Snowmass2021 - Letter of Interest

Cosmic Neutrino Probes of Fundamental Physics

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other): NF03, NF04, NF05, NF06, TF11

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Abstract: We highlight the unique power of high-energy cosmic neutrinos as probes of fundamental physics at the highest energies, spanning from the TeV–PeV range, already detected today, up to the EeV range, potentially detectable in the coming decade. High-energy cosmic neutrinos grant us access to a vast landscape of new-physics models whose discovery would represent critical progress in fundamental physics. We give an overview of the current and near-future status of physics with high-energy cosmic neutrino physics, and advocate for a comprehensive plan of exploration aimed at maximizing the opportunities for discovery in the next 10–20 years.

There is a vast landscape of physics to explore at the highest energies, and high-energy cosmic neutrinos are uniquely well-equipped for the task. [1] Their potential as probes of fundamental physics [1–5] was identified early, but they were only discovered recently, in 2013, when the IceCube Neutrino Observatory observed a diffuse flux of TeV–PeV cosmic neutrinos. [6–10] Since then, there has been a gradual shift of focus from proposing prospective tests of high-energy neutrino physics to performing real, data-driven tests, of increasing sophistication and based on progressively more and better experimental data. This, paired with a rich present and future experimental program, provides a valuable opportunity to make significant progress.

To seize this opportunity, the neutrino community needs a comprehensive exploration plan that maximizes the potential to probe neutrino properties and the discovery of new physics, identifies target experimental sensitivities, and exploits synergies between TeV–PeV neutrino experiments and their upcoming counterparts at lower and higher energies. In this letter, we express our interest in providing this plan, in the form of a contributed paper. Our goal is to stimulate progress in the next 10–20 years that is not just incremental, but also substantial, and possibly revolutionary.

Figure 1 shows why high-energy (TeV–PeV) and ultra-high-energy ($\geq$ EeV) neutrinos are incisive probes of new physics. Because they have the highest neutrino energies known—TeV to EeV—they can probe physics at energy scales that are inaccessible to us in the laboratory. Because they travel unscathed for the longest distances—up to a few Gpc, the size of the observable Universe—even tiny effects can accumulate and become observable. (Because high-energy neutrinos should be copiously produced in astrophysical environments they are also rich probes of high-energy astrophysics. [11])

Present and future experimental landscape.—IceCube, presently the largest neutrino telescope, discovered a diffuse flux of cosmic neutrinos from 10 TeV to 10 PeV. IceCube is an in-ice Cherenkov detector in Antarctica; it instruments 1 km^3 of deep underground ice with thousands of photomultipliers that collect the light emitted by particle showers initiated by high-energy neutrino interactions. From the amount of light collected and its spatial and temporal profiles, IceCube infers the energy, flavor, and arrival direction of the neutrinos. Because the bulk of their arrival directions is broadly consistent with an isotropic distribution, they are likely of predominant extragalactic origin, though their sources are unknown, save for two promising associations. [12;13] IceCube has measured the TeV–PeV neutrino-nucleon cross section [14;15] and inelasticity distribution [16] for the first time, probed charm production in neutrino interactions [16], and seen hints of the first high-energy ν_τ [17] and the Glashow resonance. [18] ANTARES, a Cherenkov detector in the Mediterranean Sea, is reaching sensitivity to the diffuse neutrino flux. [19;20] KM3NeT [20;21], P-ONE [22], and Baikal-GVD [23], under construction, will improve our sensitivity to TeV–PeV neutrinos.

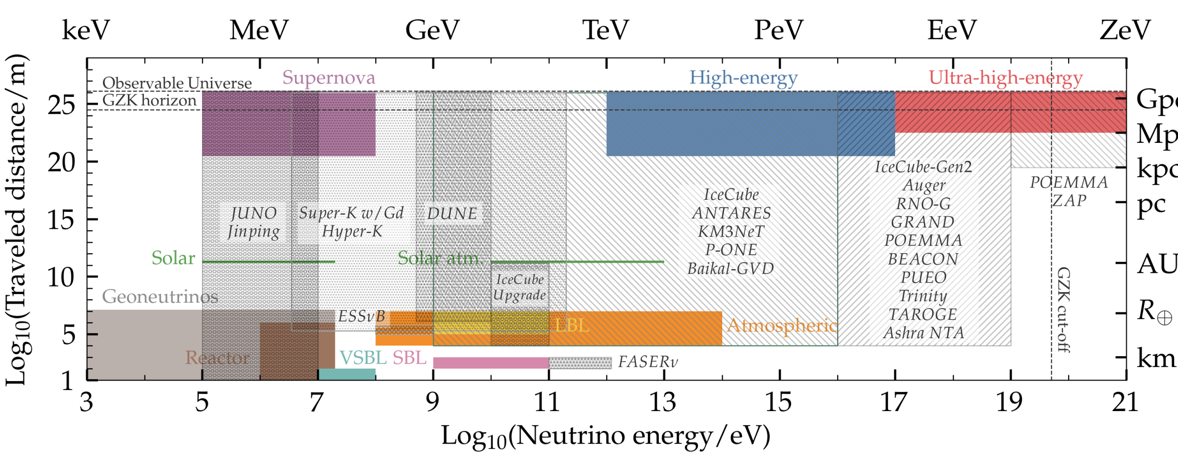

Figure 1: Distribution of neutrino sources in energy and distance traveled to the detector, and experiments aimed at detecting them, present and future. We focus on high-energy and ultra-high-energy neutrinos. Updated from [1].

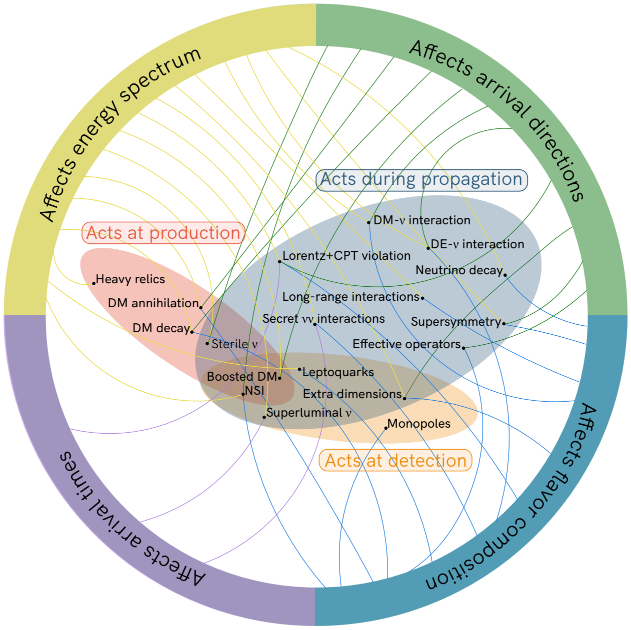

Figure 2: Models of new neutrino physics and other new physics classified according to the stage at which they act—at production, during propagation, at detection—and what feature they affect—energy spectrum, arrival directions, flavor composition, arrival times. Reproduced from[5].

In the next 10–20 years, new detectors may improve our sensitivity to neutrino energies of 100 PeV–EeV, and beyond. EeV neutrinos have long been predicted as coming from the interaction of ultra-high-energy cosmic rays with cosmic photon backgrounds[24–26], but they have not been discovered yet.[27–31] The flux of these *cosmogenic* neutrinos is expected to be low.[32–34] ZeV neutrinos might come from cosmic strings.[35;36] Next-generation, multi-purpose EeV–ZeV detectors are being planned with a variety of detection strategies: in-water and in-ice Cherenkov (IceCube-Gen2[37], AugerPrime[38]), in-air Cherenkov and fluorescence (EUSO-SPB2[39], POEMMA[40], Trinity[41], Ashra NTA[42], CTA[43]), and radio (GRAND[44], RNO-G[45], PUEO[46], BEACON[47], TAROGE[48], ZAP[49]).

