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Neutrino propagation through Earth: modeling uncertainties using `nuPyProp`

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Using the Earth as a neutrino converter, tau neutrino fluxes from astrophysical point sources can be detected by tau-lepton-induced extensive air showers (EASs). Both muon neutrino and tau neutrino induced upward-going EAS signals can be detected by terrestrial, sub-orbital and satellite-based instruments. The sensitivity of these neutrino telescopes can be evaluated with the `nuSpaceSim` package, which includes the `nuPyProp` simulation package. The `nuPyProp` package propagates neutrinos (ν_μ, ν_τ) through the Earth to produce the corresponding charged leptons (muons and tau-leptons). We use `nuPyProp` to quantify the uncertainties from Earth density models, tau depolarization effects and photo-nuclear electromagnetic energy loss models in the charged lepton exit probabilities and their spectra. The largest uncertainties come from electromagnetic energy loss modeling, with as much as a 20-50% difference between the models. We compare `nuPyProp` results with other simulation package results.

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1. Introduction

Over the last several decades, astronomers and physicists have collaborated together to study the messengers of the universe: photons, neutrinos, cosmic rays, and gravitational waves. Ultra-high-energy cosmic rays (UHECRs) ($E > 10^{18}$ eV) are highly energetic particles composed of protons and nuclei, constantly pelting Earth. They interact with Earth's atmosphere to produce a shower of other energetic particles. Because they are charged particles, they are deflected by the magnetic fields that exists in the Universe while they travel to the Earth. UHECRs can interact with matter within astrophysical sources to produce charged pions which decay to produce very-high-energy (VHE) ($E > 10^{15}$ eV) neutrinos. Neutrinos are also produced as UHECRs transit the Universe and interact with the cosmic photon background, again producing charged pions that decay. Neutrinos, being neutral and weakly interacting, won't interact with matter or get deflected by magnetic fields on their way to the Earth. Thus, by studying these UHE neutrinos we can better understand the sources, evolution and composition of UHECRs, and also find the sources of the most energetic environment in the Universe.

Beginning with cosmic ray production of charged pions, a series of decays, e.g., $\pi^+ \rightarrow \mu^+ + \nu_\mu$; $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ yields neutrinos. The initial ratio of neutrino flavours at sources is disproportionate, $N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} \sim 1 : 2 : 0$. Production of ν_τ flavour is highly suppressed at the source, but due to flavour mixings, neutrino oscillations over astronomical distances yields neutrino flavours arrive at Earth [1, 2] in proportion $N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} \sim 1 : 1 : 1$.

One of the methods of detecting UHE neutrinos is to use the Earth as a neutrino converter. Neutrinos of energy more than 40 TeV have high probability of interacting while propagating through the Earth. One of the channels that is used by current and future neutrino experiments (GRAND [3], Trinity [4], POEMMA [5], etc.) is ν_τ propagation through the Earth, interacting to produce a τ-lepton which can exit the Earth at an emergence angle β_{tr}, and decay in the atmosphere to create an upward-going Extensive Air Shower (EAS) [6, 7]. This channel is of interest because electromagnetic energy loss of τ-leptons in transit through the Earth is smaller than muons, because of both the higher mass of the τ-lepton and its shorter lifetime. When the τ-leptons decay, they regenerate tau-neutrinos which can again interact via the charged-current (CC) process to produce a τ-lepton. This is shown in fig. 1. High energy regeneration processes are not a feature of ν_μ propagation because muons have a long lifetime and many more electromagnetic loss interactions. When the muons finally decay, the decay ν_μ's have low probability to interact with matter.

To determine neutrino flux sensitivities of these experiments, there is a need for an end-to-end package to simulate the propagation of cosmic ν_μ and ν_τ through the Earth to produce EAS in the atmosphere. One such package is ν`SpaceSim` [8, 9], designed to simulate radio and optical signals in the atmosphere that originate from ν_τ's. The sensitivities of the experiments depends on the flux of τ-leptons and muons exiting the Earth, determined by the `nuPyProp` [10] simulation package, a standalone package that is part of ν`SpaceSim` package. Using `nuPyProp`, the propagation through the Earth of ν_μ and ν_τ, and the muons and τ-leptons they produce, yields charged lepton exit probabilities and energy distributions that do not depend on experiments, so `nuPyProp` is a mission independent simulation code.

