The Quest for UHE Neutrinos

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CCAPP Seminar
The Ohio State University
Department of Physics

July 16, 2019
Why Study UHE Neutrinos?

*Ultra-High Energy = >10^{16} \text{eV}

**Astrophysics Motivation:** Only probes of the highest energies at cosmic distances
- Cosmic rays >10^{19.5} \text{eV} attenuated after ~50 MPc, e.g. GZK effect
  \[ p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \]
- Photons >~10 TeV annihilate on CMB/EBL, scatter off dust

**Particle Physics Motivation:** Probe cross sections at energies above accelerators
- EeV (10^{18} \text{ eV}) neutrino in ice = COM energy of ~45 TeV
Neutrinos and Multimessenger Astronomy

Complimentary Probes
- Cosmic rays: pions from GZK process decay into neutrinos
- Probe accelerators directly—e.g., blazars

Rare Signal
- Low fluxes (~few/km³/yr) and low cross-sections (interaction length ~300km in rock)
- Need Big detectors: ~100 km³ of target volume to enable routine detections

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \]
Askaryan Effect

- Neutrino-induced showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add *coherently* → broadband (200 MHz-1.2GHz) radio pulse
- Conical emission (~56° in ice); strongest “on cone”
- Two requirements for successful experiment
  - Radio transparent medium: ice
  - Enormous volume: Antarctica

The ARA Concept

- 8 VPol & 8 HPol antennas deployed in 200m “boreholes”
- Cubical lattice at 200m depth
- 150-850 MHz bandwidth

Calibration Pulsers

Surface ice

Antenna cluster
The ARA Collaboration

USA

Cal Poly  University of Kansas
The Ohio State University  University of Maryland
Otterbein University  University of Nebraska
University of Chicago  University of Wisconsin-Madison
University of Delaware  Whittier College

International Collaborators

Chiba University  National Taiwan University
University College London  Vrije Universiteit Brussel
Weizmann Institute of Science
Triggering and Data

- **Power:** 10ns integrated power > \( 5.3 \times \) thermal noise floor
- **Coincidence:** trigger in 3/8 antennas of same polarization in \(~170\) ns
- Thresholds maintain a global \(~7\) Hz/station trigger rate \(\rightarrow 10^8\) evts/year/station
New Stations

- Entire DAQ for A4 and A5 built at OSU, with lots of undergraduate help
- Built “north” system: A6
- Supported the construction of a new low threshold-phased array system [10.1016/j.nima.2019.01.067]
  - A5 serves as the “power and communications” hub
- Refurbished DAQs for A1 and A3
Many thanks to CCAPP and CART!

Rapid prototyping and testing of electronics

RF circuit board mill.

Pick & Place machine for rapid assembly.

Anechoic chamber.

Large thermal chamber.
ARA Smart Power System (ASPS)

- Power broker enables granular control of subsystems
  - No IceCube intervention in ARA power systems
  - Only 5 station-wide “hard” restarts
- Precision Time Protocol—could sync ARA to IceCube clock

ARA Front End (ARAFE)

- Cheaper, more compact signal conditioning modules
- Contains bank of tunable attenuators to increase dynamic range of instrument
  - EX: prevent saturation of digitizers
Tunable Attenuators: Application

- With non-saturated digitizers, pulse amplitude at A4 vs A5 gives the longest horizontal-baseline measurement of \( L_\alpha \)

\[
\frac{SNR_{A5}}{SNR_{A4}} = \frac{r_4}{r_5} \frac{r_4 - r_5}{e^{L_\alpha}}
\]

New measurement:
\( L_{\alpha,1500m} = 1.43 \pm 0.25 \) km

*Measurement by Dave Besson at KU
Context

• Presenting expansion to 2013-2016 data set in A2 (A3 underway also)

• Analysis is done “boxed”—tune cuts on 10% of data, remaining 90% sets the limit

• Data is split into five configurations

• Big data
  – 58 million events in 10% sample
  – Nearly 40 TB of data in 100% sample
Run and Livetime Rejection

- Reject runs with known calibration activity—e.g., surface pulsing and visibly identifiable anthropogenic activity

- We analyze ~98% of our total recorded livetime; substantial improvement over Testbed (~62%)

<table>
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<th>Config</th>
<th>Total Livetime (days)</th>
<th>Good Livetime (days)</th>
<th>Fraction</th>
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<td>179.62</td>
<td>97%</td>
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<td>143.58</td>
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<td>3</td>
<td>100.07</td>
<td>94.45</td>
<td>94%</td>
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<td>4</td>
<td>413.01</td>
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<td>99%</td>
</tr>
<tr>
<td>5</td>
<td>265.73</td>
<td>263.76</td>
<td>99%</td>
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</tbody>
</table>
Wavefront-RMS Filter

