ASKARYAN RADIO ARRAY THE OHIO STATE UNIVERSITY CCAPP

Ultra-High Energy Neutrino Astrophysics with Radio Detectors

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PGSC Summer Seminar – Department of Physics, OSU

Photo Credit: McGill University

The Big Questions

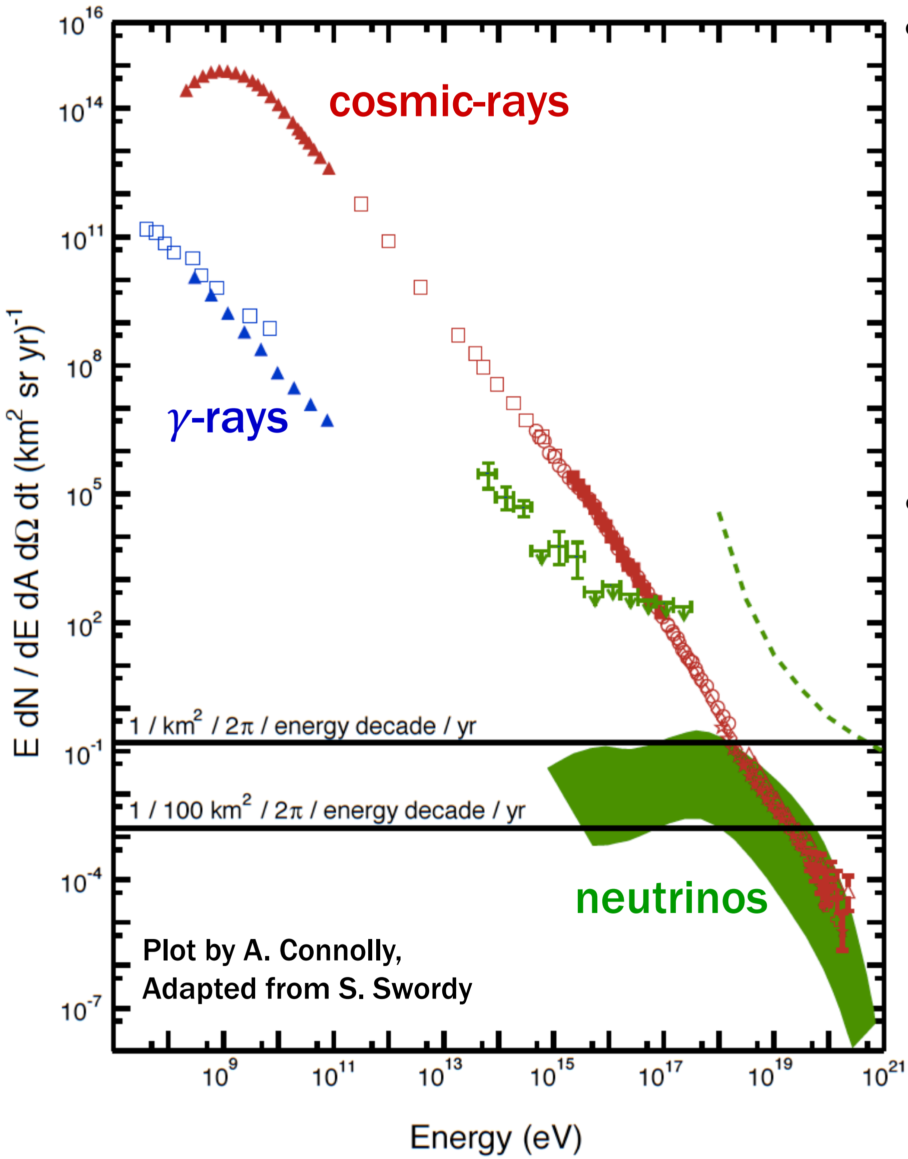
Why? ☐

How? ☐

Where? ☐

Who? ☐

Why Study Neutrinos: Astrophysical Messengers

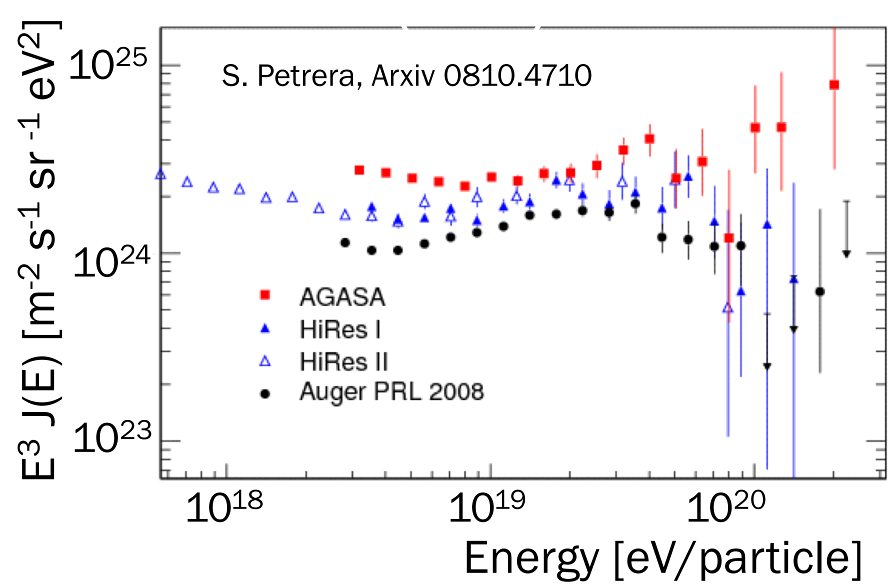


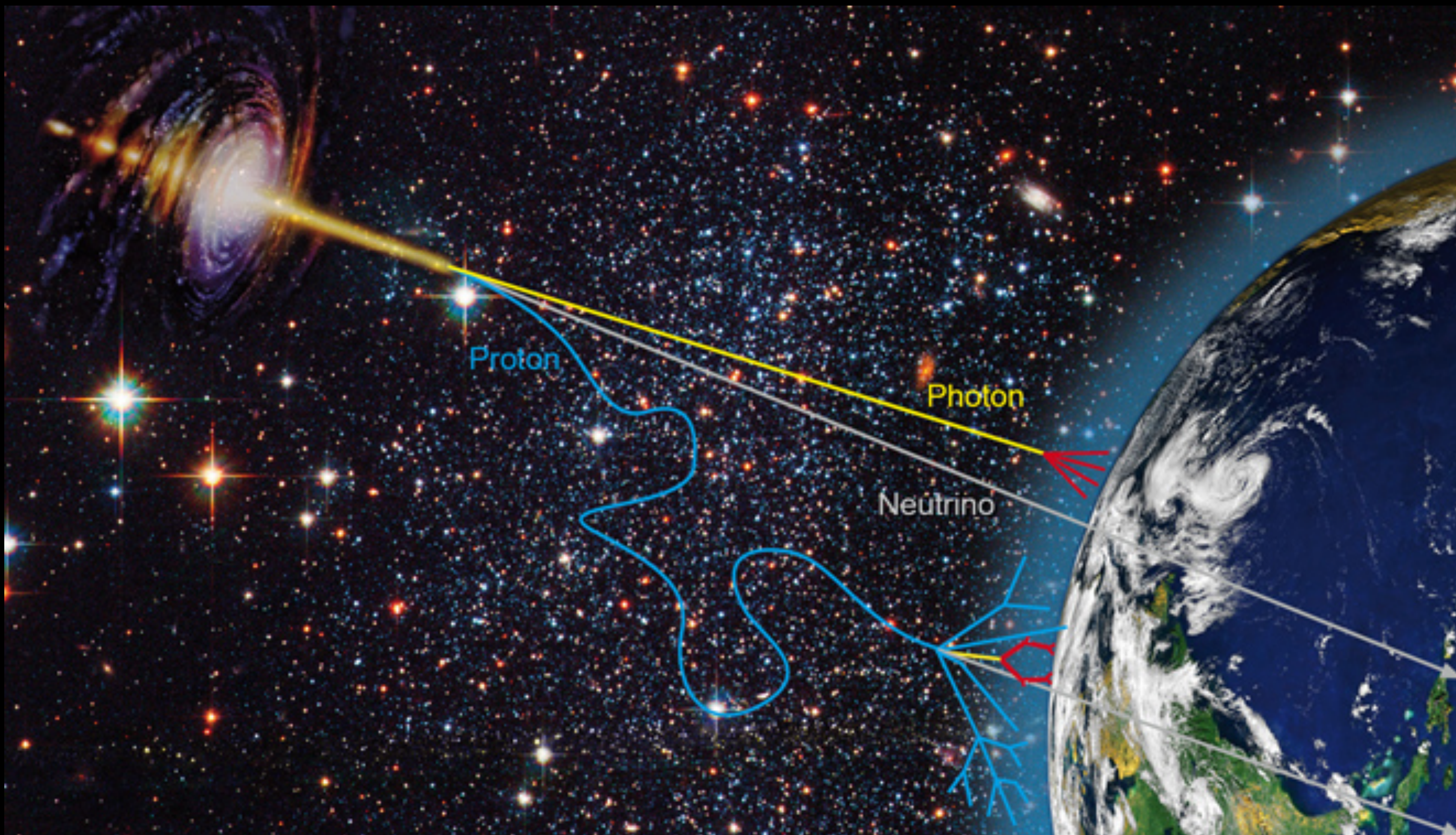
- Cosmic rays >$10^{19.5}$ eV attenuated, possibly by GZK effect, e.g.

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p(n) + \pi^{0}(\pi^{+})$$

→ Screens extragalactic (>100 MPc) sources

- γ-rays annihilate w/ CMB @ ~1 TeV



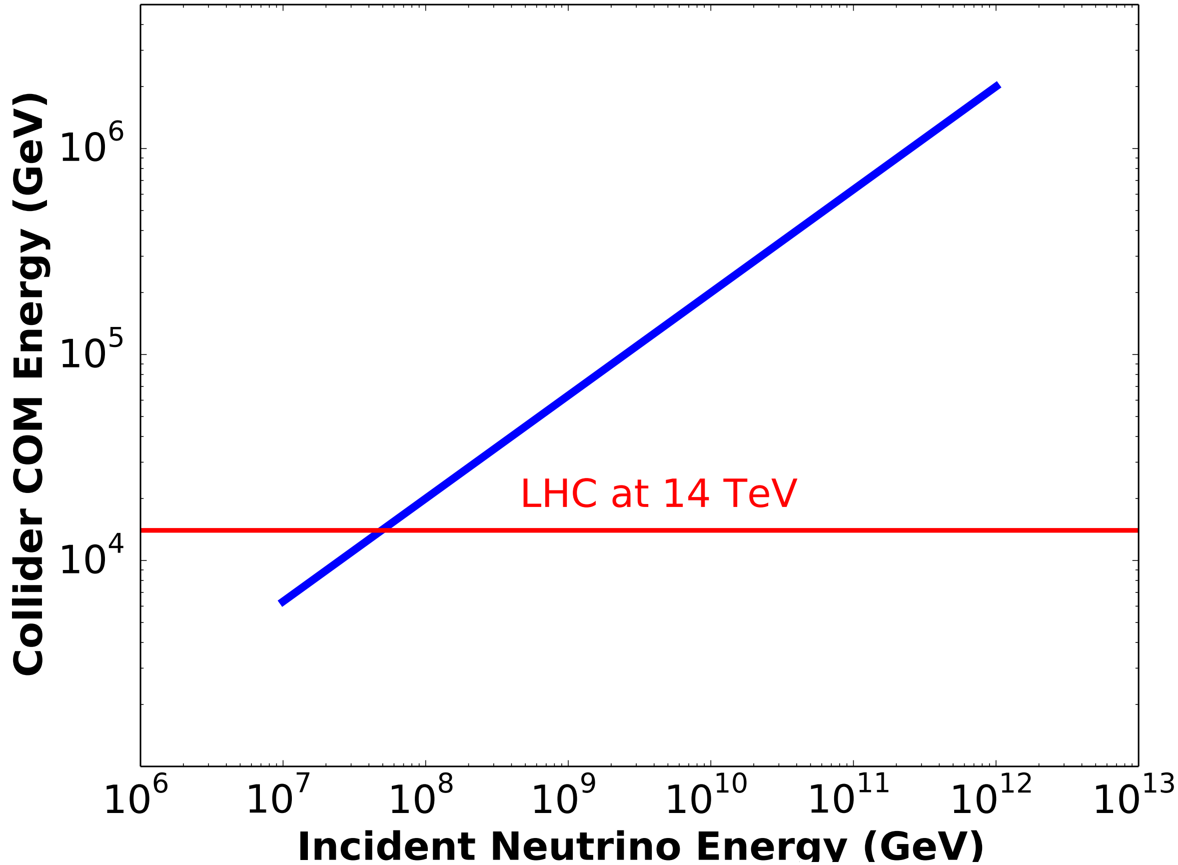

Proton
Photon
Neutrino

Why Study Neutrinos: Particle Physics Probes

- **Probe cross-sections at energies above accelerators**

- Ex: An EeV (10^{18} eV) neutrino interacting in ice has COM energy of ~60 TeV (note: LHC 14 TeV)

$$E_{COM} = \sqrt{4\, E_{\nu}\, m_n}$$



COM = Center of Momentum

Astrophysical Messengers

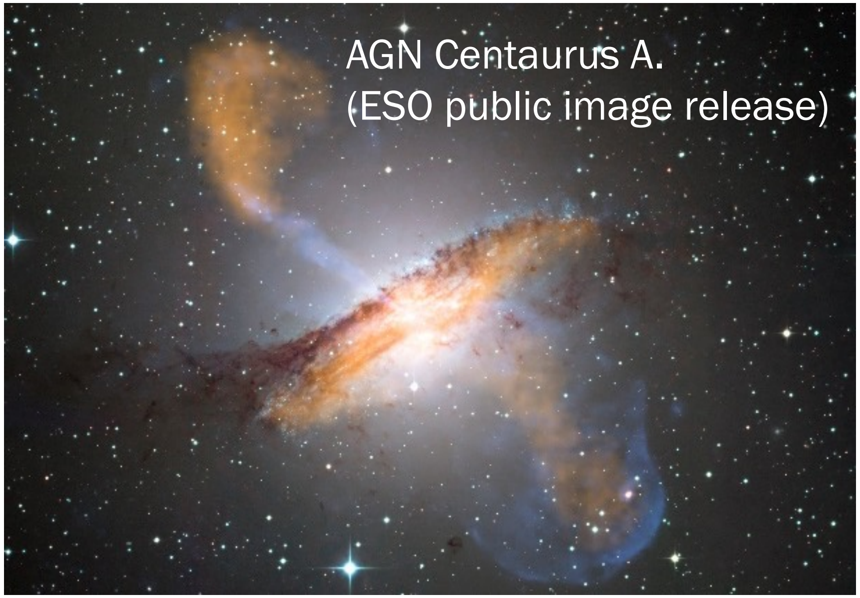
Two Sources of Neutrinos

- *Predicted* "BZ Flux": pions from GZK process decay into neutrinos
- "Source Flux": Neutrinos from the CR accelerators
  - Gamma Ray Bursts (GRB)
  - Active Galactic Nuclei (AGN)

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

Neutrinos have attractive properties

- Weakly interacting: travel cosmic distances unattenuated
- Chargeless: not deflected by (inter) galactic magnetic field $\rightarrow$ point back to source!