The next section gives an overview of the framework of `nuPyProp` and discusses the models/parametrizations used for neutrino/anti-neutrino cross-sections and electromagnetic energy loss

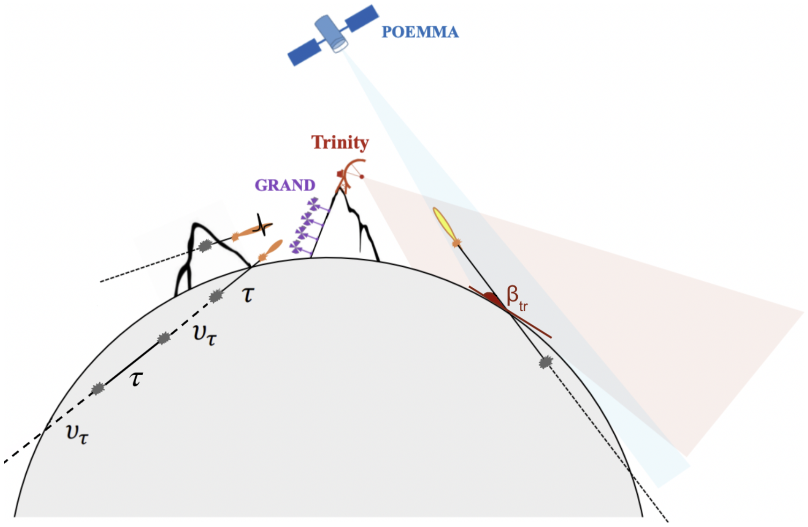

Figure 1: ν_τ propagation through the Earth, producing τ-lepton which is exiting the Earth at β_{tr} Earth emergence angle. EASs detected by neutrino experiments GRAND, TRINITY, and POEMMA. Figure reproduced from ref. [11].

cross-sections. Section 3 shows some selected results from `nuPyProp`. More details and results appear in ref. [10].

2. Framework and structure of `nuPyProp`

`nuPyProp` is a highly modular and flexible code which has only few library dependencies. It is an open-source code available on GitHub[1]. Its main purpose is to simulate neutrinos (ν_τ, ν_μ, and anti-neutrinos) propagating through the Earth, interacting to produce charged leptons (τ-leptons and muons). It is designed for the energy range of $E_\nu = 10^6 - 10^{12}$ GeV. `nuPyProp` is coded in two languages, FORTRAN 90 which handles particle propagation and Python which does data handling.

The working of `nuPyProp` is explained via the flowchart in fig. 2. We start with mono-energetic neutrinos which propagate through the Earth, first the water layer (the surface depth of the water layer can be set from $0 - 10$ km), then through rest of the Earth. If the neutrino interacts via a neutral current interaction, a lower energy neutrino is produced, and we are back at the beginning of the loop. If the neutrino interacts via a CC interaction, it produces the corresponding charged lepton. The charged lepton propagates through the Earth with electromagnetic interactions (ionization, bremsstrahlung, pair production, and photo-nuclear processes) that cause energy losses. If the charged lepton decays before exiting the Earth, it produces a lower energy (regenerated) neutrino, and we are back at the beginning of the loop. The regenerated neutrino plays an important role for τ-leptons. For charged leptons that exit the Earth, `nuPyProp` generates output lookup tables which contains information on the exit probability, energy distributions, and average polarization of the exiting charged leptons. These output tables can be used as inputs for simulating EASs by packages like ν`SpaceSim`.

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[1] https://github.com/NuSpaceSim/nupyprop

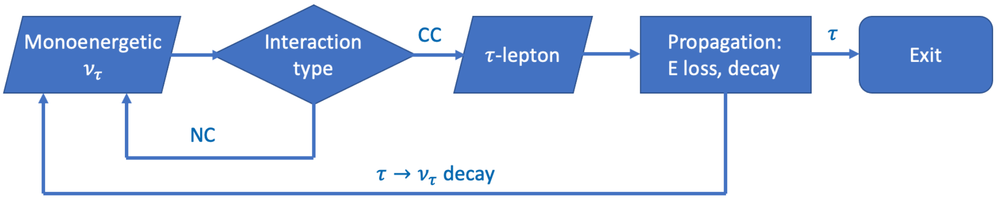

Figure 2: Flowchart explaining the particle propagation in `nuPyProp`. Figure reproduced from ref. [10].

