ASKARYAN RADIO ARRAY THE OHIO STATE UNIVERSITY CCAPP

Latest Analysis Updates from the Askaryan Radio Array

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The Ohio State University
Department of Physics and
the Center for Cosmology and Astroparticle Physics (CCAPP)

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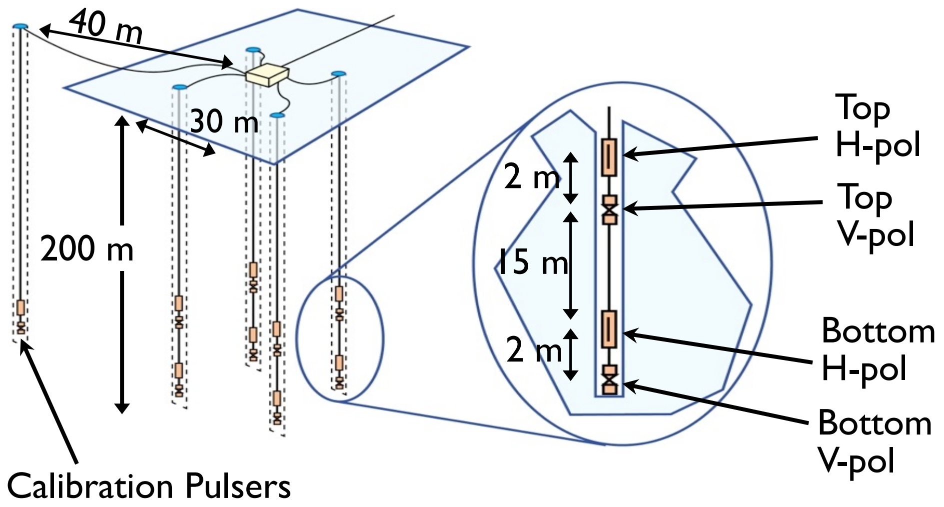
About Askaryan Radio Array

Designed to detect radio impulses from UHE neutrino-ice interactions

- 8 VPol & 8 HPol antennas deployed in 200m "boreholes"
- 5 stations deployed, the latest (A5) with enhanced phased array trigger



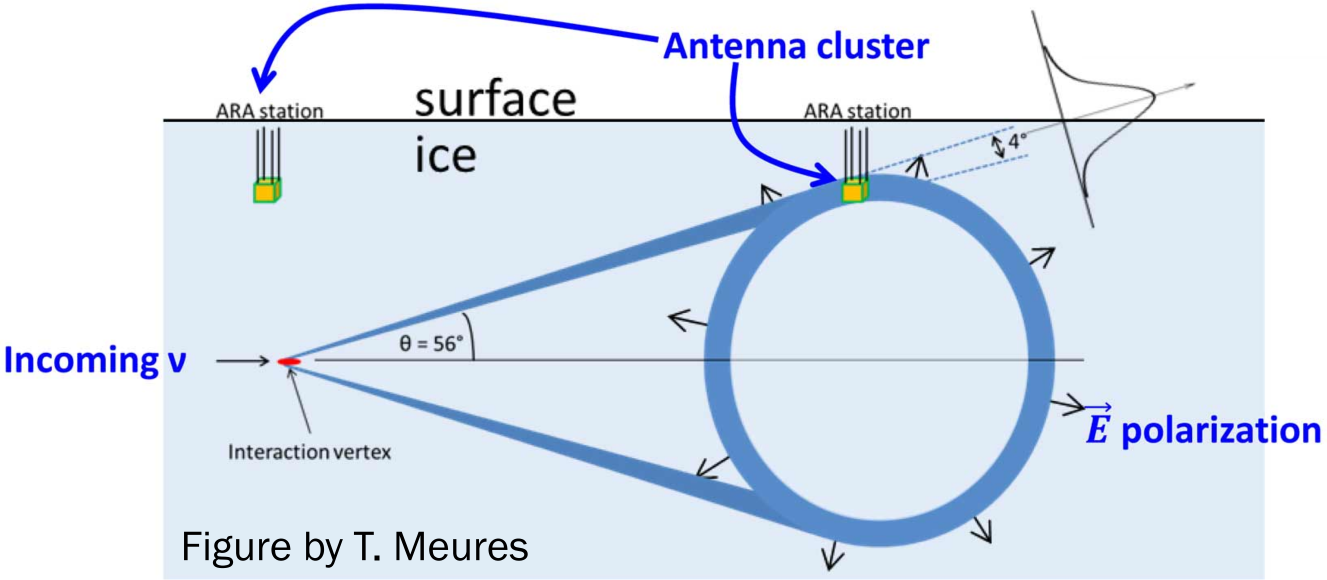
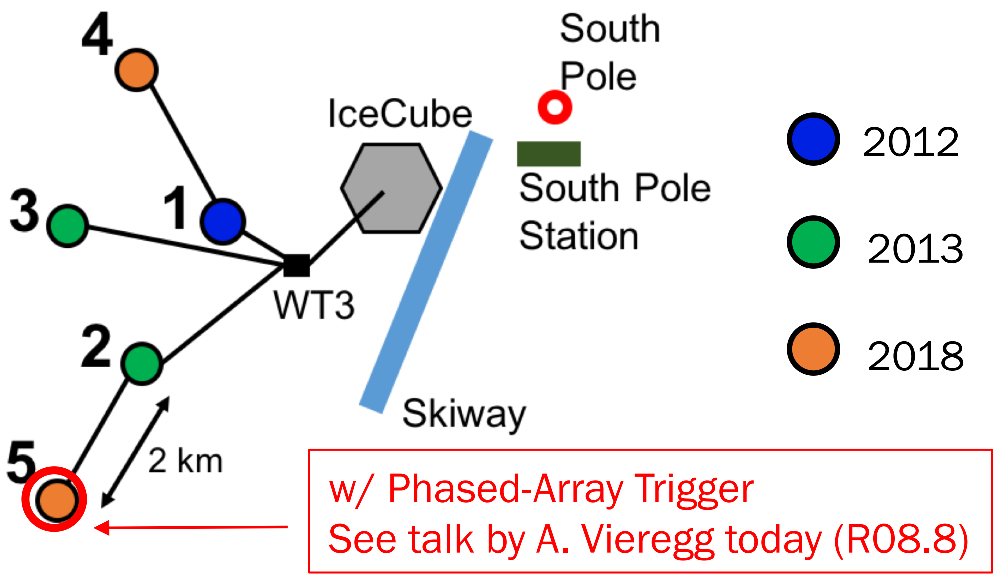


Figure by T. Meures



The ARA Collaboration

Figure credit: C. Pfendner

USA

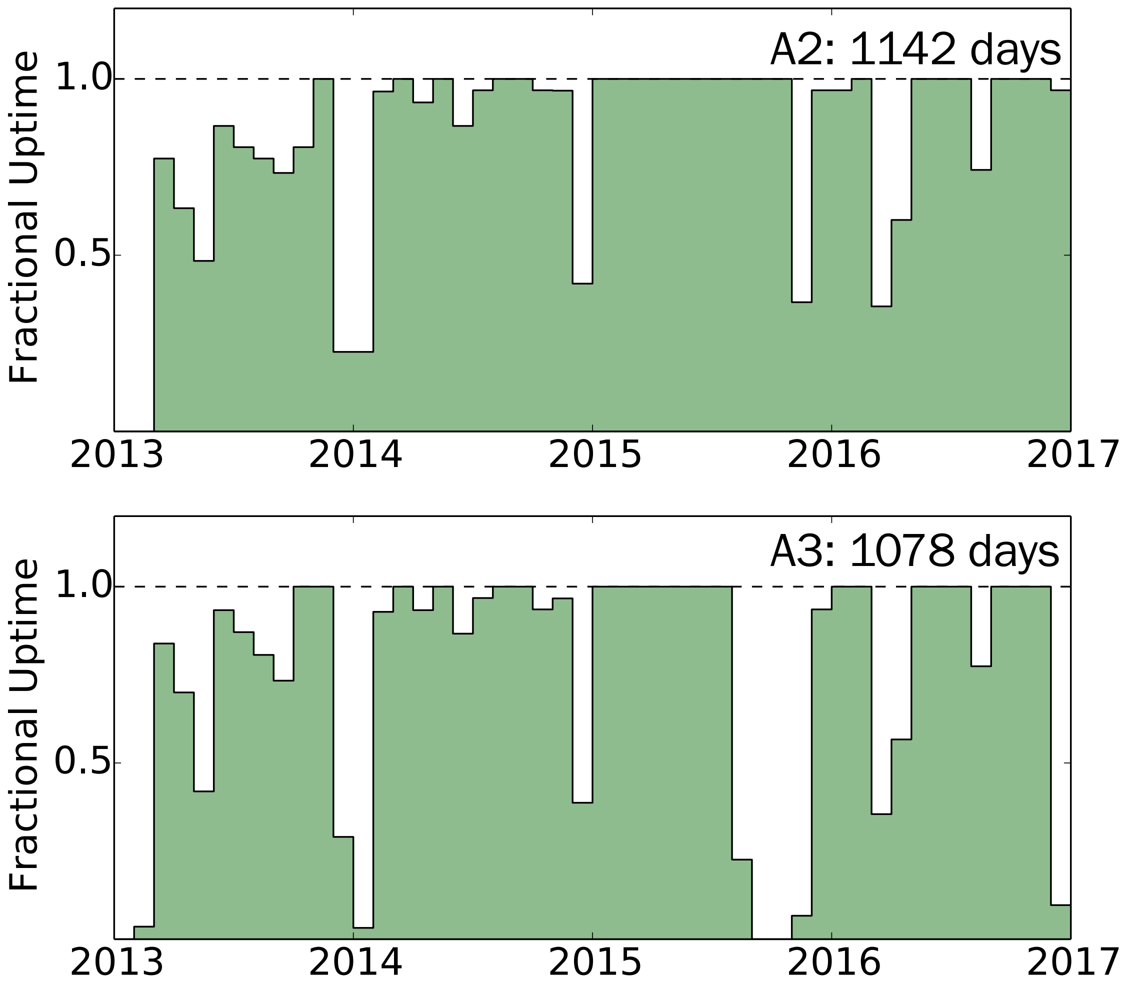
Cal Poly	University of Kansas
The Ohio State University	University of Maryland
Otterbein University	University of Nebraska
University of Chicago	University of Wisconsin-Madison
University of Delaware	Whittier College

