The Askaryan Radio Array: Detector Status and Directional Reconstruction in Neutrino Point-Source Searches

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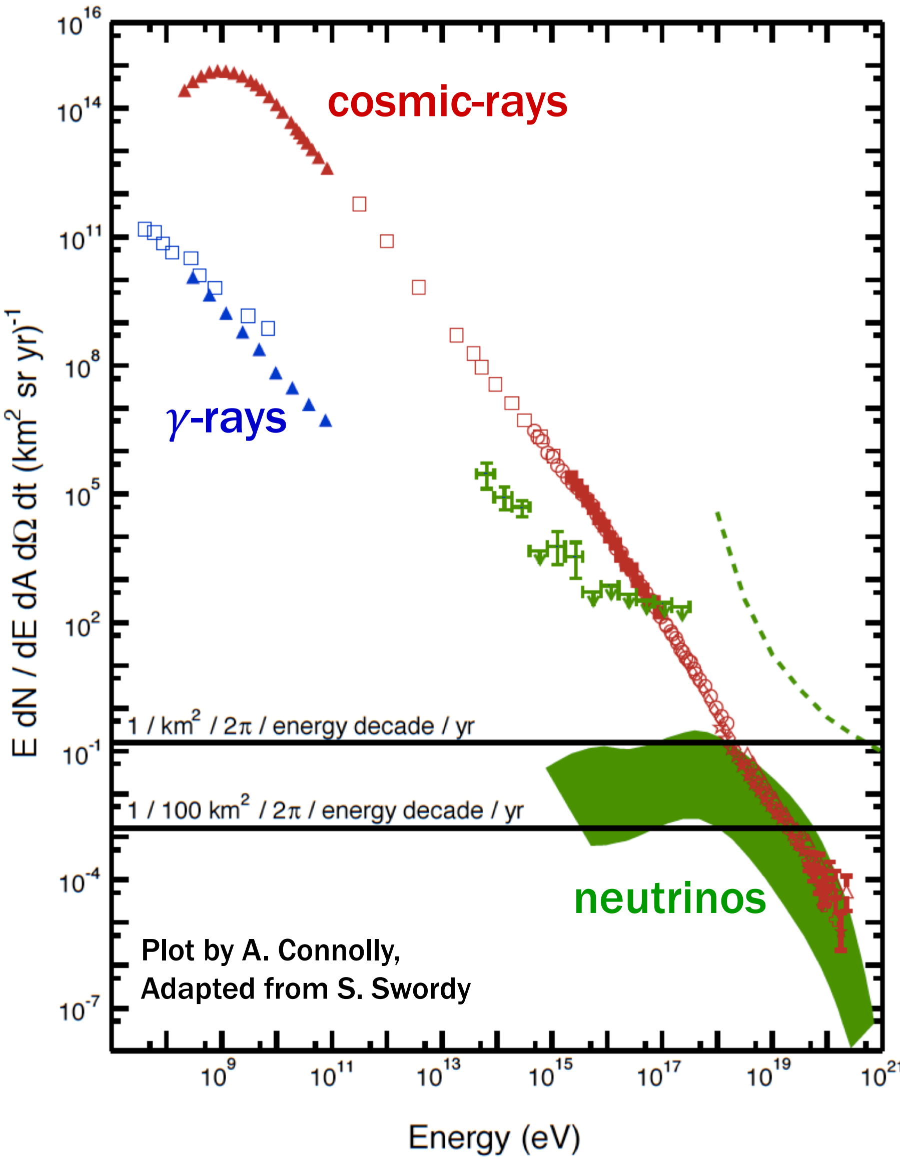
Neutrinos and ARA

Why UHE Study Neutrinos?



UHE means 10^{16} eV and above

Astrophysical Motivation: Only probes of the highest energies at cosmic distances

- Cosmic rays $>10^{19.5}$ eV attenuated by GZK effect
- Gamma rays >~1 TeV pair-annihilate on CMB/EBL

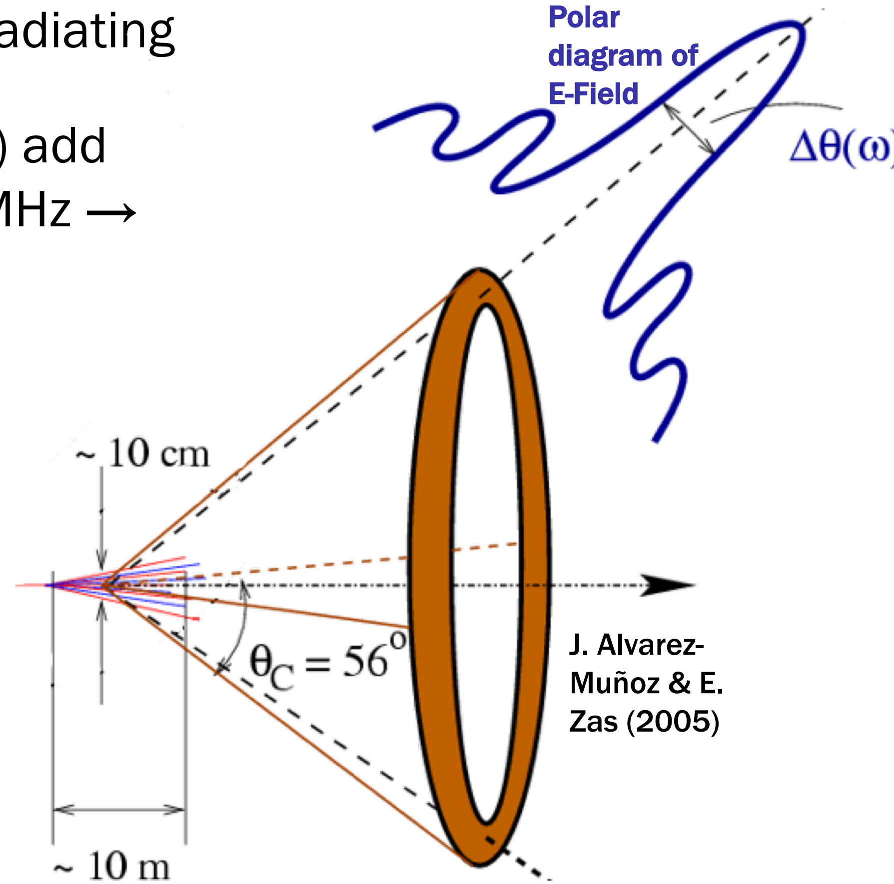
Particle Physics Motivation: Probe cross sections at energies above accelerators

- An EeV (10^{18} eV) neutrino in ice = COM energy of ~45 TeV

Detection through the Askaryan Effect

- Neutrino interaction in dense media creates shower of charged particles
- ~20% more electrons than positrons –"bunch" of particles moving through media and radiating
- Wavelengths the size of the bunch (~cm) add coherently, producing broadband (200 MHz → 1GHz) impulsive radio signal
- Conical emission, strongest signal "on cone"

- **Two requirements for successful experiment**
  - **Radio transparent medium: ice**
  - **Enormous volume: Antarctica**