The landscape of new-physics models.— New physics may affect various features of high-energy cosmic neutrinos: their energy spectrum, arrival directions, flavor composition, and arrival times. We measure these features and contrast them against predictions from astrophysical models[1;5], e.g., a power law in energy[50], an isotropic flux[51–53], a flavor composition of $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$[50;54–63], and coincident arrival of neutrinos and other messengers from transient astrophysical sources. New physics may affect these features compared to their standard expectations[1;5] (which carry uncertainties of their own). Neutrino telescopes may also probe new neutrino interactions and hypothesized particles, such as magnetic monopoles[64–68], by looking for exotic signatures.[4]

Figure 2 shows a representative part of the landscape of models of new neutrino physics that can be tested using high-energy cosmic neutrinos. Some of the outstanding questions to address today and in coming years are: How do neutrino cross sections behave at high energies?[14;15;69–94] How do flavors mix at high energies?[59;95–109] What are the fundamental symmetries of Nature?[110–128] Are neutrinos stable?[129–136] Is there evidence of dark matter in the flux of high-energy neutrinos?[51;137–160] Are there hidden interactions with cosmic backgrounds?[152;161–185] What is the origin of the anomalous EeV events seen by ANITA?[186–204]

Synergies with sub-TeV neutrino experiments.—Upcoming sub-TeV experiments will reduce uncertainties that limit the sensitivity of fundamental-physics searches using high-energy cosmic neutrinos.

First, the IceCube Upgrade[205], though geared towards low-energy neutrinos, will reduce systematic errors that affect the detection of high-energy neutrinos. Second, oscillation experiments—DUNE[206], JUNO[207], Hyper-Kamiokande[208], the IceCube Upgrade[205], KM3NeT/ORCA[21]—will reduce the uncertainties on lepton mixing parameters[209], allowing us to make more precise tests of new physics via the flavor composition of high-energy cosmic neutrinos.[59] Third, FASERν will reduce systematic uncertainties in charm production at Feynman-x close to 1, by measuring the neutrino flux from the LHC in the forward direction.[210;211] This will improve predictions of the undiscovered background of prompt atmospheric neutrinos that muddle searches of new physics with high-energy cosmic neutrinos.

Given the unique potential and rich experimental outlook of high-energy cosmic neutrinos to extend our view of fundamental physics, we feel that this topic should feature prominently in the high-energy physics program, as it pushes the boundaries for the neutrino, cosmic, energy, theory, and instrumentation frontiers.

References

[1] M. Ackermann *et al.*, "Fundamental Physics with High-Energy Cosmic Neutrinos," *Bull. Am. Astron. Soc.* **51** (2019) 215, arXiv:1903.04333 [astro-ph.HE].

[2] L. Anchordoqui and F. Halzen, "IceHEP high energy physics at the south pole," *Annals Phys.* **321** (2006) 2660, arXiv:hep-ph/0510389.

[3] L. A. Anchordoqui, V. Barger, I. Cholis, H. Goldberg, D. Hooper, A. Kusenko, J. G. Learned, D. Marfatia, S. Pakvasa, T. C. Paul, and T. J. Weiler, "Cosmic Neutrino Pevatrons: A Brand New Pathway to Astronomy, Astrophysics, and Particle Physics," *JHEAp* **1-2** (2014) 1, arXiv:1312.6587 [astro-ph.HE].

[4] M. Ahlers, K. Helbing, and C. Pérez de los Heros, "Probing Particle Physics with IceCube," *Eur. Phys. J. C* **78** no. 11, (2018) 924, arXiv:1806.05696 [astro-ph.HE].

[5] C. A. Argüelles, M. Bustamante, A. Kheirandish, S. Palomares-Ruiz, J. Salvadó, and A. C. Vincent, "Fundamental physics with high-energy cosmic neutrinos today and in the future," *PoS* **ICRC2019** (2020) 849, arXiv:1907.08690 [astro-ph.HE].

[6] **IceCube** Collaboration, M. Aartsen *et al.*, "First observation of PeV-energy neutrinos with IceCube," *Phys. Rev. Lett.* **111** (2013) 021103, arXiv:1304.5356 [astro-ph.HE].

[7] **IceCube** Collaboration, M. Aartsen *et al.*, "Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector," *Science* **342** (2013) 1242856, arXiv:1311.5238 [astro-ph.HE].

[8] **IceCube** Collaboration, M. Aartsen *et al.*, "Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data," *Phys. Rev. Lett.* **113** (2014) 101101, arXiv:1405.5303 [astro-ph.HE].

[9] **IceCube** Collaboration, M. Aartsen *et al.*, "Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube," *Phys. Rev. Lett.* **115** no. 8, (2015) 081102, arXiv:1507.04005 [astro-ph.HE].

[10] **IceCube** Collaboration, M. Aartsen *et al.*, "Observation and Characterization of a Cosmic Muon Neutrino Flux from the Northern Hemisphere using six years of IceCube data," *Astrophys. J.* **833** no. 1, (2016) 3, arXiv:1607.08006 [astro-ph.HE].

[11] M. Ackermann *et al.*, "Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos," *Bull. Am. Astron. Soc.* **51** (2019) 185, arXiv:1903.04334 [astro-ph.HE].

[12] **IceCube** Collaboration, M. Aartsen *et al.*, "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert," *Science* **361** no. 6398, (2018) 147, arXiv:1807.08794 [astro-ph.HE].

[13] R. Stein *et al.*, "A high-energy neutrino coincident with a tidal disruption event," arXiv:2005.05340 [astro-ph.HE].

[14] **IceCube** Collaboration, M. Aartsen *et al.*, "Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption," *Nature* **551** (2017) 596, arXiv:1711.08119 [hep-ex].

[15] M. Bustamante and A. Connolly, "Extracting the Energy-Dependent Neutrino-Nucleon Cross Section above 10 TeV Using IceCube Showers," *Phys. Rev. Lett.* **122** no. 4, (2019) 041101, arXiv:1711.11043 [astro-ph.HE].

[16] **IceCube** Collaboration, M. Aartsen *et al.*, "Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube," *Phys. Rev. D* **99** no. 3, (2019) 032004, arXiv:1808.07629 [hep-ex].

[17] **IceCube** Collaboration, J. Stachurska, "First Double Cascade Tau Neutrino Candidates in IceCube and a New Measurement of the Flavor Composition," *PoS* **ICRC2019** (2020) 1015, arXiv:1908.05506 [astro-ph.HE].

[18] **IceCube** Collaboration, L. Lu, "A novel method of rejecting muon backgrounds for the detection of the highest energy neutrinos," *PoS* **ICRC2019** (2019) 945. https://pos.sissa.it/358/945/.

[19] **ANTARES** Collaboration, A. Albert *et al.*, "All-flavor Search for a Diffuse Flux of Cosmic Neutrinos with Nine Years of ANTARES Data," *Astrophys. J. Lett.* **853** no. 1, (2018) L7, arXiv:1711.07212 [astro-ph.HE].

[20] **KM3NeT, ANTARES** Collaboration, P. Fermani, "Status and results from the ANTARES and KM3NeT-ARCA neutrino telescopes," *PoS* **NuFact2019** (2020) 032.

[21] **KM3Net** Collaboration, S. Adrian-Martinez *et al.*, "Letter of intent for KM3NeT 2.0," *J. Phys. G* **43** no. 8, (2016) 084001, arXiv:1601.07459 [astro-ph.IM].

