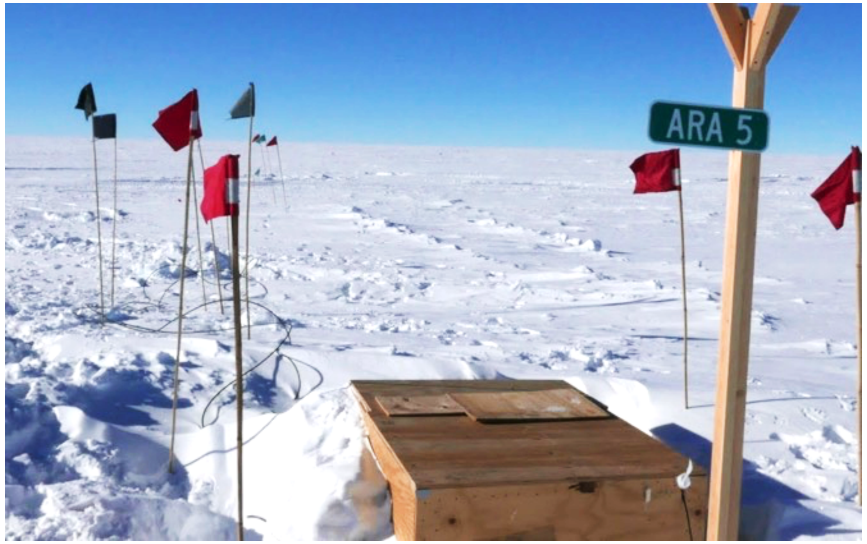
The Quest for UHE Neutrinos



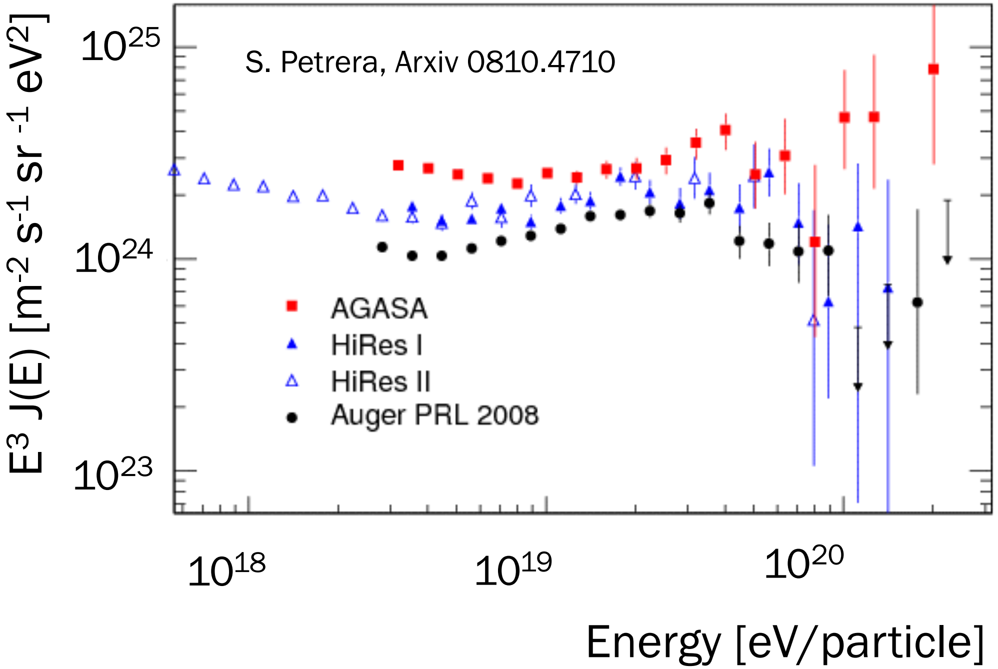
Brian Clark

CCAPP Seminar
The Ohio State University
Department of Physics

July 16, 2019

Why Study UHE Neutrinos?

*Ultra-High Energy = $>10^{16}$eV



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

- Cosmic rays $>10^{19.5}$eV attenuated after ~50 MPc, e.g. GZK effect

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

- Photons >~10 TeV annihilate on CMB/EBL, scatter off dust

Particle Physics Motivation: Probe cross sections at energies above accelerators

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

Neutrinos and Multimessenger Astronomy

Complimentary Probes

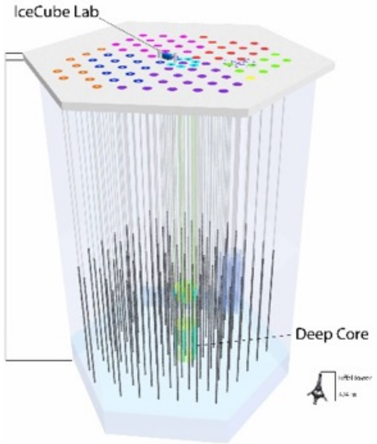
- Cosmic rays: pions from GZK process decay into neutrinos
- Probe accelerators directly—e.g., blazars

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

Rare Signal

- Low fluxes (~few/km^3/yr) and low cross-sections (interaction length ~300km in rock)
- Need Big detectors: ~100 km^3 of target volume to enable routine detections

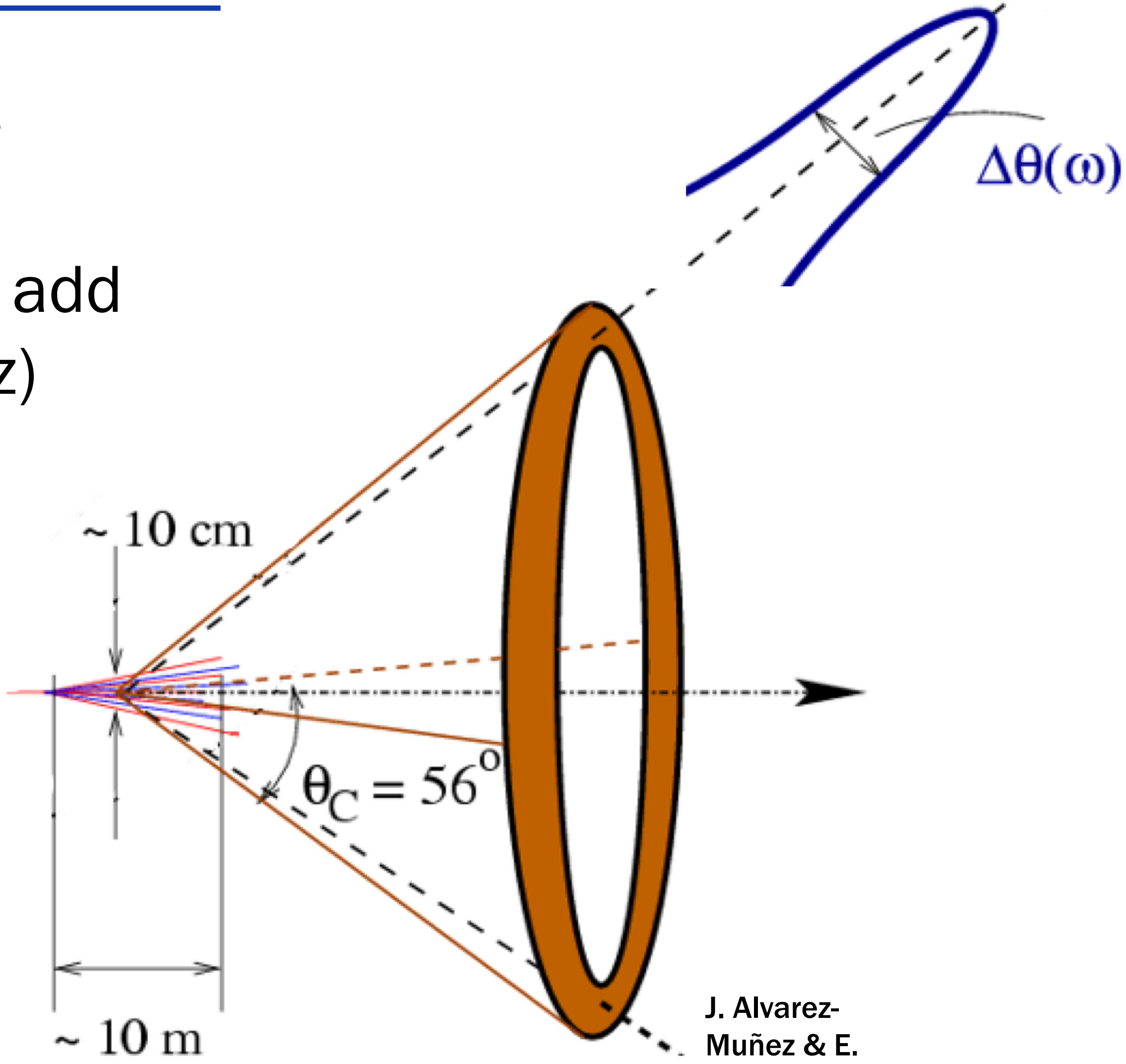
Auger
(air shower)



IceCube (optical)

Askaryan Effect

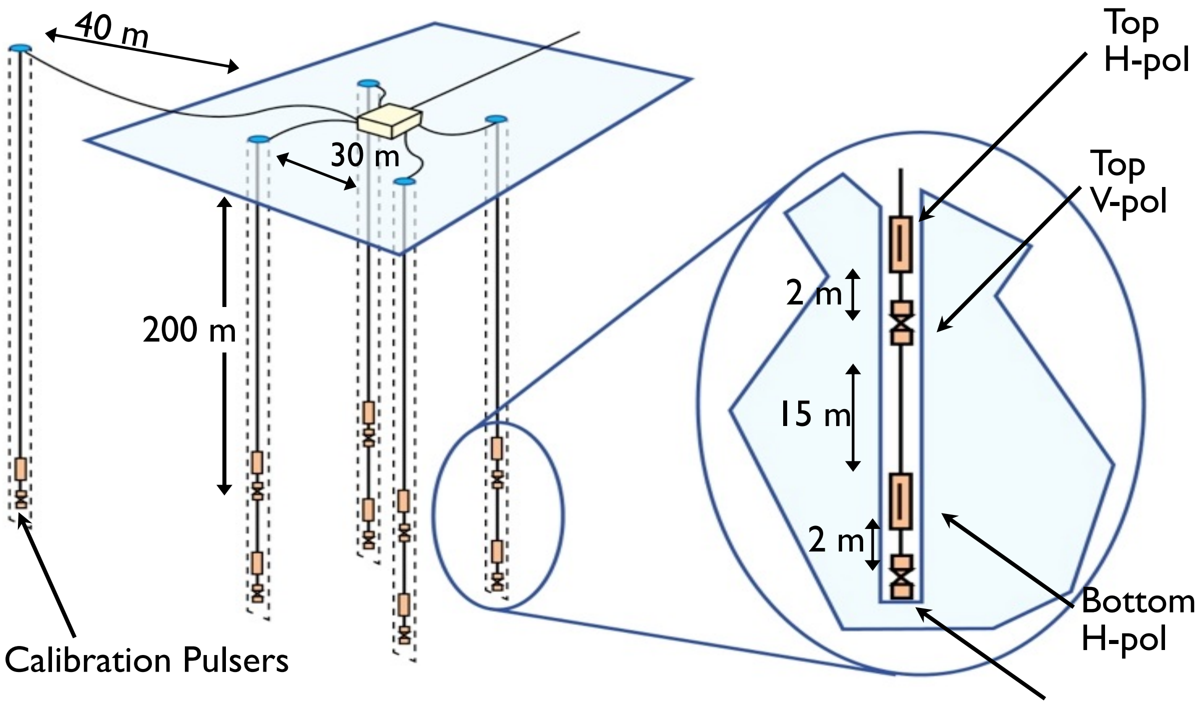
- Neutrino-induced showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add *coherently* ⟶ broadband (200 MHz-1.2GHz) radio *pulse*
- Conical emission (~56 ° in ice); strongest "on cone"
- Two requirements for successful experiment
  - – Radio transparent medium: ice
  - – Enormous volume: Antarctica

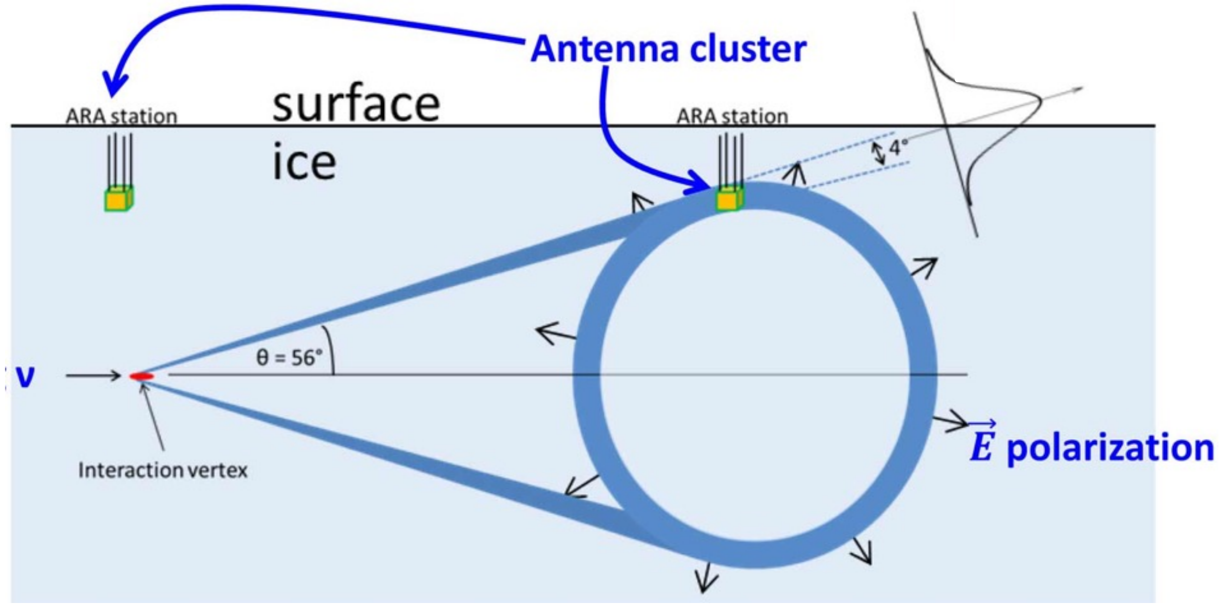


J. Alvarez-Muñez & E. Zas (2005)

The ARA Concept

- 8 VPol & 8 HPol antennas deployed in 200m “boreholes”
- Cubical lattice at 200m depth
- 150-850 MHz bandwidth





The ARA Collaboration

Figure credit: C. Pfendner

USA

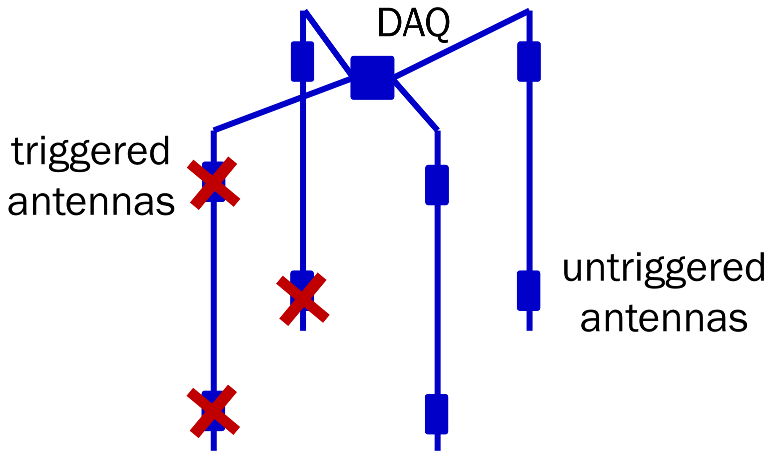
Cal Poly
The Ohio State University
Otterbein University
University of Chicago
University of Delaware
University of Kansas
University of Maryland
University of Nebraska
University of Wisconsin-Madison
Whittier College

International Collaborators

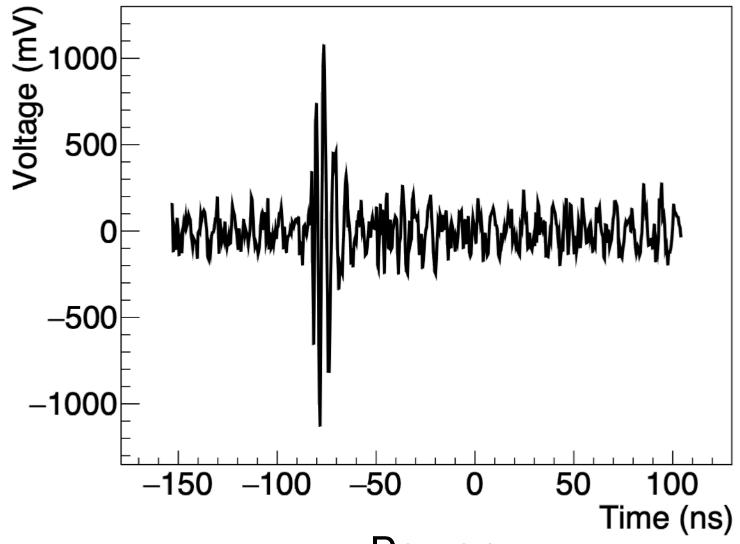
Chiba University
National Taiwan University
University College London
Vrije Universiteit Brussel
Weizmann Institute of Science

Triggering and Data

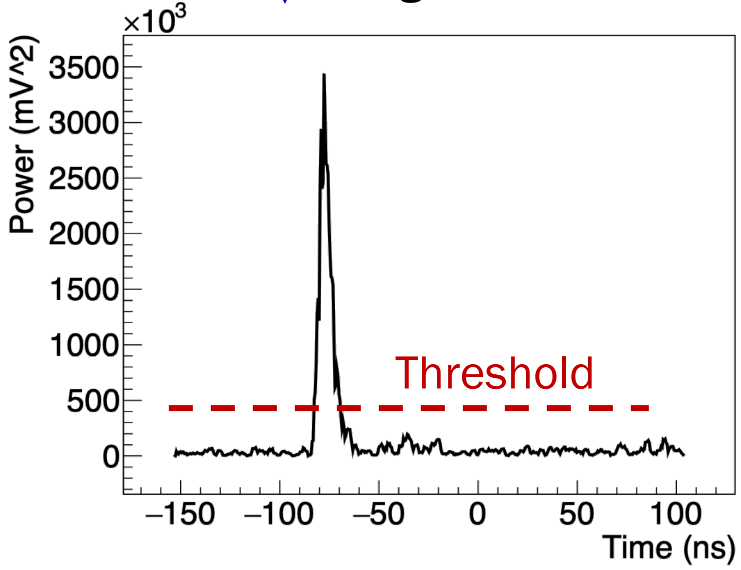
- *Power:* 10ns integrated power > 5.3 × thermal noise floor
- *Coincidence*: trigger in 3/8 antennas of same polarization in ~170 ns
- Thresholds maintain a global ~7 Hz/station trigger rate ⟶ 10^8 evts/year/station



