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Black hole astrophysics in AdS braneworlds

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Abstract: We consider astrophysics of large black holes localized on the brane in the infinite Randall-Sundrum model. Using their description in terms of a conformal field theory (CFT) coupled to gravity, deduced in ref. [1], we show that they undergo a period of rapid decay via Hawking radiation of CFT modes. For example, a black hole of mass few$\times M_\odot$ would shed most of its mass in $\sim 10^4 - 10^5$ years if the AdS radius is $L \sim 10^{-1}$ mm, currently the upper bound from table-top experiments. Since this is within the mass range of X-ray binary systems containing a black hole, the evaporation enhanced by the hidden sector CFT modes could cause the disappearance of X-ray sources on the sky. This would be a striking signature of RS2 with a large AdS radius. Alternatively, for shorter AdS radii, the evaporation would be slower. In such cases, the persistence of X-ray binaries with black holes already implies an upper bound on the AdS radius of $L \lesssim 10^{-2}$ mm, an order of magnitude better than the bounds from table-top experiments. The observation of primordial black holes with a mass in the MACHO range $M \sim 0.1 - 0.5\, M_\odot$ and an age comparable to the age of the universe would further strengthen the bound on the AdS radius to $L \lesssim$ few $\times\, 10^{-6}$ mm.

Keywords: Black Holes in String Theory, AdS-CFT and dS-CFT Correspondence, Black Holes, Cosmology of Theories beyond the SM.

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1. Introduction

In recent work [1] two of us (together with A. Fabbri) have considered black holes localized on branes in Anti-deSitter (AdS) braneworlds, as proposed by Randall and Sundrum (RS2) [2]. Our main result was deducing a connection between the classical bulk dynamics of black holes localized on branes in AdS_{D+1} and the semiclassical description of black holes in the dual CFT+gravity theory in one dimension fewer.[1] This connection is summarized in our conjecture [1] that *the black hole solutions localized on the brane, found by solving the classical bulk equations in* AdS_{D+1} *with brane boundary conditions, correspond to quantum-corrected black holes in D dimensions, rather than classical ones.* This follows naturally from the AdS/CFT correspondence adapted to AdS braneworlds. Ref. [1] provides a substantial amount of evidence supporting this result.

An immediate application of this conjecture determines the evolution of black holes in the RS2 model. The evolution of black holes larger than the AdS radius L can be fully described either by the classical bulk dynamics or by the semiclassical large N dynamics of the dual CFT+gravity. Resorting to the latter, we can see that the presence of a large number of CFT degrees of freedom accelerates the decay of a black hole via Hawking radiation. This has also been noticed in ref. [6].

This is qualitatively different from black hole evaporation in braneworld models where the curvature of extra dimensions can be ignored, as studied in [7]. Our picture applies only to models which admit a dual CFT+gravity description, which exists when the bulk is asymptotically AdS as in RS2 braneworlds (unlike, e.g. ADD scenarios [8]). Further, black holes must be *larger* than the asymptotic AdS radius L. Then, as long as the CFT+gravity dual is valid, regardless of how cold a black hole is, it can always access a large number of CFT modes, because the asymptotic AdS geometry in the bulk means

[1] The basic rules of this duality have been considered in, for example, [3]–[5].

that there is no gap to suppress the CFT emission. From the bulk point of view, this effect is a *classical* one, which arises because a black hole stuck on a brane is accelerating through the AdS bulk. The classical emission of bulk radiation by these large black holes will overshadow the quantum radiation considered in [7]. The radiation we are considering only looks quantum once one turns to the dual CFT+gravity, where the largesse of this effect compared to the emission of brane modes is due to the huge number of CFT degrees of freedom — which is in turn the dual of the huge ratio $(L/L_{P4})^2$.