[22] M. Agostini *et al.*, "The Pacific Ocean Neutrino Experiment," arXiv:2005.09493 [astro-ph.HE].

[23] **Baikal-GVD** Collaboration, A. Avrorin *et al.*, "Neutrino Telescope in Lake Baikal: Present and Future," *PoS* **ICRC2019** (2020) 1011, arXiv:1908.05427 [astro-ph.HE].

[24] K. Greisen, "End to the cosmic ray spectrum?," *Phys. Rev. Lett.* **16** (1966) 748.

[25] G. Zatsepin and V. Kuzmin, "Upper limit of the spectrum of cosmic rays," *JETP Lett.* **4** (1966) 78.

[26] V. Berezinsky and G. Zatsepin, "Cosmic rays at ultrahigh-energies (neutrino?)," *Phys. Lett. B* **28** (1969) 423.

[27] **ARA** Collaboration, M.-Y. Lu, C. G. Pfendner, and A. Shultz, "Ultra-high energy neutrino search with the Askaryan Radio Array," *PoS* **ICRC2017** (2018) 966.

[28] **Pierre Auger** Collaboration, E. Zas, "Searches for neutrino fluxes in the EeV regime with the Pierre Auger Observatory," *PoS* **ICRC2017** (2018) 972.

[29] **IceCube** Collaboration, M. Aartsen *et al.*, "Differential limit on the extremely-high-energy cosmic neutrino flux in the presence of astrophysical background from nine years of IceCube data," *Phys. Rev. D* **98** no. 6, (2018) 062003, arXiv:1807.01820 [astro-ph.HE].

[30] **ARIANNA** Collaboration, C. R. Persichilli, "Performance of the ARIANNA pilot array, and implications for the next generation of UHE neutrino detectors," *PoS* **ICRC2019** (2020) 980.

[31] **ANITA** Collaboration, P. Gorham *et al.*, "Constraints on the ultrahigh-energy cosmic neutrino flux from the fourth flight of ANITA," *Phys. Rev. D* **99** no. 12, (2019) 122001, arXiv:1902.04005 [astro-ph.HE].

[32] A. Romero-Wolf and M. Ave, "Bayesian Inference Constraints on Astrophysical Production of Ultra-high Energy Cosmic Rays and Cosmogenic Neutrino Flux Predictions," *JCAP* **07** (2018) 025, arXiv:1712.07290 [astro-ph.HE].

[33] R. Alves Batista, R. M. de Almeida, B. Lago, and K. Kotera, "Cosmogenic photon and neutrino fluxes in the Auger era," *JCAP* **1901** (2019) 002, arXiv:1806.10879 [astro-ph.HE].

[34] J. Heinze, A. Fedynitch, D. Boncioli, and W. Winter, "A new view on Auger data and cosmogenic neutrinos in light of different nuclear disintegration and air-shower models," *Astrophys. J.* **873** no. 1, (2019) 88, arXiv:1901.03338 [astro-ph.HE].

[35] V. Berezinsky, E. Sabancilar, and A. Vilenkin, "Extremely High Energy Neutrinos from Cosmic Strings," *Phys. Rev. D* **84** (2011) 085006, arXiv:1108.2509 [astro-ph.CO].

[36] L. A. Anchordoqui, "Ultra-High-Energy Cosmic Rays," *Phys. Rept.* **801** (2019) 1, arXiv:1807.09645 [astro-ph.HE].

[37] **IceCube-Gen2** Collaboration, M. Aartsen *et al.*, "IceCube-Gen2: The Window to the Extreme Universe," arXiv:2008.04323 [astro-ph.HE].

[38] **Pierre Auger** Collaboration, A. Aab *et al.*, "The Pierre Auger Observatory Upgrade - Preliminary Design Report," arXiv:1604.03637 [astro-ph.IM].

[39] J. H. Adams *et al.*, "White paper on EUSO-SPB2," arXiv:1703.04513 [astro-ph.HE].

[40] L. A. Anchordoqui *et al.*, "Performance and science reach of the Probe of Extreme Multimessenger Astrophysics for ultrahigh-energy particles," *Phys. Rev. D* **101** no. 2, (2020) 023012, arXiv:1907.03694 [astro-ph.HE].

[41] A. N. Otte, A. M. Brown, A. D. Falcone, M. Mariotti, and I. Taboada, "Trinity: An Air-Shower Imaging System for the Detection of Ultrahigh Energy Neutrinos," *PoS* **ICRC2019** (2020) 976, arXiv:1907.08732 [astro-ph.IM].

[42] M. Sasaki and G. W.-S. Hou, "Neutrino Telescope Array Letter of Intent: A Large Array of High Resolution Imaging Atmospheric Cherenkov and Fluorescence Detectors for Survey of Air-showers from Cosmic Tau Neutrinos in the PeV-EeV Energy Range," arXiv:1408.6244 [astro-ph.IM].

[43] D. F. Fiorillo, G. Miele, and O. Pisanti, "Tau Neutrinos with Cherenkov Telescope Array," arXiv:2007.13423 [hep-ph].

[44] **GRAND** Collaboration, J. Álvarez Muñiz *et al.*, "The Giant Radio Array for Neutrino Detection (GRAND): Science and Design," *Sci. China Phys. Mech. Astron.* **63** no. 1, (2020) 219501, arXiv:1810.09994 [astro-ph.HE].

[45] J. Aguilar *et al.*, "The Next-Generation Radio Neutrino Observatory – Multi-Messenger Neutrino Astrophysics at Extreme Energies," arXiv:1907.12526 [astro-ph.HE].

[46] C. Deaconu *et al.*, "Searches for Ultra-High Energy Neutrinos with ANITA," *PoS* **ICRC2019** (2020) 867, arXiv:1908.00923 [astro-ph.HE].

[47] S. Wissel *et al.*, "Prospects for High-Elevation Radio Detection of ¿100 PeV Tau Neutrinos," arXiv:2004.12718 [astro-ph.IM].

[48] J. Nam *et al.*, "High-elevation synoptic radio array for detection of upward moving air-showers, deployed in the antarctic mountains," *PoS(ICRC2019)* **358** (2019) 967. https://pos.sissa.it/358/967/.

[49] A. Romero-Wolf *et al.*, "Radio Detection of Ultra-high Energy Cosmic Rays with Low Lunar Orbiting SmallSats," arXiv:2008.11232 [astro-ph.HE].

[50] **IceCube** Collaboration, M. Aartsen *et al.*, "A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube," *Astrophys. J.* **809** no. 1, (2015) 98, arXiv:1507.03991 [astro-ph.HE].

[51] M. Ahlers, Y. Bai, V. Barger, and R. Lu, "Galactic neutrinos in the TeV to PeV range," *Phys. Rev. D* **93** no. 1, (2016) 013009, arXiv:1505.03156 [hep-ph].

[52] P. B. Denton, D. Marfatia, and T. J. Weiler, "The Galactic Contribution to IceCube's Astrophysical Neutrino Flux," *JCAP* **08** (2017) 033, arXiv:1703.09721 [astro-ph.HE].

[53] **IceCube** Collaboration, M. Aartsen *et al.*, "Constraints on Galactic Neutrino Emission with Seven Years of IceCube Data," *Astrophys. J.* **849** no. 1, (2017) 67, arXiv:1707.03416 [astro-ph.HE].

[54] O. Mena, S. Palomares-Ruiz, and A. C. Vincent, "Flavor Composition of the High-Energy Neutrino Events in IceCube," *Phys. Rev. Lett.* **113** (2014) 091103, arXiv:1404.0017 [astro-ph.HE].

