Dark dimension, the swampland, and the dark matter fraction composed of primordial black holes

Luis A. Anchordoqui,[1,2,3] Ignatios Antoniadis,[4,5,6] and Dieter Lüst[7,8]

[1]*Department of Physics and Astronomy, Lehman College, City University of New York, New York 10468, USA*
[2]*Department of Physics, Graduate Center, City University of New York, New York 10016, USA*
[3]*Department of Astrophysics, American Museum of Natural History, New York 10024, USA*
[4]*Laboratoire de Physique Théorique et Hautes Énergies - LPTHE, Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France*
[5]*SISSA, Via Bonomea 265, 34136 Trieste, Italy*
[6]*ICTP, Strada Costiere 11, 34151 Trieste, Italy*
[7]*Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, 80805 München, Germany*
[8]*Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München, 80333 München, Germany*

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Very recently, it was suggested that combining the swampland program with the smallness of the dark energy and confronting these ideas to experiment lead to the prediction of the existence of a single extra dimension (dubbed the dark dimension) with characteristic length scale in the micron range. We show that the rate of Hawking radiation slows down for black holes perceiving the dark dimension and discuss the impact of our findings in assessing the dark matter fraction that could be composed of primordial black holes. We demonstrate that for a species scale of $\mathcal{O}(10^{10}\ \text{GeV})$, an all-dark-matter interpretation in terms of primordial black holes should be feasible for masses in the range $10^{14} \lesssim M_{\rm BH}/\text{g} \lesssim 10^{21}$. This range is extended compared to that in the 4D theory by 3 orders of magnitude in the low mass region. We also show that primordial black holes with $M_{\rm BH} \sim 10^{12}$ g could potentially explain the well-known Galactic 511 keV gamma-ray line if they make up a tiny fraction of the total dark matter density.

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I. INTRODUCTION

The swampland program [1] seeks to demarcate the set of four-dimensional effective field theories (EFTs) that can be coupled to quantum gravity in a consistent way, e.g., the landscape of superstring theory vacua, and discriminate these theories from those that cannot, to strengthen the predictive power of quantum gravity in general, and superstring theory in particular. This is accomplished by enumerating criteria that an EFT must fulfill so as to be in the landscape, rather than be relegated to the "swampland." These criteria have evolved to some set of conjectures, which can be used as new guiding principles to construct compelling UV completions of the Standard Model (SM). Moreover, the UV constraints on IR physics have led to a shift in the way we approach cosmology model building. There are many swampland conjectures in the market, indeed too many to be listed here and readers are referred to comprehensive reviews [2,3].

It was argued some time ago that *the cosmological hierarchy problem*, i.e., the smallness of dark energy in Planck units ($\Lambda \sim 10^{-122} M_{\rm Pl}^4$), can be explained statistically [4] or even anthropically [5–7] by the huge number of vacua in the string landscape. However very recently, it was suggested [8] that by a combination of *the cosmological hierarchy problem* and *the distance conjecture* one naturally ends up in a peculiar corner of the string landscape, namely, with a single extra dimension characterized by a length scale in the micron range.[1]

The distance conjecture predicts the appearance of infinite towers of states that become light and imply a breakdown of the EFT in the infinite distance limits in moduli space [12]. Stated in the form of the anti–de Sitter (AdS) distance conjecture [13], it suggests that there should be an infinite tower of states, whose mass is related to the magnitude of the cosmological constant. More precisely, the mass scale m behaves as $m \sim |\Lambda|^\alpha$, as the negative AdS

[1]Large extra dimension scenarios were originally introduced to solve the electroweak hierarchy problem [9–11].

vacuum energy $\Lambda \to 0$, with α a positive constant of $\mathcal{O}(1)$. In [13] also some implications of the AdS distance conjecture for de Sitter space were discussed, namely, when assuming this scaling behavior to hold in dS (or quasi dS) space with a positive cosmological constant, approaching $\Lambda = 0$ will also lead to an unbounded number of massless modes.