Calibration Pulser
Testbed Station



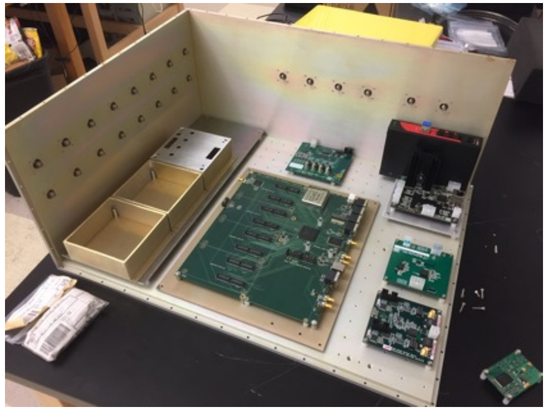
Power Integration



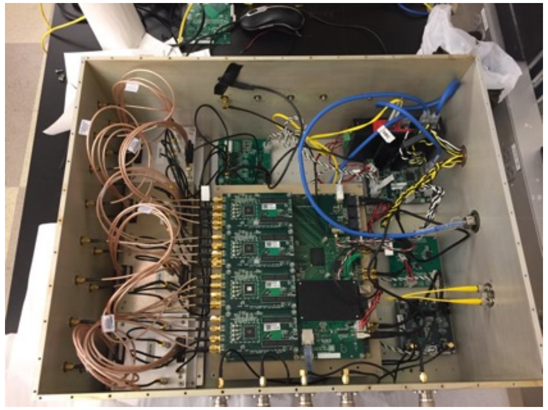
New Stations

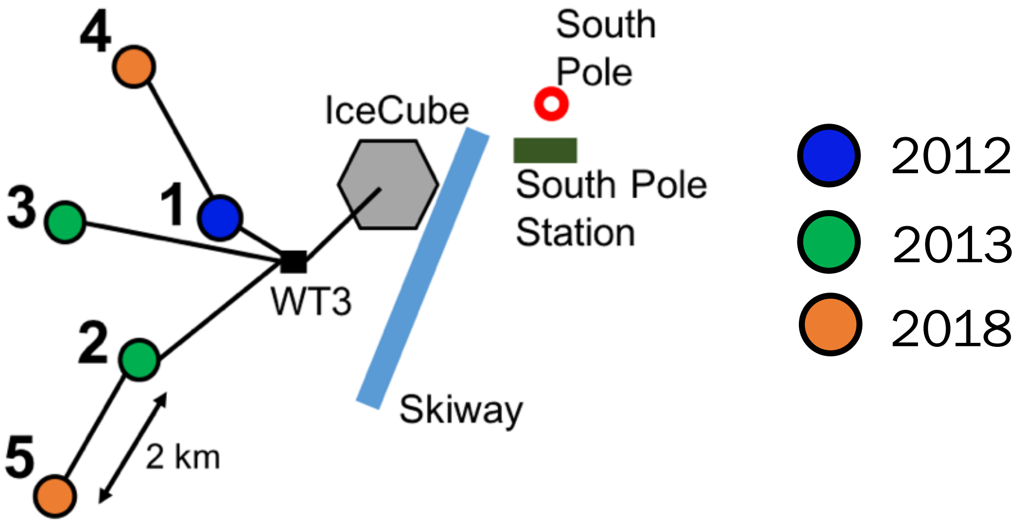
- Entire DAQ for A4 and A5 built at OSU, with lots of undergraduate help
- Built “north” system: A6
- Supported the construction of a new low threshold-phased array system [10.1016/j.nima.2019.01.067]
  - A5 serves as the “power and communications” hub
- Refurbished DAQs for A1 and A3

A4 August 2016



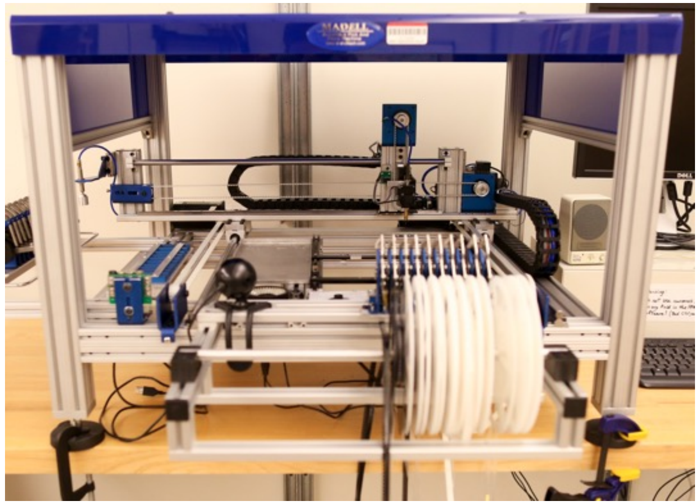
A4 April 2017





Many thanks to CCAPP and CART!

Rapid prototyping and testing of electronics



Pick & Place machine for rapid assembly.

Anechoic chamber.

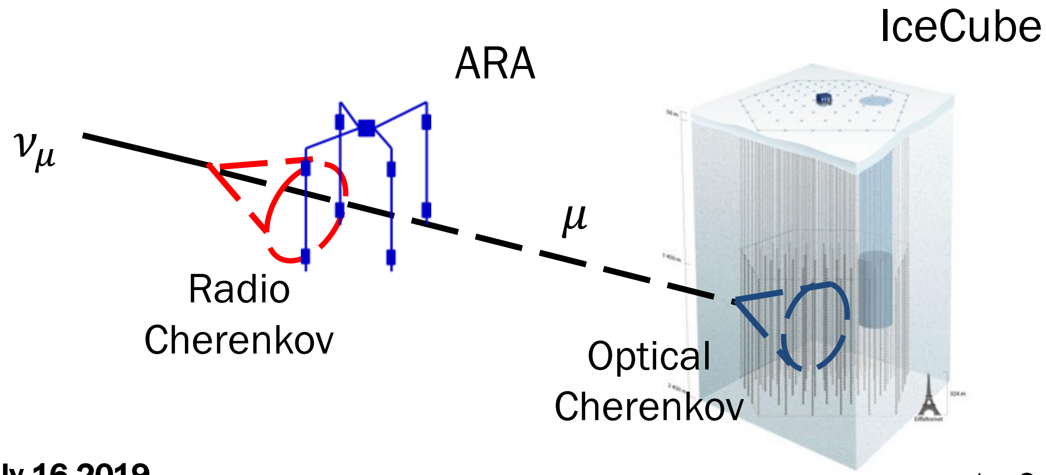
RF circuit board mill.

Large thermal chamber.

What's New

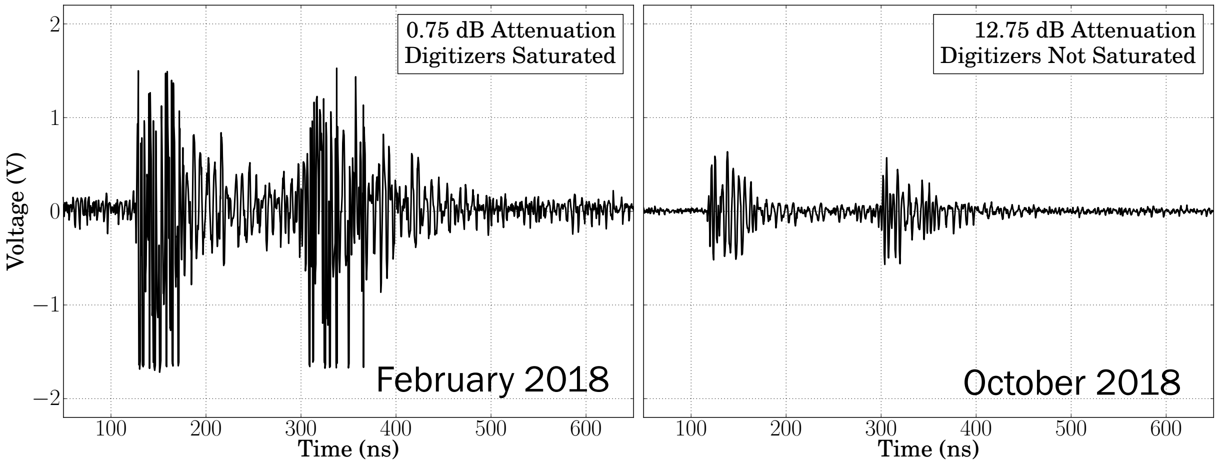
ARA Smart Power System (ASPS)

- Power broker enables granular control of subsystems
  - No IceCube intervention in ARA power systems
  - Only 5 station-wide "hard" restarts
- Precision Time Protocol—could sync ARA to IceCube clock



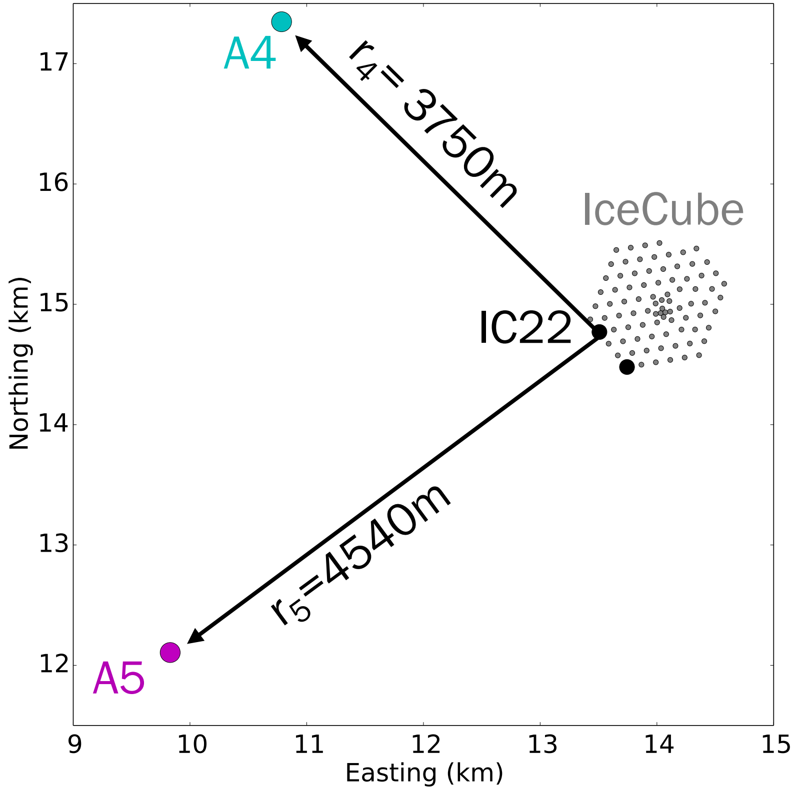
ARA Front End (ARAFE)

- Cheaper, more compact signal conditioning modules
- Contains bank of tunable attenuators to increase dynamic range of instrument
  - EX: prevent saturation of digitizers



Tunable Attenuators: Application

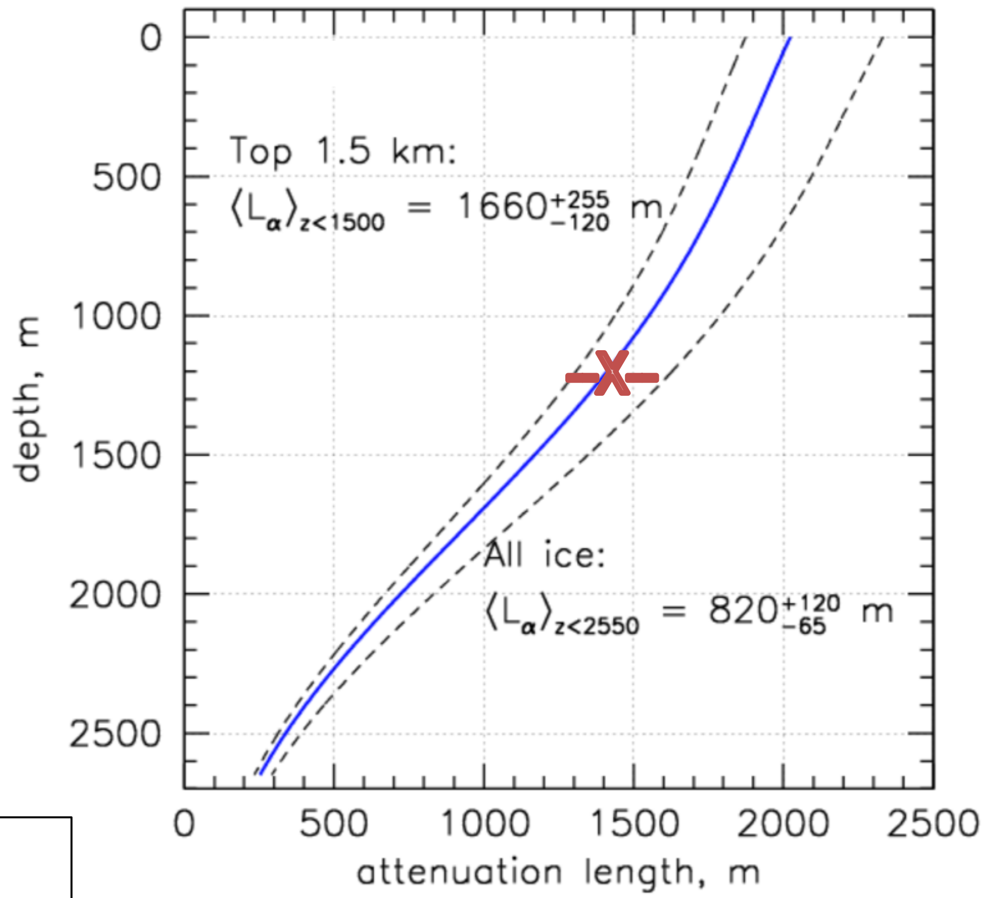
- With *non*-saturated digitizers, pulse amplitude at A4 vs A5 gives the longest horizontal-baseline measurement of L_α



$$\frac{SNR_{A5}}{SNR_{A4}} = \frac{r_4}{r_5} e^{\frac{r_4 - r_5}{L_\alpha}}$$

New measurement:
$L_{\alpha,1500m} = 1.43 \pm 0.25$ km

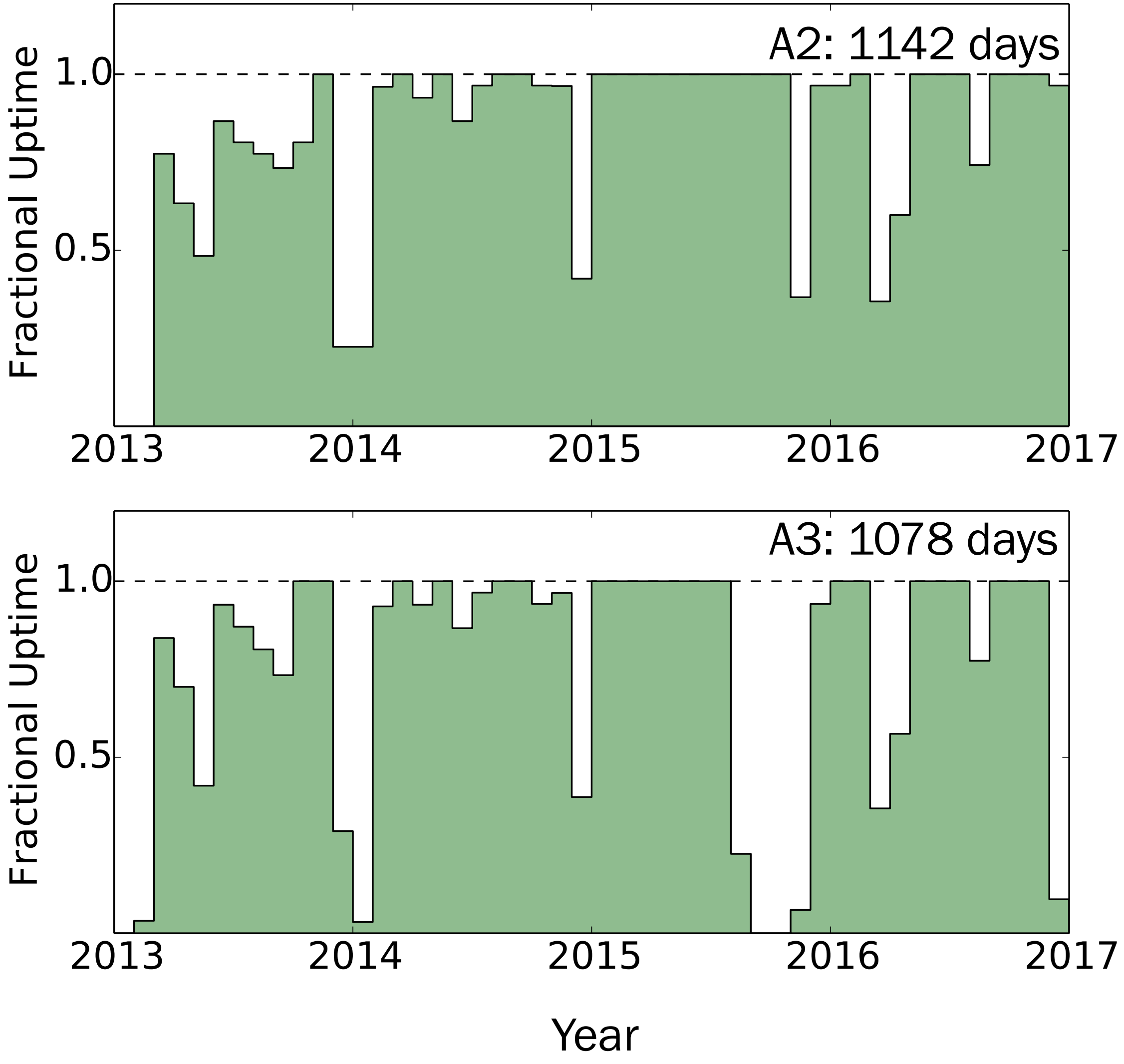
Adapted from [P. Allison *et. al.* j.astropartphys.2011.11.010]



*Measurement by Dave Besson at KU

Context

- Presenting expansion to 2013-2016 data set in A2 (A3 underway also)
- Analysis is done “boxed”—tune cuts on 10% of data, remaining 90% sets the limit
- Data is split into five *configurations*
- **Big data**
  - 58 million events in 10% sample
  - Nearly 40 TB of data in 100% sample

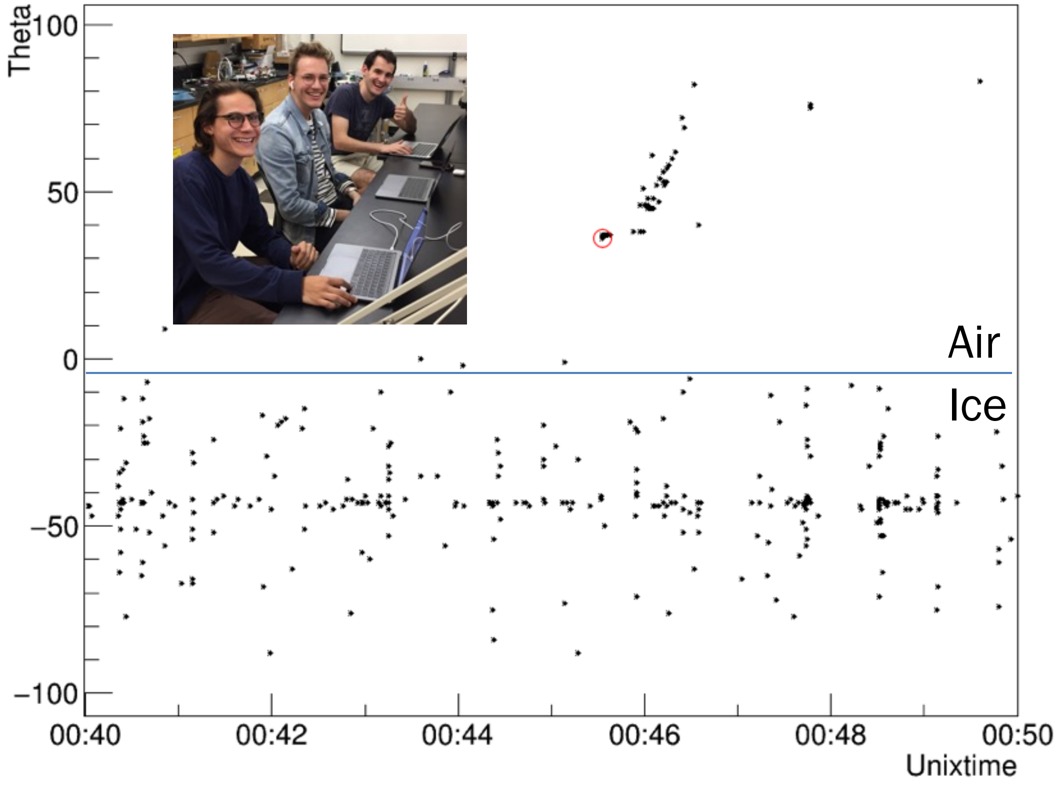


Run and Livetime Rejection

- Reject *runs* with known calibration activity—e.g., surface pulsing and visibly identifiable a anthropogenic activity

- We analyze ~98% of our total recorded livetime; substantial improvement over Testbed (~62%)

