PeV Tau Neutrinos to Unveil Ultra-High-Energy Sources

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The observation of ultra-high-energy EeV-energy cosmogenic neutrinos provides a direct path to identifying the sources of the highest energy cosmic rays; searches have so far resulted in only upper limits on their flux. However, with the realization of cubic-kilometer detectors such as IceCube and, in the near future, KM3NeT, GVD-Baikal, and similar instruments, we anticipate the observation of PeV-energy cosmic neutrinos with high statistics. In this context, we draw attention to the opportunity to identify EeV tau neutrinos at PeV energy using Earth-traversing tau neutrinos. We show that Cherenkov detectors can improve their sensitivity to transient point sources by more than an order of magnitude by indirectly observing EeV tau neutrinos with initial energies that are nominally beyond their reach. This new technique also improves their sensitivity to the ultra-high-energy diffuse neutrino flux by up to a factor of two. Our work exemplifies how observing tau neutrinos at PeV energies provides an unprecedented reach to EeV fluxes.

Introduction.— Ultra-high-energy (UHE) cosmic-rays have been detected with energies approaching $10^{21}$ eV. This endpoint could reflect either the ultimate reach in energy of the cosmic accelerators, or it could be a signature of a cosmic-ray–opaque Universe, where the UHE cosmic-ray flux is absorbed by interactions with microwave photons. This is the origin of the so-called cosmogenic—Greisen–Zatsepin–Kuzmin (GZK) [1–3]—neutrino flux from the decay of pions produced in the dominant process $p\gamma \to \Delta^+ \to n\pi^+ / \nu\pi^0$.

GZK neutrinos have been the target of km-scale [4, 5] optical neutrino detectors, such as the IceCube Neutrino Observatory at the South Pole [6]; very large arrays of water tanks, such as the Pierre Auger observatory in the Argentinian Pampas [7]; and antennas that detect the radio emission from neutrino-initiated showers, suspended from high-altitude balloons [8] or deployed either on [9] or below the Antarctic ice sheet [10], among others. This multipronged approach to discover GZK neutrinos has yielded only upper limits on their flux so far [11–18].

The observation of this so-called “guaranteed” flux is one of the primary targets of next-generation neutrino observatories—such as IceCube-Gen2, RNO-G, TAMBO, POEMMA, and others [19–23]—because it will shed light on the composition of UHE cosmic rays [24, 25], their sources and cosmological evolution [26–29], and the properties of the extragalactic background light [25, 30–38]. The nonobservation of GZK neutrinos has already provided valuable information along these lines. These experiments use a common strategy to search for GZK neutrinos, which primarily relies upon the observation of very high energy events near the horizon, often referred to as Earth-skimming neutrinos [35, 39–44]. This is because Earth is opaque to neutrinos at EeV energies; the survival probability of a primary neutrino of 100 PeV energy traversing Earth is 0.2 for $\cos \theta = -0.1$ (Earth-skimming), $2 \times 10^{-6}$ for $\cos \theta = -0.6$ (Earth-mantle-crossing), and $10^{-19}$ for $\cos \theta = -1$ (Earth-core-crossing), where $\theta$ is the zenith angle.

However, neutrinos that experience charged-current interactions produce high-energy charged leptons. These leptons will undergo catastrophic energy losses in Earth until they reach energies such that their interaction and decay lengths are comparable, at which point they produce secondary neutrinos. As pointed out for the first time in [45] and recently revisited in [46], this process is particularly important for tau neutrinos. Taus have a short lifetime and decay promptly into a secondary tau neutrino that carries a large fraction of the primary energy. Moreover, it was pointed out in [47] that the decay of the tau also contributes a non-negligible flux of secondary electron and muon antineutrinos. This process is commonly referred to as tau regeneration.

In this letter, we take advantage of the tau regeneration process to identify a complementary way to search for UHE neutrinos and discuss the connection between current PeV and forthcoming EeV neutrino measurements considering both the observation of transient sources and their diffuse flux. We find that the current point-source sensitivity to UHE neutrinos relying on muon event selections is enhanced by more than an order of magnitude for Earth-traversing directions when tau regeneration is taken into account. For the observation of the diffuse flux, we illustrate the role of tau regeneration assuming alternatively an astrophysical power-law flux and a conventional GZK spectrum. We find that the two components can be separated by measurement of their angular and energy distributions. Using this information, the
sensitivity to specific GZK neutrino models is improved by up to a factor of two compared to current techniques. Therefore, our approach impacts both the characterization of the diffuse spectra and the discovery potential of neutrino sources for detectors that operate in the PeV energy range.

