On the potential catastrophic risk from metastable quantum-black holes produced at particle colliders

R. Plaga

Franzstr. 40, D-53111 Bonn, Germany

Abstract

The question of whether collider produced of subnuclear black holes might constitute a catastrophic risk is explored in a model of Casadio & Harms (2002) that treats them as quantum-mechanical objects. A plausible scenario in which these black holes accrete ambient matter at the Eddington limit shortly after their production, thereby emitting Hawking radiation that would be harmful to Earth and/or CERN and its surroundings, is described. Such black holes are shown to remain undetectable in existing astrophysical observations and thus evade a recent exclusion of risks from subnuclear black holes by Giddings & Mangano (2008) and a similar one by Koch et al. (2009). I further question that these risk analyses are complete for the reason that they exclude plausible black-hole parameter ranges from safety consideration without giving any reason. Some feasible operational measures at colliders are proposed that would allow the lowering of any remaining risk probability.

Giddings & Mangano drew different general conclusions only because they made different initial assumptions about the properties of microscopic black holes, not because any of their technical conclusions are incorrect. A critical comment by Giddings & Mangano (2008) on the present paper and a preprint by Casadio et al. (2009) - that presents a treatment of the present issue with methods and assumptions similar to mine - are addressed in appendices.

Email address: rainer.plaga@gmx.de (R. Plaga).
1 Introduction

1.1 General outline of the problem

Theories with “extra spatial dimensions” [33], are one of the most popular extensions of the standard model of particle physics and a central plank of string theory [17]. If space had more than three dimensions the “Planck energy scale” - usually thought to lie at extremely high energies - could be reached already at energies projected for new particle accelerators [2, 37]. Gravity becomes strong near the Planck energy. As a consequence subnuclear “micro” black holes (mBHs) could be copiously produced at future high-energy particle colliders [14, 33], such as the “Large Hadron Collider” (LHC) at CERN. At a predicted rate of up to about one BH per second at the nominal LHC luminosity [14], the LHC would be a “black-hole factory” [18, 3]. The phenomenology of mBHs at colliders has been studied in great detail, see e.g. Cavaglia et al. [6].

The possibility that a collider-produced black hole (BH) - or another exotic object - might catastrophically grow by gravitationally pulling in ambient matter and thus eventually injure or kill humans deserves careful attention [43, 30, 9, 38]. A recent scientific comparative study of global risks [34] has put a risk very similar to the one considered here (from collider-produced “strangelets”) at the top “response priority” of all current “untreated risks” (such as, for example, super-volcano eruptions and asteroid impacts). Clearly this potential risk exists only if speculative theories are correct. But these theories were constructed to explore real possibilities. The probability that they are correct is not negligible.

1.2 Definition of risk scenarios

1.2.1 The scenarios discussed by Giddings & Mangano

Recently this risk has been studied in great detail in important papers by Giddings & Mangano (G & M) [22] and Koch et al. [31]. G & M consider two frameworks for the description of mBHs. In a “first scenario” (case “D0” in Koch et al. [31]) collider-produced mBHs are treated in a popular, standard manner with a semiclassical thermodynamical description (i.e. assuming a canonical ensemble). The mBH is described as a heat bath and any back reaction of the emitted particles on the mBH is neglected. mBHs are then expected to decay, via the emission of “Hawking radiation”, on extremely small 1

1 The conclusions of a report [16] by the “Isag group” at CERN on the safety of microscopic black holes are entirely based on results from this paper.
timescales after their production, thus they cannot grow and pose no danger. In a *second scenario* (case “D1-B” in Koch et al.\[31\]) G & M assume that mBHs “do not undergo Hawking decay” in a purely ad hoc manner, in order to “conduct an independent check of their benign nature”. They further plausibly assumed that mBHs shed any electrical charge they acquired due to accretion very rapidly via the Schwinger mechanism. They rightly point out that this *scenario 2*, while not being completely unphysical\[2\], is not preferred “on very general grounds”. G & M study the behaviour of mBHs after their production at the LHC in this scenario and find that for certain possible choices of parameters a collider produced mBH might accrete Earth on time scales, quote, “that are too short to provide comfortable constraints”. The existence of mBHs within this “dangerous” parameter range is then excluded by making the case that cosmic-ray produced mBHs would accrete certain observed white dwarfs with small magnetic fields on smaller time scales than their age\[3\]. G & M find that the fact that our Earth, the sun and other stars were not destroyed by “dangerous” cosmic-ray produced black holes does not exclude their existence because they would not be stopped within them after production. Koch et al.\[31\] use similar arguments and reach the same conclusions.

1.2.2 *A new scenario not discussed previously by G & M or Koch et al.: Scenario 3*

It is the aim of the present paper to explore a *third scenario*, in addition to the two presented by G & M and the ones by Koch et al.\[31\]\[4\]. Its basic difference to *scenario 1* is a completely different “microcanonical” treatment of mBH thermodynamics (i.e. one in which the total energy remains fixed)\[25,11,39,24\], leading to a strongly reduced, but not completely switched-off intensity of Hawking radiation for black holes with small masses. This treatment is thought to be more fundamental than the one from G & M’s *scenario 1* using the canonical ensemble. The mBHs are typically described as extended stringy objects, like e.g. “p-branes”. They are then a new type of elementary particle a “quantum black hole”\[26,22,27\]. It is still assumed that mBHs neutralize quasi instantenously via the Schwinger mechanism.

