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# NuLeptonSim: A practical use of a neutrino propagation code as an event generator

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To calculate the sensitivity of current and future telescopes to astrophysical neutrinos, it is necessary to understand the key properties (energy, flavor, and probability weight) of both these primary neutrinos and their secondary particles after propagation through the Earth. The properties of these particles are strongly influenced by the various interactions that both neutrinos and their secondaries are subject to, and a full treatment of the propagation is required. Many different computation schemes exist to treat this problem (NuTauSim, TauRunner, and nuPyProp being just a few examples).

In this work, we detail NuLeptonSim, an update to the NuTauSim Monte Carlo neutrino propagation code for high energy tau neutrinos. The improvements included in NuLeptonSim include i) all flavor neutrino modeling ii) Glashow Resonance interactions and iii) compatibility with detector frameworks (arbitrary definitions of detector geometry and particle trajectory, including downwards trajectories). We demonstrate the results from including these effects on the Earth emergence probability of various charged leptons and their corresponding energy distributions. Using NuLeptonSim to model propagation, we calculate the sensitivity of the Askaryan Radio Array (ARA) experiment to cosmic neutrinos. Following this calculation, we also include secondary particle interactions (radiative losses from muons and $\tau$-leptons) to improve the estimate of the sensitivity.

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## 1. Introduction

High energy neutrino astronomy offers a unique window into the most violent astrophysical phenomena in the Universe. Electrically neutral and having extremely small cross sections, neutrinos, even at the highest energies, are capable of traversing extremely large distances from their sources without absorption or magnetic deflection, affected only by the adiabatic expansion of the Universe. However, the same phenomena that makes neutrinos ideal astrophysical candidates also makes them challenging to detect. Gargantuan instrumental masses are necessary to address both the rapidly falling flux of neutrinos over increasing energy and their minuscule interaction probabilities. Many methods have been proposed to address these issues, typically using the Earth and its terrain as the interaction volume. In this work, we focus on detection of neutrino-sourced secondaries using Askaryan emission.

During the development of particle cascades in dense media, a negative charge asymmetry develops through positron annhilation and Compton scattering, allowing for the production of coherent radio emission, called Askaryan radiation. Such cascades can be sourced from neutrino interactions through either neutral-current (where the neutrino deposits energy into secondary particles via a neutral $Z^0$ boson) or charged-current (where the neutrino converts into its corresponding charged lepton and deposits energy into secondary particles via a charged $W$ boson) interactions. In addition, charged leptons produced by the latter process may also lose energy through radiative processes and decays, initiating cascades in each scenario. The attenuation length of Askaryan emission in ice is of kilometer scale, allowing for large instrumental volumes to be reached with a minimal number of antennas.

## 2. ARA

The Askaryan Radio Array (ARA) is a neutrino detector constructed at the South Pole, which is designed to measure the Askaryan emission generated by particles showers in ice, sourced from both primary and regenerated neutrino interactions and interactions of neutrino-sourced charged leptons [1].

Five ARA stations, each station spaced roughly 2 km apart, have been deployed at the South Pole with the two most recent stations (A4 and A5) being deployed in 2017-2018. Each station consists of four strings, each comprised of two vertically polarized antennas and two horizontally polarized antennas near the bottom of the string, which ranges down to depths of 200 m. The antennas are broadband and bandpass-filtered to 150-850 MHz and notch-filtered at 450 MHz. The A5 station has an additional phased array trigger string which lowers the triggering threshold. A diagram depicting the current layout of the 5 deployed ARA stations as well as the layout of a single ARA station is shown in Figure 1.

## 3. `NuLeptonSim`

`NuTauSim` is an open source, C++-based Monte Carlo code which simulates the propagation of $\tau$ neutrinos through the Earth, taking into account neutrino interactions and $\tau$-lepton energy losses