To each tower we can associate two mass scales: m, which is the mass scale of states in the tower, and $\hat{M}$, which is the scale local EFT description breaks down. The latter is the so-called "species scale" [14,15] that corresponds to the Planck scale of the higher dimensional theory, $\hat{M} = m^{n/(n+2)} M_{\rm Pl}^{2/(n+2)}$, where n is the number of effective dimensions decompactifying. Requiring the experimental bound on deviations from Newton's gravitational inverse-square law [16] to be consistent with the theoretical bound from the swampland conjectures leads to $\alpha = 1/4$ and so the mass scale of the KK modes in the tower is estimated to be $m \sim \lambda^{-1} \Lambda^{1/4}$. Consistency with neutron star heating [17] yields $n = 1$ [8], whereas consistency with the sharp cutoff observed in the cosmic ray spectrum requires $\lambda \sim 10^{-3}$ [18]. On the whole, swampland considerations combined with observational data lead to the prediction of a single extra mesoscopic dimension of length $R \sim \lambda \Lambda^{-1/4} \sim 1$ μm, where $\Lambda^{1/4} = 2.31$ meV. This extra dimension, nicknamed the dark dimension, opens up at the scale m of the tower, where physics must be described by an EFT in higher dimensions up to the species scale $\hat{M} \sim 10^{10}$ GeV.

In this paper we study some phenomenological aspects of black holes perceiving the dark dimension and, in the spirit of [19], we investigate the impact of these higher dimensional objects in assessing the fraction of dark matter that could be composed of primordial black holes, $f_{\rm PBH}$. The layout of the paper is as follows. We begin in Sec. II with an overview of existing limits on $f_{\rm PBH}$. This includes constraints from the isotropic photon backgrounds, observations of the cosmic microwave background (CMB), and measurements of the positron density at the Galactic bulge. In Sec. III we first reexamine the rate of Hawking radiation of five-dimensional black holes with the new species scale in mind, and after that we confront our predictions to experiment. In Sec. IV we reexamine within the 5D theory whether black holes evaporating right now could be responsible for the excess of 511 keV photons observed from the inner Galaxy by the SPI spectrometer on board the INTEGRAL satellite [20,21]. In Sec. V we discuss the possibility for primordial black holes to grow via the accretion. The paper wraps up with some conclusions presented in Sec. VI. Before proceeding, we pause to note that a specific realization of the model proposed in [8] should guarantee that the SM interacts with the extra dimension only gravitationally, while the cosmological constant scale is fixed by the size of the extra dimension. Although *a priori* this does not seem obvious at all, we continue here on the assumption that such a realization can indeed emerge from string theory.

II. PRIMORDIAL BLACK HOLES AS A DARK MATTER CANDIDATE

It has long been suspected that black holes could emerge from the collapse of large amplitude fluctuations in the very early universe [22–25]. Although the mass spectrum of these primordial black holes (PBHs) is not set in stone, on cosmological scales they would behave like a typical cold dark matter particle. Actually, the idea that PBHs could be interesting dark matter candidates dates back at least as far as 1975 [26], with punctuated revivals of activity following the microlensing searches for massive compact halo objects (MACHOs) in 1997 [27], and the LIGO/Virgo detections of merging binary black holes in 2016 [28]. The first microlensing searches suggested that dark matter could be composed of MACHOs with mass $\sim 0.5\ M_\odot$, which is the expected mass scale for PBHs produced during the quark-hadron phase transition [29]. However, more recent observations exclude significant contributions of MACHOs to dark matter over most of the plausible mass range [30–36]. The question of whether the LIGO/Virgo merger events correspond to black holes of astrophysical or primordial origin is still under debate [37–39], and a mixed population may also be compatible with observations [40]. However, data suggest that the binary black hole merging rate is incompatible with an all-dark-matter scenario and that PBHs could only contribute to less than 1% of the total dark matter [41,42].

The mass distribution of PBHs is usually characterized by the mass function

$$\psi(M_{\rm BH}) = \frac{M_{\rm BH}}{\rho_{\rm CDM}} \frac{dn_{\rm PBH}}{dM_{\rm BH}}, \tag{1}$$

where $M_{\rm BH}$ is the black hole mass, $dn_{\rm PBH}$ is the number density of PBHs within the mass range $(M_{\rm BH}, M_{\rm BH} + dM_{\rm BH})$, and $\rho_{\rm CDM}$ is the energy density of cold dark matter [43]. Integrating $\psi(M_{\rm BH})$ gives the total fraction of dark matter in PBHs,

$$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}}{\rho_{\rm CDM}} = \int \psi(M_{\rm BH}) dM_{\rm BH}, \tag{2}$$

where $\rho_{\rm PBH} = \int M_{\rm BH} dn_{\rm PBH}$ is the energy density of PBHs. If all of the dark matter were made of PBH, we would have $f_{\rm PBH} = 1$. A compilation of upper limits on the dark matter fraction that can be composed of PHBs is shown in Fig. 1.