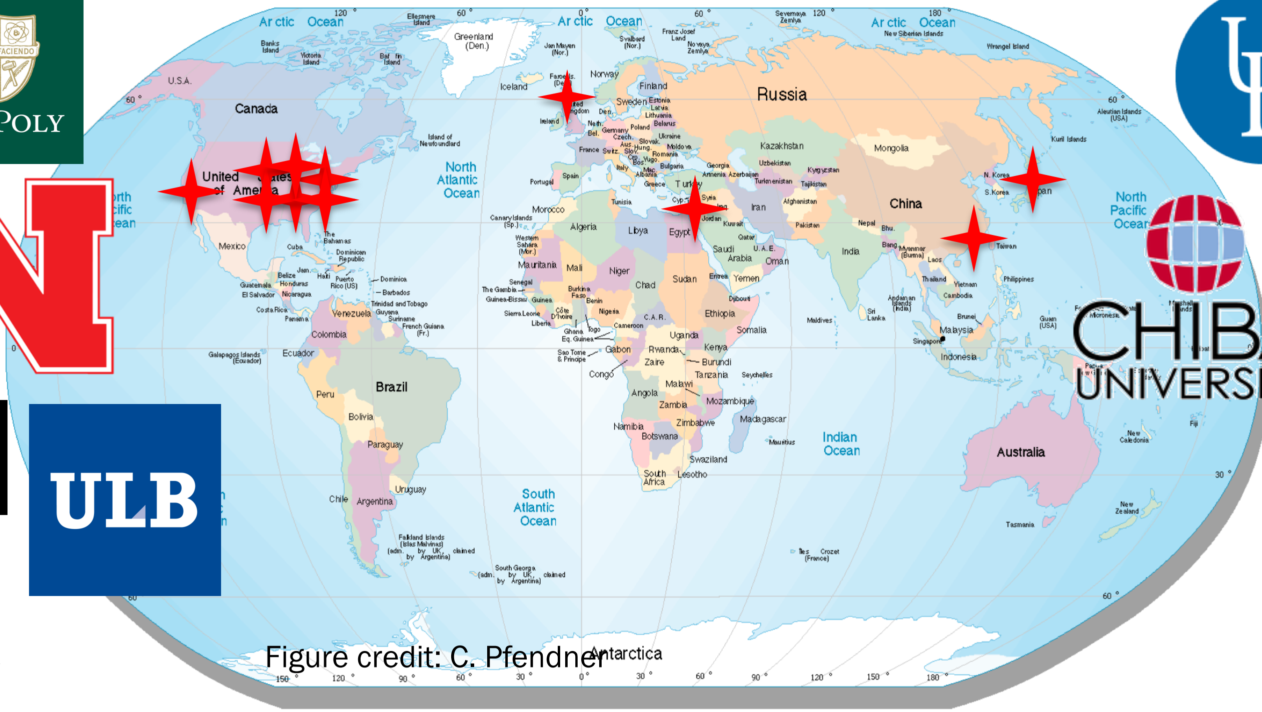


Figure credit: C. Pfendner

ARA is an International Collaboration

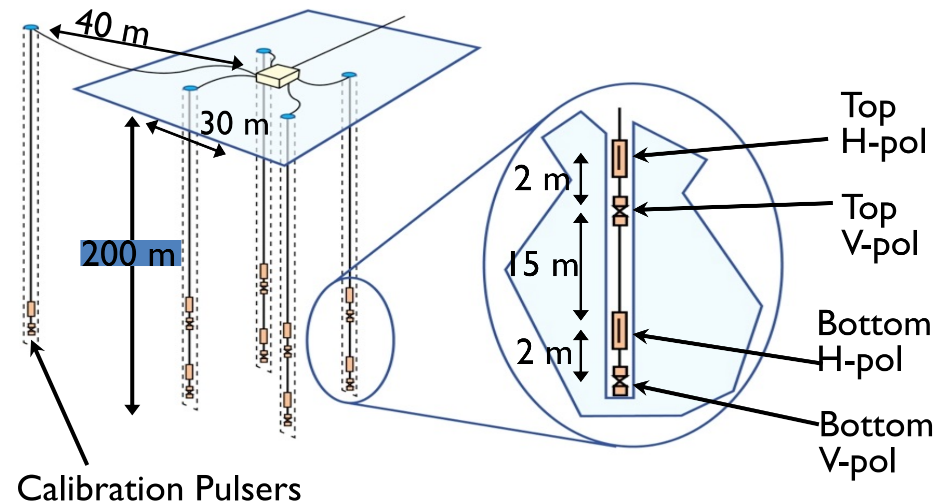
USA:

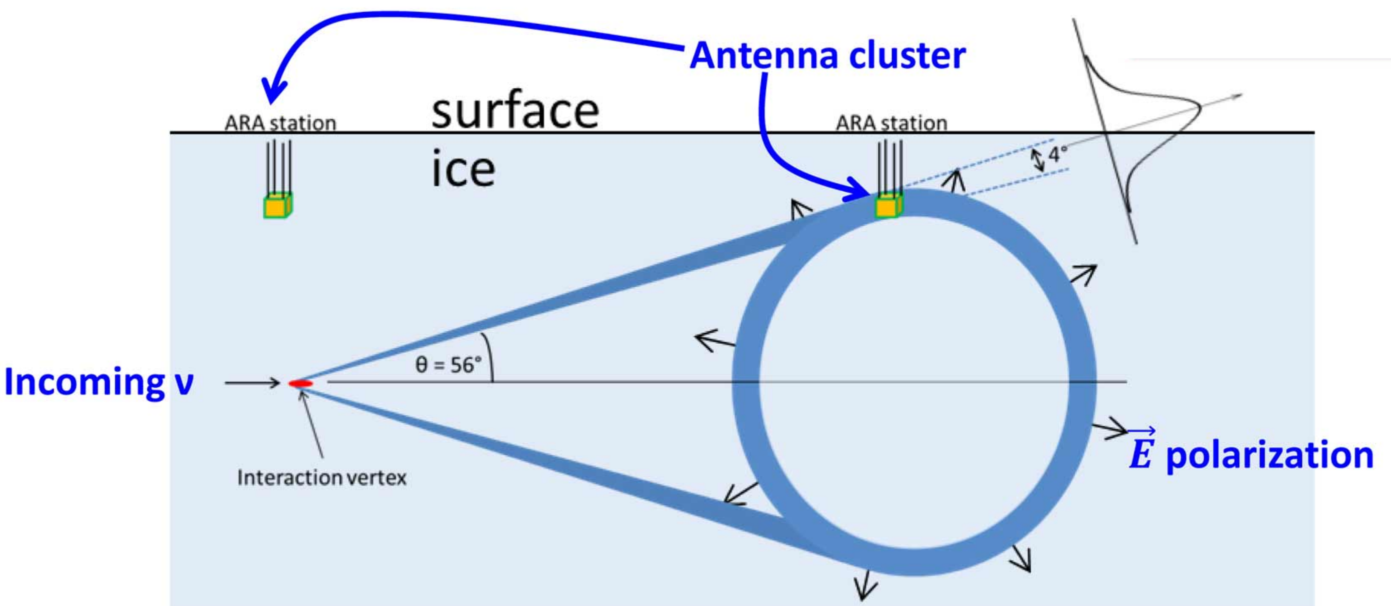
- Cal Poly
- The Ohio State University
- University of Chicago
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison

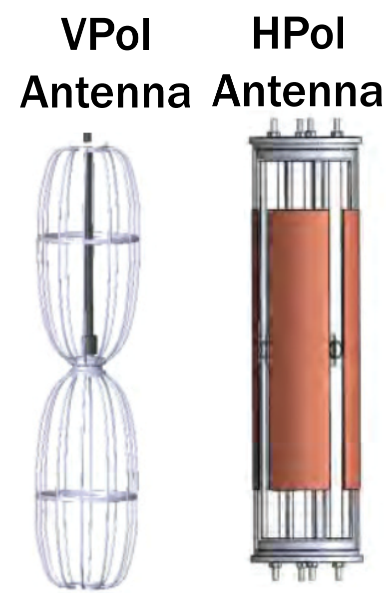
UK: University College London
Japan: Chiba University
Taiwan: National Taiwan University
Israel: Weizmann Institute of Science

Content of an ARA Station

- Antenna array looking for Askaryan emission from neutrinos
- 16 antennas (8 Vpol, 8 Hpol, 200-850 MHz bandwidth)
- Cubical lattice at 200m depth
- Energy range: $10^{16} \rightarrow 10^{19}$ eV

