The Askaryan Radio Array: Current Status and Future Plans

Brian Clark for the ARA Collaboration

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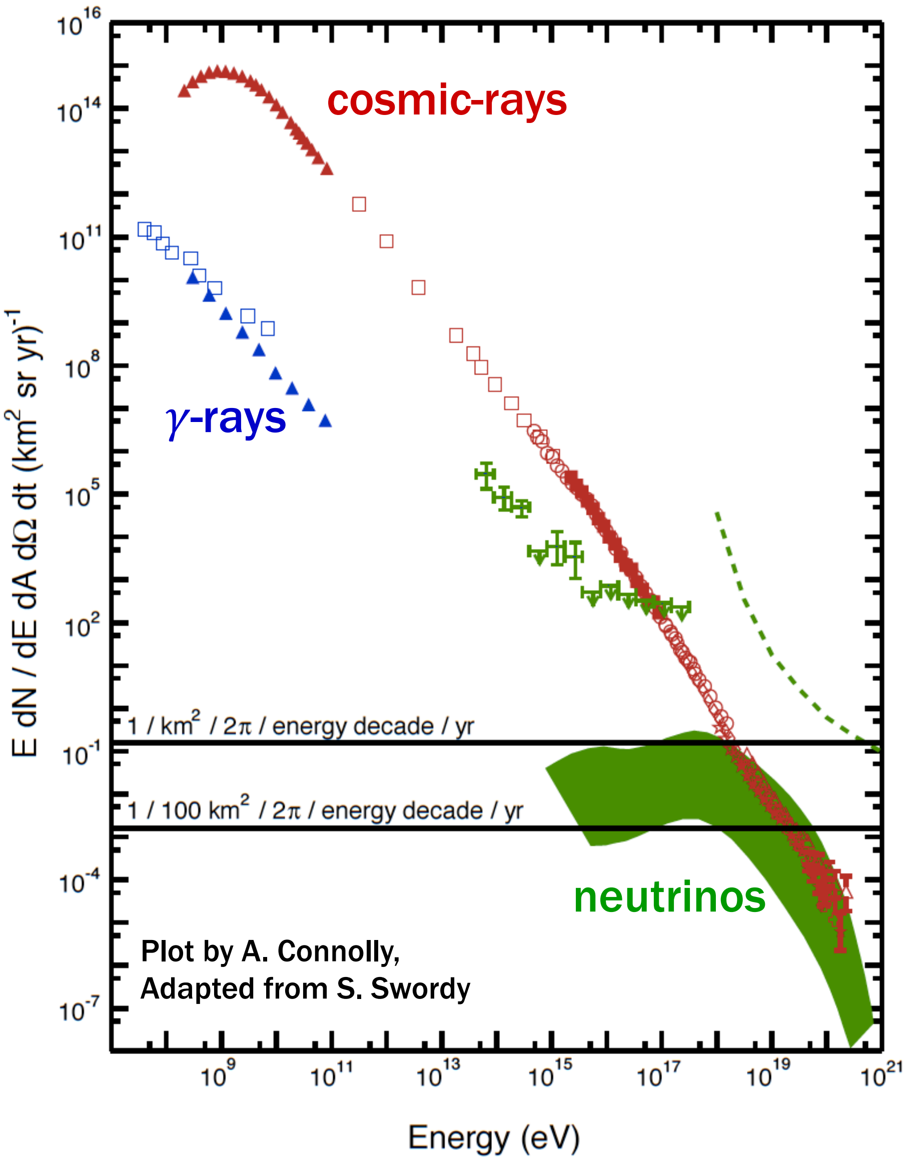
TeV Particle Astrophysics 2017—Columbus, OH

Why UHE Study Neutrinos?



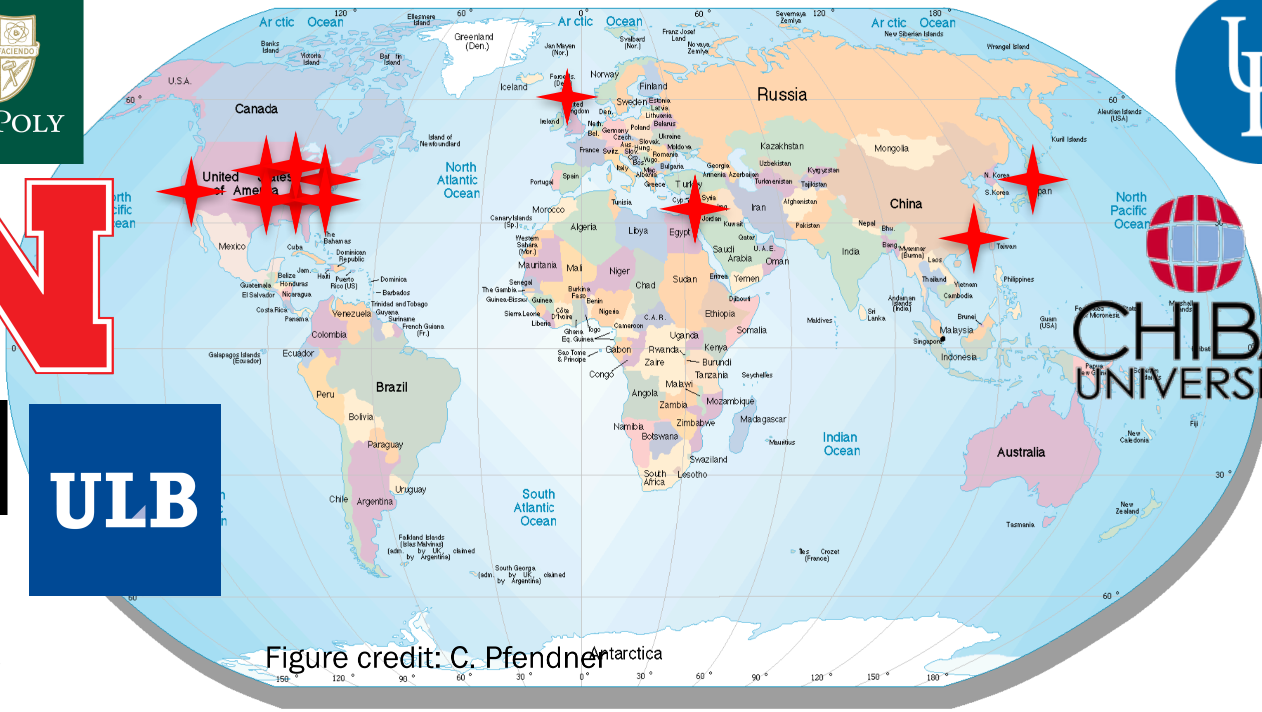
UHE means 10^{16} eV and above

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



ARA is an International Collaboration

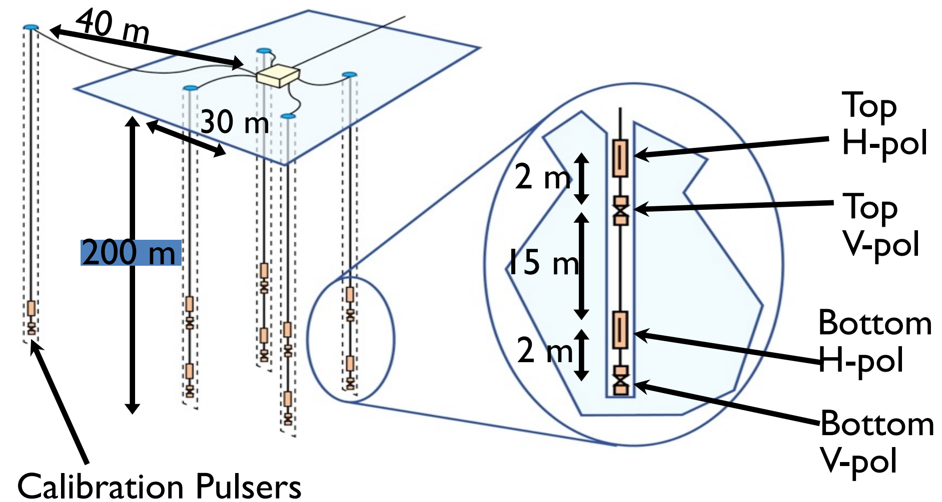
USA:

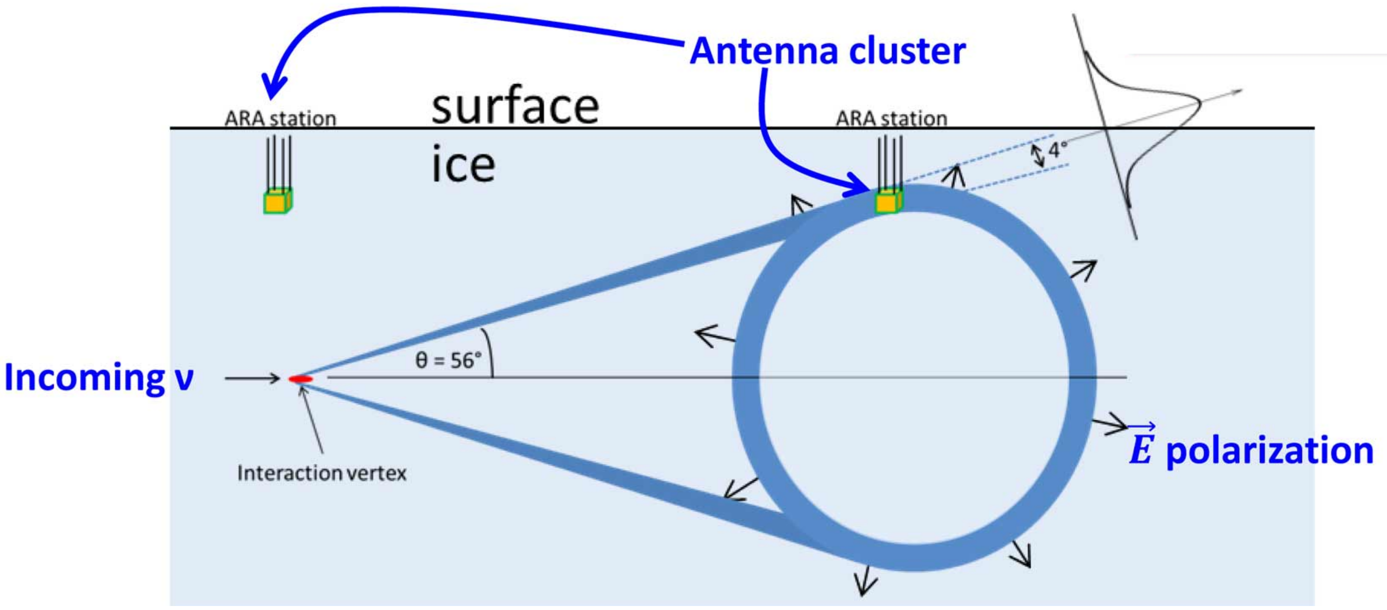
- Cal Poly
- The Ohio State University
- University of Chicago
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison

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

Content of an ARA Station

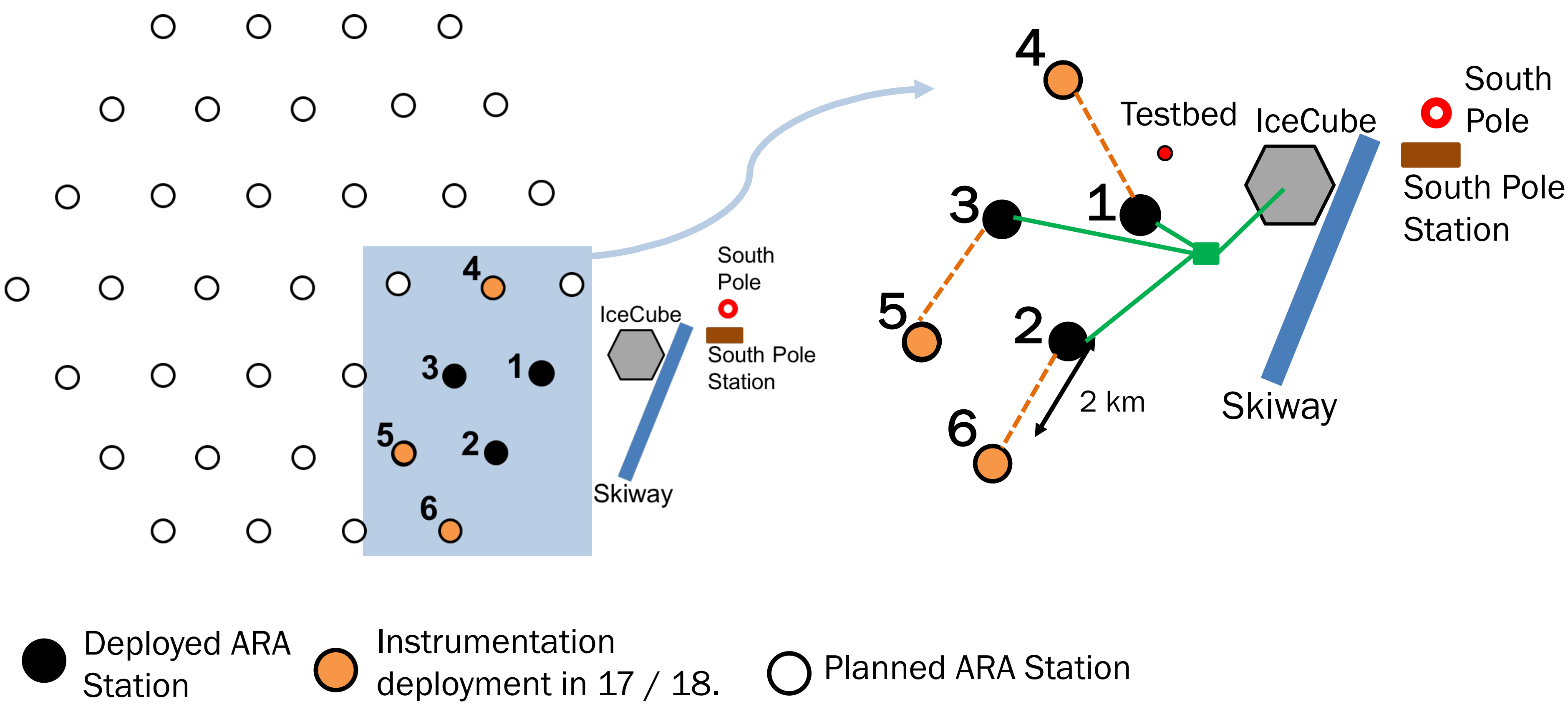
- Antenna array looking for Askaryan emission from neutrinos
- 16 antennas (8 Vpol, 8 Hpol, 200-850 MHz bandwidth)
- Cubical lattice at 200m depth
- Energy range: $10^{16} \rightarrow 10^{19}$ eV





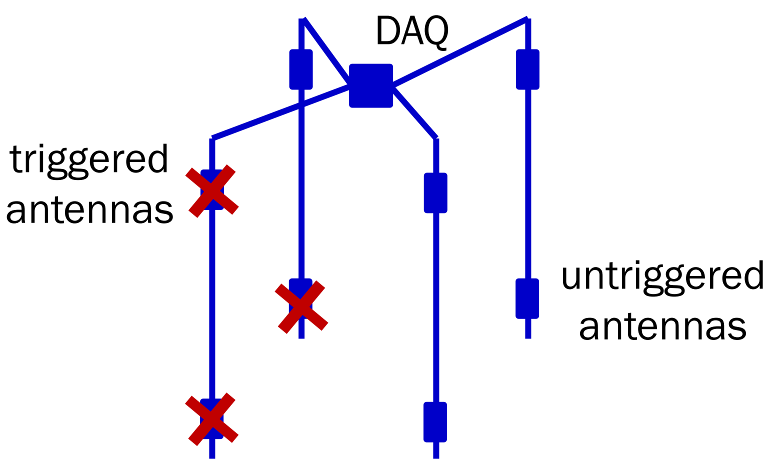
Current Status of the Instrument

- 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") + 3 stations deployed so far

