

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 km³ 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 distribution¹⁶ for the first time, probed charm production in neutrino interactions¹⁶, 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-ONE²², and Baikal-GVD²³, under construction, will improve our sensitivity to TeV–PeV neutrinos.

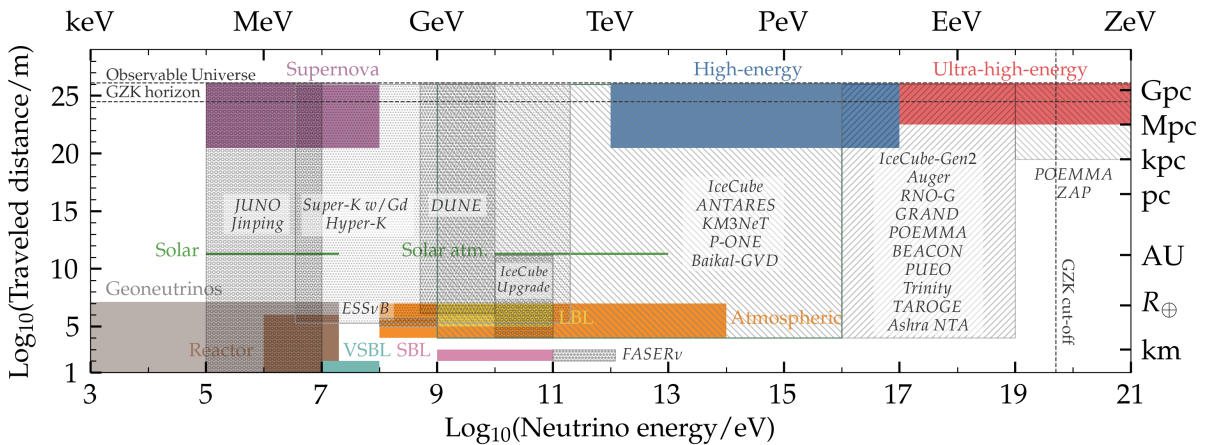


Figure 1: Distribution of neutrino sources in energy and distance traveled to the detector, and experiments aimed at detecting them, present and future. We focus on high-energy and ultra-high-energy neutrinos. Updated from¹.

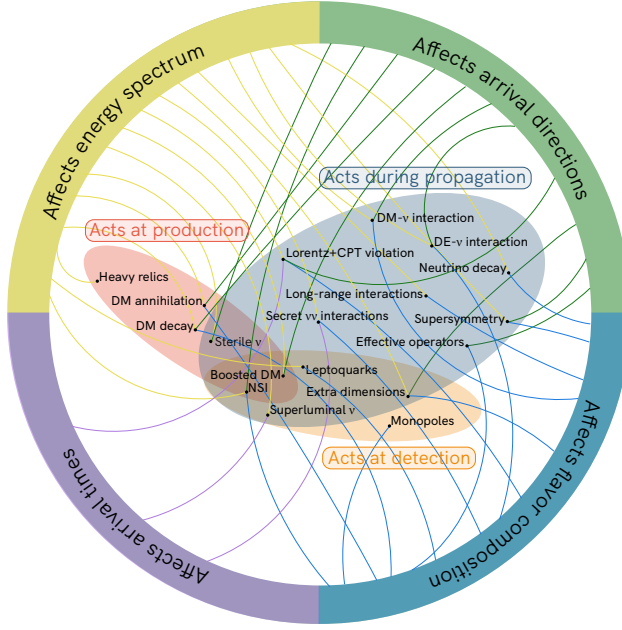


Figure 2: Models of new neutrino physics and other new physics classified according to the stage at which they act—at production, during propagation, at detection—and what feature they affect—energy spectrum, arrival directions, flavor composition, arrival times. Reproduced from⁵.

vor 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 Upgrade²⁰⁵, though geared towards low-energy neutrinos, will reduce systematic errors that affect the detection of high-energy neutrinos. Second, oscillation experiments—DUNE²⁰⁶, JUNO²⁰⁷, Hyper-Kamiokande²⁰⁸, the IceCube Upgrade²⁰⁵, KM3NeT/ORCA²¹—will reduce the uncertainties on lepton mixing parameters²⁰⁹, allowing us to make more precise tests of new physics via the flavor composition of high-energy cosmic neutrinos.⁵⁹ Third, FASER ν 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.

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-Gen2³⁷, AugerPrime³⁸), in-air Cherenkov and fluorescence (EUSO-SPB2³⁹, POEMMA⁴⁰, Trinity⁴¹, Ashra NTA⁴², CTA⁴³), and radio (GRAND⁴⁴, RNO-G⁴⁵, PUEO⁴⁶, BEACON⁴⁷, TAROE⁴⁸, ZAP⁴⁹).

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 energy⁵⁰, an isotropic flux^{51–53}, a fla-

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