The Big Questions

Why?	☑	Astro + Particle Physics
How?	☐	
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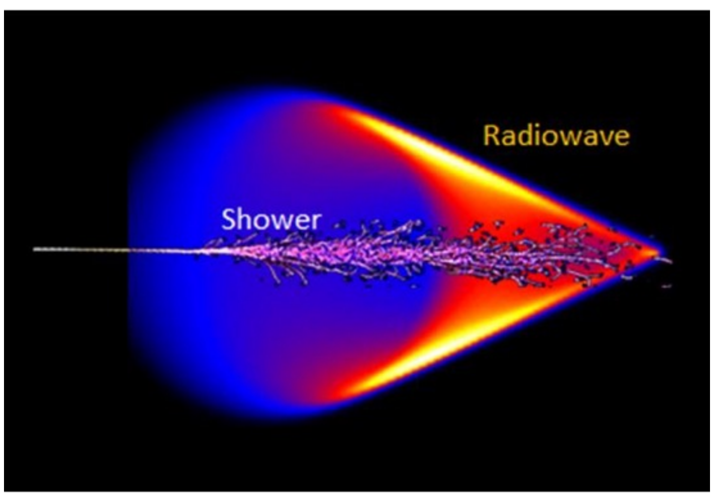
Neutrino Interactions

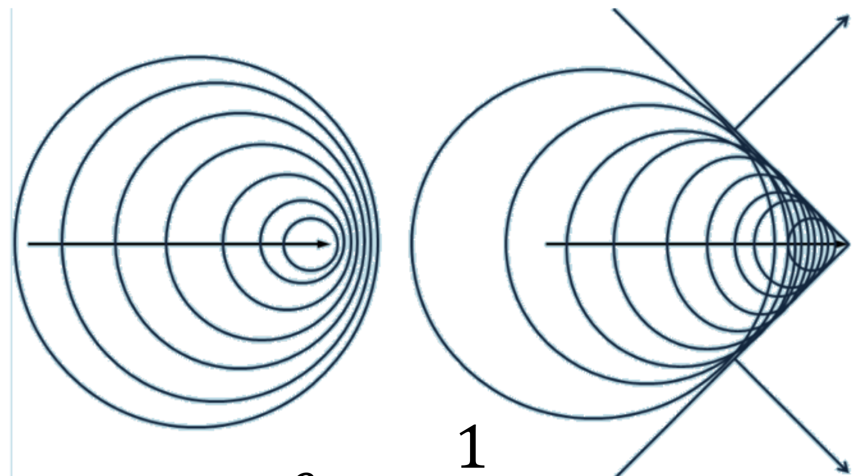
- Two varieties of interactions: Charged current (CC) and Neutral Current (NC)

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 θ_C
- Two varieties of interest: optical and radio

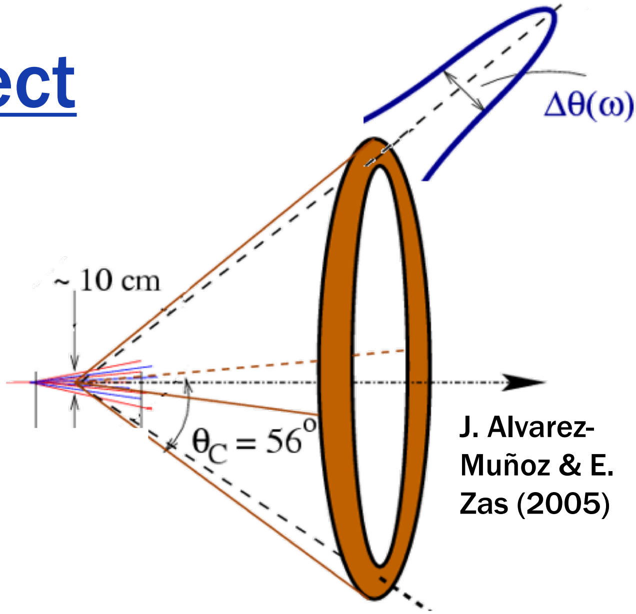




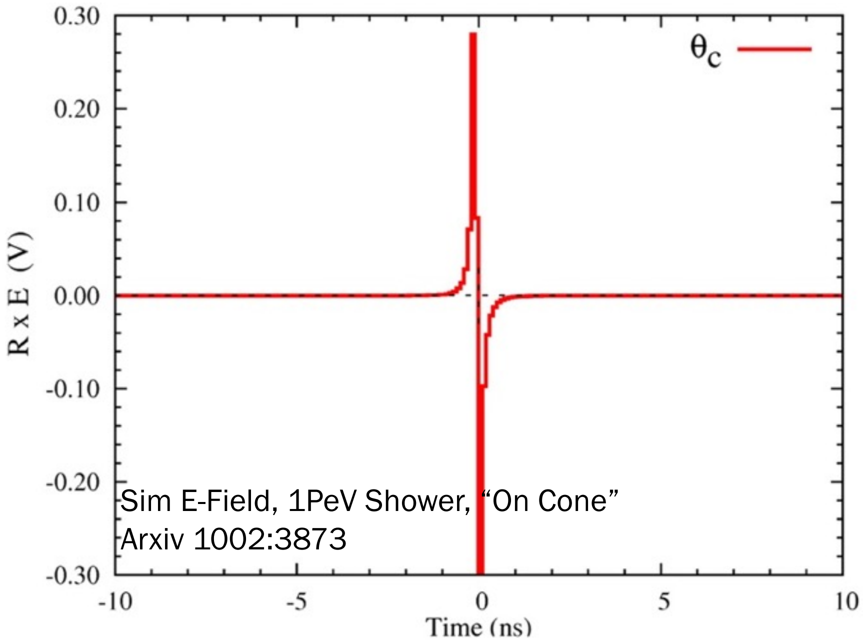
$$\cos\theta_C = \frac{1}{n\beta}$$

Radio Cherenkov Effect

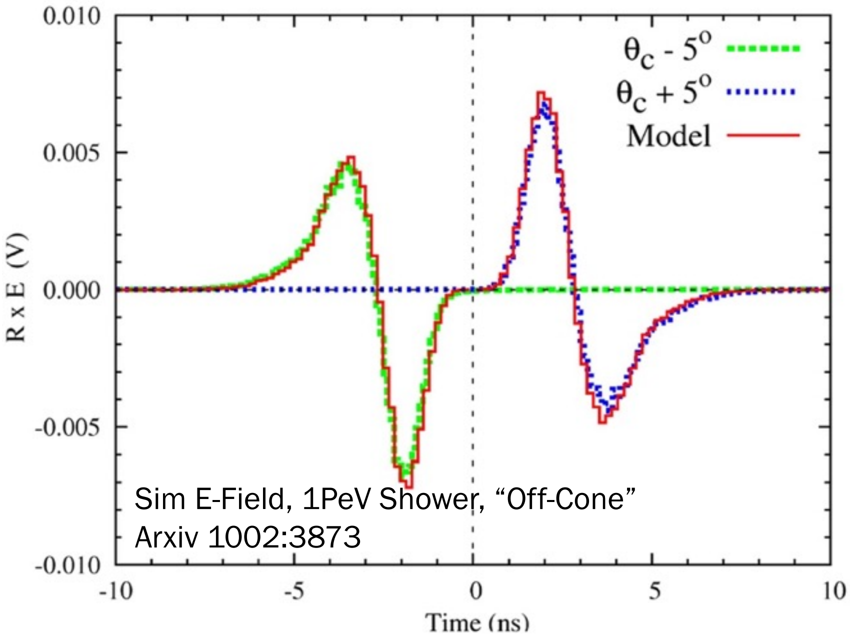
- Showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add *coherently*
- Broadband (200 MHz → 1.2GHz) radio *pulse*
- Conical emission (57° in ice)



J. Alvarez-Muñoz & E. Zas (2005)



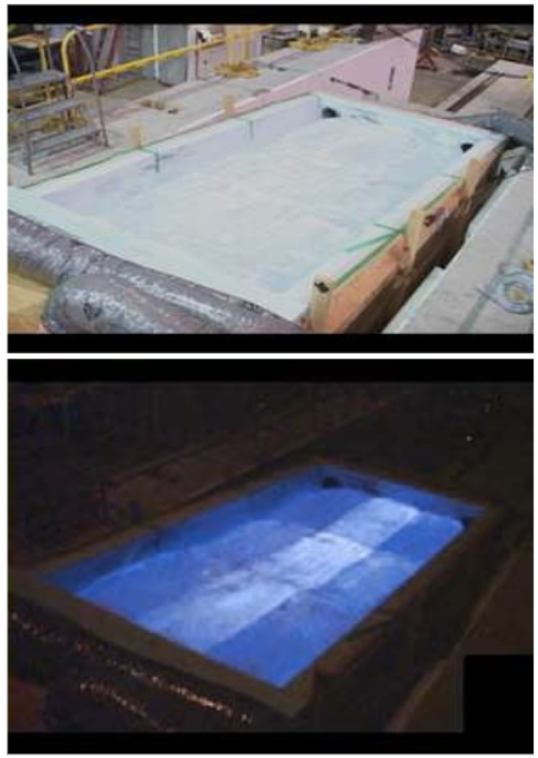
Sim E-Field, 1PeV Shower, "On Cone"
Arxiv 1002:3873



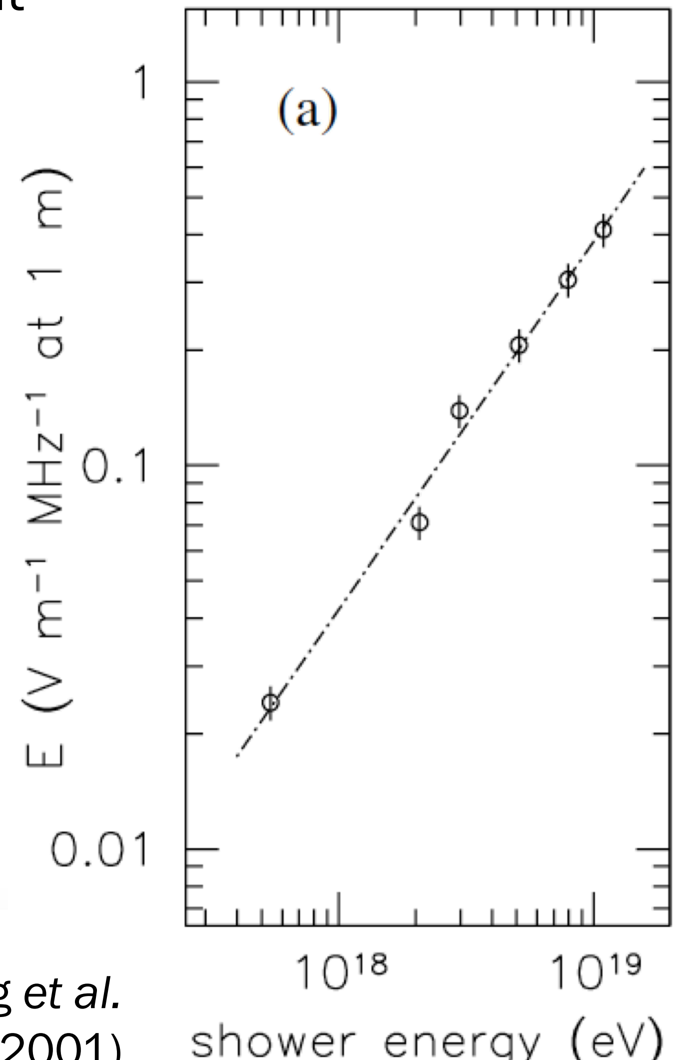
Sim E-Field, 1PeV Shower, "Off-Cone"
Arxiv 1002:3873

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 Pulses
Where?	☐	
Who?	☐	

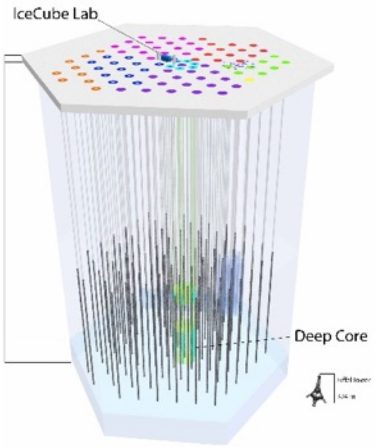
Question of Scale

- Low fluxes (~10/km^3/yr) and low cross-sections (interaction length ~300km in rock)
- Need ~100 km^3 of target volume to enable detection (e.g., dozens per year)
- Where do you find a giant chunk of radio clear medium?
  - Ask the NSF nicely?
  - Point telescope at the lunar regolith: Lunaska
  - Go to Antarctica: IceCube, ARA, ANITA, ARIANNA

LUNASKA (radio)

ANITA-III (radio)

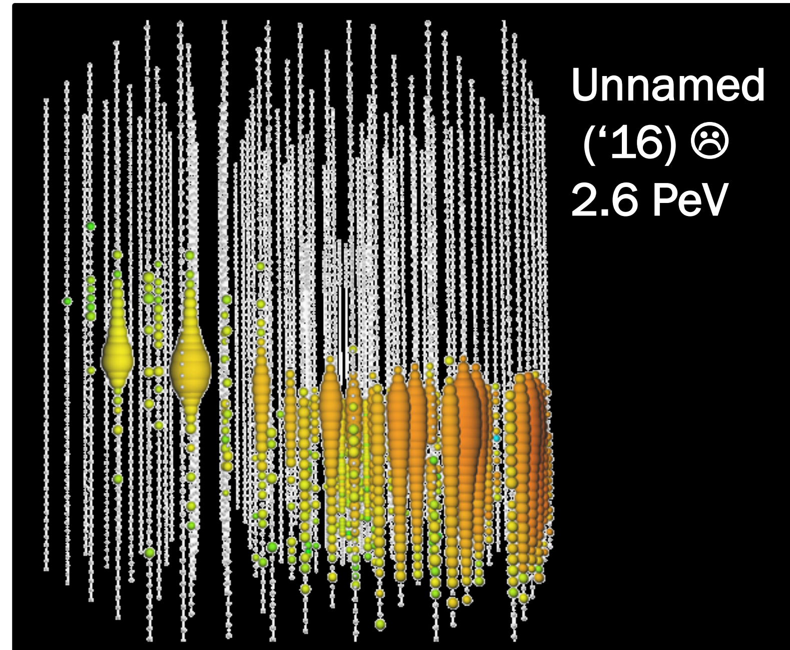
IceCube (optical)

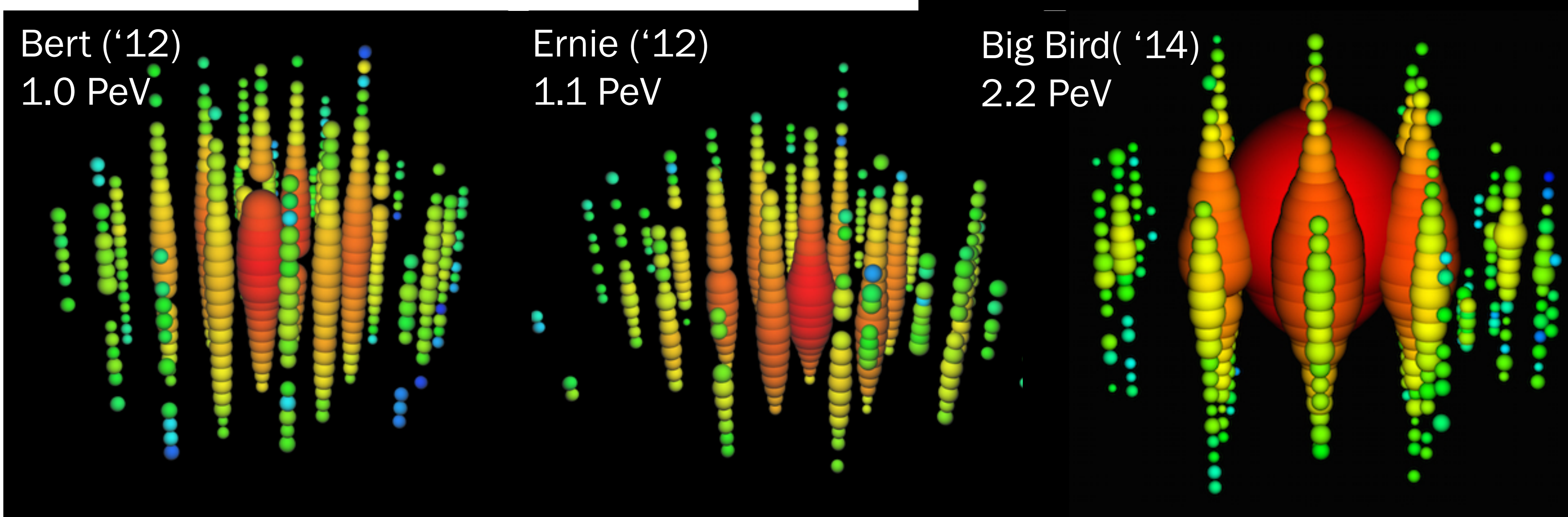


Do they exist?

