

KM3NeT 220 PeV event: A neutrino messenger from the grand unification scale?

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The 220 PeV neutrino KM3-230213A, in tension with IceCube and Auger unless the underlying spectrum is narrow (a $\sim 2\sigma$ upward fluctuation in any case), admits a two-body reading: relic decay $X \rightarrow \nu\bar{\nu}$ with $m_X \approx 4.4 \times 10^8$ GeV. Consistency with neutrino and γ -ray bounds sets $\tau/f \approx 10^{29} - 10^{30}$ s, lifetime over relic fraction. For a flavored $^1S_0$ onium, the operator scale lands in the Majorana-mass range of unified models: One Higgs insertion gives a singlet mediator, $M_{\text{med}}/|C_7|^{1/3} \approx 10^{14} - 10^{16}$ GeV across the allowed relic fraction; two give the seesaw window; Dirac or Majorana neutrinos select the branch. We give the construction and its decisive tests.

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The KM3NeT/astroparticle research with cosmics in the abyss (ARCA) detection of the muon event KM3-230213A, with reconstructed neutrino energy near 220 PeV and a 90% interval from 72 PeV to 2.6 EeV, is the highest-energy neutrino yet reported [1]. Its interpretation is set as much by nondetections as by the event. IceCube reports no comparable event [2], the Pierre Auger Observatory none in the EeV band [3–5], and Baikal-GVD sets consistent multi-PeV constraints [6]; a joint analysis finds a mild to moderate $1.6\sigma - 2.9\sigma$ tension across source hypotheses, mildest for a transient point source [7], and a cosmogenic origin is disfavored by the same EeV-band limits [8].

A narrow spectral feature at the event energy relaxes the cross-energy constraints once each is recast for a line with the assumed flux, flavor, direction, and duration (Fig. 1): A spectrum concentrated near 220 PeV is weakly constrained by the IceCube TeV–PeV limits, and the EeV-band limits from Auger and the in-ice radio arrays [9,10] are most sensitive above the line energy, pending recasts with their full response. What no spectral shape removes is the residual $\sim 2\sigma$ at the peak energy itself, an exposure effect carried by transience or by rarity, not by shape [7,11].

Two mechanisms make a narrow feature, and they do not make it equally narrow. An astrophysical accelerator can produce a resonant peak, but pion-decay kinematics typically broaden it to a factor of $\sim 2 - 3$ in energy for a quasimonoenergetic beam, the exact width depending on the parent spectrum, interaction angles, and detector response. A line, narrow to detector resolution, has a particularly economical origin, two-body decay $X \rightarrow \nu\bar{\nu}$ of a relic with $m_X = 2E_\nu \approx 4.4 \times 10^8$ GeV, a reading with an active literature in the neighboring νh and right-handed-neutrino channels [12,13] and in the collaboration's detector-level analysis, which includes the $\nu\bar{\nu}$ channel itself [14].

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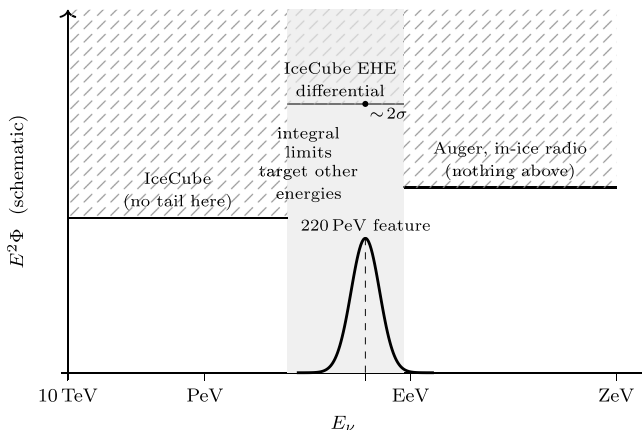


FIG. 1. Schematic of the spectral argument. A narrow feature at 220 PeV, whether the relic line developed here or the resonant astrophysical peak, falls in the energy window (shaded) between the IceCube TeV-PeV band and the EeV-band searches of Auger and the in-ice radio arrays [9,10]. Dark hatched regions indicate where those searches are most sensitive; they are flux, spectrum, flavor, direction, and duration dependent and must be recast for the assumed line rather than read as hard exclusions in energy, and electroweak radiation adds a continuum below the line. The lighter band marks IceCube’s differential extremely high-energy sensitivity, which does span the window; the dot marks the residual $\approx 2\sigma$ exposure tension at the line energy quantified in the text [2,7]. The heuristic point is only that a feature narrow in energy is weakly constrained by searches targeting other energies. Levels are indicative, not a fit.

This article develops the line reading into a quantitative, explicitly conditional claim: if the feature is a two-body decay line from a cosmologically long-lived flavored onium, and if the leading decay operator carries one electroweak-Higgs insertion with an $O(1)$ coefficient, then the neutrino energy sets the relic mass, the flux sets the lifetime-to-fraction ratio, and the lifetime sets the scale of the symmetry breaking that lets the relic decay, landing in the Majorana-mass window of unified models. We state the chain link by link, then the astrophysical alternative, and the tests that decide.

I. THE RELIC LINE AS A SCALE METER

The messenger chain. Three measured or inferred numbers map onto three theory scales. (1) Under the Galactic-end-point hypothesis, the energy fixes the mass, $m_X = 2E_\nu(1 + z_{\text{origin}}) \rightarrow 2E_\nu \approx 4.4 \times 10^8$ GeV for local decay, with the 90% interval spanning 1.4×10^8 to 5×10^9 GeV; the reconstructed energy assumes a spectral prior (Appendix); one event cannot tell end point from shoulder.

(2) The flux fixes the combination f/τ , with $f = \Omega_X/\Omega_{\text{DM}}$ the fraction of the dark matter residing in X ($f = 1$: X is all of it) and τ its lifetime; the inferred value is analysis dependent. A collaboration fit treating the event as typical returns $\tau \approx 10^{26} - 10^{27}$ s, in tension with neutrino and γ -ray bounds [14]; consistency with those bounds gives $\tau/f \approx 10^{29} - 10^{30}$ s across the $\nu\bar{\nu}$, νh , and right-handed-neutrino channels [12,13,15,16]. A public-exposure estimate anchored to the joint flux reproduces $\tau/f \approx (1-3) \times 10^{29}$ s; the collaboration’s detector-level $\nu\bar{\nu}$ fit, making the event typical of KM3NeT alone, returns the shorter value (Appendix). The ranges differ by up to 10^4 in τ but by at most a factor of ~ 5 in the scale.

(3) The lifetime, through the bound-state decay rate below, fixes an effective four-fermion coupling G_{eff} , and the operator that generates G_{eff} converts it into a mediator mass once the symmetry-breaking insertions are identified. The chain terminates, in its minimal form ($\tau/f = 10^{30}$ s, $C_7 = 1$), at $M_{\text{med}} \approx 10^{16} f^{1/6}$ GeV: 5×10^{15} GeV at the fiducial $f = 10^{-2}$ and 10^{16} GeV at

$f = 1$; the collaboration's best-fit lifetime, which makes the event typical of KM3NeT's exposure alone, would give $2\text{--}3 \times 10^{15}$ GeV but is in tension with the γ -ray and neutrino bounds (Appendix).

The flux fixes only f/τ : Both the Galactic and the extragalactic decay fluxes scale as f/τ , so the sky gradient and redshift structure (below) test the decay hypothesis and constrain the halo model but do not separate f from τ . The microscopic lifetime and hence the scale therefore carry an explicit relic-fraction dependence, $\tau = f(\tau/f)$ and $M_{\text{med}} \propto \tau^{1/6} \propto f^{1/6}$ at fixed f/τ ; the numbers below take the fiducial $f = 10^{-2}$, motivated by an axion-dominated dark sector (Appendix); $f = 1$ bounds the scale.

