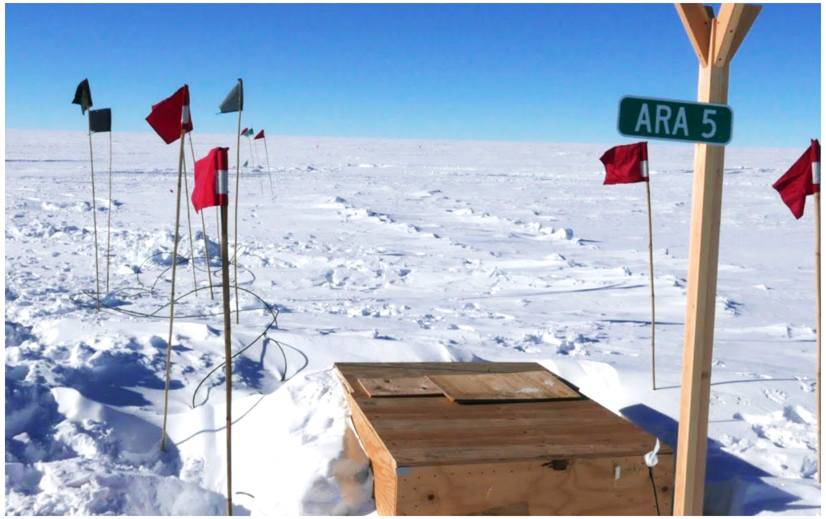
Latest Results from the Askaryan Radio Array

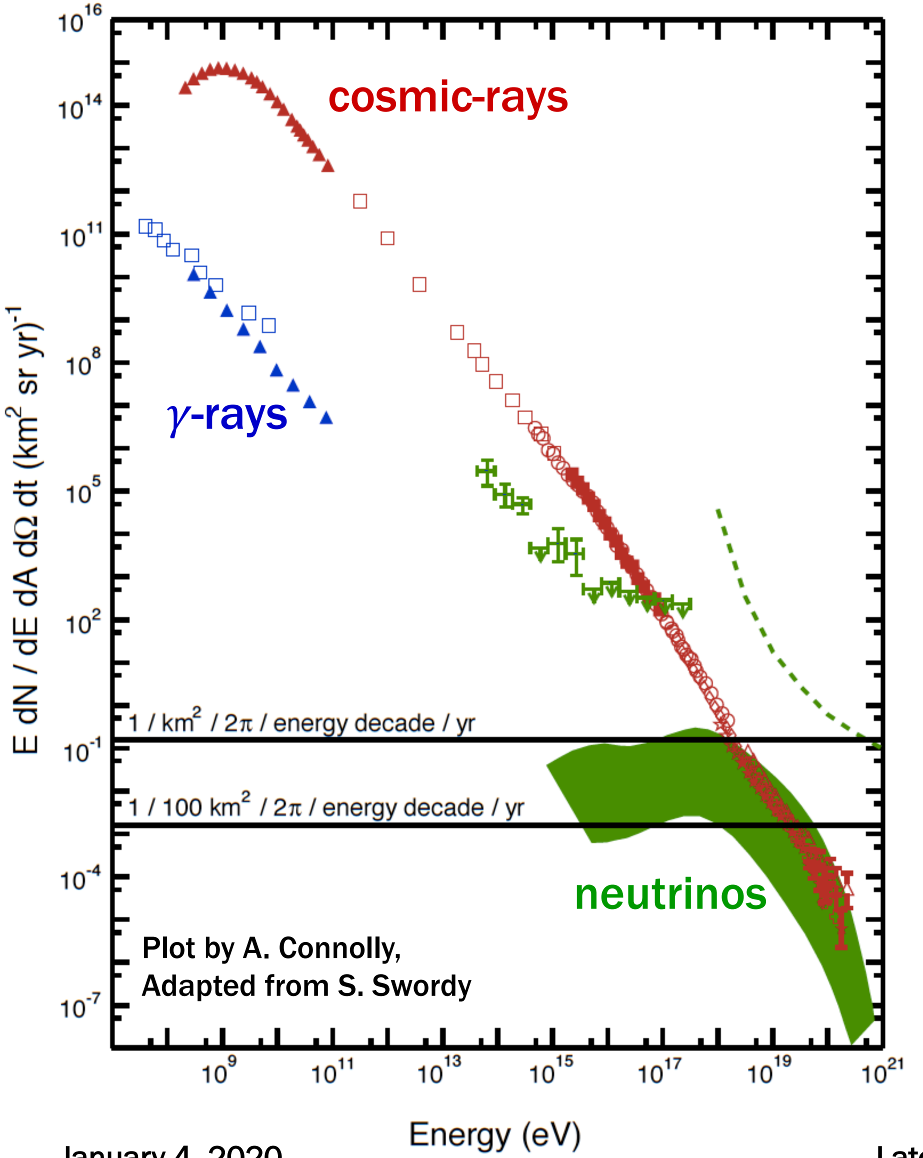


Brian Clark for the ARA Collaboration

Michigan State University
Department of Physics and Astronomy

January 4, 2020
AAPF Symposium @ AAS 235—Honolulu, HI

Why Study Neutrinos?



Unique Messengers to distant (>100Mpc) universe

- Cosmic rays >$10^{19.5}$ eV attenuated, e.g. the GZK process

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

→ Screens extragalactic (>100 MPc) sources

- γ-rays annihilate w/ CMB @ ~1 TeV

Observational Advantages

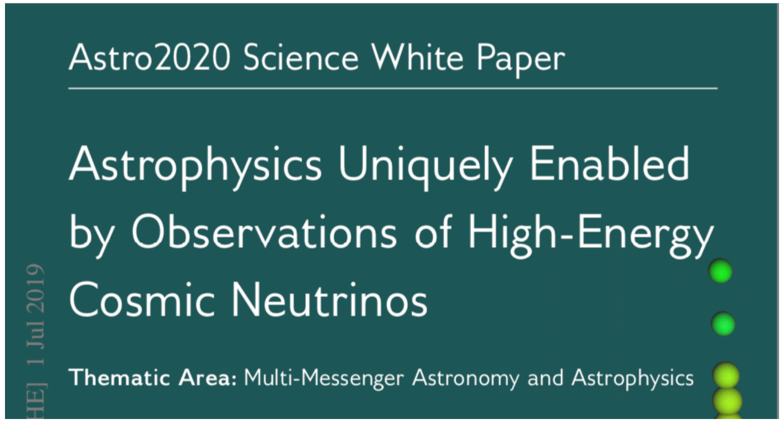
- Chargeless = point back to source
- Weakly interacting = no observation horizon

Astronνmy : Neutrinos in a Multimessenger World

arXiv 1903.04334

Complimentary Probes

- Cosmic rays: pions from GZK process decay into neutrinos
- Cosmic ray accelerators
  - Gamma Ray Bursts (GRBs)—leptonic vs hadronic models
  - Active Galactic Nuclei (AGN)

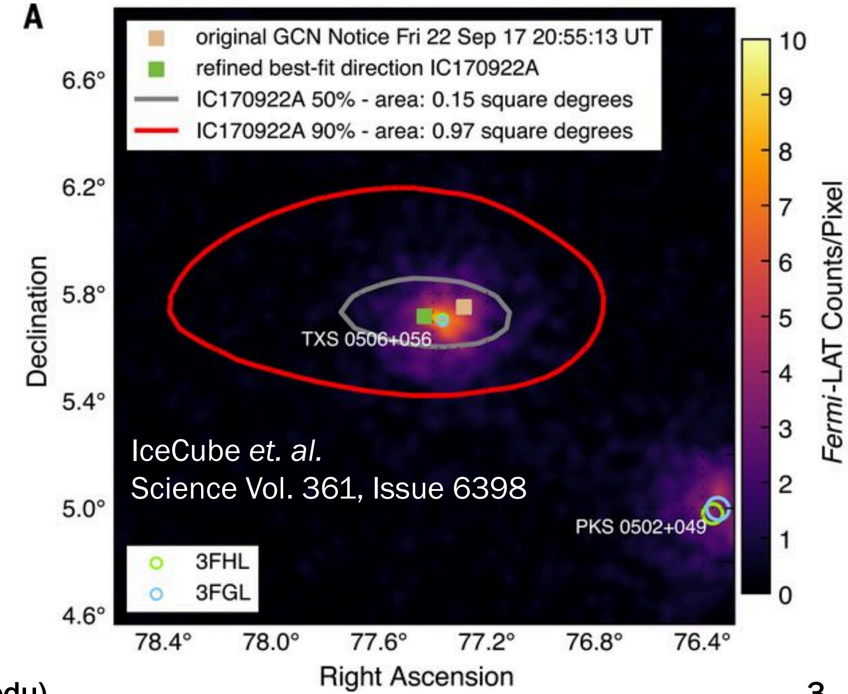

Astro2020 Science White Paper

Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos

Thematic Area: Multi-Messenger Astronomy and Astrophysics

Exciting Start!

- 2017—Binary Neutron Star (GW + Light)
- 2018—Flaring Blazar (Neutrino + Light)
- 2020—Neutrino + GW??

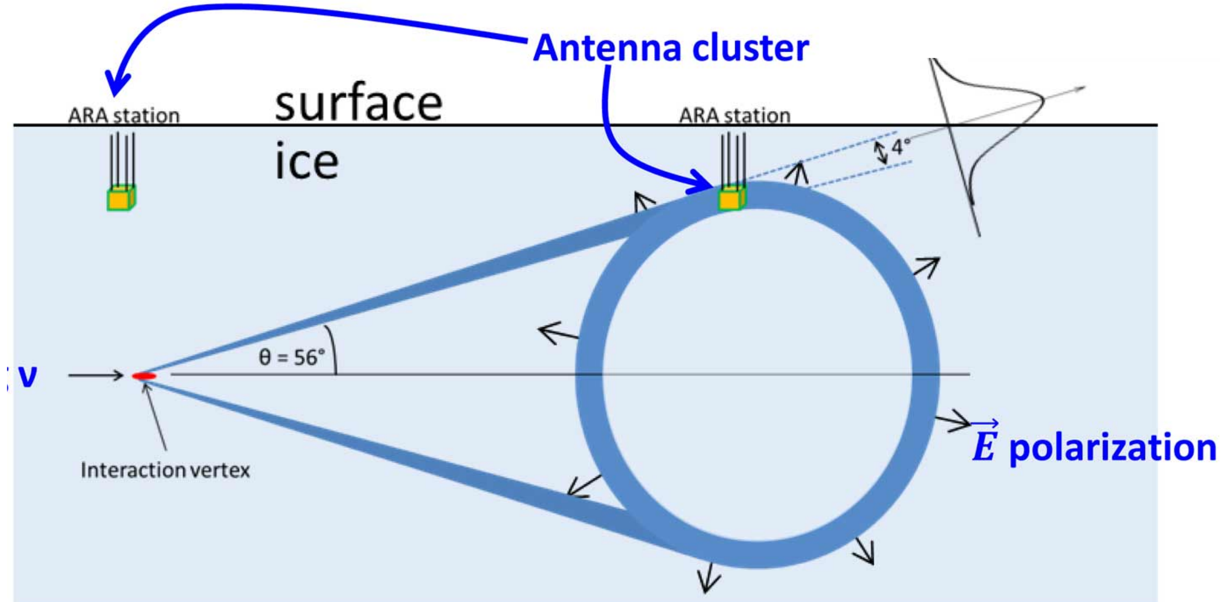


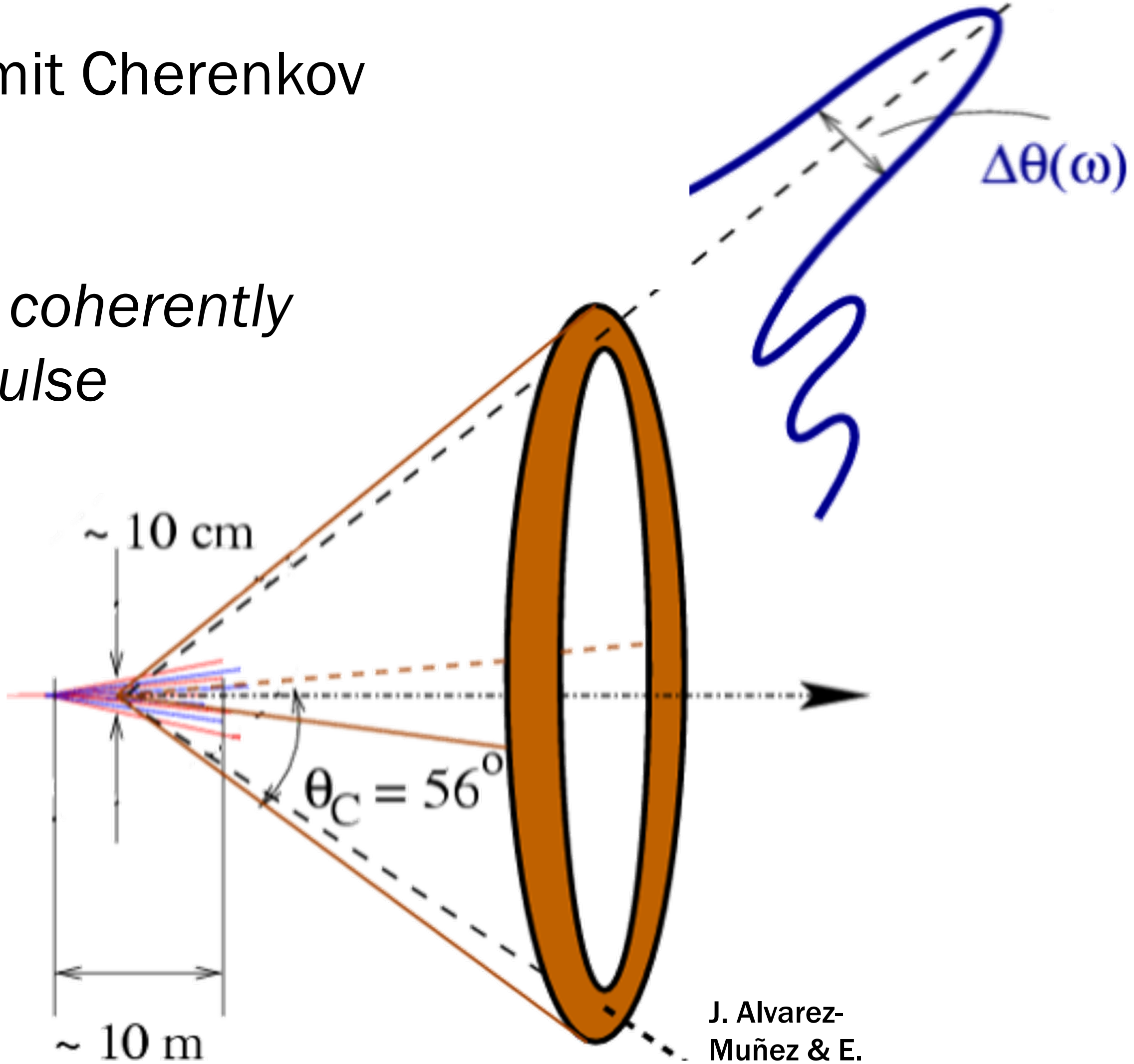
Fast, all-sky, broadband follow-up is very important!
(*Fermi*, *Swift*, ZTF, ASAS-SN, etc.)

The (Radio) Cherenkov Effect

- Relativistic neutrino-induced particle showers emit Cherenkov radiation in media

- Wavelengths the size of the bunch (~10cm) add *coherently* and form broadband (200 MHz-1.2GHz) radio *pulse*

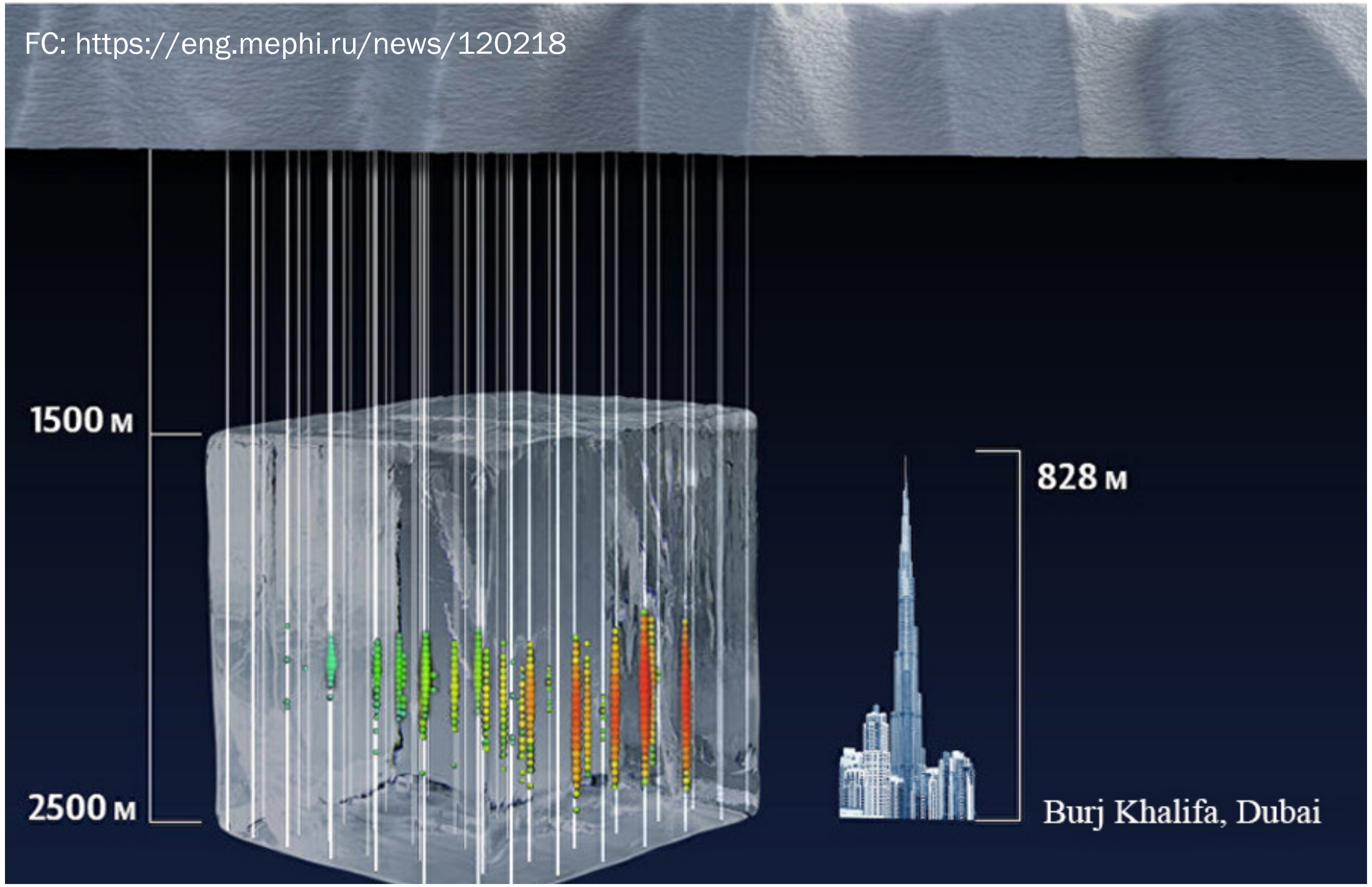




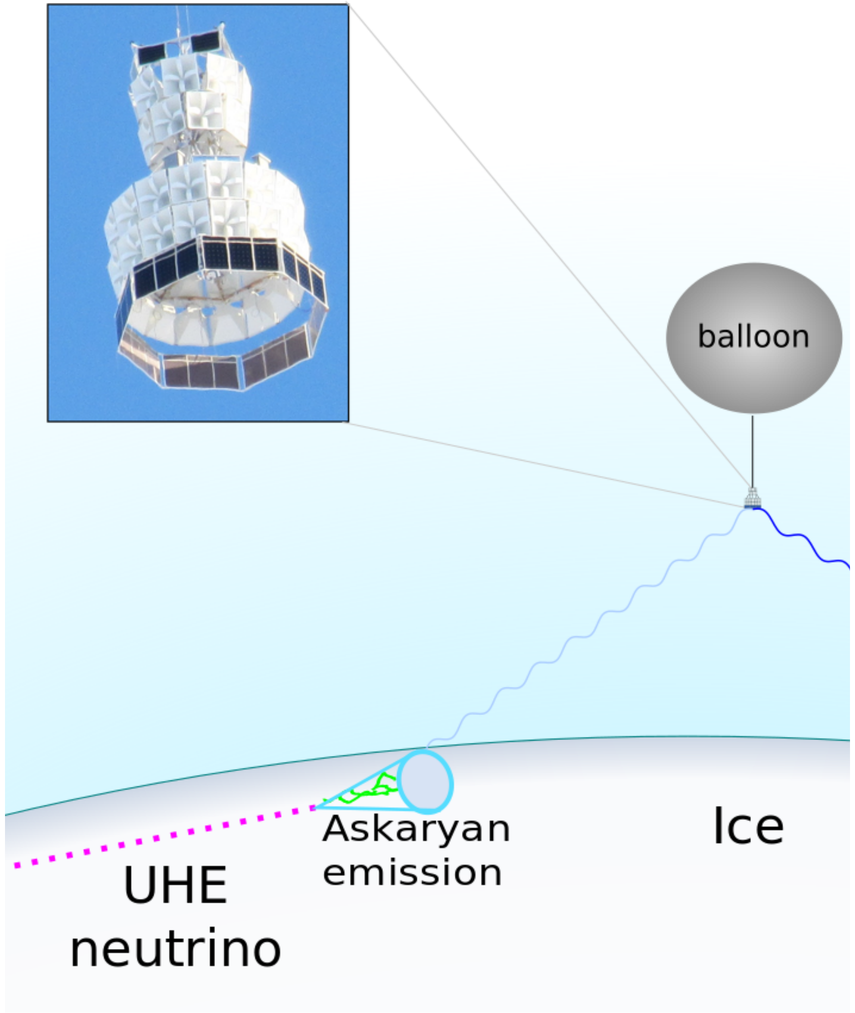
J. Alvarez-Muñez & E. Zas (2005)