[55] A. Watanabe, "The spectrum and flavor composition of the astrophysical neutrinos in IceCube," *JCAP* **08** (2015) 030, arXiv:1412.8264 [astro-ph.HE].

[56] S. Palomares-Ruiz, A. C. Vincent, and O. Mena, "Spectral analysis of the high-energy IceCube neutrinos," *Phys. Rev. D* **91** no. 10, (2015) 103008, arXiv:1502.02649 [astro-ph.HE].

[57] A. Palladino, G. Pagliaroli, F. L. Villante, and F. Vissani, "What is the Flavor of the Cosmic Neutrinos Seen by IceCube?," *Phys. Rev. Lett.* **114** no. 17, (2015) 171101, arXiv:1502.02923 [astro-ph.HE].

[58] **IceCube** Collaboration, M. Aartsen *et al.*, "Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube," *Phys. Rev. Lett.* **114** no. 17, (2015) 171102, arXiv:1502.03376 [astro-ph.HE].

[59] M. Bustamante, J. F. Beacom, and W. Winter, "Theoretically palatable flavor combinations of astrophysical neutrinos," *Phys. Rev. Lett.* **115** no. 16, (2015) 161302, arXiv:1506.02645 [astro-ph.HE].

[60] A. C. Vincent, S. Palomares-Ruiz, and O. Mena, "Analysis of the 4-year IceCube high-energy starting events," *Phys. Rev. D* **94** no. 2, (2016) 023009, arXiv:1605.01556 [astro-ph.HE].

[61] G. D'Amico, "Flavor and energy inference for the high-energy IceCube neutrinos," *Astropart. Phys.* **101** (2018) 8, arXiv:1712.04979 [astro-ph.HE].

[62] M. Bustamante and M. Ahlers, "Inferring the flavor of high-energy astrophysical neutrinos at their sources," *Phys. Rev. Lett.* **122** no. 24, (2019) 241101, arXiv:1901.10087 [astro-ph.HE].

[63] A. Palladino, "The flavor composition of astrophysical neutrinos after 8 years of IceCube: an indication of neutron decay scenario?," *Eur. Phys. J. C* **79** no. 6, (2019) 500, arXiv:1902.08630 [astro-ph.HE].

[64] P. A. M. Dirac, "Quantised singularities in the electromagnetic field,," *Proc. Roy. Soc. Lond. A* **A133** no. 821, (1931) 60.

[65] **IceCube** Collaboration, R. Abbasi *et al.*, "Search for Relativistic Magnetic Monopoles with IceCube," *Phys. Rev. D* **87** no. 2, (2013) 022001, arXiv:1208.4861 [astro-ph.HE].

[66] **IceCube** Collaboration, M. Aartsen *et al.*, "Search for non-relativistic Magnetic Monopoles with IceCube," *Eur. Phys. J. C* **74** no. 7, (2014) 2938, arXiv:1402.3460 [astro-ph.CO]. [Erratum: Eur.Phys.J.C 79, 124 (2019)].

[67] **IceCube** Collaboration, M. Aartsen *et al.*, "Searches for Relativistic Magnetic Monopoles in IceCube," *Eur. Phys. J. C* **76** no. 3, (2016) 133, arXiv:1511.01350 [astro-ph.HE].

[68] **ANTARES** Collaboration, A. Albert *et al.*, "Search for relativistic magnetic monopoles with five years of the ANTARES detector data," *JHEP* **07** (2017) 054, arXiv:1703.00424 [astro-ph.HE].

[69] V. Berezinsky and A. Smirnov, "Astrophysical upper bounds on neutrino-nucleon cross-section at energy $E \geq 3 \times 10^{17}$ eV," *Phys. Lett. B* **48** (1974) 269.

[70] F. Cornet, J. I. Illana, and M. Masip, "TeV strings and the neutrino nucleon cross-section at ultrahigh-energies," *Phys. Rev. Lett.* **86** (2001) 4235, arXiv:hep-ph/0102065.

[71] A. Kusenko and T. J. Weiler, "Neutrino cross-sections at high-energies and the future observations of ultrahigh-energy cosmic rays," *Phys. Rev. Lett.* **88** (2002) 161101, arXiv:hep-ph/0106071.

[72] J. Álvarez-Muñiz, F. Halzen, T. Han, and D. Hooper, "Phenomenology of high-energy neutrinos in low scale quantum gravity models," *Phys. Rev. Lett.* **88** (2002) 021301, arXiv:hep-ph/0107057.

[73] L. A. Anchordoqui, J. L. Feng, H. Goldberg, and A. D. Shapere, "Black holes from cosmic rays: Probes of extra dimensions and new limits on TeV scale gravity," *Phys. Rev. D* **65** (2002) 124027, arXiv:hep-ph/0112247.

[74] M. Kowalski, A. Ringwald, and H. Tu, "Black holes at neutrino telescopes," *Phys. Lett. B* **529** (2002) 1, arXiv:hep-ph/0201139.

[75] J. Álvarez-Muñiz, J. L. Feng, F. Halzen, T. Han, and D. Hooper, "Detecting microscopic black holes with neutrino telescopes," *Phys. Rev. D* **65** (2002) 124015, arXiv:hep-ph/0202081.

[76] D. Hooper, "Measuring high-energy neutrino nucleon cross-sections with future neutrino telescopes," *Phys. Rev. D* **65** (2002) 097303, arXiv:hep-ph/0203239.

[77] J. J. Friess, T. Han, and D. Hooper, "TeV string state excitation via high-energy cosmic neutrinos," *Phys. Lett. B* **547** (2002) 31, arXiv:hep-ph/0204112.

[78] L. A. Anchordoqui, J. L. Feng, H. Goldberg, and A. D. Shapere, "Neutrino bounds on astrophysical sources and new physics," *Phys. Rev. D* **66** (2002) 103002, arXiv:hep-ph/0207139.

[79] L. A. Anchordoqui, J. L. Feng, and H. Goldberg, "Particle physics on ice: Constraints on neutrino interactions far above the weak scale," *Phys. Rev. Lett.* **96** (2006) 021101, arXiv:hep-ph/0504228.

[80] S. Palomares-Ruiz, A. Irimia, and T. J. Weiler, "Acceptances for space-based and ground-based fluorescence detectors, and inference of the neutrino-nucleon cross-section above 10^{19} eV," *Phys. Rev. D* **73** (2006) 083003, arXiv:astro-ph/0512231.

[81] L. A. Anchordoqui, A. M. Cooper-Sarkar, D. Hooper, and S. Sarkar, "Probing low-x QCD with cosmic neutrinos at the Pierre Auger Observatory," *Phys. Rev. D* **74** (2006) 043008, arXiv:hep-ph/0605086.

[82] S. Hussain, D. Marfatia, D. McKay, and D. Seckel, "Cross section dependence of event rates at neutrino telescopes," *Phys. Rev. Lett.* **97** (2006) 161101, arXiv:hep-ph/0606246.

[83] E. Borriello, A. Cuoco, G. Mangano, G. Miele, S. Pastor, O. Pisanti, and P. Serpico, "Disentangling neutrino-nucleon cross section and high energy neutrino flux with a km^3 neutrino telescope," *Phys. Rev. D* **77** (2008) 045019, arXiv:0711.0152 [astro-ph].

[84] S. Hussain, D. Marfatia, and D. McKay, "Upward shower rates at neutrino telescopes directly determine the neutrino flux," *Phys. Rev. D* **77** (2008) 107304, arXiv:0711.4374 [hep-ph].

[85] V. Barger and W.-Y. Keung, "Superheavy Particle Origin of IceCube PeV Neutrino Events," *Phys. Lett. B* **727** (2013) 190, arXiv:1305.6907 [hep-ph].