International Collaborators

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

Diffuse Neutrino Search

- A2 and A3 collecting data since Feb 2013—10 months of data published previously
  [P. Allison *et. al.* 2016 PRD 93, 082003 (2016)]
- Expansion to the 2013-2016 data set underway in two parallel analyses
- Analysis is done "blind"—tune cuts on 10% of data, remaining 90% sets the limit
- Data is cleaned before analysis begins
  – Remove digitizer & system readout errors (~1/10^5 events)
  – Exclude calibration runs (~2 weeks/yr)



Diffuse Neutrino Search: Filtering

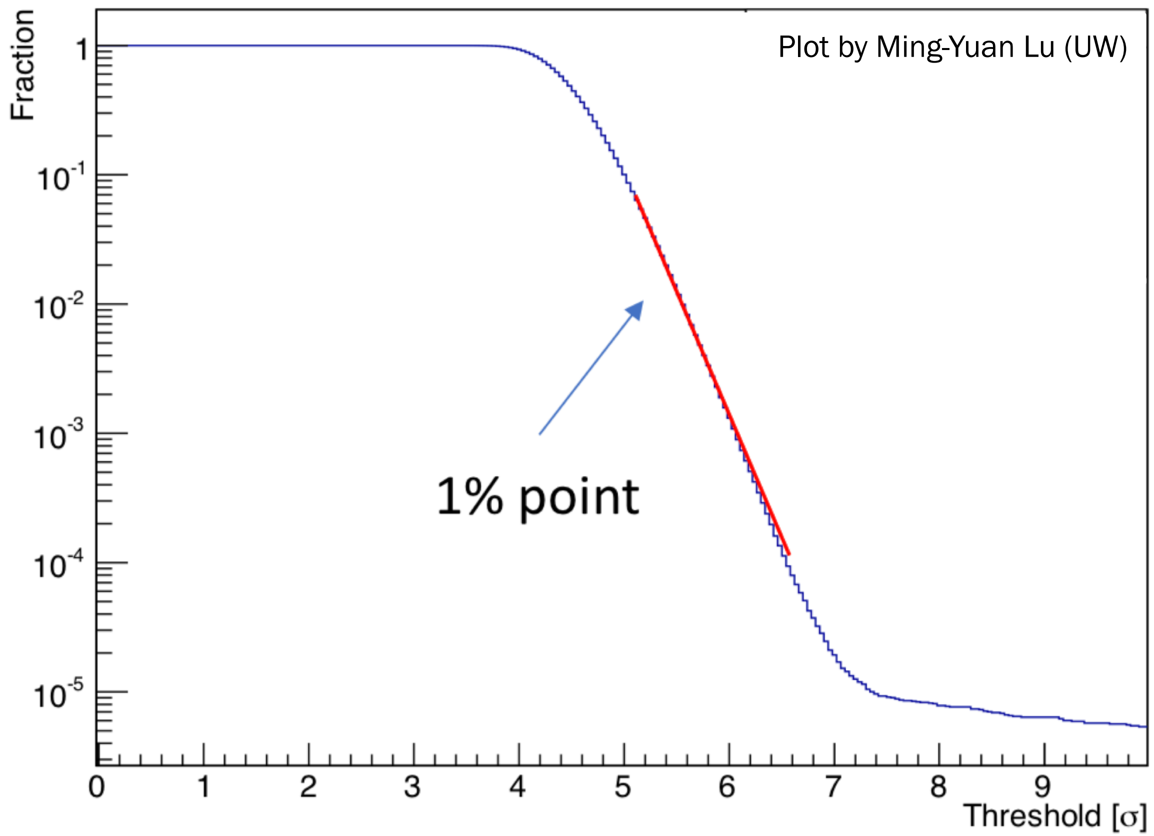
- ~5 Hz trigger rate →10^8 events/year, which are >99.9999% thermal noise

$$\frac{V_{peak}}{\sigma_{noise}} \geq N_{thresh}$$

- Apply a fast event filter to reduce data set to before attempting computationally intensive reconstructions

- Filter requires 3 VPol channels have a signal-to-noise (SNR) ratio above a threshold N_{thresh}

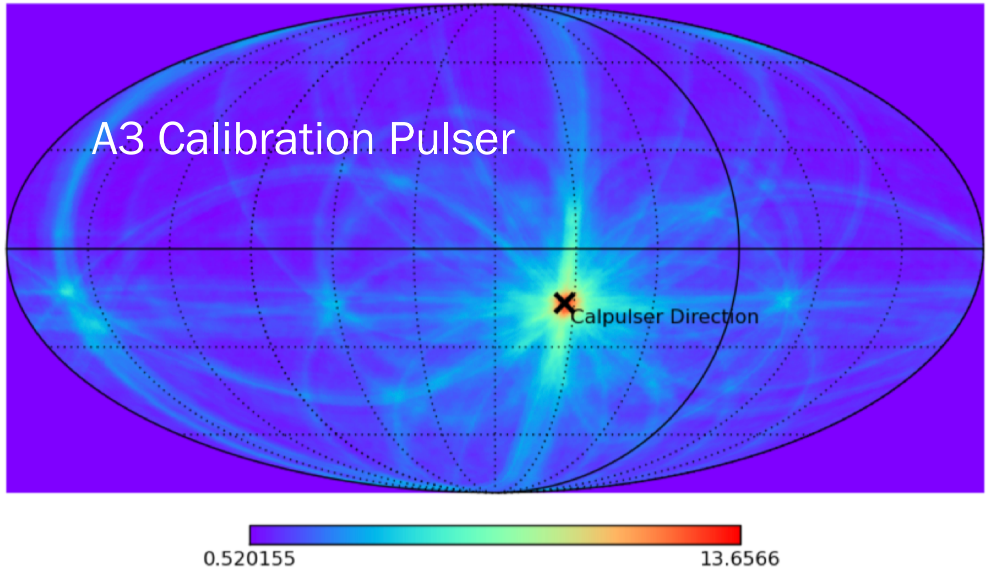
- N_{thresh} chosen to achieve 1% thermal noise passing rate

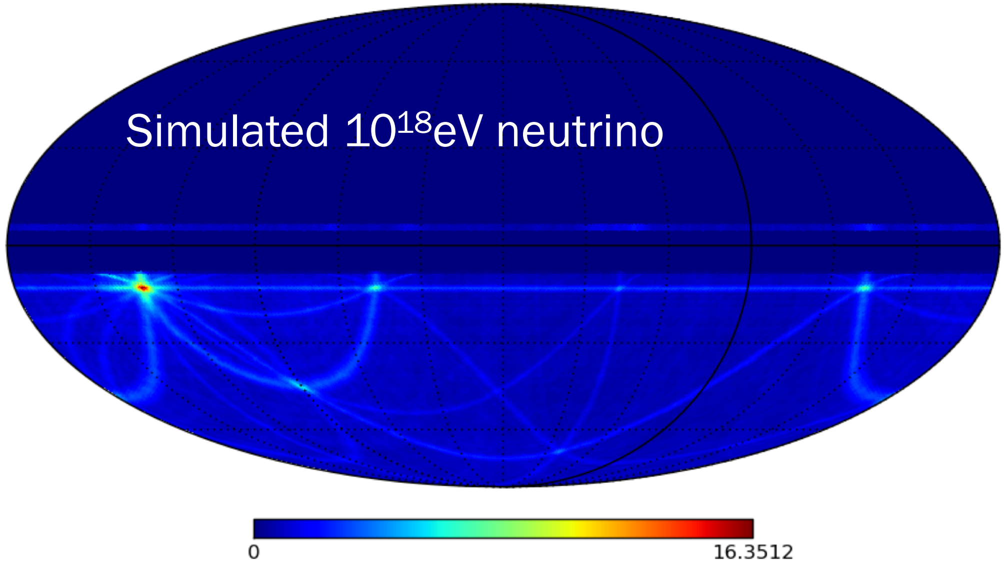


Diffuse Neutrino Search: Reconstruction

- For events surviving the filter, we perform interferometric reconstructions
  - Accounts for n(z)
  - Direct and refracted ray solutions
- Peak in the map is interpreted as the RF source direction
- Make geometric cuts to remove:
  - Events at and above the surface
  - Events in the direction of the local calibration pulser

Plots by Ming-Yuan Lu (UW)

