

Neutrinos from primordial black holes in theories with extra dimensions

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The quantum gravity scale within the dark dimension scenario ($M_* \sim 10^9$ GeV) roughly coincides with the energy scale of the KM3-230213A neutrino ($E_\nu \sim 10^8$ GeV). We propose an interpretation for this intriguing coincidence in terms of Hawking evaporation of five-dimensional (5D) primordial black holes (PBHs). 5D PBHs are bigger, colder, and longer-lived than 4D PBHs of the same mass. For brane observers, PBHs residing in the higher-dimensional bulk decay essentially invisibly (only through gravitationally and sterile coupled modes). As a consequence, constraints on the density of PBHs relative to that of dark matter from null searches of Hawking evaporation can be avoided. We demonstrate that Hawking evaporation of 5D bulk PBHs can explain the KM3-230213A neutrino, evade constraints from upper limits on the gamma-ray flux, and remain consistent with IceCube upper limits on the partial decay width of superheavy dark matter particles into neutrinos.

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I. INTRODUCTION

Scenarios with large extra dimensions offer the possibility to describe large hierarchies appearing in particle physics and cosmology [1–3]. Within these scenarios the Standard Model (SM) fields are confined to a three-dimensional (3D)-brane (our Universe), while gravity spills into the bulk of the compact space. In particular, the dark dimension scenario provides a framework to elucidate the origin of the cosmological hierarchy problem, because the anti-de Sitter distance conjecture in de Sitter space [4] connects the size of the compact space $R_\perp$ to the dark energy scale $\Lambda^{1/4}$ via $R_\perp \sim \lambda \Lambda^{-1/4}$, where $\Lambda \sim 10^{-120} M_p^4$ is the cosmological constant, M_p is the reduced Planck mass, and the proportionality factor is estimated to be $\lambda \sim 10^{-3}$ [3].¹ It is easily seen that if the compact space has a characteristic length-scale in the micron range, then the graviton tower of Kaluza-Klein (KK) excitations opens up

at the mass scale $m_{KK} \sim 1/R_\perp \sim \text{eV}$ and the 5D Planck scale (or species scale where gravity becomes strong [5–9]) is given by,

$$M_* \sim m_{KK}^{1/3} M_p^{2/3} \sim 10^9 \text{ GeV}. \quad (1)$$

Very recently, the KM3Net Collaboration reported the detection of the highest-energy neutrino ever observed, KM3-230213A [10]. The inferred neutrino energy lies in the range

$$10^{7.8} \lesssim E_\nu / \text{GeV} \lesssim 10^{8.9}. \quad (2)$$

A stunning coincidence is that the energy scale of this neutrino is just below the 5D Planck scale of the dark dimension scenario. In this paper we propose a possible association between these two scales. The proposed setup provides an explicit example of how black holes could serve as probes for UV physics closely connected to quantum gravity. This role of black holes actually emerges in the context of UV-IR mixing within the swampland program for quantum gravity [11].

Intriguingly, IceCube and the Pierre Auger Observatory have been operating with a much larger effective area than KM3Net for a considerably longer time, yet they have not

¹ $M_p \simeq 2.38 \times 10^{18} \text{ GeV} \simeq 4.33 \times 10^{-6} \text{ g}.$

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observed neutrinos with $E_\nu \gtrsim 10^{7.6}$ GeV [12,13]. This discrepancy challenges a cosmogenic neutrino origin for the KM3-230213A event. Furthermore, for a diffuse isotropic neutrino flux there is a 3.5σ tension between KM3Net and IceCube measurements, which reduces to about 2.6σ if the neutrino flux originates in transient sources [14–16].

To understand the origin of KM3-230213A, it is crucial to investigate consistency with multimessenger observations, especially constraints from gamma-ray experiments. Astrophysical sources of high-energy neutrinos would also produce a bright gamma-ray signal. Since there is no convincing evidence of gamma-rays accompanying KM3-230213A constraints can be placed on a combination of the source redshift and the intergalactic magnetic field strength between the source and Earth [17,18]. In addition, the absence of a gamma-ray signal challenges scenarios in which KM3-230213A has a Galactic origin, e.g., through the decay of dark matter clustered in the halo.