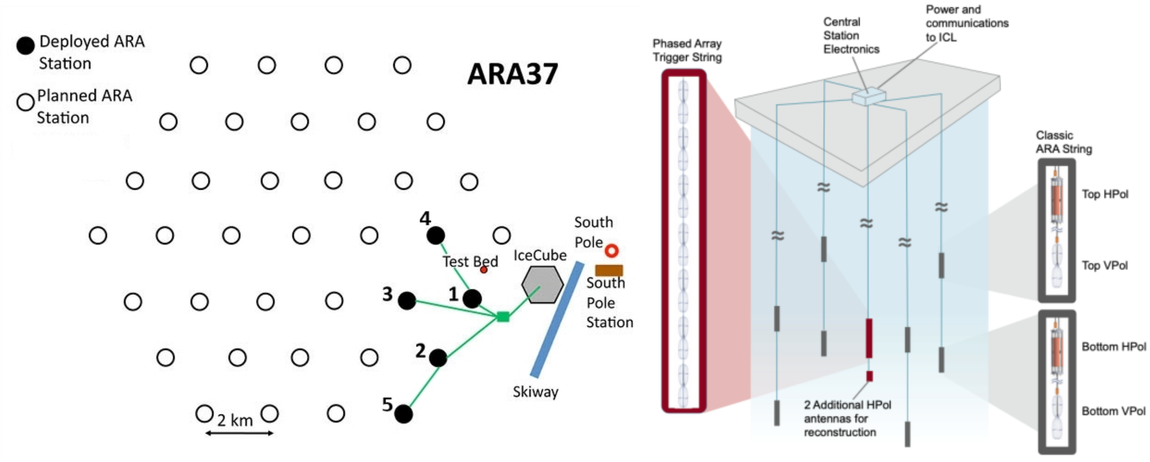


**Figure 1:** Left: locations of deployed ARA stations and future potential deployment sites. Right: diagram of a single ARA station. The centralized phase array trigger string is unique to the A5 station. [2]

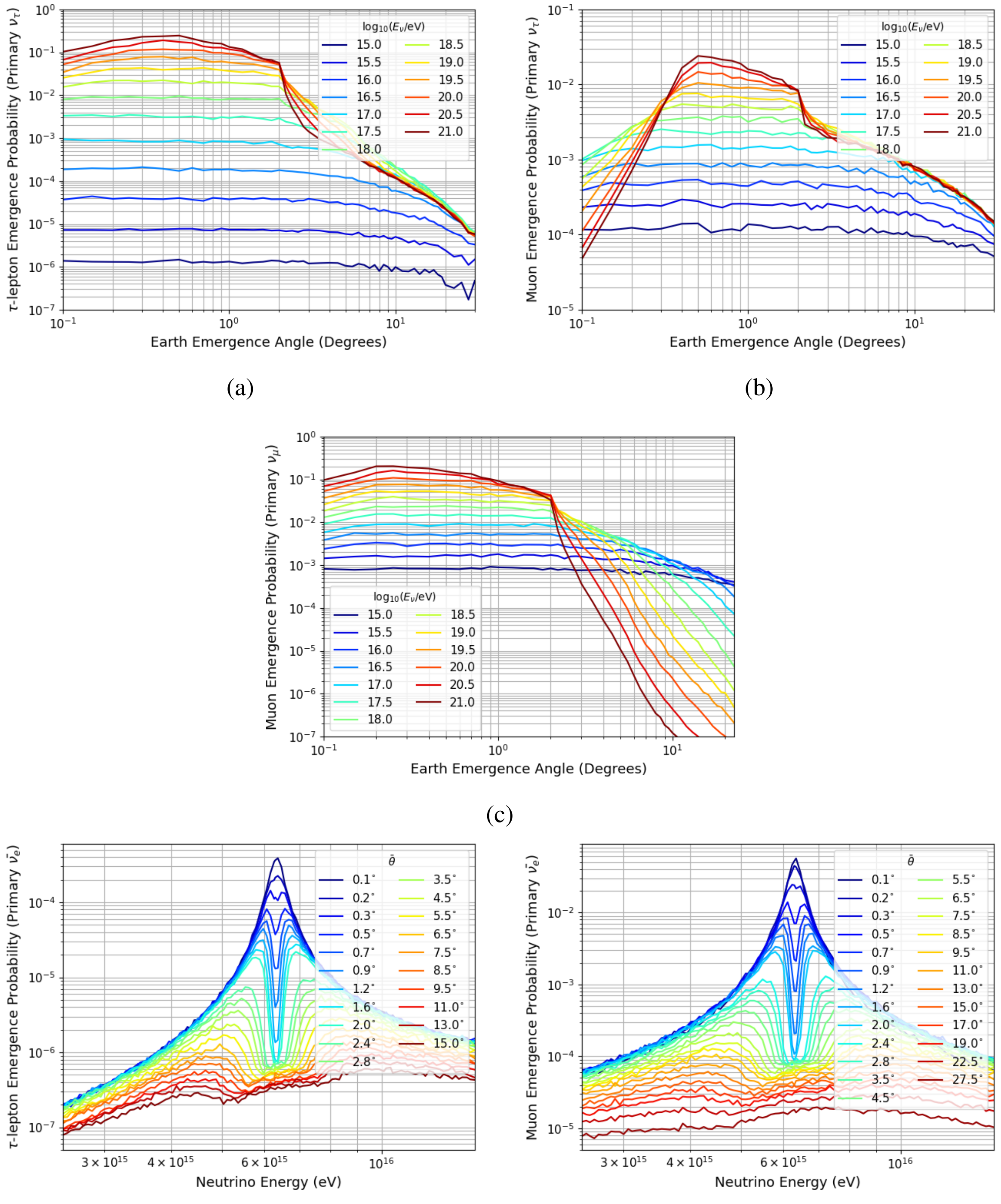
and decay under realistic models of the radial Earth density [3].

