Fundamental Physics with Askaryan Arrays

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Outline

• Introduction to radio Cerenkov technique and experiments
• Cross-sections
• Lorentz Invariance Violation
• UHE Astrophysics
• Conclusions

See tomorrow’s talk by Abby Vieregg for more details on neutrino searches
Introduction to radio Cerenkov technique and experiments
Motivations for ultra-high energy (UHE) neutrinos (>10^{18} eV)

1. **Expect UHE neutrinos from GZK (Greisen-Zatsepin-Kuzmin) process:** Cosmic rays >10^{19.5} eV slowed by cosmic microwave background (CMB) photons within ~50 Mpc:

   \[ p + \gamma_{\text{CMB}} \rightarrow \Delta^* \rightarrow n + \pi^+ \]

   *ν’s from GZK process first pointed out by Berezinsky and Zatsepin (1969)*

   \[ n \rightarrow p + e^- + (\bar{\nu}_e) \]

   \[ \pi^+ \rightarrow \mu^+ (\nu_\mu) \]

   \[ \mu^+ \rightarrow e^+ (\bar{\nu}_\mu \nu_e) \]

2. **Expect UHE neutrinos from UHECR sources:** should produce UHE neutrinos through γ-hadronic interactions
Detection Techniques

- $<10^{18}$ eV: optical dominates current constraints
- $>10^{18}$ eV: radio dominates
  - Radio thresholds dropping with experiments coming online
Radio Cerenkov Technique (Askaryan Effect)

- Coherent Cerenkov signal from net “current,” instead of from individual tracks
- A ~20% charge asymmetry develops (mainly Compton scattering)
- Excess moving with v > c/n in matter
  \[ \text{→ Cherenkov Radiation } dP \propto v \, dv \]
- If \( \lambda > R_{\text{Moliere}} \) → Coherent Emission
  \[ P \sim N^2 \sim E^2 \]
- If \( \lambda > R_{\text{Moliere}} \) → Radio/Microwave Emission

This effect has been confirmed experimentally in sand, salt, ice:
- PRL 86, 2802 (2002)
- PRD 72, 023002 (2005)
- PRD 74, 043002 (2006)

\[ R_{\text{Moliere}} \approx 10 \text{ cm}, L \sim \text{meters} \rightarrow \text{Radio!} \]
Antarctic Ice

Ice thicknesses are typically 2 km depths across the continent.

Radio Attenuation Lengths

South Pole Ice

2 km depths are typical across the continent.
Balloon Experiments

**ANITA**

- ANITA antenna array
- \(~37 \text{ km}\)
- Antarctic ice sheet
- \(1 - 4 \text{ km}\)

**Exavolt Antenna (EVA)**

- Neutrino signal V-pol

**Long duration balloon program operated by NASA**

- **ANITA 1:** 2006-2007
- **ANITA 2:** 2008-2009
- **ANITA 3:** 2014-2015

3 year NASA grant for engineering phase
Askaryan Radio Array (ARA)

University of Wisconsin, Ohio State University and CCAPP, University of Maryland and IceCube Research Center, University of Kansas and Instrumentation Design Laboratory, University of Bonn, National Taiwan University, University College London, University of Hawaii, Universite Libre de Bruxelles, Chiba Univ., Univ. of Wuppertal, Chiba Univ., Univ. of Delaware

- Radio array at the South Pole
  - Testbed station,
  - Stations 1,2&3 deployed last 3 seasons
- Phase 1: 37 stations ~100 km²
  - Establish flux
- Phase 2: ~1000 km²
  - High statistics astronomy/particle physics exploitation

NSF has funded Testbed+3 Stations. Pending approval for next phase
ARIANNA

• Radio array on Ross Ice Shelf
  http://arianna.ps.uci.edu

• On track for completing 7 station array in Dec. 2013

• Propose 960 station array

US
Sweden
New Zealand
Cross sections
Why are $\nu N$ cross sections interesting?

- Center of mass (COM) of UHE neutrino interactions with nuclei well exceed LHC energies
  
  - $\sqrt{s}=\sqrt{2M_N E_\nu}$, $E_\nu=10^{18}$ eV $\rightarrow \sqrt{s}=45$ TeV!