The question we want to address herein is whether primordial black holes perceiving the dark dimension could ameliorate the constraints on $f_{\rm PBH}$ shown in Fig. 1. In terms of the size of the extra dimension R and the string length l_s, we can distinguish three definite regimes for the black hole

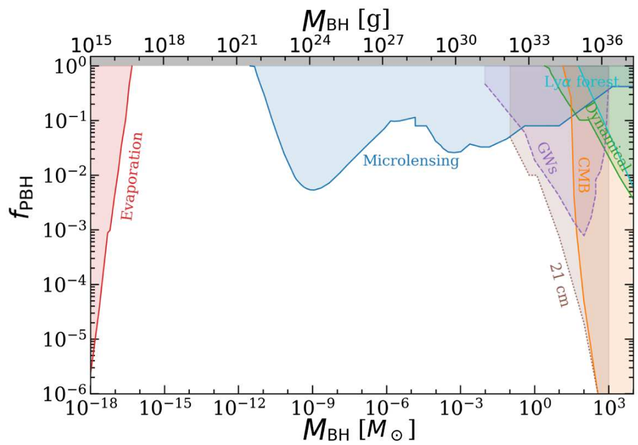

FIG. 1. (Taken from [44].) Compilation of contraints on $f_{\rm PBH}$ as a function of the PBH mass $M_{\rm BH}$, assuming a monochromatic mass function. The different probes considered are the impact of PBH evaporation (red) on the extragalactic γ-ray background [45] and on the CMB spectrum [46]; nonobservation of microlensing events (blue) from the MACHO [31], EROS [32], Kepler [33], Icarus [34], OGLE [35] and Subaru-HSC [36] Collaborations; PBH accretion signatures on the CMB (orange), assuming spherical accretion of PBHs within halos [47]; dynamical constraints, such as disruption of stellar systems by the presence of PBHs (green), on wide binaries [48] and on ultrafaint dwarf galaxies [49]; power spectrum from the Lyα forest (cyan) [50]; merger rates from gravitational waves (purple), either from individual mergers [42,51] or from searches of stochastic gravitational wave background [52]. Gravitational wave limits, denoted by dashed lines, are model dependent [53]. The dotted brown line corresponds to forecasts from the 21 cm power spectrum with SKA sensitivities [54] and from 21 cm forest prospects [55].

horizon r_s: (i) $r_s > R$, where the theory looks like 4D and $r_s \simeq M_{\rm BH}$; (ii) $l_s < r_s < R$, where the black hole perceives the higher dimensional space; (iii) $r_s < l_s$, where the black hole turns into a string state [56,57]. In our analysis, only the regime (ii) will be relevant, i.e., we will study black holes that are smaller than the size of the extra dimension, but larger than the string size.

III. RADIATION TIMESCALE OF FIVE-DIMENSIONAL BLACK HOLES

PBHs will Hawking evaporate, provided the semiclassical approximation is valid. The average number [58,59] and the probability distribution of the number [60–62] of outgoing particles in each mode obey a thermal spectrum, with temperature [63]

$$T_{\rm BH} = \frac{n+1}{4\pi r_s} \tag{3}$$

and entropy

$$S = \frac{4\pi M_{\rm BH} r_s}{n+2}, \tag{4}$$

where

$$r_s(M_{\rm BH}) = \frac{1}{M_{{\rm Pl},n}} \left[\frac{M_{\rm BH}}{M_{{\rm Pl},n}} \frac{2^n \pi^{(n-3)/2} \Gamma(\frac{n+3}{2})}{n+2}\right]^{1/(1+n)} \tag{5}$$

is the radius of a $(4+n)$-dimensional Schwarzschild black hole,

$$M_{{\rm Pl},n} = \left(\frac{m^n M_{\rm Pl}^2}{8\pi}\right)^{1/(n+2)}, \tag{6}$$

and where $\Gamma(x)$ is the Gamma function [64].