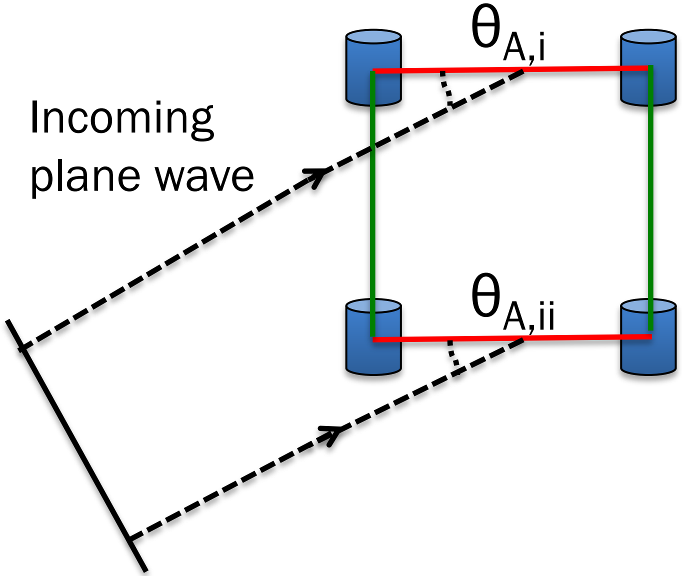
Config	Total Livetime (days)	Good Livetime (days)	Fraction
1	185.08	179.62	97%
2	143.58	143.57	99%
3	100.07	94.45	94%
4	413.01	409.86	99%
5	265.73	263.76	99%



Run 6507 HPol
Reconstructions Theta Vs Time

Wavefront-RMS Filter

- ARA records $>10^8$ events/year– need fast rejection algorithm
- Leverage regular geometry and divide station into *faces*
- Expect *wavefront-RMS* = $\log_{10}$(RMS(cosθ)) to be small for real signals, and larger for thermal noise



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

$$\downarrow$$

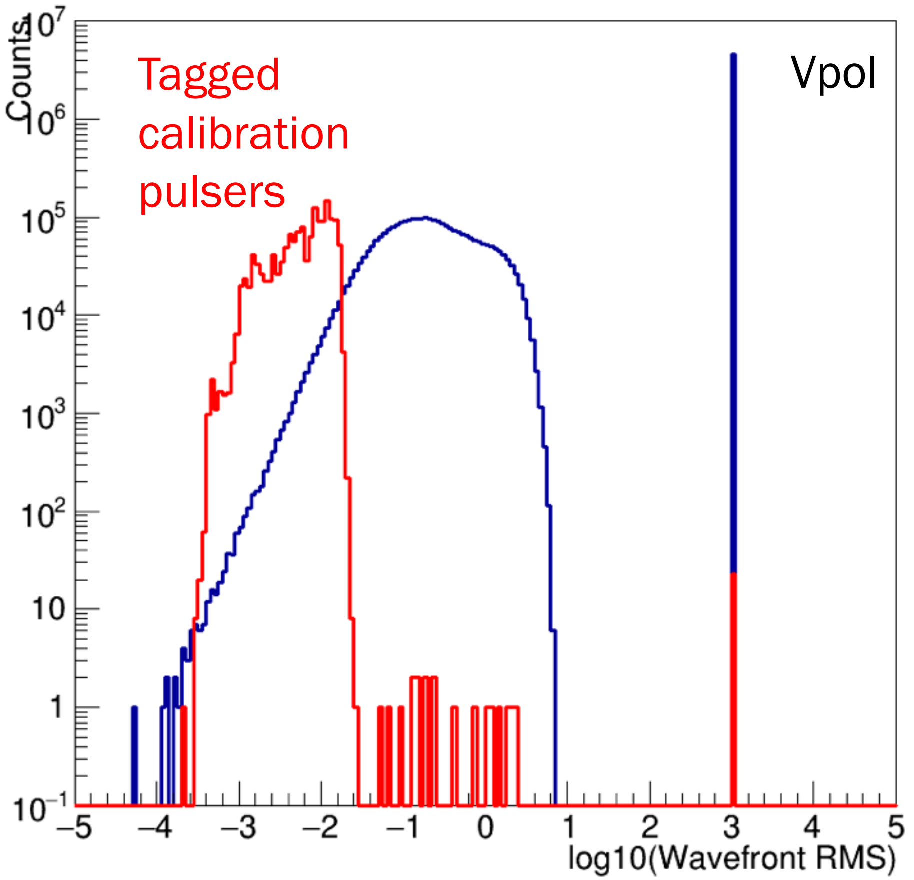
$$\cos(\theta_{A,i}) \approx \cos(\theta_{A,ii})$$

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

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

Wavefront-RMS Filter

- Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol

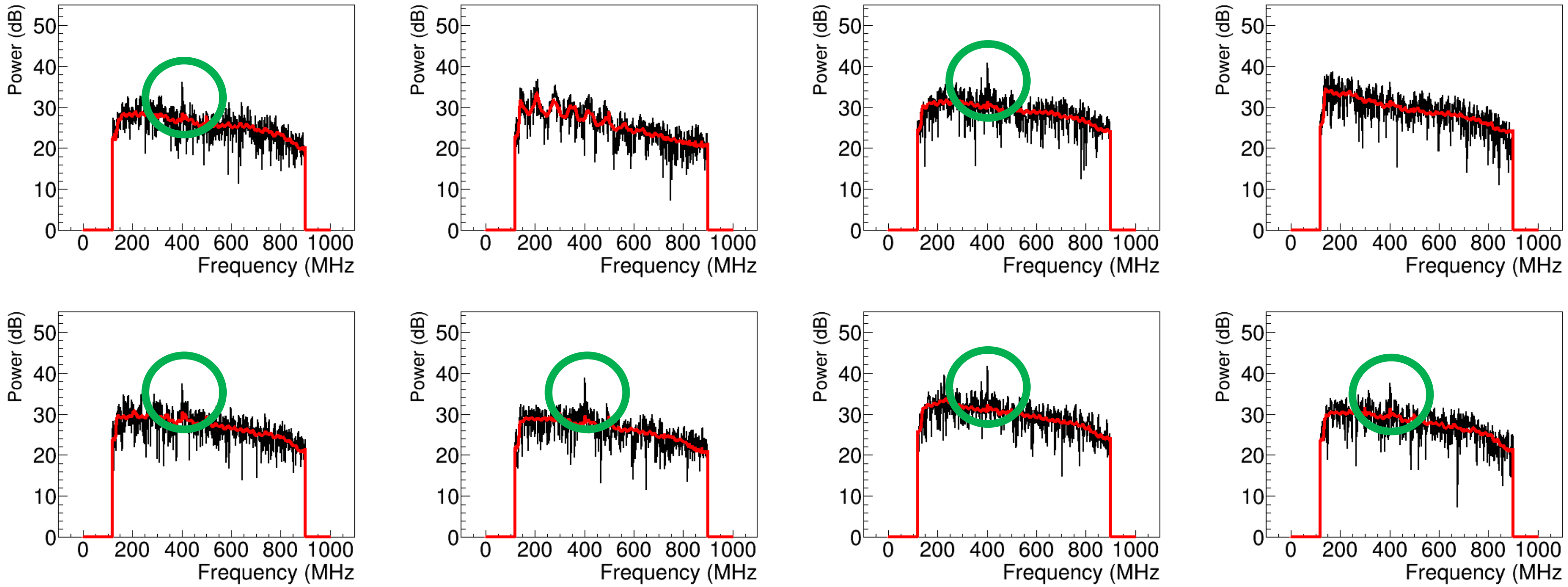


Config	V Efficiency (%)	H Efficiency (%)	H or V Efficiency (%)
1	74.7	58.0	89.8
2	69.8	48.1	85.2
3	75.6	58.1	91.1
4	75.0	58.7	90.4
5	76.4	59.4	91.7

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



Reconstruction

- Perform interferometric reconstruction
  - – Sky point (θ, ϕ) defines a delay τ
  - – Compute correlation $C_{i,j}$ between two antennas for that τ

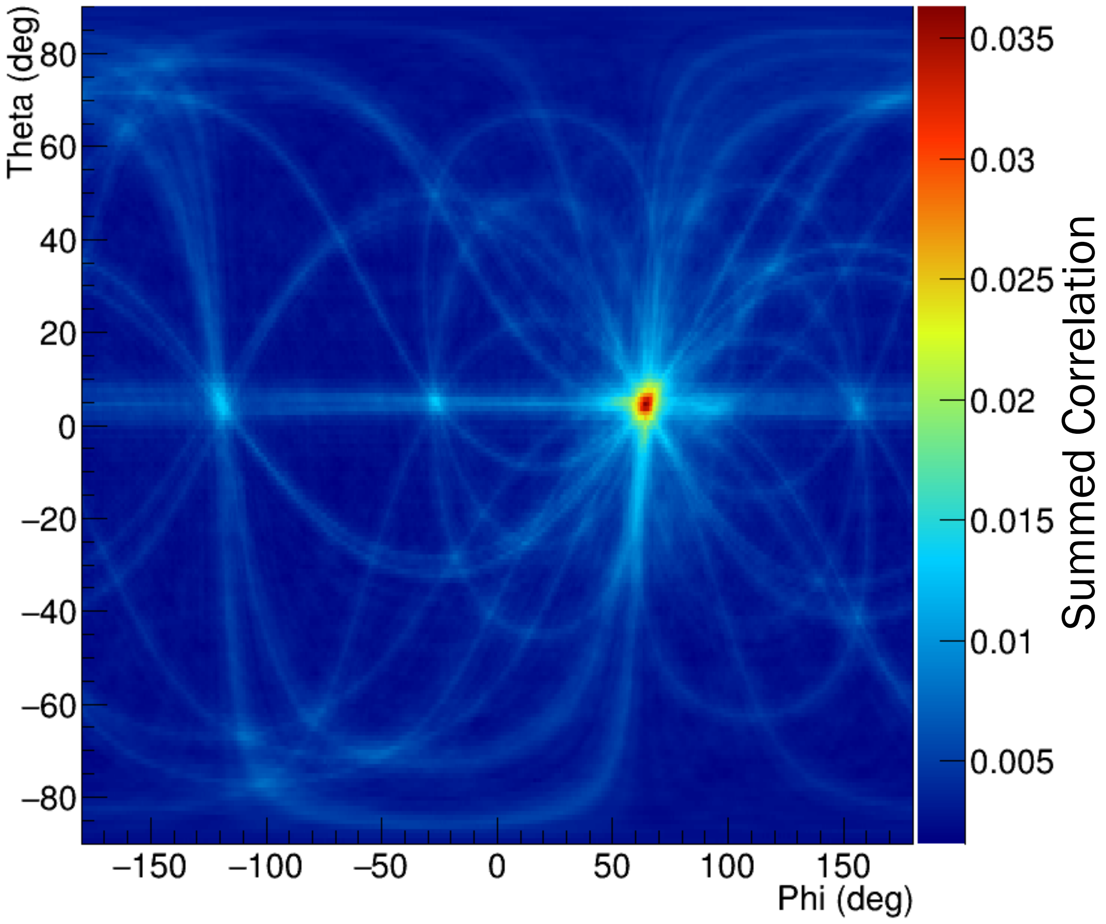
$$C_{i,j}(\tau) = \frac{SNR_i \times SNR_j \times \sum_{t=-\infty}^{\infty} V_i(t)V_j(t+\tau)}{N_{overlap} \times RMS_i \times RMS_j}$$

  - – Sum over pairs of antennas

$$C_{sky}(\theta, \phi; R) = \frac{1}{\sum_{i=1}^{n_{ant}-1} \sum_{j=i+1}^{n_{ant}} SNR_i \times SNR_j} \sum_{i=1}^{n_{ant}-1} \sum_{j=i+1}^{n_{ant}} C_{i,j}[\tau(\theta, \phi; R)]$$

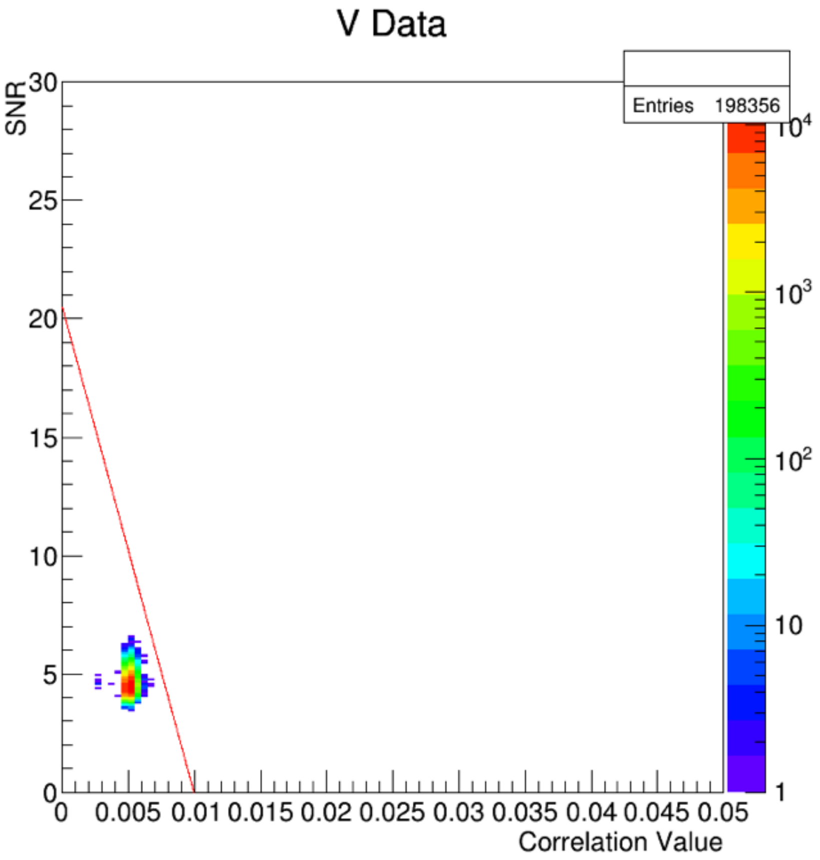
- Cut events that reconstruct to surface or in direction of pulser

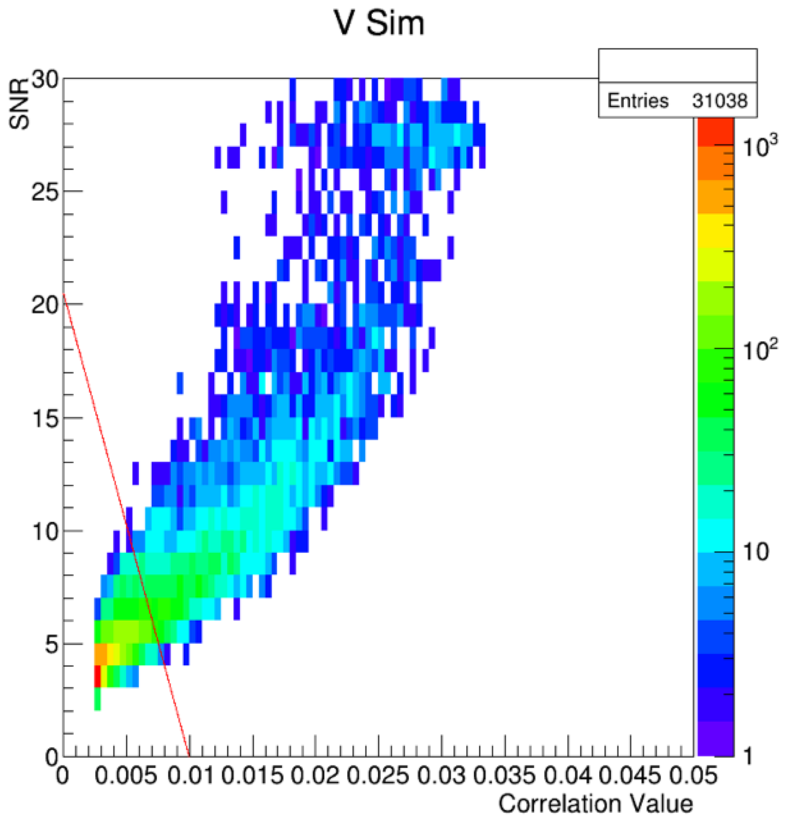
Example Calibration Pulser Event

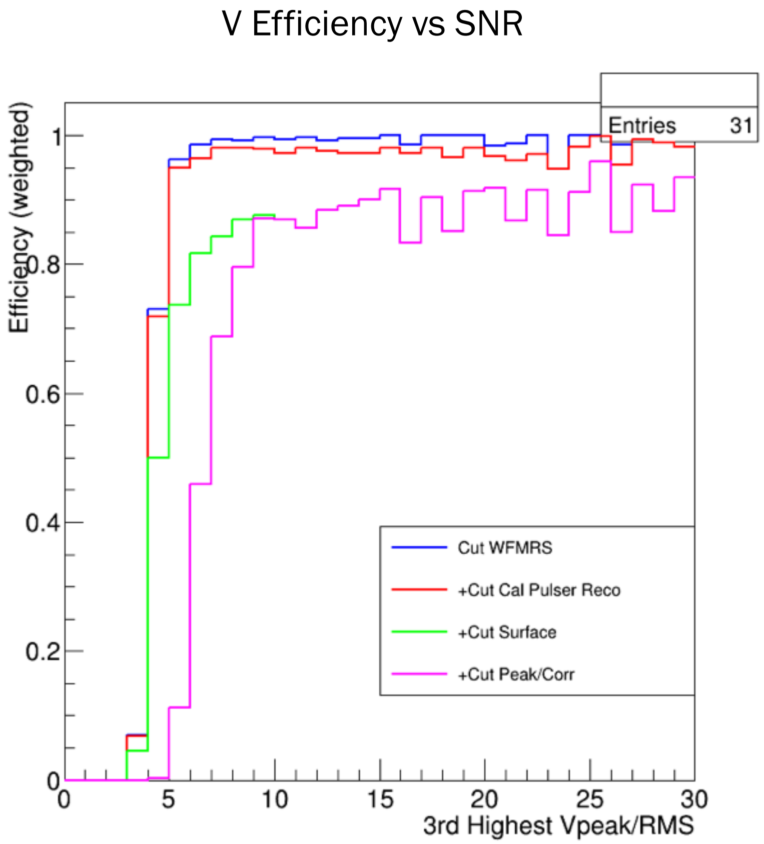


Final Cut

- Final cut of the analysis is a slanted-line; slope (*m*) and y-intercept (*d*) are optimized to set the best limit

