Letter

Probing pseudo-Dirac neutrinos with astrophysical sources at IceCube

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The recent observation of NGC 1068 by the IceCube Neutrino Observatory has opened a new window to neutrino physics with astrophysical baselines. In this paper, we propose a new method to probe the nature of neutrino masses using these observations. In particular, our method enables searching for signatures of pseudo-Dirac neutrinos with mass-squared differences that reach down to $\delta m^2 \gtrsim 10^{-21}$ eV^2, improving the reach of terrestrial experiments by more than a billion. Finally, we discuss how the discovery of a constellation of neutrino sources can further increase the sensitivity and cover a wider range of δm^2 values.

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Introduction. Since the beginning of time, humans have stared at the sky and wondered about the Universe. Through careful inspection, we discovered the patterns that rule the motions of planets, and followed a trail of questioning that led to the theory of general relativity. Now, equipped with enormous telescopes and modern particle physics, we can, for the first time, study tinier, even more elusive astrophysical signals. In this paper, we show that these observations can be used to uncover the origin and nature of the neutrino mass.

Recently, IceCube announced the observation of the first steady-state astrophysical neutrino source, the active Galactic nucleus NGC 1068 [1,2]. Assuming only that the neutrinos produced by this source follow a power-law distribution in energy, they performed a likelihood analysis and found that 79^{+22}_{-20} events originated from NGC 1068, yielding a rejection of the background-only hypothesis with a local (global) significance of 5.2 (4.2) σ [1]. Neutrinos that travel to Earth from sources like NGC 1068 must traverse megaparsecs (Mpc), a distance many orders of magnitude greater than that traveled by any solar, atmospheric, reactor- or accelerator-based neutrino ever detected. Neutrino events from extra-Galactic sources will thus allow us to study, for the first time, a whole class of new physics scenarios whose signals appear only at extremely long length scales.

One significant example of such new physics is the pseudo-Dirac model of neutrino masses [3–6].[1] In this scenario, the active neutrino mass states are accompanied by undetectable sterile states, whose masses are separated from the active ones by a tiny amount, generated by a small Majorana mass term. These mass splittings induce an oscillation between the active and sterile neutrino states. For very small Majorana masses, these oscillations are detectable only at extremely large values of the ratio L/E (where L is the baseline and E denotes the neutrino energy). These large values are achievable only for astrophysical neutrino sources [9–17]. See Fig. 1 for an artistic rendition of our main idea.

In this paper, we explore how the pseudo-Dirac neutrino scenario could be probed by observations of extra-Galactic neutrinos. We find that currently identified astrophysical neutrino sources can provide new constraints on yet unexplored mass splittings. We also predict how upcoming measurements in current and future neutrino telescopes will increase the sensitivity to these new mass splittings.

Theory of pseudo-Dirac neutrinos. Whether or not the neutrino is its own antiparticle is an unsettled question. In a wide class of beyond the Standard Model theories, the neutrino is a Majorana fermion, which is its own antiparticle. Alternately, the neutrino may be a Dirac fermion, and completely distinct from its antiparticle. An intermediate possibility is that the neutrino is a *pseudo-Dirac particle* [3–6], which is fundamentally Majorana, but acts like a

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[1]Originally, the mass term involving an active and a sterile neutrino almost degenerate in mass was called quasi-Dirac [7]. To be consistent with the recent literature [8], we call it pseudo-Dirac.

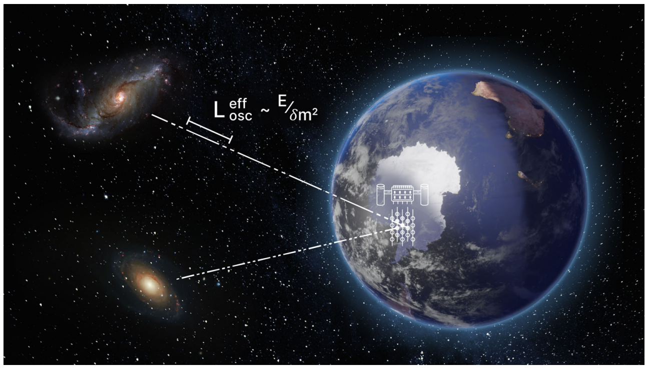

FIG. 1. An artistic rendering of neutrino propagation from extra-Galactic sources. Oscillation from active to sterile is depicted by the transition from the solid to dashed line.

