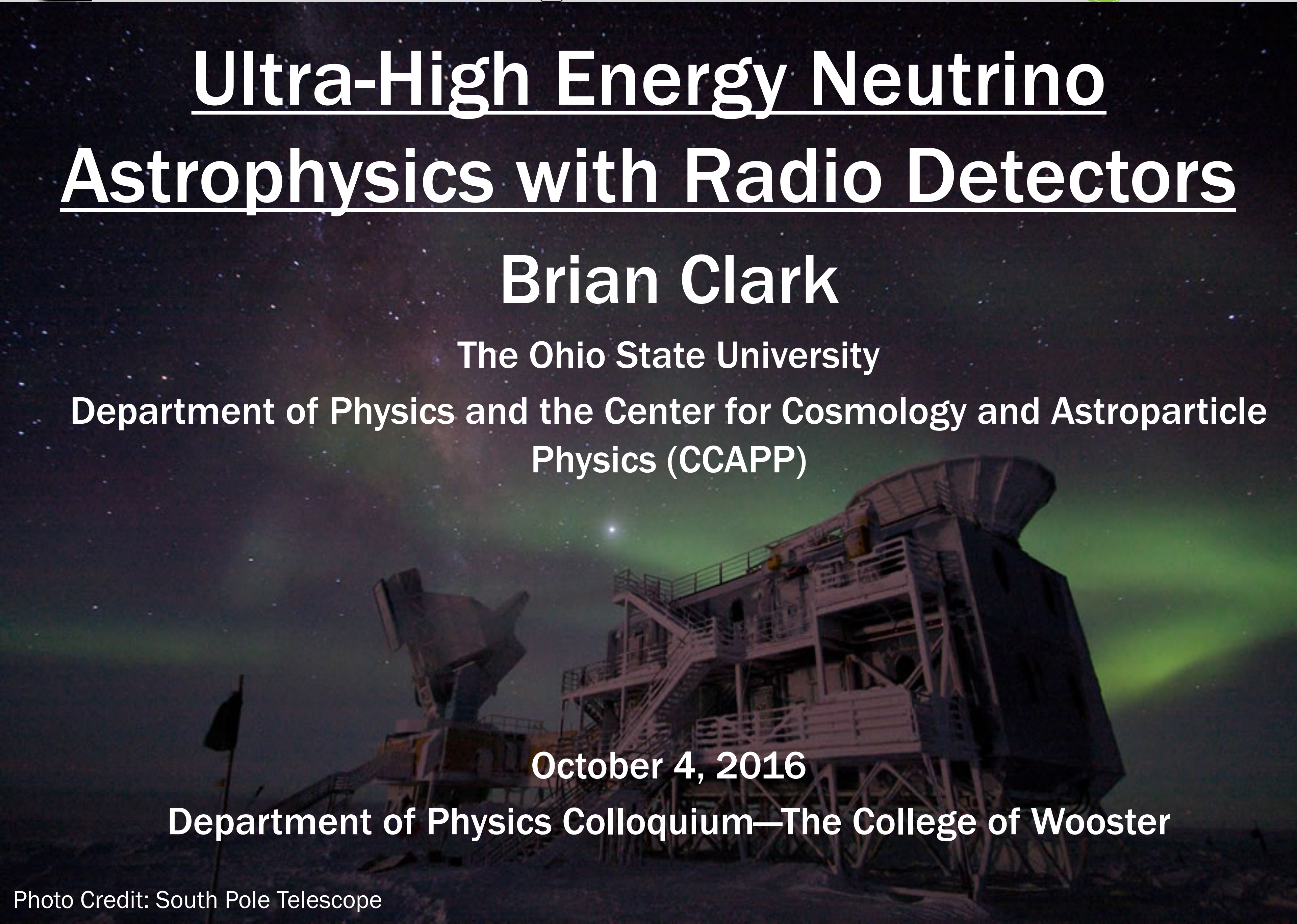

Ultra-High Energy Neutrino Astrophysics with Radio Detectors

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

October 4, 2016

Department of Physics Colloquium—The College of Wooster

Photo Credit: South Pole Telescope

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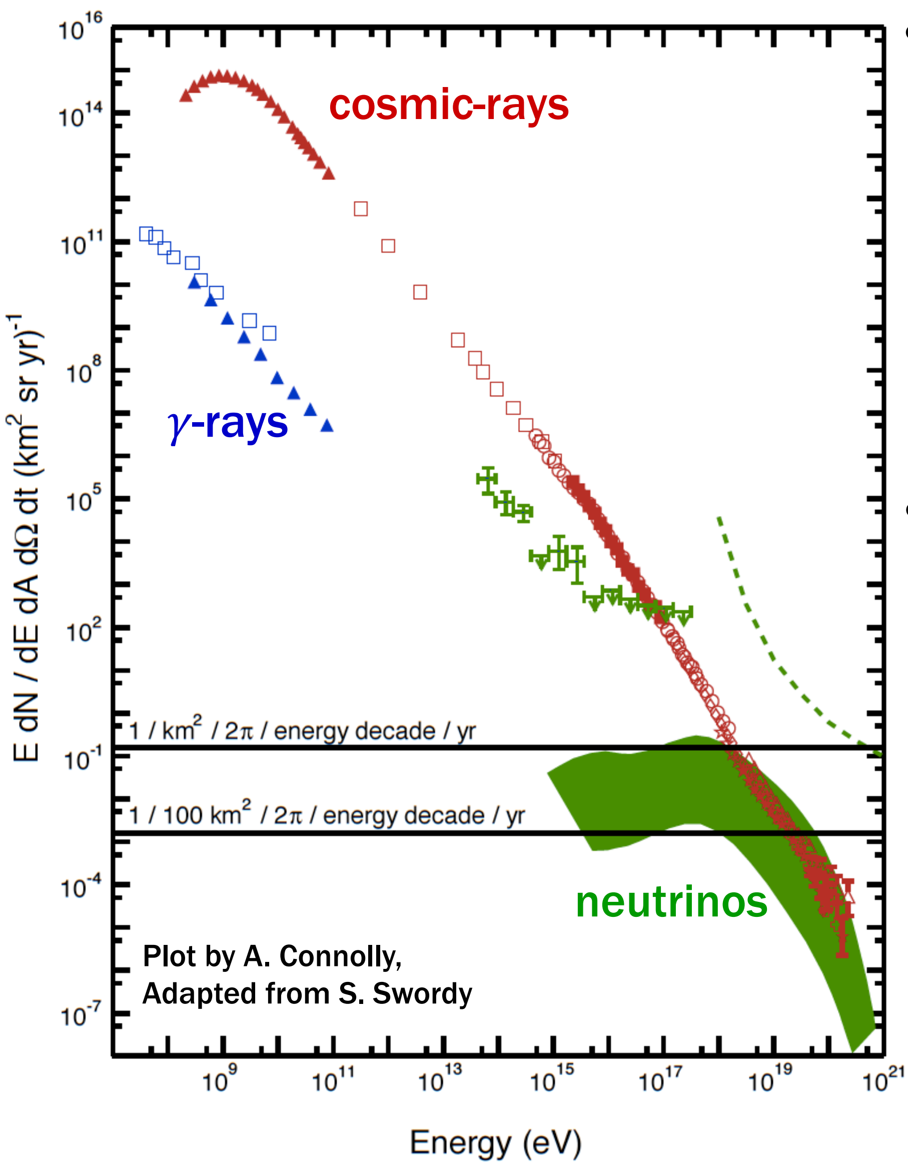
Photo Credit: McGill University

Outline

1. Why neutrinos?
2. Current experiments
3. Analyses and Results
4. Future plans

Why Neutrinos?

Why Study Neutrinos: Astrophysical Messengers

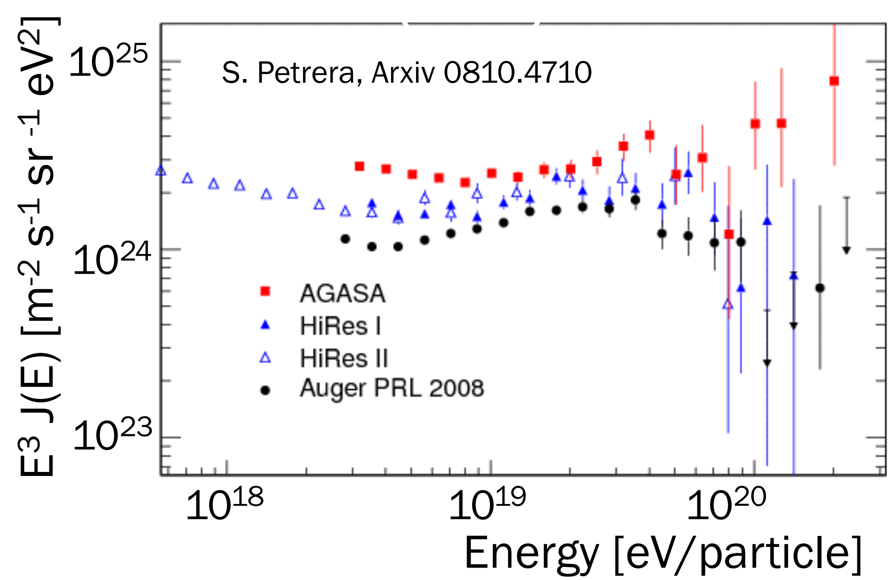


- Cosmic rays >$10^{19.5}$ eV attenuated, possibly by GZK effect, e.g.

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

→ Screens extragalactic (>100 MPc) sources

- γ-rays annihilate w/ CMB @ ~1 TeV

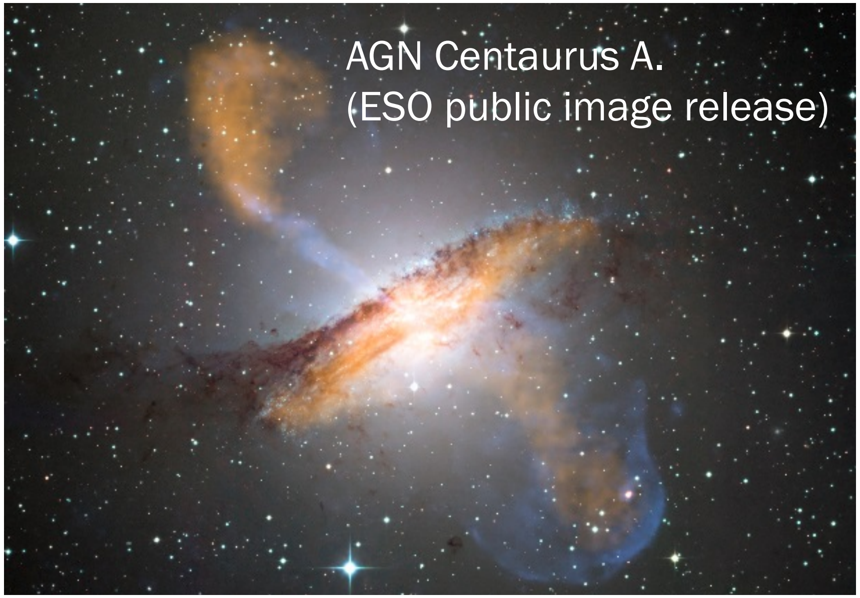


Astrophysical Messengers

Two Sources of Neutrinos

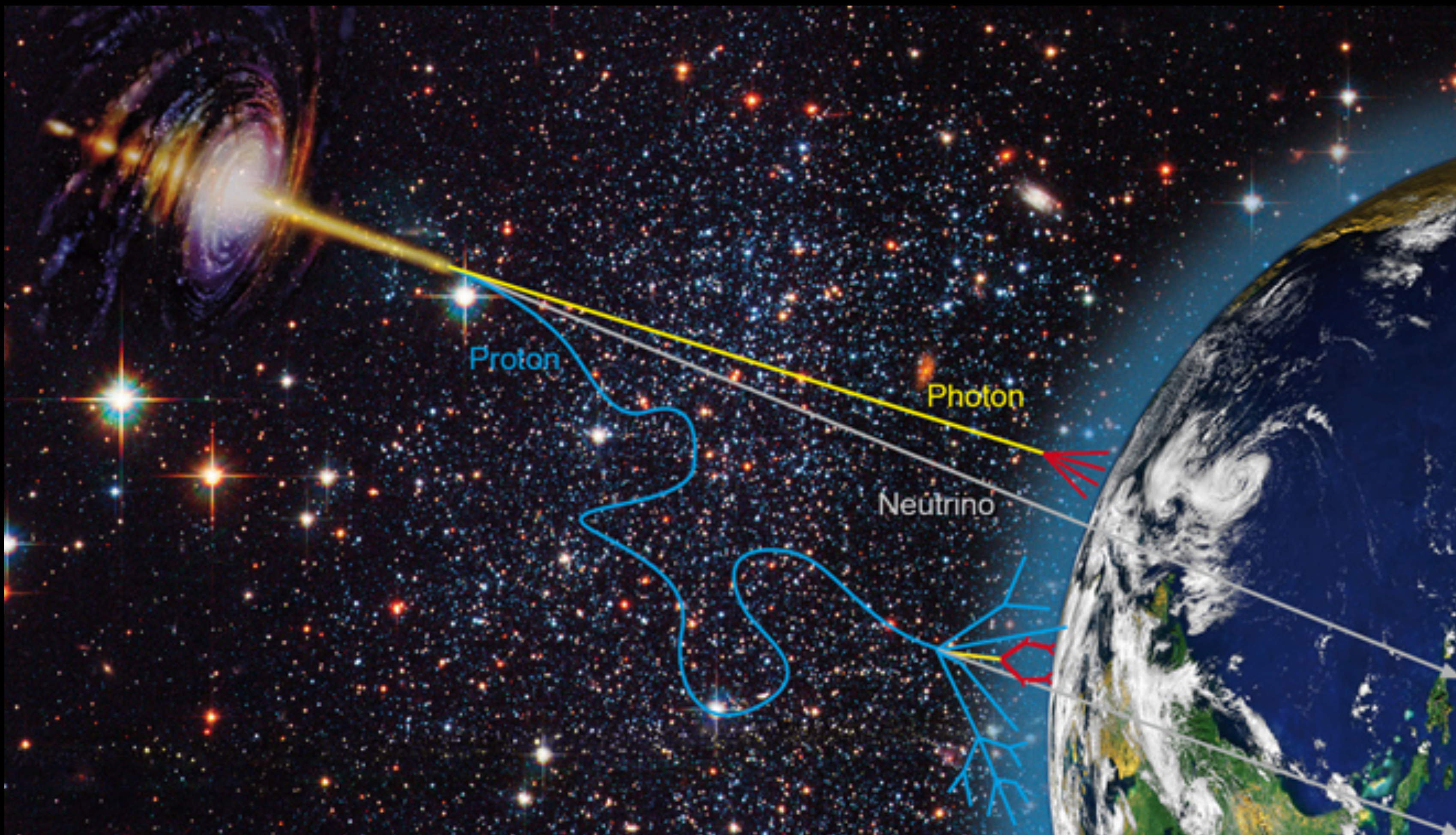
- *Predicted* "BZ Flux": pions from GZK process decay into neutrinos
- "Source Flux": Neutrinos from the CR accelerators
  - Gamma Ray Bursts (GRB)
  - Active Galactic Nuclei (AGN)

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



Neutrinos have attractive properties

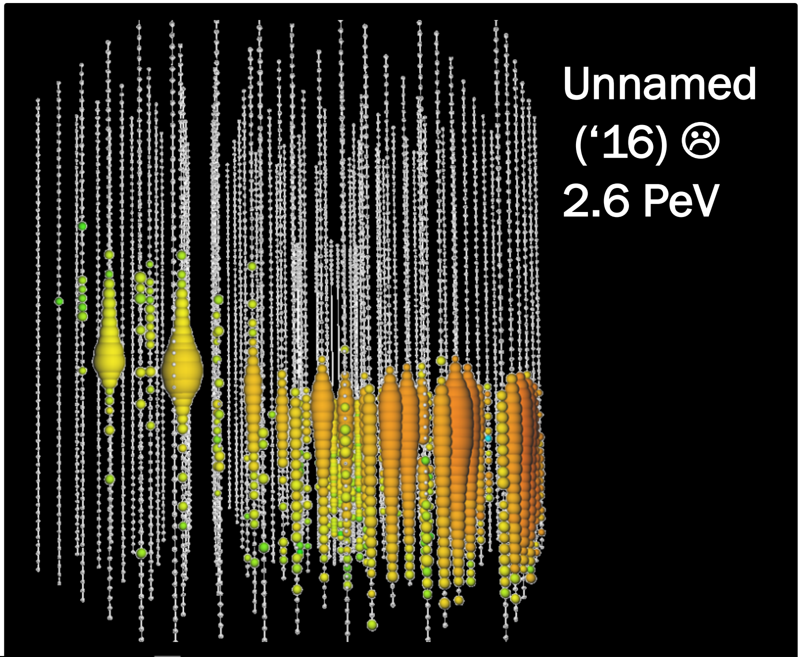
- Weakly interacting: travel cosmic distances unattenuated
- Chargeless: not deflected by (inter) galactic magnetic field
  → point back to source!