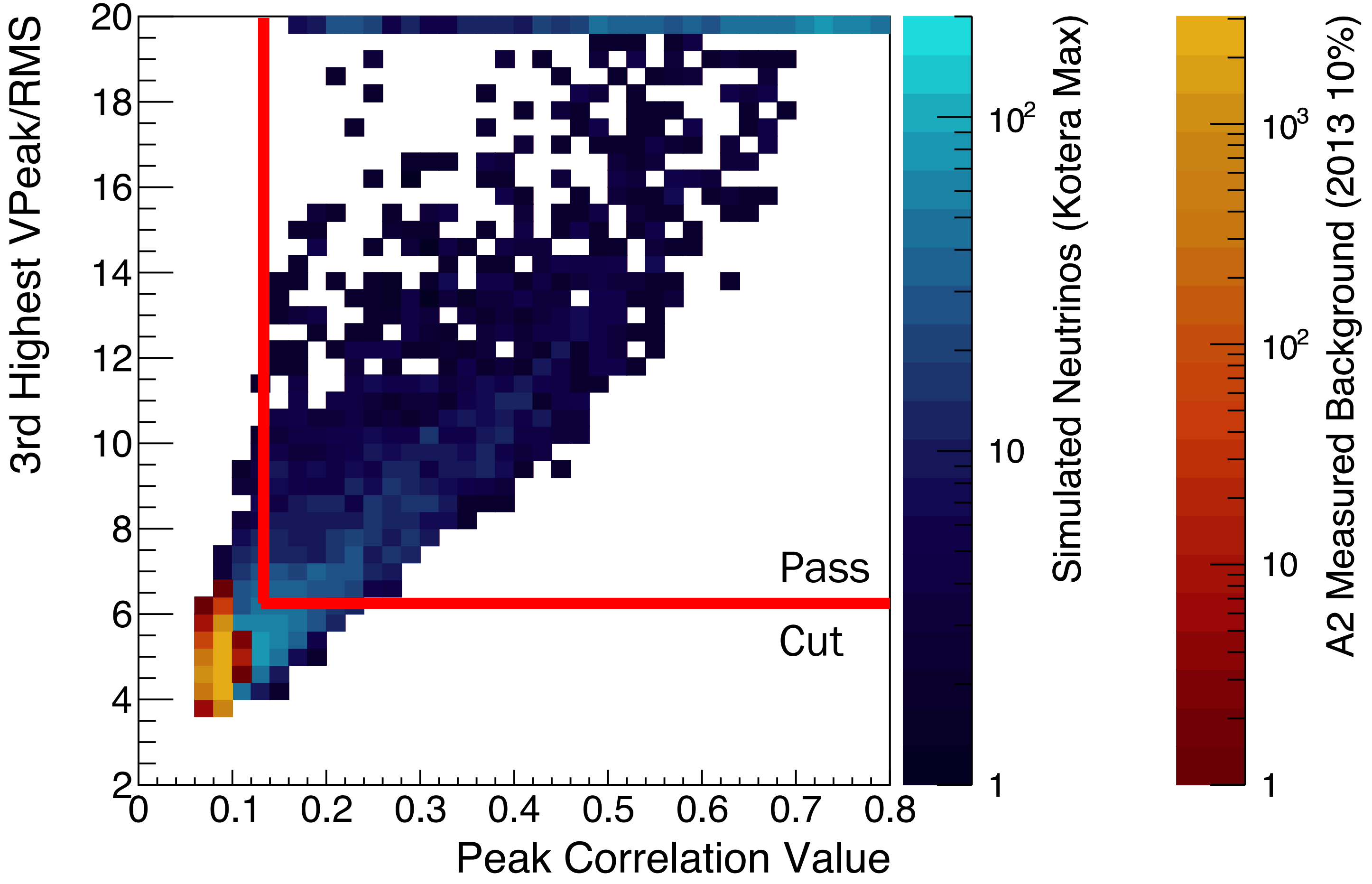




Summed cross-correlation (coherence)

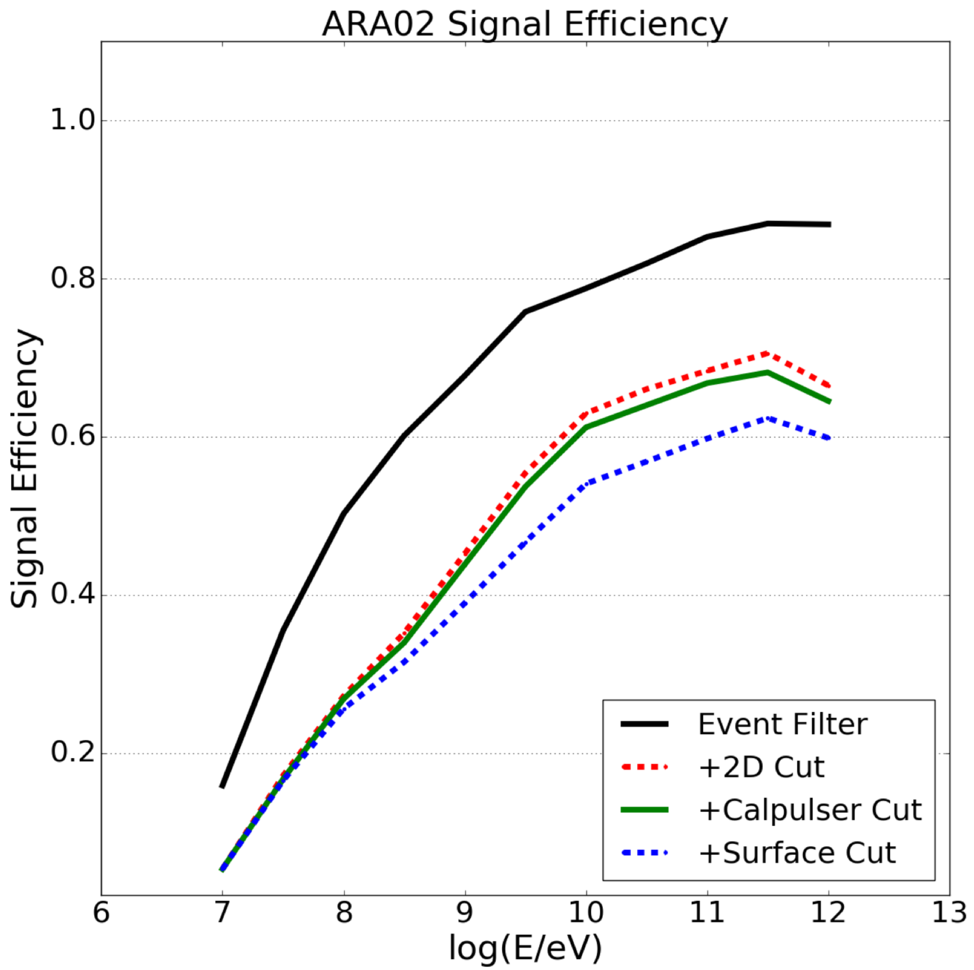
Diffuse Neutrino Search: Separating Signal and Background

- A linear discriminant in the SNR-vs-correlation plane separates backgrounds from neutrinos
- Examples:
  - Box in the plane
  - Line in the plane
- Choose line or box to achieve necessary background rejection (~0.1 passing events/year)