The black hole, however, produces an effective potential barrier surrounding the event horizon that backscatters part of the outgoing radiation, making alterations to the Planckian spectrum. The black hole absorption cross section, σ_s (a.k.a. the greybody factor), depends on (i) the spin s of particle being emitted, (ii) the particle's energy Q, and (iii) $M_{\rm BH}$ [65]. At high frequencies ($Q r_s \gg 1$) the greybody factor for each kind of particle must approach the geometrical optics limit. The integrated power emission is reasonably well approximated taking such a high energy limit. In our calculations we adopt the geometric optics approximation, where the black hole acts as a perfect absorber of a slightly larger radius, with emitting area given by

$$A_{4\subset 4+n} = 4\pi \left(\frac{n+3}{2}\right)^{2/(n+1)} \frac{n+3}{n+1} r_s^2. \tag{7}$$

Within this framework, we can conveniently write the greybody factor as a dimensionless constant normalized to the black hole surface area seen by the SM fields $\Gamma_s = \sigma_s / A_{4\subset 4+n}$, such that $\Gamma_{s=0} = 1$, $\Gamma_{s=1/2} \approx 2/3$, and $\Gamma_{s=1} \approx 1/4$ [66].

All in all, a black hole emits particles with initial total energy between $(Q, Q+dQ)$ at a rate

$$\frac{d\dot{N}_i}{dQ} = \frac{\sigma_s}{8\pi^2} Q^2 \left[\exp\left(\frac{Q}{T_{\rm BH}}\right) - (-1)^{2s}\right]^{-1} \tag{8}$$

per degree of particle freedom i. The change of variables $u = Q/T$, brings Eq. (8) into a more familiar form,

$$\dot{N}_i = f \frac{\Gamma_s}{32\pi^3} \frac{(n+3)^{(n+3)/(n+1)}(n+1)}{2^{2/(n+1)}} T_{\rm BH} \times \int \frac{u^2}{e^u - (-1)^{2s}} du. \tag{9}$$

This expression can be easily integrated using

$$\int_0^\infty \frac{z^{n-1}}{e^z - 1} dz = \Gamma(n)\zeta(n) \tag{10}$$

and

$$\int_0^\infty \frac{z^{n-1}}{e^z+1}dz = \frac{1}{2^n}(2^n-2)\Gamma(n)\zeta(n), \quad (11)$$

yielding

$$\dot{N}_i = f\frac{\Gamma_s}{32\pi^3}\frac{(n+3)^{(n+3)/(n+1)}(n+1)}{2^{2/(n+1)}}\Gamma(3)\zeta(3)T_{\rm BH}, \quad (12)$$

where $\zeta(x)$ is the Riemann zeta function and $f = 1$ ($f = 3/4$) for bosons (fermions). Therefore, the black hole emission rate is found to be

$$\dot{N}_i \approx 3.7\times 10^{21}\frac{(n+3)^{(n+3)/(n+1)}}{2^{2/(n+1)}(n+1)^{-1}}\left(\frac{T_{\rm BH}}{\rm GeV}\right)\ {\rm s}^{-1}, \quad (13)$$

$$\dot{N}_i \approx 1.8\times 10^{21}\frac{(n+3)^{(n+3)/(n+1)}}{2^{2/(n+1)}(n+1)^{-1}}\left(\frac{T_{\rm BH}}{\rm GeV}\right)\ {\rm s}^{-1}, \quad (14)$$

$$\dot{N}_i \approx 9.2\times 10^{20}\frac{(n+3)^{(n+3)/(n+1)}}{2^{2/(n+1)}(n+1)^{-1}}\left(\frac{T_{\rm BH}}{\rm GeV}\right)\ {\rm s}^{-1}, \quad (15)$$

for particles with $s = 0, 1/2, 1$, respectively [67].

