a cross-over radius of less than about 200 Å, no reliable safety argument can be made based on the existence of white dwarfs. A number of other problems with the purported "general relationship" are also described in section 8.1.4.

For the scenarios listed above in which the white dwarf argument might apply, the tortuous trail of assumptions and hypotheses which must be followed to arrive at the GM paper's conclusion leave little grounds for believing that a disaster could not possibly occur. Problems with the white dwarf argument are addressed in different sections of this paper. Uncertainties about the flux of ultrahigh-energy cosmic rays are reviewed in section 3. Uncertainties about the production of black holes in hadronic collisions are discussed in section 4. Questions about the production and trapping of black holes in white dwarfs are reviewed in section 7.1.4. Problems with the GM paper's model of accretion within white dwarfs are noted in section 8.1.4. General limitations of the white dwarf astrophysical argument are summarized in section 10.1.4, where the suitability of the proposed candidate white dwarfs are also critically examined. Finally, section 10.1.4 notes the complete lack of any evidence that the white dwarfs identified in the GM paper are not presently experiencing significant heating from black hole accretion.

Given these uncertainties, one can say, at best, that the GM paper presents an academically interesting argument, but it falls far below the standards required for a reliable "layer of safety".

11.2.3 Layer 3 - Neutron Star Argument

3. Unless cosmic rays have dominantly a very heavy composition, and moreover either the expected neutrino flux doesn't exist or has unusual gravitational couplings to hadronic matter, neutron star decay would likewise be catalyzed on time scales contradicting observation. [GMv2 p. 53]

For this layer of safety, the GM paper presents two distinct astrophysical arguments in the hope that at least one of them might be correct. The two arguments have some significant differences, so they will be reviewed separately.

The first argument, implied by the reference to cosmic rays having a "very heavy composition", is the safety argument based on neutron stars with binary partners. This argument is presented as a complement to the GM paper's white dwarf argument, with the intent that it would cover the case of $8 \leq D \leq 11$ or more dimensions, for which the white dwarf argument does not apply [GM pp. 38, 83].[187] Thus, it is not a duplicate layer of safety for the white dwarf argument.

The preamble to the list of "layers of safety" asserts that is it unlikely, "...that the composition of ultrahigh-energy cosmic ray primaries is dominantly heavy elements..." [GM p. 53] but the paper gives no quantification of this supposedly unlikely possibility. On the other hand, a recent paper co-authored by a leading theorist from CERN has proposed that iron is the dominant element injected into the cosmic ray flux [DD06 arXiv ↗].[188] (The GM paper, in fact, thanks the authors of that paper for helping to clarifying several issues related to the composition of cosmic rays [GM p. 53].) Similarly, the GM paper depends on the results of the Pierre Auger Observatory for its cosmic ray calculations [GM pp. 40, 72, 73–74, 78–79] but fails to note the published statement of the Observatory's Spokesperson Emeritus that there are indications "that the mass composition is not proton dominated at the highest energies." [Wat08b abstract] On the whole, it does not seem that the likelihood of any particular distribution of the hadronic component of the cosmic ray flux offers much in the way of a safety guarantee.

The GM paper does identify the composition of the cosmic ray flux as one clear way in which its argument could fail, but it is certainly not the only way—the paper overstates its case by claiming that, "Unless cosmic rays have dominantly a very heavy composition... neutron star decay would likewise be catalyzed...". As described in section 3, there are a number of other unresolved questions about cosmic rays which could significantly affect the argument. Uncertainties about the production of black holes in hadronic collisions, discussed in section 4, could also lead to the failure of the argument. In this case, with the relatively low expected levels of black hole

[187] The significantly lower black hole production rates for the case of $5 \leq D \leq 7$, as shown in table 9 and figure 8 [GM p. 77 ↗], is the reason it is not presented as a safety argument for these dimensions.

[188] The phrasing of this "layer of safety" uses the term "very heavy" to describe the composition of cosmic rays for the first and only time in the entire paper. The rest of the paper considers the case of a 100% iron flux. Iron is considered a "heavy ion"; the conclusion adds "very" just to give the impression that it is less likely. Furthermore, as noted in section 3, the GM paper completely ignores the contribution of ultraheavy nuclei to the cosmic ray flux.

production [GM p. 77, figure 8], the argument is very sensitive to suppression of the general production rate. Once a black hole is produced, its trapping in a neutron star would appear to be almost certain, however the possibility that black holes may not be able to penetrate deeply into the star is not fully addressed in the GM paper, and thus the overall argument could be invalid if the paper's model for the penetration of TeV-scale black holes [GM pp. 47–48] is not correct. A number of other fundamental problems with the GM paper's model of accretion within neutron stars are reviewed in section 8.1.5. The general validity of an astrophysical argument based on the observation of certain neutron stars is critiqued in section 10.1.7. Finally, the GM paper's failure to provide convincing examples of neutron star binary systems which meet its criteria, and its decision to instead simply assert that some examples must exist [GM p. 50] is critiqued in section 10.1.8.

Based on present uncertainties in the composition of the hadronic component of cosmic rays, CERN's Scientific Policy Committee rejected this line of reasoning as an acceptable safety argument [SPC p. 3]. Noting the other problems with this argument, it is clear that little faith should be placed in it as a "layer of safety".

The final safety argument presented in the GM paper's conclusion is that black holes are produced in the collision of ultrahigh-energy neutrinos with neutron stars. As noted in section 7.1.10 and acknowledged in the GM paper [GM p. 78], there is presently no empirical evidence for even the existence of such neutrinos, let alone measurements of their flux. Even if such a flux were to exist, there is a fundamental uncertainty, recognized in the terms of this "layer of safety", as to whether collisions caused by neutral leptons would be a reasonable basis for certifying the safety of collisions of positively charged hadrons. It may also be noted that while the paper claims that its argument must hold unless the anticipated neutrino flux "has *unusual* gravitational couplings to hadronic matter" [italics added], if the production of black holes is significantly suppressed for both hadron-hadron and neutrino-hadron collisions, the proposed argument could also fail.

Given these serious problems, it is no surprise that CERN's Scientific Policy Committee similarly rejected this claim as a legitimate safety argument [SPC p. 3]. All the same, one is left to wonder whether the GM paper has any minimum standards if a completely unobserved phenomenon can be spun into a bolded additional "layer of safety" in its final conclusion.

12 Summary and Conclusions of this Paper

This report has reviewed the black hole risks potentially associated with the LHC.

The first criterion for such risks is that black holes actually be produced. This would likely require TeV-scale gravity to be correct and the value of the higher-dimensional Planck mass to be less than the LHC's maximum energy of 14 TeV.

If this is the case, one may expect black holes to be produced at the LHC. As reviewed in section 4, estimates for the number of black holes range from a few billion down to a probability of less than one, depending on the number of extra dimensions, the value of Planck's mass, the inelasticity of hadronic collisions, and a number of other possible factors.

As noted in section 5, if TeV-scale black holes are produced, it remains unclear whether they will be stable or whether they will radiate. The GM paper indicates that Hawking radiation, as derived by Stephen Hawking, is not expected, and that corrections to his derivation and some of the details are needed. It is unknown if such changes will preserve the general idea of black holes radiating quickly, since one of the proposed corrections is that black holes with masses close to Planck's mass radiate very slowly.

As discussed in section 5.4, if black holes do radiate very quickly, they would rapidly reach Planck's mass, but at that point it is unknown whether they would, in general, become permanent black hole remnants, or whether only those black holes with conserved quantum numbers created through pair production would be stable against further decay.

It is also unclear whether black holes could be charged or whether they must all be neutral. As reviewed in section 6.2, in scenarios where black holes radiate, it is usually assumed that the Schwinger mechanism would rapidly neutralize the objects, but it is not clear whether this assumption would apply to black holes with masses close to Planck's mass. On the other hand, for black holes which do not radiate, the GM paper makes the heuristic argument that they must retain their charge due to similarities between the Schwinger mechanism and Hawking radiation [GM pp. 4, 9], although it does note that certain boundary conditions on the black hole's event horizon could preserve Schwinger discharge while preventing Hawking radiation [GM p. 9]. The interactions of a black hole with its medium is another independent way in which black holes could be neutralized [GM p. 18].

Given these uncertainties, this paper has considered the following 10 cases:

1. Black holes are neutral and stable
2. Black holes are neutral and radiate slowly
3. Black holes are neutral and only grow up to an equilibrium mass
4. Black holes are neutral and radiate very rapidly
5. Black holes are neutral, radiate very rapidly, and only leave remnants if pair-produced
6. Black holes are charged and stable

7. Black holes are charged and radiate very slowly
8. Black holes are charged and only grow up to an equilibrium mass
9. Black holes are charged and radiate very rapidly
10. Black holes are charged, radiate very rapidly, and only leave remnants if pair-produced

The risks associated with each of these cases are summarized below:

§ Case 1 - Black Holes are Neutral and Stable

The GM paper focuses primarily on the first case of neutral stable black holes for both its model of accretion and its astrophysical arguments for the safety of black hole production. As critiqued in section 8.1.1, the GM paper presents extremely simplistic models for the different phases of black hole accretion, which are then used to calculate a lower bound on the time required for a single black hole to destroy the Earth [GM pp. 27–28]. Even by the paper's own calculations, the production of a single black hole at the LHC could lead to the premature destruction of the planet in a number of scenarios (viz. scenarios with 5, 6, or 7 dimensions and a value of R_C significantly larger than about 200 Å [GM p. 26]).

The GM paper then tries to present an astrophysical argument against this catastrophic prediction, but it has limited options to choose from. Its general argument is that if black holes could be produced at the LHC, they could also be produced through the collisions of ultrahigh-energy cosmic rays with astronomical objects. A significant difference, however, is that black holes produced by such cosmic rays would initially be moving at highly relativistic velocities, whereas black holes produced at the LHC would be moving much more slowly. The GM paper finds that cosmic ray-produced black holes would pass harmlessly through the Earth, the Sun, and other regular stars [GM p. 33], so it turns instead to more exotic objects. Despite earlier hopes that an argument could be made based on the existence of neutron stars [Ellis08 at 30:30 ↗], such stars are protected from the direct effects of cosmic rays through their powerful magnetic fields [GM p. 85].

The authors of the GM paper then settle on white dwarfs, which have a much larger surface area and can have much weaker magnetic fields. Even these objects are problematic since most do not have sufficient column densities to guarantee stopping cosmic ray-produced black holes [cf. GM pp. 36–38]. From over 10,000 known white dwarfs [▷ ADDCITE WD Catalog ↗], CERN is able to identify 8 which it believes should have trapped black holes. Even for these white dwarfs, the GM paper's argument depends on a detailed theoretical calculation of the stopping distance for black holes which, as critiqued in section 7.1.4, itself depends on a number of assumptions and conditions.

The paper's white dwarf argument is also sensitive to a number of factors which are presently very poorly understood. The argument is based on assumptions about the properties of ultrahigh-energy cosmic rays, even though, as reviewed in section 3, there is still great uncertainty about the origin, distribution, and, indeed, the very nature of these objects. The rate of black hole production is another important unknown, reviewed in section 4, which could, on one hand, reduce the number of black holes expected at the LHC, but, on the other hand, could invalidate a safety argument based on specific rates of black hole production.

Proceeding with the assumption that a white dwarf has trapped black holes, the GM paper then attempts to estimate the maximum time required for the black holes to have a macroscopic effect on their host. As in the case of accretion within the Earth, the GM paper uses extremely simplistic models, critiqued in section 8.1.4, to arrive at its estimated bounds on white dwarf accretion times. Among their other limitations, these models apply only to non-crystallized white dwarfs [GM pp. 41–44], which, as noted in section 10.1.4, automatically disqualifies at least 4 of its 8 candidate white dwarfs. The paper also presents a few arguments, reviewed in section **??**, against an Eddington limit during the microscopic and early macroscopic phases of accretion, but implicitly acknowledges that there could well be an Eddington limit during the latter stages of the process [GM pp. 43, 64].

Based on its calculations of the maximum time required for the pre-Eddington phases of accretion within a white dwarf, the GM paper then sets a general age guideline of 100 million years which, along with the mass and magnetic field criteria, candidate white dwarfs should meet [GM p. 44]. The qualifications of the proposed candidates were reviewed in section 10.1.4 and based on that review it is far from certain that any of them meet the necessary requirements. Aside from current uncertainties about these candidates, the argument put forth in the GM paper depends on the state of these white dwarfs millions of years ago when they were originally expected to have trapped cosmic ray-produced black holes. Thus far, no data has been provided on the past history of any of the candidate white dwarfs.

Assuming that these white dwarfs would have trapped black holes, the final step of the argument is demonstrating that they have not been affected by black holes. This would therefore show that at least one link in the logical chain is invalid–preferably that such black holes do not exist, or at least are safe for white dwarfs and maybe for the Earth. Thus far, however, neither the GM paper nor CERN have presented any evidence to justify concluding that the candidate white dwarfs are not being affected by black holes. The GM paper's contention is that the candidate white dwarfs would have already been destroyed, or would have been macroscopically disrupted, by, for example, having their rate of cooling reduced [GM pp. 64–65]. While it is clear that these white dwarfs have not been destroyed, no data whatsoever has been provided to show that they have not experienced a reduction in their rate of cooling, or even that they are not presently experiencing an increase in their internal temperature. As noted in section 10.1.4, even if painstaking measurement are made with the best available astronomical equipment over the next century, it is not clear if it would even be possible to rule out the minute temperature changes involved in a reduction of a white dwarf's cooling rate.

The GM paper presents another related astrophysical argument based on the production of neutral stable black holes in the interstellar medium which can subsequently be trapped in white dwarfs regardless of their present or past magnetic field. This argument has the benefit of increasing the potential number of white dwarfs which may have been infected by black holes, but, as reviewed in section 10.1.5, it is even more sensitive to uncertainties about the production and trapping rate of black holes, since the expected number of black holes would be reduced by a factor of over

7,000 [GM p. 87]. It is also subject to the uncertainties about the GM paper's accretion models within white dwarfs. Moreover, no data on potential black hole heating has been presented for the sole candidate, Sirius-B, identified in the GM paper [GM p. 87].