In a sense such a framework is more plausible than both frameworks studied

\[2\] G & M quote Unruh & Schützhold\[42,41\] who constructed a speculative model potentially without Hawking radiation.

\[3\] G & M argue that neutron stars might survive on time scales comparable to their observed age, so that their existence does not compellingly rule out the existence of “dangerous” black holes.

\[4\] Koch et al. quote the present paper in connection with their case “D1-B” (which corresponds to *scenario 2*). If they thought that the present paper is about this case, they erred. Moreover they present three additional scenarios in which mBHs are electrically charged and turn out to be “harmless”.

3
by G & M because it can avoid a violation of unitary evolution and energy conservation \[12,8\], serious problems that are well known to beset the first scenario used by G & M \[36,22\]. Moreover it is not “ad hoc” such as scenario 2, but based on models published in the peer-reviewed literature. G & M endorse a quantum mechanical treatment of mBHs at the end of their section 2.1, but they do not develop this possibility further in their report.

Scenario 3 adopts Casadio & Harms’ (C & H) \[10\] model for mBHs. The famous “Randall-Sundrum 2 (RS 2) model” \[37\] - presented in one of the most frequently quoted papers in the recent history of high energy physics - is chosen as the description of a 4th spatial dimension. In trying to understand if mBHs could be dangerous in scenario 3 I will repeatedly resort to a use of G & M’s excellent theoretical tools. I try to assume reasonably mild worst case parameter choices, similar to the strategy of G & M \[6\]. However, I strove to introduce no “ad hoc” or fine tuned assumption, that would be deemed highly implausible to experts.

Section 2 reviews the Hawking luminosity of mBHs within scenario 3. Section 3 explains why - for certain parameter ranges - scenario 3 predicts a disaster that is not ruled out by astrophysical considerations. It also explores if such disasters could be of limited scale. Section 4 points out a gap in the astrophysical “safety arguments” of G & M that is independent of the consideration in section 3. Finally section 5 concludes. Appendix 7 answers a critical comment of G & M on the present paper and appendix 8 comments recent work of Casadio et al. on the present issue.

2 Properties of RS 2 quantum microscopic black holes in the Casadio & Harms model

2.1 Introduction

It seems likely that quantum black holes are in principle unstable, i.e. they eventually evaporate by Hawking radiation because no conserved quantum number forbids them to do so \[22\]. However within the microcanonical treatment of black holes developed by R.Casadio, B.Harms and Y.Leblanc \[12\] (assumed in my scenario 3), if their mass is smaller than a certain mass scale “M_N” of their theory, they live much longer than expected within the standard thermodynamic treatment that was employed for G & M’s scenario 1. Therefore - in contradistinction to G & M’s scenario 1 - we can neither simply assume that the mBHs evaporate before they can do harm, nor that there

---

5 Thus I follow the treatment in section III.B of C & H\[10\].
6 G& M wrote: “...at each point where we encountered an uncertainty, we have replaced it by a conservative or “worst case” assumption”.

---
is no potentially dangerous Hawking radiation (as in G & M’s scenario 2). Rather we will need to study their fate after production taking into account both accretion and possible effects from Hawking radiation in section 3. As a preparation I review the intensity of Hawking radiation of quantum mBHs in scenario 3 in this section.

2.2 Stability of microscopic black holes for various possible input parameters

If the additional curved spatial dimension of the RS 2 model exists, C & H predict a Hawking luminosity of the mBH of [10]:

\[
P_5 = \frac{M_{BH} \hbar c^6}{15360 \pi G^2 M_N^3}
\]

(1)

Casadio & Harms [10] apply this formula to black holes with a mass \(M_{BH}\) smaller than the parameter “\(M_N\)” within their theory. I follow them and all calculations in my section 3 below assume this relation. For black-hole masses exceeding \(M_N\) C & H assumed the classical canonical 4-dimensional expression for the Hawking luminosity:

\[
P_4 = \frac{\hbar c^6}{15360 \pi G^2 M_{BH}^2}.
\]

(2)

The luminosity of eq. (1) is normalized to the classical expression at the mass \(M_N\) (eq. (1) is already normalized in this way). The critical difference of this treatment to the usual, canonical one is exactly that the new microcanocial “quantum” expression eq. (1) has to be employed.

For given curvature scale “L” (a length scale associated with the warping in the RS 2 model) C & H assumed that \(M_N\) is equal to a black hole mass at which Schwarzschild radius of a 5-dimensional mBH reaches L. This gives:

\[
M_N = \frac{3\pi L^2 c^2 M_5^3}{8 \hbar^2}
\]

(3)

Here \(M_5\) is the “new” Planck scale (set to 1 TeV in all numerical estimates below). Because \(P_5 = P_4 \frac{M_{BH}^3}{M_N^3}\), the Hawking luminosity of black-holes with initial masses (typically \(10^{-23}\) kg) much below \(M_N\) (possibly \(\gg\) kg, see section 8.2) is strongly suppressed with respect to the classical value \(P_4\) [7]. However,

[7] G & M do not deny that the Hawking luminosity of 5-dimensional black holes is suppressed with respect eq. (2) [22], but the suppression is weaker in scenario 1 than it is in scenario 3.
with growing mass (e.g. by accretion) the suppression of the Hawking radiation is lifted. The geometry of mBHs with Schwarzschild radii between $L$ and $\approx 6 \times 10^5$ is not known, and it remains presently unclear if eq. (2) can be applied in this “transitional region” as assumed above. Only for black holes with masses above “$M_C$”, the mass of a mBH with a Schwarzschild radius of $6L$, above which a 4-dimensional description of the mBH is a good approximation, does this appear to be certain. $M_C$ is given as:

$$M_C \approx \frac{3Lc^2}{G}$$ (4)