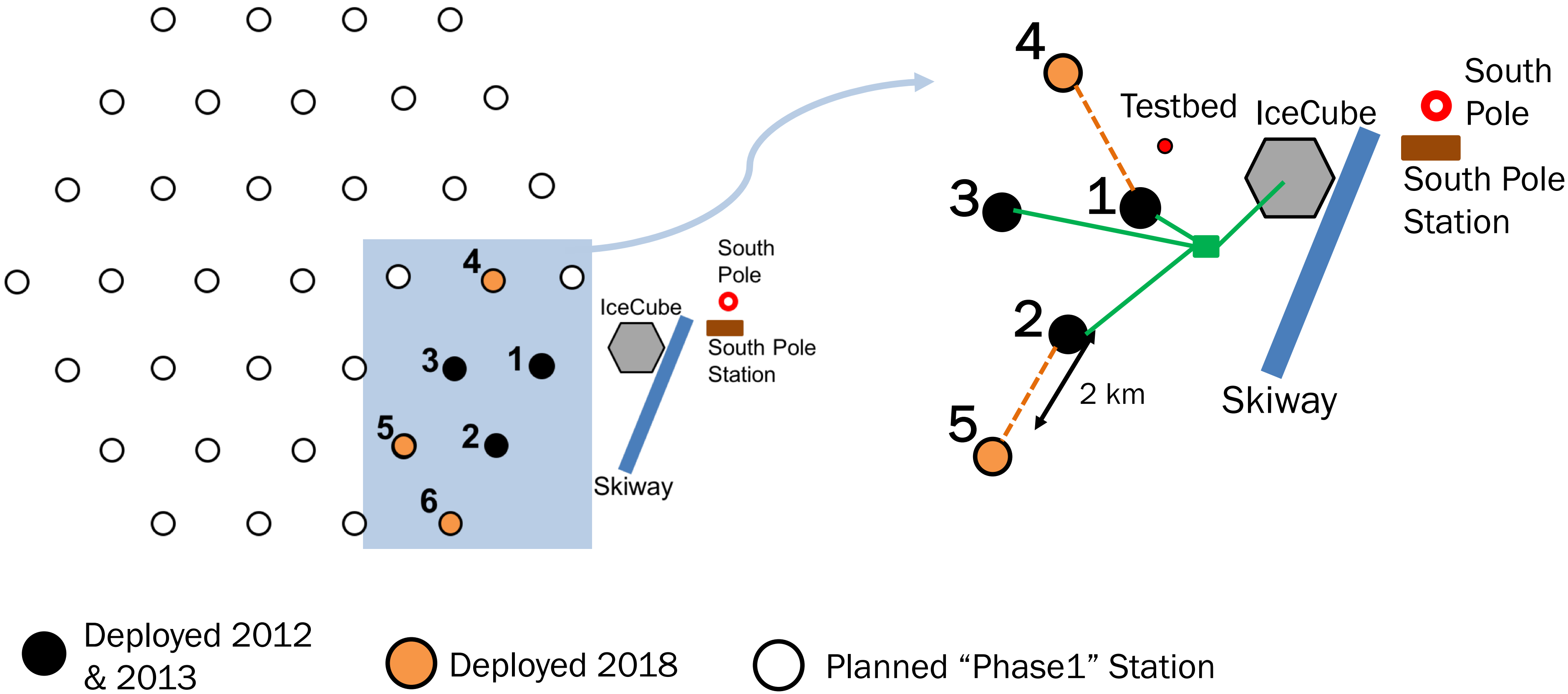






Current Status of the Instrument

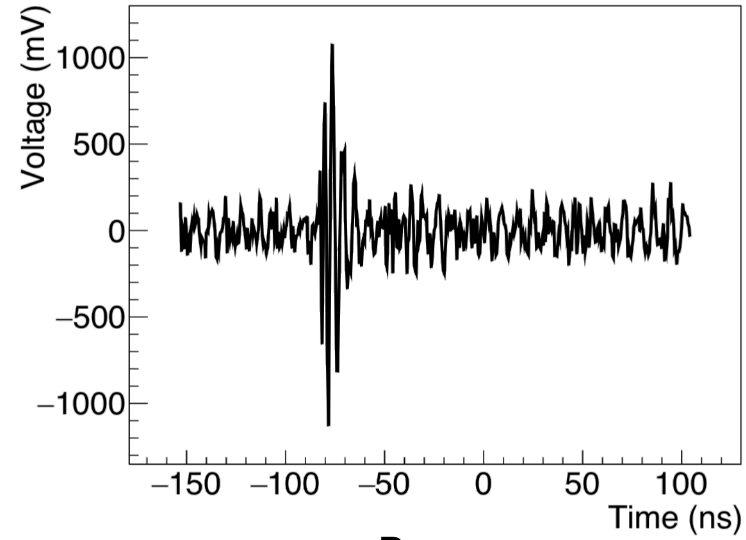
- Under phased construction in the ice near South Pole
- Phase 1 goal is ~37 stations, spaced 2km apart, covering ~100 km^2 of ice
- Prototype ("Testbed") + 5 (!) stations deployed so far



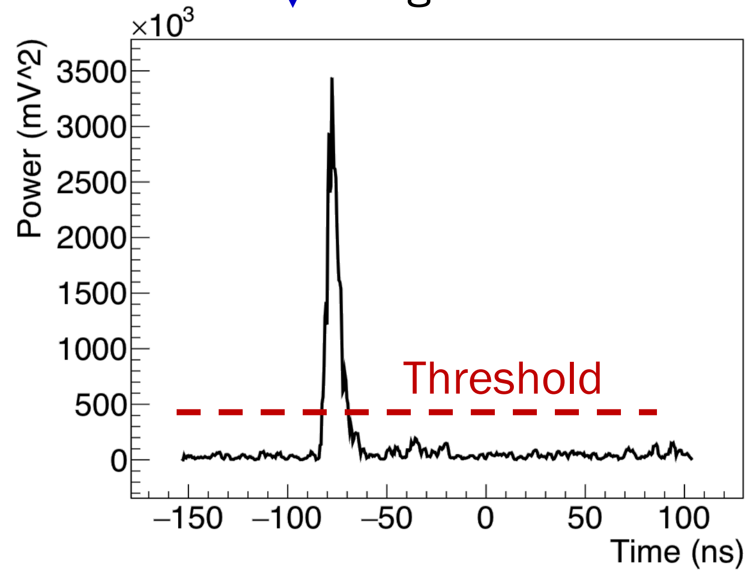
ARA Trigger and Data

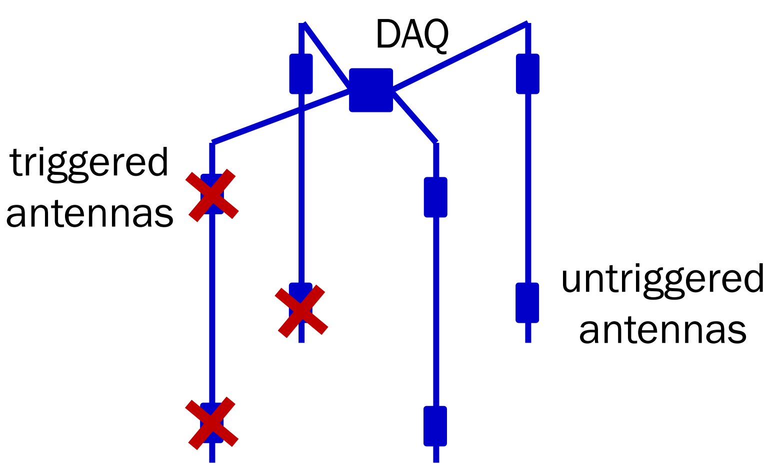
- *Power:* 10ns integrated power > 5.3 × thermal noise floor
- *Coincidence*: trigger in 3/8 antennas of same polarization in ~110 ns
- Thresholds maintain a global ~7 Hz/sta trigger rate → 10^8 evts/year/st
- We calibrate with local and distant pulsers

Calibration Pulser
Testbed Station



Power Integration

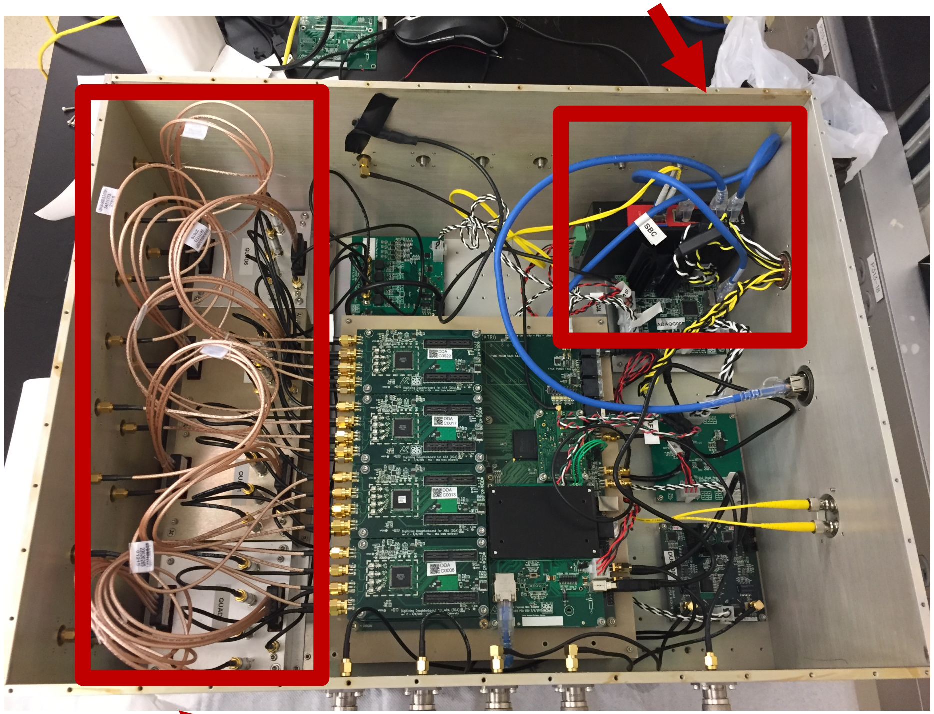




What's New

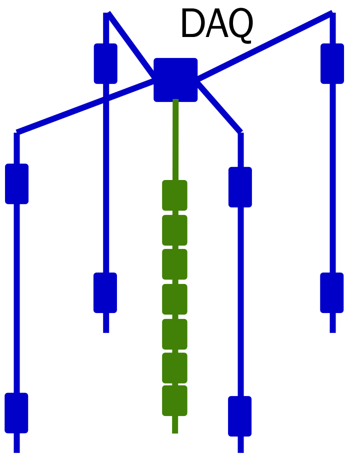
New Stations

- ARA deployed two new stations (A4, A5) in January 2018
- Robustly tested: run, fully assembled, for >1 mo in the north @ UW PSL
- DAQ runs ~4 days at -40 C in thermal chamber at OSU CCAPP Antarctic RF Test Facility
- All are equipped with new, exciting electronics
  - A power-broker to improve system monitoring and control
  - Cheaper, more compact, and more flexible signal conditioning

