The Quest for UHE Neutrinos

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The Big Questions

- Why? □
- How? □
- Where? □
- Who? □
Why Study Neutrinos: Astrophysical Messengers

- Cosmic rays >$10^{19.5}$ eV attenuated, possibly by GZK effect, e.g.
  
  $$p + \gamma \rightarrow \Delta^+ \rightarrow p(n) + \pi^0(\pi^+)$$

  → Screens extragalactic (>100 MPc) sources

- $\gamma$-rays annihilate w/ CMB @ ~1 TeV

![Plot by A. Connolly, Adapted from S. Swordy](image)
Complimentary Probes

- Cosmic rays: pions from GZK process decay into neutrinos
- Cosmic ray accelerators
  - Gamma Ray Bursts (GRB)—leptonic vs hadronic models
  - Active Galactic Nuclei (AGN)

Exciting Start!

- 2017—Binary Neutron Star—GW + Light
- 2018—Flaring Blazar—Neutrino + Light
- 2019—Neutrino + GW??

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

IceCube et. al. Science Vol. 361, Issue 6398
Chargeless. → not deflected by B fields

Weakly interacting → travel cosmic distances
Why Study Neutrinos: Fundamental Physics Probes

Astro2020 White Paper
“Fundamental physics with High-Energy Cosmic Neutrinos”
Ackerman et. al. 1903.04333

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October 23 2019
Why Study Neutrinos: Particle Physics Probes

- Probe cross-sections at energies above accelerators

\[ E_{\text{COM}} = \sqrt{4 E_v m_n} \]
The Big Questions

Why?  ✓  Astro + Particle Physics

How?

Where?

Who?
Neutrino Interactions

- Two (main) types of neutrino interactions: charged & neutral current
- Showers are ultra-relativistic ($\beta \approx 1$) $\rightarrow$ emit Cherenkov radiation in media
- Two varieties: optical and radio

\[ \cos \theta_C = \frac{1}{n\beta} \]
Askaryan Effect

- Showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add coherently → broadband (200 MHz-1.2GHz) radio pulse
Observation of Askaryan Effect

Has been experimentally observed in ice and salt

P. Gorham et al.
PRL 99, 171101 (2007)

D. Satlzberg et al.
PRL 86, 13 (2001)
The Big Questions

Why?  Astro + Particle Physics

How?  (Radio) Cherenkov Effect

Where?  

Who?  
Questions of Scale

• Low fluxes (~10/km³/yr) and low cross-sections (interaction length ~300km in rock)

• Need >1-100 km³ of target volume for statistics (e.g., few per year)

• Where do you find a giant chunk of optical & radio clear medium?
  – Ask the NSF nicely?
  – Point telescope at the lunar regolith: Lunaska
  – Go to Antarctica: IceCube, ARA, ANITA, ARIANNA
The Big Questions

Why?   [✓]  Astro + Particle Physics

How?   [✓]  (Radio) Cherenkov Effect

Where? [✓]  Antarctica

Who?   [ ]
IceCube

- 5160 photomultiplier tubes (+electronics) buried 2.5km in ice near South Pole
- Observes 1 km$^3$ of ice
- Energy range: $10^{10} \rightarrow 10^{16+}$ eV
IceCube

FC: https://eng.mephi.ru/news/120218
First HE Cosmic Neutrinos

2012: IceCube experiment sees PeV neutrinos of cosmic origin

PRL 111 (2013)

Bert (‘12)
1.0 PeV

Ernie (‘12)
1.1 PeV

Big Bird (‘14)
2.2 PeV

PRL 113 (2014)
First Potential Neutrino Source

- 290 TeV neutrino (IC 170922A) observed in coincidence with flaring blazar TXS 0506+056 ($\sim$3$\sigma$)
- Archival search in direction of TXS reveals an additional 3.5$\sigma$ excess
ANtarctic Impulsive Transient Antenna (ANITA)

- ~40 dual polarized antennas (100-1200 MHz bandwidth)
- Observes $10^6$ km$^2$ of ice
- Energy range: $10^{18}$ → $10^{21+}$ eV
- 4 flights so far, further experiments proposed...
Antarctic Ross Ice shelf ANtenna Neutrino Array (ARIANNA)