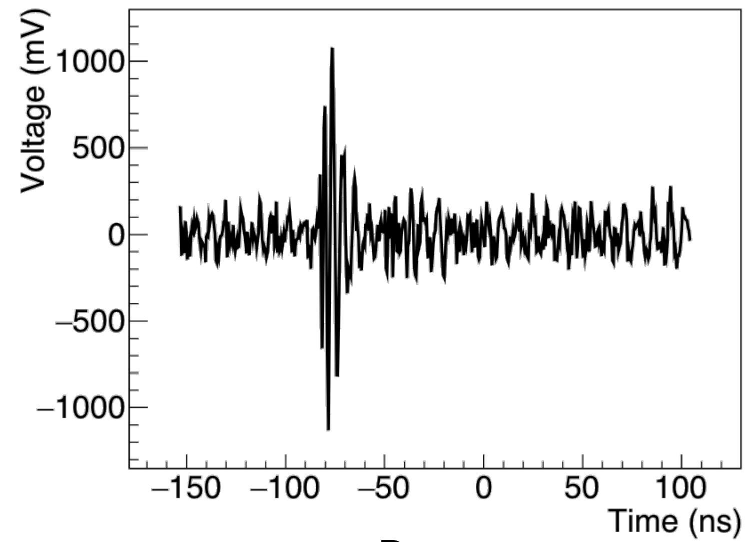


ARA Trigger and Data

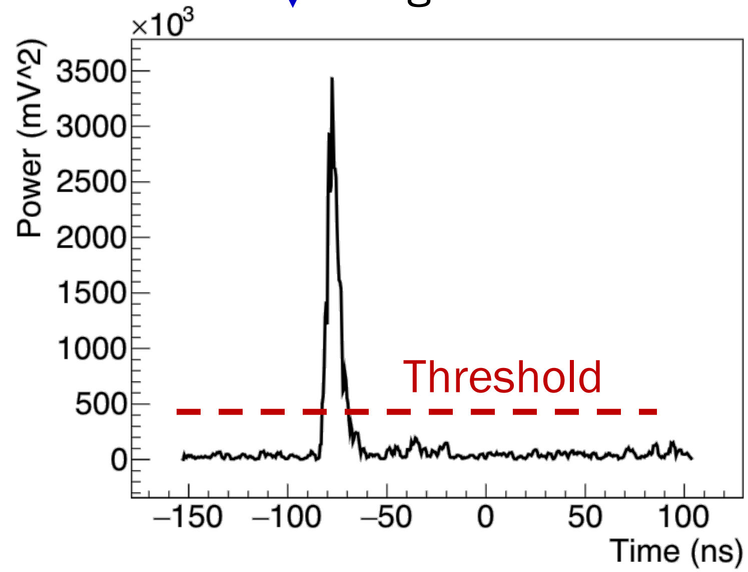
- *Power:* 10ns integrated power > 5.3 × thermal noise floor
- *Coincidence*: trigger in 3/8 antennas of same polarization in ~110 ns
- Thresholds maintain a global ~7 Hz/sta trigger rate → 10^8 evts/year/st
- We calibrate with local and distant pulsers



Calibration Pulser Testbed Station

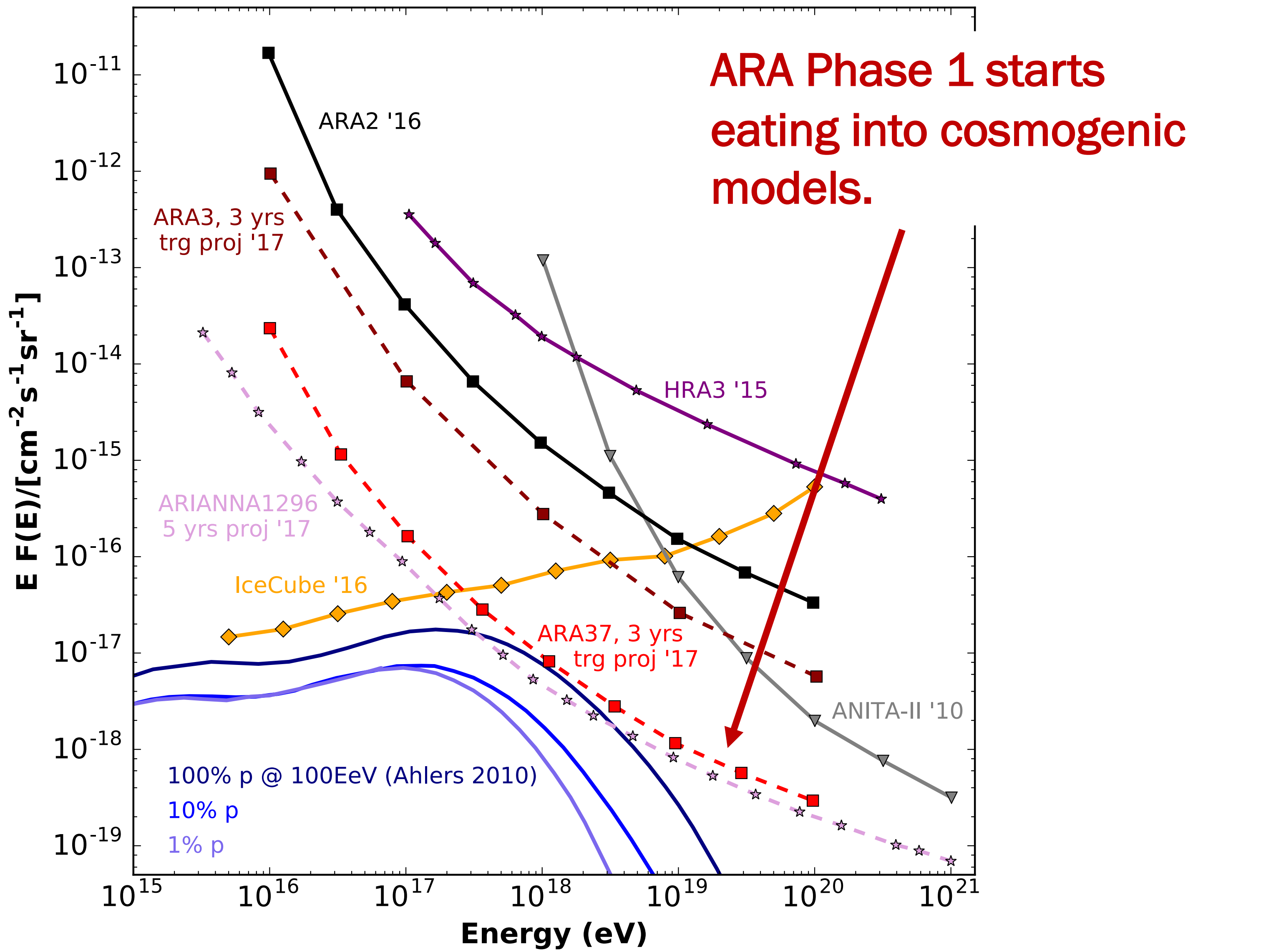


Power Integration



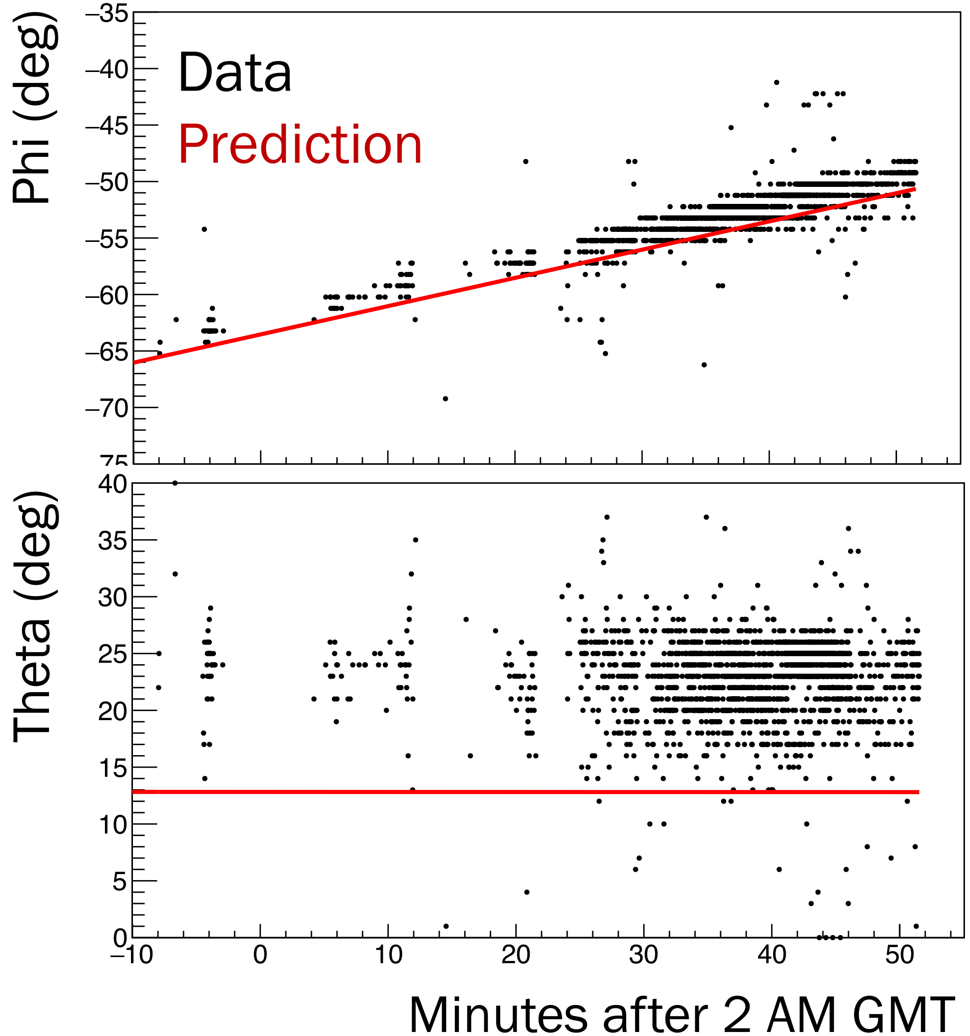
Thanks to M. Lu for plot digitization.
ARA ’17: POS (ICRC2017) 966
ARIANNA ’17: POW (ICRC2017) 977

Status of Analyses



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*
- Systematic offset in theta is possible opportunity to calibrate the array (still under study)
- **First reconstructable emission of extraterrestrial origin to trigger ARA — paper with details soon**

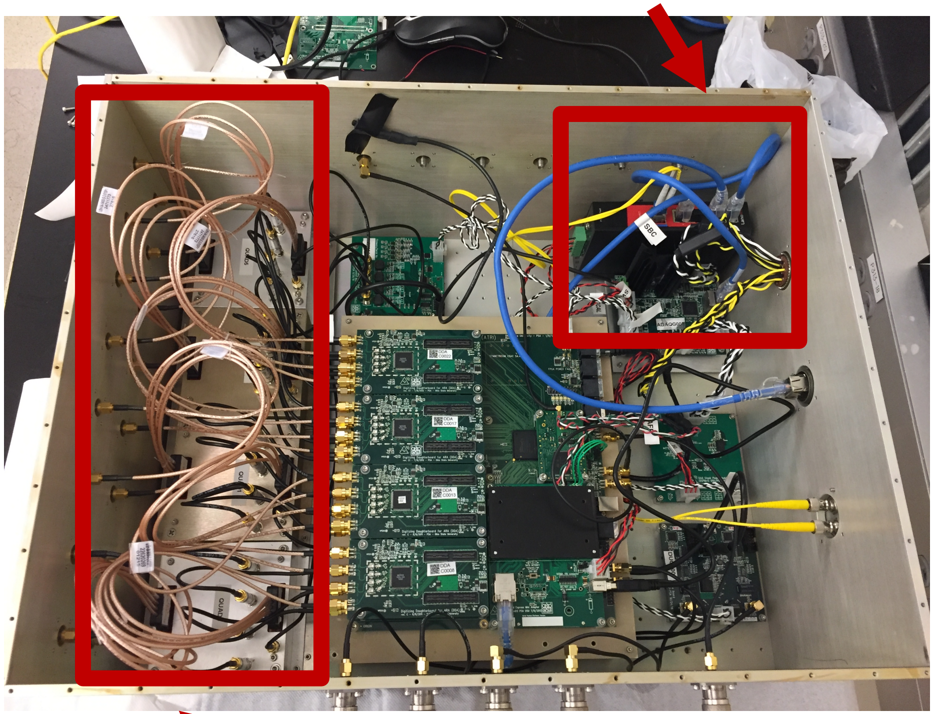


B. Clark, et al for the ARA Collaboration
2017 APS April Meeting Vol 62, No 1.

*Sun locations computed with C++ Solar Position library by the Platforma de Solar America

New Stations

- **ARA will deploy three new stations (A4, A5, A6) in 2017**
- 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
- A5 will deploy with a phased array trigger string



ARA4 DAQ Box

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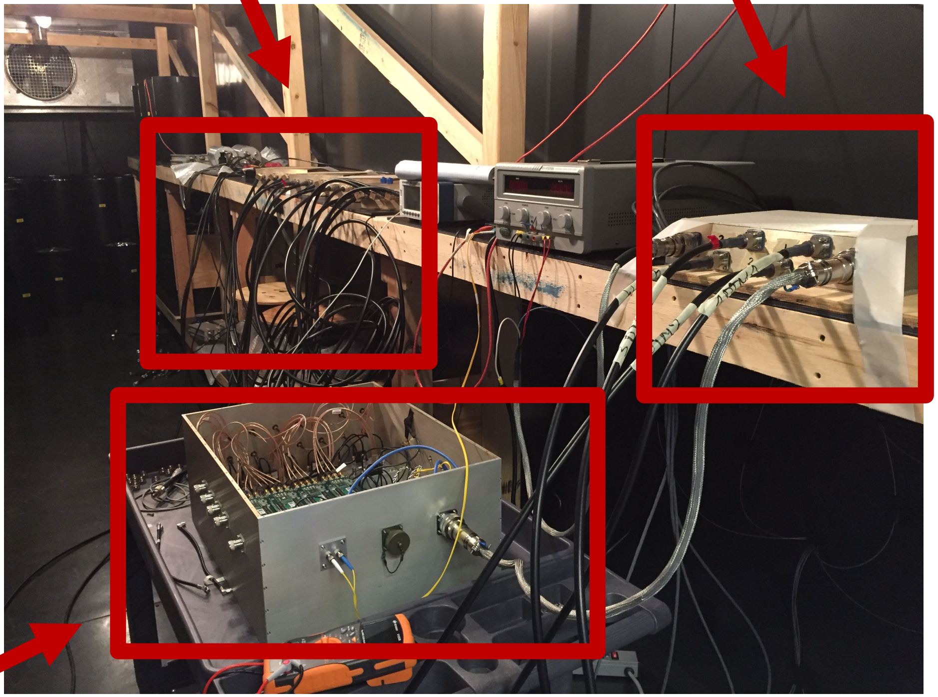
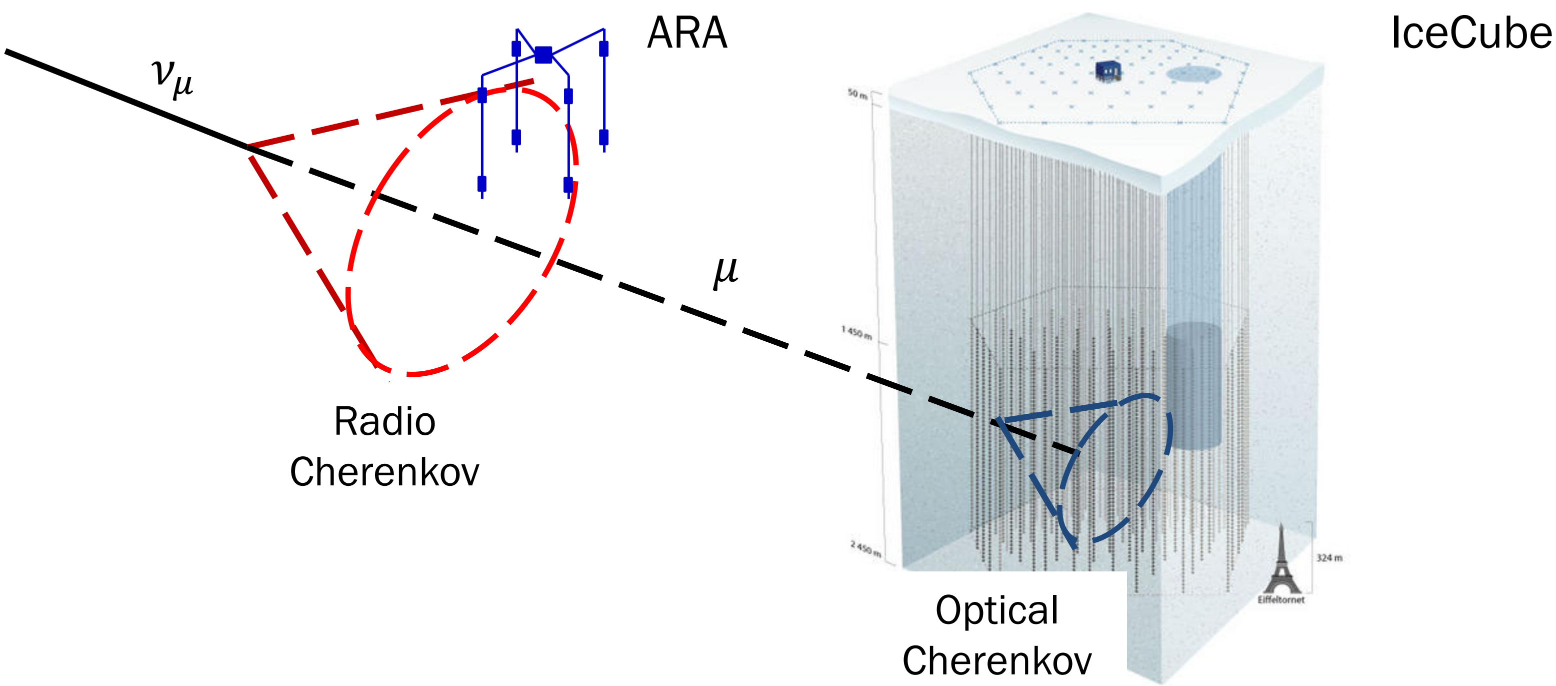