Yes!

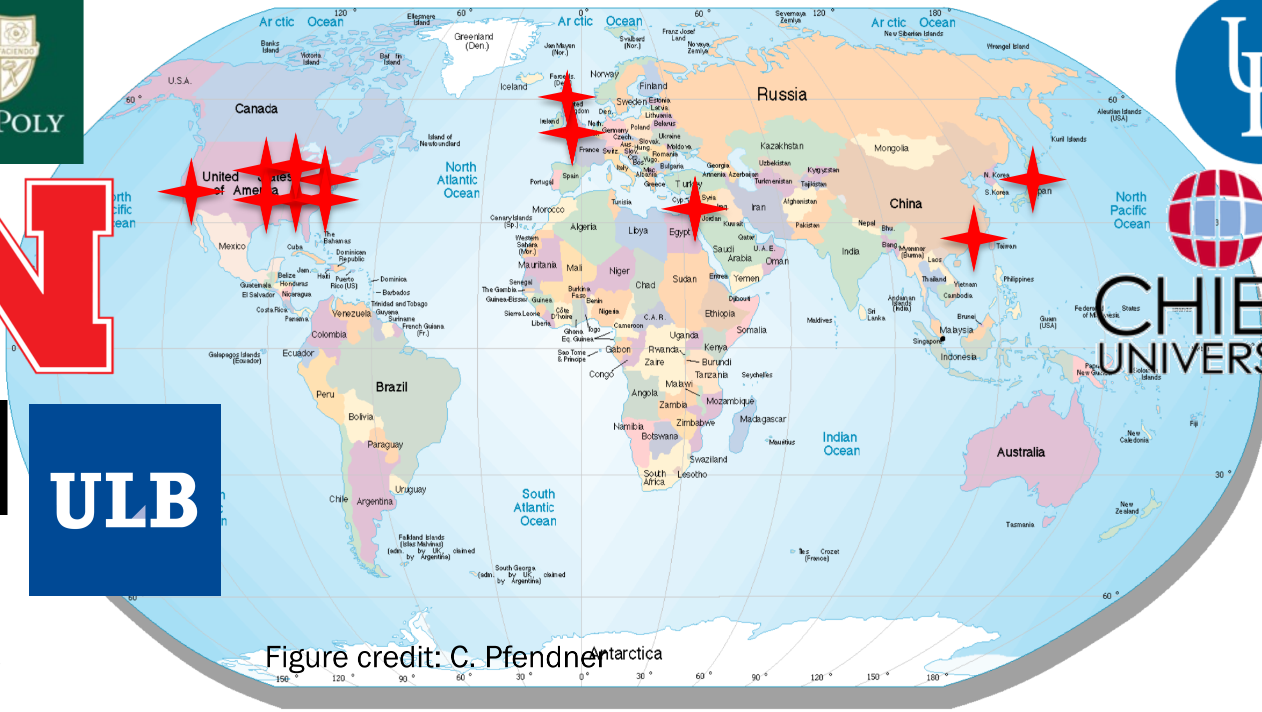
- 2012: IceCube experiment sees PeV neutrinos of cosmic origin
- Today's discussion: neutrinos x10^3 more energetic—the "UHE" regime





The Big Questions

Why?	☑	Astro + Particle Physics
How?	☑	Radio Pulses
Where?	☑	Antarctica
Who?	☐	



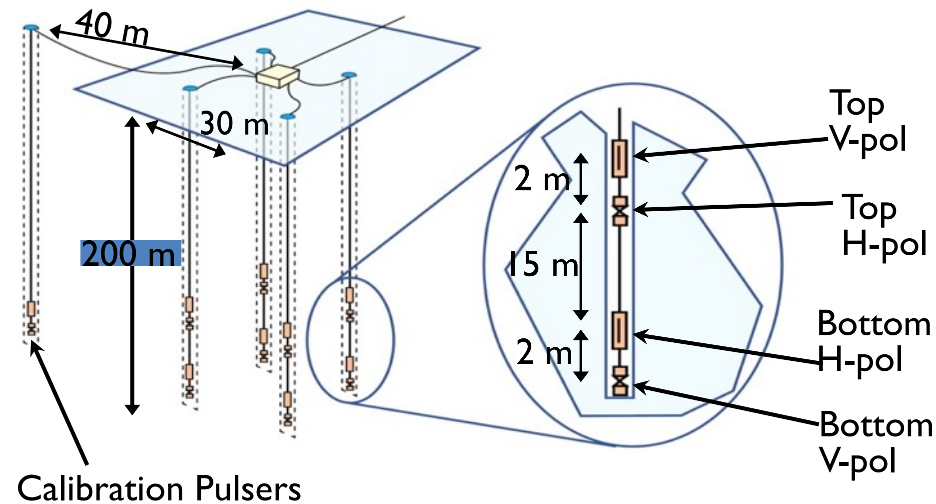
ARA is an International Collaboration

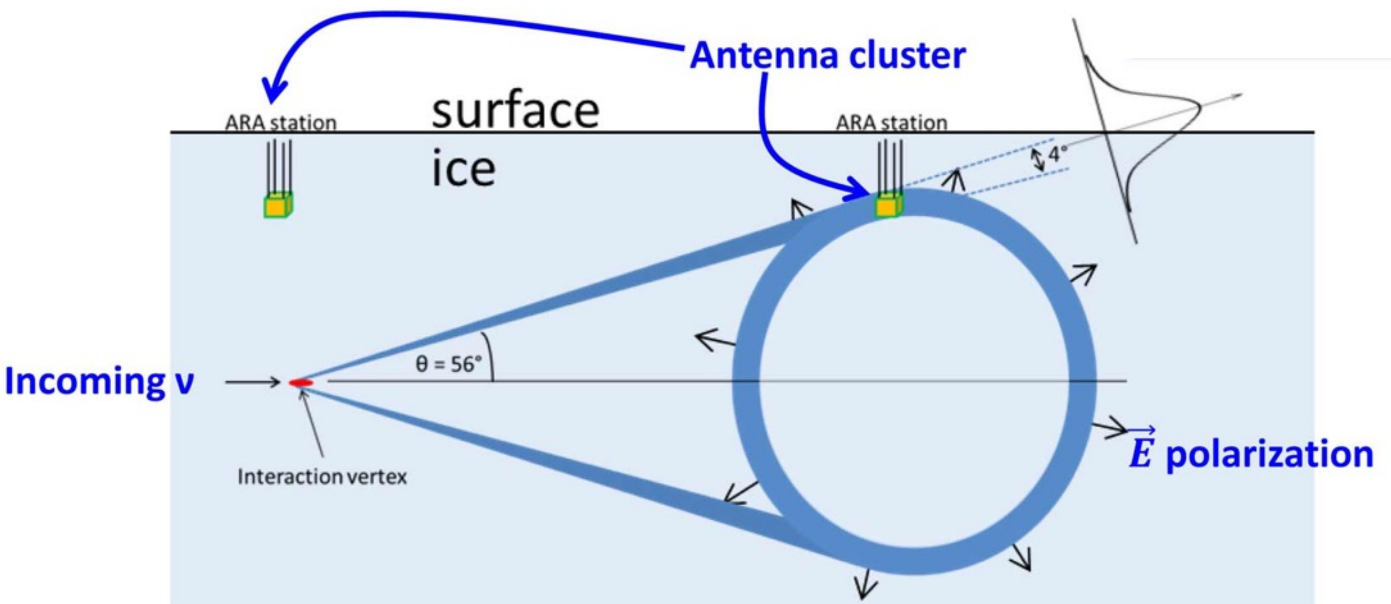
USA:
- Ohio State University
- Cal Poly
- University of Chicago
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison

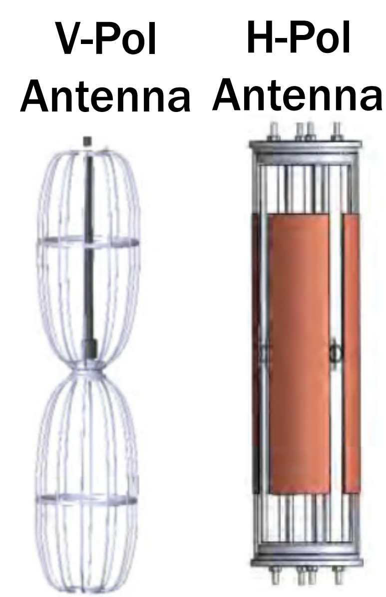
UK: University College London
Belgium: Université Libre de Bruxelles
Japan: Chiba University
Taiwan: National Taiwan University
Israel: Weizmann Institute of Science

Askaryan Radio Array (ARA)

- 16 antennas (8 vpol, 8 hpol, 200-850 MHz bandwidth)
- Cubical lattice at 200m depth
- Energy range: $10^{16} \rightarrow 10^{19}$ eV

