

Super heavy dark matter origin of the PeV neutrino event: KM3-230213AKazunori Kohri^{1,2,3,*}, Partha Kumar Paul^{4,†} and Narendra Sahu^{4,‡}¹*Division of Science, National Astronomical Observatory of Japan (NAOJ), and SOKENDAI, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*²*Theory Center, IPNS, and QUP (WPI), KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*³*Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*⁴*Department of Physics, Indian Institute of Technology Hyderabad, Kandi, Sangareddy, Telangana-502285, India* (Received 19 March 2025; revised 14 May 2025; accepted 29 July 2025; published 25 August 2025)

The recent observation of the ultrahigh-energy neutrino event KM3-230213A by the KM3NeT experiment offers a compelling avenue to explore physics beyond the Standard Model (SM). In this paper, we explore a simplest possibility that this event originates from the decay of a super-heavy dark matter (SHDM). We consider a minimal scenario where the SHDM decays to neutrino and SM Higgs. We derive constraints on the DM lifetime as a function of DM mass, ensuring consistency with IceCube, Auger upper limits, and the observed KM3-230213A event, along with the gamma-ray constraints. We find that KM3-230213A gives stringent constraint on the DM mass ranging from 1.5×10^8 GeV to 5.2×10^9 GeV with lifetime in the range: 1.42×10^{30} s to 5.4×10^{29} s. Remarkably, in our SHDM scenario, the apparent tension between the KM3NeT observation and the nonobservation of this event by IceCube and Auger can be reduced to below 1.2σ . Our results are applicable to any neutrinophilic SHDM models while evading gamma-ray constraints.

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Introduction. The KM3NeT Collaboration recently reported the detection of an exceptionally high-energy neutrino event, designated as KM3-230213A, with an energy of 220^{+570}_{-100} PeV [1]. The reported flux at 3σ confidence level is given to be $[0.02 - 47.7] \times 10^{-8}$ GeV cm⁻² s⁻¹ sr⁻¹. This makes it nearly two orders of magnitude more energetic than the most extreme neutrino previously detected by the IceCube experiment [2,3]. Understanding the origin of such an ultrahigh energetic (UHE) neutrino is of great interest, as it could provide new insights into fundamental physics and astrophysical processes. The reported high-energy neutrino event challenges a simple diffuse astrophysical power-law explanation. A flux compatible with this detection leads to a $2.5 - 3\sigma$ tension [1,4] with the null results from IceCube and Auger. Although conventional astrophysical explanations consider galactic, extragalactic, and cosmogenic sources, an alternative and intriguing possibility is that KM3-230213A originated from the decay of a super-heavy dark matter

(SHDM). In this scenario, the neutrino flux depends on the dark matter mass and lifetime, and can account for the KM3NeT event while remaining consistent with the non-observations in IceCube and Auger, thus reducing the tension inherent in the power-law interpretation. In this case, an extremely long-lived DM particle with a mass in the PeV–EeV range or beyond decays into high-energy neutrinos. This could happen through various theoretical frameworks, such as DM coupled to neutrinos via a feeble interaction or scenarios involving higher-dimensional operators that allow suppressed but nonzero decay rates. See, e.g., [5–14] where the IceCube neutrino signal is explained via the decay of a SHDM. KM3-230213A has already attracted some attentions in the community. See for instance [15–23].

In this paper, we consider a simple scenario where the SHDM decays exclusively into neutrino (ν) and SM Higgs (h). This can be realized within a minimal extension of the type-I seesaw model [24–28] featuring a singlet scalar, S , and a singlet fermion χ representing the DM. These two particles are odd under a Z_2 symmetry, whereas all other particles are even. When the scalar S obtains a vacuum expectation value (vev), χ mixes with the RHN, N , and decays to ν and h . The mixing angle is highly suppressed, ensuring a sufficiently long DM lifetime consistent with the observed high-energy neutrino event. Gamma-ray constraints can typically impose strong limits on such

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decays. However, the gamma-ray flux remains well below current observational bounds in our scenario. Additionally, the spontaneous breaking of Z_2 symmetry leads to the formation of domain walls. The disappearance of the DWs can give rise to stochastic gravitational waves (GW) [29–35], which could be detectable in future experiments [36–49]. Our main result is summarized in Fig. 2, which we discuss in detail throughout the paper. It has to be noted that our derived lower limit on the lifetime of the SHDM can be applied to any neutrinophilic DM models.