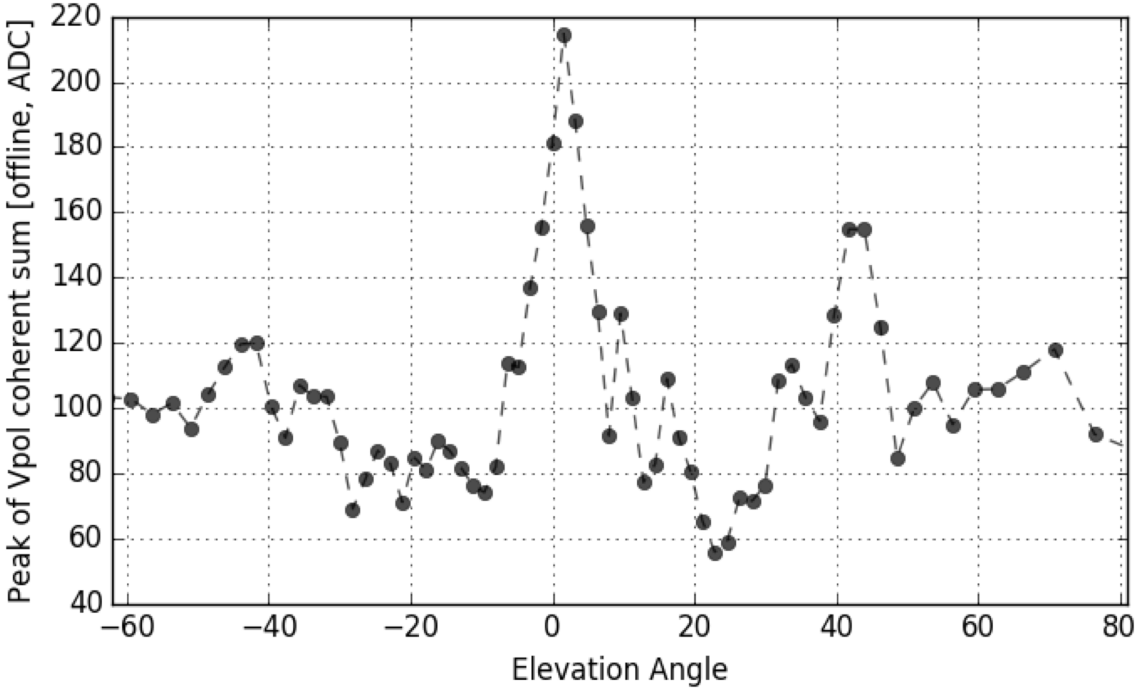


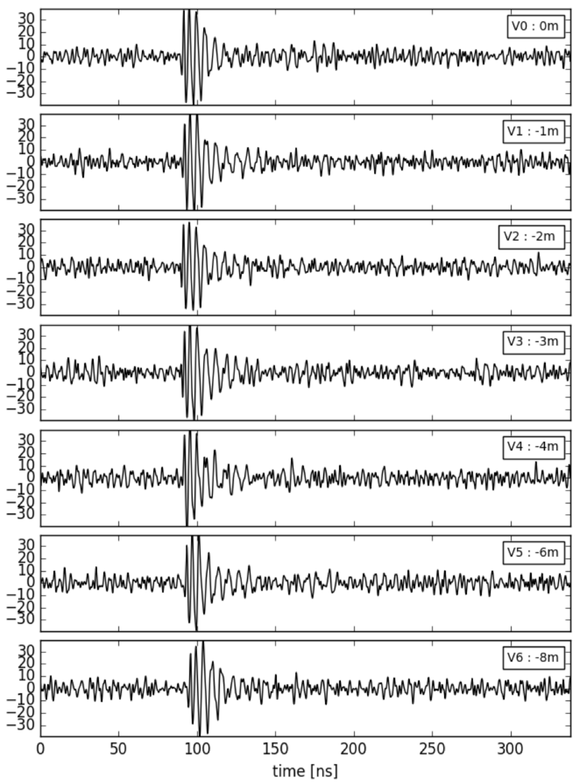
ARA4 DAQ Box

New Phased Array w/ A5

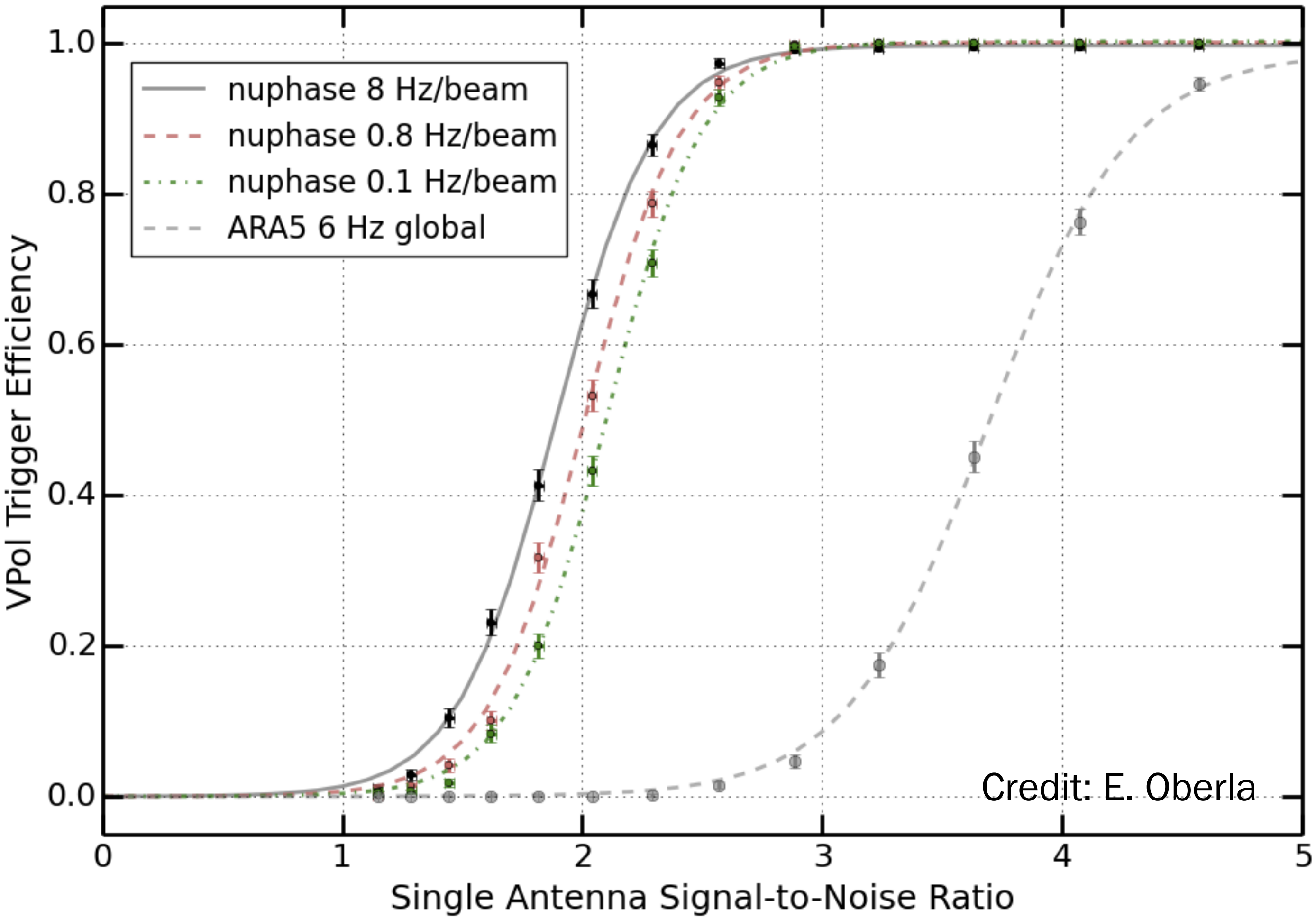


- ARA5 is equipped with a new *phased array* trigger (led by A. Vieregg @ UChicago)
- 7 VPol antennas deployed down *single* hole in the middle of A5
- Beamform *before* triggering ⟶ higher sensitivity
- Because for fixed trigger rate, threshold $\propto \sqrt{N}$