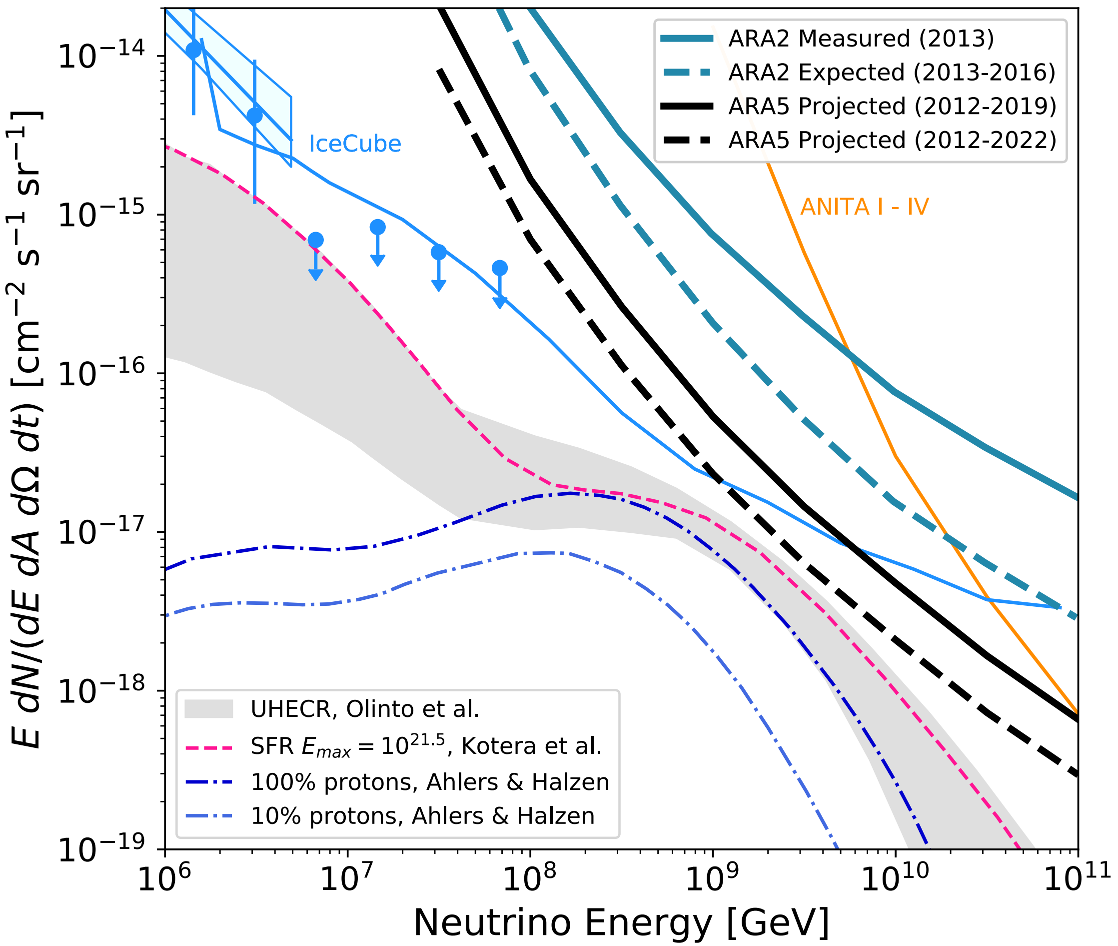


Diffuse Neutrino Search: Projected Limits

- Limits include analysis efficiencies, which are ~40% at an EeV

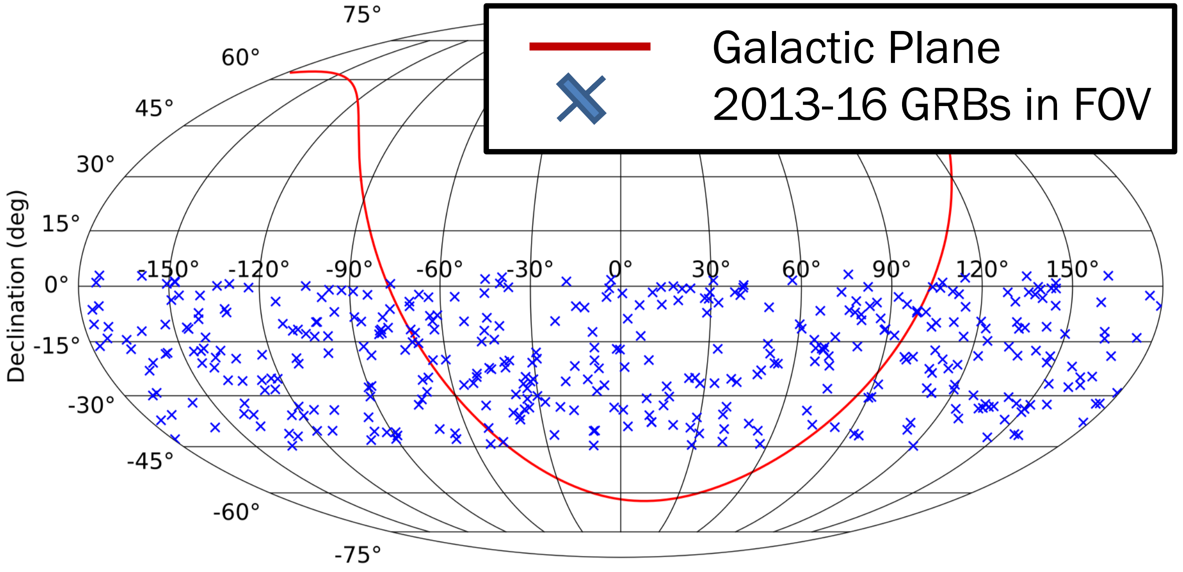


- Projections for ARA5 have exciting physics reach—world leading above 10EeV

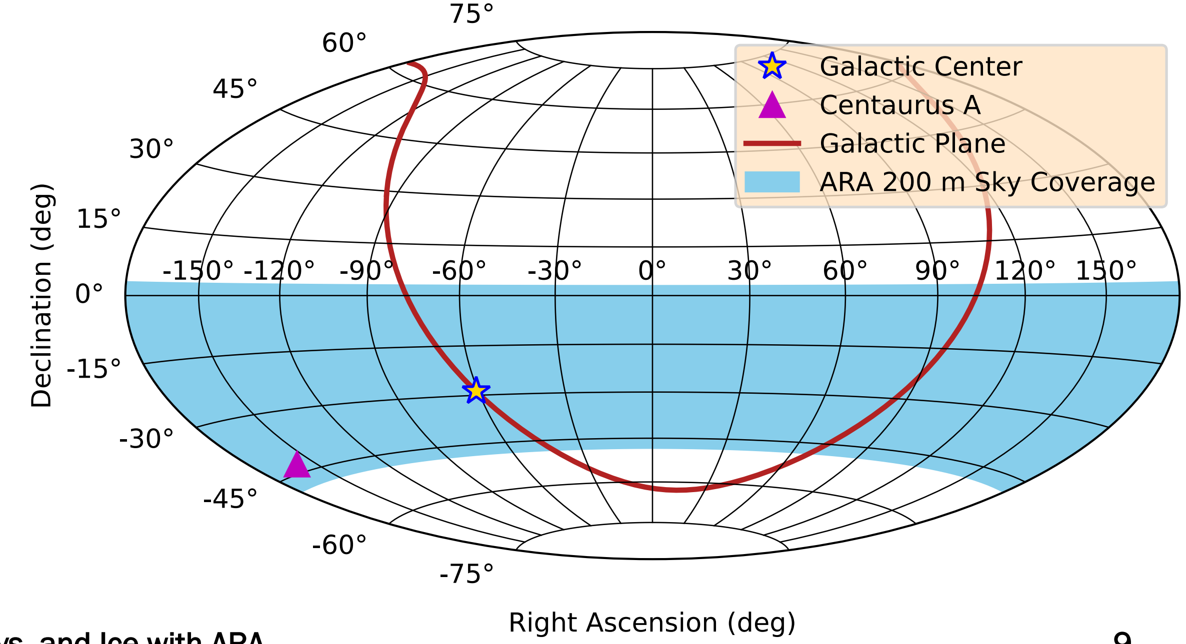


What's next: Source Searches

- ARA continuously monitors 35% of the southern sky
  - Useful multimessenger instrument
  - For both flaring and steady state sources

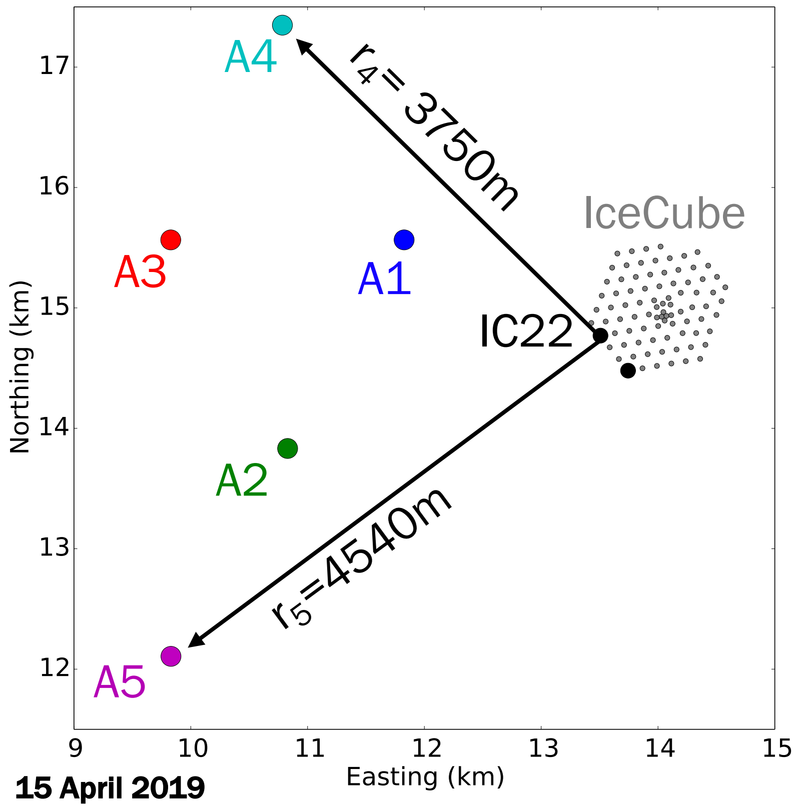


- Cen A is in the field-of-view
  - Bright in gamma rays [HESS 2009, ApJ 695:L40–L44]
  - Auger sees a spatial correlation with a handful of UHECRs [Auger 2007, Science Vol. 318, Issue 5852]
  - UHE neutrino emission is expected [e.g. Cuoco '08, Kachelriess '09]



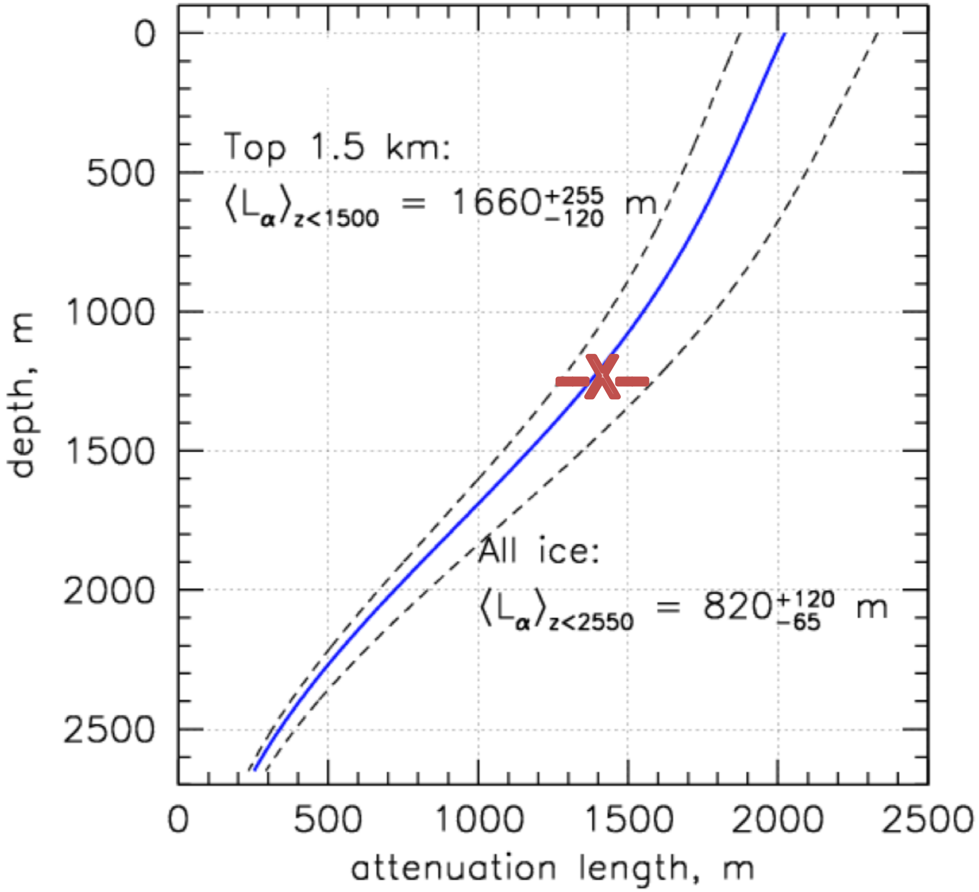
Antarctic Ice Properties: Attenuation Length

- Pulsers deployed on IceCube strings 1 and 22 illuminate the entire array
- Pulse amplitude at A4 vs A5 is the longest horizontal-baseline measurement of L_α



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

Adapted from [P. Allison *et. al.* j.astropartphys.2011.11.010]