Neutrino and gamma ray fluxes. We first calculate the galactic and extragalactic neutrino and gamma ray fluxes from a decaying DM in a model-independent way. Then we discuss a simplest model for realization.

Galactic component. As the neutrinos can travel through the galaxy without obstruction, their energy spectrum remains nearly unchanged from the source to the detection point. The differential neutrino (gamma ray) flux per energy per unit solid angle from a decaying DM within an observational volume can be expressed in terms of the DM lifetime, τ_{DM} , as [50–52]

$$\frac{d^2\Phi_{\nu(\gamma)}^G}{dE_{\nu(\gamma)}d\Omega} = \frac{1}{\tau_{\text{DM}}} \frac{\mathcal{D}}{4\pi M_{\text{DM}}} \frac{dN_{\nu(\gamma)}}{dE_{\nu(\gamma)}}, \quad (1)$$

where M_{DM} is the mass of DM, $dN_{\nu(\gamma)}/dE_{\nu(\gamma)}$ is the neutrino (gamma ray) energy spectrum, and the $\mathcal{D}$ -factor is given as

$$\mathcal{D} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_0^{s_{\text{max}}} ds \rho \left(\sqrt{R_{\text{sc}}^2 - 2sR_{\text{sc}}\cos\psi + s^2} \right), \quad (2)$$

where $\Delta\Omega$ is the angular region of observation, (b, l) are galactic coordinates, $d\Omega = \cos b db dl$, $\Delta\Omega = \int_l \int_b d\Omega$, $\cos\psi = \cos b \cos l$, $R_{\text{sc}} = 8.5$ kpc is the distance from the Solar System to the Galactic Center, $s_{\text{max}} = \sqrt{R_{\text{MW}}^2 - \sin^2\psi R_{\text{sc}}^2} + R_{\text{sc}} \cos\psi$, $R_{\text{MW}} = 40$ kpc is the size of the Milky Way, and $\rho(r)$ is the DM density in the Milky Way given as

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{(\beta-\gamma)/\alpha}}, \quad (3)$$

where α , β , and γ are slope parameters, r_s is the scale radius, and r is the distance to Earth from the DM decay point. For the NFW profile, we fix $\alpha = 1$, $\beta = 3$, $\gamma = 1$, $r_s = 20$ kpc, $R_{\text{sc}} = 8.5$ kpc, $\rho(R_{\text{sc}}) = 0.3 \text{ GeV cm}^{-3}$ [50–52].

Extragalactic component. The isotropic extragalactic neutrino (gamma ray) flux resulting from the decay of a SHDM particle with mass M_{DM} and lifetime τ_{DM} is given by

$$\begin{aligned} \frac{d\Phi_{\nu(\gamma)}^{\text{EG}}}{dE} &= \frac{1}{4\pi M_{\text{DM}}\tau_{\text{DM}}} \int_0^\infty \frac{\rho_0 c/H_0}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{1}{(1+z)^2} \\ &\times \frac{dN_{\nu(\gamma)}}{dE_{\nu(\gamma)}} dz, \end{aligned} \quad (4)$$

where $\rho_0 = 1.15 \times 10^{-6} \text{ GeV cm}^{-3}$ is the average cosmological DM density at the present epoch, $c/H_0 = 1.37 \times 10^{28} \text{ cm}$ is the proper radius of the Hubble sphere (Hubble radius), $\Omega_m = 0.315$, $\Omega_\Lambda = 0.685$ [53] are contributions of matter and vacuum energy to the total energy density of the Universe, respectively, and z is the redshift. The total flux per unit solid angle is then obtained by summing both galactic and extragalactic sources as

$$\Phi_{\nu(\gamma)} \equiv \frac{d^2\Phi_{\nu(\gamma)}^G}{dE_{\nu(\gamma)}d\Omega} + \frac{1}{4\pi} \frac{d\Phi_{\nu(\gamma)}^{\text{EG}}}{dE_{\nu(\gamma)}} \quad (5)$$