Along this line, a particularly interesting source of KM3-230213A could be the rapid, violent emission of energetic Hawking radiation [19,20] from a primordial black hole (PBH) near the end of its evaporation lifetime [21,22]. The Hawking lifetime of a 4D primordial black hole of initial mass M can be expressed as

$$\tau_H \sim S r_s \sim \frac{M^3}{M_p^4}, \quad (3)$$

where $S \sim (M/M_p)^2$ is the entropy of the black hole and $r_s \sim M/M_p^2$ its Schwarzschild radius. The black hole temperature is estimated to be [23]

$$T \sim \frac{1}{r_s} \sim M_p \frac{M_p}{M}. \quad (4)$$

Now, Eq. (3) tells us that only PBHs with an initial mass $M \gtrsim 10^{14.5}$ g could survive the current age of the Universe, $\tau_{\text{universe}} \sim 10^{17}$ s. In addition, Eq. (4) tells us that black holes of mass $M \sim 10^5$ g would Hawking radiate at $T \sim 10^8$ GeV, i.e., within the range given in (2).

The final stage emission is dictated by particle physics [24]. Following [22] we assume the degrees of freedom of the particle to be those of the SM, even at very high temperatures. This implies that the black hole would evaporate at a rate of $\gamma \div \nu = 1 \div 3$ into photons and neutrinos. Since the PBHs should be clustered in the Galactic halo the electromagnetic signal cannot be absorbed en route to Earth. Thus, the null result on photons searches carries in itself a serious challenge for the interpretation of KM3-230213A in terms of PBHs evaporating today. Besides, the energy injection through Hawking evaporation has been used to put strong constraints on primordial black holes as a dark matter candidate. An all dark matter

interpretation in terms of PBHs is only possible in the asteroid-mass window: $10^{17} \lesssim M/\text{g} \lesssim 10^{21}$, see e.g., [25–27].

Analogous proposals for the origin of KM3-2313A [28,29] rely on the assumption that PBHs experience the memory burden effect [30,31], according to which the “burden” of memory (essentially the quantum information stored inside the black hole) resists further decay by making it energetically unfavorable to offload that information. The lifetime of a burdened black hole is expected to be prolonged by the extra powers of the initial entropy

$$\tau_B \sim S^{1+k} r_s, \quad (5)$$

where k is a positive integer [32]. For $k = 1$, the rate of black evaporation coincides with the total decay width of particle species [33]. However, the $k = 1$ scenario is severely constrained by observations [34–38]. To accommodate the explanation of KM3-230213A one needs to rely on larger values of k , which are more contrived.

A seemingly different, but in fact closely related, subject is the inclusion of bulk right-handed neutrinos in theories with large extra dimensions. The presence of these SM singlets can naturally explain small 4D Dirac masses for the active neutrinos [39–41]. Besides, adding a sterile neutrino generation in the correct mass range to the SM could help ameliorate anomalies of neutrino oscillation experiments that cannot be explained by the standard three neutrino picture [42]. In this article, we demonstrate that 5D PBH evaporation into such a sterile state provides an economic way to explain the KM3-230213A neutrino event without conflicting with gamma-ray observation limits.

The layout of the paper is as follows. In Sec. II we summarize the generalities of sterile-active neutrino oscillations in scenarios with large extra dimensions. Along the way, we also briefly discuss the possibility of sterile neutrinos taking shortcuts in extra dimensions, which leads to distinct oscillation signatures [43]. In Sec. III we describe our model in detail and define its parameter space. After that we take benchmark points of this space to demonstrate (provide proof of concept) that 5D PBH evaporation can explain the origin of KM3-230213A. The paper wraps up with some conclusions presented in Sec. IV.

