

# Snowmass 2021 Letter of Interest: Ultra-High-Energy Neutrinos

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Neutrino astrophysics provides a unique window into the extreme environments of the most energetic sources in the Universe and a testbed for weak interactions at energies inaccessible through accelerators. While the discovery of TeV–PeV astrophysical neutrinos by IceCube has brought a wealth of information, ultra-high-energy (UHE) neutrinos, long-sought but not yet detected, provide the only means of directly investigating processes that occur at energy scales of EeV ( $\equiv 10^{18}$  eV) and above in the distant Universe. Discovering them would open new regimes of exploration in particle physics, astrophysics, and cosmology.

**Ultra-high-energy neutrinos**—The origin and acceleration mechanism of ultra-high-energy cosmic rays (UHECRs), with energies in excess of EeV, remains a fundamental outstanding question in astroparticle physics. The cutoff in their spectrum around 50 EeV, predicted by Greisen, Zatsepin, and Kuzmin [1, 2], and observed by the Pierre Auger Observatory [3] and the Telescope Array [4], strongly suggests that there should be a flux of “cosmogenic neutrinos” with energies of EeV and above, produced in the interaction of UHECRs with cosmic background photons [5–9]. Measurements or constraints on the neutrino energy spectrum would provide much-needed insight into high-energy particle acceleration, the evolution of sources over cosmological length scales, and the mass composition of UHECRs.

UHECRs can also interact with gas or radiation inside the sources themselves to produce UHE neutrinos. Because their interactions are so weak, these astrophysical neutrinos can travel long distances across the universe undisturbed and point back to their sources thus tracing the evolution of non-thermal sources over Gpc length scales. Despite many measurements of UHECRs, the extreme sources of UHECRs are still unidentified. Complementary information from neutrinos may be essential for learning about Nature’s most energetic environments.

**Main physics topics**—The most important questions to guide the next decade in UHE neutrino physics are:

- **Cosmogenic neutrinos:** While predictions and modeling of the flux of cosmogenic neutrinos [10–12] have been steadily improving in recent years due to more information from UHECR experiments [3, 4, 13], the uncertainty is still about an order of magnitude. A measurement of the cosmogenic neutrino spectrum will provide valuable inputs to constrain UHECR properties [14–22].
- **UHE neutrinos from point sources:** As predictions of the flux of cosmogenic neutrinos are quite uncertain, the first detected UHE astrophysical neutrinos could well be coming from powerful point sources [23–34]. A separate Letter of Interest (LoI) discusses the potential of these target-of-opportunity observations.
- **Multi-messenger connection and improved source modeling:** Because the energy generation rates of UHECRs, high-energy neutrinos, and gamma rays are comparable [35], it is natural that, at least in some cases, they are produced in the same network of processes in the same sources [6, 32, 36–42]. Coincident observations of high-energy neutrinos with gamma rays from a blazar [43, 44] and with radio and X-ray emission from a tidal disruption event [45] hint at the first sources, but the connection among different messengers remains clouded.
- **UHE neutrino interactions:** The interactions of UHE neutrinos with nucleons have center-of-mass energies of  $\sqrt{s} \sim 30$  TeV (vs.  $\sim 1$  TeV using TeV–PeV neutrinos [46, 47]), providing an excellent opportunity to probe models of the nucleon and nuclear structure [48–51], and new physics in neutrino-nucleon interactions [46, 47, 50–73].
- **Flavor transitions at the highest energies:** Both astrophysical and cosmogenic neutrinos are expected to arrive at Earth with nearly equal fluxes of each of the three flavors,  $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ , as a result of the neutrino production processes at the sources and the values of the oscillation parameters measured in terrestrial experiments. As some experiments have flavor sensitivity (particularly for  $\nu_\tau$ ) UHE neutrinos provide a key test for flavor changing processes up to the highest energies [74–84].
- **Tests of neutrino properties during propagation:** Some of the fundamental properties of neutrinos may have an energy dependence that manifests only at the highest energies. Notable examples that have received attention include the breaking of known symmetries or the appearance of new ones [77, 85–96], neutrino self-interactions [81, 97–104], neutrino-dark matter interaction [105–122], and neutrino-dark energy interaction [123, 124]. A separate LoI discusses the potential of high-energy and UHE neutrinos as probes of fundamental physics.

**Experiments and detection strategies**— Because the neutrino-nucleon cross section grows with energy, the Earth is opaque to high-energy neutrinos reducing the angular coverage for experiments to well below  $4\pi$ . Charged-current interactions ( $\text{CC}, \nu_l + N \rightarrow l + X$ , where  $l = e, \mu, \tau$  and  $X$  are final-state hadrons) remove neutrinos from the flux. Neutral-current interactions ( $\text{NC}, \nu_l + N \rightarrow \nu_l + X$ ) redistribute high-energy neutrinos to lower energies. In the TeV–PeV range, the opacity is high, but some neutrinos are still able to traverse up to thousands of km inside the Earth before reaching a detector [46, 47]. In the EeV range, the opacity is so high that neutrinos may reach the detector only if they come from directly above it or, if they travel horizontally, if they skim the surface of the Earth and only dip into the crust or ocean [125–127] for a short segment of their way.