Minimal model for dark matter. We extend the minimal type-I seesaw model with a singlet scalar S and a singlet fermion χ (representing the DM) that are odd under a Z_2 symmetry. The relevant Lagrangian can be written as

$$\begin{aligned} \mathcal{L}_{\text{seesaw+DM}} &= -\frac{M_N}{2} \bar{N}^c N - y_{NL} \bar{L} \tilde{H} N - \frac{M_\chi}{2} \bar{\chi} \chi \\ &\quad - y_{N\chi} \bar{N} S \chi + \text{H.c.}, \end{aligned} \quad (6)$$

where N is the right-handed neutrino, L is the lepton doublet and $H = (0 \ \frac{h+v}{\sqrt{2}})^T$ is the Higgs doublet. We suppress the generation indices for simplicity. Once S gets a vacuum expectation value (vev), v_S , $N - \chi$ mixing occurs. Assuming the mixing angle is θ , the two mass eigenstates: χ_1, χ_2 can be given as

$$\chi_1 = N \cos\theta + \chi \sin\theta, \quad \chi_2 = -N \sin\theta + \chi \cos\theta, \quad (7)$$

where the mixing angle is given by $\sin\theta \simeq \frac{y_{N\chi} v_S}{\sqrt{2(M_N - M_\chi)}}$. Here, χ_2 is dominantly the DM, which decays to ν, h with a suppressed mixing angle $\sin\theta$ and can explain the observed neutrino flux measured by KM3NeT [1]. On the other hand, χ_1 is dominantly the RHN, which can explain the nonzero mass of SM neutrinos via the type-I seesaw mechanism.

Neutrino and gamma ray fluxes from SHDM decay. The DM can decay to neutrino via mixing with RHN, N . The decay mode is $\chi \rightarrow \nu h$.¹ The nonobservation of such a

¹The decay modes: $\{\chi \rightarrow l^\pm W^\mp, \chi \rightarrow \nu Z\}$, are also allowed where $l^\pm$ is the charged lepton. However, these decay modes involve an additional suppression compared to $\chi \rightarrow \nu h$ due to the $N - \nu$ mixing. The $N - \nu$ mixing angle is $\sim 10^{-12}$ for the RHN mass of $M_N = 10^{14} \text{ GeV}$ and $y_{NL} = 0.575$ (as discussed in the latter part of the paper). Thus, these channels will not be relevant in our analysis.