- Predictions of SM $\nu N$ cross section ($\sigma$) at high energies rely on measurements of quark, anti-quark number densities at low $x$ (parton momentum fraction) inaccessible with accelerators
  
  - $E_\nu > 10^{17}$ eV $\rightarrow x \lesssim 10^{-5}$
  
  - HERA measures $x \gtrsim 10^{-4} - 10^{-5}$

- $\nu N \sigma$’s at all energies needed to model experiments
Once an UHE ν sample is measured:

- The distribution of ν zenith angles $\theta_z$ would be sensitive to νN cross sections

- For $E_{\nu} = 10^{18} \text{ eV}$, $E_{CM} = 45 \text{ TeV}$!
Enhanced Cross Sections

- Models with extra space-time dimensions lead to enhanced νN cross sections due to micro-black hole production


- These would modify the $\theta_z$ distributions from the Standard Model (SM) expectation

- $N_D$ = # extra dimensions, $M_D$ = reduced Planck scale, $x_{\text{min}} = M_{\text{BH}}^{\text{min}} / M_D$
**Expected Constraints**

- Black bands: systematic uncertainty on SM cross sections
- Gray bands: statistical uncertainties
- On average, with 100 events, expect to exclude:
  - $x_{min} = 1, M_D = 1, N_D \geq 2$
  - $x_{min} = 3, M_D = 1, N_D \geq 3$
  - $x_{min} = 1, M_D = 2, N_D \geq 3$

- $x_{min} = 3, M_D = 2, N_D = 7$ excluded with 110 events

Most of these already excluded by the LHC. BUT unique opportunity to probe the theory w/ UHE neutrinos
Lorentz Invariance Violation
Lorentz Invariance Violation, Really?

- Neutrinos are the only particles we can see from cosmic distances at the highest energies observed. It is natural that we should use them to test LIV.


- It has been proposed that the photon could be a Goldstone boson arising from LIV, R. Bluhm and V.A. Kostelecký, Spontaneous Lorentz Violation, Nambu-Goldstone Modes, and Gravity, Phys. Rev. D 71, 065008 (2005), Bjorken (1963).

- It has been proposed that the graviton could be a Goldstone boson arising from LIV, V.A. Kostelecký and R. Potting, Gravity from Spontaneous Lorentz Violation, Phys. Rev. D 79, 065018 (2009).

- It is possible that both the photon and graviton are both simultaneously Goldstone bosons from LIV.
Lorentz Invariance Violation (LIV)

• If neutrinos can exceed speed of light then can “brem”
  - $\nu \rightarrow \nu' e^+ e^-$ (Coleman and Glashow)
  - Neutrino loses $\sim 3/4$ of its energy

• Effectively a “decay” with time constant:
  $$\tau_\nu = \tau_{CG} E_{\nu,GeV}^{-5} \alpha_\nu^{-3} \text{ s}$$
  with $\tau_{CG}=6.5 \times 10^{-11}$ s
  - $\alpha_\nu$ is a measure of level of LIV $E_\nu=p_\nu c(1+\alpha_\nu)$

• Over cosmic distances, neutrinos above an energy will all brem, show up at lower energies

Lorentz Invariance Violation (LIV)


Attenuation vs. redshift

Observed neutrino spectra, adapting CRPropa outputs

Different energies, same $\alpha_\nu = 8 \times 10^{-26}$

Different values of $\log_{10} \alpha_\nu$
ANITA Results

- Set lower limit on LIV parameter $\alpha_v$ assuming LIV was the reason for the models evading detection

<table>
<thead>
<tr>
<th>Model &amp; references</th>
<th>ANITA/RICE predicted $N$</th>
<th>lower limit on LIV</th>
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<tbody>
<tr>
<td>Barger et al. 2006 [27]</td>
<td></td>
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<tr>
<td>ANITA-II</td>
<td>3.5</td>
<td>$2 \times 10^{-27}$</td>
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<td>RICE2011</td>
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<td>$2 \times 10^{-25}$</td>
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<td>Berezinsky 2005 [33]</td>
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<tr>
<td>Kalashev et al. 2002 [34]</td>
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<td>RICE2011</td>
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All the experimental results searching for violations of Lorentz invariance (Data Tables for Lorentz and CPT violation) published in Rev. Mod. Phys. 83:11 (2011); the annually updated version can be found here arXiv:0801.0287.

UHE Astrophysics
Neutrinos are Unique Probes of UHE Astrophysics

- **Will be only particles** \(>10^{19.5} \text{ eV from } \gtrsim 100 \text{ Mpc} \)

Plots made with the help of CRPropa 2.0

\(E^{-1}\) spectrum, flat redshift evolution
Neutrinos: Only Probes of Ultimate Cosmic Acceleration Energy

• Highest energy cosmic rays are all local - not cosmic probes

\[ E_{\text{max}} = 10^{21.5} \quad 10^{22.5} \]

A. Connolly, S. Horiuchi, N. Griffith, paper in preparation
Summary

• Although radio Cerenkov experiments built as single purpose detectors for UHE neutrinos, variety of fundamental physics results:
  - LIV
  - did not have time to discuss magnetic monopoles, quark nuggets
• once UHE neutrinos are observed, will be unique laboratories for
  - particle physics at super-LHC energies (cross sections)
  - unique view of UHE universe at cosmic distances
Backup Slides
CMS constraints for reference

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
vN Cross Section calculations

Weaker low-x dependence gives lower cross sections at high energies.


A. Connolly, R. Thorne and D. Waters (2011)

Cooper-Sarkar, Mertsch and Sarkar (2011)

M. Block, L. Durand, P. Ha, D. McKay (2013)