Why an onium. A two-fermion final state $\nu\bar{\nu}$ requires a bosonic parent; among bosonic options we take a flavored $^1S_0$ onium $\bar{Q}'Q$, the case that ties the lifetime to a high-scale operator. A single fermion's two-body decay is instead νh or νZ ; an elementary boson is viable but has no bound-state relation between rate and scale. A same-flavor onium annihilates promptly through its own gauge interactions ($\Gamma \sim \alpha_{\text{eff}}^5 m_X$) and cannot survive cosmologically; the relic must be the flavored combination, stable under an accidental flavor symmetry of the dark sector and decaying only through the operator that breaks it.

Stability places a sharp requirement on that symmetry. Quantum gravity is expected to violate global symmetries, and a Planck-suppressed dimension-6 operator $(\bar{Q}'i\gamma_5 Q)(\bar{\nu}\nu)/M_{\text{Pl}}^2$ would give $\tau \sim 10^{12}\text{--}10^{15}$ s (across reduced and unreduced M_{Pl} conventions), short of the age of the universe by a factor of at least 300 regardless of convention; the flavor symmetry therefore cannot be an accident of the low-energy Lagrangian alone but must be protected, most economically as a discrete gauge symmetry, which survives gravitational violation [17]. The selected operator then preserves the gauged Z_N and breaks only the accidental continuous flavor symmetry, which requires a lepton-sector field to carry a compensating dark charge; a ν_R so charged has its Dirac Yukawa forbidden by the same symmetry, so the ν_R entering the decay operator must be a light sterile state distinct from those generating the Dirac masses; with its Yukawa forbidden and only M_{med}^{-3} -suppressed interactions, it never thermalizes, leaving ΔN_{eff} unaffected. The protection requirement is the reason the decay proceeds only through the high-scale operator whose coefficient the lifetime then measures.

The bosonic channel is also the γ -quiet one: A fermionic relic decaying through νh puts half the energy into a Higgs cascade and faces stronger γ -ray constraints [12,13], while $\nu\bar{\nu}$ deposits everything into neutrinos up to electroweak radiation.

The symmetry can be as small as a Z_N under which Q and Q' carry different charges, provided the assignment is anomaly-free, stabilizes the flavored onium, forbids every operator below the dimension of the selected operator, admits the selected operator, and induces no faster channel through the mediator sector; the explicit charge table is completion-level work not performed here. The charge assignment fixes which insertion, and hence which operator dimension, first connects the dark bilinear to neutrinos.

The lifetime as a scale meter. The decay is a bound-state annihilation, so the rate factorizes into the wave function at contact and the constituent annihilation through the effective operator,

$$\Gamma_d(X \rightarrow \nu\bar{\nu}) = |\psi(0)|^2 \langle \sigma v \rangle_d \equiv \kappa \alpha_{\text{eff}}^3 m_X^5 G_{\text{eff}}^2, \quad G_{\text{eff}} \sim \frac{v_H^{d-6}}{M_{\text{med}}^{d-4}}, \quad (1)$$

with $|\psi(0)|^2 = (\alpha_{\text{eff}} m_X/4)^3/\pi$ for the Coulombic $^1S_0$ ground state, the state a pseudoscalar dark bilinear couples to at leading order (a scalar bilinear instead projects onto the velocity-suppressed P wave), $\langle \sigma v \rangle_d \sim G_{\text{eff}}^2 m_X^2$, $\alpha_{\text{eff}} \approx 0.05$, and $\tau_d = \Gamma_d^{-1}$; the factor κ collects the wave-function normalization, spin projection, phase space, dark-color factors, and active-neutrino multiplicity, equal to $1/(64\pi)$ for the displayed factors alone, with the complete spin-projected calculation for a specified dark gauge group modifying it at $O(1)$; equal constituent masses $m_Q = m_X/2$ are assumed throughout. Here, M_{med} is the mediator scale and v_H the vacuum expectation value (vev) of the field supplying the $(d-6)$ flavor-breaking insertions of a dimension- d operator. For reference, the remaining mass symbols of this article are the seesaw mass M_R , the Planck mass M_{Pl} , the

five-dimensional (5D) gravity scale M_* of the black-hole reading, and the black-hole mass M_{BH} of the astrophysical alternative; lowercase m_X and $m_Q = m_X/2$ are the relic and constituent masses. The benchmark $\alpha_{\text{eff}} \approx 0.05$ is the dark coupling evaluated at the Bohr momentum $\alpha_{\text{eff}} m_X/4$; any value compatible with confinement below that momentum serves, and the inference inherits only the mild $M_{\text{med}} \propto \alpha_{\text{eff}}^{1/2}$ sensitivity noted below. The observable fixes the coupling, not the scales separately: $\tau \approx 10^{30}$ s at $m_X = 4.4 \times 10^8$ GeV gives

$$G_{\text{eff}} \approx 1.8 \times 10^{-47} \kappa^{-1/2} \text{ GeV}^{-2}, \quad (2)$$

i.e., $2.5 \times 10^{-46} \text{ GeV}^{-2} \approx 2 \times 10^{-41} G_F$ at the Coulombic normalization.

The decomposition then reads off the ultraviolet. A pure four-fermion operator ($d = 6$, no insertion) needs $M_{\text{med}} \approx 0.6\text{--}2.4 \times 10^{23}$ GeV, trans-Planckian, and is forbidden by the gauged flavor symmetry above. The leading allowed operator carries one insertion. If that insertion is the electroweak Higgs, e.g., $\mathcal{O}_7 = (\bar{Q}' i \gamma_5 Q)(\bar{L} \tilde{H} \nu_R)/M_{\text{med}}^3$ for Dirac neutrinos [each decay pairs an active neutrino with a light sterile state, an $O(1)$ factor folded into f/τ], built from the gauge-invariant Dirac-neutrino Yukawa structure $\bar{L} \tilde{H} \nu_R$ (for systematic operator bases with right-handed neutrinos, see Refs. [18–20]), then $v_H = v \approx 246$ GeV and the operator coefficient C_7 enters through $G_{\text{eff}} = C_7 v/M_{\text{med}}^3$, so the observable fixes $M_{\text{med}}/|C_7|^{1/3}$, not M_{med} alone:

$$\frac{M_{\text{med}}}{|C_7|^{1/3}} \simeq 1.0 \times 10^{16} \text{ GeV} (64\pi\kappa)^{1/6} \left(\frac{\alpha_{\text{eff}}}{0.05} \right)^{1/2} \left(\frac{\tau}{10^{30} \text{ s}} \right)^{1/6} \left(\frac{m_X}{4.4 \times 10^8 \text{ GeV}} \right)^{5/6}. \quad (3)$$

At the Coulombic $\kappa = 1/(64\pi)$, with $\tau = f(\tau/f)$ at $\tau/f = 10^{30}$ s, this is $M_{\text{med}}/|C_7|^{1/3} \approx 10^{16} f^{1/6}$ GeV, i.e., 5×10^{15} GeV at the fiducial and 10^{16} GeV at $f = 1$; every rate-normalization uncertainty enters through the sixth root.

Two insertions give the onium-dressed Weinberg structure [21] $\mathcal{O}_8 = (\bar{Q}' i \gamma_5 Q)(LH)(LH)/M_{\text{med}}^4$, a $\Delta L = 2$ operator producing $\nu\nu$ at the same line energy, with $M_{\text{med}} \approx 2\text{--}8 \times 10^{12}$ GeV across κ and $f = 10^{-2}\text{--}1$, the classic seesaw window [22–25]. If the insertion is instead a high-scale flavon with $\langle \Phi \rangle \sim m_X$, the same decomposition with $v_H \sim m_X$ applies and M_{med} returns toward 10^{18} GeV.