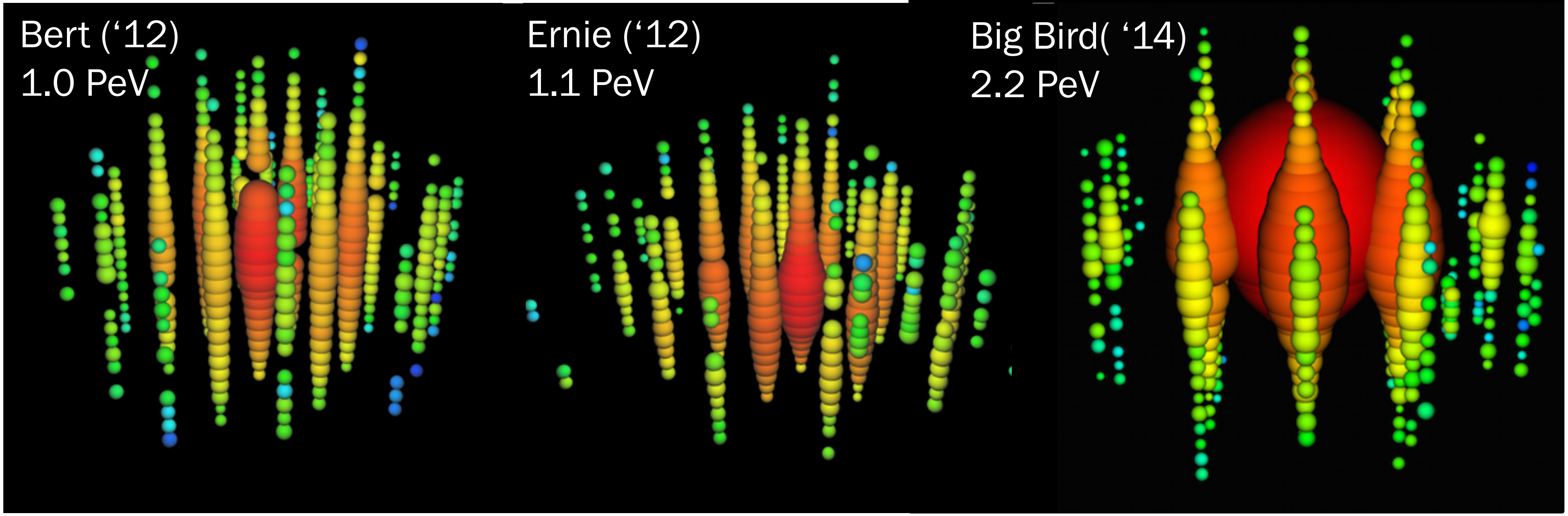

Proton
Photon
Neutrino

Cosmic Neutrinos

They Exist!

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



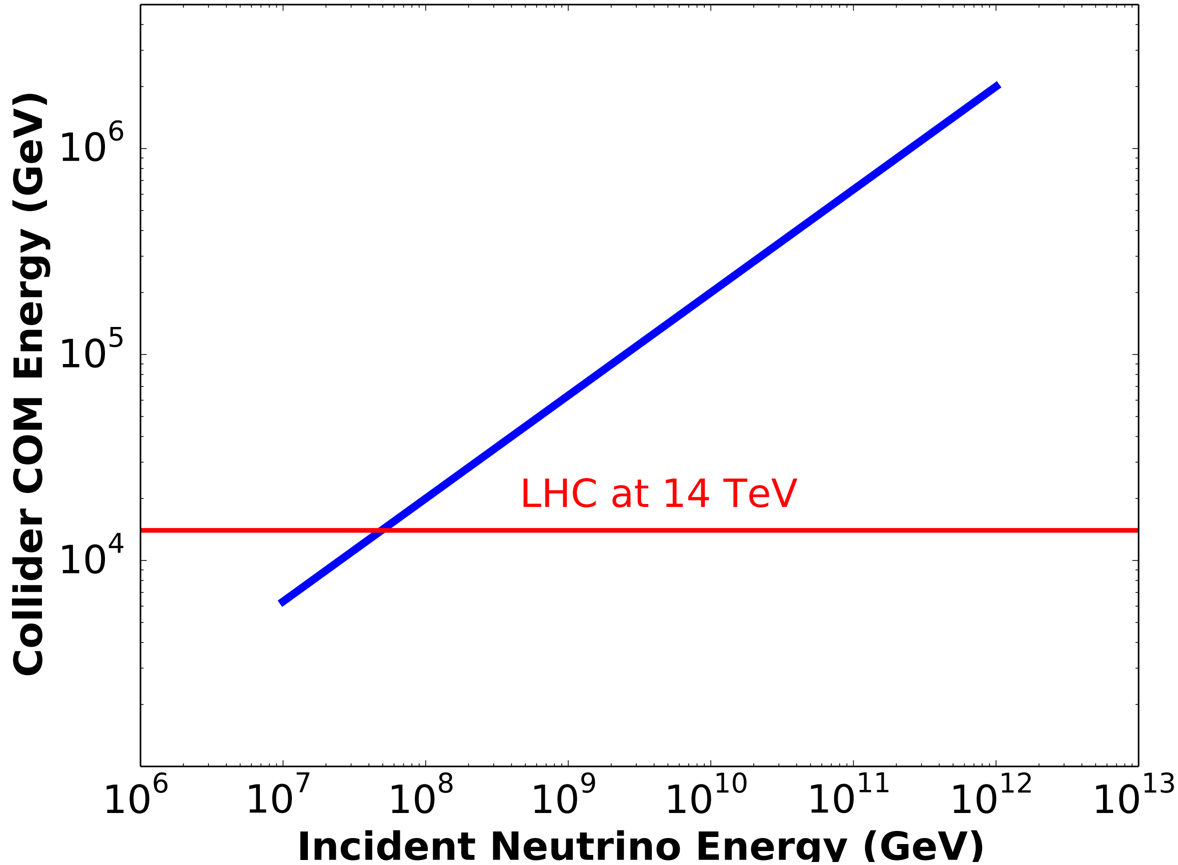


Why Study Neutrinos: Particle Physics Probes

- **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

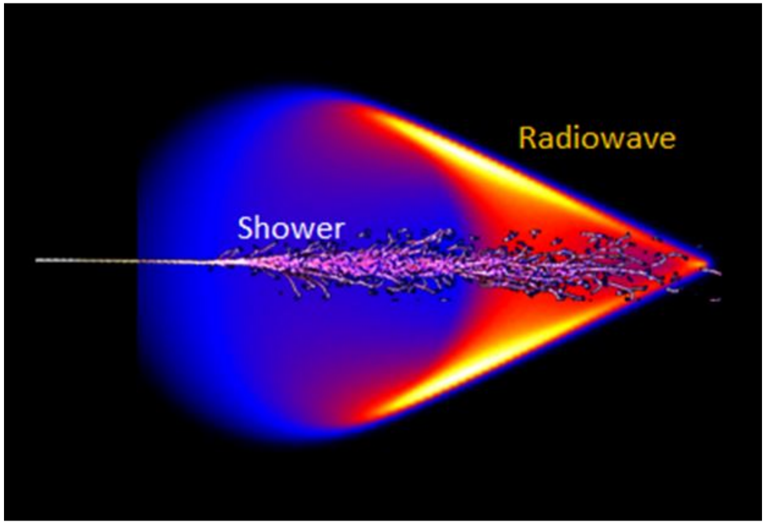
Neutrino Interactions

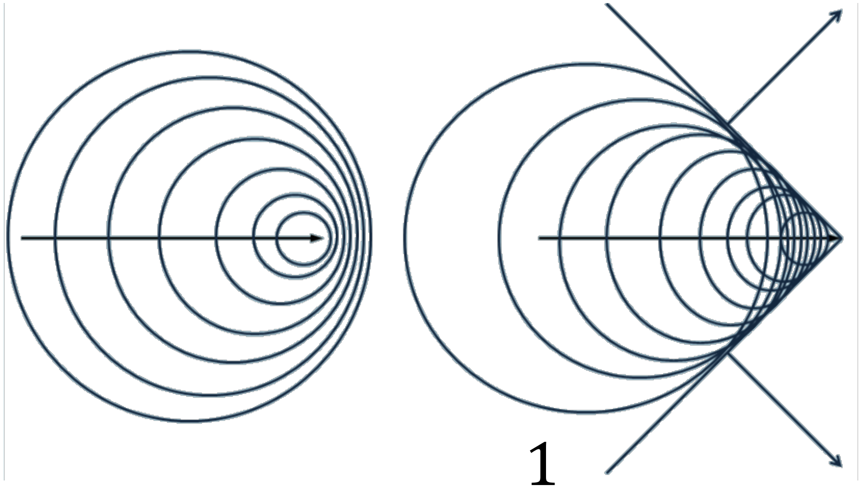
- Two varieties of interactions: Charged current (CC) and Neutral Current (NC)

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
- Intensity is greatest at Cherenkov angle θ_C
- Two varieties of interest: optical (IceCube) and radio (ARA/ANITA)

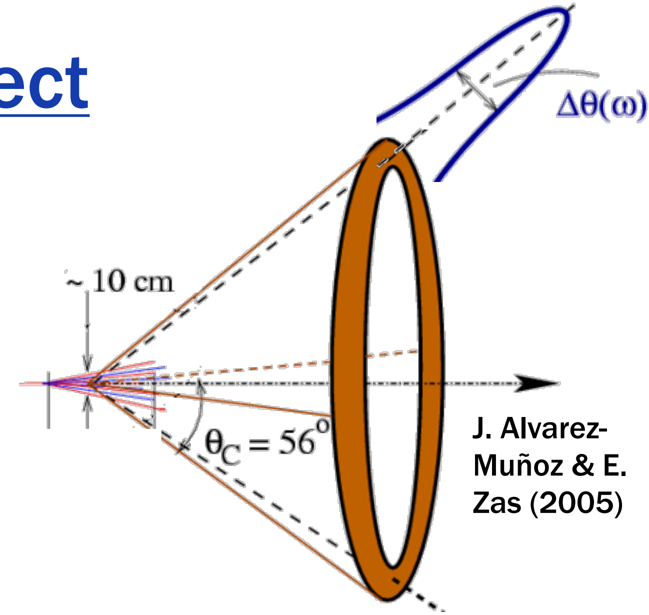




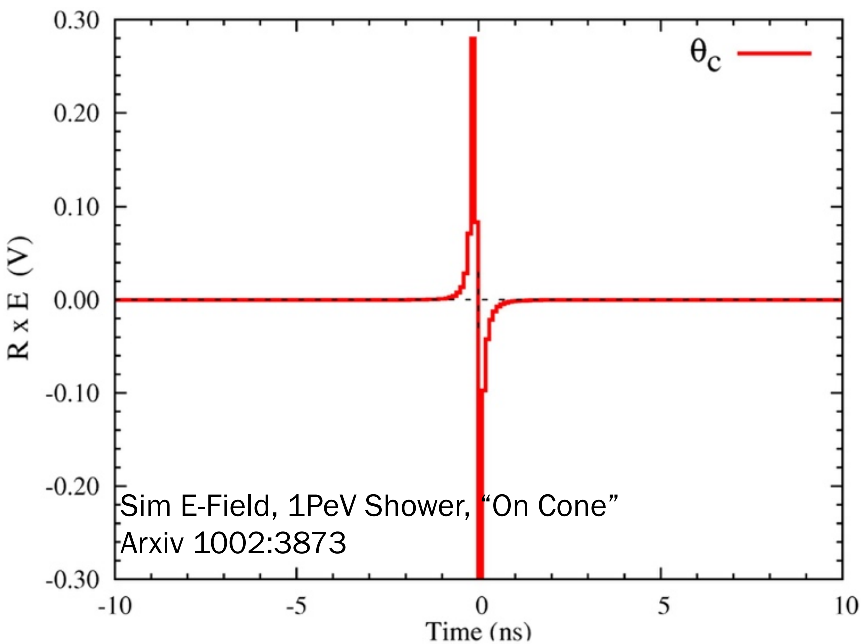
$$\cos\theta_C = \frac{1}{n\beta}$$

Radio Cherenkov Effect

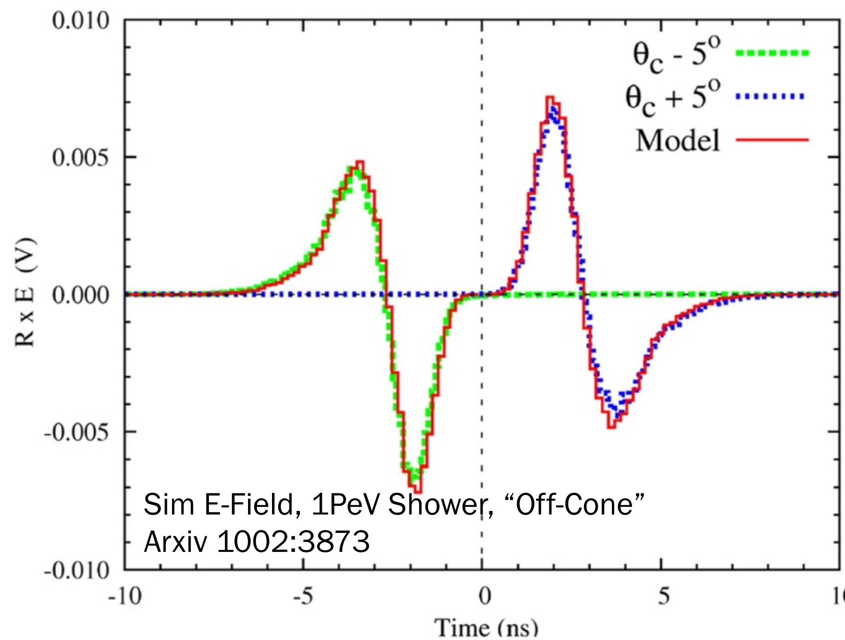
- Showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add *coherently*
- Broadband (200 MHz → 1.2GHz) radio *pulse*
- Conical emission (57 ° in ice)