[86] D. Marfatia, D. McKay, and T. Weiler, "New physics with ultra-high-energy neutrinos," *Phys. Lett. B* **748** (2015) 113, arXiv:1502.06337 [hep-ph].

[87] J. Ellis, K. Sakurai, and M. Spannowsky, "Search for Sphalerons: IceCube vs. LHC," *JHEP* **05** (2016) 085, arXiv:1603.06573 [hep-ph].

[88] P. S. B. Dev, D. K. Ghosh, and W. Rodejohann, "R-parity Violating Supersymmetry at IceCube," *Phys. Lett. B* **762** (2016) 116, arXiv:1605.09743 [hep-ph].

[89] V. Bertone, R. Gauld, and J. Rojo, "Neutrino Telescopes as QCD Microscopes," *JHEP* **01** (2019) 217, arXiv:1808.02034 [hep-ph].

[90] L. A. Anchordoqui, C. García Canal, and J. F. Soriano, "Probing strong dynamics with cosmic neutrinos," *Phys. Rev. D* **100** no. 10, (2019) 103001, arXiv:1902.10134 [hep-ph].

[91] B. Zhou and J. F. Beacom, "W-boson and trident production in TeV–PeV neutrino observatories," *Phys. Rev. D* **101** no. 3, (2020) 036010, arXiv:1910.10720 [hep-ph].

[92] S. R. Klein, *Probing high-energy interactions of atmospheric and astrophysical neutrinos*, p. 75. 2020. arXiv:1906.02221 [astro-ph.HE].

[93] K. J. Mack, N. Song, and A. C. Vincent, "Signatures of microscopic black holes and extra dimensions at future neutrino telescopes," *JHEP* **04** (2020) 187, arXiv:1912.06656 [hep-ph].

[94] P. B. Denton and Y. Kini, "Ultra-High-Energy Tau Neutrino Cross Sections with GRAND and POEMMA," arXiv:2007.10334 [astro-ph.HE].

[95] J. G. Learned and S. Pakvasa, "Detecting tau-neutrino oscillations at PeV energies," *Astropart. Phys.* **3** (1995) 267, arXiv:hep-ph/9405296.

[96] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, "Measuring flavor ratios of high-energy astrophysical neutrinos," *Phys. Rev. D* **68** (2003) 093005, arXiv:hep-ph/0307025. [Erratum: Phys.Rev.D 72, 019901 (2005)].

[97] J. F. Beacom, N. F. Bell, D. Hooper, J. G. Learned, S. Pakvasa, and T. J. Weiler, "PseudoDirac neutrinos: A Challenge for neutrino telescopes," *Phys. Rev. Lett.* **92** (2004) 011101, arXiv:hep-ph/0307151.

[98] S. Pakvasa, W. Rodejohann, and T. J. Weiler, "Flavor Ratios of Astrophysical Neutrinos: Implications for Precision Measurements," *JHEP* **02** (2008) 005, arXiv:0711.4517 [hep-ph].

[99] A. Esmaili, "Pseudo-Dirac Neutrino Scenario: Cosmic Neutrinos at Neutrino Telescopes," *Phys. Rev. D* **81** (2010) 013006, arXiv:0909.5410 [hep-ph].

[100] M. Bustamante, A. Gago, and C. Peña Garay, "Energy-Independent New Physics in the Flavour Ratios of High-Energy Astrophysical Neutrinos," *JHEP* **04** (2010) 066, arXiv:1001.4878 [hep-ph].

[101] M. Bustamante, A. Gago, and J. Jones Pérez, "SUSY Renormalization Group Effects in Ultra High Energy Neutrinos," *JHEP* **05** (2011) 133, arXiv:1012.2728 [hep-ph].

[102] P. Mehta and W. Winter, "Interplay of energy dependent astrophysical neutrino flavor ratios and new physics effects," *JCAP* **03** (2011) 041, arXiv:1101.2673 [hep-ph].

[103] A. Esmaili and Y. Farzan, "Implications of the Pseudo-Dirac Scenario for Ultra High Energy Neutrinos from GRBs," *JCAP* **12** (2012) 014, arXiv:1208.6012 [hep-ph].

[104] C. A. Argüelles, T. Katori, and J. Salvadó, "New Physics in Astrophysical Neutrino Flavor," *Phys. Rev. Lett.* **115** (2015) 161303, arXiv:1506.02043 [hep-ph].

[105] I. M. Shoemaker and K. Murase, "Probing BSM Neutrino Physics with Flavor and Spectral Distortions: Prospects for Future High-Energy Neutrino Telescopes," *Phys. Rev. D* **93** no. 8, (2016) 085004, arXiv:1512.07228 [astro-ph.HE].

[106] Y. Ahn, S. K. Kang, and C. Kim, "A Model for Pseudo-Dirac Neutrinos: Leptogenesis and Ultra-High Energy Neutrinos," *JHEP* **10** (2016) 092, arXiv:1602.05276 [hep-ph].

[107] M. González-García, M. Maltoni, I. Martínez-Soler, and N. Song, "Non-standard neutrino interactions in the Earth and the flavor of astrophysical neutrinos," *Astropart. Phys.* **84** (2016) 15, arXiv:1605.08055 [hep-ph].

[108] R. W. Rasmussen, L. Lechner, M. Ackermann, M. Kowalski, and W. Winter, "Astrophysical neutrinos flavored with Beyond the Standard Model physics," *Phys. Rev. D* **96** no. 8, (2017) 083018, arXiv:1707.07684 [hep-ph].

[109] M. Ahlers, M. Bustamante, and S. Mu, "Unitarity Bounds of Astrophysical Neutrinos," *Phys. Rev. D* **98** no. 12, (2018) 123023, arXiv:1810.00893 [astro-ph.HE].

[110] G. Amelino-Camelia, J. R. Ellis, N. Mavromatos, D. V. Nanopoulos, and S. Sarkar, "Tests of quantum gravity from observations of gamma-ray bursts," *Nature* **393** (1998) 763, arXiv:astro-ph/9712103.

[111] D. Colladay and V. Kostelecky, "Lorentz violating extension of the standard model," *Phys. Rev. D* **58** (1998) 116002, arXiv:hep-ph/9809521.

[112] V. Kostelecky and M. Mewes, "Lorentz and CPT violation in neutrinos," *Phys. Rev. D* **69** (2004) 016005, arXiv:hep-ph/0309025.

[113] M. González-García, F. Halzen, and M. Maltoni, "Physics reach of high-energy and high-statistics icecube atmospheric neutrino data," *Phys. Rev. D* **71** (2005) 093010, arXiv:hep-ph/0502223.

[114] D. Hooper, D. Morgan, and E. Winstanley, "Lorentz and CPT invariance violation in high-energy neutrinos," *Phys. Rev. D* **72** (2005) 065009, arXiv:hep-ph/0506091.

[115] L. A. Anchordoqui, H. Goldberg, M. González-García, F. Halzen, D. Hooper, S. Sarkar, and T. J. Weiler, "Probing Planck scale physics with IceCube," *Phys. Rev. D* **72** (2005) 065019, arXiv:hep-ph/0506168.

[116] L. A. Anchordoqui, C. A. García Canal, H. Goldberg, D. Gomez Dumm, and F. Halzen, "Probing leptoquark production at IceCube," *Phys. Rev. D* **74** (2006) 125021, arXiv:hep-ph/0609214.

[117] V. Kostelecky and N. Russell, "Data Tables for Lorentz and CPT Violation," *Rev. Mod. Phys.* **83** (2011) 11, arXiv:0801.0287 [hep-ph].