ARA4 in PSL Refrigerator

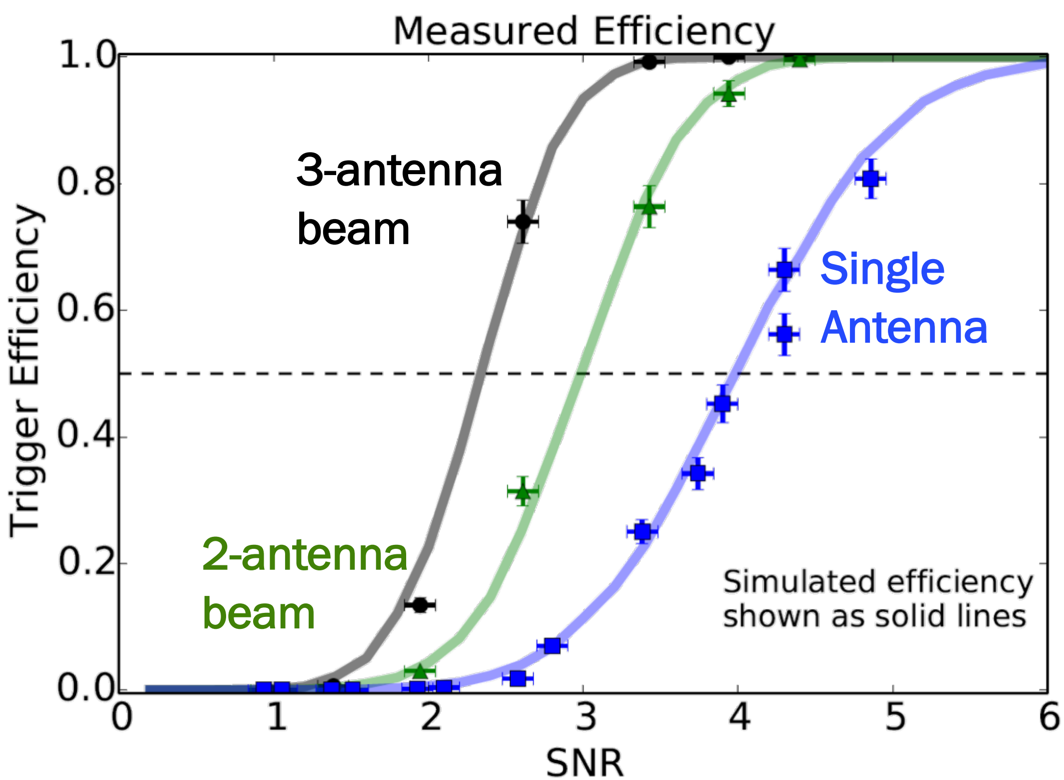
Precision Time Protocol

- Serendipitous opportunity: all new stations will be equipped with Precision Time Protocol → synchronization at ~10 ns level
- Added benefit: clock sync with IceCube White Rabbit System → At the analysis stage, can look for neutrino RF from IceCube events in multiple stations (far stretch, but high payoff)
- Work left to do: firmware and understanding potential event geometry



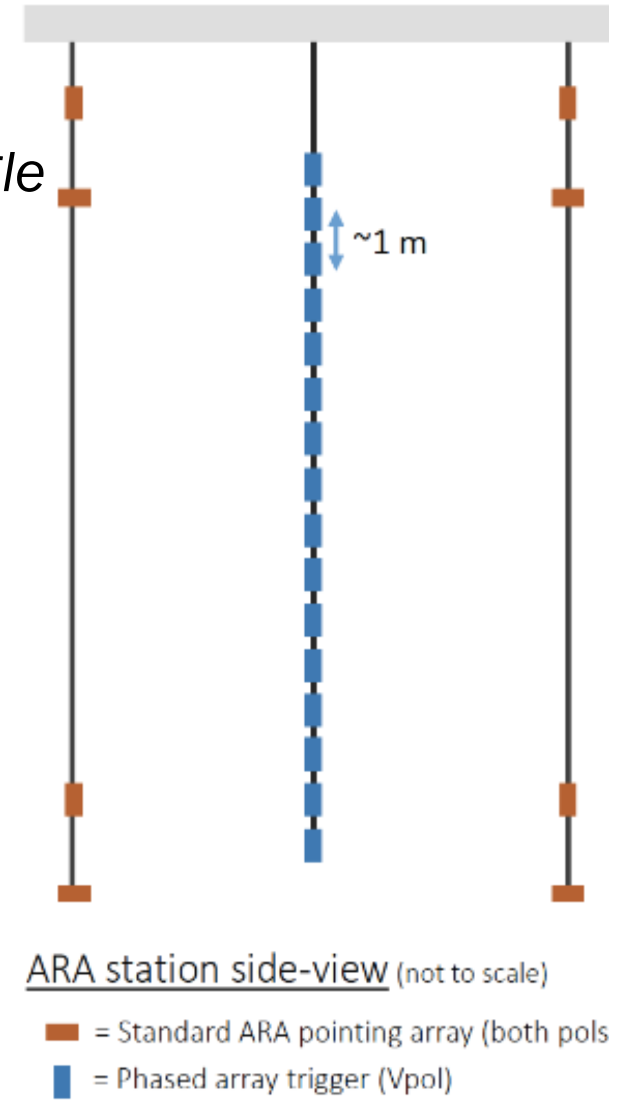
Phased Array w/ A5

- Beamform *before* triggering ⟶ higher sensitivity
- For fixed trigger rate, threshold $\propto \sqrt{N}$
- 8 VPol antenna phased array deployed down *single* hole *inside* A5



J. Avva et al., Nim A, Vol 869, 2017

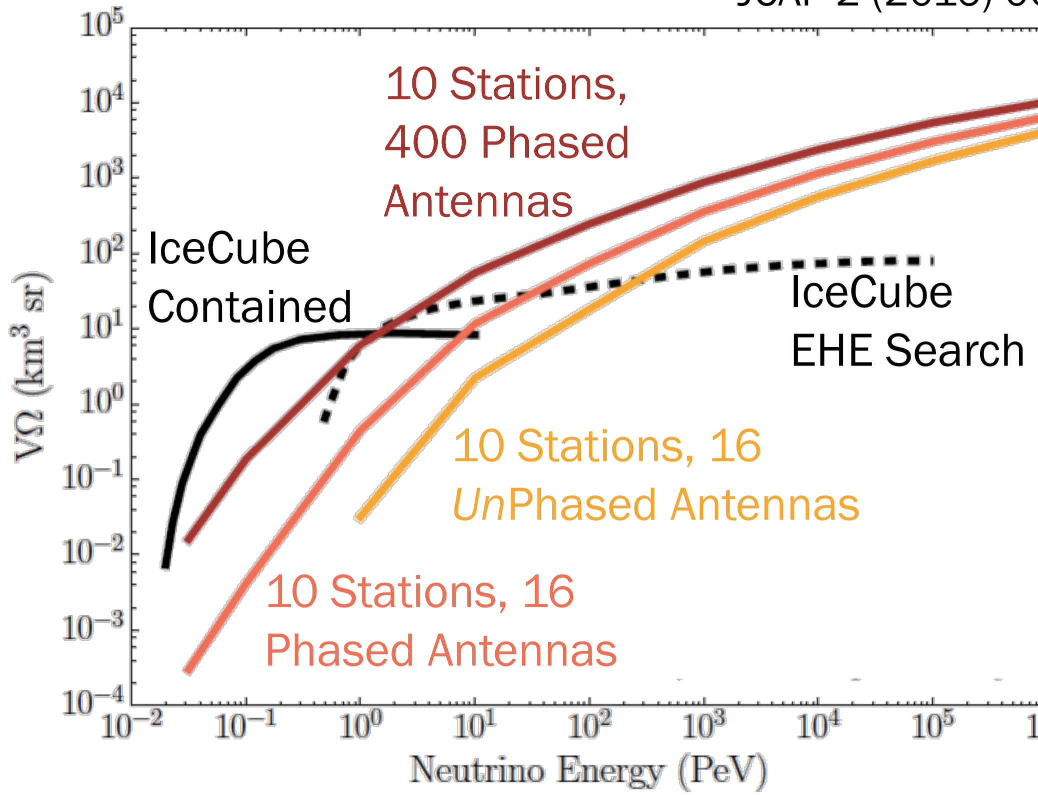
A. Vieregg, ICRC 2017 NU011



Phased Array Sensitivity

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

- An advanced system 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

Summary

- Projections for ARA sensitivity are able to probe into cosmogenic and production models.
- New stations have more *in-situ* control than every before, enhancing detector operational efficiency.
- ARA will *double* in size this next pole season.
- Phased array deployment on A5 in 2017 will demonstrate potential for reducing ARA's threshold.

BSF
United States – Israel
Binational Science Foundation

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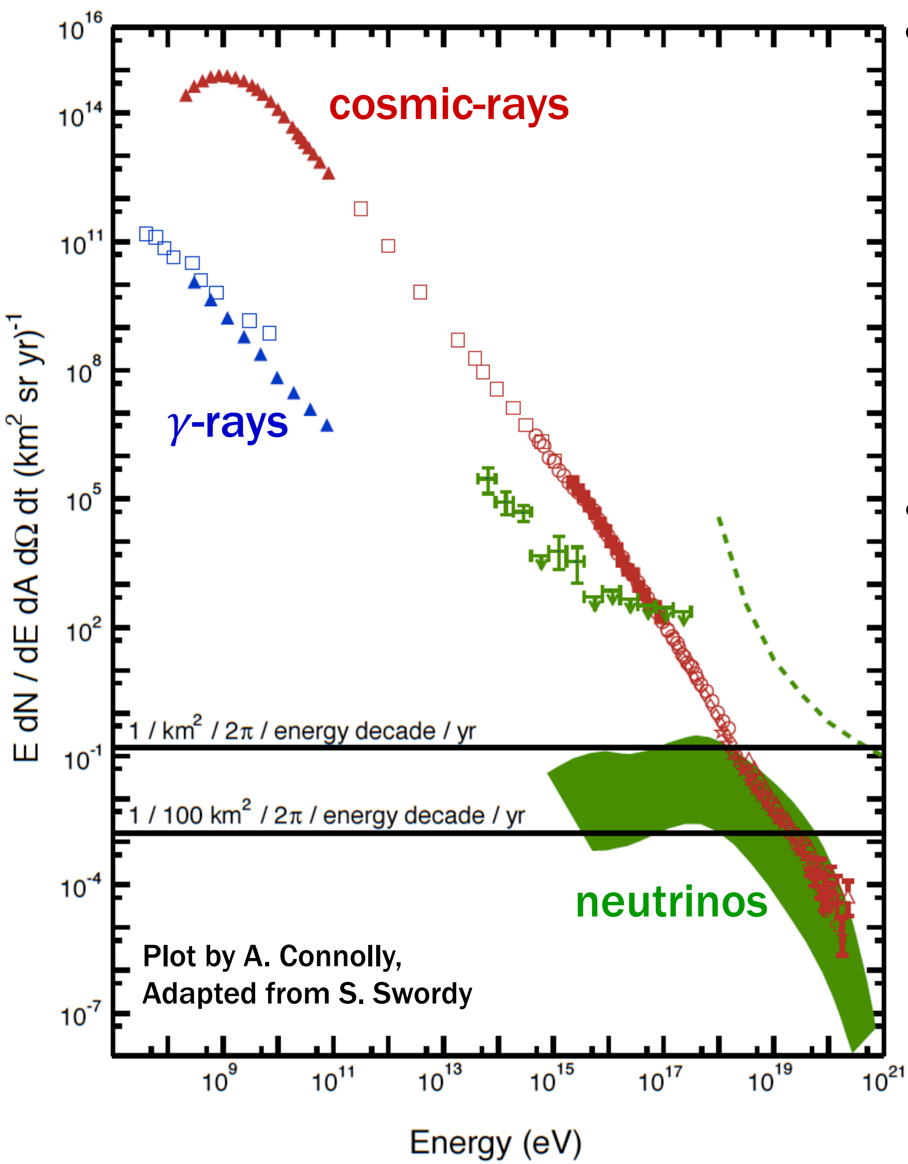
- The Ohio Supercomputer Center
- The OSU Department of Physics and Astronomy
- The OSU Center for Cosmology and Astroparticle Physics
- US-Israel Binational Science Foundation Grant 2012077

Back-up Slides

Why Study Neutrinos: Astrophysical Messengers

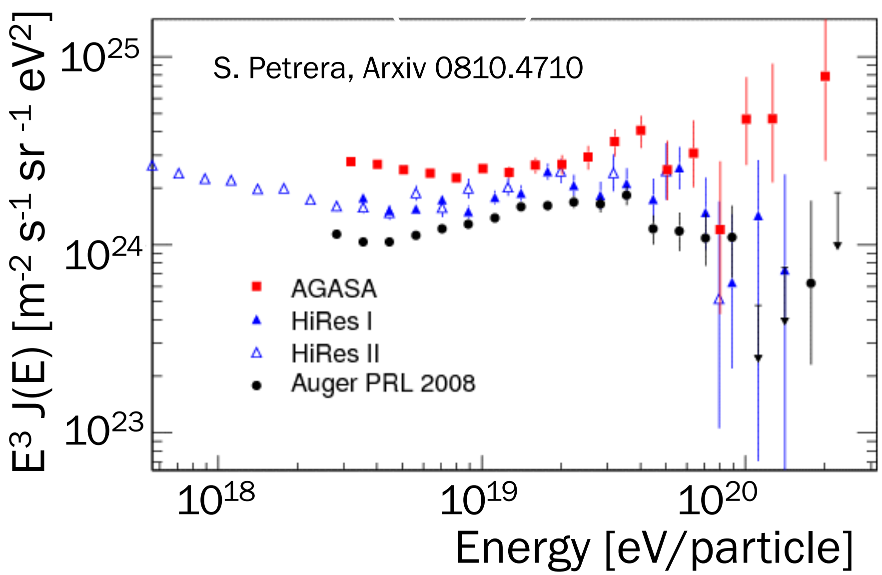


- Cosmic rays >$10^{19.5}$ eV attenuated, possibly by GZK effect, e.g.

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

→ Screens extragalactic (>100 MPc) sources

- γ-rays annihilate w/ CMB @ ~1 TeV



Astrophysical Messengers

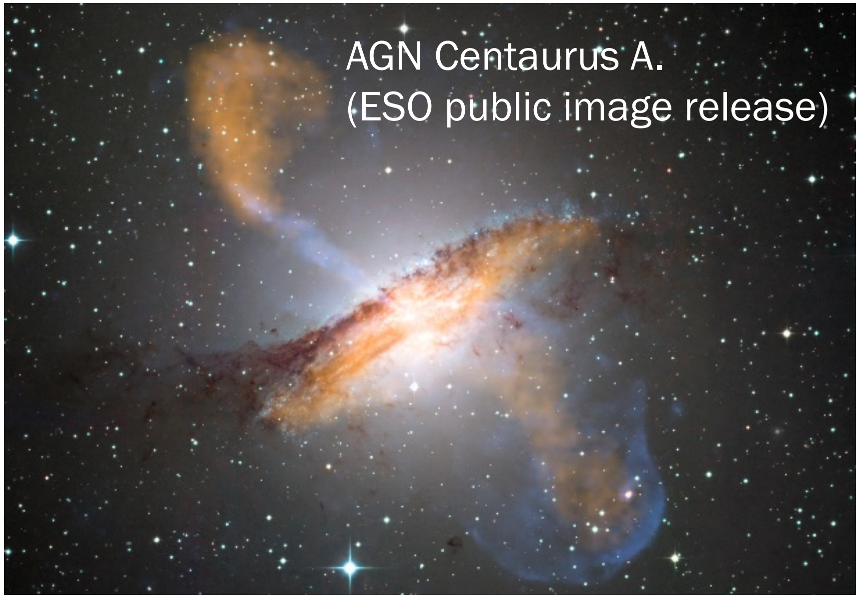
Two Sources of Neutrinos

- *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)
  - Etc.