The minimal single-Higgs reading is the one we headline; it carries a direct link, in that the required insertion is the same LH combination that enters the neutrino-mass operator, connecting the relic lifetime, the inferred scale, and the neutrino-mass sector within this reading.

The fork between the two readings is itself a neutrino-physics statement. The single-insertion operator $\mathcal{O}_7$ requires a light right-handed neutrino, natural alongside Dirac-type neutrino masses; if neutrinos are Majorana and no light ν_R exists, the leading operator is $\mathcal{O}_8$, and the meter reads the seesaw scale instead. Either way, the line is a messenger from the far-ultraviolet neutrino sector; under the minimal assumption that the leading allowed operator dominates, which decade it reports is tied to the Dirac-versus-Majorana question. The correlation is a feature of the minimal reading, not of generic models, and it breaks if $\mathcal{O}_7$ and $\mathcal{O}_8$ contribute comparably or if a flavon supplies the insertion.

The scale is stable because of the sixth root: The full lifetime range $10^{26}\text{--}10^{30}$ s spans $M_{\text{med}}/|C_7|^{1/3} \approx 2 \times 10^{15}\text{--}10^{16}$ GeV, and the 90% energy interval, entering through $G_{\text{eff}} \propto m_X^{-5/2}$, together with the span of κ and a relic fraction anywhere down to the survival floor $f \gtrsim 4 \times 10^{-12}$ (below which the population has decayed), widens this to roughly $10^{14}\text{--}10^{17}$ GeV.

The bound-consistent normalization places the mediator within a factor of a few of the unification scale, $\approx 5 \times 10^{15}$ GeV at the fiducial $f = 10^{-2}$ and 10^{16} GeV at $f = 1$; the collaboration's best fit, in tension with γ -ray bounds within the decay hypothesis, would lower it to $2\text{--}3 \times 10^{15}$ GeV. We headline the bound-consistent value. The constituents themselves are standard model singlets charged under a dark-color group (see below), so gauge coupling unification is untouched, and the mediator at M_{med} can belong to the unified sector that communicates the flavor breaking to $\bar{L} \tilde{H} \nu_R$; we present this as consistency, not derivation.

The Majorana window. The landing points bracket the scale unified models assign to neutrino mass. The seesaw relation $m_\nu = y^2 v^2/M_R$ puts $M_R \approx 1.2 \times 10^{15} y^2 (0.05 \text{ eV}/m_\nu)$ GeV, so the

one-insertion mediator at $(3\text{--}5)\times 10^{15}$ GeV corresponds to $y \approx 1.6\text{--}2$ or $m_\nu \approx 0.01\text{--}0.02$ eV (the former large, $y^2/4\pi \approx 0.2\text{--}0.3$, mildly favoring the latter reading), and the two-insertion window $10^{12}\text{--}10^{13}$ GeV to $y \approx 0.03\text{--}0.09$: Both branches sit inside the Majorana-mass range of unified models.

The gauge-unification point, 2×10^{16} GeV, probed by proton decay, lies above the landing; the mediator belongs more naturally to the seesaw sector than to the gauge sector, the singlet constituents leaving gauge-coupling running untouched. On the Dirac branch, the mediator's Majorana character is a property of the completion, so the statement is an overlap, not a derivation: The selected dimension-7 operator with an $O(1)$ coefficient lands the scale in the range unified models assign to their heavy singlets; we do not construct the completion.

II. COSMOLOGY AND SIGNATURES

Production, binding, survival. The required abundance is minute, which makes production easy. For the benchmark lifetimes, $\Omega_X h^2 = 0.12 f$ corresponds to a comoving yield $n_X/s \approx 10^{-18} f$. Such a yield is a generic outcome of nonthermal production, not a prediction of a specific reheating temperature: Gravitational particle production alone can reach it for suitable inflationary scales at $m_Q \sim 10^8$ GeV [26], and production from the bath during reheating supplies it for T_{RH} well below m_Q [27], the required value depending on the production operator, coupling, and thermal history rather than on the Boltzmann factor alone. A viable completion must supply one such mechanism; we do not fix it here. Keeping T_{RH} below m_Q also avoids a thermalized heavy-quark population, which at $m_Q \approx 2\times 10^8$ GeV would violate the unitarity bound on thermal relics [28].

Binding requires a Coulombic hierarchy, the inverse Bohr radius $\alpha_{\text{eff}} m_X/4 \approx 5.5\times 10^6$ GeV well above the dark confinement scale Λ_d , and its efficiency is a statement about confinement, not a rate competition. At a yield of 10^{-18} per unit entropy, no collisional channel operates; radiative capture into the Coulombic ground state gives $\Gamma/H \lesssim 10^{-13}$ at any temperature (Appendix). What binds the constituents is the confinement transition itself: In a dark sector with no matter below Λ_d , an isolated dark-color charge cannot be screened, so at the transition every surviving quark exits attached by a flux tube to the nearest anticharge and is drawn into a bound state with unit probability, the quirk mechanism [29–31]. The string cannot break, since nucleating a heavy pair costs $e^{-\pi m_Q^2/\Lambda_d^2}$, and for $\Lambda_d \lesssim 10^3 f^{1/3}$ GeV the string energy at the mean separation stays below $2m_Q$, so the capture is nonrelativistic; the conditions for efficient formation are therefore spectroscopic, set by the particle content of the dark sector, and are quantified in the Appendix.

The flavored-onium survival fraction after confinement then depends on the relative Q, Q' abundances, any flavor asymmetry, and the full hadron inventory of the confining sector (same-flavor onia, dark baryons, glueballs, and hybrids) with its rearrangement rates, and warrants a dedicated Boltzmann treatment we defer. We take it as an $O(1)$ factor absorbed into f , a benchmark assumption rather than a demonstrated result.

Dark confinement also disarms the constraint that kills the colored version: Constituents with standard model color would leave free-quark relics bound into anomalously heavy isotopes, excluded far below any plausible leftover fraction, so the constituents are singlets, vectorlike under the dark group.

Line shape and flavor at Earth. The spike at $m_X/2$ is broadened only by detector resolution and by the electroweak final-state radiation that necessarily dresses a $\nu\bar{\nu}$ final state at $m_X \sim 4\times 10^8$ GeV, a soft continuum computed for this channel, with electroweak corrections, in the likelihood of Ref. [16]; the νh and right-handed-neutrino analyses [12, 13], with their larger photon output, bracket the $\nu\bar{\nu}$ case conservatively. The full spectral shape carries a signature of its own: The Galactic component is a sharp edge at $m_X/2$, while the extragalactic component of the same decay arrives redshifted, filling a tail below the edge with weight concentrated within a factor of ~ 2 ($z \lesssim 1$); the predicted feature is an edge with a redshifted shoulder, not a symmetric bump (Fig. 2), and the shoulder is far too short to engage the IceCube TeV-PeV limits.

