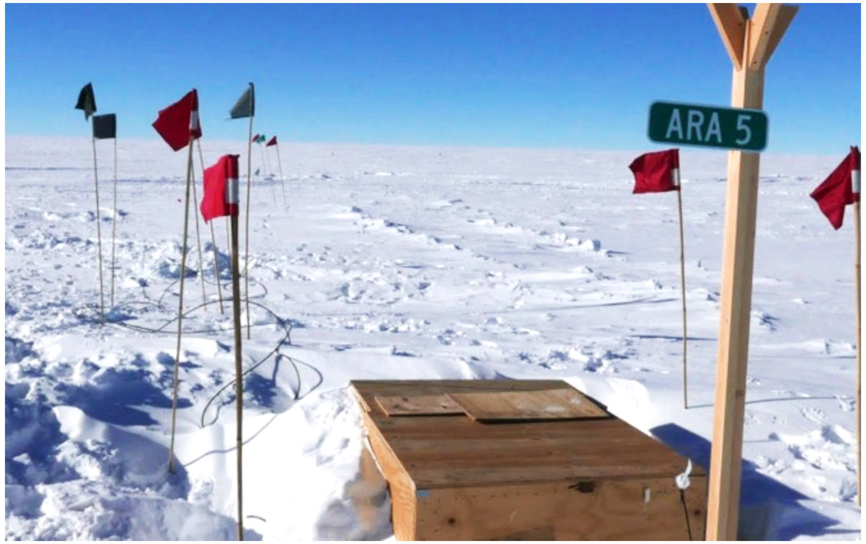
The Quest for UHE Neutrinos



Brian Clark

Astronomy Seminar
Michigan State University
Department of Physics

October 23, 2019

The Big Questions

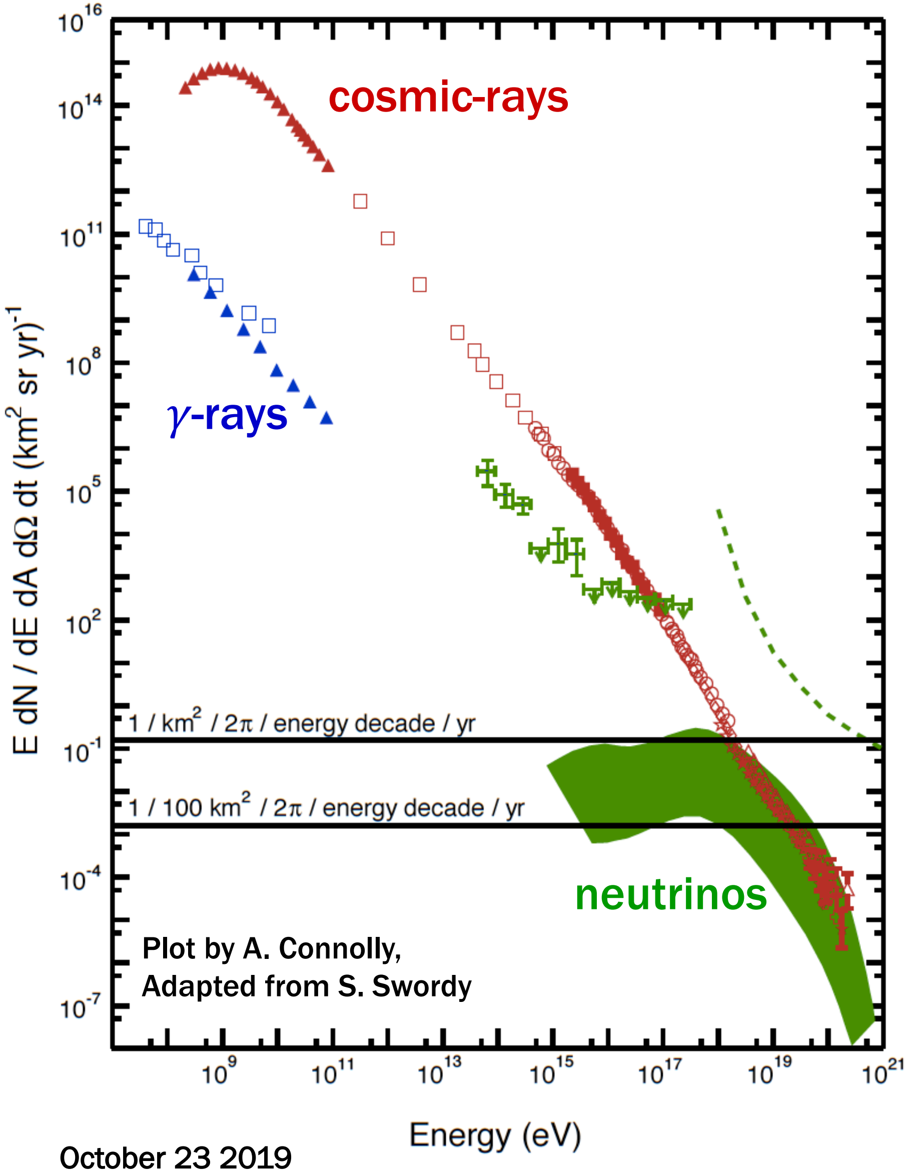
Why? ☐

How? ☐

Where? ☐

Who? ☐

Why Study Neutrinos: Astrophysical Messengers

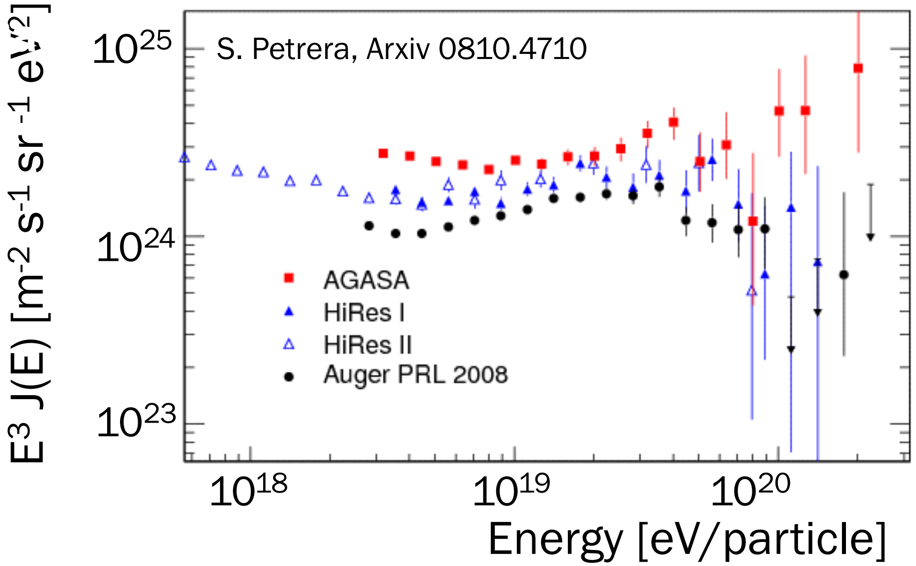


- Cosmic rays >$10^{19.5}$ eV attenuated, possibly by GZK effect, e.g.

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

→ Screens extragalactic (>100 MPc) sources

- γ-rays annihilate w/ CMB @ ~1 TeV



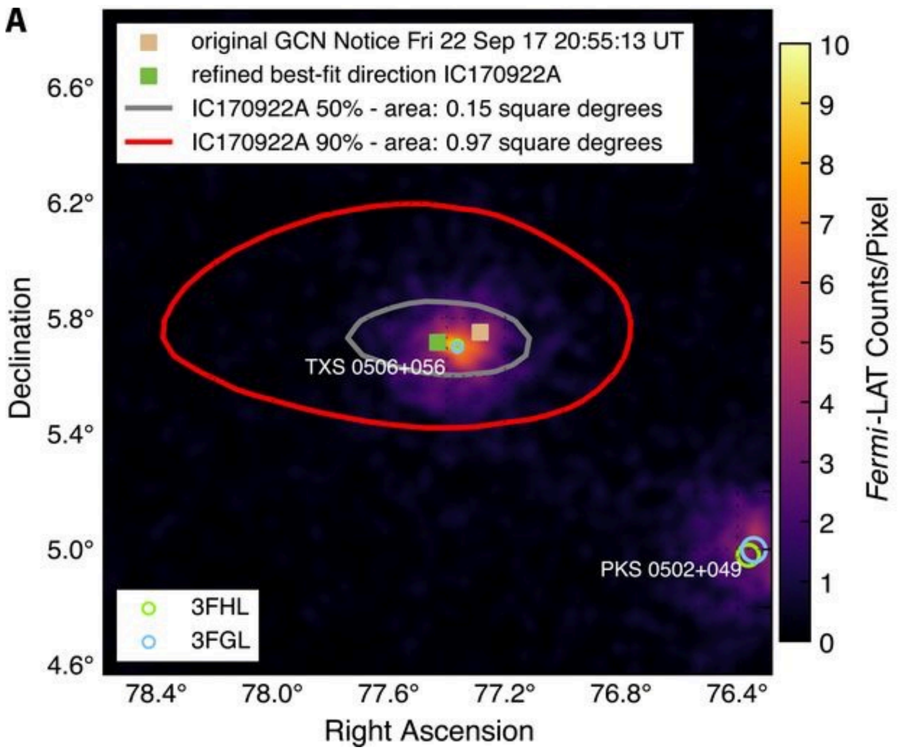
Astronνmy : Neutrinos in a Multimessenger World

Complimentary Probes

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

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

IceCube *et. al.*
Science Vol. 361, Issue 6398

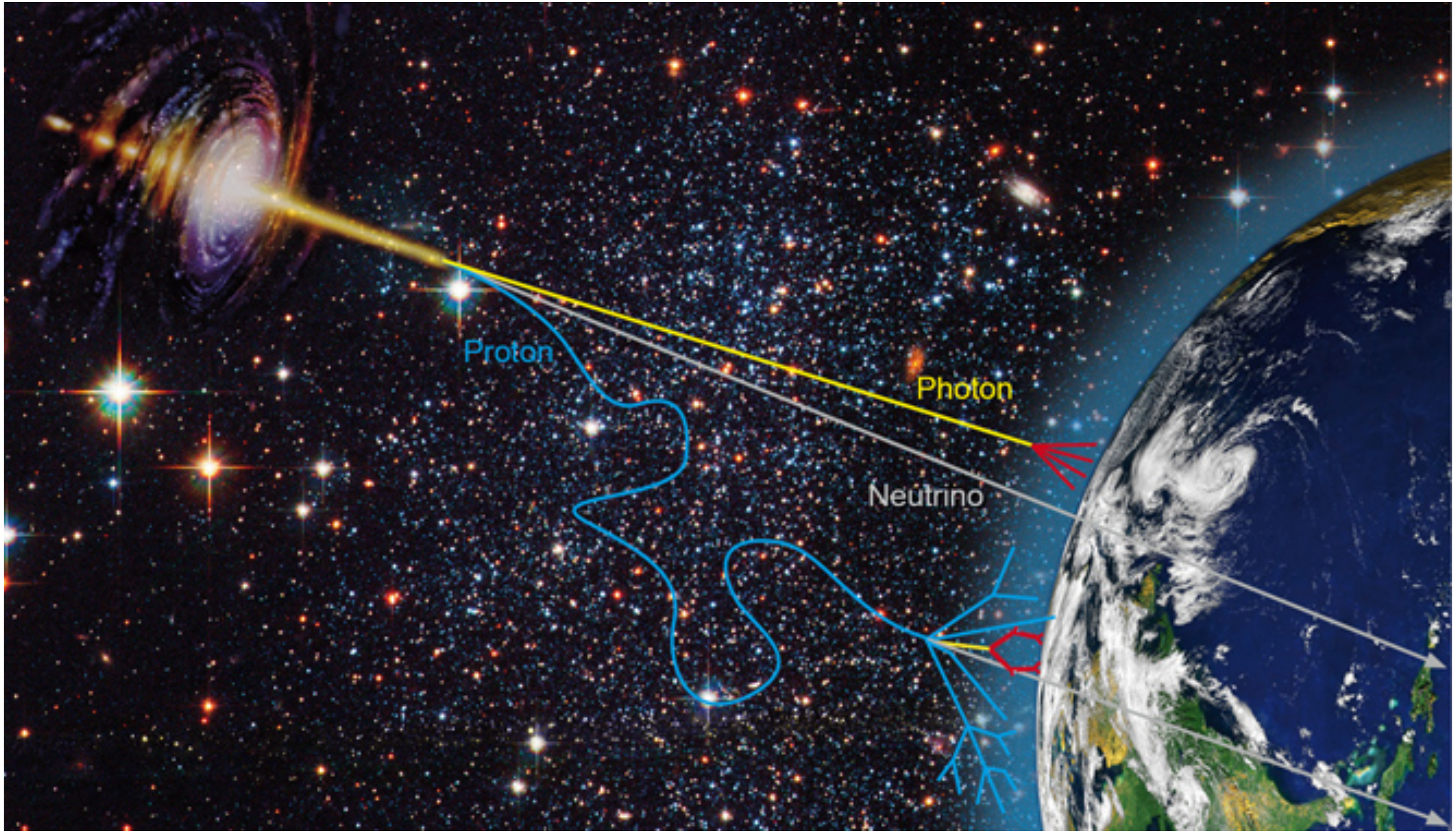


Exciting Start!

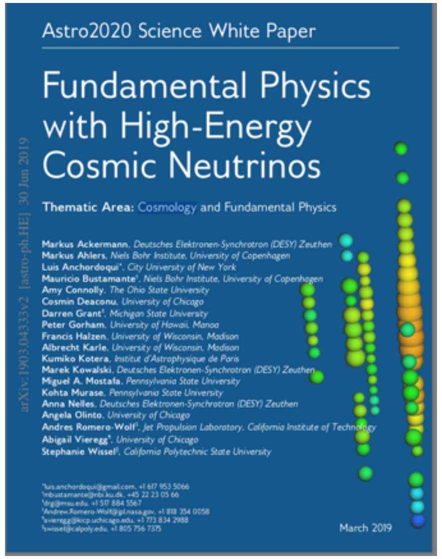
- 2017—Binary Neutron Star—GW + Light
- 2018—Flaring Blazar— Neutrino + Light
- 2019—Neutrino + GW??

Chargeless.
⟶ not deflected by B fields

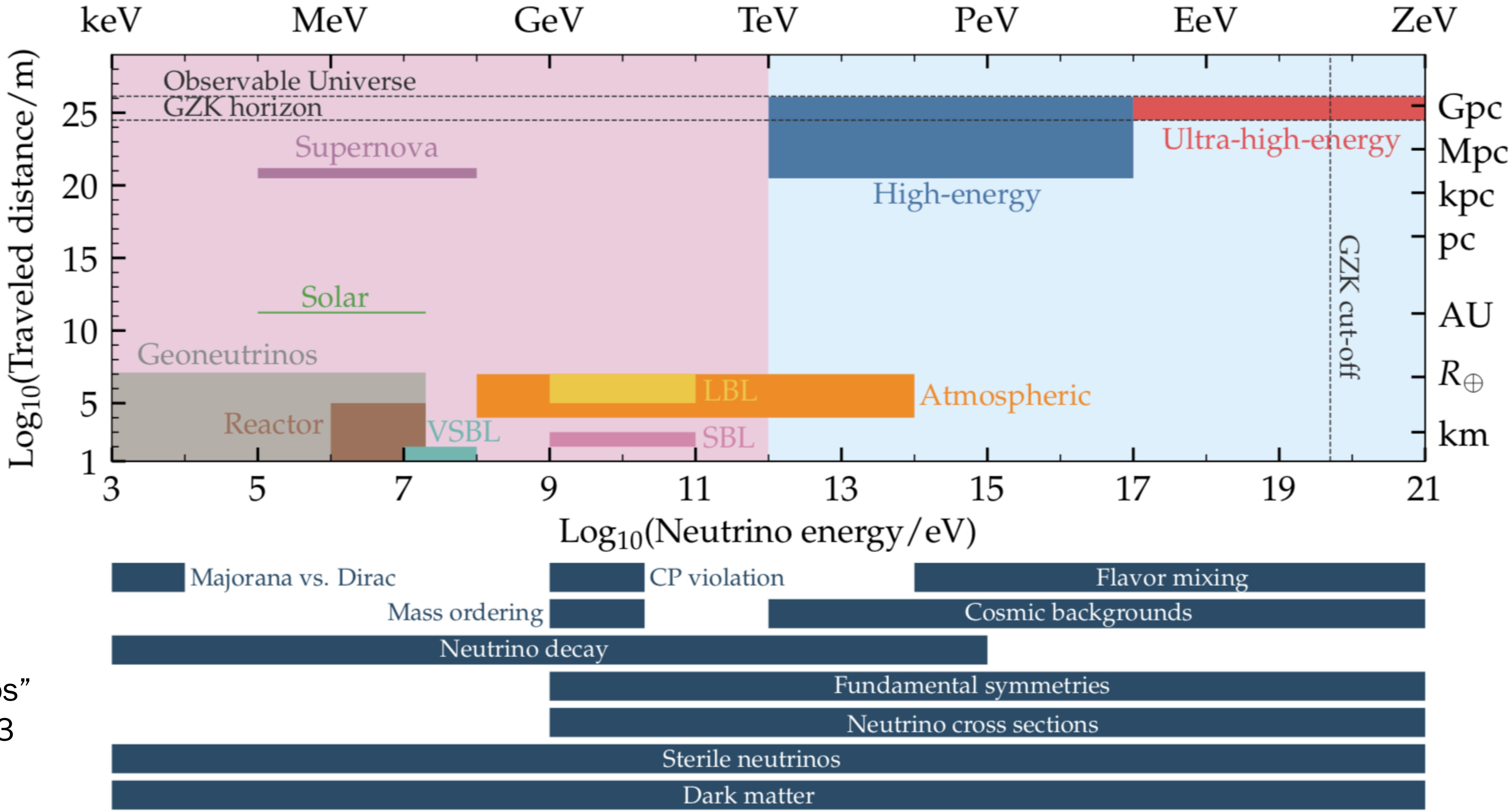
Weakly interacting
⟶ travel cosmic distances



Why Study Neutrinos: Fundamental Physics Probes

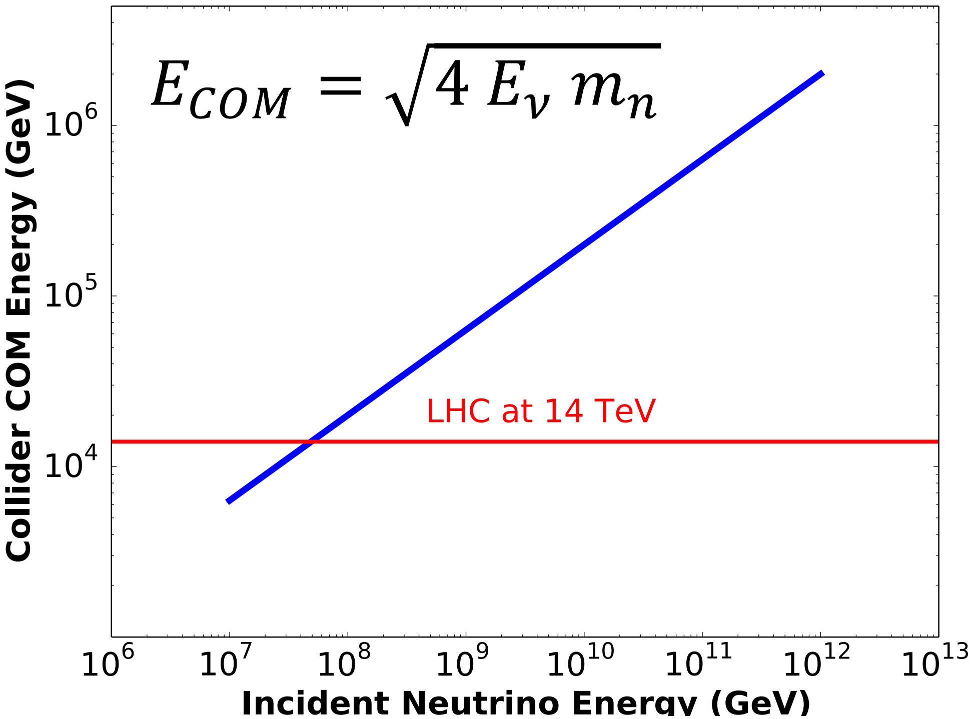


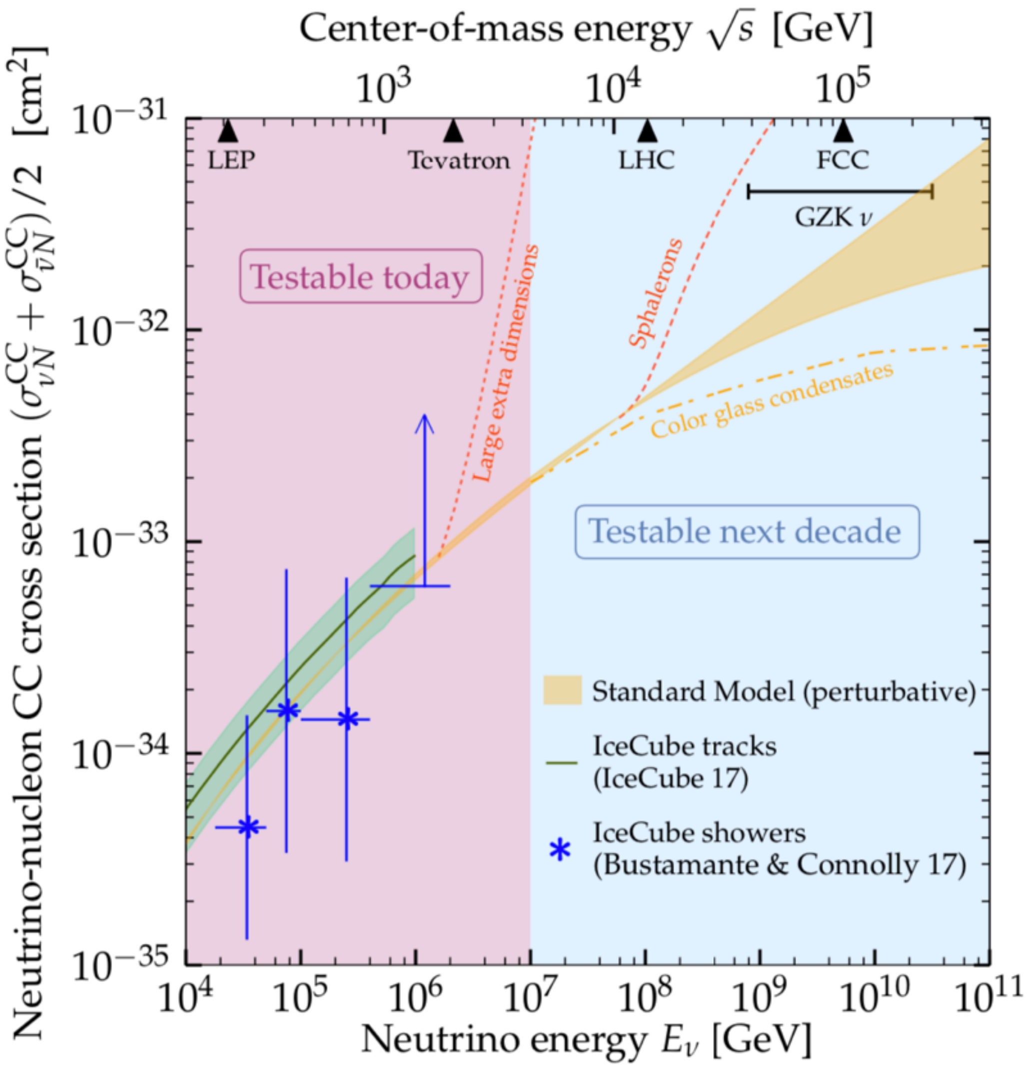
Astro 2020 White Paper "Fundamental physics with High-Energy Cosmic Neutrinos" Ackerman et. al. 1903.04333



Why Study Neutrinos: Particle Physics Probes

- Probe cross-sections at energies above accelerators



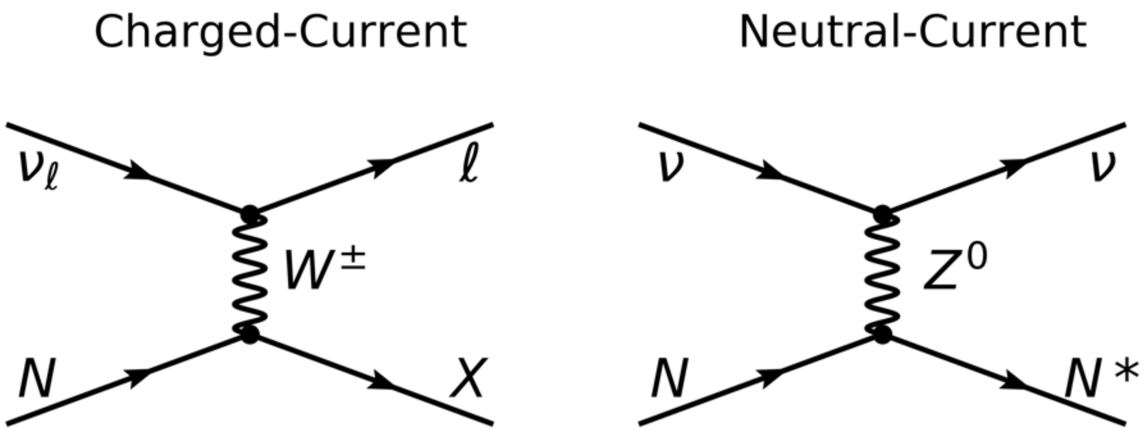


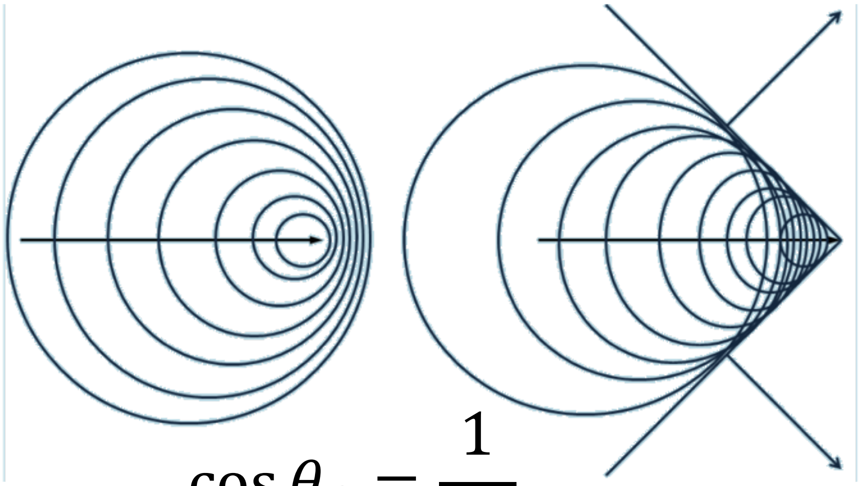
The Big Questions

Why?	☑	Astro + Particle Physics
How?	☐	
Where?	☐	
Who?	☐	

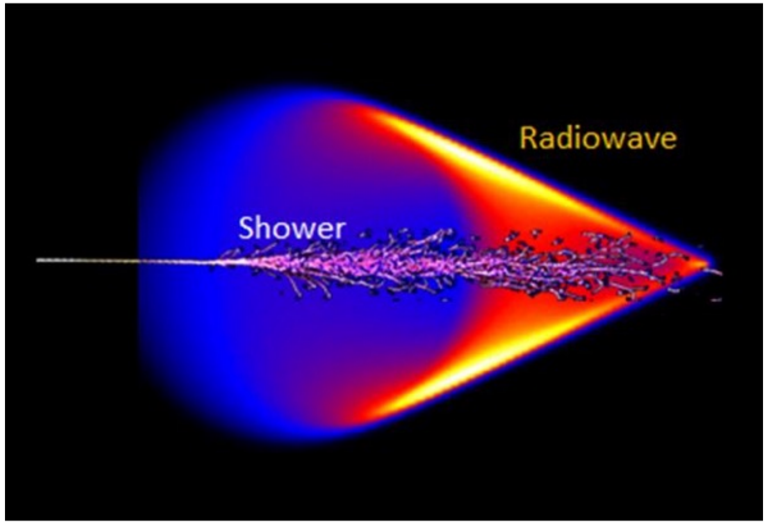
Neutrino Interactions

- Two (main) types of neutrino interactions: charged & neutral current
- Showers are ultra-relativistic ($\beta \approx 1$) → emit Cherenkov radiation in media
- Two varieties: optical and radio