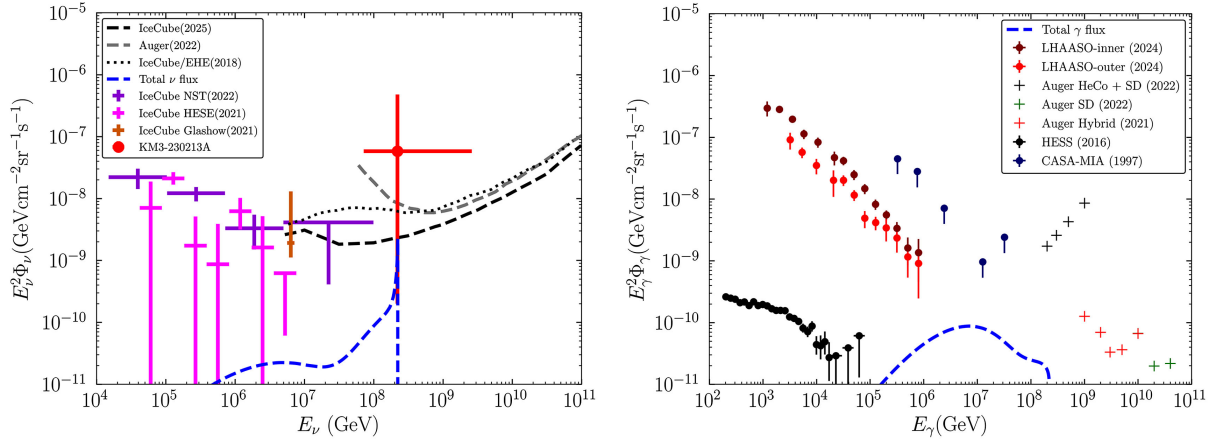


FIG. 1. Left: blue dashed line represents the neutrino flux as a function of energy of the neutrinos for $M_{\text{DM}} = 4.5 \times 10^8$ GeV, $\tau_{\text{DM}} = 1.2 \times 10^{30}$ s, and red point represent the KM3-230213A event [1]. The magenta and pink crosses represent the IceCube single-power-law fits, NST [55] and HESE [3]. The orange cross corresponds to the IceCube Glashow resonance event [56]. The black dotted line corresponds to IceCube-EHE [57]. The black dashed line corresponds to 12.6 yr of IceCube data [54], and the Auger [58] upper limit is shown with a gray dashed line. Right: gamma ray flux from the decay of a DM with mass $M_{\text{DM}} = 4.5 \times 10^8$ GeV, and lifetime $\tau_{\text{DM}} = 1.2 \times 10^{30}$ s is shown with the dashed blue line. Datas from HESS [59], CASA-MIA [60], LHAASO-inner [61], and LHAASO-outer [61] are shown with black, dark blue, dark red, and red colored points, respectively. Auger [62] limits are shown with cross. The channel for gamma-ray flux used here is $\chi \rightarrow \nu h$.

high-energy neutrino event like KM3-230213A by IceCube [54] sets the upper limit on the UHE neutrino flux. We used the IceCube limit to constrain the DM lifetime, which is consistent with the observed flux by KM3NeT. The reconstructed direction of the event is right ascension (RA) = 94.3° and declination (Dec) = -7.8° , with a 99% containment angular uncertainty of 3° . The SHDM decay predicts a neutrino flux that is expected to come from all directions, and we average over the angular region of observation. Thus, the signal does not exhibit a strong intrinsic directional preference, and the observed event's location is consistent with a random occurrence within the expected distribution from dark matter decay across the Galactic halo profile. We now calculate the neutrino flux using Eq. (5) for DM mass of 4.5×10^8 GeV, as shown in the left panel of Fig. 1. We see that the flux fitted the observation of KM3NeT for a lifetime of 1.2×10^{30} s. This gives a lower bound on the DM lifetime for a DM mass of $M_{\text{DM}} = 4.5 \times 10^8$ GeV as $\tau_{\text{DM}} > 1.2 \times 10^{30}$ s.

We note that γ rays can be produced through the same decay channel: $\chi \rightarrow \nu h$, as the Higgs boson can subsequently decay into two photons. However, the branching fraction for $h \rightarrow 2\gamma$ is $\mathcal{O}(10^{-3})$ and remain suppressed. On the other hand, Higgs can decay to SM charged fermions, which can also produce γ rays through cascade processes. Therefore, in our setup, the gamma-ray flux from the DM decay is highly suppressed in comparison to the neutrino flux. Nevertheless, we use HESS [59], LHAASO-inner [61] (inner galaxy region $|b| < 5^\circ$, $15^\circ < l < 125^\circ$), LHAASO-outer [61] (outer galaxy region $|b| < 5^\circ$, $125^\circ < l < 235^\circ$), CASA-MIA [60], Auger [62] data to constrain the flux. We computed the gamma-ray flux for the

DM mass 4.5×10^8 GeV with lifetime 1.2×10^{30} s and shown in the right panel of Fig. 1. As expected, the flux remains well below the current constraints from LHAASO [61] and CASA-MIA [60].