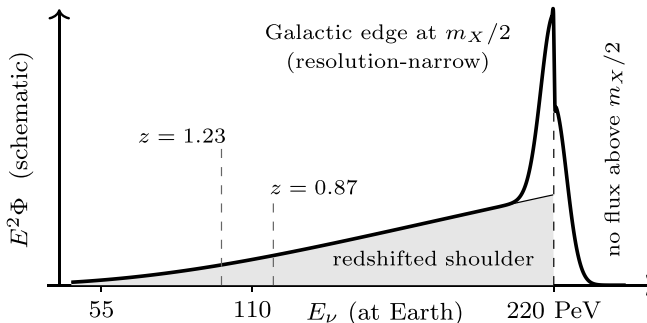


FIG. 2. Predicted shape of the relic line (schematic). The Galactic component of the decay flux is an edge at $E = m_X/2$, narrow to detector resolution; the extragalactic component of the same decay arrives redshifted, $E = (m_X/2)/(1+z)$, and fills the redshifted shoulder below the edge (shaded). Since every epoch emits at the same rest-frame energy, each energy below the edge maps to an emission redshift, weighted by the proper time the universe spends there, $dt/dz \propto [(1+z)H(z)]^{-1}$; hence, $E^2\Phi \propto [(1+z)\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}]^{-1}$, falling to $\approx 30\%$ of the edge value by $z = 1$ (110 PeV at Earth) and $\approx 6\%$ by $z = 3$; the majority of shoulder events lie within a factor of 2 of the edge. Nothing lies above $m_X/2$ beyond resolution smearing, since the decay has no higher energy to give and redshift only lowers it. Electroweak final-state radiation adds a soft continuum well below the peak (not shown). The labeled dashed verticals mark $(m_X/2)/(1+z)$ for the measured counterpart redshifts, $z = 0.87$ (PKS 0605–085) and $z = 1.23$ (PMN J0606–0724) [39]: Under the line reading, decays at the counterpart distances populate the shoulder at 118 and 99 PeV, not the 220 PeV edge. Levels are indicative, not a fit.

Flavor is observed after propagation: Over the halo and extragalactic baselines, the oscillation phases fully decohere, matter effects are negligible along halo and intergalactic paths even at 220 PeV, and decohered vacuum mixing maps source flavor onto $\sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$ at Earth. A democratic or incoherent source gives every flavor above $\approx 15\%$; a single mass eigenstate is the exception (pure ν_3 : electron fraction of a few percent), so the flavor prediction is operator dependent, and we quote it for the assumed $\bar{L}\bar{H}\nu_R$ structure with democratic lepton-flavor coefficients, giving a nonzero ν_τ component. In the Dirac operator, one of the two produced states is a light sterile state, undetected; the detectable flux is the active member, and for a charge-symmetric $X-\bar{X}$ population it is $\nu/\bar{\nu}$ symmetric, unlike the $\bar{\nu}_e$ -poor photohadronic alternative below, though $\nu/\bar{\nu}$ discrimination is statistical at best.

Sky morphology and rate. The source is the dark-matter halo, so the flux traces the line-of-sight column, diffuse with no counterpart, no time clustering, and no preferred distance. Because decay integrates the density rather than its square, the anisotropy is gentle; the Galactic-center-to-anticenter ratio is a factor of a few for standard halo profiles, and the extragalactic component is isotropic, so the morphology test needs several events.

The event direction [right ascension (RA) 94.3° , declination (Dec) -7.8°] lies toward the Galactic anticenter, near the halo minimum, where the column falls below the all-sky average by a factor of order 2 for standard profiles; this is a mild prior against the halo origin. The same f/τ that yields one event in the partial-array exposure predicts a rate scaling directly with the completed ARCA exposure and with IceCube-Gen2, with arrival directions accumulating toward the Galactic center.

The prediction is bounded rather than open ended: IceCube’s larger integrated exposure has not accumulated events at these energies, so the line hypothesis requires the KM3NeT detection to be an upward fluctuation at the level quantified by the joint-exposure analysis [7], which also caps the rate expected at the completed arrays; the accompanying electroweak-radiation photons, as computed for the $\nu\bar{\nu}$ channel in Ref. [16] and bracketed from above by the γ -richer νh and right-handed-neutrino analyses [12, 13], sit at or below existing bounds; the shower’s $O(1)$ chirality and flavor dependence is not recomputed here.

III. ALTERNATIVE READINGS

The astrophysical alternative. The reading the line must beat is a resonant peak from a flaring accelerator, and it is a serious competitor because candidate counterparts exist. A quasimonoenergetic proton beam from electrostatic gap acceleration in a black-hole magnetosphere [32–34], at $E_p \approx 20 E_v \approx 4.4$ EeV for fiducial parameters [35], interacting at the $\Delta(1232)$ resonance with the thermal infrared field of warm dust, produces a peak (the mechanism of the 30 TeV diffuse break on keV targets [36,37], with multipion production relevant in Ref. [36]) whose energy measures the target through $\varepsilon_0 E_p \approx 0.16$ GeV², selecting dust at $T \approx 150$ –300 K; an accretion-flare interpretation with a dust-echo target has been developed for the candidate MRC 0614–083 [38], and the counterpart study finds a radio flare of PMN J0606–0724 coincident with the arrival time (pretrial 0.26%, not corrected for trials), and a γ -ray flare of PKS 0605–085 peaking before it [39,40].

The peak is not a line: Pion-decay kinematics broaden it even for a delta-function beam; its composition is $\bar{\nu}_e$ poor and possibly muon damped [41]; its parent protons are strongly deflected or decay before arrival, and its cascade photons are delayed and diluted by the intergalactic field. The quantitative content, the curvature-radiation ceiling, the photopion optical depth, and the muon-damping condition, is given in the Appendix; the point here is the fork. A decisive comparison requires folding both hypotheses through the same KM3NeT energy and angular response, which we do not attempt; at the article level, width, sky distribution, and counterpart behavior are the discriminating observables. The two readings are also spectrally exclusive; Appendix makes the statement precise.

Relation to other new-physics readings. The event has drawn a range of beyond-standard-model interpretations, from modified neutrino propagation and dark-matter-induced effects along the flight path [42] and source-side dark-matter annihilation [43] to general assessments of what new physics the single event can support [44]. A dark-particle flux from a transient astrophysical source has also been proposed to remove the KM3NeT-IceCube exposure tension [45]. A beam of dark fermions X upscatters coherently in the Earth, $XN \rightarrow X'N$ through a light mediator, with $\sigma_X^{\text{coh}} \approx 2.8 \times 10^{-34} \text{ cm}^2 (g_X g_B / 10^{-4})^2$ at $m_{Z'} = 300$ MeV for their benchmark parameters; the prompt decay $X' \rightarrow X\phi$ releases a metastable scalar that decays as $\phi \rightarrow \mu^+ \mu^-$ with laboratory-frame length $\ell_d \sim 100$ km, so the observed track is a collimated pair carrying $E_{\mu^\pm} \approx E_X/4$. The rate follows the column depth ahead of the detector, $L_{\text{KM}} \approx 140$ km against $L_{\text{IC}} \approx 14$ km for this arrival direction, giving $R_{\text{IC/KM}} \approx 0.07$ and no expected IceCube counterpart. The reading requires a transient source and a rate that tracks column depth, so it is distinguished from the line by the absence of a fixed edge and by zenith and time dependence.

Most such readings modify how an astrophysical messenger travels or interacts; the line reading is different in kind because it replaces the source, making the feature's width, position, flavor, and sky distribution Lagrangian parameters rather than source properties. One other reading also replaces the source and also ties the event to a superheavy scale, the Hawking flare of a primordial black hole, and it deserves a comparison of its own (below).

The EeV-scale ANITA anomalies [46–48], which have drawn subsurface-reflection and other instrumental readings [49] alongside new-physics ones, lie well above $m_X/2$ and are unconnected to the line, whose flux ends at 220 PeV. Table I collects the readings discussed in this article and the observables that separate them.

A second superheavy-scale reading: black-hole flares. Hawking evaporation of a primordial black hole (PBH) has been proposed as the origin of the event [50,51]: Only the terminal burst reaches the required temperature, so the source must be close, and multimessenger analyses disfavor the minimal four-dimensional (4D) scenario because the accompanying preburst γ -ray and lower-energy neutrino emission should have been seen [52,53]. The dark-dimension variant [54] evades this: Five-dimensional PBHs are larger, colder, and longer-lived than four-dimensional holes of the same mass, evaporate dominantly into gravitationally coupled bulk modes invisible on the brane, and release a hot flare of standard model particles only in the final stage, at temperature

TABLE I. Readings of KM3-230213A discussed in this article. The first six are new-physics readings; the last is the astrophysical alternative the line must beat. M_{med} is the mediator scale of the decay operator and M_* is the five-dimensional gravity scale.