**Appearance of EeV neutrinos at PeV energy.**—

Though neutrinos rarely interact, their interaction cross section with nucleons grows linearly with energy up to approximately 1 TeV, after which the typical momentum transferred exceeds the weak vector-boson masses. Above this energy, the cross-section growth slows down, ultimately growing only as \( \log^2 s \) \cite{48}, where \( s \) is the center-of-mass energy squared. This scaling is a universal characteristic of the deep-inelastic proton-, neutrino-, and photon-nucleon scattering \cite{49}. The distance that a neutrino traverses Earth to reach an underground detector eventually exceeds or is comparable to the corresponding neutrino interaction length, e.g. \( \sim 2,200 \) km at 1 PeV and \( \sim 100 \) km at 1 EeV. The antineutrino interaction lengths are comparable because the interaction is dominated by sea quarks and anti quarks in the proton \cite{50}. The ratio of neutrino charged-to-neutral current interactions is approximately 2.5 \cite{50} in this energy range, which implies that more often than not, high-energy charged leptons will be produced in neutrino interactions. Alternatively, in the case of neutral-current interactions, the neutrino loses, on average, 30\% of its initial energy.

The secondary charged leptons lose energy catastrophically. At EeV energies, taus lose energy predominantly through photodisintegration processes and pair production \cite{51}. For electrons, bremsstrahlung dominates, while for muons the dominant energy loss processes are pair production and bremsstrahlung \cite{52} with a combined contribution that approximately matches the hadronic processes \cite{53}.

While muons will lose most of their energy before decaying, taus will decay without significant energy loss below 100 PeV, resulting in neutrinos with energies close to the parent neutrino energy. An EeV tau neutrino will be subject to, on average, three neutral-current and five charged-current interactions prior to crossing Earth’s diameter and reaching the detector; its typical final energy is between 10 TeV and 10 PeV. Fig. 1 shows the GZK neutrino fluxes before (blue) and after (pink) their propagation through Earth. In this figure, we have scaled the flux by the neutrino energy such that the lines are approximately proportional to the event rate. As anticipated, before Earth propagation, the flux is maximal between \( 10^8 \) and \( 10^9 \) GeV, while after propagation it peaks between \( 10^5 \) to \( 10^6 \) GeV.

**Observing sources of UHE neutrinos.**—

Astrophysical beam dumps in the vicinity of the sources of UHE cosmic rays provide the opportunity for the production of charged and neutral pions, and therefore, of neutrinos with energies exceeding tens of PeV. Potential sources of UHE neutrinos include binary neutron star (BNS) mergers \cite{54}, magnetars \cite{55–57}, young and fast spinning pulsars \cite{58}, supermassive black hole mergers \cite{59}, gamma-ray burst (GRB) afterglows \cite{60}, and blazars with a luminous dust-torus \cite{61–63}. The predicted neutrino energy spectrum peaks in the range of 10–100 PeV, energies that are typically below the sensitivity of the current generation of neutrino telescopes. However, the presence of a flux extending beyond 10 PeV presents an opportunity to probe the sources via the regenerated flux from tau neutrinos.

In order to demonstrate the power of the regeneration-based technique for identifying sources of UHE neutrinos, we compute the differential sensitivity of IceCube for a neutrino flux in the range of 1 PeV to 1 ZeV. Neutrinos with this energy traversing Earth will generate a cascade of muon and tau neutrino fluxes at the detector. In contrast to the primary all-flavor flux that is attenuated, the regenerated flux results in a substantial intensity of neutrinos of PeV energy, where the sensitivity is optimal for detection by optical Cherenkov detectors. Here, we utilize the IceCube differential sensitivity for transients \cite{64}. For each energy decade, we inject a flux of tau neutrinos, assuming the spectrum follows a \( E^{-2} \) distribution. To obtain the normalization for each bin, we determine the corresponding flux of secondary neutrinos that reaches the detector. The sensitivity of IceCube to a flux of muons arriving at the horizon constrains the flux that arrives at the detector in any direction, when excluding Earth effects. Thus, we use the sensitivity at \( \delta = 0 \) to constrain the initial flux at higher energies; that is, we constrain the nor-

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**FIG. 1. At-detector angle-integrated neutrino flux intensity.** EeV neutrinos pile up at PeV energies after propagating through Earth (pink). We integrate over the respective solid angles and define Earth-skimming as within \( 10^8 \) of the horizon. Upgoing neutrinos are accessible to water- and ice-Cherenkov detectors but fall below the threshold for radio experiments (shown as a vertical dot-dashed gray line). As an example of a baseline GZK model (blue), we use the flux given by Ahlers et al. 2010 \cite{24}.