Phased Array Performance Comparison

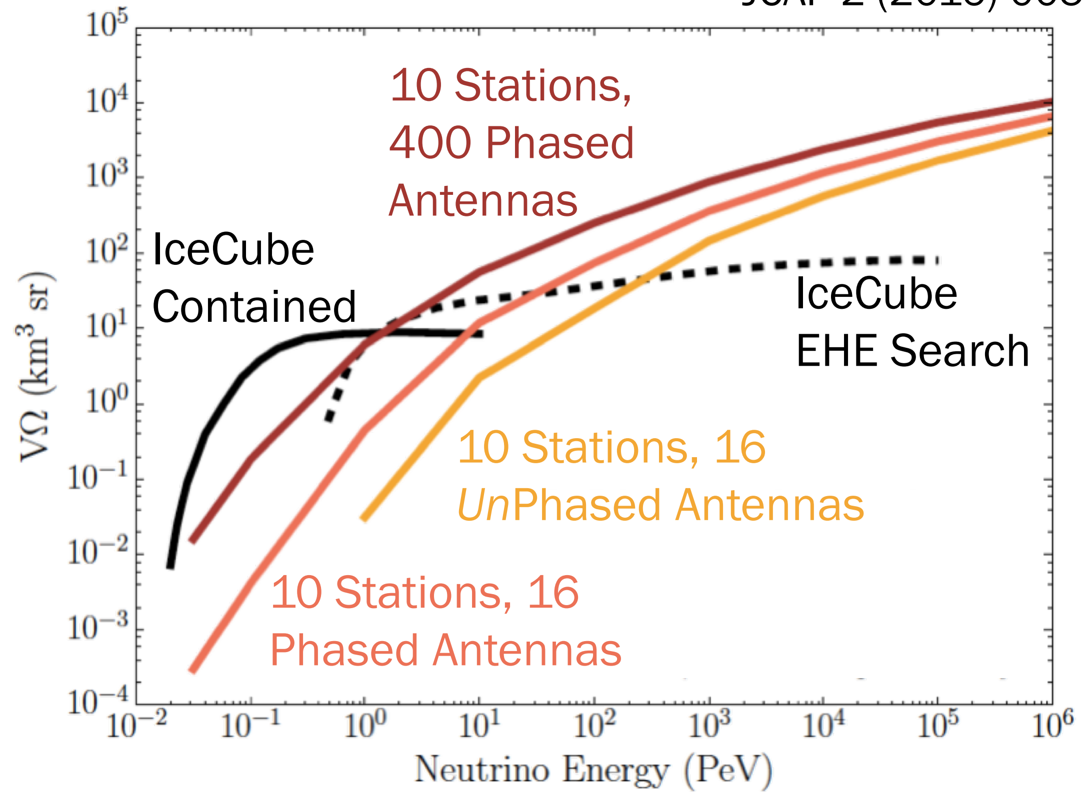


Preliminary:
PA measurement demonstrates factor ~1.8 reduction in 50% efficiency point (expected ~2.6).

Phased Array Sensitivity

A. Vieregg et al., JCAP 2 (2016) 005

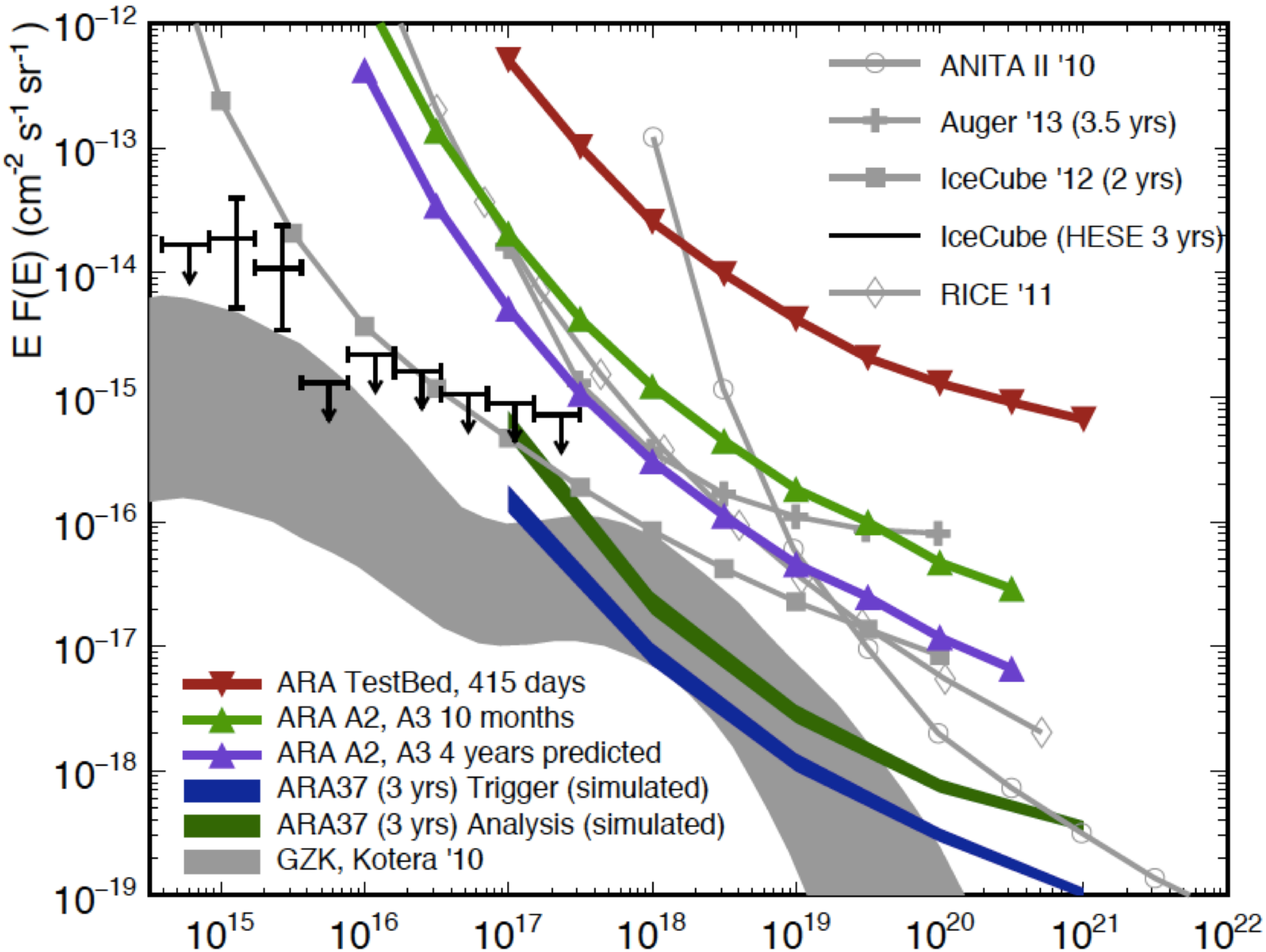
- Phased array enhances neutrino sensitivity and lowers energy threshold to ~10 PeV
- Cross-check IceCube flux
- Resolve whether IceCube is seeing a spectral cutoff



10 stations, 3 years livetime

Station Configuration	Power Law	Power Law with Cutoff	Optimistic Cosmogenic	Pessimistic Cosmogenic
16-antenna	0.9	0.0	7.7	2.3
16-antenna, phased	3.8	0.1	19.6	6.0
400-antenna, phased	18.4	2.2	52.9	15.6

Diffuse Analysis Status



C. Pfender, APS April U17.00006

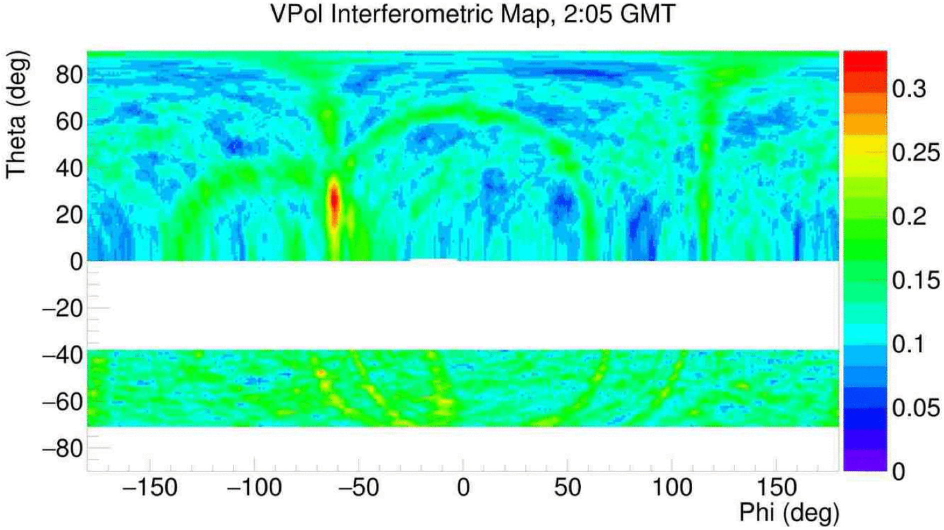
Two station, four year diffuse search in the works; Led By Carl Pfender (OSU).

