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Ultrahigh-Energy Neutrinos from Primordial Black Holes

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(Received 1 April 2025; revised 10 July 2025; accepted 28 July 2025; published 18 September 2025)

The KM3NeT Collaboration recently announced the detection of a neutrino with energy 220 PeV. One possible source of such ultrahigh-energy particles is the rapid emission of energetic Hawking radiation from a primordial black hole (PBH) near the end of its evaporation lifetime. The mass distribution for PBHs features a power-law tail for small masses; a small subset of PBHs would be undergoing late-stage evaporation today. We find that recent high-energy neutrino events detected by the IceCube and KM3NeT Collaborations, with energies $\mathcal{O}(1-10^2)$ PeV, are consistent with event-rate expectations if a significant fraction of the dark matter consists of PBHs.

DOI: 10.1103/vnm4-7wdc

Introduction—We investigate extremely energetic Hawking radiation from exploding primordial black holes (PBHs) as a possible source of ultrahigh-energy cosmic rays, such as the KM3-230213A neutrino event recently reported by the KM3NeT Collaboration [1]. The median neutrino energy required to produce the 120^{+110}_{-60} PeV muon observed by the KM3NeT ARCA detector on 13 February 2023 is 220 PeV, with a 68% confidence interval of 110–790 PeV. The KM3-230213A event is the highest-energy neutrino event ever reported, although the IceCube Collaboration has reported detection of several PeV cosmic neutrinos since 2011 with deposited energies in the detector within the range $1.01 \pm 0.16\ \text{PeV} \leq E_{\text{dep}} \leq 6.05 \pm 0.72\ \text{PeV}$ [2–5]. Whereas an IceCube neutrino event with $E_{\text{dep}} \sim \mathcal{O}(10^2\ \text{TeV})$ has been identified with emission from a blazar [6,7], these rare, higher-energy events with $E_{\text{dep}} \sim \mathcal{O}(1-10^2)$ PeV have not been conclusively linked to any astrophysical point sources [8].

As analyzed in Refs. [9,10], to minimize tension with IceCube data, the ultrahigh-energy KM3NeT neutrino most likely arose from a transient astrophysical point source rather than from the diffuse isotropic neutrino flux. In this Letter, we consider whether Hawking radiation from PBHs that are undergoing late-stage evaporation could account for rare, high-energy neutrino events. In particular, we investigate whether the small set of neutrinos detected by IceCube and KM3NeT with $E_{\text{dep}} \sim \mathcal{O}(1-10^2\ \text{PeV})$, listed in Table SI, could all have arisen from a single PBH distribution. (See Supplemental Material [11].)

PBHs were first considered as a theoretical possibility more than 50 years ago [12–14]. Since PBHs would move at nonrelativistic speeds and interact gravitationally, they have emerged in recent years as an intriguing dark matter (DM) candidate. Recent work has clarified that PBHs could constitute most or all of the dark matter if their typical mass $\bar{M}$, at the peak of the mass distribution, falls within the range $10^{17}\ \text{g} \leq \bar{M} \leq 10^{23}\ \text{g}$ [15–25]. This window is referred to as the "asteroid-mass" range, which is exponentially smaller than a solar mass ($M_\odot = 2 \times 10^{33}$ g).

The lower bound on the asteroid-mass range, $\bar{M} \geq 10^{17}$ g, comes from consideration of PBH evaporation and cosmic-ray measurements. Like any black hole, a PBH is expected to emit a thermal spectrum of Hawking radiation with an effective temperature T_H inversely proportional to its mass [26,27]. The primary emission spectrum should consist of all elementary particles with masses $m_i \lesssim T_H$. A PBH would, therefore, lose mass over time via Hawking evaporation, yielding a finite lifetime $\tau \propto M_i^3$, where M_i is the initial PBH mass at the time of its formation [28–32]. Black hole evaporation is a runaway process: As a black hole's mass falls and its temperature rises, it should emit particles with correspondingly higher energies, ending in a final burst (or "explosion") in which particles would emerge with energies presumably approaching the Planck scale, $M_{\text{pl}} \equiv 1/\sqrt{8\pi G} = 2.43 \times 10^{18}$ GeV.