- ARA records $>10^8$ events/year—need fast rejection algorithm
- Leverage regular geometry and divide station into faces
- Expect $\text{wavefront-RMS} = \log_{10}(\text{RMS}(\cos \theta))$ to be small for real signals, and larger for thermal noise

\[
\frac{\cos(\theta_A)}{2} = \frac{\cos(\theta_{A,i}) + \cos(\theta_{A,ii})}{2}
\]

\[
\text{RMS}(\cos(\theta_A)) = \sqrt{\frac{(\cos(\theta_{A,i}) - \cos(\theta_A))^2 + (\cos(\theta_{A,ii}) - \cos(\theta_A))^2}{2}}
\]
Wavefront-RMS Filter

- Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol

<table>
<thead>
<tr>
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<th>V Efficiency (%)</th>
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<td>5</td>
<td>76.4</td>
<td>59.4</td>
<td>91.7</td>
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</table>
Continuous Wave (CW) Contamination

- Events passing wavefront-RMS event filter are evaluated for CW contamination
- Most common: 403 MHz from South Pole weather balloons, launched twice-daily

Run 1548, Event 20695
Reconstruction

- Perform interferometric reconstruction
  - Sky point \((\theta, \phi)\) defines a delay \(\tau\)
  - Compute correlation \(C_{i,j}\) between two antennas for that \(\tau\)

\[
C_{i,j}(\tau) = \frac{SNR_i \times SNR_j \times \sum_{i=-\infty}^{\infty} V_i(t)V_j(t + \tau)}{N_{\text{overlap}} \times RMS_i \times RMS_j}
\]

- Sum over pairs of antennas

\[
C_{\text{sky}}(\theta, \phi; R) = \frac{1}{\sum_{i=1}^{n_{\text{ant}}-1} \sum_{j=i+1}^{n_{\text{ant}}} SNR_i \times SNR_j \sum_{i=1}^{n_{\text{ant}}-1} \sum_{j=i+1}^{n_{\text{ant}}} C_{i,j}[\tau(\theta, \phi; R)]}
\]

- Cut events that reconstruct to surface or in direction of pulser
Final Cut

- Final cut of the analysis is a slanted-line; slope ($m$) and y-intercept ($d$) are optimized to set the best limit
Efficiency

- Between 2 and 4 times more efficient than Testbed analysis
- Competitive with that of previous A23 analysis
Expected Limit

- Expect to observe 0.085 neutrinos from Kotera max flux

- Background of $1.04 \times 10^{-2}^{+0.29}_{-0.36}$ in VPol and $1.57 \times 10^{-2}^{+0.26}_{-0.29}$ in Hpol

Projected ARA sensitivity carves out exciting new parameter space, w/ real chance at a detection!
Summary

1. ARA has an expanded array with more \textit{in-situ} control than ever before

2. Station 2 analysis is nearly complete, with A3 analysis close behind

3. Projections for ARA show us closing in on world leading limits and the real chance for a discovery of a UHE neutrino

The OSU ARA Team is generously supported by:
- NSF GRFP Award DGE-1343012
- NSF Awards 1255557, 1806923, 1404212

July 16 2019
Back-up Slides
High-Energy CR Spectrum
Swordy Plot

Plot by A. Connolly, Adapted from S. Swordy

The Quest for UHE Neutrinos

July 16 2019
Neutrino Interactions

- Two varieties of interactions: Charged current (CC) and Neutral Current (NC)

  CC: $\nu_\ell + N \rightarrow \ell + X$
  $\ell \rightarrow EM\ Shower$

  NC: $\nu + N \rightarrow \nu + X$
  $X \rightarrow Hadronic\ Shower$

- Showers are ultra-relativistic ($\beta \approx 1$) → emit Cherenkov radiation in dense media
- Intensity is greatest at Cherenkov angle $\theta_C$
- Two varieties of interest: optical and radio

$$\cos \theta_C = \frac{1}{n\beta}$$
Askaryan Pulse Shape and Dependencies

\[ V(f) \propto \frac{y E_V}{R} \times \frac{f}{1150 \text{MHz}} \times \exp \left[ -\frac{1}{2} \left( \frac{f}{1 \text{ GHz}} \times \frac{\Omega}{2.2^\circ} \right)^2 \right] \]
ARA Antennas

V-Pol Antenna

H-Pol Antenna

6 in Birdcage bicone in sand August 2010
New Power Distribution

• Introduced power broker: the ARA Smart Power system (ASPS)
• Old power systems had no granularity
  – A short anywhere compromised the entire station
  – Power cycling subsystems required power cycling whole station—not ideal
• Granularity is powerful—since deployment:
  – No IceCube winter-over intervention in ARA power systems
  – Only 5 station-wide “hard” restarts
Precision Timing