Reading	Source of the event	Spectrum at Earth	Time and sky	Companion signals	Scale read off
Flavored-onium line (this article)	Two-body decay $X \rightarrow \nu \bar{\nu}$ of a halo-plus-extragalactic relic	Resolution-narrow edge at $m_X/2$ with redshifted shoulder; nothing above	Steady; gentle halo-column gradient; no counterpart	Soft electroweak-radiation γ continuum near bounds; nonzero ν_τ fraction	$M_{\text{med}} \approx 10^{14}\text{--}10^{16}$ GeV from the lifetime
Superheavy relic, other channels [12–14,16]	Relic decay to νh , right-handed neutrino, or multiparticle final states	Neutrino line plus cascade continuum alone, by channel	Steady; halo morphology	Harder γ -ray output than $\nu \bar{\nu}$; collaboration best fit in tension with bounds	τ/f ; operator scale model dependent
PBH terminal burst, 4D [50,51]	Hawking burst of a nearby evaporating hole	Broad quasithermal burst	One-time transient; single direction	Democratic preburst γ and lower-energy ν ; nonobservation disfavors this case [52,53]	PBH temperature, hence its mass
PBH flare, 5D dark dimension [54]	Terminal standard model flare of a five-dimensional hole	Monoenergetic at $T_\bullet \approx 0.1M_*$ in Ref. [54]; thermal $\Delta E/E = O(1)$ at fixed $T_\bullet$; capped near M_*	Steady population flux; halo clustered; same morphology as decay	$\gamma:\nu = 1:3$ (1:6 with Dirac ν_R) unless further suppressed; hard diffuse γ at the flare energy	$M_* \sim 10^9$ GeV
Propagation and source-side effects [42,43]	Astrophysical neutrino modified en route or at the source	Tied to the source spectrum	Follows the source population	Source dependent	New coupling and mass; no single scale
Transient dark-particle flux [45]	Dark fermions from a transient source, upscattering in the Earth to a scalar decaying to $\mu^+\mu^-$	Set by the source flux; the track carries $E_{\mu^\pm} \approx E_X/4$, no edge	Transient; rate follows column depth, so strongly zenith dependent	No neutrino counterpart required; $R_{\text{IC/KM}} \approx 0.07$ explains the IceCube null	Mediator mass and couplings; no single scale
Warm-dust peak (astrophysical) [38–40]	Δ -resonant photoproduction of a gap-accelerated beam on warm dust	Peak broadened to a factor of $\sim 2\text{--}3$ by pion kinematics	Transient; candidate counterpart flares	$\bar{\nu}_e$ poor, possibly muon damped; delayed, diluted cascade photons	Dust temperature $T \approx 150\text{--}300$ K, not a UV scale

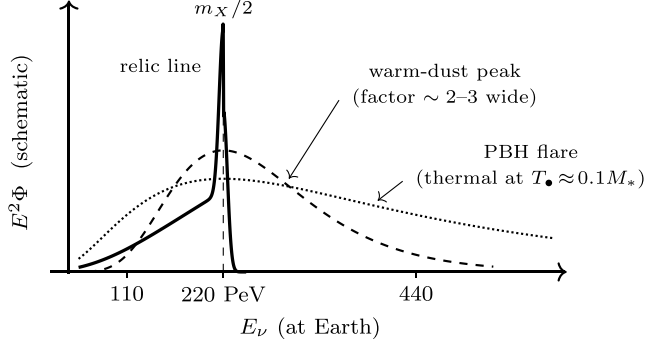


FIG. 3. Schematic comparison of the three spectral shapes at Earth, normalized near 220 PeV. The relic decay line (solid) is the shape of Fig. 2: a resolution-narrow Galactic edge at $m_X/2$ over the redshifted extragalactic shoulder, with nothing above the edge. The astrophysical warm-dust peak (dashed) is broadened to a factor of ~ 2 – 3 by pion-decay kinematics. The terminal flare of a primordial black hole (dotted) is monoenergetic at $T_\bullet \approx 0.1 M_*$ in the benchmark of Ref. [54]; drawn is the thermal spectrum of Hawking emission at that temperature, with $\Delta E/E = O(1)$ and a tail capped near M_* . The line alone terminates at $m_X/2$; both alternatives supply flux above the edge, so an event above it excludes the line, and the width test separates the line from both. Levels are indicative, not a fit.

$T_\bullet \approx 0.1 M_* \sim 10^8$ GeV for the five-dimensional gravity scale $M_* \sim 10^9$ GeV, which at once matches the event energy and mutes the constraints.

The relic decay line developed here and the five-dimensional black-hole flare [54] share a claim (a superheavy scale read off a single neutrino), and they share the exposure trade as well: With at most $\sim 10^3$ visible quanta of $\sim 10^8$ GeV per hole, no single flare is detectable, so the observable flux is the steady output of the flare population, normalized in Ref. [54] to one event per century of km^2 -scale exposure, the same upward fluctuation the line carries. They separate on two observables and converge on a third. First, spectrum: The benchmark of Ref. [54] treats the emission as monoenergetic at $T_\bullet$, so at that level both readings predict a narrow feature near the observed energy; physically, Hawking emission at fixed $T_\bullet$ is thermal, with $\Delta E/E = O(1)$ and a tail capped near M_* , while the line is resolution narrow with a hard edge, a redshifted shoulder of calculable shape, and nothing above $m_X/2$ (Fig. 3); accumulated events above the edge would favor the flare, and the edge-plus-shoulder decomposition is the line’s signature.

Second, companions: Within its standard model stage, Hawking emission is democratic across degrees of freedom, and Ref. [54] quotes the ratio, photons to neutrinos at 1:3 for standard model content, softened to 1:6 by Dirac right-handed neutrinos, with further suppression requiring supersymmetric additions or an early recoil of the hole into the bulk. The flare population therefore predicts a hard diffuse photon flux at the flare energy at a fixed fraction of the neutrino flux, whereas the line’s only photon companion is the soft electroweak-radiation continuum; the diffuse γ -ray budget at 10^8 GeV is the discriminant, and it is one sided: A detected hard photon flux at the flare energy would establish the flare and exclude the line, while deepening null results confine the flare to its suppressed variants and cost the line nothing, its photon output sitting below the bounds by construction. (The same democratic emission, arriving preburst at lower energies, is what disfavors the four-dimensional case [52,53].)

Third, time and sky converge rather than separate: The flare population is halo clustered and steady, bounded in Ref. [54] by the same IceCube halo-decay limits that constrain the line, so both readings predict steady, counterpart-free events tracing the halo column, and morphology does not choose between them. The complementarity is clean: The flare temperature reads the quantum-gravity scale M_* through $T_\bullet \approx 0.1 M_*$, the line lifetime reads the mediator scale M_{med} ; width and photon companions, both near-term observables, decide between them.