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

Neutrinos have attractive properties

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

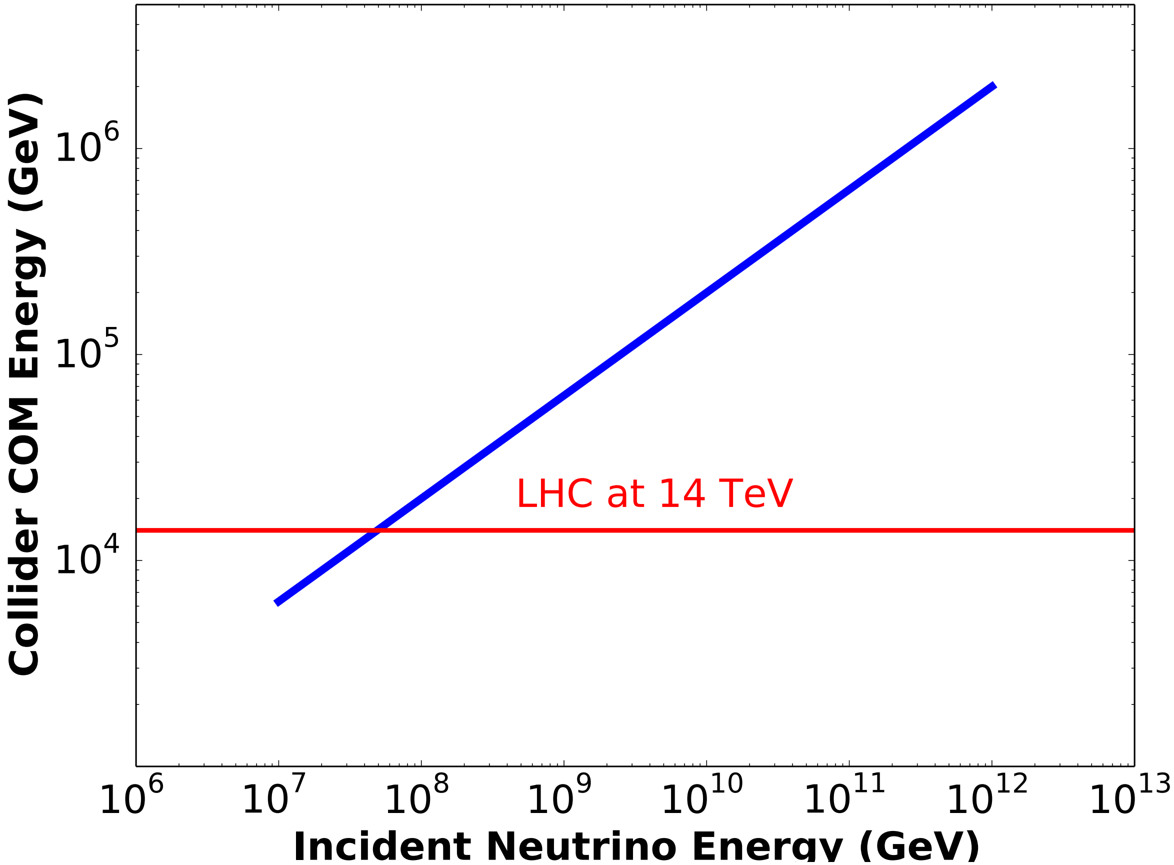


Why Study Neutrinos: Particle Physics Probes

- **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)

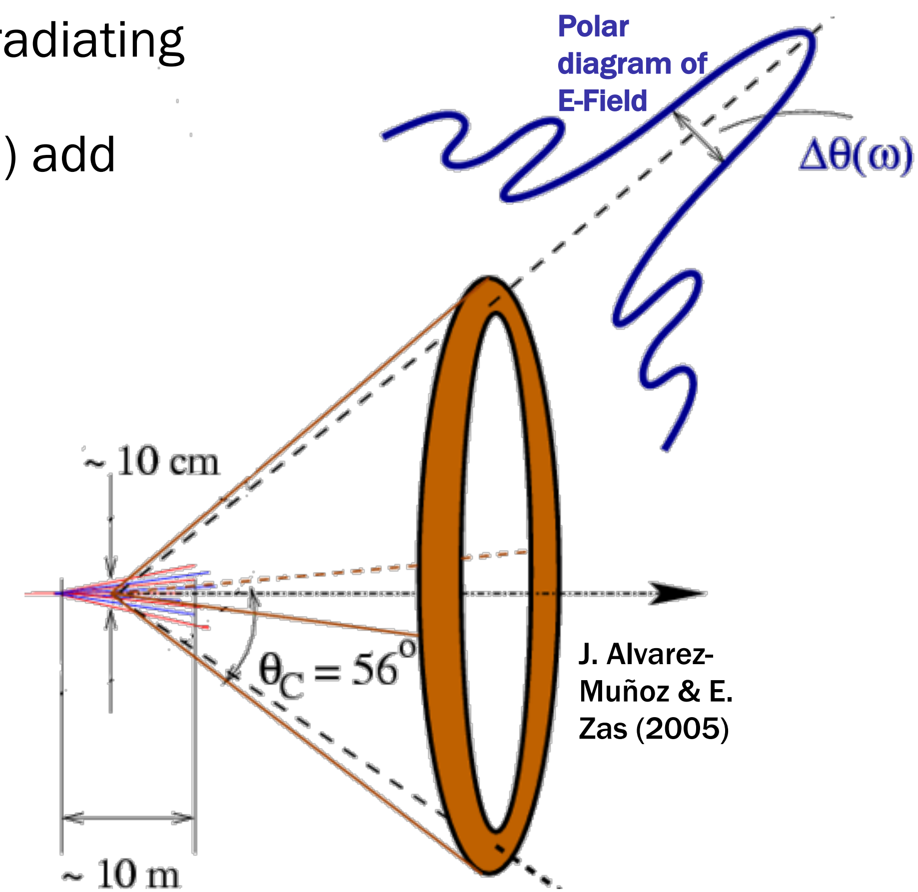
$$E_{COM} = \sqrt{4\, E_\nu\, m_n}$$



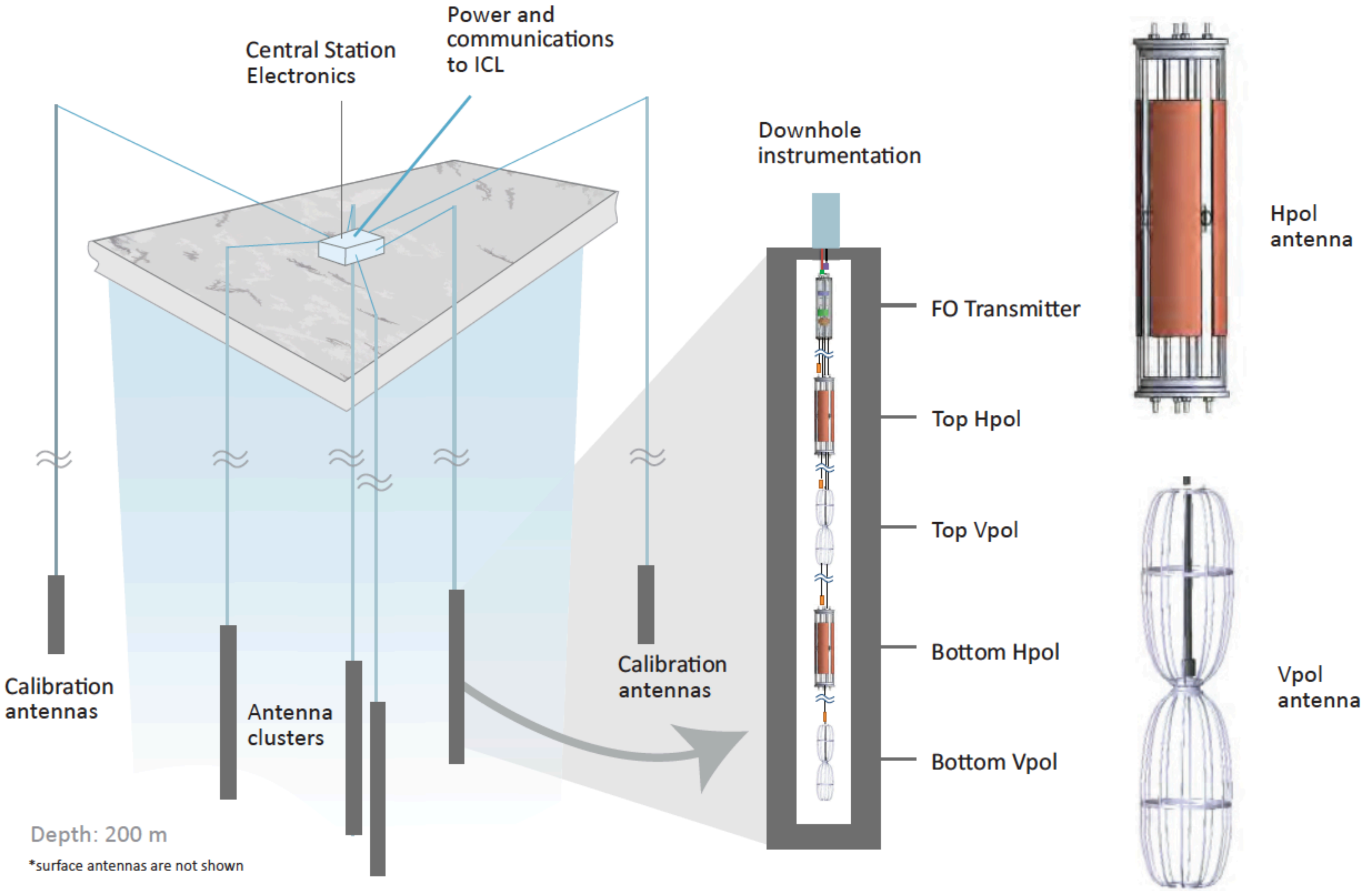
COM = Center of Momentum

Radio: 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 a characteristic broadband (200 MHz → 1GHz), bipolar, impulsive radio signal
- Conical emission, strongest signal “on cone”
- **Two requirements for successful experiment**
  - **Radio transparent medium: ice**
  - **Enormous volume: Antarctica**



Alternate Station Schematic



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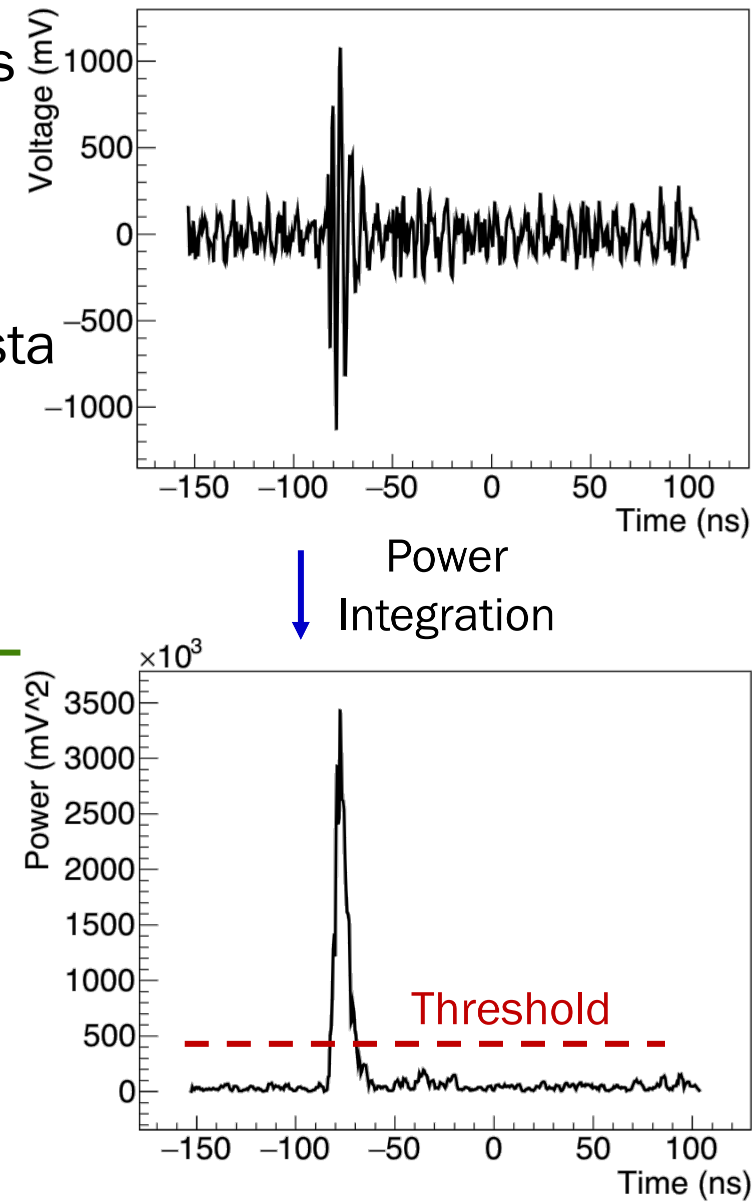
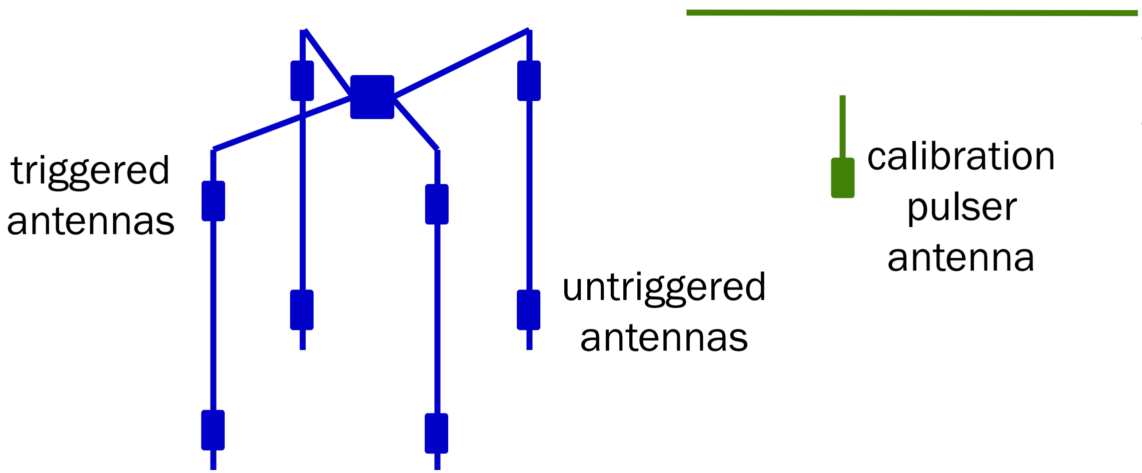
- *Coincidence requirement*: trigger in 3/8 antennas of same polarization in ~110 ns
- Thresholds set to maintain a global ~7Hz/sta trigger rate → 10^8 evts/year/st
- Event = 16 x 250ns waveforms
- We calibrate with local and distant pulsers

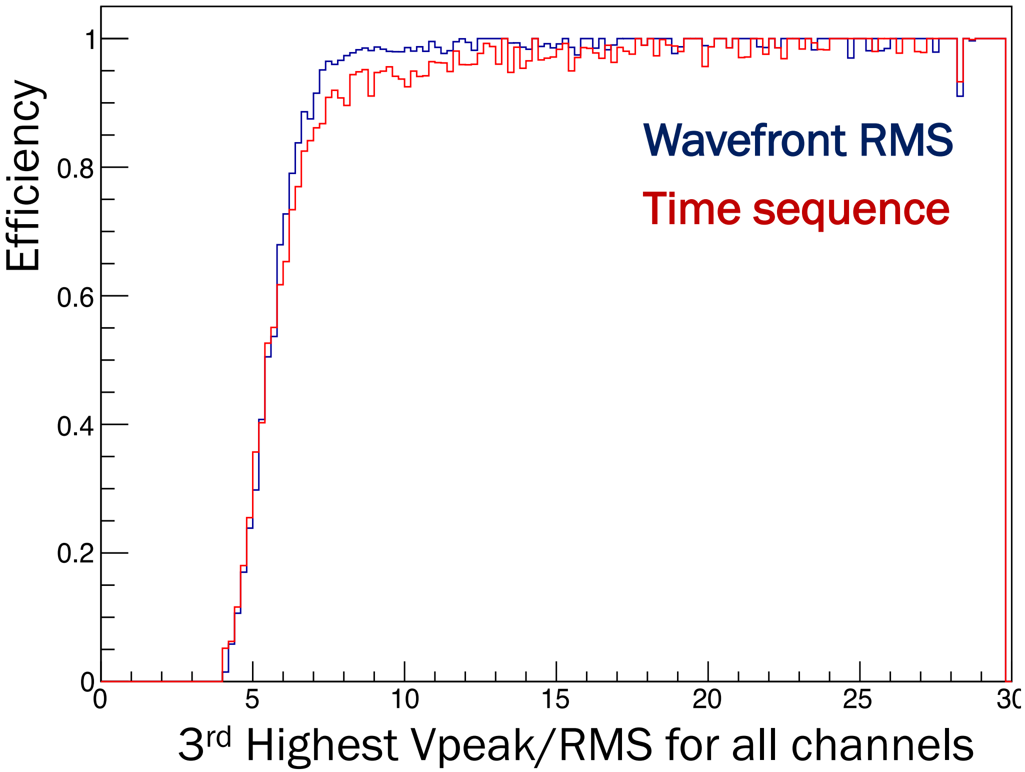
Calibration Pulser Event
Testbed Station





Filtering Data

- First analysis in 2014 did interferometry on *all* data at 150 ~ms/event, this is >4 *years* of serial compute time
- Design filters around the "hit pattern" observed in the event
  - Time-sequence filter
  - Wavefront-RMS filter
- For 10^{18}eV neutrinos and fixed signal strength, both reject 99.92% noise while keeping ~80% of neutrinos.
- Can use time intensive algorithms, like interfering one event at multiple radii (~3s/event), for remaining data

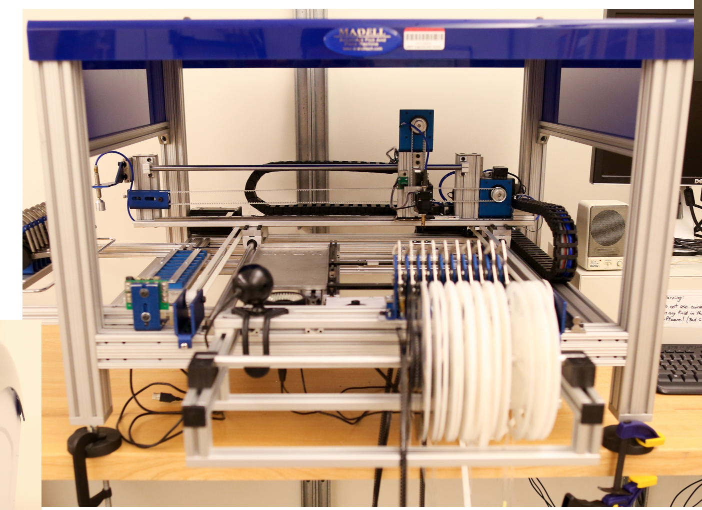


M. Lu et al. for the ARA Collaboration.
PoS (ICRC 2017) 966

Rapid prototyping and testing of electronics

Large RF/ anechoic chamber.