At any given time, the rate of decrease in the black hole mass is just the total power radiated

$$\frac{\dot{M}_{\rm BH}}{dQ} = -\sum_i c_i\frac{\sigma_s}{8\pi^2}\frac{Q^3}{e^{Q/T_{\rm BH}}-(-1)^{2s}}, \quad (16)$$

where c_i is the number of internal degrees of freedom of particle species i. A straightforward calculation yields

$$\dot{M}_{\rm BH} = -\sum_i c_i\tilde{f}\frac{\Gamma_s}{32\pi^3}\frac{(n+3)^{(n+3)/(n+1)}(n+1)}{2^{2/(n+1)}}\Gamma(4)\zeta(4)T_{\rm BH}^2, \quad (17)$$

where $\tilde{f} = 1$ ($\tilde{f} = 7/8$) for bosons (fermions). Herein, we assume that the effective high energy theory contains approximately the same number of modes as the SM (i.e., $c_{s=0} = 1$, $c_{s=1/2} = 90$, and $c_{s=1} = 27$) and we neglect the effect of graviton emission.[2]

[2]A point worth noting at this juncture is that at first sight it may appear that the KK modes must dominate Hawking radiation because there are a large number—$\mathcal{O}(R/r_s)^2$—light modes with masses below the $T_{\rm BH}$ scale. However, as noted in [68] it is incorrect to think of the individual KK modes of the bulk graviton as massive spin two fields on the brane with standard (minimal) gravitational couplings. Rather, since the KK modes are excitations in the full transverse space, their overlap with the small (higher-dimensional) black holes is suppressed by the geometric factor $(r_s/R)^2$ relative to the brane fields. Thus, the geometric suppression precisely compensates for the enormous number of modes, and the total contribution of all KK modes is only the same order as that from a single brane field.

A. Black hole radiation rate for $n = 0$

The rate of Hawking radiation is estimated to be

$$\left.\frac{dM_{\rm BH}}{dt}\right|_{n=0} \simeq -9\times 10^{73}\ {\rm GeV}^4\frac{1}{M_{\rm BH}^2}. \quad (18)$$

Ignoring accretion and thresholds, i.e., assuming that the mass of the black hole evolves according to Eq. (18) during the entire process of evaporation, we can obtain an estimate for the lifetime of the black hole,

$$\tau_{\rm BH}^{n=0} \simeq 1\times 10^{-74}\ {\rm GeV}^{-4}\int M_{\rm BH}^2 dM_{\rm BH}. \quad (19)$$

Using $\hbar = 6.58\times 10^{-25}$ GeV s, Eq. (19) can then be rewritten as

$$\tau_{\rm BH}^{n=0} \simeq 1.6\times 10^{-35}(M_{\rm BH}/{\rm g})^3\ {\rm yr}. \quad (20)$$

Note that a black hole with $M_{\rm BH} \sim 5\times 10^{14}$ g will have a lifetime of about 2 Gyr, comparable to the age of the Universe [69,70]. Therefore, PBHs with $M_{\rm BH} \lesssim 5\times 10^{14}$ g cannot form part of the observed dark matter density. PBHs with masses small enough, but still *alive* in the Universe, should emit strong photon and cosmic ray backgrounds which could be observed [71,72]. Null results from detection of these backgrounds exclude an all dark matter interpretation in terms of PBHs for masses $M_{\rm BH} \lesssim 10^{17}$ g. As shown in Fig. 1, the allowed mass range for the PHB dark matter interpretation is $10^{17} < M_{\rm BH}/{\rm g} \lesssim 10^{21}$.

B. Black hole radiation rate for $n = 1$

We now assume the black hole can be treated as a flat $(4+n)$-dimensional object. This assumption is valid for extra dimensions that are larger than the Schwarzschild radius [19]. For $M_{{\rm Pl},n} \sim 10^{10}$ GeV, the rate of Hawking radiation is estimated to be

$$\left.\frac{dM_{\rm BH}}{dt}\right|_{n=1} \simeq -4\times 10^{29}\ {\rm GeV}^3\frac{1}{M_{\rm BH}}, \quad (21)$$

and so

$$\tau_{\rm BH}^{n=1} \simeq 3\times 10^{-30}\ {\rm GeV}^{-3}\int M_{\rm BH}dM_{\rm BH}, \quad (22)$$

which implies

$$\tau_{\rm BH}^{n=1} \simeq 9\times 10^{-15}(M_{\rm BH}/{\rm g})^2\ {\rm yr}. \quad (23)$$

For $n = 1$, a black hole lives longer than a usual $n = 0$ black hole of the same mass. A black hole with $M_{\rm BH} \sim 5\times 10^{11}$ g has a lifetime approximately equal to the age of the Universe.