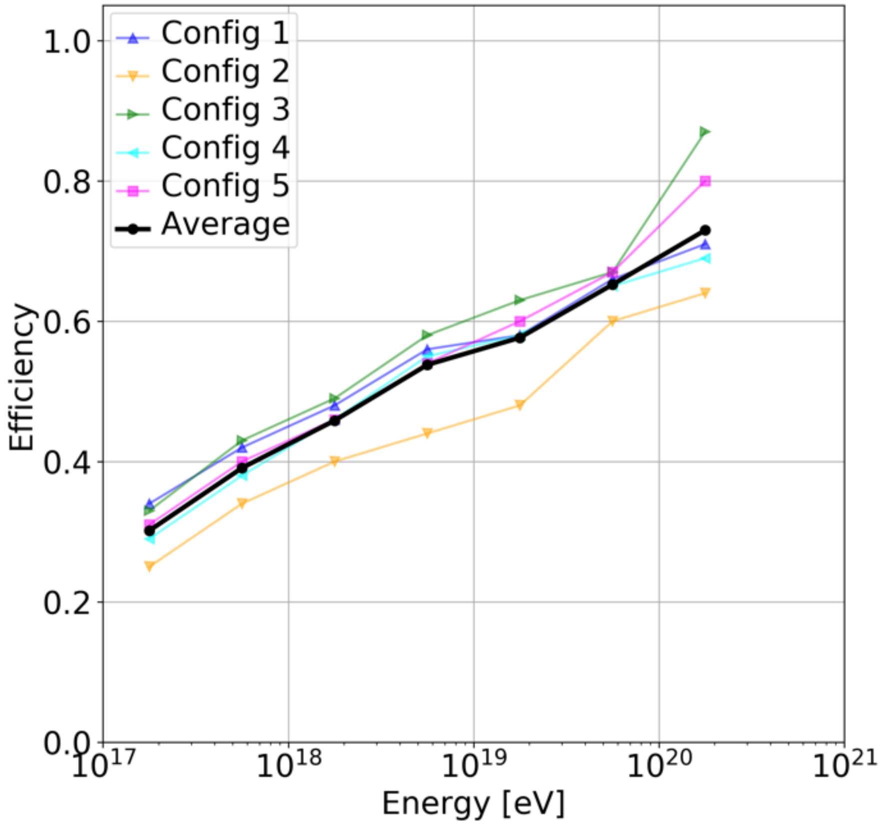


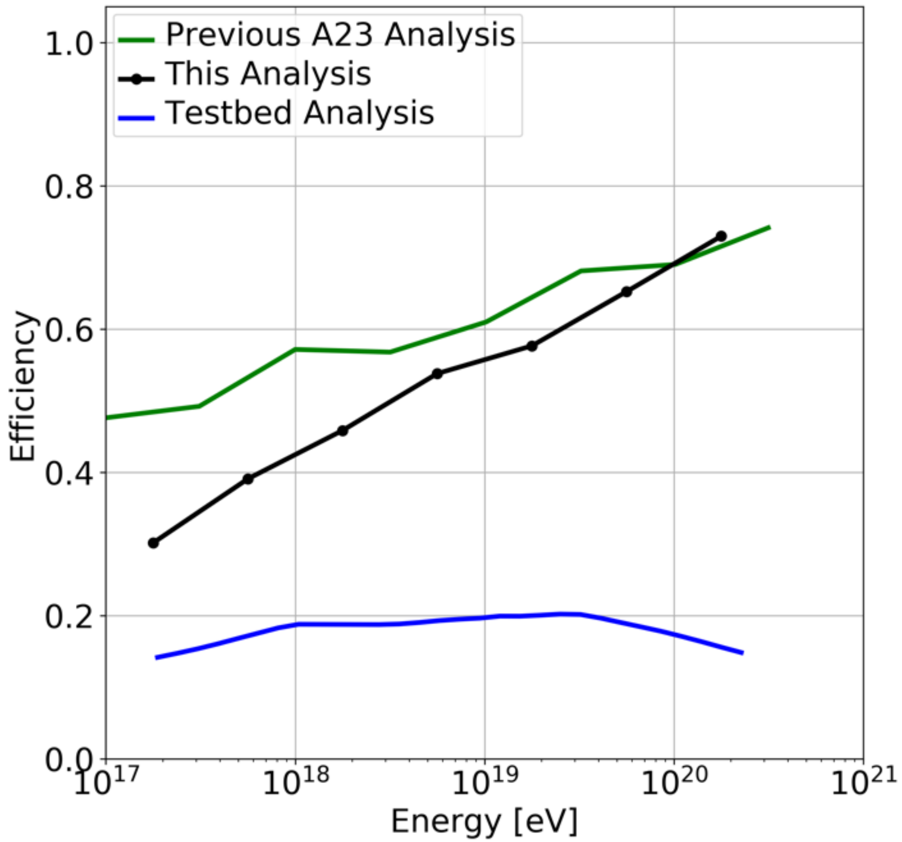




Efficiency

- Between 2 and 4 times more efficient than Testbed analysis
- Competitive with that of previous A23 analysis



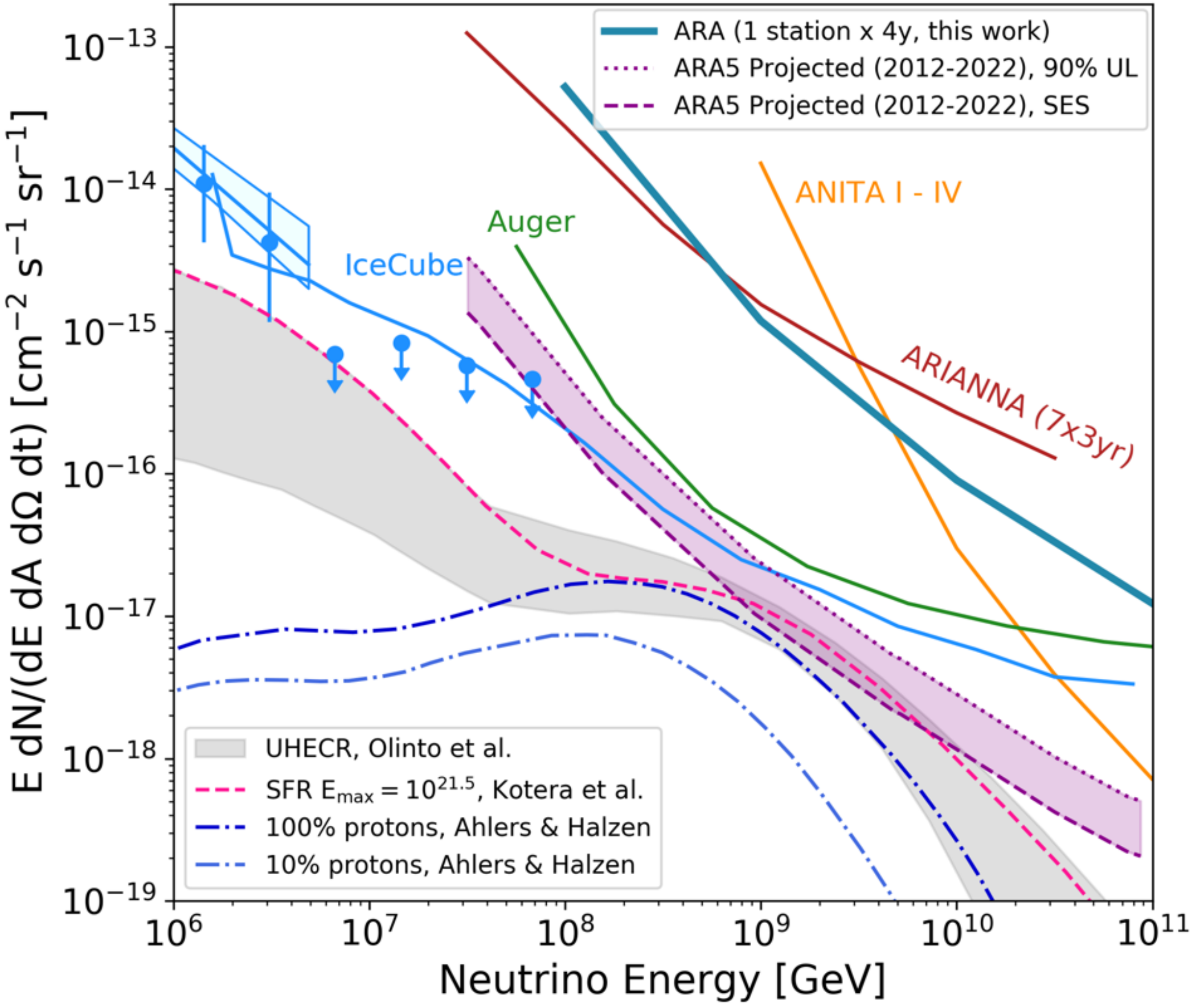


Expected Limit

- Expect to observe 0.085 neutrinos from *Kotera* max flux

- Background of $1.04\times10^{-2}{}^{+0.29}_{-0.36}$ in VPol and $1.57\times10^{-2}{}^{+0.26}_{-0.29}$ in Hpol

Projected ARA sensitivity carves out exciting new parameter space, w/ real chance at a detection!



Summary

1. ARA has an expanded array with more *in-situ* control than ever before
2. Station 2 analysis is nearly complete, with A3 analysis close behind
3. Projections for ARA show us closing in on world leading limits and the real chance for a discovery of a UHE neutrino

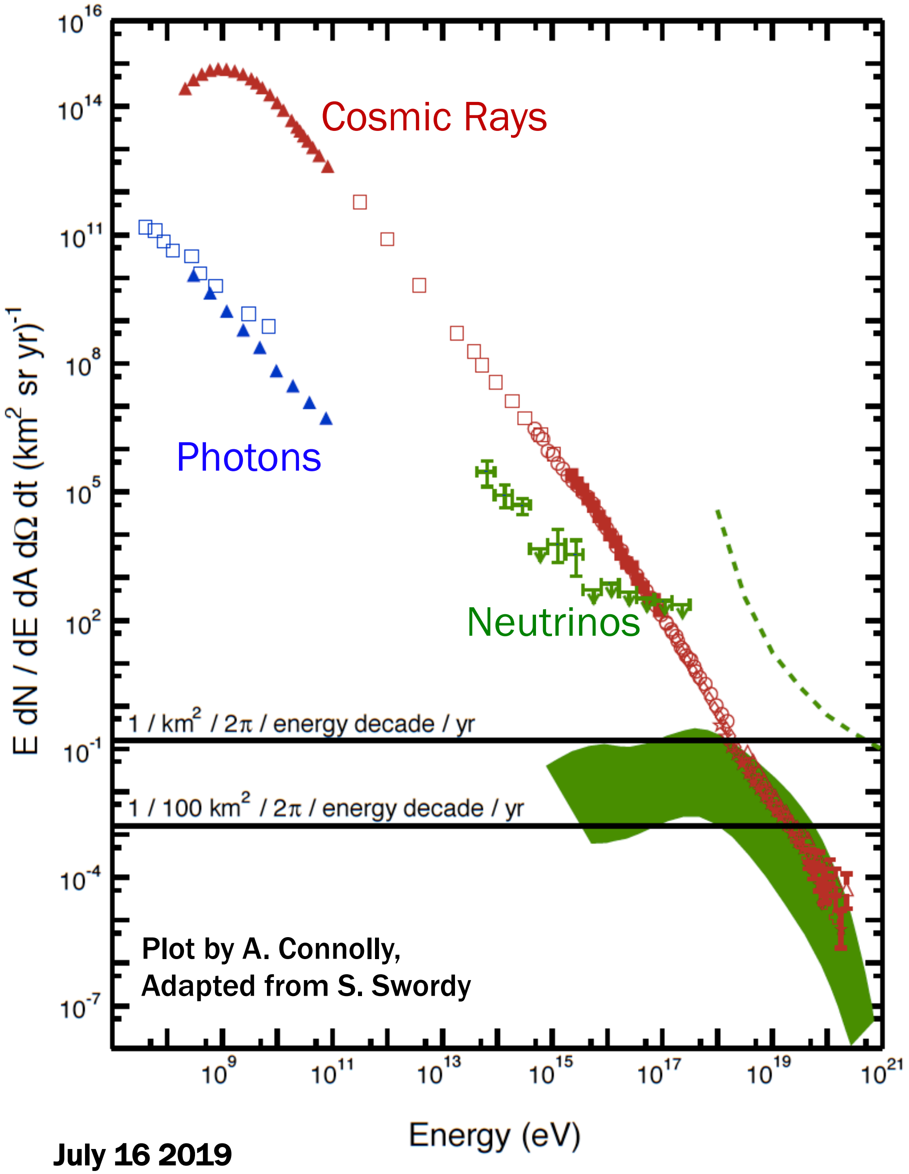
The OSU ARA Team is generously supported by:

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

Back-up Slides

High-Energy CR Spectrum

Swordy Plot



Plot by A. Connolly,
Adapted from S. Swordy

Neutrino Interactions

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

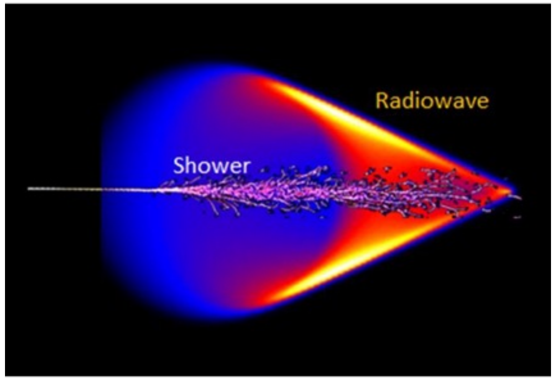
CC: $\nu_\ell + N \rightarrow \ell + X$

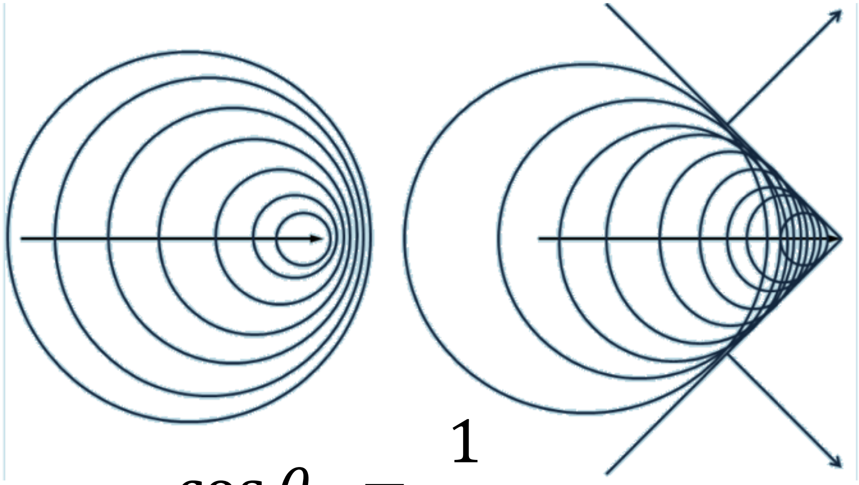
$\ell \rightarrow EM\ Shower$

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

$X \rightarrow Hadronic\ Shower$

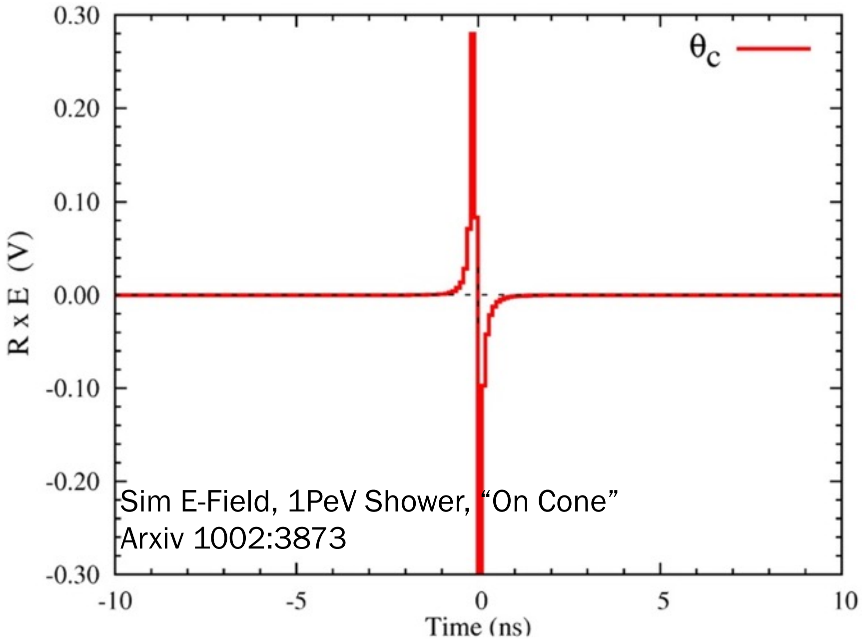
- Showers are ultra-relativistic ($\beta \approx 1$) ⟶ emit Cherenkov radiation in dense media
- Intensity is greatest at Cherenkov angle θ_C
- Two varieties of interest: optical and radio



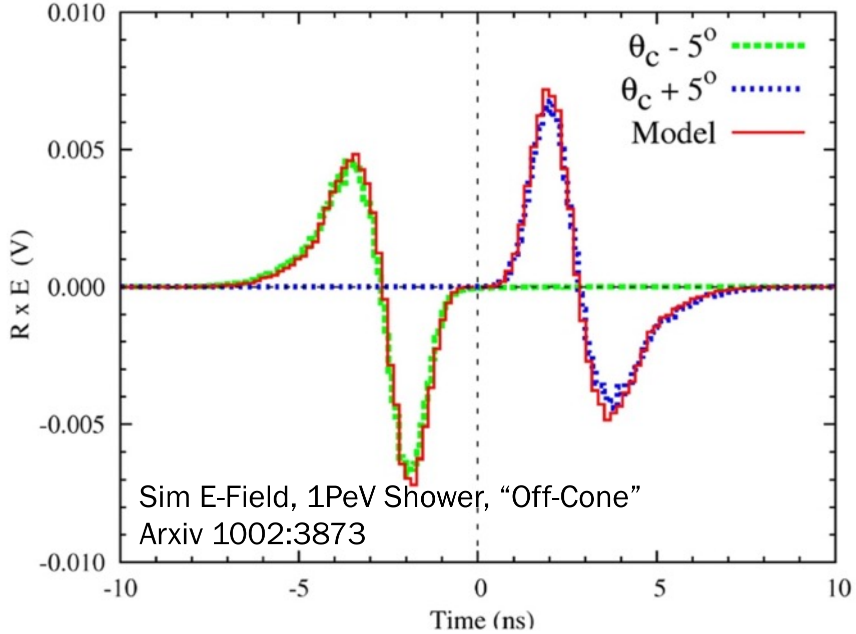


$$\cos\theta_C = \frac{1}{n\beta}$$

Askaryan Pulse Shape and Dependencies



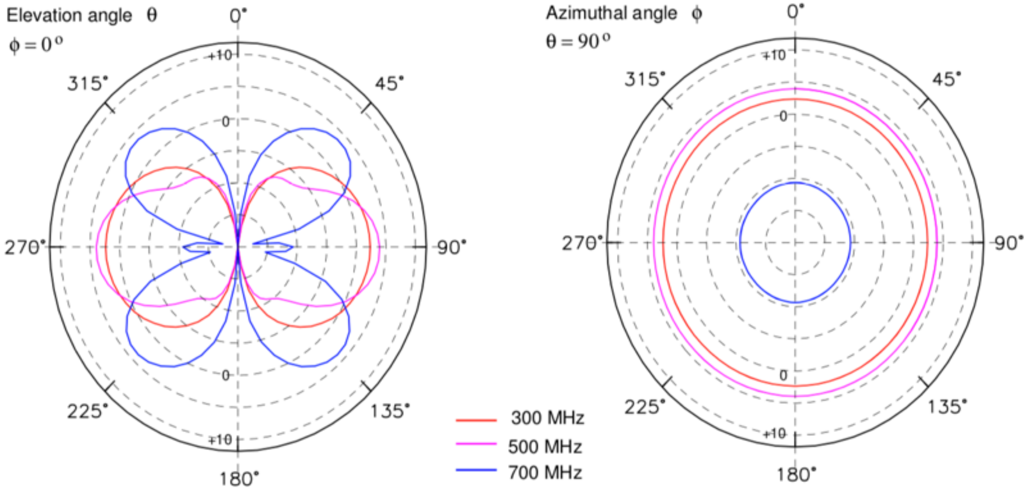
Sim E-Field, 1PeV Shower, "On Cone"
Arxiv 1002:3873