II. STERILE-ACTIVE OSCILLATION WITH SHORTCUT THROUGH EXTRA DIMENSION

A light sterile neutrino with a mass ~ 1 eV continues to be interesting because of multiple clues from terrestrial experiments [42]. This hypothesis, however, suffers from strong constraints from IceCube data [44] and is in tension with cosmological observations [45]. Consistency with the most restrictive bounds from IceCube data requires $\Delta m_{14}^2 \sim 1 \text{ eV}^2$ and $\sin^2(2\theta_{24}) \sim 10^{-2}$, where $\Delta m_{ij}^2 = m_i^2 - m_j^2$ describes the mass difference between neutrino mass eigenstates i , j , and θ_{ij} define how much these

mass eigenstates mix to form neutrino flavors, with $i = 1, 2, 3$, and 4 [44].

Beyond this observational dilemma, the mechanism behind neutrino masses remains unknown. A compelling explanation emerges from models featuring flat large extra dimensions [39–41]. Within these models right-handed neutrinos are allowed to propagate in the higher-dimensional bulk. The large volume of the extra dimensions causes a suppression of the Yukawa couplings, which naturally produces light Dirac neutrinos. A key by-product of this framework is the appearance of a KK neutrino tower. The masses of these KK states are inversely proportional to the compactification radius. In the dark dimension scenario, with $R_\perp$ around a micrometer, the KK states could mix with the SM neutrinos [46,47]. Actually, when it comes to mixing with active SM neutrinos, it is only the lower mass states of the tower that play a relevant role. Besides, the addition of bulk masses suppresses the mixing of the first KK modes to active neutrinos allowing such models to remain consistent with experimental data [48,49].

Motivated by the preceding discussion, herein we adopt a minimalistic approach and consider the extension of the SM by one sterile neutrino propagating into the bulk. For the considerations in the present work, the active-sterile oscillation can be safely approximated by a two-state system. We take as benchmark a mass-squared splitting $\delta m^2 \sim 1$ eV and we set the mixing angle to $\theta \sim 10^{-2}$.

Two possibilities emerge in the extradimensional brane-world scenario [43]. On the one hand, if the brane is rigid and flat in its embedding, then the geodesic of the sterile neutrino is the same as the geodesic of the active neutrino on the brane. On the other hand, if the brane is allowed to fluctuate in its embedding, then the sterile neutrino may have a different trajectory, with a shorter geodesic than that of the active neutrino constrained to the brane, see Fig. 1. This implies that if the active neutrino propagates on a nonrigid brane there are two sources of phase difference causing oscillation: (i) the usual kinematic one coming from the neutrino mass-squared difference, and (ii) a geometric one coming from the difference in travel times of the sterile neutrino through the bulk relative to the active neutrino confined to the brane. The two phase differences may beat against one another to produce resonant phenomena.

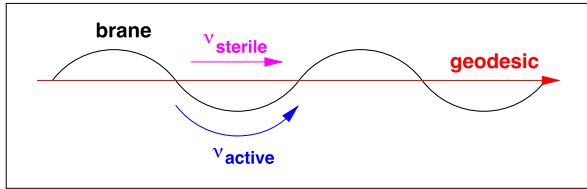


FIG. 1. Schematic representation of the propagation of a sterile neutrino through a geodesic in the bulk and an active neutrino confined to the brane [43].

For neutrinos of energy E_ν , the effective two-flavor mixing angle is given by

$$\sin^2(2\tilde{\theta}) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + \cos^2(2\theta)[1 - (E_\nu/E_{\text{res}})^2]^2}, \quad (6)$$

where

$$E_{\text{res}} = \sqrt{\frac{\delta m^2 \cos(2\theta)}{2\epsilon}}, \quad (7)$$

denotes the resonance energy, δm^2 is the mass square difference between the sterile and active neutrino states, θ is the usual active-sterile mixing angle (for a rigid brane) and $\epsilon = \delta t/t$ is the shortcut parameter, defined as the normalized difference of propagation times on the brane and in the bulk [43]. Since the value of ϵ is unknown, the resonance energy could have almost any value, *a priori*. If the KM3-230213A event was amplified through a resonant enhancement, then $\epsilon \sim 5 \times 10^{-35}$. In our calculations we adopt this value. This parameter value has to be eventually explained in a theory of brane dynamics. Such an explanation exceeds the limitations of our phenomenological analysis and is reserved for future work.