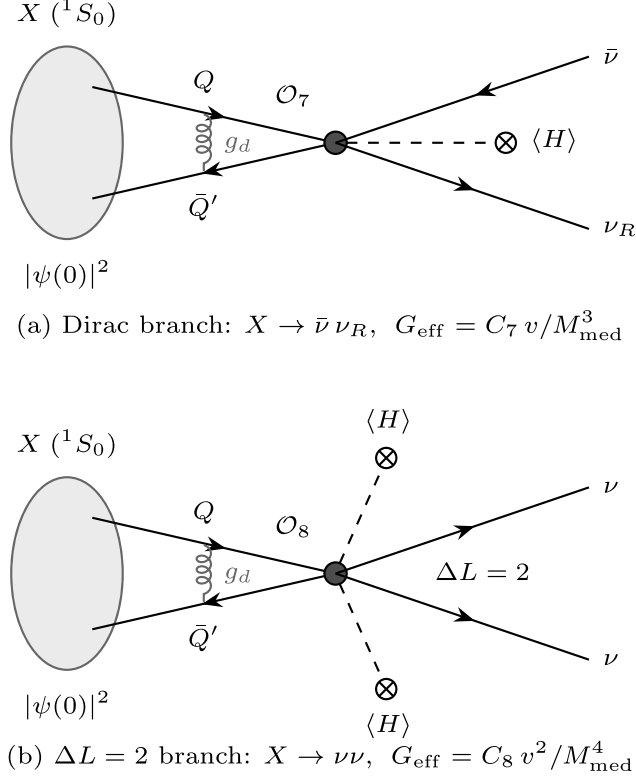


FIG. 4. Effective-operator diagrams for the two decay branches of the flavored onium. The shaded ellipse is the $^1S_0$ bound state whose contact wave function $|\psi(0)|^2$ enters Eq. (1), with the coil marking the dark-gluon binding; the filled vertex is the contact operator, with no completion assumed, and the crossed circles mark electroweak vev insertions. In panel (a), the single insertion closes $\mathcal{O}_7$ and the decay produces an active-sterile pair; in panel (b), two insertions close $\mathcal{O}_8$ and the clashing fermion-flow arrows mark $\Delta L = 2$.

IV. SPECTROSCOPY, COMPLETION, AND TESTS

Spectroscopy of the dark sector. If events accumulate, the edge position measures m_X , the normalization f/τ , the edge-to-shoulder ratio the Galactic-to-extragalactic split and halo column, and the flavor ratios the operator's chirality structure through the averaged mixing (Appendix). Galactic and extragalactic columns are comparable for standard profiles, so edge and shoulder share events roughly evenly, and the split is measured to $\sim N^{-1/2}$: Tens of events begin to constrain the split, and of order 100 approach 10% statistical precision, before backgrounds and energy resolution are folded in; the edge/shoulder decomposition is an estimate, not a likelihood forecast.

What a unified completion must deliver. The construction is a checklist rather than a model: (1) A vectorlike pair Q, Q' of standard model singlets charged under a dark-color group confining below the Bohr momentum; (2) a gauged discrete flavor symmetry distinguishing them, forbidding every operator below the selected dimension, with the lepton-sector charges compatible with the neutrino Yukawas; (3) a mediator in the inferred 10^{15} – 10^{16} GeV window (fiducial f to $f = 1$) coupling the dark bilinear to $\bar{L}\tilde{H}\nu_R$, or the double-insertion Weinberg analog at the seesaw scale (Fig. 4); and (4) a nonthermal production mechanism yielding $n_X/s \approx 10^{-18}f$. Each ingredient is individually standard; establishing that they coexist in one unified group, with the onium surviving confinement and no faster decay allowed, is the follow-up work on which a firm claim would depend.

Tests. The reading is falsifiable on a short horizon.

(1) *Morphology*. Subsequent events at 100–300 PeV tracing the halo column, with a soft gradient toward the Galactic center and no repeating position, support the line; clustering at RA 94.3°, Dec -7.8° , or a second neutrino coincident with a flare of PMN J0606–0724 or PKS 0605–085, decides for the astrophysical peak.

(2) *Width*. With several events, a spread consistent with detector resolution supports the line, with the redshifted shoulder supplying an internal consistency check once a few events exist; a factor 2–3 spread supports the peak or the flare (Fig. 3). Any confirmed event at, say, 10 EeV falsifies both single-feature hypotheses and lies beyond the reach of the terminal flare as well, whose emission is capped near the five-dimensional scale $M_* \sim 1$ EeV.

(3) *Timing*. An IceCube time-dependent search at the event position restricted to a window of $\lesssim 2$ years around February 2023 tests the transient alternative directly [11]; a null result there disfavors the tested transient models and windows, not generic astrophysical production.

(4) *Companions*. The electroweak-radiation photon shoulder is a diffuse γ -ray prediction, computed for the $\nu\bar{\nu}$ channel in Ref. [16] and bounded from above by the γ -richer νh and right-handed-neutrino channels [12,13], and a nonzero ν_τ flux component at 220 PeV follows from the averaged mixing for the assumed operator.

(5) *Theory side*. The construction requires a gauged discrete flavor symmetry and nonthermal production of the relic; neither is directly observable, and testing them requires embedding the checklist in an explicit completion, which is separate work.

(6) *Cross-check*. The two-insertion reading requires $\Delta L = 2$, so an observation of neutrinoless double-beta decay would establish the Majorana character that branch assumes, while Dirac neutrinos select the one-insertion mediator; proton decay probes the gauge sector above the window and remains complementary. The reading also degrades gracefully: If no further events arrive as the exposure grows, the same analysis converts into the strongest limit on $\nu\bar{\nu}$ -decaying relics at $m_X \approx 4 \times 10^8$ GeV, pushing τ/f upward and, through $M_{\text{med}} \propto \tau^{1/6}$, the inferred mediator scale with it.

One event cannot settle the question, but the reading is sharp, the arithmetic definite. The chain is conditional at each link, and its conclusion is concrete: If the 220 PeV feature is a two-body decay line from a cosmologically long-lived flavored onium, and if the leading operator carries one electroweak-Higgs insertion with an $O(1)$ coefficient, then the event points to the Majorana sector of unified models, with a singlet mediator at $M_{\text{med}}/|C_7|^{1/3} \approx 10^{16} f^{1/6}$ GeV, spanning 10^{14} – 10^{16} GeV across the allowed fraction, on the Dirac branch, or the seesaw window on the $\Delta L = 2$ branch, robust at the order-of-magnitude level.

This remains noteworthy without implying evidence for unification: The chain reads a mediator mass, and with it the Majorana-mass scale of unified models, off a detected neutrino. Each link has an observable consequence, and the first discriminants, morphology and width, arrive with the completed ARCA array; a detector-level line likelihood folded through the KM3NeT response is the natural next step. If the discriminants favor the line, the most energetic neutrino yet detected points to the Majorana-mass scale of grand unification; if they favor the peak, the same event probes black-hole gap acceleration on warm dust.

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DATA AVAILABILITY

No new data were created in this study. The published measurements on which the analysis relies are openly available from the KM3NeT event data release [55] and from the IceCube extremely-high-energy search data release [56].

APPENDIX

Onium lifetime ladder. With $|\psi(0)|^2 = (\alpha_{\text{eff}} m_X/4)^3/\pi$, $\alpha_{\text{eff}} \approx 0.05$, and $m_X = 4.4 \times 10^8$ GeV, Eq. (1) at $\tau = 10^{30}$ s gives $G_{\text{eff}} \approx 1.8 \times 10^{-47} \kappa^{-1/2} \text{ GeV}^{-2}$, i.e., $2.5 \times 10^{-46} \text{ GeV}^{-2}$ at the Coulombic $\kappa = 1/(64\pi)$. Inverting the decomposition $G_{\text{eff}} = v_H^{d-6}/M_{\text{med}}^{d-4}$, with each range spanning $\kappa = 1/(64\pi)$ to 1,

$$\begin{aligned} M_{\text{med}}^{(d=6)} &= G_{\text{eff}}^{-1/2} \approx 0.6\text{--}2.4 \times 10^{23} \text{ GeV}, \\ M_{\text{med}}^{(d=7, v_H=v)} &= (v/G_{\text{eff}})^{1/3} \approx 1\text{--}2.4 \times 10^{16} \text{ GeV}, \\ M_{\text{med}}^{(d=8, v_H=v)} &= (v^2/G_{\text{eff}})^{1/4} \approx 4\text{--}8 \times 10^{12} \text{ GeV}, \\ M_{\text{med}}^{(d=7, v_H=m_X)} &= (m_X/G_{\text{eff}})^{1/3} \approx 1\text{--}3 \times 10^{18} \text{ GeV}. \end{aligned} \quad (\text{A1})$$

The first line of Eq. (A1) is the pure four-fermion operator, trans-Planckian and forbidden; the second is the single electroweak-Higgs insertion, landing at the unification scale; the third is the double insertion, the seesaw window; and the fourth replaces the Higgs vev by an insertion of order the relic mass. A Planck-suppressed $d = 6$ coefficient would give $\tau \sim 10^{12}\text{--}10^{15}$ s depending on the Planck convention, in every case far short of the age of the universe, which is why the flavor symmetry must be gauged [17].