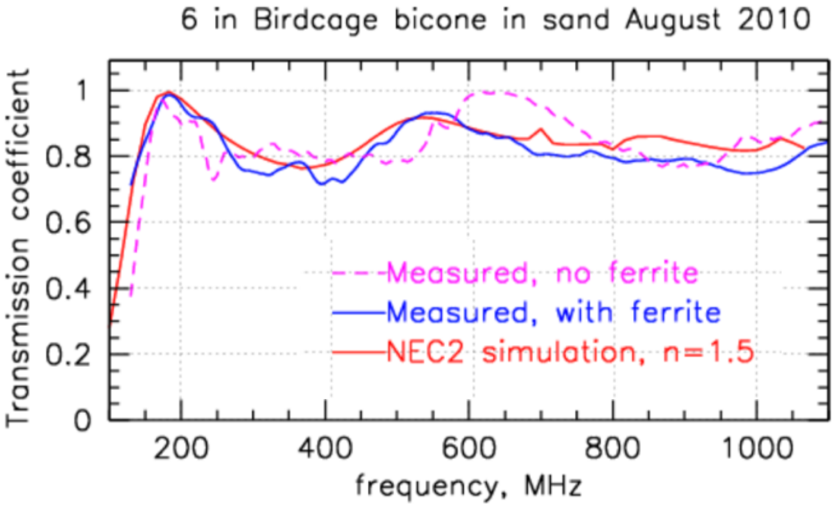


Sim E-Field, 1PeV Shower, "Off-Cone"
Arxiv 1002:3873

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

ARA Antennas

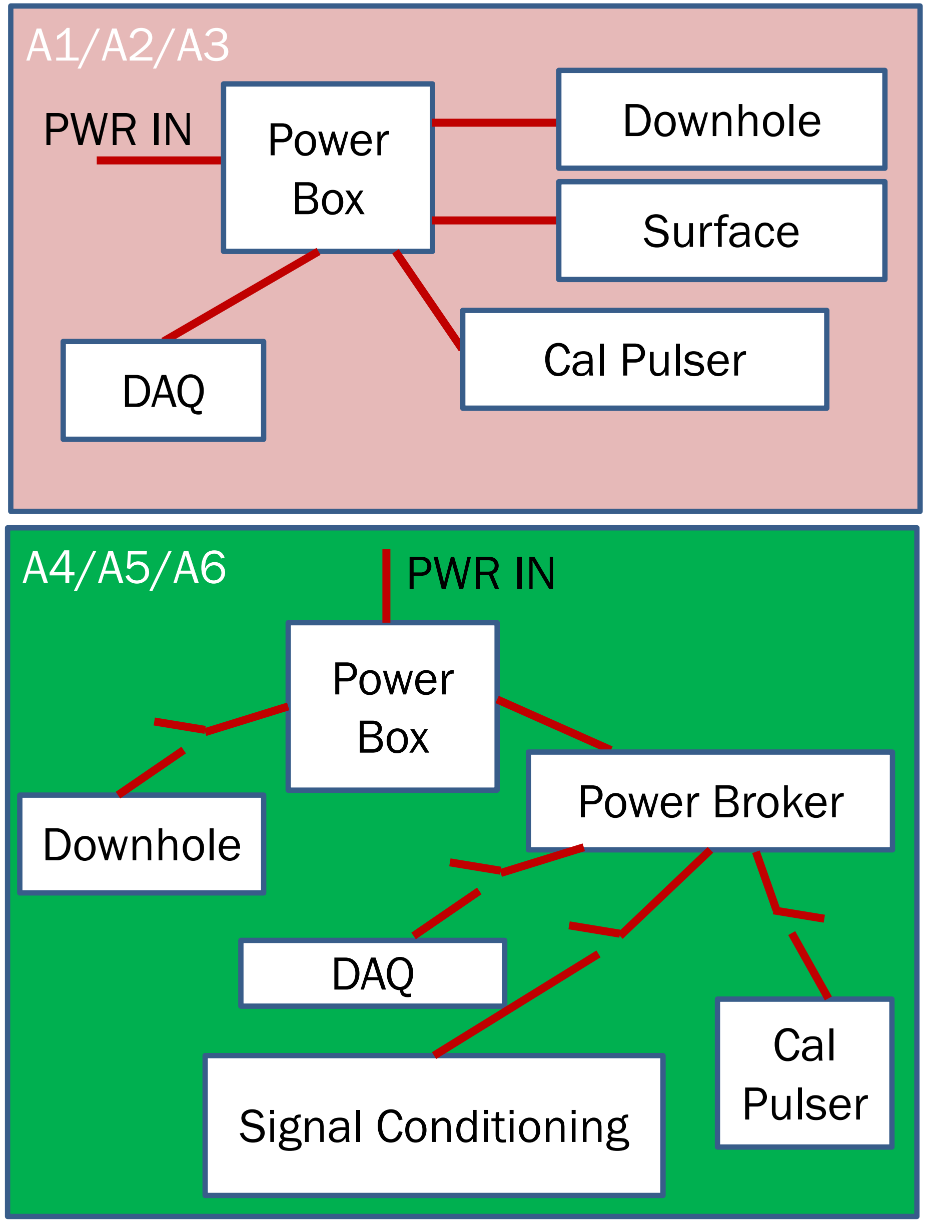




V-Pol Antenna **H-Pol Antenna**

New Power Distribution

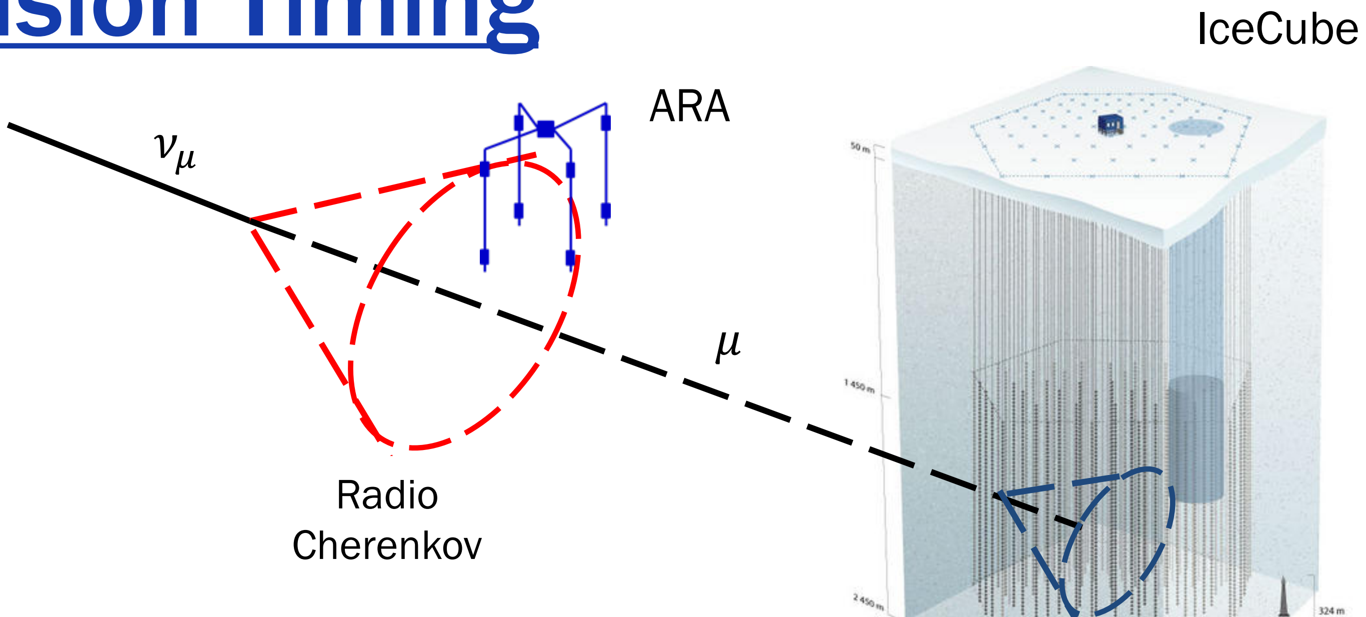
- Introduced power broker: the ARA Smart Power system (ASPS)
- Old power systems had no granularity
  - A short anywhere compromised the entire station
  - Power cycling subsystems required power cycling whole station—not ideal
- Granularity is powerful—since deployment:
  - No IceCube winter-over intervention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



Precision Timing

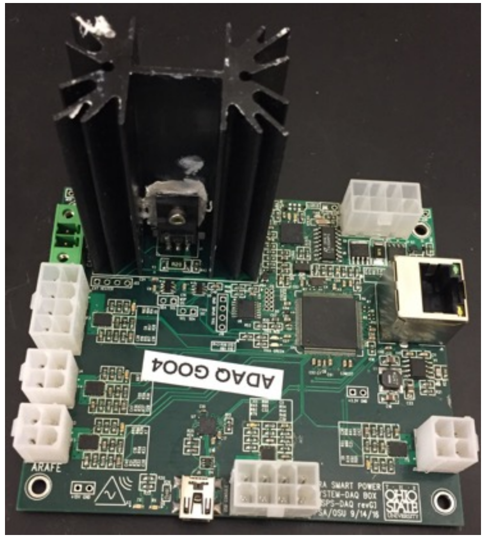
- Happy opportunity: new power broker is equipped with Precision Time Protocol

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



Radio Cherenkov

Optical Cherenkov

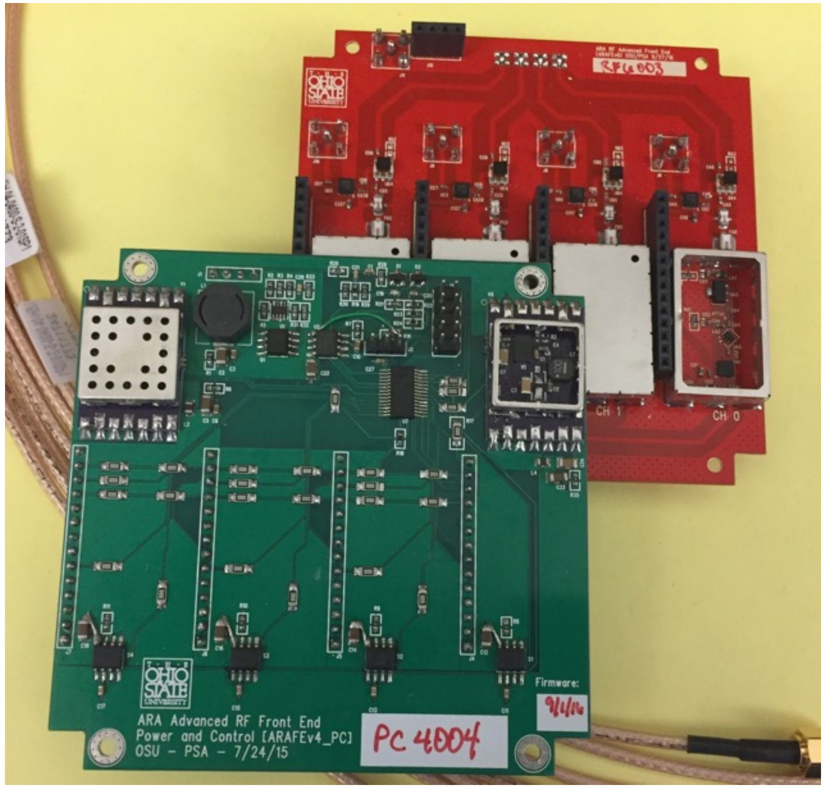


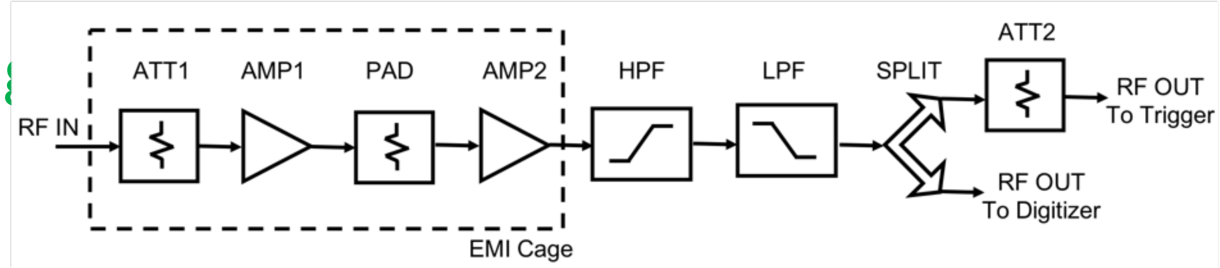
* = part of postdoc plan at MSU w/ IceCube….

New Signal Conditioning

- Old stations have static, physically fragile, and expensive (~$2k/chan) signal conditioning

- New modules, ARAFE, are cheaper (~$300/chan) and have per-channel tunable attenuators
  - Enables *in-situ* gain matching between channels (currently un-utilized)
  - Allows for “high attenuation” data takin periods





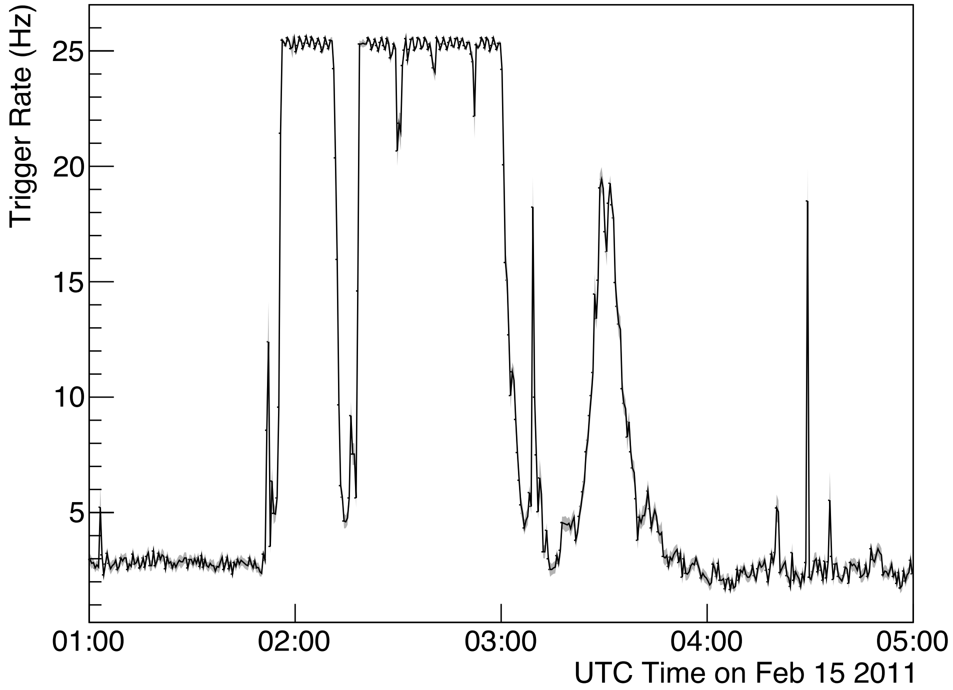
2: Test on Natural Phenomenon

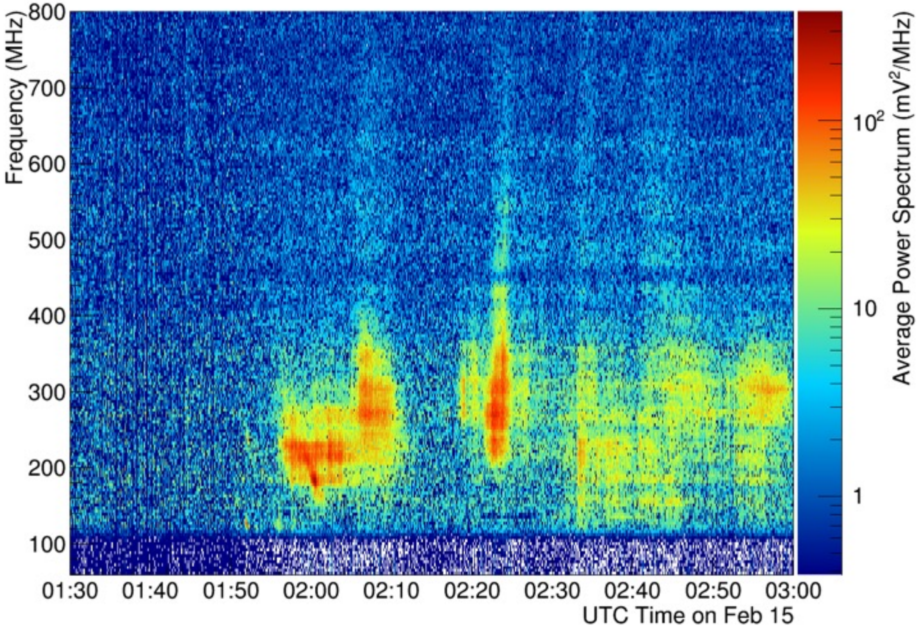
Observation of Reconstructable Radio Emission from Solar Flare

“Observation of Reconstructabe Radio Emission in Coincidence with an X-Class Solar Flare in the Askaryan Radio Array Prototype Station”
arXiv 1807.03335

Feb 15, 2011 Solar Flare

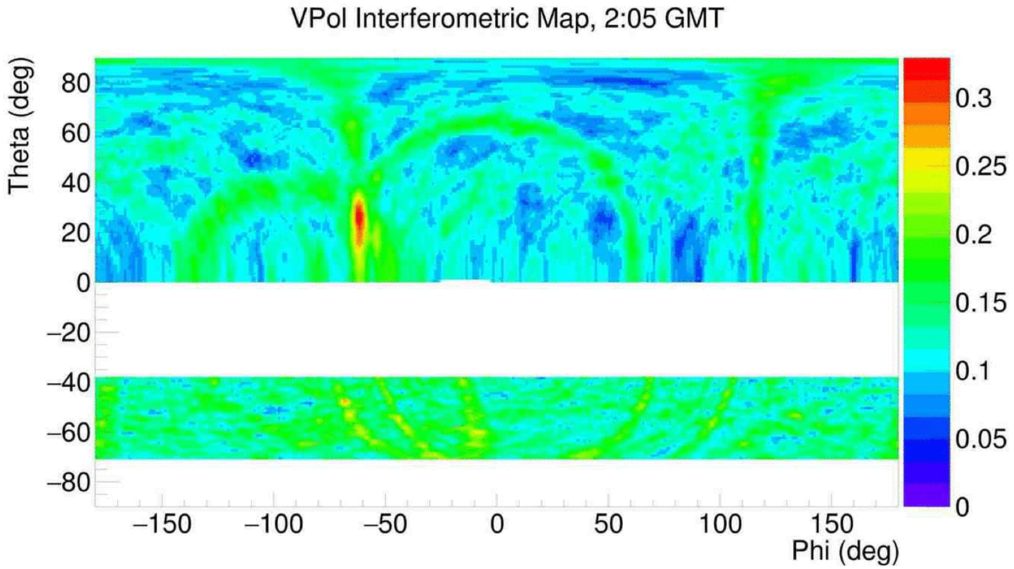
- Testbed activated in February 2011, detected Feb 15 X-2.2 Solar Flare
- Saturates the triggering system
- Observed as excess emission from 100-500 MHz

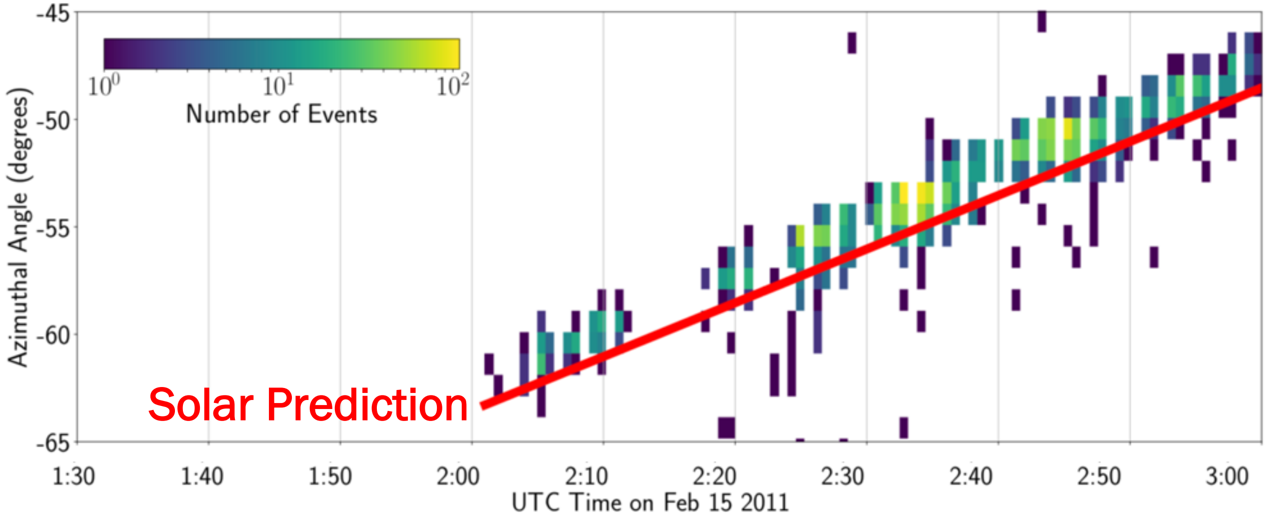




Solar Tracking

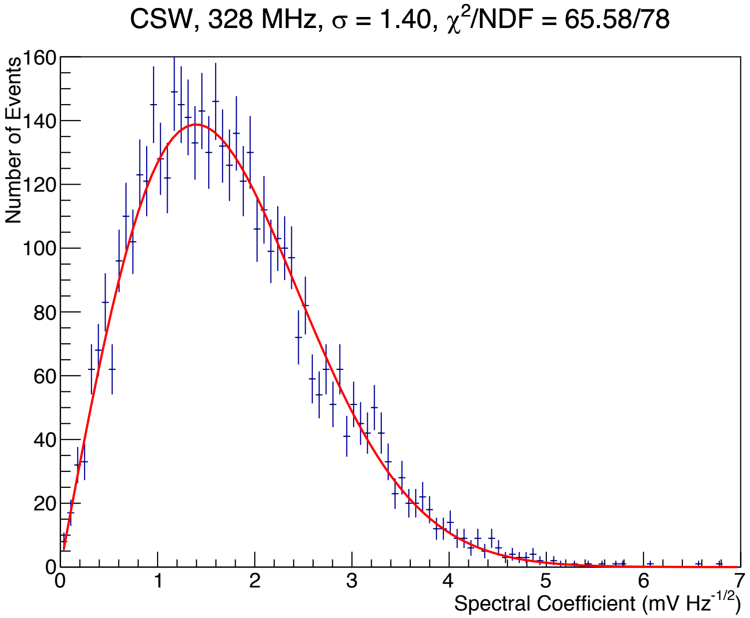
- Recorded events point back to the sun for the hour duration of the flare
- First radiation for ARA which reconstructs to extraterrestrial source on event-by-event basis
  - Excellent test of projection onto celestial coordinate system
  - Will help calibrate pointing of other above-ice radio sources,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