Black holes which are smaller than the AdS radius should radiate more slowly. Indeed, the dual CFT+gravity description breaks down, because the bulk graviton modes are needed to describe the black hole geometry itself and cannot be interpreted as dual CFT degrees of freedom [1]. The evolution of small black holes can still be described by a semiclassical bulk theory without evoking the dual CFT+gravity. This description is very sensitive to the details of the UV completion of the bulk theory. Still, one sees from it that the rate of Hawking evaporation diminishes significantly, as suggested by the classical bulk picture argument. A small black hole Hawking-radiates mostly along the brane, since the dominant s-wave channel cannot discriminate between the bulk and the localized gravity [7]. This evaporation is much slower than the emission of a large number of CFT modes.

A complete picture of the evolution of black holes in RS2 braneworlds which start out larger than the AdS radius therefore comprises of two stages: a period of rapid mass loss, during which the CFT+gravity description remains valid, and a period of slow evaporation, during which the black hole continues to lose mass at a much lower rate. The latter stage can last a very long time if the AdS radius is close to the observational bounds. However, these black holes are so small that their observational signatures are weak and could only become important due to the cumulative effect of exciting too much relativistic CFT after inflation. We will therefore focus on the effects of large black holes in what follows.

The most dramatic observable consequence of the classical picture of black hole evaporation is that the black hole lifetime can be tremendously shortened. In this article we will exploit the consequences of this observation for two complementary purposes: (1) deriving bounds on the AdS radius L in RS2 braneworlds from the observation of astrophysical black holes, and, somewhat more speculatively, (2) proposing new ways for observing large, or infinite warped extra dimensions. We find that the black hole lifetime provides the most sensitive probe of the number of CFT degrees of freedom. In the former case, they lead to bounds on L which are 3 to 5 orders of magnitude stronger than the table-top and cosmological limits, which at present constrain L to less than about 10^{-1} mm [9]–[11]. In the latter case, they lead to a rapid mass loss of large black holes, which could deplete the population of super-solar mass black holes in the universe.

2. A qualitative picture of the black hole evolution

The evaporation time of a black hole larger than the AdS_5 radius L in the RS2 setup is easily derived using the dual 4D CFT+gravity description. As a first estimate of their lifetime, to be refined below, recall that in the presence of quantum fields with a number

g_* of light degrees of freedom, a black hole will evaporate in a time roughly given by

$$\tau \sim \frac{10^{64}}{g_*} \left(\frac{M}{M_\odot} \right)^3 \text{ yr} . \tag{2.1}$$

The number of CFT degrees of freedom is related to the bulk AdS radius L by $g_* \sim (L/L_{P4})^2$ where L_{P4} is the $4D$ Planck length, so $g_* \sim 10^{64}(L/1\,\text{mm})^2$ and

$$\tau \sim \left(\frac{M}{M_\odot} \right)^3 \left(\frac{1\,\text{mm}}{L} \right)^2 \text{ yr} . \tag{2.2}$$

Hence, as described above, the decay is extremely rapid when compared to more conventional cases, such as the Standard Model (SM) coupled to $4D$ gravity, with a number of matter degrees of freedom $\sim \mathcal{O}(100)$ [12, 13]. For example, in the case of SM+gravity it would take an age of the universe for a black hole the size of Mount Everest, of mass $M \sim 10^{15}$ g, and size $R \sim 10^{-15}$ m, to completely disappear [12], whereas in RS2 with $L \lesssim 0.1\,\text{mm}$, a black hole of a few solar masses might evaporate most of its mass in a time of the order of millenia. Note that our approach is valid for $G_4 M \gtrsim L$, which is satisfied by most astrophysically relevant black holes. Indeed,

$$M \gtrsim 10^{-6} \left(\frac{L}{1\,\text{mm}} \right) M_\odot \simeq 10^{51} \left(\frac{L}{1\,\text{mm}} \right) \text{GeV} , \tag{2.3}$$

