Constraining anomalous EeV ANITA detections with PeV neutrinos

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Tau neutrinos are unique messengers, especially at extreme energies. When they undergo a charged-current interaction, the short lifetime of the tau gives rise to regenerated neutrinos at relatively high energies. ANITA recently reported two EeV showers which, at first glance, could be interpreted as emerging tau neutrinos. Their emergence angle was shown to be in tension with the expected angular distribution from isotropic astrophysical neutrinos. However, localized emission from a point source in the event’s direction can evade diffuse bounds. In this work, we present an updated and precise calculation of the tau-regeneration effect using a newly developed Monte Carlo package, \textit{TauRunner}. We describe the algorithm and the softwares capabilities, and apply it to the anomalous ANITA detections. We show that any flux from the direction of the ANITA events should be accompanied by secondary tau-neutrinos detectable at IceCube. We derive the maximum allowed secondary flux at IceCube and use it to infer the maximum number of events ANITA would detect. We find that ANITA should see not more than $10^{-6}$ events, requiring a significant over-fluctuation to account for the anomalous event in 2014.

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1. Introduction

Astrophysical neutrinos, both despite and because of their elusiveness, provide a direct probe to some of the most energetic processes in the Universe. We can see farther into some of the most violent of objects with neutrinos than we can with any other messenger. As such, features in the astrophysical spectrum encode invaluable information about cosmic-ray acceleration, mass composition, production sites, surrounding environments, and more. Since the completion of its construction in 2011, IceCube, a cubic-kilometer Cherenkov detector in the South Pole, has measured an astrophysical flux of neutrinos extending to several PeVs [1]. At higher energies, experiments like ARA and ANITA have attempted to utilize the South Pole ice in other ways to detect radio emission from the highest energy neutrinos predicted, at scales approaching EeVs, and have set competitive limits on cosmogenic neutrino fluxes [2, 3]. On top of that, next-generation proposed experiments like GRAND and POEMMA go beyond the ice, using mountains and the Earth’s atmosphere, respectively, as their effective volumes [4, 5]. There exists, however, a complementary channel that would take advantage of existing detectors like IceCube to probe the EeV universe. Particularly, tau-neutrinos traversing the earth produce a tau when they undergo a charged-current interaction, which subsequently decays emitting a daughter tau-neutrino. These secondary neutrinos emerge at energies between 100 TeV and 10 PeV, a range where IceCube is quite sensitive. In this work we describe the prescription and associated uncertainties of lepton propagation through matter and introduce a monte carlo package, TauRunner, that propagates taus and tau-neutrinos through the earth. We show the energy distribution of secondary neutrinos after earth propagation for several injected fluxes and demonstrate the capability of Cherenkov detectors like IceCube to probe the EeV universe with PeV neutrinos. In particular, we use the regeneration effect [6] to constrain the anomalous ANITA events, and show that a tau-neutrino interpretation assuming localized emission is disfavored.

2. Leptons through the Earth

Measurements of neutrino cross sections have been performed from sub-GeV up to 10 PeV. This includes a multitude of results utilizing human-made neutrinos in accelerator [7, 8] and reactor [9, 10] experiments as well as natural sources such as solar, atmospheric [11], and astrophysical neutrinos[12]; for a recent review see [13, 14]. In the future, measurements of high-energy neutrinos from collider experiments will be available in the TeV range [15]. Unfortunately, these measurements stop short of the region of interest for this work, and uncertainties from extrapolations can reach an order of magnitude above an EeV. The main issue driving these uncertainties is that the nucleon structure function cannot be derived from first principles, which causes us to instead rely on empirical measurements. Although perturbative QCD calculations show divergent behavior at high energies and small bjorken-x, successful phenomenological approaches to this problem used in the past relied on a $\ln^2(s)$ extrapolation of lower-energy measurements using a dipole model of the nucleon. This approach has been shown to be in good agreement with the total proton-proton cross-section measurements from Auger, LHC, and HERA, as well as neutrino-proton cross-sections from IceCube data. In this work, we use [16] as a benchmark, which predicts...
a gluon saturation effect beyond a PeV, effectively slowing down the growth of the cross-section.

Figure 1: The neutrino-proton cross section as a function of energy. Solid (dashed) lines correspond to charged-current (neutral-current) cross sections. Blue lines [17] correspond to the model used for the results of this work. Orange lines [18] are implemented in the software as well and can be chosen by the user.