A Question of Scale

Low fluxes (~10/km^3/yr) + low cross-sections (L_{int}~300km in rock)
→ need >1-100 km^3 of target

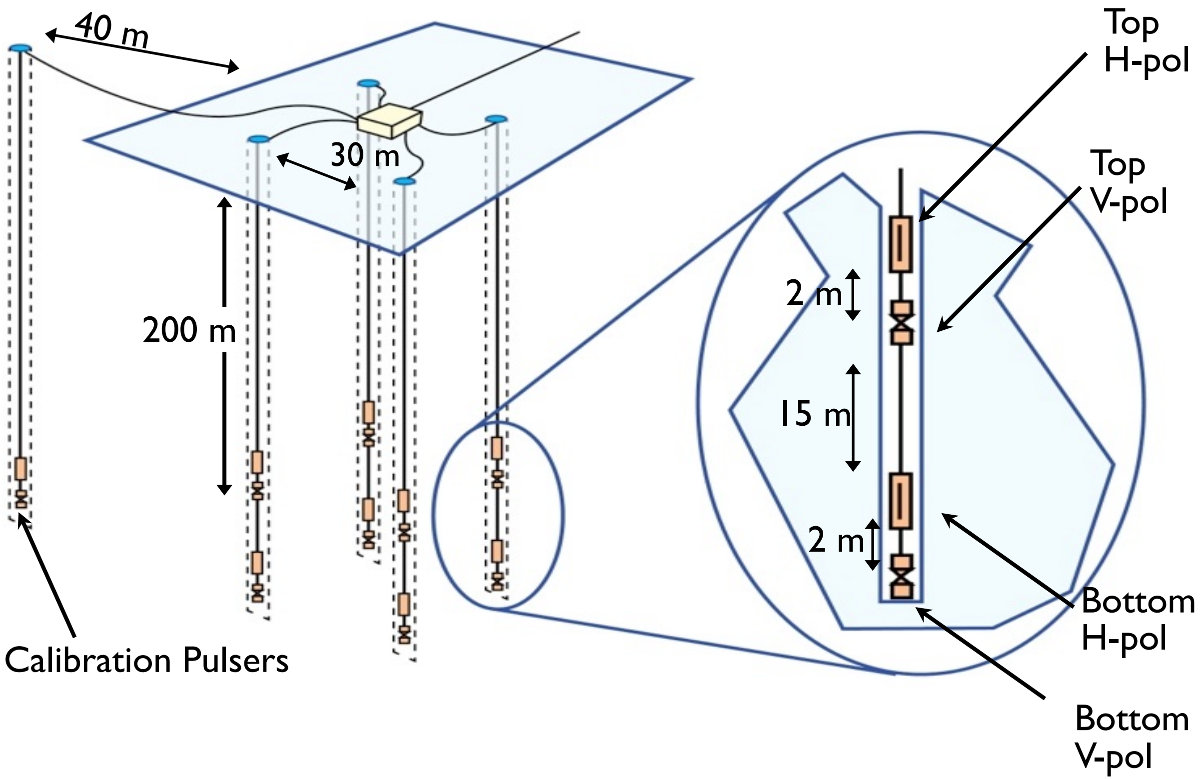


A Question of Scale

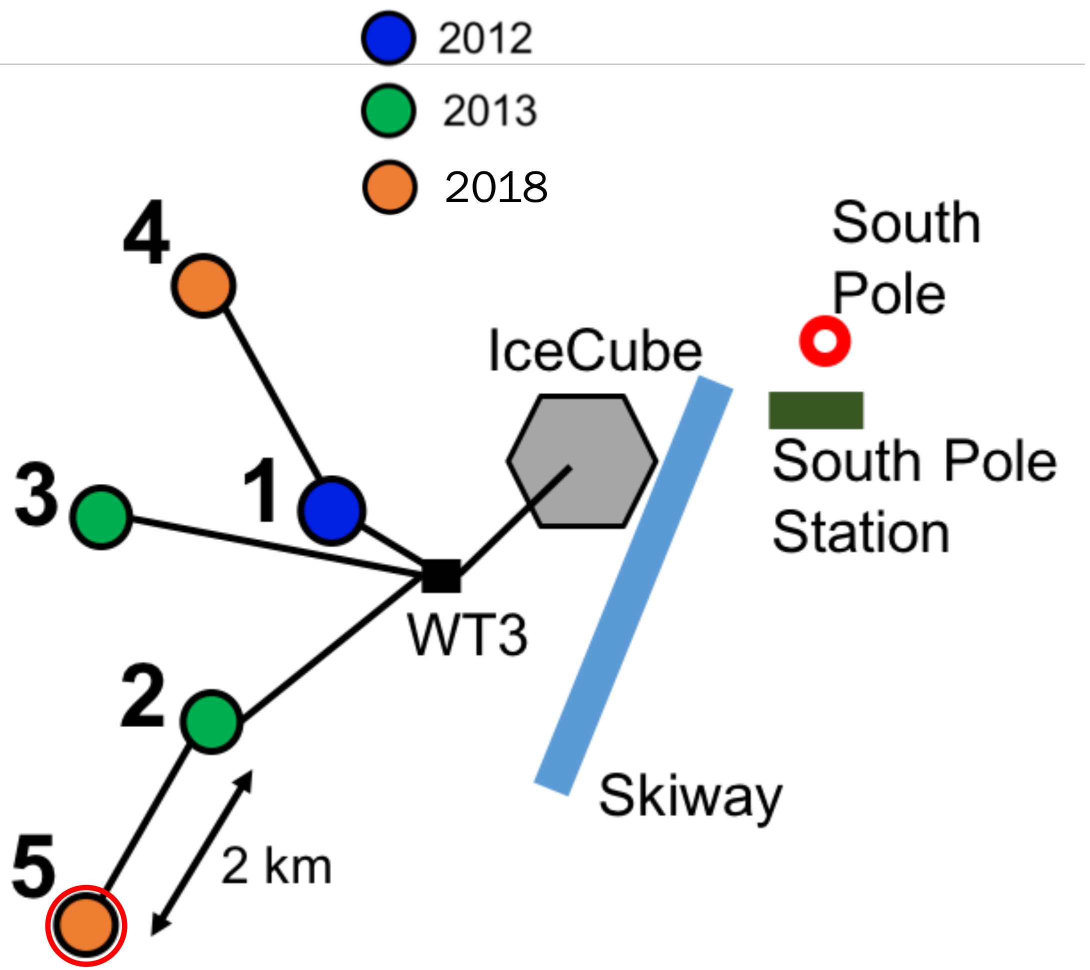


Askaryan Radio Array

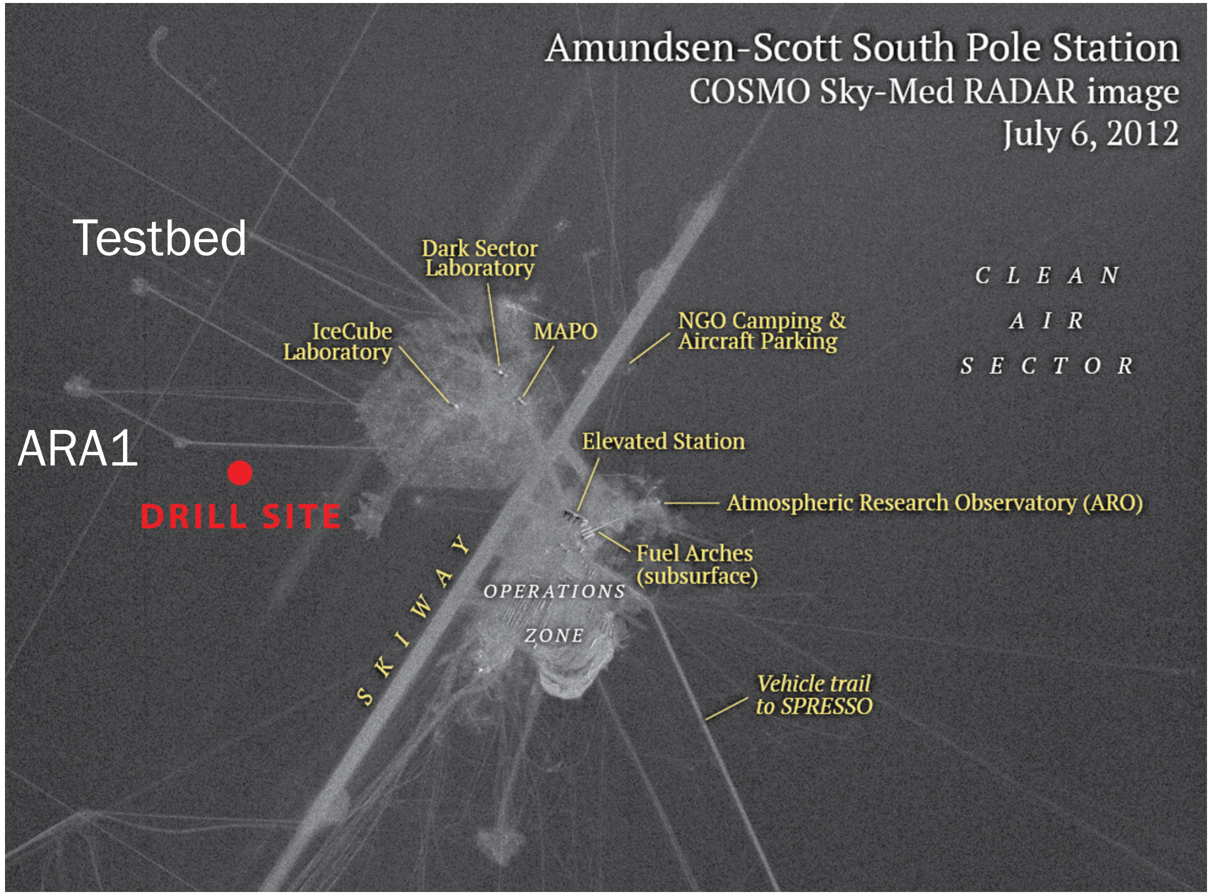
- Cubical lattice (”station”) at 200m depth; 5 stations deployed
- 8 VPol & 8 HPol antennas deployed in 200m “boreholes”
- 150-850 MHz bandwidth



ARA Instrument Status



A5 w/ phased array enhanced triggering, see arXiv 1809.04573



The ARA Collaboration

Figure credit: C. Pfendner

USA

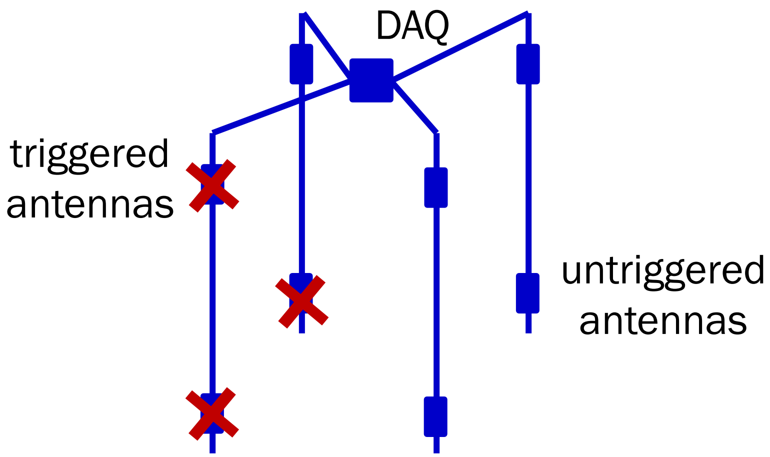
Cal Poly
Michigan State University
The Ohio State University
Otterbein University
University of Chicago
University of Delaware
University of Kansas
University of Maryland
University of Nebraska
University of Wisconsin-Madison
Whittier College

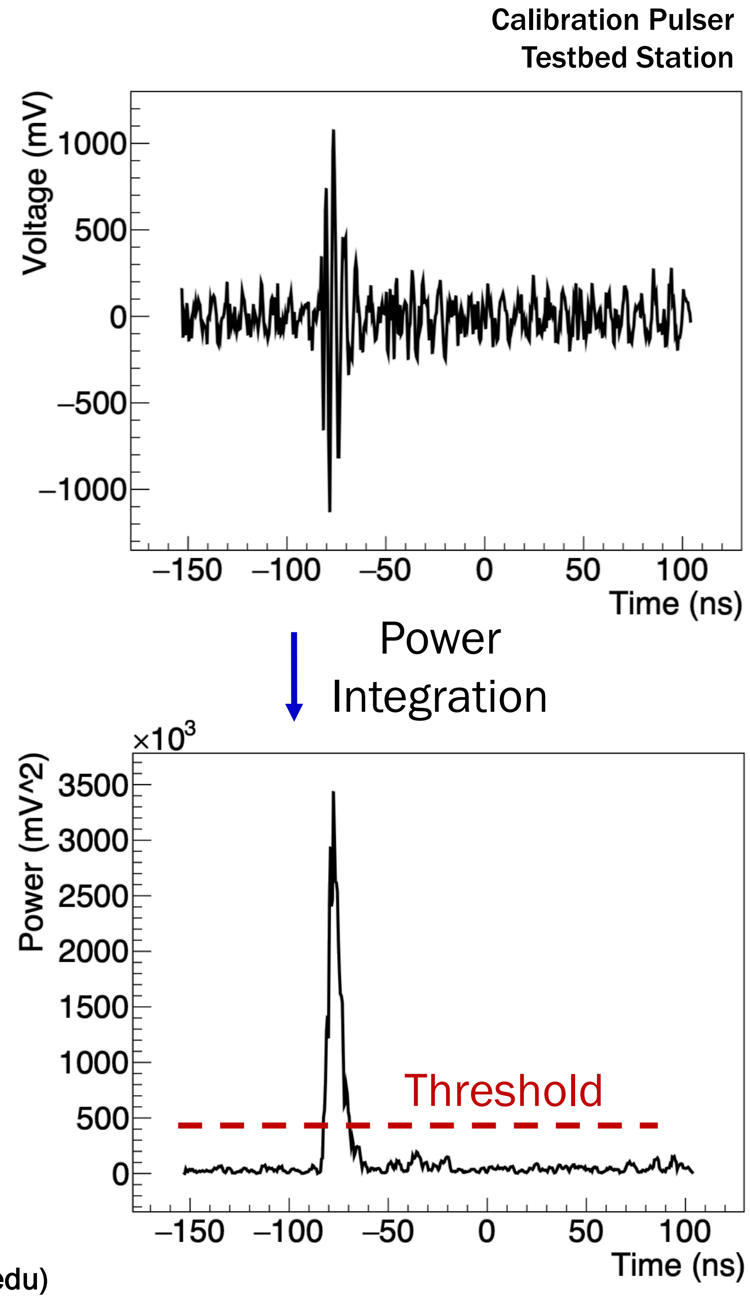
International Collaborators

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

Triggering and Data

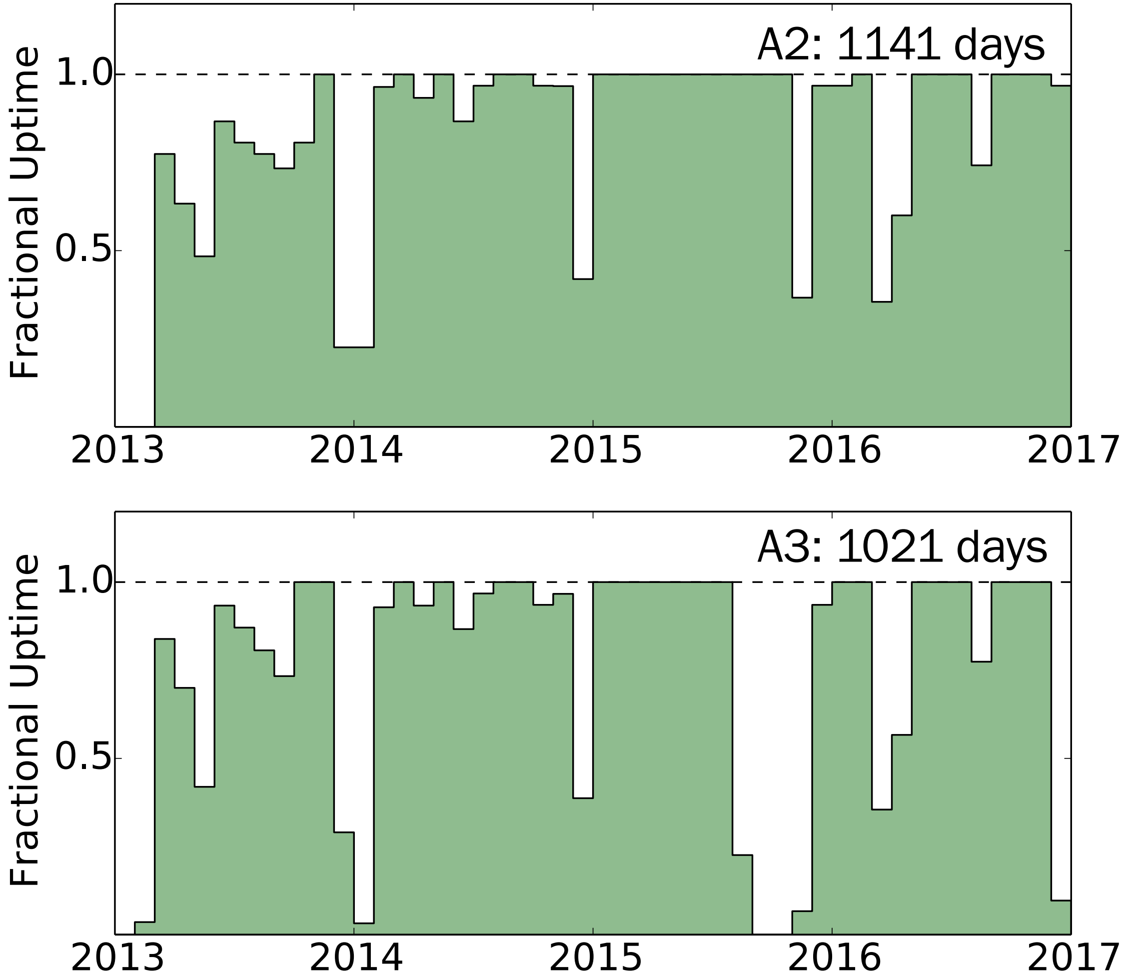
- *Power:* 10ns integrated power > 5 × thermal noise
- *Coincidence*: trigger in 3/8 antennas of same polarization in ~170 ns
- Thresholds maintain a global ~7 Hz/station trigger rate → 10^8 evts/year/station



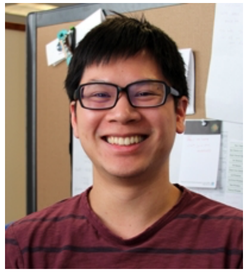


Diffuse Neutrino Search

- A2 and A3 collecting data since Feb 2013 —10 months of data published previously
- Expansion to the 2013-2016 data set recently on arXiv 1912.00987 -- nearly 5x as much data!
- Search performed "blind" in 2 parallel analyses
  - 10% of the data used as "burn" sample
  - 90% kept blind, used to search for neutrinos



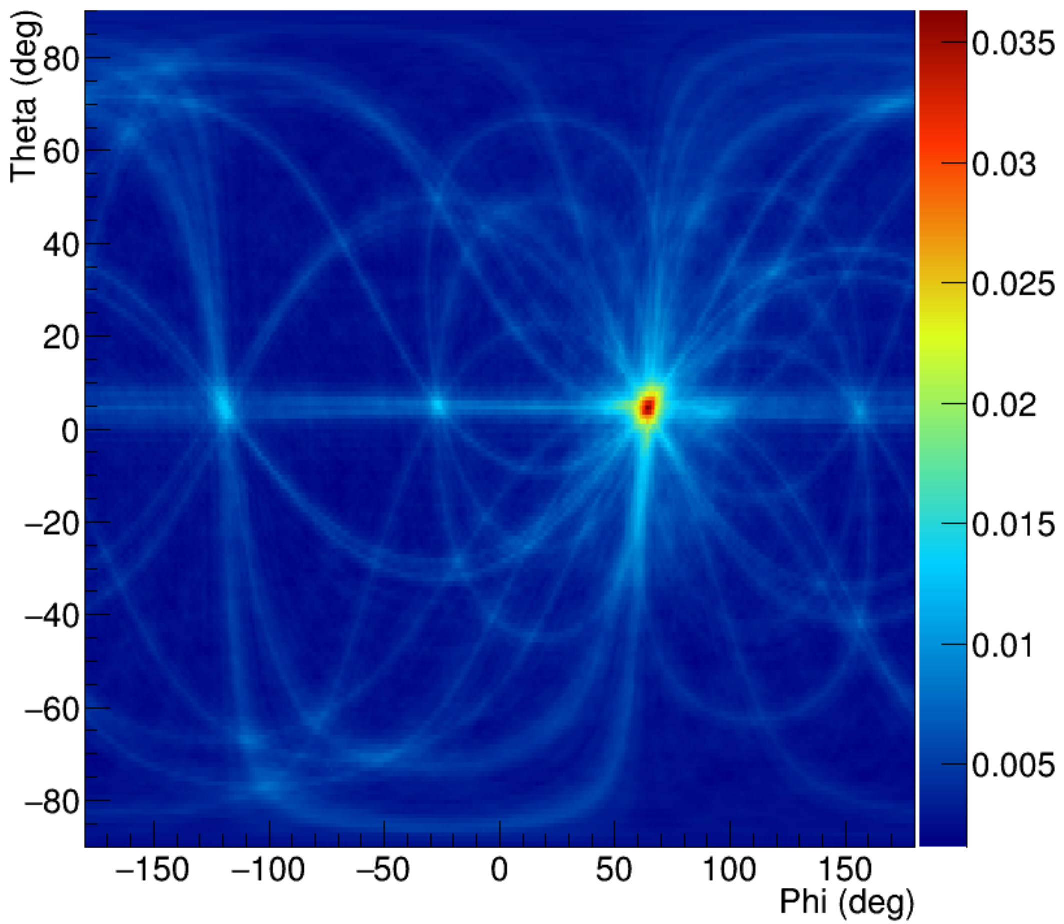
Special thanks to my co-analysts Ming-Yuan Lu and Jorge Torres (>40TB raw data, 580M events)