so we see that, even with the current upper bound from table-top experiments limit [9], $L \lesssim 0.1\,\text{mm}$, the dual CFT+gravity description of black holes applies to most of the interesting cases for astrophysical considerations, the more so the smaller L is. Thus, black holes in the range (2.3), including quite heavy ones, would evaporate away most of their mass very quickly. If this process actually takes place, it can significantly deplete the population of large, solar mass black holes in the universe. Hence, observations of such black holes would imply the absence of this effect and enable us to derive an upper bound on the number of CFT degrees of freedom g_*, which translates into a bound on the bulk AdS radius L. Alternatively, one might under special circumstances end up with a situation in which all the observed black holes come from black hole progenitors that have managed to accrete enough mass from the environment to compensate for the evaporation. In this case, one could search for the disappearance of X-ray sources on the sky, corresponding to the transition of a black hole from being larger to being smaller than the AdS radius, i.e. smaller than the bound (2.3).

We note that recently an attempt was made to study the evolution of primordial black holes (PBHs) in RS2 [14]. However [14] does not take into account the effects we study here, and therefore misses the most relevant physics for black holes larger than the AdS radius. We now turn to the more precise determination of the evaporation time.

3. The evaporation time of large black holes

We now make formula (2.2) more precise. The rate of mass loss for a neutral, non-rotating black hole in vacuum due to Hawking evaporation is

$$\frac{dM}{dt} = -\frac{\alpha}{(G_4 M)^2} , \tag{3.1}$$

where α is a factor that accounts for the Stefan-Boltzmann factors and greybody corrections for the particles of each spin that are emitted,

$$\alpha = n_0\, \alpha_0 + n_{1/2}\, \alpha_{1/2} + n_1\, \alpha_1\,. \tag{3.2}$$

Here n_0, $n_{1/2}$ and n_1 are the numbers of real scalars, Weyl (or Majorana) fermions, and gauge vectors, respectively. The coefficients α_s have been computed as[2]

$$\alpha_0 = 7.0 \times 10^{-5}\,, \qquad \alpha_{1/2} = 8.0 \times 10^{-5}\,, \qquad \alpha_1 = 3.4 \times 10^{-5}\,. \tag{3.3}$$

The specific matter content, n_s, of the dual CFT depends on the details of the UV completion of the theory, e.g. on how the model is embedded into string theory (or any consistent quantum gravity theory). In the absence of a concrete embedding, we will use the simplest case where the full space is the $\mathrm{AdS}_5 \times S^5$ background of IIB string theory. This is dual to $\mathcal{N} = 4$ supersymmetric $\mathrm{SU}(N)$ Yang-Mills theory, which for a large N yields $n_0 = 6N^2$, $n_{1/2} = 4N^2$ and $n_1 = N^2$. On the other hand, AdS/CFT gives $N^2 = \pi L^3/2G_5$ [17], while RS2 implies $G_5 = LG_4$, so $N^2 = \pi L^2/2G_4$. Thus one obtains

$$\frac{dM}{dt} = -2.8 \times 10^{-3} \left(\frac{M_\odot}{M}\right)^2 \left(\frac{L}{1\,\mathrm{mm}}\right)^2 M_\odot\, \mathrm{yr}^{-1}\,. \tag{3.4}$$

Integrating this equation and dropping the corrections of order of the critical mass of eq. (2.3), gives the time within which a large black hole initially of a mass M will shrink to below the size of L:

$$\tau \simeq 1.2 \times 10^2 \left(\frac{M}{M_\odot}\right)^3 \left(\frac{1\,\mathrm{mm}}{L}\right)^2 \mathrm{yr}\,, \tag{3.5}$$

which is larger than the estimate (2.2), that neglected greybody corrections and other factors. From eq. (3.5), we note that in the extreme case where $L \simeq 0.1\,\mathrm{mm}$, a black hole of a mass $M \lesssim 50\ M_\odot$ which could have formed by the collapse of early stars would have evaporated by today down to a small mass below the bound of Eq. (2.3). Thus the strongest bounds and signatures will come from either primordial or stellar-mass black holes.