We then scan the DM mass in the range from $10^4 - 2 \times 10^{11}$ GeV and calculate the lower limit on the lifetime of the DM. Using the limits on neutrino flux from IceCube, Auger, we show the lower limit on DM lifetime as a function of DM mass in Fig. 2. We find that the SHDM lifetime is much larger than the age of the Universe, ranging from $\tau_{\text{DM}} > 10^{28}$ s at $M_{\text{DM}} \sim 3.5 \times 10^4$ GeV to $\tau_{\text{DM}} > 4.5 \times 10^{28}$ s at $M_{\text{DM}} \sim 2 \times 10^{11}$ GeV. The KM3-230213A event gives stringent constraint on DM mass ranging from 1.5×10^8 GeV to 5.2×10^9 GeV with lifetime 1.42×10^{30} s to 5.4×10^{29} s. We present the projected sensitivities of KM3NeT for 5 and 10 yr of runtime, shown as black dashed lines in Fig. 2. All sensitivity curves are normalized to correspond to the detection of a single neutrino event, such that the region below each curve represents the parameter space where the expected number of events exceeds one. The gray dashed line denotes the 335-day dataset, scaled to one event to match the central flux inferred from the KM3-230213A detection. At the time of this event, KM3NeT was operating with only 21 active detection strings [1], whereas the full detector will eventually include 230 strings. We account for this in the future projections by scaling the expected events by a factor of 230/21, resulting in the green dashed lines for 5 and 10 yr of full-detector operation. If the KM3-230213A event indeed originated from the decay of SHDM, future KM3NeT data with increased exposure should reveal additional neutrino events with comparable energy. In contrast, the continued nonobservation of such

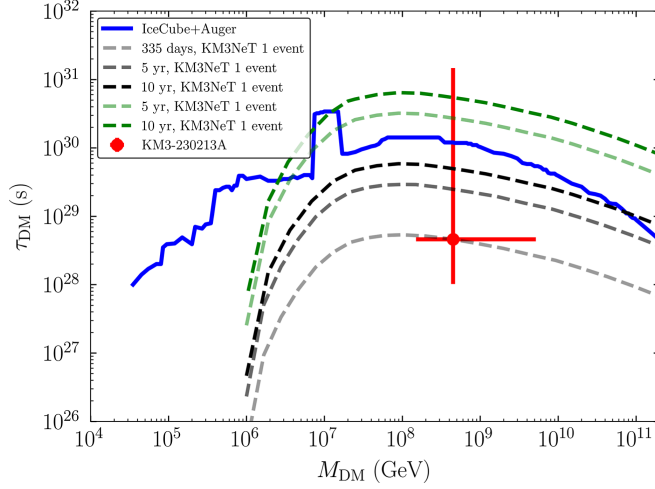


FIG. 2. Lower limit on the DM lifetime as a function of DM mass for NFW DM halo profiles assuming DM decays to νh . The blue line represents the derived limit considering IceCube and Auger neutrino fluxes. The red cross represents the KM3-230213A event observed by the KM3NeT collaboration in the plane of $\tau_{\text{DM}} - M_{\text{DM}}$. These limits are consistent with the present gamma-ray flux bounds as shown in the *right* panel of Fig. 1 for a value of DM mass $M_{\text{DM}} = 4.5 \times 10^8$ GeV with lifetime $\tau_{\text{DM}} = 1.2 \times 10^{30}$ s. The black dashed lines show KM3NeT sensitivity projections at 5 and 10 yr, based on the observation of 1 event, illustrating the potential constraints on the parameter space with continued observation along with the 335-day observation, considering 21 active strings. The green dashed lines correspond to the sensitivities for 5 and 10 yr, considering full construction of KM3NeT with 230 active strings.

events over a decade or more would place strong constraints on the parameter space favored by this interpretation, potentially ruling out SHDM as the source of the observed signal. Furthermore, the detection of similar high-energy neutrino events by other observatories such as IceCube or Auger would significantly strengthen the case for a SHDM origin.