- Shallow array of downward pointing LPDA antennas
- Observes direct and reflected radio emission from ice-shelf
Askaryan Radio Array

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

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

International Collaborators
- Chiba University
- National Taiwan University
- University College London
- Vrije Universiteit Brussel
- Weizmann Institute of Science
ARA Instrument Status
Construction
Construction
Construction
Triggering and Data

- **Power**: 10ns integrated power > 5.3 × thermal noise floor
- **Coincidence**: trigger in 3/8 antennas of same polarization in ~170 ns
- Thresholds maintain a global ~7 Hz/station trigger rate → $10^8$ evts/year/station

“It’s all about the SNR”
Backgrounds to Signal

- Radio blackbody (thermal) emission of ice
- CW wave (CW) sources: satellites, radios, human bases..
- Electromagnetic interference: static discharge
The Quest for UHE Neutrinos

The Big Questions

Why?  ✓  Astro + Particle Physics

How?  ✓  (Radio) Cherenkov Effect

Where?  ✓  Antarctica

Who?  ✓  IceCube, ARA, ANITA, etc.
What’s New...
**What’s New**

**ARA Smart Power System (ASPS)**
- Power broker enables granular control of subsystems
- 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

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![Diagram of ARA and IceCube](image.png)

**Graphs:**
- Comparison of voltage over time with 0.75 dB and 12.75 dB attenuation.
- Category: Electric Potential
  - **Label:** Voltage (V)
  - **Measurement:** Time (ns)

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**Note:**
- October 23 2019
- The Quest for UHE Neutrinos
- February 2018
- October 2018
Tunable Attenuators: Application

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

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

New measurement:

$L_{\alpha,1500m} = 1.43 \pm 0.25$ km

*Measurement by Dave Besson at KU. See arXiv 1908.10689
New Phased Array w/ A5

- ARA5 is equipped with a new *phased array* trigger
- 7 VPol antennas deployed down *single* hole in the middle of A5
- Beamform *before* triggering $\rightarrow$ higher sensitivity
- Because for fixed trigger rate, threshold $\propto \sqrt{N}$

See arXiv 1809.04573
Phased Array Performance Comparison

PA measurement demonstrates factor $\sim 1.8$ reduction in 50% efficiency point (expected $\sim 2.6$).
• Presenting expansion to 2013-2016 data set in A2 and A3

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

• Big data
  – 58 million events in 10% sample
  – Nearly 40 TB of data in 100% sample
Wavefront-RMS Filter

- ARA records $>10^8$ events/year—need fast rejection algorithm
- Leverage regular geometry and divide station into faces
- Expect wavefront-RMS to be small for real signals, and larger for thermal noise

\[ \theta_{A,i} \approx \theta_{A,ii} \]

\[
\cos(\theta_{A,i}) \approx \cos(\theta_{A,ii})
\]

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

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

• Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol, ~90% efficient for neutrinos
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 \(\tau\)

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

- Sum over pairs of antennas

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

- 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 that of prototype analysis
Projected ARA sensitivity carves out exciting new parameter space, w/ real chance at a detection!

Look for paper in next month! (for now, ICRC proceeding arXiv 1907.11125)
The Future for Neutrino Telescopes
IceCube Upgrade and Gen2
Future Radio Instruments

See arXiv 1907.12526
Summary

1. Neutrinos are important and complimentary messengers to the cosmos

2. ARA is recently expanded with enhanced triggering, and a new analysis with 4x livetime is nearly complete

3. The future is bright for neutrino astronomy, and new instruments are coming in the next decade (RNO, Gen2, etc.)

Research generously supported by:
- NSF GRFP Award DGE-1343012
- NSF AAPF Award 1903885
- NSF Awards 1255557, 1806923, 1404212
Back-up Slides


- No definitive sources yet, but eagerly awaited.