Analysis: Reconstruction

- Perform interferometric reconstruction
  - Accounts for n(z)
  - Direct and refracted ray solutions
- Direction corresponding to peak in the map is interpreted as the source direction
- Make geometric cuts to remove:
  - Events at and above the surface
  - Events in the direction of the local calibration pulser

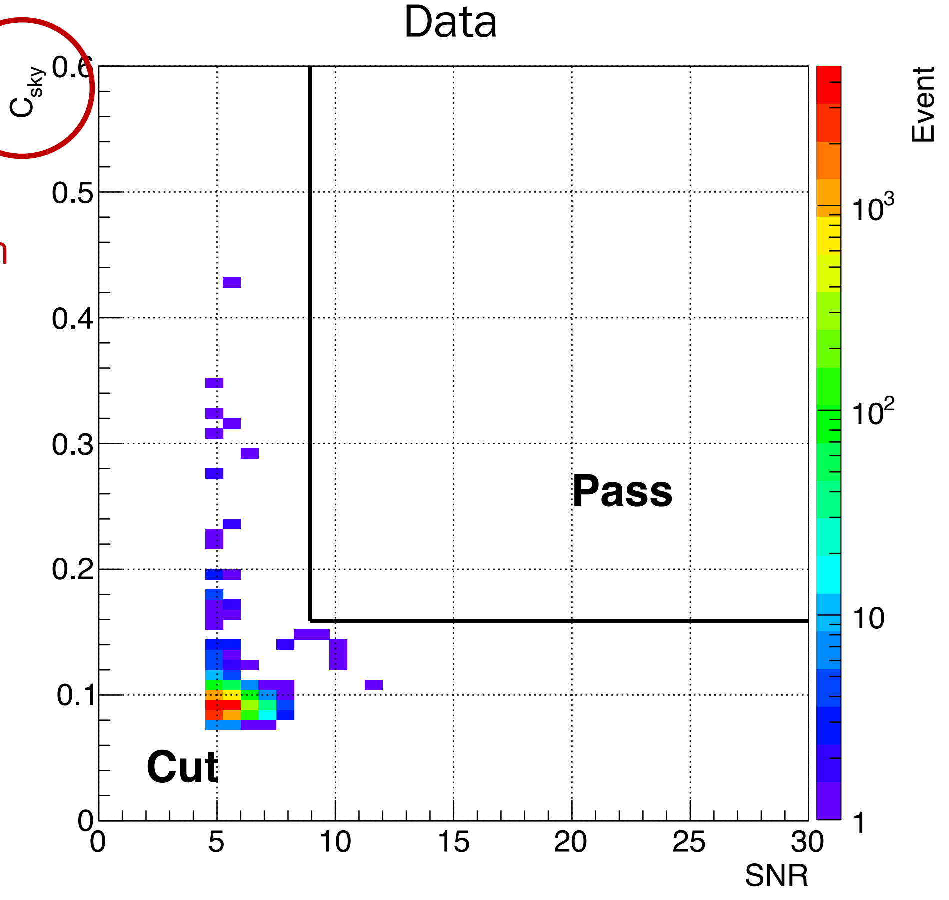
Example Calibration Event

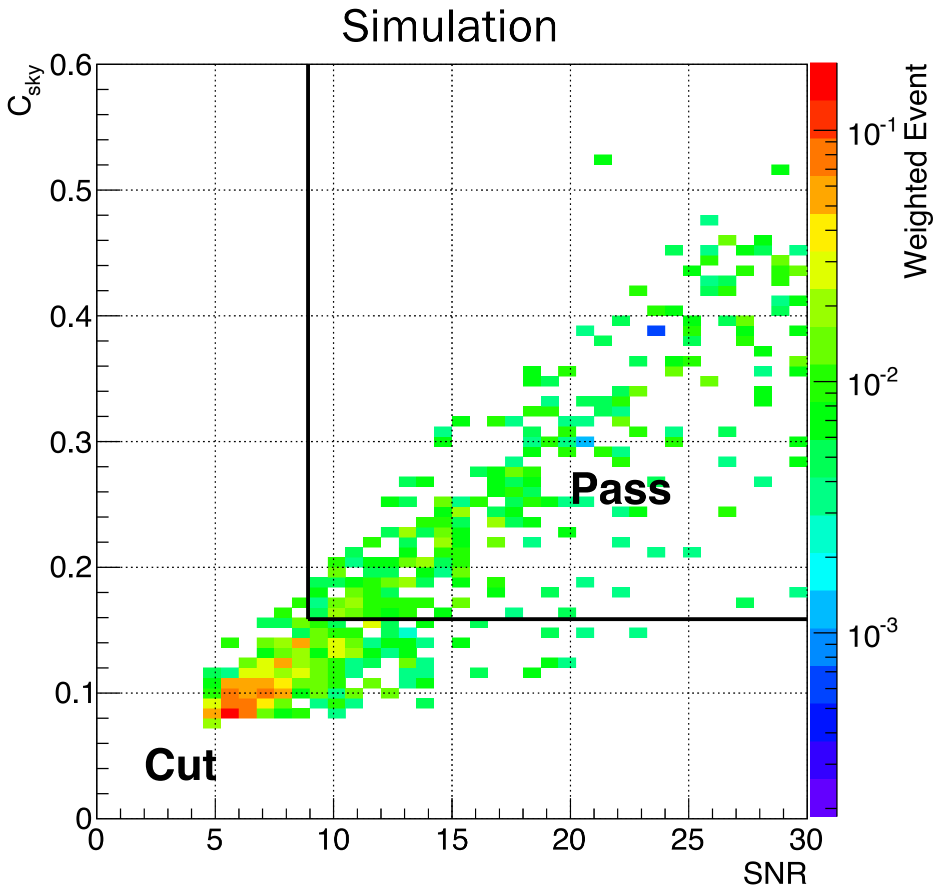


Separating Signal and Background

- Linear discriminant separates backgrounds from neutrinos
- Optimize cut for best limit (~0.1 passing events/year)

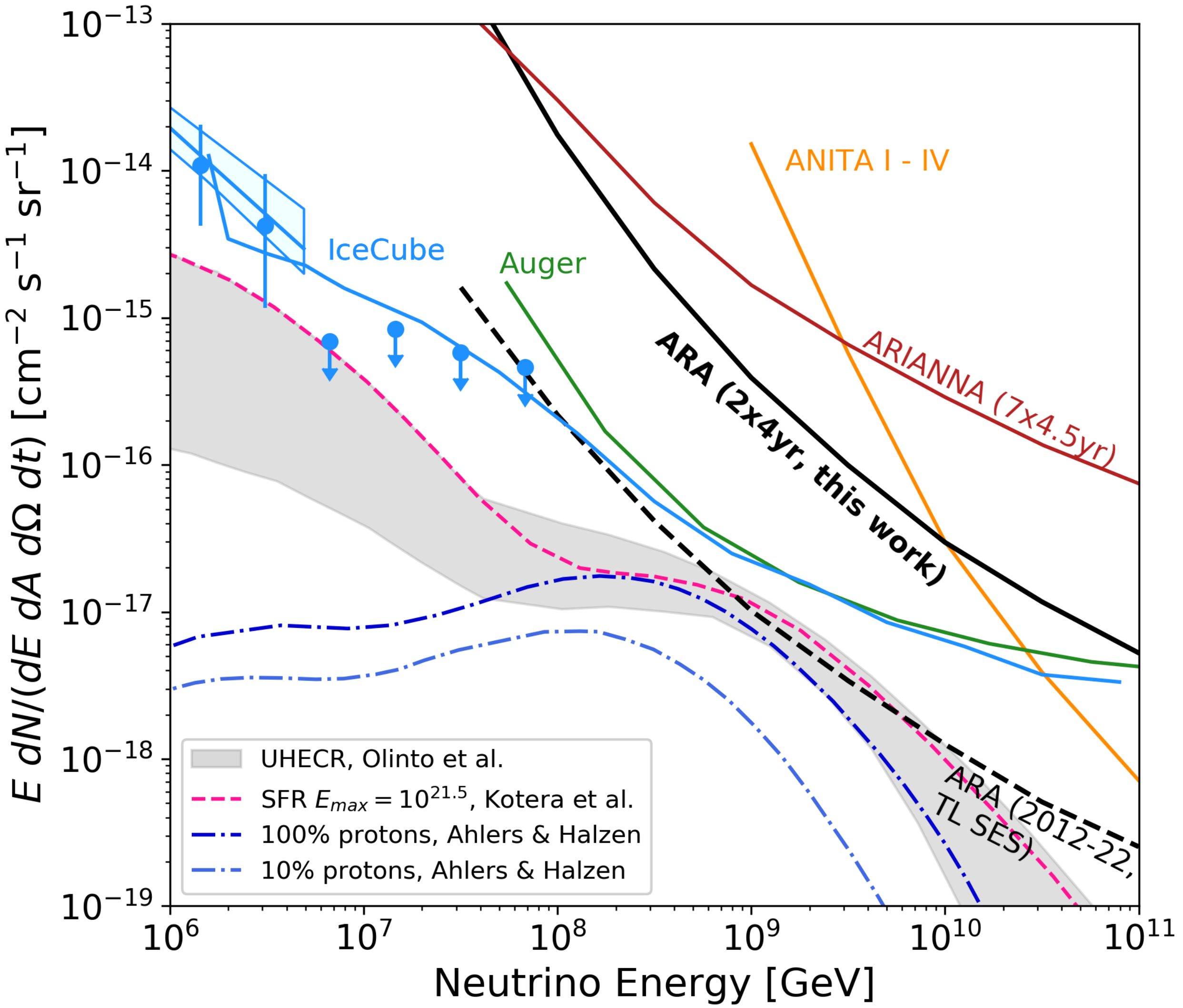
“Reconstruction quality” parameter





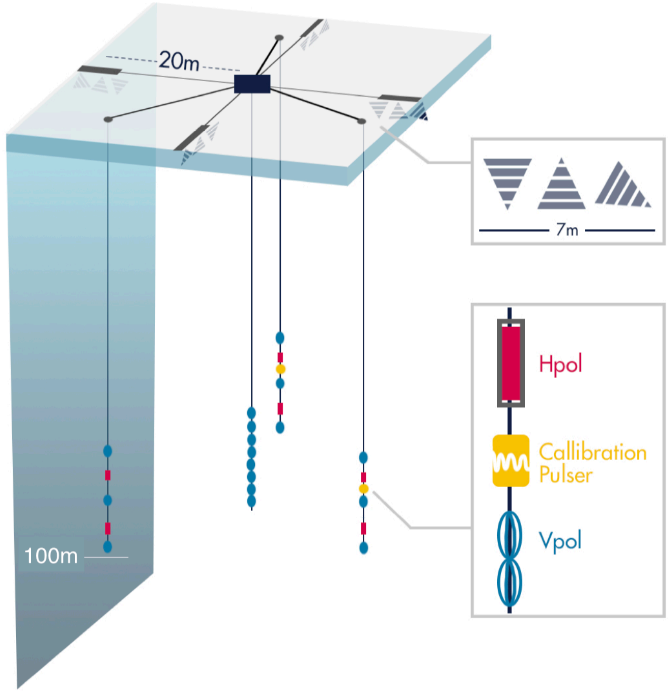
Analysis: Results

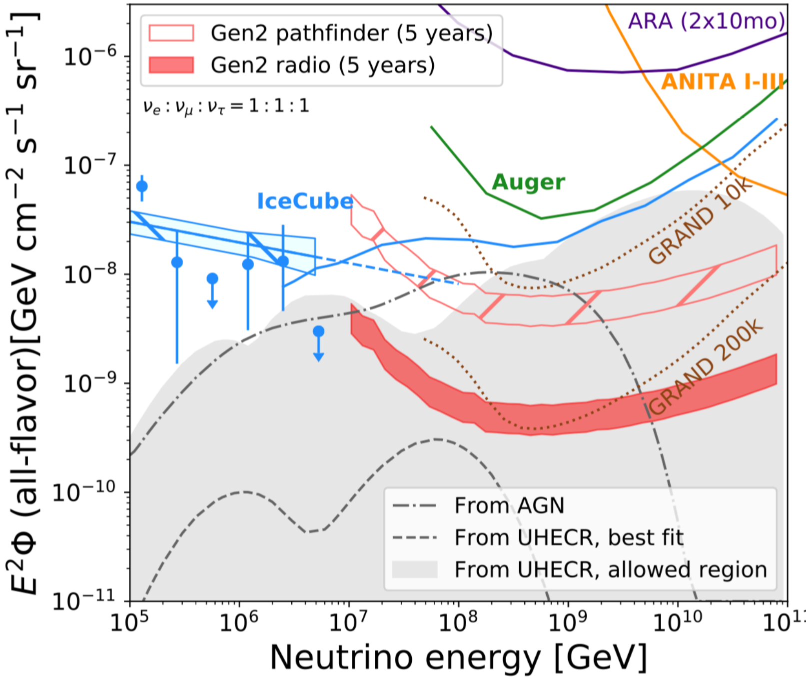
- Observe no statistically significant excess on background of 10^{-2}
- Result is best limit set by in-ice radio neutrino detector, and uses *only half the data on archive already*
- By 2022, ARA will have world-leading sensitivity and carve out exciting new parameter space

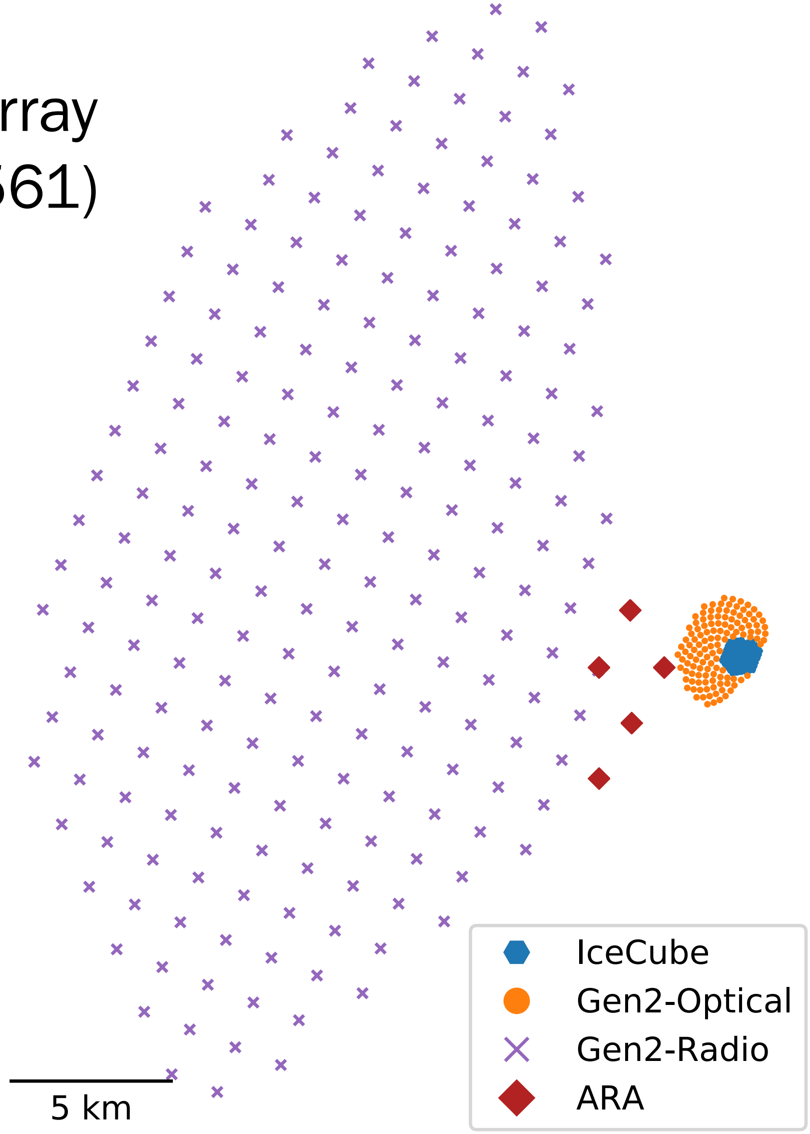


The Future of Neutrino Astronomy at South Pole

IceCube-Gen2 is planned, including a radio array (see Astro 2020 white paper, arXiv 1911.02561)







Summary

1. Neutrinos are important and complimentary messengers to the cosmos

2. ARA 2x4yr analysis is best limit by in-ice radio detector, using only ½ of available data; ARA will be world-leading by 2022

3. The future is bright for neutrino astronomy, and new instruments are coming in the next decade (Gen2, etc.)

Research generously supported by:

- NSF AAPF Award 1903885
- NSF GRFP Award DGE-1343012
- NSF Awards 1255557, 1806923, 1404212

Back-up Slides

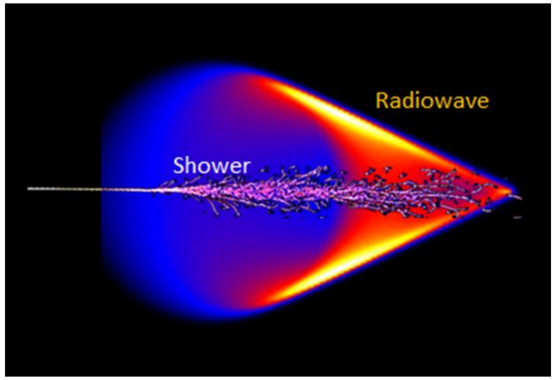
Neutrino Interactions

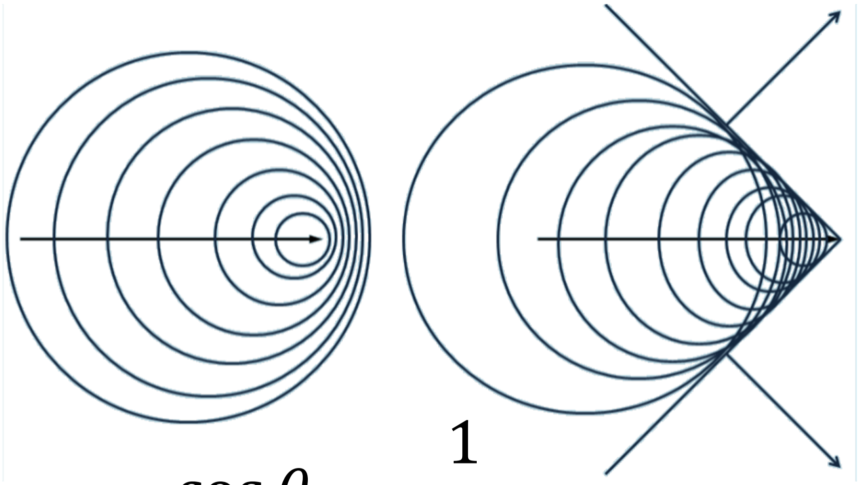
- Two varieties of interactions: Charged current (CC) and Neutral Current (NC)