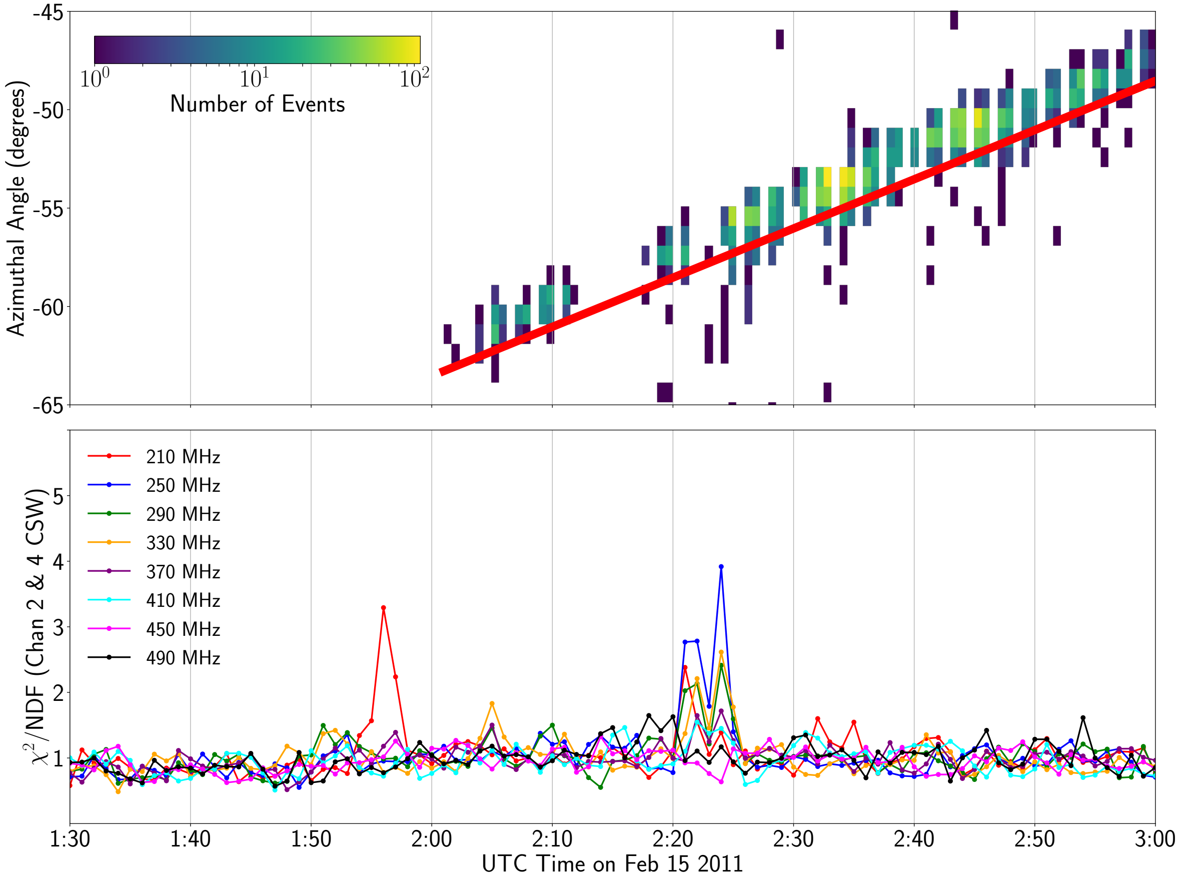




Reconstructability

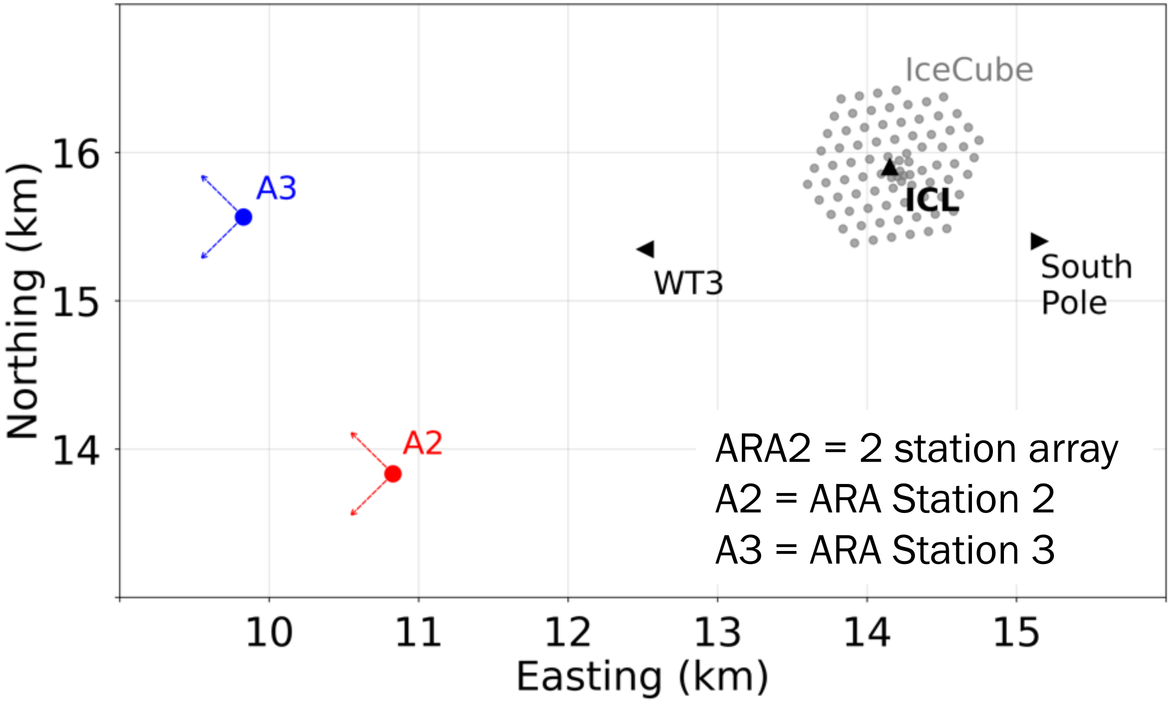
- All antennas observe same noise that was generated at the sun and traveled to earth


CSW, 328 MHz, σ = 1.40, χ^2/NDF = 65.58/78

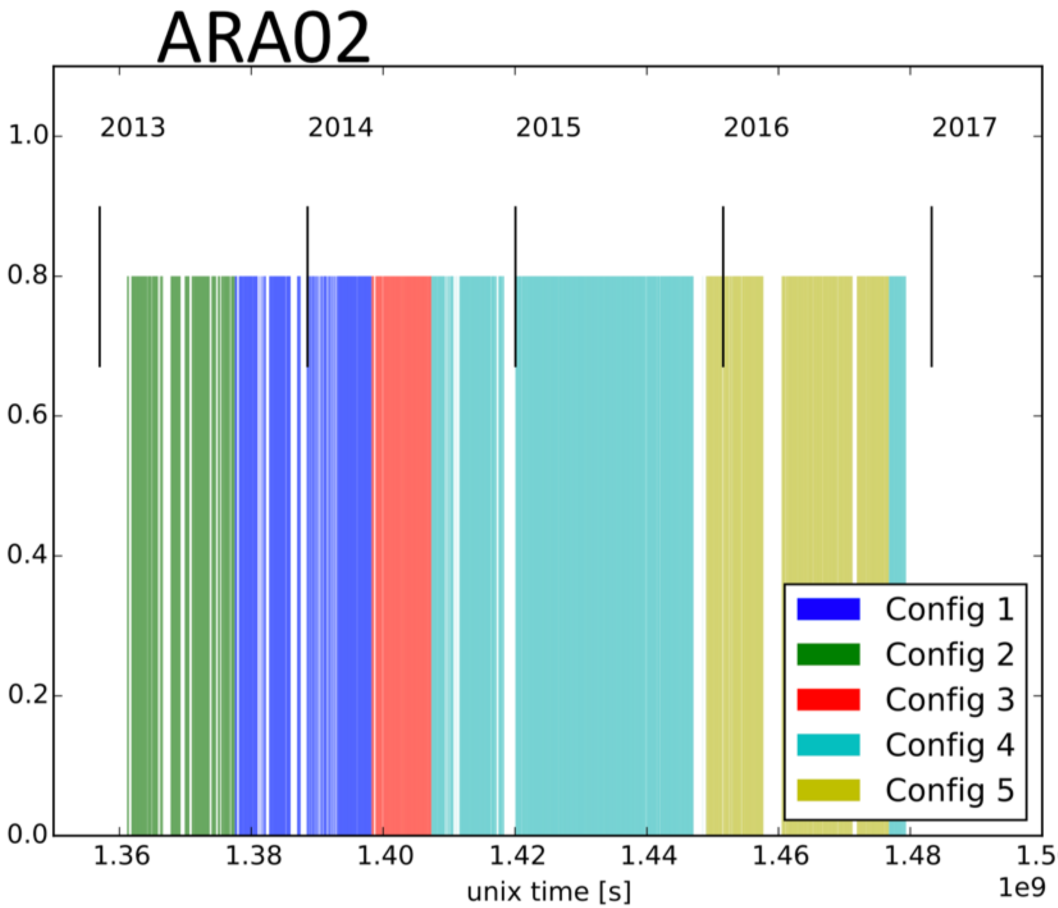


- Events only track sun when they are well described by thermal noise

The ARA2 Instrument



ARA2 = 2 station array
A2 = ARA Station 2
A3 = ARA Station 3



Full List of Exluded Runs in A2

- Reject any period of livetime with known/logged calibration activity
  - 2014 Surface Pulsing: runs 2284-2918, 2938-9
  - 2014 ICL Rooftop Pulsing: runs 3120, 3242
  - 2014 Cal Pulser Sweep: 3139-3162, 3164-3187, 3289-3312
  - 2014 L2 Scaler Mask Study: 3464-3504
  - 2014 Trigger Window Scan: 3578-3598
  - 2015 ICL Deep Pulsing: 4785, 4787, 4795-4800
  - 2015 Cal Pulser Noise Tests: 4820-5, 4850-4, 4879-4936, 5210-5277
  - 2015 Surface Pulsing: 4872-3,6
  - 2015 A2 Pulser Lift: 6513
  - 2015 ICL Rooftop Pulsing: 6527
  - 2016 Cal Pulser Sweep: 7625-7686

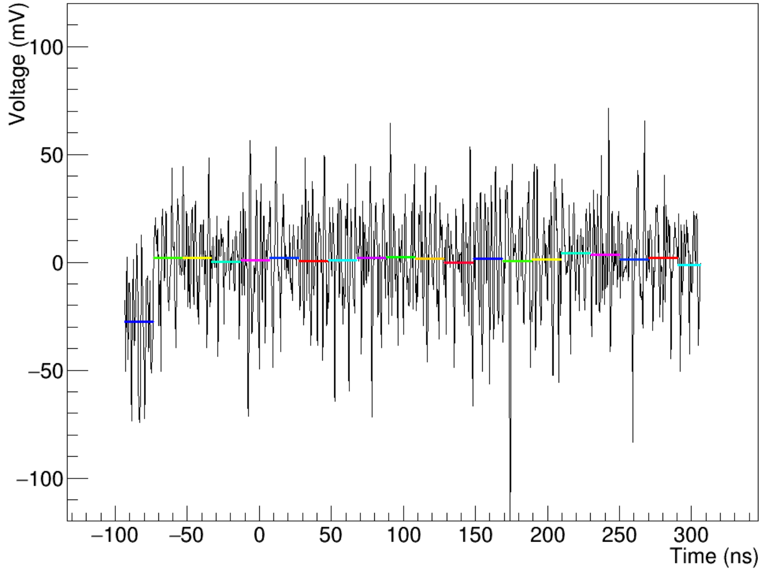
Configuration Settings

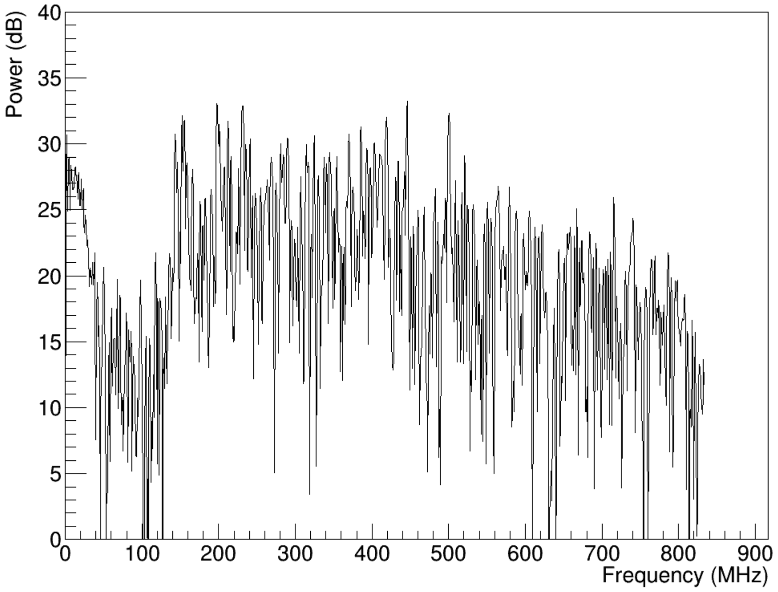
- Data is split into five *configurations*

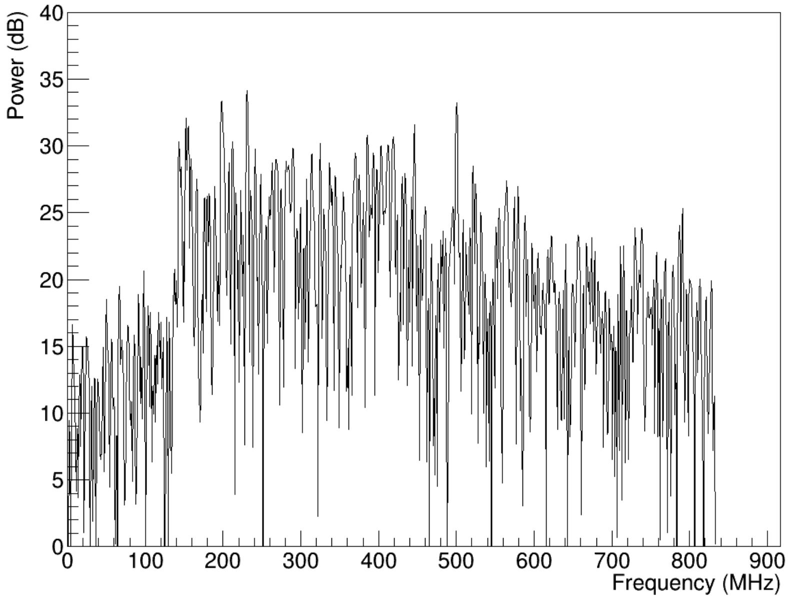
Config	L1 Trig Mask	Readout Window (ns)	Trigger Window (ns)	Trigger Delays	Livetime (days)
1	None	400	110	yes	185.08
2	None	400	110	no	143.58
3	D4BH	400	110	yes	100.07
4	D4BH	520	170	yes	413.01
5	D4BH	520	170	no	265.73

Data Conditioning

- Data must be *conditioned*
  - First block must be removed, and remaining blocks given zero mean
  - In A3, channels 3, 8, and 11 require waveform inversion
- I implemented in a standard way: `AraEventConditioner`

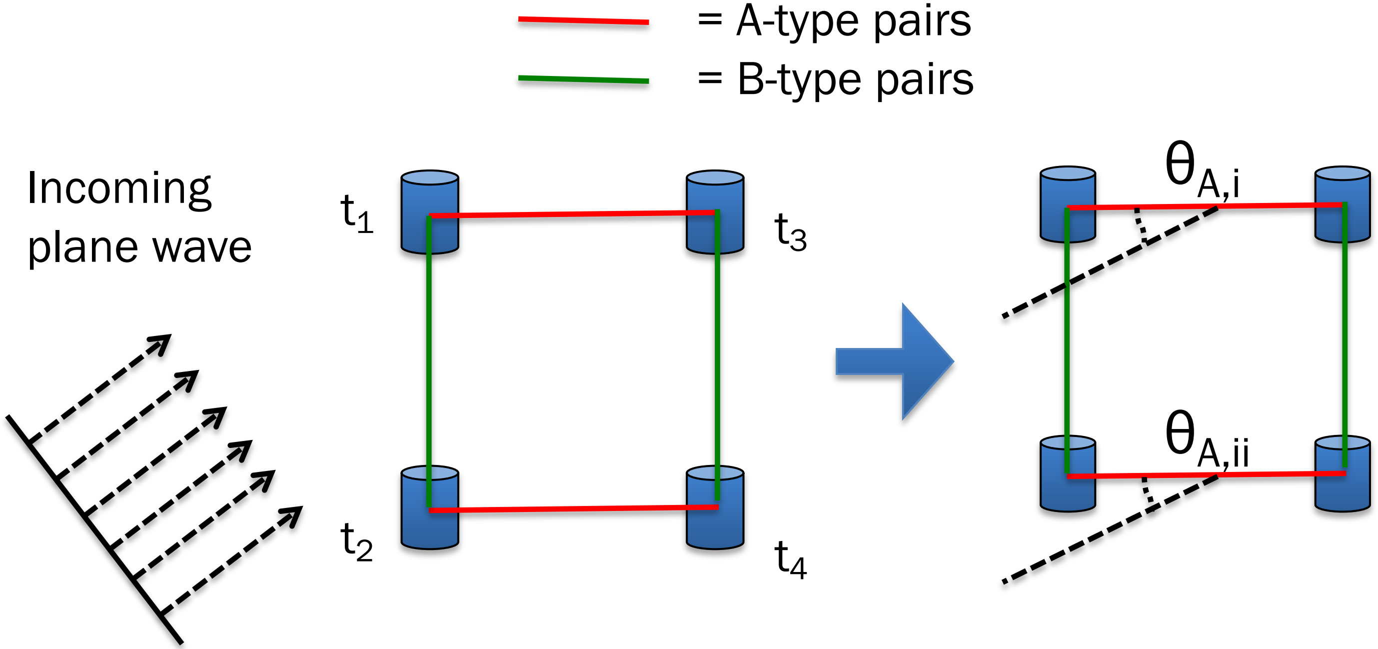

Run 2818, Event 10, Channel 5


Before first trim and zero-mean


After trim and zero mean

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



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

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

$$\begin{tikzcd} & \cos(\theta_{A,i}) \approx \cos(\theta_{A,ii}) \\ \Delta t_{A,i} \approx \Delta t_{A,ii} \arrow[r] & \theta_{A,i} \approx \theta_{A,ii} \arrow[u] \end{tikzcd}$$

