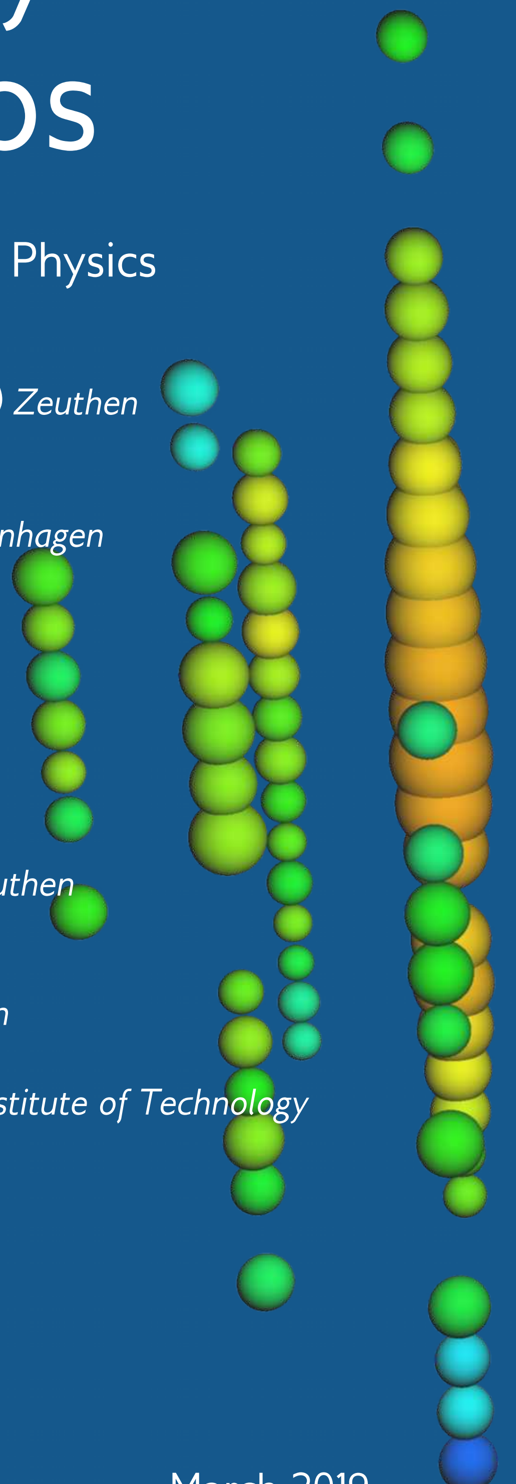
Astro2020 Science White Paper

Fundamental Physics with High-Energy Cosmic Neutrinos

Thematic Area: Cosmology and Fundamental Physics



Markus Ackermann, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Markus Ahlers, *Niels Bohr Institute, University of Copenhagen*
Luis Anchordoqui[*], *City University of New York*
Mauricio Bustamante[†], *Niels Bohr Institute, University of Copenhagen*
Amy Connolly, *The Ohio State University*
Cosmin Deaconu, *University of Chicago*
Darren Grant[‡], *Michigan State University*
Peter Gorham, *University of Hawaii, Manoa*
Francis Halzen, *University of Wisconsin, Madison*
Albrecht Karle, *University of Wisconsin, Madison*
Kumiko Kotera, *Institut d'Astrophysique de Paris*
Marek Kowalski, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Miguel A. Mostafa, *Pennsylvania State University*
Kohta Murase, *Pennsylvania State University*
Anna Nelles, *Deutsches Elektronen-Synchrotron (DESY) Zeuthen*
Angela Olinto, *University of Chicago*
Andres Romero-Wolf[§], *Jet Propulsion Laboratory, California Institute of Technology*
Abigail Vieregg[¶], *University of Chicago*
Stephanie Wissel[‖], *California Polytechnic State University*

[*]luis.anchordoqui@gmail.com, +1 617 953 5066
[†]mbustamante@nbi.ku.dk, +45 22 23 05 66
[‡]drg@msu.edu, +1 517 884 5567
[§]Andrew.Romero-Wolf@jpl.nasa.gov, +1 818 354 0058
[¶]avieregg@kicp.uchicago.edu, +1 773 834 2988
[‖]swissel@calpoly.edu, +1 805 756 7375

March 2019

Abstract

High-energy cosmic neutrinos can reveal new fundamental particles and interactions, probing energy and distance scales far exceeding those accessible in the laboratory. This white paper describes the outstanding particle physics questions that high-energy cosmic neutrinos can address in the coming decade. A companion white paper discusses how the observation of cosmic neutrinos can address open questions in astrophysics. Tests of fundamental physics using high-energy cosmic neutrinos will be enabled by detailed measurements of their energy spectrum, arrival directions, flavor composition, and timing.