CC: $\nu_\ell + N \rightarrow \ell + X$
$\ell \rightarrow EM\ Shower$

NC: $\nu + N \rightarrow \nu + X$
$X \rightarrow Hadronic\ Shower$

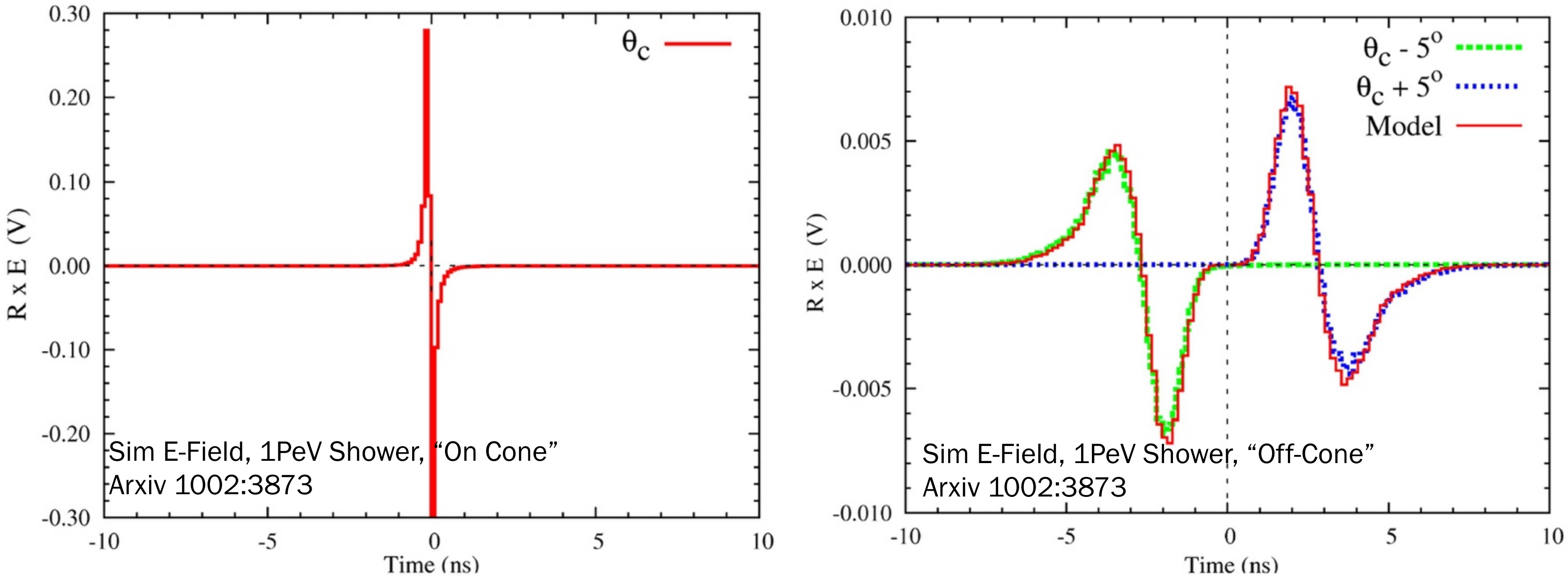
- Showers are ultra-relativistic ($\beta \approx 1$) ⟶ emit Cherenkov radiation in dense media
- Intensity is greatest at Cherenkov angle θ_C
- Two varieties of interest: optical and radio





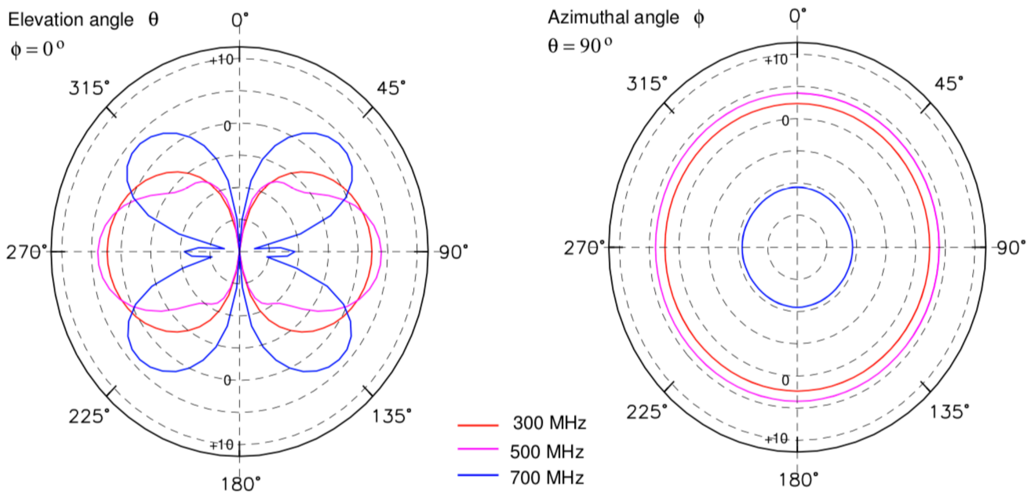
$$\cos\theta_C = \frac{1}{n\beta}$$

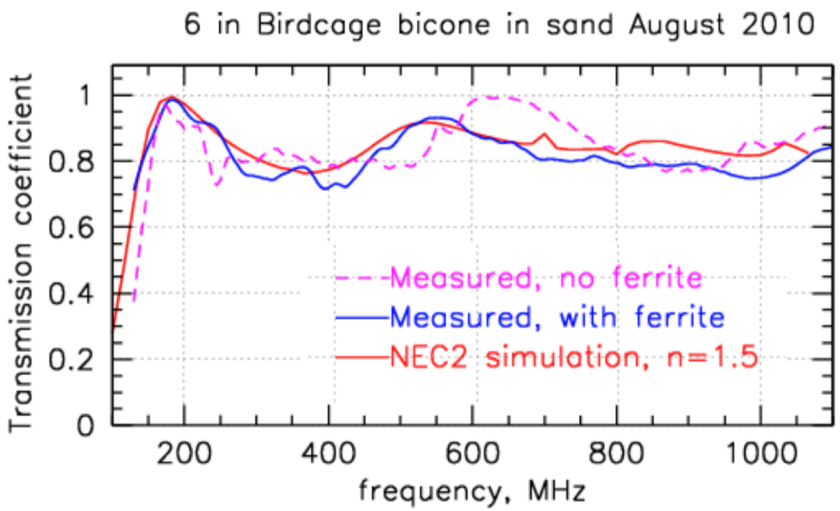
Askaryan Pulse Shape and Dependencies

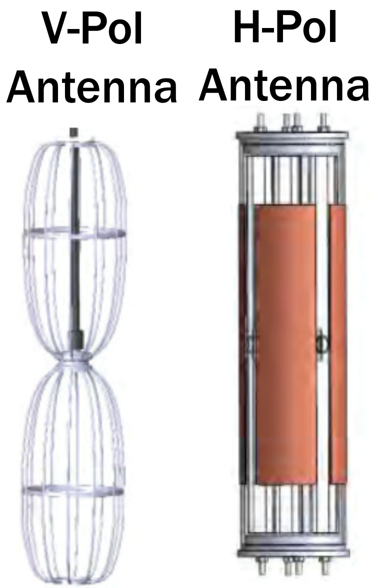


$$V(f) \propto \frac{yE_\nu}{R} \times \frac{f}{1150\text{MHz}} \times \exp\left[-\frac{1}{2}\left(\frac{f}{1\ \text{GHz}} \times \frac{\Omega}{2.2^\circ}\right)^2\right]$$

ARA Antennas

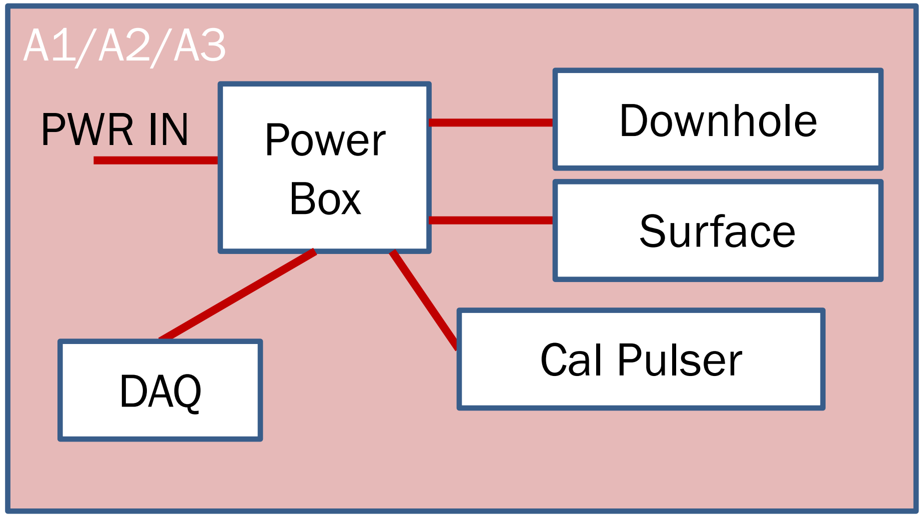


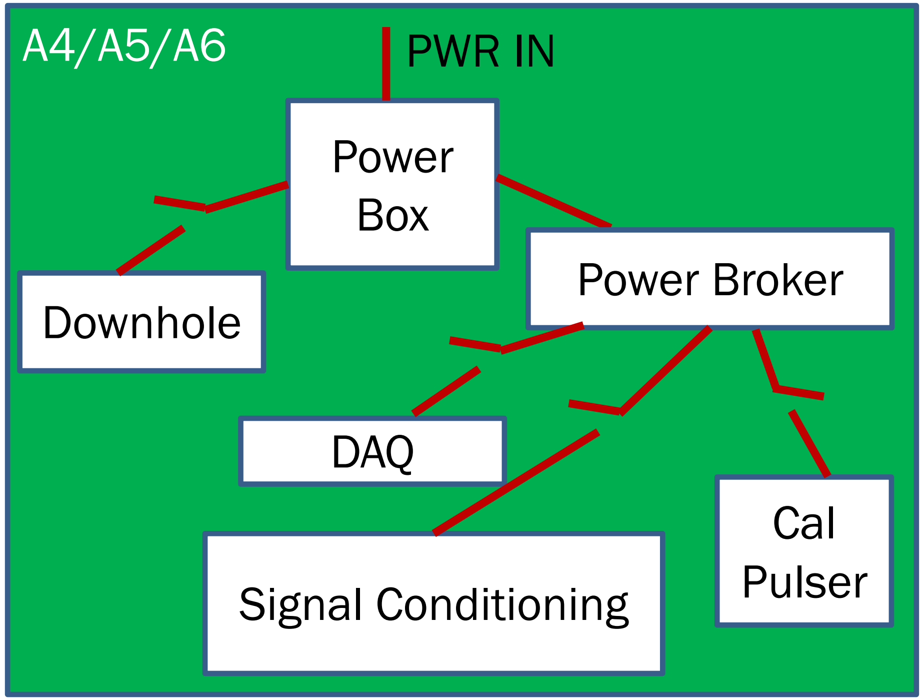




New Power Distribution

- Introduced power broker: the ARA Smart Power system (ASPS)
- Old power systems had no granularity
  - A short anywhere compromised the entire station
  - Power cycling subsystems required power cycling whole station—not ideal
- Granularity is powerful—since deployment:
  - No IceCube winter-over intervention in ARA power systems
  - Only 5 station-wide "hard" restarts

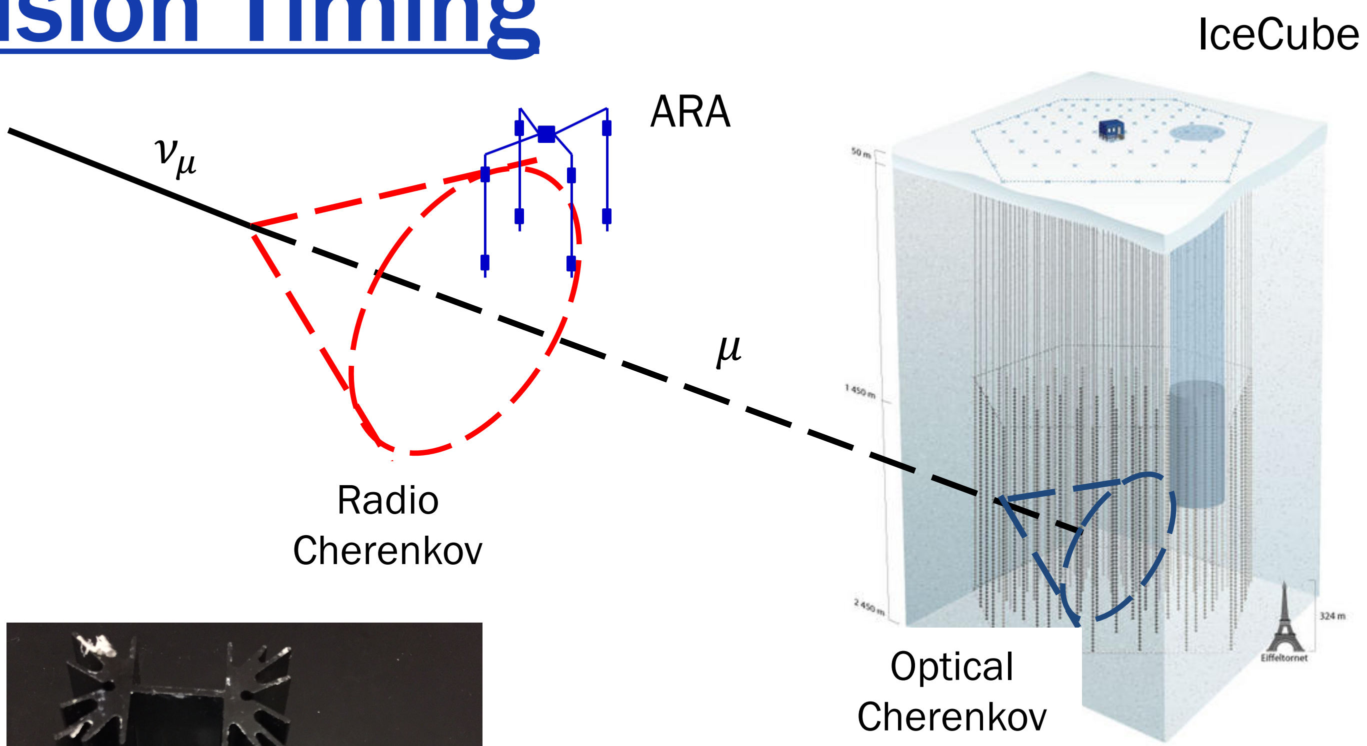


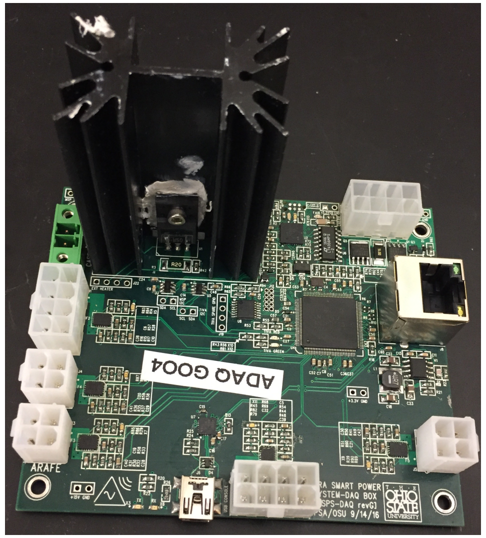


Precision Timing

- Happy opportunity: new power broker is equipped with Precision Time Protocol

- In the future, could synchronize ARA station clocks to IceCube at the ~ns level, and do optical/RF coincidence searches*

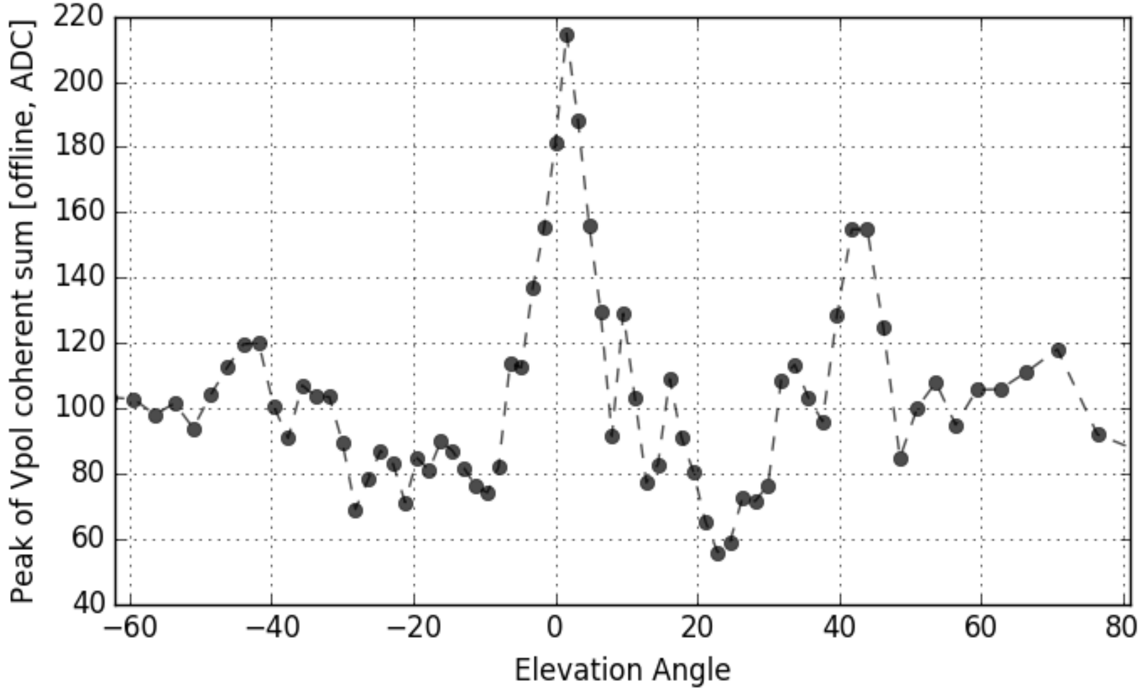


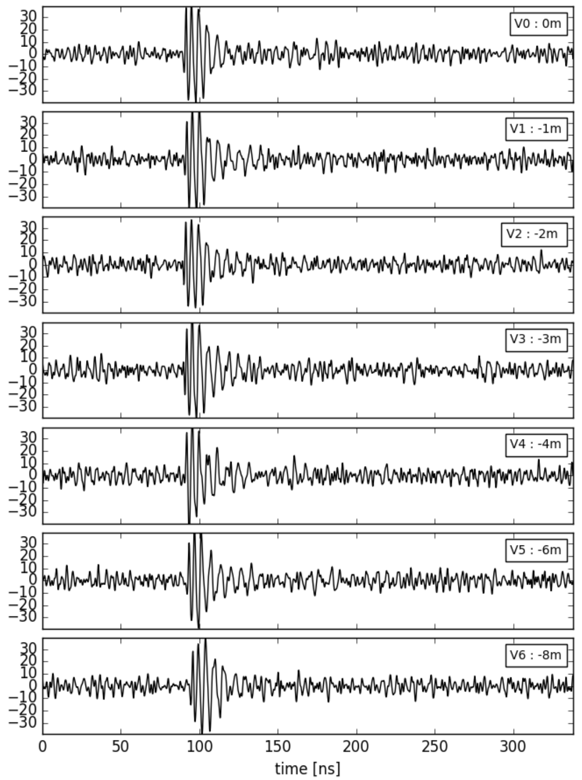


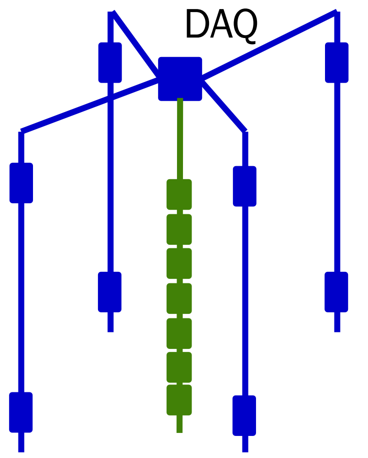
* = part of postdoc plan at MSU w/ IceCube....

