Searching for Ultra-high Energy Neutrinos

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ICRC 2019
Neutrinos: The Ideal UHE Messenger

- 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 the high energy universe evolves?

*Figures and data from e.g., Auger, ICRC 2019*
Observed IceCube neutrino flux
Probing a Wide Range of Fundamental Physics

M. Bustamante, from arXiv:1903.04333, Astro2020 Science Whitepaper
Neutrino Production: The GZK Process

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

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

Cosmic Rays + CMB = Neutrino Beam!

Discover the origin of high energy cosmic rays and neutrinos?

What is the high energy cutoff of our universe?

What is(are) the acceleration mechanism(s)?
The Problem with Ultra-high Energy Neutrino Astronomy

- Neutrinos don’t interact very often, so it is hard to detect them!
  - Need a huge detector to have a chance to see them
- The highest energy neutrinos are even more rare, so you need an even bigger detector.
  - You have to get creative (that’s the fun part!)
Method 1: Radio emission from neutrino interactions in dense material

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

$e^+, e^-, \gamma$

$\rightarrow$ Radio Emission is stronger than optical for UHE showers

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

Askaryan Effect
Observed at SLAC

ANITA Coll., PRL (2007)
Method 2: Emission (Radio or Optical) from Tau Neutrino Induced Air Showers

- Looks like an upward going cosmic ray air shower
- Observe from surface, a mountain, balloon, or space
• 1 UHE neutrino/km²/year
• $L_{\text{int}} \sim 300$ km for ice
  $\rightarrow$ 0.003 neutrinos/km³/year
• Need a huge (> 1000 km³), radio-transparent detector
• Long radio attenuation lengths in ice
  • 1 km for RF
  $\rightarrow$ Ice is good for radio detection of UHE neutrinos!
Ongoing Efforts in Radio Detection in Dense Media
ANITA: Designed for Energies > $10^{19.5}$

NASA Long Duration Balloon launched from Antarctica, four flights thus far

Instrument Overview:

• 40 horn antennas, 200-1200 MHz
• Direction calculated from timing delay between antennas (interferometry)
• In-flight calibration from ground
• Threshold limited by thermal noise
1) Neutrino-Induced Askaryan Emission in Ice

- Signals are vertically polarized

C. Deaconu
2) Radio Emission from Tau-Neutrino-Induced Air Showers

- Signals are horizontally polarized
- Comes from below the horizon

C. Deaconu
3) Radio Emission from Cosmic-Ray-Induced Air Showers

- Signals are horizontally polarized
- Polarity of reflected (below-horizon) signal is inverted compared to direct (above-horizon) signal and tau neutrino (below-horizon) signal

C. Deaconu
### ANITA3 and ANITA4 Askaryan Neutrino Search Results

<table>
<thead>
<tr>
<th></th>
<th>Number of Events in Signal Region</th>
<th>Background Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANITA3</td>
<td>1</td>
<td>0.7^{+0.5}_{-0.3} events</td>
</tr>
<tr>
<td>ANITA4</td>
<td>1</td>
<td>0.6^{+0.7}_{-0.5} events</td>
</tr>
</tbody>
</table>

*ANITA Coll. PRD 2018, PRD 2019*

See C. Deaconu Talk
ANITA Also Sees Air Showers

(Cosmic Rays + Tau Neutrinos + Anything Else That Might Make Air Showers)

- Signals are distinguishable from in-ice neutrinos via polarization
- Energy > $10^{18}$ eV
- ANITA1: 16 Air Showers
- ANITA3: 28 Air Showers
- ANITA4: 24 Air Showers

ANITA Coll., PRL 2016
ANITA Coll., PRD 2018
Polarity Flipping and Tau Neutrinos

- Polarity should be the same for all reflected cosmic ray events
- One of the 28 air showers in ANITA3 is not the same polarity as the rest
  - There was another one of these in ANITA1
- Each of these two observations is 1 event on a background of ~0.01
- Sign of an upgoing (tau neutrino?) air shower?