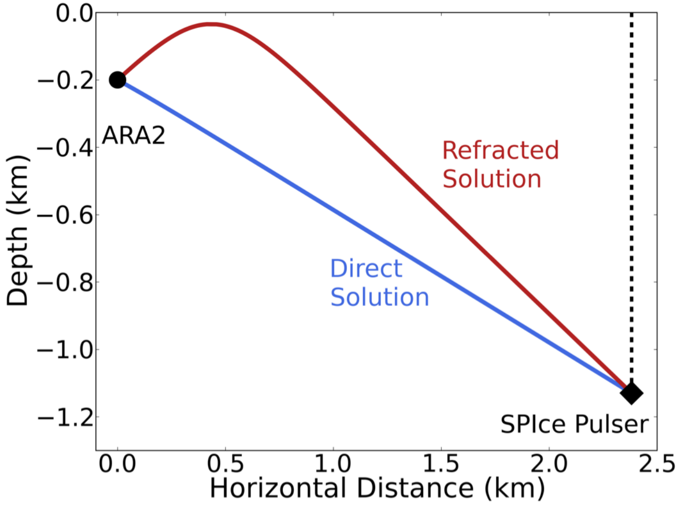
New measurement:
$L_{\alpha,1500m} = 1.43 \pm 0.25$ km

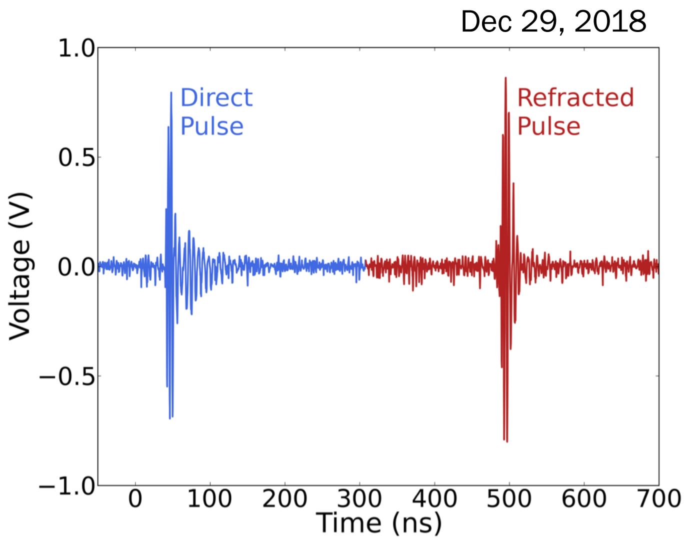
Antarctic Ice Properties: Constraining $n(z)$

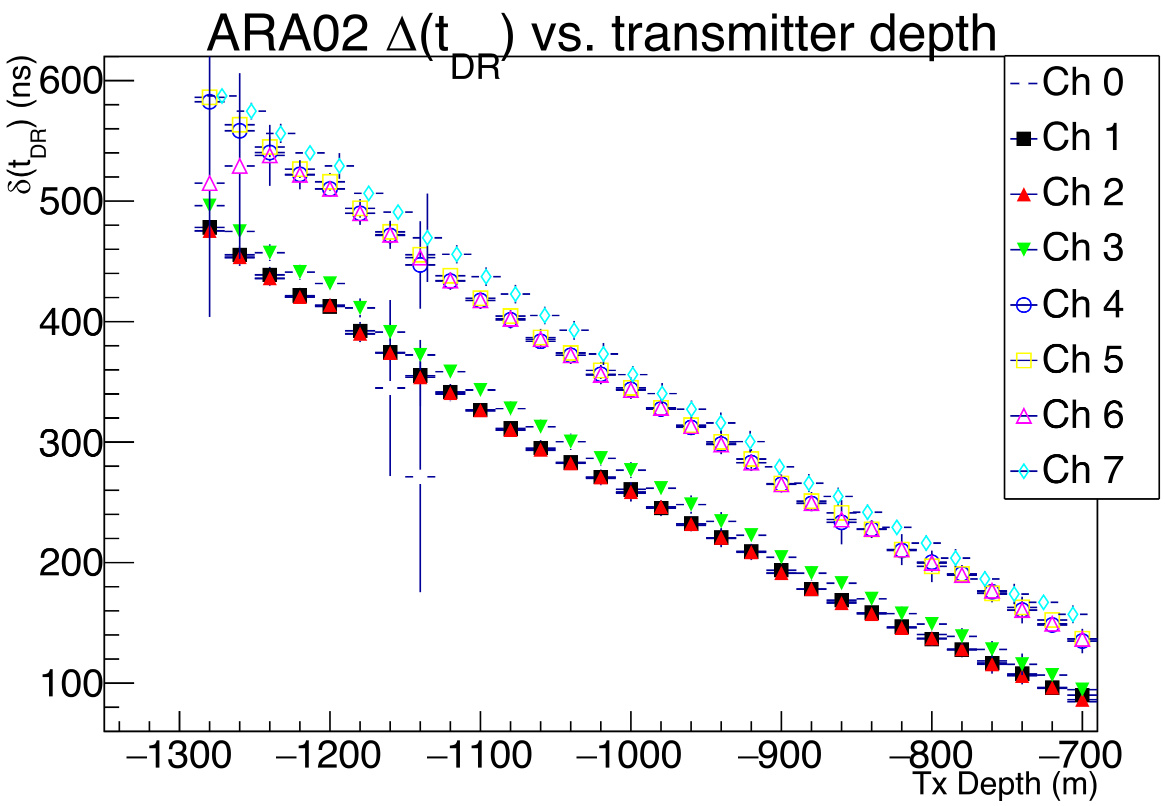
- In Austral season '18 and '19, we deployed pulsers down the South Pole IceCore (SPIce) hole

- The depth dependent index of refraction produces two solutions: direct and reflected/refracted

- Time-difference between pulses is sensitive to n(z)

