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

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Abstract

The question of whether the collider production 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 astrophysical observations and thus evade a recent exclusion of risks from subnuclear black holes by Giddings & Mangano (2008). I further question that their risk analysis is complete for the reason that it excludes plausible parameter ranges from safety consideration without giving a sufficient reason. The reasons why Giddings & Mangano drew very different general conclusions are found to be of a methodological rather than scientific nature.

Some feasible operational measures at colliders that would allow the lowering of any remaining risk probability are proposed.

1 Introduction

Theories with "extra dimensions"[27], are one of the most popular extensions of the standard model of particle physics and a central plank of string theory[13]. If extra dimensions exist the Planck scale could occur at a much lower energy than usually supposed[2,31]. Subnuclear "micro" black holes (mBHs) can then be copiously produced at future high-energy particle colliders[10,27], such as the "Large Hadron Collider" (LHC) at CERN. A production rate of up to about one BH per second could then occur at the nominal LHC

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luminosity[10], i.e. the LHC would be a "black-hole factory"[14]. The phenomenology of this possibility at colliders has received detailed attention, see e.g. Cavaglia et al.[4].

The possibility that a collider-produced black hole (BH) - or another exotic object - might catastrophically grow by accretion and thus injure or kill humans deserves careful attention[36,24,6,32]. A recent scientific comparative study of global risks[28] 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 is based on speculative theories. But these theories were constructed to explore real possibilities. The probability that they are correct is not negligible.

Recently this risk has been studied in great detail in a seminal paper by Giddings & Mangano (G & M)[18][1]. They consider two frameworks for the description of mBHs. In a standard *"first scenario"* collider produced mBHs are treated 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 timescales after their production, thus cannot grow and pose no danger.

In a *second scenario* 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 rightly point out that this second scenario, 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 the "dangerous" parameter range is then excluded by demonstrating that cosmic-ray produced mBHs would accrete white dwarfs with small magnetic fields on smaller time scales than their age. Similar arguments applied to planets and ordinary stars are shown to fail to provide general safety limits, because all neutral cosmic-ray produced mBHs are shown to escape these bodies. Such arguments remain not completely definite for neutron stars because it remains unclear if cosmic rays with sufficient energy reach their surface.

It is the aim of the present paper to explore a *third scenario*, in addition to the two presented by G & M. Alternatively mBHs may be described by the "microcanonical ensemble" (i.e. one in which the total energy remains

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[1] The conclusions of a report[12] by the "lsag group" at CERN on the safety of microscopic black holes are mainly based on this paper. A very recent preprint of Koch et al.[25] uses a similar argument than G & M to exclude their safety-critical case "D4". My conclusions therefore apply to their work, too.

[2] G & M quote Unruh & Schützhold[35] who constructed a speculative model with this property.

fixed)[20,8,33,19]. It is thought to be more fundamental than the standard canonical ensemble. The mBH 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"[21,26]. In a sense this framework is more plausible than both frameworks studied by G & M, because it can avoid a violation of unitary evolution and energy conservation[9,5], serious problems that are well known to beset the first scenario used by G & M[30,18]. 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.
A treatment of collider produced mBHs within *scenario 3* and including extra dimensions, has been provided by Casadio & Harms (C & H)[7]. In the following I will exclusively study the behaviour of mBHs in the famous "Randall-Sundrum 2 (RS 2) model"[31], presented in one of the most frequently quoted papers in the recent history of high energy physics, within C & H's framework. In trying to understand if mBHs could be dangerous I will repeatedly resort to a use of G & M's excellent theoretical tools. I try to assume reasonably mild worst case assumptions, similar to the strategy of G & M[3]. However, I strived to introduce no "ad hoc" or finely tuned assumption, that would deem highly implausible to specialists in the field.