The assumption that the matter content of the dual CFT is that of $\mathcal{N} = 4$ $\mathrm{SU}(N)$ SYM is not essential. For other embeddings of AdS_5 the final result eqs. (3.4) and (3.5) may be modified only by factors of order unity: whenever the bulk geometry is asymptotically AdS_5, the dual theory will contain a large number $\sim (L/L_{P4})^2$ of light fields. *Any* such theory must reproduce *exactly* the same Weyl anomaly, regardless of its matter content, so the final result must always be quite close to the above. This picture would not apply if the AdS_5 geometry were modified at some distance away from the brane such that the dual theory develops a mass gap greater than the black hole temperature[3]. Observe that, from the CFT+gravity viewpoint, the quickened evaporation rate is entirely due to the vast increase in the phase space available to black hole emission. The temperature of black holes

[2] $\alpha_{1/2}$ and α_1 were computed numerically in [13], while α_0 was obtained in the optical approximation in [15]. See also [16].

[3] This is one of the reasons why our arguments do not apply to ADD.

that are larger than L is essentially unaffected by the presence of the extra dimensions, taking the usual form

$$T \simeq 6 \times 10^{-8} \frac{M_\odot}{M}\,\mathrm{K}\,, \tag{3.6}$$

which is extremely small for astrophysical black holes. However, if the bulk is modified far from the brane, the dual theory has a gap and ceases to be a CFT in the IR. The gap would suppress the emission of Hawking radiation from black holes whose temperature is below it. In such instances our constraints could be significantly weakened, depending on the scale of the gap.

The main practical obstacle for deriving the bounds comes from the fact that realistic black holes do not live in a vacuum. They are surrounded by a distribution of matter, such as the thermal background photons and the interstellar medium for isolated black holes, and even more importantly, the dense environment for black holes inside galaxies. Examples are the gas of a companion star in the case of X-ray binaries, which typically form accretion disks, like in microquasars [19], and the halo of ionized infalling matter stripped from nearby stars, in the case of large quiescent black holes in the centers of galaxies. Any black hole colder than the environment will absorb energy from its surroundings and accrete mass onto itself [20]. The rate at which a black hole accretes mass depends very much on its environment and ranges from $10^{-9}\ M_\odot\,\mathrm{yr}^{-1}$, for isolated black holes and low mass X-ray binaries, to $M_\odot\,\mathrm{yr}^{-1}$ for high redshift quasars.

The processes of evaporation and accretion compete with each other. However they work quite differently: while the evaporation rate decreases with the black hole mass as M^{-2}, the accretion grows proportionally to the horizon area and hence to M^2. The dynamical law describing the rate of mass change of a black hole with accretion included is [20]

$$\dot{M} = \beta (G_4 M)^2 \rho - \frac{\alpha}{(G_4 M)^2}\,, \tag{3.7}$$

where the first term encodes the accretion of matter with energy density ρ surrounding the black hole and the second term encodes Hawking evaporation (3.4). Here β is a numerical coefficient measuring the efficiency of accretion, which may depend on the velocity of the black hole moving through the intergalactic medium. Ignoring details we will assume that it is of order unity. Now, the accretion will be smaller when the evaporation proceeds faster, i.e. when the black hole is smaller. From (3.7) we see that this will happen when $\rho(G_4 M)^4 < 10^{64}(L/1\,\mathrm{mm})^2$. For example, massive black holes in the core of AGNs have accretion rates[4] of order $1 - 10^{-4} M_\odot\,\mathrm{yr}^{-1}$, which completely overwhelm the evaporation rate (3.4).

For stellar mass black holes the situation is more complicated, but it is expected that the typical rate at which a normal star is dumping gas onto a companion black hole is around $10^{-9} M_\odot\,\mathrm{yr}^{-1}$. This gives a rather wide margin for the evaporation to dominate. Thus, isolated or smaller black holes, while harder to detect, will end up being dominated by the evaporation into CFT modes. In this instance, it is straightforward to check that the accretion of CMB photons is negligible, even if the CMB is much hotter than the black

[4]Estimated from their observed luminosity, see e.g. ref. [21].