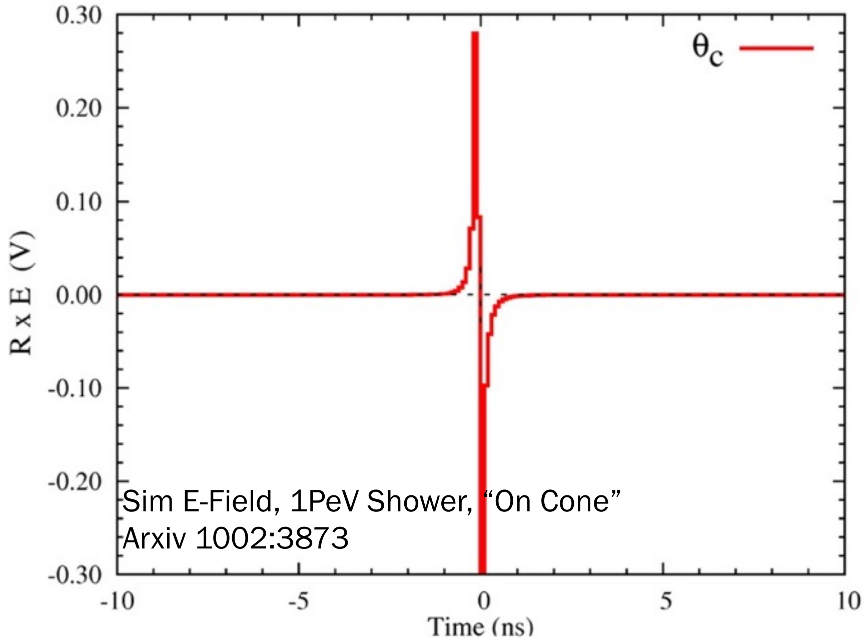


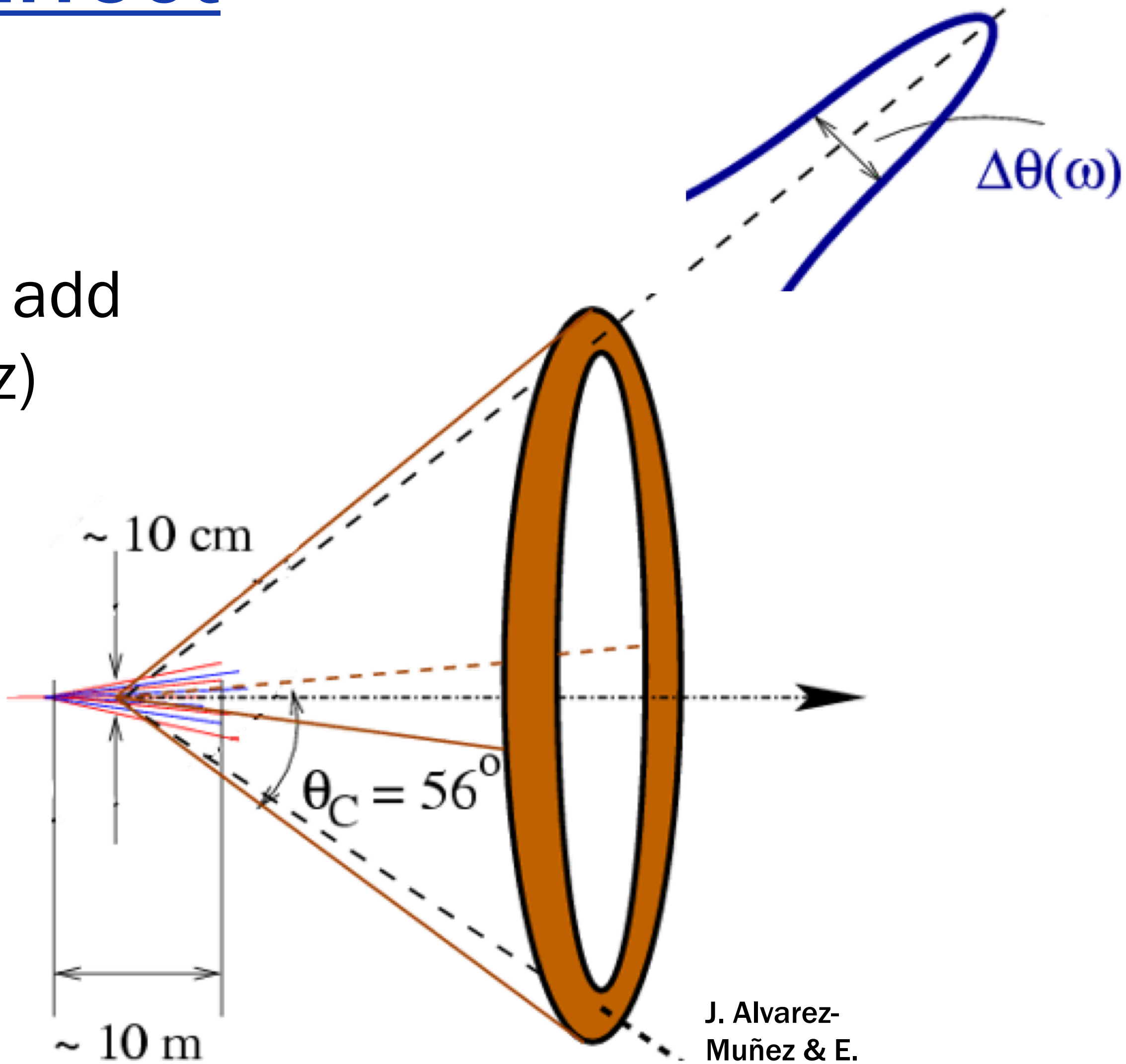
$$\cos\theta_C = \frac{1}{n\beta}$$



Askaryan Effect

- Showers develop negative charge excesses
- Wavelengths the size of the bunch (~10cm) add *coherently* → broadband (200 MHz-1.2GHz) radio *pulse*

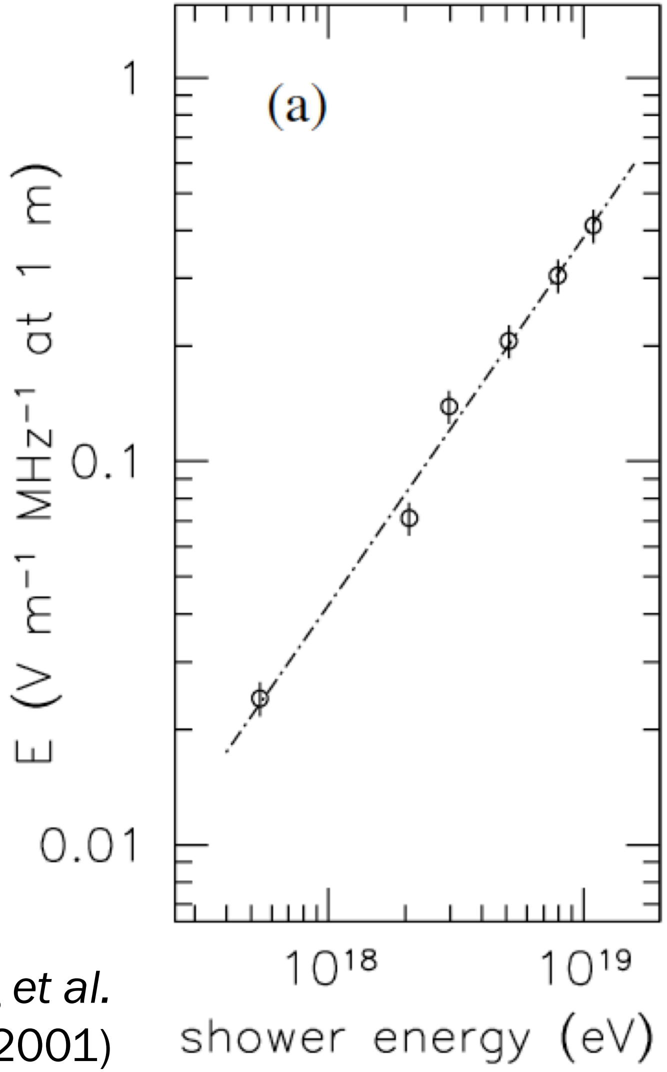




J. Alvarez-Muñez & E. Zas (2005)

Observation of Askaryan Effect

Has been experimentally observed in ice and salt



P. Gorham *et al.*
PRL 99, 171101 (2007)

D. Satlzberg *et al.*
PRL 86, 13 (2001)

The Big Questions

- Why? ☑ Astro + Particle Physics
- How? ☑ (Radio) Cherenkov Effect
- Where? ☐
- Who? ☐

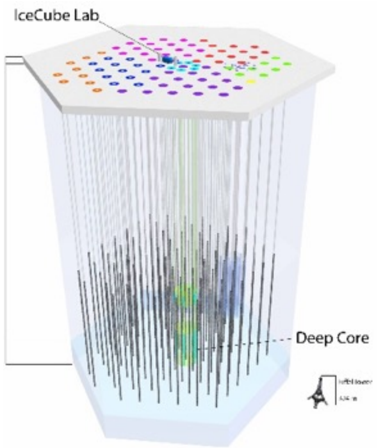
Questions of Scale

- Low fluxes (~10/km^3/yr) and low cross-sections (interaction length ~300km in rock)
- Need >1-100 km^3 of target volume for statistics (e.g., few per year)
- Where do you find a giant chunk of optical & radio clear medium?
  - Ask the NSF nicely?
  - Point telescope at the lunar regolith: Lunaska
  - Go to Antarctica: IceCube, ARA, ANITA, ARIANNA

LUNASKA (radio)

ANITA-III (radio)

IceCube (optical)



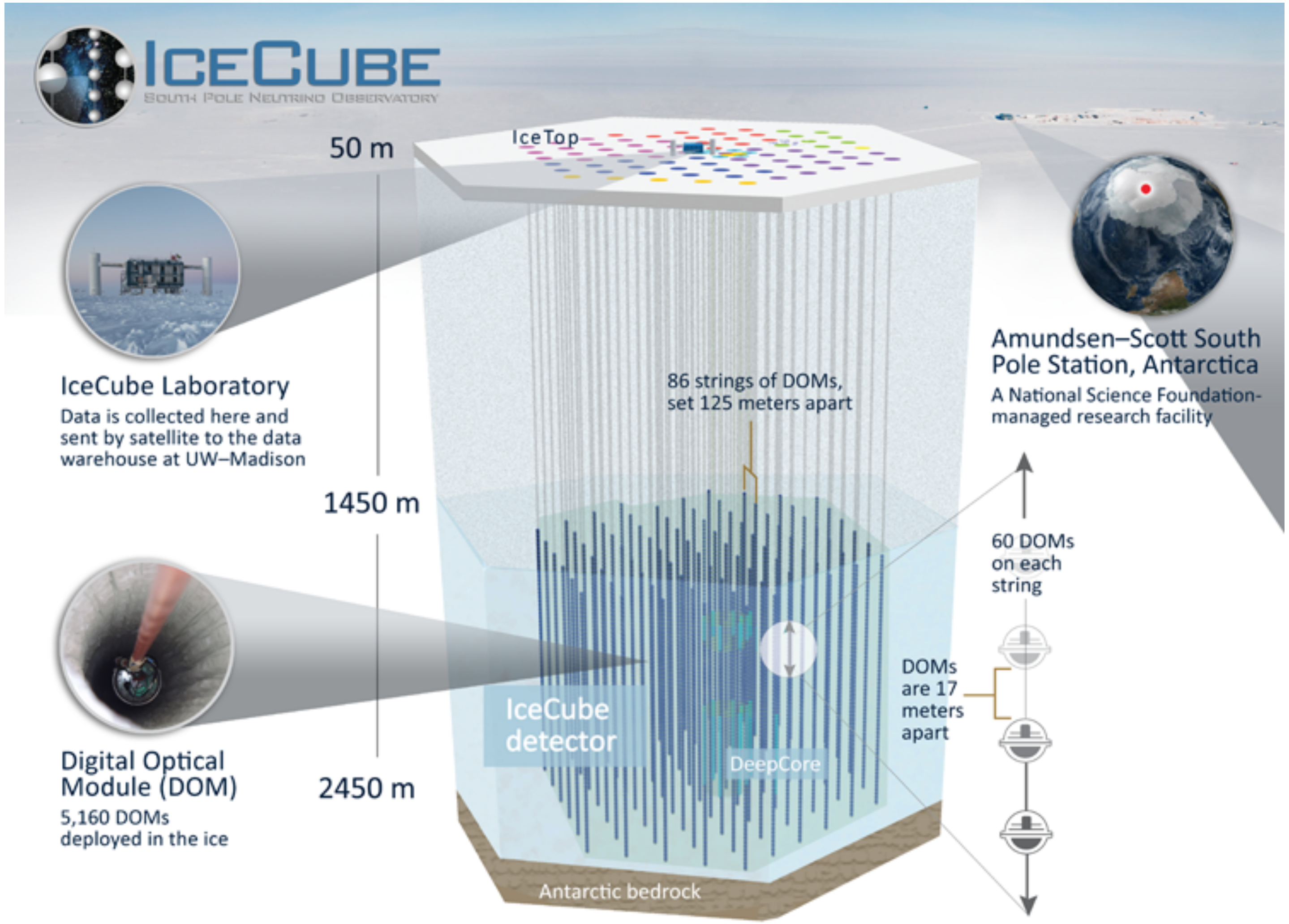
Auger (air shower)

The Big Questions

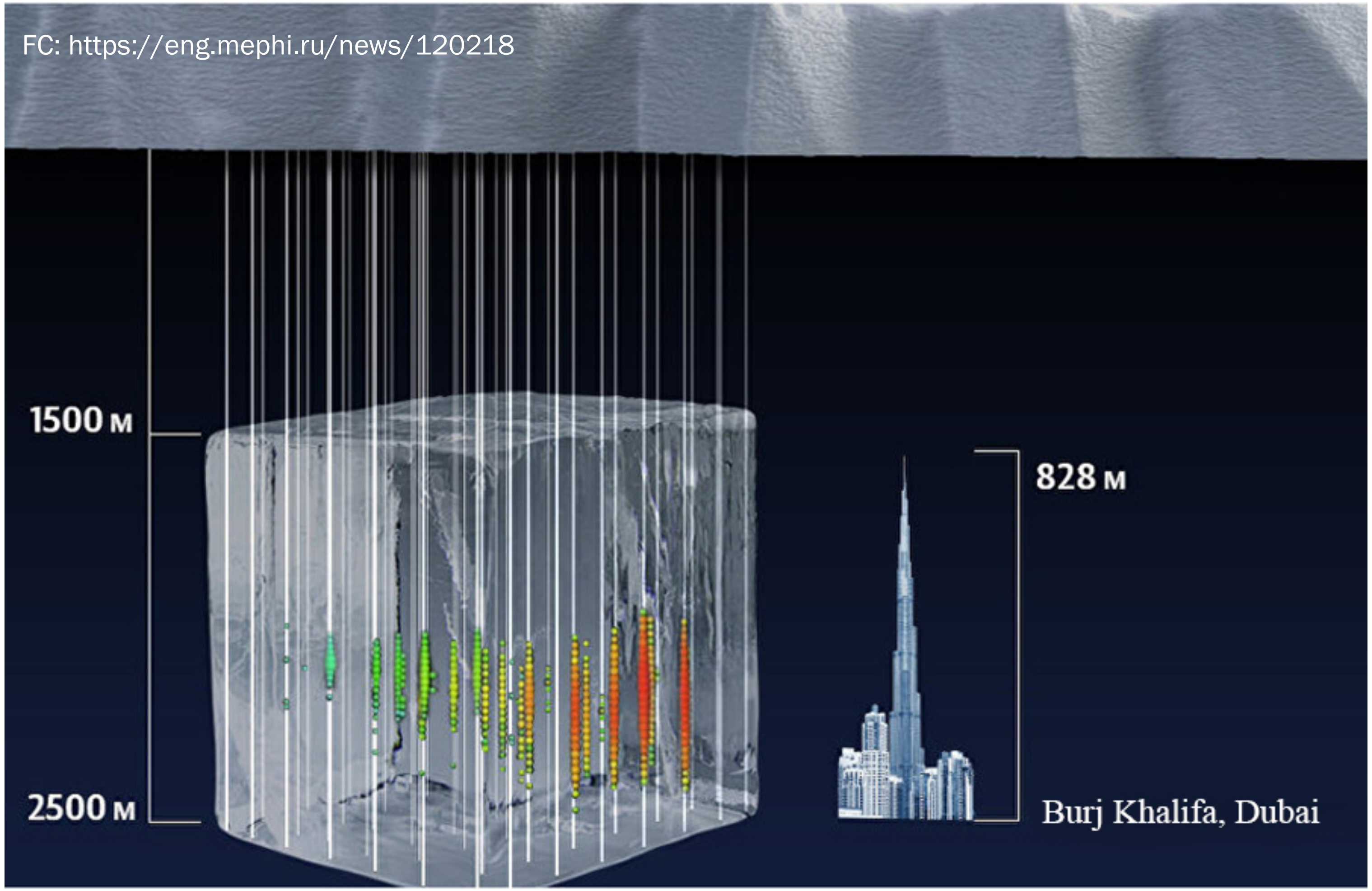
Why?	☑	Astro + Particle Physics
How?	☑	(Radio) Cherenkov Effect
Where?	☑	Antarctica
Who?	☐	

IceCube

- 5160 photomultiplier tubes (+electronics) buried 2.5km in ice near South Pole
- Observes 1 km^3 of ice
- Energy range: $10^{10} \rightarrow 10^{16+}$ eV

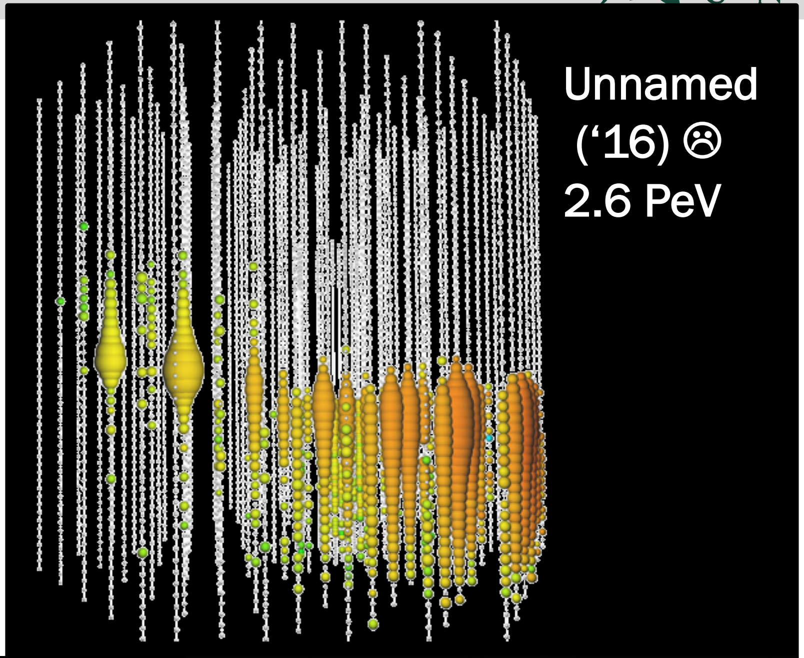


IceCube

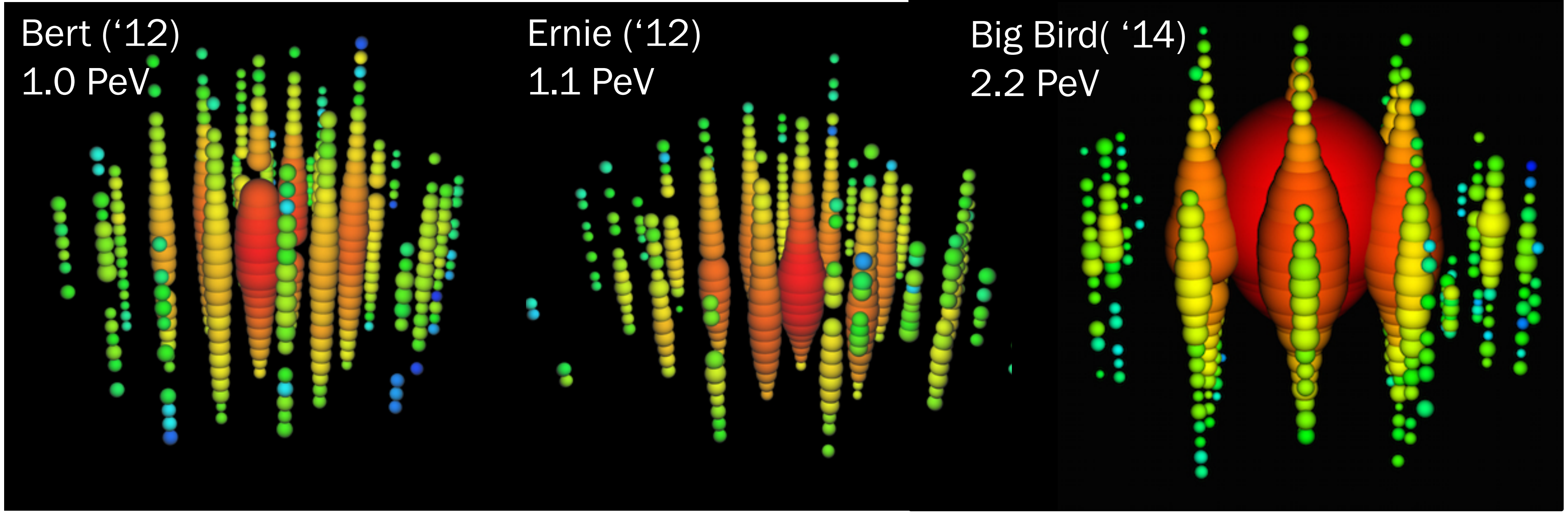

FC: https://eng.mephi.ru/news/120218
1500 м
2500 м
828 м
Burj Khalifa, Dubai

First HE Cosmic Neutrinos

2012: IceCube experiment sees PeV neutrinos of cosmic origin



PRL 111 (2013)

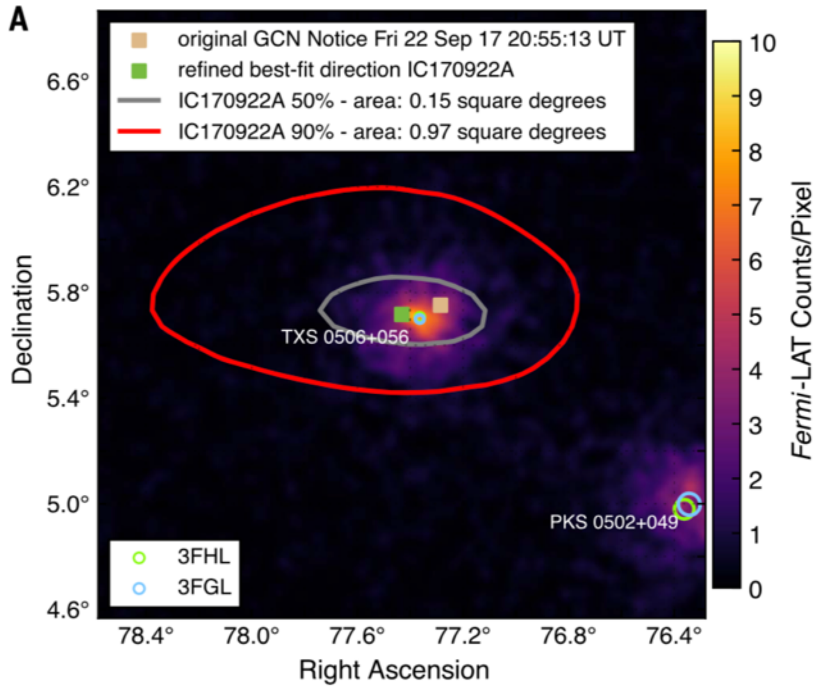


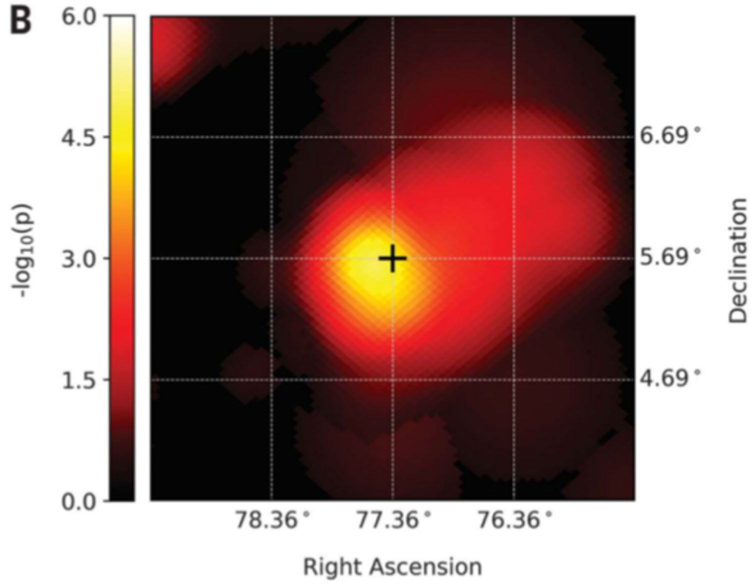
PRL 113 (2014)

First Potential Neutrino Source

Science Vol. 361, Issue 6398

- 290 TeV neutrino (IC 170922A) observed in coincidence with flaring blazar TXS 0506+056 (~3σ)
- Archival search in direction of TXS reveals an additional 3.5σ excess