Thus one might equally well normalize the luminosity equally $M_C$ setting:

$$M_N = M_C$$ (5)

The decision between normalisation in eq.(3) and eq.(5) comes down to the question of whether the luminosity of a mBH is described by the 5-dimensional (eq. (1)) or 4-dimensional (eq. (2)) expression in the transitional region between $L$ and $\approx 6L$. All one can presently say with reasonable certainty is that the correct normalisation lies at some intermediate value between (and including) the two extremes.

C & H discuss that with their normalisation metastable mBHs with lifetimes of many years exist, but only for very large values of $L$ approaching the experimentally excluded range $L > 10^{-4}$ m. It can be easily shown that with normalisation eq.(5) mBHs are quasistable for all possible values of $L$.

2.3 Summary

Summarising, mBHs can be “quasistable” in scenario 3 (in the sense of lifetimes exceeding $O(\text{msecs})$), without introducing highly implausible “ad hoc” assumptions. Because G & M concluded that 5-dimensional and sufficiently stable mBHs might accrete matter at an extremely fast rate (growth rate much below a second, see below section 3) quasistable mBHs are potentially dangerous. In contradistinction to G & M’s scenario 2, my scenario 3 is plausible as a fundamental theory of mBHs and therefore an astrophysical (or other empirical) exclusion of the existence of such mBHs is a “critical safety

---

8 This range was derived from eq.(3.26) of G & M for the scales of $L$ of interest in this manuscript: $10^{-9} \text{m} < L < 10^{-4} \text{m}$. If $L$ was smaller, mBHs in the third scenario would pose no catastrophic risk, because they would decay faster than they would grow.

9 i.e. the range from $\hbar/(c M_5)$ to $10^{-4} \text{m}$
guarantee” rather than an “additional check of their benign nature” as it was characterised by G & M for scenario 2.

3 A potential threat from microscopic black holes Hawking-radiating at the Eddington limit within scenario 3

3.1 Introduction

The mBHs in scenario 3 emit Hawking radiation, and according to eq.(1) the emitted power rises linearly with the their mass. Might this radiation be more dangerous than the mechanical action of the accretion? Unfortunately it turns out that this might be the case for certain parameter choices. In this section I choose possible and not fine-tuned parameters to study and illustrate the nature of the possible risk.

3.2 The nature of “Hawking radiation risk” for one exemplary choice of input parameters

For purely illustrative purposes - as one concrete instantiation of scenario 3 - I set $L=10^{-7}$ m below. Let us further assume that $M_N = 1.9 \times 10^5$ kg, a value intermediate between the one given by first and second normalisation (section 2). According to eq.(1) mBHs would then have a lifetime of about 2 seconds. A collider-produced mBH that has been captured and slowed down to thermal velocities, accretes and quickly grows by the “subatomic accretion mechanism” (the sucking in of particle within an atom by the mBH) characterised in section 4.2 of G & M. According to G & M’s eq.(4.22) it will take about 0.15 msec until the so called “electromagnetic radius” reaches atomic sizes. Thereafter the accretion is well described as Bondi accretion (the sucking in of whole atoms by the mBH) and according to eq.(4.40) in G& M it will take about 2.2 msec until the mBH’s Schwarzschild radius reaches $L=10^{-7}$ m at a mass of 0.54 kg. The further evolution of the mBH’s shape and size in the “transitional region” between 5 and 4-dimensional behaviour (see section 2) is not well understood. For simplicity I will assume that the radius remains constant at $L$ (a radius increase logarithmic with the mBH’s mass would not change the results appreciably.). For the input parameters chosen in this subsection, eq.(4.31) of G & M predicts an increase of the mBHs mass at a rate of $1.9 \times 10^4$ kg/sec. It will then take about 20 $\mu$sec until its mass reaches about 1 kg. At this

---

10 A conservative thermal velocity of 1500 m/sec was used to convert the units in eq.(4.22) to a time.
mass the luminosity of the mBH is predicted by eq.(11) to be $5.1 \times 10^{16}$ W or a mass equivalent of $\frac{dm}{dt} = 0.57$ kg/sec. It is easy to verify that the five-dimensional Eddington limit (eq.(B.25) of G & M)

$$dM/dt = \frac{2.44 \times 8\pi m_p R_B c_s^2}{\eta \sigma c}$$

has the same magnitude for an efficiency $\eta = 1$. Here $m_p$ is the mass of the proton, $R_B$ the Bondi radius (4.1 mm for our parameters), $c_s$ the velocity of sound in the interior of Earth (5200 m/sec) and $\sigma$ the Thomson cross section. Therefore the radiation pressure of this Hawking radiation is intense enough to limit the mass of accreted matter to the mass-energy radiated away: $\frac{dm}{dt} = dM/dt$ i.e. the mBHs accretes at the 5-dimensional Eddington limit. All accreted mass is then reradiated, and the mBH’s mass remains constant on average. G & M discussed the possibility of a radiation-limited accretion and excluded it, but only because in their scenario 2 the Hawking radiation is completely switched off.