Dirac fermion in most experimental settings. The mass matrix spanning the active species ν_a and its Dirac partner ν_s have the form (with multiple flavors)

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}. \tag{1}$$

If $M_R = 0$ in Eq. (1), the lepton number is preserved, and the neutrino is a Dirac particle; if $M_R \neq 0$, it is a Majorana particle; and if, in the eigenvalue sense, $|M_R| \ll |m_D|$, it is a pseudo-Dirac particle.

Phenomenologically, a pseudo-Dirac neutrino is one logical possibility in the context of neutrino mass generation. At first sight, the condition $|M_R| \ll |m_D|$ may not look natural since M_R is a gauge-invariant mass term in the SM, which could be much larger than the electroweak-symmetry-breaking scale, as e.g., in the original *seesaw mechanism* [18–21]. Furthermore, the smallness of the neutrino mass, which is proportional to $|m_D|$ in this scenario, would remain unexplained. However, there are theories where M_D is naturally small and $M_R = 0$ at the renormalizable level. Nonzero elements of M_R are induced via higher-dimensional operators suppressed by the inverse Planck scale. This is the case in the *Dirac seesaw scenario* [22–27], which is realized naturally in the mirror Universe model [28–30]. Such theories provide a better understanding of parity (P) violation, since P is an unbroken (or spontaneously broken) symmetry in this context. They provide mirror partners for every SM fermion, including lepton doublets $\Psi' = (\nu', \ell')$ of a mirror $SU(2)'_L$ symmetry which are the partners of the usual $SU(2)_L$ lepton doublet $\Psi = (\nu, \ell)$. In this context, ν' plays the role of sterile neutrinos, with its mass protected by the $SU(2)'_L$ gauge symmetry. A Dirac mass term connecting ν and ν' would arise from a generalized seesaw mechanism.

Operators of the type $(\Psi\Psi')(HH')/M_N$, where H and H' are the Higgs doublets of $SU(2)_L$ and mirror $SU(2)'_L$, respectively, are induced once a heavy neutral lepton N is integrated out. Specifically, N has interactions given by $(\Psi N H) + (\Psi' N' H') + (M_N/2)NN'$. The lepton number remains unbroken in this scenario, which also explains why the Dirac mass term $m_D = vv'/M_N$ (where v and v' are the vacuum expectation values of H and H' respectively) is very small. Alternatively, a bidoublet Higgs $\Phi(2,2)$ with the couplings $\Psi\Psi'\Phi + \mu HH'\Phi^*$ could lead to the same operator with a coefficient (μ/M_Φ^2), once the Φ field is integrated out.