We first describe how the small number of neutrino events detected by IceCube and KM3NeT with deposited energy $E_{\text{dep}} \geq 1$ PeV could arise from a population of PBHs exploding in the Milky Way DM halo. We find that the reported IceCube neutrino flux at 1 PeV and, therefore, the five high-energy IceCube neutrino events with $E_{\text{dep}} \sim \mathcal{O}(1)$ PeV are consistent with an averaged, isotropic PBH explosion rate throughout the Milky Way Galaxy of $n_0 = 1.41^{+0.80}_{-0.71} \times 10^3\ \text{pc}^{-3}\,\text{yr}^{-1}$ (68% confidence interval), which

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is compatible with the current most stringent upper bounds on n_0 from γ-ray and other high-energy cosmic-ray searches [33–37]. Next, we find that, given this inferred value of n_0 from the IceCube events, there is a nontrivial probability to find at least one rare PBH explosion close enough to Earth to be consistent with the KM3-230213A neutrino event. We treat this "local" PBH explosion, which meets the transient point source criteria proposed by Ref. [9], as a Poisson-distributed event drawn from the same underlying PBH distribution that sources the isotropic IceCube high-energy neutrino flux.

We then compute the expected explosion rate if PBHs constitute some fraction of all dark matter, based on a well-motivated PBH mass distribution. We identify regions of parameter space for values of $\bar{M} \sim 10^{17}$ g, near the lower end of the open asteroid-mass range, within which the expected PBH explosion rates are compatible (within $\sim 2\sigma$) with those inferred by our analysis of the IceCube and KM3NeT neutrino fluxes. This congruence suggests a possible explanation for as-yet-unexplained rare high-energy neutrino events.

High-energy neutrinos from Hawking radiation—PBHs within the asteroid-mass range that arise from collapse of inflationary-era overdensities typically form with vanishing spin and charge [38–42], so we consider Hawking emission from Schwarzschild black holes [43]. Whether and how the semiclassical Hawking-radiation formalism might need to be modified at late stages of black hole evaporation remains an open question [46–49]. As a conservative analysis, we work with the standard formalism for Hawking radiation [26–32], updated to include the present-day set of standard model (SM) degrees of freedom.

The *primary emission* rate per particle degree of freedom from a Schwarzschild black hole of mass M is [28,31]

$$\frac{d^2N_s^{(1)}}{dtdQ} = \frac{\Gamma_s}{2\pi\hbar}\left[\exp\left(\frac{Q}{\hbar c^3/8\pi GM}\right) - (-1)^{2s}\right]^{-1} \quad (1)$$

for emitted particles with spin s and energy Q. In Table SII, we list relevant parameters for all SM particles [11]. The dynamics of scattering the field off the black hole potential are captured in the graybody factor Γ_s [28,31,50,51]. The bracketed term on the right-hand side of Eq. (1) has the form of a blackbody spectrum for an emitter at temperature $T_H = \hbar c^3/[8\pi GM]$.

The PBH lifetime is governed by primary Hawking emission. The mass of a PBH obeys [32]

$$\frac{dM}{dt} = -\sum_j g_j \int_{m_{\mathrm{eff},j}}^{\infty} dQ \frac{Q}{c^2}\frac{d^2N_{s_j}^{(1)}}{dtdQ} = -5.34\times 10^{25}\frac{f(M)}{M^2}\,\mathrm{g\ s^{-1}}, \quad (2)$$

where g_j counts the degrees of freedom per particle species and $f(M)$ is known as the Page factor. We follow the method of Ref. [32] to compute $f(M)$ but use the updated particle masses listed in Table SII [11] and include terms for the Higgs, W, and Z bosons, which were not included in the original work. The Page factor can be computed via

$$f(M) \simeq \mathcal{P}_\gamma + \mathcal{P}_\nu + \sum_j \mathcal{P}_j \exp\left(-\frac{M}{M_j}\right), \quad (3)$$

where the Page coefficients $\mathcal{P}_j$ are listed in column 8 in Table SII [11], the characteristic PBH masses M_j are listed in column 6, and the sum runs over the remaining 15 standard model particles. We consider only SM particles here. Including hypothetical beyond-SM particles could either raise or lower the integrated number of high-energy neutrinos emitted in model-dependent ways [52,53].

Because the exploding PBHs we consider are so light and hot, we must consider the net *secondary emission* rates for SM particles, which are modified by particle decays, jet fragmentation, and hadronization [31,32]. We denote secondary spectra as $d^2N^{(2)}/dtdQ$. The secondary spectra are computed numerically with BlackHawk v2.2 [59,60] and HDMSpectra [61].