In Fig. 2 we show $\sin^2(2\tilde{\theta})$ for $\theta \sim 10^{-2}$ as a function of energy. For energies much larger than the resonance energy E_{res} , the sterile state decouples from the active state, as $\sin^2(2\tilde{\theta}) \rightarrow 0$. For energies much smaller than E_{res} , the effective active-sterile mixing angle is suppressed unless a significant mixing between the active and sterile states occurs. For $0.95 \lesssim E_\nu/(10^8 \text{ GeV}) \lesssim 1.05$, we have $\sin^2(2\tilde{\theta}) \gtrsim 0.04$.

Putting all the pieces together, the probability of sterile-active oscillation after a propagation distance D is given by

$$P_{sa} = \sin^2(2\tilde{\theta}) \sin^2(\delta H D / 2), \quad (8)$$

with

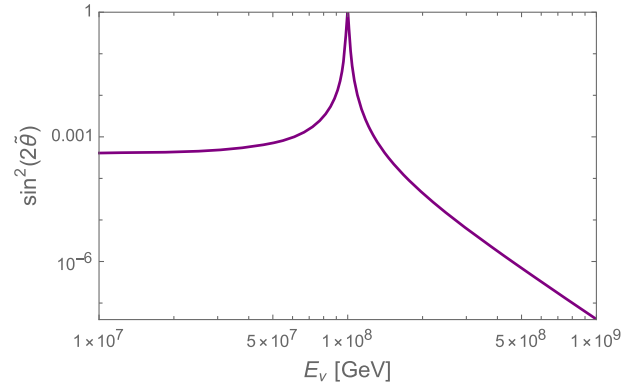


FIG. 2. Oscillation amplitude $\sin^2(2\tilde{\theta})$ as a function of the neutrino energy E_ν , for a resonance energy of $E_{\text{res}} = 10^8$ GeV.

$$\delta H = \frac{\delta m^2}{2E_\nu} \sqrt{\sin^2(2\theta) + \cos^2(2\theta) \left[1 - \left(\frac{E_\nu}{E_{\text{res}}} \right)^2 \right]^2}. \quad (9)$$

For $E_\nu \sim 10^8$ GeV, we have $\delta H \sim 8 \times 10^{-16} \text{ cm}^{-1}$. Therefore, for a travelling distance D in the parsec scale, the term $\sin^2(\delta H D/2)$ oscillates fast, and phase averaging then sets $\langle \sin(\delta H D/2) \rangle$ to zero and $\langle \sin^2(\delta H D/2) \rangle$ to $1/2$. All in all, for the energy range of interest $0.95 \lesssim E_\nu/(10^8 \text{ GeV}) \lesssim 1.05$, the oscillation probability between sterile and active states can be bounded from below: $P_{sa} \gtrsim 10^{-2}$.

III. 5D PBH EVAPORATION

Now, in light with our stated plan, we examine the evaporation of 5D PBHs within the context of the dark dimension. The PBHs perceiving the dark dimension are bigger, colder, and longer-lived than a usual 4D black hole of the same mass [50–53]. Indeed, the Schwarzschild radius of a d -dimensional black hole scales as [54]

$$r_s \sim \frac{1}{M_*} \left(\frac{M}{M_*} \right)^{1/(d-3)}, \quad (10)$$

whereas its temperature scales as

$$T \sim M_* \left(\frac{M_*}{M} \right)^{1/(d-3)}. \quad (11)$$

The black hole lifetime is estimated to be

$$\tau_H \sim S r_s = \frac{1}{M_*} \left(\frac{M}{M_*} \right)^{(d-1)/(d-3)}, \quad (12)$$

because its entropy scales as [55]