Now, quantum gravity corrections are expected to break all global symmetries, such as the lepton number. One would then expect dimension-5 Weinberg operators [31] of the type $(\Psi\Psi HH)/M_{\rm Pl}$ and $(\Psi'\Psi' H'H')/M_{\rm Pl}$ would then be induced by gravity, with coefficients presumably of order unity. This would result in small diagonal entries of M_ν in Eq. (1), implying a pseudo-Dirac neutrino. In the mirror neutrino scenario, one would expect the active-sterile mass splitting to be on the order of $\delta m^2 \approx (2, 0.3) \times 10^{-7}$ eV^2 [using $m_a \simeq (0.05, 0.007)$ eV for the larger two of the active neutrino masses with normal ordering]. However, such mass splitting values are already excluded by solar neutrino data, which requires $\delta m^2 \lesssim 10^{-11}$ eV^2 [8], with Ref. [32] finding a small preference for $\delta m^2 \simeq 1.2 \times 10^{-11}$ eV^2.[2] This difficulty can be evaded by gauging the $B - L$ symmetry, which is anomaly-free in the presence of sterile neutrinos. This gauge symmetry is spontaneously broken by a singlet scalar field, S, carrying two units of $B - L$ charge. The Weinberg operators would then be modified to the form $(\Psi\Psi HHS)/M_{\rm Pl}^2$, leading to diagonal elements of M_ν on the order of $v^2 v_{BL}/M_{\rm Pl}^2$. For the $B - L$ symmetry breaking scale of $v_{BL} = (10^4\text{–}10^{14})$ GeV[3] this would lead to a mass splitting of order $(10^{-22}\text{–}10^{-12})$ eV^2. As we show below, a significant portion of this well-motivated range of v_{BL} would be probed by the high-energy neutrinos detected at IceCube. There are other models where light Dirac neutrinos arise from quantum loop corrections that also predict pseudo-Dirac neutrinos; see, e.g., Refs. [37–43]. It is interesting to note that certain string landscape (swampland) constructions also predict that neutrinos are necessarily pseudo-Dirac [44–46].

In all the pseudo-Dirac scenarios mentioned above, the mixing between active and sterile states, given by $\tan 2\theta = 2m_D/M_R$, is nearly maximal due to the pseudo-Dirac condition. The mass eigenstates of Eq. (1) are $\nu_S = \sin\theta\nu_a + \cos\theta\nu_s$ and $\nu_A = (-i)(\cos\theta\nu_a - \sin\theta\nu_s)$. For very large mixing angles, those states coincide with the symmetric and antisymmetric combinations of the active and sterile neutrinos, with their mass difference being proportional to M_R.

Neutrino evolution on astrophysical scales. The time evolution of each neutrino flavor state is obtained by

[2] There also exist bounds on $\delta m^2 \lesssim 10^{-8}$ eV^2 from big bang nucleosynthesis considerations [33,34].

[3] $v_{BL} \lesssim 10^4$ GeV is disfavored by the LHC null results on heavy Z'-resonance searches, assuming coupling strength similar to the weak interaction strength [35,36].

solving the Schrörinder equation along the neutrino trajectory. The Hamiltonian describing the evolution ($\mathcal{H}(t) = U\mathcal{M}^2U^*/E(t)$) depends on the lepton mixing matrix, which relates the mass and flavor states, $|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$, and the squared neutrino masses.

In the case of extra-Galactic sources, the expansion of the Universe modifies the phase of the flavor state as neutrinos propagate, having an impact on the final flavor distribution if the oscillations are not averaged out. In the case of a homogeneous and isotropic universe, the expansion is encoded in the scale factor ($a(t)$) that depends on the redshift (z) as $1+z = a_0/a$, a_0 being the scale factor today ($a_0 = 1$ for a flat universe). The expansion rate of the Universe is given by the Hubble parameter $H = \dot{a}/a$, where $\dot{a} \equiv da/dt$. As the Universe expands, there is a redshift in the neutrino energy that will also affect the phase of the flavor states. The relation between the initial (E'_ν) and the redshifted (E_ν) neutrino energies is $E_\nu = E'_\nu/(1+z)$. The time integration of the Hamiltonian is given by

$$\int \mathcal{H}(t)dt = \frac{U\mathcal{M}^2U^*}{E_\nu}\int\frac{dz}{H(z)(1+z)^2} \equiv \frac{U\mathcal{M}^2U^*}{E_\nu}L_{\mathrm{eff}}. \quad (2)$$

The Hubble function $H(z)$ depends on the fractions of matter (Ω_m), dark energy (Ω_Λ), and H_0, the present value of the Hubble constant. For those parameters, we used the best-fit value from the Planck [47] results. On astrophysical scales, the phase the flavor states get depends on the Universe's expansion via the effective distance (L_{eff}).