J. Alvarez-Muñoz & E. Zas (2005)



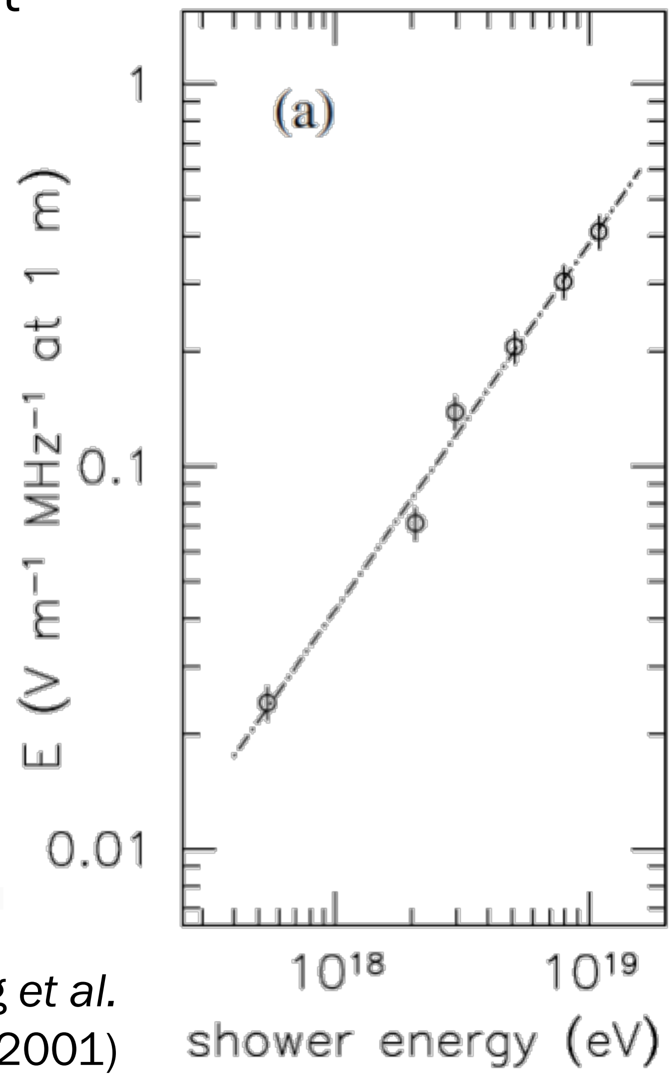
Sim E-Field, 1PeV Shower, "On Cone"
Arxiv 1002:3873



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)

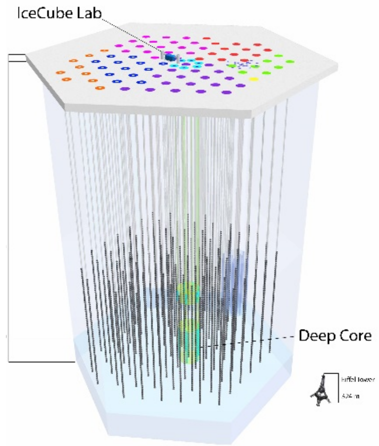
Current Experiments

Detecting an UHE Neutrino

- 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)
- Several Options:
  - Balloon experiments: radio
  - Ground based arrays: air shower, radio
  - *In-Situ* experiments: optical, radio

ANITA-III (radio)

IceCube (optical)

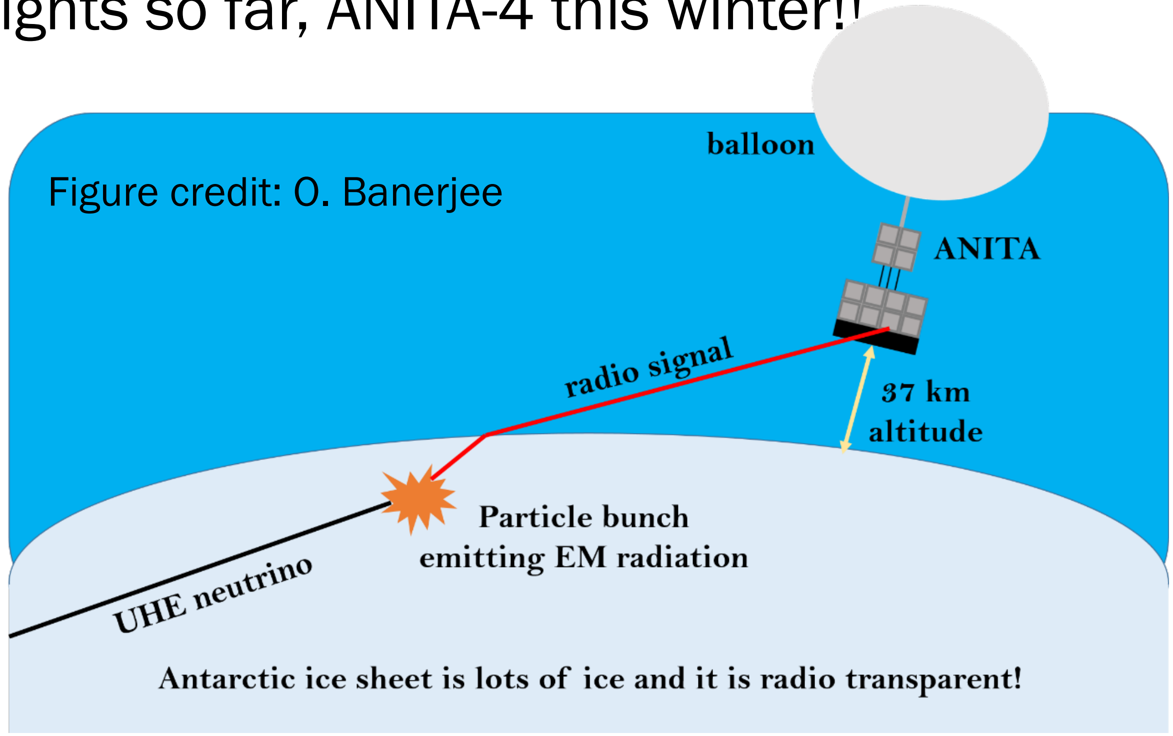


LUNASKA (radio)

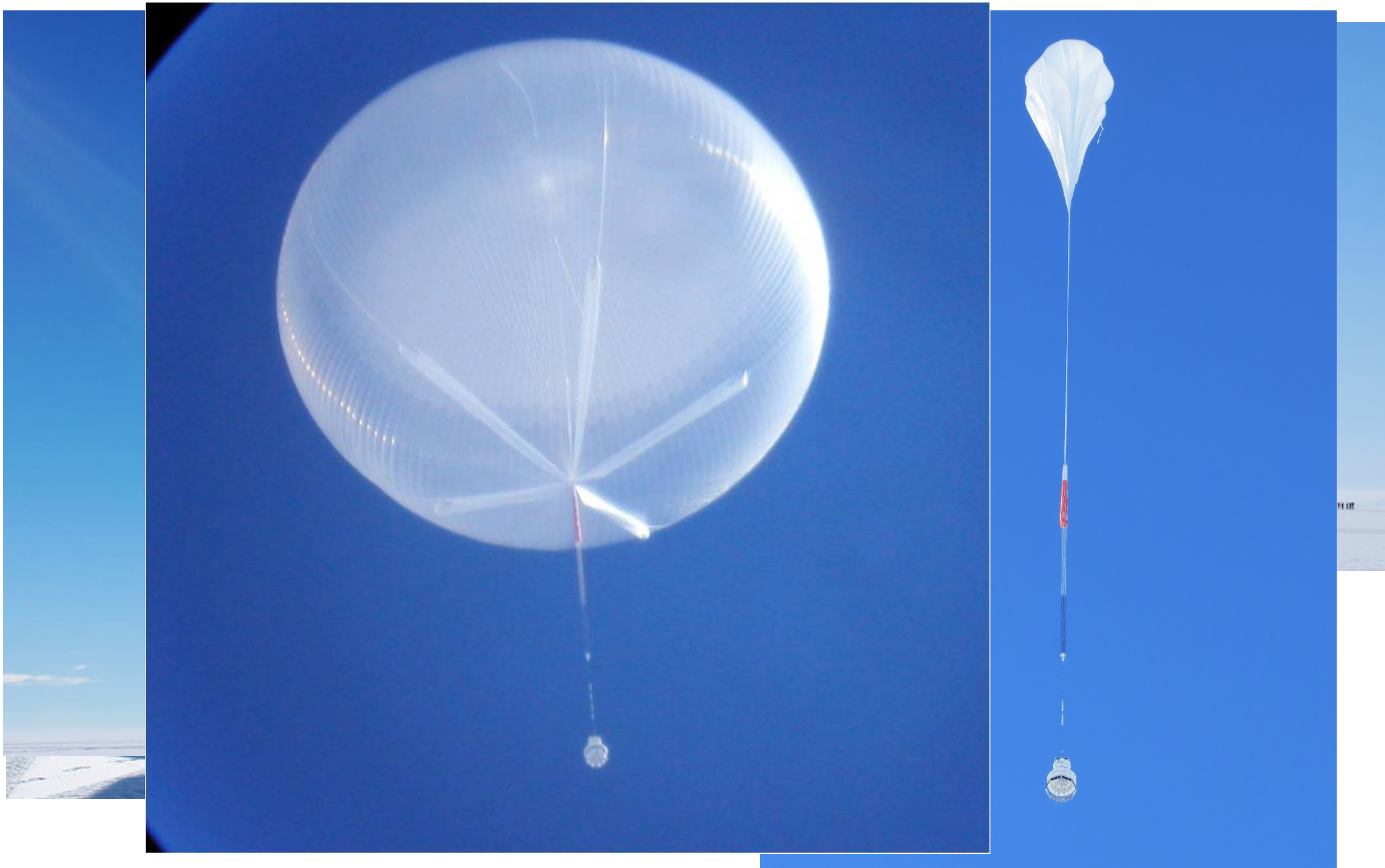
Auger (air shower)

ANtarctic Impulsive Transient Antenna (ANITA)

- ~40 dual polarized antennas (100-1200 MHz bandwidth)
- Flown by NASA balloon; altitude 40 km
- Observes 10^6 km^2 of ice
- Energy range: $10^{18} \rightarrow 10^{21+}$ eV
- 3 flights so far, ANITA-4 this winter!!



High energy threshold, but *huge* effective volume




South Atlantic Ocean
Cutaway View of Ice Sheet
Weddell Sea
Queen Maud Land
Flight Path
Enderby Land
Indian Ocean
South Pole
West Antarctica
Marie Byrd Land
Ross Ice Shelf
East Antarctica
Ross Sea
Victoria Land
Wilkes Land
South Pacific Ocean
McMurdo Station

ANITA Collaboration

USA:

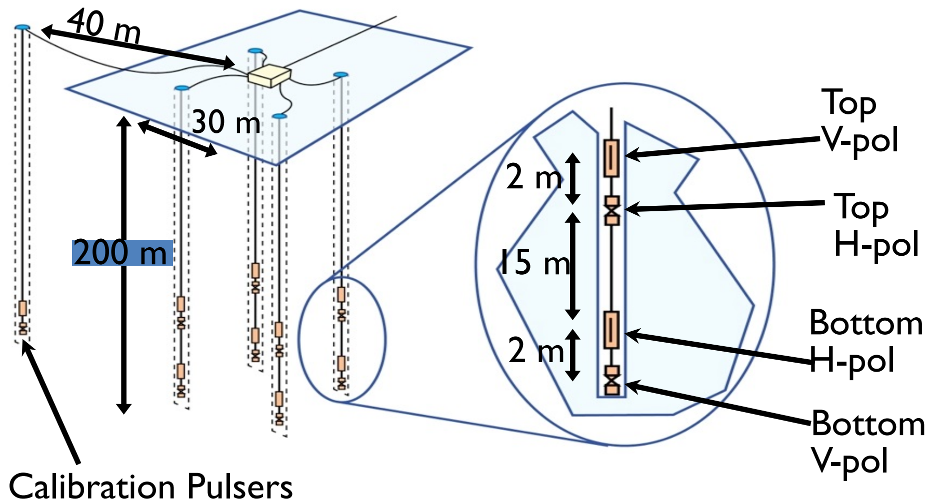
- Ohio State University
- Cal Poly
- University of California Los Angeles
- University of Chicago
- University of Delaware
- University of Kansas
- University of Hawaii
- Washington University in St. Louis

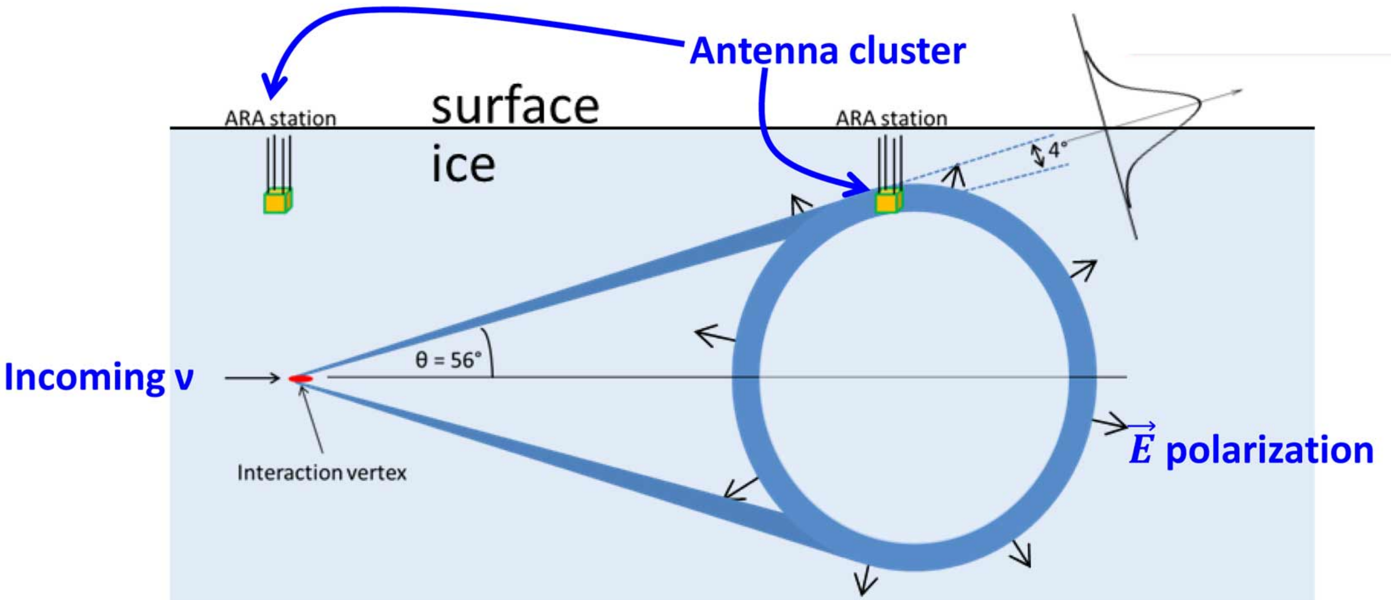
UK: University College London

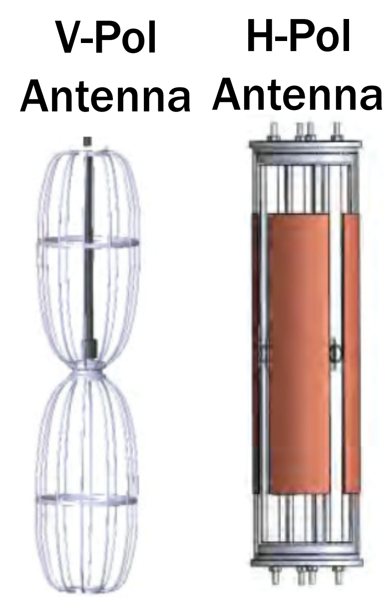
Taiwan: National Taiwan University

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







THE OHIO STATE UNIVERSITY

CAL POLY

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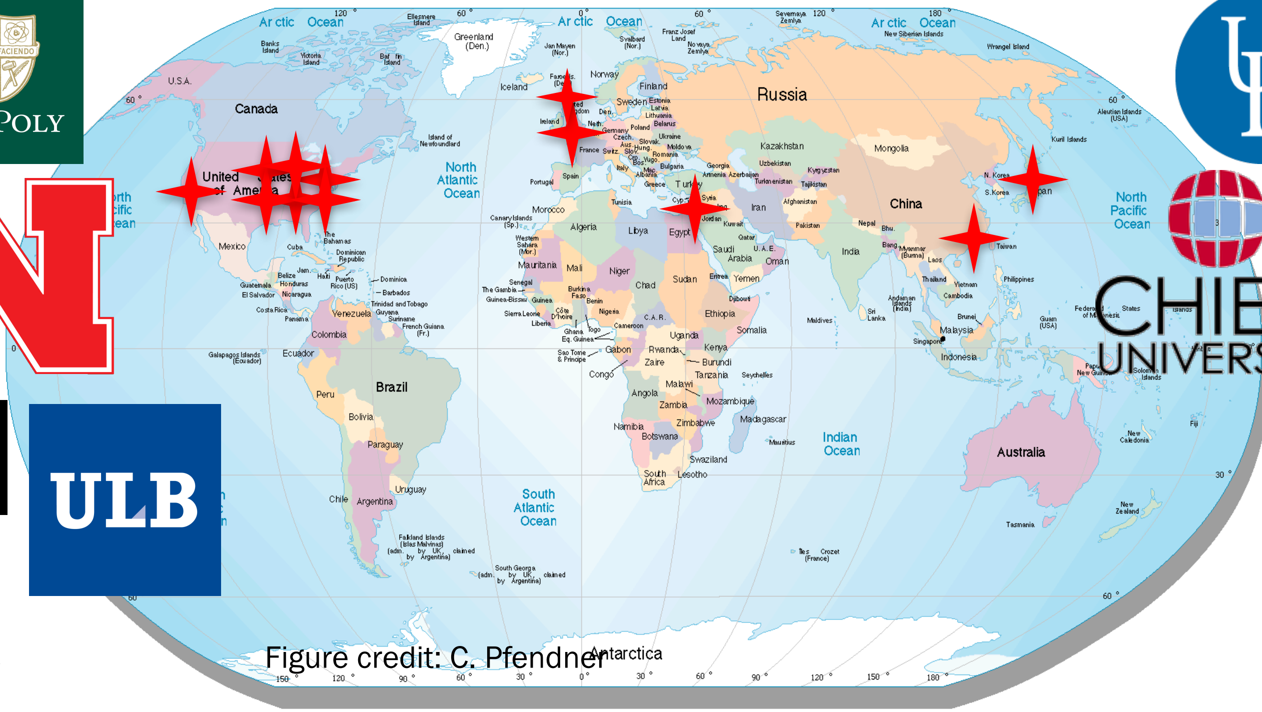
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE



UNIVERSITY OF DELAWARE

THE UNIVERSITY OF CHICAGO 1890

CHIBA UNIVERSITY

UNIVERSITY OF MARYLAND 1856

National Taiwan University

USA:

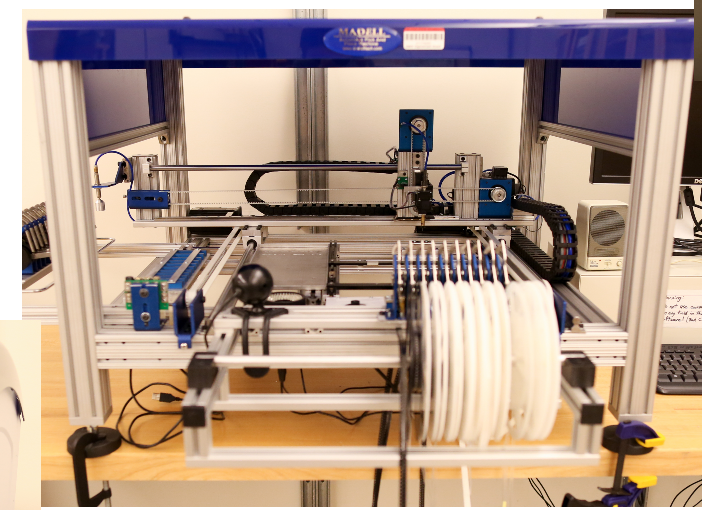
Ohio State University
Cal Poly
University of Chicago
University of Delaware
University of Kansas
University of Maryland
University of Nebraska
University of Wisconsin – Madison

ARA is an International Collaboration

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

Rapid prototyping and testing of electronics

Large RF/ anechoic chamber.



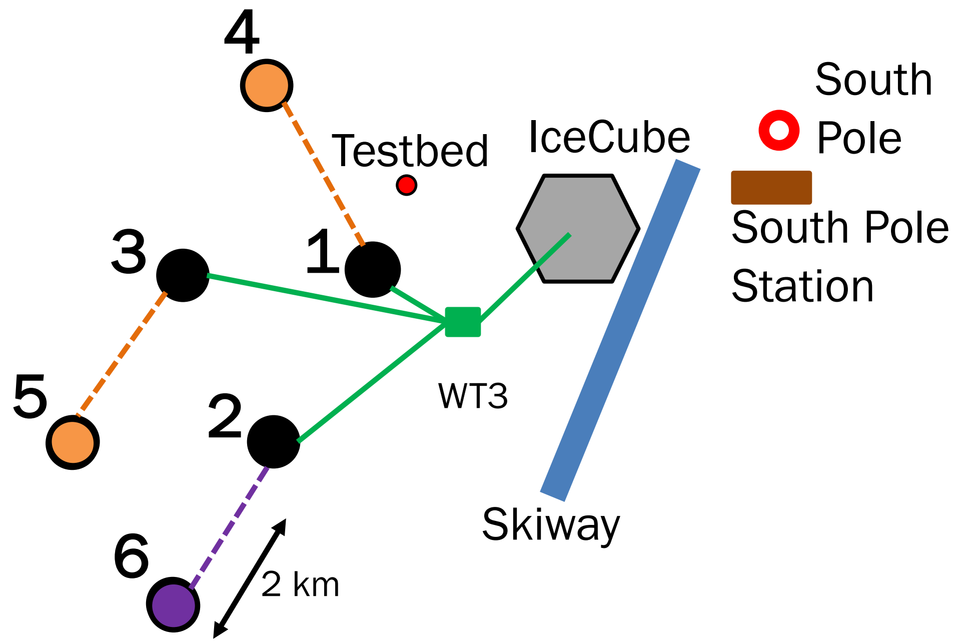
Pick & Place machine for rapid assembly.

RF circuit board mill.

Large thermal chamber.

ARA Current Status

- Under phased construction in the ice near South Pole
- Prototype (“Testbed”) + 3 stations deployed so far
- Two more stations in 2017!



Deployed ARA Station

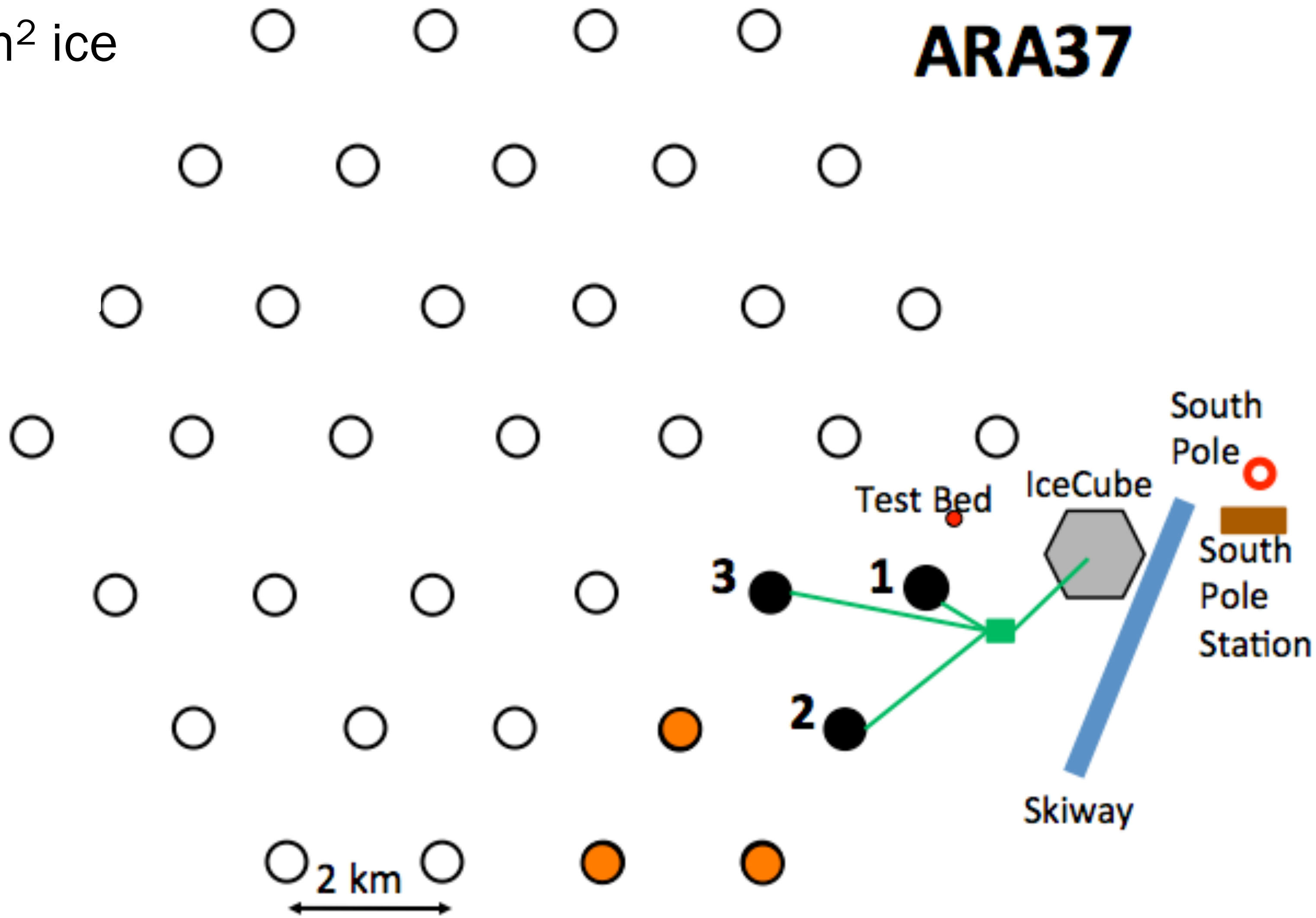
Instrumentation deployment in 17 / 18. Site / road preparation in 16 / 17.

Potential if support is available

Low energy threshold, sparse instrumentation.

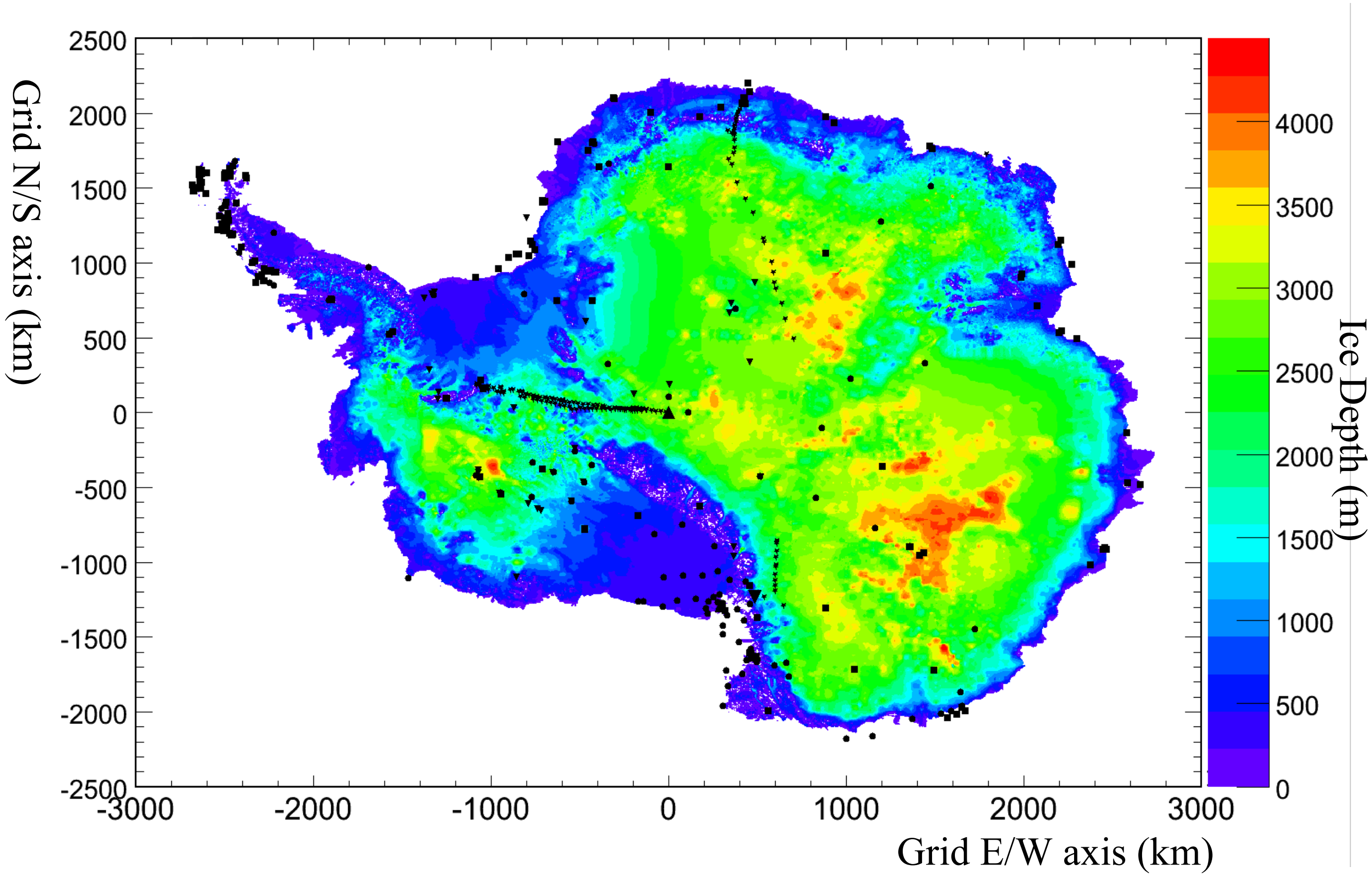
ARA Long Term Plans

Full array, ARA37, will cover ~100 km^2 ice



Backgrounds to Signal

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



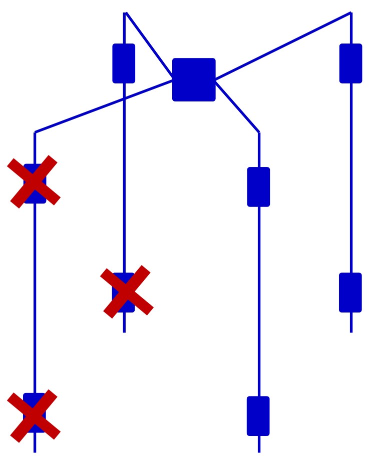
Signal Identification: In Hardware

Impulsive

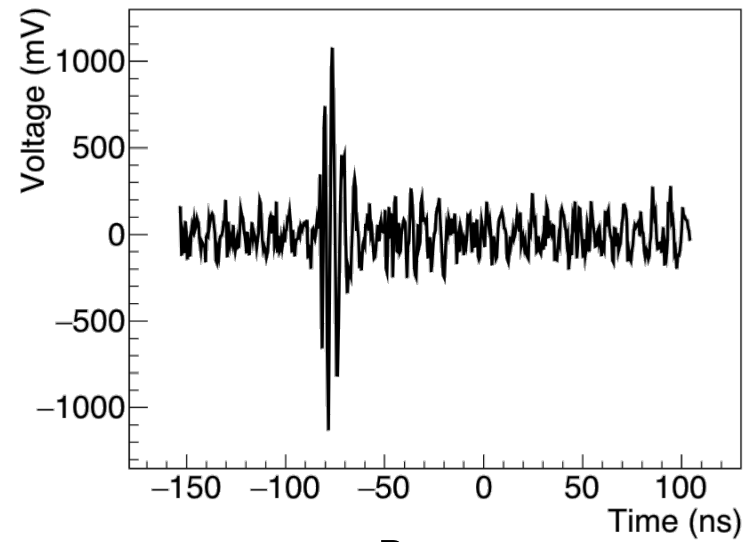
- *Power Trigger:* integrated power over ~10ns must be > threshold
- *Effective at identifying neutrinos*: pulses have large integrated power