Endorsers

Kevork N. Abazajian[1], Sanjib Kumar Agarwalla[2], Juan Antonio Aguilar Sánchez[3], Marco Ajello[4], Roberto Aloisio[5 6], Jaime Álvarez-Muñiz[7], Rafael Alves Batista[8], Hongjun An[9], Karen Andeen[10], Shin'ichiro Ando[11], Gisela Anton[12], Ignatios Antoniadis[13 14], Katsuaki Asano[15], Katie Auchettl[16], Jan Auffenberg[17], Hugo Ayala[18], Xinhua Bai[19], Gabriela Barenboim[20], Vernon Barger[21], Imre Bartos[22], Steve W. Barwick[1], John Beacom[23], James J. Beatty[23], Nicole F. Bell[24], José Bellido[25], Segev BenZvi[26], Douglas R. Bergman[27], José Bernabéu[20], Elisa Bernardini[28 29], Mario Bertaina[30], Gianfranco Bertone[11], Peter F. Bertone[31], Francesca Bisconti[32], Jonathan Biteau[33], Erik Blaufuss[34], Summer Blot[29], Julien Bolmont[35], Zeljka Bosnjak[36], Olga Botner[37], Federica Bradascio[29], Esra Bulbul[38], Alexander Burgman[37], Francesco Cafagna[39], Regina Caputo[40], Rossella Caruso[41], Marco Casolino[5], Karem Peñaló Castillo[42], Silvia Celli[43], Andrew Chen[44], Yaocheng Chen[45], Talai Mohamed Cherif[46], Nafis Rezwan Khan Chowdhury[20], Eugene M. Chudnovsky[47], Brian A. Clark[23], Pablo Correa[48], Doug F. Cowen[18], Paschal Coyle[49], Linda Cremonesi[50], Jane Lixin Dai[51], Basudeb Dasgupta[52], André de Gouvêa[53], Sijbrand de Jong[55 56], Simon De Kockere[48], João R. T. de Mello Neto[54], Krijn D. de Vries[48], Valentin Decoene[57], Peter B. Denton[58], Tyce DeYoung[59], Rebecca Diesing[60], Markus Dittmer[61], Klaus Dolag[62], Michele Doro[28], Michael A. DuVernois[21], Toshikazu Ebisuzaki[63], John Ellis[64], Rikard Enberg[37], Ralph Engel[65], Johannes Eser[66], Arman Esmaili[67], Ke Fang[68], Jonathan L. Feng[1], Gustavo Figueiredo[69], George Filippatos[66], Chad Finley[70], Derek Fox[18], Anna Franckowiak[29], Elizabeth Friedman[34], Toshihiro Fujii[71], Daniele Gaggero[72], Alberto M. Gago[73], Thomas Gaisser[74], Shan Gao[29], Carlos García Canal[75], Daniel García-Fernández[29], Simone Garrappa[29], Maria Vittoria Garzelli[76 77], Christian Glaser[1], Allan Hallgren[37], Jordan C. Hanson[78], Andreas Haungs[65], John W. Hewitt[79], Jannik Hofestädt[12], Benjamin Hokanson-Fasig[21], Dan Hooper[80 60], Shunsaku Horiuchi[81], Feifei Huang[82], Patrick Huber[81], Tim Huege[65], Kaeli Hughes[60], Naoya Inoue[83], Susumu Inoue[63], Fabio Iocco[84], Kunihito Ioka[71], Clancy W. James[85], Eleanor Judd[86], Daniel Kabat[47], Fumiyoshi Kajino[87], Takaaki Kajita[15], Marc Kamionkowski[88], Alexander Kappes[61], Dimitra Karabali[47], Timo Karg[29], Teppei Katori[89], Uli F. Katz[12], Norita Kawanaka[71], Azadeh Keivani[90], John L. Kelley[21], Myoungchul Kim[91], Shigeo S. Kimura[18], Spencer Klein[92], Stefan Klepser[29], David Koke[61], Hermann Kolanoski[93], Lutz Köpke[94], Joachim Kopp[94 95], Claudio Kopper[59], Jason Koskinen[16], V. Alan Kostelecký[96], Dmitriy Kostunin[29], Antoine Kouchner[97], Ilya Kravchenko[98], John Krizmanic[99], Naoko Kurahashi Neilson[100], Michael Kuss[101], Evgeny Kuznetsov[102], Uzair Abdul Latif[103], John G. Learned[104], Jean-Philippe Lenain[13], Rebecca K. Leane[105], Shirley Weishi Li[106], Lu Lu[91], Francesco Longo[107], Andrew Ludwig[60], Cecilia Lunardini[108], Paolo Lipari[109], James Madsen[110], Keiichi Mase[91], Manuela Mallamaci[111], Karl Mannheim[112], Danny Marfatia[104], Raffaella Margutti[53], Cristian Jesús Lozano Mariscal[61], Szabolcs Marka[90], Olivier Martineau-Huynh[35], Oscar Martínez-Bravo[113], Manuel Masip[114], Nikolaos E. Mavromatos[64], Frank McNally[115], Olga Mena[20], Kevin-Druis Merenda[66], Philipp Mertsch[17], Peter Mészáros[18], Matthew Mewes[116], Hisakazu Minakata[15], Nestor Mirabal[40], Lino Miramonti[117], Omar G. Miranda[118], Razmik Mirzoyan[119], John W. Mitchell[40], Irina Mocioiu[18], Teresa Montaruli[120], Maria Elena Monzani[106], Roger Moore[121], Shigehiro Nagataki[63], Masayuki Nakahata[15], Jiwoo Nam[45], Kenny C. Y. Ng[122], Ryan Nichol[50], Valentin Niess[123], David F. Nitz[124], Samaya Nissanke[11], Eric Nuss[125], Eric Oberla[60], Stefan Ohm[29], Kouji Ohta[71], Foteini Oikonomou[126], Roopesh Ojha[99 40], Nepomuk Otte[127], Timothy A. D. Paglione[47], Sandip Pakvasa[104], Andrea Palladino[29], Sergio Palomares-Ruiz[20], Vasiliki Pavlidou[128], Carlos Pérez de los Heros[37], Christopher Persichilli[1], Piergiorgio Picozza[5 129], Zbigniew Plebaniak[130], Vlad Popa[131], Steven Prohira[23], Bindu Rani[40], Brian Flint Rauch[132], Soebur Razzaque[133], Mary Hall Reno[134], Elisa Resconi[135], Marco Ricci[5], Jarred M. Roberts[136], Nicholas L. Rodd[86 92], Werner Rodejohann[43], Juan Rojo[137], Carsten Rott[138], Iftach Sadeh[29], Benjamin R. Safdi[139], Naoto Sakaki[63], David Saltzberg[140], Jordi Salvadó[142], Dorothea Samtleben[141], Marcos Santander[143], Fred Sarazin[66], Konstancja Satalecka[29], Michael Schimp[144], Olaf Scholten[145], Harm Schoorlemmer[43], Sergio J. Sciutto[75], Valentina Scotti[146], David Seckel[74], Pasquale D. Serpico[147], Shashank Shalgar[16], Jerry Shiao[45], Kenji Shinozaki[30], Ian M. Shoemaker[81], Günter Sigl[148], Lorenzo Sironi[90], Tracy R. Slatyer[105], Radomir Smida[60], Alexei Yu Smirnov[43], Jorge F. Soriano[47], Daniel Southall[60], Glenn Spiczak[110], Anatoly Spitkovsky[149], Maurizio Spurio[150], Juliana Stachurska[29], Krzysztof Z. Stanek[23], Floyd Stecker[40], Christian Stegmann[29], Robert Stein[29], Anna M. Suliga[16], Greg Sullivan[34], Jacek Szabelski[130], Ignacio Taboada[127], Yoshiyuki Takizawa[63], Irene Tamborra[16], Xerxes Tata[104], Todd A. Thompson[23], Charles Timmermans[55 56], Kirsten Tollefson[59], Diego F. Torres[151], Jorge Torres[23], Simona Toscano[3], Delia Tosi[21], Matías Tueros[75], Sara Turriziani[63], Elisabeth Unger[37], Michael Unger[65], Martin Unland Elorrieta[61], José Wagner Furtado Valle[20], Lawrence Wiencke[66], Nick van Eijndhoven[48], Jakob van Santen[29], Arjen van Vliet[29], Justin Vandenbroucke[21], Gary S. Varner[104], Tonia Venters[40], Matthias Vereecken[48], Alex Vilenkin[152], Francesco L. Villante[153], Aaron Vincent[154], Philip von Doetinchem[104], Alan A. Watson[155], Thomas Weiler[156], Christoph Welling[29], Nathan Whitehorn[140], Dawn R. Williams[143], Walter Winter[29], Hubing Xiao[111], Donglian Xu[157], Tokonatsu Yamamoto[87], Lili Yang[158], Gaurang Yodh[1], Shigeru Yoshida[91], Tianlu Yuan[21], Danilo Zavrtanik[159], Arnulfo Zepeda[118], Bing Zhang[160], Hao Zhou[161], Anne Zilles[57], Stephan Zimmer[162], Juan de Dios Zornoza[20], Renata Zukanovich Funchal[8], and Juan Zúñiga[20]

[1]*University of California, Irvine* [2]*Institute of Physics, Bhubaneswar* [3]*Université Libre de Bruxelles*
[4]*Clemson University* [5]*Istituto Nazional di Fisica Nucleare (INFN)* [6]*Gran Sasso Science Institute (GSSI)*
[7]*Universidade de Santiago de Compostela* [8]*Universidade de São Paulo* [9]*Chungbuk National University*
[10]*Marquette University* [11]*Universiteit van Amsterdam* [12]*Friedrich-Alexander-Universität Erlangen-Nürnberg*
[13]*Sorbonne Université* [14]*Université de Berne* [15]*University of Tokyo*
[16]*Niels Bohr Institute, University of Copenhagen* [17]*Rheinisch-Westfälische Technische Hochschule Aachen*
[18]*Pennsylvania State University* [19]*South Dakota School of Mines and Technology*

[20]*Institut de Física Corpuscular, Universitat de València* [21]*University of Wisconsin, Madison*
[22]*University of Florida* [23]*The Ohio State University* [24]*University of Melbourne* [25]*University of Adelaide*
[26]*University of Rochester* [27]*University of Utah* [28]*Università degli Studi di Padova*
[29]*Deutsches Elektronen-Synchrotron (DESY) Zeuthen* [30]*Università degli Studi di Torino*
[31]*NASA Marshall Space Flight Center* [32]*Istituto Nazional di Fisica Nucleare (INFN), Sezione di Torino*
[33]*Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, Université Paris-Saclay*
[34]*University of Maryland, College Park*
[35]*Institut National de Physique Nucléaire et de Physique des Particules (IN2P3)* [36]*University of Zagreb*
[37]*Uppsala Universitet* [38]*Center for Astrophysics, Harvard & Smithsonian*
[39]*Istituto Nazional di Fisica Nucleare (INFN), Sezione di Bari* [40]*NASA Goddard Space Flight Center*
[41]*Università degli Studi di Catania* [42]*Florida State University* [43]*Max-Planck-Institut für Kernphysik, Heidelberg*
[44]*University of the Witwatersrand* [45]*National Taiwan University* [46]*Badji Mokhtar University of Annaba*
[47]*City University of New York* [48]*Vrije Universiteit Brussels*
[49]*Centre de Physique des Particules de Marseille (CPPM)* [50]*University College London*
[51]*The University of Hong Kong* [52]*Tata Institute of Fundamental Research, Mumbai (TIFR)*
[53]*Northwestern University* [54]*Universidade Federal do Rio de Janeiro* [55]*Radboud Universiteit Nijmegen*
[56]*Nikhef* [57]*Institut d'Astrophysique de Paris* [58]*Brookhaven National Laboratory* [59]*Michigan State University*
[60]*University of Chicago* [61]*Westfälische Wilhelms-Universität Münster*
[62]*Ludwig-Maximilians-Universität München* [63]*RIKEN* [64]*King's College London*
[65]*Karlsruher Institut für Technologie* [66]*Colorado School of Mines*
[67]*Pontificia Universidade Catolicá do Rio de Janeiro* [68]*Stanford University* [69]*Oklahoma State University*
[70]*Stockholm Universitet* [71]*Kyoto University* [72]*Instituto de Física Teórica UAM-CSIC*
[73]*Pontificia Universidad Católica del Perú* [74]*Bartol Research Institute, University of Delaware*
[75]*Universidad Nacional de La Plata* [76]*Eberhard Karls Universität Tübingen* [77]*Università degli Studi di Firenze*
[78]*Whittier College* [79]*University of North Florida* [80]*Fermi National Accelerator Laboratory*
[81]*Virginia Polytechnic Institute and State University* [82]*Institut Pluridisciplinaire Hubert Curien (IPHC)*
[83]*Saitama University*
[84]*International Center for Theoretical Physics – South American Institute for Fundamental Research*
[85]*International Centre for Radio Astronomy Research, Curtin University* [86]*University of California, Berkeley*
[87]*Konan University* [88]*Johns Hopkins University* [89]*Queen Mary University of London* [90]*Columbia University*
[91]*Chiba University* [92]*Lawrence Berkeley National Laboratory* [93]*Humboldt-Universität zu Berlin*
[94]*Johannes Gutenberg-Universität Mainz* [95]*CERN* [96]*Indiana University*
[97]*Laboratoire AstroParticule et Cosmologie* [98]*University of Nebraska-Lincoln*
[99]*University of Maryland, Baltimore County* [100]*Drexel University*
[101]*Istituto Nazional di Fisica Nucleare (INFN), Sezione di Pisa* [102]*University of Alabama in Huntsville*
[103]*University of Kansas* [104]*University of Hawaii, Manoa* [105]*Massachusetts Institute of Technology*
[106]*SLAC National Accelerator Lab* [107]*Università degli Studi di Trieste* [108]*Arizona State University*
[109]*Sapienza – Università di Roma* [110]*University of Wisconsin-River Falls*
[111]*Istituto Nazional di Fisica Nucleare (INFN), Sezione di Padova* [112]*Julius-Maximilians-Universität Würzburg*
[113]*Benemérita Universidad Autónoma de Puebla* [114]*Universidad de Granada* [115]*Mercer University*
[116]*California Polytechnic State University* [117]*Università degli Studi di Milano*
[118]*Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Cinvestav)*
[119]*Max-Planck-Institut fur Physik, München* [120]*Université de Genève* [121]*University of Alberta*
[122]*Weizmann Institute of Science* [123]*Université Clermont Auvergne* [124]*Michigan Technological University*
[125]*Université de Montpellier* [126]*European Southern Observatory* [127]*Georgia Institute of Technology*
[128]*University of Crete* [129]*Università degli Studi di Roma Tor Vergata* [130]*Naradowe Centrum Badań Jądrowych*
[131]*Institutul de Științe Spațiale* [132]*Washington University in St. Louis* [133]*University of Johannesburg*
[134]*University of Iowa* [135]*Technische Universität München* [136]*University of California, San Diego*
[137]*Vrije Universiteit Amsterdam* [138]*Sungkyunkwan University (SKKU)* [139]*University of Michigan, Ann Arbor*
[140]*University of California, Los Angeles* [141]*Universiteit Leiden* [142]*Universitat de Barcelona*
[143]*University of Alabama* [144]*Bergische Universität Wuppertal* [145]*Rijksuniversiteit Groningen*
[146]*Università degli Studi di Napoli Federico II*
[147]*Université Grenoble Alpes, Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh)*
[148]*Universität Hamburg* [149]*Princeton University* [150]*Università degli Studi di Bologna*