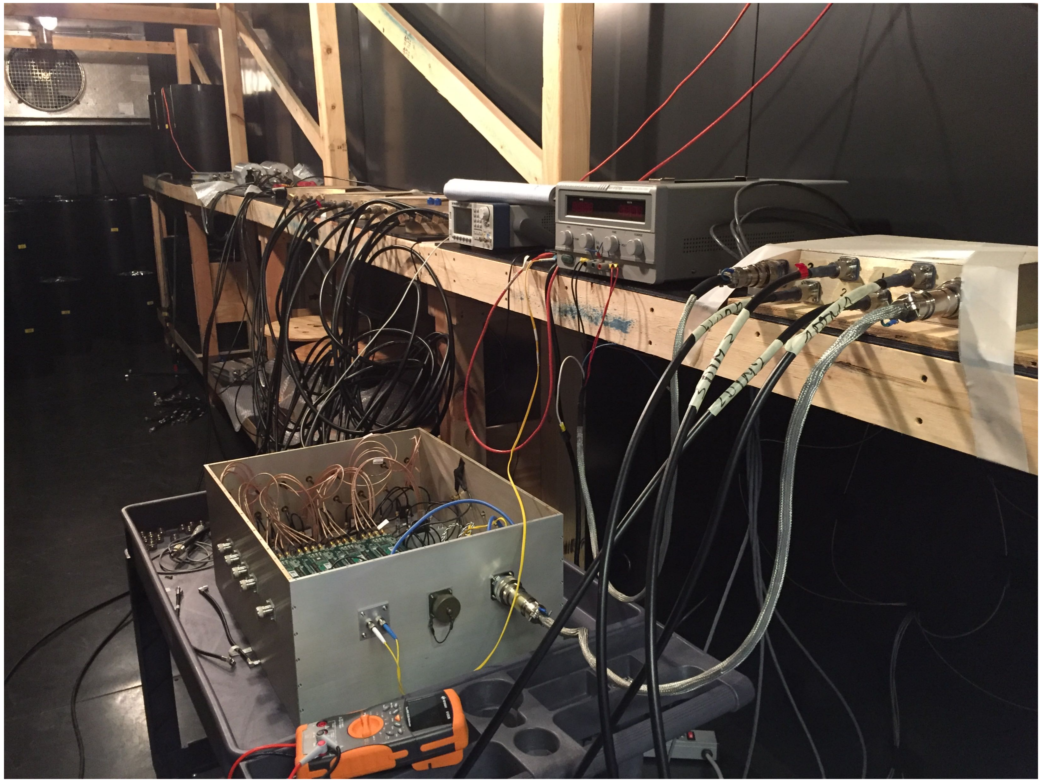
RF circuit board mill.



Pick & Place machine for rapid assembly.

Large thermal chamber.

Testing at cold at OSU.

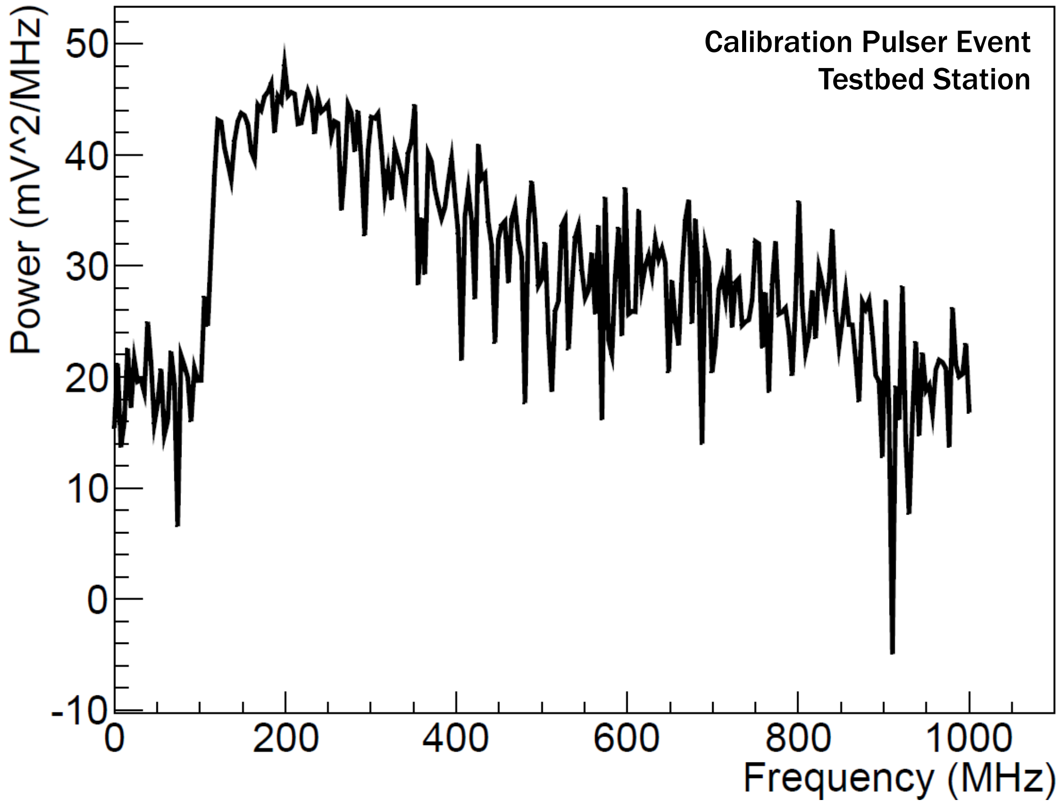


Full station assembled in freezer at UW-Madison.

Signal Identification: In Software

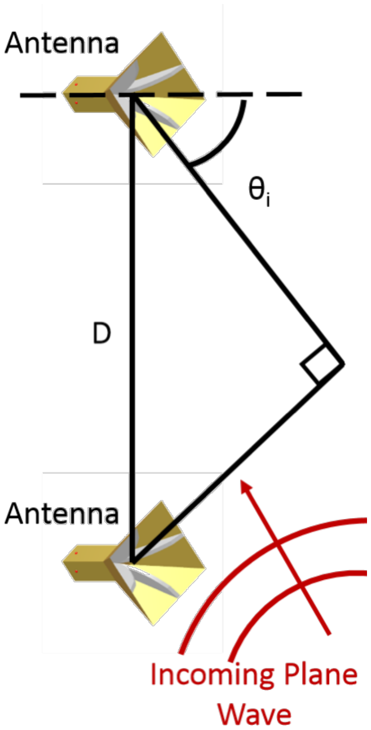
Signal Must be Broad in Frequency

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

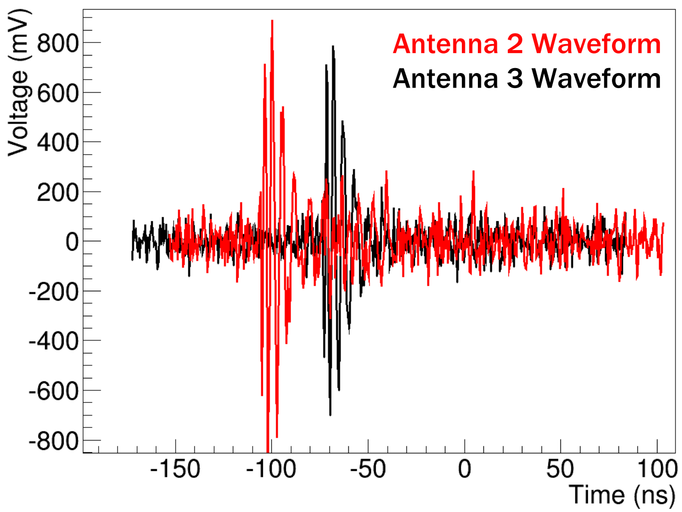


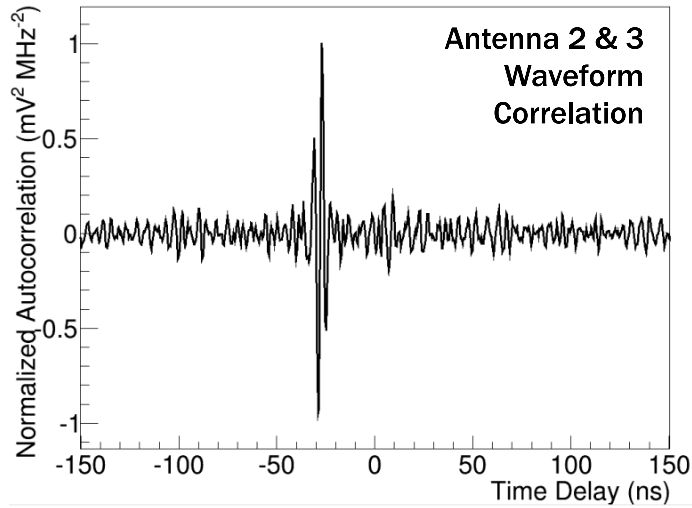
How to Analyze Data: Interferometric Maps

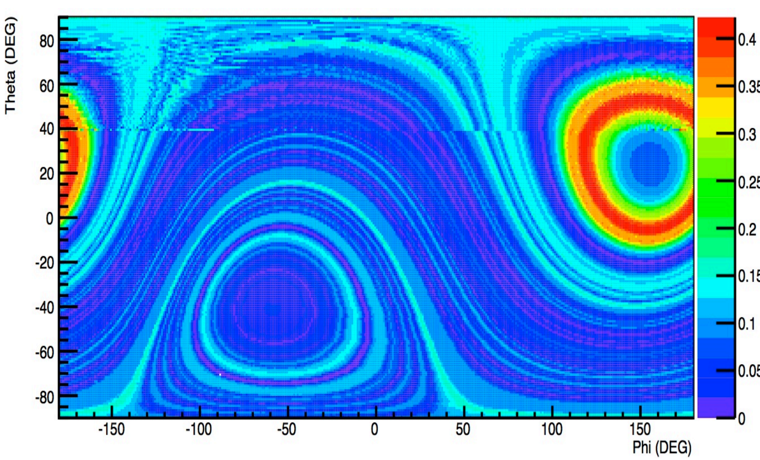
- Punitive source angle ⟶ Time Delay ⟶ Correlation Value for that delay
- Take Hilbert envelope to interpret as *power*

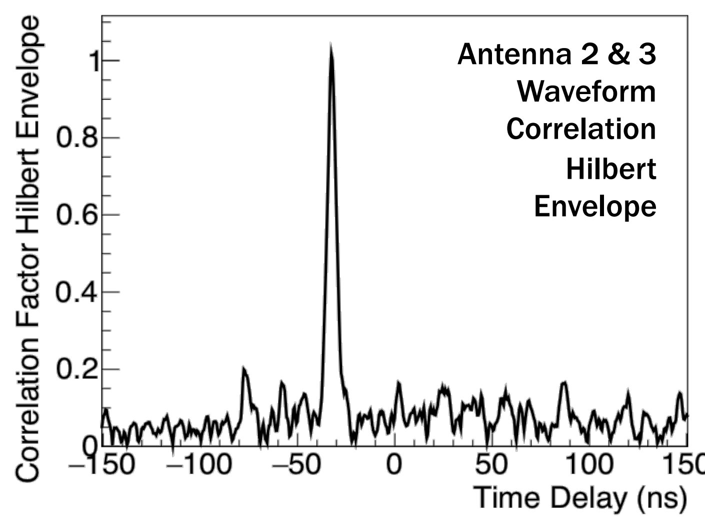


$$\theta_i = \arcsin\left(\frac{c\,\Delta t}{D}\right)$$





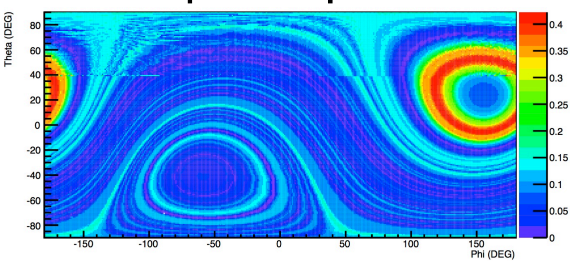




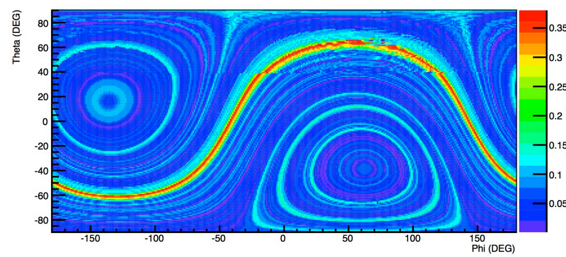
How to Analyze Data: Interferometric Maps

- 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

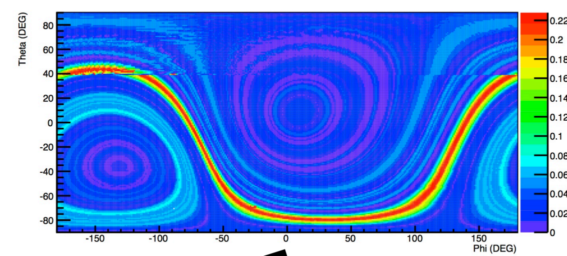
Map from pair 1



Map from pair 2



Map from pair 3



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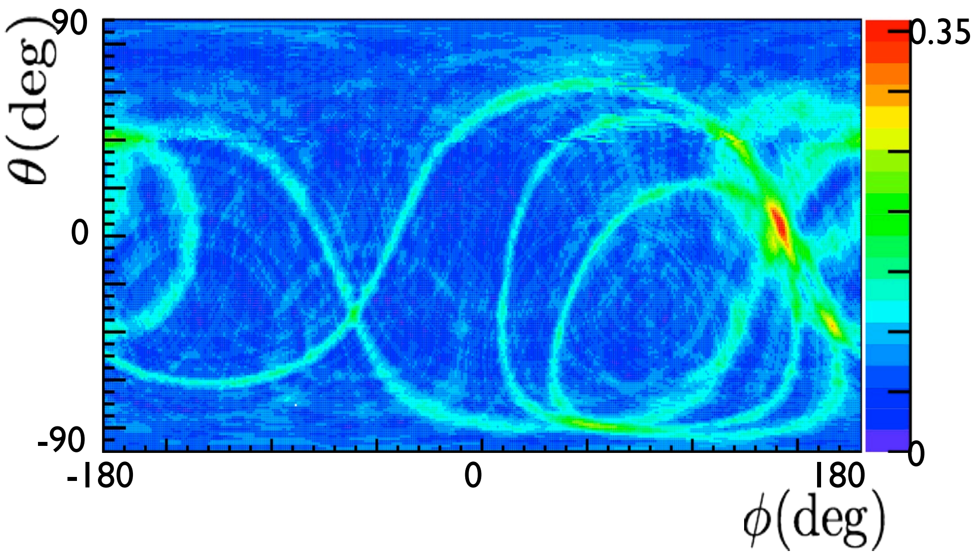
Figures by E. Hong