In the pseudo-Dirac scenario, the mixing between the flavor and the mass eigenstates is $\nu_\alpha = U_{\alpha i}(\nu_{iS} + \nu_{iA})/\sqrt{2}$, where $U_{\alpha i}$ is the Pontecorvo-Maki-Nakagawa-Sakata matrix. Considering redshift dependence in the neutrino evolution, the probability that a flavor state ν_α oscillates into a flavor state ν_β is given by

$$P_{\alpha\beta} = \frac{1}{4}\left|\sum_{j=1}^{3} U_{\beta j}U^*_{\alpha j}\left\{e^{\left(\frac{im^2_{jS}L_{\mathrm{eff}}}{2E_\nu}\right)} + e^{\left(\frac{im^2_{jA}L_{\mathrm{eff}}}{2E_\nu}\right)}\right\}\right|^2, \quad (3)$$

where m^2_{jA} and m^2_{jS} are the masses of the symmetric and antisymmetric combinations of the active and sterile states, respectively. The oscillation probability has two well-separated oscillation lengths: For $\Delta m^2_{ij} = m^2_{iS/A} - m^2_{jS/A} \sim 10^{-3}$ eV^2 (atmospheric mass splitting) or $\sim 10^{-5}$ eV^2 (solar mass splitting), the oscillation length is of the order of $L_{\mathrm{osc}} = 4\pi E/\Delta m^2_{ij} \sim 10^7$–$10^9$ km for $E_\nu \sim 10$ TeV, which is comparable to the Earth-Sun distance. But for the active-sterile mass splitting (δm^2), the oscillation length will be much larger, depending on the magnitude of M_R. Taking the average over the large mass splittings, the oscillation probability becomes

$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3}|U_{\beta j}|^2|U_{\alpha j}|^2\left[1 + \cos\left(\frac{\delta m^2_j L_{\mathrm{eff}}}{2E_\nu}\right)\right]. \quad (4)$$

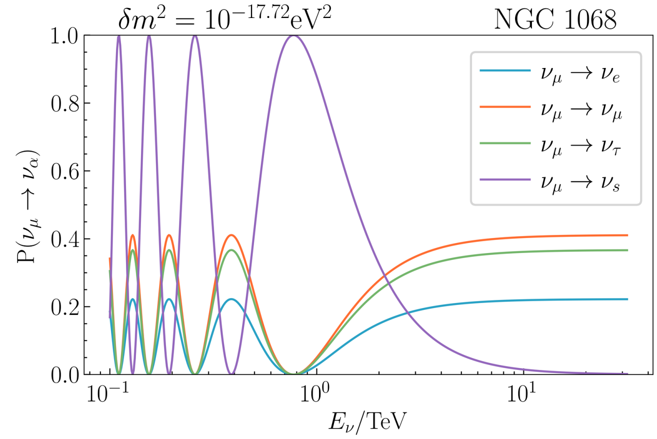

FIG. 2. Oscillation probability of ν_μ into active and sterile components as a function of the neutrino energy for a benchmark value of $\delta m^2 = 10^{-17.72}$ eV^2 for all three active-sterile pairs, and for the redshift of NGC 1068 ($z = 0.0038$).

Thus, the oscillation probability depends only on the three mass splittings, one for each pair of degenerate masses. For illustration, in Fig. 2 we show the probability of muon neutrinos oscillating into active and sterile neutrinos for all three mass splittings equal to $\delta m^2 = 10^{-17.72}$ eV^2 and redshift $z = 0.0038$, corresponding to NGC 1068. With regard to the lepton-mixing matrix, we used the best fit from [48]. For this mass splitting, and $E_\nu \sim$ TeV, all the muon neutrinos arrive to the Earth as sterile states.