New Phased Array w/ A5

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

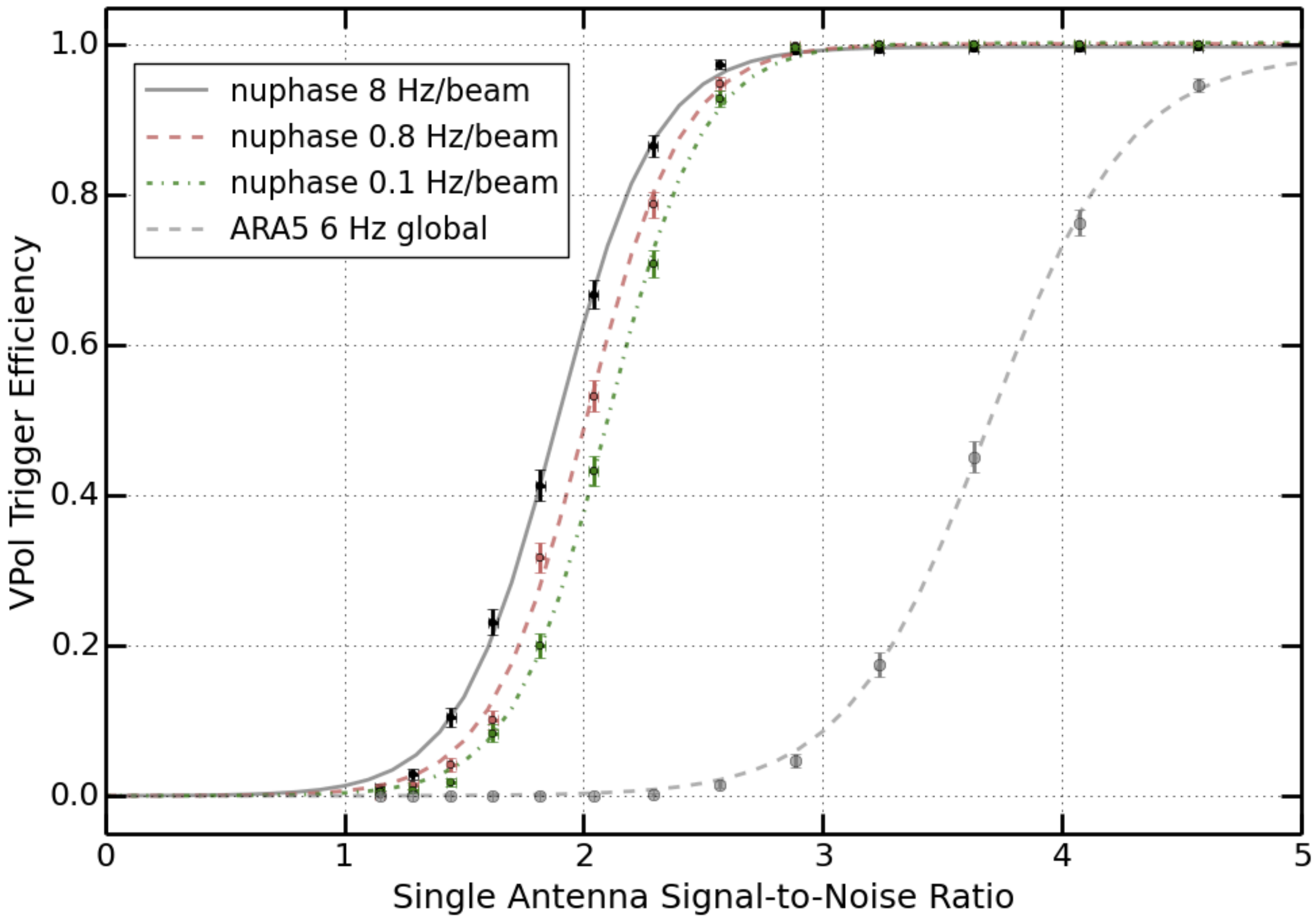






See arXiv 1809.04573

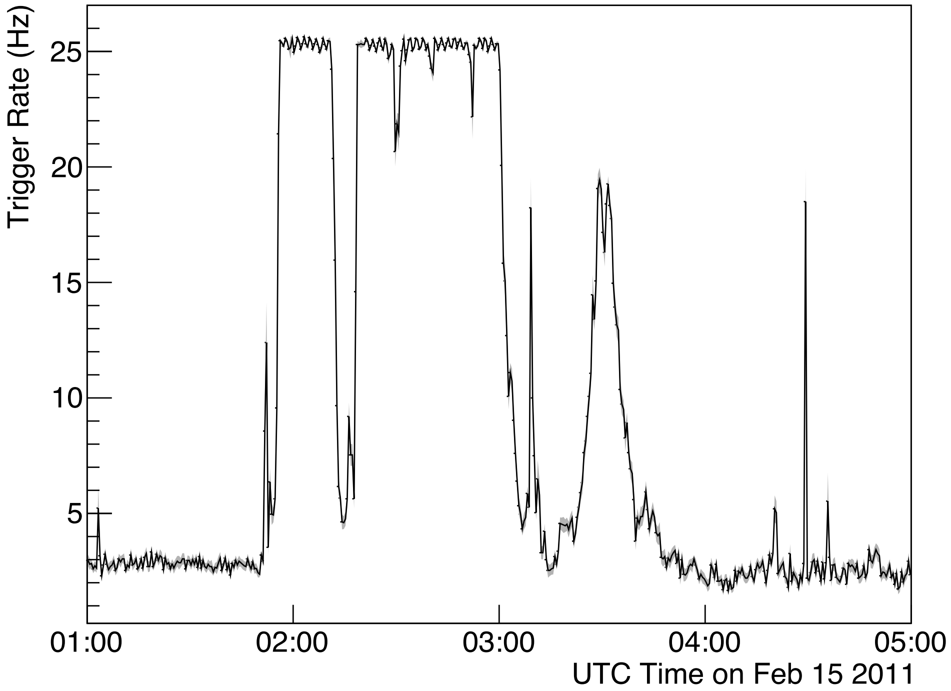
Phased Array Performance Comparison

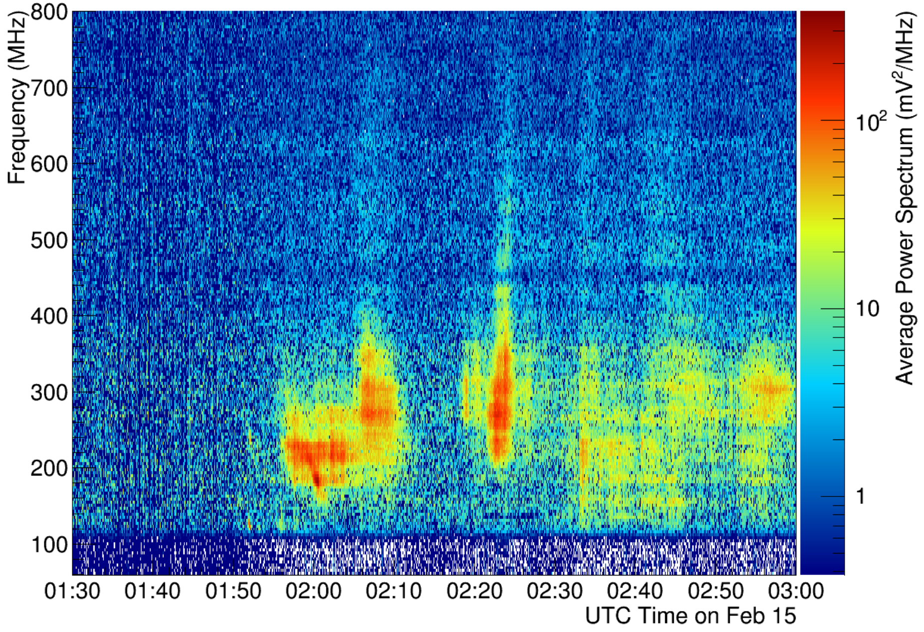


PA measurement demonstrates factor ~1.8 reduction in 50% efficiency point (expected ~2.6).

Feb 15, 2011 Solar Flare

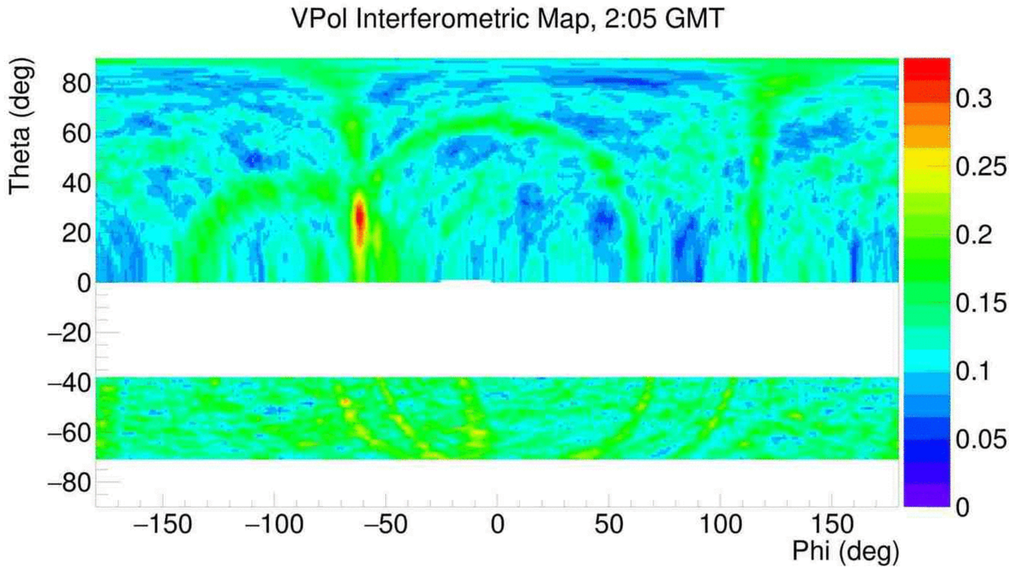
- Testbed activated in February 2011, detected Feb 15 X-2.2 Solar Flare
- Saturates the triggering system
- Observed as excess emission from 100-500 MHz

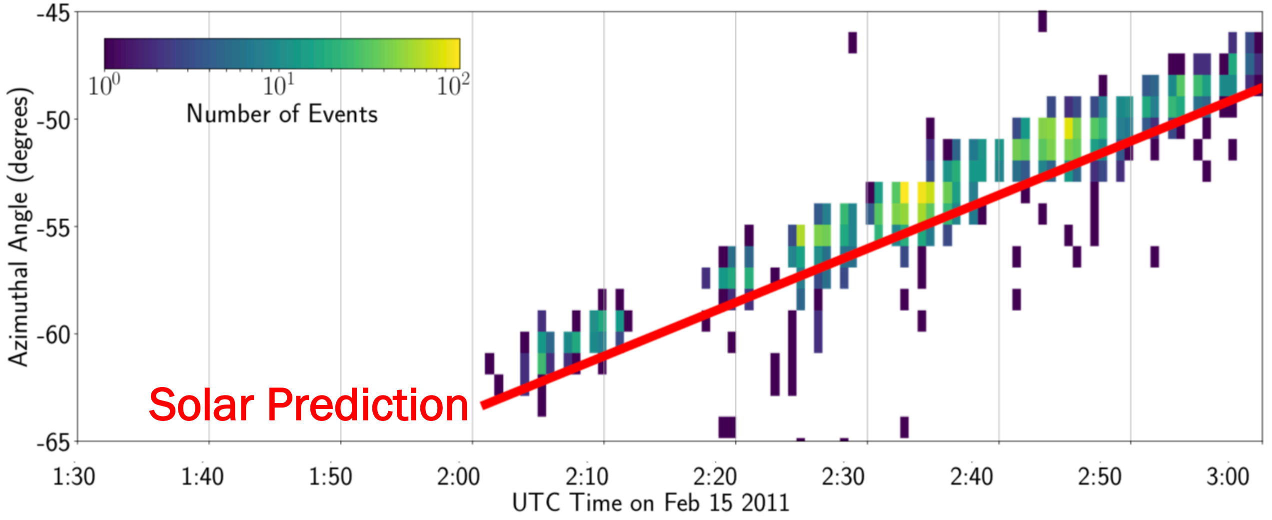




Solar Tracking

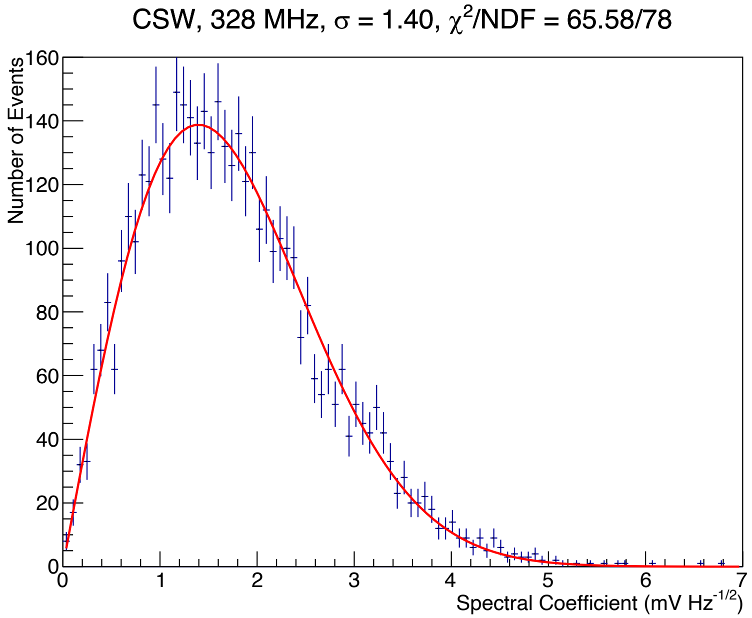
- Recorded events point back to the sun for the hour duration of the flare
- First radiation for ARA which reconstructs to extraterrestrial source on event-by-event basis
  - Excellent test of projection onto celestial coordinate system
  - Will help calibrate pointing of other above-ice radio sources, e.g., cosmic rays

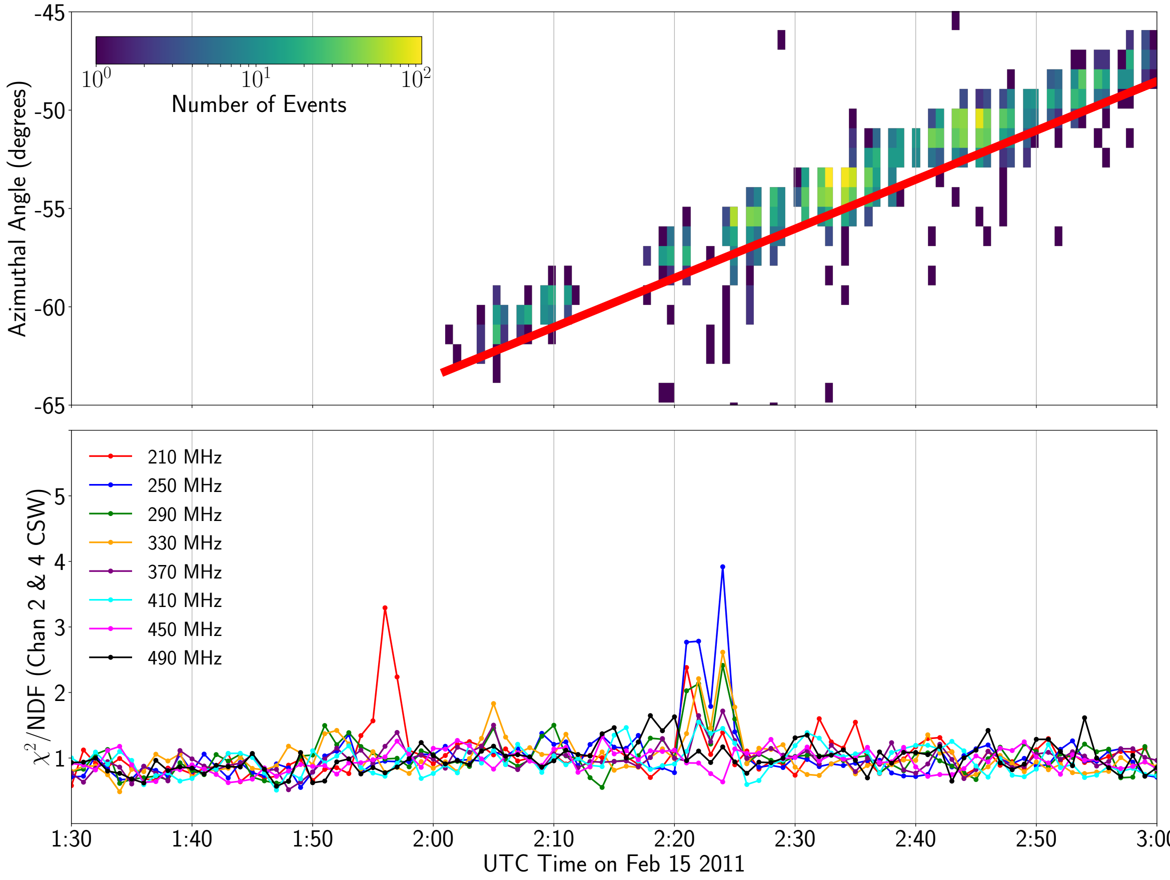




Reconstructability

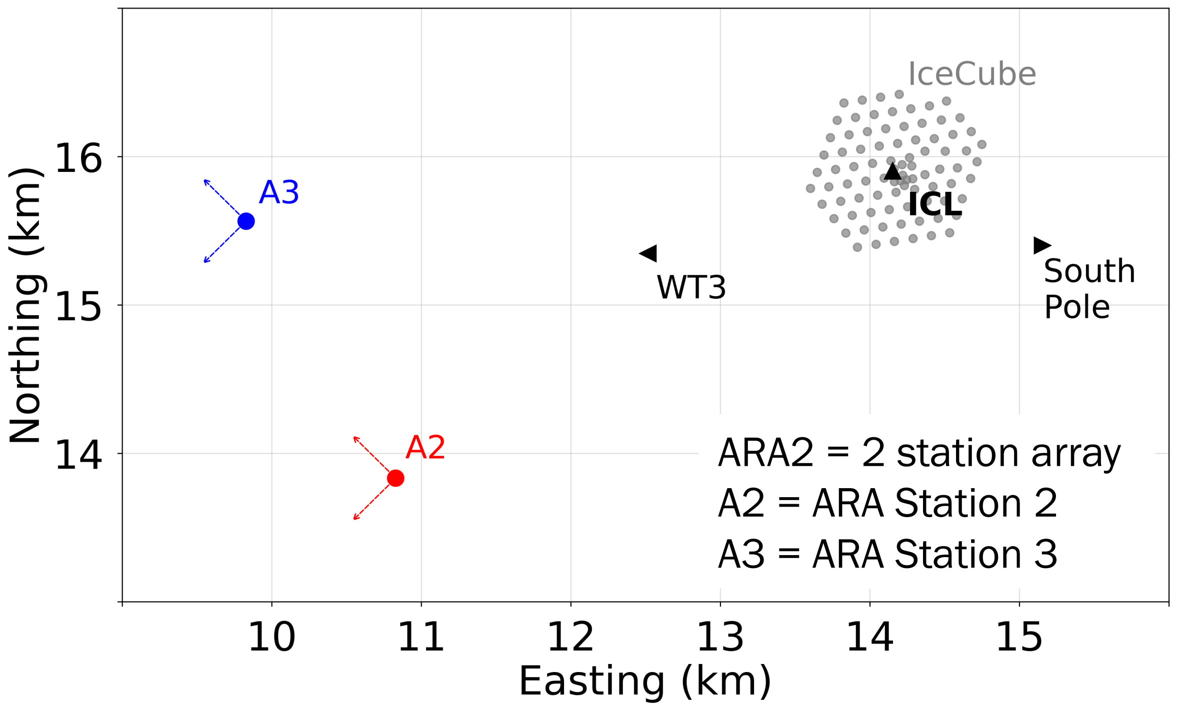
- All antennas observe same noise that was generated at the sun and traveled to earth

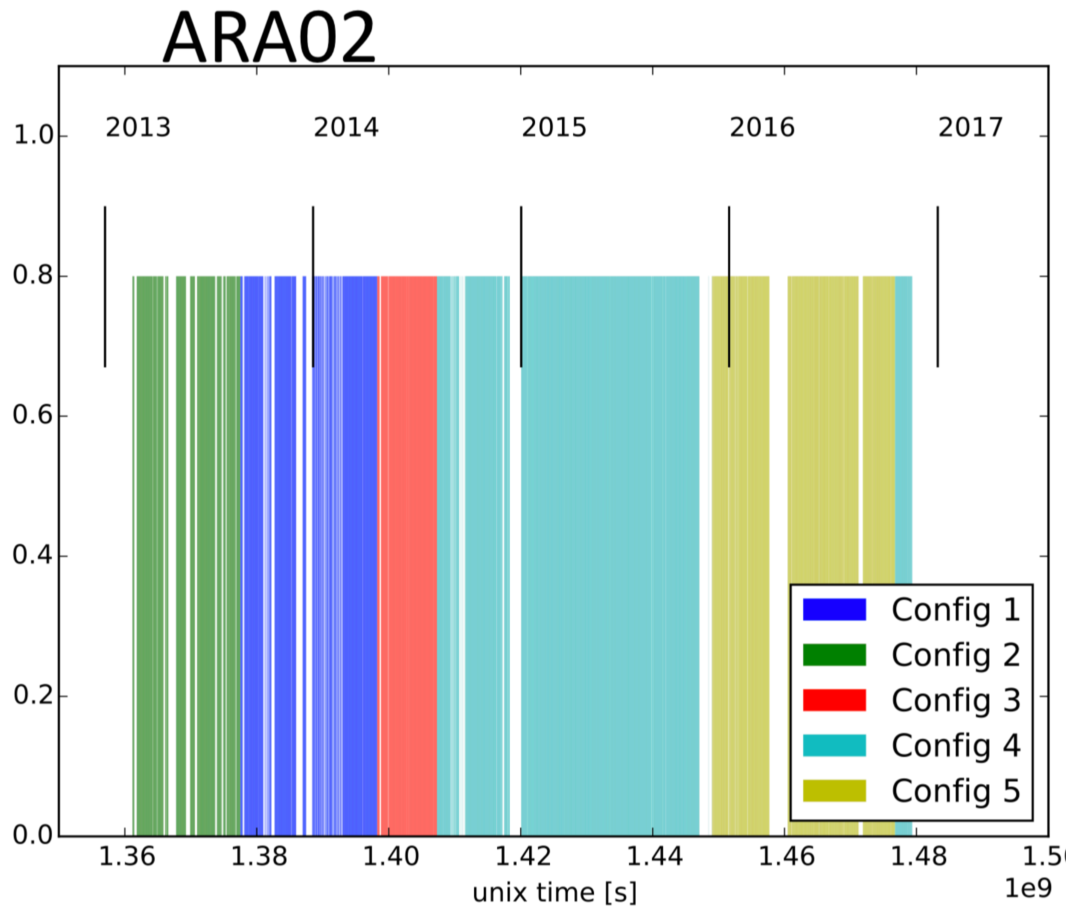




- Events only track sun when they are well described by thermal noise

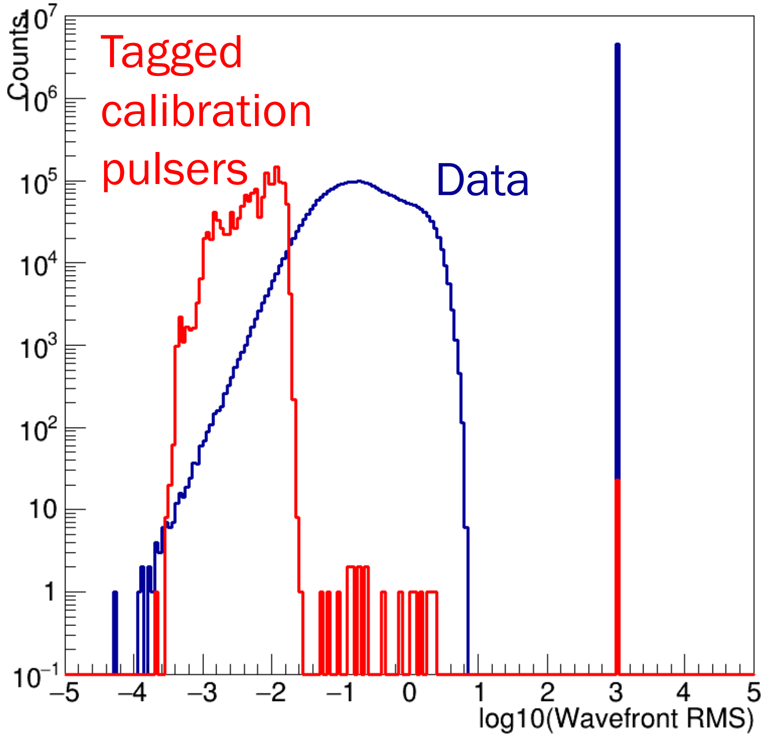
The ARA2 Instrument

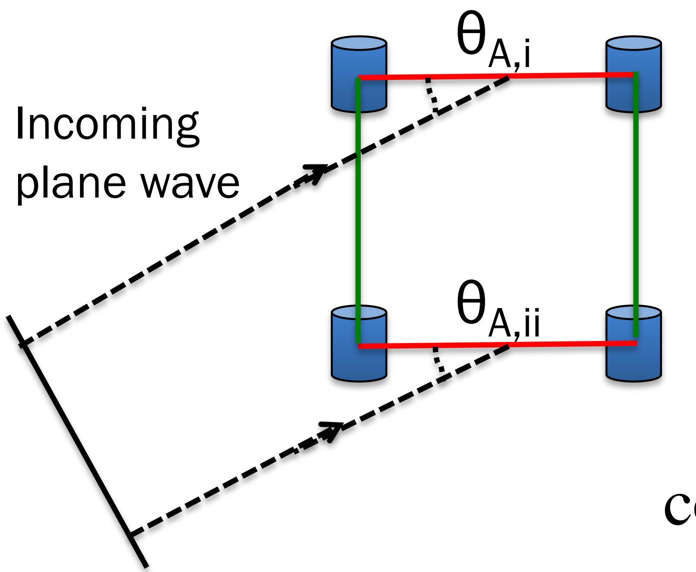




Analysis: Filtering

- Apply thermal noise cut to reduce data set by order of magnitude or more
- Example: wavefront-RMS filter