Tau energy losses are negligible below 10 PeV and decay-on-the-spot is usually a good approximation. For energies greater than an EeV, however, taus are highly boosted and their decay length becomes larger than the mean interaction length. In this regime, taus lose energy through ionization, bremsstrahlung, pair production, and photo-nuclear interactions. Ionization and bremsstrahlung are sub-dominant at these energies. The photo-nuclear cross-section depends on the lepton’s mass and energy and dominates the losses for tau tracks at or above an EeV [19]. Therefore, the same uncertainties on the nucleon structure function arise, and have to be addressed here. For consistency, we use the same model of the nucleon structure function implemented for the neutrino-proton cross-section. We use a modified version of the publicly available Muon Monte Carlo (MMC) package to propagate taus [20].

3. TauRunner

TauRunner is a Python package that propagates taus and neutrinos through a given medium. It begins by calculating the neutrino’s free-streaming distance which depends on the total cross-section and medium properties. We use the Preliminary Reference Earth Model (PREM) [21] for the work presented here, although in principle the code is able to handle any model of segmented densities. At the point of interaction, the specific process, Neutral- (NC) or Charged- (CC) current is chosen via the accept or reject procedure. If a particle experiences a NC interaction, the energy loss is sampled from the differential cross sections, and a new free-streaming distance is sampled. For CC interactions, a tau-lepton is created whose energy is also sampled from the corresponding differential cross sections. Tau energy losses are then calculated through MMC [20].
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Figure 2: Schematic of lepton propagation through the Earth. There are three possible signatures from EeV tau-neutrino secondaries, described here from left to right. Left: A through-going tau-track, which is possible for taus at or above 10 PeV. Center: The interaction vertex is contained in the fiducial volume of the detector in this case, producing a cascade from the charged-current interaction, along with an outgoing tau track. Right: The tau decays before reaching the detector, producing a muon in \( \approx 18\% \) of the cases, which can subsequently enter the detector.

Using MMC, the tau final energy and distance traveled before decay are recorded. The tau-decay distribution for different modes has been parametrized in [22], from which we sample the energy of the daughter tau-neutrino. From there, only the leading tau-neutrino is tracked and the process repeats. Propagation continues until the leading particle reaches the final distance, at which point the particle identity and final energy are recorded, along with a detailed history of undergone losses and interactions.

3.1 Emerging secondary flux

Using TauRunner, we calculate the resulting tau and neutrino energy distributions after propagating through the Earth. For illustration, we fix the zenith angle to be 30 degrees below the horizon and vary the incoming neutrino energy. We choose one energy value per energy decade from 100 GeV to 1 ZeV. For angles greater than 20 degrees below the horizon and energies above an EeV, the secondary neutrino spectra are identical. The reason for the primary energy degeneracy stems from the tau losses. The dominant energy losses grow with energy, which effectively means that the tau loses more energy per column density traveled. This results in the flattening of the tau range. That coupled with the short tau lifetime causes the tau to travel roughly the same distance, and then decay around the same energy (10-100 PeV), regardless of its initial energy. That is counter-intuitive as one would expect that a higher-energy incoming neutrino creates a higher-energy tau in a CC interaction, which would result in emerging neutrinos at higher energies, but that is not the case. Therefore, the only differences in the secondary distributions are due to the varying interaction length of the initial tau-neutrino. For large enough distances, this difference
is negligible. For earth-skimming neutrinos, however, the width of the first interaction point is comparable to the chord length, and this effect has been discussed here \[19, 22, 23, 24, 25, 26\].

Figure 3 shows the secondary neutrino energy distributions after propagation through the earth, for a fixed emergence angle of 30 degrees. The gray line is the expected survival probability calculated using analytical exponential suppression, where the exponent is the ratio of the propagated distance to the neutrino mean interaction length. Peaks in the bins represent the fraction of surviving neutrinos, and agree well with the expectation.