Analysis. The discovery of high-energy extra-Galactic neutrinos by the IceCube Neutrino Observatory [49,50] marked the beginning of a new era of neutrino astronomy. According to the latest results [1], the three astrophysical sources identified with the most significance are the active Galactic nuclei NGC 1068, PKS 1424 + 240, and TXS 0506 + 056, with local significance of 5.2σ, 3.7σ, and 3.5σ respectively. These sources are located at different redshifts $z = 0.0038$ [51], 0.6047 [52], and 0.3367 [53], corresponding to approximately 16 Mpc, 2.6 Gpc, and 1.4 Gpc, respectively. IceCube's point-source search used only tracklike events, which have an excellent angular resolution [54,55] ($\Delta\delta < 1°$). They assumed that the neutrino flux followed a power law. Their results found that the event distribution of each source was best described by spectral indices $\hat{\gamma} = 3.2$, 3.5, and 2.0, and total event counts $\hat{n}_s = 79$, 77, and 5; see the Supplemental Material [56].

We calculate the expected number of IceCube tracklike events from each source under the standard and pseudo-Dirac hypotheses. We include the contribution from taus decaying into muons. To predict the expected number of events, we use the effective area given in Ref. [54]. We assume that the neutrino production mechanism is charged pion decay. As a benchmark scenario, we consider an initial neutrino flux following an unbroken power-law distribution in energy from 100 GeV on, with spectral indices given by

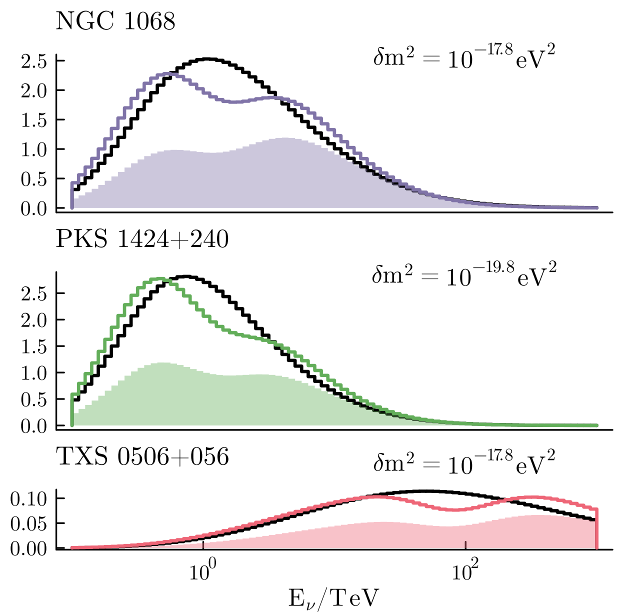

FIG. 3. Calculated event distributions for the three most significant sources under the SM (black) and the pseudo-Dirac (filled color) hypotheses. When we maximize the likelihood that the pseudo-Dirac hypothesis can describe SM-like data, by allowing the flux parameters to vary, (color) the difference between the two distributions is reduced.

the best-fit values from Ref. [1]; see the Supplemental Material [56]. We compute the expected number of events in a reconstructed energy bin by integrating the flux and effective area over true energy, weighted by the reconstruction probability. For the energy resolution, we use a Gaussian distribution with 30% uncertainty in log-energy scale [57]. We explore the effect of varying the energy resolution in the Supplemental Material [56].

The expected event distributions for NGC 1068, PKS $1424 + 240$, and TXS $0506 + 056$ for a lifetime of 3168 days are shown in Fig. 3. The pseudo-Dirac expectations, plotted in color, predict fewer events than the SM (black curve), since neutrinos that oscillate from active to sterile become undetectable. Since each source has a different initial flux and a different redshift value, each is sensitive to different regions of the pseudo-Dirac parameter space.

We calculate IceCube's sensitivity to a pseudo-Dirac signal by performing a likelihood ratio test. For each value of an active-sterile mass splitting we calculate the Poisson likelihood of observing events distributed accorded to the SM prediction under a pseudo-Dirac hypothesis. In order to account for the possibility of features in the source spectra, we consider three possible models for the fitted flux of the alternative hypothesis: a simple power law, a power law with an exponential cutoff, and a log parabola

$$\phi(E) = \phi_0 \cdot (E/E_0)^{-(\alpha+\beta\log_{10}(E/E_0))}.$$

The exponential cutoff model can describe sources with a spectral cutoff, while the log-parabola model mimics a bumplike spectrum like that of many models found in recent literature [58]. We treat the normalization and the other parameters of these models as nuisance parameters, without any priors.