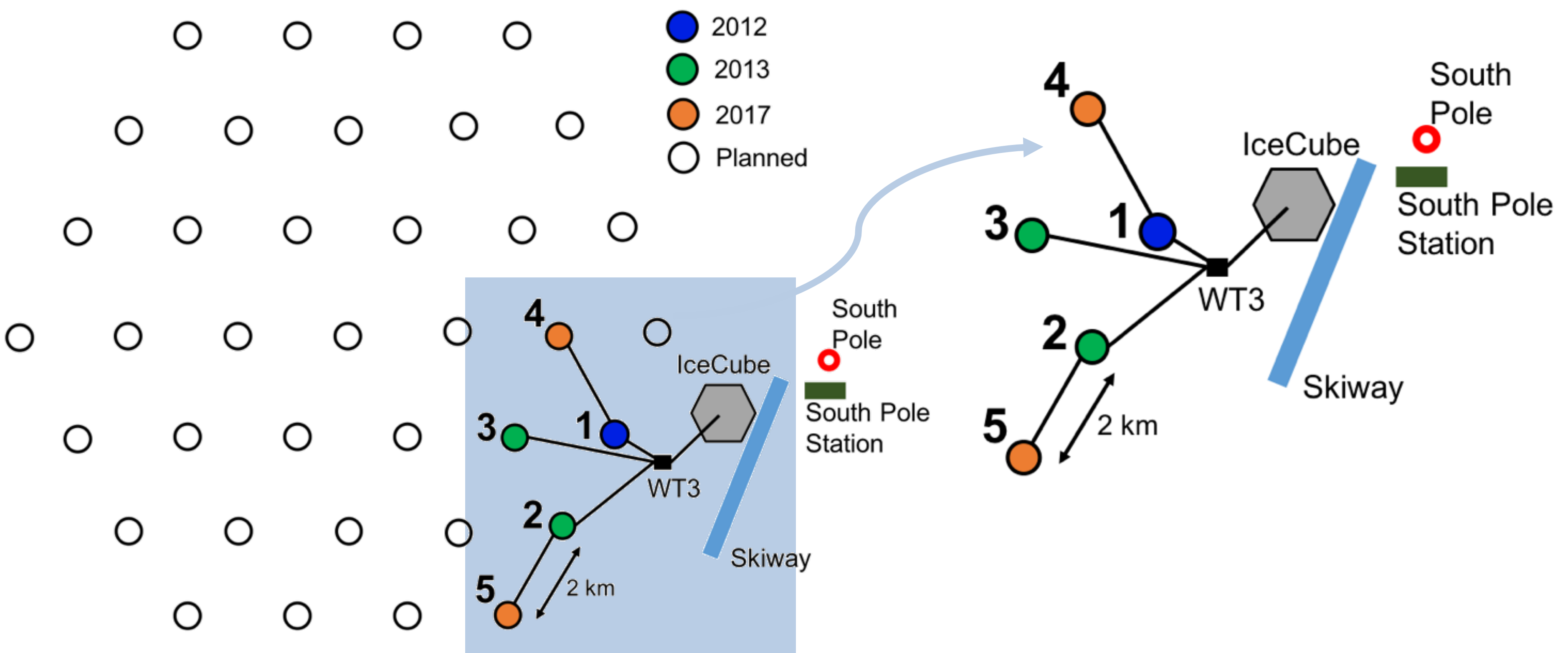




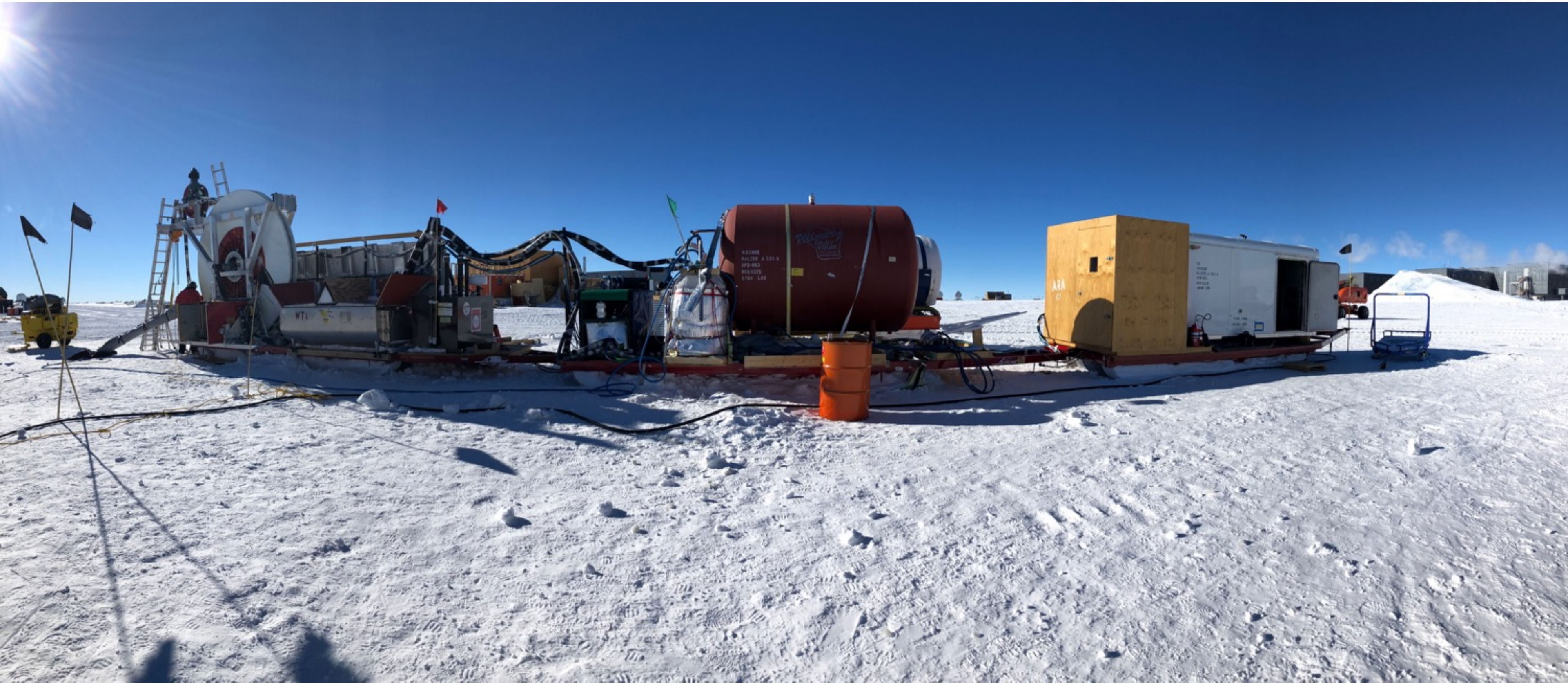


Current Status of the Instrument

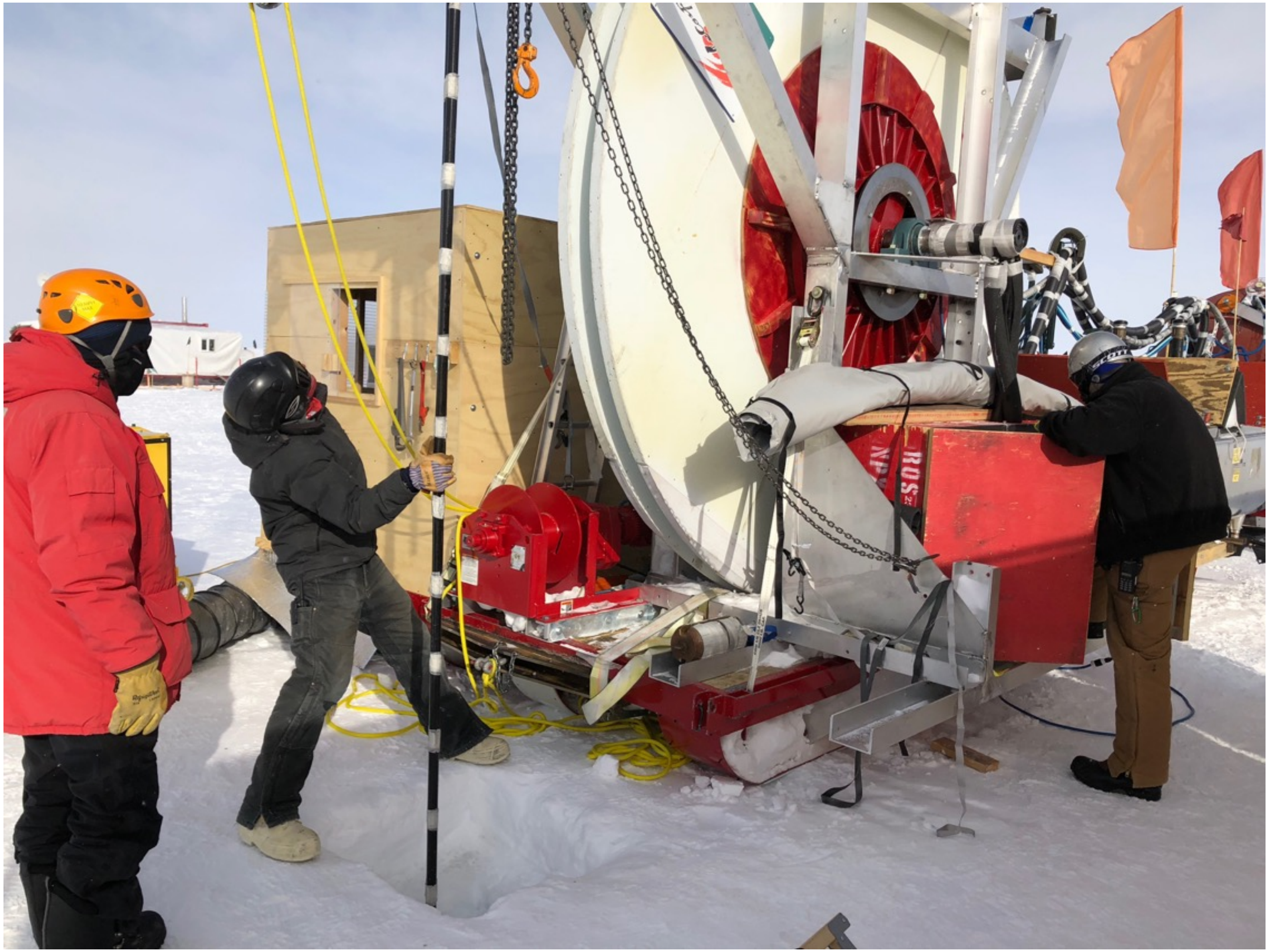
- Under phased construction in the ice near South Pole
- Phase 1 goal is ~37 stations, spaced 2km apart, covering ~100 km^2 of ice
- Prototype ("Testbed") + 5 (!) stations deployed so far



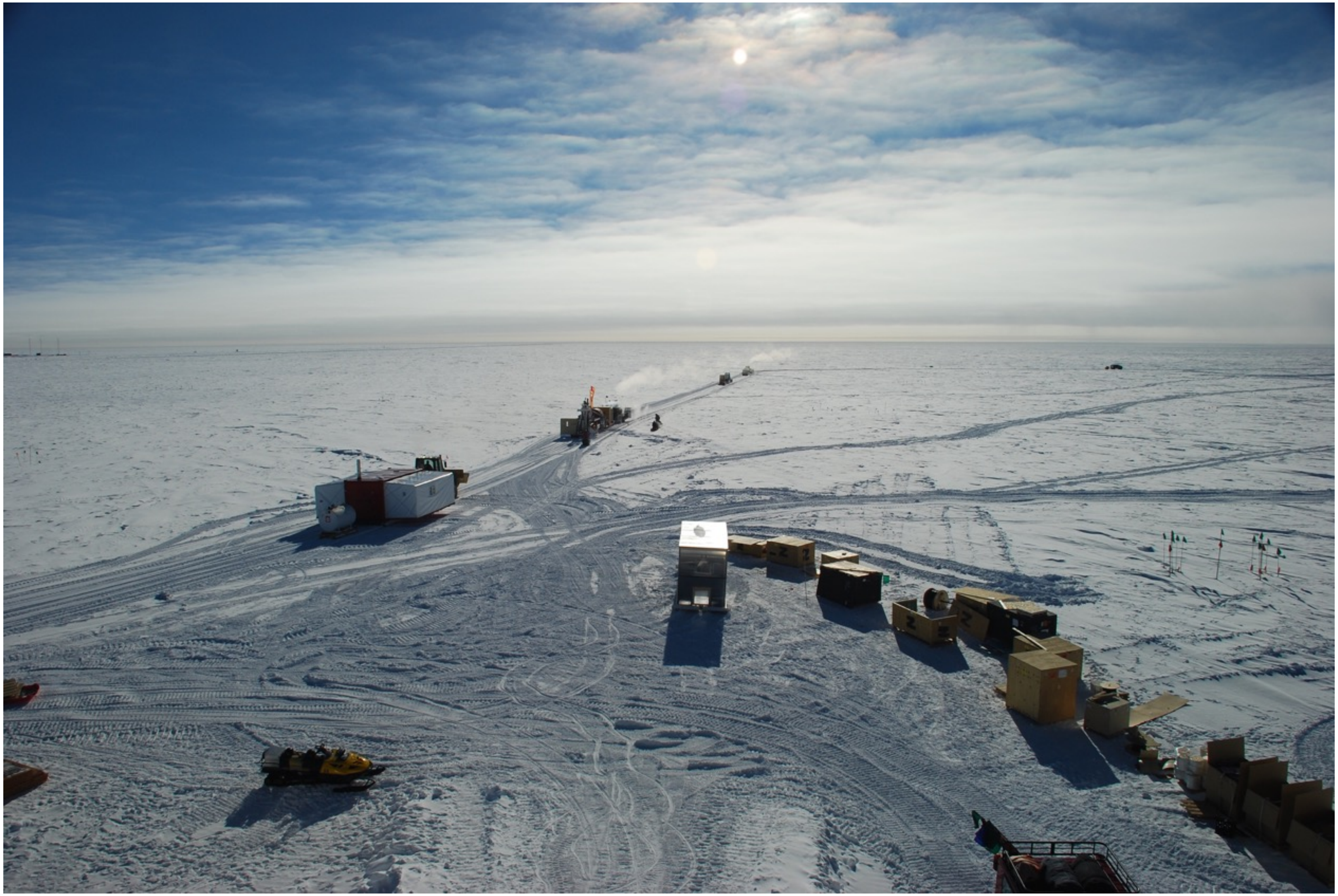
Construction



Construction



Construction



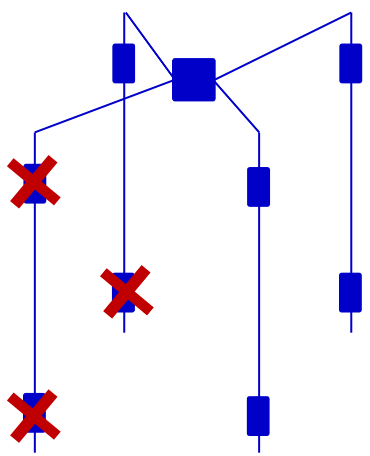
Signal Identification: In Hardware

Impulsive

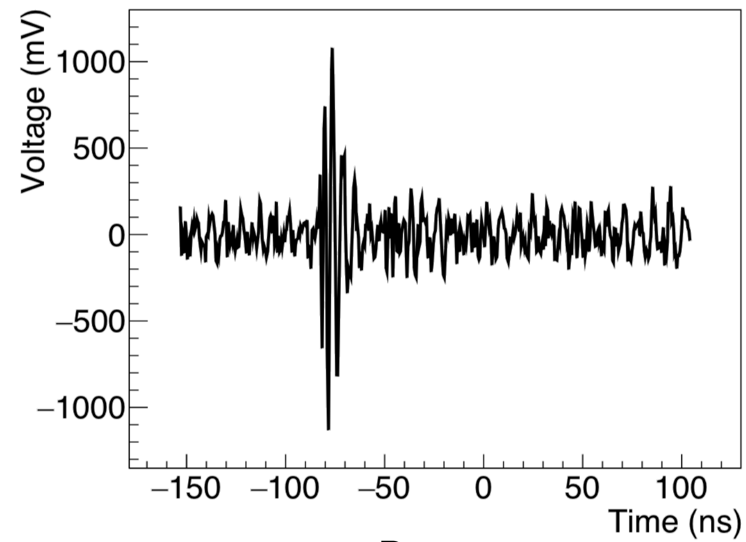
- *Power Trigger:* integrated power over ~10ns must be > threshold
- *Effective at identifying neutrinos*: pulses have large integrated power

Coincidence

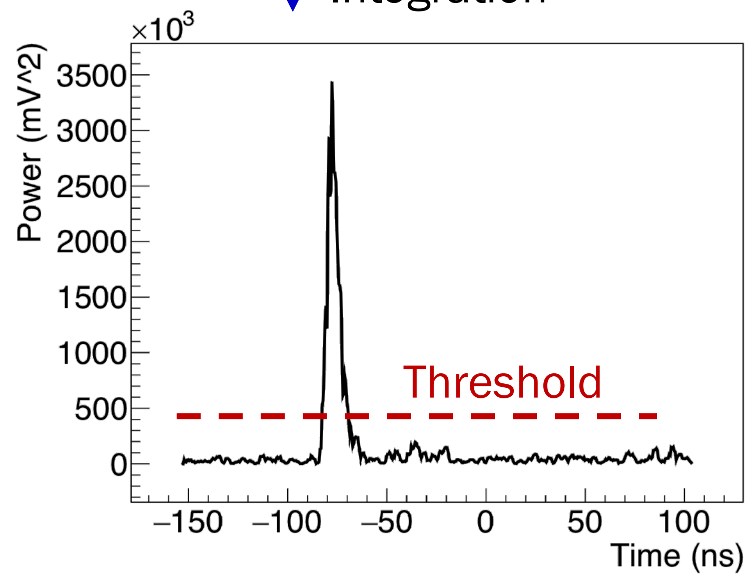
- *Coincident requirement*: trigger in 3/8 antennas
- *Good at rejecting thermal noise:* noise "rarely" fluctuate high in 3/8 simultaneously



Calibration Pulser Event
Testbed Station



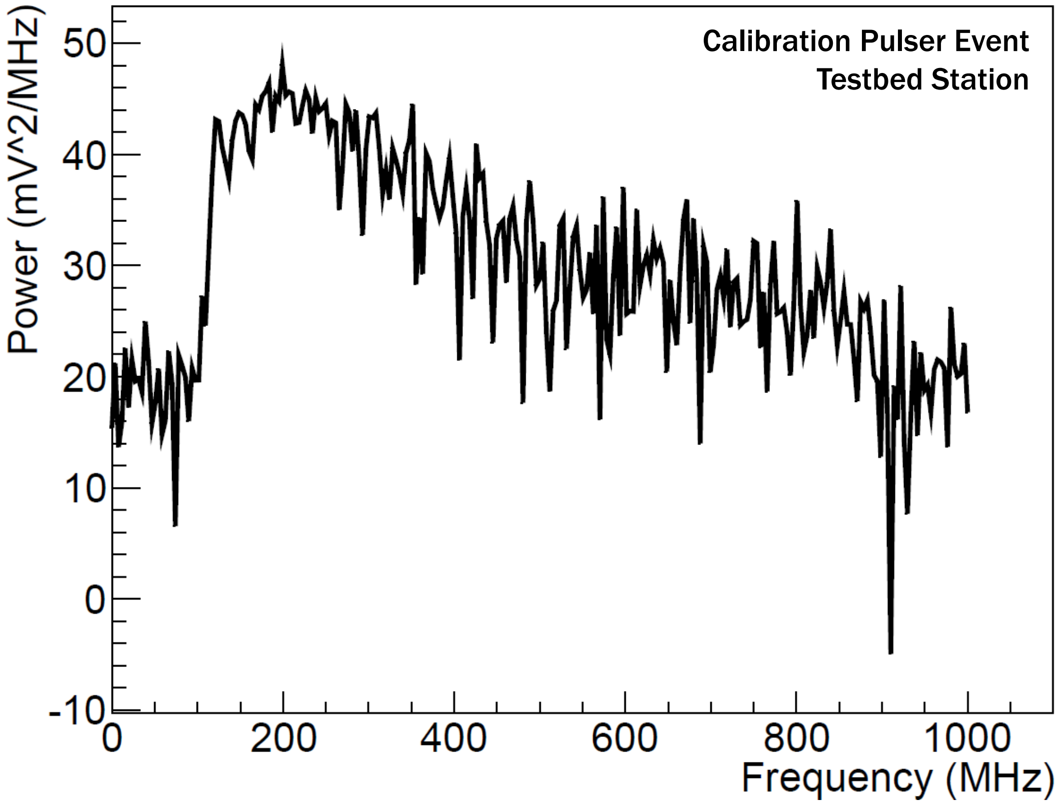
Power Integration



Signal Identification: In Software

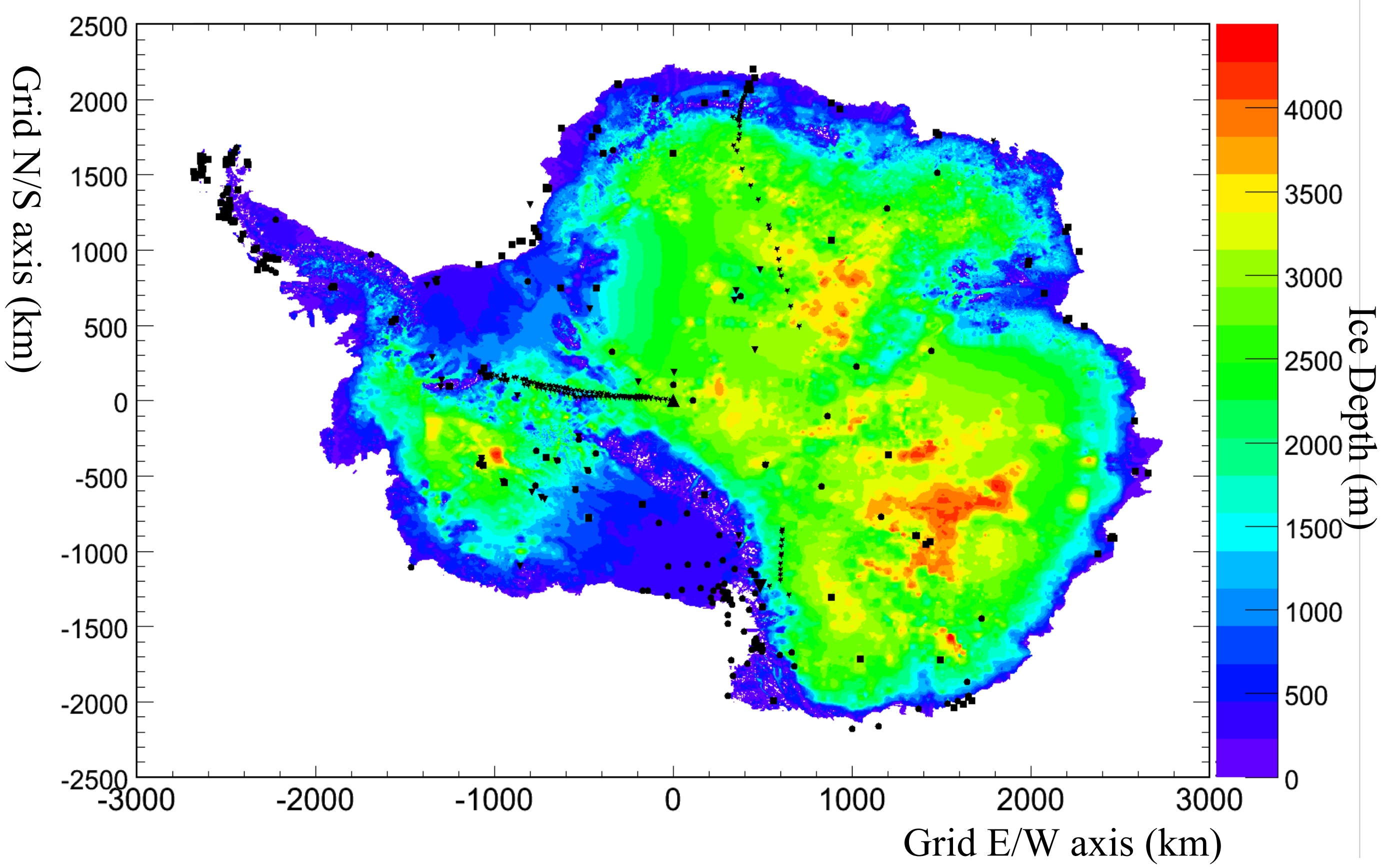
Signal Must be Broad in Frequency

- *Impulsive signals are broadband*
- Anthropogenic backgrounds are usually narrow band (people talking on radio, for example)