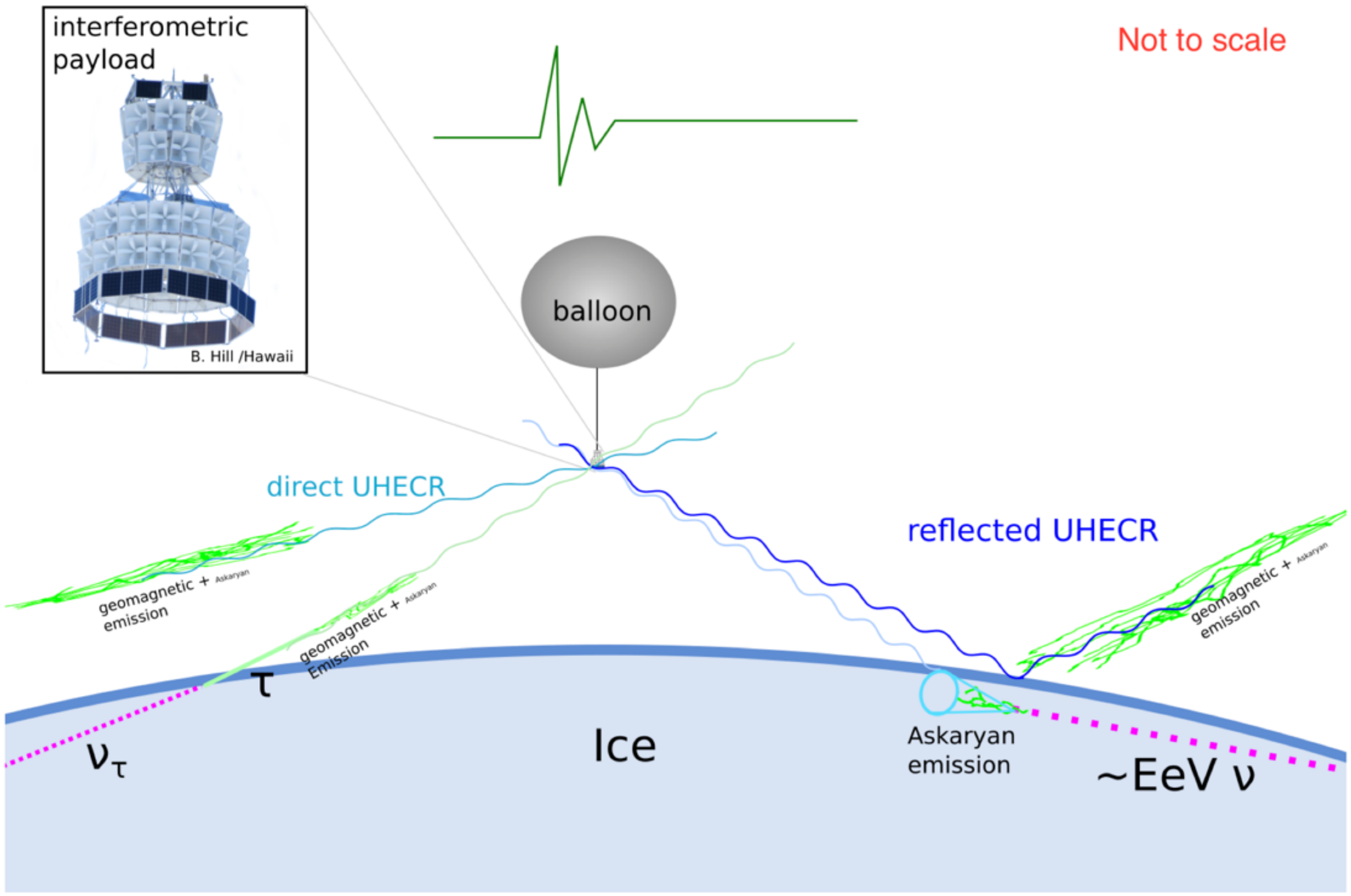




Science

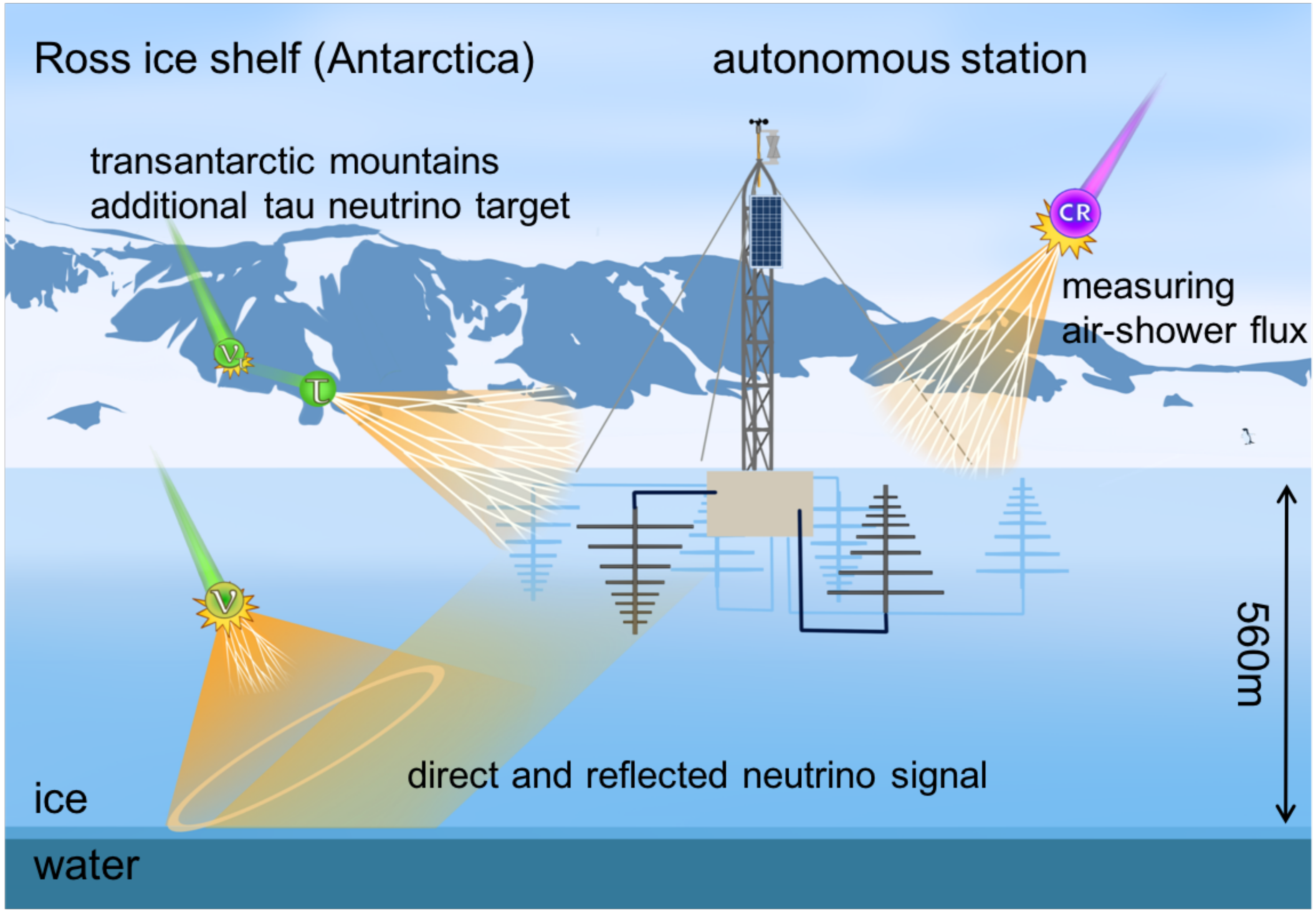
ANtarctic Impulsive Transient Antenna (ANITA)

- ~40 dual polarized antennas (100-1200 MHz bandwidth)
- Observes 10^6 km^2 of ice
- Energy range: $10^{18} \rightarrow 10^{21+}$eV
- 4 flights so far, further experiments proposed…



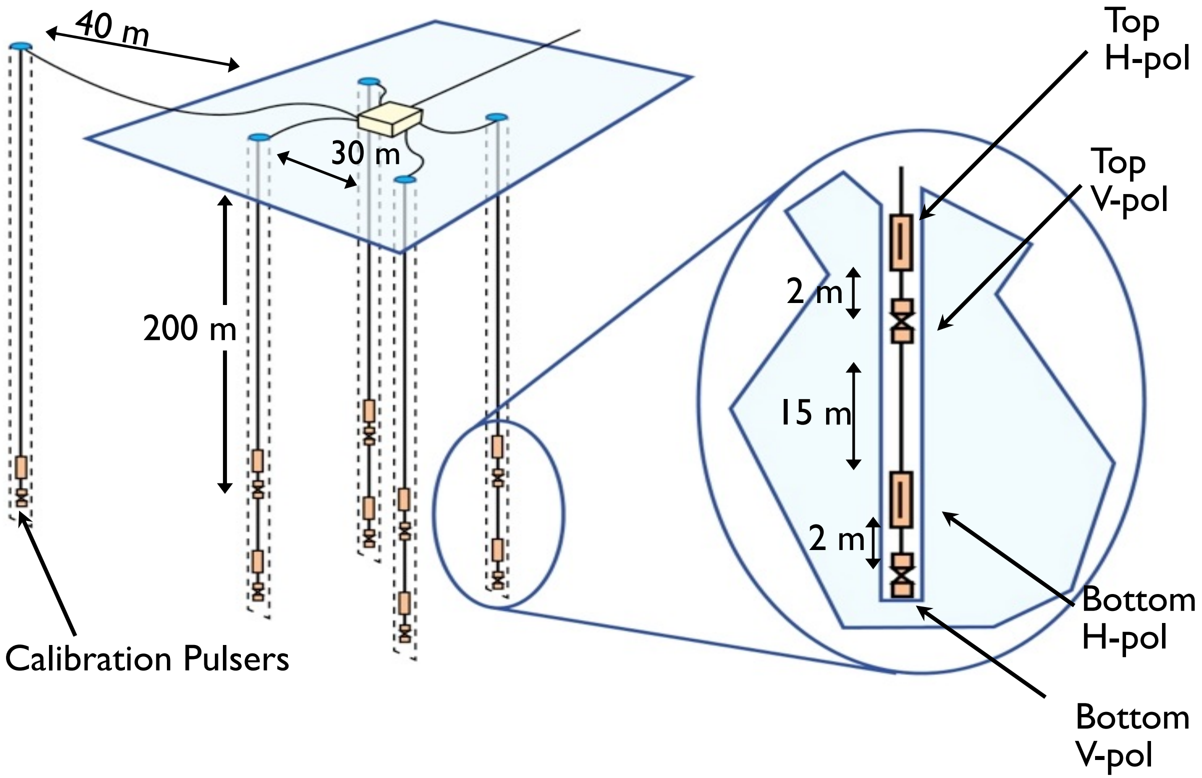
Antarctic Ross Ice shelf ANtenna Neutrino Array (ARIANNA)

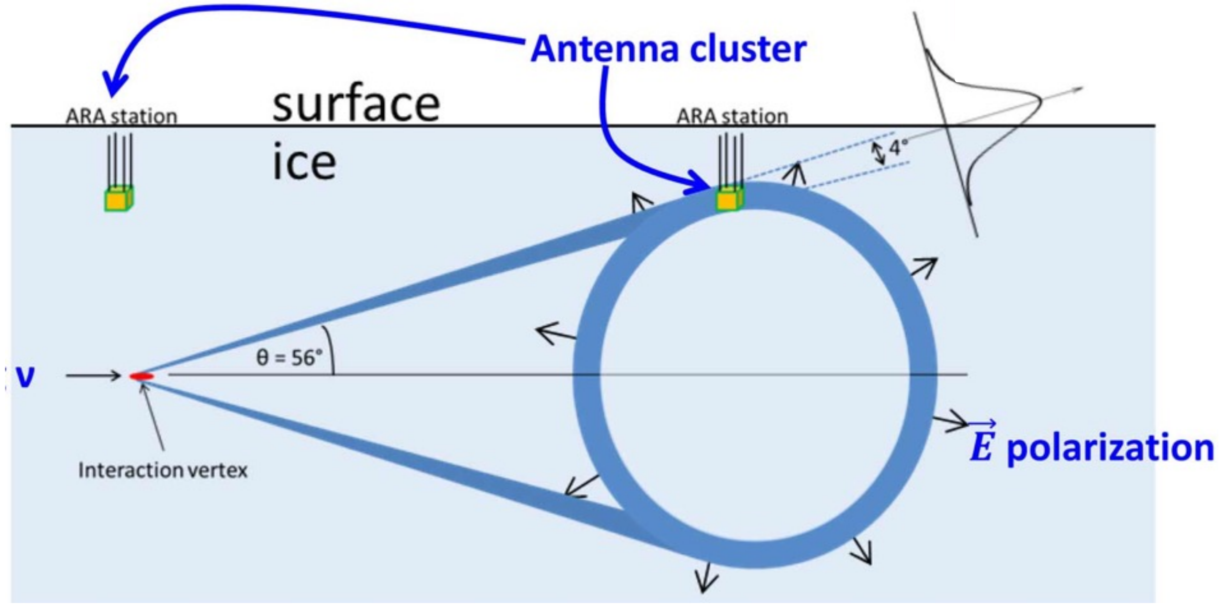
- Shallow array of downward pointing LPDA antennas
- Observes direct and reflected radio emission from ice-shelf