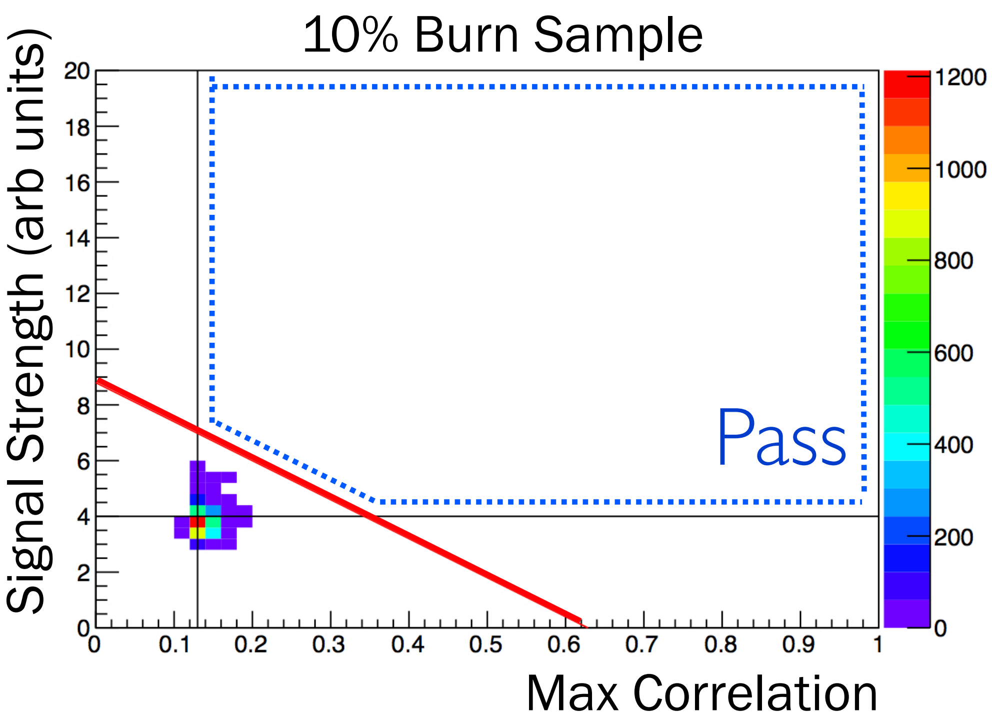


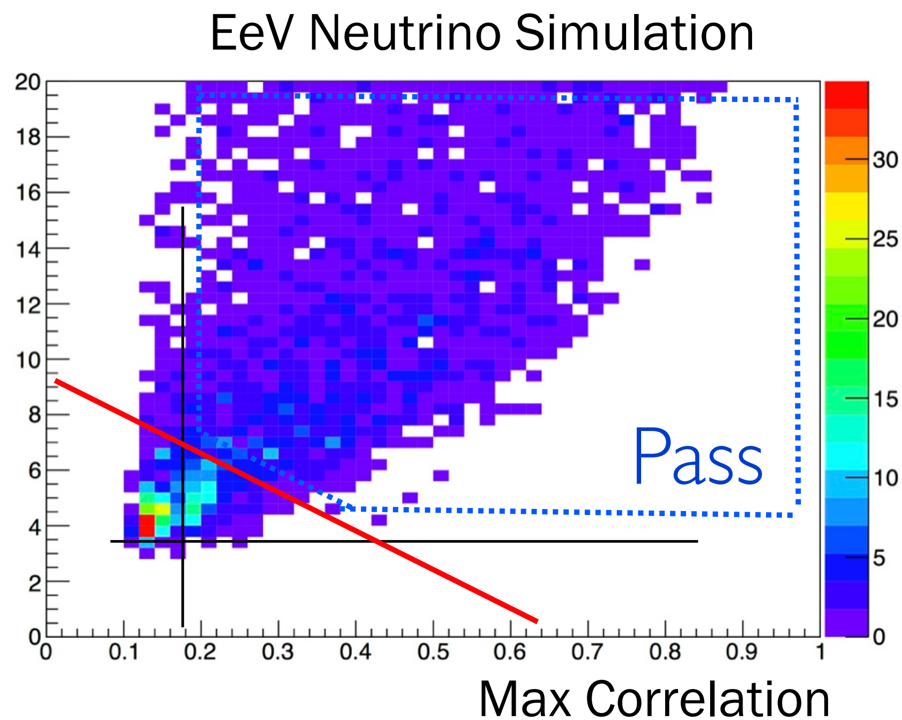
Peak in final map gives source direction

Searching for Diffuse Neutrinos

Signal Strength

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



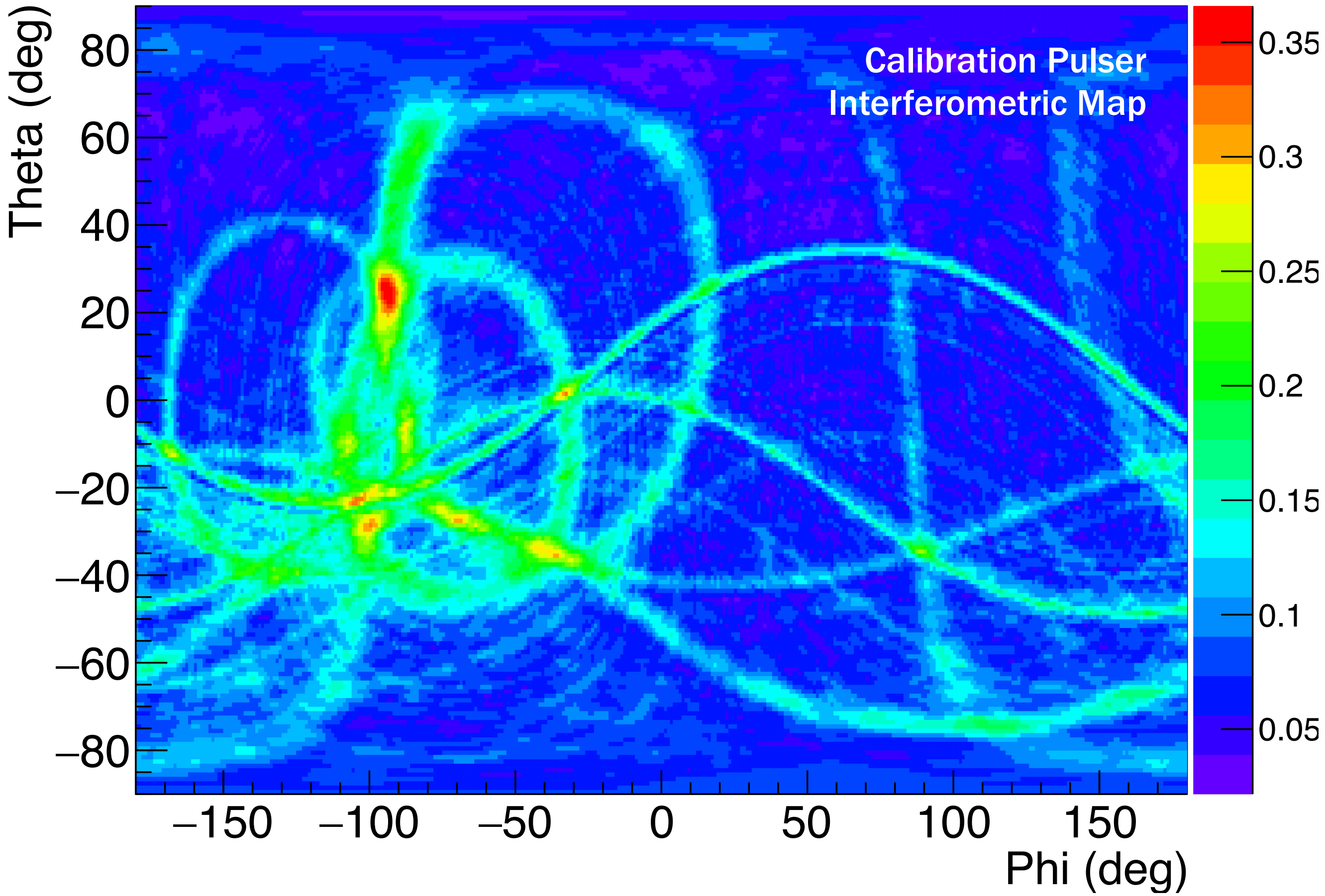


Figures by C. Pfendner

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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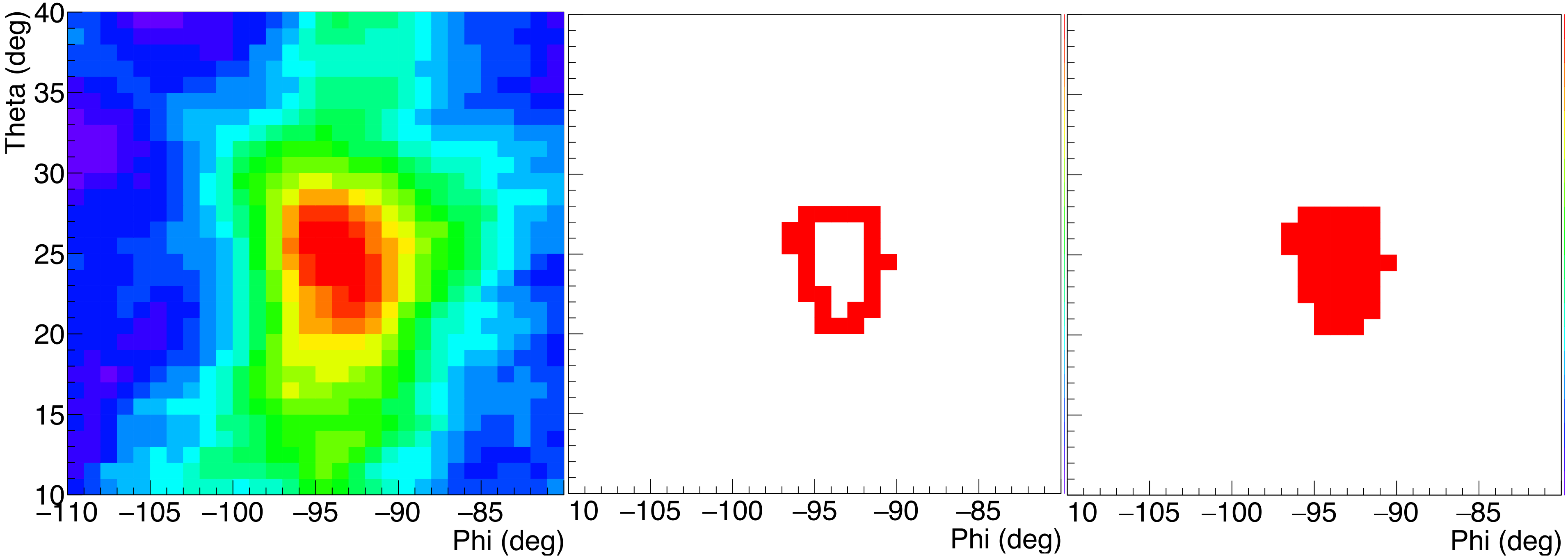
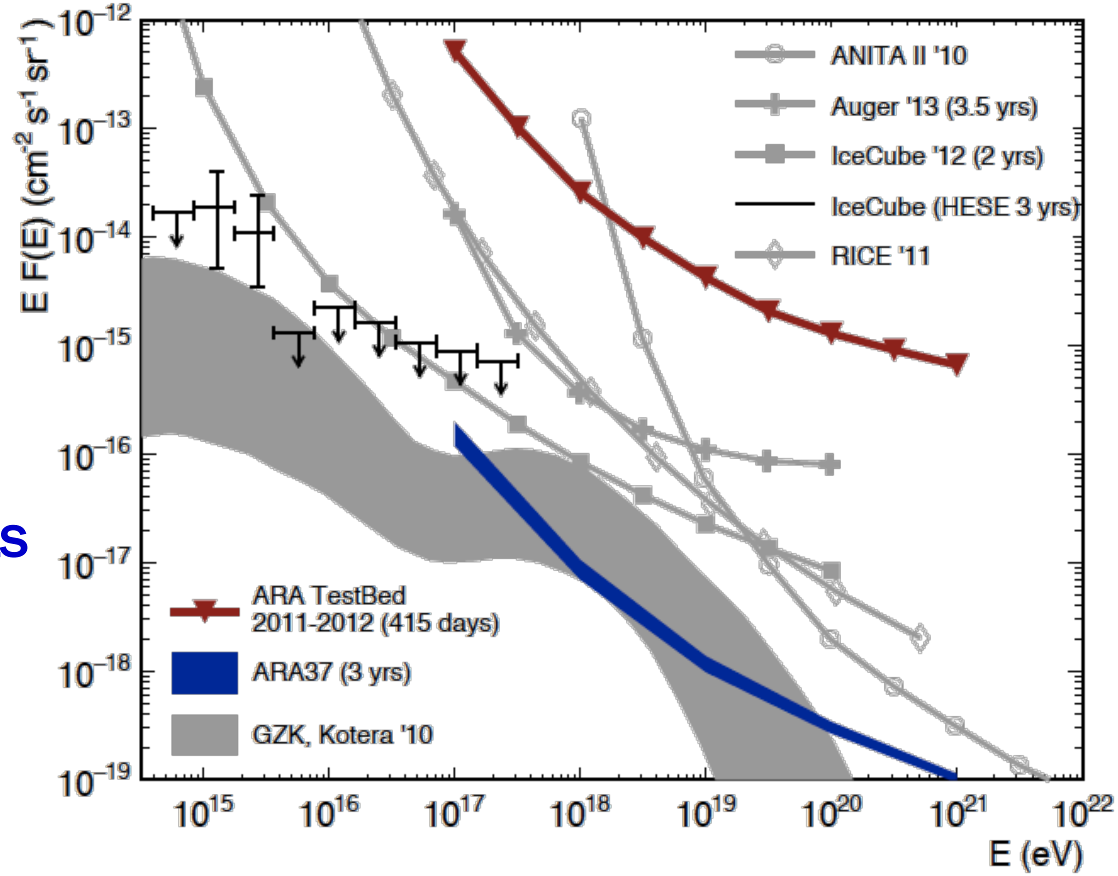


Vpol Calibration Pulser Map Peak → **85% Peak Contour** → **36 deg^2 on Map**

Testbed Search 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 (blue line) are competitive and capable of model discrimination.

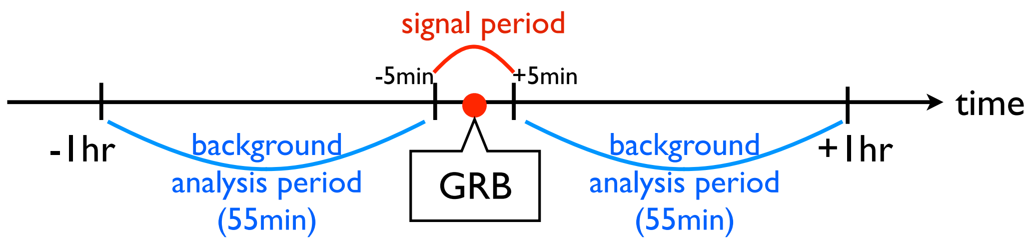


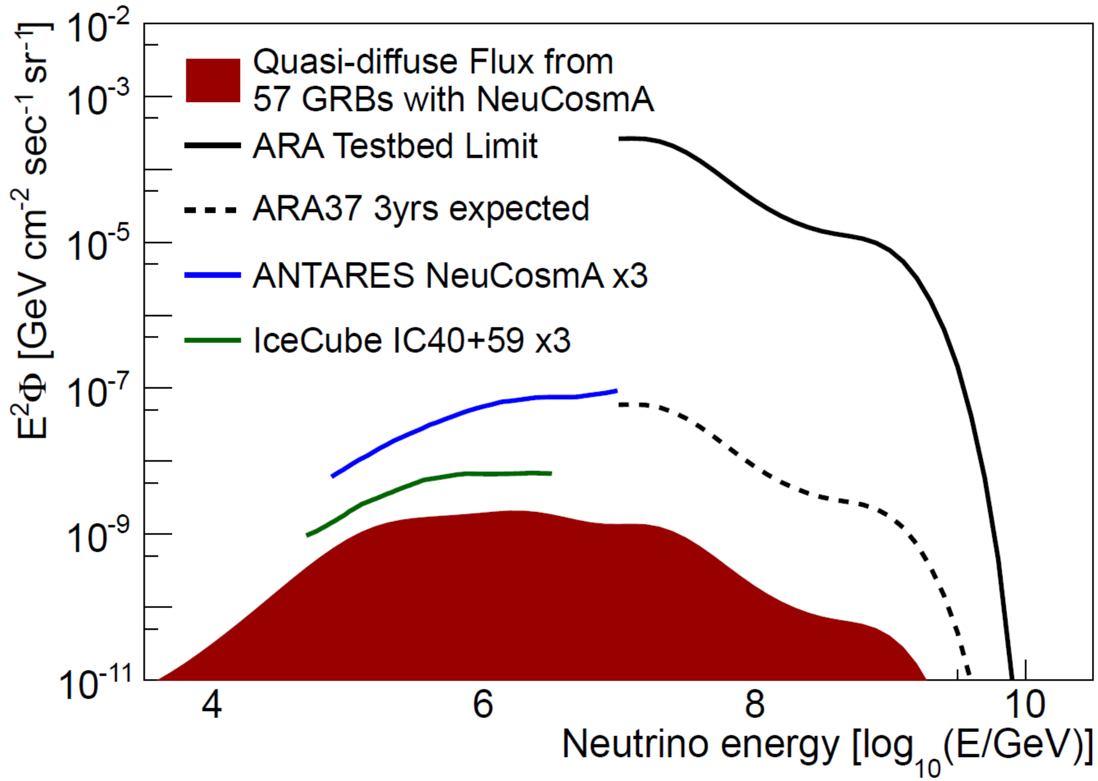
P. Allison et al for the ARA Collaboration
Astropart Phys, Vol 70 (2015).

