Radio Detection of Ultra-high Energy Neutrinos

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We know there are sources up to $10^{20}$ eV (1 Joule)!!

How are these particles accelerated?

- Active Galactic Nucleii (black holes accreting mass)?
- Blazars (Jets emitted in our direction by AGN)?
- Gamma Ray Bursts (most luminous events in the universe)?

(Reminder: IceCube $<10^{15}$ eV)
Possible Messenger Particles:
- Photons lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei deflect in magnetic fields
- Neutrons decay
- **Neutrinos: point back to sources, travel unimpeded through universe**

### UHE Neutrino Detectors:
- Open a unique window into the universe
  - Highest energy observation of extragalactic sources
  - Very distant sources
  - Deep into opaque sources
- How does the high energy universe evolve?
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?

What is the high energy cutoff of our universe?
Why is UHE Neutrino Astronomy Interesting?

A Particle Physics Case

Probe particle physics interactions at energies not achievable on earth

- $E_{CM}$ is ~200 TeV (LHC “only” 14 TeV)
  - Measure neutrino-nucleon cross section in a new regime
    - $L_{int} \sim 300$ km: use Earth-shielding as cross-section analyzer (count events with different path lengths through the earth)
    - Probe exotic models

A. G. Vieregg
Detection Principle: The Askaryan Effect

- EM shower in dielectric (ice) → moving negative charge excess
- Coherent radio Cherenkov radiation ($P \sim E^2$) if $\lambda >$ Moliere radius

\[ e^+, e^-, \gamma \rightarrow \text{Radio Emission is much stronger than optical for UHE showers} \]

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

G. Askaryan
Askaryan Effect Observed at SLAC

Beamtest at SLAC: proof of Askaryan effect in ice

28.5 GeV shower x $10^9$ particles/shower

- Coherent ($P \sim E^2$)
- Linearly Polarized

Askaryan Effect also seen in the lab in sand and salt

7.5 tons of ice
Models & Current Constraints

• Best current limits:
  – $>10^{18}$ eV: Radio Detection, ANITA
  – $<10^{18}$ eV: Optical Detection, IceCube

• Starting to constrain some models (source evolution and cosmic ray composition)

• How do we get a factor of $\sim 100$ 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.
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>
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UHE Neutrino Radio Detector Requirements

- $\sim 1\text{-}10$ GZK neutrinos/km$^2$/year
- $L_{\text{int}} \sim 300$ km
  $\rightarrow \sim 0.01$ neutrinos/km$^3$/year
- Need a huge ($>> 100$ km$^3$), radio-transparent detector
- 3 media: salt, sand, and ice
- Long radio attenuation lengths in south pole ice
  - 1 km for RF (vs. $\sim 100$ m for optical signals used by IceCube)

$\rightarrow$ Ice is good for radio detection of UHE neutrinos!

- Flight scheduled this year
- 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
• Idea: Ground-based array of antennas on the surface of the Ross Ice Shelf
• Currently: 3 stations operating well, 4 more coming in December
• Plan: proposal submitted for full array (1000 detectors)
• Solar Power: stations have operated through 58% of the year on solar power alone

ARIANNA Coll. See arXiv:1207.3846
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: Proposal pending for next stage of deployment (10 stations)

ARA Testbed Data Analysis

- 2011 and 2012 testbed station data
- Three independent blind analyses, look at 10% sample
- Cut-based analysis:
  - Reconstruction cuts → reject thermal noise background
  - Impulsiveness cuts → reject continuous wave background
  - Directionality cuts → reject man-made background
- Future: much more volume instrumented, trigger and analysis improvements for full 37-station array

Greenland Neutrino Observatory

- Idea: array of 100 near-surface stations at Summit Station, Greenland
- 3 km thick ice
- Year-round NSF operated station with LC-130 access and annual overland traverse
- Northern Sky Coverage
- Use power from Summit Station, could use solar (10 mo/year) for large array
- Plans for a new station with expanded capacity, construction begins 2014
Summit Site Characterization June 2013

• Measured the attenuation length of the ice: 997 +/-150m for top 1.5 km of ice at 300 MHz
  – Comparable to South Pole, better than other sites
• Measured firn properties: shallower surface layer than South Pole
• First-pass measurement of RF backgrounds
• Plan: deploy first neutrino-hunting station in 2015
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
- Full Balloon: similar sensitivity to full, 3-year of ground-based arrays

Gorham et al. (2011)

→ Feed design: dual-polarization, broadband, sinuous antennas on inner membrane
EVA Scale Model Test Results

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

Gorham et al. (2011)
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.
Summary

- Probing lots of fundamental particle physics and astrophysics
- Radio technique has been proven, current results constrain models (see many other talks)
- ANITA-III 2014, IceCube ongoing
- Large forward-looking efforts in initial stages: ARIANNA, ARA, GNO, EVA
- In 5-10 years, we hope to have a real UHE neutrino observatory and to observe for many years