![Figure 3: Mono-energetic tau neutrinos are injected at a set of initial energies (specified in the legend) and propagated through Earth to calculate the resulting spectrum as they emerge. The spike in each distribution represents the fraction of neutrinos that did not interact, while the secondary energy spectrum is represented by the curve to the left of each spike. The gray line shows the expected survival probability of the primary flux calculated analytically for the same chord length and Earth model.](image)

### 4. ANITA and its anomalous events

The ANtarctic Impulsive Transient Antenna (ANITA) collaboration has reported the detection of two events that at first glance are consistent with an upgoing astrophysical tau-neutrino \[27\]. This interpretation requires the decay of a tau from a tau-neutrino CC interaction which produces an extensive air shower (EAS). This is distinguishable from a reflected cosmic-ray induced EAS, as it acquires a phase reversal from reflection off of the Antarctic ice, while an upgoing tau-induced EAS does not display this phase reversal. While it has been noted that these events are unlikely from isotropic emission \[28, 29, 30\], localized emission could evade these constraints. Beyond Standard Model explanations have also been proposed, including axion-photon conversion \[31\], sterile neutrinos \[30, 32\], and heavy BSM particle decays \[33, 34\]. Here, we investigate the idea of localized emission and show that any observation of EeV neutrinos at ANITA can be ruled out by the non-observation of TeV - PeV neutrinos with other neutrino telescopes, such as IceCube.

The number of events detected by ANITA due to tau showers in the atmosphere from an incident neutrino flux \(\Phi(E_\nu)\) is given by
\[ N_\nu = \int dE_\nu dE'_\nu \Phi(E_\nu) \frac{dN_\nu}{dE'_\nu} (E'_{\nu}; E_\nu) \hat{\xi}_{acc}(E'_\nu) \Delta T, \]  

(4.1)

where \( dN(E'_\nu)/dE'_\nu \) is the energy distribution of secondary tau-neutrinos near the ice surface, \( \Delta T \) is the time of observation, \( \hat{\xi}_{acc}(E'_\nu) \) is the ANITA acceptance which encodes the probability of neutrinos interacting in the ice, as well as the probability of a tau decay shower being induced in the upper atmosphere where ANITA is most sensitive [28]. To remove the Earth absorption effects present in the reported differential acceptance, we set the acceptance at all angles to be that at the horizon. For the incoming flux, we take the minimalistic assumption of a delta function in energy, \( \Phi(E_\nu) = \Phi_0 \delta(E_\nu - E_0) \), where \( \Phi_0 \) is the normalization with units \( cm^{-2}s^{-1} \), and \( E_0 \) has been tuned to result in the maximum probability of a tau reaching ANITA.

As was discussed above, this incident flux of EeV neutrinos is guaranteed to be associated with a secondary flux of TeV - PeV neutrinos. We find the maximum allowed normalization of the ANITA flux by comparing the secondary neutrino distribution with the reported IceCube diffuse astrophysical flux from the High Energy Starting Event selection (HESE) [35]. Results are shown in Figure 4. The unfolded HESE spectrum is folded back to the detector using TauRunner. The 90% upper limit on the EeV flux normalization is set by comparing both secondary distributions and requiring that the secondaries produced by the primary EeV flux do not exceed HESE at more than 90% confidence level. Given that the time profile of the intrinsic flux is unknown, we place limits on the time-integrated flux. Using the maximum allowed flux, we calculate the expected number of events at ANITA. We find that the maximum allowed \( N_\nu \) is less than \( 10^{-6} \), which makes it highly unlikely for the reported event to be caused by a high-energy tau-neutrino.

5. Summary

In this work we developed a monte carlo package, TauRunner, that calculates neutrino and tau distributions after propagating through the Earth, taking into account tau energy losses. We find that incoming neutrinos with energies above an EeV emerge from the Earth at energies between 100 TeV and 10 PeV, and manifest as upgoing tracks in IceCube. We use the recently detected ANITA events to demonstrate this technique, and find that a tau-neutrino interpretation of these events is inconsistent with the TeV-PeV flux detected by IceCube. While radio detectors hope to find EeV neutrinos by detecting tau decay showers from mountain- or earth-skimming neutrinos, existing Cherenkov detectors with larger overall exposure like IceCube can play a major role in the hunt for cosmogenic neutrinos. By looking for regenerated tau-neutrinos that have traversed the Earth, IceCube provides a complementary channel to measure the cosmogenic flux, as well as cross-check radio detections of Earth-traversing neutrinos, such as the ones reported by ANITA.

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Figure 4: Maximum allowed flux of EeV neutrinos (maroon arrow), given an injected mono-energetic neutrino flux at or above the detected ANITA event energy (AAE141220). The normalization of the secondary flux is set to the maximum that does not exceed IceCube’s diffuse astrophysical flux (black bins). The flux needed to produce one event in the third flight of ANITA (blue marker) exceeds the upper limit by many orders of magnitude. We use the published spectrum based on six years of high energy starting events.

References