This procedure results in an optimistic sensitivity, since it does not account for the uncertainty in the background removal. A slightly more conservative result could be achieved by using an effective likelihood with modeling uncertainty [59].

Our results focus on the scenario where the three mass splittings are equal. This subset of the pseudo-Dirac parameter space contains the points to which we are most sensitive, because all the mass states contribute to the active-sterile oscillation at the same energies. Sensitivity to the scenario where two mass splittings differ from zero independently is explored in the Supplemental Material [56].

Results. In this paper, we perform a combined analysis of the expected event distribution of the three most significant astrophysical sources (NGC 1068, PKS $1424 + 240$, and TXS $0506 + 056$) observed by IceCube. Because the sources are unequally distant from the Earth and have different spectral indices, they are each sensitive to different regions of the δm^2 parameter space. Combining them, we explore for the first time mass splittings in the range $\delta m^2 \in [10^{-21}, 10^{-16}]$ eV^2.

The results of the sensitivity study are shown in Fig. 4. The sensitivity to a pseudo-Dirac hypothesis, assuming a power-law flux model, is plotted as a black curve; the stacked shaded regions below indicate the contribution of each source. The dashed black curve shows the reduced sensitivity after marginalizing over the power-law, exponential cutoff, and log-parabola flux models. We explore the sensitivity as a function of different flux models in more depth in the Supplemental Material [56].

For TeV sources, the redshift of each source fixes the effective distance, $L_{\rm eff}$, and thus the scale of the mass splittings to which it is sensitive. The spectral index of each source sets the distribution of its events over energy, which controls the width of the range of mass splittings to which it is sensitive. Thus NGC 1068 and PKS $1424 + 240$, which both have relatively soft spectra but have redshifts 3 orders apart, are sensitive to two very different, concentrated regions of parameter space. Conversely, TXS $0506 + 056$, which has a much softer spectra, is sensitive to a wide region, although its sensitivity is limited by its small best-fit event count (5 events). Mass splittings on the same order have previously been explored at the 3σ level using data from supernova SN1987A [17]. The vertical line to the left of the plot indicates the left edge of the region motivated by a $B - L$ gauge symmetry. The current sensitivity, using a power-law flux model, is at most 2σ, at $\delta m^2 \sim 10^{-20}$ eV^2 and $\delta m^2 \sim 10^{-18}$ eV^2.