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hole. For example, for a solar mass black hole in theories where $L \sim 0.1\,\mathrm{mm}$, the mass increase due to the accretion of CMB photons at temperatures below the MeV is negligible compared to the mass loss coming from CFT Hawking evaporation. Thus even primordial black holes will end up mostly evaporating CFT throughout their lifetime. This allows us to place bounds on L, and also argue for new ways of looking for the signatures of RS2. We now turn to the best sources of the bounds.

4. The bounds on L

Sub-solar-mass black holes and MACHOs. It is clear from the arguments above that CFT evaporation affects most dramatically smaller black holes, whose horizon exceeds the AdS radius L just barely, such that they are the hottest black holes allowing dual CFT+gravity description. Specifically, the sub-solar-mass black holes will yield the strongest bounds. They could not have formed by collapse of matter because of the Oppenheimer-Volkoff bounds, and hence must be primordial, forming during some violent process in the very early universe [22]–[24]. Such black holes must have lived at least as long as the age of the Universe, $\tau_U \sim 14\,\mathrm{Gyr}$. An observation of a single such black hole would thus strongly constrain the parameter L. From this τ_U and eq. (3.5) we obtain

$$L \lesssim 10^{-4} \left(\frac{M}{M_\odot}\right)^{3/2} \mathrm{mm}\,. \tag{4.1}$$

Hence any evidence for a small black hole with mass in the range $M \sim 0.1 - 1 M_\odot$ would impose a bound on L that may be as tight as

$$L \lesssim \mathrm{few} \times 10^{-6}\,\mathrm{mm}\,, \tag{4.2}$$

which is some five orders of magnitude stronger than the current limits from table-top experiments and cosmology [9]–[11].

What are the chances of observing such black holes? It has been argued recently that they might actually comprise a significant portion of the dark matter in the galaxy halo, to avoid problems with having too many baryons if the MACHOs were all brown dwarfs [25]. If this is true, the most obvious difficulty for their detection is to distinguish the PBH MACHOs from other compact, nonluminous objects in the *same* mass range. At present, the best strategy for identifying such light objects as black holes is to search for the gravitational waves emitted during the merger phase of a coalescing binary containing a black hole [26]. This challenge has apparently been taken by the GEO-600 collaboration, which has plans to search for binaries containing black holes in the MACHO range [27].

Isolated few-solar-mass black holes. CFT emission could have played a significant role for black holes with a mass in the range $1 - 100 M_\odot$, formed by stellar collapse, if they were old enough. If the AdS radius L is sufficiently large, say, more than a fraction of a micron, this will be the case for black holes formed in the supernova explosion of first-generation stars, $t \sim 5 \times 10^9\,\mathrm{yr}$ ago. An additional requirement is that the black hole be isolated, so it does not accrete from a companion star. While their detection is

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difficult, it is possible in principle, through the emission of X-rays via accretion of gas from the interstellar medium (ISM), see ref. [28]. It has been argued by Brown and Bethe [29] that there must be a large population ($\sim 10^9$) of black holes in our galaxy with a mass around $1.5 M_\odot$. If so, there should be many microlensing events with such a mass towards the galactic bulge. In the future such black hole candidates spotted with microlensing can be checked with X-ray measurements by XMM and Chandra, which could give crucial information about the low-mass black holes in the galaxy. As a first step, recently both MACHO and OGLE collaborations have claimed discovery of nearby black holes through long-lasting microlensing events [30, 31].