Coincidence

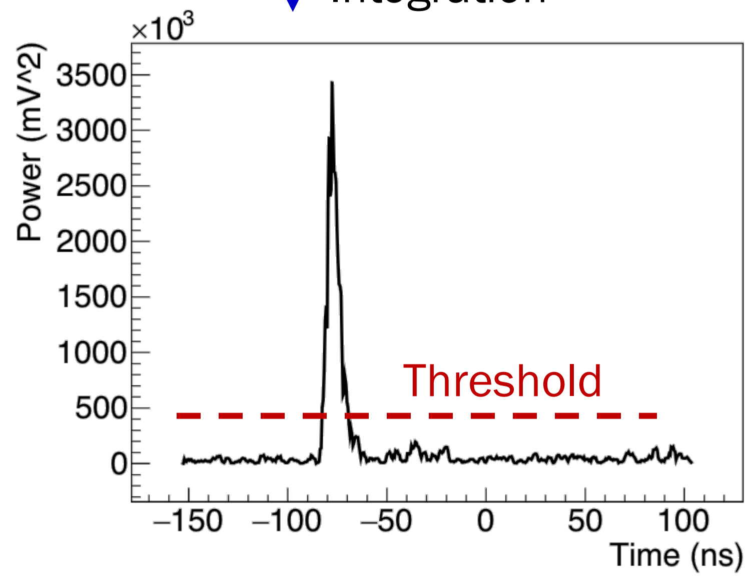
- *Coincident requirement*: trigger in 3/8 antennas
- *Good at rejecting thermal noise:* noise "rarely" fluctuate high in 3/8 simultaneously



Calibration Pulser Event
Testbed Station



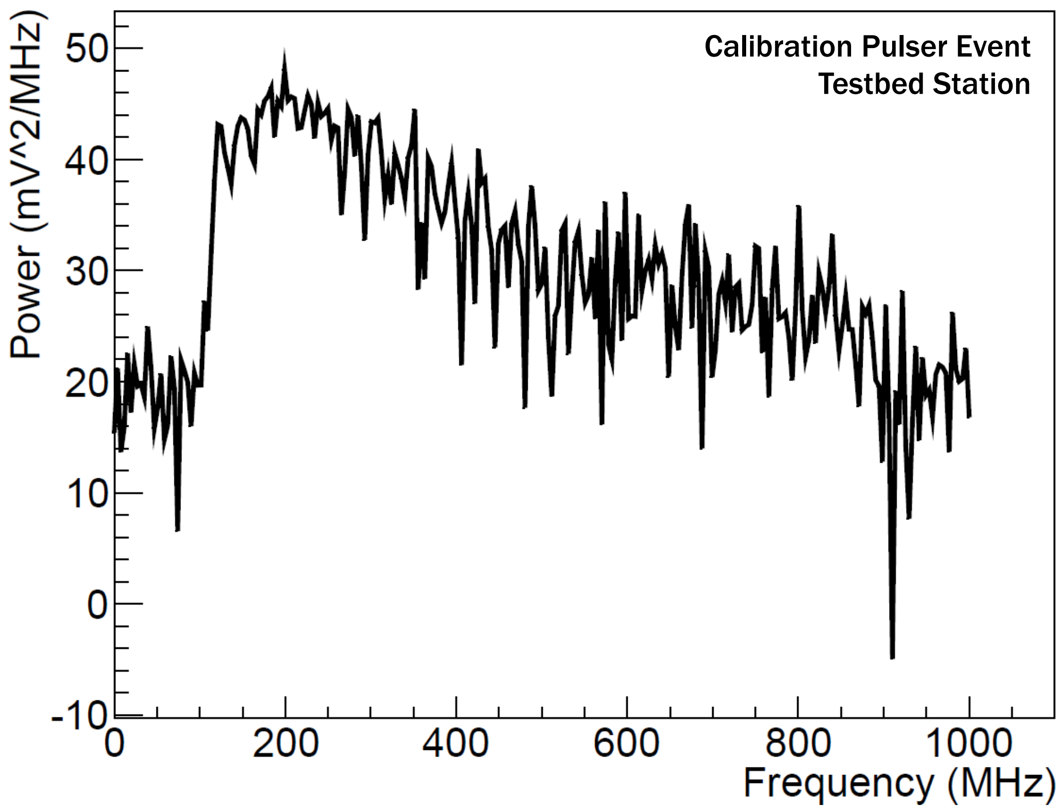
Power Integration



Signal Identification: In Software

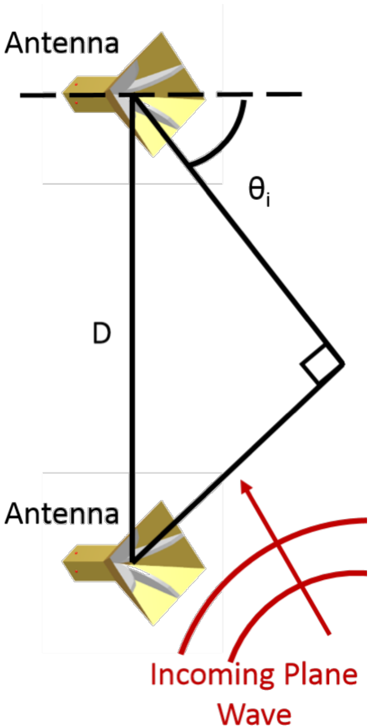
Signal Must be Broad in Frequency

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

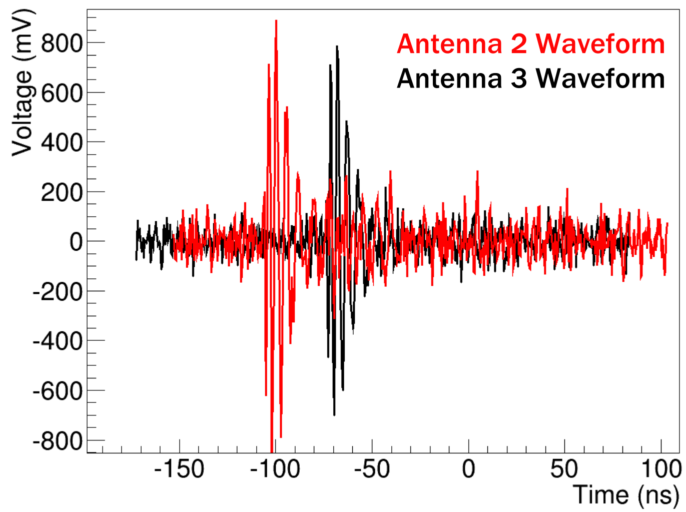


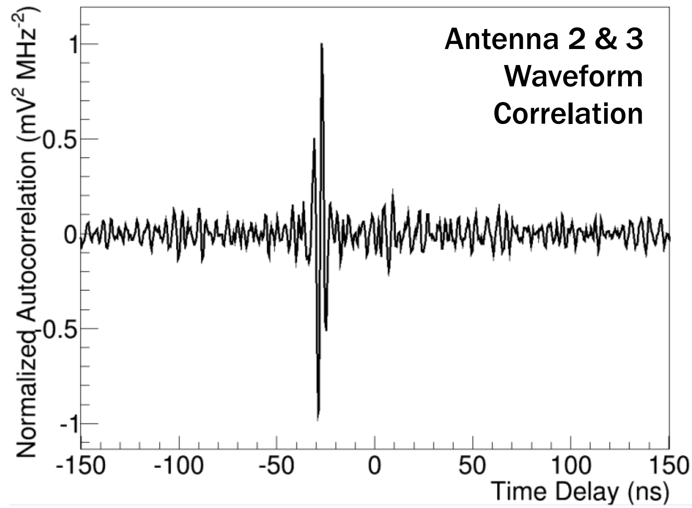
Interferometric Maps: Directional Reconstruction

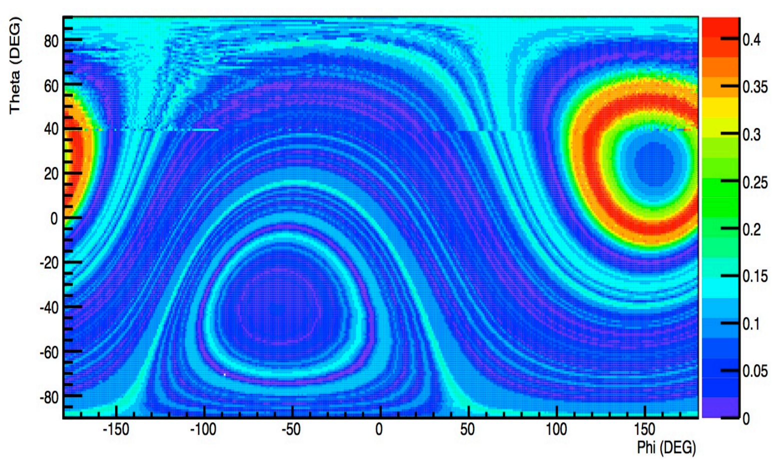
- Timing information ⟶ geometry information
- Punitive source angle ⟶ Time Delay ⟶ Correlation Value for that delay
- Take Hilbert envelope to interpret as *power*

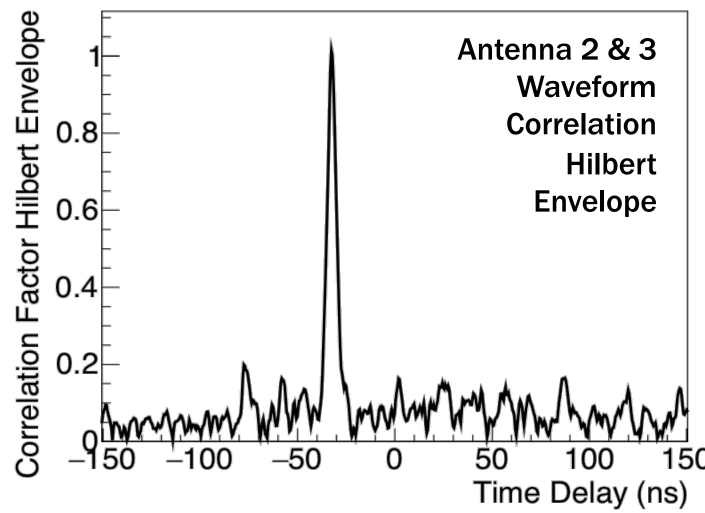


$$\theta_i = \arcsin\left(\frac{c\,\Delta t}{D}\right)$$





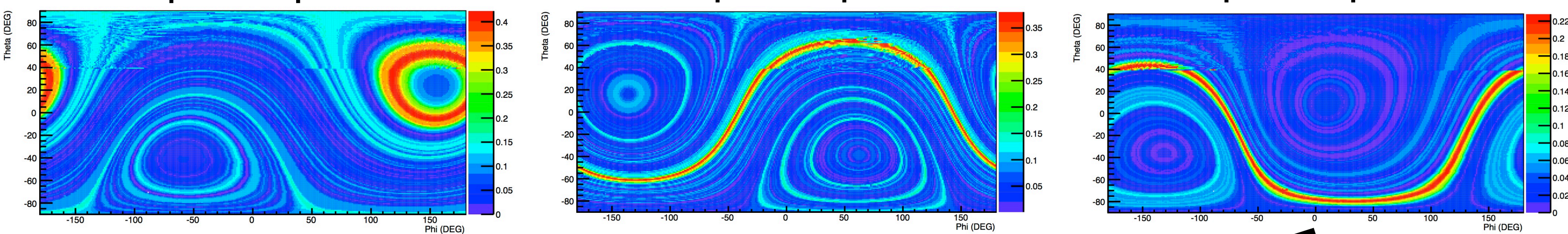




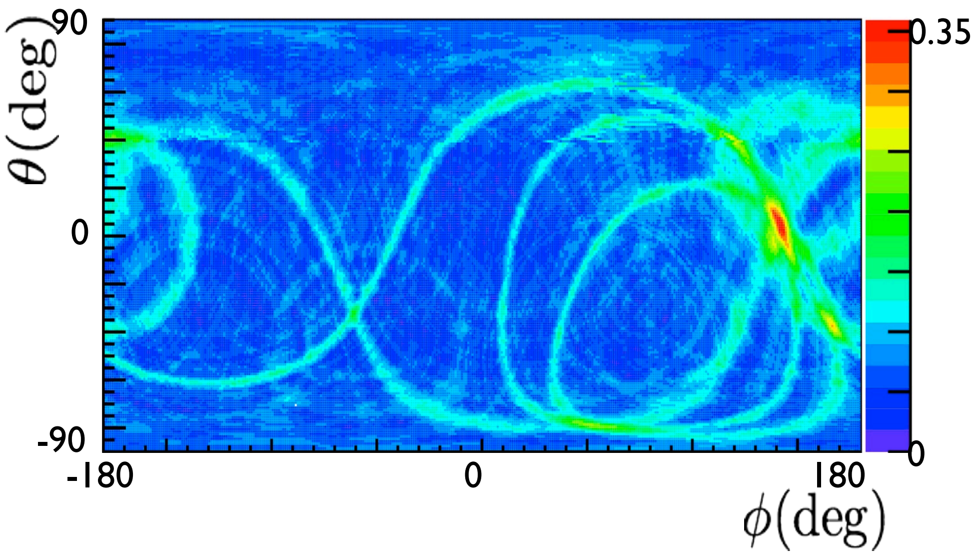
Interferometric Maps

- 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

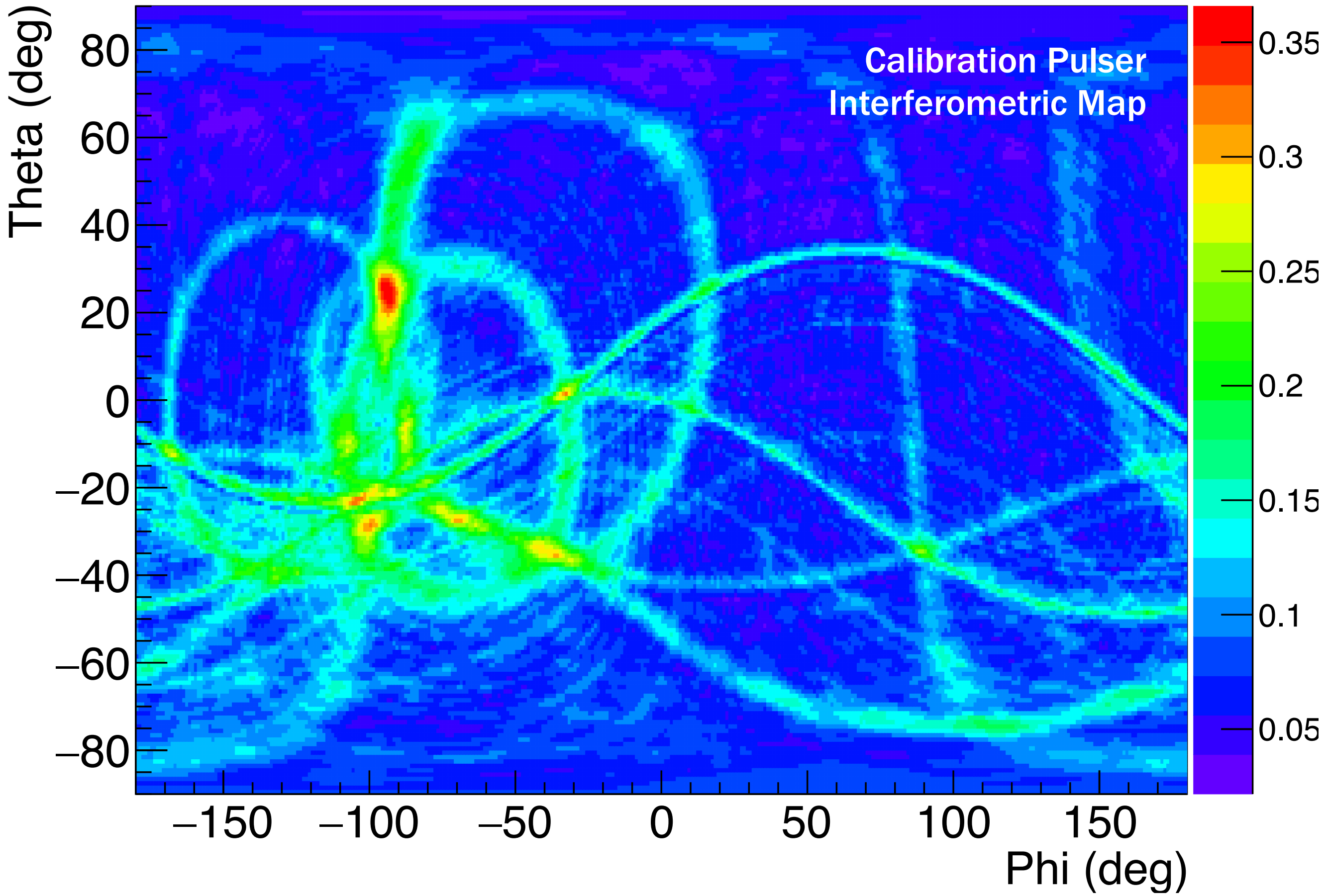
Analyses and Results

1. Search for diffuse neutrinos
2. Search for point sources

Searching for Diffuse Neutrinos

Interferometry

- Ask for unique, well defined peaks: rejects >95% of thermal noise
- Reject all events from human campsites or that have repeating RF direction