[118] A. Kostelecky and M. Mewes, "Neutrinos with Lorentz-violating operators of arbitrary dimension," *Phys. Rev. D* **85** (2012) 096005, arXiv:1112.6395 [hep-ph].

[119] P. Gorham *et al.*, "Implications of ultra-high energy neutrino flux constraints for Lorentz-invariance violating cosmogenic neutrinos," *Phys. Rev. D* **86** (2012) 103006, arXiv:1207.6425 [astro-ph.HE].

[120] E. Borriello, S. Chakraborty, A. Mirizzi, and P. D. Serpico, "Stringent constraint on neutrino Lorentz-invariance violation from the two IceCube PeV neutrinos," *Phys. Rev. D* **87** no. 11, (2013) 116009, arXiv:1303.5843 [astro-ph.HE].

[121] J. S. Díaz, A. Kostelecky, and M. Mewes, "Testing Relativity with High-Energy Astrophysical Neutrinos," *Phys. Rev. D* **89** no. 4, (2014) 043005, arXiv:1308.6344 [astro-ph.HE].

[122] F. W. Stecker and S. T. Scully, "Propagation of Superluminal PeV IceCube Neutrinos: A High Energy Spectral Cutoff or New Constraints on Lorentz Invariance Violation," *Phys. Rev. D* **90** no. 4, (2014) 043012, arXiv:1404.7025 [astro-ph.HE].

[123] L. Anchordoqui, V. Barger, H. Goldberg, J. Learned, D. Marfatia, S. Pakvasa, T. Paul, and T. Weiler, "End of the cosmic neutrino energy spectrum," *Phys. Lett. B* **739** (2014) 99, arXiv:1404.0622 [hep-ph].

[124] F. W. Stecker, S. T. Scully, S. Liberati, and D. Mattingly, "Searching for Traces of Planck-Scale Physics with High Energy Neutrinos," *Phys. Rev. D* **91** no. 4, (2015) 045009, arXiv:1411.5889 [hep-ph].

[125] G. Amelino-Camelia, D. Guetta, and T. Piran, "Icecube Neutrinos and Lorentz Invariance Violation," *Astrophys. J.* **806** no. 2, (2015) 269.

[126] G. Tomar, S. Mohanty, and S. Pakvasa, "Lorentz Invariance Violation and IceCube Neutrino Events," *JHEP* **11** (2015) 022, arXiv:1507.03193 [hep-ph].

[127] J. Liao and D. Marfatia, "IceCube's astrophysical neutrino energy spectrum from CPT violation," *Phys. Rev. D* **97** no. 4, (2018) 041302, arXiv:1711.09266 [hep-ph].

[128] J. Ellis, N. E. Mavromatos, A. S. Sakharov, and E. K. Sarkisyan-Grinbaum, "Limits on Neutrino Lorentz Violation from Multimessenger Observations of TXS 0506+056," *Phys. Lett. B* **789** (2019) 352, arXiv:1807.05155 [astro-ph.HE].

[129] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, "Decay of High-Energy Astrophysical Neutrinos," *Phys. Rev. Lett.* **90** (2003) 181301, arXiv:hep-ph/0211305.

[130] L. Anchordoqui, T. Han, D. Hooper, and S. Sarkar, "Exotic neutrino interactions at the Pierre Auger Observatory," *Astropart. Phys.* **25** (2006) 14, arXiv:hep-ph/0508312.

[131] P. Baerwald, M. Bustamante, and W. Winter, "Neutrino Decays over Cosmological Distances and the Implications for Neutrino Telescopes," *JCAP* **10** (2012) 020, arXiv:1208.4600 [astro-ph.CO].

[132] G. Pagliaroli, A. Palladino, F. Villante, and F. Vissani, "Testing nonradiative neutrino decay scenarios with IceCube data," *Phys. Rev. D* **92** no. 11, (2015) 113008, arXiv:1506.02624 [hep-ph].

[133] M. Bustamante, J. F. Beacom, and K. Murase, "Testing decay of astrophysical neutrinos with incomplete information," *Phys. Rev. D* **95** no. 6, (2017) 063013, arXiv:1610.02096 [astro-ph.HE].

[134] P. B. Denton and I. Tamborra, "Invisible Neutrino Decay Could Resolve IceCube's Track and Cascade Tension," *Phys. Rev. Lett.* **121** no. 12, (2018) 121802, arXiv:1805.05950 [hep-ph].

[135] M. Bustamante, "New limits on neutrino decay from the Glashow resonance of high-energy cosmic neutrinos," arXiv:2004.06844 [astro-ph.HE].

[136] A. Abdullahi and P. B. Denton, "Visible Decay of Astrophysical Neutrinos at IceCube," *Phys. Rev. D* **102** no. 2, (2020) 023018, arXiv:2005.07200 [hep-ph].

[137] B. Feldstein, A. Kusenko, S. Matsumoto, and T. T. Yanagida, "Neutrinos at IceCube from Heavy Decaying Dark Matter," *Phys. Rev. D* **88** no. 1, (2013) 015004, arXiv:1303.7320 [hep-ph].

[138] A. Esmaili and P. D. Serpico, "Are IceCube neutrinos unveiling PeV-scale decaying dark matter?," *JCAP* **11** (2013) 054, arXiv:1308.1105 [hep-ph].

[139] Y. Bai, R. Lu, and J. Salvadó, "Geometric Compatibility of IceCube TeV-PeV Neutrino Excess and its Galactic Dark Matter Origin," *JHEP* **01** (2016) 161, arXiv:1311.5864 [hep-ph].

[140] Y. Ema, R. Jinno, and T. Moroi, "Cosmic-Ray Neutrinos from the Decay of Long-Lived Particle and the Recent IceCube Result," *Phys. Lett. B* **733** (2014) 120, arXiv:1312.3501 [hep-ph].

[141] A. Bhattacharya, M. H. Reno, and I. Sarcevic, "Reconciling neutrino flux from heavy dark matter decay and recent events at IceCube," *JHEP* **06** (2014) 110, arXiv:1403.1862 [hep-ph].

[142] J. Zavala, "Galactic PeV neutrinos from dark matter annihilation," *Phys. Rev. D* **89** no. 12, (2014) 123516, arXiv:1404.2932 [astro-ph.HE].

[143] C. Rott, K. Kohri, and S. C. Park, "Superheavy dark matter and IceCube neutrino signals: Bounds on decaying dark matter," *Phys. Rev. D* **92** no. 2, (2015) 023529, arXiv:1408.4575 [hep-ph].

[144] A. Esmaili, S. K. Kang, and P. D. Serpico, "IceCube events and decaying dark matter: hints and constraints," *JCAP* **12** (2014) 054, arXiv:1410.5979 [hep-ph].

[145] C. S. Fong, H. Minakata, B. Panes, and R. Zukanovich Funchal, "Possible Interpretations of IceCube High-Energy Neutrino Events," *JHEP* **02** (2015) 189, arXiv:1411.5318 [hep-ph].

[146] K. Murase, R. Laha, S. Ando, and M. Ahlers, "Testing the Dark Matter Scenario for PeV Neutrinos Observed in IceCube," *Phys. Rev. Lett.* **115** no. 7, (2015) 071301, arXiv:1503.04663 [hep-ph].

[147] C. El Aisati, M. Gustafsson, and T. Hambye, "New Search for Monochromatic Neutrinos from Dark Matter Decay," *Phys. Rev. D* **92** no. 12, (2015) 123515, arXiv:1506.02657 [hep-ph].