$$\theta_{A,i} \approx \theta_{A,ii}$$

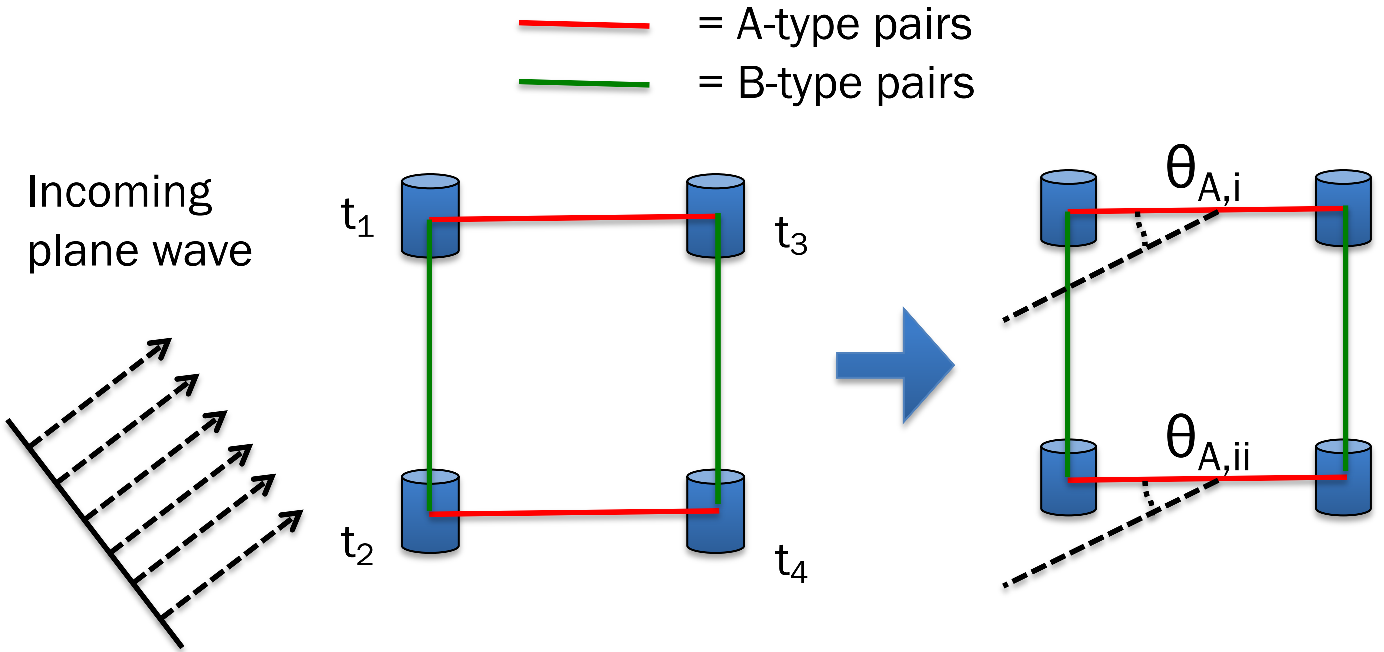
$$\cos(\theta_{A,i}) \approx \cos(\theta_{A,ii})$$

$$\overline{\cos(\theta_A)} = \frac{\cos(\theta_{A,i}) + \cos(\theta_{A,ii})}{2}$$

$$\mathrm{RMS}(\cos(\theta_A)) = \sqrt{\frac{\left(\cos(\theta_{A,i}) - \overline{\cos(\theta_A)}\right)^2 + \left(\cos(\theta_{A,ii}) - \overline{\cos(\theta_A)}\right)^2}{2}}$$

Wavefront-RMS Filter

- ARA records 10^8 events/year, which are >99% noise
- Need fast rejection algorithm
- Leverage regular geometry—divide station into *faces*
- Compute ”hit-times” for signal arrival at each antenna in the face, convert into arrival angle



$$\Delta t_{A,i} = t_3 - t_1$$

$$\Delta t_{A,ii} = t_4 - t_2$$

$$\Delta t_{A,i} \approx \Delta t_{A,ii} \longrightarrow \theta_{A,i} \approx \theta_{A,ii}$$

$$\cos(\theta_{A,i}) \approx \cos(\theta_{A,ii})$$

Wavefront-RMS Filter

- Find the RMS around the average arrival angle

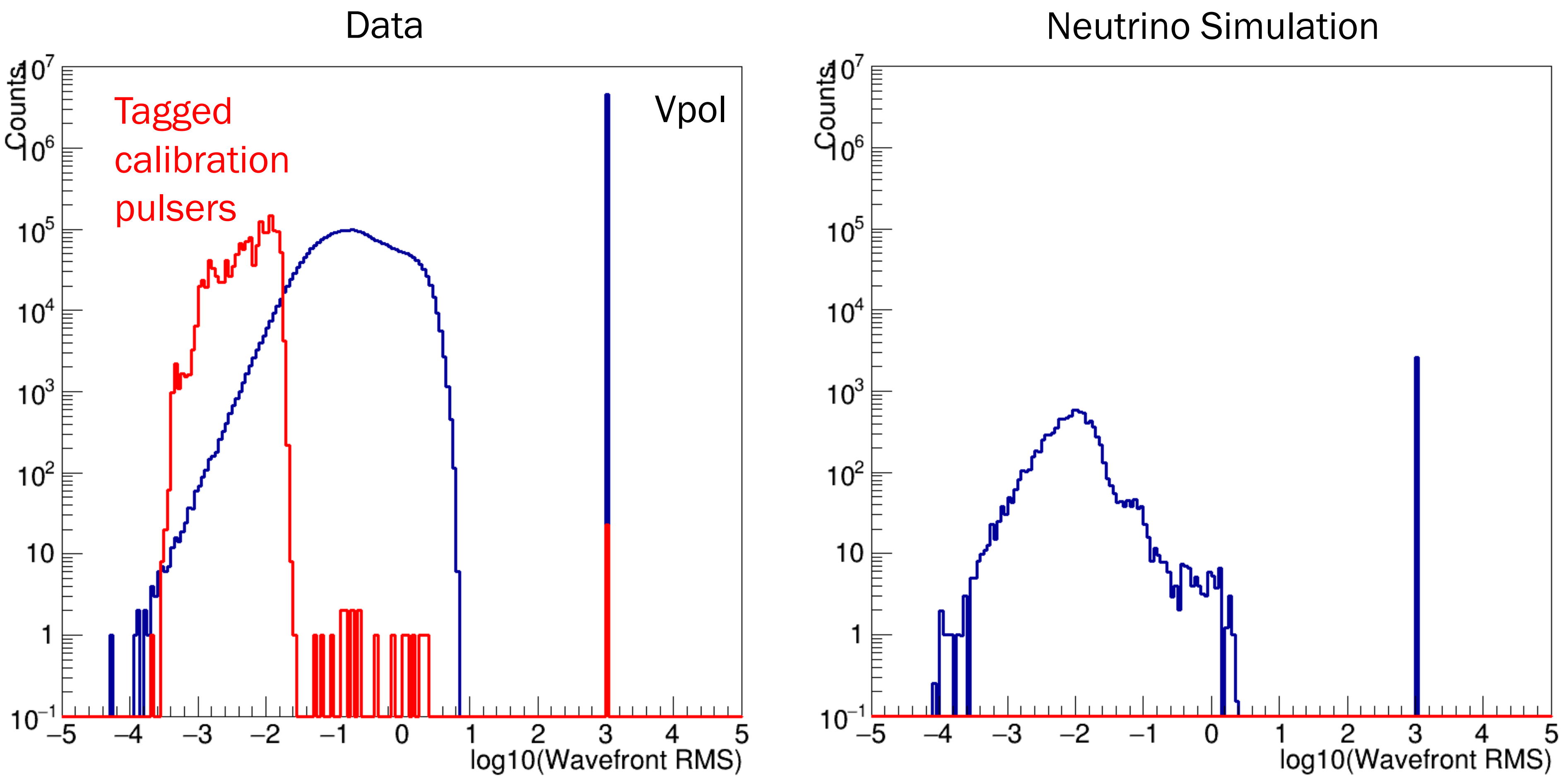
$$\overline{\cos\left(\theta_A\right)} = \frac{\cos\left(\theta_{A,i}\right) + \cos\left(\theta_{A,ii}\right)}{2}$$

$$\mathrm{RMS}\left(\cos(\theta_A)\right) = \sqrt{\frac{\left(\cos\left(\theta_{A,i}\right) - \overline{\cos\left(\theta_A\right)}\right)^2 + \left(\cos\left(\theta_{A,ii}\right) - \overline{\cos\left(\theta_A\right)}\right)^2}{2}}$$

- Expect *wavefront-RMS* = $\log_{10}(\mathrm{RMS}(\cos\theta))$ to be small for real signals, and larger for thermal noise

Wavefront-RMS Filter

- Performance on VPol data and simulation from A2 configuration 1



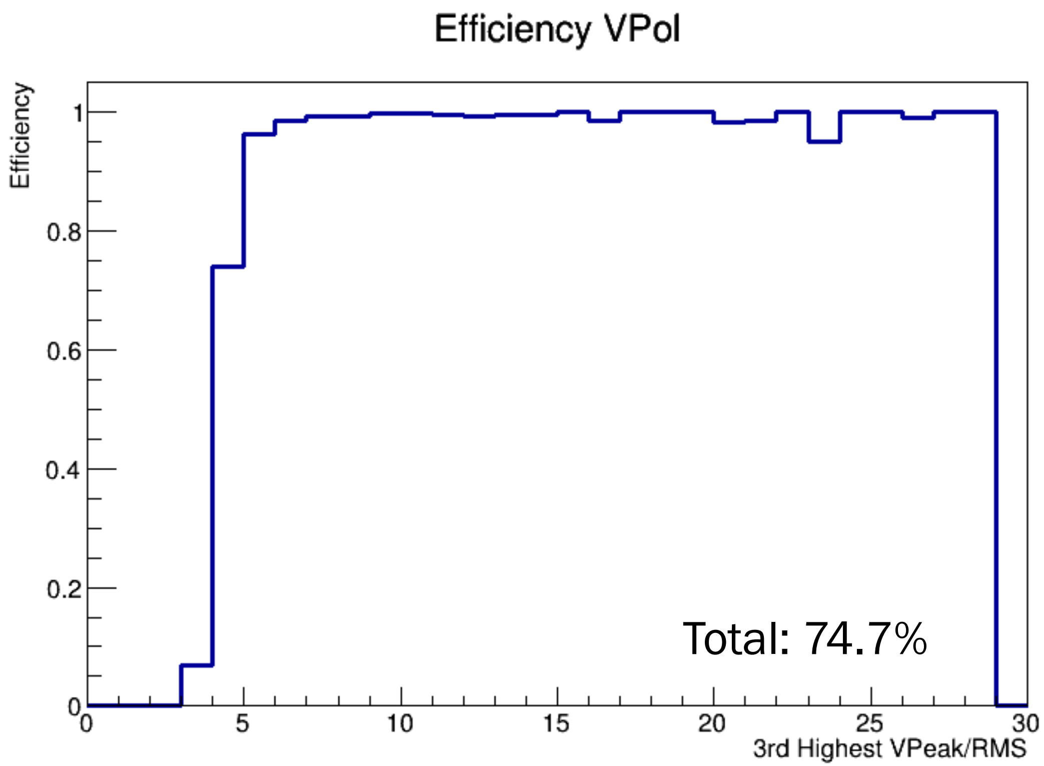
Wavefront-RMS Filter

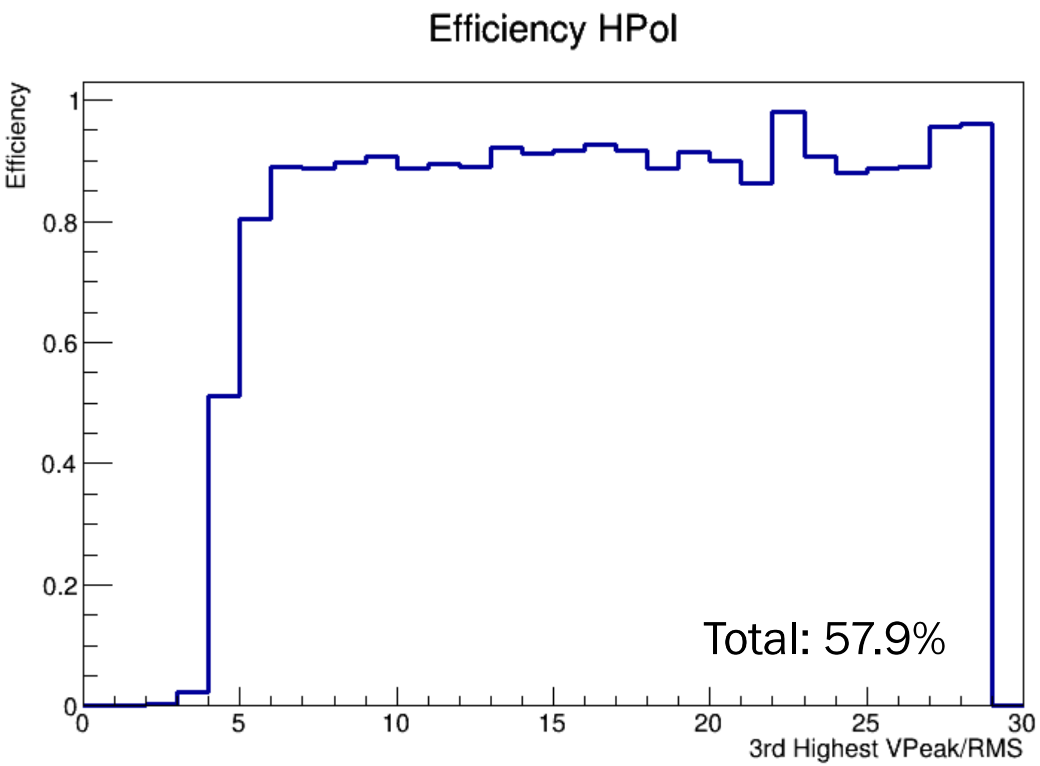
- Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol
- These values reduce data to 5-10% of original size (per polarization) while keeping fraction of neutrino events cut by wavefront-RMS *alone* to <5%
- Total efficiency of the filter for neutrinos, before other cuts, is ~90%

Config	V Passing Rate	H Passing Rate	H or V Passing Rate
1	74.7	58.0	89.8
2	69.8	48.1	85.2
3	75.6	58.1	91.1
4	75.0	58.7	90.4
5	76.4	59.4	91.7

Wavefront-RMS Filter

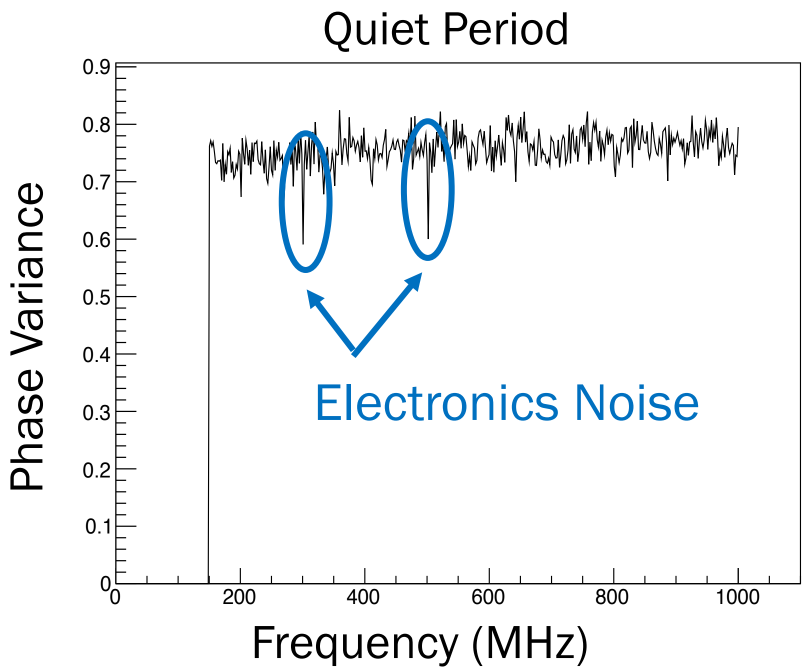
- Efficiency of filter can be measured as a function of the signal-to-noise ratio





CW Filtering

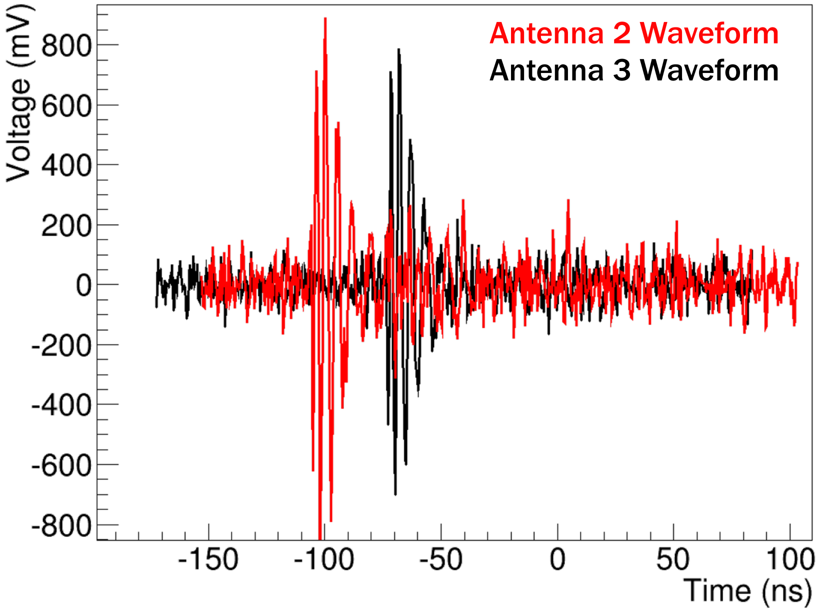
- Flag a frequency as CW if it comes from "peaks above base line" or "phase variance"
  - Phase variance frequently flags 125, 300 and 500 MHz as systems noise—we ignore these
  - Adjacent frequencies merged into notches