`NuLeptonSim` is a substantial upgrade to `NuTauSim` which extends the computation scheme to consider all neutrino (and antineutrino) flavors [4]. The models for charged-current and neutral current interactions used in `NuTauSim` are extended to lower energies to account for muonic processes, and Glashow Resonance is included for propagating $\overline{\nu_e}$. For propagating muons and $\tau$-leptons, `NuLeptonSim` includes options for considering fully stochastic energy losses, taking into account Bremsstrahlung, pair-production, and photonuclear processes. Arbitrary detector geometries are also included in `NuLeptonSim`, allowing for the saving of any interactions or decays within a preset volume, as well as 3-dimensional particle trajectories through the Earth.

Figure 2 shows the potential of the `NuLeptonSim` computation scheme, by illustrating the Earth emergence probability (the probability for a charged lepton to exit the Earth for a single neutrino event) as a function of neutrino energy and Earth emergence angle for different charged lepton/neutrino flavor combinations. The behavior of the given curves is physically well motivated, and specifically for $\tau/\nu_\tau$ and $\mu/\nu_\mu$ combinations, matches well with the results of the `TauRunner` [5] and `nuPyProp` [6] neutrino propagation codes.

## 4. PyREx

PyREx (**Py**thon package for **R**adio **Ex**periments) is a python package developed to simulate and propagate Askaryan emission from neutrino interactions for in-ice antenna arrays. The work was developed by the ARA collaboration but is broadly applicable to a wide array of in-ice radio experiments (ARIANNA, RNO, IceCube Gen2). PyREx takes, as input, arbitrary layouts of antennas and calculates the Askaryan emission from neutrino interactions (given their position, energy, direction, and type) via the model given by Alvarez-Muñiz, Romero-Wolf, and Zas [7]. To accurately model Askaryan radiation in ARA, Pyrex simulates antenna responses using models



(a) (b)

(c)

(d) (e)

**Figure 2:** Earth emergence probability of charged leptons from primary neutrinos as a function of neutrino energy and Earth emergence angle (angle with respect to ground), calculated with the `NuLeptonSim` Monte Carlo framework. (a) and (b) represent, respectively, $\tau$-leptons and muons sourced from primary tau neutrinos, while (c) shows that of muons sourced from primary muon neutrinos. (d) and (e) correspond, respectively, to $\tau$-leptons and muons sourced from electron anti-neutrinos, and demonstrate Glashow Resonance.

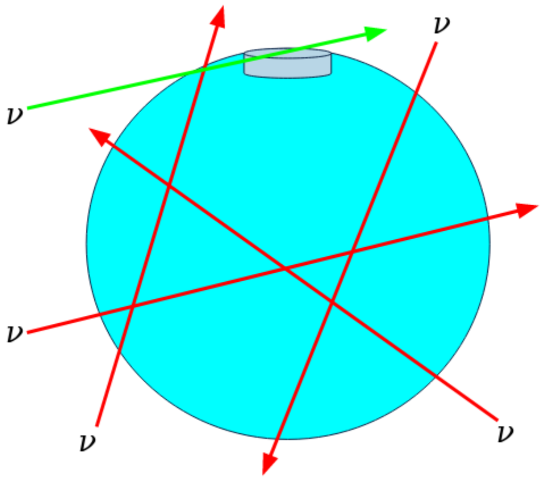


**Figure 3:** Diagram of isotropic trajectory generation for neutrino acceptance calculations, where red and green lines correspond respectively to trajectories which are rejected and accepted.

borrowed from the ARA Collaboration's main simulation framework, `AraSim`, and passes the estimated voltage response through a trigger diode. After passing the signal through the tunnel diode, the trigger threshold is evaluated.

