Radio detection of neutrinos

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Highest energies?

Figure 9: The spectral flux of neutrinos from the eight-year upgoing track analysis (red fit) and the six-year HESE analysis (magenta fit) compared to the flux of unresolved extragalactic γ-ray sources (blue data) and ultra-high-energy cosmic rays (green data). The neutrino spectra are indicated by the best-fit power-law (solid line) and 1σ uncertainty range (shaded range). We highlight the various multimessenger interfaces:

A: The joined production of charged pions (±) and neutrons (0) in cosmic-ray interactions lead to the emission of neutrinos (dashed blue) and γ-rays (solid blue), respectively.

B: Cosmic ray emission models (solid green) of the most energetic cosmic rays imply a maximal flux (calorimetric limit) of neutrinos from the same sources (green dashed).

C: The same cosmic ray model predicts the emission of cosmogenic neutrinos from the collision with cosmic background photons (GZK mechanism).

Note, that the relative production rates of pionic γ-rays and neutrinos only depend on the ratio of charged-to-neutral pions produced in cosmic-ray interactions, denoted by $K_{π} = \frac{N_{π^±}}{N_{π^0}}$.

Pion production of cosmic rays in interactions with photons can proceed resonantly in the processes

$$p + \gamma \rightarrow Nπ^± + Nπ^0 + n$$

These channels produce charged and neutral pions with probabilities 2/3 and 1/3, respectively. However, the additional contribution of nonresonant pion production changes this ratio to approximately 1/2 and 1/2. In contrast, cosmic rays interacting with matter, e.g., hydrogen in the Galactic disk, produce equal numbers of pions of all three charges:

$$p + p \rightarrow Nπ^0$$

From above arguments we have $K_{π}^\prime = \frac{2}{3}$ for cosmic ray interactions with gas (pp) and $K_{π}^\prime = \frac{1}{3}$ for interactions with photons ($p\gamma$).

With this approximation we can combine Eqs. (1) and (2) to derive a simpler relation between
Even higher energies

Cosmic Ray Spectrum

Neutrino Spectrum

Detector volumes of ~100 bigger than current IceCube needed
Why radio?

- Large volumes of dense medium with reasonable attenuation length, at no cost
Why radio?

- Large volumes of dense medium with reasonable attenuation length, at no cost

- Air shower arrays (LOFAR, AERA, Tunka-Rex, …) have shown feasibility:

  ![Diagram of South pole, cold ice: 1km](image1)

  ![Diagram of Ice-shelf, “warmer” ice: 400m](image2)

  ![Diagram of Direction](image3)

  ![Diagram of Energy](image4)

  ![Diagram of Xmax](image5)

  ![Diagram of Emission mechanism](image6)
Askaryan effect

- Neutrino interaction creates (hadronic/electromagnetic) shower
- During shower development, shower front accumulates negative charge
- Macroscopic: Changing current along axis, changing as function of time/distance propagated
- Changing current induces electric emission
- Subtle differences between hadronic and electromagnetic showers
Cherenkov-like effects

- Shower is faster than its emission at $n > 1$
Cherenkov-like effects

- Shower is faster than its emission at $n > 1$
- Signal gets enhanced when it arrives in phase = coherence
- Enhancement at the Cherenkov angle
Experimental concepts

- Several concepts compete to detect ultra-high energy neutrinos

In, on, above ice

this talk
and more detail in Neutrino Astronomy 3, Wed
Experimental concepts

• Several concepts compete to detect ultra-high energy neutrinos

In, on, above ice

Near, on, at mountains

GRAND, TAROGE, BEACON, …

this talk
and more detail in Neutrino Astronomy 3, Wed

see talk Tuesday by Kotera and poster by Bustamante
Experimental concept

- Several concepts compete to detect ultra-high energy neutrinos
- Main difference: Deep vs. shallow
  - Attached: cost/effective volume, background rejection, sky coverage, energy and direction resolution, power consumption, …
Experimental concept