For the next $3 \times 10^{17}$ years, a time span vastly exceeding the life time of our sun as a normal star, the mBH will radiate at the quoted, constant luminosity. The power of $5.2 \times 10^{16}$ W is 1300 times larger than the total geothermal power emitted by Earth[1], and only 3 times less than the total power Earth receives from the sun. The radiated power exceeds the total seismic power if the Earth by an estimated factor of many millions[15]. 17000 metric tons of ambient matter would be converted to radiation each year. While the exact phenomenology provoked by such a mBH accreting at the Eddington limit remains to be worked out, eventually catastrophic consequences due to global heating on an unprecedented scale and global-scale earth-quakes would seem certain.

3.3 Can the risk be ruled out with astrophysical arguments?

Disturbingly the effects of such a mBH on a white dwarf or neutron star would be negligible. Assuming the same mBH parameters as above and the theory of section 7 in G & M, the luminosity of the mBH accreting at the centre of a white dwarf is predicted to be $5.9 \times 10^{19}$ W or a fraction of $1.5 \times 10^{-7}$ of the solar luminosity. This is about $10^4$ times smaller than the cooling rate of white dwarfs in G & M’s sample[22,28] and thus cannot be detected[11]. The accretion time of a white dwarf would exceed their present age by a large

[11] G & M find that many mBHs are produced in white dwarfs in the course of time. However, these mBHs will also tend to merge over time, so that the total number of black holes in a given white dwarf might remain small. This question needs further study.
factor of $>10^{10}$. Therefore no conclusions about mBHs can be drawn from
the observed existence of such objects with ages exceeding a billion years. The
conditions for a neutron star would be similarly unspectacular. Therefore the
astrophysical argument of G & M fails to exclude the existence of mBHs in
scenario 3 that are dangerous not because they accrete the whole Earth but
because of their intense Hawking radiation.

3.4 A local accident at CERN?

The luminosity of a mBH accreting at the Eddington limit with the parameters
assumed above corresponds to 12 Mt TNT equivalent/sec\[15\], or the energy
released in a major thermonuclear explosion per second. If such a mBH would
accrete near the surface of Earth the damage they create would be much larger
than deep in its interior. With the very small accretion timescale ($\ll 1$ second)
that was found with the parameters in subsection 3.2 a mBH created with
very small (thermal or subthermal) velocities in a collider would appear like a
major nuclear explosion in the immediate vicinity of the collider. The risk from
collider-produced black holes is not necessarily an Armageddon, but could be
a locally contained catastrophe.

3.5 Conclusion

If black holes are described by scenario 3 the Hawking radiation from collider-
produced black holes might be dangerous. The input parameters used in this
section were only one example. It can however be shown that there is a wide
range of values for L and $M_N$ that lead to dangerous mBHs accreting at the
Eddington limit with various luminosities.
In general the example developed above demonstrates that widely held in-
tuitions - namely that accretion by mBHs must be extremely slow\[5\], and
that events which are catastrophic for Earth must also be for compact stel-
lar objects (necessary for any safety argument based on such objects) - are
insufficient as safety guarantees.

4 Does the observed existence of old white dwarfs with a low mag-
netic field rule out “dangerous” stable black holes? - A gap in G &
M’s exclusion of their scenario 2

In this section I point out a fundamental weakness of G & M’s argument that
cosmic rays impinging on white dwarfs rule out the existence of dangerous
mBHs. This argument puts into question whether scenario 2 as defined in the introduction is really ruled out by existing astrophysical observations. In the text following their eq. (E.2) G & M formulate the following assumption:

\[ M_{\text{min}} > 3 \, M_5 \]  

(7)

Thereby G & M introduce the assumption that mBHs in general have a minimal mass \( M_{\text{min}} \) that exceeds the new Planck scale by at least a factor of 3. This constraint is motivated by the fact that the thermodynamical, semiclassical treatment of mBHs in their scenario 2 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 \( M_{\text{min}} \) cannot be produced. It rather means that we are presently unable to reliably predict the behaviour of such mBHs.\[12\]

This fact raises a fundamental doubt about G & M’s exclusion of “dangerous mBHs” by way of observationally constraining the age of a certain class of white dwarfs. This exclusion depends on their careful and detailed demonstration in their section 5 that “dangerous” mBHs are stopped in white dwarfs after their production in collisions of cosmic rays. However, this demonstration is based on an assumed validity of the semiclassical approximation. mBHs deep in the “quantum gravity” regime (violating eq.(7)) might have smaller scattering cross section than expected in the semiclassically and escape white dwarfs, just as they could escape ordinary stars.\[13\] This would void G & M’s exclusion of the existence of potentially “dangerous” black holes.

Concluding, G & M did not demonstrate with reasonable certainty that white dwarfs stop cosmic-ray produced mBHs in general. Their exclusion of dangerous mBHs thus remains not definite.