Backgrounds to Signal

- Radio blackbody (thermal) emission of ice
- CW wave (CW) sources: satellites, radios, human bases..
- Electromagnetic interferneces: lights, static discharge



The Big Questions

Why? ☑ Astro + Particle Physics

How? ☑ Radio Pulses

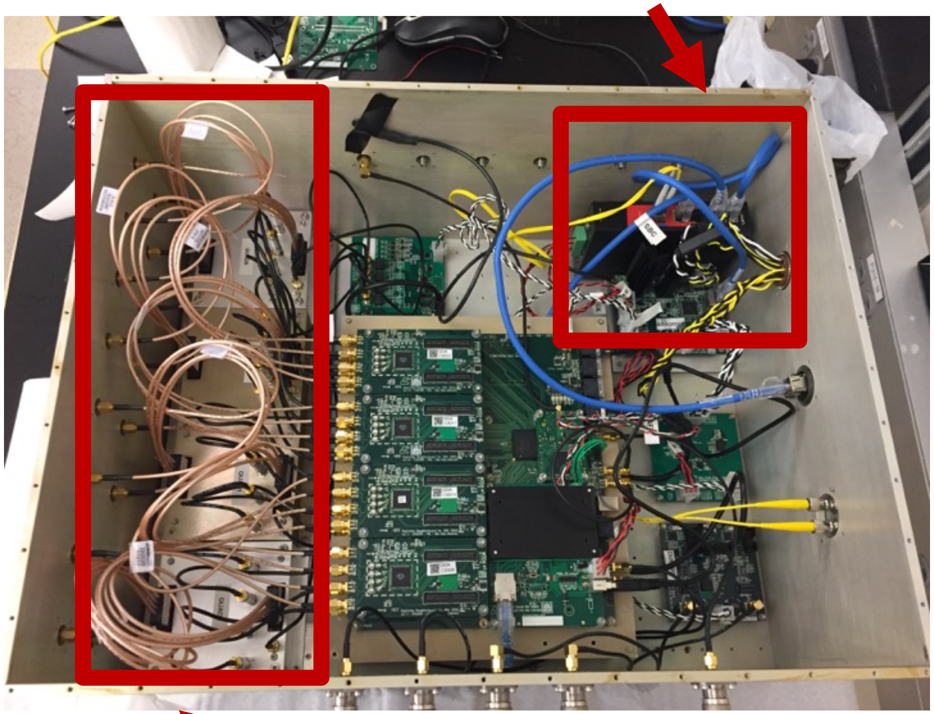
Where? ☑ Antarctica

Who? ☑ ARA

What's New

New Stations

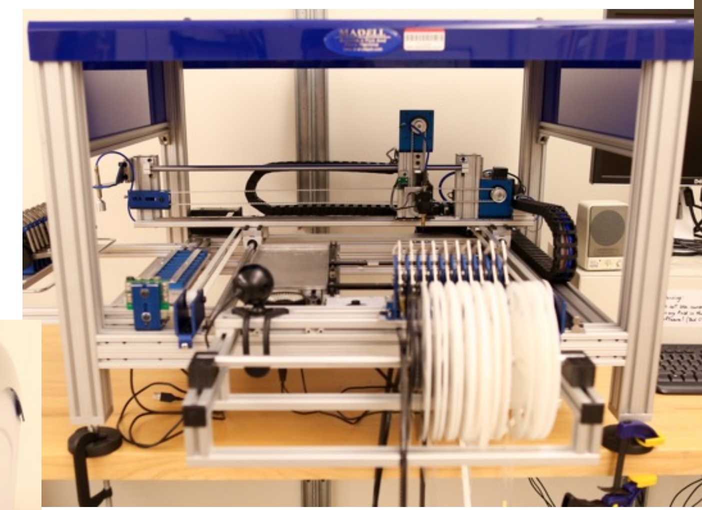
- ARA deployed two new stations (A4, A5) in January 2018
- Robustly tested: run, fully assembled, for >1 mo in the north @ UW PSL
- DAQ runs ~4 days at -40 C in thermal chamber at OSU CCAPP Antarctic RF Test Facility
- All are equipped with new, exciting electronics
  - A power-broker to improve system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



ARA4 DAQ Box

Rapid prototyping and testing of electronics

Large RF/ anechoic chamber.



Pick & Place machine for rapid assembly.

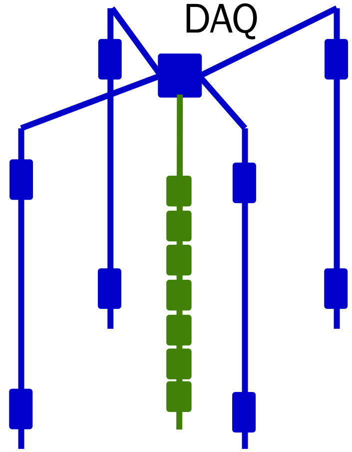
RF circuit board mill.

Large thermal chamber.

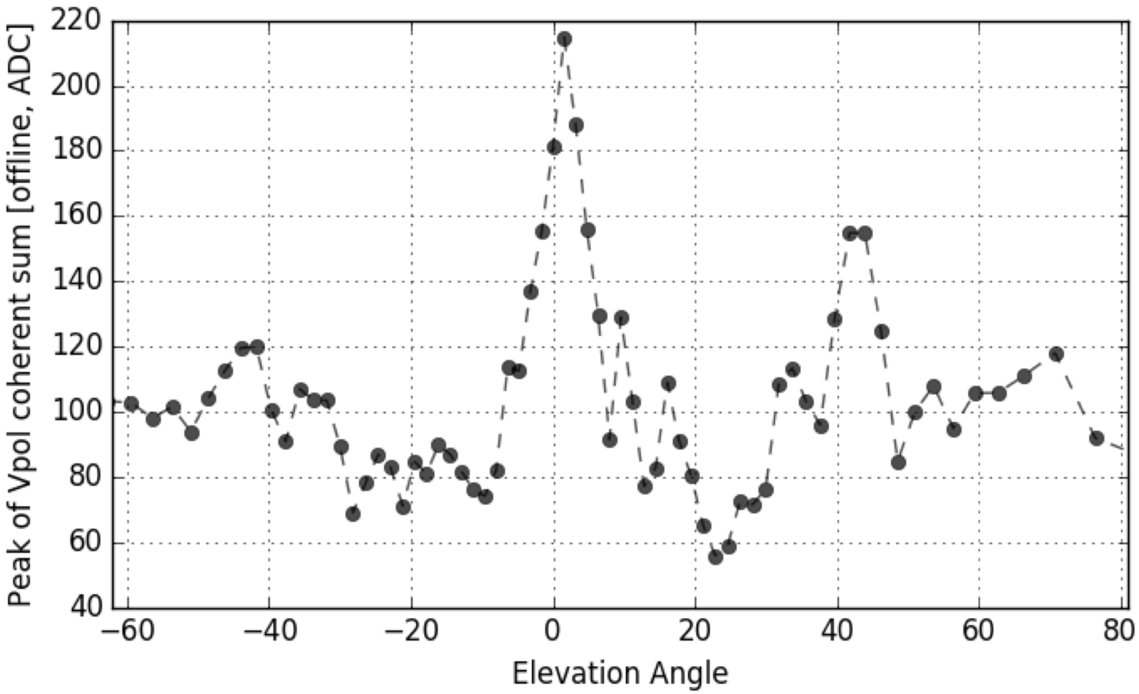
New Stations

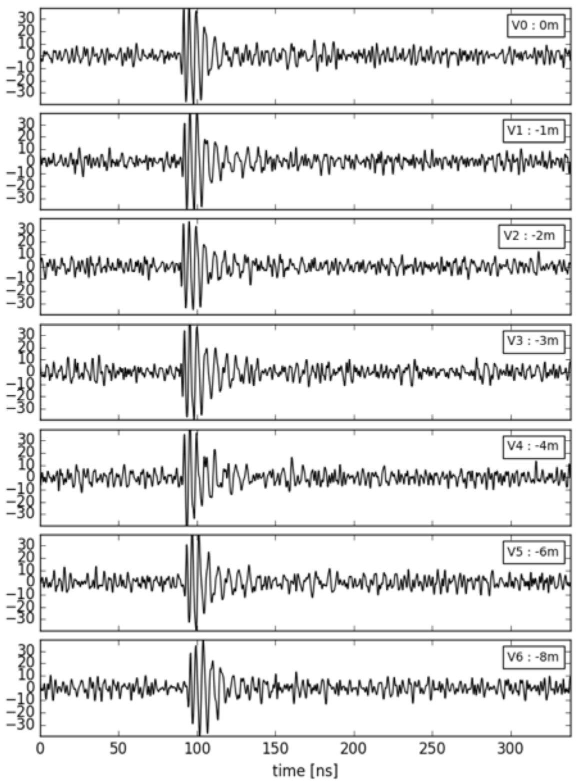
New Stations

New Phased Array w/ A5

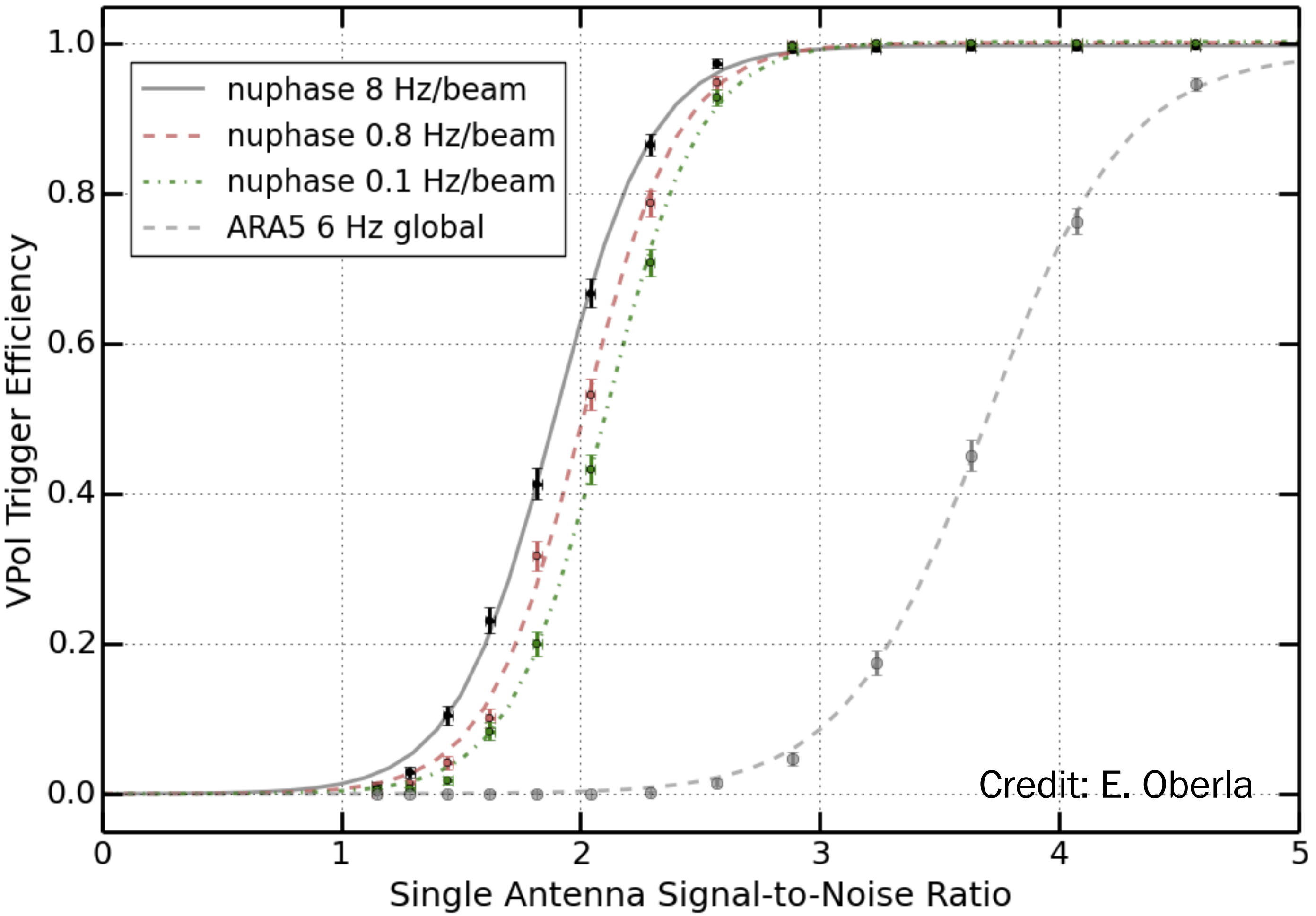


- ARA5 is equipped with a new *phased array* trigger (led by A. Vieregg @ UChicago)
- 7 VPol antennas deployed down *single* hole in the middle of A5
- Beamform *before* triggering → higher sensitivity
- Because for fixed trigger rate, threshold $\propto \sqrt{N}$





Phased Array Performance Comparison

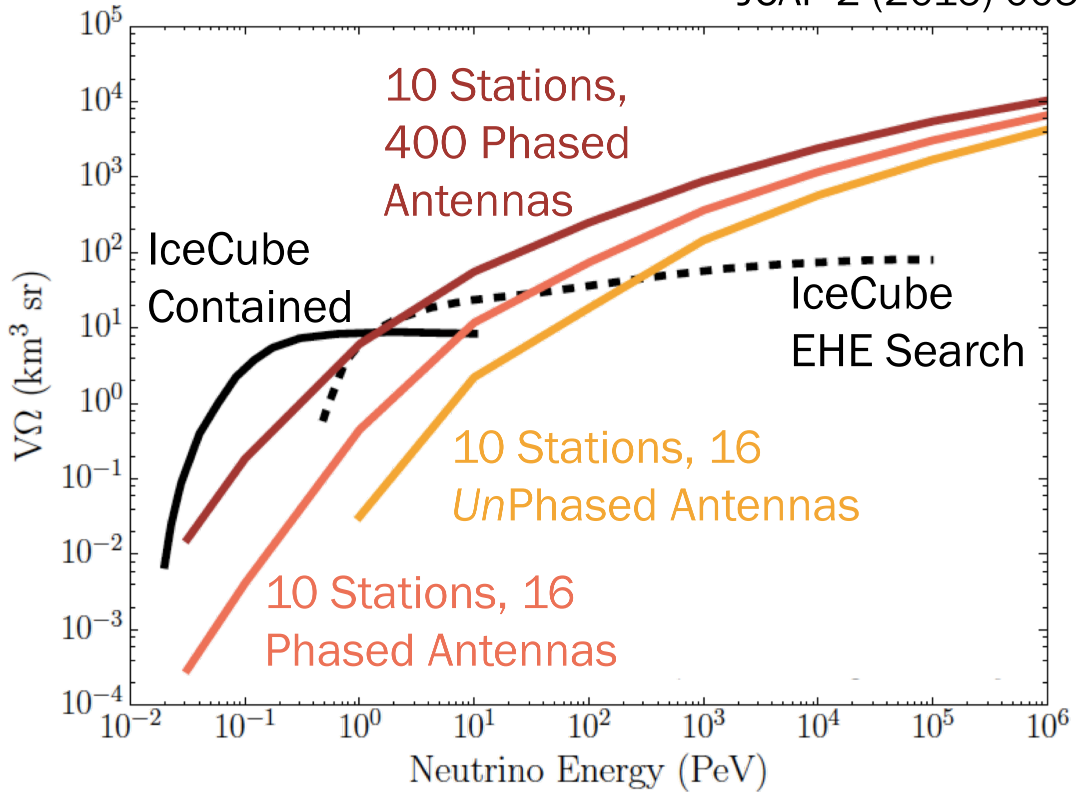


Preliminary:
PA measurement demonstrates factor ~1.8 reduction in 50% efficiency point (expected ~2.6).