Isolated black holes are expected to accrete ISM matter at a very low rate [28], $\dot{M}_{\rm accr} \sim 1.5 \times 10^{-11}\, M_\odot\, {\rm yr}^{-1}$, and therefore their rate of evaporation into CFT modes (3.4) would be significantly larger $|\dot{M}_{\rm evap}| \sim 1.2 \times 10^{-3}\, (L/1\,{\rm mm})^2\, M_\odot\, {\rm yr}^{-1}$, unless the AdS radius is $L < 10^{-4}$ mm. In this case a few-solar-mass black hole could retain most of its mass for few billion years. Verifying the existence of a population of black holes with masses of few $M_\odot$ would therefore impose a stringent bound on L,

$$L \lesssim {\rm few} \times 10^{-4}\, {\rm mm}\,, \tag{4.3}$$

about three orders of magnitude stronger than the limits from table-top experiments [9].

Black holes in X-ray binaries. The best observational candidates for black holes are X-ray binaries. They come in two classes, low mass (LMXB) and high mass (HMXB) X-ray binaries, depending on the mass of the companion, which can be determined reliably from the orbital properties of the companion in a binary system. Most of the best known black holes, with masses measured to better than 10% error, correspond to LMXB and, more precisely, to the so called Soft X-ray Transients, also known as *X-ray Novae* [32]. A dozen of them are known to date, with their orbital properties and masses detailed in Table 1. of ref. [33]. Their average mass is $\langle M \rangle \sim 7\, M_\odot$, but the dispersion is large, since the masses range from $3\, M_\odot$ to $14\, M_\odot$. Most of these LMXB were formed when the heavy star of the binary exploded in a supernova, without completely blowing the system apart, and leaving behind a black hole. Their typical accretion rates from their companion stars are of order of $\dot{M}_{\rm accr} = 10^{-10}\, M_\odot\, {\rm yr}^{-1}$ [32]. This accretion rate sets a benchmark with which to compare the emission of Hawking radiation in the CFT sector.

Unfortunately, less is known about the lifetimes of X-ray binaries. Most black holes in binaries were formed from heavy stars in the disk of the galaxy, so their lifetime is estimated to be $t < t_{\rm disk} \sim 10\,{\rm Gyr}$. However, reliable ages are difficult to determine, and there are very few examples of reliable estimates. These involve young binary systems, such as the X-ray transient XTE J1118+480 and the microquasar GRO J1655-40 (also known as Nova Scorpii 1994). The mass of the black hole in XTE J1118+480 is $M = 6.8 \pm 0.4\, M_\odot$, and its age has been estimated by using the properties of its eccentric halo orbit which happened to pass close to Earth. This led to the suggestion that this black hole may have originated in the galaxy disk 240 Myr ago and went out of the plane due to a supernova explosion [34]. Substituting the mass and the age in eq. (3.5), we find the bound on L to be

$$L \lesssim 1.3 \times 10^{-2}\, {\rm mm}\,, \tag{4.4}$$

already an order of magnitude better than table-top experiments. A systematic uncertainty in the age of the black hole towards larger values [34] could give a somewhat stronger constraint on L. This alone would make it hard for table-top experiments to detect the subleading corrections to $4D$ gravity in RS2. We note that the age estimate of XTE J1118+480 has been questioned in [34, 35], where the possibility was raised that the black hole may have originated in a globular cluster 7 Gyr ago and followed a path in the halo characteristic of globular clusters. This would significantly improve the bound on the AdS radius, leading to

$$L \lesssim 2.4 \times 10^{-4}\,\mathrm{mm}\,, \tag{4.5}$$

which is three orders of magnitude better than the bounds from table-top experiments.

The GRO J1655-40 microquasar has a black hole whose mass is $M = 5.4 \pm 0.3\, M_\odot$ [36]. Its age can be estimated from a peculiar chemical abundance of the surface of the companion, with elements that can be traced back to a supernova explosion of type II. Since the rate at which the companion loses matter towards the accretion disk is known, one can place the limit of $\lesssim 10^6$ yr on the age of the black hole [37, 38]. Very recently, multiple wavelength observations of GRO J1655-40 were used to determine its velocity and possible origin in the sky [39]. From these observations, providing the first direct evidence for stellar black hole formation in supernovae explosions, one can estimate the age of the black hole to be 0.7 Myr [39]. Altogether this gives only a mild bound on $L \lesssim 0.2$ mm, comparable to table-top experiments.