- Several concepts compete to detect ultra-high energy neutrinos
- Main difference: Deep vs. shallow
  - Attached: cost/effective volume, background rejection, energy and direction resolution, power consumption

see Strutt, Neutrino Astronomy 3
Experimental concept

• The future: pick and choose the best components

For example:

• **Deep**: better ice, larger effective volume per antenna, farther away from human background, higher costs, limited by borehole geometry, likely better energy resolution

• **Shallow**: better cosmic ray rejection, more flexibility in antenna design, cheaper, likely better polarization (=direction) resolution

• Combine the best of both
Experimental concept

+ some “technical details” …

Power:

Comms:

DAQ boards, trigger strategy, …
Results so far

ARIANNA: Moore’s Bay

RICE & ARA: South Pole

BACKGROUNDs

SIGNALs

SENSITIVITIES

Protons (Kampert & Unger, 2011)
Transition
Iron
IceCube 2017
IceCube $E^{-2.5}$ (2015)
IceCube muon (x3) (2017)
ARIANNA South Pole 5yr.

Time-domain Response of the ARIANNA Detector,
Astroparticle Physics, Volume 62, March 2015, Pages 139–151
Backgrounds

- If detector can distinguish in-air signals from in-ice signals, no particle physics background

- Astronomical background:
  Diffuse Galactic emission (not pulse-like) and solar flares (point to sun)

![Figure 3: (Top) A background-subtracted spectrogram of Channel 20 feet testbed, for the hour from the beginning of the flare. The background sample is taken from an identical time period on Feb. 11th (four days prior) when the sun was not flaring. (Bottom) A background-subtracted spectrogram produced from the coherently-summed waveform from two channels (Channels 3 and 4) given the delay relative to one another that gives the strongest cross-correlation value. Note that the coherently-summed spectrogram demonstrates that many features are shared between antennas. We only use two channels, as opposed to four channels combined with a directional hypothesis, to avoid a reduction in the signal strength due to any timing misalignments for a given directional hypothesis.]

3.2. Directional Reconstruction

The most striking feature of these events is how well they "reconstruct" uniquely to the sun, tracking the motion of the sun in azimuth during that hour. In other words, considering all hypothesized directions across the sky, we found the highest cross-correlation values in a direction within 2° in azimuth of the sun, without distinctly different directions also giving competitive cross-correlations for the same event. The azimuthal angle of the reconstruction peak has a 2° systematic offset from the true value of the sun's azimuth. The events also track the solar position in elevation, but with a significant systematic offset, appearing ~10° higher in the sky than the true solar elevation. In this section, first we will review the method that we use to calculate cross-correlation values associated with positions on the sky before showing cross-correlation maps for a typical flare event. We also describe our calculations of coherently summed waveforms that we use to investigate the nature of the correlated noise component of these events.

3.2.1. Reconstruction in ARA Analyses

In order to determine the direction of the source of radio signals, we use an interferometric technique similar to the one used in a search for a flux of diffuse neutrons using data from the ARA Testbed station that takes into account the index of refraction of the ice surrounding the antennas [4]. We first map the cross-correlation function from pairs of waveforms from two different antennas to expected arrival delays from different putative source directions. For each direction on the sky, the mapped cross-correlations from many pairs of antennas are added together and where the delays between different pairs of antennas signals have the strongest agreement, there is a peak in the correlation map.

For a given pair of antenna waveforms, the cross-correlation between the voltage waveform on the $i$-th antenna ($f_i(t)$) and the voltage waveform on the $j$-th antenna ($g_j(t)$) as a function of time lag $\tau$ can be found from Eq. 1:

$$C_{i,j}(\tau) = \frac{1}{T} \sum_{t=1}^{T} f_i(t) g_j(t+\tau)$$

The time lag $\tau$ depends on the position of the source relative to the array, characterized as elevation angle $\theta$, azimuthal angle $\phi$, and the distance $R$ to the source; the origin of this coordinate system is defined as the average of the positions of the antennas contributing to the map. As in [4], we only consider two hypothesized distances, 30 m and 3000 m. In the original diffuse analysis, these were chosen because 30 m is roughly the distance of the local calibration pulser, and 3000 m is an estimate for a far-field emitter like a neutrino interaction. The total cross-correlation strength for a given point on the sky ($\theta, \phi$) is given by summing over all like polarization pairs...
Backgrounds