To evaluate the compatibility of the KM3NeT neutrino event with the nonobservations reported by IceCube and Auger, we perform a joint likelihood analysis across all three experiments under the assumption that the event originates from the decay of SHDM, as detailed in the Supplemental Material [63]. The expected flux depends on the dark matter mass M_{DM} , and lifetime τ_{DM} , enabling us to identify a parameter region where the flux is sufficient to explain the KM3NeT event without exceeding the expected number of events at IceCube and Auger. The combined test statistic (TS) reaches a minimum for $M_{\text{DM}} = 4.5 \times 10^8$ GeV and $\tau_{\text{DM}} = 3.1 \times 10^{29}$ s, representing the best-fit values. The value of lifetime 1.2×10^{30} s as shown in Fig. 1 yields a combined tension of only 1.11σ . In contrast, a standard astrophysical power-law explanation assuming a common origin across the three experiments results in a significantly higher tension of $2.5 - 3\sigma$ [1,4]. This result

illustrates that the SHDM framework can effectively reconcile the apparent discrepancy between the observed event by KM3NeT and the null results by IceCube and Auger, thereby offering a competitive and testable new physics interpretation.

Stochastic gravitational waves from disappearing domain walls. When the scalar S acquires a vev, the Z_2 symmetry is spontaneously broken. A key consequence of this discrete symmetry breaking is the formation of domain walls (DWs), which arise due to the existence of distinct vacuum regions separated by energy barriers. The energy density of the DWs varies as a^{-1} , where a is the scale factor of expansion, whereas the energy densities of matter and radiation decrease as a^{-3} and a^{-4} , respectively. Thus, these DWs will soon overclose the Universe, which will contradict the present cosmological observations. However, they can be made unstable by introducing an explicit Z_2 -breaking term in the potential (say $\mu_b^3 S$). This induces a pressure difference across the walls, causing them to collapse and release their energy in the form of stochastic gravitational waves [29–35]. Note that these domain walls must vanish before the big bang nucleosynthesis epoch so that light nuclei can be synthesized in the early Universe.

For a DM mass of $M_{\text{DM}} = 4.5 \times 10^8$ GeV, a lifetime of 1.2×10^{30} s implies $y_{NL} \sin \theta \sim 3.48 \times 10^{-31}$. Now, for an RHN mass of $M_N = 10^{14}$ GeV, to get the light neutrino mass to be $m_\nu \sim 0.1$ eV, the Yukawa coupling must be $y_{NL} = 0.575$. Thus, the mixing angle is 6.05×10^{-31} . For this set of parameters, we then get $y_{N\chi} v_S \sim 8.55 \times 10^{-17}$ GeV. Now, taking four different values of v_S , we compute the GW amplitude and show the spectrum in Fig. 3. The benchmark

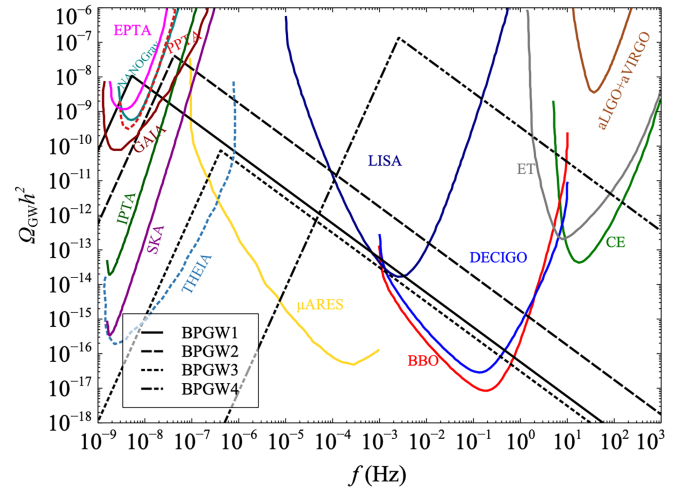


FIG. 3. Gravitational wave spectrum from annihilating domain walls for four benchmark points listed in Table I. Sensitivity curves of various gravitational wave experiments, BBO [36], CE [37], DECIGO [38], NANOGrav [39,40], EPTA [41], PPTA [42], ET [43], GAIA [44], IPTA [45], LISA [46], SKA [47], THEIA [44], aLIGO [48], aVIRGO, μARES [49], are shown in different colors.