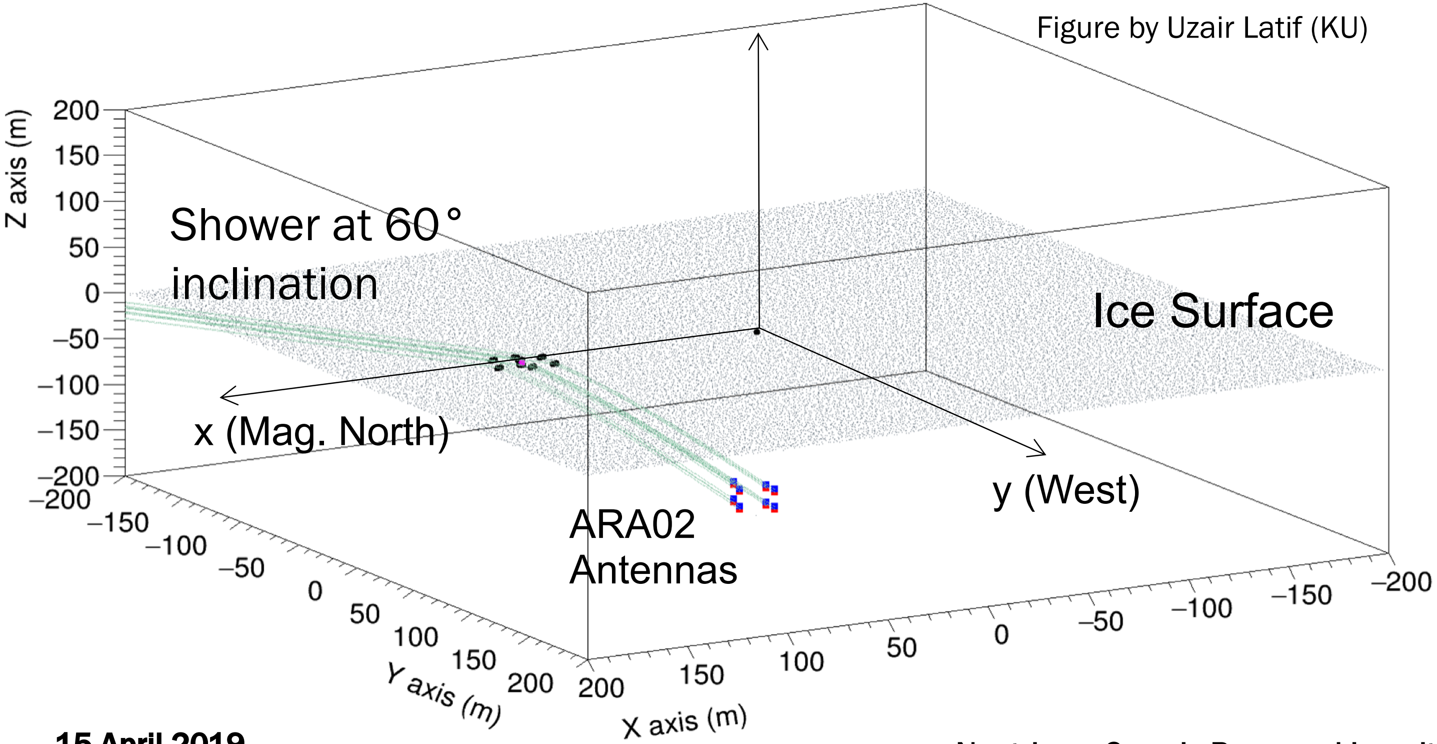


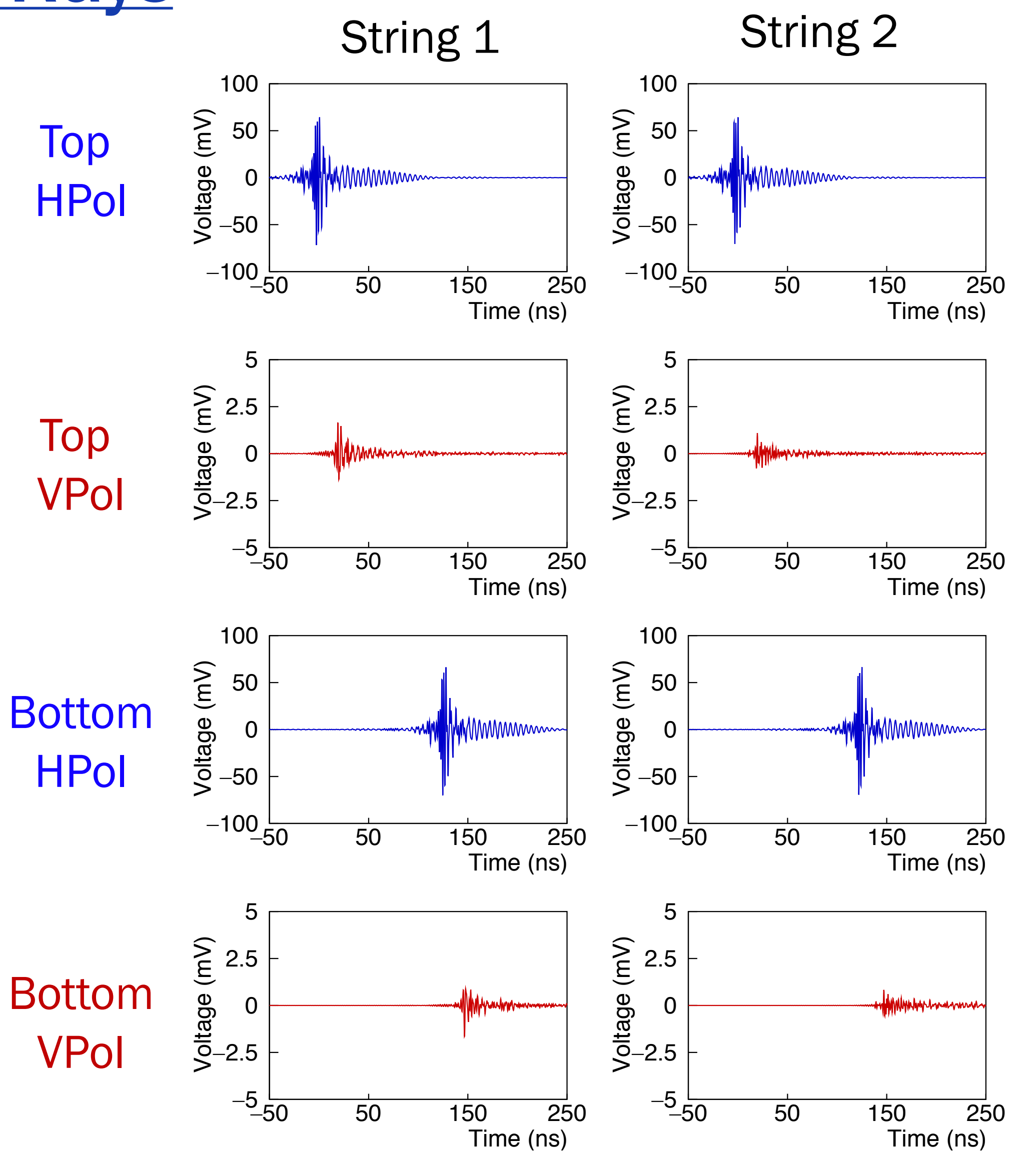




Search for Cosmic Rays

- Cosmic rays are useful “test beam”
- Use CoREAS to generate templates
- Emission is dominant in HPol, as expected from geomagnetic emission at South Pole





Summary

1. New neutrino search with 4x the livetime is nearly complete—**ARA is closing in on world leading limits**

2. Measurements of the Antarctic ice will improve our detector modelling and reconstruction capabilities

3. A template-based search for CR's is underway, and will serve as important "calibration beam" for ARA

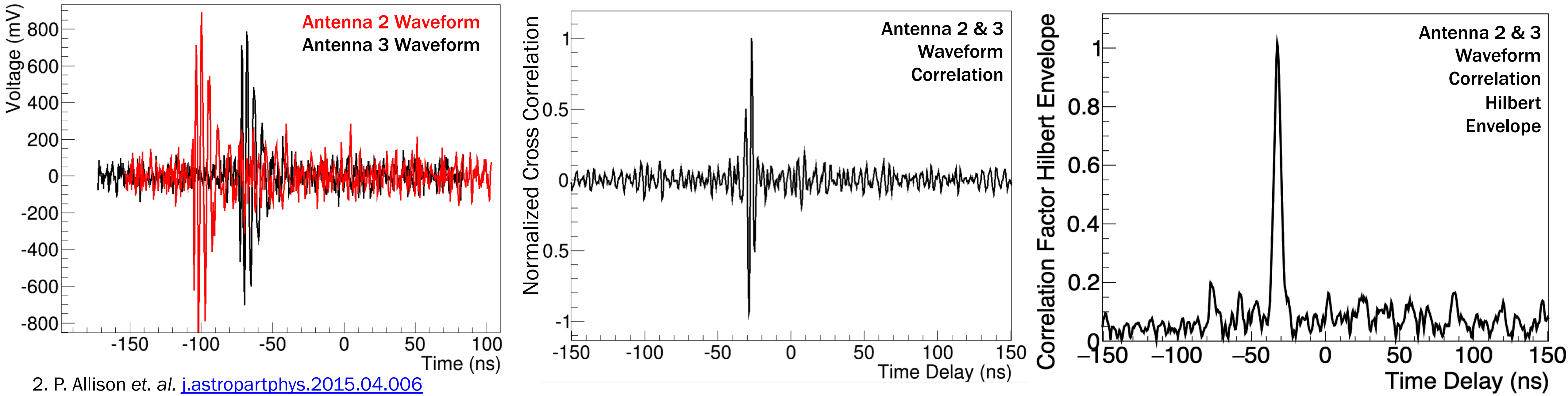
The OSU ARA Team is generously supported by:

- NSF GRFP Award DGE-1343012
- NSF Awards 1255557, 1806923, 1404212

Back-up Slides

Reconstruction Details

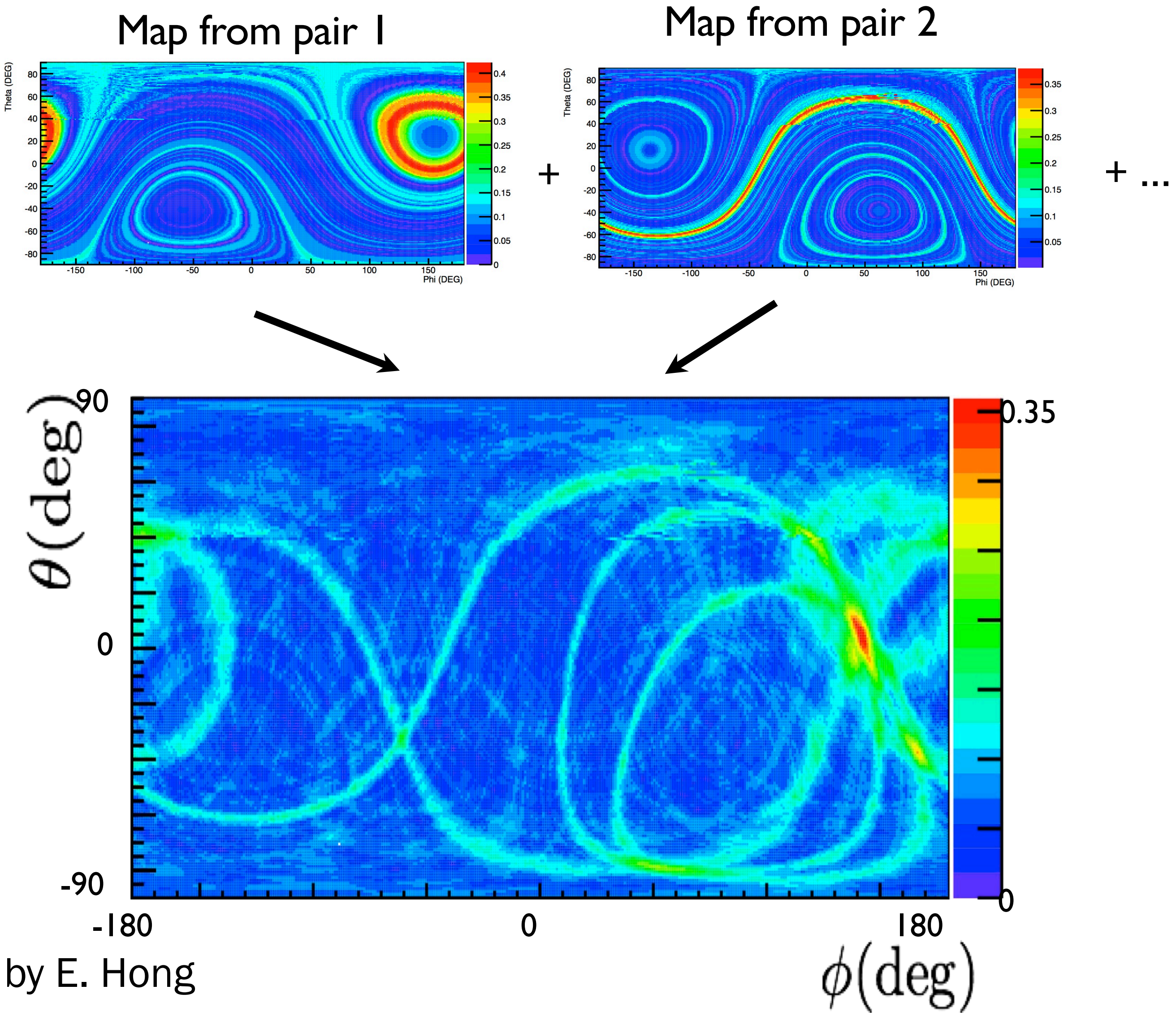
- Interferometry based reconstruction:
  - Putative source angle → Time Delay between antennas → Correlation Value
  - Take Hilbert envelope to interpret as power



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, θ, and ϕ
  - Trace ray from source to array center
- Sum up correlation value for many pairs of antennas
- **Interpret peak in map as source direction**