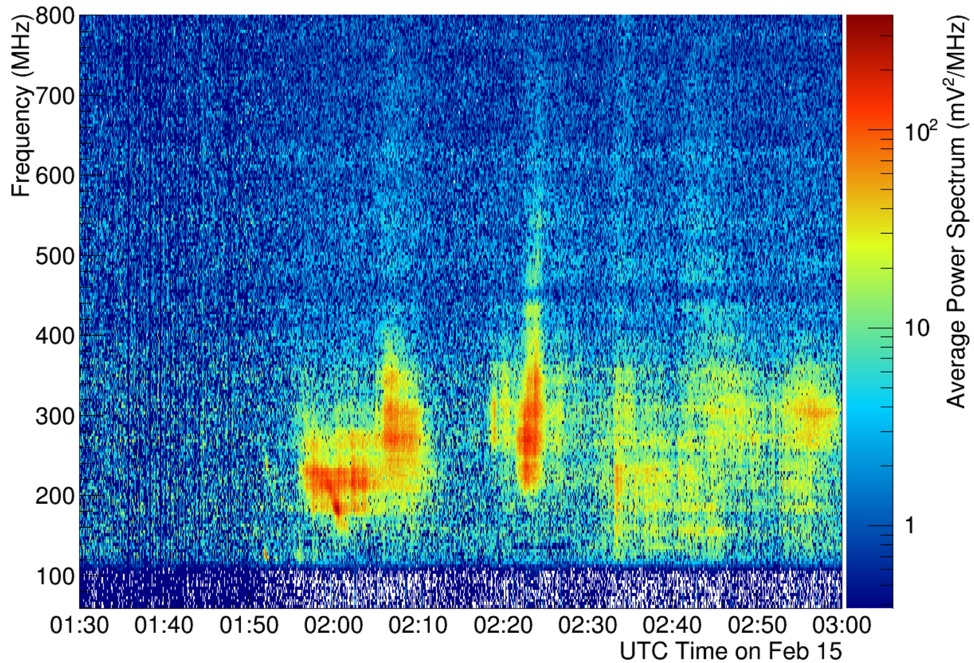
ARA becomes competitive with Auger/IceCube at high energies.

Phase 1 array should probe even pessimistic cosmogenic models.

Solar Flare in the Testbed Prototype

- Testbed activated in February 2011, detected Feb 15 X-2.2 Solar Flare
- The V-Pol RF reconstruction peak tracks the sun across the sky (with some systematic offsets under study)
- Powerful calibration source: can confirm coordinate projection onto celestial sphere
- First reconstructable emission of extraterrestrial origin to trigger ARA — paper with details soon

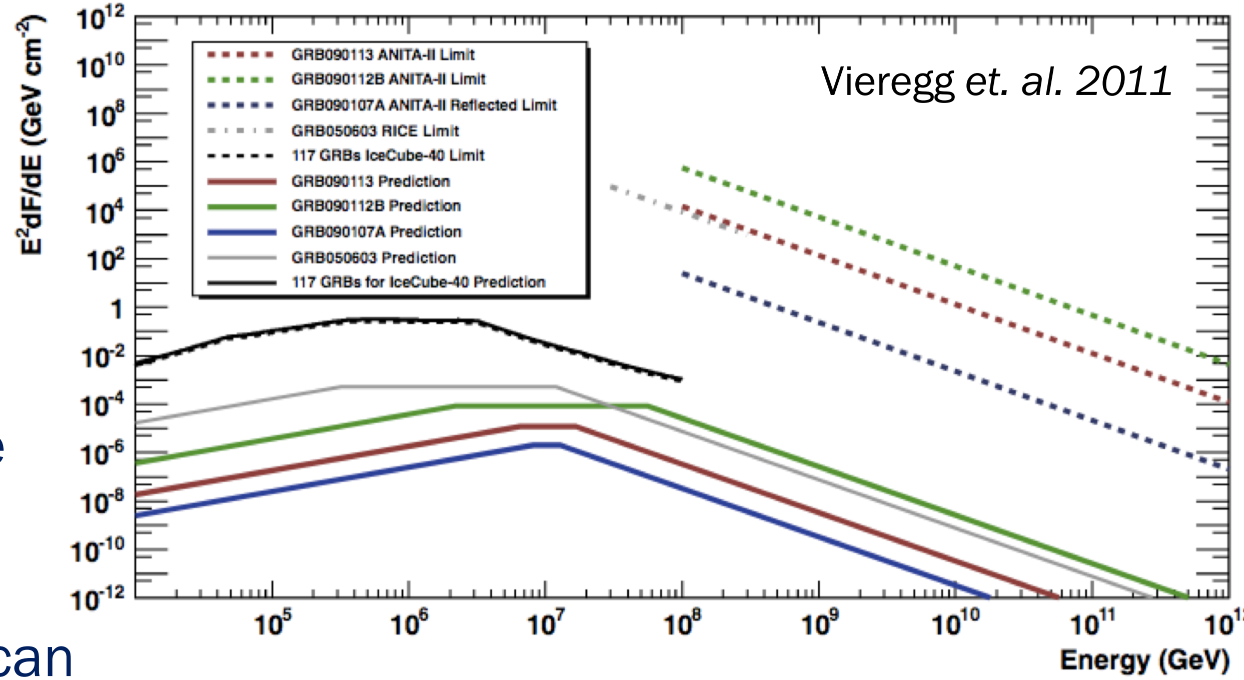




Pointing and GRBs

Motivation

Idea: reduce analysis thresholds for neutrino source searches

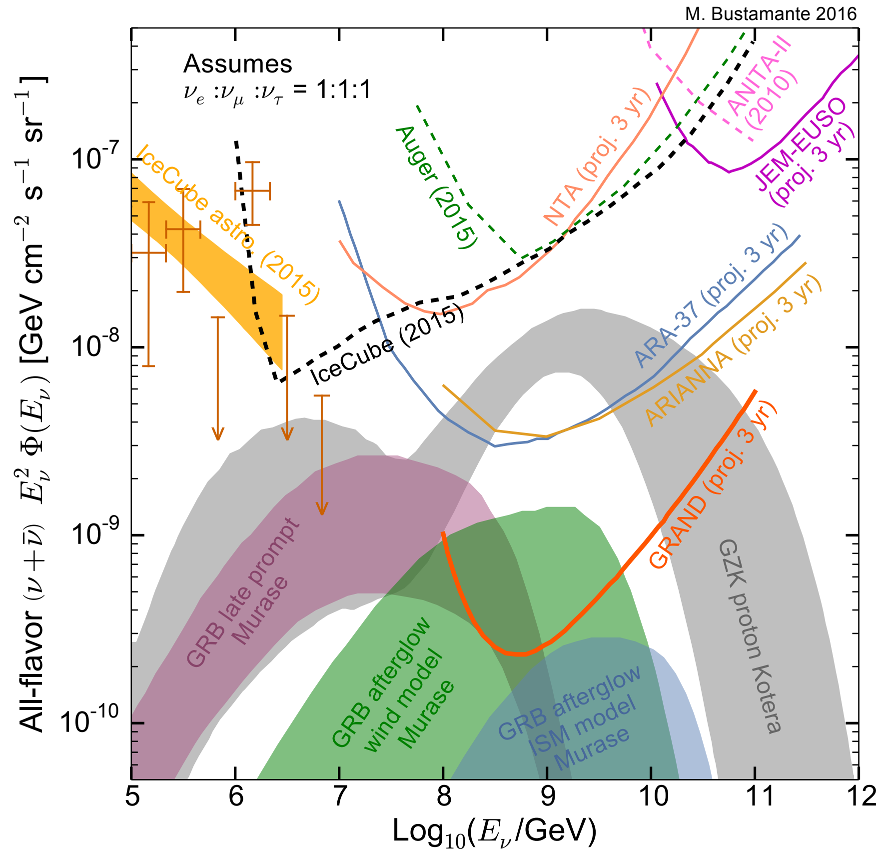


- A standard, *diffuse* searches require the *strictest* cuts
  - Neutrinos can come from "anywhere, anytime" → RF background can come from "anywhere, anytime"
- In a transient search, straightforward way to lossen cuts: restricted timing
  - ANITA-II searched for *prompt* neutrinos from GRBs [A. Vieregg *et. al.* ApJ 736 (2011) 50] 10-minute signal window, 12 GRBs in the sample