The GM paper further claims that it has found a "general relationship" between accretion times within the Earth and white dwarfs [GM p. 51], but, as critiqued in sections 8.1.4 and 10.1.4, the proposed relationship applies only to a single phase of black hole growth and would not be a reliable basis for making any safety predictions.

Aside from the scenarios discussed above in which its accretion model predicts premature destruction, the GM paper also identifies scenarios in which its accretion model predicts a long period of late microscopic and early macroscopic accretion, which is held up as sufficient proof, in those scenarios, for the safety of black hole production at the LHC [GM p. 53]. These scenarios include cases of 5, 6 or 7 dimensions with values of R_C less than about 15 Å [GM pp. 43, 53], as well as the cases of 8 or more unwarped dimensions with extra dimensions of identical radii [GM p. 52].

This safety claim is based almost entirely on simplistic accretion assumptions, which, as outlined in section 8.1.1, could fail for a number of independent reasons. Moreover, the accretion predictions apply only to a single black hole trapped in the Earth. The paper justifies ignoring multiple black holes in these scenarios with the assertion that they are "firmly excluded" [GM p. 83] by the authors' neutron star argument, even though CERN's own Scientific Policy Committee rejected that argument [SPC p. 3].

As noted above, initial hopes for an argument based on ultrahigh-energy cosmic rays directly striking neutron stars were dashed by the powerful magnetic fields surrounding all known neutron stars. As an attempt to save the argument, the GM paper suggests that ultrahigh-energy neutrinos striking neutron stars could produce TeV-scale black holes [GM p. 47], but this argument requires one to overlook the possibility that collisions caused by neutral leptons may be fundamentally different from collisions caused by positive hadrons [GM pp. 47, 53], and the fact that not a single ultrahigh-energy neutrino has ever been observed [GM p. 78].

Another alternative construction for the neutron star argument is to have neutral stable black holes produced through cosmic ray collisions with the companions of neutron stars in binary systems. One of the principle difficulties with this argument is that it significantly reduces the rate of cosmic ray-induced black hole production. With radii in the range of only 10 km, neutron stars already present a very small target for ultrahigh-energy cosmic rays, and this target is further reduced by the requirement that a cosmic ray first strike a binary companion along a path leading to the neutron star. The consequent reduction in the expected rate of black hole production is so great that the argument is not viable in the case of a cosmic ray flux dominated by heavy ions, and for this reason CERN's SPC rejected the argument [SPC p. 3].

A number of other problems with the argument are detailed in section 10.1.8, but a very basic one is the absence of convincing examples of neutron stars in binary systems which have survived much longer than would otherwise be expected. The GM paper does cite one example, SAX J1808.4–3658 [GM p. 86], however, as discussed in section 10.1.8, the age of this system appears to be much less than the billion years that may be needed [BC01 p. 294, figure 2]. No other example is given in the GM paper, and instead the authors simply encourage readers to assume that a suitable binary system must exist somewhere [GM p. 50].

One further construction that the GM paper mentions is the possibility of neutral stable black holes being created through cosmic ray collisions with the interstellar medium. In this case, however, it acknowledges that the expected black hole production rates are too low for an astrophysical argument based on the existence of neutron stars [GM p. 87].

For all the constructions involving neutron stars, it should be further noted that the predicted accretion times do not apply to scenarios with 12 or more dimensions since the GM paper's sub-nuclear accretion time estimates are restricted to $6 \leq D \leq 11$ [GM p. 49]. Furthermore, arguments against an Eddington limit are only given for scenarios with $R_D \gtrsim 1$ Å, which places a significant restriction on the range for which a neutron star argument might be applicable. These issues and other problems with the proposed neutron star accretion models are discussed further in section 8.1.5.

Based on the above considerations, it would seem that significant catastrophic risks are associated with neutral stable black hole production at the LHC. For scenarios with 5, 6, or 7 dimensions and a crossover radius significantly greater than 200 Å, the accretion time estimates predicting that a single trapped black hole could prematurely destroy the Earth are a very legitimate basis for concern. The counterargument that the existence of certain massive and ultramassive white dwarfs rules out this risk is fraught with a number of serious problems and cannot be accepted as a compelling reason to ignore the apparent risk.

For other scenarios in which CERN expects single black hole accretion to take an exceedingly long time, the possibility of multiple trapped black holes presents an uncontrolled risk for the planet. The astrophysical arguments that the GM paper presents for these scenarios are even weaker than the white dwarf argument and lack some of the basic elements required by their intended chain of reasoning. This leaves the purely theoretical accretion estimates of the GM paper as the only potential safety factor for single black hole accretion in these scenarios, but the questionable nature of the paper's accretion assumptions suggests that much faster accretion rates may well be possible.

On the whole, the production of neutral stable black holes at the LHC should be considered an unacceptable risk.

§ Case 2 - Black Holes are Neutral and Radiate Slowly

The case of neutral slowly radiating black holes, and all the other cases of radiating black holes (cases 3, 4, 5, 7, 8, 9, and 10), have not been addressed in the GM paper, either through a theoretical analysis of the expected accretion rates, or through astrophysical safety arguments.

Neutral slowly radiating black holes can be expected to pose safety risks that are similar to the case of neutral stable black holes. Their rate of accretion may or may not be slightly less, and they may reach an Eddington-limited phase of growth at a slightly lower mass, but the differences may not be significant from a safety assessment point of view. Similarly, astrophysical safety arguments for neutral slowly radiating black holes may be essentially the same as that for neutral stable black holes, with the possibility of a slight improvement in the trapping of black holes within white dwarfs being counterbalanced by a possible increase in the expected accretion times.

Given the similarities between these two cases, the assessment that the production of neutral stable black holes is an unacceptable risk would equally apply to the production of neutral slowly radiating black holes.

§ Case 3 - Black Holes are Neutral and Only Grow up to an Equilibrium Mass

The specific risks associated with neutral equilibrium mass black holes depend on the mass range of the equilibrium point. If a black hole can grow to the point where it physically disrupts the planet (but does not completely destroy it), then the risks are essentially the same as cases 1 and 2.

If the equilibrium mass is much smaller, then the risks may be considered qualitatively similar to case 4, discussed below. For case 4, the internal heat production caused by black holes would be proportionate to the number of trapped black hole remnants (each with a mass close to the higher-dimensional Planck's mass. For this case, the heat production can be considered roughly proportionate to the number of black holes multiplied by a mass-dependent factor. Depending on the number and size of the black holes involved, this could pose a serious risk to the stability of the planet.

The astrophysical arguments are significantly weakened in this case—possibly to the point of irrelevance. The precise level of a black hole's equilibrium mass (or even the existence of a mass limit) may be different in white dwarfs and neutron stars when compared to the Earth, but if the rate of black hole accretion is significantly reduced, or if their growth is limited to a mass below that required to cause observable disruptions, there may be very little which can be inferred from the existence of certain white dwarfs or neutron stars.

Thus, in this case as well, there appear to be unacceptable risks associated with black hole production.

§ Case 4 - Black Holes are Neutral and Radiate Very Rapidly

The case of neutral rapidly radiating black holes is theoretically preferred by CERN, but the organization has thus far failed to address the risks associated with it.

In this case, black holes produced at the LHC rapidly radiate their mass above the higher-dimensional Planck's mass, leaving a remnant which cannot significantly increase its mass, but which would continue to convert mass into high-energy radiation. This process of mass-energy conversion has indeed been patented as a possible future energy source [StöckPat ↗], but the environmental effects of black hole remnants circulating throughout the planet have been ignored. A convincing bound must be established on the maximum possible internal heat generation associated with this case before the possibility of a global catastrophe can be ruled out.

There is little scope for an astrophysical argument in this case since the heating effects of black hole remnants within white dwarfs or neutron stars would probably not be visible from light years away.

§ Case 5 - Black Holes are Neutral, Radiate Very Rapidly, and Only Leave Remnants if Pair-Produced

This case is a variation of case 4 which acknowledges the possibility that independently-produced black holes could somehow decay completely, and only pair-produced black holes with conserved quantum numbers would be stable against decay. Independently-produced black holes which decay completely do not appear to pose any threat beyond their radiative effects near the LHC itself. Thus, the only significant risk would be from stable remnants of pair-produced black holes.

The risks associated with this case may therefore be considered similar to case 4, with a reduction factor based on the fraction of black holes which are pair-produced. The GM paper does not indicate what this fraction might be, and, given the theoretical uncertainties about the process of TeV-scale black hole production, it may be difficult to make any such estimate. Despite this unknown factor, if a bound could be established on the catastrophic risks associated with case 4, the risks should be further reduced in this case.

§ Case 6 - Black Holes are Charged and Stable

The case of charged stable black holes differs from that of neutral stable black holes (case 1) in a number of significant ways. Firstly, the effects of a black hole's charge could result in a very different process of accretion during both the microscopic and macroscopic stages. Unfortunately, the GM paper presents no model for charged black hole accretion, and it remains unclear whether the effects of charge retention would retard or accelerate the accretion process.

Secondly, the likelihood of being trapped in the Earth may be several orders of magnitude higher for charge-retaining black holes compared to their rapidly neutralized counterparts. A substantial fraction of charged black holes which pass through a reasonable portion of the planet after production at the LHC would probably be trapped (if there are electromagnetic interactions which slow such black holes down). The sheer number of black holes which could be involved calls for an extremely careful examination of the risks associated with this case.

The possible astrophysical safety arguments are also completely different from those for neutral stable black holes. In this case, the GM paper contends that ultrarelativistic black holes produced through ultrahigh-energy cosmic ray collisions with the Earth would be trapped in the planet if their initial mass is less than about 7 TeV [GM p. 10]. As discussed in section 7.6.1, the argument depends on a theoretical model for the interaction of TeV-scale black holes with ordinary matter within the Earth, which may or may not turn out to be correct. The paper also leaves almost no safety margin for this part of its argument, since the maximum mass which it theoretically predicts could be trapped is assumed to be the relevant safety limit.

If cosmic ray-produced black holes with initial masses up to 7 TeV could be trapped in the Earth, this would imply a bound on some of their most dramatic effects. The possibility that a single charged stable black hole could rapidly destroy the planet would be much less than one might otherwise expect. (This possibility cannot be completely ruled out since the desired safety argument could be negated through a significant reduction in the hadronic component of ultrahigh-energy cosmic rays, or a suppression in the general rate of black hole production, or a sufficient combination of the two.)

If charged stable black holes could be trapped in the Earth and, in fact, have already been trapped, then the focus of a risk assessment would shift to a comparison of the numbers of black holes expected from the LHC with the number of black holes that are already within the Earth. If the LHC programme could produce a significant increase in the number of trapped black holes (relative to the Earth's sensitivity to such increases), then the possibility of catastrophic environmental effects would be a serious concern.

For the case of charged stable black holes with masses greater than 7 TeV, the GM paper turns to the Sun and argues that such black holes would easily be trapped by the Sun's dense core [GM p. 10]. This might be a potentially useful astrophysical argument, but the GM paper fails to show what the effects of such black holes would then be on the Sun. If one could argue that the guaranteed effects of such black holes are contradicted by confirmed observations of the Sun, then one could conclude that such black holes either do not exist, or their production rate through cosmic ray collisions are insufficient to ensure the trapping of a single black hole. If such black holes do not exist, then clearly there would be no associated risks for the Earth. If the production rate from cosmic ray collisions is too low, then the implications for the Earth would depend on whether the low rate is due to an unexpectedly low hadronic component of the ultrahigh-energy cosmic ray flux (in which case there would be no safety benefits for the Earth), or due to a general suppression of black hole production from hadronic collisions (in which case there would be a proportionate reduction in the number of black holes expected from the LHC).

Unfortunately, the GM paper does not even attempt such an argument, and simply asserts that, "The continued health of the Sun on multi-billion year time scales. . . thus apparently immediately rules out any risk from charged TeV-scale black holes." [GM p. 10] Since the Sun is radiating energy at a rate ~ 10,000,000,000,000 times greater than the heat generated within the Earth [NSSDC:Sun ↗] [GM p. 28], it seems rather foolish to consider the "health of the Sun" as a guarantee of the safety of charged black holes within the Earth.

No astrophysical argument is presented for charged stable black holes based on the existence of either white dwarfs or neutron stars. Indeed, during his lecture at CERN on the safety of the LHC, Professor John Ellis states that the retention of charges by black holes could, in theory, account for the continued existence of both white dwarfs and neutron stars [Ellis08 at 26:37 ↗].

Based on the above considerations, it seems possible that a safety argument could be constructed for charged stable black holes with initial masses below 7 TeV, although there may still be a number of ways that such an argument could fail. On the other hand, for charged stable black holes with masses above 7 TeV, no significant safety argument has thus far been presented, and it is not clear if an acceptable argument could even be developed.

Unless much stronger safety arguments are presented, the potentially catastrophic effects of numerous charged stable black holes being produced at the LHC and trapped in the Earth is too great to be considered an acceptable risk.

§ Case 7 - Black Holes are Charged and Radiate Slowly

The case of charged slowly radiating black holes has not been addressed in the GM paper.

The risks associated with their production may be quite similar to that of charged stable black holes (case 6). The possible differences could include a different rate of accretion and a slightly lower mass for the start of an Eddington-limited phase. The potential astrophysical safety arguments may also be similar to those for charged stable black holes.

If the safety of charged stable black holes can be established, then the safety of charged slowly radiating black holes may similarly be expected, however, as described above, this has not yet been done. In the absence of stronger safety arguments, the production of charged slowly radiating black holes at the LHC should be considered an unacceptable risk.

§ Case 8 - Black Holes are Charged and Only Grow up to an Equilibrium Mass

As was the case for neutral equilibrium mass black holes (case 3), the specific risks for charged equilibrium mass black holes depend on the mass range of the equilibrium point.