Future measurements of the dozen or so X-ray novae with XMM and Chandra satellites may reveal their origin and their age. Any black hole as old as the galaxy would then impose a strong bound on the AdS radius, of order

$$L \lesssim \mathrm{few} \times 10^{-3}\,\mathrm{mm}\,. \tag{4.6}$$

Improved bounds from rotating black holes. So far we have been considering evaporating black holes which are static, without any angular momentum. This is probably unrealistic: most black holes are expected to be spinning, some with angular momenta close to the unattainable extremal limit $a \equiv J^2/M^2 = a_{\mathrm{max}} = 1$ in geometric units. There is some observational evidence for black holes in the stellar mass range with spins up to $a = 0.94$, and also of galactic black holes with similarly large spins [40, 41].

A black hole loses its angular momentum by Hawking emission of particles with both orbital and intrinsic angular momentum [42]. Indeed, a quickly rotating black hole is more likely to emit particles of higher spin, an amplification closely related to superradiance [43]–[45]. Explicit calculations show that the addition of some spin to the black hole does not, in fact, change its lifetime by more than a factor of about 2 [42]. Hence our estimates above which ignored the effects of spin are still reliable.

However, there remains the possibility that measurements of the spin of a black hole, rather than of the mass, may yield improved bounds on the number of CFT modes, and thus on the curvature scale L of the extra dimension. A quickly spinning black hole, $a \lesssim 1$, will shed off a large fraction of its spin quite fast until it is reduced to more modest values of a. In our context, the enhanced evaporation rate into CFT modes will amplify this

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effect and prevent a black hole from retaining a large angular momentum for a long time. From the analysis in [42] we infer that a black hole with an angular momentum above $a = 0.9$ will spin-down below this value in a time equal to around 1/50 of its total lifetime. Thus, the existence of angular momenta in the range $0.9 \leq a < 1$ that have been held for a sufficiently long time will further improve the bounds on L by as much as an order of magnitude beyond those obtained from the total lifetime of the black hole. As an example, if the candidate spinning black hole of ref. [40, 41] is as old as 10^9 yr, then

$$L < 10^{-4}\,\text{mm}\,. \tag{4.7}$$

5. Black hole detonations as a signature of RS2

So far we have been focusing on the bounds on the AdS radius which come from requiring that black holes with masses $\lesssim$ few $\times\, M_\odot$ evaporate sufficiently slowly to be around today, even if they were formed billions of years ago. However, the numbers of the observational black hole candidates in this mass range are in the teens. Thus while it may not be very likely, it is possible that those which really are black holes ended up surviving for so long because of accretion, that might have won over fast CFT emission. This would give rise to an exciting possibility for very significant signatures of RS2 with as large an AdS radius as currently allowed by observations, given by our eq. (4.4), $L \lesssim 0.01\,\text{mm}$.

In this instance, Hawking evaporation of CFT modes from a black hole with a mass close to a solar mass in a X-ray binary in the last stages of evaporation would lead to a decay time τ of order of few million years, rendering the mass time-dependent, $M(t) = M_{\rm BH}(1 - t/\tau)^{1/3}$. In the final stages of the evaporation into the CFT sector, the mass of the black hole would change rapidly: it would reduce to one-tenth of its initial value in the final millenium, and to one-hundredth in the last year, and so forth. Since these time scales are much shorter than any dynamical (gravitational collapse) time scales, the potential well holding the rotating accretion disk together (as well as the companion star in its orbit) would disappear suddenly, and the disk would fly apart by the action of centrifugal forces, sending the companion outward like a slingshot. No events of this kind have been observed yet. However, if the initial mass function for stellar formation favors the formation of lower-mass objects, there could be a large population [29] of solar mass black holes ready to go away. An observation of such a dramatic event would immediately suggest sudden black hole evaporation. One could also imagine searching for stars that have been catapulted in the past from their place of origin, e.g. away from the plane of the galaxy, and estimate the force required. If it exceeds the force which could have been exerted by a supernova, it might suggest an event of the sudden evaporation of a solar mass black hole which ejected its companion. This could be taken as an indication of a gapless CFT in the hidden sector, as in the RS2 framework. We note however that even a slight improvement of our bound (4.4) would prolong the decay time of such black holes, deferring the detonations to much larger timescales which would make their observations much less likely.