[151]*Institute of Space Sciences (IEEC-CSIC)* [152]*Tufts University* [153]*Università degli Studi dell'Aquila*
[154]*Queen's University* [155]*University of Leeds* [156]*Vanderbilt University* [157]*Tsung-Dao Lee Institute*
[158]*Sun Yet-sen University* [159]*Univerza v Novi Gorici* [160]*University of Nevada, Las Vegas*
[161]*Los Alamos National Laboratory* [162]*Leopold-Franzens-Universität Innsbruck*

High-Energy Cosmic Neutrinos

What are the fundamental particles and interactions of Nature? High-energy cosmic neutrinos are uniquely poised to explore them in an uncharted and otherwise unreachable energy and distance regime. They allow us to explore the cosmic and energy frontiers of particle physics, complementing current and future colliders that will explore the energy and intensity frontiers.

Despite the spectacular success of the Standard Model (SM) of particle physics, we know that it must be extended to account for at least the existence of neutrino mass, dark matter, and dark energy. A common feature of many theories beyond the Standard Model (BSM) is that their effects are more clearly apparent the higher the energy of the process, where new particles, interactions, and symmetries, undetectable at lower energies, could make themselves evident. Yet, particle colliders have failed to find clear evidence of BSM physics up to TeV energies, the highest reachable in the lab. To access particle interactions beyond the TeV scale, we must use particle beams made by natural cosmic accelerators. They produce the most energetic neutrinos, photons, and charged particles known, with energies orders of magnitude higher than in man-made colliders.

Cosmic neutrinos are especially fitting probes of fundamental physics beyond the TeV scale, as shown in Fig. 1. First, cosmic neutrinos reach higher energies than neutrinos made in the Sun, supernovae, the atmosphere of Earth, particle accelerators, and nuclear reactors. Further, they reach Earth with energies higher than that of gamma rays and likely as high as ultra-high-energy (UHE) cosmic rays. Second, because most cosmic neutrinos come from extragalactic sources located at cosmological distances, even tiny BSM effects could accumulate up to observable levels as neutrinos travel to Earth, having crossed essentially the observable Universe. And, third, because the propagation of neutrinos from the sources to the detectors is well understood and predicted by the SM, BSM effects could be more easily spotted than in charged particles.

Tests of fundamental physics using cosmic neutrinos are possible in spite of astrophysical and cosmological uncertainties. Yet this endeavor is not without challenges: the neutrino detection cross section is tiny and cosmic neutrino fluxes are expected to fall rapidly with neutrino energy. Nevertheless, we show below that these obstacles are either surmountable or can be planned for.

Open Questions: What Can High-Energy Cosmic Neutrinos Test?

Fig. 1 shows the wide breadth of important open questions in fundamental physics that cosmic neutrinos can address [1–3]. They complement questions tackled by neutrinos of lower energies.

Cosmic neutrinos span a wide range in energy. In the TeV–PeV range, astrophysical neutrinos are regularly detected by IceCube [4–9] from what are likely mainly extragalactic sources [10–16]. At the EeV scale, cosmogenic neutrinos, produced by UHE cosmic rays interacting with photon backgrounds through the GZK effect [17,18], are predicted but have not yet been observed [19–21]. See Ref. [22] for a discussion of astrophysics enabled by observations of cosmic neutrinos.

How do neutrino cross sections behave at high energies? The neutrino-nucleon cross section in the TeV–PeV range was measured for the first time using astrophysical and atmospheric neutrinos [23–25], extending [26–30] measurements that used GeV neutrinos from accelerators [31–33]. Fig. 2 shows that the measurements agree with high-precision SM predictions [34]. Future measurements in the EeV range would probe BSM modifications of the cross section at center-of-momentum energies of 100 TeV [3,35–43] and test the structure of nucleons [44–54] more deeply than colliders [55,56].

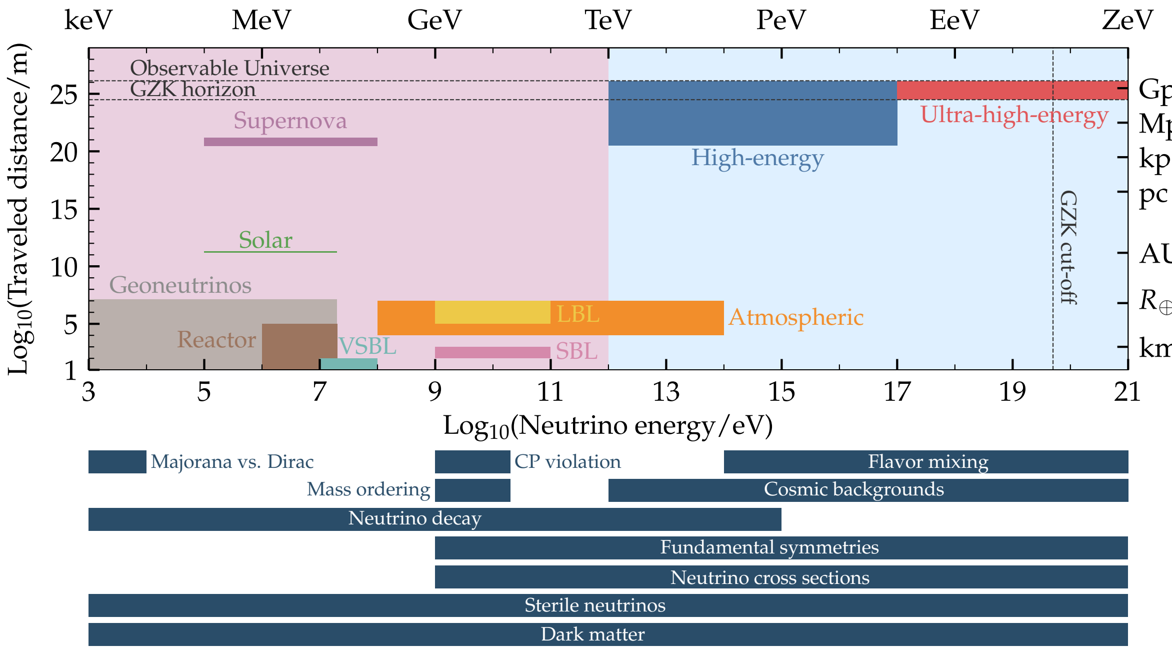


Figure 1: Tests of fundamental physics accessible with neutrinos of different energies.

How do flavors mix at high energies? Experiments with neutrinos of up to TeV energies have confirmed that the different neutrino flavors, ν_e, ν_μ, and ν_τ, mix and oscillate into each other as they propagate [33]. Figure 3 shows that, if high-energy cosmic neutrinos en route to Earth oscillate as expected, the predicted allowed region of the ratios of each flavor to the total flux is small, even after accounting for uncertainties in the parameters that drive the oscillations and in the neutrino production process [57]. However, at these energies and over cosmological propagation baselines [58], mixing is untested; BSM effects could affect oscillations, vastly expanding the allowed region of flavor ratios and making them sensitive probes of BSM [57, 59–68].

What are the fundamental symmetries of Nature? Beyond the TeV scale, the symmetries of the SM may break or new ones may appear. The effects of breaking lepton number or CPT and Lorentz invariance [69], cornerstones of the SM, are expected to grow with neutrino energy and affect multiple neutrino observables [70–81]. Currently, the strongest constraints in neutrinos come from high-energy atmospheric neutrinos [82]; cosmic neutrinos could provide unprecedented sensitivity [62,71,73,76,78,83–90]. Further, detection of ZeV neutrinos, well beyond astrophysical expectations, would probe Grand Unified Theories [43, 91–94].