* Mauricio Bustamante
Neutrino Interactions

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

\[ \text{CC: } \nu_\ell + N \rightarrow \ell + X \]
\[ \ell \rightarrow \text{EM Shower} \]

\[ \text{NC: } \nu + N \rightarrow \nu + X \]
\[ X \rightarrow \text{Hadronic Shower} \]

- 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

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

V-Pol Antenna

H-Pol Antenna

6 in Birdcage bicone in sand August 2010

Transmission coefficient

- Measured, no ferrite
- Measured, with ferrite
- NEC2 simulation, n=1.5

frequency, MHz

200 400 600 800 1000

0 0.2 0.4 0.6 0.8 1
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
• 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 same noise that was generated at the sun and traveled to earth
  
- Events only track sun when they are well described by thermal noise
  
\[
\text{CSW, 328 MHz, } \sigma = 1.40, \chi^2/\text{NDF} = 65.58/78
\]
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</th>
<th>Readout Window (ns)</th>
<th>Trigger Window (ns)</th>
<th>Trigger Delays</th>
<th>Livetime (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>400</td>
<td>110</td>
<td>yes</td>
<td>185.08</td>
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<td>None</td>
<td>400</td>
<td>110</td>
<td>no</td>
<td>143.58</td>
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<td>110</td>
<td>yes</td>
<td>100.07</td>
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<td>520</td>
<td>170</td>
<td>yes</td>
<td>413.01</td>
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<tr>
<td>5</td>
<td>D4BH</td>
<td>520</td>
<td>170</td>
<td>no</td>
<td>265.73</td>
</tr>
</tbody>
</table>
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`
**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

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

• Find the RMS around the average arrival angle

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

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

• Expect \textit{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
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%

<table>
<thead>
<tr>
<th>Config</th>
<th>V Passing Rate</th>
<th>H Passing Rate</th>
<th>H or V Passing Rate</th>
</tr>
</thead>
<tbody>
<tr>
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<td>74.7</td>
<td>58.0</td>
<td>89.8</td>
</tr>
<tr>
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<td>69.8</td>
<td>48.1</td>
<td>85.2</td>
</tr>
<tr>
<td>3</td>
<td>75.6</td>
<td>58.1</td>
<td>91.1</td>
</tr>
<tr>
<td>4</td>
<td>75.0</td>
<td>58.7</td>
<td>90.4</td>
</tr>
<tr>
<td>5</td>
<td>76.4</td>
<td>59.4</td>
<td>91.7</td>
</tr>
</tbody>
</table>
Wavefront-RMS Filter

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

Efficiency VPol

Total: 74.7%

3rd Highest VPeak/RMS

Efficiency HPol

Total: 57.9%

3rd Highest VPeak/RMS
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 → Time Delay between antennas → Correlation Value
  - Take Hilbert envelope to interpret as power

2. P. Allison et. al. j.astropartphys.2015.04.006
3. P. Allison et. al. j.astropartphys.2016.12.003
**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

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1. P. Allison et. al. [j.astropartphys.2015.04.006](http://example.com)
2. P. Allison et. al. [j.astropartphys.2016.12.003](http://example.com)

Interferograms by E. Hong
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 ~111° in A2 and ~21° 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°!
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

SNR

Correlation Value

SNR

$10^3$ $10^2$ $10$ $1$
Efficiency

• 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.
### Total Analysis Efficiencies

- Total efficiency of the analysis

<table>
<thead>
<tr>
<th>Config</th>
<th>V Efficiency</th>
<th>H Efficiency</th>
<th>Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.2%</td>
<td>33.5%</td>
<td>49.0%</td>
</tr>
<tr>
<td>2</td>
<td>32.4%</td>
<td>19.7%</td>
<td>36.8%</td>
</tr>
<tr>
<td>3</td>
<td>41.0%</td>
<td>34.5%</td>
<td>50.8%</td>
</tr>
<tr>
<td>4</td>
<td>38.2%</td>
<td>31.5%</td>
<td>47.0%</td>
</tr>
<tr>
<td>5</td>
<td>38.8%</td>
<td>32.3%</td>
<td>47.7%</td>
</tr>
</tbody>
</table>
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

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

$$EF(E)_i = \frac{2.44}{ln10 \ d \ log_{10} E_i \ T \ [A\Omega]_{eff}}$$
Comparison

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

\[ V_{\text{eff}} \]

\[ A_{\text{eff}} \text{ m}^2 \]

\[ 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \]

\[ 10^{17} \quad 10^{18} \quad 10^{19} \quad 10^{20} \]

Energy [eV]

Graph showing the comparison between Brian's analysis and Thomas' analysis.
Future Radio Instruments

Giant Radio Array for Neutrino Detection

10 km

Radio emission

Extensive air shower

See arXiv 1810.09994