If a charged black hole can grow to a size which physically disrupts the planet (but does not completely destroy it), then the risks are comparable to those of cases 6 and 7.

If the equilibrium mass limit is much lower, the effects of such black holes can be considered similar to that of charged black hole remnants, discussed below in case 9, multiplied by a factor to account for the higher energy generation rate of these black holes. If such black holes have already been trapped in the Earth, then the question becomes a comparison of the existing number with the additional contribution from the LHC (and an analysis of the sensitivity of the planet to possible increases). If no such black holes have ever been trapped in the Earth, then a direct estimate of the possible heat generation from LHC-produced black holes would be an essential part of any catastrophic risk assessment.

Thus far, no genuine attempt has been made to address the possible risks associated with producing charged equilibrium mass black holes at the LHC. Unless satisfactory bounds can be shown on the possibility that the physical accretion or heat generation of such black holes could disrupt the planet, their production at the LHC should be considered an unacceptable risk.

§ Case 9 - Black Holes are Charged and Radiate Very Rapidly

The case of charged rapidly radiate black holes is similar to that of neutral rapidly radiating black holes (case 4), but there are also a couple important differences.

If the stopping power of charged black holes is much higher than that of neutral black holes, one may expect a much greater number of black hole remnants trapped in the Earth. The rate of accretion and subsequent radiation by charged black hole remnants could also be significantly different from that of neutral black hole remnants, although whether it would be higher or lower may depend on a number of factors.

There is, however, the possibility in this case of an astrophysical argument based on the premise that the Earth may have already trapped numerous black hole remnants with masses up to 7 TeV (and possibly higher). If this assumption is correct, then the risk analysis is by and large reduced to a comparison of the estimated number of black hole remnants presently trapped in the Earth with the additional number expected from the LHC. Doing this risk analysis would require both an estimate of the integrated flux of cosmic rays with per parton energies comparable to that expected from the LHC, and an analysis of the sensitivity of the Earth to possible increases in its internal heat generation. Another important question is the permance of charged black hole remnants within the Earth. If such black hole remnants can be destroyed over the course of millions or billions of years through, for example, infrequent pair annihilation events, or if there is a random probability of black hole remnants escaping from the Earth, then the relative increase caused by production at the LHC would be proportionately greater.

For the case of black holes with initial masses above 7 TeV (or whatever is the trapping limit for charged rapidly radiating black holes), there would not be a safety argument based on charged black hole remnants already being trapped in the Earth. In this case, the risks would be qualitatively similar to case 4, but quantitatively modified to account for the expected increased in the number of LHC-produced trapped black hole remnants and any differences in the rate of radiation generation.

Based on the above considerations, the production of charged rapidly radiating black holes at the LHC should presently be considered an unacceptable risk.

§ Case 10 - Black Holes are Charged, Radiate Very Rapidly, and Only Leave Remnants if Pair-Produced

As noted in the corresponding neutral case (case 5), if independently-produced, rapidly radiating black holes can decay completely, their associated risks would be limited to the vicinity of the LHC. The potential catastrophic risks would then be restricted to pair-produced charged black holes which are stable against decay.

It is not known what fraction pair-produced black holes would be of all TeV-scale black holes, but one can assume that the risks associated with case 9 would be reduced by such a factor. Unless this factor can be shown to be exceedingly small, the assessment that the risks associated with case 9 are unacceptable would also apply to this case.

Overall Assessment

The beginning of this section summarized the present uncertainties about whether black holes are stable or radiate, how fast they might radiate, and whether they might be charged or must all be neutral. Given these uncertainties, a reasonably cautious approach would be to avoid black hole production if even one of these cases carries an unacceptable risk. The above review has shown, however, that almost all of these cases pose unacceptable risks to the planet. In such a situation, there can be little doubt that black hole production at the LHC would be an unacceptable and irresponsible risk.

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References

[Alt07] L.G. Althaus, E. Garcia-Berro, J. Isern, A.H. Corsico and R.D. Rohrmann, "The age and colors of massive white dwarf stars", *Astron. Astrophys.* **465** (1) (1 Apr 2007) 249–255.
doi: 10.1051/0004-6361:20066059
bibcode: 2007A&A...465..249A, 2007yCat..34650249A
arXiv: astro-ph/0702024v1 1 Feb 2007 ↗

[Alt07.xls] L.G. Althaus, E. Garcia-Berro, J. Isern, A.H. Corsico and R.D. Rohrmann, "The age and colors of massive white dwarf stars" [data tables], *Research Group of Stellar Evolution and Pulsations Website* (6 Feb 2007; accessed 23 Aug 2009).
url: http://www.fcaglp.unlp.edu.ar/evolgroup/TRACKS/colors.tar.gz

[Ams08] C. Amsler *et al.* (Particle Data Group), "Review of Particle Physics", *Physics Letters* **B667** (Sep 2008) 1–1340.
url: http://pdg.lbl.gov/2009/download/rpp-2008-plB667.pdf
doi: 10.1016/j.physletb.2008.07.018
bibcode: 2008PhLB..667....1P

[AFGS02] L.A. Anchordoqui, J.L. Feng, H. Goldberg and A.D. Shapere, "Black holes from cosmic rays: Probes of extra dimensions and new limits on TeV-scale gravity", *Phys. Rev.* **D65** (12) (June 2002) id. 124027 (17pp.), NUB-3224-Th-01, MIT-CTP-3216, UCI-TR-2001-42, UK/01-12.
doi: 10.1103/PhysRevD.65.124027
bibcode: 2002PhRvD..65l4027A
arXiv: hep-ph/0112247v3 30 Apr 2002 ↗

[AADD98] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, "New dimensions at a millimeter to a Fermi and superstrings at a TeV", *Phys. Lett.* **B436** (3–4) (Sep 1998) 257–263, SLAC-PUB-7801, SU-ITP-98/28, CPTH-S608.0498, IC/98/39.
doi: 10.1016/S0370-2693(98)00860-0
bibcode: 1998PhLB..436..257A
arXiv: hep-ph/9804398v1 24 Apr 1998 ↗

[ADMR98] P.C. Argyres, S. Dimopoulos and J. March-Russell, "Black Holes and Sub-millimeter Dimensions", *Phys. Lett.* **B441** (1–4) (26 Nov 1998) 98–104, CLNS-98/1577, SU-ITP-98/53, CERN-TH/98-267.
doi: 10.1016/S0370-2693(98)01184-8

bibcode: 1998PhLB..441...96A
arXiv: hep-th/9808138v1 21 Aug 1998 ↗

[ADD98] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, "The hierarchy problem and new dimensions at a millimeter", *Phys. Lett.* **B429** (3–4) (Jun 1998) 263–272, SLAC-PUB-7769, SU-ITP-98/13
doi: 10.1016/S0370-2693(98)00466-3
bibcode: 1998PhLB..429..263A
arXiv: hep-ph/9803315v1 11 Mar 1998 ↗

[ATLAS-Can09] ATLAS-Canada, "ATLAS Canada Collaborators", *ATLAS-Canada Website* (last modified 25 Nov 2009; accessed 5 Jan 2010)
url: http://www.atlas-canada.ca/lista.html

[BLV05] C. Barcelo, S. Liberati and M. Visser, "Analogue gravity", *Living Rev. Rel.* **8** (Dec 2005; accessed 6 Oct 2009) id. 12 (113pp.). ↗
url: http://www.livingreviews.org/lrr-2005-12
bibcode: 2005LRR.....8...12B
arXiv: gr-qc/0505065v2 1 Jun 2005 ↗

[Bar05] M.A. Barstow, H.E. Bond, J.B. Holberg, M.R. Burleigh, I. Hubeny and D. Koester, "Hubble Space Telescope Spectroscopy of the Balmer lines in Sirius B", *Mon. Not. R. Astron. Soc.* **362** (4) (2005) 1134–1142, ST ScI Eprint 1669.
doi: 10.1111/j.1365-2966.2005.09359.x
bibcode: 2005MNRAS.362.1134B ↗
arXiv: astro-ph/0506600v1 24 Jun 2005 ↗

[Bar93] M.A. Barstow, T.A. Fleming, C.J. Diamond, D.S. Finley, A.E. Sansom, S.R. Rosen, D. Koester, M.C. Holberg, J.B. Marsh and K. Kidder, "ROSAT studies of the composition and structure of DA white dwarf atmospheres", *Mon. Not. R. Astron. Soc.* **264** (1) (Sep 1993) 16–34.
bibcode: 1993MNRAS.264...16B ↗

[Beg78] M.C. Begelman, "Black holes in radiation-dominated gas: an analogue of the Bondi accretion problem", *Mon. Not. R. Astr. Soc.* **184** (Jul 1978) 53–67.
bibcode: 1978MNRAS.184...53B ↗

[Berg91] P. Bergeron, K.M. Kidder, J.B. Holberg, J. Liebert, F. Wesemael and R.A. Saffer, "The isolated massive DA white dwarf GD 50", *Astrophys. J., Part 1* **372** (1 May 1991) 267–272.
doi: 10.1086/169972
bibcode: 1991ApJ...372..267B ↗

[BSL92] P. Bergeron, R.A. Saffer and J. Liebert, "A spectroscopic determination of the mass distribution of DA white dwarfs", *Astrophys. J., Part 1* **394** (20 Jul 1992) 228–247.
doi: 10.1086/171575
bibcode: 1992ApJ...394..228B ↗

[BCG04] E. Berti, M. Cavaglià, and L. Gualtieri, "Gravitational energy loss in high energy particle collisions: Ultrarelativistic plunge into a multidimensional black hole", *Phys. Rev.* **D69** (12) (11 Jun 2004) id. 124011 (13pp.).
doi: 10.1103/PhysRevD.69.124011
bibcode: 2004PhRvD..69l4011B
arXiv: hep-th/0309203v2 25 Mar 2004 ↗

[Bild09] L. Bildsten, "Faculty Page", *Kavli Institute for Theoretical Physics Website* (2008?; accessed 2 Aug 2009).
url: http://www.kitp.ucsb.edu/~bildsten/

[BC01] L. Bildsten and D. Chakrabarty, "A Brown Dwarf Companion for the Accreting Millisecond Pulsar SAX J1808.4–3658", *Astrophys. J.* **557** (1) (Aug 2001) 292–296. ↗
doi: 10.1086/321633
bibcode: 2001ApJ...557..292B
arXiv: astro-ph/0104153v1 9 Apr 2001 ↗

[Birch52] F. Birch, "Elasticity and Constitution of the Earth's Interior", *J. Geophys. Res.* **57** (2) (Jun 1952) 227–286.
doi: 10.1029/JZ057i002p00227
bibcode: 1952JGR....57..227B

[LSSG] J.-P. Blaizot, J. Iliopoulos, J. Madsen, G.G. Ross, P. Sonderegger and H.-J. Specht (LHC Safety Study Group), "Study of potentially dangerous events during heavy-ion collisions at the LHC: Report of the LHC safety study group", CERN-2003-001 (28 Feb 2003) 20pp.
url: http://doc.cern.ch/yellowrep/2003/2003-001/p1.pdf
ISBN: 978-92-9083-204-1

[Bon52] H. Bondi, "On Spherically Symmetrical Accretion", *Mon. Not. R. Astron. Soc.*, **112** (1952) 195–204.
bibcode: 1952MNRAS.112..195B ↗

[BH44] H. Bondi and F. Hoyle, "On the Mechanism of Accretion by Stars" *Mon. Not. R. Astron. Soc.*, **104** (1944) 273–282.
bibcode: 1944MNRAS.104..273B ↗

[BRB95] A. Bragaglia, A. Renzini and P. Bergeron, "Temperatures, gravities, and masses for a sample of bright DA white dwarfs and the initial-to-final mass relation", *Astrophys. J., Part 1* **443** (2) (20 Apr 1995) 735–752.
doi: 10.1086/175564
bibcode: 1995ApJ...443..735B ↗

[SPC] P. Braun-Munzinger, M. Cavalli-Sforza, G. 't Hooft, B. Webber and F. Zwirner (CERN Scientific Policy Committee Panel on LSAG Documents) (author of summary?), "SPC Report on LSAG Documents" (summary of the SPC Panel opinion on LSAG documents), CERN (published 20 Jun 2008; accessed 3 Aug 2009) 4pp.
url: http://cdsweb.cern.ch/record/1113558/files/cer-002766289.pdf

[BM86] J.M. Brown and R.G. McQueen, "Phase Transitions, Grüneisen Parameter, and Elasticity for Shocked Iron Between 77 GPa and 400 GPa", *J. Geophys. Res.* **91** (B7) (10 Jun 1986) 7485–7494.
doi: 10.1029/JB091iB07p07485
bibcode: 1986JGR....91.7485B

[CGHS92] C.G. Callan, S.B. Giddings, J.A. Harvey and A. Strominger, "Evanescent black holes", *Phys. Rev.* **D45** (4) (15 Feb 1992) 1005–1009.
doi: 10.1103/PhysRevD.45.R1005
bibcode: 1992PhRvD..45.1005C
arXiv: hep-th/9111056v1 28 Nov 1991 ↗

[CDL03] V. Cardoso, Ó.J.C. Dias, and J. Lemos, "Gravitational radiation in *D*-dimensional spacetimes", *Phys. Rev.* **D67** (6) (31 Mar 2003) id. 064026 (13pp.).
doi: 10.1103/PhysRevD.67.064026
bibcode: 2003PhRvD..67f4026C
arXiv: hep-th/0212168v3 3 Apr 2003 ↗

[CL02] V. Cardoso and J. Lemos, "Gravitational radiation from collisions at the speed of light: a massless particle falling into a Schwarzschild black hole", *Phys. Lett.* **B538** (1–2) (27 Jun 2002) 1–5.
doi: 10.1016/S0370-2693(02)01961-5
bibcode: 2002PhLB..538....1C
arXiv: gr-qc/0202019v2 15 Jun 2002 ↗