For PBHs that form via the well-studied process of "critical collapse" [62], the peak of the PBH mass distribution $\bar{M}$ scales with the mass enclosed within a Hubble sphere (known as the "horizon mass" M_H) at formation time t_i: $\bar{M}(t_i) = \eta M_H(t_i)$, with $\eta \simeq 0.2$ [14,23,62,63]. Assuming standard ΛCDM cosmological evolution since the end of cosmic inflation, we may then use the evolution of $M_H(t)$ to infer that a population of PBHs that formed within the asteroid-mass range, with $10^{17}\ \mathrm{g} \le \bar{M} \le 10^{23}\ \mathrm{g}$, formed at times $10^{-21}\ \mathrm{s} \le t_i \le 10^{-16}\ \mathrm{s}$ after the end of inflation [42]. PBHs in our Galaxy today would, therefore, have been evolving over the entire age of the observable Universe: $t_0 = (13.787 \pm 0.020)\times 10^9$ yr [64]. Additionally, for PBHs with $M \ll M_\odot$, accretion remains exponentially suppressed, with $\Delta M/M_i < \mathcal{O}(10^{-2})$ between t_i and t_0 [65–67], so we neglect accretion when considering PBH evolution. [Here, $M_i \equiv M(t_i)$].

Numerically integrating Eq. (2) allows us to solve for the PBH mass at formation time that corresponds to a lifetime equal to the current age of the Universe, t_0. This yields the cutoff mass $M_* \simeq 5\times 10^{14}$ g. In other words, a PBH that formed with $M_i = M_*$ would be undergoing its final evaporation process and exploding today. Treating the Page factor as varying slowly with M, the lifetime of a PBH that forms with mass M_i may be approximated as [32] $\tau(M_i) \simeq 1.98\times 10^{-34}\ M_i^3 f(M_i)^{-1}$ yr, with M_i measured in grams.

We compute the total number of emitted neutrinos with $Q \ge Q_{\mathrm{min}}$ produced during a PBH explosion. We consider two cases: $Q_{\mathrm{min}} = 1$ PeV, the typical energy scale of the IceCube high-energy neutrino events, and $Q_{\mathrm{min}} = 60$ PeV, which corresponds to the lower bound on the 68% confidence

TABLE I. Parameters for PBHs producing neutrinos with energies above 1 and 60 PeV, respectively. Here, τ is the PBH's remaining lifetime when $M = M_0$. Note that we use $Q_{\rm peak} = 4.53 T_H$, appropriate for fermions [32].

$Q_{\rm peak}$ [PeV]	M_0 [g]	T_0 [PeV]	τ [s]
1	4.79×10^7	0.221	4.57×10^{-5}
60	7.98×10^5	13.2	2.21×10^{-10}

interval (CI) for the KM3-230213A event deposition. See Table I for the relevant PBH parameters for each case.

To estimate the number of emitted neutrinos with energies $E_\nu \geq 1$ PeV, we make a well-motivated assumption that all particles emitted during the explosion of a PBH of mass $M_0 \lesssim 10^7$ g have energy $Q \approx Q_{\rm peak}(M_0)$. This is justified because the PBH lifetime—the time required for a PBH of mass M to convert all its mass to Hawking radiation—scales as $\tau(M) \propto M^3$. The fraction of time a PBH spends with mass below some mass M is, therefore, highly suppressed compared to the lifetime of reference mass $M_0 > M$. For example, by the time a PBH evaporates to have mass $M_0 = 4.79 \times 10^7$ g, it will spend 90% of its *remaining* lifetime with mass in the range 2.22×10^7 g $\leq M \leq 4.79 \times 10^7$ g, corresponding to Hawking emission with 1.00 PeV $\leq Q_{\rm peak} \leq 2.16$ PeV.