Wavefront-RMS Filter

- Find the RMS around the average arrival angle

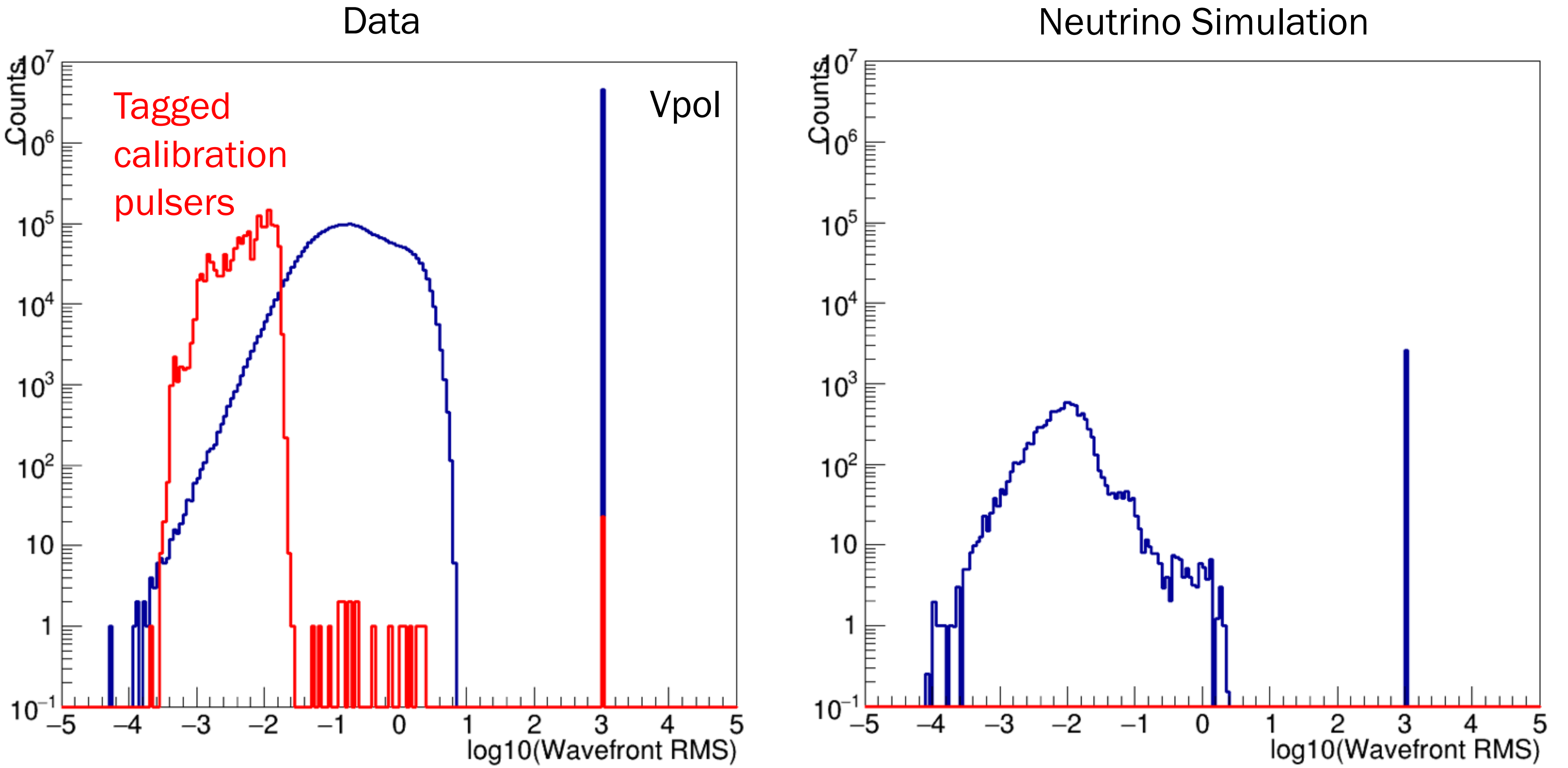
$$\overline{\cos(\theta_A)} = \frac{\cos(\theta_{A,i}) + \cos(\theta_{A,ii})}{2}$$

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

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

Wavefront-RMS Filter

- Performance on VPol data and simulation from A2 configuration 1



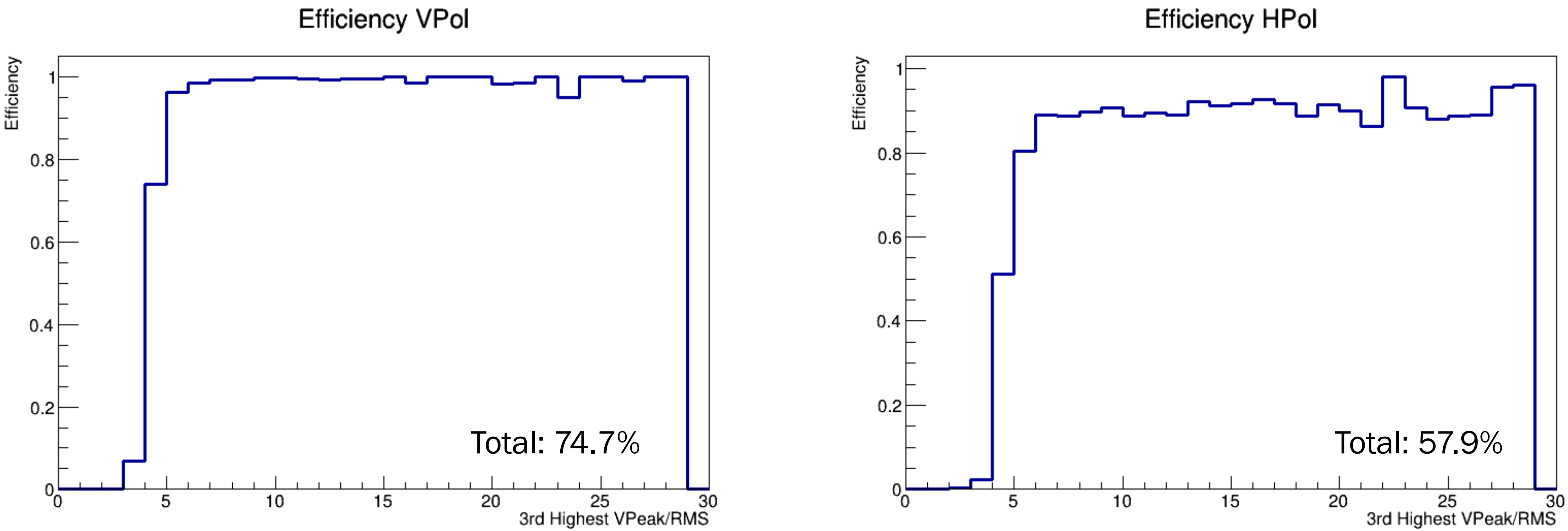
Wavefront-RMS Filter

- 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

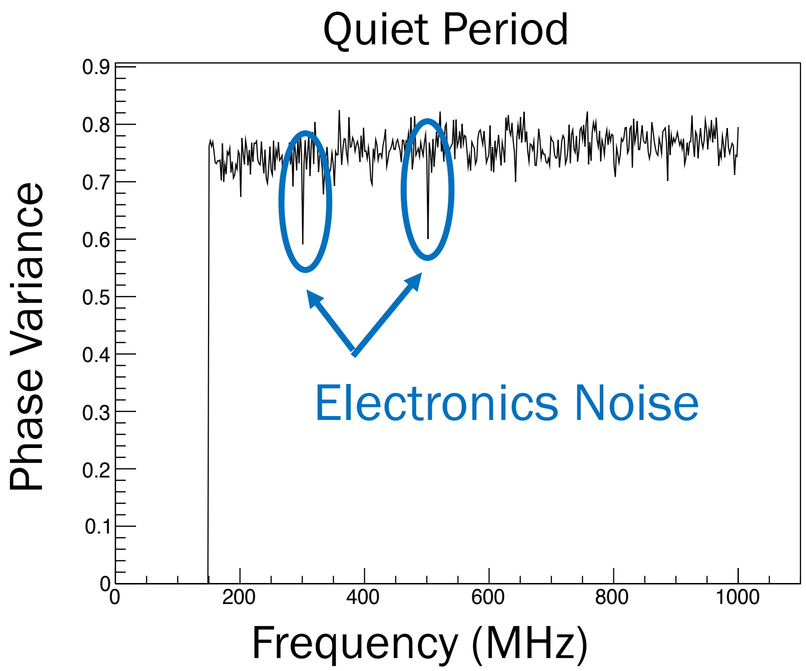
Wavefront-RMS Filter

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



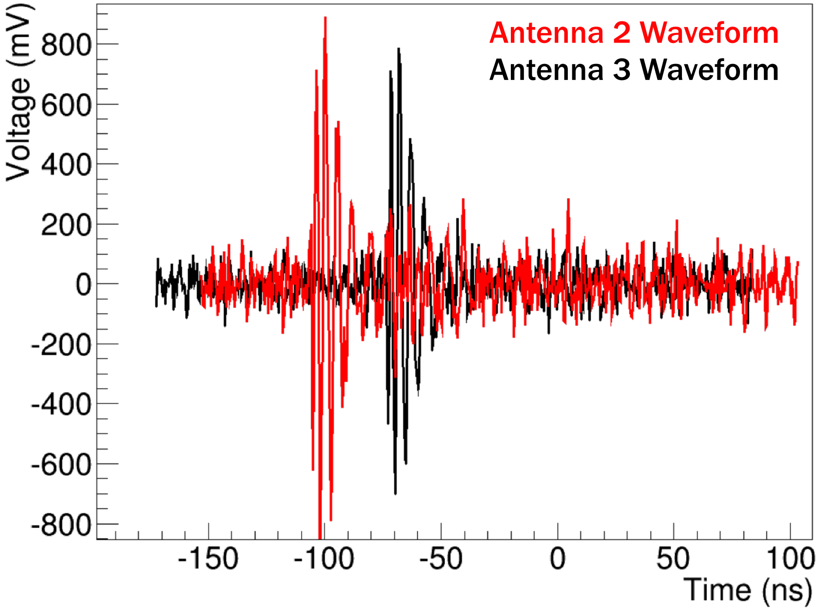
CW Filtering

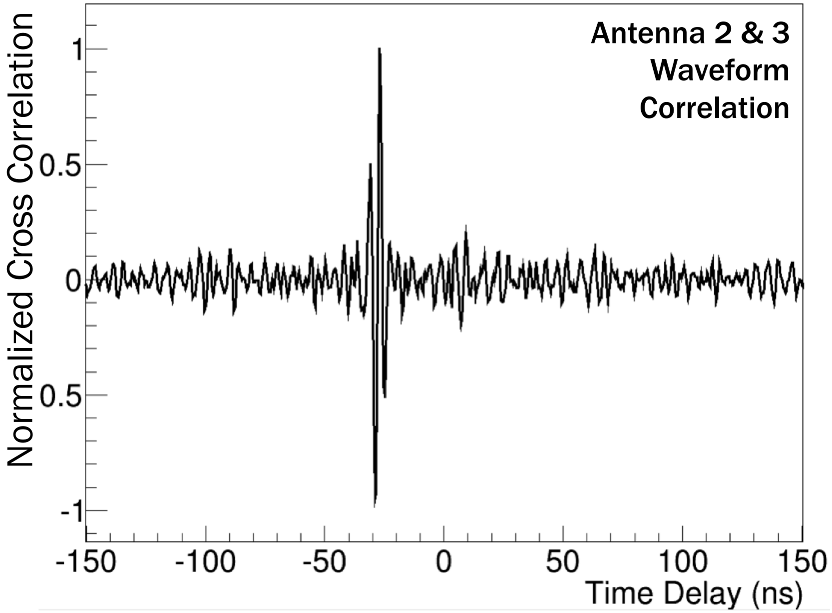
- Flag a frequency as CW if it comes from “peaks above base line” or “phase variance”
  - Phase variance frequently flags 125, 300 and 500 MHz as systems noise—we ignore these
  - Adjacent frequencies merged into notches
- CW frequencies are filtered with ANITA Geometric Filter—first time we have filtered waveforms in ARA
  - Originally designed by Brian Dailey at OSU
  - Used in the ANITA-III analysis [Phys. Rev. D 98, 022001 (2018)]

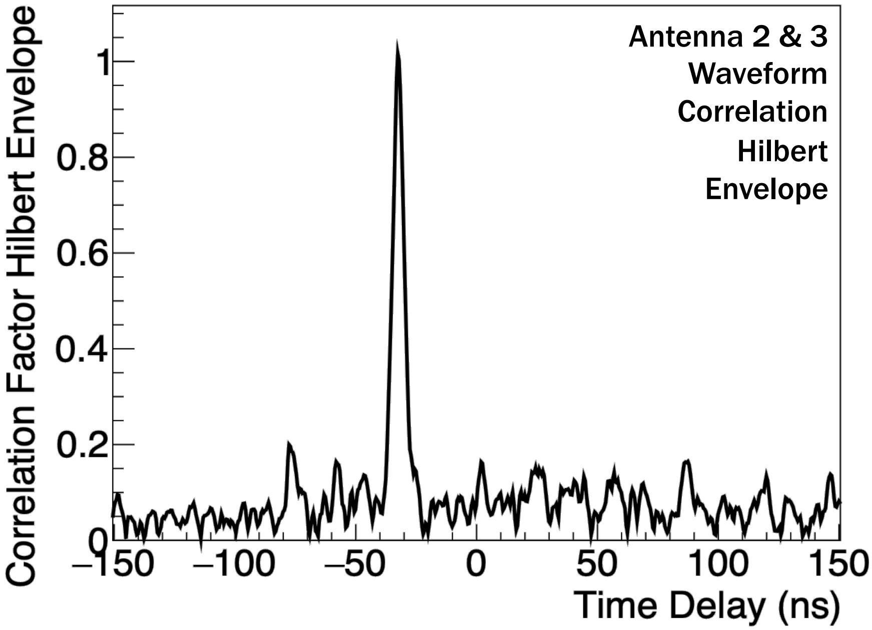


Reconstruction Details

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







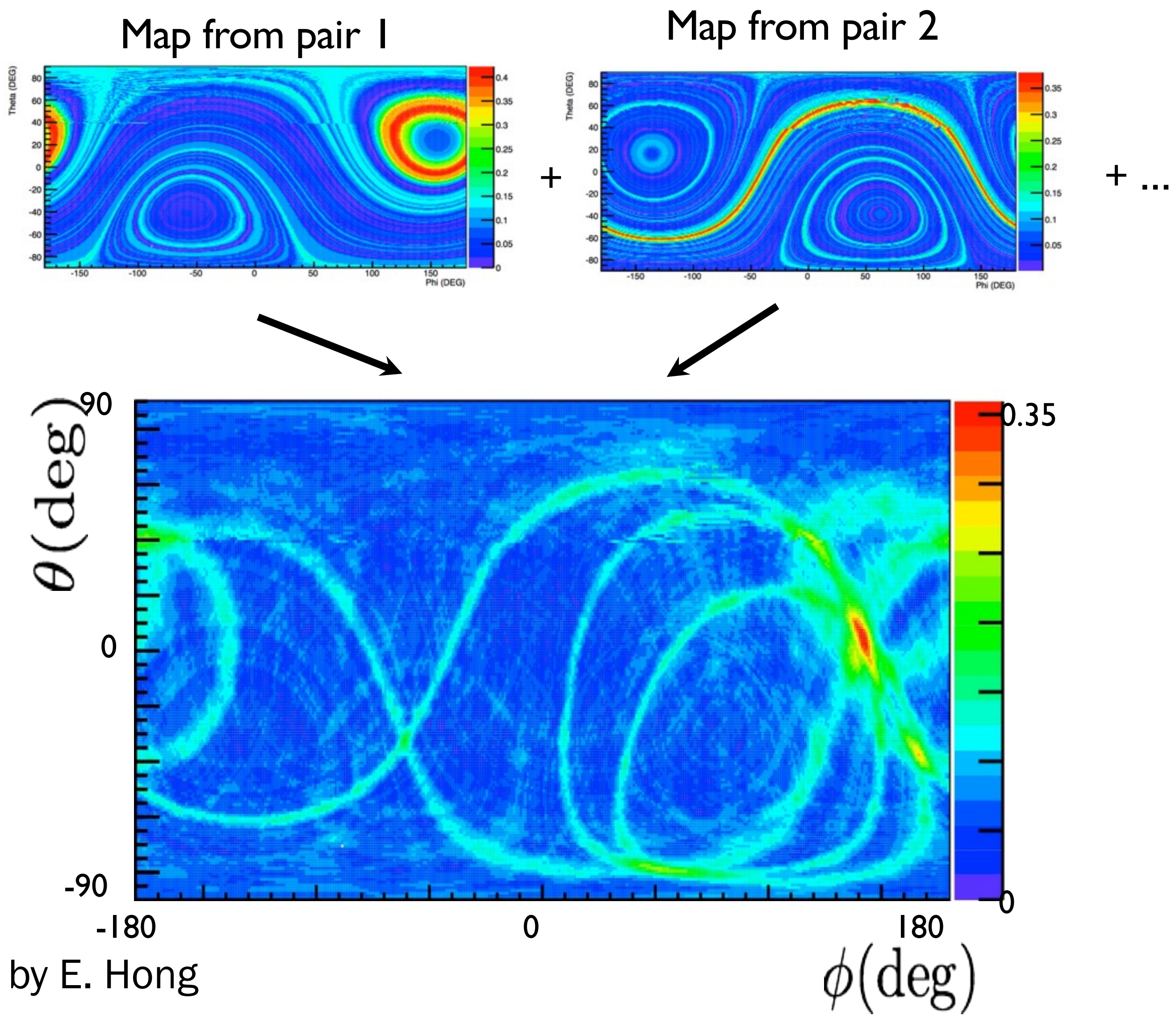
2. P. Allison *et. al.* j.astropartphys.2015.04.006
3. P. Allison *et. al.* j.astropartphys.2016.12.003