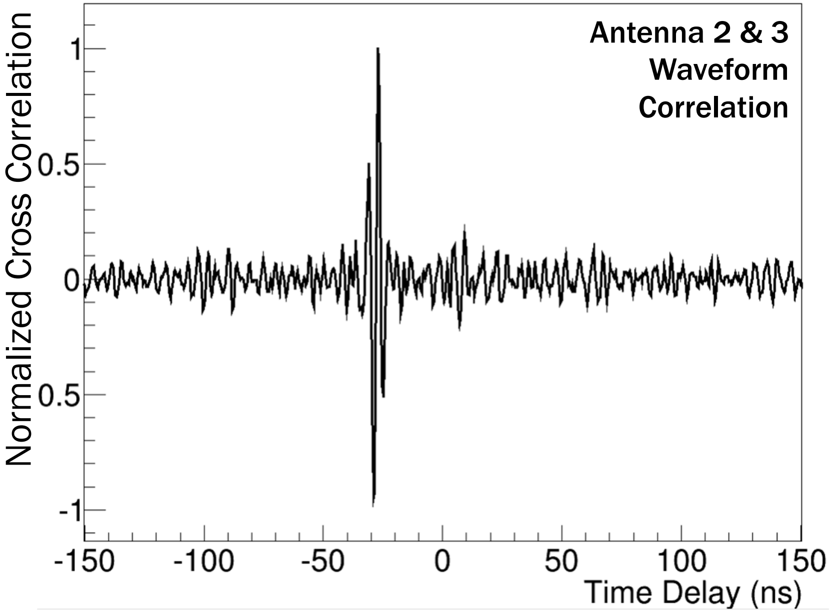


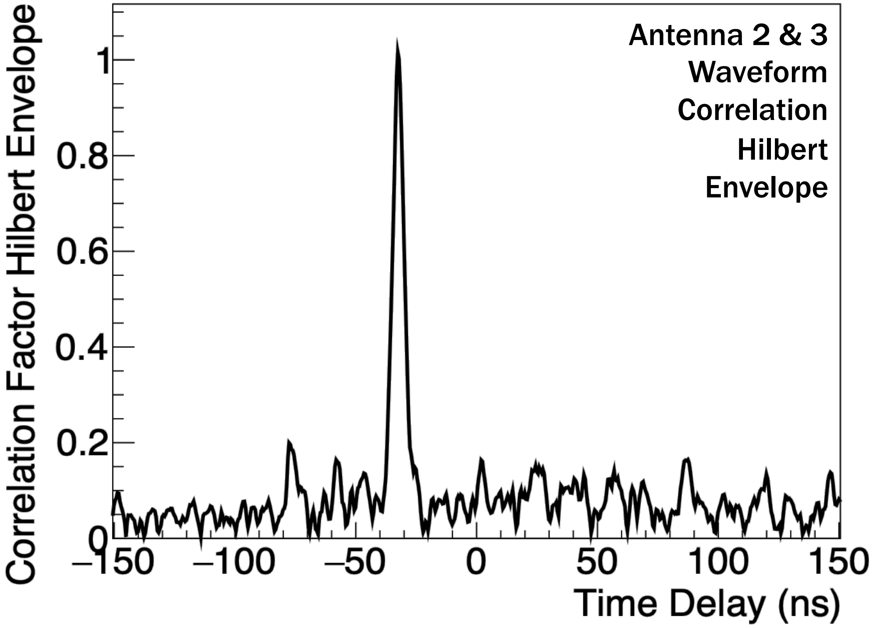
- CW frequencies are filtered with ANITA Geometric Filter—first time we have filtered waveforms in ARA
  - Originally designed by Brian Dailey at OSU
  - Used in the ANITA-III analysis [Phys. Rev. D 98, 022001 (2018)]

Reconstruction Details

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



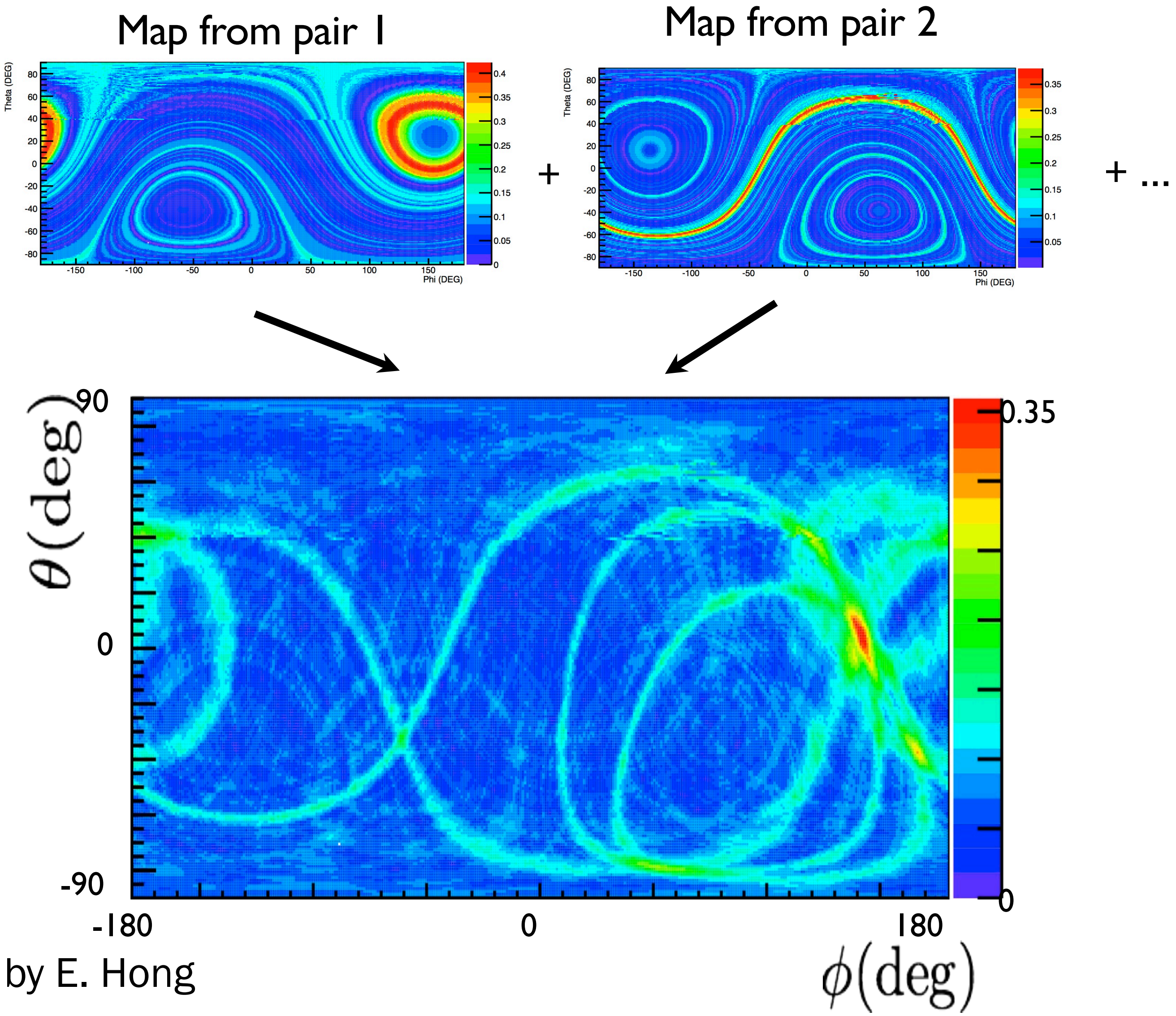




2. P. Allison *et. al.* j.astropartphys.2015.04.006
3. P. Allison *et. al.* j.astropartphys.2016.12.003

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**



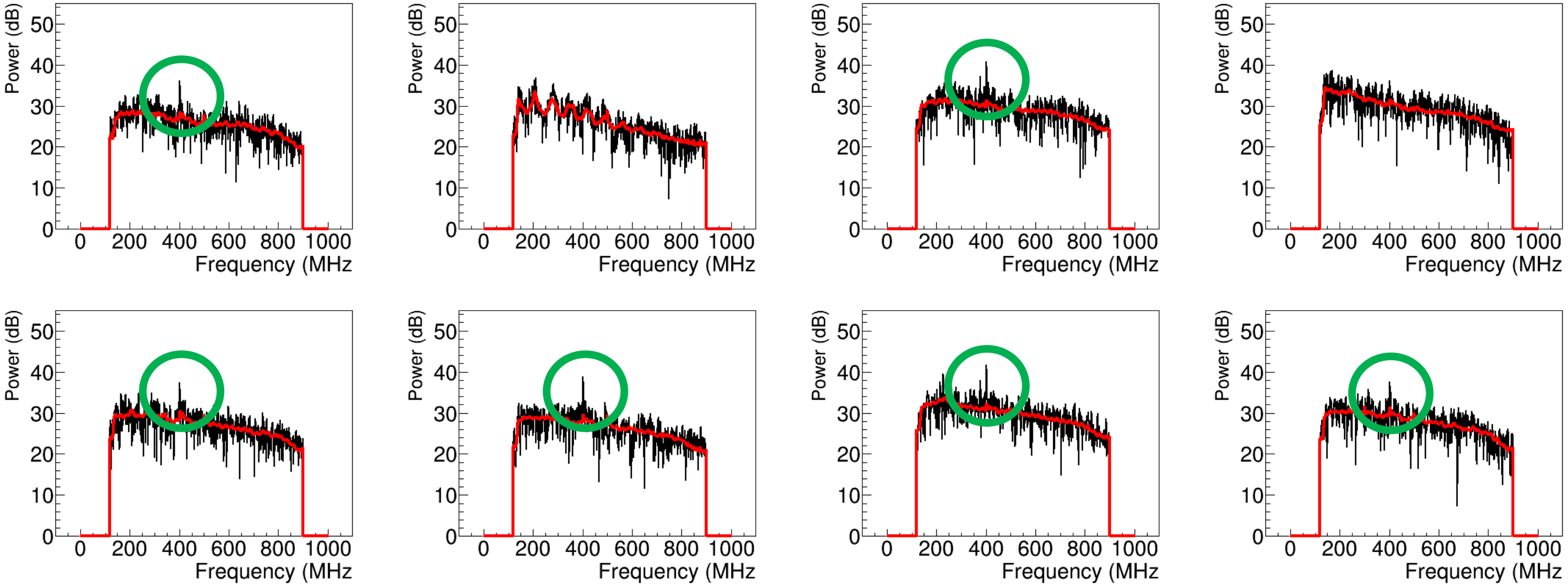
Interferograms by E. Hong

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

Continuous Wave (CW) Contamination

- Events passing wavefront-RMS event filter are evaluated for CW contamination
- Most common: 403 MHz from South Pole weather balloons, launched twice-daily

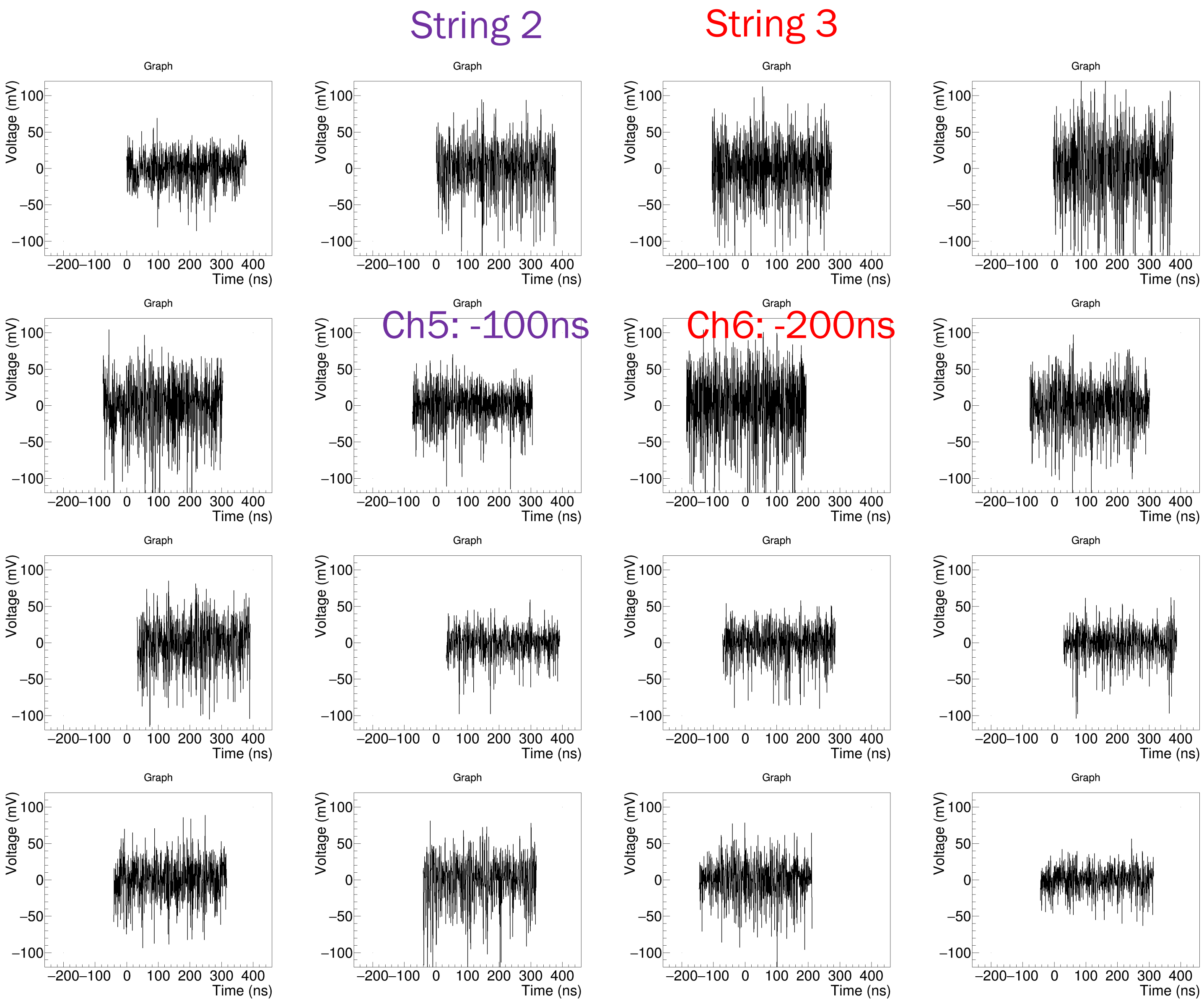
Run 1548, Event 20695



Phi Anisotropy

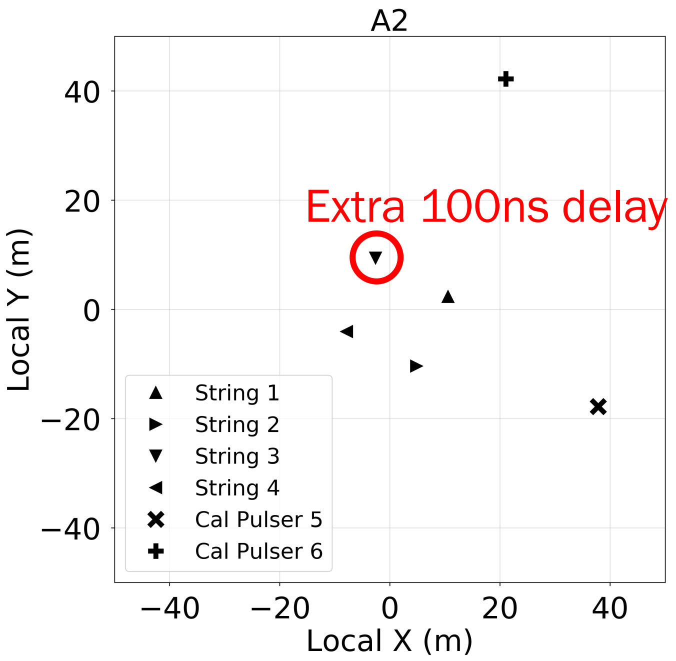
- In A2 and A3, one cable was too long
  - A2 String 3
  - A3 String 2
- In both stations, that string has an extra 100ns of cable delay
- E.g., in A2, string 3 waveforms start earlier than in the other strings (eg. string 2)

A2, Run 1449, Iterator Event 1



Phi Anisotropy

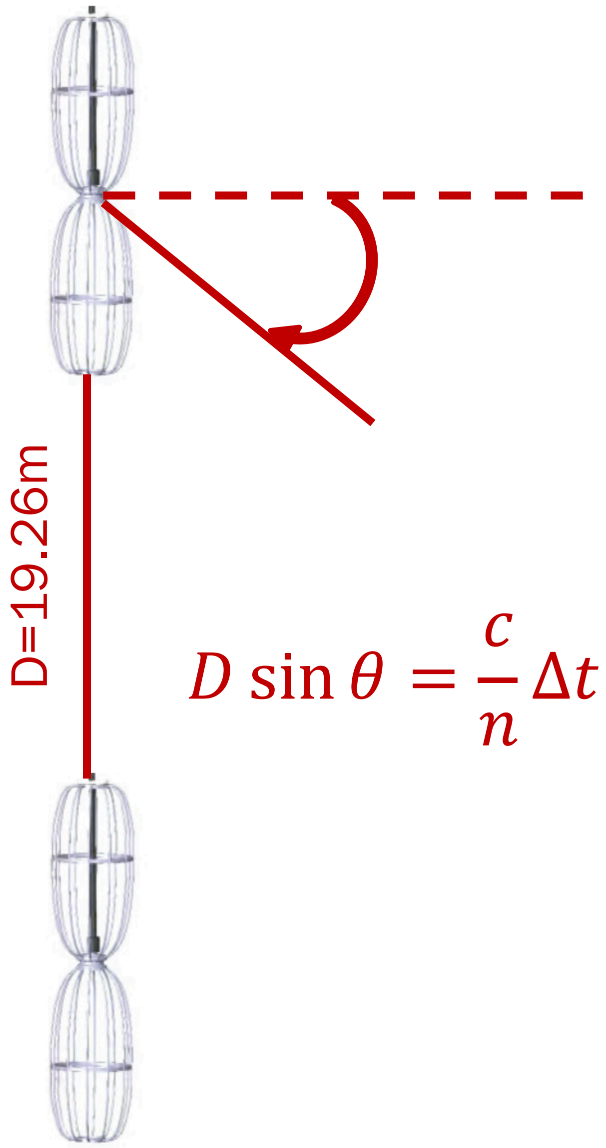
- When signal present—signal dominates correlation function
- When noise dominates (most cases), the extra trace length at the beginning means the longer string *systematically looks* like it lags the other strings
- This pulls the reconstruction in the direction of the longer string
- Which is ~111° in A2 and ~21 ° in A3



Theta Anisotropy

- The top and bottom antennas are separated by ~19m of cable, in which light travels 0.255m/ns, amounting to ~75 ns of delay between the two

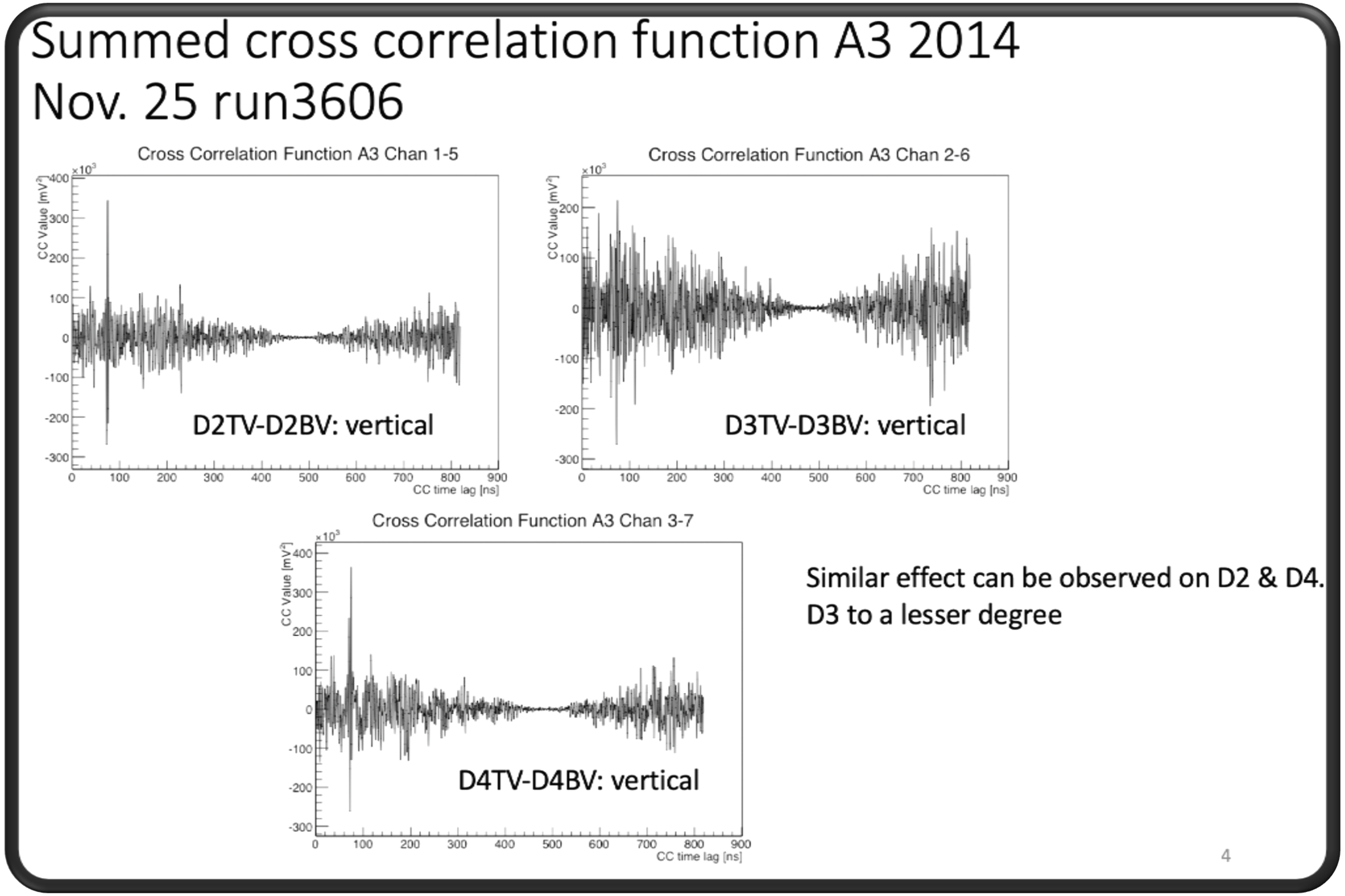
- Take A2 D1TV and D1BV as an example
  - Known geometric distance between antennas=19.26 m
  - If Δt=75ns
  - Then the reconstructed zenith is -41°!