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\[ E_{\nu} \Phi \] (km \( ^2 \) s \( ^{-1} \))

\[ 10^{-19} \]

\[ 10^{-18} \]

\[ 10^{-17} \]

\[ 10^{-16} \]

\[ 10^{-15} \]

\[ 10^{-16} \]

\[ 10^{-17} \]

\[ 10^{-18} \]

\[ 10^{-19} \]
FIG. 2. Improved point source sensitivity with \( \nu_\tau \). Differential sensitivity to an \( E^{-2} \) time-integrated flux for transient UHE sources at a fixed declination (\( \delta = 30^\circ \)). The current sensitivity of IceCube is shown in blue, while the sensitivity to muons from tau neutrinos is shown in pastel pink. The projected sensitivity resulting from our method for IceCube-Gen2 (optical-only) is shown as a dashed line. To illustrate the power of our method, we compare it to the predicted time-integrated neutrino flux from newborn magnetars (green) [57] for a distance of 0.3 Mpc and GRB afterglows (orange) [60] at 20 Mpc.

We illustrate the importance of tau regeneration in searching for GZK neutrinos with an illustrative analysis. We evaluate the response of IceCube to neutrinos with energy above 100 TeV, where the atmospheric neutrino component is subdominant [65]. The muon-neutrino effective area is taken from [66]. We consider two isotropic components: an astrophysical component modeled by a power-law whose parameters have been determined using an independent cascade set of data and a GZK spectrum that we model according to [24]. The two components can be differentiated by their energy dependence as well as their angular distribution. This difference is caused by a contrasting amount of absorption as a function of energy and traversed column depth.

To quantify the significance of the Earth-traversing contribution, we use a binned Poisson likelihood to compare our prediction to a baseline expectation. We compute the number of muons produced by the interactions of muon and tau neutrinos in the vicinity of the detector. We bin the resulting muons linearly using twenty bins in zenith and logarithmically using two bins per decade in reconstructed energy. We model the detector energy resolution by introducing an 80% smearing of the initial energy assuming a normal distribution [67]. We compute the 90\% CL. upper limit on the Ahlers-Halzen GZK model normalization, \( \phi_0 \), using an Asimov data set, i.e., we set the observed number of events to be the expected mean number of events in the absence of a GZK component. When considering only Earth-skimming neutrinos, namely declinations such that \( \delta < 10^\circ \), we get sensitivities that are comparable to current IceCube constraints [67]. However, when we include the Earth-traversing component, the sensitivity improves by approximately a factor of two, with most of the improvement coming from the range between 10\(^\circ\) to 30\(^\circ\) below the horizon.

**Conclusions.**—The search for UHE neutrinos has been approached using two deeply interconnected techniques: lower-threshold optical neutrino detectors and higher-threshold radio detectors with enhanced sensitivity. This letter demonstrates how the observation of Earth-traversing neutrinos of PeV energy provides information on, and enhanced sensitivity to, their EeV neutrino flux. We showcase how the technique significantly improves the reach of lower-threshold optical neutrino detectors to transient UHE sources. We find that the sensitivity to UHE sources is improved by at least an order of magnitude above 10\(^9\) GeV. Interestingly, optical and radio detectors are more intertwined than originally thought, which implies that the interplay between these energy regimes needs to be taken into account when designing next-generation neutrino telescopes. In addition, a study of the diffuse flux component demonstrates a gain in sensitivity that is not penalized by the reduced growth of the neutrino cross section with energy [49]. However, the observed high-energy astrophysical flux acts as background in this regime, rendering the identification of GZK events possible only by aggregating statistics [68]. Despite this competition between increasing
rate and background, we find that we can improve the current sensitivity by up to a factor of two.

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