Motivation

- But, not every source search allows for such small time windows
- Example: *afterglow* neutrino fluxes > *prompt* fluxes above ~$10^{17.5}$ eV, where ANITA is more sensitive
- Which is challenging, because afterglows require larger signal windows:
  - Prompt neutrino search: ~10 min signal window [A. Vieregg *et. al* ApJ 736 (2011) 50, *P. Allison et. al.* Astropart.Phys. 88 (2017) 7-16]
  - Afterglow neutrino search: >2-3 hrs signal window [K. Murase *et. al.* PRD 76 (2007) 123001, J. Thomas *et. al.* arXiv 1710.04025]
- So, need another way to reduce thresholds…

Plot by M. Bustamante



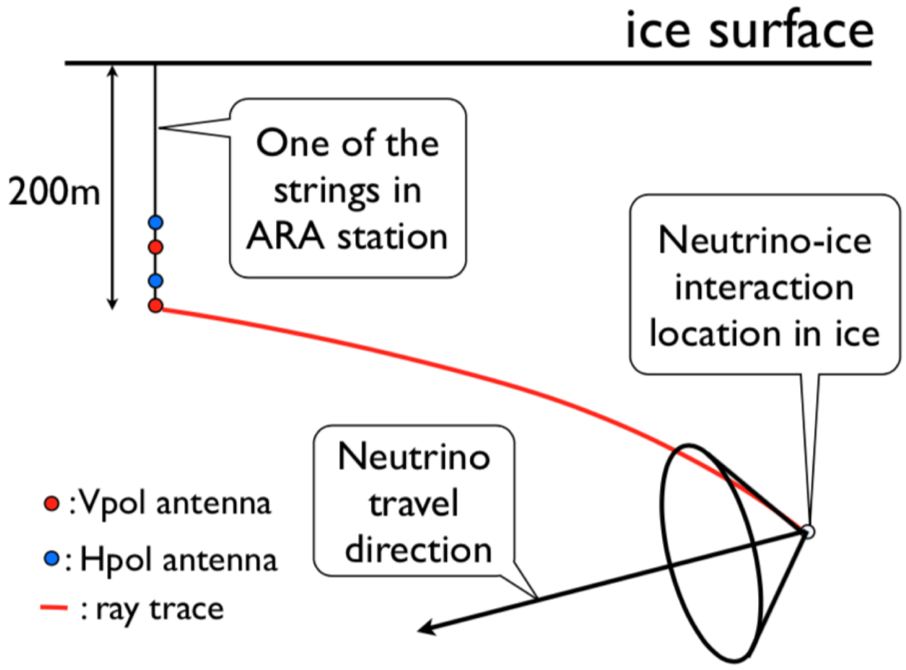
The Goal

Develop techniques to cut on the *direction* of an RF source

- Need another way to reduce thresholds… RF source direction is the natural next thing

- For a transient search: cut on timing and direction
  – Enables *wider* timing windows

- For steady-source search: cut on direction only



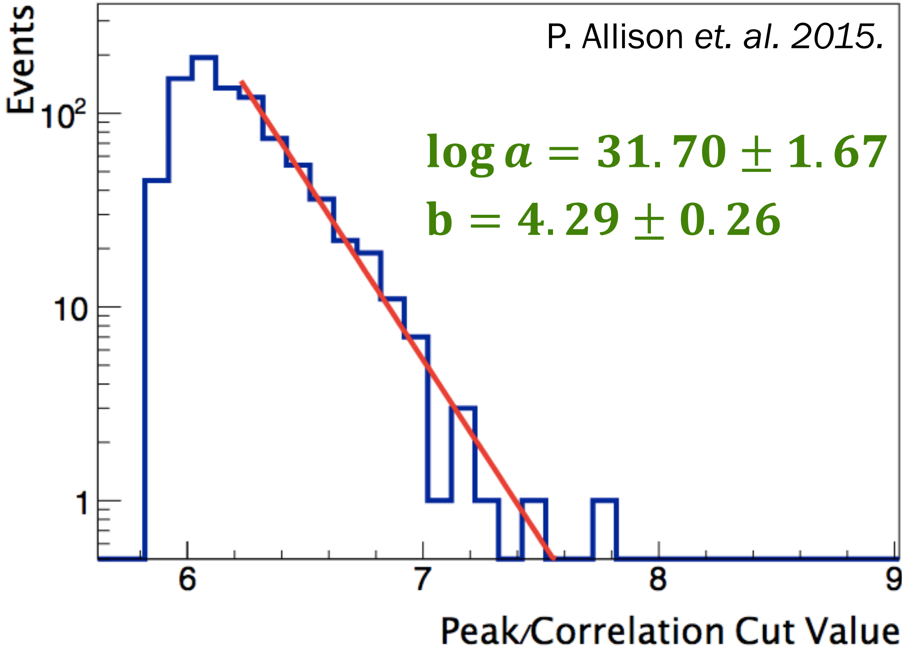
Oindree Banerjee working on afterglow neutrino search in ANITA-III

Prediction for Improvement

- Case study: exponential background model
  - Used in:
    ARA diffuse search
    ARA GRB search
    ANITA-III diffuse search
- Models background with an exponential
  - Plot is distribution of the final cut parameter in the data
  - Line is exponential fit to the data:

$$\frac{dN}{dx} = ae^{-bx}$$

- Background estimate: integrate model from cut value x_i to infinity



$$N_{\text{back},i} = \int_{x_i}^{\infty} ae^{-bx}\,dx = \frac{a}{b}e^{-bx_i}$$

Prediction for Improvement (cont.)

- For a search, have:
  - Background prediction: N_{back}
  - Neutrino efficiency: $N_{\text{pass}}/N_{\text{predicted}}$

- **Question: with a cut on timing/direction, and a fixed N_{back}, how much can we loosen our final cut parameter?**

- Suppose we reduce the number of events after directional restriction by a factor $\alpha > 0$: $a_{\text{new}} = a_{\text{old}}/\alpha$

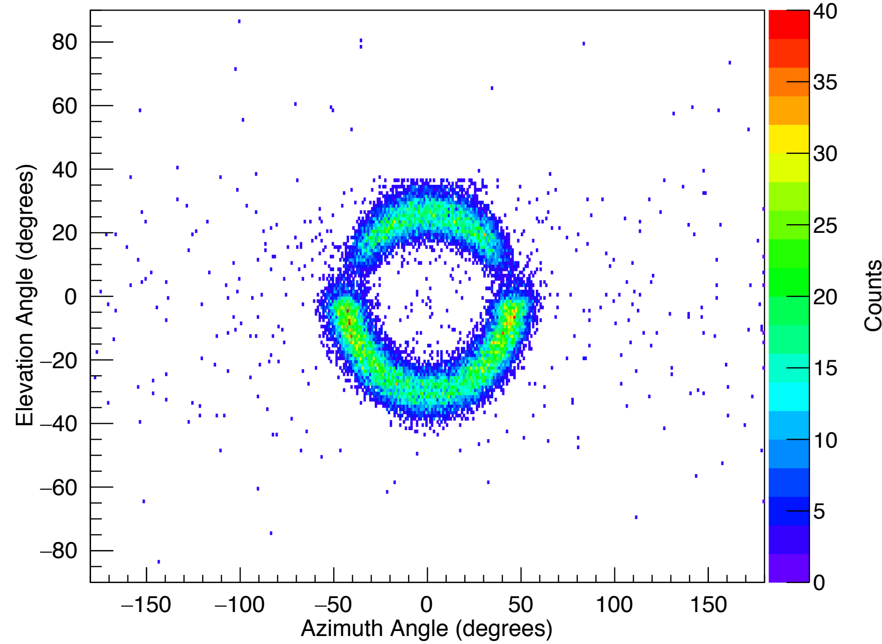
- We can predict the reduction in threshold:

$$x_{\text{old}} - x_{\text{new}} = \frac{\ln \alpha}{b}$$

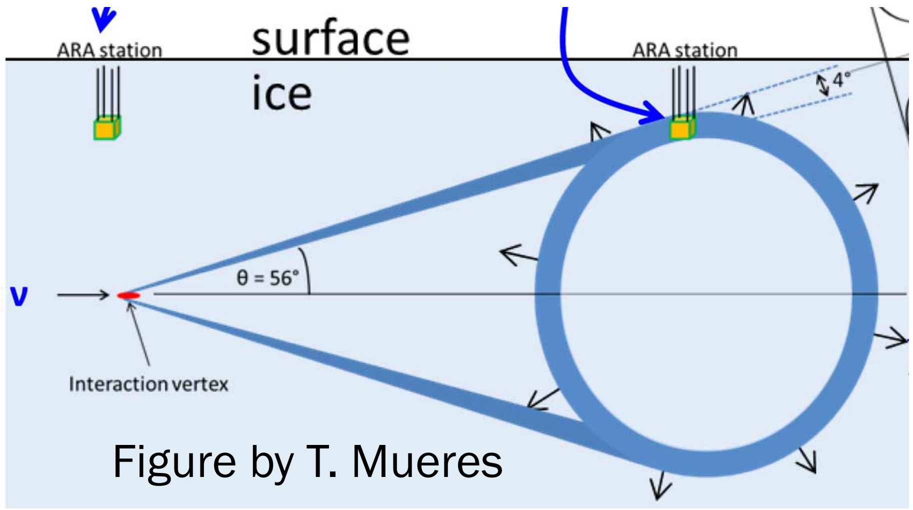
Prediction for Improvement (cont.)