Are neutrinos stable? Neutrinos are essentially stable in the SM [95–97], but BSM physics could introduce new channels for the heavier neutrinos to decay into the lighter ones [98–100], with shorter lifetimes. During propagation over cosmological baselines, neutrino decay could leave imprints on the energy spectrum and flavor composition [65, 101–104]. The associated sensitivity outperforms existing limits obtained using neutrinos with shorter baselines [103]. Comparable sensitivities are expected for similar BSM models, like pseudo-Dirac neutrinos [65, 105, 106].

What is dark matter? Cosmic neutrinos can probe the nature of dark matter. Dark matter may decay or self-annihilate into neutrinos [107–110], leaving imprints on the neutrino energy spectrum, *e.g.*, line-like features. Searches for these features have yielded strong constraints on dark matter in the Milky Way [111–113] and nearby galaxies [114]. High-energy cosmic neutrinos

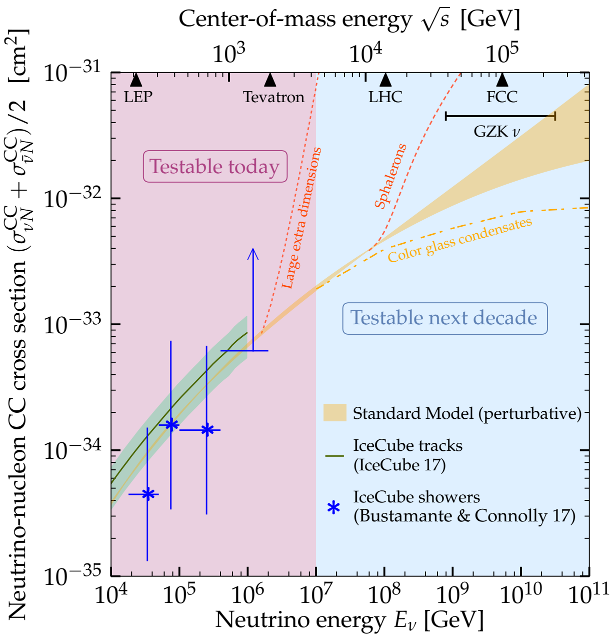


Figure 2: Neutrino-nucleon cross section. Below 1 PeV, measurements [23, 24] are compared to the SM uncertainty band [141] (see also Ref. [34]) that encloses predictions [34, 141–144]. The cross section may change due to new physics — *e.g.*, large extra dimensions [36] (TeV-scale, in tension with LHC results), electroweak sphalerons [42] (9-TeV barrier height) — or non-perturbative effects — *e.g.*, color glass condensate [44] (model BGBK$_{\text{III}}$).

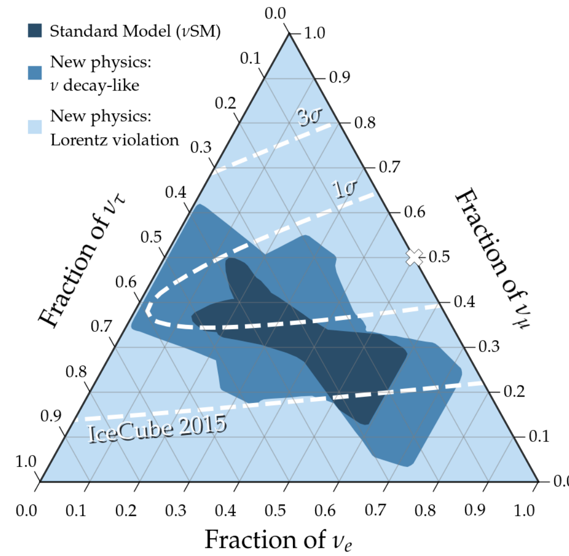


Figure 3: Flavor composition at Earth of high-energy cosmic neutrinos, indicating the "theoretically palatable" [57] regions accessible with the Standard Model with massive neutrinos (νSM), with new physics similar to neutrino decay, and with new physics similar to Lorentz-invariance violation. The neutrino mixing parameters are generously varied within their uncertainties at 3σ. The tilt of the tick marks indicates the orientation along which to read the flavor content.

can probe both superheavy dark matter with PeV masses [115–126] and light dark matter [117, 125, 127, 128]. Multi-messenger constraints are crucial to assess dark matter explanations of the observed neutrino spectrum [10, 122, 128–130]. Further, anisotropies in the neutrino sky towards the Galactic Center can reveal dark matter decaying [131] or interacting with neutrinos [132].

Are there hidden interactions with cosmic backgrounds? High-energy cosmic neutrinos may interact with low-energy relic neutrino backgrounds via new interactions [65, 133–136], with large-scale distributions of matter via new forces [137], or with dark backgrounds [138], including dark energy [139, 140]. These interactions may mimic the existence of neutrino mass, affect the neutrino flavor composition, and induce anisotropies in the high-energy neutrino sky.

Neutrino Observables: What Do We Use to Probe Fundamental Physics?

To probe fundamental physics, we look at four neutrino observables, individually or together.

Energy spectrum: The spectrum of neutrinos depends on their production processes, but BSM effects could introduce identifiable features, *e.g.*, peaks, troughs, and cut-offs. Present neutrino telescopes reconstruct the energy E of detected events to within 0.1 in $\log_{10}(E/\text{GeV})$ [145]. For TeV–PeV astrophysical neutrinos, the spectrum is predicted to be a featureless power law. IceCube data are consistent with that, but also with a broken power law [146–149]. For EeV cosmogenic

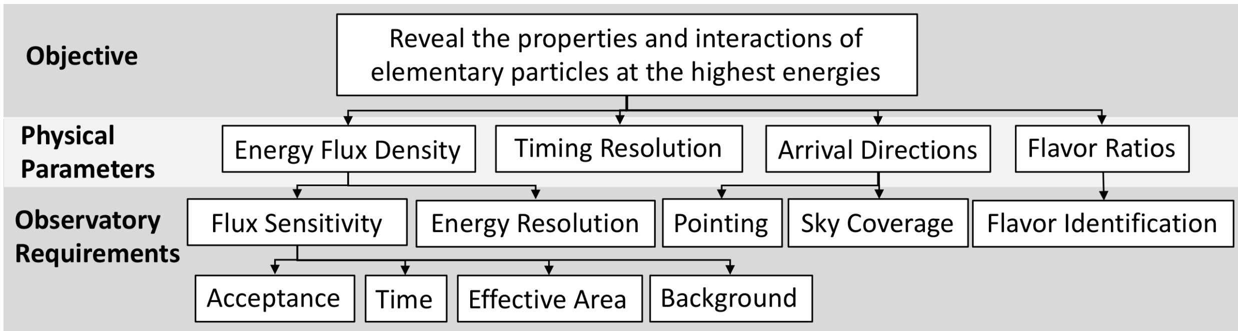


Figure 4: Observatory requirements to test fundamental physics with cosmic neutrinos.

neutrinos, the spectrum has a different but predictable shape [150–169], so BSM effects, *e.g.*, modifications of neutrino-nucleon cross sections [3, 35–43], may also be apparent.

Arrival directions: If the diffuse flux of cosmic neutrinos comes from an isotropic distribution of sources, then it should be isotropic itself. However, interactions with cosmic backgrounds might induce anisotropies. For instance, they could create a neutrino horizon, whereby high-energy neutrinos could only reach us from a few nearby sources [134, 135, 170]. Similarly, neutrino interactions with dark matter could introduce an anisotropy towards the Galactic Center [132]. Presently, the pointing resolution at neutrino telescopes is sub-degree for events initiated by ν_μ — tracks — and of a few degrees for events initiated by other ν_e and ν_τ — showers [145].

Flavor composition: At the neutrino sources, high-energy cosmic neutrinos are believed to be produced in the decay of pions, *i.e.*, $\pi^+ \to \mu^+ \nu_\mu$ followed by $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$. This results in an initial flavor composition of $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$, adding ν and $\bar{\nu}$. Upon reaching Earth, oscillations have transformed this into nearly $(1 : 1 : 1)_\oplus$ [171]. The detection of ν_τ is minimally required for testing this standard oscillation scenario [172, 173]. While there are variations on this canonical expectation [174–176], the expected flavor ratios fall within a well-defined region [57]. However, numerous BSM models active during propagation may modify this [63, 67], including neutrino decay and Lorentz invariance violation, as shown in Fig. 3. A precise measurement of the flavor composition could distinguish between these two classes of models [57]. Presently, measuring flavor at neutrino telescopes is challenging, since the showers made by ν_e and ν_τ look similar [147, 177], which makes the contours of allowed flavor composition in Fig. 3 wide.

Timing: A violation of Lorentz invariance would modify the energy-momentum relation of neutrinos and photons [178–180], causing them to have different speeds at different energies. This would manifest in neutrinos [181], photons [182–185], and gravitational waves [186] emitted at the same time from transient sources arriving at Earth at different times. Presently, electronics in neutrino telescopes can timestamp events to within a few nanoseconds [187].