Example operators (Fig. 4): $\mathcal{O}_7 = (\bar{Q}' i \gamma_5 Q)(\bar{L} \tilde{H} \nu_R)/M_{\text{med}}^3$ (Dirac, $\bar{\nu}\nu$) and $\mathcal{O}_8 = (\bar{Q}' i \gamma_5 Q)(LH)(LH)/M_{\text{med}}^4$ (Majorana, $\Delta L = 2, \nu\nu$), the onium-dressed Weinberg operator [21]; the pseudoscalar dark bilinear couples to the $^1S_0$ ground state at leading order, while a scalar bilinear projects onto the velocity-suppressed P wave, and the electroweak factor of $\mathcal{O}_7$ is the gauge-invariant Dirac-neutrino Yukawa structure (for systematic bases with right-handed neutrinos, see Refs. [18–20]). The chirality structure shifts κ but not the line energy $m_X/2$.

Event-level line normalization. The bound-consistent lifetime follows from public numbers, with the detector acceptance canceling because the line sits at the reference energy. The joint fit across the KM3NeT, IceCube, and Auger exposures quotes a single-flavor $\nu + \bar{\nu}$ intensity $E^2 \Phi \approx 7.5 \times 10^{-10} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ across the 90% band [7]; integrating over the band gives an equivalent intensity $I_1 \approx 1 \times 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at 220 PeV. The Galactic decay line delivers $I = (f/4\pi)(D/(m_X \tau)) \xi$, with D the line-of-sight decay column and $\xi \sim 2/3$ the per-flavor multiplicity after mixing. For the event direction near the anticenter, $D \approx 10^{22} \text{ GeV cm}^{-2}$ (about half the all-sky average), with a comparable extragalactic term [14], $I = I_1$ requires $\tau/f \approx (1\text{--}3) \times 10^{29}$ s. This is the bound-consistent normalization by construction, the anchor being the joint flux, and it agrees with the dedicated $\nu\bar{\nu}$, νh , and right-handed-neutrino fits [12, 13, 16]. Folded through Eq. (3), this normalization fixes $M_{\text{med}}/|C_7|^{1/3} \approx (3\text{--}4) \times 10^{15} \text{ GeV}$ at the fiducial $f = 10^{-2}$ and $(7\text{--}8) \times 10^{15} \text{ GeV}$ at $f = 1$.

The collaboration’s detector-level analysis, which includes the $\nu\bar{\nu}$ channel and prefers masses above ~ 100 PeV consistent with $2E_\nu$, instead returns the lifetime that makes the event typical of KM3NeT’s own exposure, $\tau \approx 10^{26}\text{--}10^{27}$ s, in tension with the γ -ray and neutrino bounds [14]; the two normalizations differ by $10^2\text{--}10^3$ in τ/f but a factor of 2–3 in the scale. The two spectra are also distinguishable in shape, the line’s Galactic edge plus redshifted shoulder against the smooth continuum of the multiparticle channels, so accumulated events separate them. At the bound-consistent normalization, the single detection is an upward fluctuation of KM3NeT’s own exposure, the 2.2σ quoted in the discovery paper, where one such event is expected in 70 years of the analyzed configuration [1]; that trade is intrinsic to every bound-consistent reading, ours included.

The halo fraction of X is taken equal to the cosmological f : A cold, collisionless relic with adiabatic perturbations clusters identically to the dominant dark matter, since the collisionless dynamics carries no particle-mass dependence, with free streaming and dynamical friction negligible

at this mass; if the dominant component were instead ultralight and cored, X would cluster at least as strongly, making fD conservative. The tracing is fraction independent, a trace population being a test distribution in the common potential at any f : Birth momenta redshift below m_Q deep in the radiation era, leaving negligible free streaming; shot noise is irrelevant at these densities; and the floor's $O(1)$ decayed fraction depletes halo and cosmic densities alike, absorbed by defining f today.

This is an order-of-magnitude public-area estimate, not a detector-level likelihood: The acceptance cancellation is approximate, since the E^{-2} normalization integrates the full energy and direction response while a line samples one energy and direction, the broad muon-to-neutrino energy likelihood entering both; the $O(1)$ factors in D , the extragalactic fraction, ξ , and the acceptance recast are the stated uncertainties; a folded likelihood is the necessary next step.

Relic abundance and binding. The line flux fixes f/τ ; $\Omega_X h^2 = 0.12f$ corresponds to $n_X/s \approx 10^{-18}f$. Production from the thermal bath during reheating, with Boltzmann-suppressed yield $\propto e^{-2m_Q/T_{\text{RH}}}$ up to prefactors set by the production operator, reaches this for $T_{\text{RH}} \approx m_Q/(20-30)$ [27], with gravitational production a floor [26] and the unitarity bound [28] excluding a thermalized population.

Bound-state formation deserves a quantitative statement, because at this dilution no collisional channel operates. Radiative capture into the Coulombic ground state, $\sigma v \sim C \alpha_{\text{eff}}^5/m_Q^2$ with $C = O(1-10^2)$ collecting the capture-channel sum, gives $\Gamma/H \approx 10^{-15}-10^{-13}$ at $T \sim m_Q/25$, falling linearly with T ; even a geometric cross section $\sigma \sim \Lambda_d^{-2}$ among confined states, the mechanism that resets colored-relic abundances after the QCD transition [29], gives $\Gamma/H \approx 4 \times 10^{-3} (\Lambda_d/\text{GeV})^{-1/2}$ at $T \sim \Lambda_d$ once the thermal velocity $v \simeq \sqrt{3T/m_Q}$ is included (both Γ/H values are quoted at $f = 1$, the conservative choice since the rates scale linearly with f ; here and in the next paragraph the numerical coefficients take $g_* \approx 50$).

Formation instead proceeds with unit probability at the confinement transition, because the dark sector contains no matter below Λ_d : Dark color cannot be screened, so each surviving quark exits the transition joined by a flux tube to the nearest anticharge [29–31], at mean separation $d = n_Q^{-1/3} \approx 2.8 \times 10^5 f^{-1/3} (\text{GeV}/\Lambda_d) \text{ GeV}^{-1}$, with $n_Q \approx 2 \times 10^{-18} f$ s the constituent number density at the transition. The conditions for this to produce ground-state onia are spectroscopic. (1) The string cannot break: Nucleating a heavy pair is Schwinger suppressed by $e^{-\pi m_Q^2/\Lambda_d^2}$, negligible for any $\Lambda_d \ll m_Q$, and no lighter dark flavor exists to break it. (2) The stored string energy $\Lambda_d^2 d \approx 2.8 \times 10^5 f^{-1/3} (\Lambda_d/\text{GeV}) \text{ GeV}$ stays below $2m_Q$ for $\Lambda_d \lesssim 1.6 \times 10^3 f^{1/3} \text{ GeV}$, so the capture is nonrelativistic; the string network carries $\rho_{\text{string}}/\rho_{\text{rad}} \approx 4 \times 10^{-13} f^{2/3}$, independent of Λ_d , and perturbs neither the transition nor the expansion. (3) The pair, oscillating with a period of order the light-crossing time $2d$, radiates dark glue and cascades toward the Coulombic ground state, for which $\Lambda_d \ll \alpha_{\text{eff}} m_X/4 \approx 5.5 \times 10^6 \text{ GeV}$ is required; the window $\Lambda_d \lesssim 10^3 f^{1/3} \text{ GeV}$, $\approx 2 \times 10^2 \text{ GeV}$ at the fiducial $f = 10^{-2}$, satisfies (1)–(3) at once and still spans several decades.