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6. Summary and future directions

In this article we have discussed phenomenological and astrophysical aspects of black holes in the infinite Randall-Sundrum model [2]. Our analysis is based on the conjecture proposed in [1, 6], whereby a black hole larger than the AdS radius, which is stuck on the brane, is described in the dual CFT+gravity as a copious source of Hawking CFT radiation. This will in general shorten the lifetime of a black hole, and specifically, it will make large black holes lose a huge part of their mass very quickly. We have shown that because of this effect black holes are the most sensitive indicator of the presence of a large number of CFT degrees of freedom in the hidden sector. A black hole with a mass $\lesssim M_\odot$ would impose stronger constraints on the AdS radius L than the table-top experiments [9] and cosmology [10, 11]. Already at the moment, X-ray binaries require that $L \lesssim 10^{-2}$ mm. The bounds could be as strong as $L \lesssim$ few $\times\, 10^{-9}$ m if MACHOs are proven to be primordial black holes. We note that it is quite fascinating that the bounds are still fairly weak, in spite of the fact that the ensuing number of CFT degrees of freedom may be huge, as large as $\lesssim 10^{60}$. This is a consequence of the weakness of gravity and the weakness of direct couplings of CFT to the visible sector [2, 46]. We have also seen that there remains a less likely, but exciting prospect of black hole detonations as a signature of RS2, in the case when the AdS radius is close to the observational bounds.

We close with some remarks on cosmological implications of black holes in RS2 and more generally in any theory with a large number of CFT degrees of freedom in the hidden sector in IR. Black hole physics in such models can lead to stringent bounds on the models of the early universe in theories with a large number of CFT degrees of freedom. Namely the hidden sector CFT and the visible sector (including the Standard Model) interact with each other only very weakly, with direct couplings that are weaker than gravitational in the infrared. Black holes provide for a stronger channel of interaction between these two sectors. Indeed, because CFT and CMB couple only very weakly, they can be viewed essentially as two separate vessels of gas, insulated from each other. A black hole acts as a pipe connecting these two vessels. The gas can flow through the pipe from the hotter into the colder vessel as long as there is a temperature gradient, or until the flow of heat deteriorates the pipe, i.e. when the black hole completely evaporates away. If the universe starts mostly populated by the visible sector particles, ie CMB, black holes will mostly accrete hot CMB, and will mostly evaporate colder CFT, which has many more flavors to take away the entropy. Thus black holes will eventually lead to the heating of the CFT sector in the universe.

On the other hand, having a realistic cosmology requires that there was very little production of CFT radiation in the early universe, to avoid disturbing the fine balances required for nucleosynthesis. As shown in [10, 11], the weak direct CFT-visible sector couplings lead to a very slow production of the CFT radiation, consistent with nucleosynthesis, as long as $L \lesssim 1\,\mathrm{mm}$. Black holes can accelerate the conversion of the visible sector into CFT radiation if their primordial abundances were large. Thus requiring that the initial abundance of primordial black holes is low enough so that the CFT radiation remains cold enough during nucleosynthesis will give new constraints on the early cosmology of

RS2 with a large L. There may also arise bounds from structure formation, because CFT would behave as hot dark matter (a possibility touched upon in [46]). However, we refrain from a detailed investigation of these issues here because the new bounds will depend on the specifics of the early universe evolution and on the details of CFT self-interactions. They may be a useful guide for building the early universe models in RS2.

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