Askaryan Radio Array

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

International Collaborators

Chiba University

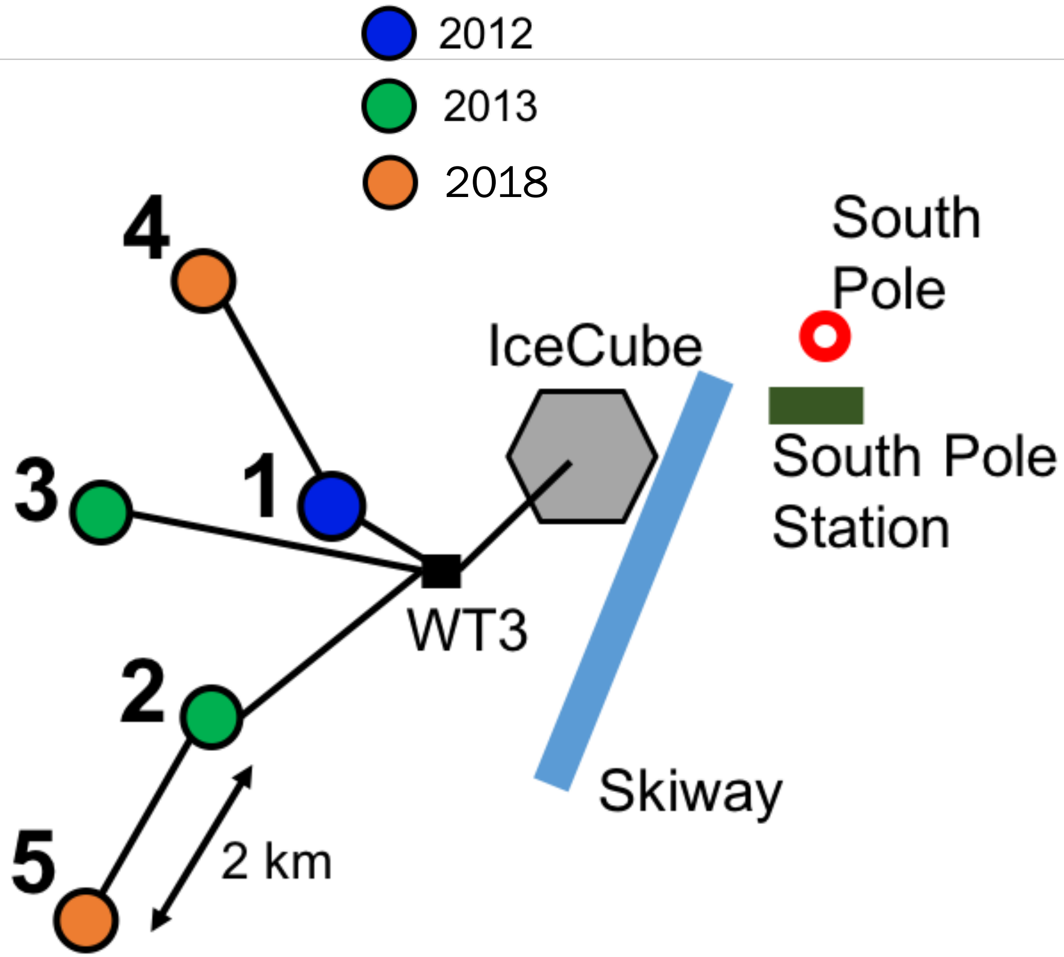
National Taiwan University

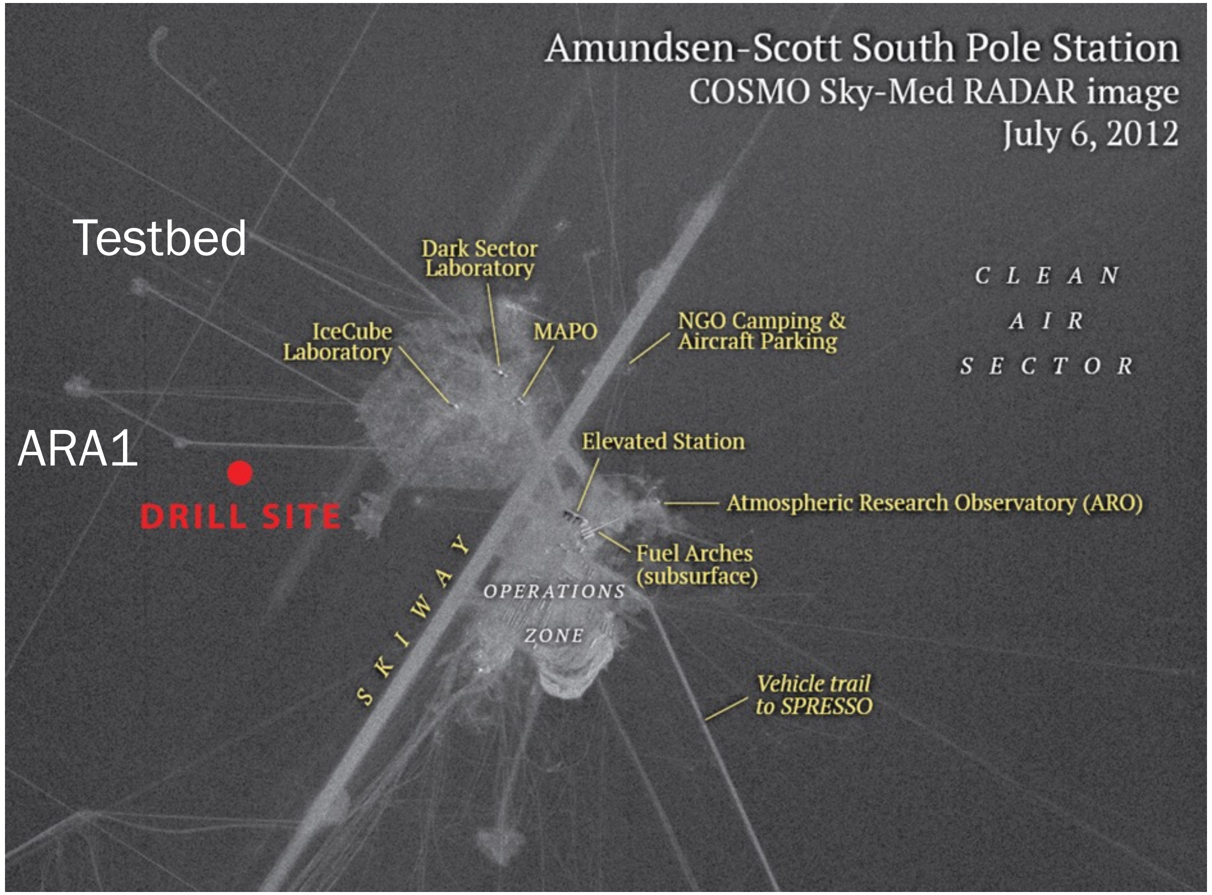
University College London

Vrije Universiteit Brussel

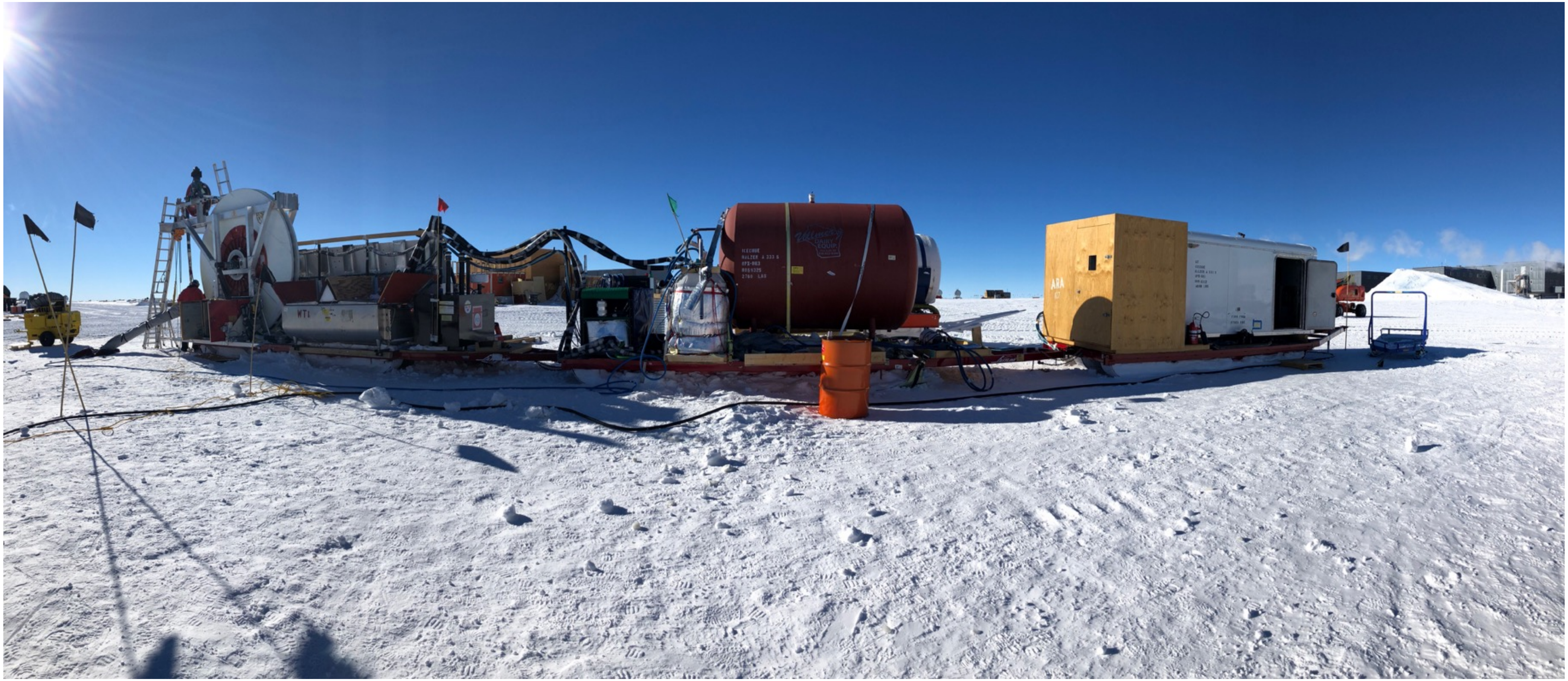
Weizmann Institute of Science

ARA Instrument Status

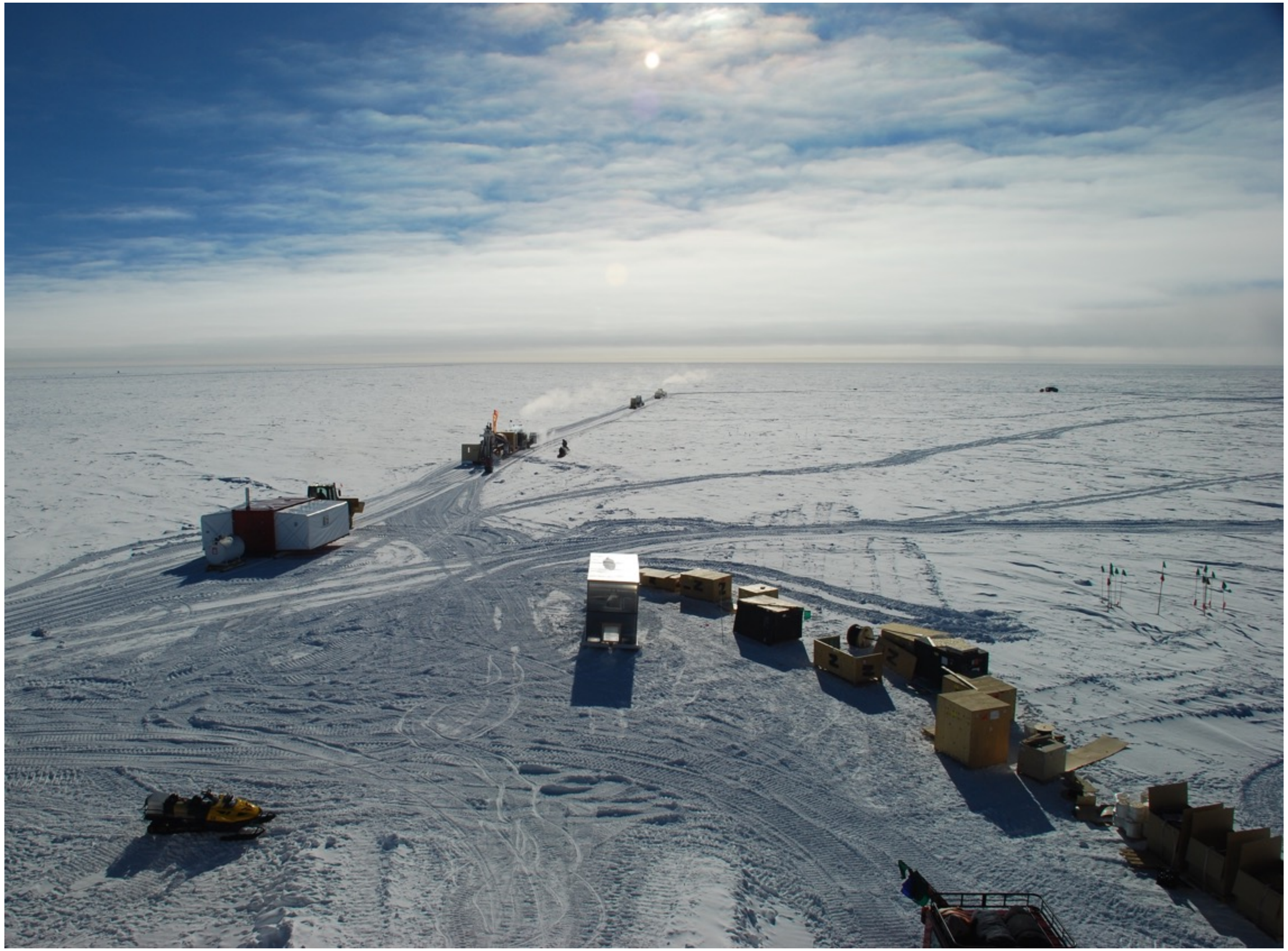




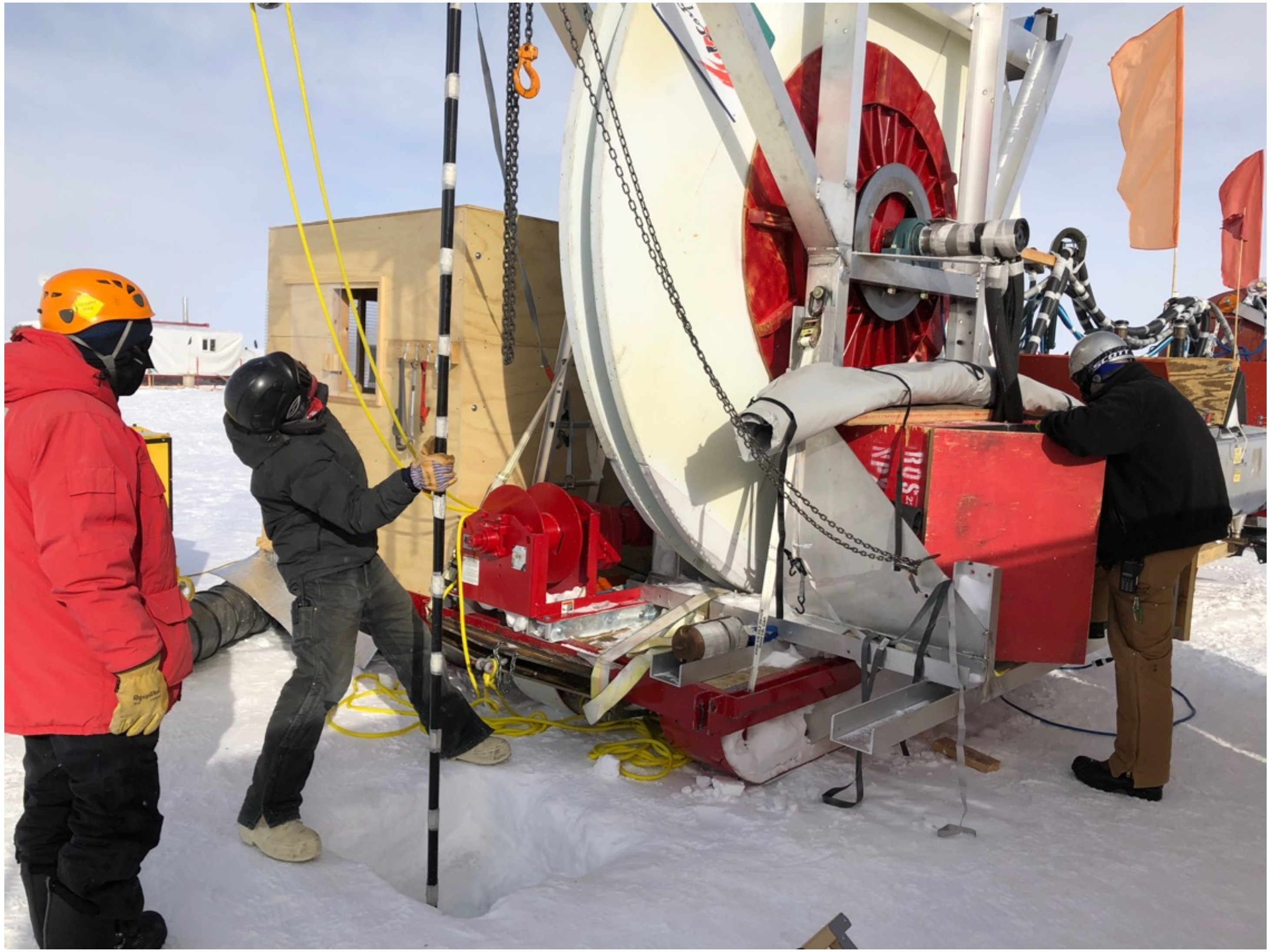
Construction



Construction

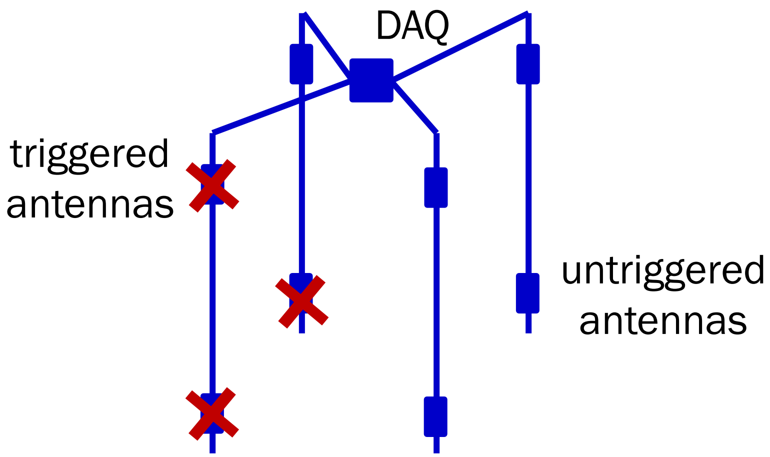


Construction

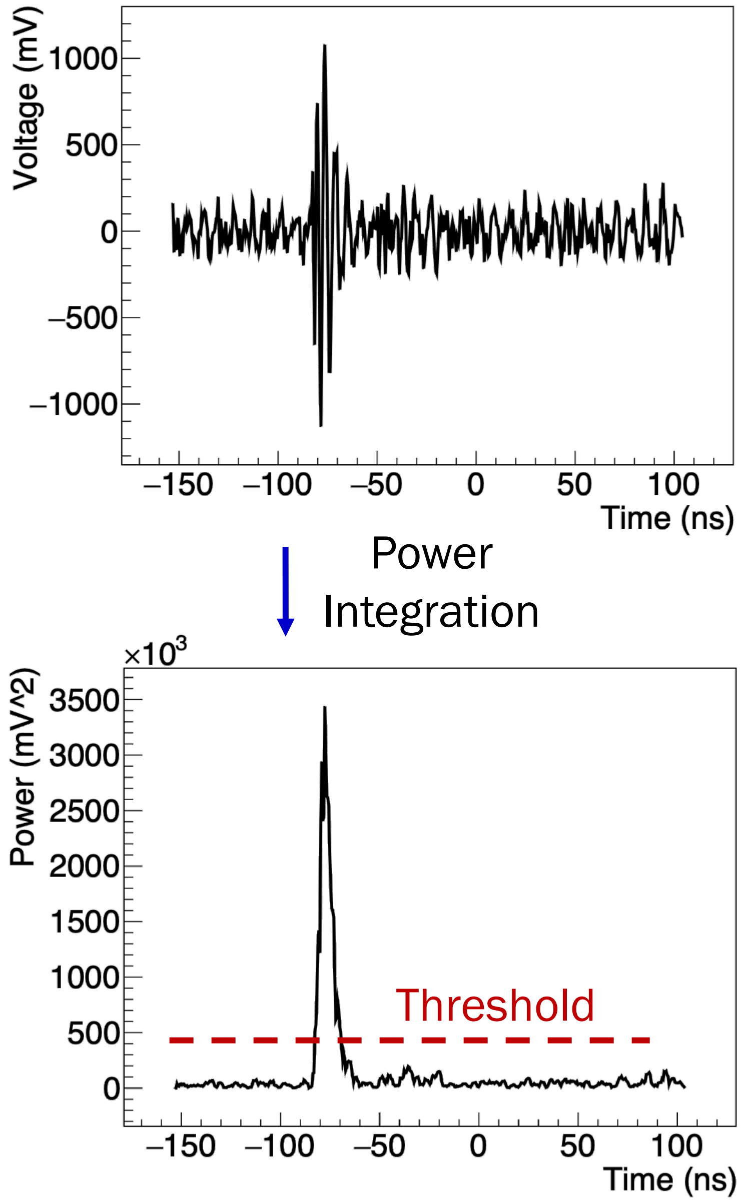


Triggering and Data

- *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



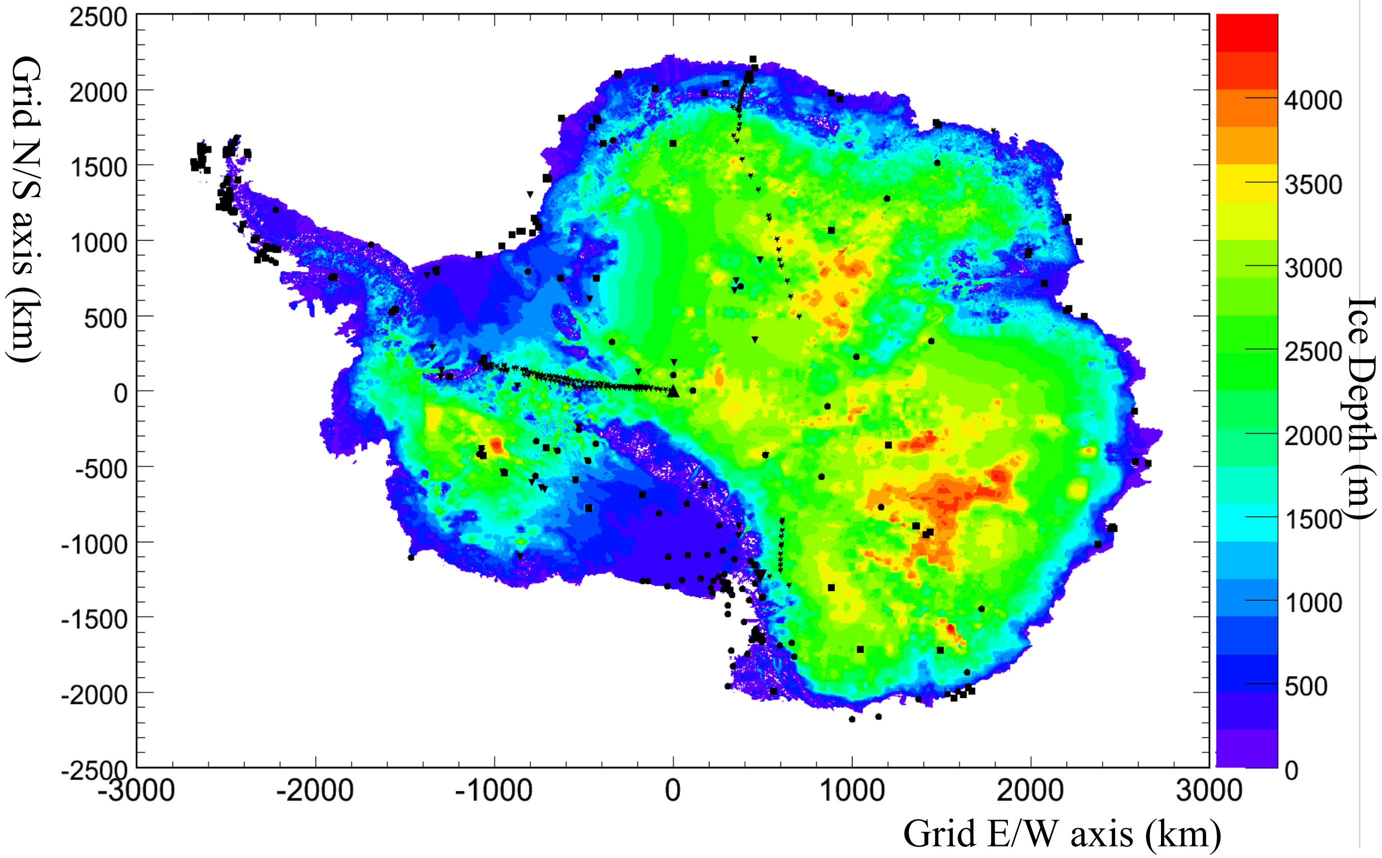
Calibration Pulser
Testbed Station



"It's all about the SNR"

Backgrounds to Signal

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



The Big Questions

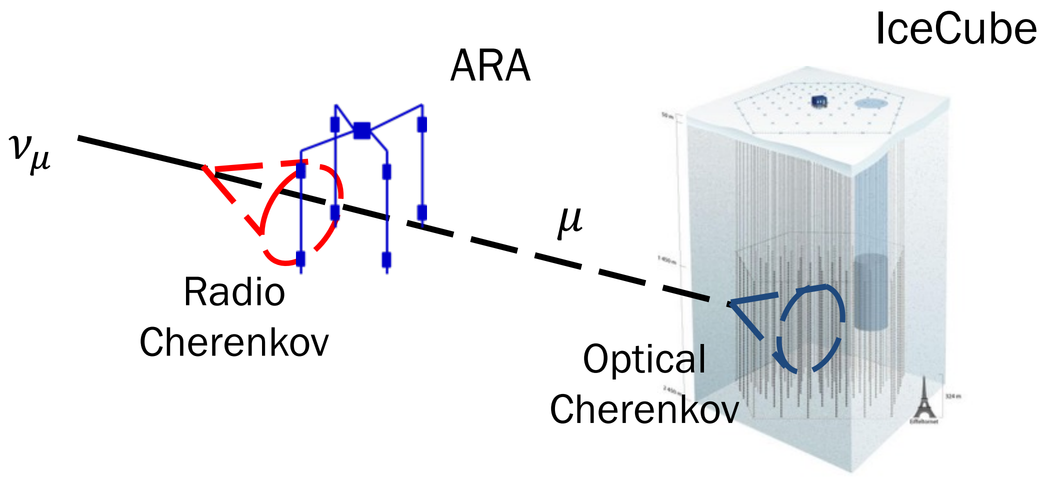
Why?	✓	Astro + Particle Physics
How?	✓	(Radio) Cherenkov Effect
Where?	✓	Antarctica
Who?	✓	IceCube, ARA, ANITA, etc.

What’s New…

What's New

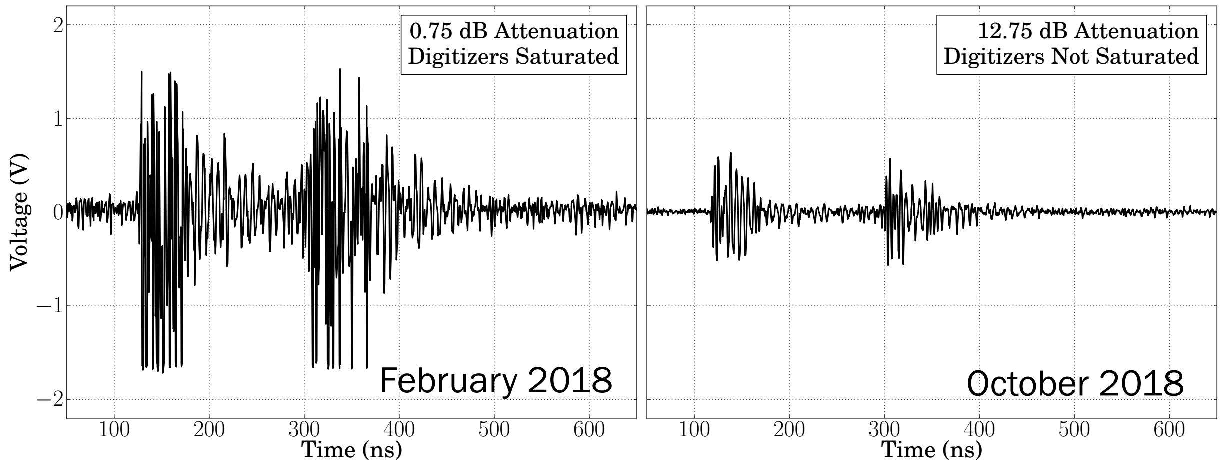
ARA Smart Power System (ASPS)

- Power broker enables granular control of subsystems
- Precision Time Protocol—could sync ARA to IceCube clock



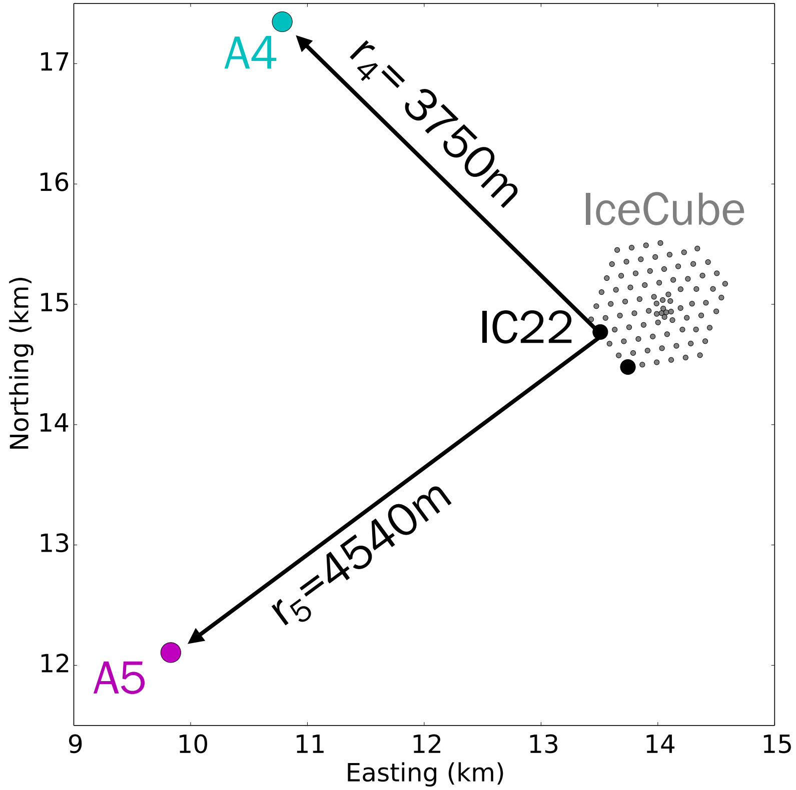
ARA Front End (ARAFE)

- 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

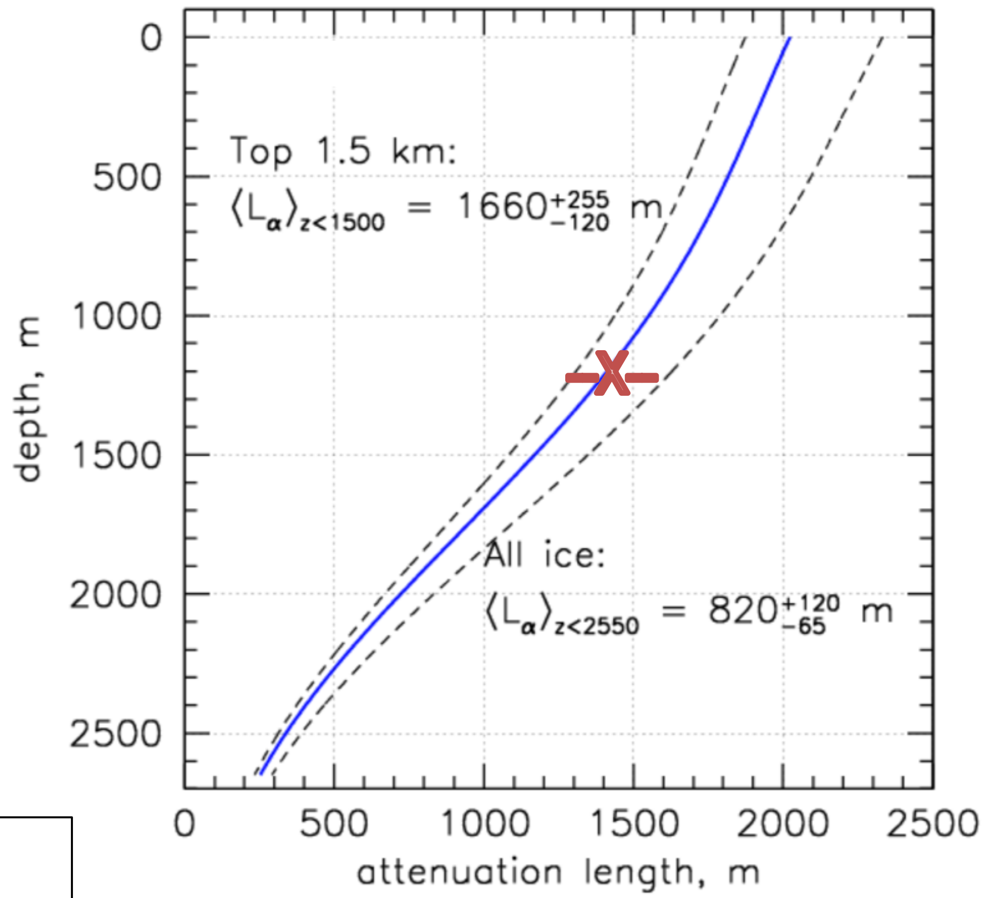
- With *non*-saturated digitizers, pulse amplitude at A4 vs A5 gives the longest horizontal-baseline measurement of L_α



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

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

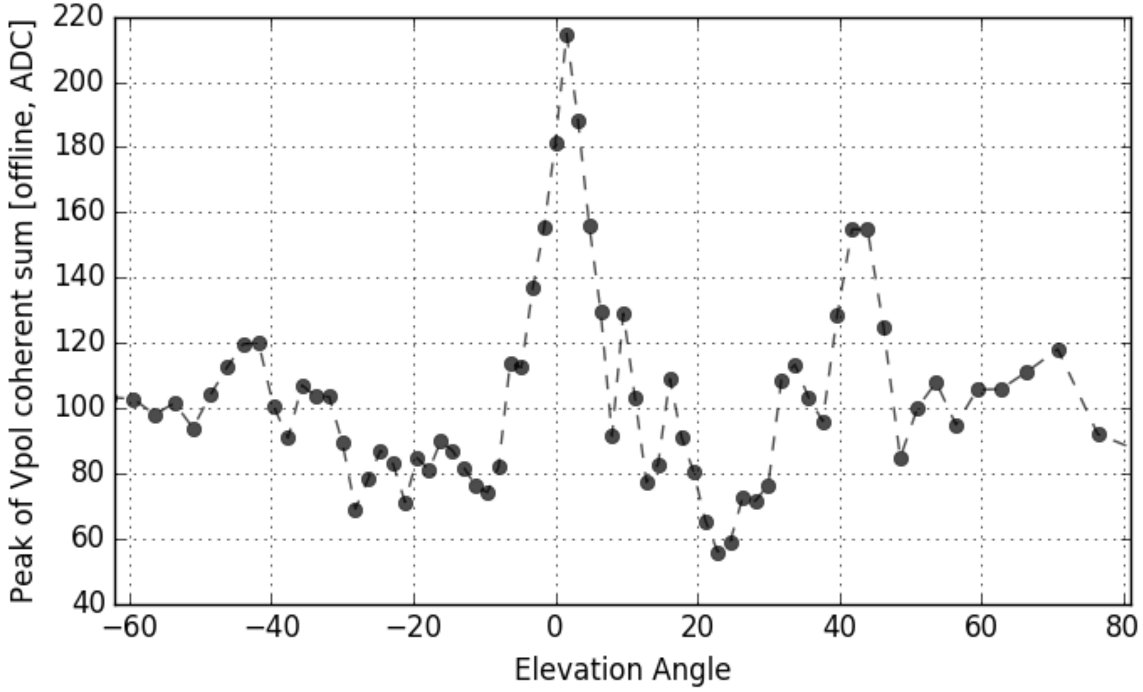
Adapted from [P. Allison *et. al.* j.astropartphys.2011.11.010]

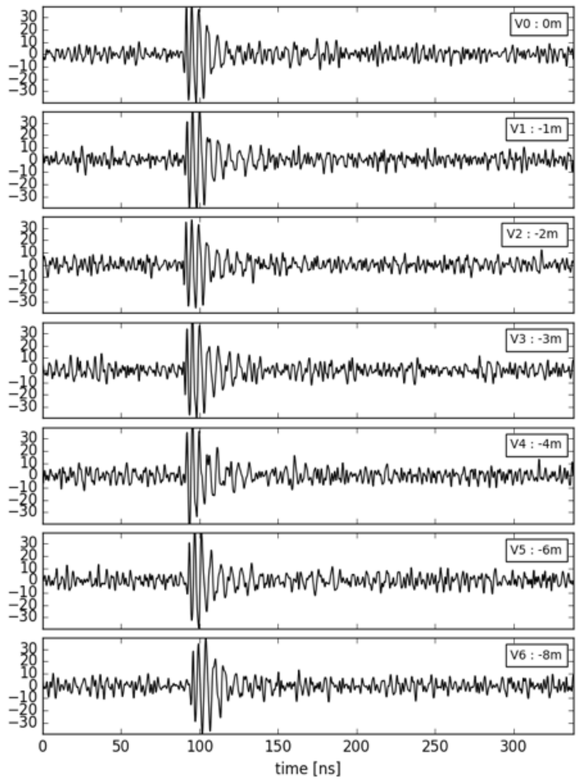


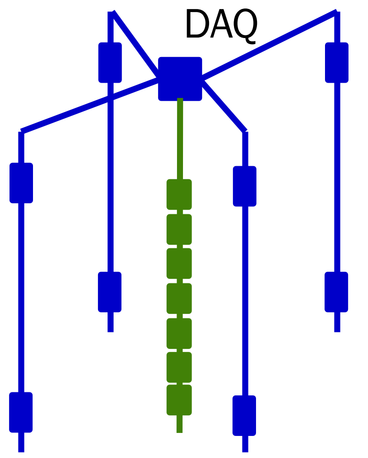
*Measurement by Dave Besson at KU.
See arXiv 1908.10689

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 ∝ $\sqrt{N}$

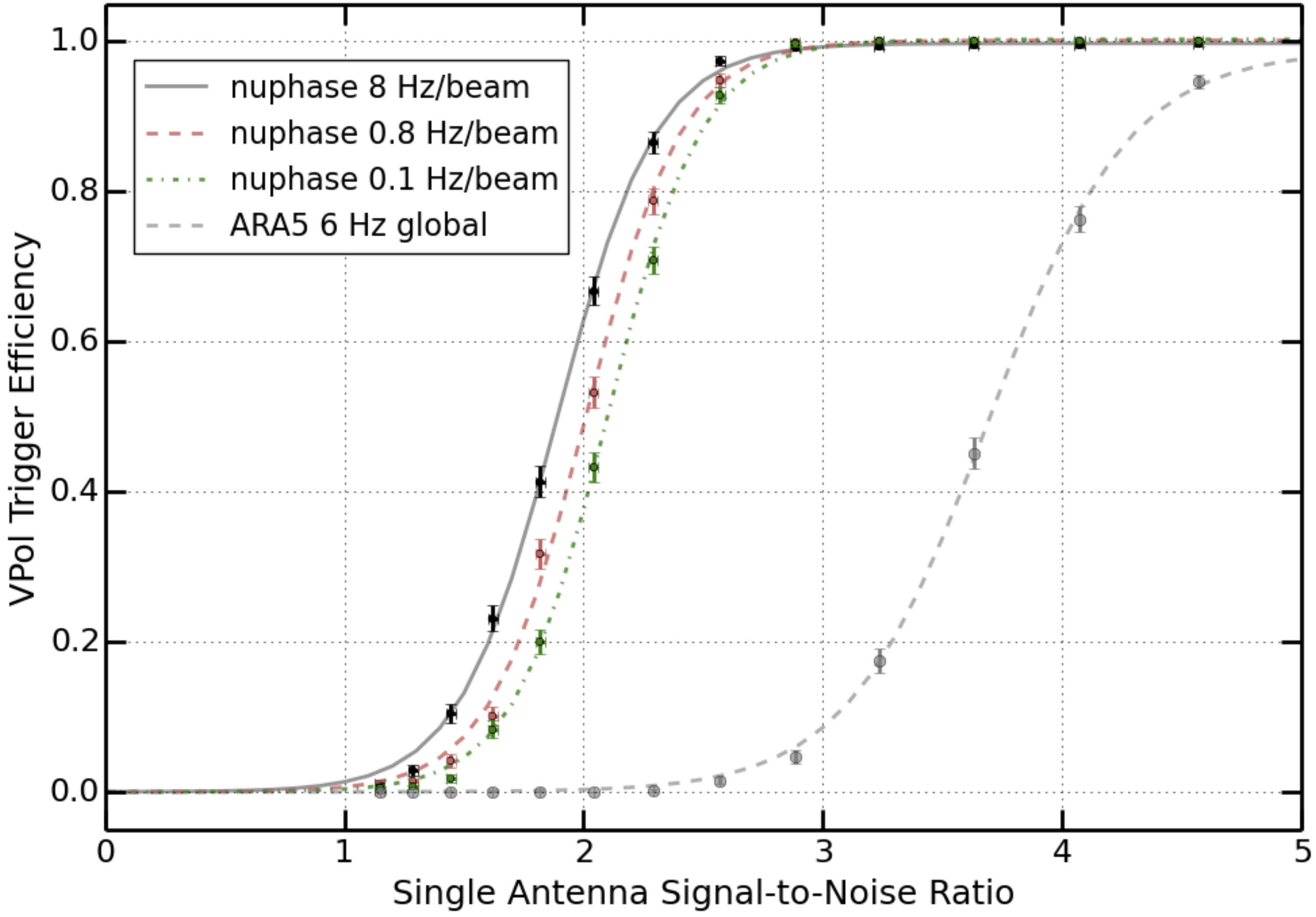






See arXiv 1809.04573

Phased Array Performance Comparison



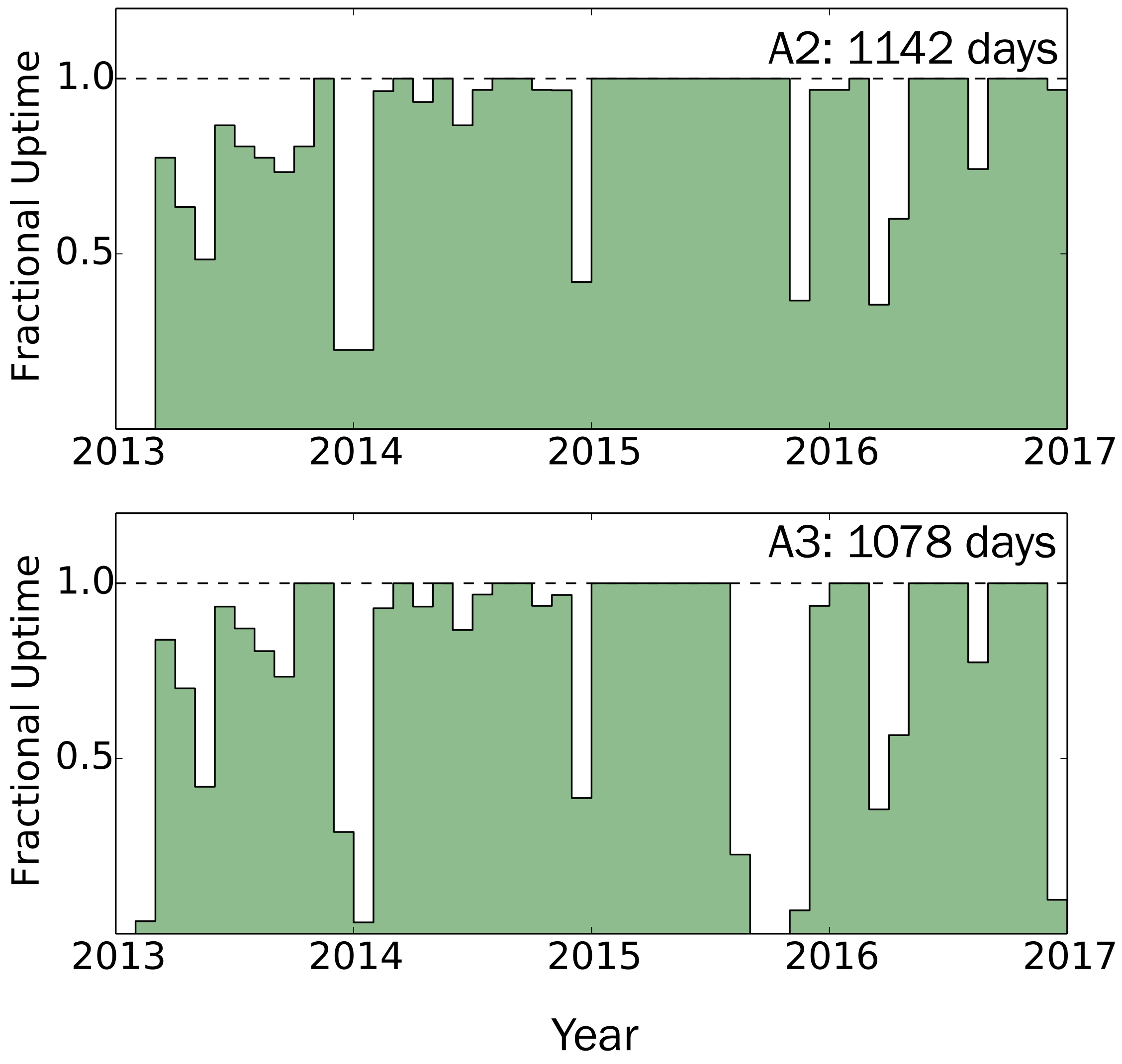
PA measurement demonstrates factor ~1.8 reduction in 50% efficiency point (expected ~2.6).