Under this simplifying assumption, we may estimate the total number of emitted neutrinos with $Q \geq Q_{\rm min}$ during the PBH's final explosion. We first integrate over the secondary spectrum:

$$\frac{dN_\nu(M, Q_{\rm min})}{dt} = \int_{Q_{\rm min}}^{\infty} dQ \frac{d^2 N_\nu^{(2)}(M, Q)}{dt dQ}. \tag{4}$$

Then we use the PBH mass-loss rate from Eq. (2) to evaluate

$$N_\nu(Q_{\rm min}) = \int_{10^0\ {\rm g}}^{10^{10}\ {\rm g}} dM \frac{dN_\nu(M, Q_{\rm min})}{dt} \left(\frac{dM}{dt}\right)^{-1}. \tag{5}$$

Integrating up to $M \leq 10^{10}$ g suffices, given how sharply the integrand falls off for $M > M_0$ (see Fig. 1). We compute this integral numerically, interpolating $dN_\nu(M, Q_{\rm min})/dt$ over a list of values in our desired mass range generated numerically from secondary emission spectra. The results for N_ν are shown in Table SI [11], indicating $N_\nu \sim 10^{24}$ for $Q_{\rm min} = 1$ PeV while $N_\nu \sim 10^{20}$ for $Q_{\rm min} = 60$ PeV. In each case, we calculate the total number summed over all three neutrino flavors and their antiparticles because the IceCube and KM3NeT detectors are sensitive to all three neutrino flavors [68].

Inferred PBH explosion rate from high-energy IceCube neutrino flux—Reference [69] reports that the detected IceCube flux for each neutrino flavor for energies above

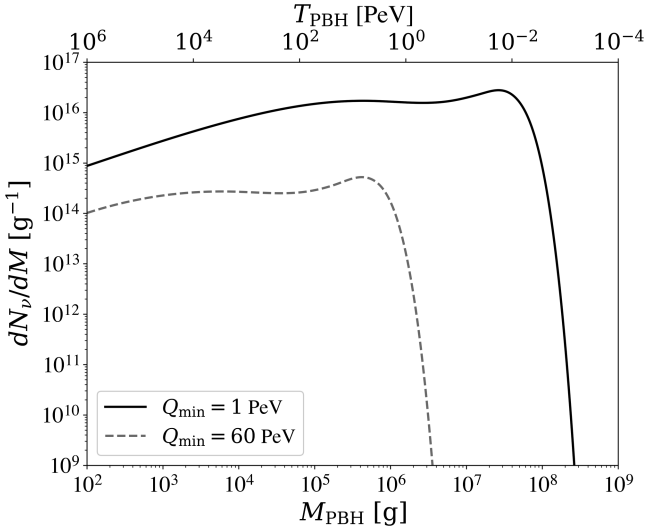


FIG. 1. Differential emission rate for neutrinos with energies $Q \geq Q_{\rm min}$ during a PBH explosion. The mass $M_{\rm PBH}$ refers to the PBH mass at the time of particle emission. Note that neutrino emission rates peak for $M_{\rm PBH} \simeq M_0$ for M_0 values listed in Table I.

13.7 TeV is best fit with a broken power law, parametrized as $\Phi_\nu^{\rm IC}(E_\nu) = \Phi_b (E_\nu/E_{\rm break})^{-\gamma_i}$, where $\log_{10}(E_{\rm break}/{\rm GeV}) = 4.39^{+0.09}_{-0.08}$ and $\gamma_1 = 1.31^{+0.50}_{-1.21} (E < E_{\rm break})$, $\gamma_2 = 2.74^{+0.06}_{-0.07} (E \geq E_{\rm break})$ (68% confidence intervals). Given the reported flux at $E_\nu = 100$ TeV [69], this corresponds to $\Phi_b = 83.0^{+48.2}_{-43.0}$ per neutrino flavor, in units of 10^{-18} GeV^{-1} cm^{-2} sr^{-1} s^{-1} [70]. We may calculate the corresponding volumetric PBH explosion rate n_0 that would yield such a flux.

As discussed in Supplemental Material [11], neutrino events with $E_\nu \geq 1$ PeV that originate from PBH explosions outside the Milky Way Galaxy would contribute a subdominant fraction to the expected event rate, so we focus on PBH explosions within our Galaxy. We adopt a modified Navarro-Frenk-White (NFW) [71] parametrization for the spatial distribution $\rho_{\rm DM}(r, z)$ of the Milky Way DM halo [72,73]:

$$\rho_{\rm DM}(r, z) = \frac{\rho_0}{L(1+L)^2} \exp\left[-\left(\frac{L r_0}{r_{\rm vir}}\right)^2\right], \tag{6}$$