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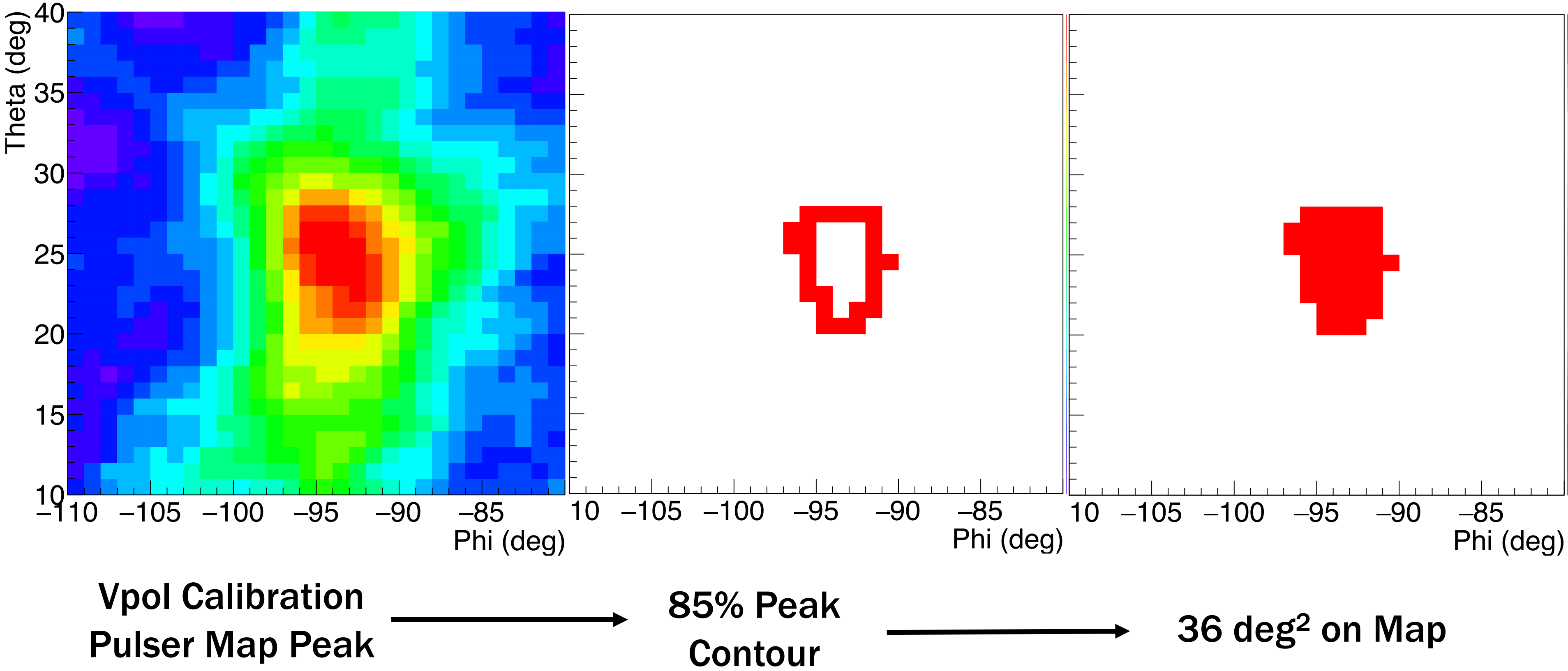
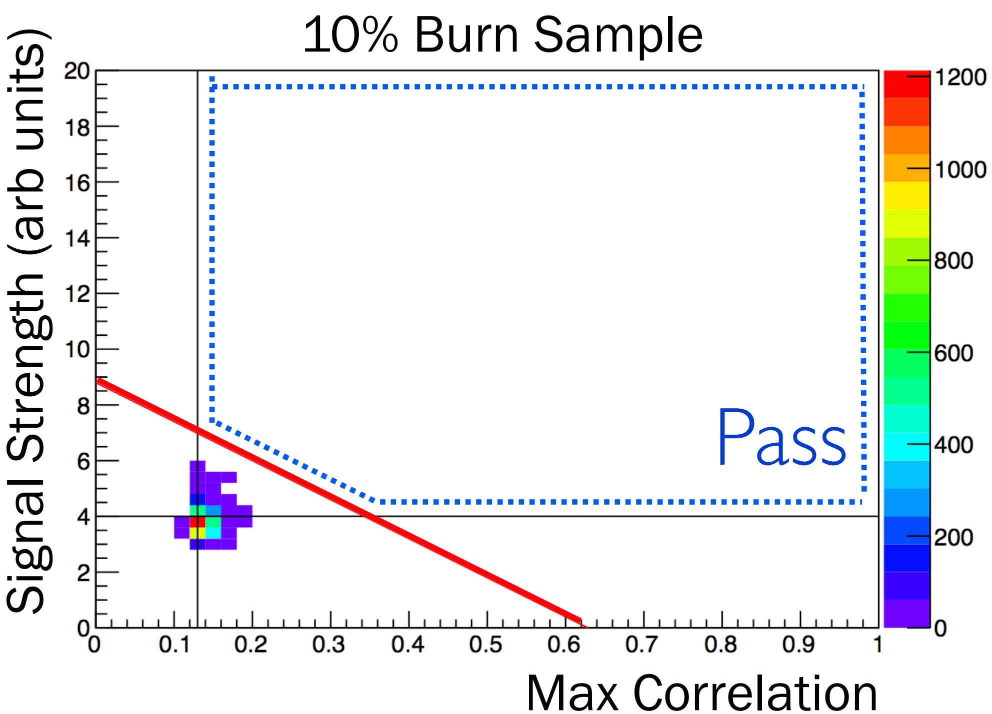
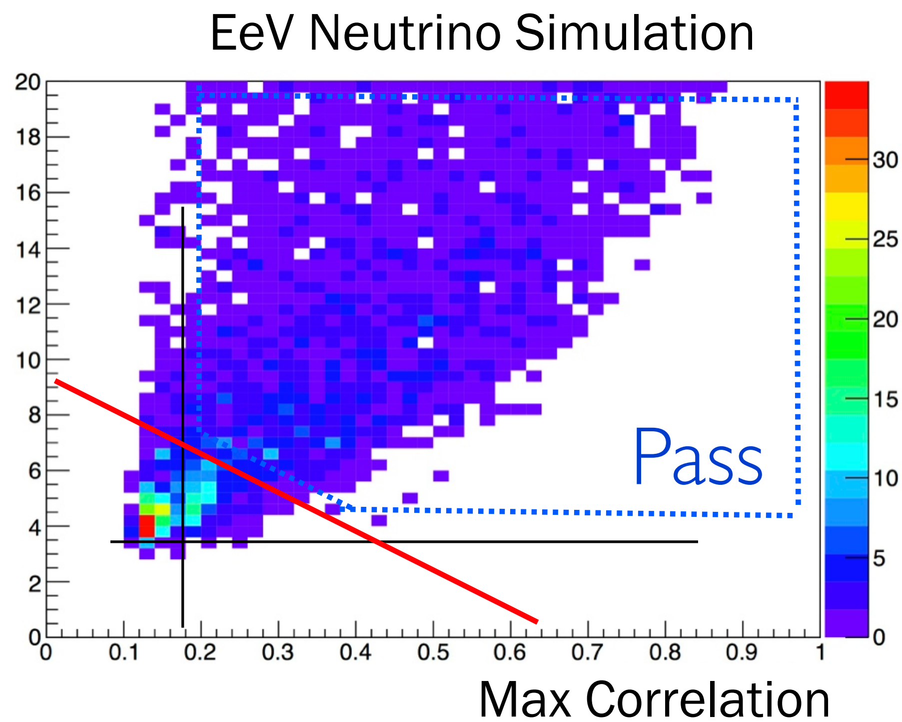


Searching for Diffuse Neutrinos

Signal Strength

- Combination cut on signal and correlation strength
- Tune cuts on 10% of data
- Choose cut line for best expected flux limit

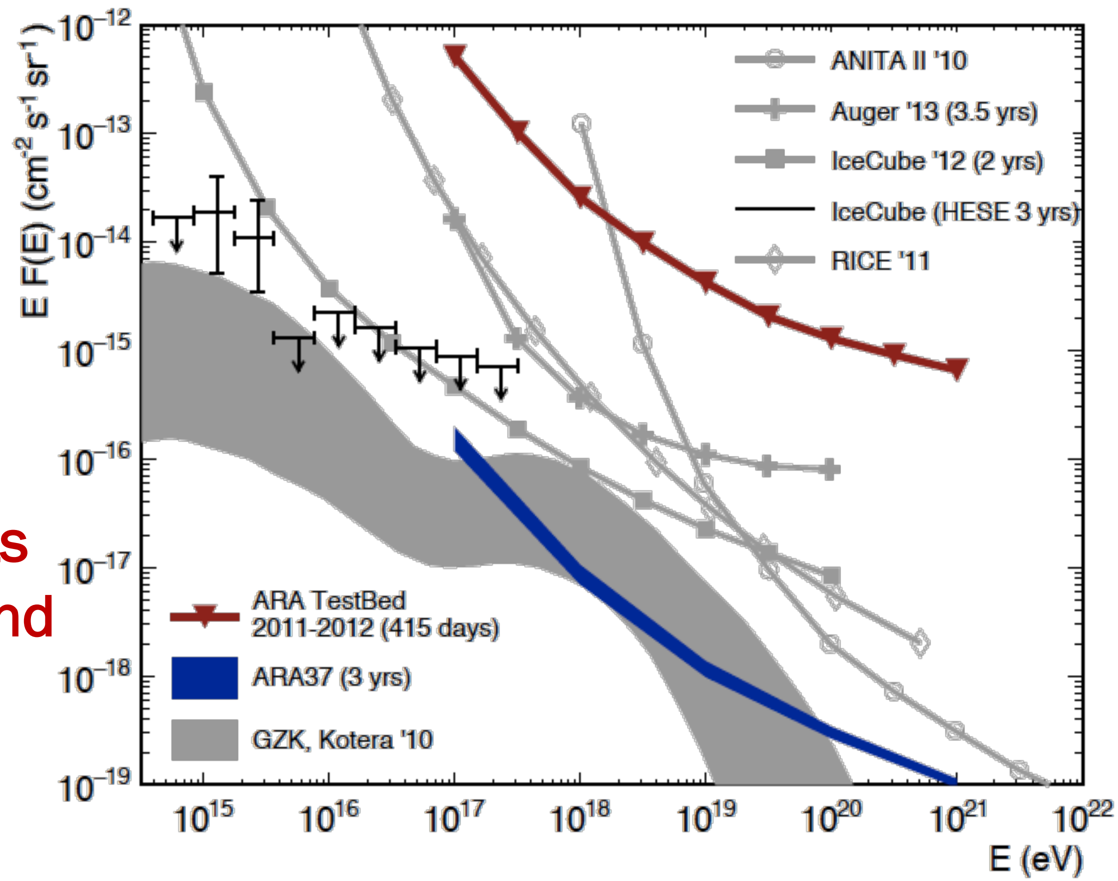




Figures by C. Pfendner

Searching for Diffuse Neutrinos

- Expected background: 0.06, Expected neutrinos: 0.02, 0 Events survived cuts
- Limits on diffuse neutrino flux from 415 days of ARA Testbed.
- Predictions for ARA 37 limits (red line) are competitive and capable of model discrimination.