A2 and A3 Diffuse Analysis

- Presenting expansion to 2013-2016 data set in A2 and A3

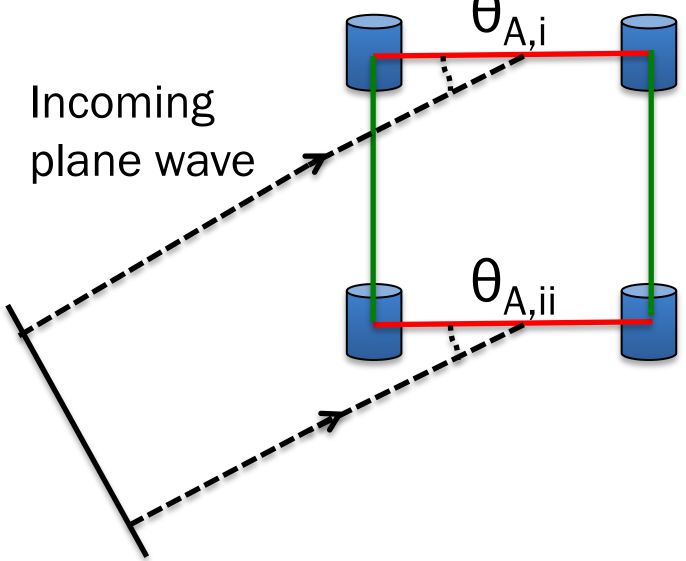
- Analysis is done "blind"—tune cuts on 10% of data, remaining 90% sets the limit

- **Big data**
  - 58 million events in 10% sample
  - Nearly 40 TB of data in 100% sample



Wavefront-RMS Filter

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



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

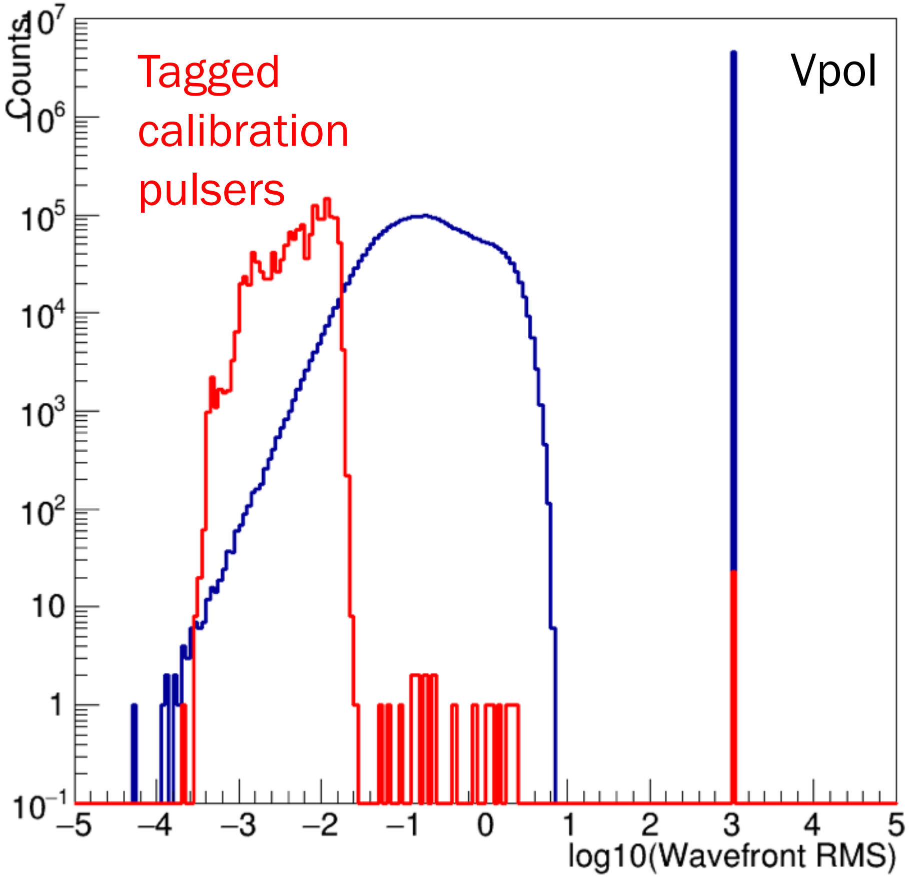
$$\cos(\theta_{A,i}) \approx \cos(\theta_{A,ii})$$

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

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

Wavefront-RMS Filter

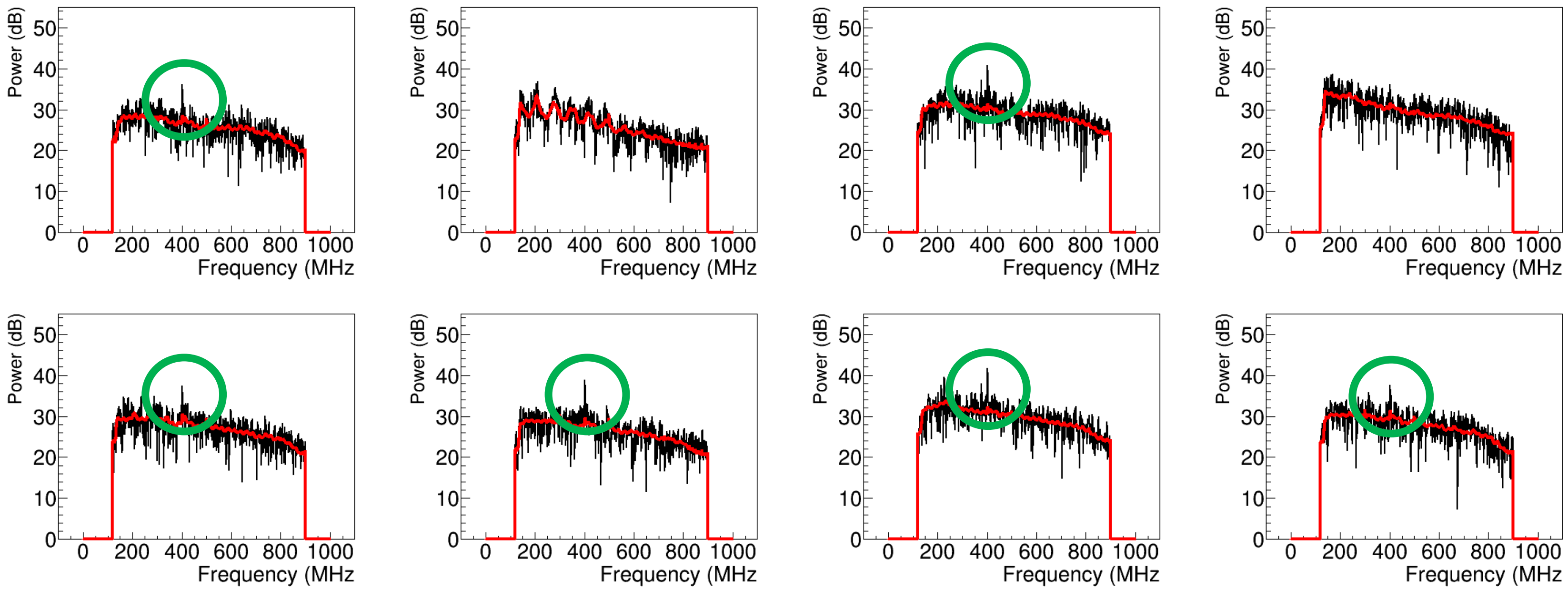
- Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol, ~90% efficient for neutrinos



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

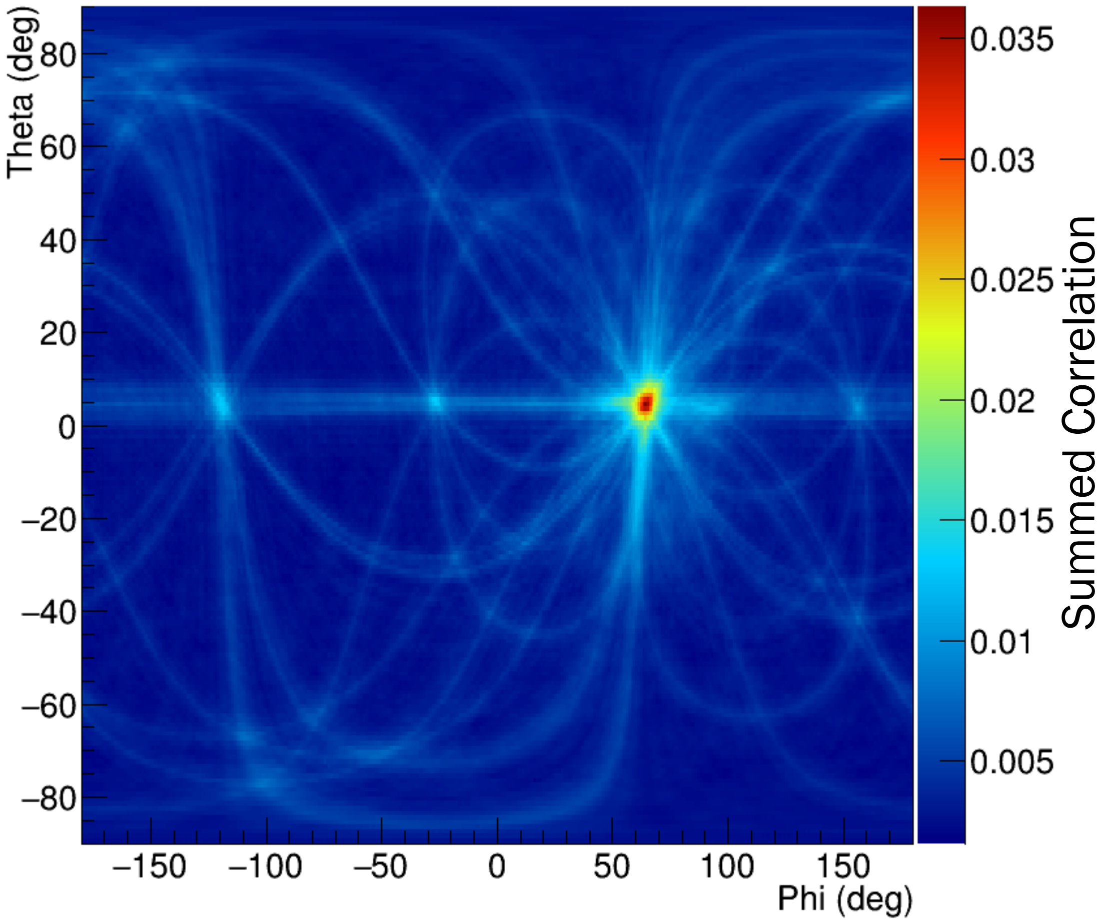
$$C_{i,j}(\tau) = \frac{SNR_i \times SNR_j \times \sum_{t=-\infty}^{\infty} V_i(t)V_j(t+\tau)}{N_{overlap} \times RMS_i \times RMS_j}$$

  - Sum over pairs of antennas

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

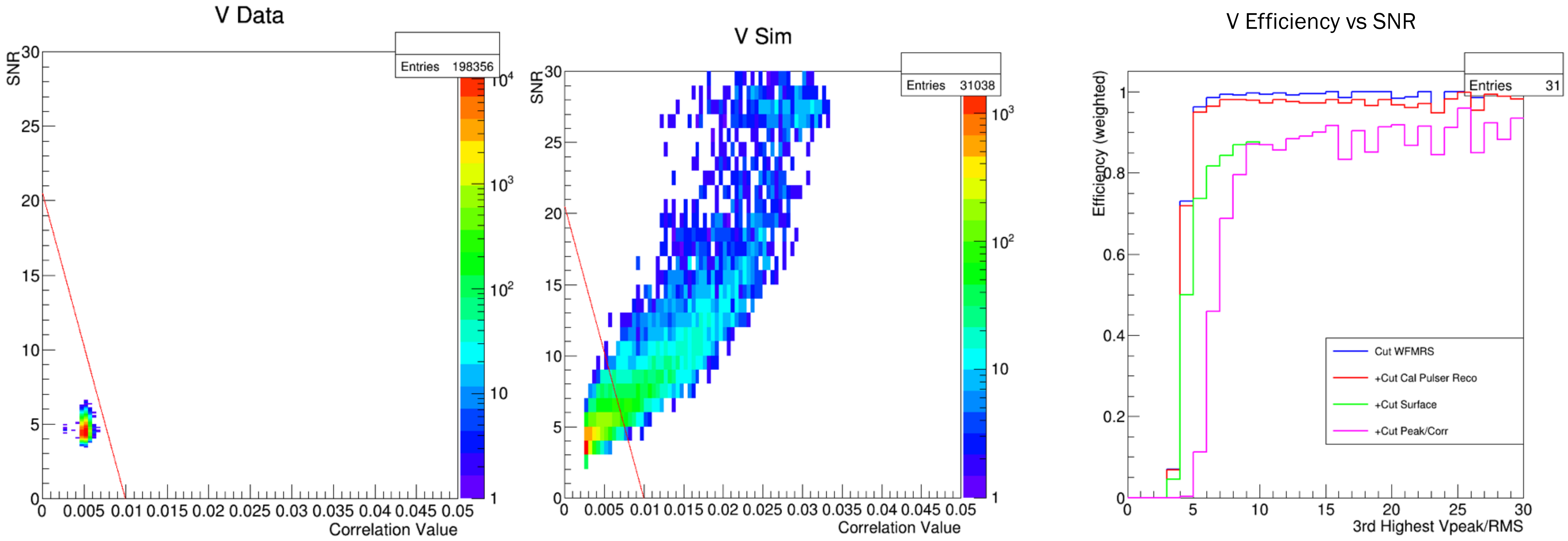
- Cut events that reconstruct to surface or in direction of pulser

Example Calibration Pulser Event



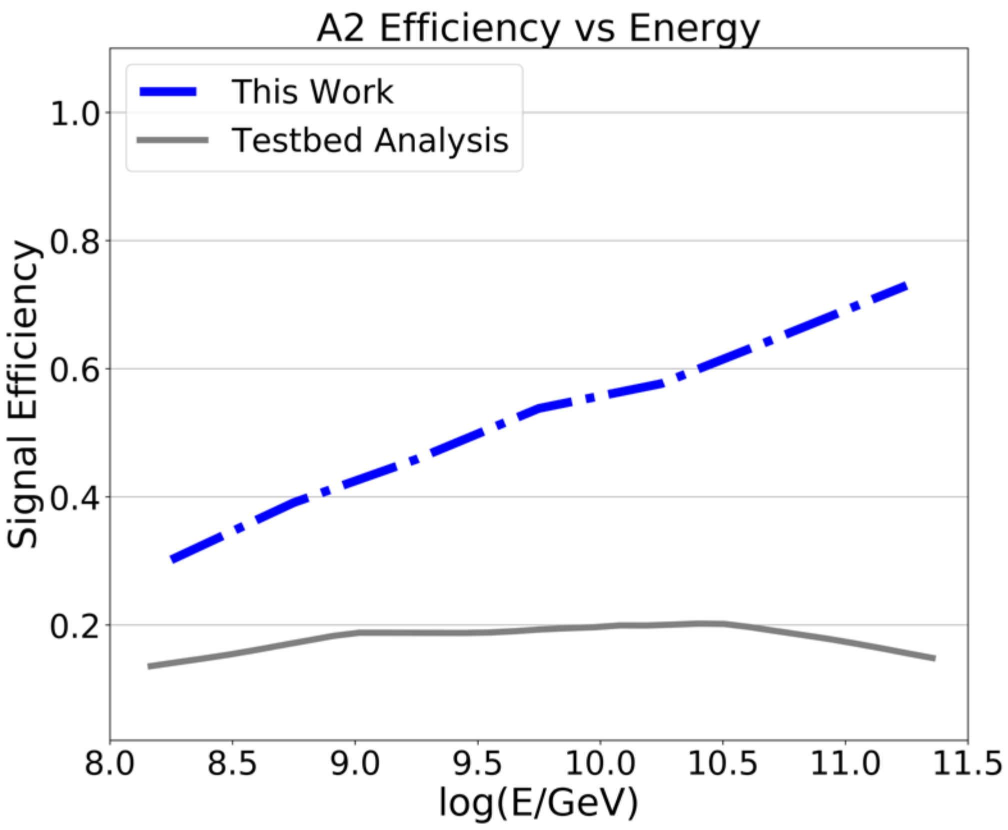
Final Cut

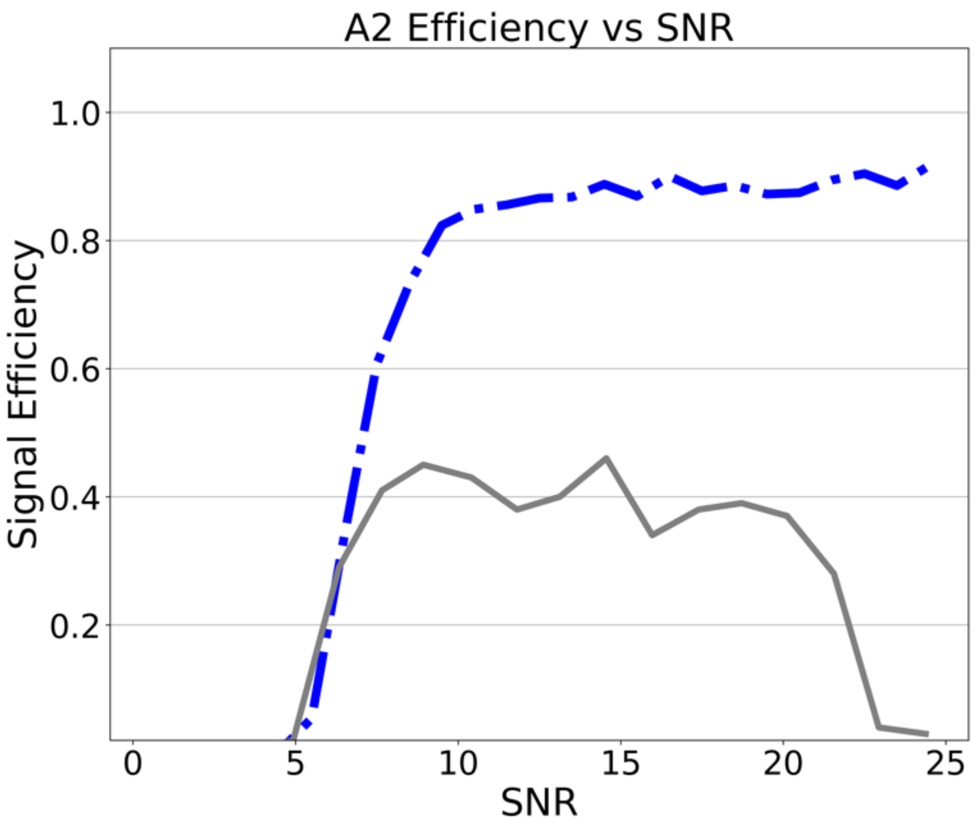
- Final cut of the analysis is a slanted-line; slope (*m*) and y-intercept (*d*) are optimized to set the best limit



Efficiency

- Between 2 and 4 times more efficient than that of prototype analysis

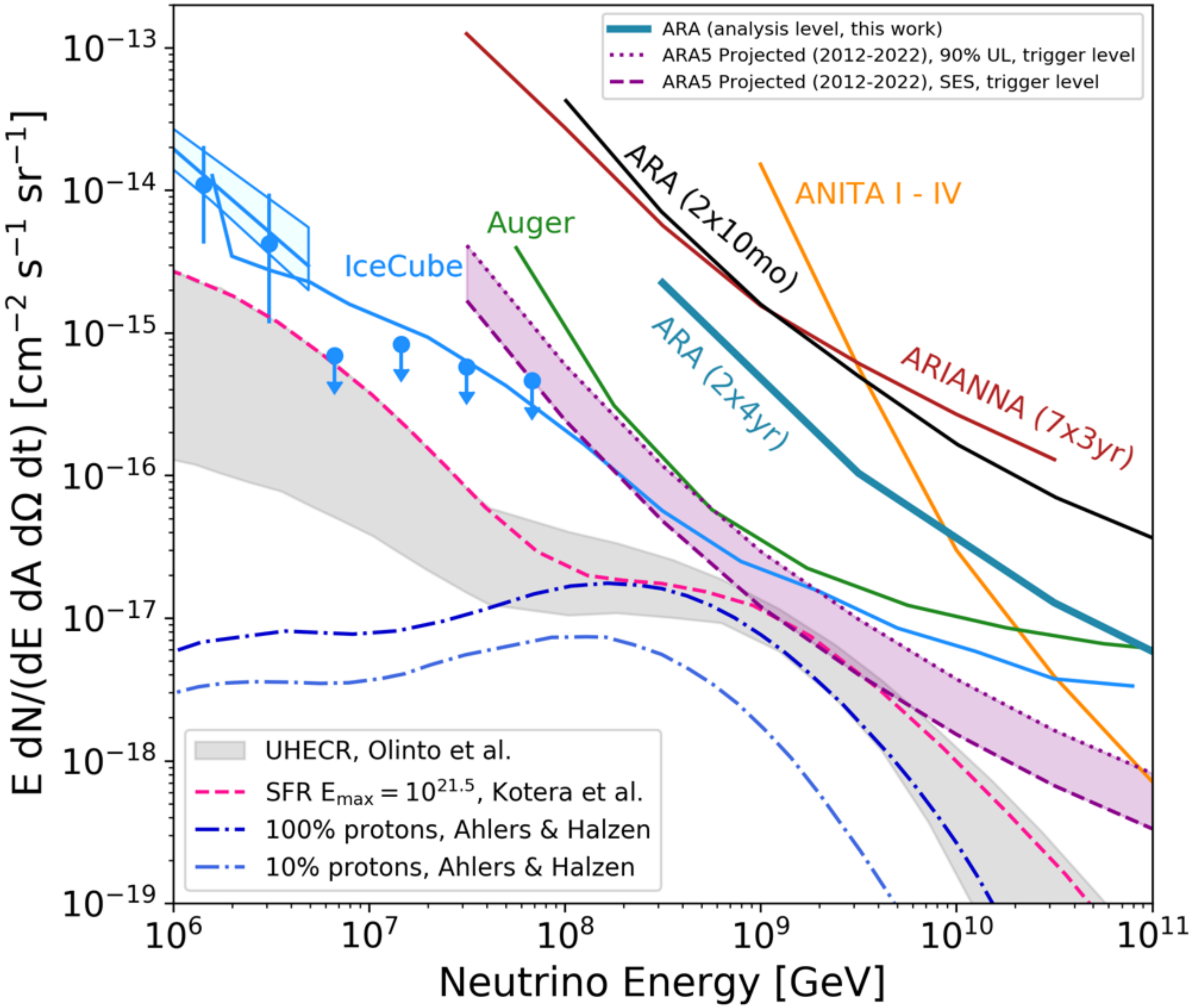




Expected Limit

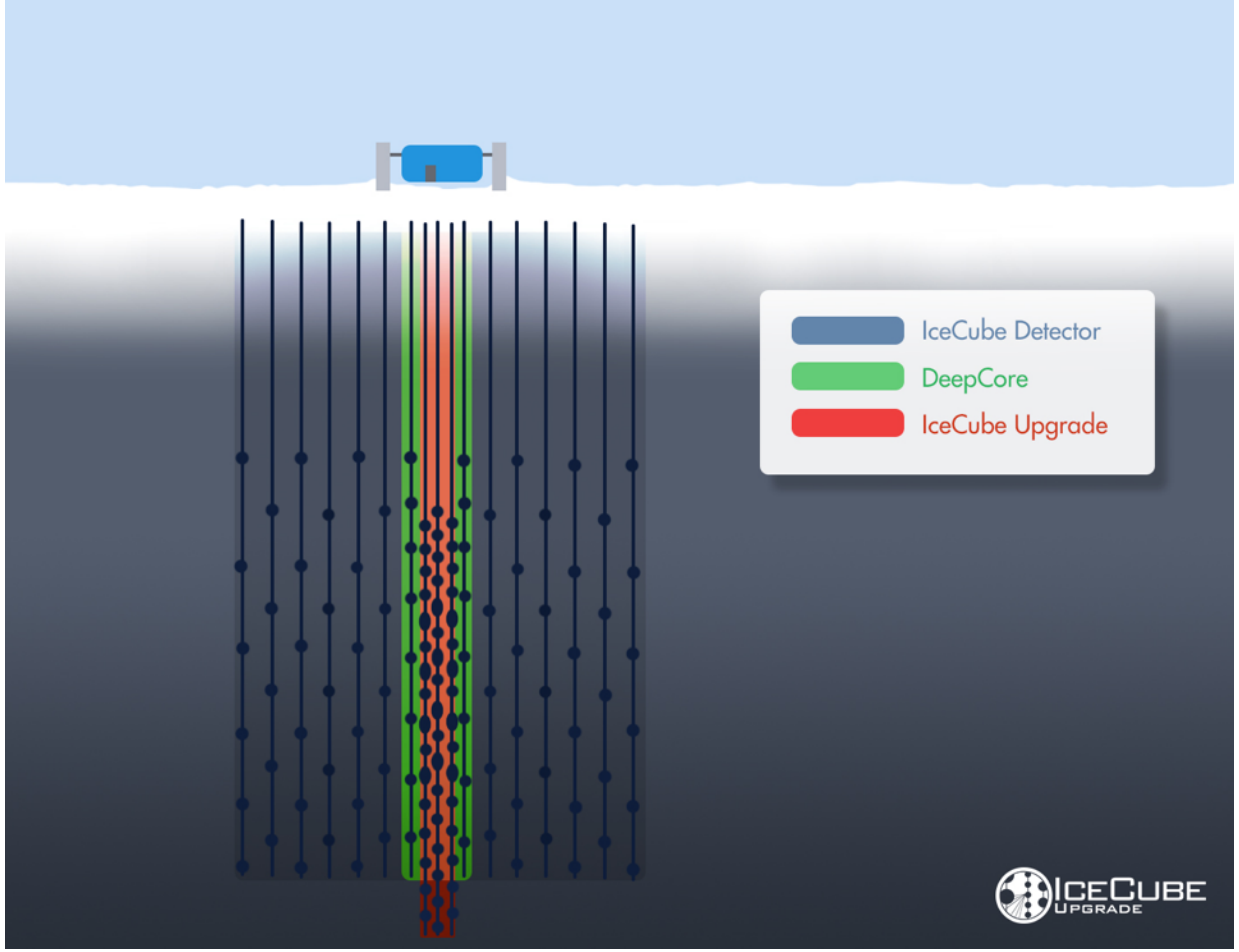
Projected ARA sensitivity carves out exciting new parameter space, w/ real chance at a detection!