Today, the strength of the tests performed using these observables is limited at PeV energies, where data is scant, but event statistics are growing and there are ongoing efforts to improve the reconstruction of neutrino properties. Once neutrinos of higher energies are detected, the same observables can be used to test fundamental physics in a new energy regime.

Observatory Requirements to Achieve the Science Goals

Answering fundamental physics questions requires improving the precision with which neutrino observables are measured, which is currently limited by the low numbers of events. The statistics in the TeV–PeV energy range will grow using existing neutrino detectors and their planned upgrades. This will be supplemented by improved techniques to reconstruct neutrino energy, direction, and flavor. At the EeV scale, our ability to address fundamental physics questions is contingent on the discovery of neutrinos at these energies. In addition to emphasizing the importance of improved statistics, we highlight two measurements that can be improved in the coming decade: the neutrino cross section and flavor composition.

Presently, the measurement of the TeV–PeV neutrino cross section in multiple energy bins is sorely statistics-limited [24]. In this energy range, where the measured cross section is compatible with SM expectations, large BSM deviations are unlikely. But smaller deviations are still possible, especially close to PeV energies. To extract the cross section, Ref. [24] used about 60 shower events collected by IceCube in six years across all energies. A detector that is five times larger [188] would collect 300 showers in the same time, reducing the statistical error in the extracted cross sections by a factor of $\sqrt{6}/6 \approx 0.4$ [189]. At that point, the statistical and systematic errors would become comparable, with a size of about 0.2 in the logarithm of the cross section (in units of cm^2).

At the EeV scale, measuring the cross section to within an order of magnitude could distinguish between SM predictions and BSM modifications; see Fig. 2. This target is achievable with tens of events in the PeV–EeV energy range. Detection will be challenging, since the flux is expected to decrease fast with energy and the cross section is expected to grow with energy, making the Earth opaque to neutrinos. Facing significant uncertainties in the predicted flux of cosmogenic neutrinos [160, 162, 165, 166, 169], we advocate for the construction of larger neutrino observatories to boost the chances of discovering and collecting a sufficiently large number of cosmogenic neutrinos.

Flavor composition must be measured with a precision better than 40% to match the theoretical SM uncertainty band and identify BSM deviations, as shown in Fig. 3. Reaching this target at TeV–PeV energies requires supplementing the larger event statistics with the detection of flavor-specific signals [58, 190, 191]. With 20% precision, we could distinguish between models similar to neutrino decay or to Lorentz invariance violation. Improved statistics will also permit searches for a potential energy dependence of mixing, which could point to the presence of BSM effects [57, 63].

In the EeV range, we advocate exploring new methods to measure flavor in existing and upcoming experiments (*e.g.*, Ref. [192]). Some planned EeV detectors will be sensitive primarily [193] to ν_τ [194–199], while others will be sensitive to all flavors [188, 200–204], but might not be able to distinguish between them easily. Thus, we should consider combining data from the two types of experiments in order to infer at least the ν_τ fraction.

Further, with the available sub-degree pointing resolution, we can begin to probe anisotropies in the neutrino sky that may result, *e.g.*, from Lorentz-invariance violation [205] or BSM matter interactions [132]. Additionally, we can cull a set of neutrino events that are truly extragalactic, by using only those that point away from the Galactic Center, which allows us to make robust searches for BSM effects that are enhanced over cosmological distances (*e.g.*, Ref. [103]).

We advocate for a strategy for the coming decade that improves precision on flavor identification and improves statistics across a broad energy scale, from 10 TeV up to the EeV scale. While this strategy targets mainly cross section and flavor measurements, it will impact other neutrino observables and relentlessly test the predictions of the SM and of many BSM scenarios.

References

[1] M. Ahlers, K. Helbing, and C. Pérez de los Heros, "Probing Particle Physics with IceCube," *Eur. Phys. J. C* **78** (2018) 924, `1806.05696`.

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

[3] D. Marfatia, D. W. McKay, and T. J. Weiler, "New physics with ultra-high-energy neutrinos," *Phys. Lett. B* **748** (2015) 113, `1502.06337`.

[4] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "First observation of PeV-energy neutrinos with IceCube," *Phys. Rev. Lett.* **111** (2013) 021103, `1304.5356`.

[5] S. Razzaque, "The Galactic Center Origin of a Subset of IceCube Neutrino Events," *Phys. Rev. D* **88** (2013) 081302, `1309.2756`.

[6] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector," *Science* **342** (2013) 1242856, `1311.5238`.

[7] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data," *Phys. Rev. Lett.* **113** (2014) 101101, `1405.5303`.

[8] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube," *Phys. Rev. Lett.* **115** (2015) 081102, `1507.04005`.

[9] **IceCube** Collaboration, M. G. 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** (2016) 3, `1607.08006`.

[10] M. Ahlers and K. Murase, "Probing the Galactic Origin of the IceCube Excess with Gamma-Rays," *Phys. Rev. D* **90** (2014) 023010, `1309.4077`.

[11] L. A. Anchordoqui *et. al.*, "Cosmic Neutrino Pevatrons: A Brand New Pathway to Astronomy, Astrophysics, and Particle Physics," *JHEAp* **1-2** (2014) 1, `1312.6587`.

[12] M. Ahlers, Y. Bai, V. Barger, and R. Lu, "Galactic neutrinos in the TeV to PeV range," *Phys. Rev. D* **93** (2016) 013009, `1505.03156`.

[13] P. B. Denton, D. Marfatia, and T. J. Weiler, "The Galactic Contribution to IceCube's Astrophysical Neutrino Flux," *JCAP* **1708** (2017) 033, `1703.09721`.

[14] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Constraints on Galactic Neutrino Emission with Seven Years of IceCube Data," *Astrophys. J.* **849** (2017) 67, `1707.03416`.

[15] **Liverpool Telescope, MAGIC, H.E.S.S., AGILE, Kiso, VLA/17B-403, INTEGRAL, Kapteyn, Subaru, HAWC, Fermi-LAT, ASAS-SN, VERITAS, Kanata, IceCube, Swift NuSTAR** Collaboration, M. G. Aartsen *et. al.*, "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," *Science* **361** (2018) eaat1378, `1807.08816`.

[16] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert," *Science* **361** (2018) 147, `1807.08794`.

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

[18] G. T. Zatsepin and V. A. Kuzmin, "Upper limit of the spectrum of cosmic rays," *JETP Lett.* **4** (1966) 78. [Pisma Zh. Eksp. Teor. Fiz. 4, 114 (1966)].

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

[20] **IceCube** Collaboration, M. G. 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** (2018) 062003, `1807.01820`.

[21] **ANITA** Collaboration, P. W. Gorham *et. al.*, "Constraints on the ultra-high energy cosmic neutrino flux from the fourth flight of ANITA," `1902.04005`.

[22] M. Ackermann *et. al.*, "Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos," *White paper submitted to the Astro2020 decadal survey.*

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

[24] M. Bustamante and A. Connolly, "Extracting the Energy-Dependent Neutrino-Nucleon Cross Section Above 10 TeV Using IceCube Showers," *Phys. Rev. Lett.* **122** (2019) 041101, `1711.11043`.

[25] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Measurements using the inelasticity distribution of multi-TeV neutrino interactions in IceCube," *Phys. Rev. D* **99** (2019) 032004, `1808.07629`.

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

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

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

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

[30] S. Hussain, D. Marfatia, and D. W. McKay, "Upward shower rates at neutrino telescopes directly determine the neutrino flux," *Phys. Rev. D* **77** (2008) 107304, 0711.4374.

[31] J. M. Conrad, M. H. Shaevitz, and T. Bolton, "Precision measurements with high-energy neutrino beams," *Rev. Mod. Phys.* **70** (1998) 1341, hep-ex/9707015.

[32] J. A. Formaggio and G. P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales," *Rev. Mod. Phys.* **84** (2012) 1307, 1305.7513.

[33] **Particle Data Group** Collaboration, M. Tanabashi *et. al.*, "Review of Particle Physics," *Phys. Rev. D* **98** (2018) 030001.

[34] A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, "The high energy neutrino cross-section in the Standard Model and its uncertainty," *JHEP* **08** (2011) 042, 1106.3723.

[35] 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, hep-ph/0106071.

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

[37] 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, hep-ph/0112247.

[38] 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, hep-ph/0102065.

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

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

[41] 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, hep-ph/0504228.

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

[43] L. A. Anchordoqui, "Ultra-High-Energy Cosmic Rays," 1807.09645.

[44] E. M. Henley and J. Jalilian-Marian, “Ultra-high energy neutrino-nucleon scattering and parton distributions at small x,” *Phys. Rev. D* **73** (2006) 094004, hep-ph/0512220.

[45] N. Armesto, C. Merino, G. Parente, and E. Zas, “Charged current neutrino cross-section and tau energy loss at ultra-high energies,” *Phys. Rev. D* **77** (2008) 013001, 0709.4461.

[46] R. Enberg, M. H. Reno, and I. Sarcevic, “Prompt neutrino fluxes from atmospheric charm,” *Phys. Rev. D* **78** (2008) 043005, 0806.0418.

[47] A. Yu. Illarionov, B. A. Kniehl, and A. V. Kotikov, “Ultrahigh-energy neutrino-nucleon deep-inelastic scattering and the Froissart bound,” *Phys. Rev. Lett.* **106** (2011) 231802, 1105.2829.

