Ultra-High Energy Astrophysical Neutrino Detection, and the
Search for Lorentz-Invariance Violations

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A growing class of ultra-high energy neutrino observatories based on the
Askaryan effect and Antarctic ice is able to search for Lorentz-invariance vi-
olation. The ARA, ARIANNA, ANITA, and EVA collaborations have the
power to constrain the Standard-Model Extension by measuring the flux and
energy distribution of neutrinos created through the GZK process. The future
expansion of ARA, at the South Pole, pushes the discovery potential further.

1. The GZK Process and EeV neutrinos at the Earth

Ultra-high energy neutrino (UHE-ν) observations are a long-desired
achievement in astroparticle physics. Clues about cosmic ray origins and
potential electroweak interaction measurements from $10^{16}-10^{19}$ eV are con-
tained within this flux. PeV-scale neutrino observations in IceCube\textsuperscript{2,3}
have made possible learning about UHE-ν physics from beyond the so-
lar system. A UHE-ν could be produced via the GZK process, given the
UHE-p\textsuperscript{+} spectral cutoff at $10^{19.5}$ eV.\textsuperscript{4} The next generation of UHE-ν detec-
tors is designed around the Askaryan effect, which produces radiated
radiofrequency power.\textsuperscript{5–8} Antarctic ice provides a convenient medium for
Askaryan radiation.\textsuperscript{9} The RICE collaboration\textsuperscript{12} began the field, and efforts
such as ANITA, ARA, ARIANNA, and proposed EVA\textsuperscript{13,14,16,17} have made
progress in developing sensitivity to UHE-ν fluxes.

There is a connection between Lorentz-invariance violation (LIV) and
UHE-ν, through flux limits, via the Standard-Model Extension (SME).\textsuperscript{18}
The SME includes LIV terms of varying dimension, proportional to small
coefficients. LIV in the neutrino sector could modify the UHE-ν spectrum
at Earth by introducing vacuum energy loss.\textsuperscript{19} The UHE-ν detectors can
place constraints on SME coefficients.
2. Experimental detection efforts

The Antarctic Impulse Transient Antenna (ANITA) is a balloon-borne detector with radiofrequency (RF) antennas as payload. ANITA-1 flew in 2007-2008 with 32 separate RF channels, modified in subsequent seasons (40 channels for ANITA-2 and 48 for ANITA-3). ANITA detects man-made noise, thermal noise, and RF pulses from UHE-\(p^+\). ANITA has a UHE-\(\nu\) threshold \(E_{th} \approx 10\) EeV, limited by RF propagation to the payload (\(\approx 35\) km). The balloon altitude allows the detector to observe instantaneously \(V_{eff}\Omega \approx 100\) km\(^3\) str of ice at 10 EeV (the effective volume times the viewable solid angle)\(^{13}\).

The Askaryan Radio Array (ARA) is an \textit{in situ} array of RF detectors at the South Pole.\(^{14}\) Three detectors are deployed, using AC power from the Amundsen-Scott base. \textit{In situ} detectors lower \(E_{th}\) by being \(\approx 1\) km from typical events. For example, ARA is projected to have \(V_{eff}\Omega \approx 1000\) km\(^3\) str at 10 EeV, and 100 km\(^3\) str at 0.1 EeV\(^{14,15}\). With an analysis using 2 of 37 planned stations, ARA is already competitive with ANITA below \(E_\nu \approx 10\) EeV and with the IceCube high-energy analysis above \(E_\nu \approx 100\) EeV. ARA is projected to detect \(\approx 100\) GZK neutrinos in 3 years.\(^{1,14}\)

The Antarctic Ross Ice Shelf Antenna Neutrino Array (ARIANNA) is another \textit{in situ} detector, located on the Ross Ice Shelf.\(^{16}\) The Hexagonal Radio Array (HRA) is the seven-station prototype. The ocean/ice boundary provides a mirror for RF signal collection, boosting effective volume through increased visible solid angle.\(^9\) Extensive air showers have been observed\(^{10}\), and final UHE-\(\nu\) sensitivity is projected to be equal to ARA. The final array design requires a \(31 \times 31\) station array, with stations separated by 1 km, from in-ice attenuation length measurements.\(^{11}\)

The ExaVolt Antenna (EVA) is a proposed balloon-borne detector with a boosted RF effective area.\(^{17}\) The balloon itself is the antenna, and technological improvements in balloon design are expected to boost flight durations. The EVA project is currently in the proposal stage.

3. LIV tests in the Askaryan-based neutrino experiments

The SME allows for UHE-\(\nu\) energy loss while propagating in a vacuum.\(^{19}\) One example is the vacuum Chernokov effect: \(\nu \rightarrow \nu e^+e^-\). UHE-\(\nu\) with relatively higher energies disappear, and an abundance of lower-energy UHE-\(\nu\) appears. The energy loss may be treated like a decay with half life \(\tau_\nu\) given by
\[ \frac{\tau_{\nu}}{s} = \tau_{CG} \left( \frac{E_{\nu}}{\text{GeV}} \right)^{-5} \frac{1}{\alpha_{\nu}}, \]  

(1)

with \( \tau_{CG} = 6.5 \times 10^{-11} \text{s} \), and \( \alpha_{\nu} \) being the constrained SME parameter.

Attributing the nonobservation of a GZK flux to LIV, one can place \textit{lower limits} on \( \alpha_{\nu} \).\textsuperscript{19} Figure 1 demonstrates the LIV modification\textsuperscript{14,19} to a UHE-\( \nu \) flux by a non-zero value of \( \alpha_{\nu} \). Observation of one UHE-\( \nu \) places \textit{upper limits} on \( \alpha_{\nu} \) lower than those from atmospheric neutrinos, due to the energies and cosmological distances of GZK models. SME constraints will therefore be improved by enhanced ARA volume and the low-energy enhancement near \( 10^{17} \text{eV} \).

![Graph](https://via.placeholder.com/150)

**Fig. 1.** The GZK-neutrino flux \( F(E) \) times the energy \( E_{\nu} \), vs. \( E_{\nu} \), are shown as the thick gray lines, with \( \alpha_{\nu} = 0 \), \( \log_{10}(\alpha_{\nu}) = -27 \), and \( \log_{10}(\alpha_{\nu}) = -24 \). The current ARIANNA (HRA-3), ARA02/ARA03, and projected ARA-37 upper limits are shown as squares, circles, and the thin black line, respectively. The UHE-\( \nu \) spectra are adapted from Gorham \textit{et al.} \textsuperscript{19}
4. Future work

This flavor blind UHE-ν LIV scenario could be pushed further by at least two ideas. First, the charged leptons should cascade on the CMB/IR backgrounds, producing diffuse γ-rays. Combining Fermi-LAT diffuse γ-ray observations and nonobservation of UHE-ν would lead to a restricted range for αν. Secondly, non-renormalizable, higher-dimensional SME operators also generate UHE-ν energy-loss, and the effect should increase dramatically with increasing energy, making UHE-ν an ideal messenger. Recomputing the effective αν from these operators would produce the first limits on those SME coefficients. The effect should increase with energy, making UHE-ν analysis ideal.

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