[CRIG08] S. Catalán, I. Ribas, J. Isern and E. García-Berro, "WD0433+270: an old Hyades stream member or an Fe-core white dwarf?", *Astron. Astrophys.* **477** (3) (Jan 2008) 901–906.
doi: 10.1051/0004-6361:20078230
bibcode: 2008A&A...477..901C
arXiv: 0710.3999v1 [astro-ph] 22 Oct 2007 ↗

[CERN:Conv] CERN, "Convention for the establishment of a European organization for nuclear research", Paris, 1 Jul 1953 (as amended with effect 17 Jan 1971), (CERN, Paris, 1971) 57pp.
url: http://cdsweb.cern.ch/record/330625/files/cm-p00046871.pdf url: http://dsu.web.cern.ch/dsu/ls/conventionE.htm

[CERN07] CERN Web Communications, DSU-CO, "LHC and black holes?", Ask an Expert section, *CERN Website* (posted 2007; accessed 15 Nov 2009).
url: http://askanexpert.web.cern.ch/AskAnExpert/en/Accelerators/LHCblackholes-en.html

[CERN08a] CERN Press Office, DSU-CO, "CERN Council looks forward to LHC start-up" [press release], *CERN Website* (posted 20 Jun 2008; accessed 15 Nov 2009).
url:
http://public.web.cern.ch/press/PressReleases/Releases2008/PR05.08E.html

[CERN08b] CERN Web Communications, DSU-CO, "The safety of the LHC", *CERN Website* (posted 2008; accessed 6 Mar 2010).
url: http://public.web.cern.ch/public/en/LHc/Safety-en.html

[CERN08c] "Membership of the Scientific Policy Committee", *CERN Website* (2008?; accessed 1 May 2008).
url: http://dsu.web.cern.ch/dsu/of/csSPCmembership.html

[SPC08b] CERN Scientific Policy Committee, "The Scientific Reach of a SLHC: Assessment by the SPC", CERN/SPC/911/Rev., CERN/2814/Rev. (9 Dec 2008) 14pp.
url: http://indico.cern.ch/getFile.py/access?subContId=0&contribId=2&resId=0&materialId=1&confId=45597

[CM98] D. Chakrabarty and E.H. Morgan, "The two-hour orbit of a binary millisecond X-ray pulsar", *Nature* **394** (23 Jul 1998) 346–348.
doi: 10.1038/28561
bibcode: 1998Natur.394..346C
arXiv: astro-ph/9804248v2 21 Jul 1998 ↗

[CTAI97] X. Chen, R.E. Taam, M.A. Abramowicz and I.V. Igumenshchev, "On the morphology of accretion flows with small, non-zero specific angular momentum", *Mon. Not. R. Astron. Soc.* **285** (2) (Feb 1997) 439–448.
bibcode: 1997MNRAS.285..439C ↗
arXiv: astro-ph/9612123v1 13 Dec 1996 ↗

[Choi06] C.Q. Choi, "Despite Rumors, Black Hole Factory Will Not Destroy Earth" [Special Report], *livescience.com Website* (08:58 ET 19 Sep 2006; accessed 2 Aug 2009).
url: http://www.livescience.com/environment/060919_black_holes.html

[CF77] S.M. Christensen and S.A. Fulling, "Trace anomalies and the Hawking effect", *Phys. Rev.* **D15** (8) (15 Apr 1977) 2088–2104.
doi: 10.1103/PhysRevD.15.2088
bibcode: 1977PhRvD..15.2088C

[Cox08] B. Cox, "Re: CERN recieves Death Threats?" [online posting], *Scientific Concerns: Safety, Ethics, and Issues Board* (posted 10:21 UTC 5 Sep 2008; accessed 13 Dec 2009).
url: http://www.scientificconcerns.com/Forums/viewtopic.php?f=18&t=361

[Cuad04] R.A. Cuadrado, S. Jordan, R. Napiwotzki, H.M. Schmid, S.K. Solanki and G. Mathys, "Discovery of kilogauss magnetic fields in three DA white dwarfs", *Astron. Astrophys.* **423** (Sep 2004) 1081–1094. ↗
doi: 10.1051/0004-6361:20040355
bibcode: 2004A&A...423.1081
arXiv: astro-ph/0405308v2 18 May 2004 ↗

[DSS06] D-C. Dai, G.D. Starkman, and D. Stojkovic, "Production of black holes and their angular momentum distribution in models with split fermions", *Phys. Rev.* **D73** (10) (31 May 2006) id. 104037 (10pp.).
doi: 10.1103/PhysRevD.73.104037
bibcode: 2006PhRvD..73j4037D
arXiv: hep-ph/0605085v3 5 Jul 2006 ↗

[DD06] A. Dar and A. De Rújula, "A Theory of Cosmic Rays", *Phys. Rept.* **466** (6) (Sep 2008) 179–241.
doi: 10.1016/j.physrep.2008.05.004
bibcode: 2008PhR...466..179D
arXiv: hep-ph/0606199v2 7 May 2008 ↗

[DDH99] A. Dar, A. De Rújula and U. Heinz, "Will relativistic heavy-ion colliders destroy our planet?", *Phys. Lett.* **B470** (1–4) (16 Dec 1999) 142–148, CERN-TH/99-324.
doi: 10.1016/S0370-2693(99)01307-6
bibcode: 1999PhLB..470..142D
arXiv: hep-ph/9910471v1 25 Oct 1999 ↗

[D'EP92] P.D. D'Eath and P.N. Payne, "Gravitational radiation in black hole collisions at the speed of light. III. Results and conclusions", *Phys. Rev.* **D46** (2) (15 Jul 1992) 694–701.
doi: 10.1103/PhysRevD.46.694
bibcode: 1992PhRvD..46..694D

[DKK99] E.V. Derishev, V.V. Kocharovsky and Vl.V. Kocharovsky, "Cosmological gamma-ray bursts from a neutron star collapse induced by a primordial black hole", *JETP Lett.* **70** (10) (Nov 1999) 652–658.
doi: 10.1134/1.568241
bibcode: 1999JETPL..70..652D

[Pisma Zh. Eksp. Teor. Fiz. **70** (Nov 1999) 642.
bibcode: 1999ZhPmR..70..642D]

[DL01] S. Dimopoulos and G.L. Landsberg, "Black Holes at the Large Hadron Collider", *Phys. Rev. Lett.* **87** (16) (15 Oct 2001) id. 161602 (4pp.), Stanford ITP-01/31.
doi: 10.1103/PhysRevLett.87.161602
bibcode: 2001PhRvL..87p1602D
arXiv: hep-ph/0106295v1 27 Jun 2001 ↗

[Dob06] P.D. Dobbie, R. Napiwotzki, N. Lodieu, M.R. Burleigh, M.A. Barstow and R.F. Jameson, "On the origin of the ultramassive white dwarf GD50", *Mon. Not. R. Astron. Soc.* **373** (1) (Nov 2006) L45–L49.
doi: 10.1111/j.1745-3933.2006.00240.x
bibcode: 2006MNRAS.373L..45D ↗
arXiv: astro-ph/0608671 30 Aug 2006 ↗

[DVC02] J. Dupuis, S. Vennes and P. Chayer, "A Search for Helium in Ultramassive White Dwarfs", *Astrophys. J.* **580** (1 Dec 2002) 1091–1099. ↗
doi: 10.1086/343846
bibcode: 2002ApJ...580.1091D

[DRS03] S.I. Dutta, M.H. Reno and I. Sarcevic, "Ultrahigh energy neutrinos", *Int. J. Mod. Phys.* **A18** (2003) 4085–4096, presented at Neutrinos and Implications for Physics Beyond the Standard Model, Stony Brook, NY, 11–13 Oct 2002.
bibcode: 2003nipb.conf..339D
arXiv: hep-ph/0302178v1 19 Feb 2003 ↗

[DGKN01] G. Dvali, G. Gabadadze, M. Kolanovic, and F. Nitti, "Power of brane-induced gravity", *Phys. Rev.* **D64** (8) (5 Sep 2001) id. 084004 (13pp.), NYU-TH-00/02/01, HEP-MN-1940.
doi: 10.1103/PhysRevD.64.084004
bibcode: 2001PhRvD..64h4004D
arXiv: hep-ph/0102216v3 4 Jul 2001 ↗

[DGKN02] G. Dvali, G. Gabadadze, M. Kolanovic, and F. Nitti, "Scales of gravity", *Phys. Rev.* **D65** (2) (Jan 2002) id. 024031 (27pp.), NYU-TH-01/06/03, TPI-MINN-01/26.
doi: 10.1103/PhysRevD.65.024031
bibcode: 2002PhRvD..65b4031D
arXiv: hep-th/0106058v2 15 Jul 2001 ↗

[Ellis08] J.R. Ellis (CERN) [speaker], "The LHC is safe" [streaming video], CERN Colloquium, CERN (Main Auditorium), Geneva (14 Aug 2008).
url: http://cdsweb.cern.ch/record/1120625/

[Ellis08.ppt] J.R. Ellis (CERN), "The LHC is Safe" [powerpoint presentation], accompanying the CERN Colloquium "The LHC is safe", CERN, Geneva (14 Aug 2008).
url: http://indico.cern.ch/getFile.py/access?resId=0&materialId=slides&confId=39099

[LSAG] J. Ellis, G. Giudice, M.L. Mangano, I. Tkachev and U. Wiedemann (LHC Safety Assessment Group), "Review of the Safety of LHC Collisions", CERN Preprint (20 Jun 2008) (15pp.).
url: http://lsag.web.cern.ch/lsag/LSAG-Report.pdf
arXiv: 0806.3414v1 [hep-ph] 20 Jun 2008 ↗

[LSAGAdd] J. Ellis, G. Giudice, M.L. Mangano, I. Tkachev and U. Wiedemann (LHC Safety Assessment Group), "Review of the Safety of LHC Collisions: Addendum on strangelets", CERN Preprint (20 Jun 2008) (11pp.).
url: http://lsag.web.cern.ch/lsag/LSAG-Report_add.pdf

[LSAGJPhysG] J. Ellis, G. Giudice, M.L. Mangano, I. Tkachev and U. Wiedemann (LHC Safety Assessment Group), "Review of the safety of LHC Collisions", *J. Phys.* **G35** (11) (Nov 2008) id. 115004 (18pp.).
url: http://stacks.iop.org/JPhysG/35/115004
doi: 10.1088/0954-3899/35/11/115004
bibcode: 2008JPhG...35k5004E

[LSAGv2] J. Ellis, G. Giudice, M.L. Mangano, I. Tkachev and U. Wiedemann (LHC Safety Assessment Group), "Review of the Safety of LHC Collisions" (including addendum), CERN-PH-TH/2008-136 (2008).
arXiv: 0806.3414v2 [hep-ph] 18 Sep 2008 ↗

[LSAGSum] J. Ellis *et al.* (authors of summary?), "The safety of the LHC" (Summary of the main arguments in the LSAG report), *CERN Website* (published 20 Jun 2008; accessed 3 Aug 2009).
url: http://environmental-impact.web.cern.ch/environmental-impact/Objects/LHCSafety/LSAGSummaryReport2008-en.pdf

[EHM00] R. Emparan, G.T. Horowitz, and R.C. Myers, "Black Holes Radiate Mainly on the Brane", *Phys. Rev. Lett.* **85** (3) (17 Jul 2000) 499–502.
doi: 10.1103/PhysRevLett.85.499
bibcode: 2000PhRvL..85..499E
arXiv: hep-th/0003118 6 Jun 2000 ↗

[EOIS05] S. Enomoto, E. Ohtani, K. Inoue and A. Suzuki, "Neutrino geophysics with KamLAND and future prospects".
arXiv: hep-ph/0508049v2 20 Oct 2005 ↗

[Esp08] G. Esposito-Farèse, "Summary of session A4: alternative theories of gravity", Proc. 18th International Conference on General Relativity and Gravitation (GRG18) and 7th Edoardo Amaldi Conference on Gravitational Waves (Amaldi7), Sydney, Australia, 8–13 Jul 2007, *Class. Quantum Grav.* **25** (11) (Jun 2008) 114017 (8pp.).
doi: 10.1088/0264-9381/25/11/114017
bibcode: 2008CQGra..25k4017E
arXiv: 0711.0332v1 [gr-qc] 2 Nov 2007 ↗

[ES09] Euroscience, "Euroscience Media Awards", *Euroscience Website* (posted 14 Oct 2009; accessed 22 Oct 2009).
url: http://www.euroscience.org/?module=agenda&action=ViewDetail&agendaParam%5Bcmpref%5D=33529&lang=en

[FS01] J.L. Feng and A.D. Shapere, "Black hole production by cosmic rays", *Phys. Rev. Lett.* **88** (2) (14 Jan 2002) id. 021303 (4pp.), MIT-CTP-3182, UCI-TR-2001-27, UK/01-07.
doi: 10.1103/PhysRevLett.88.021303
bibcode: 2002PhRvL..88b1303F
arXiv: hep-ph/0109106v2 19 Dec 2001 ↗

[FZ08] E. Fernandez and F. Zwirner, Untitled [online posting], posting attached to "Doomsday Lawsuit Dissed", Author/Editor A. Boyle, *Cosmic Log Blog* (comment posted 04:37 EDT 25 Jun 2008; accessed 10 Oct 2009).
url: http://cosmiclog.msnbc.msn.com/archive/2008/06/24/1165649.aspx

[Fiq01] G. Fiquet, J. Badro, F. Guyot, H. Requardt and M. Krisch, "Sound Velocities in Iron to 110 Gigapascals", *Science* **291** (5503) (19 Jan 2001) 468-471.
doi: 10.1126/science.291.5503.468
bibcode: 2001Sci...291..468F