where r and z are cylindrical coordinates in the Galactocentric frame, $L \equiv [(r/r_0)^2 + (z/[q r_0])^2]^{1/2}$, and best-fit parameters are $\rho_0 = 0.0196\, M_\odot {\rm pc}^{-3}$, $r_0 = 15.5$ kpc, $r_{\rm vir} = 287$ kpc, and $q = 1.22$. The PBH explosion rate n_0 would then scale with the DM density profile as

$$n_0(\vec{r}|n_{\rm NFW}) = \frac{n_{\rm NFW}}{\rho_0} \rho_{\rm DM}(r, z), \tag{7}$$

where $n_{\rm NFW}$ is a normalization constant with units of pc^{-3} yr^{-1}. Note that we have made no assumption about the fraction $f_{\rm PBH}$ of DM contributed by PBHs; we assume only that the spatial distribution of any exploding PBHs that

might exist tracks the overall DM density profile. Furthermore, we do not make any assumptions about the underlying PBH mass function. We neglect any potential effects due to PBH interactions, clustering, or binaries [22].

The isotropic flux of neutrinos with $E_\nu \geq Q_{\rm min}$ at Earth is given by a volume integral over the DM halo:

$$\Phi_\nu(n_{\rm NFW}, Q_{\rm min}) = \frac{1}{4\pi Q_{\rm min}} \int_V \frac{dV N_\nu(Q_{\rm min})}{4\pi(\vec{r}-\vec{R}_\odot)^2} n_0(\vec{r}|n_{\rm NFW}), \quad (8)$$

where Φ_ν has dimensions $\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$, $R_\odot = 8.3$ kpc is the location of the Solar System [73], and we take V to be a sphere of radius $r_{\rm vir}$ centered at the center of the Milky Way. Upon solving for the normalization constant $n_{\rm NFW}$ such that $Q_{\rm min} = 1$ PeV and $\Phi_\nu(n_{\rm NFW}, Q_{\rm min}) = 3\Phi_\nu^{\rm IC}(Q_{\rm min})$, we then find the PBH explosion rate in the neighborhood of our Solar System to be $n_0 = n_{\rm NFW}[\rho_{\rm DM}(R_\odot, 0)/\rho_0] = 1.41^{+0.80}_{-0.71} \times 10^3\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$ (68% CI). (The wide error bars in n_0 arise largely from the uncertainty in $E_{\rm break}$ in the parametrized broken power law for the IceCube flux.) This inferred value of n_0 is compatible with the current most stringent upper bound $n_0 < 3.40^{+0.40}_{-0.10} \times 10^3\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$ (99% CI) reported by the HAWC Collaboration based on γ-ray searches [37]. Repeating the above analysis using the reported KM3NeT flux for 60 PeV neutrinos [1], we determine that the volumetric explosion rate necessary to source the KM3NeT isotropic flux is $n_0 = 1.48^{+1.29}_{-0.47} \times 10^6\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$, which is approximately 10^3 times larger than the IceCube result. These inferred explosion rates are, therefore, in tension at $\gtrsim 3\sigma$, as are the reported isotropic fluxes, as noted by Ref. [9].

To resolve this tension, we use the inferred value of n_0 from the isotropic IceCube neutrino flux at 1 PeV to estimate the probability for at least one PBH explosion to occur within some distance b of Earth during an observing window T. We assume that such a rare event would be governed by Poisson statistics: $\mathrm{Prob}(1\ \mathrm{event\ in}\ T) = (rT)\exp[-rT]$, where r is the rate. During an observing window T, the volume to which Earthbound detectors would be sensitive as Earth moves through the DM halo is $V(b, T) = (4\pi/3)b^3 + \pi b^2 v_{\rm avg} T$. We estimate $v_{\rm avg}$, the average relative velocity between Earth and the local DM, by averaging over a Maxwellian velocity distribution with $v_{\rm rms} = 270$ km/s up to the escape velocity $v_{\rm esc} = 544$ km/s [74,75], which yields $v_{\rm avg} = 246$ km/s. In order for at least one ultrahigh-energy neutrino with $E_\nu \geq 60$ PeV to strike some area A on Earth, we require $b_{\rm max} = [N_\nu A/(4\pi)]^{1/2}$. Using $N_\nu(60\ \mathrm{PeV}) = 4.02 \times 10^{20}$ from Table SI [11], $A = (50\ \mathrm{km})^2$, and $r = n_0 V(b_{\rm max}, T = 14\ \mathrm{yr})$, we find $\mathrm{Prob}(1\ \mathrm{event\ since\ 2011}) = 0.076$. This yields a nontrivial likelihood to have one detectable PBH explosion within $b_{\rm max} \simeq 1890$ AU since 2011.