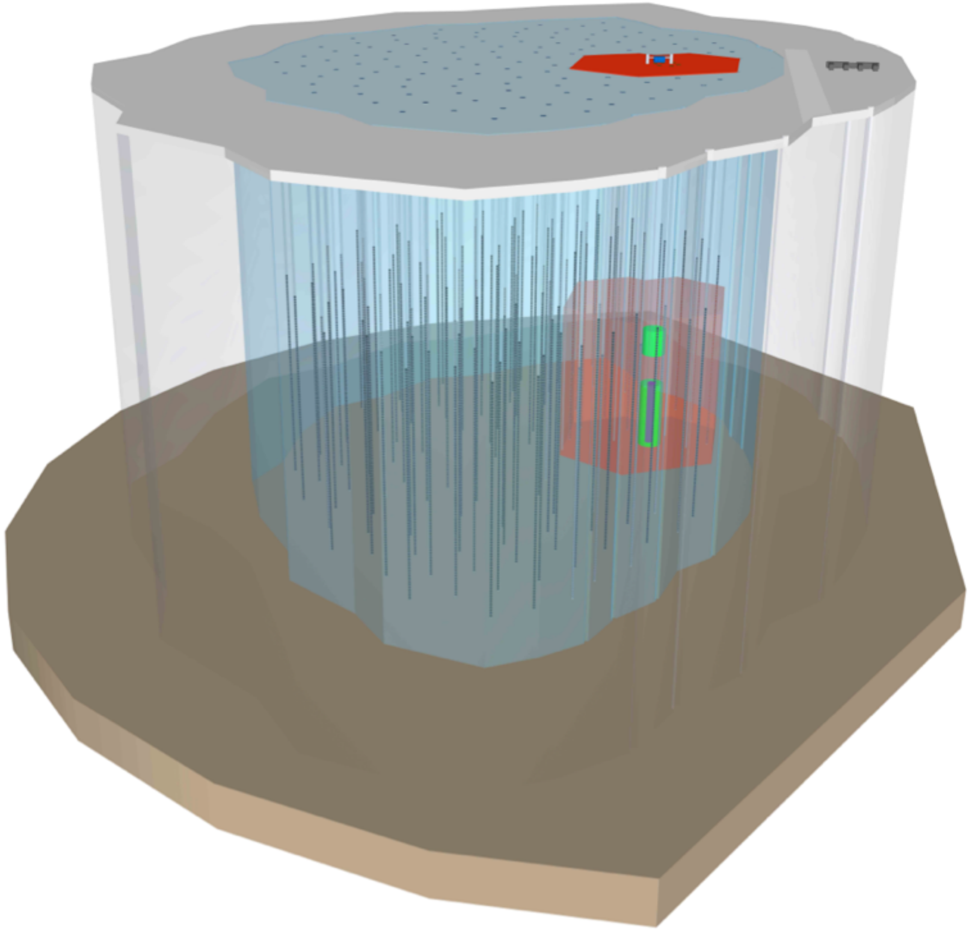
Look for paper in next month! (for now, ICRC proceeding arXiv 1907.11125)



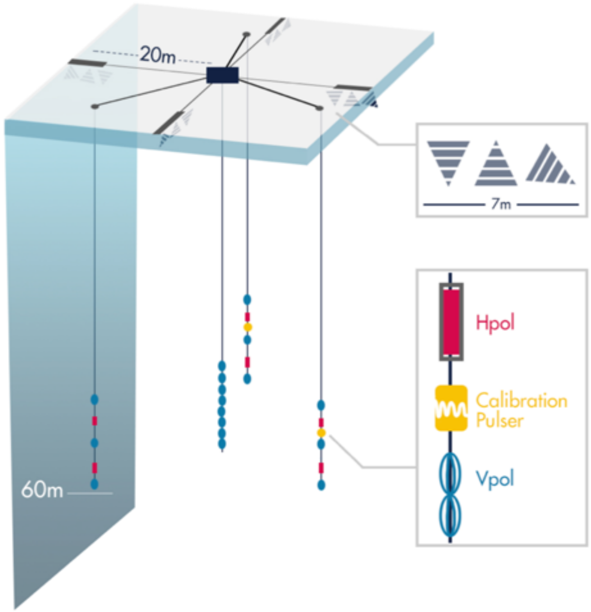
The Future for Neutrino Telescopes

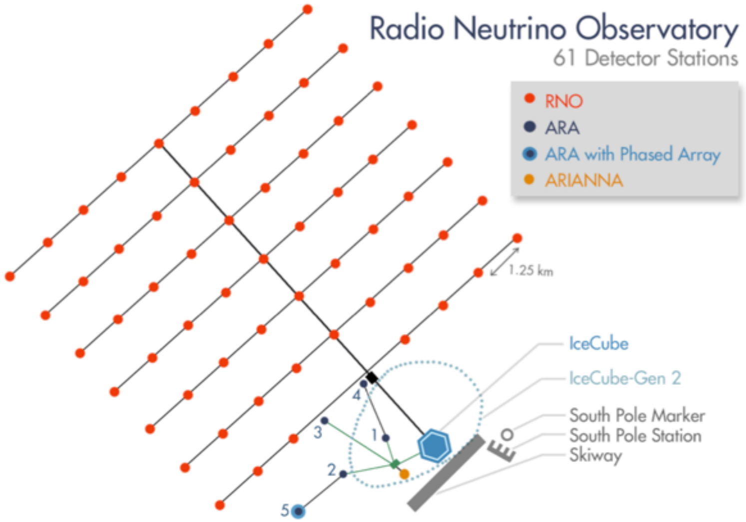
IceCube Upgrade and Gen2

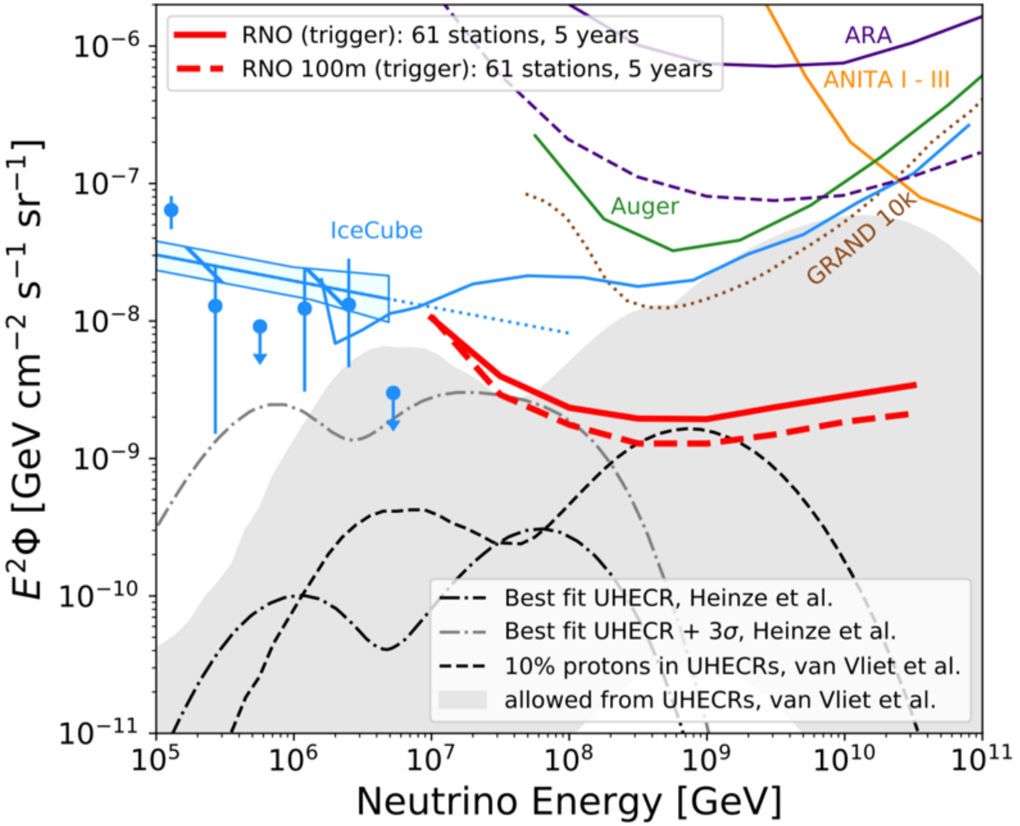




Future Radio Instruments







See arXiv **1907.12526**

Summary

1. Neutrinos are important and complimentary messengers to the cosmos

2. ARA is recently expanded with enhanced triggering, and a new analysis with 4x livetime is nearly complete

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

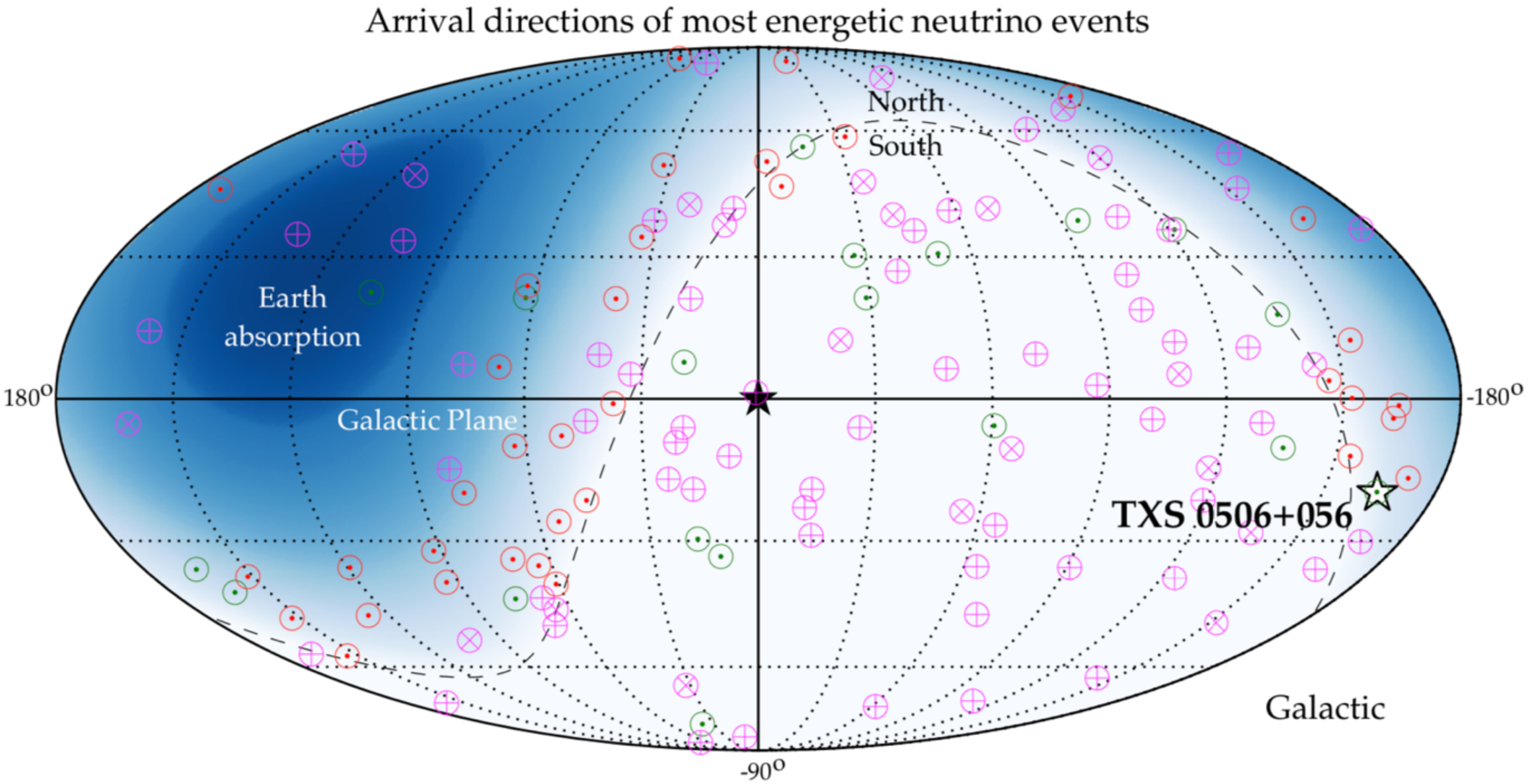
Research generously supported by:

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

Back-up Slides

Astronνmy*

- No definitive sources yet, but eagerly awated



* Mauricio Bustamante

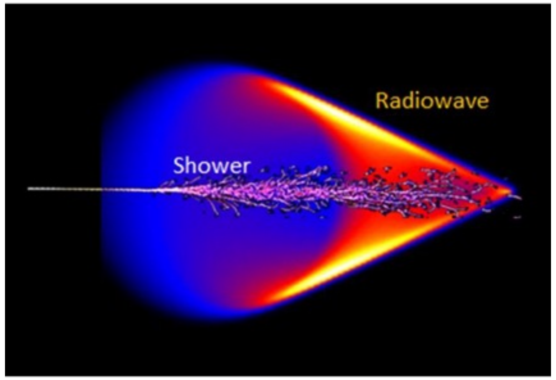
Neutrino Interactions

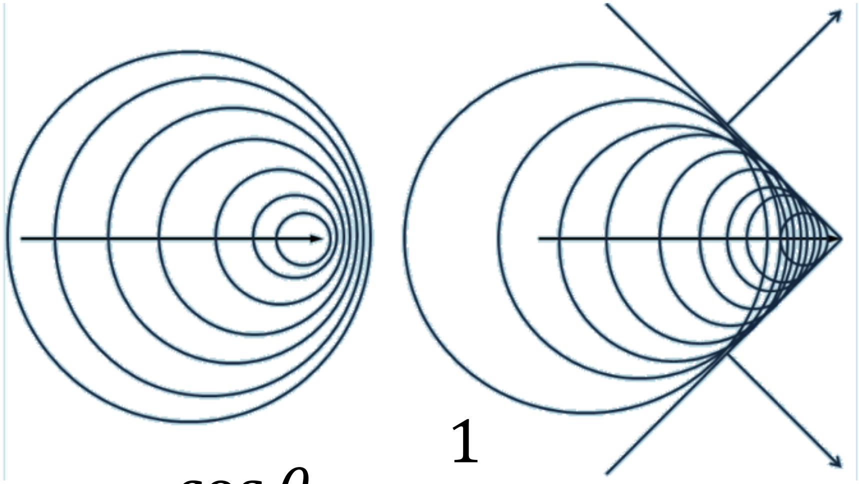
- Two varieties of interactions: Charged current (CC) and Neutral Current (NC)

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

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

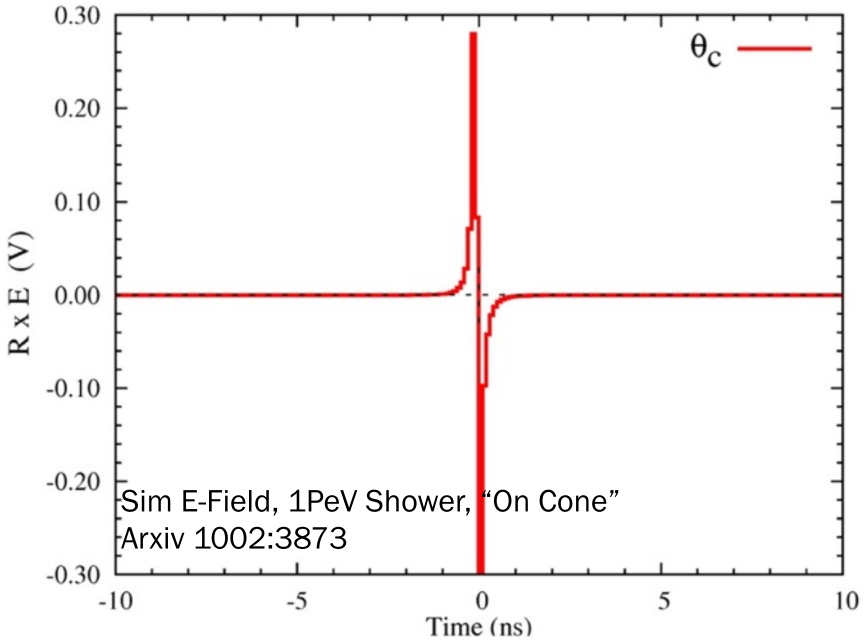
- Showers are ultra-relativistic ($\beta \approx 1$) ⟶ emit Cherenkov radiation in dense media
- Intensity is greatest at Cherenkov angle θ_C
- Two varieties of interest: optical and radio

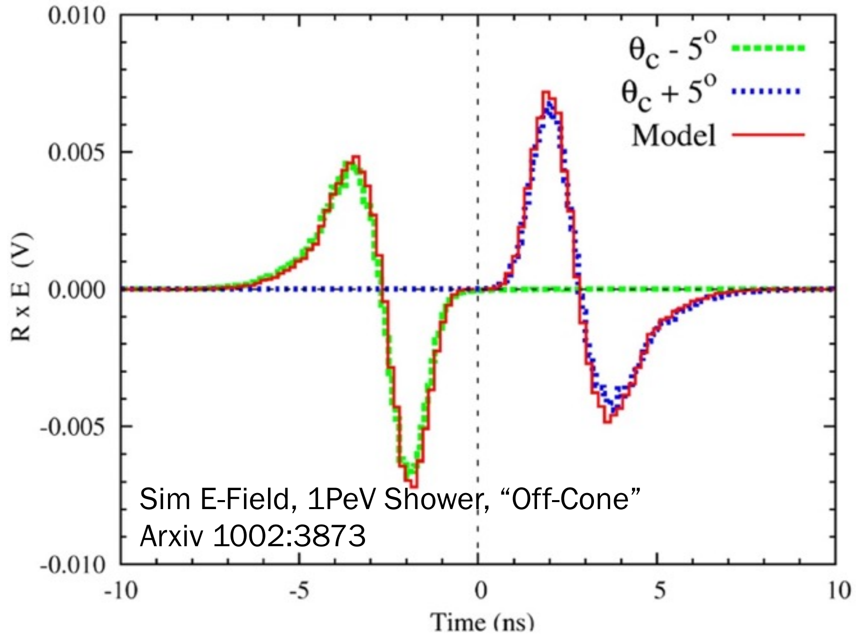




$$\cos\theta_C = \frac{1}{n\beta}$$

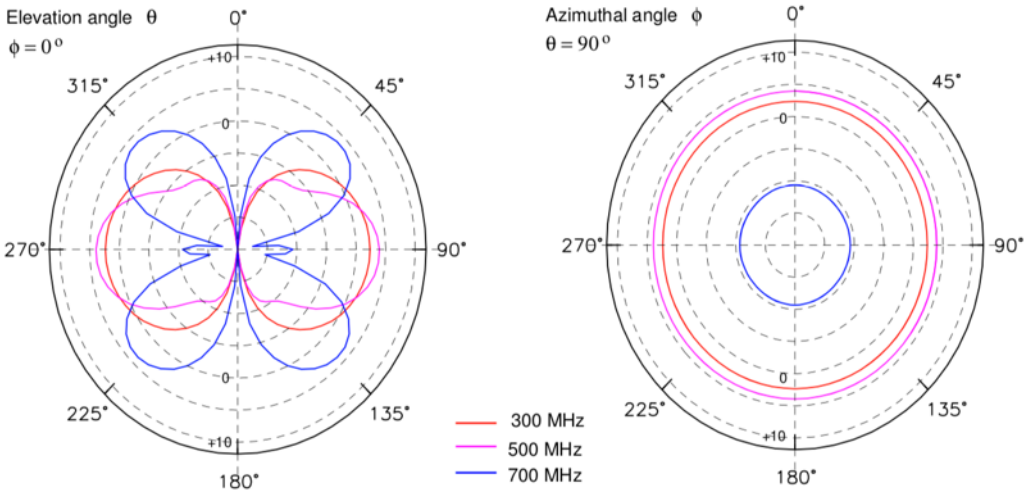
Askaryan Pulse Shape and Dependencies

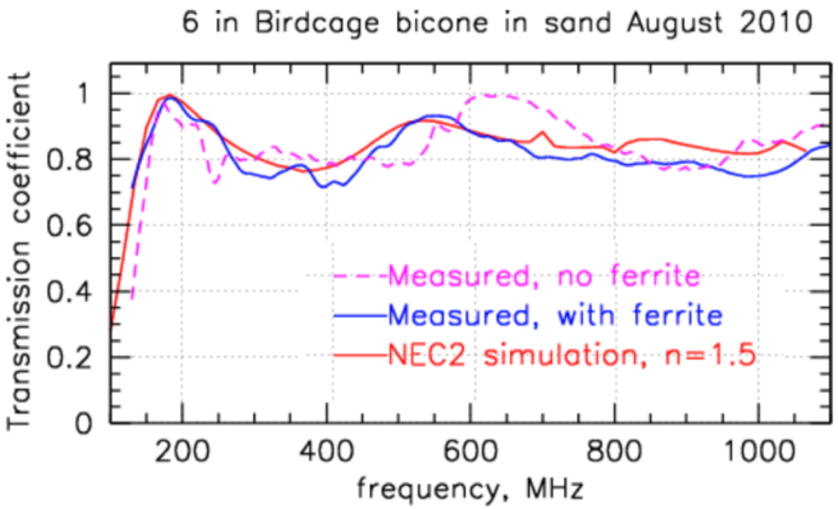




$$V(f) \propto \frac{yE_\nu}{R} \times \frac{f}{1150\text{MHz}} \times \exp\left[-\frac{1}{2}\left(\frac{f}{1\ \text{GHz}} \times \frac{\Omega}{2.2^\circ}\right)^2\right]$$

ARA Antennas



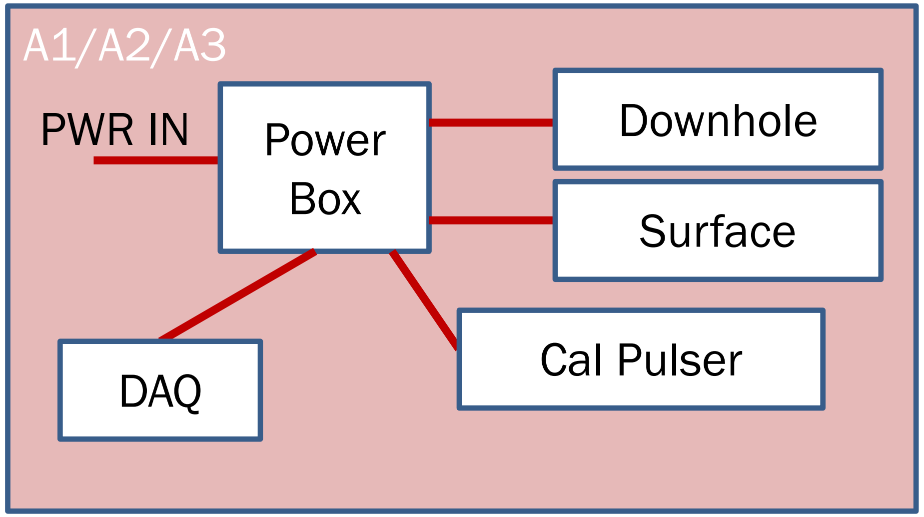


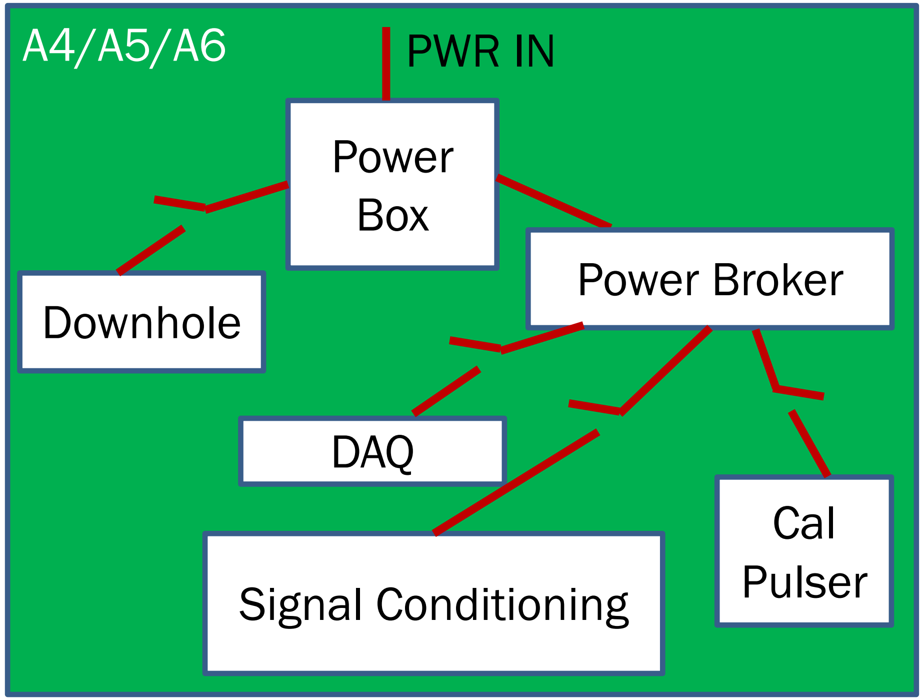
V-Pol Antenna

H-Pol Antenna

New Power Distribution

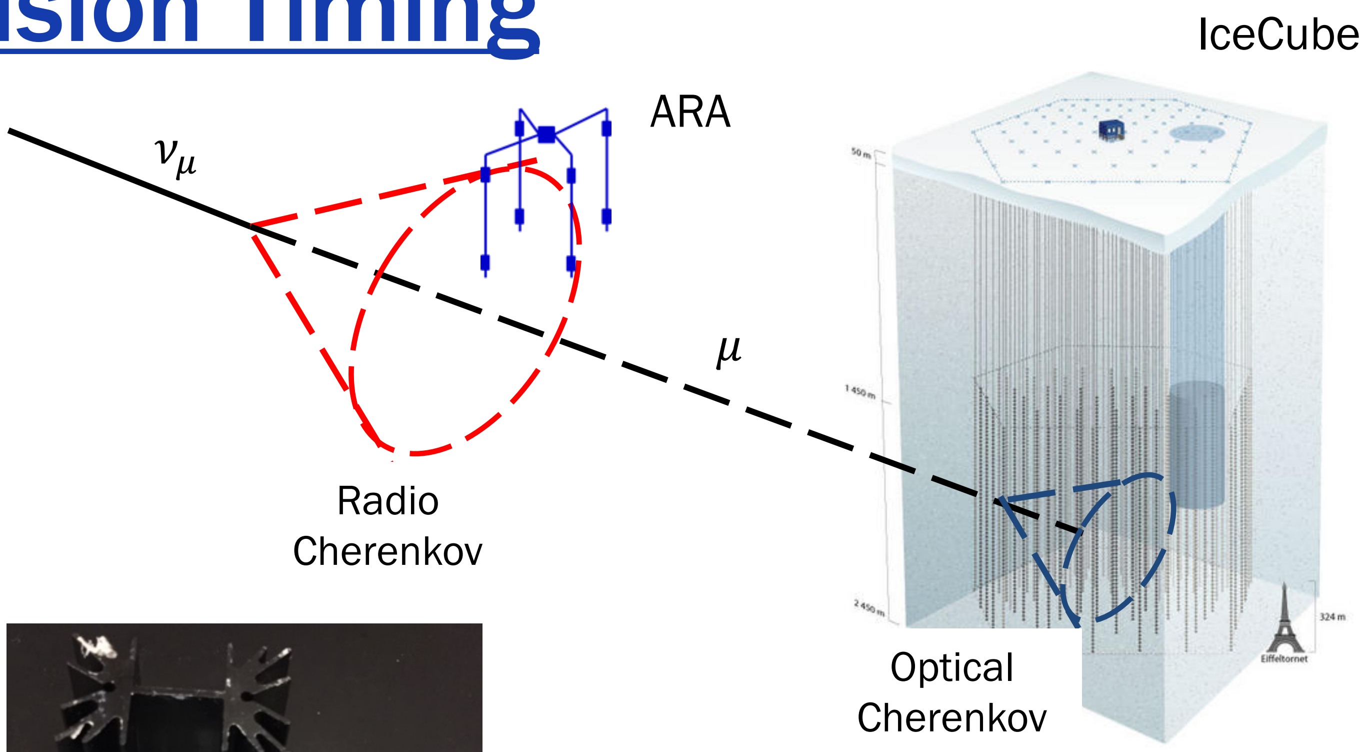
- Introduced power broker: the ARA Smart Power system (ASPS)
- Old power systems had no granularity
  - A short anywhere compromised the entire station
  - Power cycling subsystems required power cycling whole station—not ideal
- Granularity is powerful—since deployment:
  - No IceCube winter-over intervention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

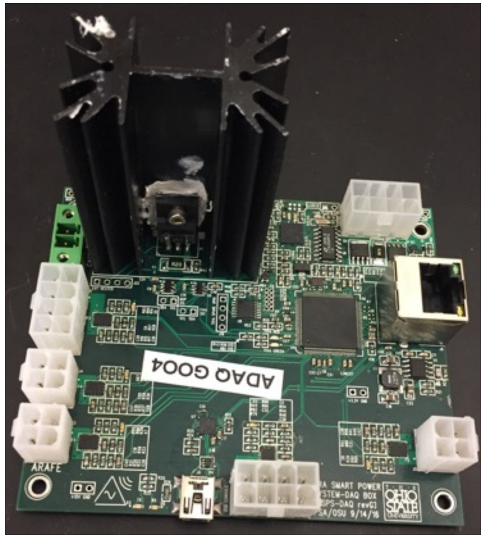




Precision Timing

- 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*



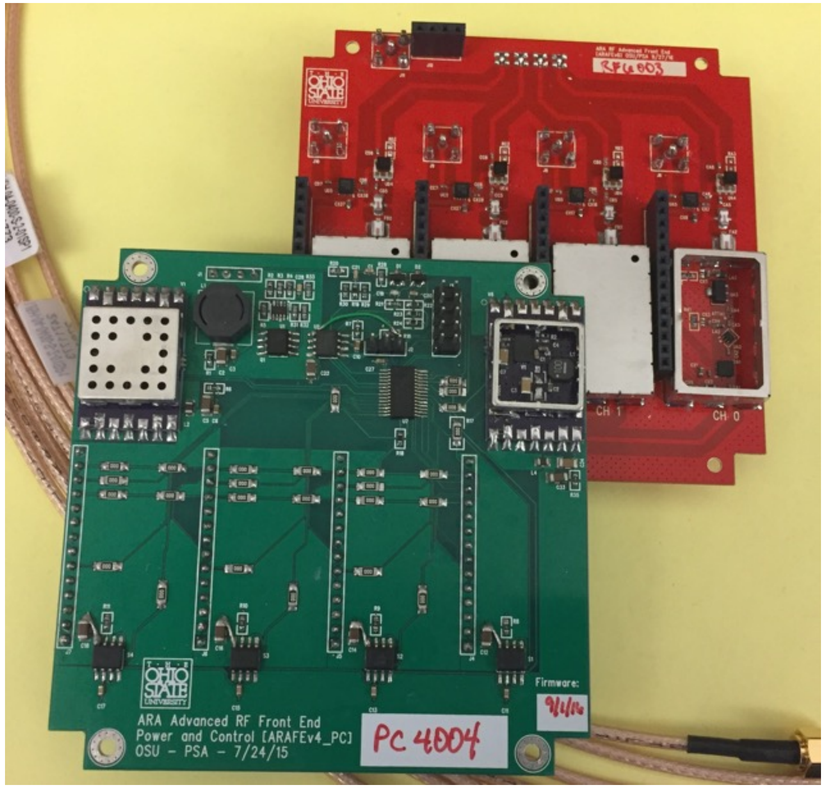


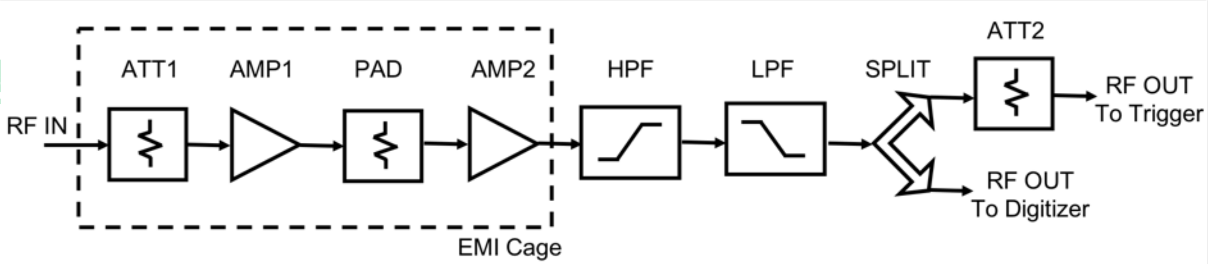
* = part of postdoc plan at MSU w/ IceCube....