[148] L. A. Anchordoqui, V. Barger, H. Goldberg, X. Huang, D. Marfatia, L. H. M. da Silva, and T. J. Weiler, "IceCube neutrinos, decaying dark matter, and the Hubble constant," *Phys. Rev. D* **92** no. 6, (2015) 061301, arXiv:1506.08788 [hep-ph]. [Erratum: Phys. Rev. D 94, 069901 (2016)].

[149] S. Troitsky, "Search for Galactic disk and halo components in the arrival directions of high-energy astrophysical neutrinos," *JETP Lett.* **102** no. 12, (2015) 785, arXiv:1511.01708 [astro-ph.HE].

[150] M. Chianese, G. Miele, S. Morisi, and E. Vitagliano, "Low energy IceCube data and a possible Dark Matter related excess," *Phys. Lett. B* **757** (2016) 251, arXiv:1601.02934 [hep-ph].

[151] M. Chianese, G. Miele, and S. Morisi, "Dark Matter interpretation of low energy IceCube MESE excess," *JCAP* **01** (2017) 007, arXiv:1610.04612 [hep-ph].

[152] C. A. Argüelles, A. Kheirandish, and A. C. Vincent, "Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos," *Phys. Rev. Lett.* **119** no. 20, (2017) 201801, arXiv:1703.00451 [hep-ph].

[153] A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz, and I. Sarcevic, "Probing decaying heavy dark matter with the 4-year IceCube HESE data," *JCAP* **07** (2017) 027, arXiv:1706.05746 [hep-ph].

[154] M. Chianese, G. Miele, and S. Morisi, "Interpreting IceCube 6-year HESE data as an evidence for hundred TeV decaying Dark Matter," *Phys. Lett. B* **773** (2017) 591, arXiv:1707.05241 [hep-ph].

[155] **IceCube** Collaboration, M. Aartsen *et al.*, "Search for neutrinos from decaying dark matter with IceCube," *Eur. Phys. J. C* **78** no. 10, (2018) 831, arXiv:1804.03848 [astro-ph.HE].

[156] Y. Sui and P. Bhupal Dev, "A Combined Astrophysical and Dark Matter Interpretation of the IceCube HESE and Throughgoing Muon Events," *JCAP* **07** (2018) 020, arXiv:1804.04919 [hep-ph].

[157] A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz, and I. Sarcevic, "Update on decaying and annihilating heavy dark matter with the 6-year IceCube HESE data," *JCAP* **05** (2019) 051, arXiv:1903.12623 [hep-ph].

[158] **IceCube** Collaboration, C. A. Argüelles and H. Dujmovic, "Searches for Connections Between Dark Matter and Neutrinos with the IceCube High-Energy Starting Event Sample," *PoS* **ICRC2019** (2020) 839, arXiv:1907.11193 [hep-ph].

[159] M. Chianese, D. F. Fiorillo, G. Miele, S. Morisi, and O. Pisanti, "Decaying dark matter at IceCube and its signature on High Energy gamma experiments," *JCAP* **11** (2019) 046, arXiv:1907.11222 [hep-ph].

[160] **ANTARES, IceCube** Collaboration, A. Albert *et al.*, "Combined search for neutrinos from dark matter self-annihilation in the Galactic Centre with ANTARES and IceCube," arXiv:2003.06614 [astro-ph.HE].

[161] T. J. Weiler, "New Physics in Neutrino Telescopes." https://icecube.wisc.edu/tev/presentations/weiler_plen.pdf. Presented at TeV Particle Astrophysics (TeVPA) 2006, Madison, WI, USA.

[162] D. Hooper, "Detecting MeV Gauge Bosons with High-Energy Neutrino Telescopes," *Phys. Rev. D* **75** (2007) 123001, arXiv:hep-ph/0701194.

[163] J. Lykken, O. Mena, and S. Razzaque, "Ultrahigh-energy neutrino flux as a probe of large extra-dimensions," *JCAP* **12** (2007) 015, arXiv:0705.2029 [hep-ph].

[164] L. Anchordoqui, V. Barger, H. Goldberg, and D. Marfatia, "Phase transition in the fine structure constant," *Phys. Lett. B* **660** (2008) 529, arXiv:0711.4055 [hep-ph].

[165] S. Ando, M. Kamionkowski, and I. Mocioiu, "Neutrino Oscillations, Lorentz/CPT Violation, and Dark Energy," *Phys. Rev. D* **80** (2009) 123522, arXiv:0910.4391 [hep-ph].

[166] J. Barranco, O. G. Miranda, C. A. Moura, T. I. Rashba, and F. Rossi-Torres, "Confusing the extragalactic neutrino flux limit with a neutrino propagation limit," *JCAP* **10** (2011) 007, arXiv:1012.2476 [astro-ph.CO].

[167] O. Miranda, C. Moura, and A. Parada, "Sterile neutrinos, dark matter, and resonant effects in ultra high energy regimes," *Phys. Lett. B* **744** (2015) 55, arXiv:1308.1408 [hep-ph].

[168] K. Ioka and K. Murase, "IceCube PeV–EeV neutrinos and secret interactions of neutrinos," *PTEP* **2014** no. 6, (2014) 061E01, arXiv:1404.2279 [astro-ph.HE].

[169] K. C. Y. Ng and J. F. Beacom, "Cosmic neutrino cascades from secret neutrino interactions," *Phys. Rev. D* **90** no. 6, (2014) 065035, arXiv:1404.2288 [astro-ph.HE]. [Erratum: Phys. Rev. D 90, 089904 (2014)].

[170] M. Ibe and K. Kaneta, "Cosmic neutrino background absorption line in the neutrino spectrum at IceCube," *Phys. Rev. D* **90** no. 5, (2014) 053011, arXiv:1407.2848 [hep-ph].

[171] A. DiFranzo and D. Hooper, "Searching for MeV-Scale Gauge Bosons with IceCube," *Phys. Rev. D* **92** no. 9, (2015) 095007, arXiv:1507.03015 [hep-ph].

[172] P. de Salas, R. Lineros, and M. Tórtola, "Neutrino propagation in the galactic dark matter halo," *Phys. Rev. D* **94** no. 12, (2016) 123001, arXiv:1601.05798 [astro-ph.HE].

[173] J. F. Cherry, A. Friedland, and I. M. Shoemaker, "Short-baseline neutrino oscillations, Planck, and IceCube," arXiv:1605.06506 [hep-ph].

[174] M. M. Reynoso and O. A. Sampayo, "Propagation of high-energy neutrinos in a background of ultralight scalar dark matter," *Astropart. Phys.* **82** (2016) 10, arXiv:1605.09671 [hep-ph].

[175] N. Klop and S. Ando, "Effects of a neutrino-dark energy coupling on oscillations of high-energy neutrinos," *Phys. Rev. D* **97** no. 6, (2018) 063006, arXiv:1712.05413 [hep-ph].

[176] M. Bustamante and S. K. Agarwalla, "Universe's Worth of Electrons to Probe Long-Range Interactions of High-Energy Astrophysical Neutrinos," *Phys. Rev. Lett.* **122** no. 6, (2019) 061103, arXiv:1808.02042 [astro-ph.HE].

[177] K. J. Kelly and P. A. Machado, "Multimessenger Astronomy and New Neutrino Physics," *JCAP* **10** (2018) 048, arXiv:1808.02889 [hep-ph].

[178] Y. Farzan and S. Palomares-Ruiz, "Flavor of cosmic neutrinos preserved by ultralight dark matter," *Phys. Rev. D* **99** no. 5, (2019) 051702, arXiv:1810.00892 [hep-ph].

[179] J. Alvey and M. Fairbairn, "Linking Scalar Dark Matter and Neutrino Masses with IceCube 170922A," *JCAP* **07** (2019) 041, arXiv:1902.01450 [hep-ph].