5 Conclusion

5.1 Summary of reasons for concern

I showed in section 3 that within scenario 3 (as outlined in section 1.2.2), mBHs produced at a collider can be captured by Earth and accrete at the

\[\text{12} \quad \text{In a previous paper}[21] \text{ Giddings wrote: “For masses of order the fundamental Planck scale [i.e. } M_5 \text{] there is no control over quantum gravity effects which are likely to invalidate the semiclassical ... picture.”}\]

\[\text{13} \quad \text{This is a real concern because the “safety critical” black holes in theories with 2 extra dimensions cannot be excluded anymore if their scattering cross section is smaller by less than a mere factor 10 than semiclassically expected (see fig.2 of G & M[22]).}\]
Eddington limit. Thereby they might emit Hawking radiation that might be
dangerous to Earth as a whole or the inhabitants of CERN and its surround-
ings. The astrophysical argument by G & M\[22\] and Koch et al.\[31\] does not
exclude this scenario, because it allows for lifetimes of white dwarfs and neu-
tron stars with Eddington accreting mBHs (section 3) far exceeding the age of
the universe. Such stars could still exist, even if they harboured a microscopic
accreting black hole since the dawn of time.

Moreover - in section 4 - I outlined another independent gap in the “astro-
physical exclusion” of potentially dangerous mBHs.

Thus, at the present stage of knowledge there is a definite residual risk from
mBH production at colliders. This final conclusion differs from the one drawn
by G & M. This is not because of any disagreement over any specific conclu-
sion of their excellent paper. Rather the difference is the sole result of either
employing the alternative, physically plausible scenario 3 for the physics of
mBHs or including parameter regions in which mBHs are not expected to be
well described by a semiclassical approximation of quantum gravity into the
safety analysis.

5.2 Proposal for risk mitigating measures

It is not the aim of the present paper to recommend or discuss consequences
for the future operation of colliders comprehensively. Here I just put up for
further discussion three feasible measures for risk mitigation, at least in the
start up phase of LHC:

1. Increase of collision energy by reasonably small factors (say, 2) in one step
and proceed to higher energies only after excluding any indication for poten-
tially dangerous processes. Currently it is planned to perform the first produc-
tion runs at LHC at an energy more than five times higher than previously
reached\[35,14\]. This might result in the copious production of completely novel
states, which production was exponentially suppressed at the previous ener-
gies. “Proceeding in small steps” mitigates this risk.

2. No operation in which no or only a very tiny fraction of events are analysed.
Currently it is planned to eventually record and analyse only a fraction of 10^{-7}
of all events\[40\]. This is the equivalent of entering new territory and to be on
the lookout only for the interesting but not the potentially dangerous.

3. Safety considerations influence the trigger and operational procedures. Meta-
stable black holes might not yield very spectacular events, but it seems de-
sirable to ensure that their presence is immediately and reliably detected. An
immediate interruption of operation and detailed off-line study of the event
might be a possible risk-mitigating measure.

\[14\] Due to technical problems, very recently a reduction of this value to 3.5 times
higher has been decided\[7\].
Measures 1. only reduces the risk if measure 3. is also taken. To take such safety measures would not exclude but reduce any remaining risk. Methodologically similar measures have been taken in other areas of fundamental research under analogous circumstances, e.g. in biotechnology[4].

6 Acknowledgements

I thank G.t’Hooft, M.Jarnot, M.Leggett and S.Pezzoni for critical comments on a previous version of the present manuscript. I thank R.Casadio for his patient and helpful explanations of his theory.

7 Appendix - Answer to the manuscript “Comments on claimed risk from metastable black holes” by S.Giddings & M.Mangano

In a preprint[23] S.Giddings and M.Mangano (G & M) raise five objections against the conclusions of the present manuscript. I answer them below and raise, as a sixth point, an omission in their report.

1. They “find a negligible power output [from a black hole with the properties described in section 3 of the present manuscript] of the size 0.1 \(\mu\text{W}\), differing by a factor of \(10^{23}\) from [my] claim.”

My reply:
G & M employ their eq.(1)[22] - i.e. they assume scenario 1 (see section 1.2 of my paper) - to calculate the power output of a 5-dimensional microscopic black hole with a radius of \(10^{-7}\) m within the canonical thermodynamic description of microscopic black holes. They correctly find it to be 23 orders of magnitude smaller than the power output calculated in section 3 of my paper for a black hole of the same size and conclude that my result is erroneous. They claim that I mistakenly applied their eq.(1) “written in terms of the mass using the four-dimensional relationship between radius and mass”.

However it is the crucial point of my paper to introduce scenario 3 that does not employ their eq.(1) or my eq.(2) i.e. a thermodynamic, canonical description to calculate the power output of the black hole. Rather, following Casadio & Harms[10], it exclusively employs my eq.(1) (eq. (28) in [10]) which has a qualitatively different form. Following Casadio & Harms [10] (sentence after their eq.(28)), my eq.(2) was only used to normalize the luminosity eq.(1) at the mass \(M_N\).