## 5. Calculation of ARA Acceptance

Trajectories of potential events are generated by isotropically sampling both an entrance and exit position on the Earth's surface and drawing a line between them. If the line is determined to pass through a large cylindrical volume centered on the ARA detector, the start and end coordinates are recorded. As the attenuation length of radio emission in ice is of kilometer scale, in practice, the selected volume should be substantially larger than the instrumental volume, so as to allow for distant interactions which may still trigger. In the case of this computation, we consider a cylindrical volume with radius 15 km and depth of 2.8 km.

When a satisfactory number of usable trajectories has been thrown, they are passed to the NuLeptonSim propagation code. For the results presented here, the number of unique trajectories accepted is 100,000. A diagram of the trajectory generation is shown in Figure 3, illustrating which trajectories are rejected (red) and accepted (green).

Neutrinos are propagated using the `NuLeptonSim` computation scheme along the trajectories guaranteed to pass through the cylindrical volume. Any interactions that occur inside the volume with an energy deposit larger than a preset threshold are recorded. In the case of this calculation, we take a conservative value for deposition threshold of 10 PeV. Potential interactions include: charged-current, neutral-current, and Glashow Resonance interactions of neutrinos as well as radiative losses (via Bremsstrahlung emission, electron-positron pair production, and photonuclear interactions) and decays of propagating charged leptons. Multiple interactions along a trajectory are identified via trajectory number identifiers. For each interaction, the interaction type, deposition

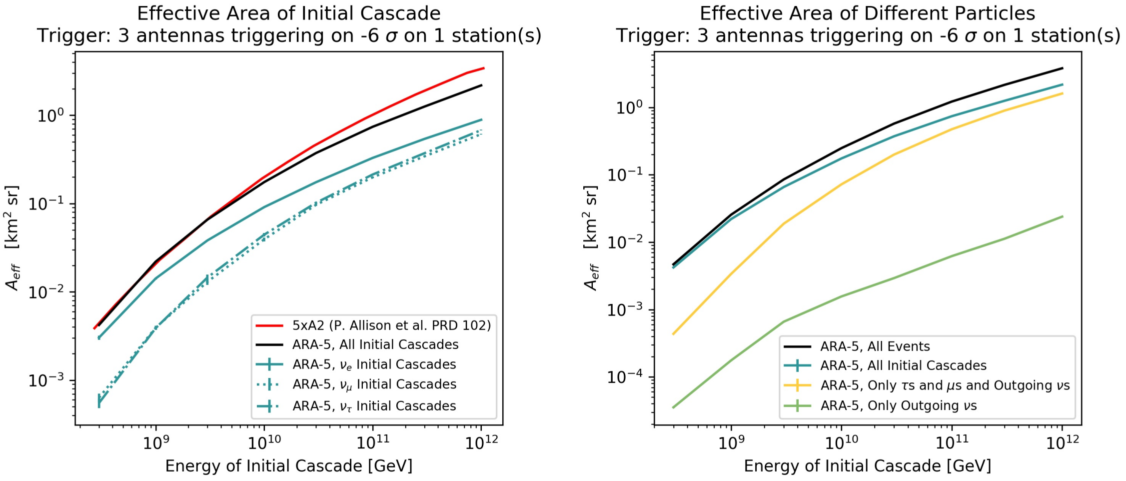


**Figure 4:** Left Panel: Simulated ARA-5 effective area to primary neutrino interactions, calculated using `NuLeptonSim` as an event generator, and PyREx as a signal propagator and detector response simulator. Also shown in red is the effective area of the A2 antenna station scaled by a factor of 5 for comparison [8]. Right Panel: Simulated ARA-5 effective area to primary neutrino interactions and secondaries.

location and direction, and deposited energy are recorded and passed to the PyREx radio generation and detector response modeling code. To increase statistics, between 1,000 and 10,000 primary neutrinos are simulated for each unique trajectory, depending on flavor and energy.

Askaryan radiation from in-ice showers is calculated and propagated to the ARA-5 antenna layout (that of the deployed ARA stations shown in Figure 1) using the PyREx simulation code, which then models the detector response. It is sufficient to model the in-ice showers as generated either by a $\gamma$ or proton primary as all modeled interactions result in emitted $\gamma$'s, electrons, or hadrons. A detection is considered for 3 triggered antennas observing signals $6\sigma$ above background.