$$S \sim (M/M_*)^{(d-2)/(d-3)}. \quad (13)$$

Of particular interest here is the relative suppression of black evaporation into the brane compared to evaporation in the bulk. The in-brane to bulk phase space suppression factor can be approximated by $(\mathcal{T}/r_s)^{d-4}$, where $\mathcal{T} \sim 1/M_*$ is the 3-brane thickness that is relevant for SM excitations [56]. One can check by inspection of Fig. 3 that there should be a large suppression of the SM modes until the final-stage emission of the black hole when r_s approaches $\mathcal{T}$. Whether the PBH would emit or not into the brane also depends on whether the PBH stays attached to the brane as $r_s \rightarrow \mathcal{T}$ or if it can wander off into the transverse bulk of the dark dimension. Without model dependent assumptions of the bulk and brane theory it is not possible to calculate the probability of such wandering in detail. However, as r_s approaches $\mathcal{T}$, the recoil effect due to graviton emission may impart to the black hole a relative kick velocity with respect to the brane that would tend to

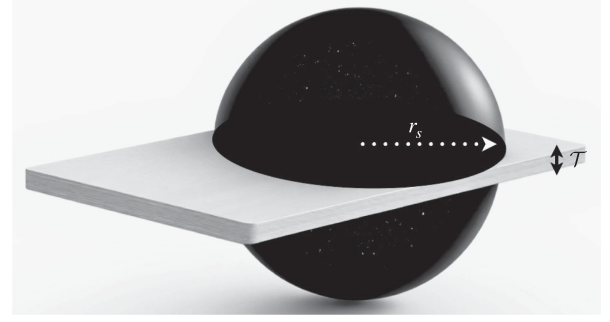


FIG. 3. Schematic representation of a 5D black hole localized on the brane.

make it escape into the bulk in the final stages of its life [57,58]. Actually, it is always possible that the PBH formed in the bulk to start with [59]. If this were the case, then the PBH would radiate in the bulk (off the brane), where it cannot emit any of the SM fields localized to the brane. In our calculations we implicitly assume that 5D PBHs are localized within the dark dimension, away from any branes.

At this stage, to develop some sense for the orders of magnitude involved, we make contact with experiment. The required number density of neutrinos for detection of one event per every hundred years in a km^2 -area detector can be approximated by

$$n_\nu \sim \frac{1}{A_{\text{eff}} t} \sim 10^{-30} \text{ cm}^{-3}, \quad (14)$$

where $A_{\text{eff}} \sim 1 \text{ km}^2$ is the KM3Net effective area [10] and where we have increased the KM3Net time of data taking t by a factor of 100 to accommodate the tension with IceCube observations (viz., IceCube has been taking data by about ten years with a factor of 10 larger effective area).

Now, using (11) it is straightforward to see that a 5D PBH near the end of its evaporation lifetime and today has a mass $M_* \sim 10^{11} \text{ GeV}$ would emit at a temperature of 10^8 GeV . Furthermore, using (13) it follows that such a PBH will almost instantaneously emit about $S \sim 10^3$ secondaries. The PBH emission is thermal in character, following a Planckian distribution with temperature T . The fraction of particles emitted in the energy interval (ΔE) of interest $0.95 \lesssim E/(10^8 \text{ GeV}) \lesssim 1.05$ is given by

$$f_{\Delta E} = \frac{\int_{0.95}^{1.05} \frac{x^2}{e^x - 1} dx}{\int_0^\infty \frac{x^2}{e^x - 1} dx} \sim 10^{-2}, \quad (15)$$

where $x = E/T$.