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

Quantum black holes are in principle unstable, i.e. they evaporate because no conserved quantum number forbids them to do so[18]. However, it is well known that their Hawking luminosity is strongly suppressed with respect to semiclassical expectations for black-hole masses below the Planck mass[9] in 4 space-time dimensions. If the additional curved spatial dimension of the RS 2 model exists, C & H predict a Hawking luminosity of the mBH of[7]:

$$P_5 = \frac{M_{\mathrm{BH}}\hbar c^6}{15360\pi G^2 M_N^3} \tag{1}$$

This formula is expected to be valid for black holes with sizes for which their metric can be well described by a 5-dimensional Schwarzschild solution. M_{BH} is the mass of the black hole and M_N is the smallest mass for which the usual 4 dimensional expression for the Hawking luminosity:

$$P_4 = \frac{\hbar c^6}{15360\pi G^2 M_{\mathrm{BH}}^2} \tag{2}$$

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[3] G& M wrote: "...at each point where we encountered an uncertainty, we have replaced it by a conservative "worst case" assumption".

is a good approximation. For given curvature scale “L” (associated with the warping in the RS 2 model) C & H assume that M$_N$ is equal to black hole mass at which the 5 dimensional Schwarzschild radius reaches is equal L. This gives:

$$M_N = \frac{3\pi L^2 c^2 M_5^3}{8\hbar^2} \tag{3}$$

Here M$_5$ is the “new” Planck scale (set to 1 TeV in all numerical estimates below). This normalisation ensures that eq.(1) surely applies. Because usually M$_N$ $\gg$ M$_5$ the Hawking luminosity P$_5$ of mBHs with a radius < L is strongly suppressed with respect to the standard 4-dimensional expression P$_4$.
The geometry of mBHs with Schwarzschild radii between L and $\approx$ 6 × L[4] is not known, and it remains presently unclear if eq.(2) can be applied in this “transitional region”. 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:

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

One might equally well normalize the luminosity equally M$_C$ setting:

$$M_N = M_C \tag{5}$$

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 $\approx$ 6 L. 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[23]. It can be easily shown that with normalisation eq.(5) mBHs are quasistable for all possible values of L[5].
Summarising, mBHs may very well be generally “quasistable” (in the sense of lifetimes exceeding years), without introducing any implausible “ad hoc” assumptions. These mBHs do emit Hawking radiation, but with a reduced

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[4] This range was derived from eq.(3.26) of G & M for the scales of L of interest in this manuscript: 10^{-9} m < L < 10^{-4} m. If L was smaller, mBHs in the third scenario would pose no catastrophic risk.

[5] i.e. the range from 1/M$_5$ to 10^{-4} m

luminosity with respect to the standard 4-dimensional Hawking radiation luminosity by the very large dimensionless factor $(\frac{\hbar}{cLM_5})^6$ (this expression is valid for the first normalisation (eq.(3))). In *scenario 3 and 1* (i.e. the scenarii without an artificial "switch off" of Hawking radiation) Schwinger radiation is expected to neutralize mBHs on a very short time scale due to Schwinger radiation[17,16], i.e. mBHs can be assumed to be neutral. Because G & M concluded that 5-dimensional 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 the light of the *scenario 3*, without an "a priori safety guarantee", an astrophysical (or other) exclusion of the existence of such mBHs is a "critical safety 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 that Hawking-radiate at the Eddington limit?

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 this might be the case for certain parameter choices. For purely illustrative purposes 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 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" characterised in section 4.2 of G & M. According to their eq.(4.22) it will take about 0.15 msec until the so called "electromagnetic radius" reaches atomic sizes[6]. Thereafter the accretion is well described as Bondi accretion and according to eq.(4.40) in G& M it will take about 2.2 msec until the mBH's Schwarzschild radius reaches L 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[15] would not change the results appreciably.). For the exemplary numbers chosen, eq.(4.31) of G & M predicts an increase of the mBHs mass at a rate of 1.9×10^4 kg/sec. It will take about 20 μsec until its mass reaches about 1 kg. At this mass the luminosity of the mBH is predicted by eq.(1) to be 5.1×10^{16} W or an mass equivalent of dm/dt = 0.57 kg/sec

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[6] A conservative thermal velocity of 1500 m/sec was used to convert the units in eq.(4.22) to a time.

being emitted as UV radiation. It is easy to verify that the five-dimensional Eddington limit (eq.(B.25) of G & M)

$$dM/dt = \frac{2.44 \times 8\pi m_p R_B c_s^2}{\eta\sigma c} \tag{6}$$

has the same magnitude for an efficiency η=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 σ the Thomson cross section. Therefore the radiation pressure of this Hawking radiation is intense enough to limit the amount of accreted matter to the same amount: dm/dt = dM/dt i.e. the mBHs accretes at the 5-dimensional Eddington limit. All accreted mass is then reradiated as light and the mBH's mass remains constant. G & M discussed the possibility of an radiation limited accretion in detail and excluded it because in *scenario 2* the Hawking radiation is completely switched off.