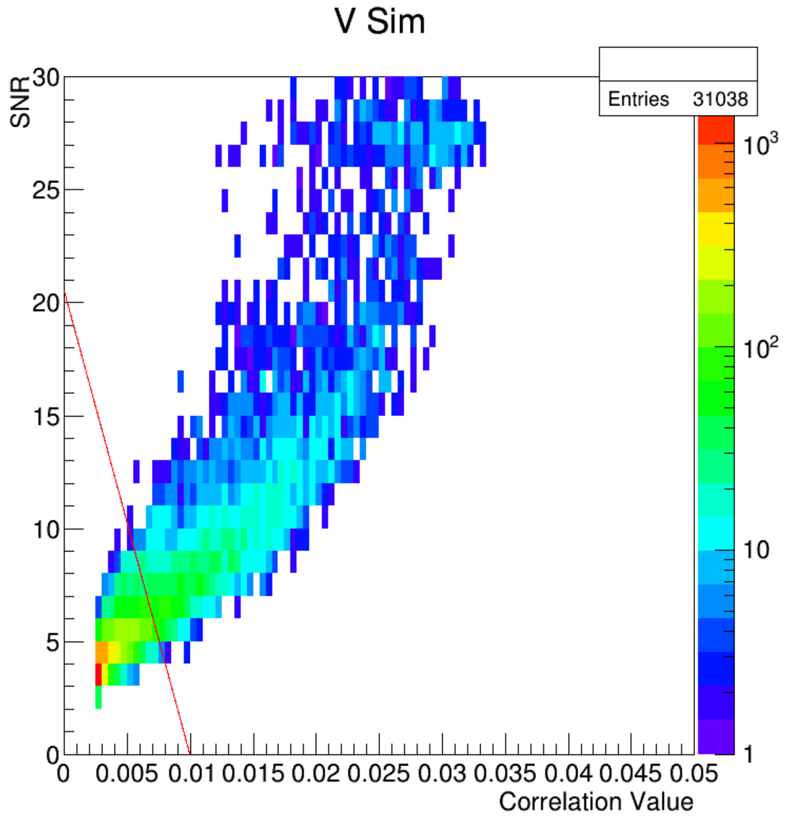
Theta Anisotropy

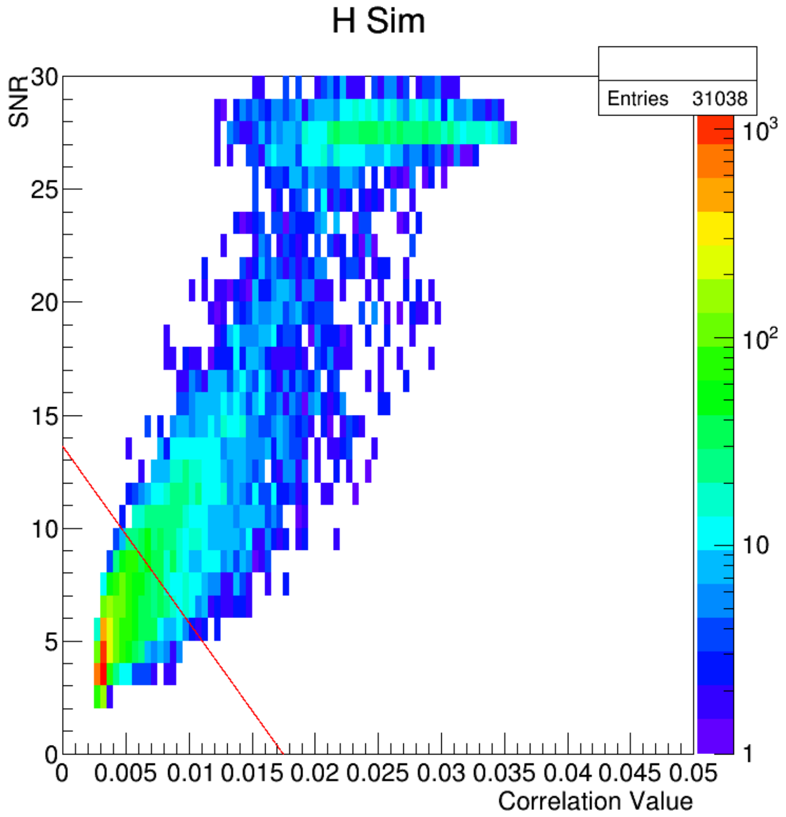
- Is this "phantom" 75ns observed in practice? Yes!
- Source unclear:
  - Low level cross-talk?

Slide from MYL

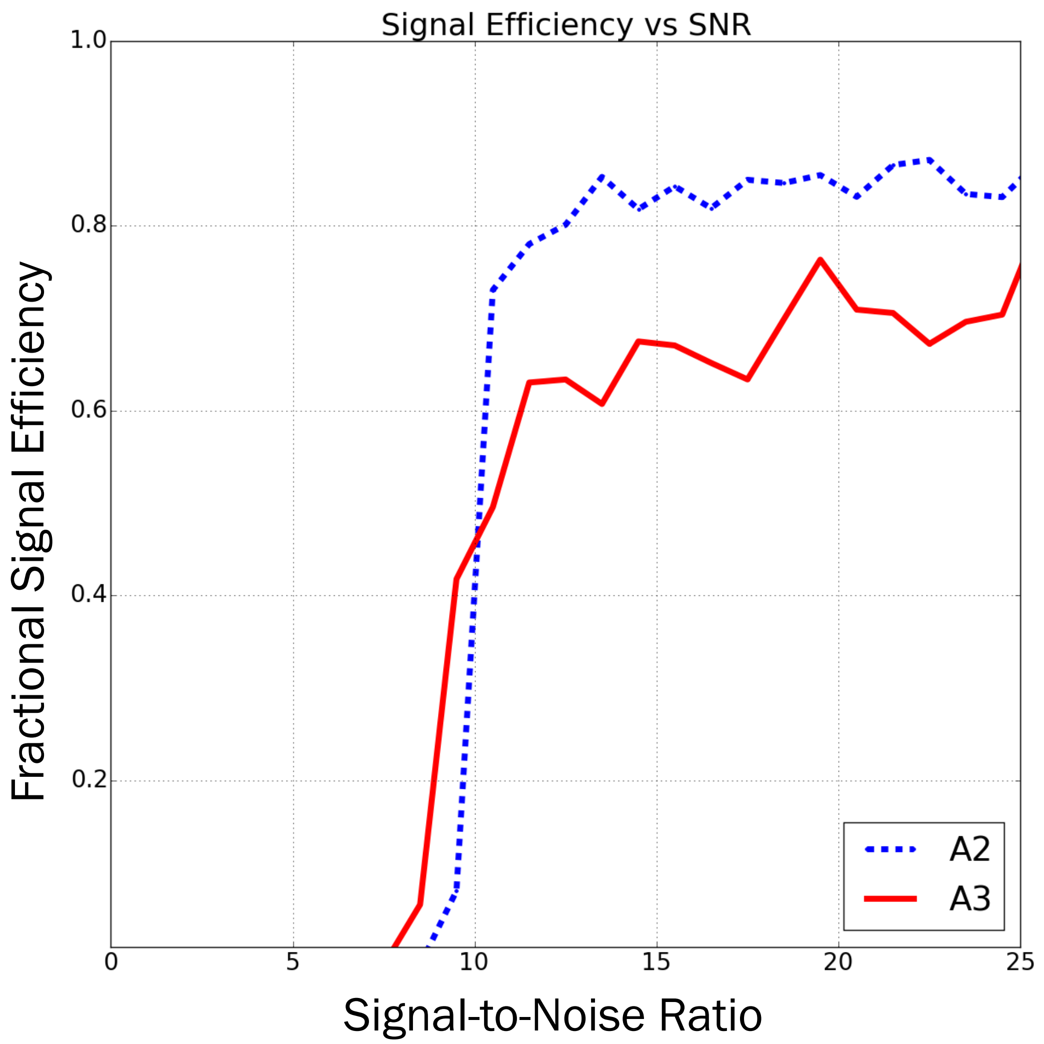


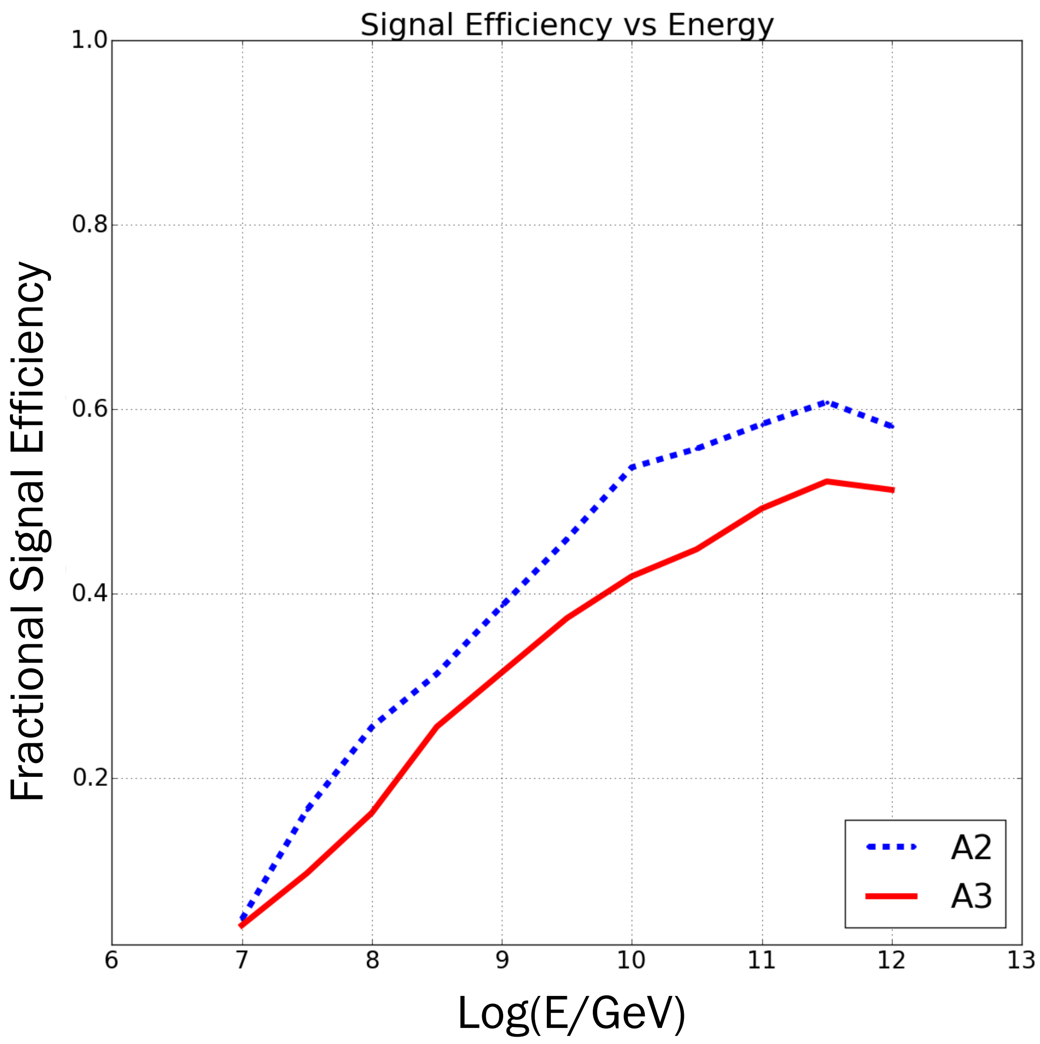
H vs V Comparison





Analysis: Efficiency





Effective Volumes

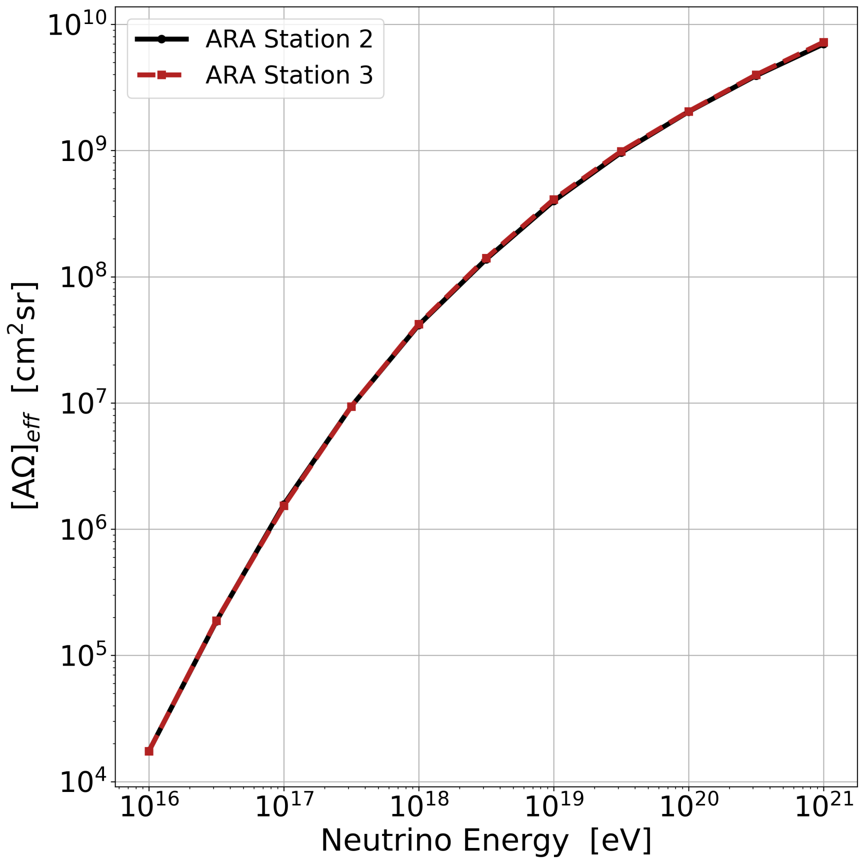
- Compute effective volume at trigger level from simulation

$$V_{eff} = V_{thrown} \frac{N_{det}}{N_{thrown}}$$

- Simulation was altered to take into account trigger delays, masked channels, etc. in a configuration specific way

- Get effective area through division by interaction length

$$A_{eff} = V_{eff}/L_{int}$$

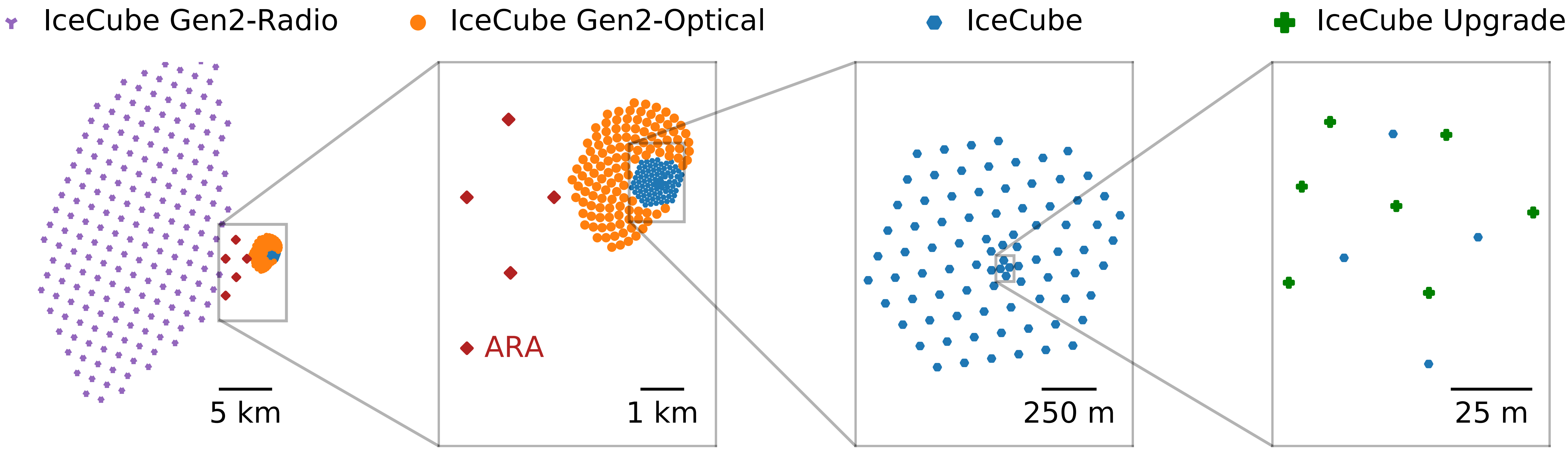


Projected Final Limit

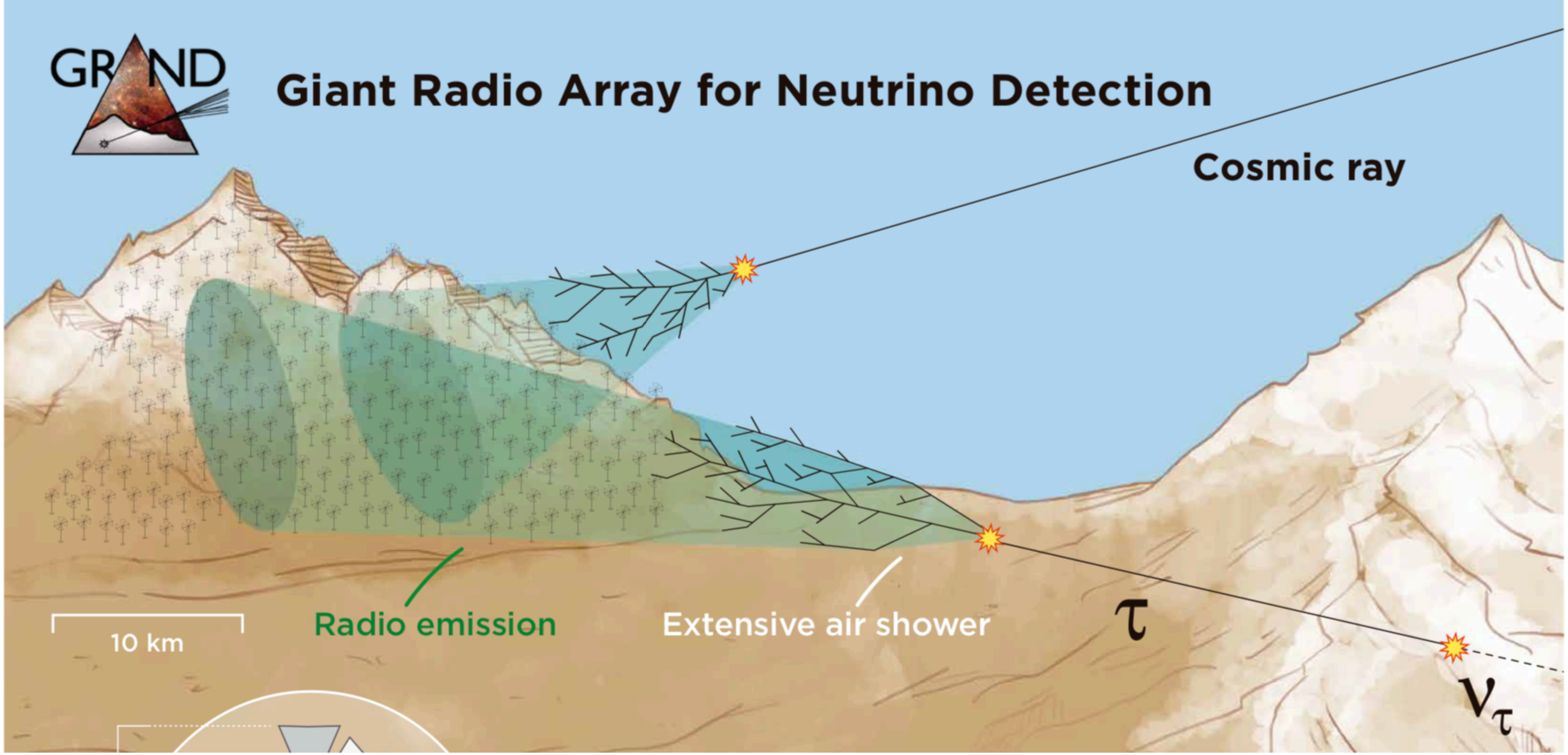
- Assume non-observation in the 100% sample

- Compute 90% UL on the maximum size the flux, $EF(E)$, can be in an energy bin E_i

$$EF(E)_i = \frac{2.44}{ln10 \; d \log_{10} E_i \;\; T \; [A\Omega]_{eff}}$$


IceCube Gen2-Radio
IceCube Gen2-Optical
IceCube
IceCube Upgrade
ARA
5 km
1 km
250 m
25 m

Future Radio Instruments



See arXiv 1810.09994