[180] G. Barenboim, P. B. Denton, and I. M. Oldengott, "Constraints on inflation with an extended neutrino sector," *Phys. Rev. D* **99** no. 8, (2019) 083515, arXiv:1903.02036 [astro-ph.CO].

[181] K.-Y. Choi, J. Kim, and C. Rott, "Constraining dark matter-neutrino interactions with IceCube-170922A," *Phys. Rev. D* **99** no. 8, (2019) 083018, arXiv:1903.03302 [astro-ph.CO].

[182] S. Koren, "Neutrino – Dark Matter Scattering and Coincident Detections of UHE Neutrinos with EM Sources," *JCAP* **09** (2019) 013, arXiv:1903.05096 [hep-ph].

[183] K. Murase and I. M. Shoemaker, "Neutrino Echoes from Multimessenger Transient Sources," *Phys. Rev. Lett.* **123** no. 24, (2019) 241102, arXiv:1903.08607 [hep-ph].

[184] M. Bustamante, C. Rosenstrøm, S. Shalgar, and I. Tamborra, "Bounds on secret neutrino interactions from high-energy astrophysical neutrinos," *Phys. Rev. D* **101** no. 12, (2020) 123024, arXiv:2001.04994 [astro-ph.HE].

[185] C. Creque-Sarbinowski, J. Hyde, and M. Kamionkowski, "Resonant Neutrino Self-Interactions," arXiv:2005.05332 [hep-ph].

[186] **ANITA** Collaboration, P. Gorham *et al.*, "Characteristics of Four Upward-pointing Cosmic-ray-like Events Observed with ANITA," *Phys. Rev. Lett.* **117** no. 7, (2016) 071101, arXiv:1603.05218 [astro-ph.HE].

[187] J. F. Cherry and I. M. Shoemaker, "Sterile neutrino origin for the upward directed cosmic ray showers detected by ANITA," *Phys. Rev. D* **99** no. 6, (2019) 063016, arXiv:1802.01611 [hep-ph].

[188] **ANITA** Collaboration, P. Gorham *et al.*, "Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA," *Phys. Rev. Lett.* **121** no. 16, (2018) 161102, arXiv:1803.05088 [astro-ph.HE].

[189] L. A. Anchordoqui, V. Barger, J. G. Learned, D. Marfatia, and T. J. Weiler, "Upgoing ANITA events as evidence of the CPT symmetric universe," *LHEP* **1** no. 1, (2018) 13, arXiv:1803.11554 [hep-ph].

[190] G.-y. Huang, "Sterile neutrinos as a possible explanation for the upward air shower events at ANITA," *Phys. Rev. D* **98** no. 4, (2018) 043019, arXiv:1804.05362 [hep-ph].

[191] J. H. Collins, P. Bhupal Dev, and Y. Sui, "R-parity Violating Supersymmetric Explanation of the Anomalous Events at ANITA," *Phys. Rev. D* **99** no. 4, (2019) 043009, arXiv:1810.08479 [hep-ph].

[192] B. Chauhan and S. Mohanty, "Leptoquark solution for both the flavor and ANITA anomalies," *Phys. Rev. D* **99** no. 9, (2019) 095018, arXiv:1812.00919 [hep-ph].

[193] L. A. Anchordoqui and I. Antoniadis, "Supersymmetric sphaleron configurations as the origin of the perplexing ANITA events," *Phys. Lett. B* **790** (2019) 578, arXiv:1812.01520 [hep-ph].

[194] L. Heurtier, Y. Mambrini, and M. Pierre, "Dark matter interpretation of the ANITA anomalous events," *Phys. Rev. D* **99** no. 9, (2019) 095014, arXiv:1902.04584 [hep-ph].

[195] K. D. de Vries and S. Prohira, "Coherent transition radiation from the geomagnetically-induced current in cosmic-ray air showers: Implications for the anomalous events observed by ANITA," *Phys. Rev. Lett.* **123** no. 9, (2019) 091102, arXiv:1903.08750 [astro-ph.HE].

[196] D. Hooper, S. Wegsman, C. Deaconu, and A. Vieregg, "Superheavy dark matter and ANITA's anomalous events," *Phys. Rev. D* **100** no. 4, (2019) 043019, arXiv:1904.12865 [astro-ph.HE].

[197] J. M. Cline, C. Gross, and W. Xue, "Can the ANITA anomalous events be due to new physics?," *Phys. Rev. D* **100** no. 1, (2019) 015031, arXiv:1904.13396 [hep-ph].

[198] I. M. Shoemaker, A. Kusenko, P. K. Munneke, A. Romero-Wolf, D. M. Schroeder, and M. J. Siegert, "Reflections On the Anomalous ANITA Events: The Antarctic Subsurface as a Possible Explanation," *Ann. Glaciology* (2020) 1, arXiv:1905.02846 [astro-ph.HE].

[199] I. Esteban, J. López-Pavón, I. Martínez-Soler, and J. Salvadó, "Looking at the axionic dark sector with ANITA," *Eur. Phys. J. C* **80** no. 3, (2020) 259, arXiv:1905.10372 [hep-ph].

[200] L. Heurtier, D. Kim, J.-C. Park, and S. Shin, "Explaining the ANITA Anomaly with Inelastic Boosted Dark Matter," *Phys. Rev. D* **100** no. 5, (2019) 055004, arXiv:1905.13223 [hep-ph].

[201] S. Chipman, R. Diesing, M. H. Reno, and I. Sarcevic, "Anomalous ANITA air shower events and tau decays," *Phys. Rev. D* **100** no. 6, (2019) 063011, arXiv:1906.11736 [astro-ph.HE].

[202] D. Borah, A. Dasgupta, U. K. Dey, and G. Tomar, "Connecting ANITA anomalous events to a nonthermal dark matter scenario," *Phys. Rev. D* **101** no. 7, (2020) 075039, arXiv:1907.02740 [hep-ph].

[203] M. Abdullah, B. Dutta, S. Ghosh, and T. Li, "$(g-2)_{\mu,e}$ and the ANITA anomalous events in a three-loop neutrino mass model," *Phys. Rev. D* **100** no. 11, (2019) 115006, arXiv:1907.08109 [hep-ph].

[204] A. Esmaili and Y. Farzan, "Explaining the ANITA events by a $L_e - L_\tau$ gauge model," *JCAP* **12** (2019) 017, arXiv:1909.07995 [hep-ph].

[205] **IceCube** Collaboration, A. Ishihara, "The IceCube Upgrade – Design and Science Goals," *PoS* **ICRC2019** (2020) 1031, arXiv:1908.09441 [astro-ph.HE].

[206] **DUNE** Collaboration, B. Abi *et al.*, "Long-baseline neutrino oscillation physics potential of the DUNE experiment," arXiv:2006.16043 [hep-ex].

[207] **JUNO** Collaboration, W. Wu, "Neutrino oscillation studies in JUNO," *PoS* **NuFact2019** (2019) 030.

[208] **Hyper-Kamiokande** Collaboration, J. Walker, "Physics potential of Hyper-Kamiokande for neutrino oscillation measurements," *PoS* **NuFact2019** (2019) 040.

[209] S. A. R. Ellis, K. J. Kelly, and S. W. Li, "Current and Future Neutrino Oscillation Constraints on Leptonic Unitarity," arXiv:2008.01088 [hep-ph].

[210] **FASER** Collaboration, H. Abreu *et al.*, "Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC," *Eur. Phys. J. C* **80** no. 1, (2020) 61, arXiv:1908.02310 [hep-ex].

[211] **FASER** Collaboration, H. Abreu *et al.*, "Technical Proposal: FASERnu," arXiv:2001.03073 [physics.ins-det].