[48] A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic, and A. Stasto, “Perturbative charm production and the prompt atmospheric neutrino flux in light of RHIC and LHC,” *JHEP* **06** (2015) 110, 1502.01076.

[49] M. V. Garzelli, S. Moch, and G. Sigl, “Lepton fluxes from atmospheric charm revisited,” *JHEP* **10** (2015) 115, 1507.01570.

[50] F. Halzen and L. Wille, “Upper Limit on Forward Charm Contribution to Atmospheric Neutrino Flux,” 1601.03044.

[51] F. Halzen and L. Wille, “Charm contribution to the atmospheric neutrino flux,” *Phys. Rev. D* **94** (2016) 014014, 1605.01409.

[52] A. Bhattacharya, R. Enberg, Y. S. Jeong, C. S. Kim, M. H. Reno, I. Sarcevic, and A. Stasto, “Prompt atmospheric neutrino fluxes: perturbative QCD models and nuclear effects,” *JHEP* **11** (2016) 167, 1607.00193.

[53] M. Benzke, M. V. Garzelli, B. Kniehl, G. Kramer, S. Moch, and G. Sigl, “Prompt neutrinos from atmospheric charm in the general-mass variable-flavor-number scheme,” *JHEP* **12** (2017) 021, 1705.10386.

[54] A. V. Giannini, V. P. Gonçalves, and F. S. Navarra, “Intrinsic charm contribution to the prompt atmospheric neutrino flux,” *Phys. Rev. D* **98** (2018) 014012, 1803.01728.

[55] 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, hep-ph/0605086.

[56] V. Bertone, R. Gauld, and J. Rojo, “Neutrino Telescopes as QCD Microscopes,” *JHEP* **01** (2019) 217, 1808.02034.

[57] M. Bustamante, J. F. Beacom, and W. Winter, “Theoretically palatable flavor combinations of astrophysical neutrinos,” *Phys. Rev. Lett.* **115** (2015) 161302, 1506.02645.

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

[59] 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, hep-ph/0307025. [Erratum: Phys. Rev. D 72, 019901 (2005)].

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

[61] M. Bustamante, A. M. Gago, and J. Jones Perez, "SUSY Renormalization Group Effects in Ultra High Energy Neutrinos," *JHEP* **05** (2011) 133, 1012.2728.

[62] M. Bustamante, A. M. Gago, and C. Pena-Garay, "Energy-independent new physics in the flavour ratios of high-energy astrophysical neutrinos," *JHEP* **04** (2010) 066, 1001.4878.

[63] P. Mehta and W. Winter, "Interplay of energy dependent astrophysical neutrino flavor ratios and new physics effects," *JCAP* **1103** (2011) 041, 1101.2673.

[64] C. A. Argüelles, T. Katori, and J. Salvado, "New Physics in Astrophysical Neutrino Flavor," *Phys. Rev. Lett.* **115** (2015) 161303, 1506.02043.

[65] 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** (2016) 085004, 1512.07228.

[66] M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, and N. Song, "Non-standard neutrino interactions in the Earth and the flavor of astrophysical neutrinos," *Astropart. Phys.* **84** (2016) 15, 1605.08055.

[67] 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** (2017) 083018, 1707.07684.

[68] M. Ahlers, M. Bustamante, and S. Mu, "Unitarity Bounds of Astrophysical Neutrinos," *Phys. Rev. D* **98** (2018) 123023, 1810.00893.

[69] D. Colladay and V. A. Kostelecky, "Lorentz violating extension of the Standard Model," *Phys. Rev. D* **58** (1998) 116002, hep-ph/9809521.

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

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

[72] V. A. Kostelecky and N. Russell, "Data Tables for Lorentz and CPT Violation," *Rev. Mod. Phys.* **83** (2011) 11, 0801.0287.

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

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

[75] 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** (2013) 116009, 1303.5843.

[76] 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** (2014) 043012, 1404.7025.

[77] L. A. Anchordoqui, V. Barger, H. Goldberg, J. G. Learned, D. Marfatia, S. Pakvasa, T. C. Paul, and T. J. Weiler, "End of the cosmic neutrino energy spectrum," *Phys. Lett. B* **739** (2014) 99, 1404.0622.

[78] G. Tomar, S. Mohanty, and S. Pakvasa, "Lorentz Invariance Violation and IceCube Neutrino Events," *JHEP* **11** (2015) 022, 1507.03193.

[79] G. Amelino-Camelia, D. Guetta, and T. Piran, "Icecube Neutrinos and Lorentz Invariance Violation," *Astrophys. J.* **806** (2015) 269.

[80] J. Liao and D. Marfatia, "IceCube's astrophysical neutrino energy spectrum from CPT violation," *Phys. Rev. D* **97** (2018) 041302, 1711.09266.

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

[82] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube," *Nature Phys.* **14** (2018) 961, 1709.03434.

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

[84] M. C. Gonzalez-Garcia, F. Halzen, and M. Maltoni, "Physics reach of high-energy and high-statistics icecube atmospheric neutrino data," *Phys. Rev. D* **71** (2005) 093010, hep-ph/0502223.

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

[86] J. L. Bazo, M. Bustamante, A. M. Gago, and O. G. Miranda, "High energy astrophysical neutrino flux and modified dispersion relations," *Int. J. Mod. Phys. A* **24** (2009) 5819, 0907.1979.

[87] J. S. Diaz, A. Kostelecky, and M. Mewes, "Testing Relativity with High-Energy Astrophysical Neutrinos," *Phys. Rev. D* **89** (2014) 043005, 1308.6344.

[88] 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** (2015) 045009, 1411.5889.

[89] 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, 1807.05155.

[90] R. Laha, "Constraints on neutrino speed, weak equivalence principle violation, Lorentz invariance violation, and dual lensing from the first high-energy astrophysical neutrino source TXS 0506+056," 1807.05621.

[91] G. Sigl, S. Lee, D. N. Schramm, and P. Coppi, "Cosmological neutrino signatures for grand unification scale physics," *Phys. Lett. B* **392** (1997) 129, astro-ph/9610221.

[92] V. Berezinsky, K. D. Olum, E. Sabancilar, and A. Vilenkin, "UHE neutrinos from superconducting cosmic strings," *Phys. Rev. D* **80** (2009) 023014, 0901.0527.

[93] V. Berezinsky, E. Sabancilar, and A. Vilenkin, "Extremely High Energy Neutrinos from Cosmic Strings," *Phys. Rev. D* **84** (2011) 085006, 1108.2509.

[94] C. Lunardini and E. Sabancilar, "Cosmic Strings as Emitters of Extremely High Energy Neutrinos," *Phys. Rev. D* **86** (2012) 085008, 1206.2924.

[95] P. B. Pal and L. Wolfenstein, "Radiative Decays of Massive Neutrinos," *Phys. Rev. D* **25** (1982) 766.

[96] Y. Hosotani, "Majorana Masses, Photon Gas Heating and Cosmological Constraints on Neutrinos," *Nucl. Phys. B* **191** (1981) 411. [Erratum: Nucl. Phys. B 197, 546 (1982)].

[97] J. F. Nieves, P. B. Pal, and D. G. Unger, "Photon Mass in a Background of Thermal Particles," *Phys. Rev. D* **28** (1983) 908.

[98] Y. Chikashige, R. N. Mohapatra, and R. D. Peccei, "Spontaneously Broken Lepton Number and Cosmological Constraints on the Neutrino Mass Spectrum," *Phys. Rev. Lett.* **45** (1980) 1926. [, 921 (1980)].

[99] G. B. Gelmini, S. Nussinov, and M. Roncadelli, "Bounds and Prospects for the Majoron Model of Left-handed Neutrino Masses," *Nucl. Phys. B* **209** (1982) 157.

[100] R. Tomas, H. Pas, and J. W. F. Valle, "Generalized bounds on Majoron - neutrino couplings," *Phys. Rev. D* **64** (2001) 095005, hep-ph/0103017.

[101] 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, hep-ph/0211305.

[102] P. Baerwald, M. Bustamante, and W. Winter, "Neutrino Decays over Cosmological Distances and the Implications for Neutrino Telescopes," *JCAP* **1210** (2012) 020, 1208.4600.

[103] M. Bustamante, J. F. Beacom, and K. Murase, "Testing decay of astrophysical neutrinos with incomplete information," *Phys. Rev. D* **95** (2017) 063013, 1610.02096.

[104] P. B. Denton and I. Tamborra, "Invisible Neutrino Decay Could Resolve IceCube's Track and Cascade Tension," *Phys. Rev. Lett.* **121** (2018) 121802, 1805.05950.

[105] 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, hep-ph/0307151.

[106] A. S. Joshipura, S. Mohanty, and S. Pakvasa, "Pseudo-Dirac neutrinos via a mirror world and depletion of ultrahigh energy neutrinos," *Phys. Rev. D* **89** (2014) 033003, 1307.5712.

[107] J. L. Feng, "Dark Matter Candidates from Particle Physics and Methods of Detection," *Ann. Rev. Astron. Astrophys.* **48** (2010) 495, 1003.0904.

[108] J. F. Beacom, N. F. Bell, and G. D. Mack, "General Upper Bound on the Dark Matter Total Annihilation Cross Section," *Phys. Rev. Lett.* **99** (2007) 231301, astro-ph/0608090.