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 taking periods





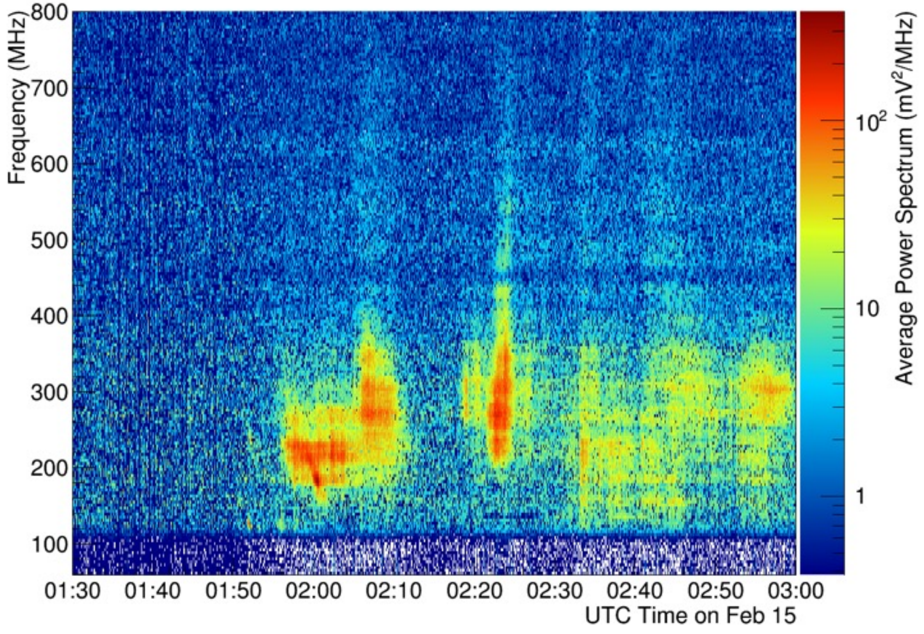
2: Test on Natural Phenomenon

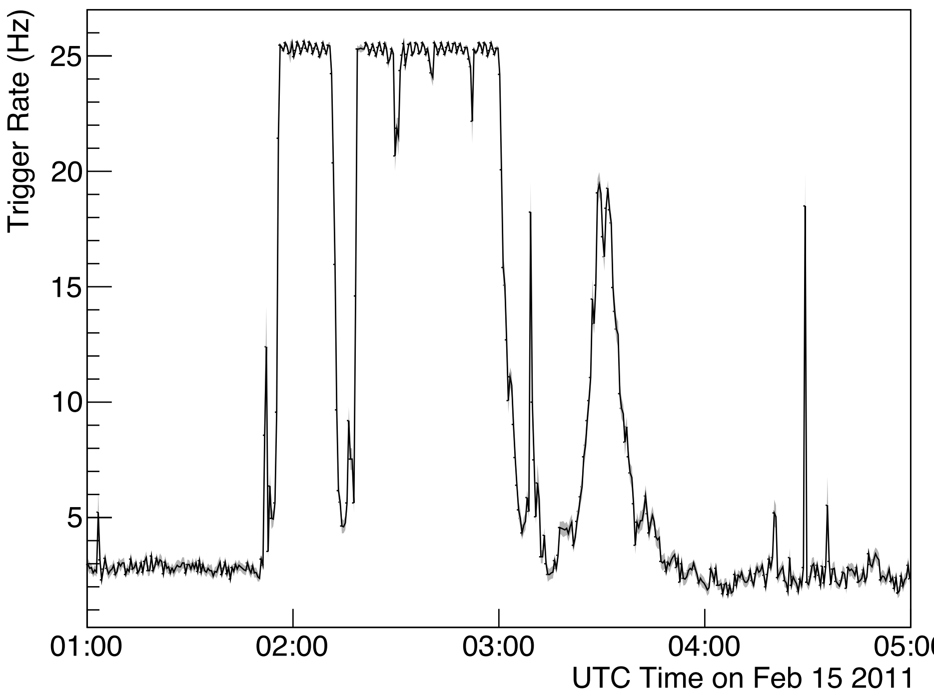
Observation of Reconstructable Radio Emission from Solar Flare

"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

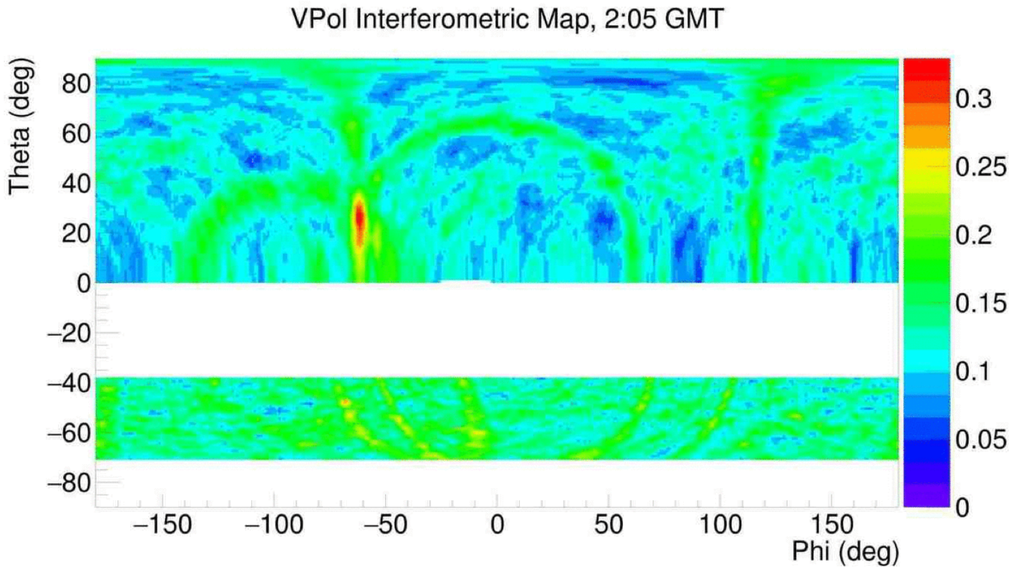
- Testbed activated in February 2011, detected Feb 15 X-2.2 Solar Flare
- Saturates the triggering system
- Observed as excess emission from 100-500 MHz

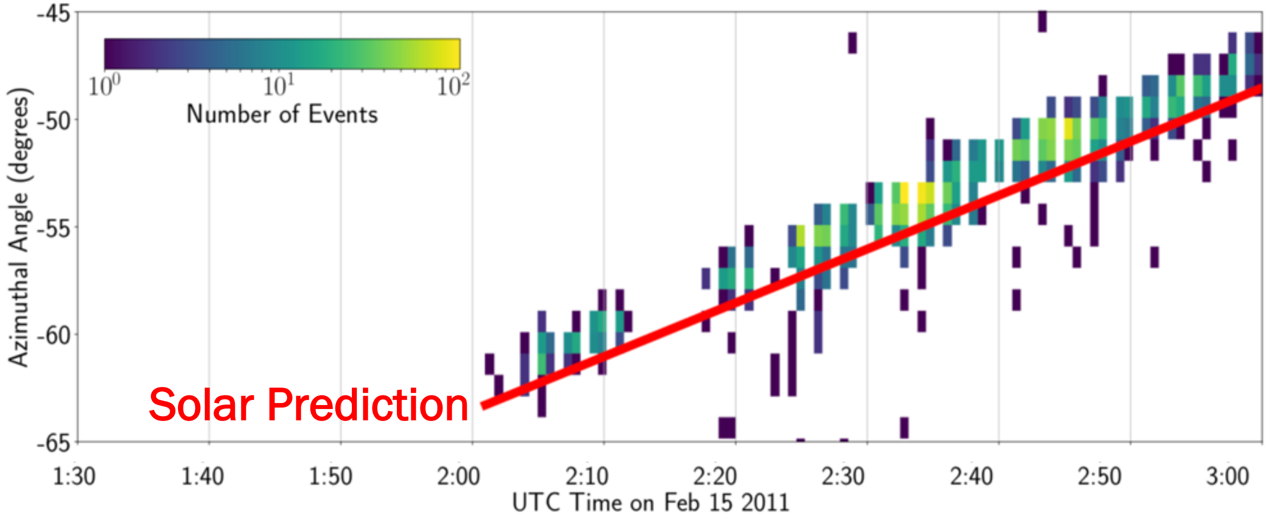




Solar Tracking

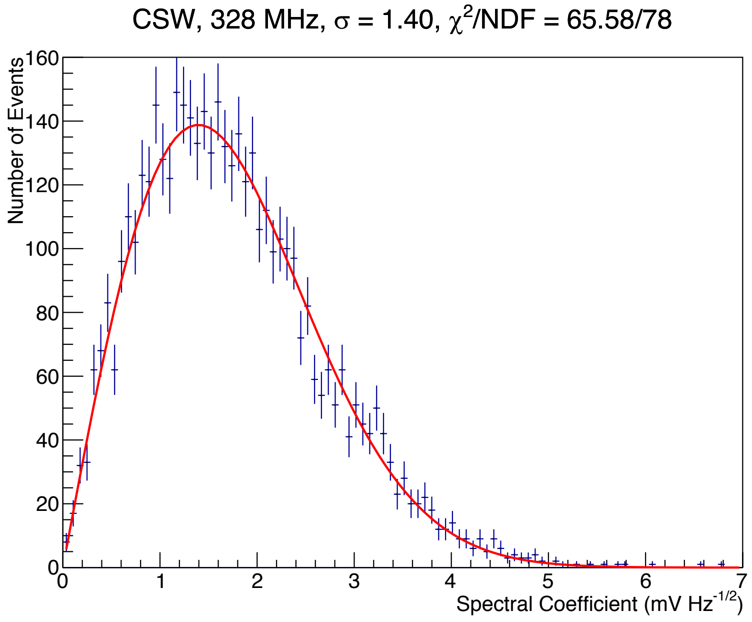
- Recorded events point back to the sun for the hour duration of the flare
- First radiation for ARA which reconstructs to extraterrestrial source on event-by-event basis
  - Excellent test of projection onto celestial coordinate system
  - Will help calibrate pointing of other above-ice radio sources,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

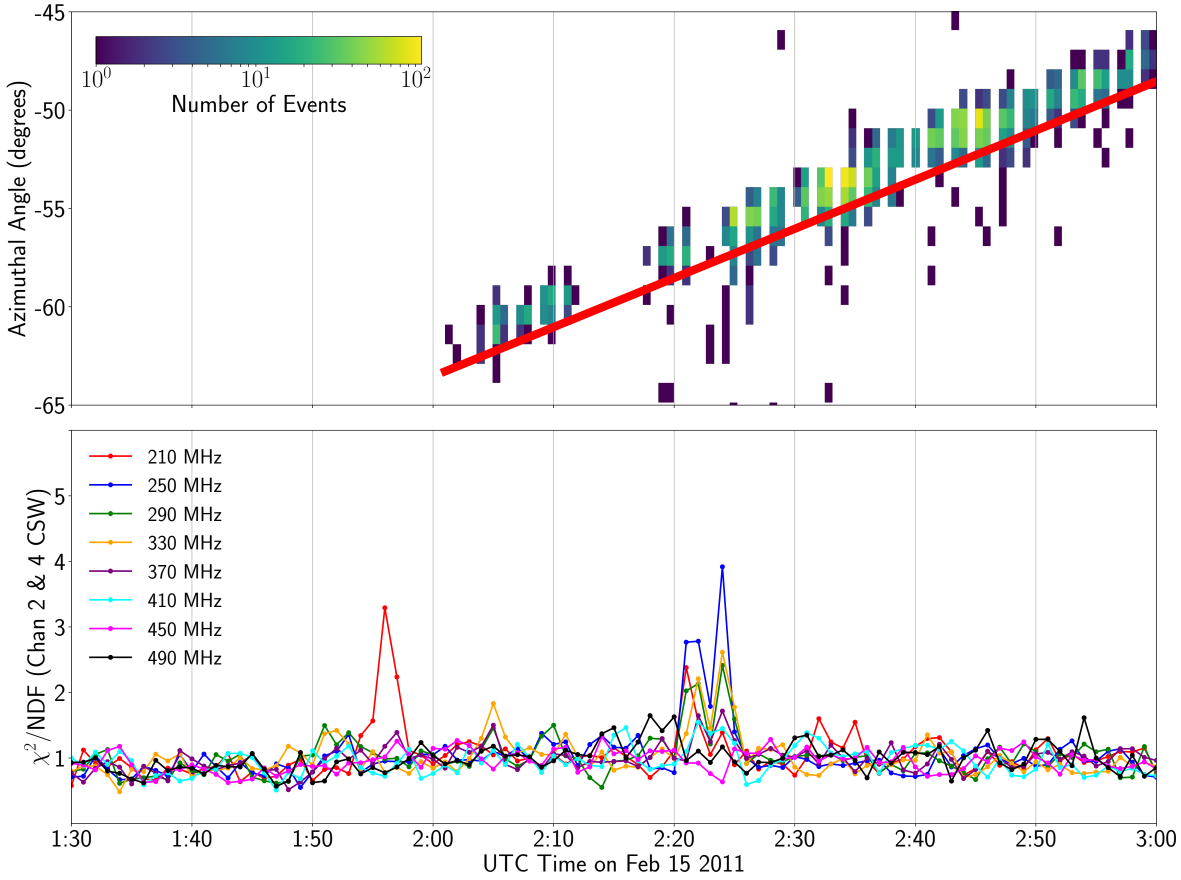




Reconstructability

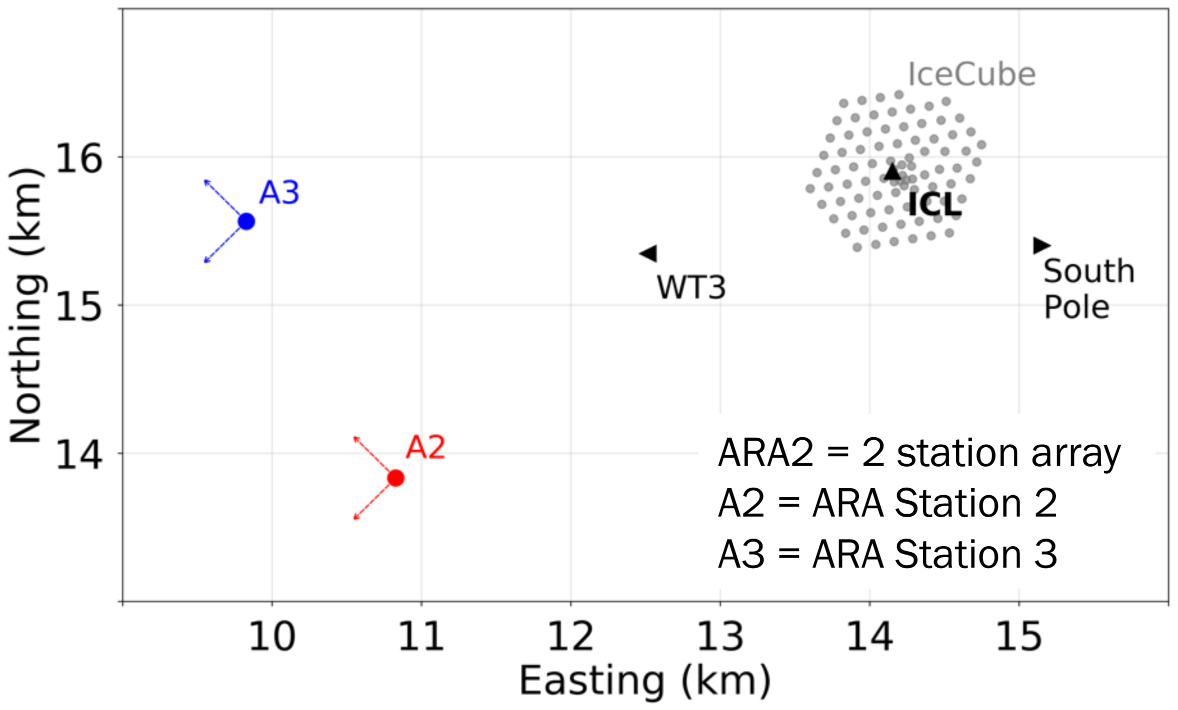
- All antennas observe same noise that was generated at the sun and traveled to earth

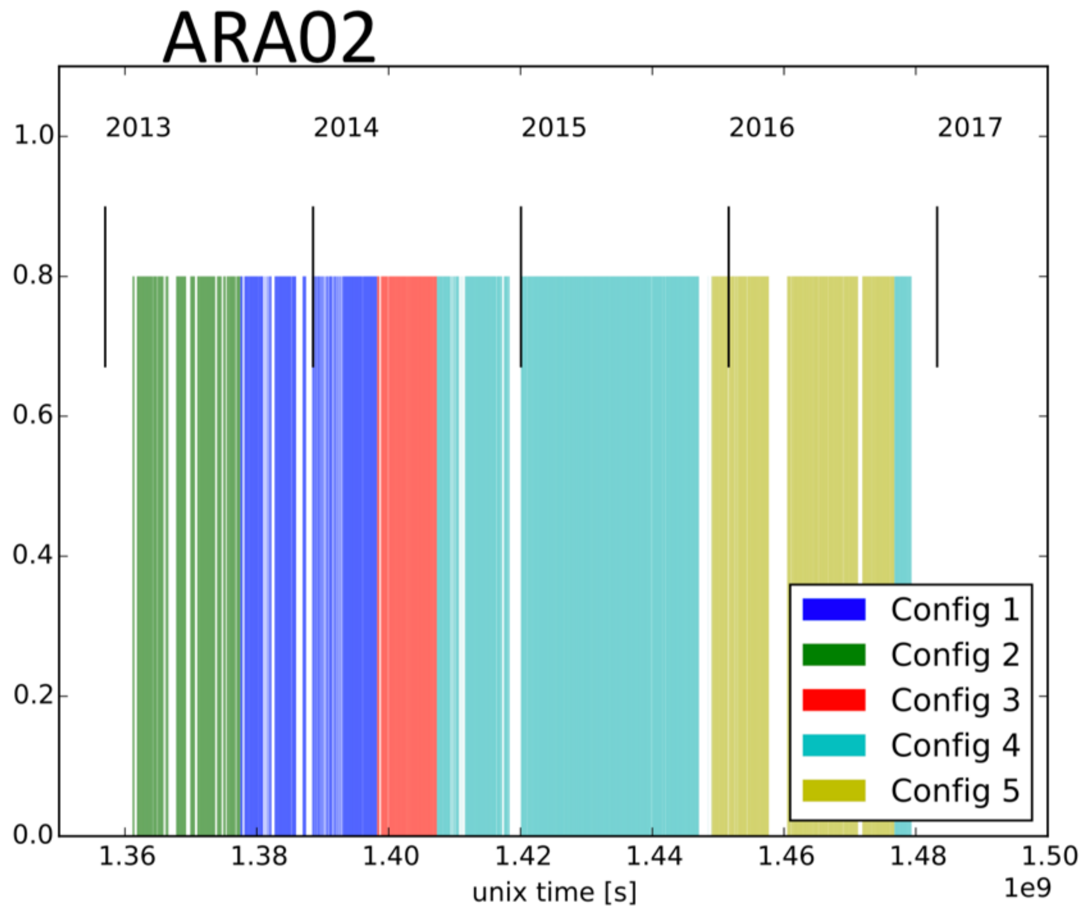




- Events only track sun when they are well described by thermal noise

The ARA2 Instrument





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

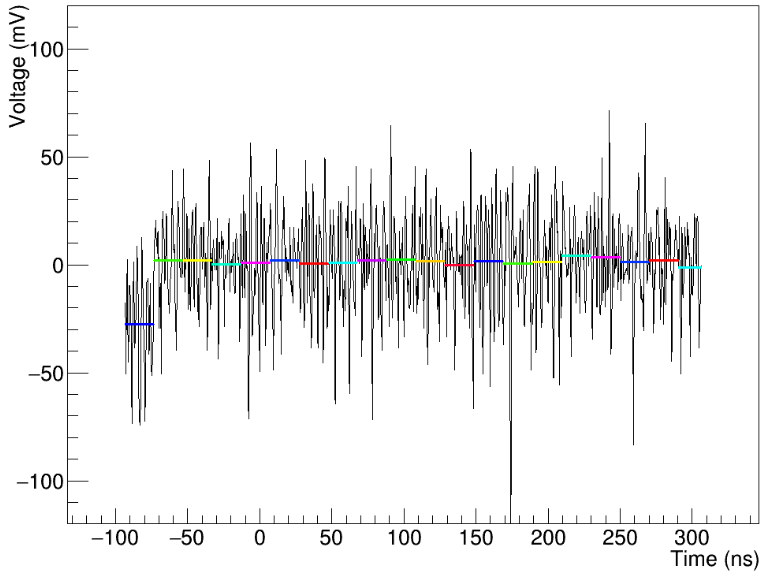
- Data is split into five *configurations*

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

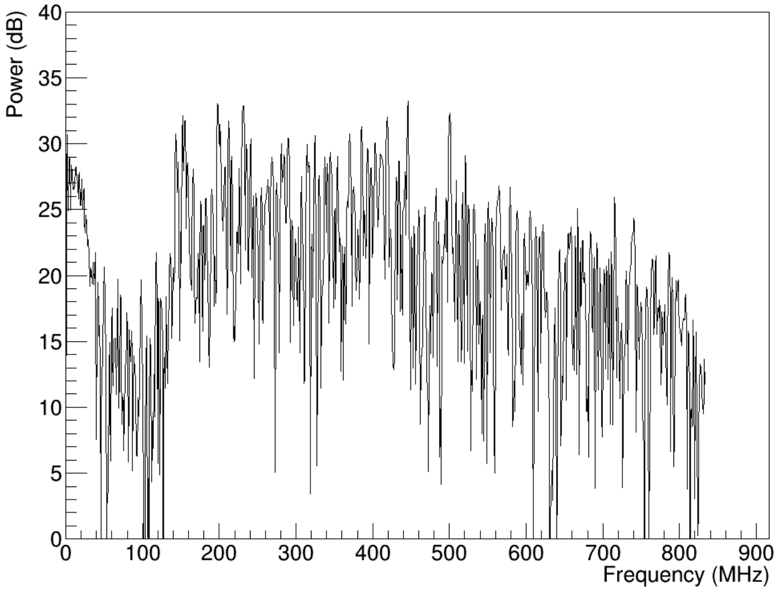
Data Conditioning

- 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`

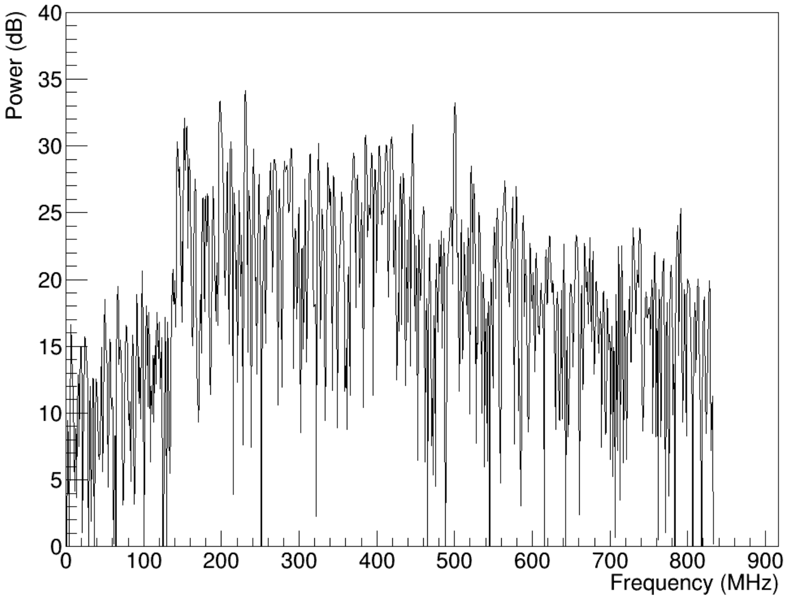
Run 2818, Event 10, Channel 5



Before first trim and zero-mean

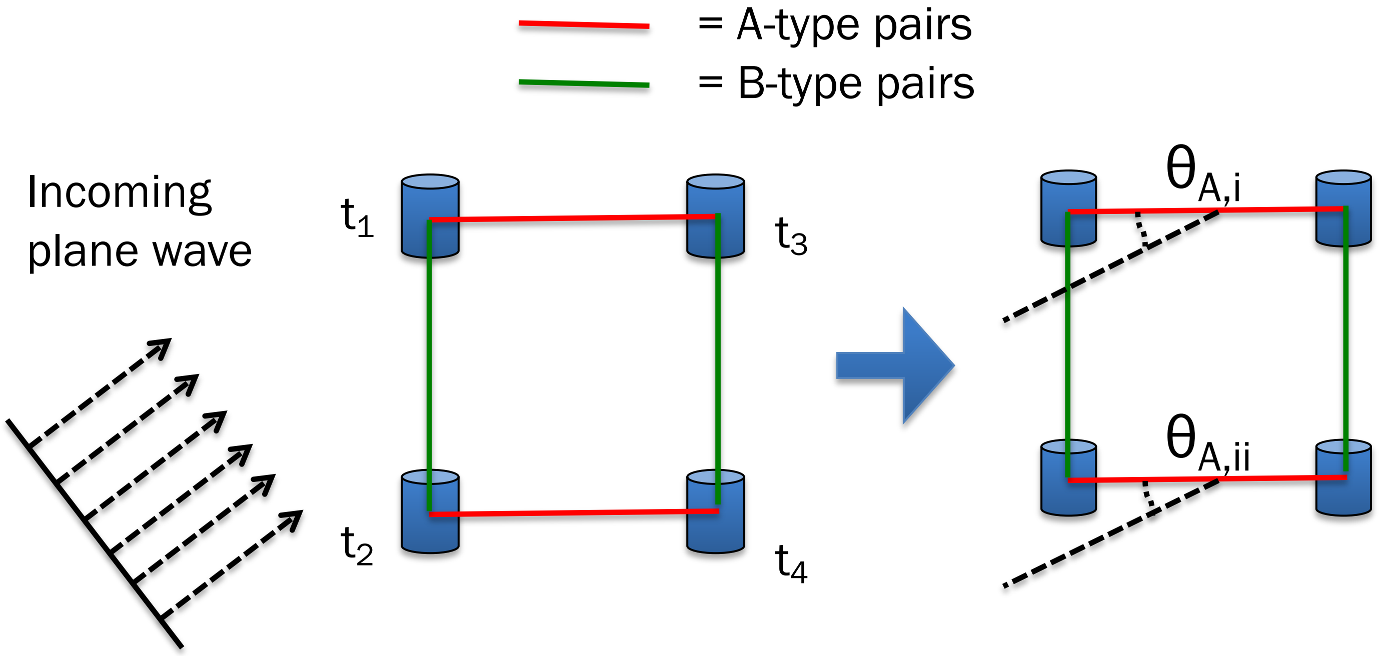


After trim and zero mean



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



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

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

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

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

Wavefront-RMS Filter

- Find the RMS around the average arrival angle

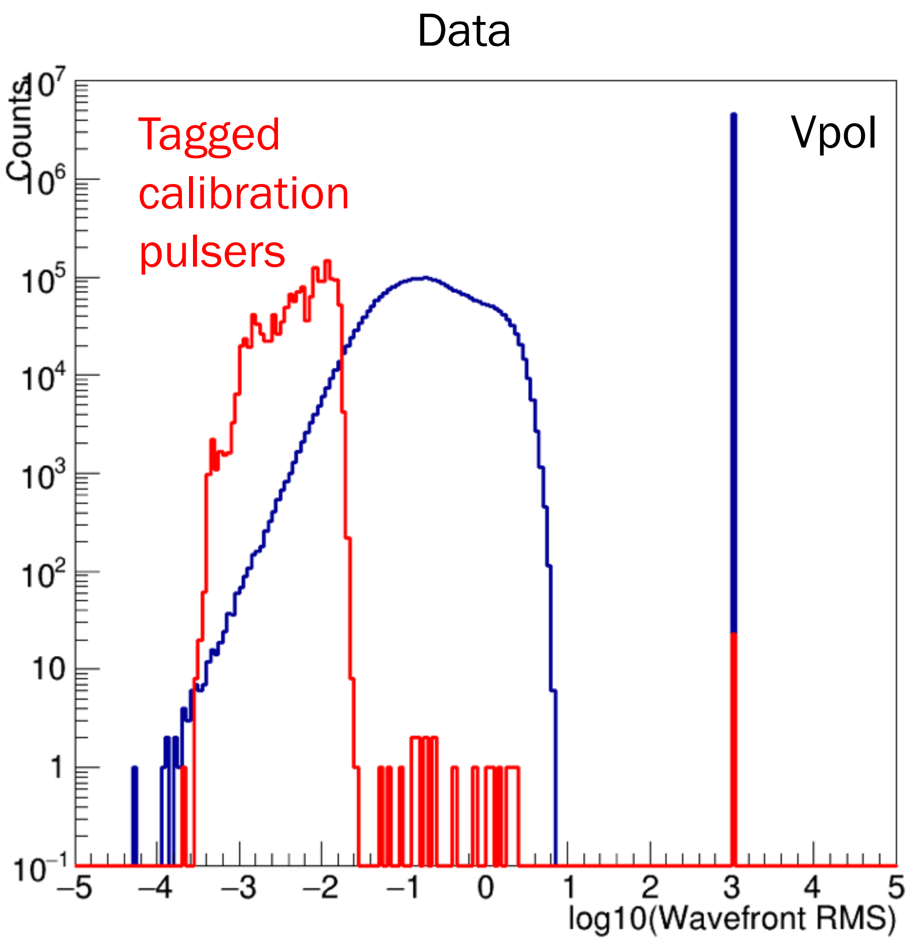
$$\overline{\cos\left(\theta_A\right)} = \frac{\cos\left(\theta_{A,i}\right) + \cos\left(\theta_{A,ii}\right)}{2}$$