[FBB90] D.S. Finley, G. Basri and S. Bowyer, "The temperature scale of hot DA white dwarfs: Temperatures from far-ultraviolet continuum fluxes", *Astrophys. J., Part 1* **359** (20 Aug 1990) 483–498.
doi: 10.1086/169080
bibcode: 1990ApJ...359..483F ↗

[FLM07] G. Fiorentini, M. Lissia and F. Mantovani, "Geo-neutrinos and Earth's interior", *Phys. Rept.* **453** (5–6) (Dec 2007) 117–172.
doi: 10.1016/j.physrep.2007.09.001
bibcode: 2007PhR...453..117F
arXiv: 0707.3203v2 [physics.geo-ph] 18 Aug 2007 ↗

[FKRT03] Z. Fodor, S.D. Katz, A. Ringwald and H. Tu, “Bounds on the cosmogenic neutrino flux”, *JCAP* **03** (11) (27 Nov 2003) id. 015, WUB 03-10, ITP-BUDAPEST 601, DESY 03-114.
doi: 10.1088/1475-7516/2003/11/015
bibcode: 2003JCAP...11..015F
arXiv: hep-ph/0309171v1 15 Sep 2003 ↗

[FBB01] G. Fontaine, P. Brassard and P. Bergeron, “The Potential of White Dwarf Cosmochronology” [invited review], based, in part, on the C. S. Beals Lecture presented by G. Fontaine at the Annual General Meeting of the Canadian Astronomical Society held in Vancouver, May 2000, *Publications of the Astro. Soc. of the Pacific* **113** (782) (Apr 2001) 409–435. ↗
doi: 10.1086/319535
bibcode: 2001PASP..113..409F

[FKR02] J. Frank, A. King and D. Raine, *Accretion Power in Astrophysics*, 3rd ed. (Cambridge University Press, Cambridge, UK, Feb 2002), 398pp.
url:
http://www.cambridge.org/catalogue/catalogue.asp?isbn=9780521620536
ISBN: 978-0-521-62053-6 hardback
ISBN: 978-0-511-07443-1 eBook (Adobe Reader)
bibcode: 2002apa..book.....F

[GP05] G. Giacomelli and L. Patrizii, “Magnetic monopole searches”, Lecture at the 7th School on Non-Accelerator Astroparticle Physics, ICTP, Trieste, 2004, SLIM 2005/4.
arXiv: hep-ex/0506014v1 7 Jun 2005 ↗

[Gid94] S.B. Giddings, “Quantum mechanics of black holes”, Lectures presented at 1994 Summer School in High Energy Physics and Cosmology, ICTP, Trieste, 13 Jun – 29 Jul 1994, UCSBTH-94-52.
bibcode: 1995hepc.conf..530G
arXiv: hep-th/9412138v1 16 Dec 1994 ↗

[Gid95] S.B. Giddings, “The Black Hole Information Paradox”, Lecture presented at PASCOS symposium/Johns Hopkins Workshop, Baltimore, MD, 22–25 Mar 1995 UCSBTH-95-24.
arXiv: hep-th/9508151v1 28 Aug 1995 ↗

[Gid01] S.B. Giddings, "Black Hole Production in TeV-Scale Gravity, and the Future of High Energy Physics", Proc. APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass Village, Colorado, 30 Jun – 21 Jul 2001, Ed. N. Graf, eConf C010630 (2001) id. P328 (11pp.). ↗
url: http://www.slac.stanford.edu/econf/C010630/papers/P328.PDF
bibcode: 2001hep.ph...10127G
arXiv: hep-ph/0110127v3 1 Nov 2001 ↗

[Gid07] S.B. Giddings, "High-energy black hole production", Proc. 13th International Symposium on Particles, Strings, and Cosmology (PASCOS–07), London, UK, 2–7 Jul 2007, Eds. A. Rajantie, C. Contaldi, P. Dauncey and H. Stoica, *AIP Conf. Proc.* **957** (Nov 2007) 69–78.
doi: 10.1063/1.2823829
bibcode: 2007AIPC..957...69G
arXiv: 0709.1107 [hep-ph] 5 Oct 2007 ↗

[GM] S.B. Giddings and M.L. Mangano, "Astrophysical implications of hypothetical stable TeV-scale black holes" [version 1], CERN-PH-TH/2008-025 (2008).
arXiv: 0806.3381v1 [hep-ph] 20 Jun 2008 ↗

[GM.ltx] S.B. Giddings and M.L. Mangano, "Astrophysical implications of hypothetical stable TeV-scale black holes" [version 1 - LaTeXsource file].
url: http://arxiv.org/e-print/0806.3381v1
arXiv: 0806.3381v1 [hep-ph] 20 Jun 2008

[GMPhysD] S.B. Giddings and M.L. Mangano, "Astrophysical implications of hypothetical stable TeV-scale black holes" [published version], *Phys. Rev.* **D78** (3) (18 Aug 2008) id. 035009 (47pp.).
url: http://link.aps.org/doi/10.1103/PhysRevD.78.035009
doi: 10.1103/PhysRevD.78.035009
bibcode: 2008PhRvD..78c5009G

[GMv2] S.B. Giddings and M.L. Mangano, "Astrophysical implications of hypothetical stable TeV-scale black holes" [version 2].
arXiv: 0806.3381v2 [hep-ph] 23 Sep 2008 ↗

[GMv2.ltx] S.B. Giddings and M.L. Mangano, "Astrophysical implications of hypothetical stable TeV-scale black holes" [version 2 - LaTeXsource file].
url: http://arxiv.org/e-print/0806.3381v2
arXiv: 0806.3381v2 [hep-ph] 23 Sep 2008

[GMreply08] S.B. Giddings and M.L. Mangano, "Comments on claimed risk from metastable black holes" (reply to [Pla08v1]).
arXiv: 0808.4087v1 [hep-ph] 29 Aug 2008 ↗

[GT02] S.B. Giddings and S.D. Thomas, "High energy colliders as black hole factories: The end of short distance physics", *Phys. Rev.* **D65** (5) (Mar 2002) id. 056010 (12pp.).
doi: 10.1103/PhysRevD.65.056010
bibcode: 2002PhRvD..65e6010G
arXiv: hep-ph/0106219v4 26 Jun 2002 ↗

[Ging06] D.M. Gingrich, "Black Hole Cross-Section at the LHC", *Int. J. Mod. Phys.* **A21** (32) (30 Dec 2006) 6653–6676.
doi: 10.1142/S0217751X06035087
bibcode: 2006IJMPA..21.6653G
arXiv: hep-ph/0609055v2 22 Dec 2006 ↗

[Ging09] D.M. Gingrich, "Quantum black holes with charge, colour, and spin at the LHC".
arXiv: 0912.0826v3 [hep-ph] 28 Jan 2010 ↗

[GTTT08] D.S. Gorbunov, P.G. Tinyakov, I.I. Tkachev and S.V. Troitsky, "On the interpretation of the cosmic-ray anisotropy at ultra-high energies".
arXiv: 0804.1088v1 [astro-ph] 7 Apr 2008 ↗

[GLL02] P. Gorham, J. Learned and N. Lehtinen, "Neutrino-induced Collapse of Bare Strange Stars Via TeV-scale Black Hole Seeding".
arXiv: astro-ph/0205170v1 13 May 2002 ↗

[GMS01] D.E. Groom, N.V. Mokhov and S.I. Striganov, "Muon Stopping Power and Range Tables, 10 MeV–100 TeV", *At. Data Nucl. Data Tables* **78** (2) (Jul 2001) 183–356.
url: http://pdg.lbl.gov/2008/AtomicNuclearProperties/
doi: 10.1006/adnd.2001.0861
bibcode: 2001ADNDT..78..183G

[Gub07] S.S. Gubser, "Heavy ion collisions and black hole dynamics", *Gen. Relativ. Gravit.* **39** (10) (Oct 2007) 1533–1538. ↗
doi: 10.1007/s10714-007-0473-8
bibcode: 2007GReGr..39.1533G

[HH02] F. Halzen and D. Hooper, "High-energy neutrino astronomy: The cosmic ray connection", *Rept. Prog. Phys.* **65** (7) (Jul 2002) 1025–1078, MADPH-02-1265.
doi: 10.1088/0034-4885/65/7/201
bibcode: 2002RPPh...65.1025H
arXiv: astro-ph/0204527v2 8 Jul 2002 ↗

[Haw71] S. Hawking, "Gravitationally collapsed objects of very low mass", *Mon. Not. R. Astron. Soc.* **152** (1971) 75–78.
bibcode: 1971MNRAS.152...75H ↗

[Haw75] S.W. Hawking, "Particle Creation By Black Holes", *Commun. Math. Phys.* **43** (3) (Aug 1975) 199–220.
doi: 10.1007/BF02345020
bibcode: 1975CMaPh..43..199H

[Haw76] S.W. Hawking, "Breakdown of predictability in gravitational collapse", *Phys. Rev.* **D14** (10) (15 Nov 1976) 2460–2473.
doi: 10.1103/PhysRevD.14.2460
bibcode: 1976PhRvD..14.2460H

[Hern93] J.M. Herndon, "Feasibility of a Nuclear Fission Reactor at the Center of the Earth as the Energy Source for the Geomagnetic Field", *J. Geomag. Geoelectr.* **45** (5) (1993) 423–437.
url: http://www.nuclearplanet.com/Herndon%20JGG93.pdf
url: http://www.journalarchive.jst.go.jp/jnlpdf.php?cdjournal=jgg1949&cdvol=45&noissue=5&startpage=423&lang=en&from=jnltoc

[Hern94] J.M. Herndon, "Planetary and protostellar nuclear fission: implications for planetary change, stellar ignition, and dark matter", *Proc. R. Soc. Lond. A* **445** (1924) (9 May 1994) 453–461. ↗
doi: 10.1098/rspa.1994.0071
bibcode: 1994RSPSA.445..453H

[Hern96] J.M. Herndon, "Substructure of the inner core of the Earth", *Proc. Natl. Acad. Sci. USA* **93** (2) (23 Jan 1996) 646–648. ↗
bibcode: 1996PNAS...93..646H

[Hern03] J.M. Herndon, "Nuclear georeactor origin of oceanic basalt ^{3}He/^{4}He, evidence, and implications", *Proc. Natl. Acad. Sci. USA* **100** (6) (18 Mar 2003) 3047–3050. ↗
doi: 10.1073/pnas.0437778100
bibcode: 2003PNAS..100.3047H

[HC05a] A.M. Hofmeister and R.E. Criss, "Earth's heat flux revised and linked to chemistry", *Tectonophys.* **395** (3–4) (20 Jan 2005) 159–177.
doi: 10.1016/j.tecto.2004.09.006
bibcode: 2005Tectp.395..159H
[full text not accessed for this paper].

[HC05b] A.M. Hofmeister and R.E. Criss, "Reply to comments by R. Von Herzen, E.E. Davis, A.T. Fisher, C.A. Stein and H.N. Pollack on "Earth's heat flux revised and linked to chemistry", *Tectonophys.* **409** (1–4) (16 Nov 2005) 199–203.
doi: 10.1016/j.tecto.2005.08.004
bibcode: 2005Tectp.409..199H
url: http://www.es.ucsc.edu/~afisher/Research/Appen/H_Cresponse2005.pdf

[HH01] D.F. Hollenbach and J.M. Herndon, "Deep-Earth reactor: Nuclear fission, helium, and the geomagnetic field", *Proc. Natl. Acad. Sci. USA* **98** (20) (25 Sep 2001) 11085–11090. ↗
doi: 10.1073/pnas.201393998
bibcode: 2001PNAS...9811085H

['tH96] G. 't Hooft, "The scattering matrix approach for the quantum black hole: an overview", *Int. J. Mod. Phys.* **A11** (26) (1996) 4623–4688.
doi: 10.1142/S0217751X96002145
bibcode: 1996IJMPA..11.4623T
arXiv: gr-qc/9607022v1 9 Jul 1996 ↗

[Hoss04] S. Hossenfelder, "Suppressed black hole production from minimal length", *Phys. Lett* **B598** (1–2) (Sep 2004) 92–98.
doi: 10.1016/j.physletb.2004.07.056
bibcode: 2004PhLB..598...92H
arXiv: hep-th/0404232v2 29 Jul 2004 ↗

[Hoss06] S. Hossenfelder, "What Black Holes Can Teach Us", in *Focus on Black Hole Research*, Ed. P.V. Kreitler (Nova Science Publishers, New York, 2006), 121–158.
ISBN: 978-1-59454-460-6
bibcode: 2006fbhr.book..121H
arXiv: hep-ph/0412265v1 17 Dec 2004 ↗

[Hoss07] S. Hossenfelder, "Micro Black Day", *BackRe(Action) Blog* (posted 16 Jan 2007; accessed 10 Dec 2009).
url: http://backreaction.blogspot.com/2007/01/micro-black-day.html

[Hoss08] S. Hossenfelder, "Is there life after CERN", *BackRe(Action) Blog* (posted 23 Jul 2008; accessed 1 Aug 2008).
url: http://backreaction.blogspot.com/2008/07/is-there-life-after-cern.html

[HKB05] S. Hossenfelder, B. Koch and M. Bleicher, "Trapping Black Hole Remnants".
arXiv: hep-ph/0507140v1 12 Jul 2005 ↗

[HL39a] F. Hoyle and R.A. Lyttleton, "The effect of interstellar matter on climatic variation", *Proc. Camb. Phil. Soc.*, **35** (3) (Jul 1939) 405–415.
doi: 10.1017/S0305004100021150
bibcode: 1939PCPS...35..405H
[Cited by the GM paper; not directly accessed for this paper]

[HL39b] F. Hoyle and R.A. Lyttleton, "The evolution of the stars", *Proc. Camb. Phil. Soc.*, **35** (4) (Nov 1939) 592–609.
doi: 10.1017/S0305004100021368
bibcode: 1939PCPS...35..592H
[Not directly accessed for this paper]