- If detector can distinguish in-air signals from in-ice signals, no particle physics background

- Astronomical background: Diffuse Galactic emission (not pulse-like) and solar flares (point to sun)

- Most dangerous background: humans
(One) Signal search strategy

Simulated signal

Time-domain Response of the ARIANNA Detector, Astroparticle Physics, Volume 62, March 2015, Pages 139–151

Simulated signal
(One) Signal search strategy

Simulated signal

6 ns

Hardware response
(One) Signal search strategy

Simulated signal

Hardware response

Signal in detector

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(One) Signal search strategy

Simulated signal

Hardware response

Signal in detector

Correlation of templates with data

Electric Field @ 1m (V/m)

$\theta_{\text{obs}} = -1 \text{ deg}$

$\theta_{\text{obs}} = 0 \text{ deg}$

$\theta_{\text{obs}} = +1 \text{ deg}$

6 ns

140 ns
(One) Signal search strategy

Simulated signal

Hardware response

Signal in detector

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Neutrino Template Matching

Simulated Neutrino Signal (ZHS)

Antenna Response

Amplifier Response

Neutrino Template

1GHz

70°

140 ns

6 ns

Correlation of templates with data
Cosmic rays

- Event detected in Moore’s Bay 2016
- Since arrays are very small, no neutrino detection yet
- But cosmic rays act as proof-of-principle
- Both calibration signals and science case itself
Cosmic rays

- Neutrino detectors work in a different frequency range than cosmic ray radio detectors
- Broad-band response provides opportunities, but new algorithms needed

- For example: Combination out integral and slope is excellent energy estimator
- Work in progress
Polar ice has a density gradient with depth.

Classically, signals will be bent towards higher densities, leading to “forbidden” regions.

Strongly affects effective volume of neutrino detectors as certain signals will be unable to reach detector.
Signal propagation

- ARIANNA station at South Pole:
- Use deep pulsers to study ice and station performance
Signal propagation

- Excellent angular reconstruction of pulse in deep ice
- Resolution of 0.8 degrees for station
- Systematic offset likely related to station geometry and uncertainties in the ice modeling
But ...
But …

“Forbidden”

Data Moore’s Bay
But …

- At South Pole, Moore’s Bay and Greenland also signals observed that should be ‘forbidden’

- **Tentative explanation:** Ice is layered, not smooth gradient as usually assumed

- Density fluctuation lead to ray trapping and horizontal propagation
But …

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Data Moore’s Bay

“Forbidden”
Signal propagation

- Understanding of ice propagation is coming together
- Modeling critical for understanding signal propagation
Simulation: NuRadioMC

ARASim

• Non-modular, very specific to location and detector design

ShelfMC

• Modular, python based, open source

NuRadioMC
https://github.com/nu-radio/NuRadioMC

Event Generation
• Cross-section
• Flavor-ratio
• Arrival direction
• …

Signal Generation
• Phase and frequency
• LPM
• …

Signal Propagation
• Realistic ice models
• (analytic) Ray-tracing
• …

Detector Simulation
• Frequency and phase response
• Fully flexible station layout
• …
Sensitivities to neutrinos

- Diffuse flux from cosmic rays and cosmic microwave background

- "Sensitivity a linear function of money"
- Needs a target sensitivity

Here:
- 300 stations, South Pole
- 5 years, 90% uptime
- 90% analysis efficiency
Sensitivities to neutrinos

- Transient flux from explosive events (here NS-NS merger)

- Radio arrays will have excellent sensitivity to explosive events
- Already existing arrays, promising sensitivity — uptime a challenge in Antarctica
Outlook - Large neutrino array

• Radio detection is a intriguing (new) technique to detect neutrinos of the highest energies and solve long-standing questions

• Emission properties well understood

• Sufficient previous experiences in building detectors

• Neutrino community is coming together to propose a large array which has discovery potential