As shown in Fig. 1, PBHs in the 4D theory with $10^{15} \lesssim M_{\rm BH}/{\rm g} \lesssim 10^{17}$ are incompatible with an all-dark-matter interpretation. However, black holes sensing the dark dimension slow down the Hawking radiation. For a given mass, the black hole lives longer in the 5D theory than in the 4D theory. This implies that black holes sensing the extra mesoscopic dimension emit less particles and so the limits from isotropic photon backgrounds [71,72], CMB observations [73,74], and measurements of the positron density at the Galactic bulge [75,76] can be relaxed. Via a direct comparison of our calculations with the limits shown in Fig. 1 we can conclude that an all-dark-matter interpretation in terms of PBHs in the 5D theory should be feasible for $10^{14} \lesssim M_{\rm BH}/{\rm g} \lesssim 10^{21}$, thus extending the allowed mass range by 3 orders of magnitude.

Three observations are in order: (i) The temperature of PBHs evaporating today may not be enough to emit all the SM degrees of freedom. Herein we are interested in the order of magnitude estimate and we take this to fall within errors. (ii) The lack of femtolensing detection in the gamma-ray burst data have been interpreted as evidence that PBHs in the mass range $5 \times 10^{17} < M_{\rm BH}/{\rm g} < 10^{20}$ cannot constitute a major fraction of dark matter. This interpretation, however, has been disputed [77]. (iii) For $M_{\rm BH} \sim 5 \times 10^{11}$ g, the Schwarzschild radius is $r_s \sim 5 \times 10^{-5}$ μm, whereas for $M_{\rm BH} \sim 10^{17}$ g, we have $r_s \sim 2 \times 10^{-2}$ μm, justifying our assumption that these black holes are five-dimensional objects. It is noteworthy that a black hole with $M_{\rm BH} \sim 1 \times 10^{21}$ g has a horizon radius $r_s \sim 2$ μm, saturating the range of validity of our 5D description. In Fig. 2 we illustrate how the longer lifetime of PBH perceiving the mesoscopic-scale extra dimension modifies the constraints on $f_{\rm PBH}$. Moreover, the Hawking temperature of the lightest PBHs evaporating today, with $M_{\rm BH} \sim 10^{12}$ g, is roughly 1 MeV. For this mass scale, Hawking radiation could potentially explain the well-known Galactic 511 keV gamma-ray line. It is this that we now turn to study.

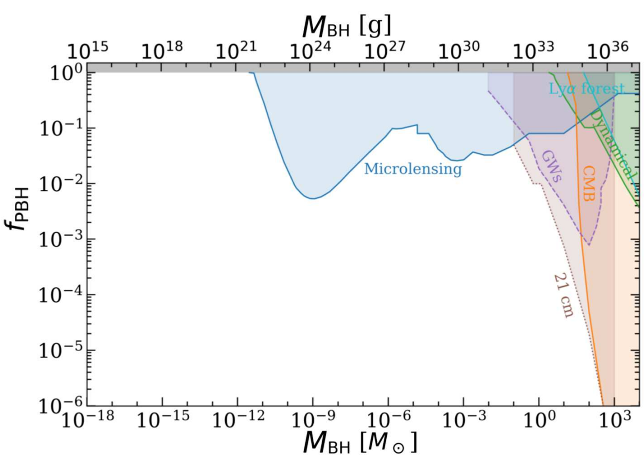

FIG. 2. Compilation of constraints on $f_{\rm PBH}$ in the 5D theory as a function of the PBH mass $M_{\rm BH}$, assuming a monochromatic mass function. See Fig. 1 for details of the different probes considered.

IV. A NEW PBH WINDOW FOR EXPLAINING THE GALACTIC 511 keV LINE

It has long been known that electron-positron annihilation proceeds at a surprisingly high rate in the central region of the Galaxy [78]. In particular, the SPI spectrometer on the INTEGRAL satellite has detected an intense 511 keV gamma ray line flux aligned with the Galactic center (bulge component) [20,21], and also provided evidence for the line in the disk or halo component [79].