This objection criticises something I did not do and did not intend to do. Therefore it does not apply to my paper. Implicitly G & M simply insist, here and in the third objection below, on a canonical treatment of mBHs, i.e. to employ their scenario 1, without stating any reason for implicitly ruling out
scenario 3.
2. They claim that “even ignoring the inconsistency” above, the bounds established in Giddings & Mangano\[22\] on Eddington limited accretion (like established in their eq.(B13)) still apply.
I reply:
As already pointed out in the 4th sentence after my eq.(6) all results on Eddington limited accretion of G&M were derived for their scenario 2 with “switched off” Hawking radiation and therefore do not apply for the case “Hawking-radiation limited” accretion at the Eddington limit, considered in my section \[3\].
3. They feel that a “serious difference between the microcanonical picture and the usual Hawking calculation appears implausible in the large black hole region” I considered (following Casadio & Harms).
I reply:
G & M give reason for this evaluation - which, I note, is also in flat contradiction to the work of Casadio & Harms\[10\] - so I need to wait for their promised “further comments” to take a position.
In light of our poor understanding of black-hole evaporation in general (see quote below) I feel that in any case it will be difficult to rule out such a serious difference with reasonable certainty.
4. G & M rightly point out that in my quote: “...at each point where we encountered an uncertainty, we have replaced it by a conservative or “worst case” assumption”. The bold “or” was missing. I corrected this oversight in the revised version.
5. G & M further propose that I quote from an abstract of a talk by W.Unruh\[41\], in addition to the references of my paper. I hereby accept their suggestion.
An excerpt from Unruh’s abstract reads: “...Black Hole evaporation is one of the most puzzling features of gravity and quantum theory. The derivation by Hawking is nonsense, in that it uses features of the theory in regimes where we know the theory is wrong. Analog models of gravity have given us a clue that despite the shaky derivation, the effect is almost certainly right. Where then are the particles in black hole evaporation really created?...”
From this quote I conclude: theories with extra dimensions robustly predict the existence of microscopic collider-producible black holes and Hawking radiation. But the detailed decay properties presently remain very uncertain. It then seems important to study the safety issue assuming plausible, literature-based alternatives to the standard thermodynamical treatment of Hawking radiation. This is the aim of my paper.
6. Finally G & M’s comment did not address section 4 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.
I stand by my general conclusion that there is a residual catastrophic risk from metastable microscopic black holes produced at particle colliders.
8 Appendix - Comment on the manuscript “On the possibility of Catastrophic Black Hole Growth in the Warped Brane World Scenario at the LHC” by Casadio et al.

8.1 Identity of the general approach of Casadio et al. and the present paper

In a recent important preprint\[13\], Casadio et al. studied the same question as the present manuscript: might collider-produced black holes grow catastrophically? Based on their own earlier groundbreaking work\[10\] they assume the same theoretical approaches for the behaviour of quantum black holes as I did. For the calculation of accretion (the sucking in of matter by gravitational forces) we both used the results of Giddings & Mangano\[22\]. As a consequence, e.g., the calculated lifetimes of black holes in the left-handed panel of their fig. 4\[16\] are reproduced by my eq.(1). We will see below that with identical parameter choices their results on black-hole accretion also broadly agree with the ones obtained by the methods employed in the present manuscript\[17\]. Casadio et al.\[13\] and I study the evolution of collider-produced metastable black holes under the same general assumptions that correspond to scenario 3 discussed in the introduction to the present manuscript. This disagrees with the criticism of the CERN team\[23\] of my manuscript that basically denied the possibility of my third scenario (see above section 7). Still, Casadio et al. “argue against the possibility of catastrophic black hole growth” whereas I find a “residual risk” for it. Let us examine in detail how their parameter choices differ from mine.

8.2 Analysis of parameter choices of Casadio et al.

8.2.1 The crucial difference is that Casadio et al. assumed that $M_c < 10^4\ kg$

For the parameter values generally assumed by Casadio et al.\[13\] (new Planck scale $M_5 = 1\ TeV/c^2$, atomic number accreted nuclei $A=53$, material constant $K=224\ J/m^2$, number of dimensions $D=5$) I find from eq.(4.22) of Giddings & Mangano\[22\] that a black hole needs a time $t_{\text{accr}} \approx 0.6\ msec$.

---

15 Casadio & Harms (2002) Ref.\[10\] is in the “top cite 100+” category of High-Energy Physics Literature Database “Spires” and one of the earliest and most frequently cited papers on microscopic black holes.

16 My discussion refers exclusively to their final version 2 of their manuscript.

17 Casadio et al. modelled the evolution of quantum black holes numerically, whereas I merely used analytical approximations from Giddings & Mangano\[22\] for the accretion.

18 Given in their section II.C and IV.B.
to reach a size of 1 Å via “subatomic accretion” (i.e. via gravitationally sucking in elementary particles within one atom). When the expected lifetime of the black holes “t\textsubscript{decay}” exceeds t\textsubscript{accr} the black hole can reach this size before decaying and at later times “Bondi accretion” (the sucking in of whole atoms) takes over which is even faster than subatomic accretion for the assumed parameters (its time scale is about 0.1 msec) and leads to exponential, catastrophic growth. However, one sees from fig. 4 in Casadio et al.\cite{13} that t\textsubscript{decay} remains below t\textsubscript{accr} just for the range of critical masses M\textsubscript{c} < 10\textsuperscript{4} kg considered by Casadio et al.\cite{13} (M\textsubscript{c} is a “free parameter” of the theory of Casadio & Harms\cite{10}, i.e. its value is not fixed). Therefore, I completely agree with the technical conclusion of Casadio et al.\cite{13}: If M\textsubscript{c} < 10\textsuperscript{4} kg, collider-produced black holes never reach the Bondi regime and growth to catastrophic sizes is not expected.

However, the crucial question clearly is: can M\textsubscript{c} exceed a critical value of about 1.3 × 10\textsuperscript{4} kg, which would make the predicted lifetime t\textsubscript{decay} of quantum black holes in the theory of Casadio & Harms exceed the accretion time t\textsubscript{accr}, needed to reach the catastrophic Bondi regime? In section 3 of the present paper I chose M\textsubscript{c} = 1.9 × 10\textsuperscript{5} kg (called M\textsubscript{N} there), thus implying that it can. On the other hand Casadio et al.\cite{10} call values of M\textsubscript{c} exceeding 10\textsuperscript{4} kg “physically unreasonable”. Let us analyse how they reached this conclusion, that directly led them to the exclusion of a catastrophic risk.