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

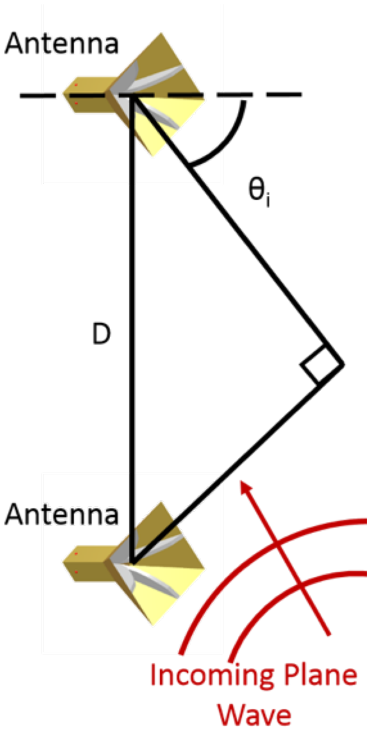
Station Configuration	Power Law	Power Law with Cutoff	Optimistic Cosmogenic	Pessimistic Cosmogenic
16-antenna	0.9	0.0	7.7	2.3
16-antenna, phased	3.8	0.1	19.6	6.0
400-antenna, phased	18.4	2.2	52.9	15.6

Analyses and Results

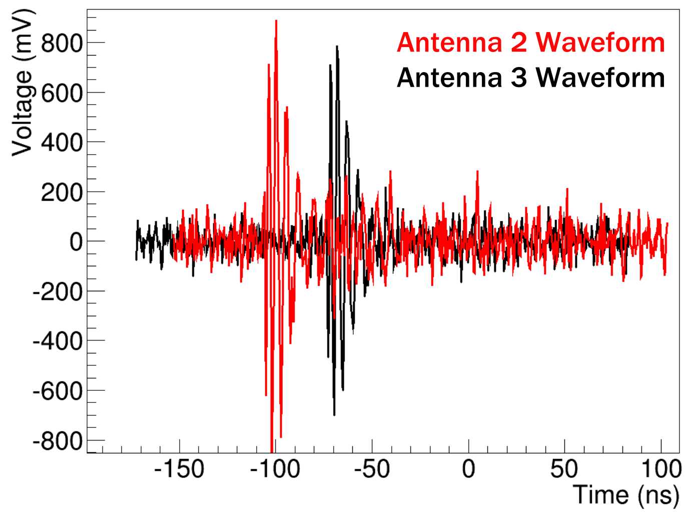
1. Solar Flares
2. Diffuse neutrinos
3. GRB Neutrinos

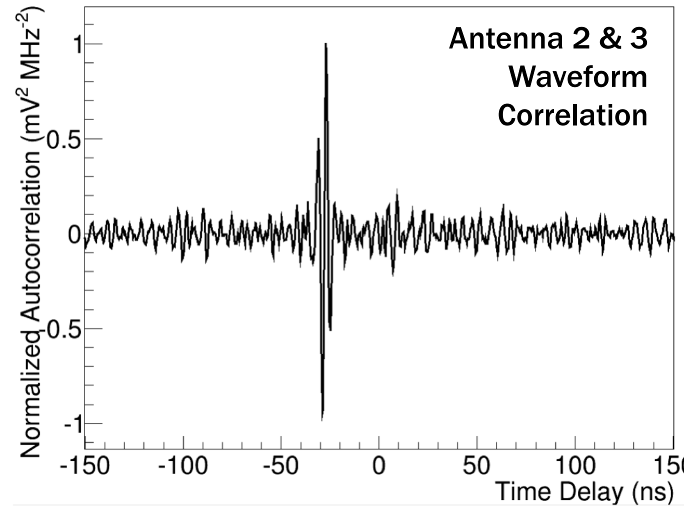
Interferometric Maps: Directional Reconstruction

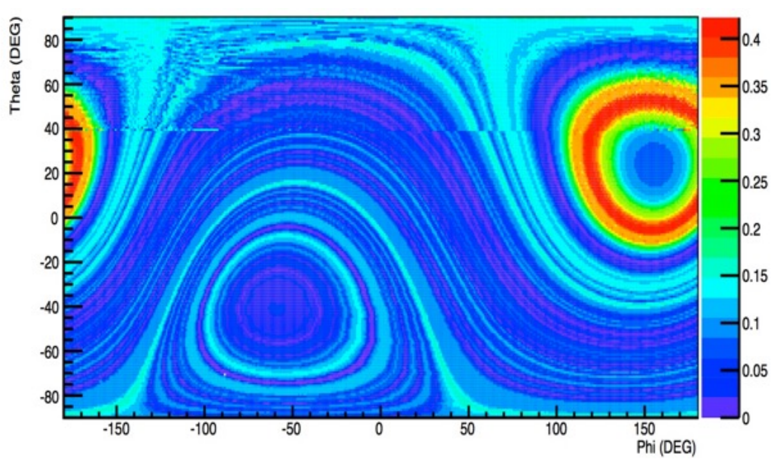
- Timing information ⟶ geometry information
- Punitive source angle ⟶ Time Delay ⟶ Correlation Value for that delay
- Take Hilbert envelope to interpret as *power*

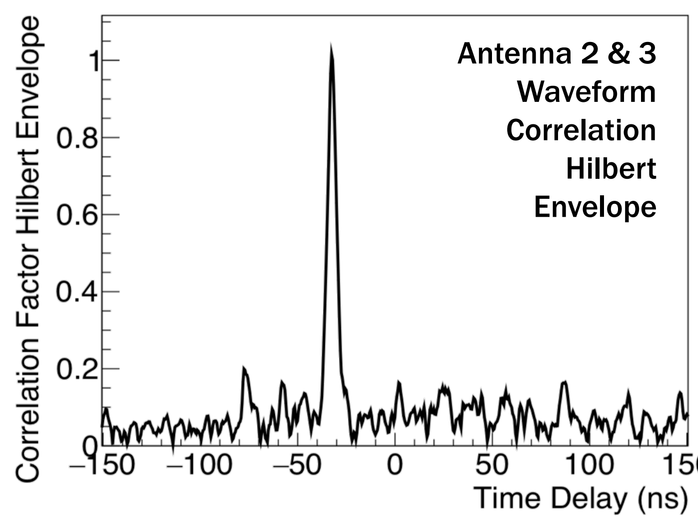


$$\theta_i = \arcsin\left(\frac{c\,\Delta t}{D}\right)$$





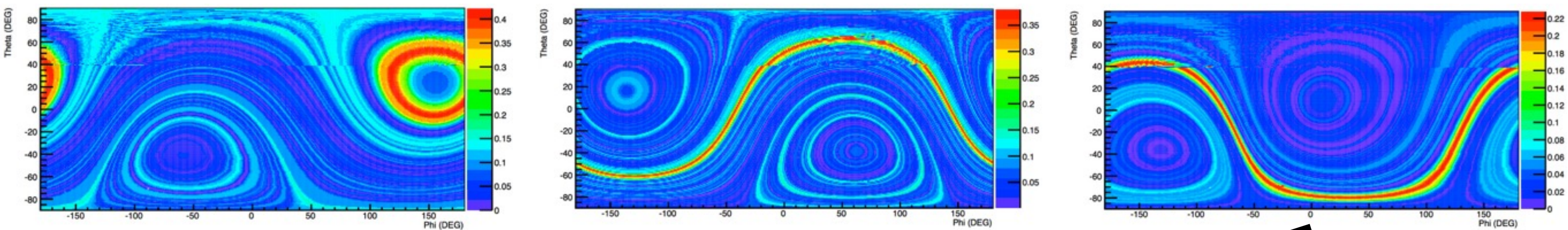




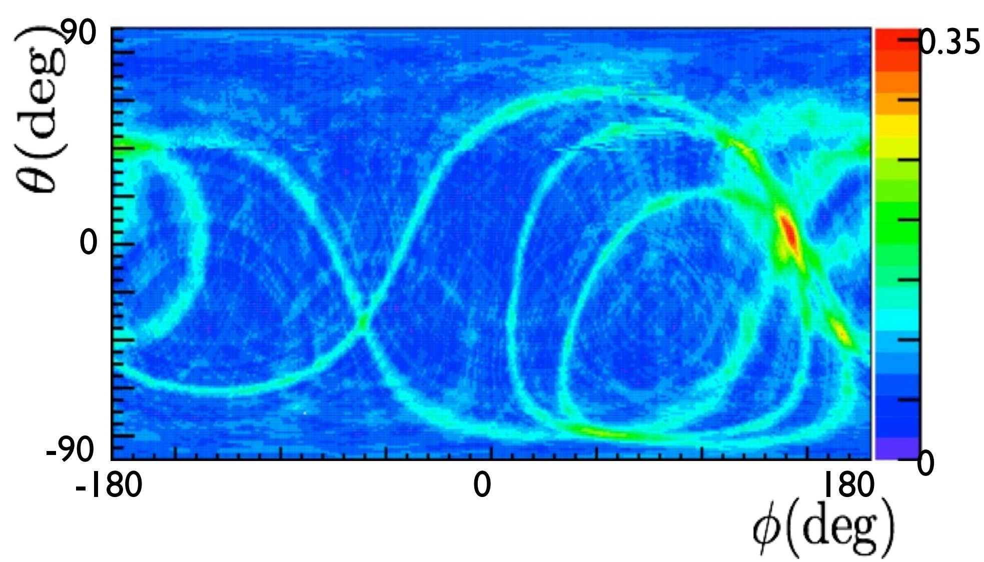
Interferometric Maps

- Punitive source angle → Time Delay → Correlation Value for that delay
- Plot that correlation value for all points on the sky, for all pairs of antennas

Map from pair 1 | Map from pair 2 | Map from pair 3 ...