A variety of potential astrophysical sources explaining this signal have been proposed [80], including PHBs [81,82]. The source of positrons responsible for the 511-keV line must generate $\mathcal{O}(10^{50})$ positrons per year [83]. However, if these positrons are injected at even mildly relativistic energies, higher-energy gamma rays will also be produced. Diffuse Galactic gamma-ray data strongly constrain the positron injection energy to be $\lesssim 3$ MeV [84]. Another key constraint comes from the local e^+e^- flux as measured by Voyager 1 [85].

In the 4D theory the black temperature scales as

$$T_{{\rm BH},4D} \simeq 1.05 \left(\frac{M_{\rm BH}}{10^{16}\ {\rm g}}\right)^{-1} {\rm MeV}. \tag{24}$$

Herein we are particularly interested in black holes with masses above the evaporation limit. In this mass range, PBHs are Hawking evaporating today, emitting particles with a characteristic spectrum centered around tens of MeV. Note that most of these PBHs would be excluded by Galactic gamma-ray observations.

In the 5D theory discussed herein, PBHs evaporating today are bigger, longer-lived, and colder than in the 4D theory; the PBH temperature scales as

$$T_{{\rm BH},5D} \sim \left(\frac{M_{\rm BH}}{10^{12}\ {\rm g}}\right)^{-1/2} {\rm MeV}. \tag{25}$$

In the most recent data analysis it was shown that in 4D theory primordial black holes in mass range of $1 < M_{\rm BH}/10^{16}\ {\rm g} < 4$ could potentially produce the 511 keV gamma-ray signal if $10^{-4} < f_{\rm PBH} < 4 \times 10^{-3}$ [86]. This study takes into account the gamma-ray fluxes measured by INTEGRAL in the 0.1–0.2, 0.2–0.6, 0.6–1.8 MeV bands, and by COMPTEL in the 1–3, 3–10, 10–30 MeV bands, as well as the local Voyager constraint on the flux of e^+e^-. Remarkably, the regions of parameter space in which PBHs could accommodate the observed 511-keV excess require a PBH number density in the vicinity of the Solar System of

$$n_{\rm PBH}^{\rm local} = \frac{f_{\rm PBH}\rho_{\rm DM}^{\rm local}}{M_{\rm BH}} \simeq 1.2\times 10^{-4}\ {\rm AU}^{-3} \times \left(\frac{f_{\rm PBH}}{10^{-3}}\right)\left(\frac{M_{\rm BH}}{2\times 10^{16}\ {\rm g}}\right)^{-1}, \qquad (26)$$

where $\rho_{\rm DM}^{\rm local} = 0.4\ {\rm GeV/cm}^3$ is the local dark matter density [86]. Since we have seen that black holes in the 5D theory with temperature of 1 MeV have masses roughly 4 orders of magnitude smaller, to a first approximation a simple rescaling of the result of (26) while demanding the same number density suggests that an interpretation of the 511-keV line would be, in principle, possible for $f_{\rm PBH} \sim 10^{-7}$.

As already noted in [86], for such particular number density, the closest PBH would be located at a distance

$$d \sim \left(\frac{3}{4\pi n_{\rm PBH}^{\rm local}}\right)^{1/3} \sim \mathcal{O}(10\ {\rm AU}). \qquad (27)$$

This suggests that the Solar System could contain several hundred black holes at any given moment and detectability of their Hawking evaporation could be at reach of future gamma-ray telescopes [87]. Moreover, e-ASTROGAM [88] would not only be able to detect the Hawking radiation from a PBH population responsible for the 511 keV excess, it would be able to characterize the properties of such a population with remarkable precision [87]. A simultaneous study of the allowed $(M_{\rm BH}, f_{\rm PBH})$ parameter space could then be used to disentangle a PBH evaporating in four dimensions from one evaporating in five dimensions.

V. BLACK HOLE GROWTH BY ACCRETION

In Sec. III we estimated the black hole lifetime assuming that black holes do not accrete. In general, the net change of the black hole mass is given by

$$\frac{dM_{\rm BH}}{dt} = \frac{dM_{\rm BH}}{dt}\bigg|_{\rm accr} + \frac{dM_{\rm BH}}{dt}\bigg|_{\rm evap}, \qquad (28)$$

where $dM_{\rm BH}/dt|_{\rm evap}$ is given by Eq. (17) and

$$\frac{dM_{\rm BH}}{dt}\bigg|_{\rm accr} \approx \pi\left(\frac{n+3}{2}\right)^{2/(n+1)} \frac{n+3}{n+1} r_s^2 \varepsilon, \qquad (29)$$

where ε is the energy density of the plasma in the vicinity of the event horizon [89]. Note, however, that any correction from the $dM_{\rm BH}/dt|_{\rm accr}$ term will tend to enlarge the black hole lifetime, and so the conclusions presented in Sec. III would still hold.