Module	Model/Parametrization/Type
Earth Density	PREM [12]
$\nu/\bar{\nu}$ Cross-Section	`allm` [13, 14], `bdhm` [15], `nct15` [16], `ct18nlo` [17], `ctw` [18]
Lepton Photo-Nuclear interaction	`allm` [13, 19], `bdhm` [15], `ckmt` [20], `bb` [21]
Energy Loss Mechanism	Stochastic, Continuous

Table 1: Input lookup table parameters used in `nuPyProp` for simulating particle propagation through Earth.

The `nuPyProp` code requires millions of neutrinos propagating through the Earth to get good statistics for the output lookup tables. To reduce the computational time, `nuPyProp` does interpolations using the input lookup tables that contain Earth trajectories (based on Earth density), neutrino/anti-neutrino cross-sections and energy distributions, and electromagnetic energy loss interactions and energy distributions. The input lookup tables are made using the models shown in table 1.

3. Results and Discussion

In this section, we compare the results obtained from varying different parameters and models used in `nuPyProp` to get information on the uncertainties arising from different input parameters. We vary: 1) the depth of the water layer around Earth, 2) the Earth density models, and 3) the electromagnetic interaction models. Additionally, we study the effects of τ-lepton depolarization. Furthermore, we also show a comparison between `nuPyProp` and other Earth propagating neutrino codes. The results shown here use default parameters of `nuPyProp` [10], unless otherwise specified.

We show the exit probability of τ-leptons as a function of Earth emergence angles in fig. 3 (left), and we compare PREM Earth density models of water layer depths of 3 km (PREM-3) and the `nuPyProp` default of 4 km (PREM-4) (right). The difference in τ-lepton exit probabilities between the two cases is mainly seen for $\beta_{tr} = 1.7° - 2.3°$. The water-rock interface for 3 km water depth layer is at $\beta_{tr} = 1.76°$, and for 4 km water depth layer is at $\beta_{tr} = 2.03°$. The particles traversing the 3 km water depth layer plus rock undergo more energy losses as they hit the rock layer, than the particles traversing the 4 km water depth layer plus rock, thus the exit probability shows a sharper decrease for smaller β_{tr} for the 3 km water depth case. For $E_\nu = 10^8$ GeV, the difference between the two cases is $\sim$ 10% at the water-rock interface, whereas for $E_\nu = 10^{10}$ GeV, it is about $\sim$ 60%. The shape and approximate magnitude of the ratio of the exit probability is similar to the inverse of

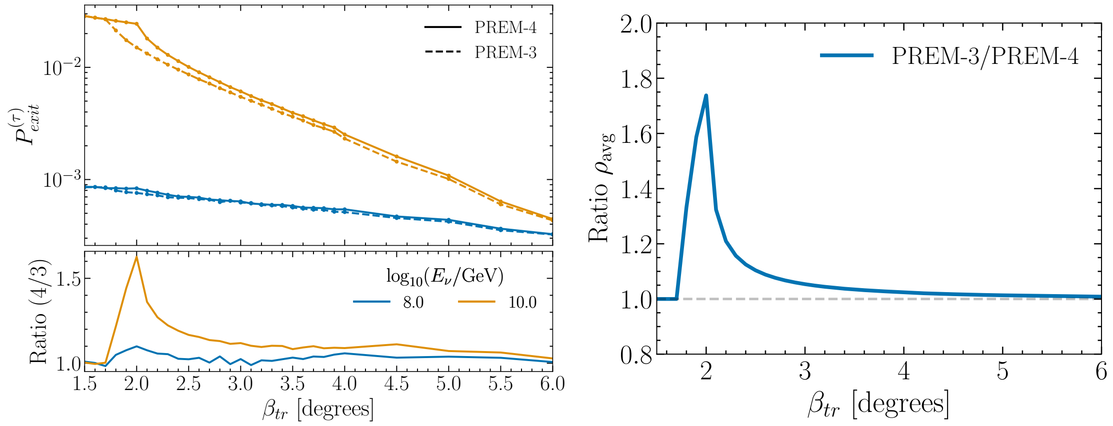

Figure 3: Left: Exit probability of τ-lepton as a function of β_{tr} for PREM model for 3 and 4 km depth of water layer. Right: Ratio of average density of Earth for PREM model with 3 and 4 km water depth. Figure reproduced from ref. [10].