[HL40a] F. Hoyle and R.A. Lyttleton, "On the accretion of interstellar matter by stars", *Proc. Camb. Phil. Soc.*, **36** (3) (Jul 1940) 325–330.
doi: 10.1017/S0305004100017369
bibcode: 1940PCPS...36..325H
[Cited by the GM paper; not directly accessed for this paper]

[HL40b] F. Hoyle and R.A. Lyttleton, "On the physical aspects of accretion by stars", *Proc. Camb. Phil. Soc.*, **36** (4) (Oct 1940) 424–437.
doi: 10.1017/S0305004100017461
bibcode: 1940PCPS...36..424H,
[Cited by the GM paper; not directly accessed for this paper]

[IPCC99] Intergovernmental Panel on Climate Change (IPCC), "Procedures for the Preparation, Review, Acceptance, Adoption, Approval and Publication of IPCC Reports", Appendix A to the "Principles Governing IPCC Work" adopted at the IPCC's Fifteenth Session (San Jose, 15–18 April 1999) amended at the Twentieth Session (Paris, 19-21 February 2003) and Twenty-first Session (Vienna, 3 and 6-7 November 2003) 15pp.
url: http://www.ipcc.ch/pdf/ipcc-principles/ipcc-principles-appendix-a.pdf

[IPCC07] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Cambridge University Press, Cambridge, UK, 2007) 996pp.
url: http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm
url:
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

[JBSW00] R.L. Jaffe, W. Busza, F. Wilczek and J. Sandweiss, "Review of speculative "disaster scenarios" at RHIC", *Rev. Mod. Phys.* **72** (4) (Oct 2000) 1125–1140, MIT-CTP-2908.
doi: 10.1103/RevModPhys.72.1125
bibcode: 2000RvMP...72.1125J
arXiv: hep-ph/9910333v3 14 Jul 2000 ↗

[John01] G. Johnson, "Physicists Strive to Build A Black Hole" [electronic version], Science section, *New York Times* (11 Sep 2001; accessed 2 Aug 2009).
url: http://www.nytimes.com/2001/09/11/science/physicists-strive-to-build-a-black-hole.html?sec=&spon=&pagewanted=all

[Kahn84] S.M. Kahn, F. Wesemael, J. Liebert, J.C. Raymond, J.E. Steiner and H.L. Shipman, "Photospheric soft X-ray emission from hot DA white dwarfs", *Astrophys. J., Part 1* **278** (1 Mar 1984) 255–265.
doi: 10.1086/161789
bibcode: 1984ApJ...278..255K ↗

[Kaw07] A. Kawka, S. Vennes, G.D. Schmidt, D.T. Wickramasinghe and R. Koch, "Spectropolarimetric Survey of Hydrogen-Rich White Dwarf Stars", *Astrophys. J.* **654** (1) (1 Jan 2007) 499–520. ↗
doi: 10.1086/509072
bibcode: 2007ApJ...654..499K
arXiv: astro-ph/0609273v1 11 Sep 2006 ↗

[Kep07] S.O. Kepler, S.J. Kleinman, A. Nitta, D. Koester, B.G. Castanheira, O. Giovannini, A.F.M. Costa and L. Althaus, "White dwarf mass distribution in the SDSS", *Mon. Not. R. Astron. Soc.* **375** (4) (Mar 2007) 1315–1324.
url: http://www.fcaglp.unlp.edu.ar/~acorsico/Papers/althauskepler.pdf
doi: 10.1111/j.1365-2966.2006.11388.x
bibcode: 2007MNRAS.375.1315K
arXiv: astro-ph/0612277v2 17 Jan 2007 ↗

[Kid91] K.M. Kidder, "Atmospheric parameters of a soft X-ray selected set of hot DA white dwarfs", Ph.D. Thesis, Arizona Univ., Tucson AZ, 1991, 154pp., AAT 9210327.
bibcode: 1991PhDT.........5K
[Cited by Bar93; not directly accessed for this paper]

[KM01] D.P. Kilcrease and N.H. Magee Jr., "Plasma non-ideality effects on the photon-electron scattering contribution to radiative opacities", *J. of Quantitative Spectroscopy & Radiative Transfer* **71** (2–6) (Oct 2001) 445–453.
doi: 10.1016/S0022-4073(01)00088-7
bibcode: 2001JQSRT..71..445K

[Kirk07SG] J. Kirkby, "Cosmic Rays and Climate", *Surveys in Geophysics* **28** (5–6) (Nov 2007) 333–375.
doi: 10.1007/s10712-008-9030-6
bibcode: 2007SGeo...28..333K
[not directly accessed for this paper].

[Kirk08CERN] J. Kirkby, "Cosmic Rays and Climate", CERN-PH-EP/2008-005 (original 26 Mar 2008, revised 16 Apr 2008) 44pp.
url: http://doc.cern.ch/archive/electronic/cern/preprints/phep/phep-2008-005.pdf

[Kirk08arXiv] J. Kirkby, "Cosmic Rays and Climate" [revised version of Kirk08CERN].
arXiv: 0804.1938v1 [physics.ao-ph] 11 Apr 2008 ↗

[Koch07] B. Koch, "Black hole production and graviton emission in models with large extra dimensions", Ph.D. Thesis, Johann Wolfgang Goethe–Universität Frankfurt am Main, Frankfurt am Main (2007) 158pp.
url: http://th.physik.uni-frankfurt.de/~koch/Dokumente/PHDfinal.pdf

[KBH05] B. Koch, M. Bleicher and S. Hossenfelder, "Black hole remnants at the LHC", *JHEP* **10** (17 Oct 2005) id. 053 (20pp.). ↗
url: http://jhep.sissa.it/archive/papers/jhep102005053/jhep102005053.pdf
doi: 10.1088/1126-6708/2005/10/053
bibcode: 2005JHEP...10..053K
arXiv: hep-ph/0507138v2 11 Oct 2005 ↗

[KBS08v1] B. Koch, M. Bleicher and H. Stöcker, "Exclusion of black hole disaster scenarios at the LHC".
arXiv: 0807.3349v1 [hep-ph] 22 Jul 2008 ↗

[KBS08v2] B. Koch, M. Bleicher and H. Stöcker, "Exclusion of black hole disaster scenarios at the LHC", *Phys. Lett.* **B672** (1) (Feb 2009) 71–76.
doi: 10.1016/j.physletb.2009.01.003
bibcode: 2009PhLB..672...71K
arXiv: 0807.3349v2 [hep-ph] 27 Sep 2008 ↗

[KSW79] D. Koester, H. Schulz, and V. Weidemann, "Atmospheric Parameters and Mass Distribution of DA White Dwarfs", *Astron. Astrophys.* **76** (3) (Jul 1979) 262–275.
bibcode: 1979A&A....76..262K ↗

[Kol07] E. Kolbert, "Crash Course: Can a seventeen-mile-long collider unlock the universe?" [electronic version], Annals of Science section *The New Yorker* (14 May 2007; accessed 2 Aug 2009).
url: http://www.newyorker.com/reporting/2007/05/14/070514fa_fact_kolbert?currentPage=all

[KLA01] D.G. Korycansky, G. Laughlin and F.C. Adams, "Astronomical Engineering: A Strategy for Modifying Planetary Orbits", *Astrophys. Space Sci.* **275** (4) (Mar 2001) 349–366.
doi: 10.1023/A:1002790227314
bibcode: 2001Ap&SS.275..349K
arXiv: astro-ph/0102126v1 7 Feb 2001 ↗

[KMK05] M.R. Krumholz, C.F. McKee and R.I. Klein, "Bondi-Hoyle Accretion in a Turbulent Medium", *Astrophys. J.* **638** (1) (Feb 2006) 369–381. ↗
doi: 10.1086/498844
bibcode: 2006ApJ...638..369K
arXiv: astro-ph/0510410v1 13 Oct 2005 ↗

[Land06] G. Landsberg, "Black Holes at Future Colliders and Beyond: a Topical Review", *J. Phys.* **G32** (9) (Sep 2006) R337–R365.
doi: 10.1088/0954-3899/32/9/R02
bibcode: 2006JPhG...32R.337L
arXiv: hep-ph/0607297v1 26 Jul 2006 ↗

[LBD99] X.-D. Li, I. Bombaci, M. Dey, J. Dey and E.P.J. van den Heuvel, "Is SAX J1808.4–3658 a Strange Star?" *Phys. Rev. Lett.* **83** (19) (8 Nov 1999) 3776–3779.
doi: 10.1103/PhysRevLett.83.3776
bibcode: 1999PhRvL..83.3776L
arXiv: hep-ph/9905356v2 21 May 1999 ↗

[LBH05] J. Liebert, P. Bergeron and J.B. Holberg, "The Formation Rate, Mass and Luminosity Functions of DA White Dwarfs from the Palomar Green Survey", *Astrophys. J. Suppl.* **156** (1) (Jan 2005) 47–68. ↗
doi: 10.1086/425738
bibcode: 2005ApJS..156...47L
arXiv: astro-ph/0406657v2 7 Sep 2004 ↗

[Lieb05] J. Liebert, P.A. Young, D. Arnett, J.B. Holberg and K.A. Williams, "The Age and Progenitor Mass of Sirius B", *Astrophys. J.* **630** (1) (Sep 2005) L69–L72 ↗, LA-UR-05-4652.
doi: 10.1086/462419
bibcode: 2005ApJ...630L..69L
arXiv: astro-ph/0507523v2 26 Jul 2005 ↗

[Lor05] D.R. Lorimer, "Binary and Millisecond Pulsars", *Living Rev. Rel.* **8** (Nov 2005; accessed 10 Jan 2010) id. 7 (82pp.). ↗
url: http://relativity.livingreviews.org/Articles/lrr-2005-7/
bibcode: 2005LRR.....8....7L
arXiv: astro-ph/0511258v1 9 Nov 2005 ↗

[Mad98] J. Madsen, "Physics and Astrophysics of Strange Quark Matter", in *Hadrons in Dense Matter and Hadrosynthesis*, Proc. Eleventh Chris Engelbrecht Summer School, Cape Town, South Africa, 4–13 Feb 1998, *Lect. Notes Phys.* **516** (1999) 162–203.
doi: 10.1007/BFb0107314
bibcode: 1999LNP...516..162M
arXiv: astro-ph/9809032v1 3 Sep 1998 ↗

[Mad06] J. Madsen, "Strangelets, Nuclearites, Q-balls—A Brief Overview", Invited talk at Workshop on Exotic Physics with Neutrino Telescopes, Uppsala, Sweden, Sep 2006.
arXiv: astro-ph/0612740v1 27 Dec 2006 ↗

[Mang04] M. Mangano, "Conclusions and personal recommendations, Villars meeting of the SPSC, Sept 22–28 2004" [powerpoint presentation], *CERN Website*.
url: http://indico.cern.ch/materialDisplay.py?contribId=s25t3&sessionId=19&materialId=0&confId=a043551

[Mang08] M.L. Mangano, "Fortsetzung Interview: Chaos, Verschwörung, schwarze Löcher", Interviews by M. Liebe (questions provided by O.E. Rössler), *Golem.de Website* (8 Feb 2008; accessed 2 Aug 2009).
url: http://www.golem.de/0802/57477-5.html

[Mang08.en] M.L. Mangano, "Fortsetzung Interview: Chaos, Verschwörung, schwarze Löcher", Interviews by M. Liebe (questions provided by O.E. Rössler), Trans. J. Tankersley Jr. (?), *LHC Facts Website* (posted 5 Jul 2008; accessed 6 Aug 2009).
url: http://www.lhcfacts.org/?cat=27

[Marsh97] M.C. Marsh, M.A. Barstow, D.A. Buckley, M.R. Burleigh, J.B. Holberg, D. Koester, D. O'Donoghue, A.J. Penny and A.E. Sansom, An EUV-selected sample of DA white dwarfs from the *ROSAT* All-Sky Survey – I. Optically derived stellar parameters", *Mon. Not. R. Astron. Soc.* **286** (2) (Apr 1997) 369–383.
bibcode: 1997MNRAS.286..369M ↗

[MCF08] T. Di Matteo, C.L. Carilli and A.C. Fabian, "Limits on the Accretion Rates onto Massive Black Holes in Nearby Galaxies", *Astrophys. J.* **547** (2) (1 Feb 2001) 731–739. ↗
doi: 10.1086/318405
bibcode: 2001ApJ...547..731D
arXiv: astro-ph/0005516v1 25 May 2000 ↗

[MM99] P.F.L. Maxted and T.R. Marsh, "The fraction of double degenerates among DA white dwarfs", *Mon. Not. R. Astron. Soc.* **307** (1) (Jul 1999) 122–130.
doi: 10.1046/j.1365-8711.1999.02635.x
bibcode: 1999MNRAS.307..122M ↗
arXiv: astro-ph/9901273v2 23 May 2000 ↗

[MMM00] P.F.L. Maxted, T.R. Marsh and C.K.J. Moran, "Radial velocity measurements of white dwarfs", *Mon. Not. R. Astron. Soc.* **319** (1) (Nov 2000) 305–317.
doi: 10.1046/j.1365-8711.2000.03840.x
bibcode: 2000MNRAS.319..305M ↗
arXiv: astro-ph/0007129v2 31 Jul 2000 ↗

[McM89] R.K. McMahan, "Spectroscopy of the DA white dwarfs: Automatic atmospheric parameterization and mass distribution", *Astrophys. J., Part 1* **336** (1 Jan 1989) 409–420.
doi: 10.1086/167020
bibcode: 1989ApJ...336..409M ↗

[MR07] P. Meade and L. Randall, "Black holes and quantum gravity at the LHC", *JHEP* **0805** (2 May 2008) id. 003 (38pp.). ↗
doi: 10.1088/1126-6708/2008/05/003
bibcode: 2008JHEP...05..003M
arXiv: 0708.3017v1 [hep-ph] 22 Aug 2007 ↗