The mesoscopic-size dimension imposes generic constraints on the production of PBHs. Namely, as in the context of large extra dimensions [90,91], the universe should remain 4D at the nucleosynthesis MeV temperature, even if the compactification scale is much smaller (at meV). This is attributed to the stabilization of the extra dimension which should happen actually even before the reheating temperature. This of course assumes that the inflation mechanism can be re-adapted in a higher dimensional theory and implements also the stabilization. Hence, the 5D PBHs should be produced after inflation but before reheating.

Since black holes and dark matter are diluted by cosmic expansion in the same way, in the absence of accretion and decay the PBH mass function given in (1) is a constant over time. Although a precise characterization of $\psi(M_{\rm BH})$ is beyond the scope of this paper, we note that the bigger, longer-lived, and colder 5D black holes are more prompted to growth through accretion than those in the 4D theory. As noted in [92] PBHs may accrete and increase their mass by several orders of magnitude. Moreover, accretion may play a critical role in explaining the LIGO-VIRGO events in terms of PBHs [93]. However, we stress once more that the 5D description breaks down for $M_{\rm BH} \gtrsim 10^{-12}\ M_\odot$, and so while the 5D enhanced accretion effects could influence $\psi(M_{\rm BH})$ in the golden window of black-hole mass range ($10^{14} \lesssim M_{\rm BH}/{\rm g} \lesssim 10^{21}$) where PBHs can account for all of the dark matter content of the Universe, it will play a negligible role in the mass growth of $M_\odot$-scale black holes.

VI. CONCLUSIONS

We have studied some phenomenological aspects of black holes perceiving the dark dimension and analyzed the impact of these higher dimensional objects in assessing the fraction of dark matter that could be composed of PBHs. We have shown that the rate of Hawking radiation slows down for five-dimensional black holes and thereby an all-dark-matter interpretation in terms of PBHs for $10^{14} \lesssim M_{\rm BH}/{\rm g} \lesssim 10^{21}$ should be possible. We have also shown that an explanation of the Galactic 511-keV line could be possible for $M_{\rm BH} \sim 10^{12}$ g if $f_{\rm PBH} \sim 10^{-7}$. Of course, for a PBH distribution that peaks at $M_{\rm BH} \sim 10^{15}$ g, one can, in principle, obtain a simultaneous all-dark-matter interpretation, with an explanation of the Galactic 511 keV gamma-ray signal. These results are strongly dependent on the choice of $M_{{\rm Pl},n}$ and to a lesser degree on the behavior of σ_s with Q.

It is interesting to note that a rotating black hole would first shed its spin radiating particles, dominantly in the equatorial plane. Roughly 25% of its mass is lost in the so-called "spin down phase" [94]. Spin down leaves a Schwarzschild black hole which continues to Hawking radiate in the "Schwarzschild phase." Since the radiation temperature in the Schwarzschild phase is larger than the one in the spin-down phase [95], we conclude that existing limits on spinning PBHs [96] would also be relaxed. All in all, our results are also valid for PBHs produced with angular momentum.

It is also interesting to note that the black hole decay rate could be slowed down due to quantum effects, when compared to the semiclassical Hawking radiation adopted in our calculations [97]. These quantum corrections would become important if the black hole half-time is comparable to the age of the Universe.

In summary, within the 5D model proposed in [8], with a species scale at 10^{10} GeV, PBHs sensing the extra dimension would have a larger horizon radius, which scales as $M_{\mathrm{Pl},n}^{-(2+n)/(1+n)}$ as shown in (5). From (3) we see that a larger horizon radius in turn implies a smaller black hole temperature T_{BH}. Now, one can check in (17) that the Hawking radiation $\propto T_{\mathrm{BH}}^2$, and therefore the PBHs in the 5D theory live longer, automatically relaxing existing bounds on f_{PBH}. In conclusion, the PBHs as dark matter candidates could provide a complete picture for the swampland and its cosmology.

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