Testbed GRB Search

- "Relaxed" diffuse search: stricter cuts on timing and source direction
- Blinded search strategy, using surrounding background to set cuts
- Expected background: 0.12, Expected neutrinos: 1.7e-5,

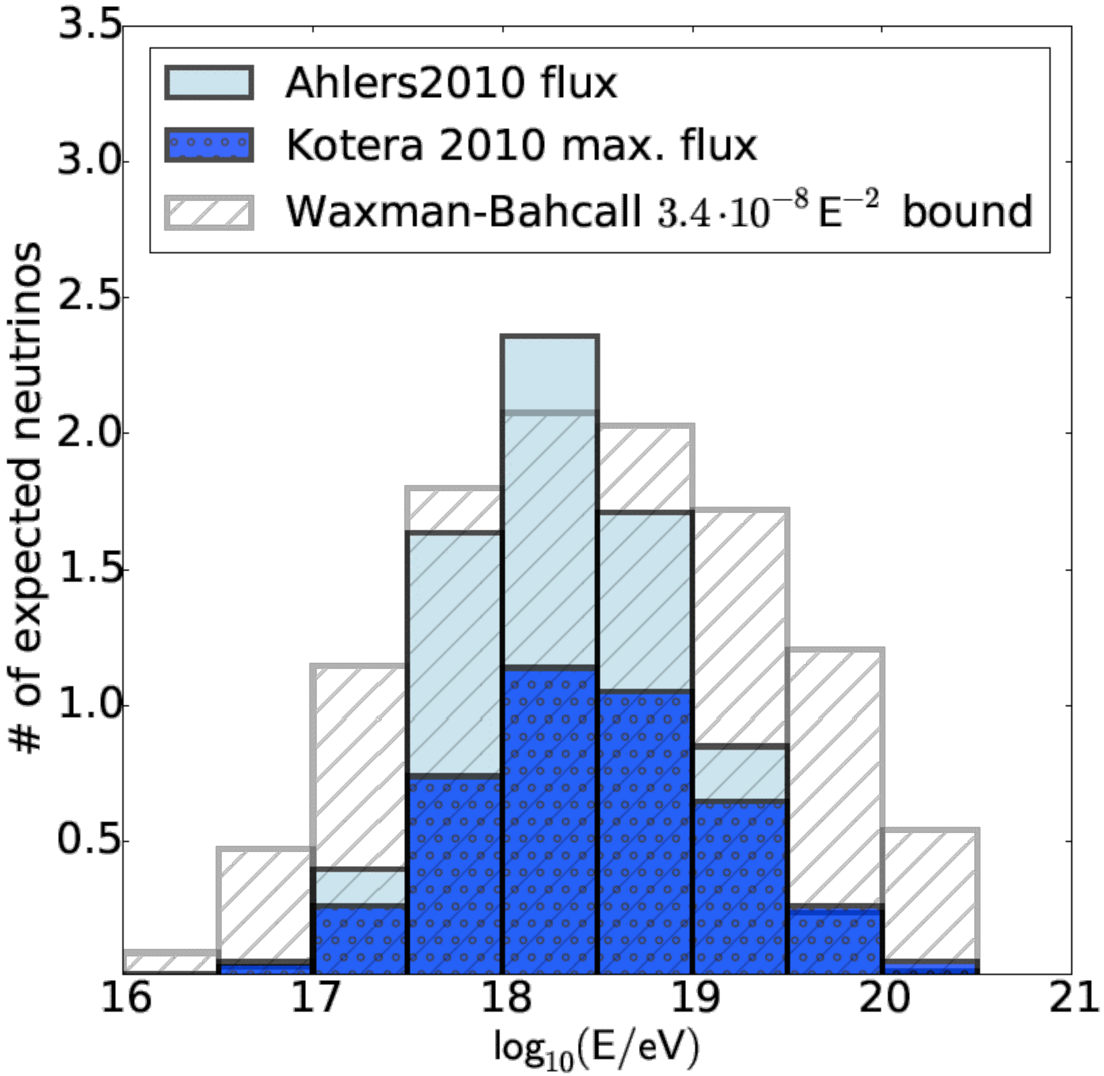
  0 events survived cuts
- Limits on the GRB flux from 57 GRBs from 224 days of ARA testbed
- First quasi-diffuse flux limit above 10^{16} eV





P. Allison et al, for the ARA Collaboration.
Astropart Phys, Vol 88 (2017).

Two Stations Diffuse Limit



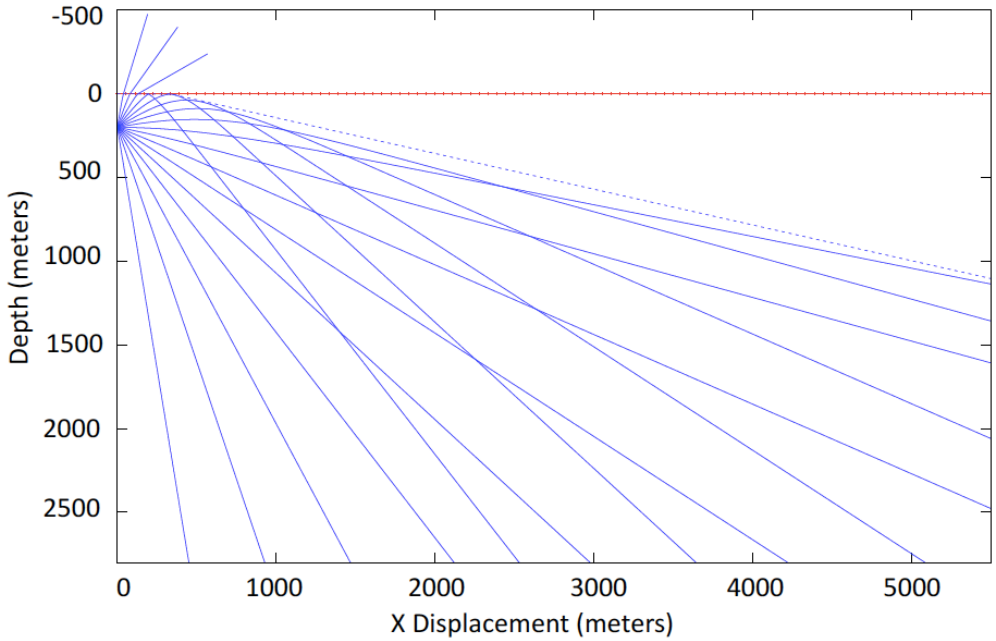
Projected event numbers for three models of the UHE neutrino flux with 37 stations and 3 years livetime.

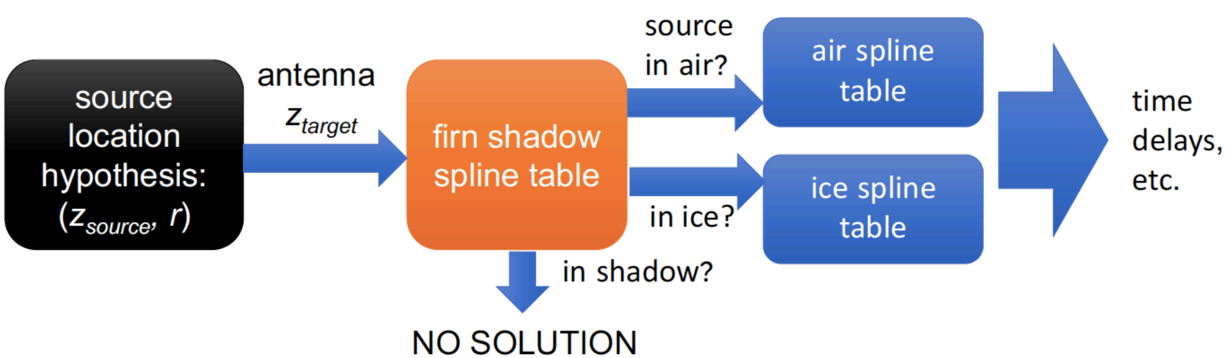
Power to discriminate between models after 3 years livetime.

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

Faster Reconstruction Techniques

- *Radiospline*: utilizes pre-computed delay tables for allowed paths through the ice
- Parallelized with OpenCL and implemented on GPUs
- 3 times faster than previous technique (120ms/event → 50ms/event)

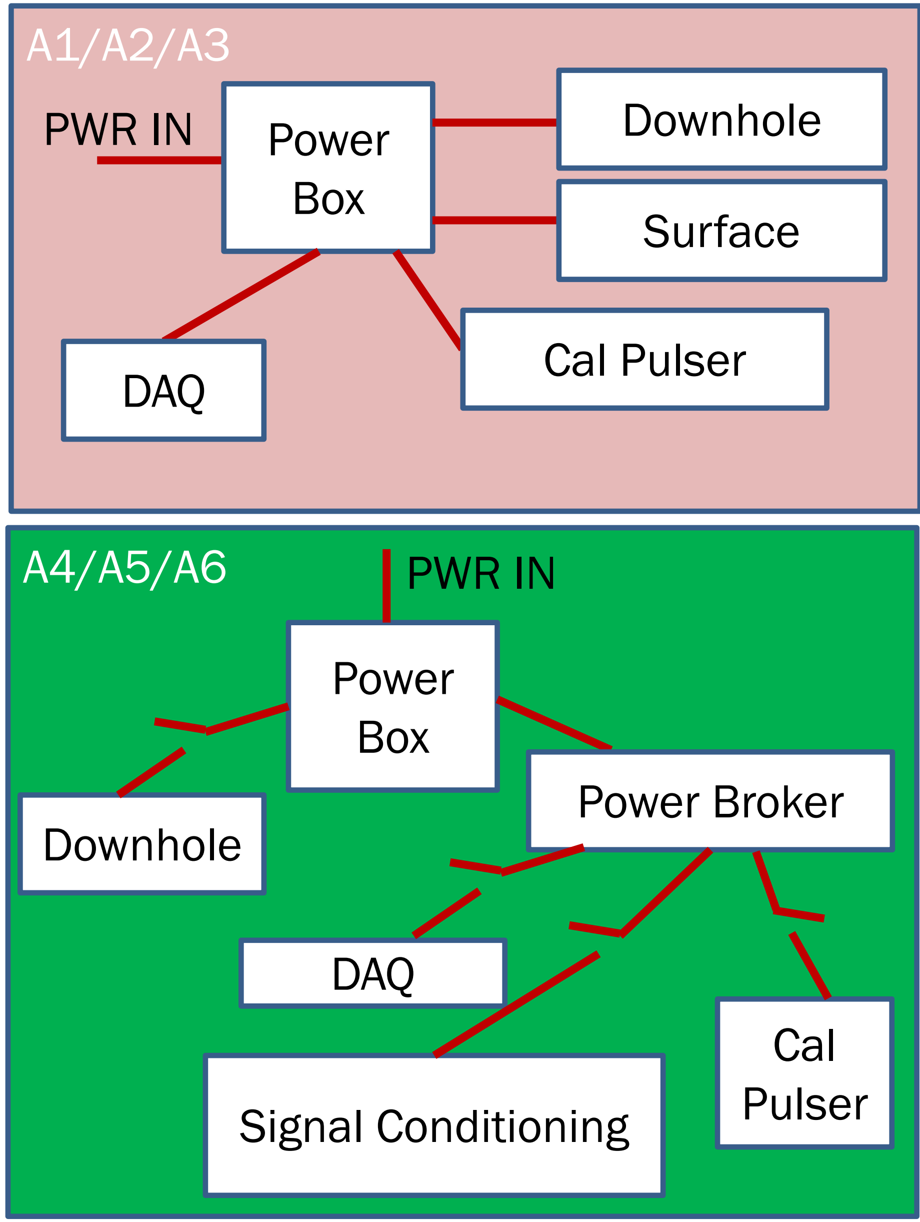




M. Beheler-Amass, et al. for the ARA Collaboration
PoS (ICRC 2017) 1054

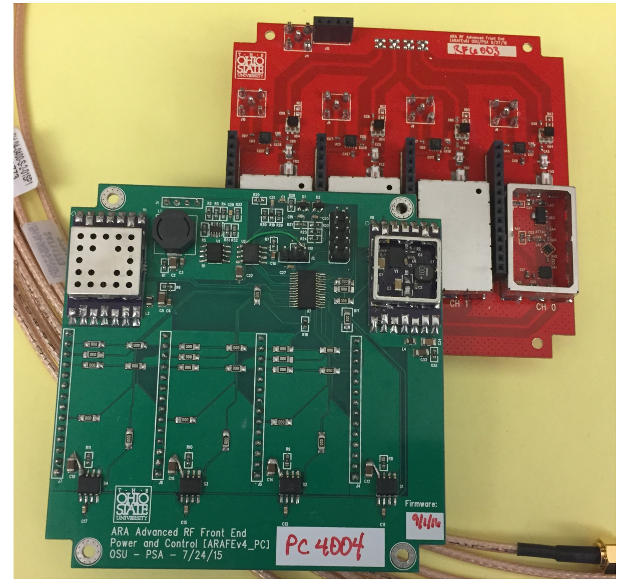
ARA Smart Power System (ASPS)

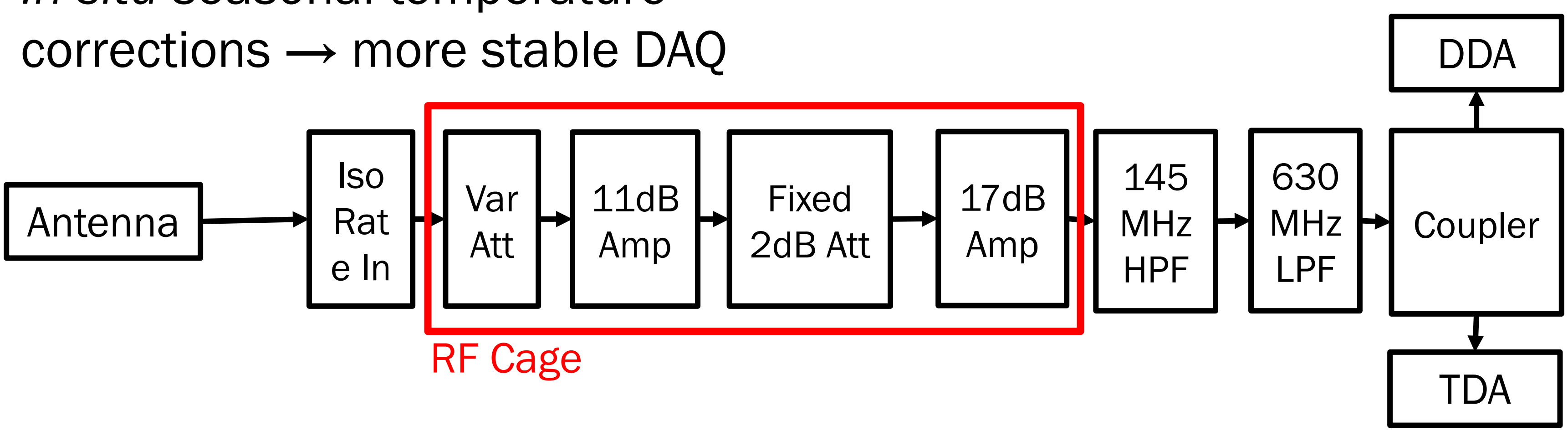
- Previous stations had no power granularity
- Any subsystem shutdown strained the entire electronics chain
- So, we introduced a power broker and monitoring interface
- The uC we chose (Tiva TM4C) gives all new stations PTP (precision-time-protocol) capability
  - Cross station clock syncing → Multi-station events
  - Clock sync to IceCube White Rabbit system → ARA+IceCube coincidence w/ sub-s precision