• Happy opportunity: new power broker is equipped with Precision Time Protocol

• In the future, could synchronize ARA station clocks to IceCube at the ~ns level, and do optical/RF coincidence searches*

* = part of postdoc plan at MSU w/ IceCube....
New Signal Conditioning

- Old stations have static, physically fragile, and expensive (~$2k/chan) signal conditioning

- New modules, ARAFE, are cheaper (~$300/chan) and have per-channel tunable attenuators
  - Enables *in-situ* gain matching between channels (currently un-utilized)
  - Allows for “high attenuation” data taking periods
2: Test on Natural Phenomenon
Observation of Reconstructable Radio Emission from Solar Flare

“Observation of Reconstructable Radio Emission in Coincidence with an X-Class Solar Flare in the Askaryan Radio Array Prototype Station”
arXiv:1807.03335
Feb 15, 2011 Solar Flare

- Testbed activated in February 2011, detected Feb 15 X-2.2 Solar Flare
- Saturates the triggering system
- Observed as excess emission from 100-500 MHz
Solar Tracking

- Recorded events point back to the sun for the hour duration of the flare

- First radiation for ARA which reconstructs to extraterrestrial source on event-by-event basis
  - Excellent test of projection onto celestial coordinate system
  - Will help calibrate pointing of other above-ice radio sources, e.g., cosmic rays
Reconstructability

- All antennas observe the same noise that was generated at the sun and traveled to earth.

- Events only track the sun when they are well described by thermal noise.

![Graph showing number of events vs. spectral coefficient](image-url)
The ARA2 Instrument

ARA2 = 2 station array
A2 = ARA Station 2
A3 = ARA Station 3
Full List of Excluded Runs in A2

- Reject any period of livetime with known/logged calibration activity
  - 2014 Surface Pulsing: runs 2284-2918, 2938-9
  - 2014 ICL Rooftop Pulsing: runs 3120, 3242
  - 2014 Cal Pulser Sweep: 3139-3162, 3164-3187, 3289-3312
  - 2014 L2 Scaler Mask Study: 3464-3504
  - 2014 Trigger Window Scan: 3578-3598
  - 2015 ICL Deep Pulsing: 4785, 4787, 4795-4800
  - 2015 Surface Pulsing: 4872-3,6
  - 2015 A2 Pulser Lift: 6513
  - 2015 ICL Rooftop Pulsing: 6527
  - 2016 Cal Pulser Sweep: 7625-7686
Configuration Settings

- Data is split into five configurations

<table>
<thead>
<tr>
<th>Config</th>
<th>L1 Trig Mask</th>
<th>Readout Window (ns)</th>
<th>Trigger Window (ns)</th>
<th>Trigger Delays</th>
<th>Livetime (days)</th>
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<td>110</td>
<td>yes</td>
<td>185.08</td>
</tr>
<tr>
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<tr>
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<td>520</td>
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<td>D4BH</td>
<td>520</td>
<td>170</td>
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Data Conditioning

• Data must be *conditioned*
  – First block must be removed, and remaining blocks given zero mean
  – In A3, channels 3, 8, and 11 require waveform inversion
• I implemented in a standard way: `AraEventConditioner`

Run 2818, Event 10, Channel 5

Before first trim and zero-mean

After trim and zero mean
**Wavefront-RMS Filter**

- ARA records $10^8$ events/year, which are >99% noise
- Need fast rejection algorithm
- Leverage regular geometry—divide station into faces
- Compute "hit-times" for signal arrival at each antenna in the face, convert into arrival angle

\[
\Delta t_{A,i} = t_3 - t_1 \\
\Delta t_{A,ii} = t_4 - t_2 \\
\Delta t_{A,i} \approx \Delta t_{A,ii} \\
\cos(\theta_{A,i}) \approx \cos(\theta_{A,ii}) \\
\theta_{A,i} \approx \theta_{A,ii}
\]
Wavefront-RMS Filter

- Find the RMS around the average arrival angle

\[
\cos(\theta_A) = \frac{\cos(\theta_{A,i}) + \cos(\theta_{A,ii})}{2}
\]

\[
\text{RMS}(\cos(\theta_A)) = \sqrt{\frac{\left(\cos(\theta_{A,i}) - \cos(\theta_A)\right)^2 + \left(\cos(\theta_{A,ii}) - \cos(\theta_A)\right)^2}{2}}
\]

- Expect wavefront-RMS = \(\log_{10}(\text{RMS}(\cos\theta))\) to be small for real signals, and larger for thermal noise
Wavefront-RMS Filter

- Performance on VPol data and simulation from A2 configuration 1

![Graphs showing performance comparison between VPol data and Neutrino Simulation](image)
Wavefront-RMS Filter

• Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol

• These values reduce data to 5-10% of original size (per polarization) while keeping fraction of neutrino events cut by wavefront-RMS alone to <5%

• Total efficiency of the filter for neutrinos, before other cuts, is ~90%

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<th>H or V Passing Rate</th>
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Wavefront-RMS Filter

- Efficiency of filter can be measured as a function of the signal-to-noise ratio

Efficiency VPol

Total: 74.7%

Efficiency HPol

Total: 57.9%
CW Filtering

- Flag a frequency as CW if it comes from “peaks above base line” or “phase variance”
  - Phase variance frequently flags 125, 300 and 500 MHz as systems noise—we ignore these
  - Adjacent frequencies merged into notches

- CW frequencies are filtered with ANITA Geometric Filter—first time we have filtered waveforms in ARA
  - Originally designed by Brian Dailey at OSU
  - Used in the ANITA-III analysis [Phys. Rev. D 98, 022001 (2018)]
Reconstruction Details

- Interferometry based reconstruction:
  - Putative source angle $\rightarrow$ Time Delay between antennas $\rightarrow$ Correlation Value
  - Take Hilbert envelope to interpret as power

Interferometry (cont.)

- For pair of antennas, compute time delays and correlation values for all points on the sky
  - Propose a source distance, $\theta$, and $\phi$
  - Trace ray from source to array center

- Sum up correlation value for many pairs of antennas

- Interpret peak in map as source direction

---

1. P. Allison et. al. j.astropartphys.2015.04.006
2. P. Allison et. al. j.astropartphys.2016.12.003
Phi Anisotropy

- In A2 and A3, one cable was too long
  - A2 String 3
  - A3 String 2
- In both stations, that string has an extra 100ns of cable delay
- E.g., in A2, string 3 waveforms start earlier than in the other strings (eg. string 2)
Phi Anisotropy

- When signal present—signal dominates correlation function
- When noise dominates (most cases), the extra trace length at the beginning means the longer string systematically looks like it lags the other strings
- This pulls the reconstruction in the direction of the longer string
- Which is $\sim 111^\circ$ in A2 and $\sim 21^\circ$ in A3
Theta Anisotropy

• The top and bottom antennas are separated by ~19m of cable, in which light travels 0.255m/ns, amounting to ~75 ns of delay between the two.

• Take A2 D1TV and D1BV as an example
  – Known geometric distance between antennas=19.26 m
  – If Δt=75ns
  – Then the reconstructed zenith is -41°! 

\[ D \sin \theta = \frac{c}{n} \Delta t \]
Theta Anisotropy

- Is this "phantom" 75ns observed in practice? Yes!

- Source unclear:
  - Low level cross-talk?
H vs V Comparison

V Sim

H Sim

Entries 31038

Correlation Value

Correlation Value

SNR 30

SNR 30

10^3

10^2

10

1
• Finally, by allowing an event to pass in VPol or HPol, we can compute the efficiency as a function of energy.

• Example of A2 config 1: ~30% near $10^{17}$ eV climbing to ~60% near $10^{19}$ eV.

**A2 Configuration 1 Efficiency**
Total Analysis Efficiencies

- Total efficiency of the analysis

<table>
<thead>
<tr>
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<th>V Efficiency</th>
<th>H Efficiency</th>
<th>Total Efficiency</th>
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<td>49.0%</td>
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<td>32.4%</td>
<td>19.7%</td>
<td>36.8%</td>
</tr>
<tr>
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<td>41.0%</td>
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Background Pseudo-Experiments

New Slope: \[ \beta'_{1,i} = \beta_{1,i} + \sigma_{\beta_{1,i}} \eta_1 \]

New Intercept: \[ \beta'_{2,i} = \beta_{2,i} + \rho_i \sigma_{\beta_{2,i}} \eta_1 + \sigma_{\beta_{2,i}}\eta_2 \sqrt{1 - \rho_i^2} \]
Effective Volumes

- Compute effective volume at trigger level from simulation

- Simulation was altered to take into account trigger delays, masked channels, etc. in a configuration specific way

- Get effective area through division by interaction length

\[ A_{eff} = \frac{V_{eff}}{L_{int}} \]

\[ V_{eff} = V_{thrown} \frac{N_{det}}{N_{thrown}} \]
Projected Final Limit

- Assume non-observation in the 100% sample

- Compute 90% UL on the maximum size the flux, $EF(E)$, can be in an energy bin $E_i$

$$EF(E)_i = \frac{2.44}{\ln 10 \, d \log_{10} E_i \, T \, [A\Omega]_{eff}}$$
\[ V_{\text{eff}} \text{ Comparison} \]

- There are discrepancies between our effective volumes and those quoted in previous studies
- The discrepancy is under study