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**



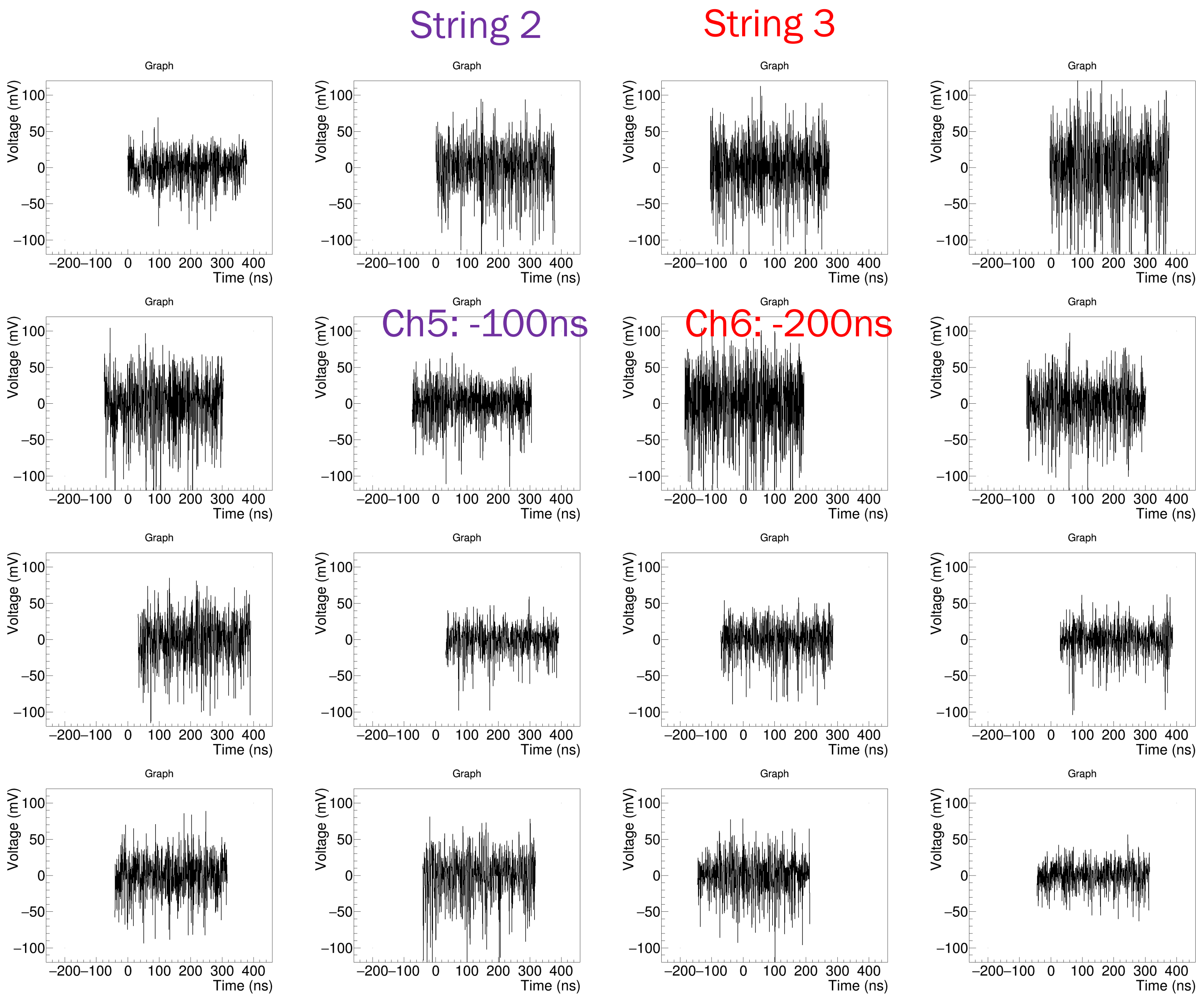
Interferograms by E. Hong

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

A2, Run 1449, Iterator Event 1

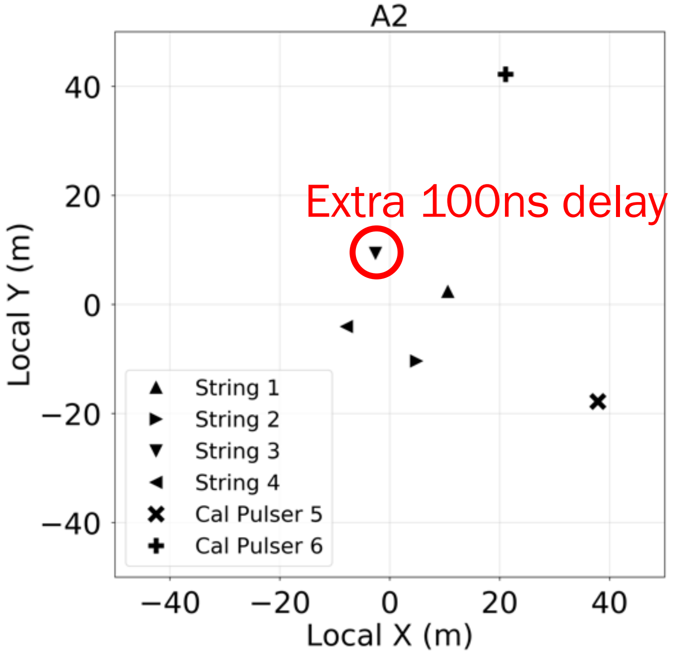
Phi Anisotropy

- 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)


String 2
String 3
Ch5: -100ns
Ch6: -200ns

Phi Anisotropy

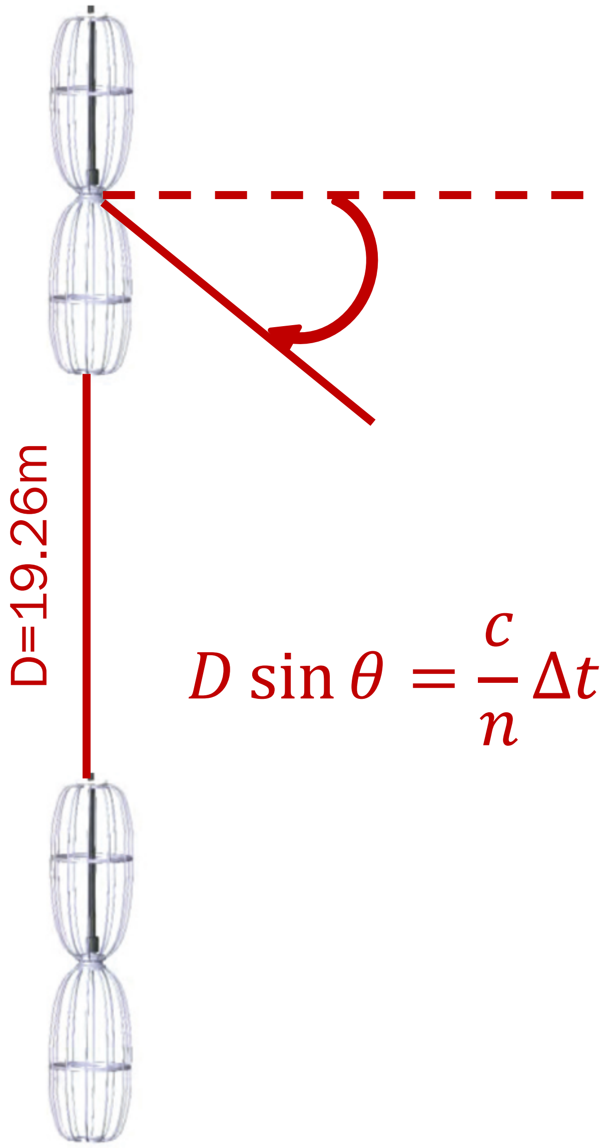
- When signal present—signal dominates correlation function
- When noise dominates (most cases), the extra trace length at the beginning means the longer string *systematically looks* like it lags the other strings
- This pulls the reconstruction in the direction of the longer string
- Which is ~111°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

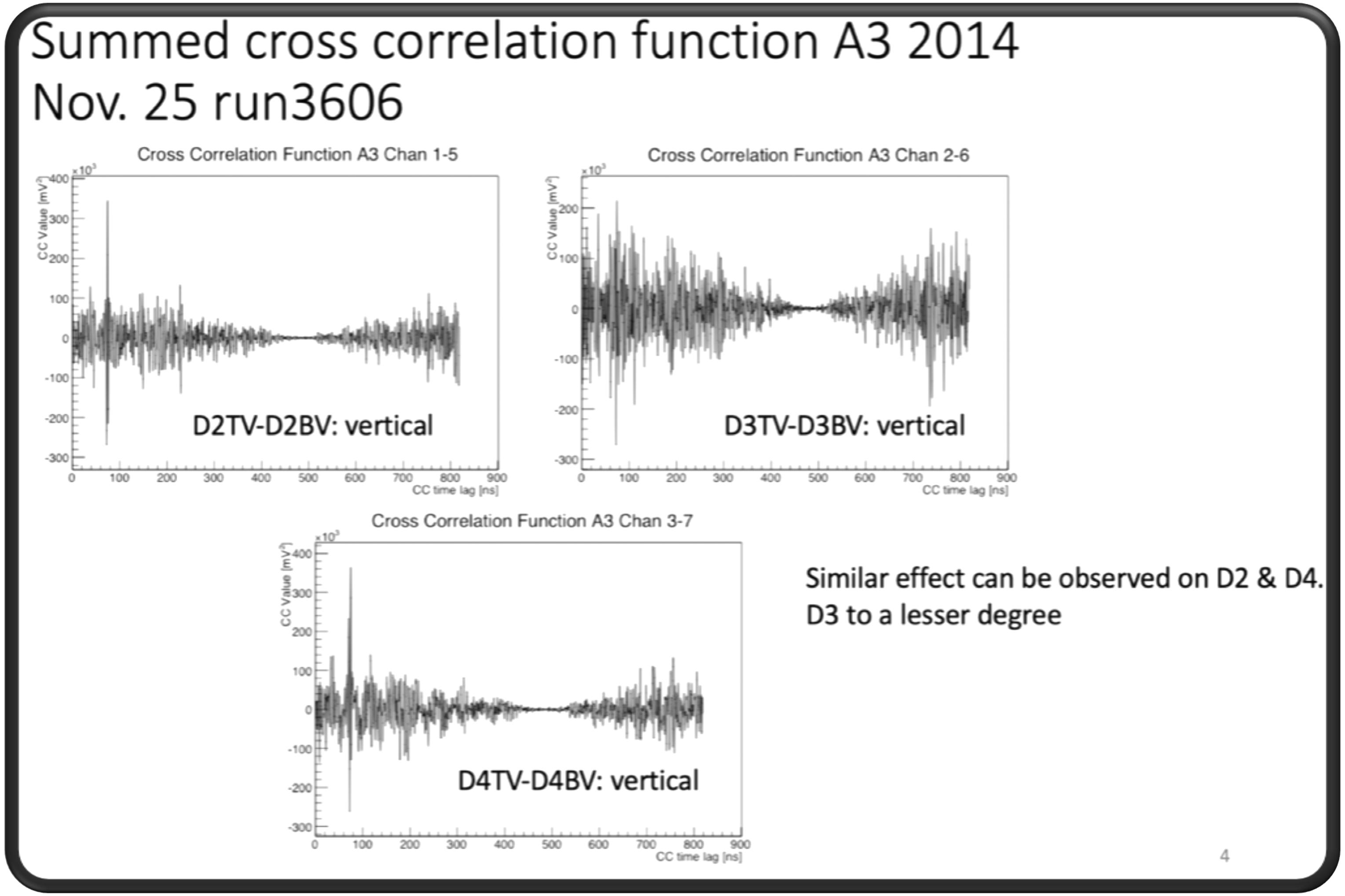


$$D \sin\theta = \frac{c}{n}\Delta t$$

Theta Anisotropy

Slide from MYL

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

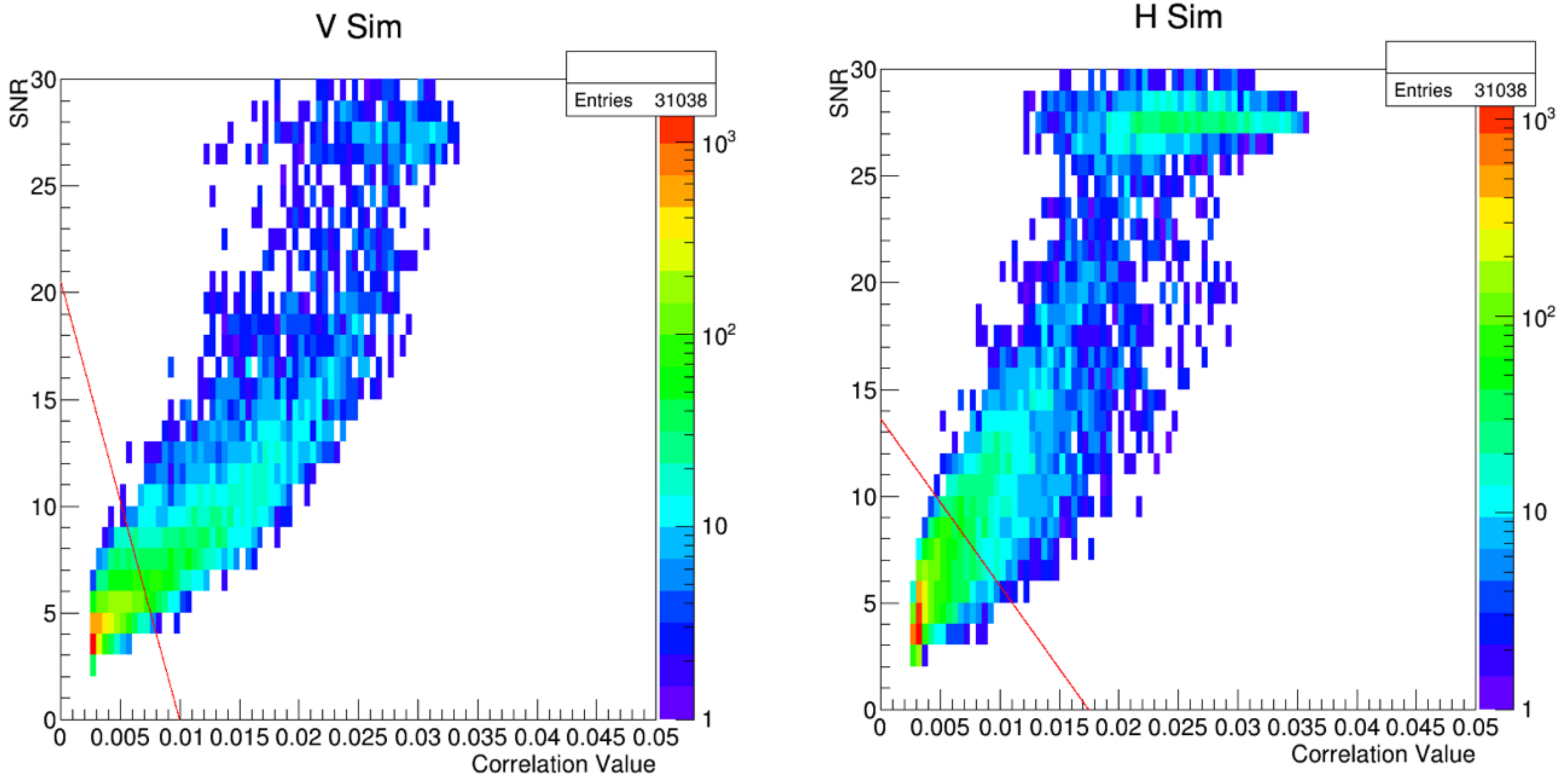


Summed cross correlation function A3 2014 Nov. 25 run3606

Similar effect can be observed on D2 & D4.
D3 to a lesser degree

4

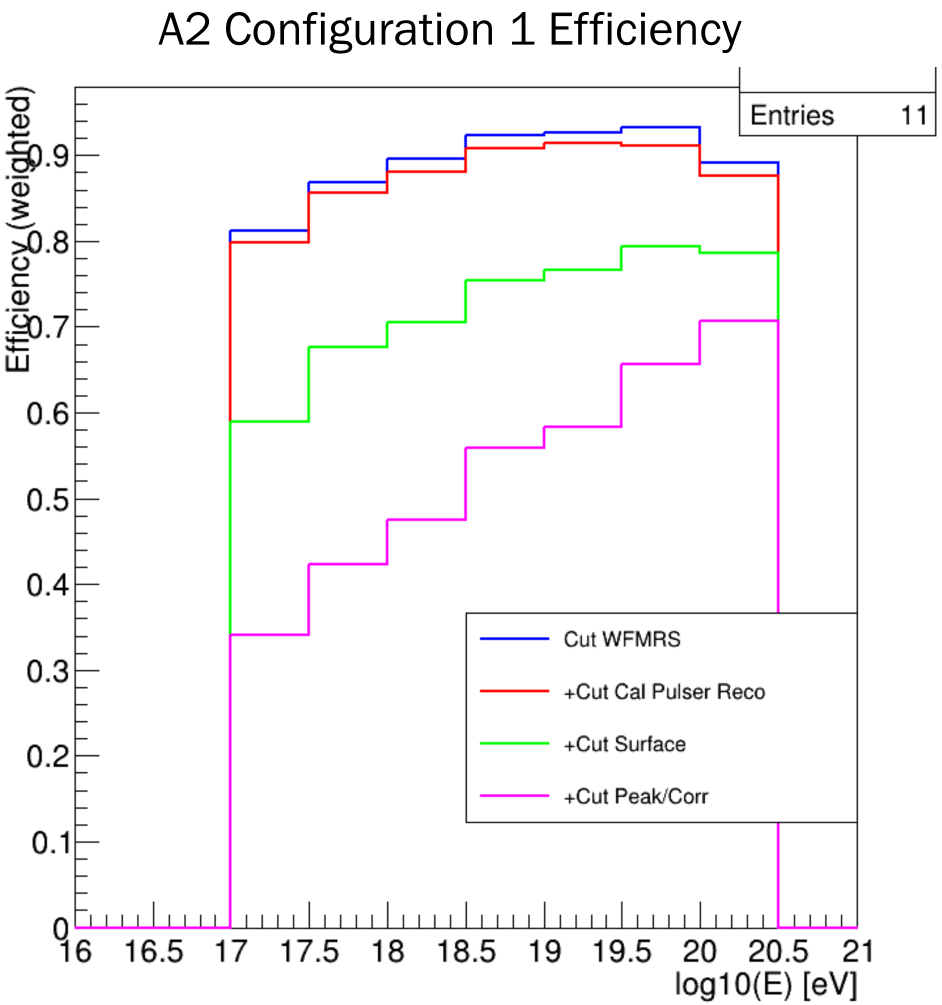
H vs V Comparison



Efficiency

- Finally, by allowing an event to pass in VPol or HPol, we can compute the efficiency as a function of energy

- Example of A2 config 1: ~30% near 10^{17}eV climbing to ~60% near 10^{19} eV



Total Analysis Efficiencies

- Total efficiency of the analysis

Config	V Efficiency	H Efficiency	Total Efficiency
1	40.2%	33.5%	49.0%
2	32.4%	19.7%	36.8%
3	41.0%	34.5%	50.8%
4	38.2%	31.5%	47.0%
5	38.8%	32.3%	47.7%

Background Pseudo-Experiments

New Slope: $\beta'_{1,i} = \beta_{1,i} + \sigma_{\beta_1,i}\eta_1$

New Intercept: $\beta'_{2,i} = \beta_{2,i} + \rho_i\sigma_{\beta_2,i}\eta_1 + \sigma_{\beta_2,i}\eta_2\sqrt{1-\rho_i^2}$

Effective Volumes

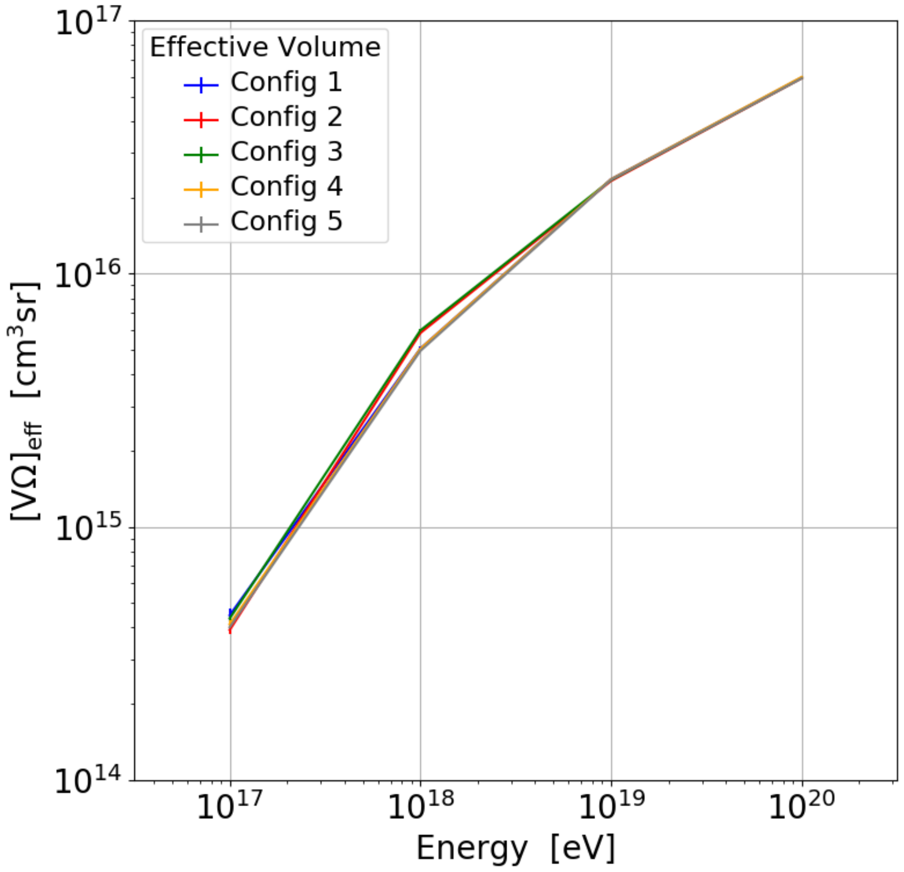
- Compute effective volume at trigger level from simulation

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

- 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

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

V_{eff} Comparison

- There are discrepancies between our effective volumes and those quoted in previous studies

- The discrepancy is under study