We assume that the bulk PBH emission consists of: five degrees of freedom of 5D dimensional graviton, six degrees of freedom of the right-handed neutrinos (and corresponding antineutrinos), and four degrees of freedom of the sterile Dirac fermion. Thus, 27% of the particles emitted by the black hole would be eV-scale sterile neutrinos. The total

number of such sterile states emitted per PBH in the range $0.95 \lesssim E_\nu / (10^8 \text{ GeV}) \lesssim 1.05$ is given by

$$\zeta_{\nu_s} \sim 0.27 S f_{\Delta E}. \quad (16)$$

After oscillation en route to Earth the number of active neutrinos is

$$\zeta_{\nu_a} \sim 0.27 S f_{\Delta E} P_{sa} \sim 0.027. \quad (17)$$

All told, the number density of these PBHs scales as

$$n_{\text{PBH}} \sim \frac{1}{\zeta_{\nu_a}} \frac{E_\nu}{M_*} n_\nu \sim 4 \times 10^{-32} \text{ cm}^{-3}. \quad (18)$$

Thus, the required energy density in PBHs to accommodate the KM3-230213A neutrino is estimated to be

$$\rho_{\text{PBH}} \sim M_* n_{\text{PBH}} \sim 4 \times 10^{-21} \text{ GeV/cm}^3. \quad (19)$$

By comparing (19) with the local dark matter density

$$\rho_{\text{DM}} \sim 0.4 \text{ GeV/cm}^3, \quad (20)$$

we estimate the fraction of PBH emitting neutrinos relative to the total dark matter density to be pocket sized,

$$f_{\text{PBH}} \equiv \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}} \sim 10^{-20}. \quad (21)$$

At this point it is pertinent to connect with IceCube searches of superheavy dark matter particles X decaying to neutrinos. The IceCube Collaboration reported lower limits on the lifetime of the X particles on the assumption that X 's are clustered in the Galactic halo and that the superheavy dark matter density saturates the dark matter density [60]. These null results can then be translated into a bound of the X partial decay width to neutrinos times the fraction of the superheavy dark matter relative to the total dark matter density [61]. For PBHs, the IceCube bound can be reinterpreted as

$$\Gamma_{\text{PBH}} f_{\text{PBH}} \lesssim 10^{-29.7} \text{ s}^{-1}, \quad (22)$$

where

$$\Gamma_{\text{PBH}} \sim 10^{-17} \left(\frac{M}{10^{10.4} \text{ g}} \right)^{-2} \text{ s}^{-1} \quad (23)$$

is the PBH decay width. To derive (23) we have used (12), taking the age of the Universe to be $\mathcal{O}(10^{17} \text{ s})$. When (21) and (23) are substituted into (22), the IceCube bound is straightforwardly satisfied.

At this stage, it is constructive to connect with contrasting and complementary perspectives to comment on caveats of our analysis. The expected signal from

Hawking emission is broad in energy, producing a wide primary spectrum of gravitons and sterile neutrinos. Nevertheless, as shown in Sec. II, a linelike feature would emerge via the resonant effect of neutrino oscillation if sterile states take shortcuts through the extra dimension. The suppression of the sterile-active oscillation at lower energies naturally depends θ . A slight adjustment to the mixing angle θ may be required to align with the observed data. However, we emphasize that a substantial region within the allowed parameter space could provide considerable flexibility for this adjustment, given that $f_{\text{PBH}} \sim 10^{-20}$ and $\Gamma_{\text{BH}} f_{\text{BH}} \sim 10^{-37}$ is more than eight orders of magnitude below the IceCube bound, where we have taken $M \sim 10^{10.4} \text{ g}$.

Besides, the most immediate impact of the discovery of astrophysical neutrinos is that the flux level observed is exceptionally high by astronomical standards. As a matter of fact, the magnitude of the flux measured with IceCube may be as large as $10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ around 30 TeV [62]. This finding leads directly to the inference that if sources of TeV-PeV neutrinos are transparent to γ rays, a strong tension with the isotropic diffuse γ -ray background measured by the *Fermi* satellite [63] becomes unavoidable—independently of the neutrino production mechanism [64]. Therefore, it is evident that the sources of the astrophysical neutrinos observed by IceCube must be hidden cosmic ray accelerators, in which neutrinos are produced through $\pi^\pm$ decay, but the photon emission from π^0 decay is absorbed by interactions at the source [64,65]. As a sharp reader might have noticed, the emitted radiation from evaporation of bulk PBHs resembles that of astrophysical hidden sources. A reliable estimate of the best fit parameters that can accommodate the high-energy ($\gtrsim 10 \text{ TeV}$) spectra of photons and neutrinos together with their corresponding upper limits demands a sophisticated numerical analysis. Such an ambitious project, however, is beyond the scope of this paper.