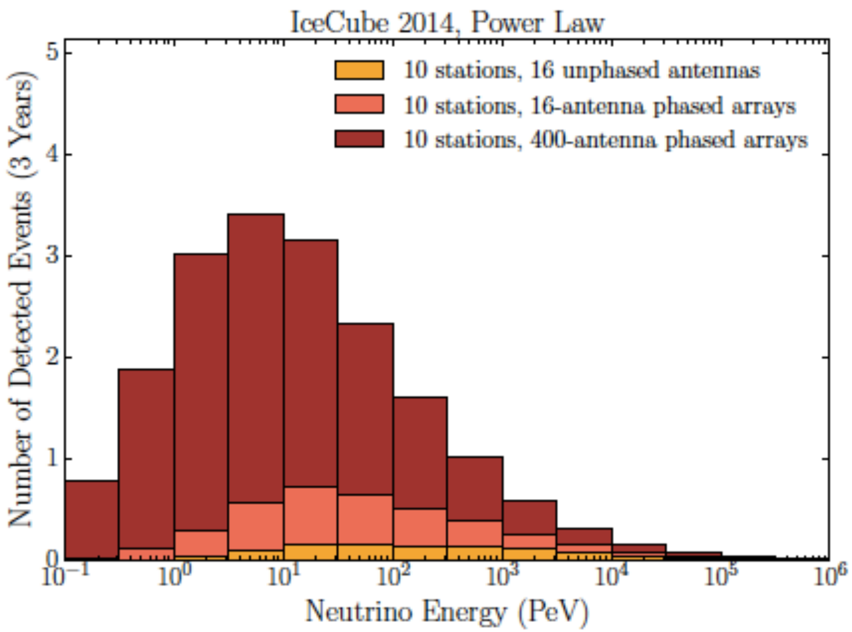


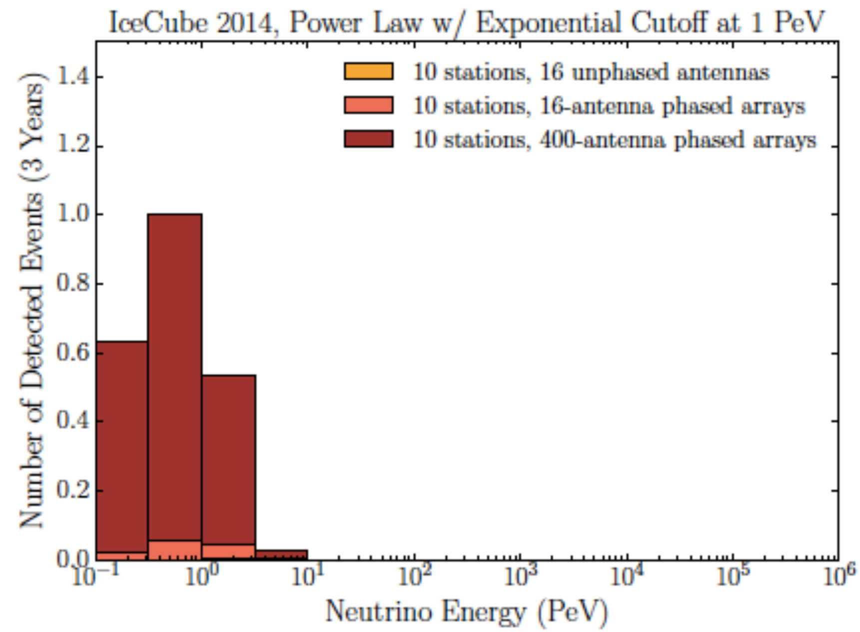
ARA Advanced Front End System (ARAFE)

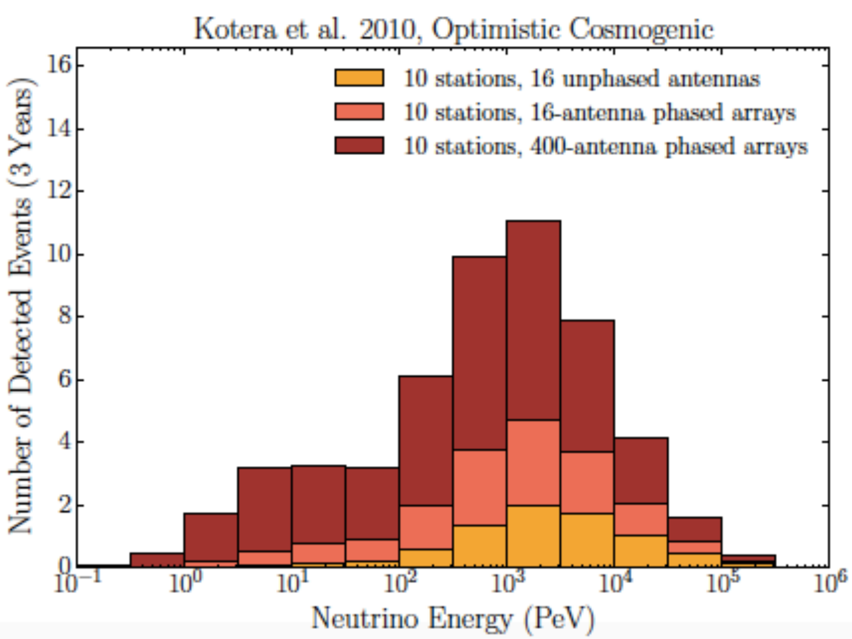
- Old stations have static, physically fragile, and expensive (~$2k/chan) signal conditioning
- Gain is unmatched between channels and subject to seasonal variations
- So, we switched to micro-controlled 0.25 dB digital step attenuators
  - Better use of ARA dynamic range, easier analyses
  - *In-situ* seasonal temperature corrections ⟶ more stable DAQ






IceCube 2014, Power Law
10 stations, 16 unphased antennas
10 stations, 16-antenna phased arrays
10 stations, 400-antenna phased arrays
Number of Detected Events (3 Years)
Neutrino Energy (PeV)


IceCube 2014, Power Law w/ Exponential Cutoff at 1 PeV
10 stations, 16 unphased antennas
10 stations, 16-antenna phased arrays
10 stations, 400-antenna phased arrays
Number of Detected Events (3 Years)
Neutrino Energy (PeV)


Kotera et al. 2010, Optimistic Cosmogenic
10 stations, 16 unphased antennas
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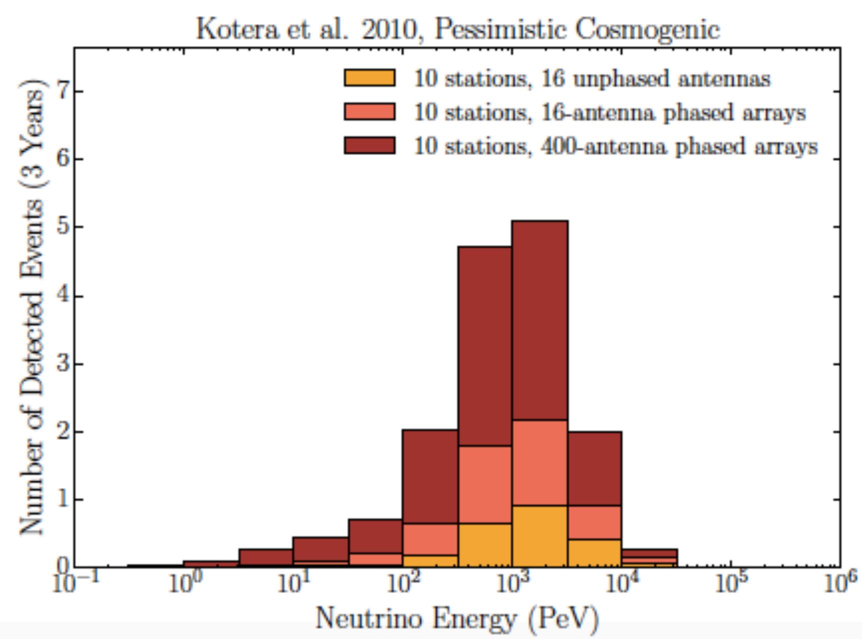
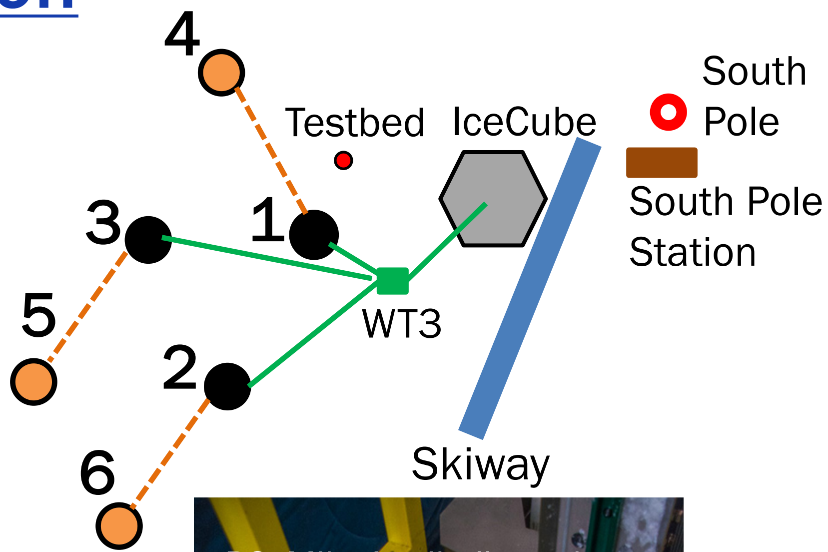
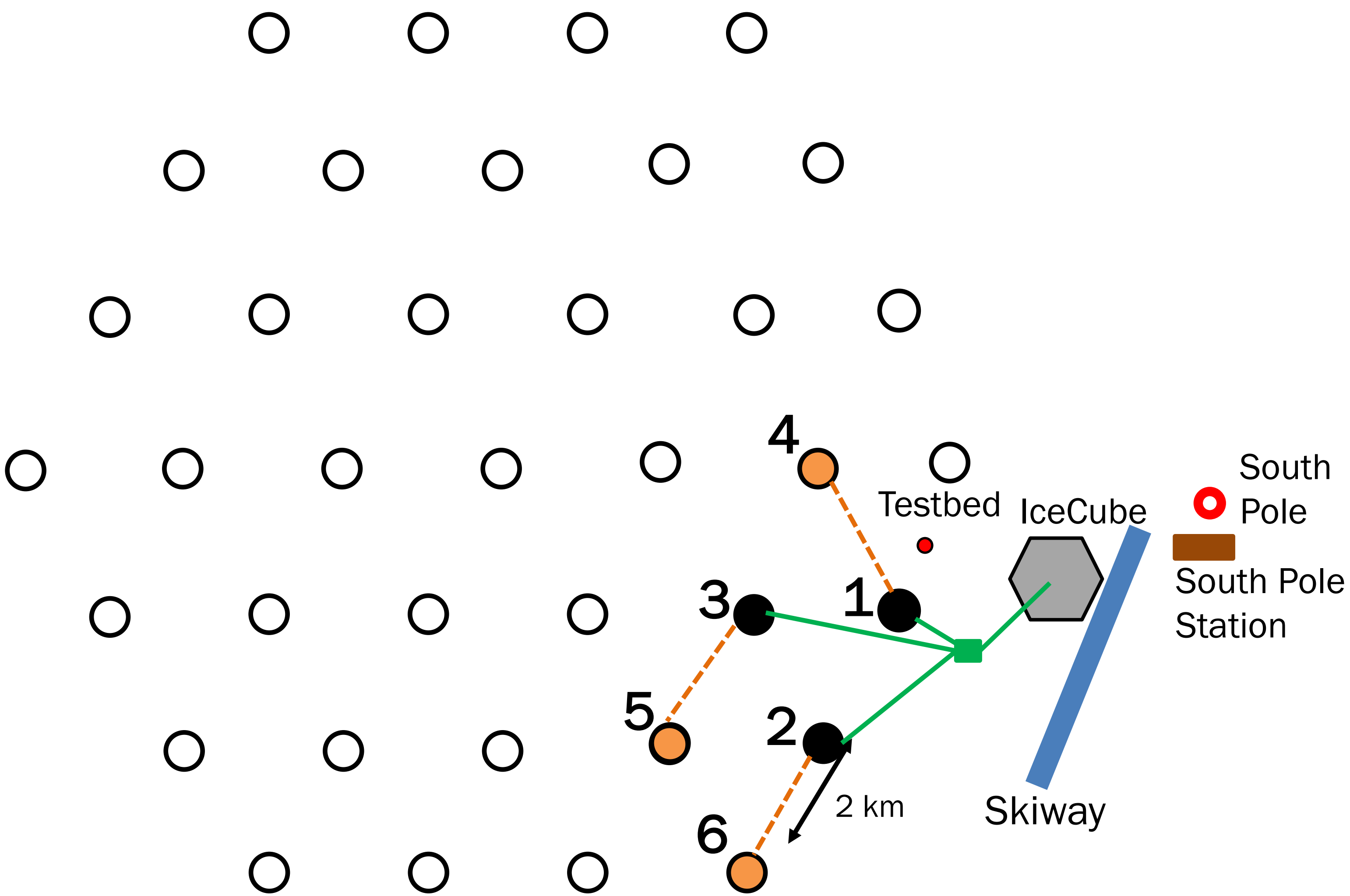
Number of Detected Events (3 Years)
Neutrino Energy (PeV)

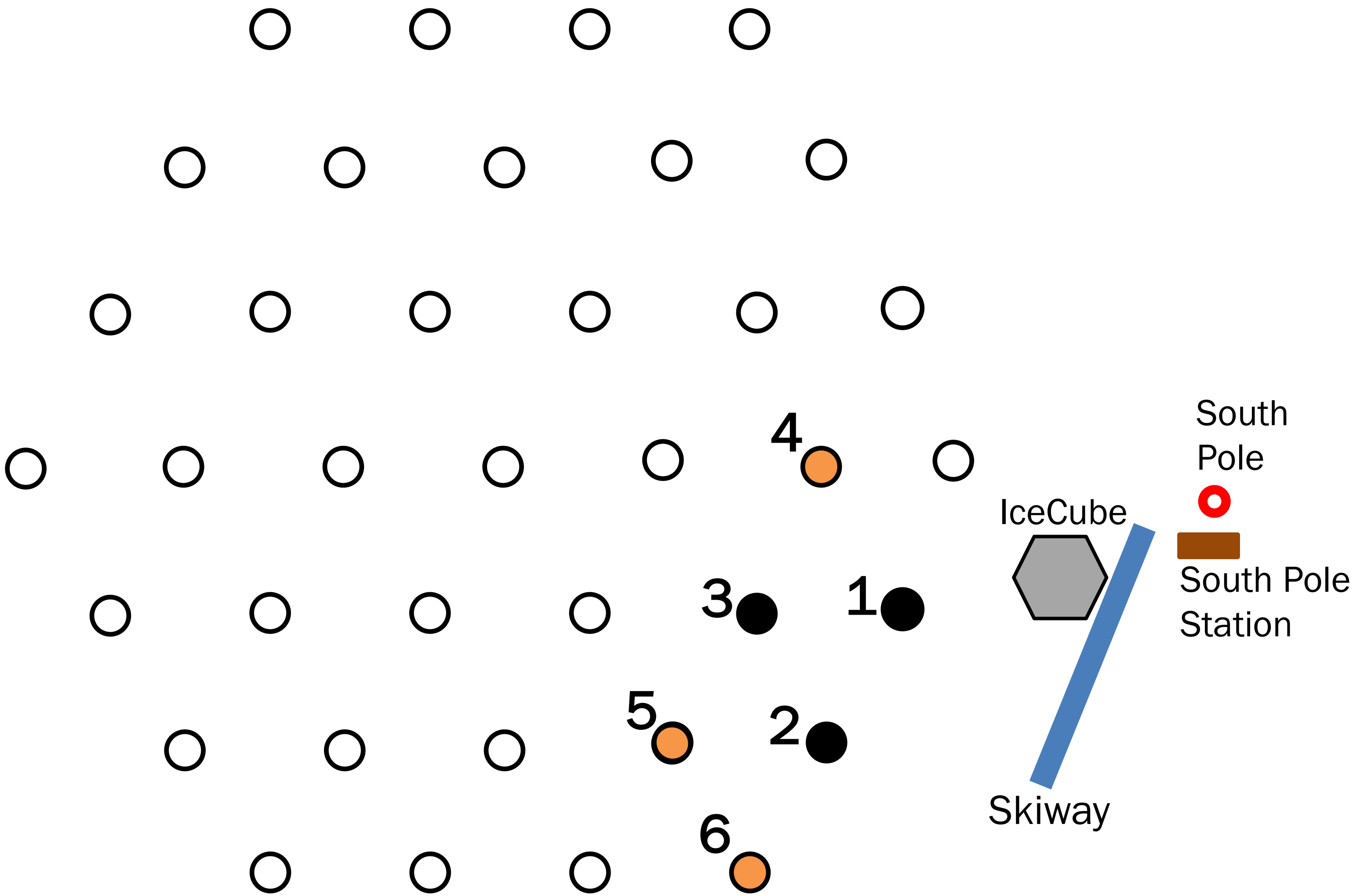

Kotera et al. 2010, Pessimistic Cosmogenic
10 stations, 16 unphased antennas
10 stations, 16-antenna phased arrays
10 stations, 400-antenna phased arrays
Number of Detected Events (3 Years)
Neutrino Energy (PeV)

Calibration

- Deep (1751m), South Pole Ice Core hole drilled in Jan 2016 near WT3
- We will deploy a pulser to ~800m, raise it with cm depth precision, while firing RF at the ARA stations
- Should give us details about radio propagation in the ice around the stations
- See C. Pfendner's talk on simulation work which would benefit from this data.




4
Testbed
IceCube
South
Pole
South Pole
Station
3
1
5
2
2 km
6
Skiway


4
3
1
5
2
6
IceCube
South
Pole
South Pole
Station
Skiway