UHE neutrinos may be detected through a variety of techniques implemented in several experiments currently operating and planned for the coming decade. Some experiments search for all flavors of UHE neutrinos in ice or water. Other detection techniques identify UHE  $\nu_\tau$  via the air showers produced after they interact in the Earth.

**Detection of UHE  $\nu$  in ice and in water**—Signatures of EeV neutrinos can be detected via optical Cherenkov emission in currently operating and planned experiments in both ice and water. Radio techniques can also be used to cover the large areas ( $\mathcal{O}(100)$  km<sup>2</sup>) required to detect the expected low neutrino flux with reduced instrumentation.

- **Optical detection in ice and water:** IceCube [128] and ANTARES [129] search for the optical Cherenkov emission from neutrino-induced showers and tracks from all flavors of neutrinos. Optical Cherenkov experiments are sensitive to UHE neutrinos directly [130] and indirectly through the cascading down of EeV  $\nu_\tau$  to PeV energies [131]. IceCube-Gen2 [132] will have enhanced sensitivity and broad energy coverage through a larger optical array [132]. Upcoming detectors include KM3Net [133], Baikal-GVD [134], and P-ONE [135].
- **Radio detection in ice:** In dense media like ice, compact electromagnetic showers generated through neutrino interactions emit coherent Askaryan radiation at the Cherenkov angle. The long attenuation lengths of radio frequencies allow the signal to propagate over long distances. These experiments have sensitivity to all three flavors [136, 137], and may have power to discriminate flavor based on different event topologies [137, 138]. ARA [139] and ARIANNA [140] (and the planned ARIANNA-200 [141]) consist of radio antennas buried in the Antarctic ice. RNO-G is a planned radio detector in Greenland, currently under development [142]. IceCube-Gen2 will include an expansive, sparse radio array, building on the experience gained in these experiments [132]. Radar bounces off the in-ice showers is also being explored as a method for detecting neutrinos [143–145].
- **Radio detection from or in space:** ANITA is a balloon-borne radio detector that searches for in-ice neutrino interactions via the radio emission that refracts out of the ice [146]. The high altitude of ANITA grants it a large effective area at the highest energies [147]. PUEO [148] is a planned upgrade to ANITA. NuMoon searches for radio emission from neutrino interactions in the lunar regolith [149].

**Detection of air showers from UHE  $\nu_\tau$** —Tau neutrinos uniquely experience the process known as  $\nu_\tau$  regeneration [131, 150–153], wherein a high-energy  $\nu_\tau$  interacts in the Earth in a CC interaction creating a tau lepton which then decays before losing too much energy, producing another  $\nu_\tau$ . If a  $\nu_\tau$  interacts underground, at a depth comparable to the travel range of the tau that it produces, the tau can escape and decay in air to produce an extensive air shower [154]. Therefore,  $\nu_\tau$ , unlike  $\nu_e$  and  $\nu_\mu$ , generate a unique signature, detectable with standard air shower techniques. This signal is free from atmospheric neutrino backgrounds and mostly free from contamination from other flavors of UHE neutrinos, since, for  $\nu_\mu$ , the decay length of the final-state muon is too long to mimic the signal from  $\nu_\tau$  and, for  $\nu_e$ , the final-state electrons undergo significant energy losses even before exiting from underground.

- **Surface particle detection:** The Pierre Auger Observatory (Auger) is a long-running large-scale array of surface water tanks for detection of Cherenkov light from shower particles. It is designed to detect UHECRs, but is used also to look for horizontal showers initiated by UHE neutrinos [155]. The Telescope Array (TA) [156] and HAWC [157] use a similar strategy, but have poorer sensitivity. TAMBO is a planned array of water tanks to be located on one side of an Andean canyon, designed to detect the showers initiated by UHE taus emerging from the opposite side [158].
- **Radio detection in the atmosphere:** BEACON [159], in prototype phase, TAROGE [160], and TAROGE-M [161] are compact antenna arrays in elevated locations that aim to detect UHE  $\nu_\tau$  emerging upwards via the radio emission of the air showers that they trigger. ANITA [148] and PUEO [148] are also sensitive to upgoing  $\nu_\tau$ , from a higher elevation. GRAND [162] is a planned experiment that will cover large areas with a sparse antenna array to detect the radio emission from air showers triggered by UHE  $\nu_\tau$ , cosmic rays, and gamma rays.
- **Air-shower imaging from the ground:** Several air-shower imaging instruments, although optimized for cosmic-ray and gamma-ray detection, have demonstrated that the imaging of air showers via their Cherenkov and fluorescence light is a viable method to search for UHE  $\nu_\tau$ 's [163–167]. Two planned instruments optimized for the detection of UHE neutrinos are Trinity [168] and Ashra NTA [169].
- **Cherenkov and fluorescence from space:** POEMMA is a planned satellite detector designed to detect the Cherenkov light from UHE  $\nu_\tau$ -initiated showers coming from the limb of the Earth and can rapidly reposition itself for multi-messenger studies [127, 170]. EUSO-SPB2 is a super-pressure balloon to fly at high altitude and will serve as a pathfinder for POEMMA and could detect UHE neutrinos as well [171].

Given the potential of UHE neutrinos to extend our view of astrophysics and particle physics at the absolute highest energies, and the richness of the experimental landscape in the coming decade, we feel that this topic should be at the forefront of the high-energy physics program, as it pushes the boundaries for the neutrino, cosmic, energy, theory, and instrumentation frontiers.

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