## 6. Results

The simulated effective area of ARA-5 to neutrino induced cascades (no triggers on charged leptons) using the `NuLeptonSim` and PyREx computation schemes is shown in the left panel of Figure 4, separated by primary neutrino flavor. Also shown is the simulated effective area of the A2 antenna station scaled by a factor of 5 for a rough estimate of the ARA-5 effective area [8].

The effective area of the A2 antenna station shown in the left panel of Figure 4 was calculated assuming the neutrino cross sections and inelasticity distributions of [9] and also includes the full signal chain and a realistic model of the antennas. This is in contrast to the calculation performed in this work, where the `NuLeptonSim` formalism uses the parameterization of [10] to model the neutrino inelasticity and only considers a simple threshold based trigger. Despite this, the two methods agree remarkably well, particularly at low energies, suggesting the robustness of this simulation pipeline. At $10^{21}$ eV, the curves presented here are smaller than the scaled A2 effective area by $\sim$ 35%, which can largely be explained by coincidence rates between antenna stations as the intensity of emission is able to compete with in-ice attenuation. While a full analysis of the effect is outside the scope of this work, we have estimated the rate of coincidence of primary neutrino interactions within ARA-5 to be $\sim$ 30% at $10^{21}$ eV. A future study of event topology will be carried out following the results of this work.

The simulated effective area of ARA-5 to an all-flavor neutrino flux (both neutrino induced cascades and secondary particles) is shown in the right panel of Figure 4. The curve labeled "All Initial Cascades" corresponds to events which triggered on the initial neutrino cascade, even if a corresponding charged lepton or regenerated neutrino also triggered. This is in contrast to the other two curves, which correspond to charged leptons and regenerated $\nu_\tau$ triggering without a trigger on the primary neutrino. By including secondary particles, the effective area of the ARA-5 detector is increased by nearly a factor of 2 at the highest energies. The major contribution to this increase in effective area comes from radiative losses (and to a lesser extent, decays) of propagating charged leptons, with regenerated neutrino interactions comprising less than $\sim$ 1% of triggered vertices. This is in close agreement with the work of [11], which has considered detection of secondary particles for arbitrary in-ice radio detectors. No sensitivity to Glashow Resonance events is demonstrated, due to the minuscule cross sections at the $> 10^{17}$ eV energies required for detection.

In addition to improving the overall effective area by increasing the number of triggered events over primary neutrino interactions, the radiative losses of charged leptons also allow for events with multiple triggers, which become more probable with increasing energy, becoming the dominant channel of observation above primary neutrino energies of $10^{20}$ eV. The topology of such events provides improved trigger capabilities (lowering the effective SNR threshold for detection), reconstruction methods, and flavor discrimination. A full study of multi-track events is beyond the scope of this work, but will be analyzed in a follow-up study of the event topology described here.

## 7. Summary

In this work, we have developed a robust simulation pipeline to model the sensitivity of the ARA-5 experiment to cosmic neutrinos. To accomplish this task, we have simulated monoenergetic, isotropic, all-flavor fluxes of neutrinos, and propagated them through the Earth using the 3-Dimensional `NuLeptonSim` Monte Carlo neutrino propagator, saving all interactions that occur within a large volume that encapsulates the ARA-5 detector, including radiative losses of propagating charged leptons and interactions of regenerated $\nu_\tau$. We have then generated and propagated the Askaryan emission sourced from these interactions to the various antenna stations of ARA-5 with the PyREx package and, using a reasonable threshold based trigger, calculated an acceptance.

The results of this study are in agreement with the scaled effective area of the A2 antenna station to primary neutrino interactions calculated in [8], with the results presented here being $\sim$ 35% smaller at $10^{21}$ eV which is consistent with coincidence rates at the same energy. In addition, the studies presented here illustrate the importance of considering secondary particle interactions in the ARA detection scheme, an effect which becomes more dominant with increasing energy, and improves the effective area by nearly a factor of 2 over only neutrino interactions at the highest energies. This is in agreement with secondary sensitivity calculations of generic in-ice radio experiments [11]. We also show that regenerated neutrino interactions provide a small improvement to the effective area of ARA-5, comprising close to $\sim 1\%$ of triggered events.

The topology of secondary particle interactions is of significant interest, particularly in terms of improving trigger efficiency, event reconstruction, and flavor identification. A future study of the properties of secondary events will follow this work and investigate these improvements in greater detail, focusing on analysis of multi-track behavior within the ARA experiment.

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