[109] H. Yuksel, S. Horiuchi, J. F. Beacom, and S. Ando, "Neutrino Constraints on the Dark Matter Total Annihilation Cross Section," *Phys. Rev. D* **76** (2007) 123506, 0707.0196.

[110] K. Murase and J. F. Beacom, "Constraining Very Heavy Dark Matter Using Diffuse Backgrounds of Neutrinos and Cascaded Gamma Rays," *JCAP* **1210** (2012) 043, 1206.2595.

[111] **ANTARES** Collaboration, S. Adrian-Martinez *et. al.*, "Search of Dark Matter Annihilation in the Galactic Centre using the ANTARES Neutrino Telescope," *JCAP* **1510** (2015) 068, 1505.04866.

[112] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "All-flavour Search for Neutrinos from Dark Matter Annihilations in the Milky Way with IceCube/DeepCore," *Eur. Phys. J. C* **76** (2016) 531, 1606.00209.

[113] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Search for Neutrinos from Dark Matter Self-Annihilations in the center of the Milky Way with 3 years of IceCube/DeepCore," *Eur. Phys. J. C* **77** (2017) 627, 1705.08103.

[114] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "IceCube Search for Dark Matter Annihilation in nearby Galaxies and Galaxy Clusters," *Phys. Rev. D* **88** (2013) 122001, 1307.3473.

[115] B. Feldstein, A. Kusenko, S. Matsumoto, and T. T. Yanagida, "Neutrinos at IceCube from Heavy Decaying Dark Matter," *Phys. Rev. D* **88** (2013) 015004, 1303.7320.

[116] A. Esmaili and P. D. Serpico, “Are IceCube neutrinos unveiling PeV-scale decaying dark matter?,” *JCAP* **1311** (2013) 054, 1308.1105.

[117] T. Higaki, R. Kitano, and R. Sato, “Neutrinoful Universe,” *JHEP* **07** (2014) 044, 1405.0013.

[118] C. Rott, K. Kohri, and S. C. Park, “Superheavy dark matter and IceCube neutrino signals: Bounds on decaying dark matter,” *Phys. Rev. D* **92** (2015) 023529, 1408.4575.

[119] E. Dudas, Y. Mambrini, and K. A. Olive, “Monochromatic neutrinos generated by dark matter and the seesaw mechanism,” *Phys. Rev. D* **91** (2015) 075001, 1412.3459.

[120] 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, 1312.3501.

[121] J. Zavala, “Galactic PeV neutrinos from dark matter annihilation,” *Phys. Rev. D* **89** (2014) 123516, 1404.2932.

[122] K. Murase, R. Laha, S. Ando, and M. Ahlers, “Testing the Dark Matter Scenario for PeV Neutrinos Observed in IceCube,” *Phys. Rev. Lett.* **115** (2015) 071301, 1503.04663.

[123] 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** (2015) 061301, 1506.08788. [Erratum: Phys. Rev. D 94, 069901 (2016)].

[124] S. M. Boucenna, M. Chianese, G. Mangano, G. Miele, S. Morisi, O. Pisanti, and E. Vitagliano, “Decaying Leptophilic Dark Matter at IceCube,” *JCAP* **1512** (2015) 055, 1507.01000.

[125] N. Hiroshima, R. Kitano, K. Kohri, and K. Murase, “High-energy neutrinos from multibody decaying dark matter,” *Phys. Rev. D* **97** (2018) 023006, 1705.04419.

[126] 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, 1707.05241.

[127] C. S. Fong, H. Minakata, B. Panes, and R. Zukanovich Funchal, “Possible Interpretations of IceCube High-Energy Neutrino Events,” *JHEP* **02** (2015) 189, 1411.5318.

[128] T. Cohen, K. Murase, N. L. Rodd, B. R. Safdi, and Y. Soreq, “Gamma-ray Constraints on Decaying Dark Matter and Implications for IceCube,” *Phys. Rev. Lett.* **119** (2017) 021102, 1612.05638.

[129] 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, 1403.1862.

[130] A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz, and I. Sarcevic, “Probing decaying heavy dark matter with the 4-year IceCube HESE data,” *JCAP* **1707** (2017) 027, 1706.05746.

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

[132] C. A. Argüelles, A. Kheirandish, and A. C. Vincent, "Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos," *Phys. Rev. Lett.* **119** (2017) 201801, 1703.00451.

[133] J. Lykken, O. Mena, and S. Razzaque, "Ultrahigh-energy neutrino flux as a probe of large extra-dimensions," *JCAP* **0712** (2007) 015, 0705.2029.

[134] K. Ioka and K. Murase, "IceCube PeV–EeV neutrinos and secret interactions of neutrinos," *PTEP* **2014** (2014) 061E01, 1404.2279.

[135] K. C. Y. Ng and J. F. Beacom, "Cosmic neutrino cascades from secret neutrino interactions," *Phys. Rev. D* **90** (2014) 065035, 1404.2288. [Erratum: Phys. Rev. D 90, 089904 (2014)].

[136] K. Blum, A. Hook, and K. Murase, "High energy neutrino telescopes as a probe of the neutrino mass mechanism," 1408.3799.

[137] 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** (2019) 061103, 1808.02042.

[138] F. Capozzi, I. M. Shoemaker, and L. Vecchi, "Neutrino Oscillations in Dark Backgrounds," *JCAP* **1807** (2018) 004, 1804.05117.

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

[140] N. Klop and S. Ando, "Effects of a neutrino-dark energy coupling on oscillations of high-energy neutrinos," *Phys. Rev. D* **97** (2018) 063006, 1712.05413.

[141] A. Connolly, R. S. Thorne, and D. Waters, "Calculation of High Energy Neutrino-Nucleon Cross Sections and Uncertainties Using the MSTW Parton Distribution Functions and Implications for Future Experiments," *Phys. Rev. D* **83** (2011) 113009, 1102.0691.

[142] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic, "Neutrino interactions at ultrahigh energies," *Phys. Rev. D* **58** (1998) 093009, hep-ph/9807264.

[143] M. M. Block, L. Durand, and P. Ha, "Connection of the virtual $\gamma^* p$ cross section of ep deep inelastic scattering to real γp scattering, and the implications for νN and ep total cross sections," *Phys. Rev. D* **89** (2014) 094027, 1404.4530.

[144] C. A. Argüelles, F. Halzen, L. Wille, M. Kroll, and M. H. Reno, "High-energy behavior of photon, neutrino, and proton cross sections," *Phys. Rev. D* **92** (2015) 074040, 1504.06639.

[145] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Energy Reconstruction Methods in the IceCube Neutrino Telescope," *JINST* **9** (2014) P03009, 1311.4767.

[146] K. Murase, M. Ahlers, and B. C. Lacki, "Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube," *Phys. Rev. D* **88** (2013) 121301, 1306.3417.

[147] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube," *Astrophys. J.* **809** (2015) 98, 1507.03991.

[148] L. A. Anchordoqui, M. M. Block, L. Durand, P. Ha, J. F. Soriano, and T. J. Weiler, "Evidence for a break in the spectrum of astrophysical neutrinos," *Phys. Rev. D* **95** (2017) 083009, 1611.07905.

[149] A. C. Vincent, S. Palomares-Ruiz, and O. Mena, "Analysis of the 4-year IceCube high-energy starting events," *Phys. Rev. D* **94** (2016) 023009, 1605.01556.

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

[151] V. S. Berezinsky and A. Yu. Smirnov, "Cosmic neutrinos of ultra-high energies and detection possibility," *Astrophys. Space Sci.* **32** (1975) 461.

[152] F. W. Stecker, "Diffuse Fluxes of Cosmic High-Energy Neutrinos," *Astrophys. J.* **228** (1979) 919.

[153] C. T. Hill and D. N. Schramm, "Ultrahigh-Energy Cosmic Ray Neutrinos," *Phys. Lett. B* **131** (1983) 247. [, 495 (1983)].

[154] S. Yoshida and M. Teshima, "Energy spectrum of ultrahigh-energy cosmic rays with extragalactic origin," *Prog. Theor. Phys.* **89** (1993) 833.

[155] R. Engel, D. Seckel, and T. Stanev, "Neutrinos from propagation of ultrahigh-energy protons," *Phys. Rev. D* **64** (2001) 093010, astro-ph/0101216.

[156] L. A. Anchordoqui, H. Goldberg, D. Hooper, S. Sarkar, and A. M. Taylor, "Predictions for the Cosmogenic Neutrino Flux in Light of New Data from the Pierre Auger Observatory," *Phys. Rev. D* **76** (2007) 123008, 0709.0734.

[157] H. Takami, K. Murase, S. Nagataki, and K. Sato, "Cosmogenic neutrinos as a probe of the transition from Galactic to extragalactic cosmic rays," *Astropart. Phys.* **31** (2009) 201, 0704.0979.

[158] M. Ahlers, L. A. Anchordoqui, and S. Sarkar, "Neutrino diagnostics of ultra-high energy cosmic ray protons," *Phys. Rev. D* **79** (2009) 083009, 0902.3993.