PBH distribution and expected explosion rates—We follow Refs. [76,77] and define the PBH number distribution at the time of formation t_i:

$$\phi(M_i) = \frac{1}{n_{\rm PBH}} \frac{dn}{dM_i}, \quad (9)$$

where $n_{\rm PBH} = f_{\rm PBH}\rho_{\rm DM}/\int_0^\infty dM_i M_i \phi(M_i)$ is the total number density of PBHs that form at t_i. The initial number distribution is normalized: $\int_0^\infty dM_i \phi(M_i) = 1$. As individual PBHs undergo Hawking emission, their masses will change over time. Assuming that the Page factor $f(M)$ varies slowly over time [78], we may solve Eq. (2) for the mass $M(t|M_i)$ at some time $t > t_i$ [76]:

$$M(t|M_i) = \left(M_i^3 \frac{f(M)}{f(M_i)} - 3\tilde{\alpha} t f(M)\right)^{1/3}, \quad (10)$$

where $\tilde{\alpha} = 5.34 \times 10^{25}\ \mathrm{g}^3\ \mathrm{s}^{-1}$. The interval dM and the function $\phi(M, t)$ will also evolve over time. Again taking $f(M)$ to vary slowly, we have $\phi(M, t) \simeq M^2 \phi(M_i)(M^3 + 3f(M)\tilde{\alpha}t)^{-2/3}$ [76]. The fraction of PBHs that remain at time $t > t_i$ is $F(t) \equiv \int_0^\infty dM \phi(M, t)$, and $1 - F(t)$ is the cumulative fraction of PBHs that have completely evaporated by time t. To compute the instantaneous PBH explosion rate per unit volume, we therefore write

$$\dot{N}(t) = n_{\rm PBH} \frac{d}{dt}(1 - F(t)). \quad (11)$$

We use $\dot{N}(t)$ to compute the average volumetric PBH explosion rate $\mathcal{N}$ within a time interval $[t_0 - \Delta T, t_0]$ within the neighborhood of our Solar System. For a given PBH number distribution $\phi(M|\{\theta_j\})$ that depends on some set $\{\theta_j\}$ of j tunable parameters, we evaluate

$$\mathcal{N}(\{\theta_j\}) = \frac{1}{\Delta T} \int_{t_0 - \Delta T}^{t_0} dt \dot{N}(t|\{\theta_j\}) \simeq \dot{N}(t_0|\{\theta_j\}), \quad (12)$$

where the last step follows since we are interested in durations $\Delta T \sim \mathcal{O}(10\ \mathrm{yr})$ compared to $t_0 \sim \mathcal{O}(10^{10}\ \mathrm{yr})$.

The quantity $\mathcal{N}$ is the time-averaged PBH explosion rate per unit volume with units of $\mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$, which depends on the underlying PBH number distribution $\phi(M, t)$, which, in turn, depends on $n_{\rm PBH}$ as defined below Eq. (9). Given that $\rho_{\rm DM}(r, z)$ in Eq. (6) is nearly constant over length scales $r \leq \mathcal{O}(1\ \mathrm{kpc})$ and we are considering distances of the order of $b_{\rm max} \sim \mathcal{O}(10^3\ \mathrm{AU}) \sim \mathcal{O}(10^{-5}\ \mathrm{kpc})$, we may set $\rho_{\rm DM} = \rho_\odot = 0.0155 M_\odot\ \mathrm{pc}^{-3}$. Present evaporation constraints limit $f_{\rm PBH} < 1$ for mass functions that peak with $\bar{M} \lesssim 10^{17}$ g [16–25]. From the parametrization in Ref. [25] of the most recent 511 MeV γ-ray constraints reported by Ref. [21], the end points of the "realistic" 3σ confidence interval within which $f_{\rm PBH} = 1$ lie within the range $(1.5\text{–}2.5) \times 10^{17}$ g. We use the representative value of 2.0×10^{17} g and set $f_{\rm PBH} \simeq (\bar{M}/[2 \times 10^{17}\ \mathrm{g}])^3$ for $\bar{M} \leq 2 \times 10^{17}$ g.