[Mink02] J.R. Minkel, "Black Holes from Heaven", *Physical Review Focus* (ISSN 1539-0748) Vol. **9**, story 3 (11 Jan 2002; accessed 2 Aug 2009).
url: http://focus.aps.org/story/v9/st3

[NM04] M. Należyty and J. Madej, "A catalogue of isolated massive white dwarfs", *Astron. Astrophys.* **420** (Jun 2004) 507–513. ↗
doi: 10.1051/0004-6361:20040123
bibcode: 2004A&A...420..507N

[NGS99] R. Napiwotzki, P.J. Green and R.A. Saffer, "A Comparative Study of the Mass Distribution of Extreme-Ultraviolet–Selected White Dwarfs", *Astrophys. J.* **517** (1) (20 May 1999) 399–415. ↗
doi: 10.1086/307170
bibcode: 1999ApJ...517..399N
arXiv: astro-ph/9901027v1 4 Jan 1999 ↗

[Nas05] H.S. Nastase, "The RHIC fireball as a dual black hole".
arXiv: hep-th/0501068v3 22 Mar 2006 ↗

[Nas06] H.S. Nastase, "More on the RHIC fireball and dual black holes". arXiv: hep-th/0603176v1 22 Mar 2006 ↗

[Nas07] H.S. Nastase, "A "black hole" solution of scalar field theory". arXiv: hep-th/0702037v2 13 Feb 2007 ↗

[NSSDC:Earth] National Space Science Data Center (NSSDC), National Aeronautics and Space Administration (NASA), D.R. Williams (Author/Curator), "Earth Fact Sheet", *NASA Website* (20 May 2009; accessed 10 Dec 2009). url: http://nssdc.gsfc.nasa.gov/planetary/factsheet/earthfact.html

[NSSDC:Moon] National Space Science Data Center (NSSDC), National Aeronautics and Space Administration (NASA), D.R. Williams (Author/Curator), "Moon Fact Sheet", *NASA Website* (10 Feb 2006; accessed 10 Dec 2009). url: http://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html

[NSSDC:Sun] National Space Science Data Center (NSSDC), National Aeronautics and Space Administration (NASA), D.R. Williams (Author/Curator), "Sun Fact Sheet", *NASA Website* (1 Sep 2004; accessed 10 Dec 2009). url: http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

[PAB00] J.A. Panei, L.G. Althaus and O.G. Benvenuto, "The evolution of iron-core white dwarfs", *Mon. Not. R. Astron. Soc.* **312** (3) (Mar 2000) 531–539. doi: 10.1046/j.1365-8711.2000.03236.x bibcode: 2000MNRAS.312..531P ↗ arXiv: astro-ph/9911371v1 19 Nov 1999 ↗

[PAB01] J.A. Panei, L.G. Althaus and O.G. Benvenuto, "The evolution of iron white dwarf stars", Proc. IX Latin American Regional IAU Meeting, "Focal Points in Latin American Astronomy", Tonantzintla, México, 9–13 Nov 1998, Eds. A. Aguilar and A. Carramiñana, *Rev Mex AA (Serie de Conferencias)* **4** (Jul 2001) 35–36. bibcode: 2001RMxAC..11...35P ↗

[Pla08v1] R. Plaga, "On the potential catastrophic risk from metastable quantum-black holes produced at particle colliders" [version 1]. arXiv: 0808.1415v1 [physics.gen-ph] 10 Aug 2008 ↗

[Pla08v2] R. Plaga, "On the potential catastrophic risk from metastable quantum-black holes produced at particle colliders" [version 2]. arXiv: 0808.1415v2 [physics.gen-ph] 26 Sep 2008 ↗

[Pla08v3] R. Plaga, "On the potential catastrophic risk from metastable quantum-black holes produced at particle colliders" [version 3].
arXiv: 0808.1415v3 [physics.gen-ph] 9 Aug 2009 ↗

[Pogge97] R.W. Pogge, "The Once and Future Sun", hypertext version of public lecture given at the Perkins Observatory, Delaware, Ohio, 12 Jun 1997, *New Vistas in Astronomy* lecture series (1997; updated 17 Nov 2007; accessed 31 Jul 2009).
url: http://www.astronomy.ohio-state.edu/~pogge/Lectures/vistas97.html

[PHJ93] H.N. Pollack, S.J. Hurter and J.R. Johnson, "Heat Flow from the Earth's Interior: Analysis of the Global Data Set", *Rev. Geophys.* **31** (3) (Aug 1993) 267–280. ↗
doi: 10.1029/93RG01249
bibcode: 1993RvGeo..31..267P

[PB03] D. Proga, M.C. Begelman, "Accretion of low angular momentum material onto black holes: two-dimensional hydrodynamical inviscid case", *Astrophys. J.* **582** (1 Jan 2003) 69–81. ↗
doi: 10.1086/344537
bibcode: 2003ApJ...582...69P
arXiv: astro-ph/0208517v1 28 Aug 2002 ↗

[PSHT98] J.L. Provencal, H.L. Shipman, E. Høg and P. Thejll, "Testing the White Dwarf Mass-Radius Relation with *HIPPARCOS*", *Astrophys. J.* **494** (20 Feb 1998) 759–767. ↗
doi: 10.1086/305238
bibcode: 1998ApJ...494..759P

[Pum02] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P. Nadolsky and W.K. Tung, "New generation of parton distributions with uncertainties from global QCD analysis", *JHEP* **0207** (9 Aug 2002) id. 012 (47pp.) ↗, MSU-HEP-011101.
doi: 10.1088/1126-6708/2002/07/012
bibcode: 2002JHEP...07..012P
arXiv: hep-ph/0201195v3 3 Feb 2002 ↗

[RS99] L. Randall and R. Sundrum, "A large mass hierarchy from a small extra dimension", *Phys. Rev. Lett.* **83** (17) (25 Oct 1999) 3370–3373, MIT-CTP-2860, PUPT-1860, BUHEP-99-9.
doi: 10.1103/PhysRevLett.83.3370
bibcode: 1999PhRvL..83.3370R
arXiv: hep-ph/9905221v1 4 May 1999 ↗

[Reid95] G.C. Reid, "The sun-climate question: Is there a real connection?" [electronic version], in *U.S. National Report to International Union of Geodesy and Geophysics 1991-1994 American Geophysical Union Website* (1995; accessed 2 Aug 2009).
url: http://www.agu.org/revgeophys/reid00/reid00.html

Original: *Rev. Geophys.* **33** (S1) (1995) 535–538.
doi: 10.1029/95RG00103
bibcode: 1995RvGeo..33..535R,

[Rid07] J. Ridky (Pierre Auger Collaboration), "Measurement of Cosmic Ray Energy with the Pierre Auger Observatory", Proc. C2CR07: Colliders to Cosmic Rays, Eds. S.M. Tripathi and R.E. Breedon, *AIP Conf. Proc.* **928** (Aug 2007) 39–46.
doi: 10.1063/1.2775894
bibcode: 2007AIPC..928...39R

[Rind09] D. Rind, "Do Variations in the Solar Cycle Affect Our Climate System?", Science Briefs, *NASA Goddard Institute for Space Studies Website* (22 Jan 2009; accessed 2 Aug 2009).
url: http://www.giss.nasa.gov/research/briefs/rind_03/

[rite08] "ritebkatya" [alias], Untitled [online posting], posting on discussion topic "Black holes in cern", *Team Liquid Website* (posting last modified 06:30 13 Jun 2008; accessed 31 Dec 2009)
url: http://www.teamliquid.net/forum/viewmessage.php?currentpage=All&topic_id=72988

[Riz02] T.G. Rizzo, "Black Hole Production at the LHC: Effects of Voloshin Suppression", *JHEP* **0202** (14 Feb 2002) 011 ↗, SLAC-PUB-9127.
doi: 10.1088/1126-6708/2002/02/011
bibcode: 2002JHEP...02..011R
arXiv: hep-ph/0201228v1 23 Jan 2002 ↗

[Riz07] T.G. Rizzo, "Black hole production at the LHC by Standard Model bulk fields in the Randall–Sundrum model", *Phys. Lett* **B647** (1) (29 Mar 2007) 43–48.
doi: 10.1016/j.physletb.2007.01.045
bibcode: 2007PhLB..647...43R
arXiv: hep-ph/0611224v3 27 Nov 2006 ↗

[RW05] S.P. Robinson and F. Wilczek, "Relationship between Hawking Radiation and Gravitational Anomalies", *Phys. Rev. Lett.* **95** (1) (Jun 2005) id. 011303 (4pp.)., MIT-CTP-3561.
doi: 10.1103/PhysRevLett.95.011303
bibcode: 2005PhRvL..95a1303R
arXiv: gr-qc/0502074v3 23 Aug 2005 ↗

[Rose95] S.J. Rose, "The Effect of Degeneracy on the Scattering Contribution to the Radiative Opacity", *Astrophys. J.* **453** (1 Nov 1995) L45–L47. ↗
doi: 10.1086/309736
bibcode: 1995ApJ...453L..45R ↗

[SS95] G.D. Schmidt and P.S. Smith, "A Search for Magnetic Fields among DA White Dwarfs", *Astrophys. J.* **448** (20 Jul 1995) 305–314.
doi: 10.1086/175962
bibcode: 1995ApJ...448..305S ↗

[SS08] K.-P. Schröder and R.C. Smith, "Distant future of the Sun and the Earth revisited", *Mon. Not. R. Astron. Soc.* **386** (1) (May 2008) 155–163.
doi: 10.1111/j.1365-2966.2008.13022.x
bibcode: 2008MNRAS.386..155S
arXiv: 0801.4031v1 [astro-ph] 25 Jan 2008 ↗

[SW81] H. Schulz and G. Wegner, "Spectroscopy of Suspected Peculiar DA White Dwarfs – II. Atmospheric Parameters and Radii", *Astron. Astrophys.* **94** (Feb 1981) 272–279.
bibcode: 1981A&A....94..272S ↗

[Sch51] J.S. Schwinger, "On Gauge Invariance and Vacuum Polarization", *Phys. Rev.* **82** (5) (1 Jun 1951) 664–679.
doi: 10.1103/PhysRev.82.664
bibcode: 1951PhRv...82..664S

[ST83] S.L. Shapiro and S.A. Teukolsky, *Black Holes, White Dwarfs, and Neutron Stars*, (John Wiley & Sons, New York, 1983) 663pp.
ISBN: 978-0-471873174
bibcode: 1983bhwd.book.....S
[Cited by the GM paper; not directly accessed for this paper]

[SQS08] P. Sharma, E. Quataert and J.M. Stone, "Spherical Accretion with Anisotropic Thermal Conduction", *Mon. Not. R. Astron. Soc.* **389** (4) (Oct 2008) 1815–1827.
doi: 10.1111/j.1365-2966.2008.13686.x
bibcode: 2008MNRAS.389.1815S
arXiv: 0804.1353v1 [astro-ph] 8 Apr 2008 ↗

[Silv01] N.M. Silvestri, T.D. Oswalt, M.A. Wood, J.A. Smith, I.N. Reid and E.M. Sion, "White Dwarfs in Common Proper Motion Binary Systems: Mass Distribution and Kinematics", *Astron. J.* **121** (1) (Jan 2001) 503–516. ↗
doi: 10.1086/318005
bibcode: 2001AJ....121..503S

[Sol02] S.N. Solodukhin, "Classical and quantum cross-section for black hole production in particle collisions", *Phys. Lett.* **B533** (1–2) (2 May 2002) 153–161.
doi: 10.1016/S0370-2693(02)01589-7
bibcode: 2002PhLB..533..153S
arXiv: hep-ph/0201248v2 7 Feb 2002 ↗

[SPIRES:DL01] SPIRES High Energy Physics database (SPIRES-HEP), Search for citations of "HEP-PH 0106295", search conducted 31 Jul 2009.
url: http://www-spires.slac.stanford.edu/spires/find/hep/www?rawcmd=FIND+C+HEP-PH+0106295&FORMAT=www&SEQUENCE=ds

[SSC02] G. Steinle-Neumann, L. Stixrude and R.E. Cohen, "Physical Properties of Iron in the Inner Core", in *Core Structure, Dynamics and Rotation*, Eds. V. Dehant, K. Creager, S.-I. Karato and S. Zatman (Geodynamics Series 31, American Geophysical Union, Washington, DC, Jan 2003), 137-161.
ISBN: 978-0875905334
bibcode: 2002physics...4055S
arXiv: physics/0204055v1 [physics.geo-ph] 18 Apr 2002 ↗

[Stöck06] H. Stöcker, "Mini black holes in the first year of the LHC: discovery through di-jet suppression, multiple mono-jet emission and ionizing tracks in ALICE", Proceedings of the International Conference on Strangeness in Quark Matter (SQM2006), University of California, Los Angeles, 26–31 March 2006, Eds. K. Barish, H.Z. Huang, J. Kapusta, G. Odyniec, J. Rafelski, and C.A. Whitten Jr., *J. Phys.* **G32** (12) (Dec 2006) S429–S437.
doi: 10.1088/0954-3899/32/12/S52
bibcode: 2006JPhG...32S.429S

[Stöck06arXiv] H. Stöcker, "Mini Black Holes in the first year of the LHC: Discovery Through Di-Jet Suppression, Multiple Mono-Jet Emission and ionising tracks in ALICE".
arXiv: hep-ph/0607165v3 24 Jul 2006 ↗

[StöckPat] H. Stöcker, "Verfahren zur Energiegewinnung durch Umwandlung von Masse in Energie", *Deutsches Patent- und Markenamt* **DE 10 2006 007 824 A1** 2007.08.30.
url: http://publikationen.dpma.de/DPMApublikationen/pdf_any_all.do?docId=DE102006007824A1&id=8903446

[StöckPat.en] H. Stöcker, "Method for Production of Energy by Conversion of Mass into Energy", International Application No. PCT/EP2007/001364, International Filing Date: 16 Feb 2007, Pub. No. WO/2007/093434, Publication Date: 23 Aug 2007, *World Intellectual Property Organization (WIPO) Website*.
url: http://www.wipo.int/pctdb/en/wo.jsp?WO=2007093434&IA=EP2007001364