IV. CONCLUSIONS

We have proposed a new model to explain the origin of the KM3-230213A neutrino [10]. Our model is based on the evaporation of 5D PBHs within the dark dimension scenario. We have assumed that these black holes live in the bulk and thus only radiate gravitons and sterile neutrinos. Moreover, in the last stage of evaporation they radiate particles with energies just above the Hagedorn temperature. Since the species scale in the dark dimension scenario is $\mathcal{O}(10^9 \text{ GeV})$ the average energy of the radiated sterile neutrinos is naturally consistent with the energy of KM3-230213A. These sterile states could take shortcuts through the dark dimension and oscillate en route to Earth into active neutrinos. Our proposal is also consistent with IceCube upper limits on the partial decay width of superheavy dark matter particles into neutrinos [60].

A point worth noting at this juncture is the role played by the dark dimension in our proposal. One may wonder why we did not adopt a more economic perspective and argue that the photon-to-neutrino ratio of 4D PBH emission can be suppressed via beyond SM physics. For example, to explain neutrino oscillations a minimal extension of the SM is to introduce three right-handed neutrinos along with their Yukawa interactions with the Higgs field to generate Dirac neutrino masses. In principle the right-handed neutrinos can live in four dimensions. This minimal SM extension leads to $\gamma \div \nu = 1 \div 6$. This ratio can be further suppressed in 4D supersymmetric models [24], where e.g., light modulinos can oscillate into SM neutrinos [66] and of course with the addition of sterile neutrinos. Though such a 4D extension would suppress direct photon emission, hadronization of quarks and gluons would still produce a flux of π^0 which on decay could give rise to a photon signal. Markedly different, 5D PBHs radiate gravitons and sterile neutrinos in the bulk for most of their lifetime, and only in the last stage of evaporation do they radiate SM modes with energies just above the Hagedorn temperature. Thus, the way in which 5D PBHs localized on the brane evolve over time could help to reduce (though not fully eliminate) the tension with nonobservation of a photon signal.

Indeed, using Eq. (4) it is straightforward to see that 4D PBHs of $M \sim 10^{39}$ GeV Hawking radiate at $T \sim 5$ MeV. As a consequence, such 4D PBHs would emit $\mathcal{O}(10^{39}$ GeV) of energy into dangerous energetic modes. In sharp contrast, even if 5D PBHs stay localized on the brane, they emit at most $\mathcal{O}(10^{11}$ GeV) amount of energy into visible SM modes, a suppression factor of 10^{-28} relative to 4D PBHs of the same mass. Correspondingly, all evaporation constraints on the density of PBHs [25–27] are significantly weakened in the dark dimension scenario. As might be expected, however, if 5D PBHs live in the bulk then there is no emission into visible SM modes on the

brane. Thus, we can safely conclude that evaporation of bulk PBHs can explain the origin of the KM3-230213A neutrino, while evading constraints from upper limits on the gamma-ray flux. The model predicts a distinctive neutrino-line feature without a photon counterpart. Future observations by the IceCube neutrino telescope, as well as those from next generation neutrino experiments, may provide a definitive answer to the ideas introduced in this paper.

In closing, we note that the relative suppression of black hole radiation into the brane compared to gravitons radiated off into the bulk would also characterize 5D memory-burdened PBHs. As a consequence, evaporation constraints on the density of memory-burdened PBHs [34–38] are also significantly weakened within the dark dimension scenario. In particular, constraints from γ -ray experiments and primordial nucleosynthesis light element destruction [35] are alleviated completely even for $k = 1$ (i.e., a slowdown of evaporation by only a single power of entropy). Memory-burdened PBHs perceiving the dark dimension could thus constitute all of the dark matter in the Universe if $M \gtrsim 100$ g and perhaps be the source of the KM3-230213A neutrino.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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