The residual excitation at the end of the cascade is the one model-dependent element; it enters the lifetime only through $|\psi(0)|^2$ and hence M_{med} through the sixth root, a factor of 10 in $|\psi(0)|^2$ moving M_{med} by a factor of 1.5. After formation, same-flavor onia annihilate promptly; flavored onia at 10^{-18} per unit entropy are collisionless thereafter (rearrangement with $\sigma = \pi a_B^2$ has $\Gamma/H \lesssim 10^{-11}$), and the binding and survival fractions are $O(1)$ factors absorbed into f .

The order of magnitude of f is a production question, not a free dial: Gravitational production fixes it as a function of m_Q and the inflationary scale [26], production from the bath as a function of the portal coupling and reheating history [27], so a specified completion predicts it. The two-component sector is the no-coincidence option: Nothing analogous to freeze-out ties this yield to $\Omega_{\text{DM}} h^2 = 0.12$, so $f = 1$ would be an accident, whereas the axion misalignment abundance, fixed by the strong- CP solution, naturally saturates the dark matter; the value 10^{-2} is representative, not derived.

Observation bounds it from below: The flux fixes f/τ , so survival to the present, $\tau \gtrsim t_0$, requires $f \gtrsim t_0(f/\tau) \approx 4 \times 10^{-12}$, quoted at the conservative end of the band, $\tau/f = 10^{29} \text{ s}$ (at 10^{30} s the floor is 4×10^{-13}), and near the floor the decayed fraction reshapes the shoulder and suppresses the

edge-to-shoulder ratio, giving spectroscopy direct sensitivity to small f . Across the allowed range, the sixth root compresses twelve decades of f into two of scale, $M_{\text{med}}/|C_7|^{1/3} \approx 10^{14}$ GeV at the floor (where $\tau = t_0$ pins it) to 10^{16} GeV at $f = 1$, spanning $y \approx 0.3\text{--}1.3$ in the seesaw relation for $m_\nu = 0.05\text{--}0.01$ eV: Every allowed f lands the mediator inside the Majorana window, so the branch identification is f robust while the position within the window awaits the production calculation.

Line shape and flavor propagation. The predicted spectral shape is shown in Fig. 2, whose dashed verticals place the measured counterpart redshifts $z = 0.870$ and 1.227 [39] at 118 and 99 PeV, on the shoulder rather than at the edge. Under the line hypothesis, the counterpart coincidence is therefore a chance alignment and the observed 220 PeV energy reads as decay at $z \approx 0$, dominantly the Galactic column; under the flare hypothesis, the same redshifts instead fix the emitted energy near $(1+z) \times 220$ PeV ≈ 0.4 EeV at the source. More generally, $m_X = 2E_\nu(1+z_{\text{origin}})$, so a single event fixes the mass only up to the redshift of its origin; the edge, pinned by the Galactic component once events accumulate, removes the ambiguity.

One reading is excluded outright: Taking 220 PeV as the observed energy of a line emitted at the counterpart itself, i.e., decays in a dark-matter concentration bound to the blazar with $m_X = 2(1+z) \times 220$ PeV $\approx 8 \times 10^8$ GeV, fails on column arithmetic, since decay flux is linear in the dark-matter column and even a maximal bound concentration of $\sim 10^9 M_\odot$ at the counterpart distance supplies of order 10^{-14} of the Milky Way halo column; the lifetime that yields one blazar-line event would flood the detectors with halo events. The edge is therefore calibrated locally, at $z \approx 0$. The surviving readings are then spectrally exclusive. In the line reading, the energy is a mass, common to every decay at every epoch, so the accumulated spectrum is an edge at $m_X/2$ with its redshifted shoulder, and the counterpart coincidence is chance; in the flare reading, the energy is environmental, set by the accelerator and target of a single source with no m_X entering the interpretation, so the accumulated spectrum is the broad resonance peak, observed a factor $(1+z)$ below the emitted energy at the counterpart. Accumulating events therefore show either a line at $m_X/2$ or a continuum below the counterpart's emitted energy, but not both; the spectrum decides.

One prior does enter the energy itself: The 220 PeV median unfolds the reconstructed muon energy under an E^{-2} spectral assumption [1]; a monochromatic prior reweights the same muon-energy likelihood and shifts the median somewhat, a dependence bracketed by the 90% interval propagated into the m_X band throughout. Electroweak final-state radiation dresses $X \rightarrow \nu\bar{\nu}$ at $m_X \sim 4 \times 10^8$ GeV with a soft continuum carrying a modest energy fraction [the $\alpha_2/4\pi$ cost per emission is offset by the double logarithm $\ln^2(m_X^2/m_W^2) \approx 10^3$, so the radiation cannot be switched off], computed for this channel in Ref. [16]; the hard spike remains resolution narrow.

For halo and intergalactic propagation, the oscillation phases decohere and the matter potential $\sqrt{2}G_F n_e$ stays many orders of magnitude below $\Delta m^2/2E$ (the MSW-resonant density at 220 PeV is $\sim 10^{-7}$ g cm $^{-3}$, approached only deep inside accretion-flow environments irrelevant to halo decay), so decohered vacuum mixing applies: The Earth ratio is $\sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$ acting on the source flavor composition; every flavor exceeds $\approx 15\%$ for a democratic or incoherent source, e.g., $(1:0:0)_S \rightarrow (0.55:0.17:0.28)_\oplus$ and $(0:1:0)_S \rightarrow (0.17:0.45:0.38)_\oplus$; a single source mass eigenstate is the exception (pure ν_3 gives an electron fraction of a few percent).

Warm-dust peak conditions. The gap potential $e\Phi \approx 2 \times 10^{20}$ eV ($a/M_{\text{BH}})(B/10^4 \text{ G})$ ($M_{\text{BH}}/10^9 M_\odot$) [35], with M_{BH} the black-hole mass and a its spin, and gap fraction $\eta \approx 0.02$, places the required 4.4 EeV a factor ~ 2 below the curvature-radiation ceiling, where operation sharpens the beam. The Δ -resonance condition on a thermal field [57–59] selects $\varepsilon_0 \approx 0.036\text{--}0.07$ eV (head-on to 90°), dust at $T \approx 150\text{--}300$ K, and a photopion optical depth $\tau_{p\gamma} \approx n_{\text{IR}} \sigma_{\Delta} R \approx 8 L_{45} (R/\text{pc})^{-1} (\varepsilon_0/0.036 \text{ eV})^{-1}$ reaching order unity after thermal, angular, and geometric dilution. Muon damping needs $B \gtrsim 10$ G at $E_\mu \approx 0.7$ EeV, deep in the torus cavity, so the composition is generically mixed. Parent protons never arrive: Neutrons (≈ 3.5 EeV) decay within ~ 32 kpc, protons deflect and arrive $> 10^4$ years late, and the π^0 cascade falls below the Fermi Large Area Telescope (LAT) bound [60].

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