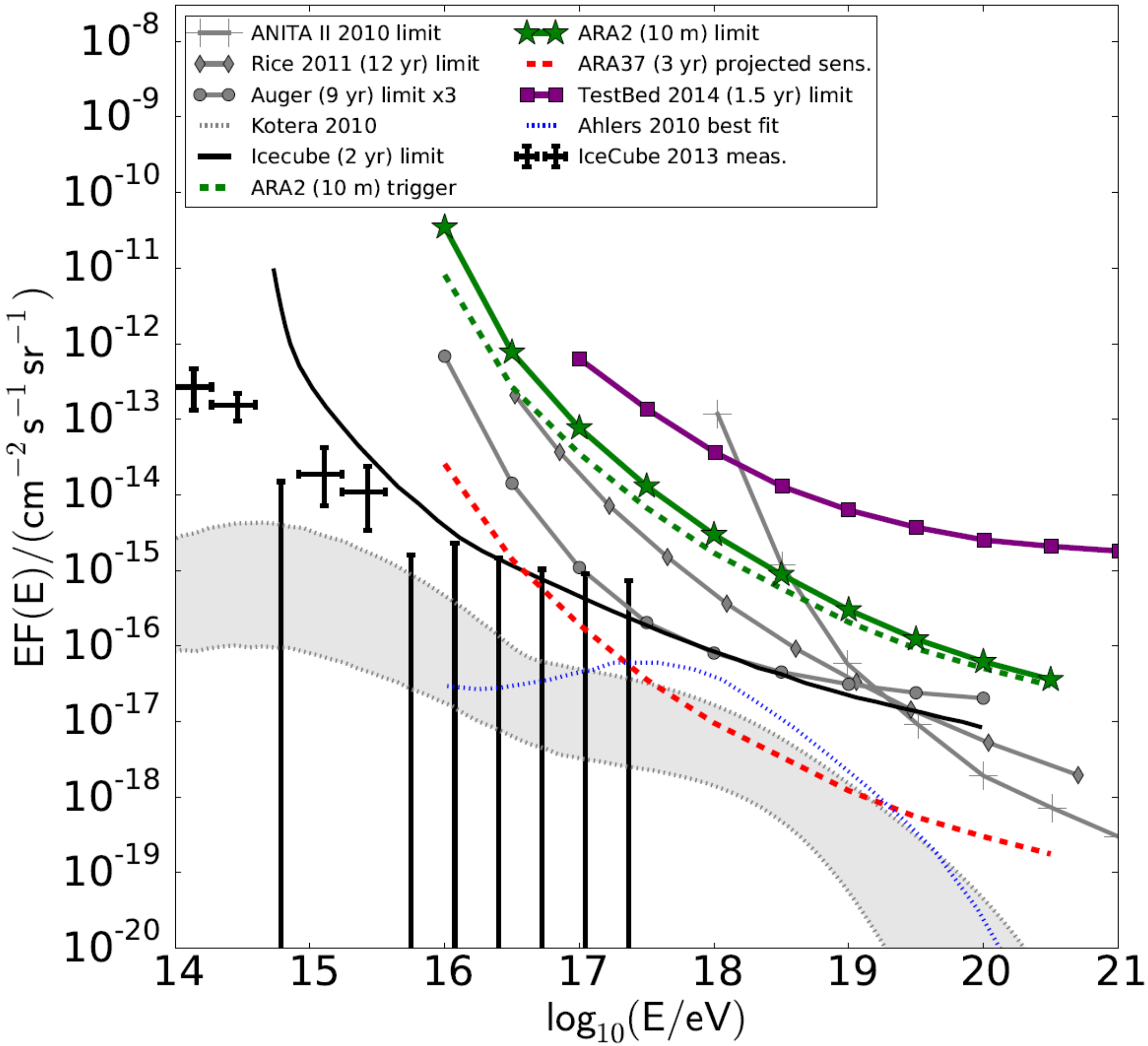


P. Allison et al for the ARA Collaboration
Astropart Phys, Vol 70 (2015).

Two Stations Diffuse Limit

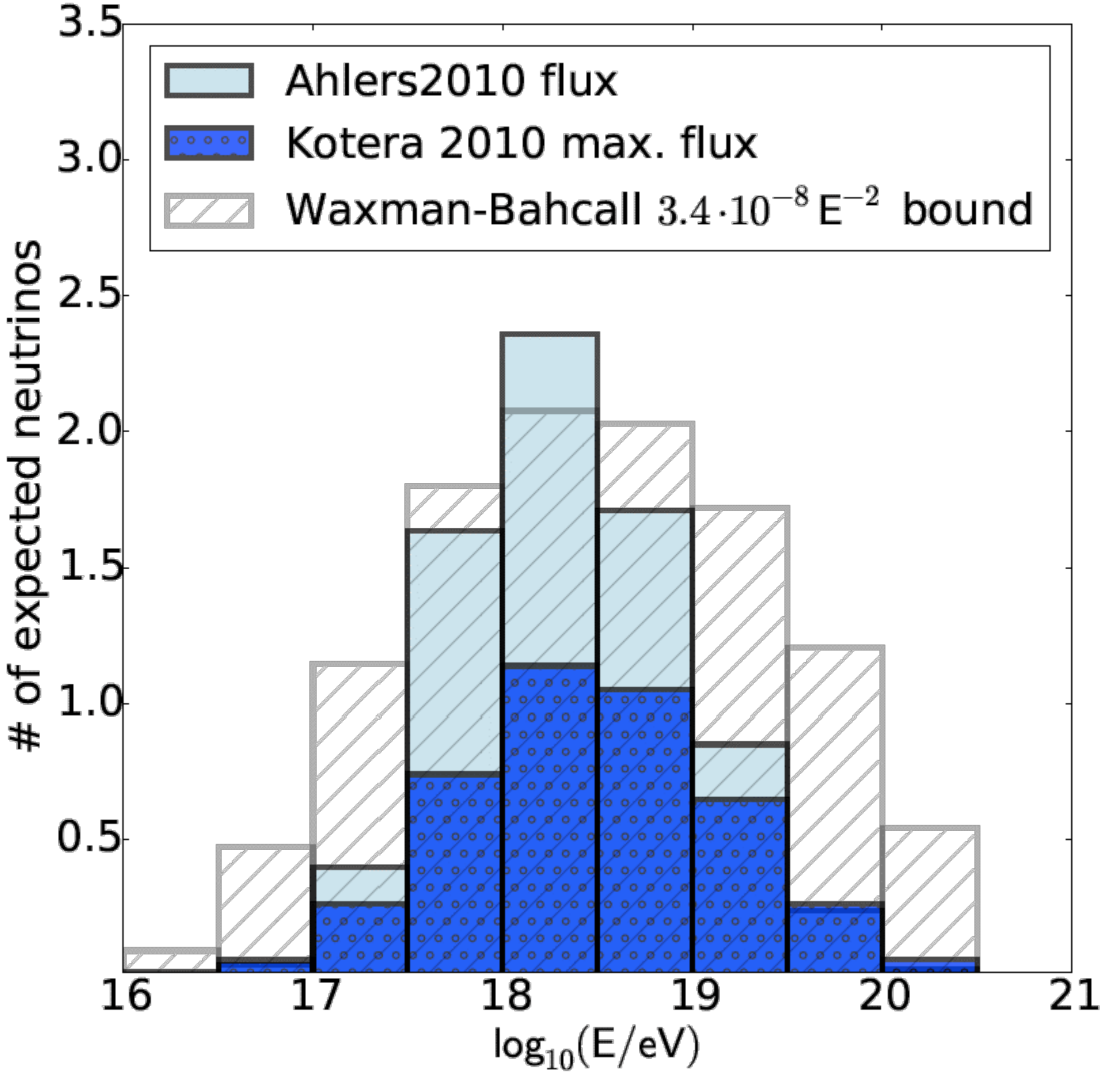
Limits on diffuse neutrino flux from 10 months of two stations.

Predictions for ARA 37 limits (red line) are competitive and capable of model discrimination.



P. Allison et al, for the ARA Collaboration.
Phys. Rev. D 93, 082003 (2016).

Two Stations Diffuse Limit



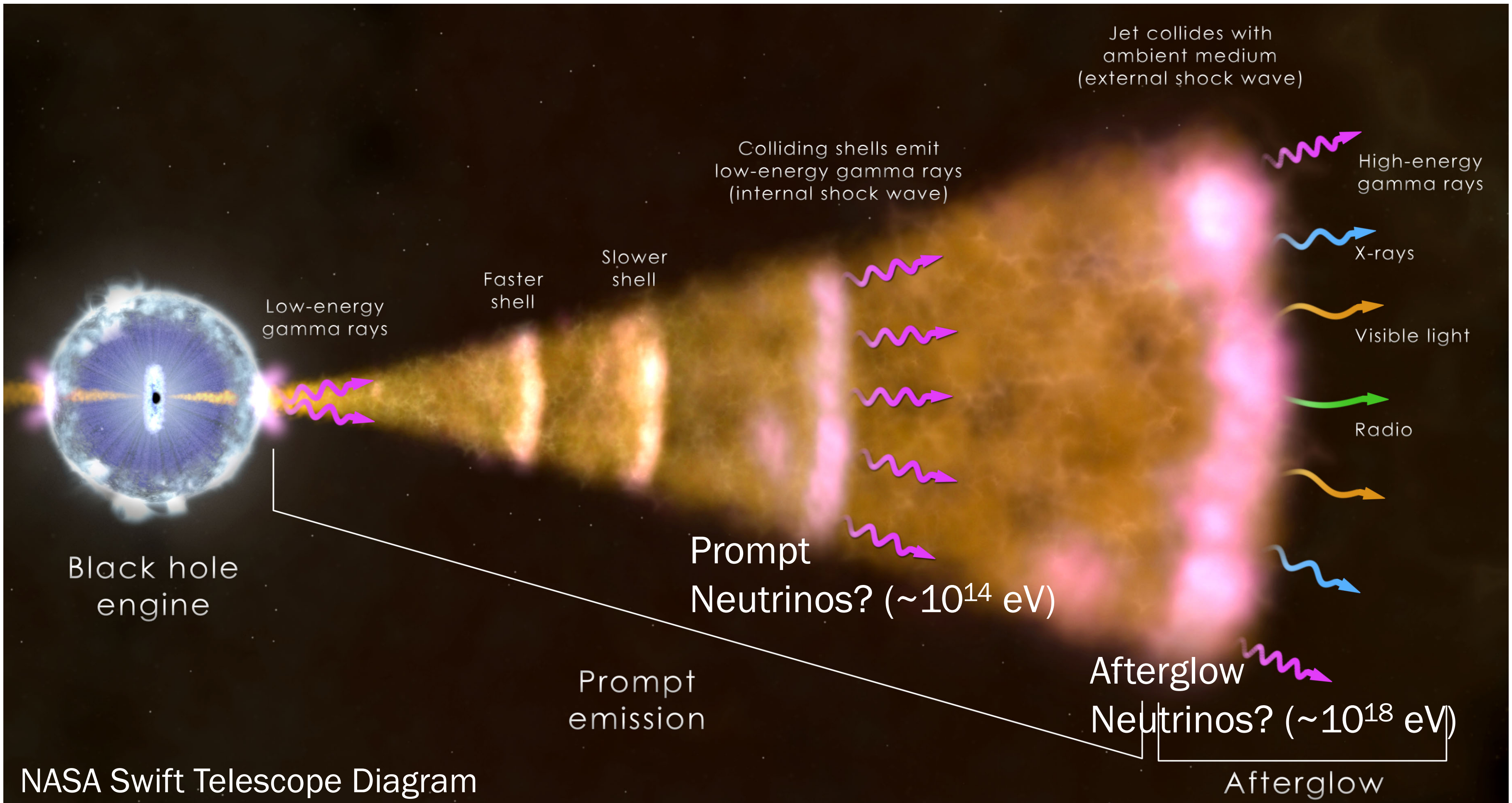
Projected event numbers for three models of the UHE neutrino flux with 37 stations and 3 years livetime.

Power to discriminate between models after 3 years livetime.

P. Allison et al, for the ARA Collaboration.
Phys. Rev. D 93, 082003 (2016).

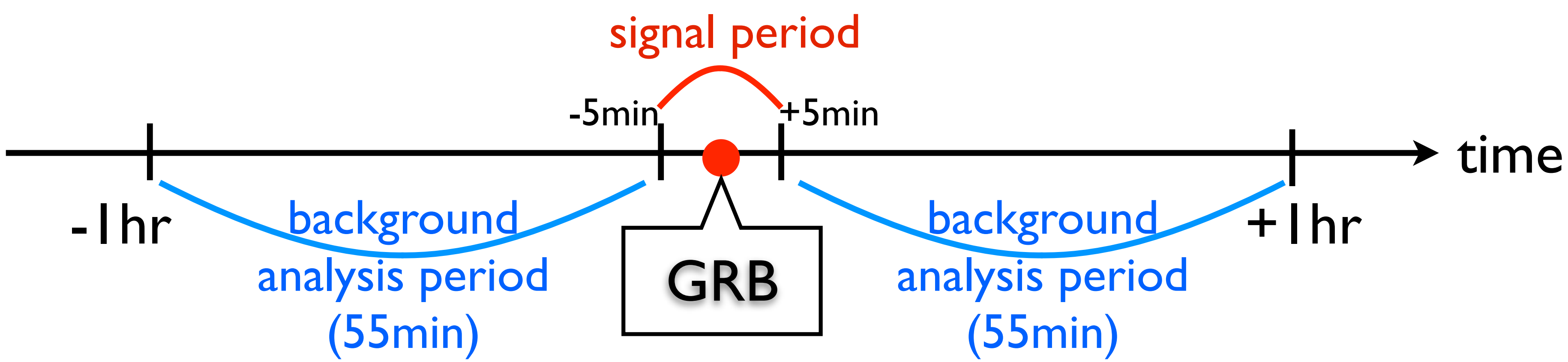
Searching for Neutrinos from GRBs

- Some (untested) models for GRBs require the emission of neutrinos
- Testbed was live and has good data for 57 GRBs



Searching for Neutrinos from GRBs

- "Relaxed" diffuse search: GRB allows strict cuts on timing and source direction
- Blinded search strategy
  - Optimize cuts for best limit, using 10% of background region
  - Check in remaining 90% of background region
  - Search in the signal period

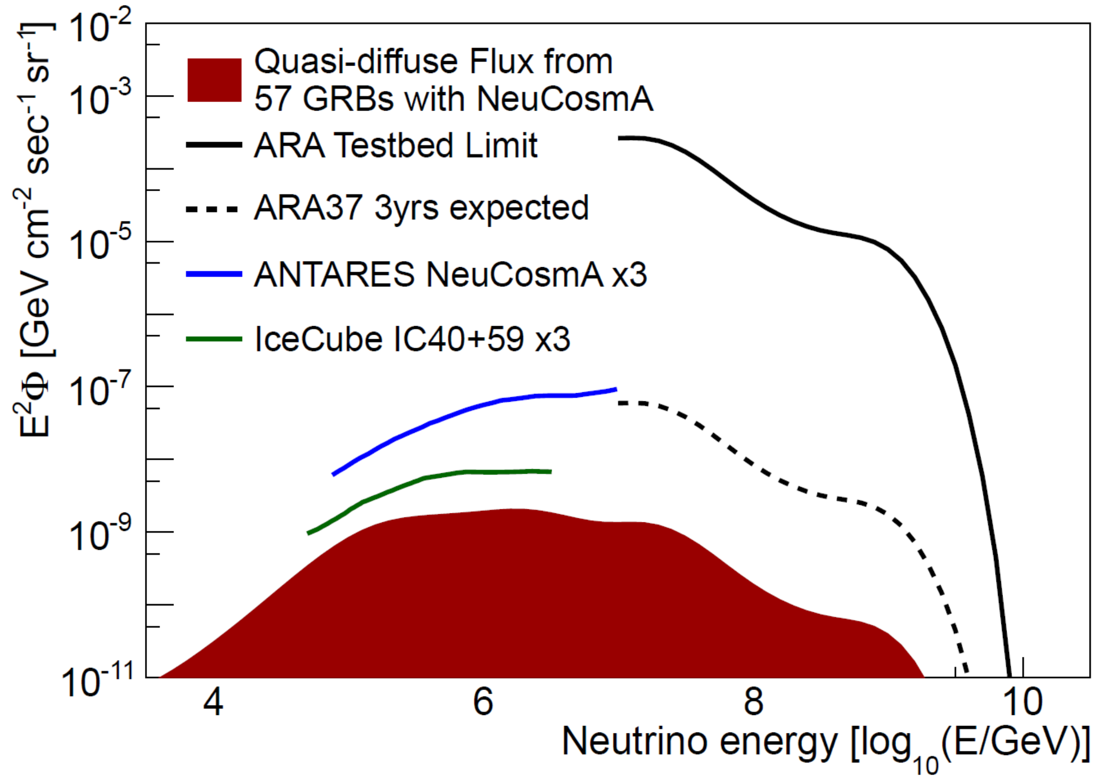


Testbed GRB Flux Limit

- Expected backround: 0.12, Expected neutrinos: 1.7e-5, 0 events survived cuts

- Limits on the GRB flux from 57 GRBs from 224 days of ARA testbed

- First quasi-diffuse flux limit above 10^{16} eV



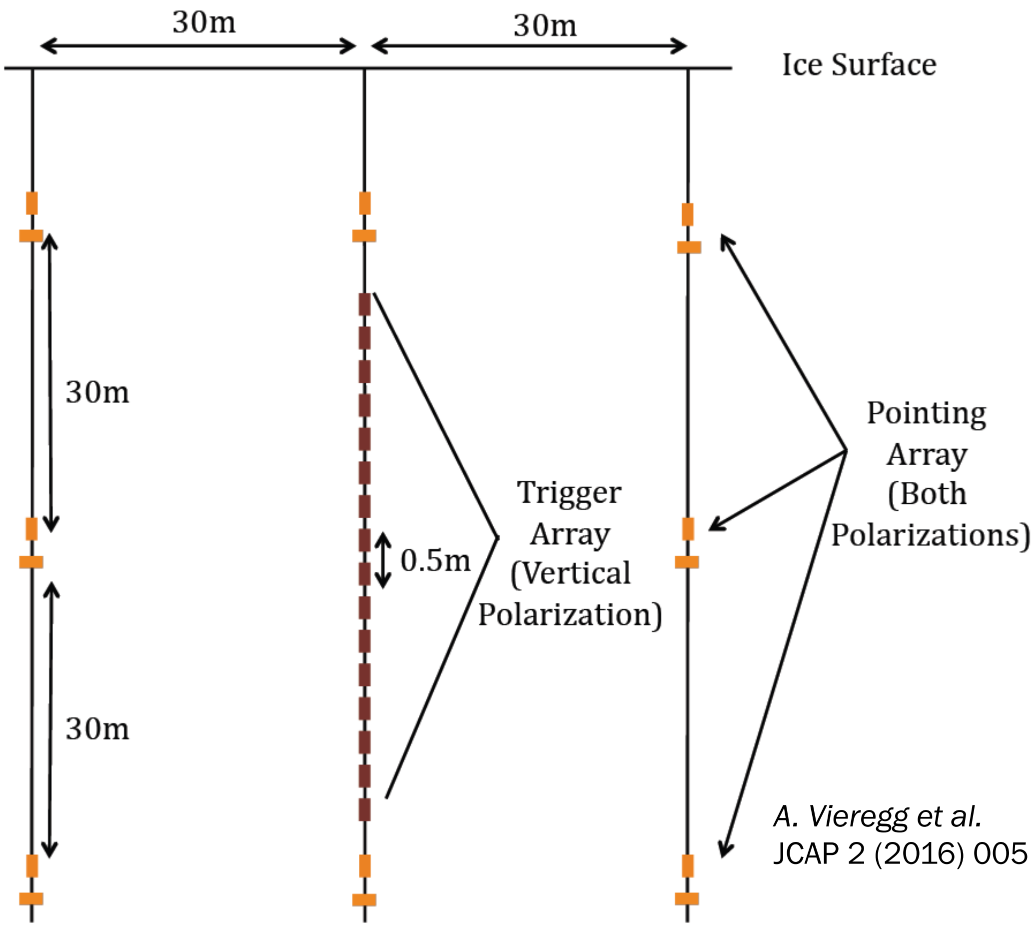
P. Allison et al, for the ARA Collaboration.
Arxiv 1507.00100v1