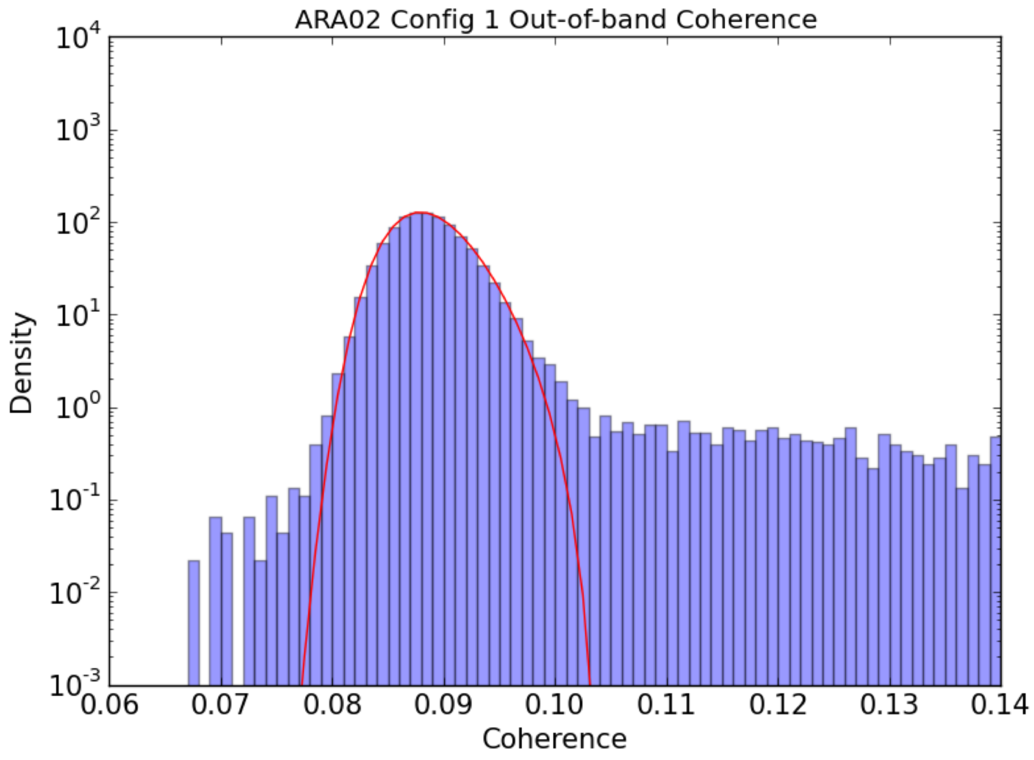


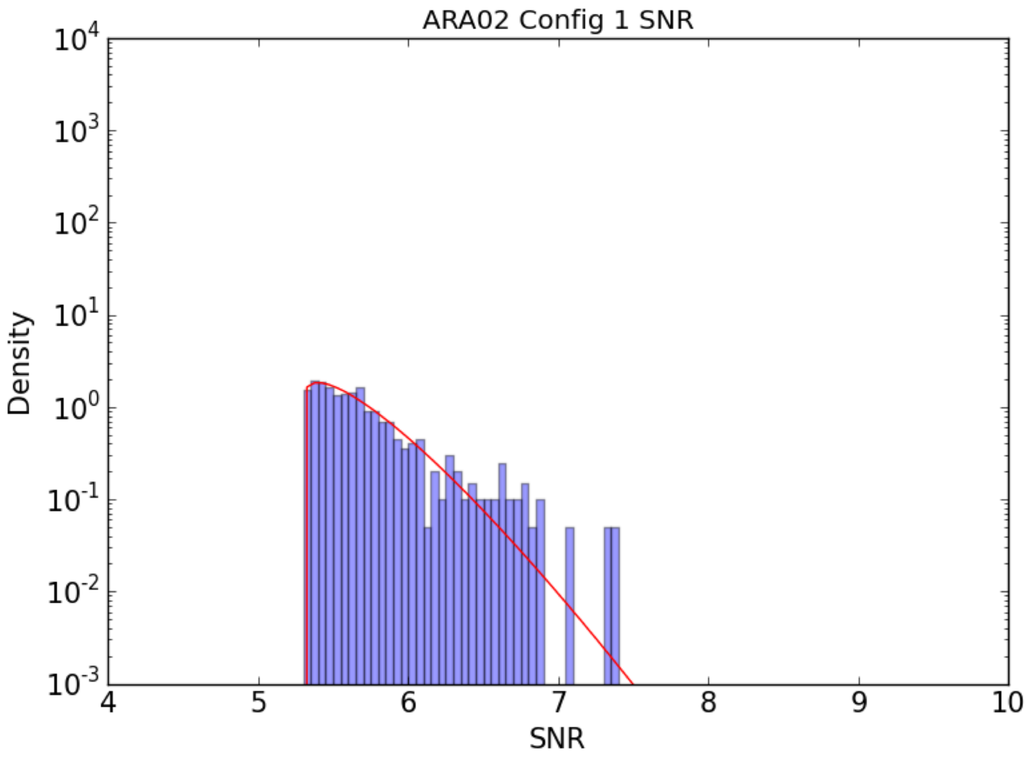
Interferograms by E. Hong

1. P. Allison *et. al.* [j.astropartphys.2015.04.006]
2. P. Allison *et. al.* [j.astropartphys.2016.12.003]

Choosing a Box Cut

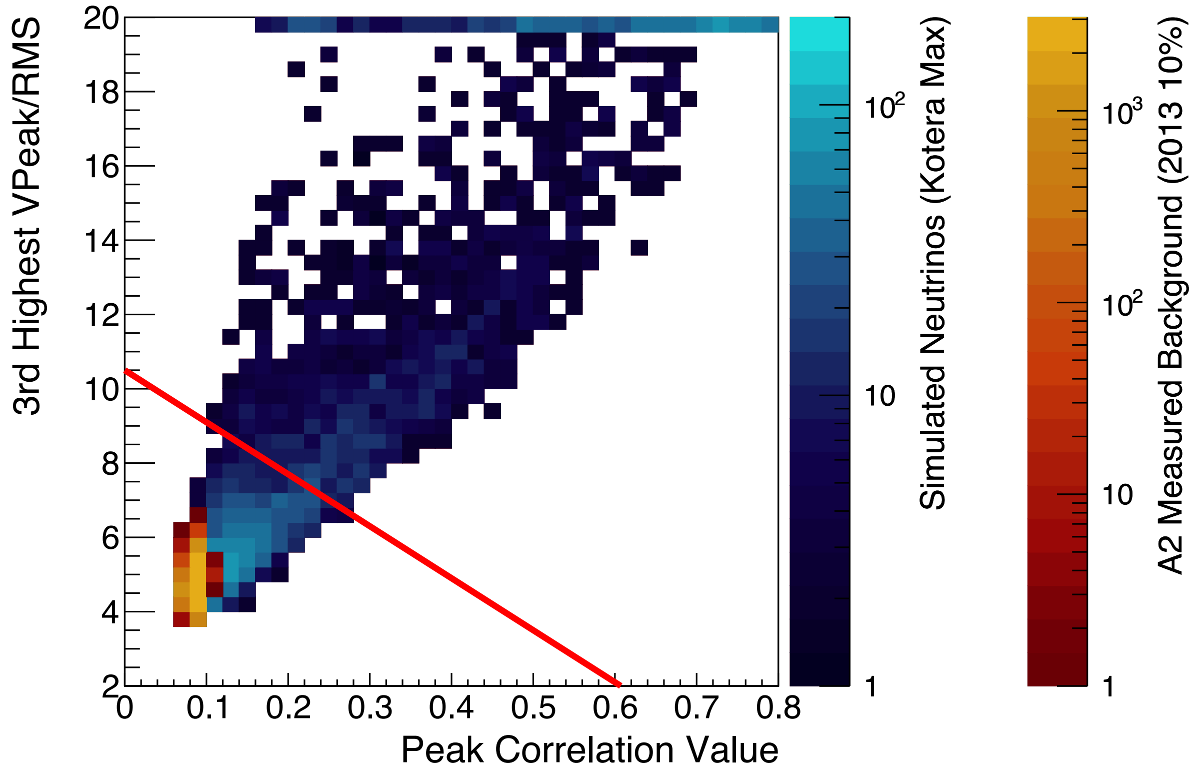
- Thermal cut: fit coherence distribution with GEV, determine the 10^-8 background rejection cut value
- SNR Cut: Fit Weibull distribution, extrapolate to same background rate (~0.1/yr)