[SSD06] D. Stojkovic, G.D. Starkman and D-C. Dai, "Why Black Hole Production in Scattering of Cosmic Ray Neutrinos Is Generically Suppressed", *Phys. Rev. Lett.* **96** (4) (1 Feb 2006) id. 041303 (4pp.).
doi: 10.1103/PhysRevLett.96.041303
bibcode: 2006PhRvL..96d1303S
arXiv: hep-ph/0505112v3 20 Feb 2006 ↗

[Sub08] J.P. Subasavage, T.J. Henry, P. Bergeron, P. Dufour and N.C. Hambly, "The Solar Neighborhood. XX. Discovery and Characterization of 21 New Nearby White Dwarf Systems", *Astron. J.* **136** (3) (Sep 2008) 899–908.
doi: 10.1088/0004-6256/136/3/899
bibcode: 2008AJ....136..899S
arXiv: 0805.2515 [astro-ph] 16 May 2008 ↗

[Sub09] J.P. Subasavage, W.-C. Jao, T.J. Henry, P. Bergeron, P. Dufour, P.A. Ianna, E. Costa, and R.A. Méndez, "The Solar Neighborhood. XXI. Parallax Results from the CTIOPI 0.9m Program: 20 New Members of the 25 Parsec White Dwarf Sample", *Astron. J.* **137** (6) (Jun 2009) 4547–4560.
doi: 10.1088/0004-6256/137/6/4547
bibcode: 2009AJ....137.4547S
arXiv: 0902.0627v1 [astro-ph.GA] 3 Feb 2009
http://arxiv.org/pdf/0902.0627v1↗

[Tak98] Y. Takahashi (JACEE Collaboration), "Elemental Abundance of High Energy Cosmic Rays", *Nucl. Phys. B (Proc. Suppl.)* **60** (3) (Jan 1998) 83–92.
doi: 10.1016/S0920-5632(97)00503-3
bibcode: 1998NuPhS..60...83T

[Tank08a] J. Tankersley Jr., Untitled [online posting], posting attached to "Doomsday Lawsuit Dissed", Author/Editor A. Boyle, *Cosmic Log* (comment posted 22:26 EDT 24 Jun 2008; accessed 10 Oct 2009).
url: http://cosmiclog.msnbc.msn.com/archive/2008/06/24/1165649.aspx

[Tank08b] J. Tankersley Jr., Untitled [online posting], posting attached to "The 2008 LSAG Safety Report", Author/Editor J. Tankersley, *LHC Facts* (comment posted 03:44 27 Jun 2008; accessed 10 Oct 2009).
url: http://www.lhcfacts.org/?p=63

[TB05] M. Tegmark and N. Bostrom, "Is a doomsday catastrophe likely?", *Nature* **438** (7069) (8 Dec 2005) 754.
doi: 10.1038/438754a
bibcode: 2005Natur.438..754T

[TB05arXiv] M. Tegmark and N. Bostrom, "How Unlikely is a Doomsday Catastrophe?".
arXiv: astro-ph/0512204v2 21 Dec 2005 ↗
[See TB05 for shorter published version]

[Tel08] "'Big Bang' Large Hadron Collider is switched on" *Telegraph.co.uk* (10 Sep 2008; accessed 10 Oct 2009).
url: http://www.telegraph.co.uk/news/2775052/Big-Bang-Large-Hadron-Collider-is-switched-on.html

[TCC06] N. Tolich, Y.-D. Chan, C.A. Currat, M.P. Decowski, B.K. Fujikawa, R. Henning, K.T. Lesko, A.W.P. Poon, K. Tolich and J. Wang, "A Geoneutrino Experiment at Homestake", *Earth, Moon, and Planets* **99** (1–4) (Dec 2006) 229–240.
doi: 10.1007/s11038-006-9112-8
bibcode: 2006EM&P...99..229T
arXiv: physics/0607230v1 [physics.geo-ph] 25 Jul 2006 ↗

[UCSBP:fac] University of California, Santa Barbara, Department of Physics, "Faculty Directory", *UCSB Physics Department Website* (7 Jul 2009; accessed 2 Aug 2009).
url: http://www.physics.ucsb.edu/people/faculty/index.php

[US04] W.G. Unruh and R. Schützhold, "Universality of the Hawking effect", *Phys. Rev.* **D71** (2) (24 Jan 2005) id. 024028 (11pp.).
doi: 10.1103/PhysRevD.71.024028
bibcode: 2005PhRvD..71b4028U
arXiv: gr-qc/0408009v2 22 Dec 2004 ↗

[Unr07] W.G. Unruh, "Where do the particles come from?", abstract for talk at the workshop *Effective Models of Quantum Gravity*, Perimeter Institute, Waterloo, Ontario, 9-11 Nov 2007.
url: http://www.perimeterinstitute.ca/Events/Effective_Models_of_Quantum_Gravity/Abstracts/

[Ven99] S. Vennes, "Properties of Hot White Dwarfs in Extreme-Ultraviolet/Soft X-Ray Surveys", *Astrophys. J.* **525** (10 Nov 1999) 995–1008. ↗
doi: 10.1086/307949
bibcode: 1999ApJ...525..995V

[VBD96] S. Vennes, S. Bowyer and J. Dupuis, "Discovery of Photospheric Helium in the Ultra-Massive DA White Dwarf GD 50", *Astrophys. J.* **461** (20 Apr 1996) L103–L106.
doi: 10.1086/310014
bibcode: 1996ApJ...461L.103V ↗

[VK08] S. Vennes and A. Kawka, "On the empirical evidence for the existence of ultramassive white dwarfs", *Mon. Not. R. Astron. Soc.* **389** (3) (Sep 2008) 1367–1374.
doi: 10.1111/j.1365-2966.2008.13652.x
bibcode: 2008MNRAS.389.1367V
arXiv: 0806.4742v2 [astro-ph] 3 Jul 2008 ↗

[VTGD97] S. Vennes, P.A. Thejll, R.G. Galvan and J. Dupuis, Hot White Dwarfs in the *Extreme Ultraviolet Explorer* Survey. II. Mass Distribution, Space Density, and Population Age", *Astrophys. J.* **480** (10 May 1997) 414–434. ↗
doi: 10.1086/303981
bibcode: 1997ApJ...480..714V

[Vol01] M.B. Voloshin, "Semiclassical suppression of black hole production in particle collisions", *Phys. Lett.* **B518** (1–2) (Oct 2001) 137–142.
doi: 10.1016/S0370-2693(01)01061-9
bibcode: 2001PhLB..518..137V
arXiv: hep-ph/0107119v1 10 Jul 2001 ↗

[Vol02] M.B. Voloshin, "More remarks on suppression of large black hole production in particle collisions", *Phys. Lett* **B524** (3–4) (10 Jan 2002) 376–382, TPI-MINN-01/48-T, UMN-TH-2030-01.
doi: 10.1016/S0370-2693(01)01401-0
bibcode: 2002PhLB..524..376V
arXiv: hep-ph/0111099v1 8 Nov 2001 ↗

[Vol05E] M.B. Voloshin, "Erratum to: "More remarks on suppression of large black hole production in particle collisions" [Phys. Lett. B 524 (2002) 376]", *Phys. Lett.* **B605** (3–4) (13 Jan 2005) 426.
doi: 10.1016/j.physletb.2004.11.076
bibcode: 2005PhLB..605..426V

[VH05] R. Von Herzen, E.E. Davis, A.T. Fisher, C.A. Stein and H.N. Pollack, "Comments on "Earth's heat flux revised and linked to chemistry" by A.M. Hofmeister and R.E. Criss", *Tectonophys.* **409** (1–4) (16 Nov 2005) 193–198.
doi: 10.1016/j.tecto.2005.08.003
bibcode: 2005Tectp.409..193V
url: http://www.es.ucsc.edu/~afisher/CVpubs/pubs/VonHerzen2005_TectComment.pdf

[Wat08a] A.A. Watson, "Highlights from the Pierre Auger Observatory - the birth of the Hybrid era", Based on Highlight Talk at the 30th International Cosmic Ray Conference (ICRC'07), Mérida, México, 3–11 Jul 2007.
arXiv: 0801.2321v1 [astro-ph] 15 Jan 2008 ↗

[Wat08a.ppt] A.A. Watson, "Highlights from the Pierre Auger Observatory - the birth of the Hybrid era" [powerpoint presentation], Slides accompanying Highlight Talk at the 30th International Cosmic Ray Conference (ICRC'07), Mérida, México, 3–11 Jul 2007.
url: http://indico.nucleares.unam.mx/getFile.py/access?contribId=1322&sessionId=38&resId=0&materialId=slides&confId=4
url: http://www.auger.org/technical_info/pdfs/icrc2007/Watson_Merida_Highlights.pdf

[Wat08b] A.A. Watson (Pierre Auger Collaboration), "Recent results from the Pierre Auger Observatory—Including comparisons with data from AGASA and HiRes" *Nucl. Instrum. Meth.* **A588** (1–2) (Apr 2008) 221–226.
url: http://www.p-ng.si/public/pao/bibl/ricapp_2007_aaw.pdf
doi: 10.1016/j.nima.2008.01.083
bibcode: 2008NIMPA.588..221F

[Weiss02] P. Weiss, "The Black Hole Next Door: Mighty particle collisions may bring black holes to venues near you", *Science News* **161** (12) (23 Mar 2002) 187–188.
url: http://www.jstor.org/stable/4013117
url: http://www.thefreelibrary.com/The+black+hole+next+door%3B+mighty+particle+collisions+may+bring+black+...-a084546024

[Wiki:PhysLaw] Wikipedia contributors, "Physical law", *Wikipedia, The Free Encyclopedia* (06:41 UTC 29 Jul 2009; accessed 2 Aug 2009).
url: http://en.wikipedia.org/w/index.php?title=Physical_law&oldid=304829825

[Wikt:Law] Wiktionary contributors, "Law", *Wiktionary, The Free Dictionary* (17:36 UTC 16 Jul 2009; accessed 2 Aug 2009).
url: http://en.wiktionary.org/w/index.php?title=law&oldid=6991438

[Wig05] P. Wignall, "The link between large igneous provinces eruptions and mass extinctions", *Elements* **1** (5) (Dec 2005) 293–297. ↗
doi: 10.2113/gselements.1.5.293

[Wig07] P. Wignall, "The End-Permian mass extinction - how bad did it get?", *Geobiology* **5** (4) (15 Nov 2007) 303–309.
url: http://www.see.leeds.ac.uk/research/essi/seddies/wignall/WignallGB.pdf
doi: 10.1111/j.1472-4669.2007.00130.x

[Wil04] F. Wilczek, "The Universe is a Strange Place" [keynote talk], Proceedings of the Second International Conference on Particle and Fundamental Physics in Space (SpacePart '03), Washington, DC, 10–12 Dec 2003, Eds. R. Battiston, M. Salamon, E. Katsavounidis, and K. Scholberg, *Nucl. Phys. B (Proc. Suppl.)* **134** (Sep 2004) 3-12.
doi: 10.1016/j.nuclphysbps.2004.08.001
bibcode: 2004NuPhS.134....3W
arXiv: astro-ph/0401347v2 16 Jan 2004 ↗

[Yam07] T. Yamamoto (Pierre Auger Collaboration), "The UHECR spectrum measured at the Pierre Auger Observatory and its astrophysical implications", Proc. 30th International Cosmic Ray Conference (ICRC'07), Mérida, México, 3–11 Jul 2007, Eds. R. Caballero, J.C. D'Olivo, G. Medina-Tanco, L. Nellen, F.A. Sánchez and J.F. Valdés-Galicia, Universidad Nacional Autónoma de México, México City, México, 2008, Vol. **4** (High Energy Phenomena, Part 1) 335–338.
url: http://indico.nucleares.unam.mx/getFile.py/access?contribId=318&sessionId=10&resId=0&materialId=paper&confId=4
bibcode: 2008ICRC....4..335Y
arXiv: 0707.2638v3 [astro-ph] 13 Aug 2007 ↗

[Yao06] W.-M. Yao *et al.* (Particle Data Group), "Review of Particle Physics", *J. Phys.* **G33** (1) (Jul 2006) 1–1232.
url: http://pdg.lbl.gov/2006/download/rpp-2006-book.pdf
doi: 10.1088/0954-3899/33/1/001
bibcode: 2006JPhG...33....1Y

[YM06] H. Yoshino and R.B. Mann, "Black hole formation in the head-on collision of ultrarelativistic charges", *Phys. Rev.* **D74** (4) (1 Aug 2006) id. 044003 (10pp.).
doi: 10.1103/PhysRevD.74.044003
bibcode: 2006PhRvD..74d4003Y
arXiv: gr-qc/0605131v3 5 Aug 2006 ↗

[YR05] H. Yoshino and V.S. Rychkov, "Improved analysis of black hole formation in high-energy particle collisions", *Phys. Rev.* **D71** (10) (May 2005) id. 104028 (13pp.), DPNU-05-01, ITFA-2005-09.
doi: 10.1103/PhysRevD.71.104028
bibcode: 2005PhRvD..71j4028Y
arXiv: hep-th/0503171v2 1 May 2005 ↗

[Erratum: *Phys. Rev.* **D77** (8) (Apr 2008) id. 089905(E) (1 p.)
doi: 10.1103/PhysRevD.77.089905
bibcode: 2008PhRvD..77h9905Y
Erratum not accessed for this paper.]

[ZK66] G.T. Zatsepin and V.A. Kuz'min, "Upper Limit of the Spectrum of Cosmic Rays", *JETP Lett.* **4** (Aug 1966) 78–80.
bibcode: 1966JETPL...4...78Z

[Pisma Zh. Eksp. Teor. Fiz. **4** (3) (1 Aug 1966) 114–117
bibcode: 1966ZhPmR...4..114Z]