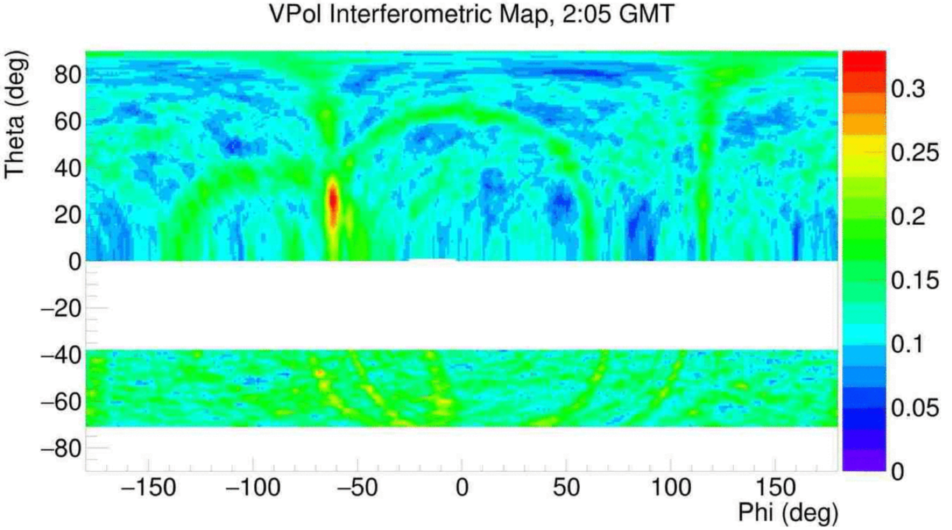
Figures by E. Hong

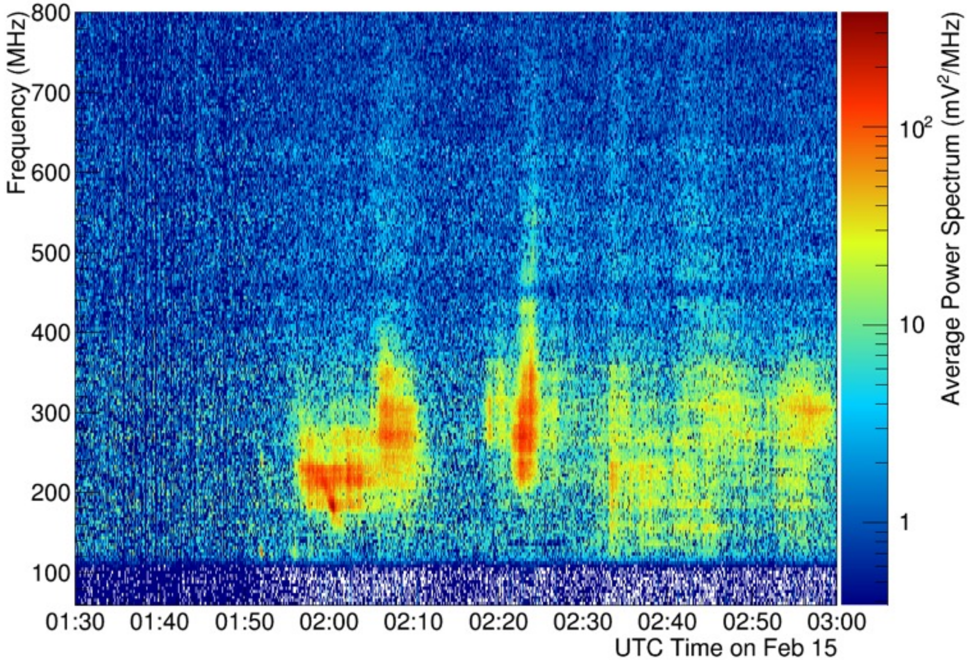


Peak in final map gives source direction

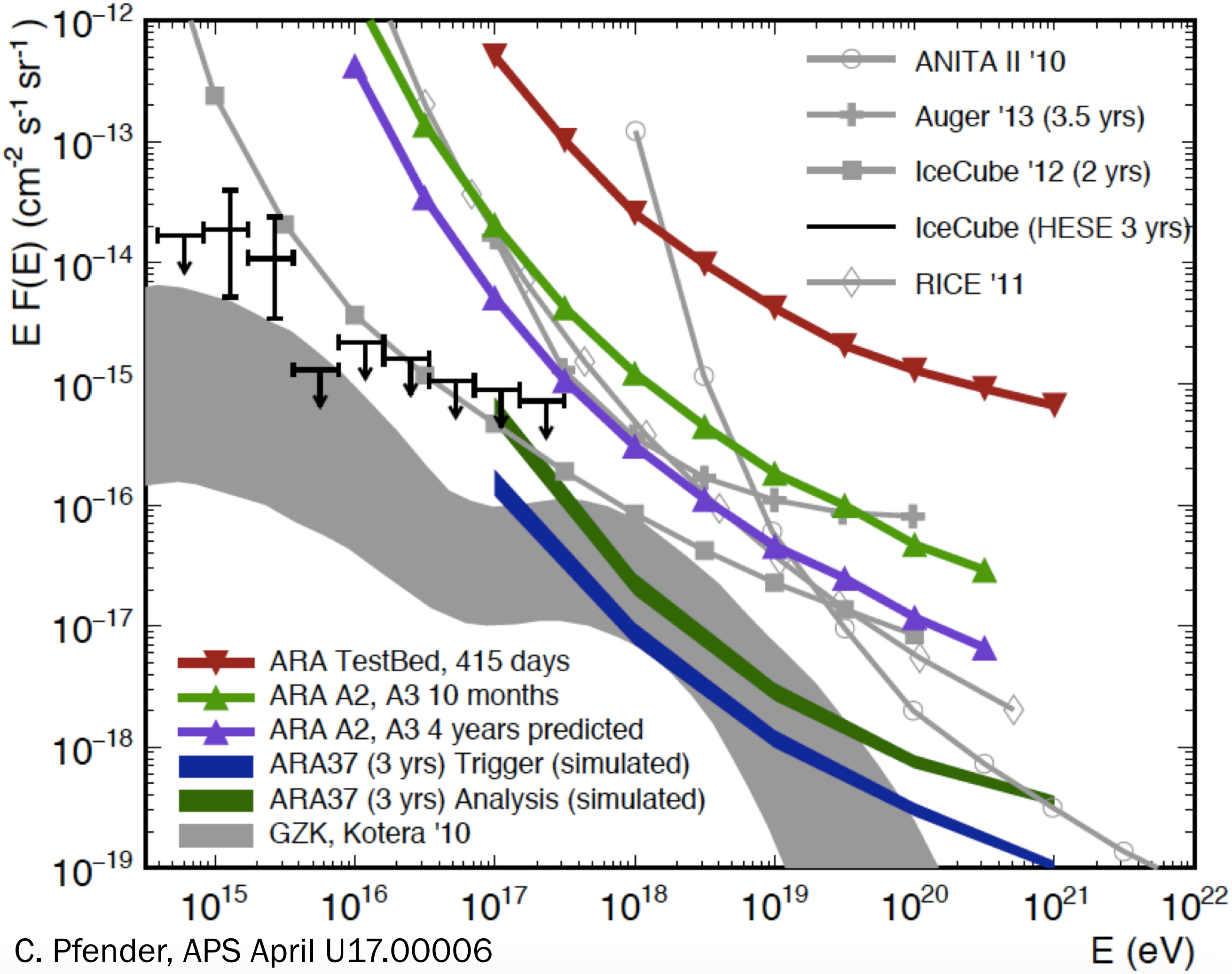
Solar Flare in the Testbed Prototype

- 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





Diffuse Analysis Status



C. Pfender, APS April U17.00006

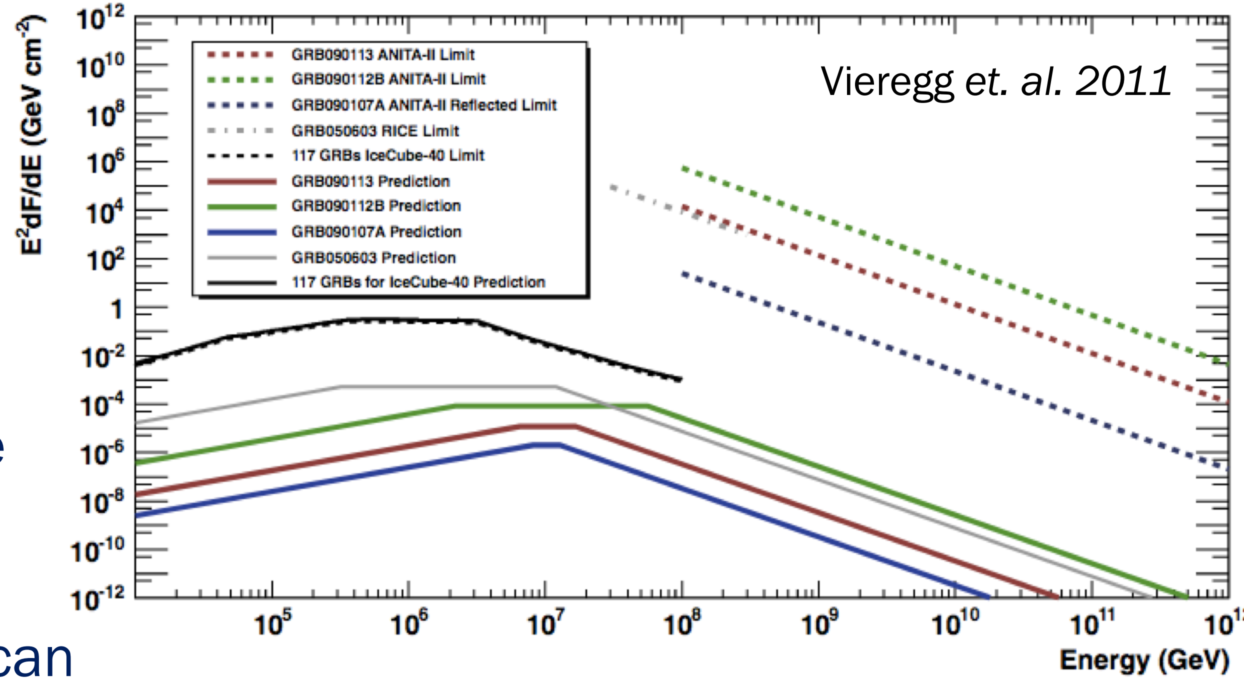
Two station, four year diffuse search in the works; Led By Carl Pfender (OSU).

ARA becomes competitive with Auger/IceCube at high energies.

Phase 1 array should probe even pessimistic cosmogenic models.

New Techniques: Motivation

Idea: reduce analysis thresholds for neutrino source searches

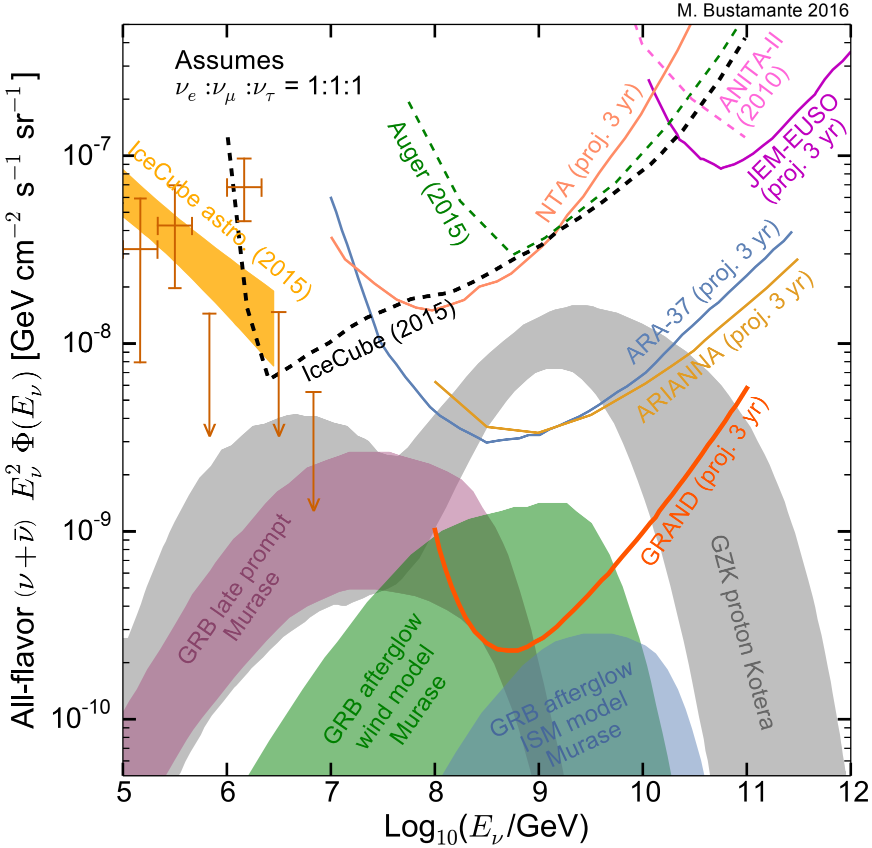


- A standard, *diffuse* searches require the *strictest* cuts
  - Neutrinos can come from "anywhere, anytime"
    → RF background can come from "anywhere, anytime"
- In a transient search, straightforward way to loosen cuts: restricted timing
  - ANITA-II searched for *prompt* neutrinos from GRBs [A.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

New Techniques: Motivation

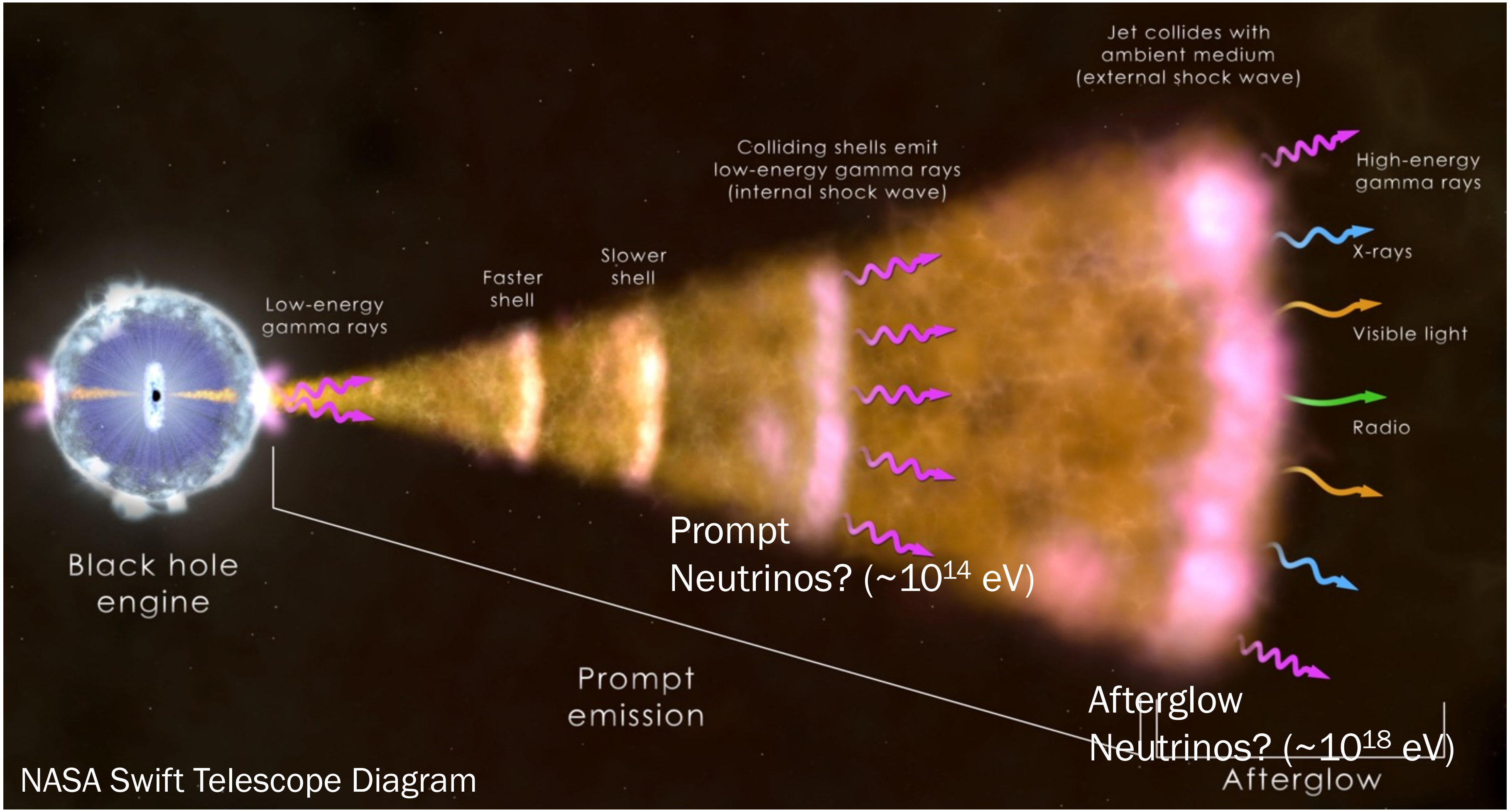
- But, not every source search allows for such small time windows
- Example: *afterglow* neutrino fluxes > *prompt* fluxes above ~$10^{17.5}$ eV, where ANITA is more sensitive
- Which is challenging, because afterglows require larger signal windows:
  - Prompt neutrino search: ~10 min signal window [A. 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



Searching for Neutrinos from GRBs

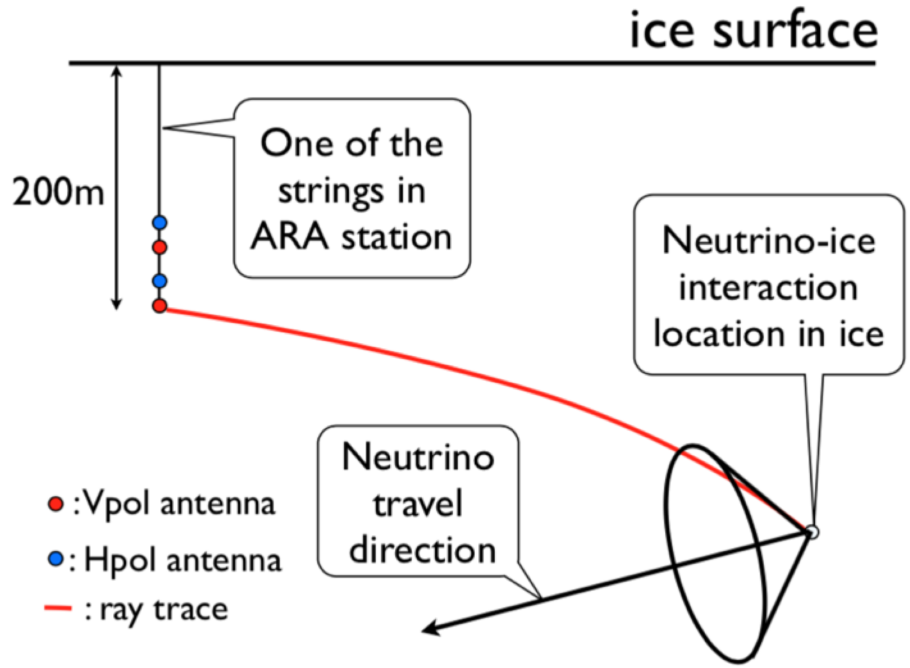
- Some (untested) models for GRBs require the emission of neutrinos