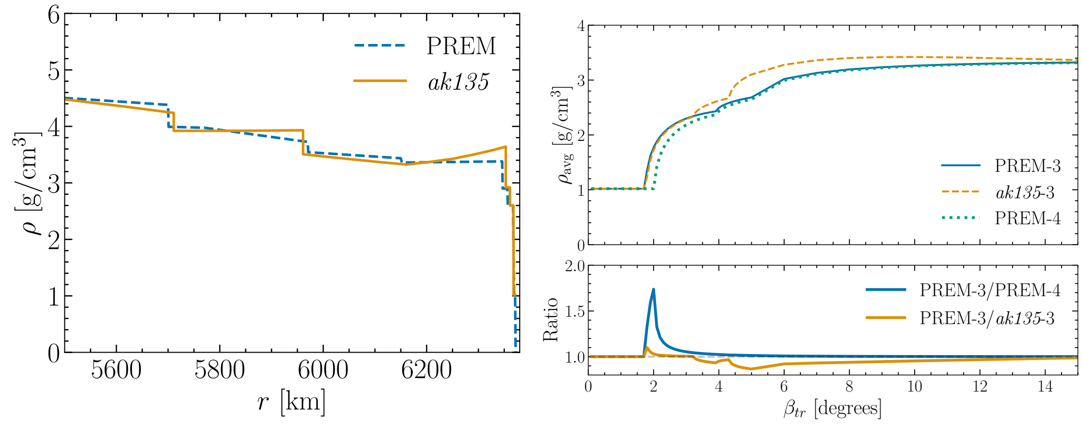

Figure 4: Left: Earth density for PREM and *ak135* model as a function of radial distance from center of Earth (r). Right: Average density of Earth for PREM model with 3 and 4 km depth, and *ak135* model with 3 km depth of water layer. Figure reproduced from ref. [10].

the ratio of average Earth density for PREM model with 3 km and 4 km water depth layer shown in fig. 3 (right).

The Earth's density as a function of radial distance to the center of the Earth is updated in the *ak135* [22] Earth density model, which used an improved analysis of seismic wave data as compared to the PREM model. A comparison between the two models is shown in fig. 4 (left). Comparisons of the average Earth density as a function of β_{tr} for the PREM models with 3 and 4 km water depth layers and the *ak135* model with 3 km water depth layer (labelled *ak135*-3) are shown in fig. 4 (right). The difference in average Earth density between PREM-3 and *ak135*-3 is of order $\sim 10-15\%$. Analogous to the impact of the water depth layer on the exit probability of τ-leptons, different Earth density models have $\sim 10-15\%$ differences on the exit probabilities of τ-leptons. One conclusion is that the main Earth density effect is at the water-rock interface and comes from the depth of the water layer considered.

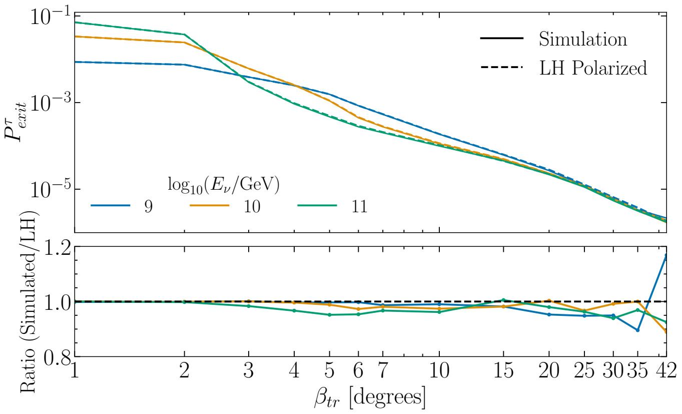

Figure 5: Exit probability of τ-lepton as a function of β_{tr} for simulated (solid) and LH (dashed) polarized case. Figure reproduced from ref. [10].