Typical Cosmic Ray Event

Mystery Event

ANITA Coll., PRL 2018
Problem with a Tau Neutrino Interpretation

- Both events are too steeply upgoing to nicely fit the standard model for a diffuse flux of tau neutrinos.
- Maybe it is Transition Radiation (Motloch et al. 2017, de Vries & Prohira 2019) from cosmic ray air showers?
- Or (more mundane) maybe there is some non-physics background we have not yet accounted for?
- Maybe it is beyond-standard-model physics? (e.g. Fox et al. 2019)
PUEO: The Payload for Ultrahigh Energy Observations

PUEO Neutrino Sensitivity Projections

Follow up on ANITA observations with greatly improved sensitivity
Especially large instantaneous effective volume, for transient, point source, and multimessenger searches
PUEO’s Improvements Over ANITA

- Order-of-magnitude improvement enabled by:
  - interferometric phased array trigger
  - real-time digital filtering
  - x2 more antenna collecting area above 300 MHz
  - Improved pointing resolution
ARIANNA: Ross Ice Shelf, Antarctica

- Reliable, low power ~5W
- Autonomously powered: solar power + wind
  - current prototype survives harsh Antarctic conditions and powers Antarctic station for ~40% of the time
- Iridium satellite + WiFi communication
- Can be used at any location (Moore’s Bay, South Pole, Greenland, etc.)
ARIANNA Neutrino Search: 8 Station-Years of Data

- Uses Askaryan template matching search

ICRC 2019, see C. Glasier Talk
ARA: In-Ice Radio Detector at South Pole
An Upgrade for ARA in 2017/2018

- Installed 2 new stations (bringing the total to 5)
- One with a real-time interferometric phased array trigger system
  - New DAQ – has been perfectly stable since deployment
  - Trigger performance matches simulations exactly
  - Improvement x2 effective volume achieved already
• 8 station-year analysis nearing unblinding

• 5 stations are now running, all with high livetimes over the last few years

• Projected sensitivity of data in the can by 2022 is shown in pink

See A. Connolly Talk
Lunar Detection (e.g. LOFAR)

- Sensitive at highest energies, beyond GZK
- Multiple radio telescopes have done this search (GLUE, Parkes, etc.)
Toward IceCube Gen2

- IceCube Gen2: a multi-component facility to reach the broadest range of energies.

A. Nelles, from Astro2020 Whitepaper
The Path to a UHE Neutrino Observatory: What Is Needed Now?

- Demonstrated scaling of technology to the many 10’s of stations level, with a path forward to 100’s of stations for IceCube Gen2
- Continued analysis technique development to match improving trigger techniques
- Continued simulation development (a field-wide joint effort has been remarkably successful)
- With a detector of this scale, we’ll also discover ultra-high energy neutrinos!
A Near-Term R&D Path Toward IceCube Gen2: Greenland

- NSF-Operated Year-round Summit Station
- 3km thick glacial ice
- Site is good for Solar/Wind generation
- 2013: Attenuation Length Measurement
- 2015: Prototype of phased array system
- 2020: First deployment of stations with scalable design
Station Design for Greenland

- A lightweight version of the proposed RNO design, which is suitable for the Summit Station site
- Deep detector with phased array trigger (100m deep) to maximize effective volume and sensitivity
- Surface detector with cosmic-ray detection and veto
- Antennas at multiple depths and on multiple strings to optimize reconstruction
Sky Coverage for Multi-Messenger Astronomy

C. Glasier
• Observe from the surface (Auger, GRAND, ARIANNA, etc.), a mountain (TAROGE, BEACON, etc.), balloon (ANITA), space (POEMMA)
GRAND

- Giant network of $20 \times 10^3$ radio antennas to be deployed at different locations in the world in 203x.
- Simulations indicate sensitivity to neutrinos, FoV (~full sky) & angular resolution (~0.2°) sufficient to do UHE neutrino astronomy.
- Details of design to be informed by GRANDProto300 (+ other experiments)
- See O. Martineau Talk

**Simulated event** ($E_n = 2 \times 10^{19}$eV; $\theta = 87^\circ$)

- Trigged antennas
- $\tau$ decay
- $\nu$ CC interaction

**Graphs:**
- Cosmic ray flux vs. energy
- Neutrino energy vs. flux
- Trigged antennas vs. sensor voltage
GRANDProto300

- 300 self-triggered antennas to be deployed in LengHu, QingHai, China in 2020-2021.
- Designed for very inclined showers (>70°) and ~100% data collection.
- Demonstrate GRAND detection principle thru reconstruction of CR properties in 30PeV-1EeV.
- Testbench for further stages of GRAND
- See V. Decoene talk
POEMMA

Detecting optical Cherenkov signal from upward-going tau neutrinos

- A satellite mission to detect UHECRs and UHE Neutrinos

Transient Source Sensitivity

Summary

- Observation of UHE neutrinos would open a new window onto the universe.

- The Askaryan radio technique can probe a new energy regime – from the highest energies down to (hopefully) PeV energies, and a mid-scale detector is needed now.

- The tau neutrino EAS channel is promising, and is accessible from a balloon, mountain, or surface configuration.