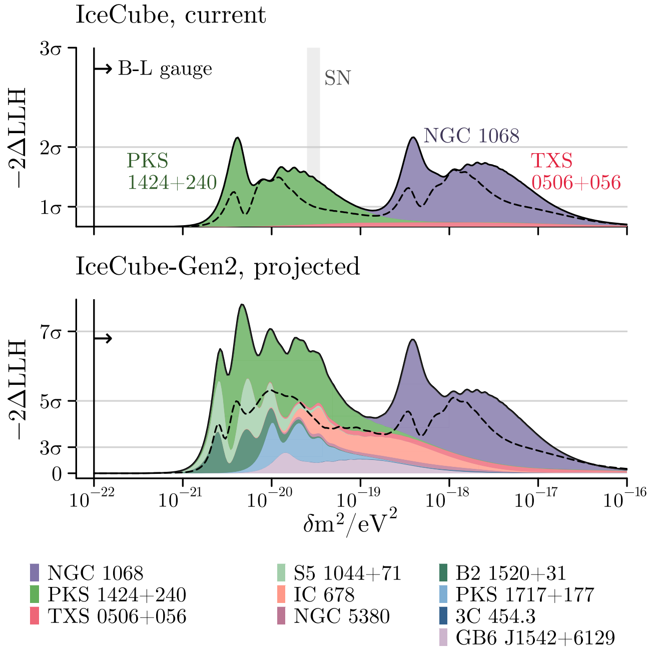

FIG. 4. Top: total sensitivity assuming a power-law flux model (black), computed by stacking that of each of the three currently significant sources (plotted separately in color). The dashed black curve indicates the sensitivity obtained after marginalizing over different source hypotheses. The gray-shaded region indicates the 3σ region excluded by SN 1987 A. Bottom: projected sensitivity of IceCube Gen2, using nine astrophysical sources and assuming 8x statistics.

In supplemental analyses, we also consider whether a pseudo-Dirac signal would be recoverable. In the Supplemental Material [56] we calculate the likelihood of SM and pseudo-Dirac hypotheses, given event distributions simulated under a pseudo-Dirac hypothesis. We find that the maximum-likelihood point recovers the injected value. A pseudo-Dirac reality would also impact studies of source fluxes, by shifting the inferred spectral index with respect to the true value. We explore this possibility in the Supplemental Material [56], and find the effect could be as large as an 8% shift. This effect could also impact diffuse neutrino fluxes, since distortions to the source flux caused by pseudo-Dirac disappearances could accumulate. Finally, in the Supplemental Material [56] we explore the possibility of improving IceCube's current sensitivity by separating events into tracks which start within the detector volume, which have superior energy resolution, and those which traverse it.

In the lower part of Fig. 4, we show the projected sensitivity of IceCube-Gen2. For this analysis, we included all the sources which IceCube can currently identify with at least 1.1σ local significance, and for which there exists a published redshift value; see the Supplemental Material [56]. Additionally, we multiply all statistics by a factor of 8, as projected by Ref. [60]. We find that the combined sensitivity is well past 3σ over a wide range of mass splittings.

Conclusions. In this paper, we investigated IceCube's current and future sensitivity to the pseudo-Dirac neutrino mass scenario. The combined analysis of the three most significant astrophysical sources observed by IceCube probes active-sterile mass splittings in the range $10^{-20}\ \mathrm{eV}^2 < \delta m^2 < 10^{-16}\ \mathrm{eV}^2$, but its sensitivity is limited by statistics and poor energy resolution. However, by including sources observed by IceCube with a significance larger than 1.1σ, and assuming 8 times greater statistics, we found that IceCube-Gen2 will be able to explore a large range of masses with a significance over 5σ.

Next-generation neutrino telescopes [61–68] will unveil a constellation of neutrino sources, opening the possibility of exploring very long baseline neutrino physics. By combining many astrophysical sources, over a wide range of distances, we will gain access to a broad and hitherto unexplored range of active-sterile mass splittings. The expected signal, a dip in the neutrino spectra, due to the oscillation into the sterile state, must be observed in all the sources sharing a common L_{eff}/E. This signature is robust under uncertainties in astrophysical neutrino fluxes, which at this early point are significant.

The pseudo-Dirac hypothesis can also modify the flavor ratio of high-energy neutrinos at IceCube. Depending on the flavor structure of the mass matrix (1), active-sterile oscillations may shift the flavor composition at Earth away from the conventional $(1:1:1)$ for a $(1:2:0)$ source [69]. Unfortunately, reconstructing the flavor triangle in this case will require both cascade and track events from the identified sources. Identifying cascade events will be difficult, as they have poor angular resolution ($\Delta\delta \sim 1°$, as compared to $\Delta\delta \lesssim 0.1°$ for tracks), but it may be possible with future neutrino telescopes.

This paper strongly motivates a full likelihood-based analysis by the IceCube Collaboration. A more descriptive flux hypothesis would alter the significance of the source identification and the maximum likelihood parameters. This full likelihood analysis should be unbinned, consider background and signal simultaneously, and include a full treatment of detector systematics. Only such a study would be able to unambiguously resolve the pseudo-Dirac nature of neutrinos.

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