What α might be possible?

- Example:
  - Simulate flux of 10^{18} eV neutrinos
  - Do interferometry on every (w/ 300 m source distance hypothesis)
- Given this:
  - Might expect $\alpha \sim \frac{20{,}000\ \mathrm{deg}^2}{1{,}600\ \mathrm{deg}^2} \sim 12$
  - Which is is a reduction: $x_{\mathrm{old}} - x_{\mathrm{new}} \sim 0.5$

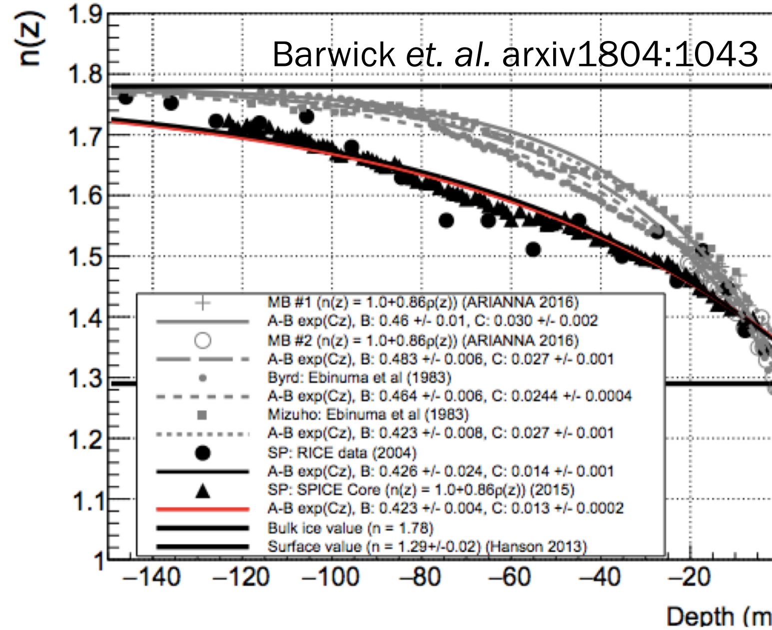


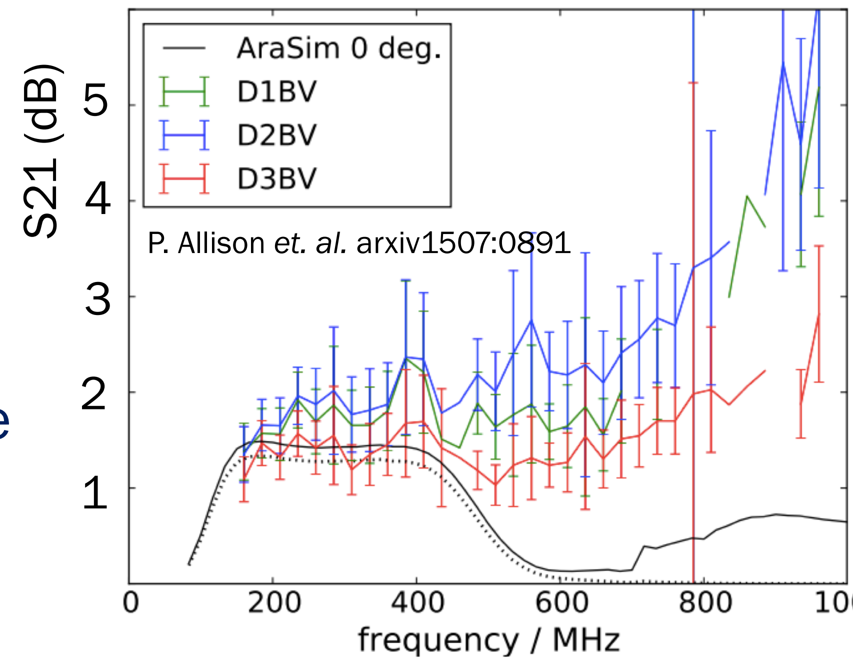
- Don't forget: signal events are *steeply* falling distributions of x_i. Small reductions in x_i significantly affect neutrino acceptance.



Ongoing Work

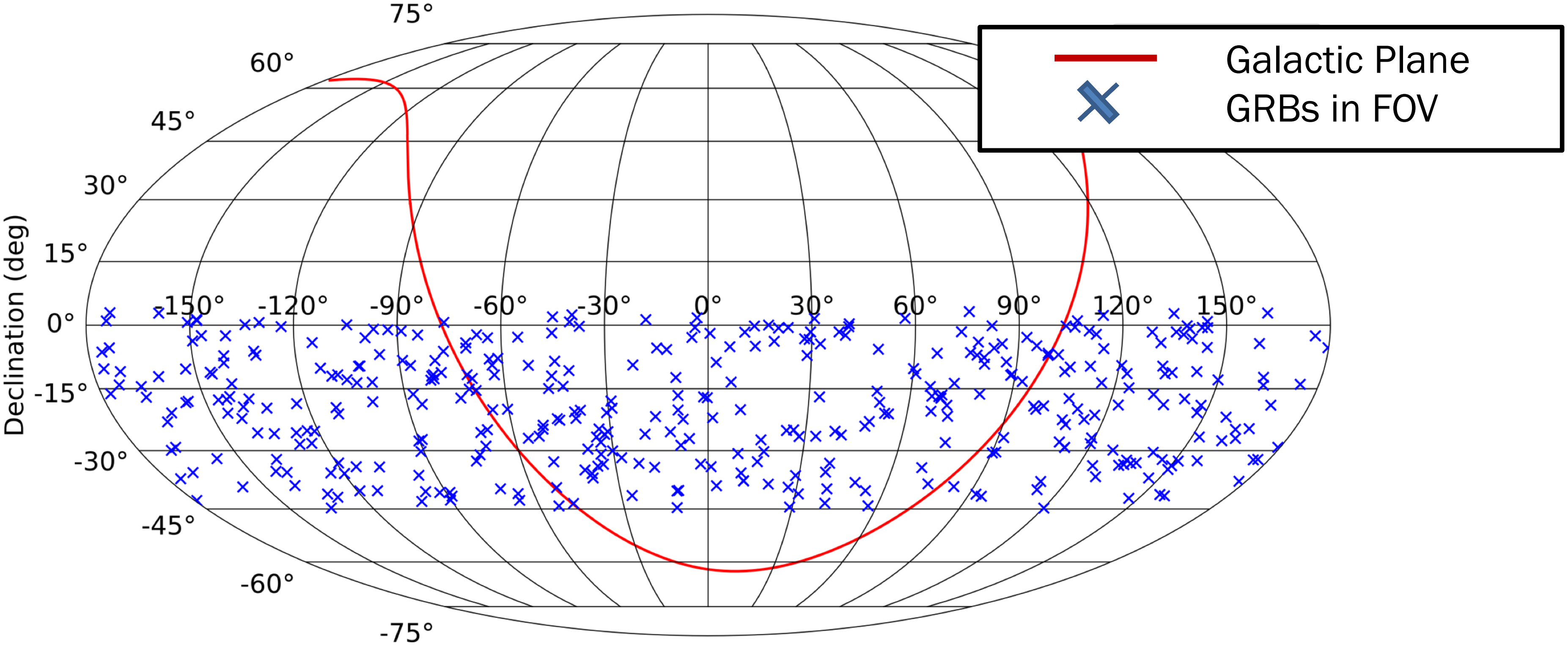
- Systematic Uncertainties on Reconstruction Algorithms
  - Ice modeling: what is *n(z)*
  - Geometry calibrations
- Need a way to determine *where* on the Cherenkov cone a candidate signal might be
  - Can look at VPol vs HPol signal strength (polarization)
  - And frequency information (spectral slope, etc.)
  - Both will require a more complete understanding of antenna response





Application to new ARA GRB Study

- Utilize IceCube catalog for all GRBs occurring in the four year (2013-16) two-station (A2, A3) livetime currently undergoing a diffuse analysis
- Require events be in the ARA field-of-view: -5º → 45º in elevation
- Sample has 391 GRBs (without accounting for system livetime)



Summary

- Neutrinos are a key messenger to the distant, high energy universe
- ARA has two new stations with more *in-situ* control than every before, enhancing detector operational efficiency.
- Phased array prototype on A5 demonstrates improved sensitivity and the power of phased triggering
- Restricting on direction of an RF source should enable reduced thresholds in point source searches.

United States – Israel
Binational Science Foundation

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