TABLE I. Benchmark points for gravitational wave. Here M_S is the mass of S , λ_S is the quartic coupling of the scalar S , σ is the surface energy density or the tension of the DW defined as $\sigma \simeq 2/3 M_S v_S^2$, and T_{ann} is the temperature at which the DWs annihilate.

BPs	M_S (GeV)	v_S (GeV)	T_{ann} (GeV)	λ_S	σ (TeV ³)
BPGW1	1.47×10^5	9.73×10^5	0.22	1.14×10^{-2}	9.28×10^7
BPGW2	9.11×10^5	4.53×10^6	1.65	2.02×10^{-2}	1.25×10^{10}
BPGW3	1.23×10^6	8×10^6	16.03	8.75×10^{-3}	5.25×10^{10}
BPGW4	1.35×10^9	1.02×10^{10}	9.66×10^4	1.67×10^{-2}	9.31×10^{19}

points are shown in Table I. We find that the gravitational wave frequencies spanning from nHz to kHz range can be produced from DW annihilation, which can be observed at various GW detectors such as BBO [36], CE [37], DECIGO [38], NANOGrav [39,40], EPTA [41], PPTA [42], ET [43], GAIA [44], IPTA [45], LISA [46], SKA [47], THEIA [44], aLIGO [48], aVIRGO, μ ARES [49].

Conclusions and future directions. We explore the possibility that the recently observed high-energy neutrino event, KM3-230213A, reported by the KM3NeT collaboration, originates from the decay of super-heavy dark matter (SHDM). We consider an extension of the Standard Model that includes a right-handed neutrino (N), a singlet scalar (S), and a singlet fermion (χ), which serves as the DM candidate. The model is supplemented by a discrete Z_2 symmetry, under which S and χ are odd, while all other particles remain even. This Z_2 symmetry is spontaneously broken when S acquires a vacuum expectation value (vev), leading to a mixing between χ and N . Consequently, the DM can decay into neutrinos. We constrain the DM lifetime using IceCube's upper limits, along with the KM3NeT observation of KM3-230213A. Given the large uncertainties in the observed flux, we find that the event can be explained while remaining consistent with IceCube's upper bound for a DM mass of 4.5×10^8 GeV and a lifetime of 1.2×10^{30} s. We place limits on the lifetime of SHDM as a function of its mass. In our model, DM can also produce gamma rays. However, we find that current gamma-ray constraints are significantly weaker than the predicted flux for the same parameters that explain the KM3NeT observation, ensuring the viability of our framework. Furthermore, the breaking of the Z_2 symmetry leads to the formation of domain walls, whose subsequent collapse can generate a stochastic gravitational wave background. We estimated the expected GW spectrum and discussed its detectability in future observatories. The presence of such a GW signal would provide an

independent probe of the model, offering a multimessenger approach to study SHDM through neutrinos, gamma rays, and gravitational waves.

If the reheating temperature (T_{RH}) of the Universe is less than the mass of the DM, the DM relic might be produced through the dilute plasma or some nonthermal processes. One of the typical scenarios would be that the DM relic can be directly produced by the inflaton (ϕ) decay. In this case, the abundance of the DM can be given by, e.g., $Y_{\text{DM}} = (3/4)\mathcal{B}rT_{\text{RH}}/M_\phi$ where M_ϕ is the mass of the inflation and $\mathcal{B}r$ is the branching fraction of ϕ decay to the DM.

The future observations from next-generation neutrino and ultrahigh-energy cosmic ray observatories such as IceCube-Gen2 [64], AugerPrime [65], and the expanded KM3NeT/ARCA [66] configuration are expected to significantly improve our understanding of SHDM and the origin of UHE particles. The current lack of events above tens of PeV in IceCube and Auger, along with the detection of only one event in KM3NeT, highlights the need for further investigation. Enhanced sensitivity, increased exposure, and multimessenger approaches will be essential to test the viability of the SHDM decay hypothesis.

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

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