8.2.2 Can M\textsubscript{c} > 10\textsuperscript{4} kg be excluded?

Casadio et al.\cite{13} employed their eq.(18) (in section II.C) and eq.(25) (in section III.A)\cite{21} as the “defining condition” to estimate the value M\textsubscript{c} as a function of the warping scale “L”, a free parameter in the RS2 theory of extra dimensions\cite{37,22}. Using eq.(18) (eq.(25)) I find that M\textsubscript{c} exceeds the critical value of M\textsubscript{c} of about 1.3 × 10\textsuperscript{4} kg where the growth becomes catastrophic if L > 15.3 \(\mu\text{m}\) (L > 12.2 micrometer). As pointed out by Casadio et al. the current best experimental current limit on L is L < 44 \(\mu\text{m}\)\cite{29}. This limit is a 95 % upper limit, i.e. there is a chance of 5 % that L actually exceeds 44 \(\mu\text{m}\). I conclude therefore that there is certainly no comprehensible reason to exclude values of L between 15.3 and 44 \(\mu\text{m}\).

\[\text{more precisely: to reach an electromagnetic capture radius “R_{EM}”}.
\]

\[\text{A thermal velocity of 1500 m/sec of the ambient atoms was assumed.}
\]

\[\text{The derivation of eq.(25) is based on the requirement that the so called “electromagnetic capture radius” of a black hole with a mass of M_{c} shall always be smaller than L. I do not understand what plausible connection there could be between the capture radius and black hole properties. However, in view of our limited understanding of black holes with radii near L their eq.(25) might accepted; besides their eq.(16) and eq.(18), as another “possible choice” for the estimation of M_{c}.
}\]

\[\text{L specifies the length over which a fourth spatial dimension is significantly curved.}
\]
In section II.C directly after pointing out that \( L \lesssim 44 \mu m \), Casadio et al. continue: “For example setting \( L \approx 1 \mu m \) ... gives ... \( M_c \approx 10^2 \text{ kg} \)” This is correct, but in the rest of their paper, the latter value is suddenly and without giving any reason, treated as an upper limit on \( M_c \). To me only the value of \( M_c \) obtained with \( 44 \mu m \) is comprehensible as the upper limit. Inserting \( L=44 \mu m \) into eq.(18) (eq.(25)) of Casadio et al. one obtains \( M_c=1.1 \times 10^5 \text{ kg} \) (\( 2.2 \times 10^6 \text{ kg} \)) as the presently valid upper limit. The predicted lifetime of the black hole assuming \( M_c = 1.1 \times 10^5 \text{ kg} \) \( t_{\text{decay}} = 0.3 \text{ sec} \), exceeds the accretion time scale \( t_{\text{accr}}=0.6 \text{ msec} \) by a factor of 50: in this case growth is catastrophic. Moreover - as pointed out by Casadio et al.[13] - within the uncertainties of their theory, eq.(16) is, quote, “another possible choice” for the estimation of \( M_c \). Inserting \( L=44 \mu m \) into eq.(16) of Casadio et al. one obtains the huge value \( M_c=5.9 \times 10^{22} \text{ kg} \). With this choice for \( M_c \) growth is found to be catastrophic for all reasonable values of \( L \). Until reasons are brought forward to exclude values of \( L \) exceeding \( 15.3 \mu m \) and the use of their eq.(16) to estimate \( M_c \), catastrophic growth remains a possibility.

8.3 The “astrophysical” safety argument of G & M in the light of the model of Casadio et al.

Giddings & Mangano[22] did not categorically exclude the possibility of catastrophic growth, but argued that if it happened certain astrophysical objects would be completely consumed by cosmic-ray produced black holes on time scales smaller than their age, which is contrary to observations. In the current manuscript (section 3) I discussed a mechanism that invalidates this argument in the case of metastable black holes (“third scenario”) because their growth by accretion is eventually stopped at intermediate sizes via their emission of Hawking radiation. The question of which other mechanisms in the evolution of quantum black holes in a microcanonical framework might avoid G & M’s basic safety argument needs further scrutiny.

8.4 Summary

Summarizing, the work of Casadio et al.[13] confirms the validity and plausibility of my “scenario 3” based on their microcanonical description of metastable black holes. This scenario was completely excluded from the safety analysis

\[ ^{23} \text{I discuss these alternative choices in my section 2. I call Casadio et al.’s } M_c \ 	ext{“} M_N \text{”} \text{, their eqs.(16),(18) correspond to my eqs.(5),(3). My choice of } M_c=1.9 \times 10^5 \text{ kg in section 3.2 is justified when assuming eq.(16) in Casadio et al.} \]
conducted by CERN\cite{22} without providing any reason for this, at least up to now (see third bullet point in section\cite{7}). Casadio et al. correctly and usefully identify the range of a crucial theoretical parameter $M_c$ for which black-hole growth is not catastrophic, but offer no argument of how to exclude that the real $M_c$ lies outside this range.

Acknowledgement
I thank M.Jarnot, M.Leggett, L.Lueptow, E.Penrose and S.Pezzoni for helpful remarks on previous versions of this section and R.Casadio and B.Harms for answering some questions about their manuscript.

References

[1] T.Araki et al., Nature 436, 499-503 (2005).