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



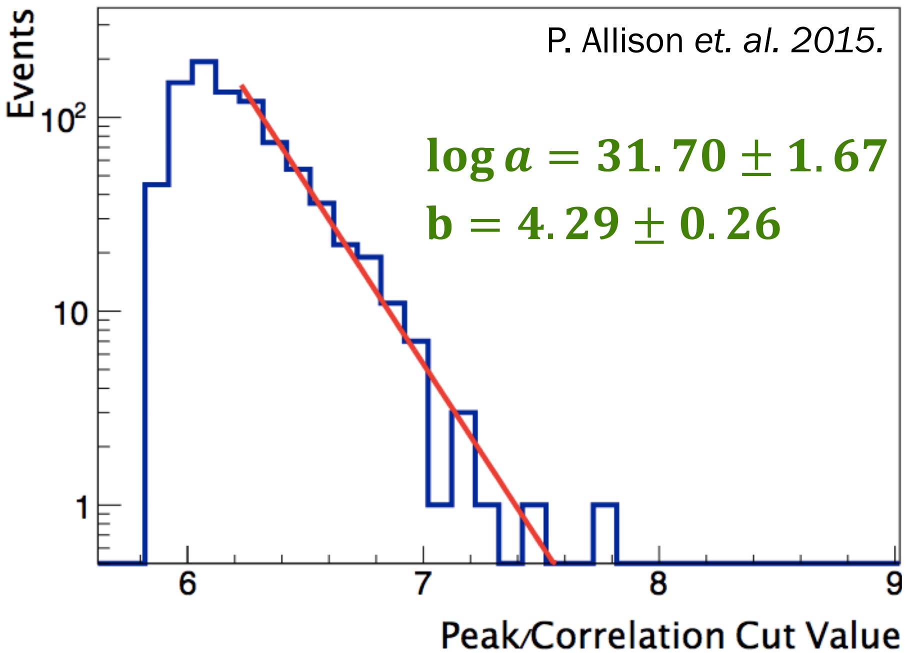
Oindree Banerjee working on afterglow neutrino search in ANITA-III

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 $\alpha > 0$: $a_{\text{new}} = a_{\text{old}}/\alpha$

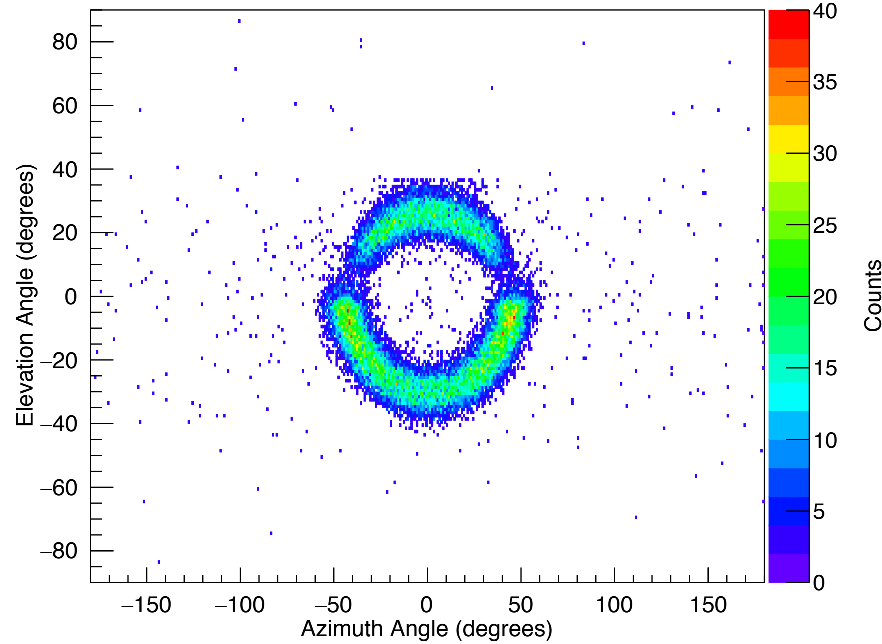
- We can predict the reduction in threshold:

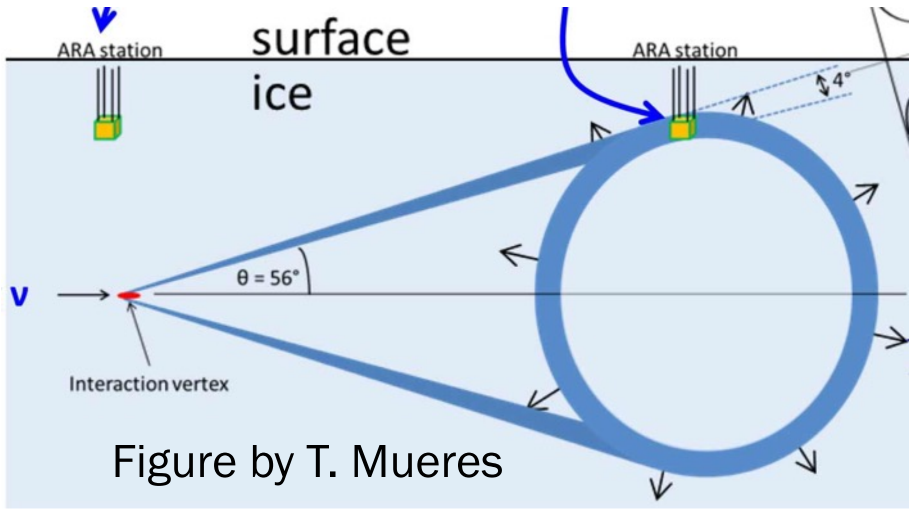
$$x_{\text{old}} - x_{\text{new}} = \frac{\ln \alpha}{b}$$

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 $\alpha \sim \frac{20{,}000 \text{ deg}^2}{1{,}600 \text{ deg}^2} \sim 12$
  - Which is is a reduction: $x_{\text{old}} - x_{\text{new}} \sim 0.5$

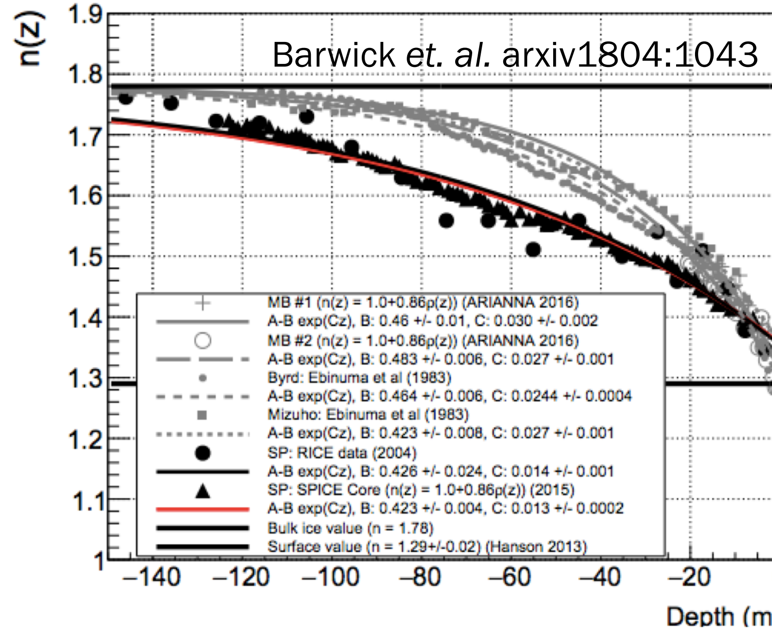


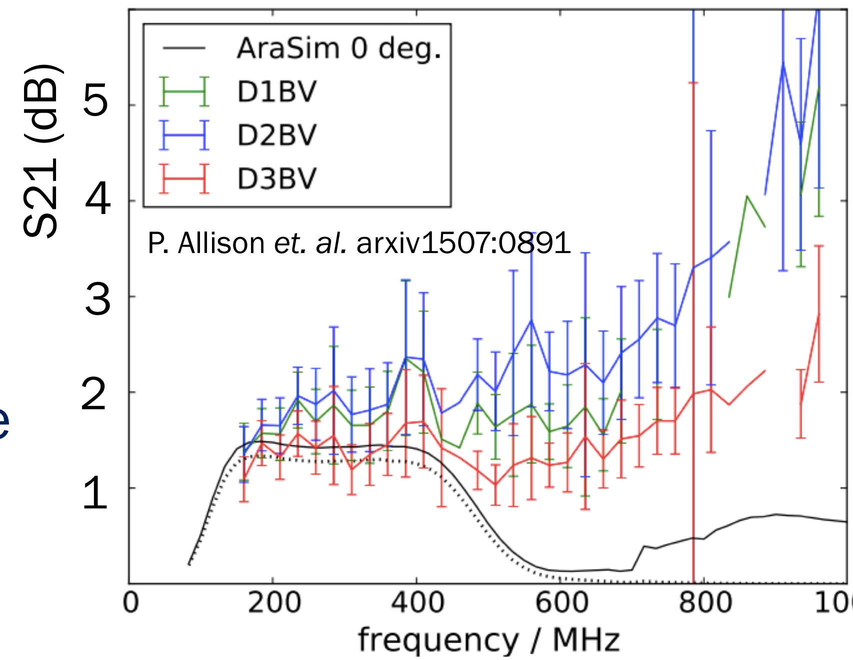


- Don't forget: signal events are *steeply* falling distributions of x_i. Small reductions in x_i significantly affect neutrino acceptance.

Ongoing Work

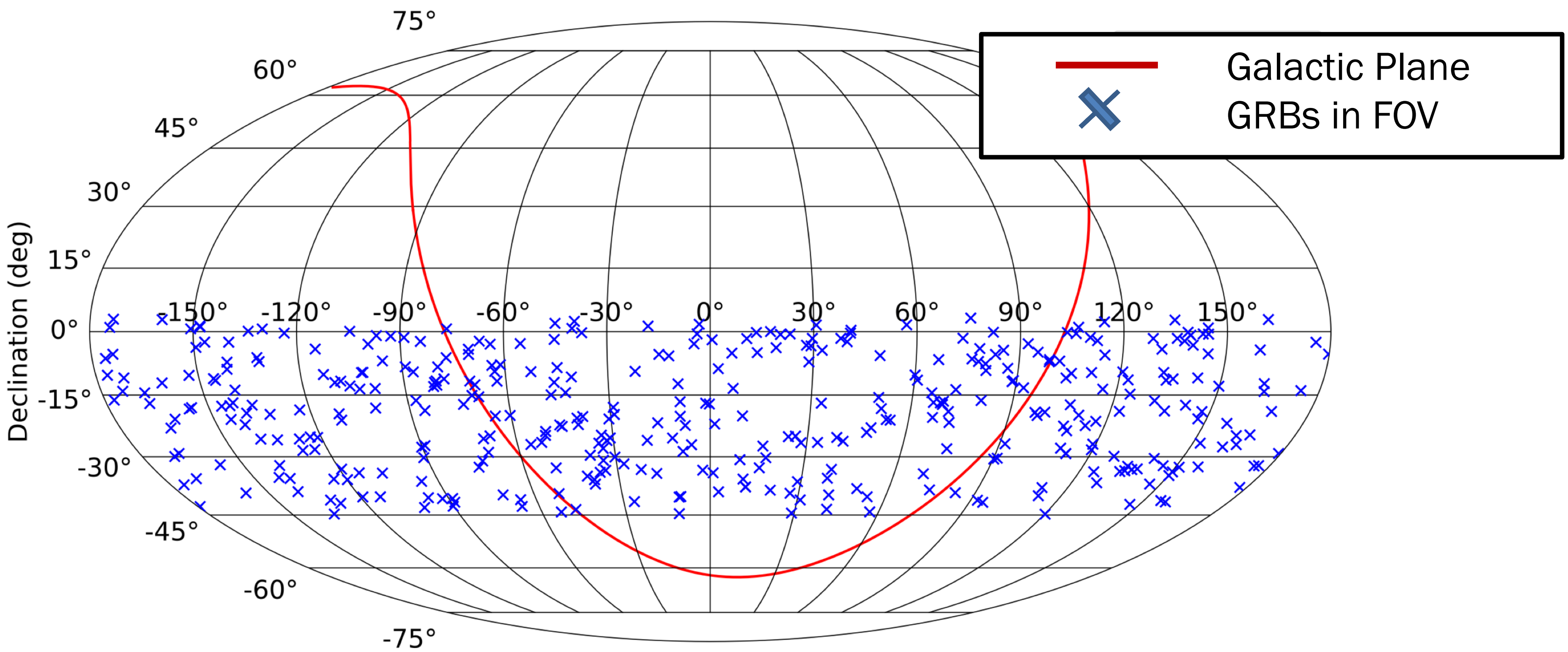
- Systematic Uncertainties on Reconstruction Algorithms
  - Ice modeling: what is *n(z)*
  - Geometry calibrations
- Need a way to determine *where* on the Cherenkov cone a candidate signal might be
  - Can look at VPol vs HPol signal strength (polarization)
  - And frequency information (spectral slope,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



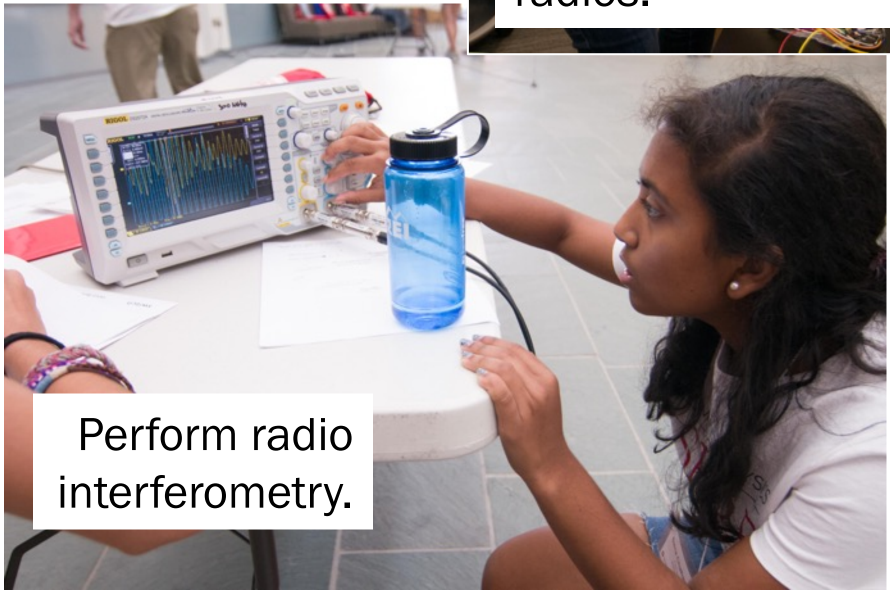
DEPARTMENT OF PHYSICS

ASPIRE

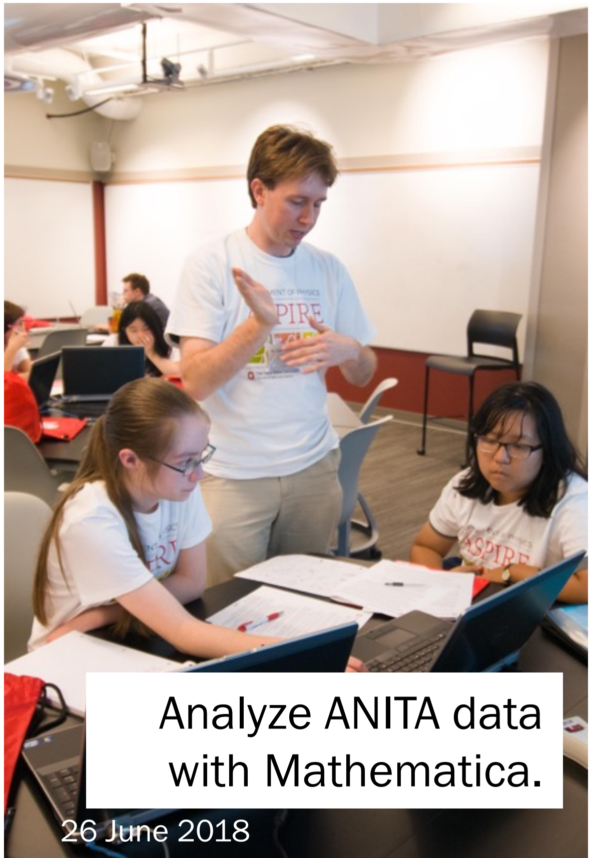
- NSF funded workshop for high school women
- **Hands on projects**

Check us out!
u.osu.edu/aspire

Build and program microcontroller radios.



Perform radio interferometry.



Analyze ANITA data with Mathematica.

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.

NSF
NASA

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- The Ohio Supercomputer Center
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- The OSU Center for Cosmology and Astroparticle Physics
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Thanks!

Questions?

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