The Future of Ultra-high Energy (GZK) Neutrino Searches

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Harvard CfA
31 July 2013
Neutrinos: The Ideal UHE Messenger

- Photons lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei suffer curvature induced by B fields
- But: we know there are sources up to $10^{20}$ eV!!

UHE Cosmic Ray Flux

- Highest energy observation of extragalactic sources
- Very distant sources
- Deep into opaque sources

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Neutrino Production: The GZK Process

GZK process: Cosmic ray protons (E > 10^{19.5} eV) interact with CMB photons

\[ p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

Discover the origin of high energy cosmic rays through neutrinos?

= Neutrino Beam!
Possible Mechanisms for Detection

Bright, broadband radio emission: the Askaryan Effect
- EM shower in dielectric (ice) → moving negative charge excess
- Coherent radio Cherenkov radiation ($P \sim E^2$) if $\lambda >$ Moliere radius

Typical Dimensions:
- $L \sim 10$ m
- $R_{\text{moliere}} \sim 10$ cm

Other detection techniques:
- Optical Cherenkov emission
- Acoustic signal
Models & Current Constraints

- Best current limits:
  - ANITA at highest energies (>10^{19} eV)
  - IceCube at lower energies (<10^{18} eV)
- Starting to constrain some models (source evolution and cosmic ray composition)
- How do we get a factor of ~100 to dig into the interesting region and make a real UHE neutrino observatory?
- Why bother? Not a fishing expedition! There is a floor on the expectation (unlike some other search experiments)
ANITA-I & ANITA-II: Best Limit > $10^{19}$ eV

NASA Long Duration Balloon, launched from Antarctica
ANITA-I: 35 day flight 2006-07
ANITA-I: 30 day flight 2008-09

Instrument Overview:

- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas
- In-flight calibration from ground
- Threshold limited by thermal noise

UHE Neutrino Search Results:

<table>
<thead>
<tr>
<th></th>
<th>ANITA-I</th>
<th>ANITA-II</th>
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<tbody>
<tr>
<td>Neutrino Candidate Events</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Expected Background</td>
<td>1.1</td>
<td>0.97 +/- 0.42</td>
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</tbody>
</table>
• ~1-10 GZK neutrinos/km²/year
• $L_{\text{int}} \sim 300$ km → ~0.01 neutrinos/km³/year
• Need a huge (>> 100 km³), radio-transparent detector
• 3 media: salt, sand, and ice
• Long radio attenuation lengths in south pole ice
  – 1 km for RF (vs. ~100 m for optical signals used by IceCube)
→ Antarctic ice is good for radio detection of UHE neutrinos!

- Flight scheduled for 2014
- More antennas
- Digitize longer traces
- New: interferometric trigger
- Lower noise front-end RF system

→ Factor of 5 improvement in neutrino sensitivity compared to ANITA-II
Beyond ANITA: Going to the Ground

Why go to the ground?
- Much more livetime
- Understandable man-made background
- Lower energy threshold
- Use more antennas than on a balloon
- But: smaller instrumented volume
ARIANNA

• Idea: Ground-based array of antennas on the surface of the Ross Ice Shelf
• Currently: 4 stations operating well, 3 more coming in December
• Plan: future proposal for many more stations
• Attempting to use wind power: very promising but the kinks have not all been worked out

ARIANNA Coll. See arXiv:1207.3846
ARIANNA Data from 3 Months of Station 3

- Dec 15 2012 - Mar 15 2013
- 552473 events collected at 5 sigma thresholds on each channel
- Cuts to data before this plot was made:
  - Too much power below highpass
  - CW power (peaks in frequency domain)
  - Time-domain waveform shape
- Complete separation (for this sample) of background events from the signal region
- No directional reconstruction used yet

From ARIANNA ICRC Talk – S. Barwick
ARA: Askaryan Radio Array

- Idea: 37-station array of antennas buried 200m below the surface at the South Pole
- Currently: 3 stations + testbed deployed and working
- Plan: 3 more stations this year, propose pending for next stage of deployment

ARA Calibration Pulser Event Reconstruction

- Underice pulsers @ 1 Hz
- Really useful: trigger efficiency, event timing
- Cross-correlate waveforms from different antennas to find system delays

- Alive and triggering
- Nice event reconstruction!
- Exercises analysis code

ARA Testbed Data Analysis

- 20 Feb 2012 – 30 Jun 2012, look at 10% sample
- Two independent blind analyses
- Cut-based analysis:
  - Impulsiveness cut ($V_{\text{peak}}/V_{\text{rms}}$)
  - Directionality cuts
  - CW cut

Analysis Efficiency: $10^{17.5}$ eV neutrinos
Summit Station Greenland

- 3 km thick ice at Summit Station
- Measurements by glaciologists (Paden et al.) suggest as good radio properties as the best Antarctic ice
- Radio quiet site (small station)?
- Logistical advantages: longer season, easier deployment

→ Site characterization visit June 2013 – directly measure radio properties (ground bounce and borehole). Results forthcoming and promising.
→ Next: Prototype station ready by summer 2014?
EVA: ExaVolt Antenna

- Idea: Turn an entire NASA super pressure balloon into the antenna
- Currently: 3 year NASA grant for developing 1/5 scale engineering test, full RF + float test summer 2014
- Full Balloon: similar sensitivity to full, 3-year ARA, and ARIANNA

→ Feed design: dual-polarization, broadband, sinuous antennas on inner membrane

[Image: Gorham et al. (2011)]
EVA Scale Model Test Results

- Microwave scale model testbed
- 1/35 and 1/26 scale models
- Measured directivity ~22dB

Gorham et al. (2011)
Other Ways of Seeing UHE Neutrinos

- Auger: Earth-skimming neutrinos and deep downgoing showers

- SKA: sensitivity to neutrinos interacting in the lunar regolith

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• Best current limit <10^{19} \text{ eV}
• IceCube prospects: a factor of a couple more?
Projected UHE Neutrino Sensitivity

What the sensitivity of a next-generation UHE neutrino detector looks like:

→ With tens of events per year, we’ll have a real high-energy neutrino observatory for particle physics and astrophysics
• It is an exciting time in the search for UHE neutrinos!
• Probing lots of fundamental particle physics and astrophysics
• Radio technique has been proven, current results constrain models
• ANITA-III 2014, IceCube ongoing
• Large forward-looking efforts in initial stages: ARIANNA, ARA, EVA
• In 5-10 years, we hope to have a real UHE neutrino observatory and to observe for many years