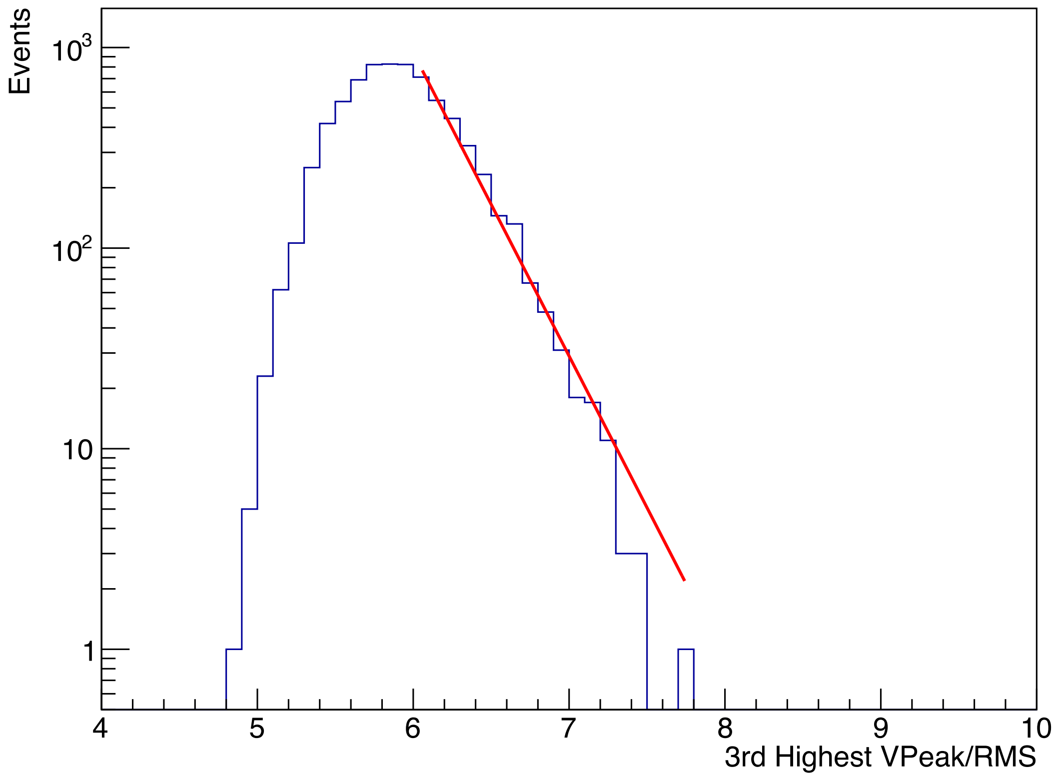




Choosing a Slanted Cut

- Optimize the slope and intercept to achieve best limit on a Kotera flux of neutrinos
- Background estimate comes from exponential fit to the data when projected onto the SNR axis

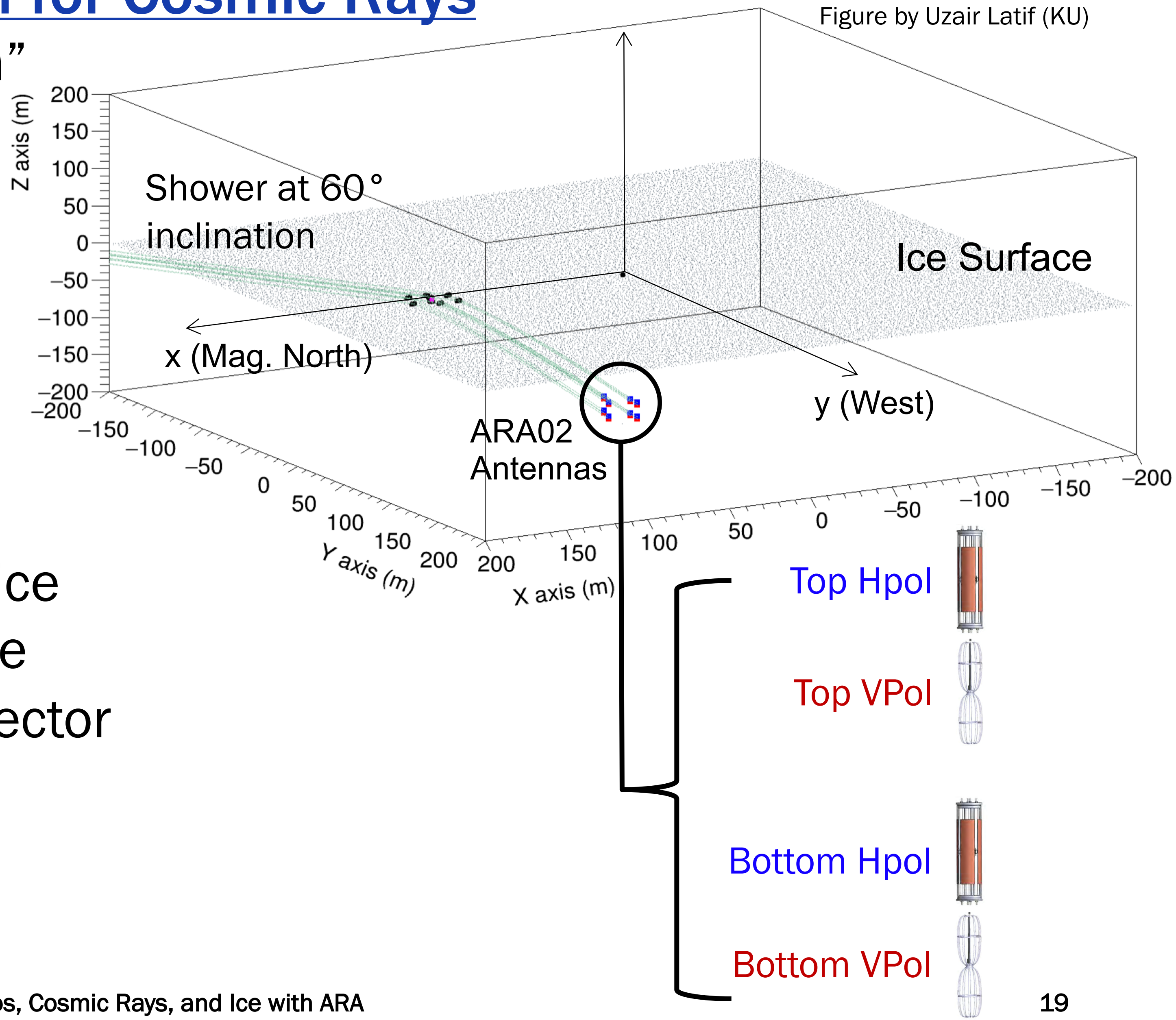




Search for Cosmic Rays

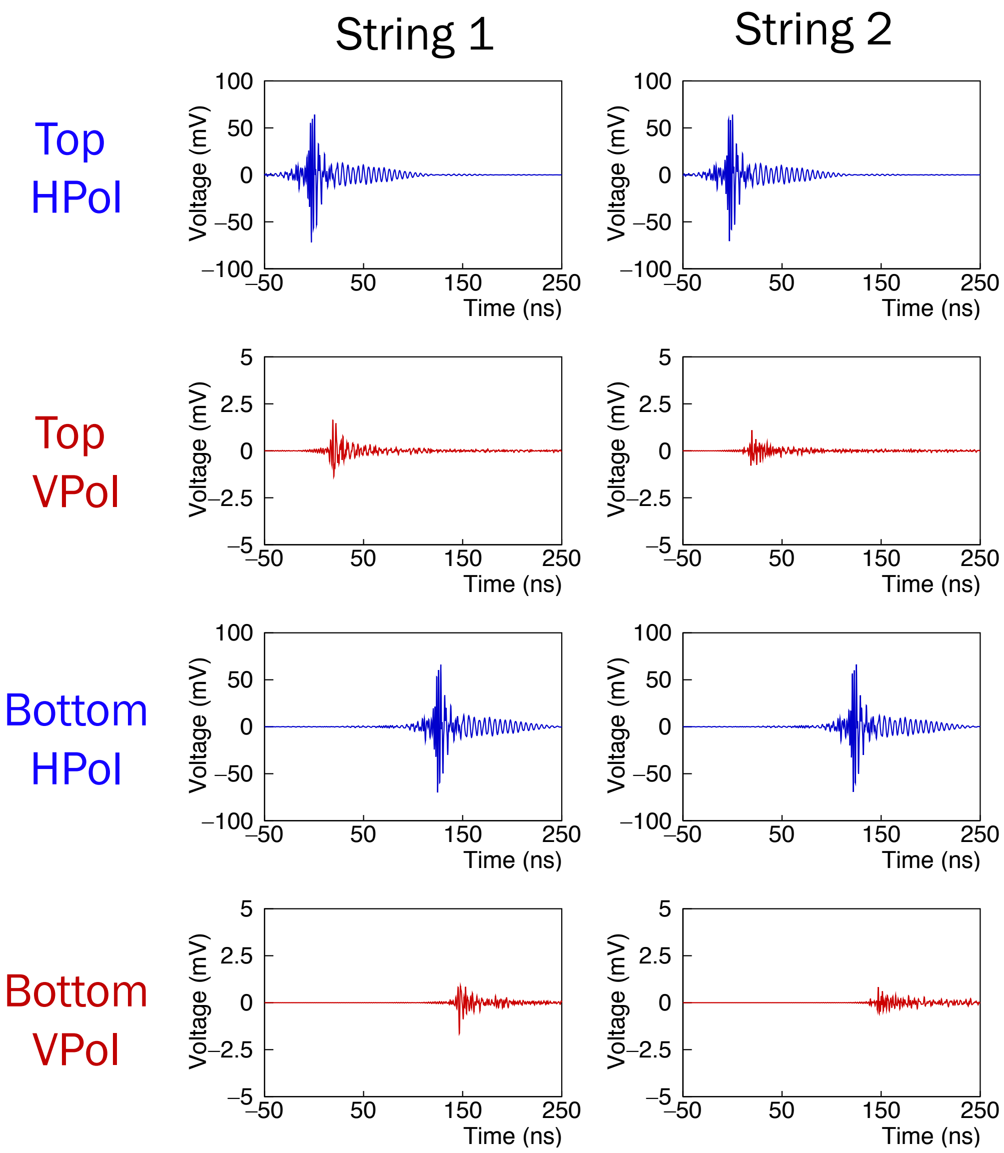
- Cosmic rays are useful "test beam" (flux and the physics of geomagnetic emission is well understood, e.g., ANITA, AERA, Tunka-Rex)

- CoREAS provides emission at the ice surface, which is propagated to the antennas, and folded with the detector response



Search for Cosmic Rays: Templates

- Example CoREAS template
  - EeV shower at 60° inclination
  - Hadronic modelling with QGSJETII.04 UrQMD 1.3
- CoREAS provides emission at the ice surface, which is propagated to the antennas, and folded with the detector response
- Emission is dominant in HPol channels, as expected from geomagnetic emission at South Pole



The ARA Field-of-View

"Zenith angle distribution of detected neutrino arrival directions for a range of neutrino energies. Events are detected over a range from ~ 45◦ above the horizon to ~5◦ below it."

P. Allison *et. al.* "*Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole.*" Astroparticle Physics (2011). https://www.sciencedirect.com/science/article/pii/S092765051100209X