For the next 3×10^{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 5.2×10^{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[11]. 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 catasrophic consequences due to global heating on an unprecedented scale and global Earth quakes would seem certain.

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 5.9×10^{19} W or a fraction of 1.5×10^{-7} of the solar luminosity. This is about 10^4 times smaller than the cooling rate of white dwarfs in G & M's sample[18,22] and thus cannot be detected[7]. The accretion time of a white dwarf would exceed their present age by a large factor of $> 10^{10}$. Therefore no conclusions about mBHs can be drawn from the observed existence of such objects. The conditions for a neutron star would be similarly unspectacular. Completely independent of the doubt raised in section 5, the argument of G & M fails to exclude the existence of mBHs that are dangerous because of their intense Hawking radiation.

The numbers given in this section were chosen for an illustrative but not fine tuned parameter choice. There is a wide range of values for L and M_N that

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[7] 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.

lead to dangerous mBHs accreting at the Eddington limit with various luminosities.

In general the example developed above demonstrates that the intuitions that mBHs accretion must be slow, and that events which are catastrophic for Earth must also be for compact objects, can be wrong.

4 A catastrophe at CERN?

The luminosity of a mBH accreting at the Eddington limit with the parameters assumed above corresponds to 12 Mt TNT equivalent/sec[11], 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 section 3, 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.

5 Does the observed existence of old white dwarfs with a low magnetic field rule out "dangerous" quasistable black holes?

The doubt raised into the generality of one argument if G & M in this section applies to all scenarios discussed in the introduction.

In the text following their eq. (E.2) G & M formulate the following assumption:

$$M_{\text{min}} > 3\ M_5 \tag{7}$$

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].

This fact raises a fundamental doubt about G & M's exclusion of "dangerous

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[8] In a previous paper[17] Giddings wrote: "For masses of order the fundamental Planck scale [i.e. M_5] there is no control over quantum gravity effects which are likely to invalidate the semiclassical ... picture."

mBHs" by way of observing a certain class of white dwarfs. The 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 behave differently and escape white dwarfs, just as they could escape ordinary stars in the semiclassical approximation.
Concluding, G & M have not demonstrated that white dwarfs stop cosmic-ray produced mBHs in general. Their exclusion of dangerous mBHs thus remains not definite.

6 Conclusion

Treating mBHs as quantum objects in one possible consistent way, leads to the possibility that a mBH produced at a collider is captured by Earth and accretes at the Eddington limit, thereby emitting Hawking radiation that might be dangerous to as a whole and/or the inhabitants of CERN and its surroundings. The astrophysical arguments by G & M do not apply in this scenario, because the lifetime of white dwarfs with Eddington accreting mBHs turns out to be extremely long (section 3).
Moreover, for another independent reason, the exclusion of mBHs that threaten to accrete Earth by G & M cannot be considered definite in general (section 5).
At the present stage of knowledge there is a definite risk from mBHs production at colliders. This final conclusion differs completely from the one drawn by G & M. This is not because of any disagreement over the purely scientific content of their excellent paper. Rather the difference is the sole result of employing an alternative plausible scenario for the physics of mBHs and including parameter regions in which mBHs are not expected to be well described by the semiclassical scenario in the safety analysis.
It is not the aim of the present paper to recommend or discuss consequences for the future operation of colliders, beyond proposing to introduce (not yet implemented) safety regulations. I put up for further dicussion three feasable 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. Currently it is planned to perform the first runs at LHC at an energy more than 5 times higher than previously reached[29]. This might result in the copious production of completely novel states, which production was exponentially suppressed at the previous energies. "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[34]. 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 desirable to ensure that their presence is immediately and reliably detected. An immediate interruption of operation and detailed offline study of the event might be a possible risk mitigating measure.
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[3].

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