Future Plans

Future Plans: Phased Array

- **Strategy for improving sensitivity: reduce background with signal averaging**
- Place a phased trigger string amongst pointing array
- Coherently sum many antenna waveforms before triggering: "beamform"

$$SNR \propto \frac{V_{signal}}{V_{noise}} \propto \frac{N}{\sqrt{N}} \propto \sqrt{N}$$

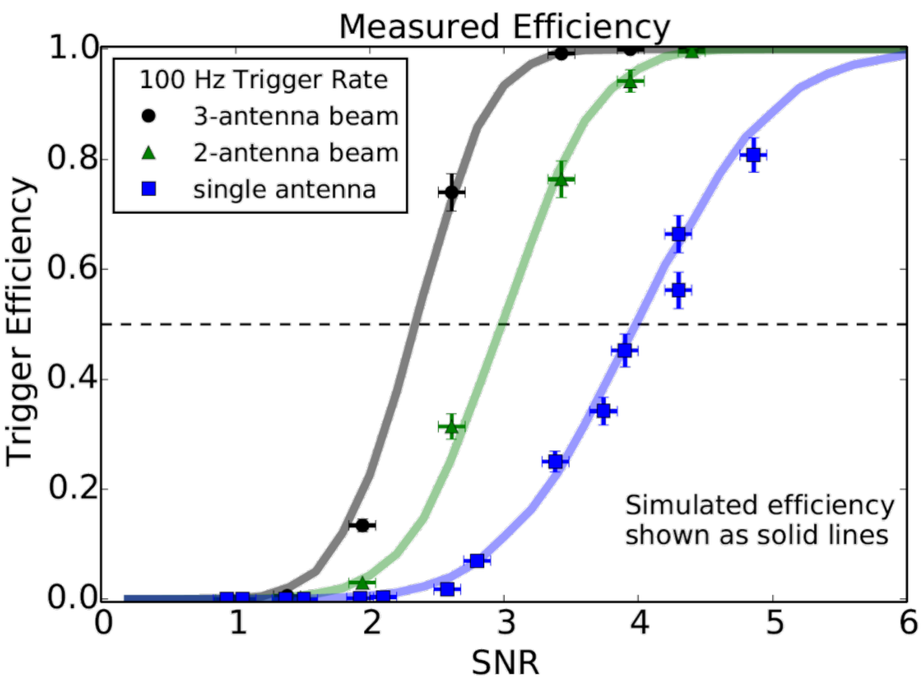


A. Vieregg et al. JCAP 2 (2016) 005

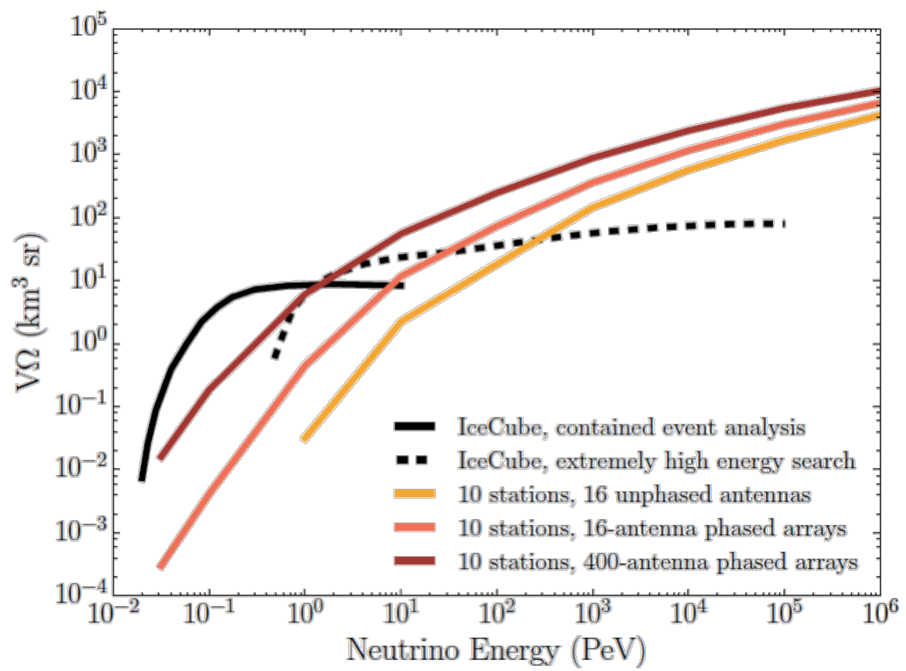
Future Plans: Phased Array

- **Higher sensitivity!**
- Lower thresholds, higher efficiency, larger effective volumes
- Ability to turn off "loud" beams

Funded! Will be deployed on ARA5 in 2017! Led by A. Vieregg at U Chicago.



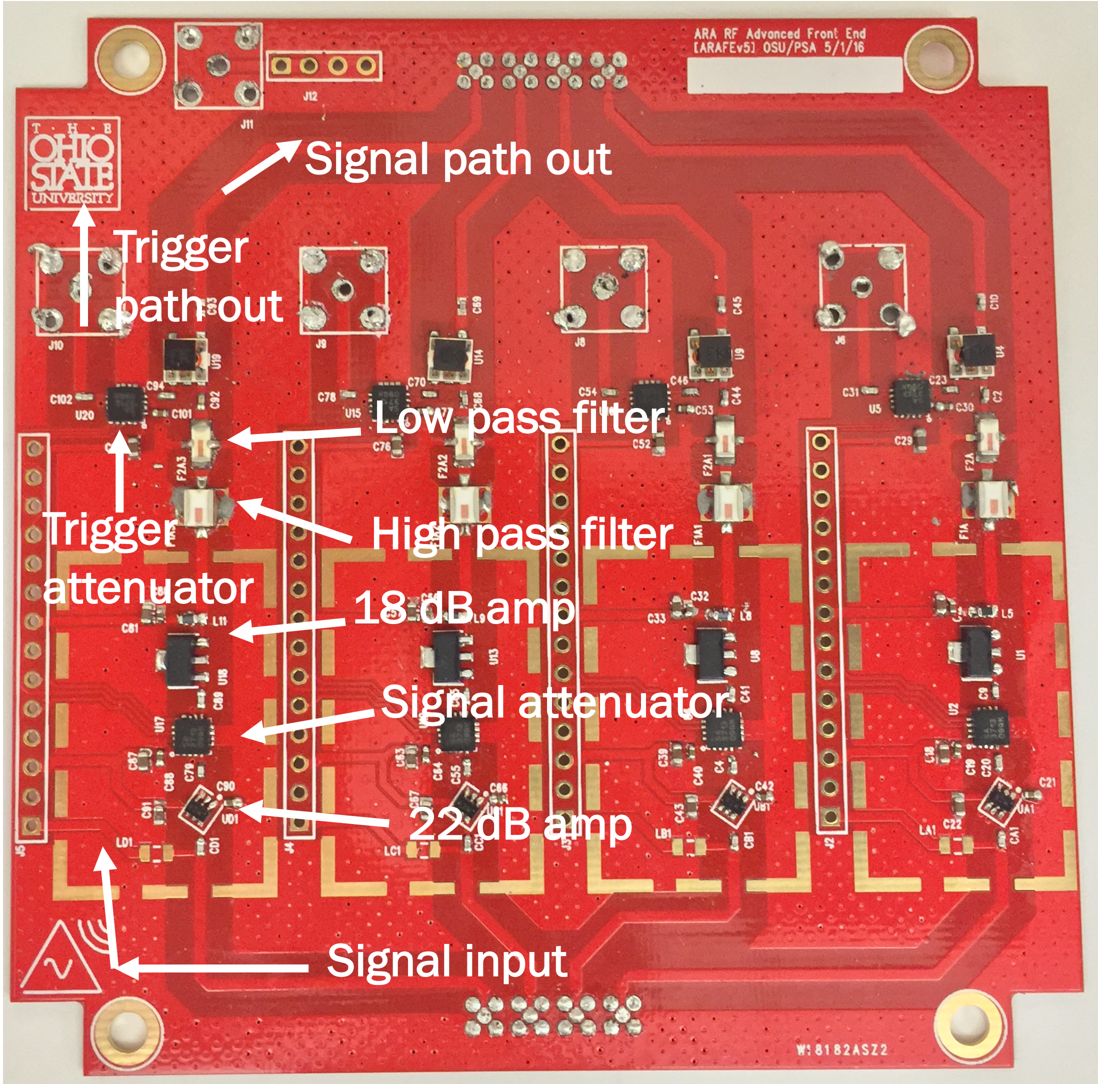
J. Avva et al., Arxiv: 1605: 03525



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

Future Plans: Dynamic Signal Attenuation

- What's new
  - Microcontrolled variable attenuators
  - Dynamic correction to season variation in signal chain gain
- Advantages
  - Better utilization of system dynamic range
  - No partnered parts problems
  - Simpler analysis



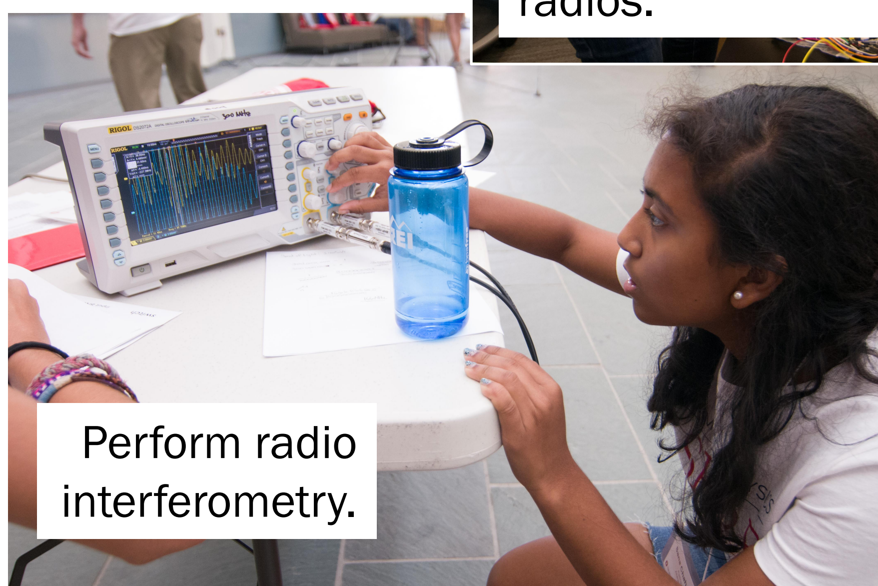
DEPARTMENT OF PHYSICS

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 key windows to fundamental physics
- Smarter analyses, better electronics, and new designs will continue to enhance sensitivity
- The next generation of UHE neutrino observatories will contribute greatly to the era of multi-messenger astronomy

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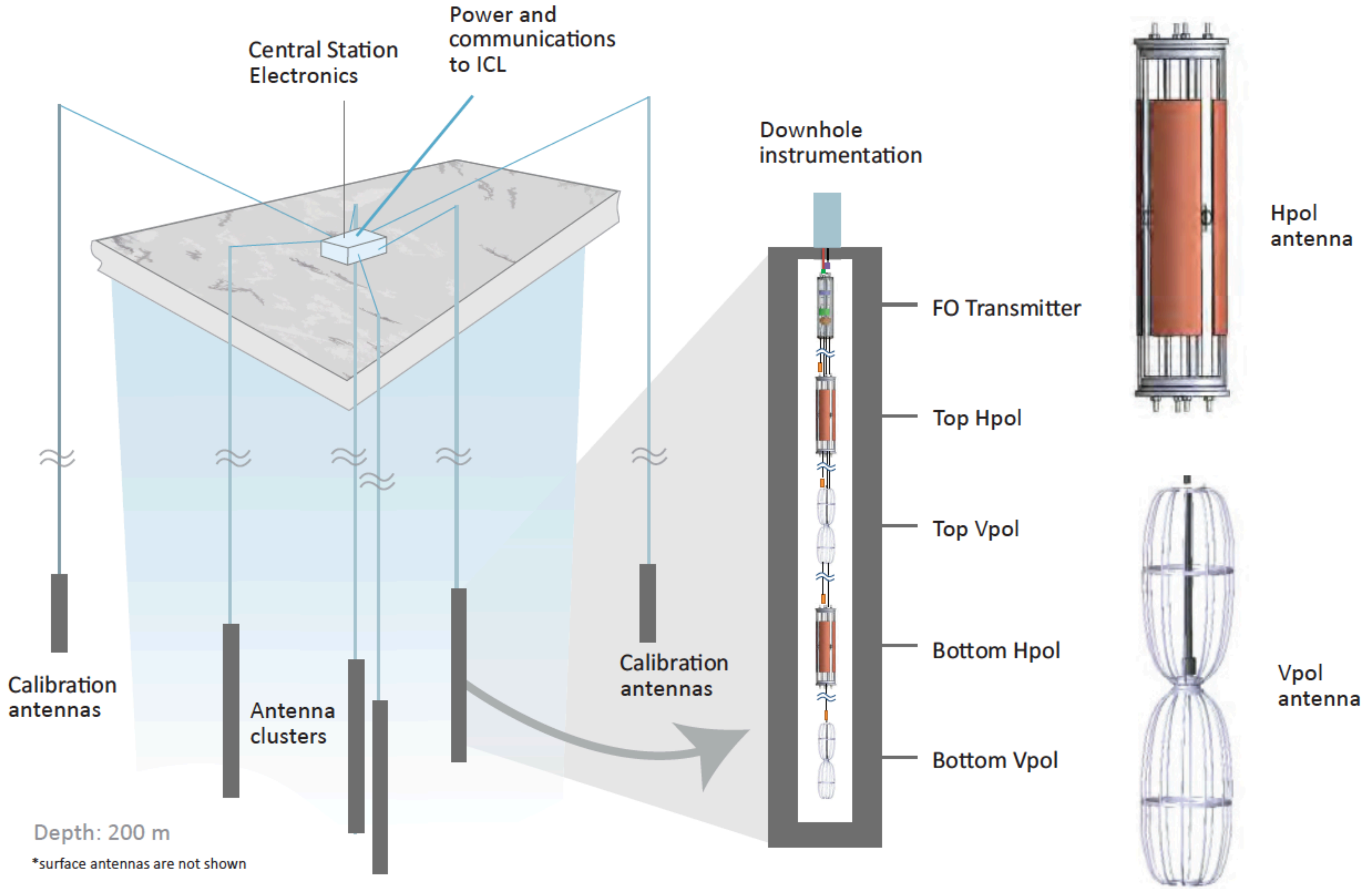
- The OSU Center for Cosmology and Astroparticle Physics
- US-Israel Binational Science Foundation Grant 2012077

Back-up Slides

Alternate Station Schematic



Phased Array Capability