Decades of detailed numerical-relativity simulations indicate that PBHs form via a process known as "critical

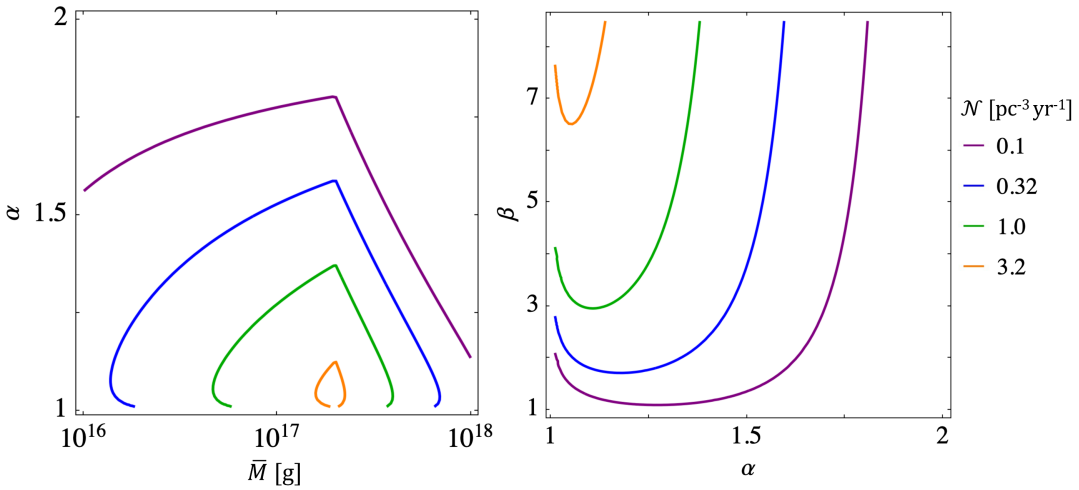


FIG. 2. Predicted volumetric PBH explosion rate $\mathcal{N}$ from the PBH number distribution $\phi_{\rm GCC}(M_i)$ of Eq. (13) as a function of $\bar{M}$ and α with $\beta = 8$ (left) and as a function of α and β with $\bar{M} = 2 \times 10^{17}$ g (right). Note that a predicted rate of $\mathcal{N} \geq 1$ pc^{-3} yr^{-1} (green curves) is within 1.98σ of the mean value for n_0 inferred from the IceCube data, given the residual uncertainty on $E_{\rm break}$ in the parametrized high-energy IceCube neutrino flux. When calculating $\mathcal{N}$, we incorporate present constraints on $f_{\rm PBH}$ for $\bar{M} < 2 \times 10^{17}$ g.

collapse." (For reviews, see Refs. [62,63].) Critical collapse yields a nontrivial mass distribution $\psi(M_i)$ for the resulting PBH population that is sharply peaked at a value $\bar{M}$, with a power-law tail for masses $M_i < \bar{M}$ and an exponential falloff for $M_i > \bar{M}$ [80–82]. As analyzed in Ref. [83], the generalized critical collapse (GCC) mass distribution $\psi_{\rm GCC}(M_i)$ yields the closest fit to the PBH mass distributions arising from several known spectra of primordial curvature perturbations. The associated GCC number distribution $\phi_{\rm GCC}(M_i)$ may be written

$$\phi_{\rm GCC}(M_i) = \frac{\beta}{\mu\Gamma\left(\frac{\alpha}{\beta}\right)}\left(\frac{M_i}{\mu}\right)^{\alpha-1}\exp\left[-\left(\frac{M_i}{\mu}\right)^{\beta}\right], \quad (13)$$

with $\beta > 0$ and $\alpha > 1$ [83,84]. The peak mass $\bar{M}$ is related to the parameter μ as $\bar{M} = \mu[(\alpha-1)/\beta]^{1/\beta}$.