[2] N.Arkani-Hamed, S.Dimopoulos, G.Dvali, Phys.Lett. B429, 263-272 (1998) [hep-ph/9803315].

[3] A.Barrau, J.Grain, CERN Courier, November 2004.

[4] Berg, P. et al., Proc. Nat. Acad. Sci. 72, 1981-1984 (1975); http://en.wikipedia.org/wiki/Asilomar_conference_on_recombinant_DNA accessed July 23, 2008.

[5] M.Bleicher, Eur.J.Phys 28, 509-516 (2007); arXiv:physics/0703062

[6] M.Cavaglia, R.Godang, L.M.Cremaldi, D.J.Summers, JHEP06, 055 (2007).

[7] A.Cho, Science 325, 522 (2009).

[8] C.G.Callan, J.M. Maldacena, Nucl. Phys. B472, 591 (1996).

[9] F.Calogero, Interdisciplinary Science Reviews 25,191-202 (2000).

[10] R.Casadio, B.Harms, Int.J.Mod.Phys. A17, 4635-4646 (2002) [hep-th/0110255].

[11] R.Casadio, B.Harms, Phys.Rev. D 64, 024016 (2001).

[12] R.Casadio, B.Harms, Y.Leblanc, Phys. Rev. D 58, 044014 (1998).

[13] R.Casadio, S.Fabi, B.Harms, [arXiv.org:0901.2948v2] (2009).

\textsuperscript{24} Even in a revised version of their report with “updated references” (\cite{22} v2 of the arXiv version) that was prepared after its authors had quoted Ref.\cite{10} in Ref.\cite{23} they fail to even quote Casadio & Harms\cite{10} or indeed any paper on the microcanonical approach to black hole physics. The revised manuscript still contains sentences such as “Thus, on very general grounds such [with a mass of about 10 TeV] black holes are expected to be extremely short-lived... $t_D \approx 10^{-27}$ sec...” which completely fly into the face of Casadio et al.’s conclusions: they argue that lifetimes exceeding $t_D$ by about 17 orders of magnitude are possible.
[14] S.Dimopoulos, G.Landsberg, Phys.Rev.Lett. 87,161602 (2001).

[15] http://en.wikipedia.org/wiki/Richter_magnitude_scale, accessed July, 17, 2008.

[16] J.Ellis et al., cern.ch/lsag/LSAG-Report.pdf (2008).

[17] S.Forste, Fortsch.Phys. 50, 221-403 (2002).

[18] S.B.Giddings, Gen.Rel.Grav. 34, 1775-1779 (2002) [hep-ph/0205205v1].

[19] S.B.Giddings, Phys.Rev. D67, 126001 (2003).

[20] S.B.Giddings, [hep-ph/0709.1107v3].

[21] S.B.Giddings, S.Thomas, Phys. Rev. D 65, 056010 (2002).

[22] S.B.Giddings, M.Mangano, CERN-PH-TH/2008-025,[hep-ph/0806.3381v1],
Phys.Rev.D78, 035009 (2008).

[23] S.B.Giddings, M.Mangano, CERN-PH-TH/2008-184,[hep-ph/0808.4087v1].

[24] D.M.Gingrich, K.Martell, J. Phys. G: Nucl. Part. Phys. 35, 035001 (2008).

[25] B.C.Harms, Y.Leblanc, Phys.Rev. D46, 2334-2340 (1992).

[26] B.C.Harms, Y.Leblanc, Phys. Rev. D47, 2438 - 2445 (1993).

[27] C.F.E. Holzhey, F. Wilczek, Nucl. Phys. B, 380, 447 - 477 (1992).

[28] J.Isern et al., [astro-ph/0806.2807v1], ApJL in the press (2008).

[29] D.J.Kapner et al., Phys.Rev.Lett. 98, 021101 (2007).

[30] A.Kent, Risk Anal. 24,157-168 (2004).

[31] B.Koch, M.Bleicher, H.Stöcker, [hep-ph/0807.3349v1] (2008), Phys.Lett. B672,
71-76 (2009).

[32] E.Keski-Vakkuri, P.Kraus, Nucl.Phys. B491, 249 (1997).

[33] G.Landsberg, J.Phys. G32, R337-R365 (2006).

[34] L.M.W.Leggett, Futures 38, 778 - 809 (2006).

[35] LHC commissioning home,
http://lhccommissioning.web.cern.ch/lhc-commissioning/ accessed May 27, 2008.

[36] T.Banks, M.E.Peskin, L.Susskind, Nucl.Phys. 244,125 (1984); M.K.Parikh,
hep-th/0402166v2.

[37] L.Randall,R.Sundrum, Phys.Rev.Lett. 83,4690 (1999).

[38] M.Rees, Our Final Hour: A Scientist’s Warning: How Terror, Error, and
Environmental Disaster Threaten Humankind’s Future In This Century On
Earth and Beyond, Basic books (2003).
[39] T.G. Rizzo, Class. Quant. Grav. 23, 4263-4280 (2006).

[40] S. Stapnes, Nature 448, 290-296 (2007).

[41] W. Unruh, http://www.perimeterinstitute.ca/Events/Effective_Models_of_Quantum_Gravity/Abstracts

[42] W.G. Unruh, R. Schützhold, Phys. Rev D71, 024028 (2005) [gr-qc/0408009].

[43] W.L. Wagner, F. Wilczek, Letters to the editor, Scientific American, July 1999.