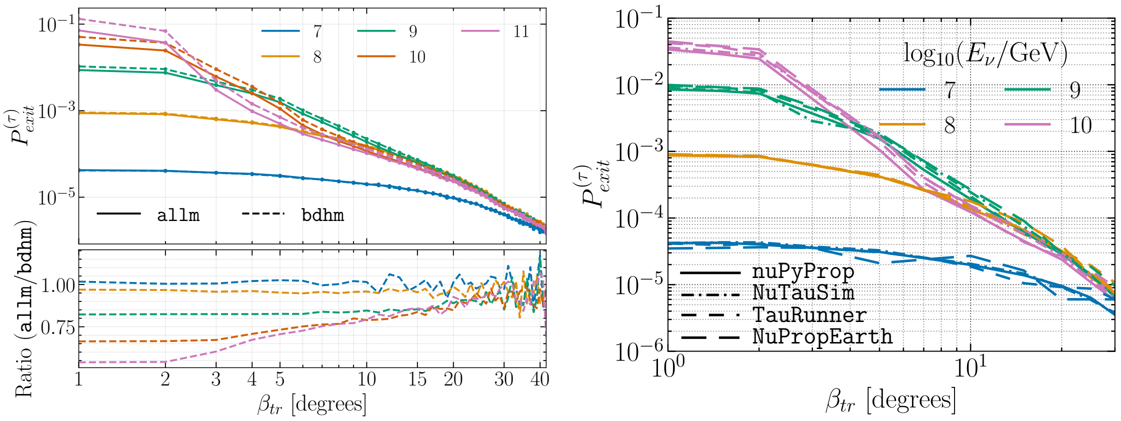

Figure 6: Left: Exit probability of τ-lepton as a function of β_{tr} for `allm` and `bdhm` models for electromagnetic interactions. Right: Exit probability of τ-lepton as a function of β_{tr} for different Monte-Carlo simulation codes. Figure reproduced from ref. [10].

At VHE, the τ-lepton produced from the ν_τ is 100% polarized [23], but with subsequent electromagnetic interactions, the τ-lepton can get depolarized. This is potentially important to study because the polarization value of τ-leptons impacts the regenerated neutrino energy distributions, as described in detail in refs. [10, 23]. The exit probabilities of τ-leptons are shown in fig. 5 for two cases: the simulated case where the depolarization of τ-lepton is considered for every photo-nuclear electromagnetic interaction; and for left-handed (LH) polarized case where the τ-lepton is considered to be LH for all electromagnetic interactions. Depolarization has a $\sim 5\%$ effect for small Earth emergence angles, and a $\sim 10\%$ effect for larger angles. Overall, the depolarization effect on the exit probability of τ-leptons is small.

The τ-lepton electromagnetic energy loss modeling has a larger impact on τ-lepton exit probabilities than any other modeling done in `nuPyProp`. The exit probabilities of τ-leptons as a function of β_{tr} for two different electromagnetic energy loss models, `allm` and `bdhm`, are shown in fig. 6 (left). The lower panel shows the ratio of the exit probabilities for the two models for different initial tau-neutrino energies. For $E_\nu = 10^7$ GeV, the ratio is about unity but it starts decreasing for higher energies. This is because the energy loss parameter for photo-nuclear interaction for `allm` model is bigger than for `bdhm` model as shown in ref. [10], and so the τ-leptons exiting the Earth are fewer under the `allm` evaluation than for `bdhm` evaluation. This accounts for the largest uncertainty in the τ-lepton exit probabilities of about $\sim 20-50\%$ for $E_\nu \geq 10^9$ GeV. It arises from the extrapolations of the F_2 electromagnetic structure function for small-x and large Q^2 region (x is the fraction of nucleon's momentum carried by the struck quark and Q^2 is the momentum carried by the virtual photon in an electromagnetic interaction).

Other Monte-Carlo simulation codes that propagate neutrinos through the Earth include `NuTauSim` [24], `TauRunner` [25], and `NuPropEarth` [26]. A detailed comparison of these codes is in ref. [27]. A comparison of these codes with `nuPyProp` on the exit probability of τ-leptons is shown in fig. 6 (right). There is a good agreement between different codes across various tau-neutrino energies and angles.

As we have shown here, the flexibility and modularity of `nuPyProp` allows users to import different input parameters which makes it easy to make comparisons between them and understand the uncertainties arising from different models.

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