In Fig. 2, we show the expected present-day isotropic volumetric explosion rate $\mathcal{N}(\{\theta_j\})$ for the GCC distribution. To account for the neutrino events with $E_{\rm dep} \geq 1$ PeV in a way that is consistent both with the reported IceCube high-energy neutrino flux and with the anomalous KM3NeT transient event, we require $\mathcal{N} \geq n_0 = 1.41^{+0.80}_{-0.71} \times 10^3$ pc^{-3} yr^{-1}. We find narrow regions of parameter space $\{\bar{M}, \alpha, \beta\}$ for which the expected explosion rate $\mathcal{N}$ is within $\sim 2\sigma$ of the mean value of n_0 inferred from the IceCube isotropic flux. For those same regions of parameter space, we find that the spectrum of lower-energy neutrinos ($1\,{\rm keV} \leq E_\nu \leq 10^2$ TeV) remains comparable to but below the so-called "grand unified neutrino spectrum" expected from other sources [85,86].

Discussion—Over the past 15 years, a small number of high-energy neutrino events have been detected by the IceCube and KM3NeT Collaborations with energies $E_\nu \geq 1$ PeV. To date, no astrophysical acceleration mechanism has been identified that could account for these specific events. The isotropic fluxes and inferred explosion rates from these few IceCube and KM3NeT events are incompatible with each other [9]. However, we have shown that if this collection of high-energy neutrino events arose from the late-stage evaporation of primordial black holes within the dark matter halo of the Milky Way Galaxy, then the recent ultrahigh-energy KM3NeT neutrino event with $E_\nu \sim \mathcal{O}(100)$ PeV *would* be compatible with the reported high-energy neutrino flux from IceCube. The KM3NeT event could have originated from a rare, nearby transient PBH explosion drawn from the same underlying PBH distribution that sources the IceCube isotropic neutrino flux for $E_\nu \gtrsim 1$ PeV. Moreover, the inferred PBH explosion rate n_0 consistent with these detections is compatible with the current most stringent upper bound on n_0 set by the HAWC Collaboration, based on γ-ray searches [37].

Not only does the hypothesis that these high-energy neutrino events each arose from PBH explosions reduce the tension between the reported IceCube and KM3NeT fluxes, it also enables us to estimate *ab initio* the expected number of such events. If PBHs formed via critical collapse very early in cosmic history, the resulting population would necessarily follow a nontrivial mass distribution, including a power-law tail for masses below the peak of the distribution [24,80–83]. Given the wide error bars on the inferred isotropic PBH explosion rate from the IceCube data (driven by the uncertainty in the energy $E_{\rm break}$ in the broken power-law parametrization of the high-energy IceCube flux), we find regions of parameter space in which a population of PBHs with $f_{\rm PBH} \simeq 1$ would include a small fraction of PBHs that are undergoing their final Hawking evaporation and exploding today at a rate consistent (within

$\sim 2\sigma$) with the rate required to account for all reported neutrino events to date with $E_\nu \geq 1$ PeV.

At least three different inputs could test or constrain the scenario presented here, each coming from quite distinct research communities. First, additional high-energy neutrino events from IceCube and/or KM3NeT will reduce uncertainties on reported fluxes and further test the compatibility between expected PBH explosion rates and observed neutrino fluxes. Second, upcoming high-energy γ-ray detectors, such as the Large High Altitude Air Shower Observatory (LHAASO) [87], could be sensitive to local PBH explosion rates as low as $n_0 \simeq 1200\ \mathrm{pc}^{-3}\ \mathrm{yr}^{-1}$, comparable to the inferred rate from present-day IceCube data. And third, other astrophysical probes of the PBH asteroid-mass range, including gravitational perturbations [88–91] and cosmic rays [79], could further constrain the parameter space within which $f_{\mathrm{PBH}} \simeq 1$, thereby modifying expected PBH explosion rates.

With more neutrino detection events for $E_\nu \geq 1$ PeV, we may further clarify whether higher event rates originate from the direction of the Galactic center, where the dark matter density is greatest. Predicting the magnitude of such a directional anisotropy remains the subject of further research.

Acknowledgments—We are grateful to Michael Baker, Shyam Balaji, Bryce Cyr, Peter Fisher, Anne Green, Joaquim Iguaz Juan, Evan McDonough, Benjamin Lehmann, Dario Lorenzoni, Chris Schmidt, Aidan Symons, Thomas Steingasser, Hayden Tedrake, Jesse Thaler, Andrea Thamm, and Rainer Weiss for helpful discussions. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 2141064. Portions of this work were conducted in MIT's Center for Theoretical Physics—A Leinweber Institute and supported in part by the U.S. Department of Energy under Contract No. DE-SC0012567.

Data availability—The data that support the findings of this Letter are not publicly available. The data are available from the authors upon reasonable request.

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