[159] M. Ahlers, L. A. Anchordoqui, M. C. Gonzalez-Garcia, F. Halzen, and S. Sarkar, "GZK Neutrinos after the Fermi-LAT Diffuse Photon Flux Measurement," *Astropart. Phys.* **34** (2010) 106, 1005.2620.

[160] K. Kotera, D. Allard, and A. V. Olinto, "Cosmogenic Neutrinos: parameter space and detectabilty from PeV to ZeV," *JCAP* **1010** (2010) 013, 1009.1382.

[161] S. Yoshida and A. Ishihara, "Constraints on the origin of the ultra-high energy cosmic-rays using cosmic diffuse neutrino flux limits: An analytical approach," *Phys. Rev. D* **85** (2012) 063002, `1202.3522`.

[162] M. Ahlers and F. Halzen, "Minimal Cosmogenic Neutrinos," *Phys. Rev. D* **86** (2012) 083010, `1208.4181`.

[163] R. Aloisio, D. Boncioli, A. di Matteo, A. F. Grillo, S. Petrera, and F. Salamida, "Cosmogenic neutrinos and ultra-high energy cosmic ray models," *JCAP* **1510** (2015) 006, `1505.04020`.

[164] J. Heinze, D. Boncioli, M. Bustamante, and W. Winter, "Cosmogenic Neutrinos Challenge the Cosmic Ray Proton Dip Model," *Astrophys. J.* **825** (2016) 122, `1512.05988`.

[165] A. Romero-Wolf and M. Ave, "Bayesian Inference Constraints on Astrophysical Production of Ultra-high Energy Cosmic Rays and Cosmogenic Neutrino Flux Predictions," *JCAP* **1807** (2018) 025, `1712.07290`.

[166] 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, `1806.10879`.

[167] K. Møller, P. B. Denton, and I. Tamborra, "Cosmogenic Neutrinos Through the GRAND Lens Unveil the Nature of Cosmic Accelerators," `1809.04866`.

[168] A. van Vliet, R. Alves Batista, and J. R. Hörandel, "Determining the fraction of cosmic-ray protons at ultra-high energies with cosmogenic neutrinos," `1901.01899`.

[169] 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," `1901.03338`.

[170] J. F. Cherry, A. Friedland, and I. M. Shoemaker, "Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube," `1411.1071`.

[171] S. Pakvasa, "Neutrino Flavor Goniometry by High Energy Astrophysical Beams," *Mod. Phys. Lett. A* **23** (2008) 1313, `0803.1701`.

[172] A. Palladino, C. Mascaretti, and F. Vissani, "The importance of observing astrophysical tau neutrinos," *JCAP* **1808** (2018) 004, `1804.04965`.

[173] S. Parke and M. Ross-Lonergan, "Unitarity and the three flavor neutrino mixing matrix," *Phys. Rev. D* **93** (2016) 113009, `1508.05095`.

[174] G. Barenboim and C. Quigg, "Neutrino observatories can characterize cosmic sources and neutrino properties," *Phys. Rev. D* **67** (2003) 073024, `hep-ph/0301220`.

[175] T. Kashti and E. Waxman, "Flavoring astrophysical neutrinos: Flavor ratios depend on energy," *Phys. Rev. Lett.* **95** (2005) 181101, `astro-ph/0507599`.

[176] P. Lipari, M. Lusignoli, and D. Meloni, "Flavor Composition and Energy Spectrum of Astrophysical Neutrinos," *Phys. Rev. D* **75** (2007) 123005, 0704.0718.

[177] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube," *Phys. Rev. Lett.* **114** (2015) 171102, 1502.03376.

[178] G. Amelino-Camelia, J. Kowalski-Glikman, G. Mandanici, and A. Procaccini, "Phenomenology of doubly special relativity," *Int. J. Mod. Phys. A* **20** (2005) 6007, gr-qc/0312124.

[179] J. Christian, "Testing quantum gravity via cosmogenic neutrino oscillations," *Phys. Rev. D* **71** (2005) 024012, gr-qc/0409077.

[180] J. S. Diaz, "Neutrinos as probes of Lorentz invariance," *Adv. High Energy Phys.* **2014** (2014) 962410, 1406.6838.

[181] J. S. Diaz, "Testing Lorentz and CPT invariance with neutrinos," *Symmetry* **8** (2016) 105, 1609.09474.

[182] M. J. Longo, "Tests of Relativity From SN1987A," *Phys. Rev. D* **36** (1987) 3276.

[183] Z.-Y. Wang, R.-Y. Liu, and X.-Y. Wang, "Testing the equivalence principle and Lorentz invariance with PeV neutrinos from blazar flares," *Phys. Rev. Lett.* **116** (2016) 151101, 1602.06805.

[184] J.-J. Wei, X.-F. Wu, H. Gao, and P. Mészáros, "Limits on the Neutrino Velocity, Lorentz Invariance, and the Weak Equivalence Principle with TeV Neutrinos from Gamma-Ray Bursts," *JCAP* **1608** (2016) 031, 1603.07568.

[185] S. Boran, S. Desai, and E. O. Kahya, "Constraints on differential Shapiro delay between neutrinos and photons from IceCube-170922A," 1807.05201.

[186] B. Baret *et. al.*, "Bounding the Time Delay between High-energy Neutrinos and Gravitational-wave Transients from Gamma-ray Bursts," *Astropart. Phys.* **35** (2011) 1, 1101.4669.

[187] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "The IceCube Neutrino Observatory: Instrumentation and Online Systems," *JINST* **12** (2017) P03012, 1612.05093.

[188] **IceCube** Collaboration, M. G. Aartsen *et. al.*, "IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica," 1412.5106.

[189] L. A. Anchordoqui, C. Garcia Canal, and J. F. Soriano, "Probing strong dynamics with cosmic neutrinos," 1902.10134.

[190] S. L. Glashow, "Resonant Scattering of Antineutrinos," *Phys. Rev.* **118** (1960) 316.

[191] S. W. Li, M. Bustamante, and J. F. Beacom, "Echo Technique to Distinguish Flavors of Astrophysical Neutrinos," 1606.06290.

[192] S.-H. Wang, P. Chen, M. Huang, and J. Nam, "Feasibility of Determining Diffuse Ultra-High Energy Cosmic Neutrino Flavor Ratio through ARA Neutrino Observatory," *JCAP* **1311** (2013) 062, 1302.1586.

[193] D. Fargion, A. Aiello, and R. Conversano, "Horizontal tau air showers from mountains in deep valley: Traces of UHECR neutrino tau," in *Proceedings, 26th International Cosmic Ray Conference (ICRC), August 17-25, 1999, Salt Lake City: Invited, Rapporteur, and Highlight Papers*, p. 396, 1999. astro-ph/9906450.

[194] A. V. Olinto *et. al.*, "POEMMA: Probe Of Extreme Multi-Messenger Astrophysics," *PoS* **ICRC2017** (2018) 542, 1708.07599. [35, 542 (2017)].

[195] M. Sasaki and T. Kifune, "Ashra Neutrino Telescope Array (NTA): Combined Imaging Observation of Astroparticles – For Clear Identification of Cosmic Accelerators and Fundamental Physics Using Cosmic Beams – ," *JPS Conf. Proc.* **15** (2017) 011013.

[196] S. Wissel *et. al.*, "A New Concept for High-Elevation Radio Detection of Tau Neutrinos," *accepted EPJ Web Conf.* (2018). Presented at the Acoustic and Radio EeV Neutrino Detection Activities Conference 2018 (ARENA 2018), Catania, Italy, June 12–15, 2018 https://indico.cern.ch/event/667036/contributions/3005761/.

[197] **TAROGE** Collaboration, T. Liu, "The status of the second station of Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emissions (TAROGE-II)," *PoS* **ICRC2017** (2018) 234.

[198] **GRAND** Collaboration, J. Alvarez-Muñiz *et. al.*, "The Giant Radio Array for Neutrino Detection (GRAND): Science and Design," 1810.09994.

[199] A. N. Otte, "Trinity: An Air-Shower Imaging System for the Detection of Cosmogenic Neutrinos," 1811.09287.

[200] P. Allison *et. al.*, "Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole," *Astropart. Phys.* **35** (2012) 457, 1105.2854.

[201] S. W. Barwick *et. al.*, "Design and Performance of the ARIANNA HRA-3 Neutrino Detector Systems," *IEEE Trans. Nucl. Sci.* **62** (2015) 2202, 1410.7369.

[202] **ANITA** Collaboration, P. W. Gorham *et. al.*, "The Antarctic Impulsive Transient Antenna Ultra-high Energy Neutrino Detector Design, Performance, and Sensitivity for 2006-2007 Balloon Flight," *Astropart. Phys.* **32** (2009) 10, 0812.1920.

[203] **KM3Net** Collaboration, S. Adrian-Martinez *et. al.*, "Letter of intent for KM3NeT 2.0," *J. Phys. G* **43** (2016) 084001, 1601.07459.

[204] C. W. James *et. al.*, "Overview of lunar detection of ultra-high energy particles and new plans for the SKA," *EPJ Web Conf.* **135** (2017) 04001, 1704.05336.

[205] **IceCube** Collaboration, R. Abbasi *et. al.*, "Search for a Lorentz-violating sidereal signal with atmospheric neutrinos in IceCube," *Phys. Rev. D* **82** (2010) 112003, 1010.4096.