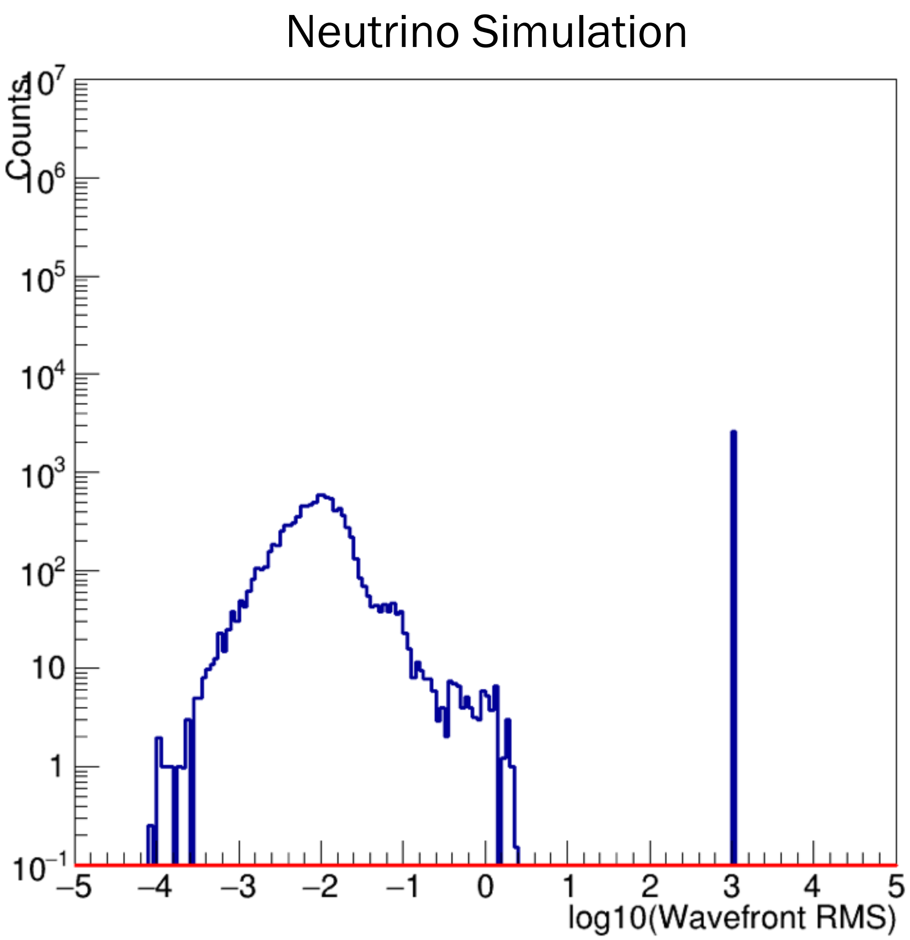
$$\mathrm{RMS}\left(\cos(\theta_A)\right) = \sqrt{\frac{\left(\cos\left(\theta_{A,i}\right) - \overline{\cos\left(\theta_A\right)}\right)^2 + \left(\cos\left(\theta_{A,ii}\right) - \overline{\cos\left(\theta_A\right)}\right)^2}{2}}$$

- Expect *wavefront-RMS* = $\log_{10}$(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





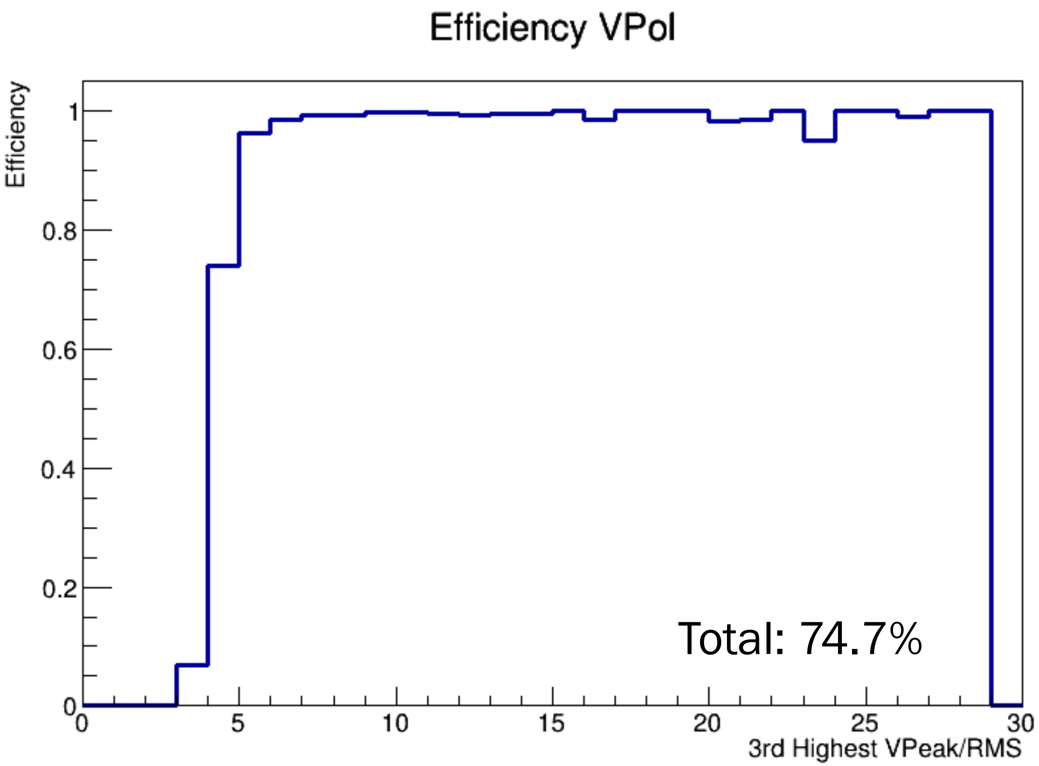
Wavefront-RMS Filter

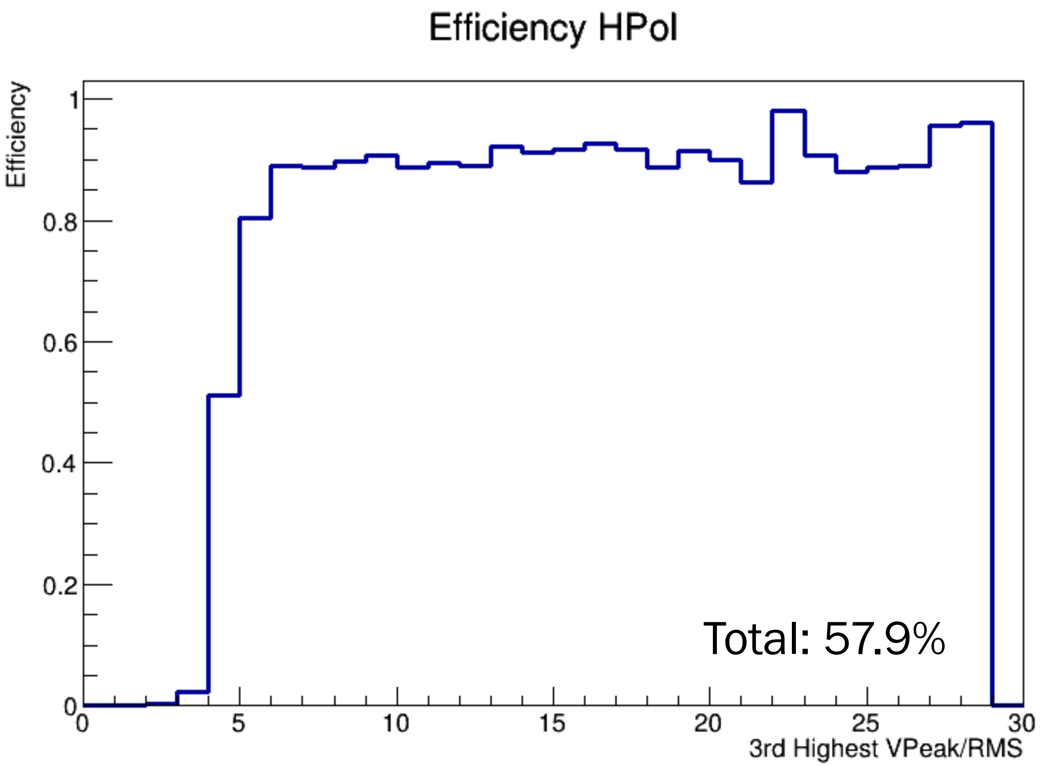
- Cut an event if wavefront-RMS > -1.3 for VPol or >-1.4 for Hpol
- These values reduce data to 5-10% of original size (per polarization) while keeping fraction of neutrino events cut by wavefront-RMS *alone* to <5%
- Total efficiency of the filter for neutrinos, before other cuts, is ~90%

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

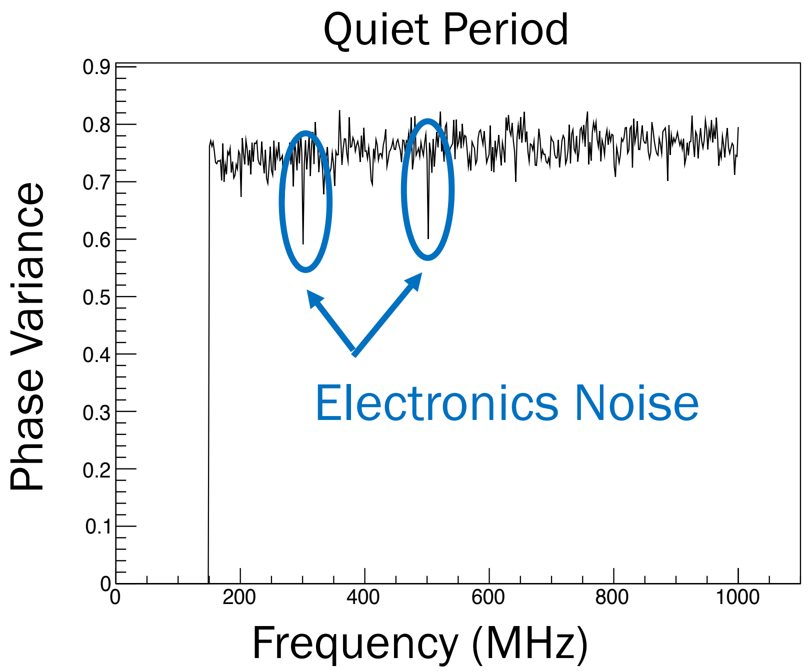




CW Filtering

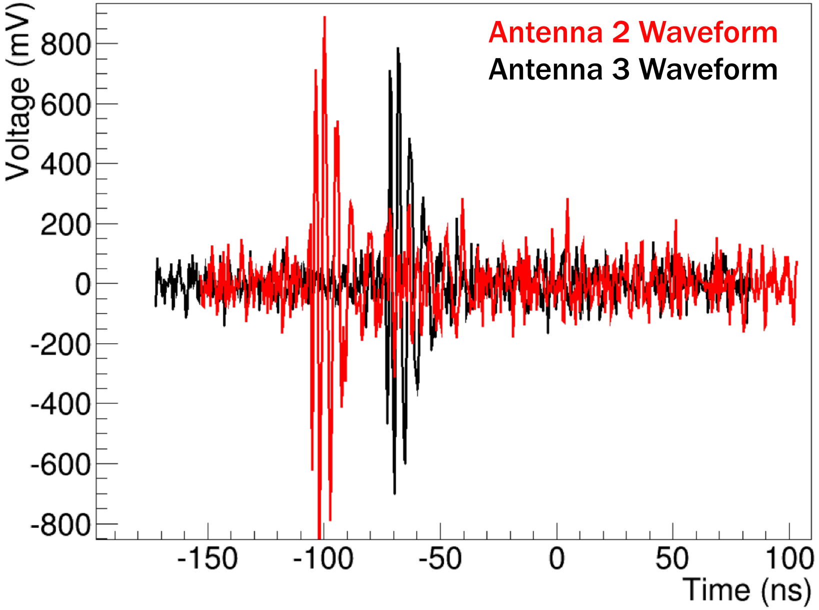
- Flag a frequency as CW if it comes from “peaks above base line” or “phase variance”
  - Phase variance frequently flags 125, 300 and 500 MHz as systems noise—we ignore these
  - Adjacent frequencies merged into notches

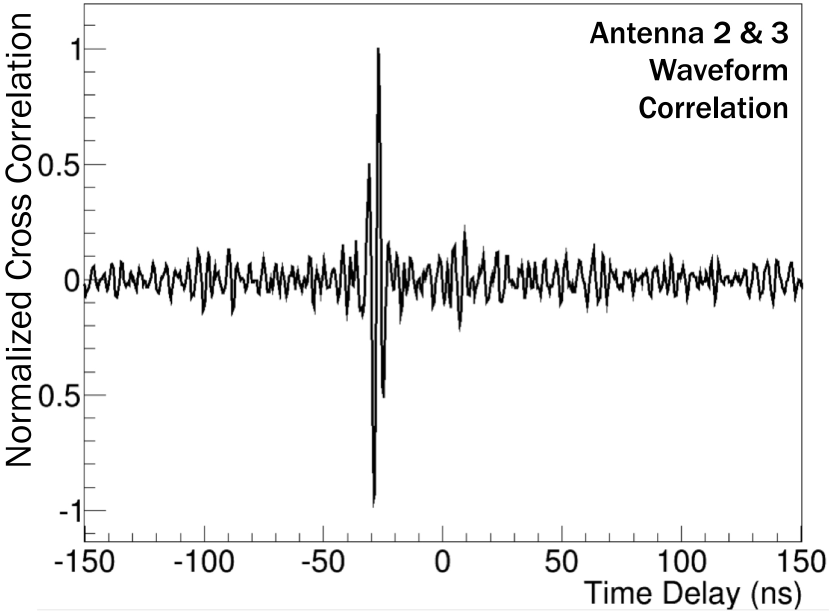
- CW frequencies are filtered with ANITA Geometric Filter—first time we have filtered waveforms in ARA
  - Originally designed by Brian Dailey at OSU
  - Used in the ANITA-III analysis [Phys. Rev. D 98, 022001 (2018)]

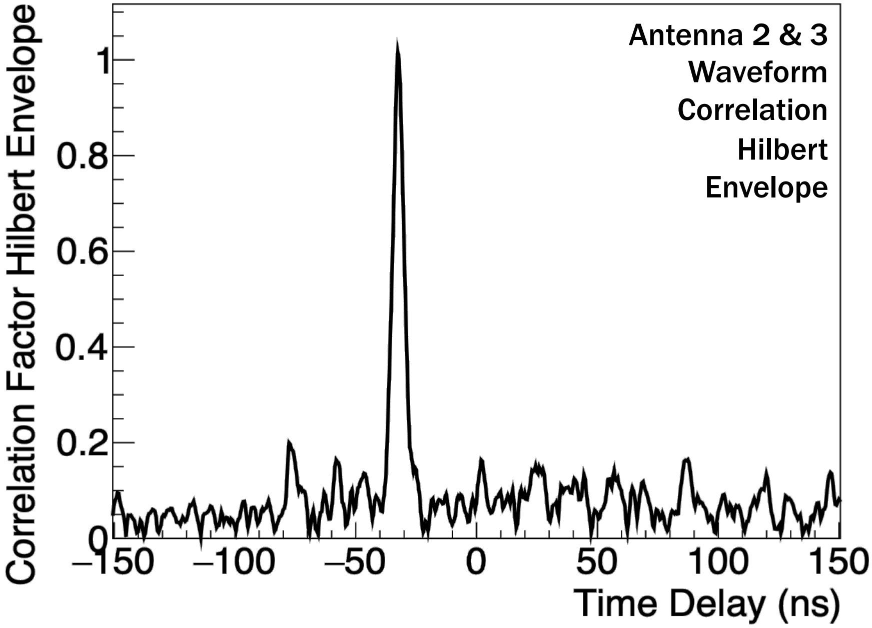


Reconstruction Details

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







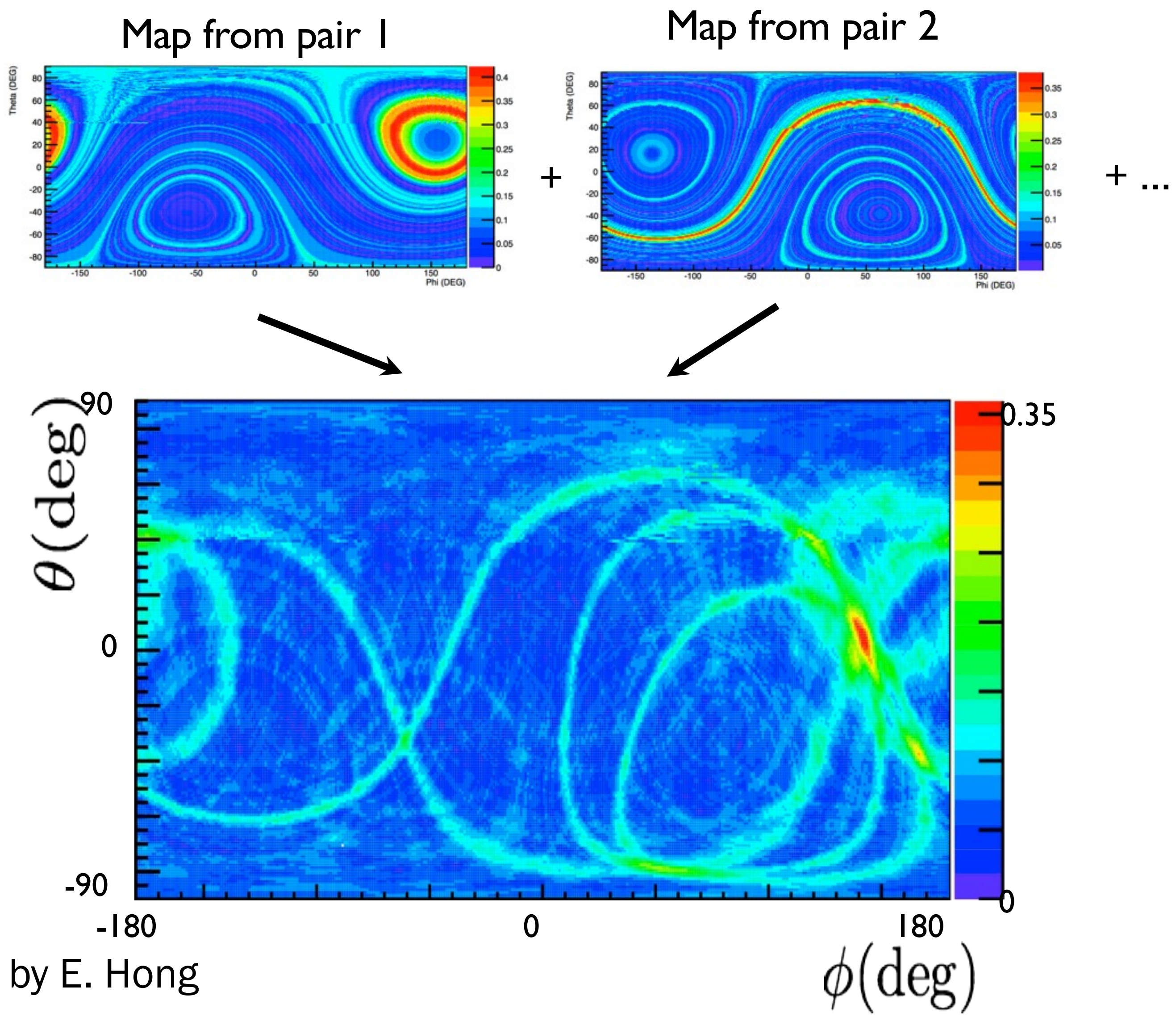
2. P. Allison *et. al.* j.astropartphys.2015.04.006
3. P. Allison *et. al.* j.astropartphys.2016.12.003

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**

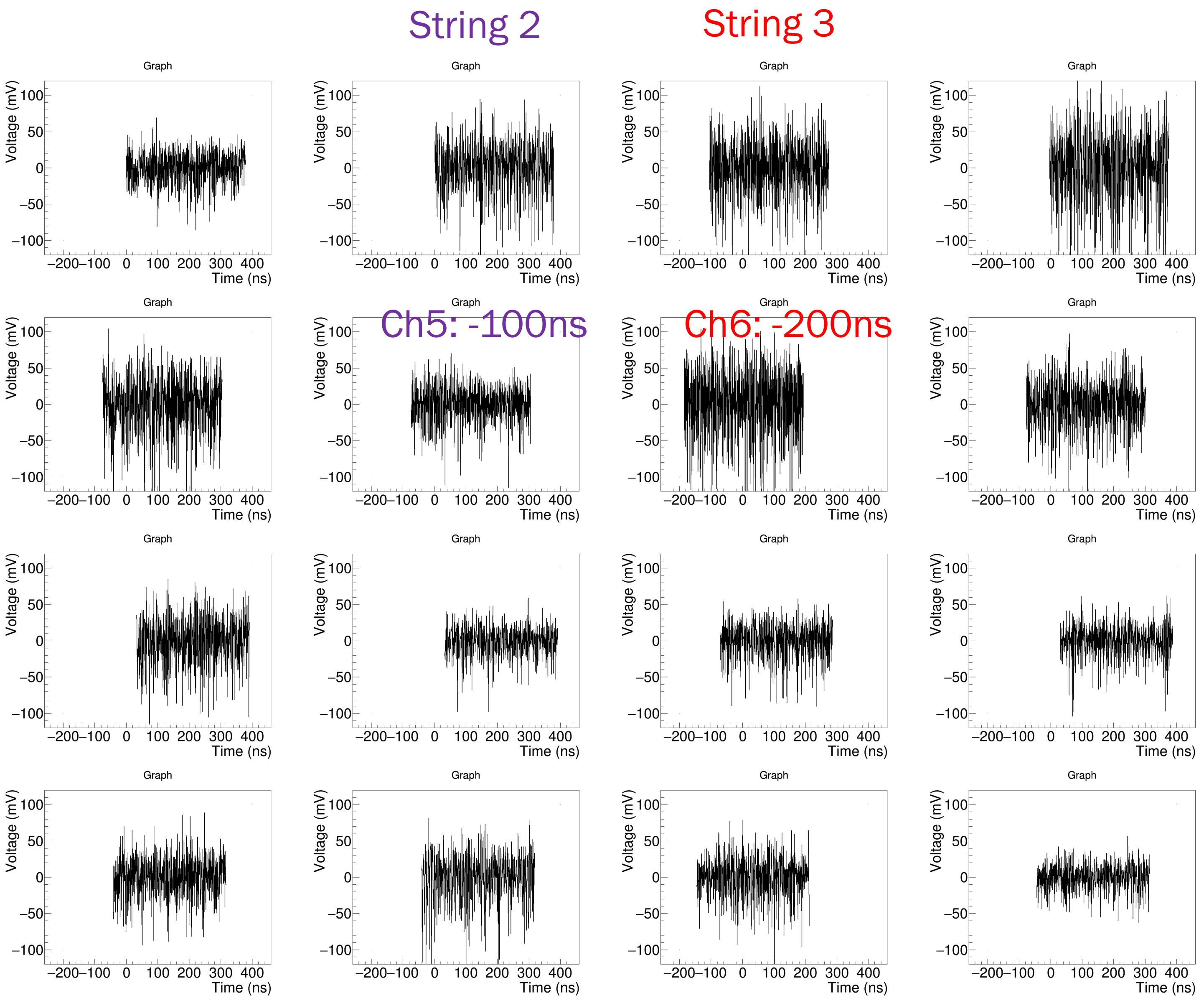


Interferograms by E. Hong

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

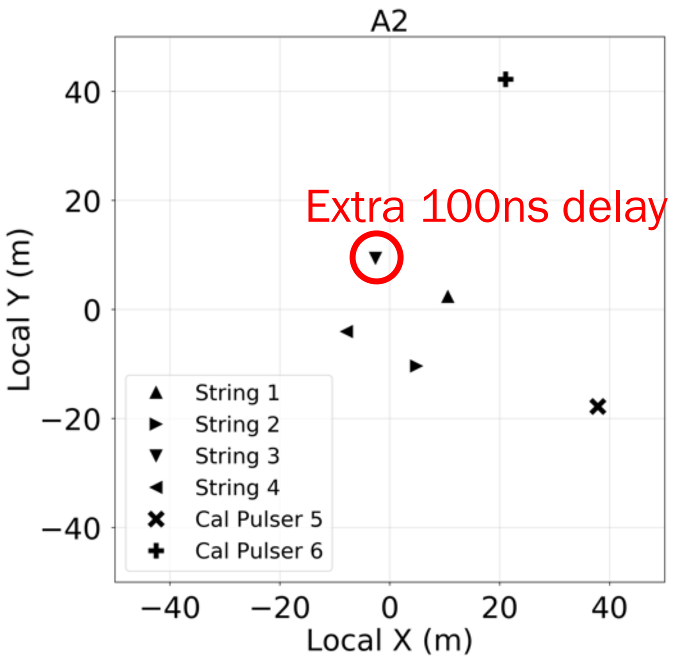
Phi Anisotropy

- 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)



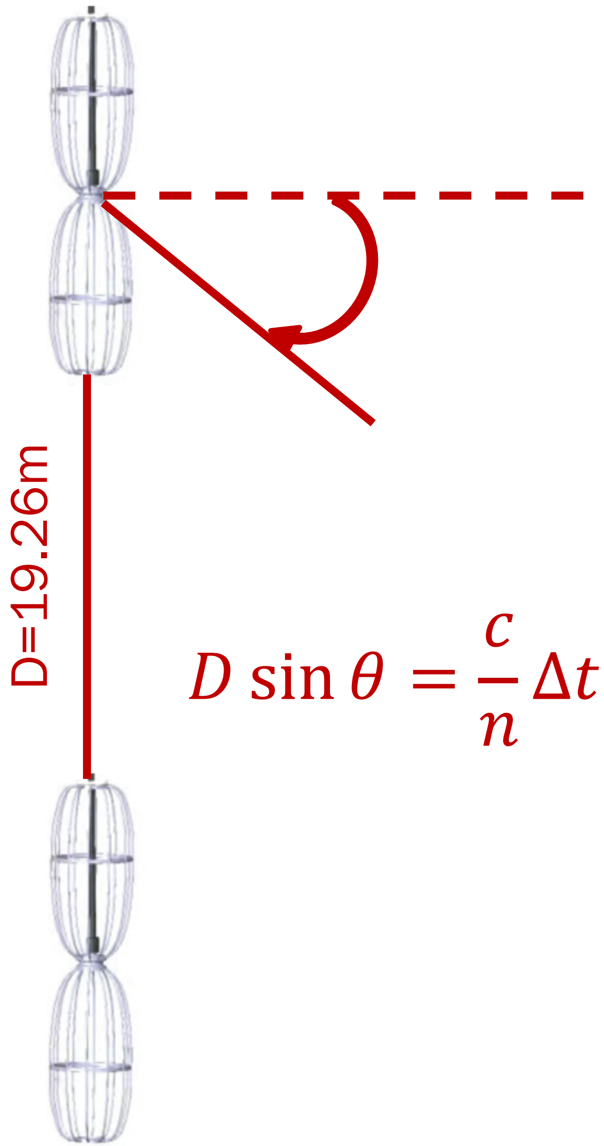
Phi Anisotropy

- 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°!

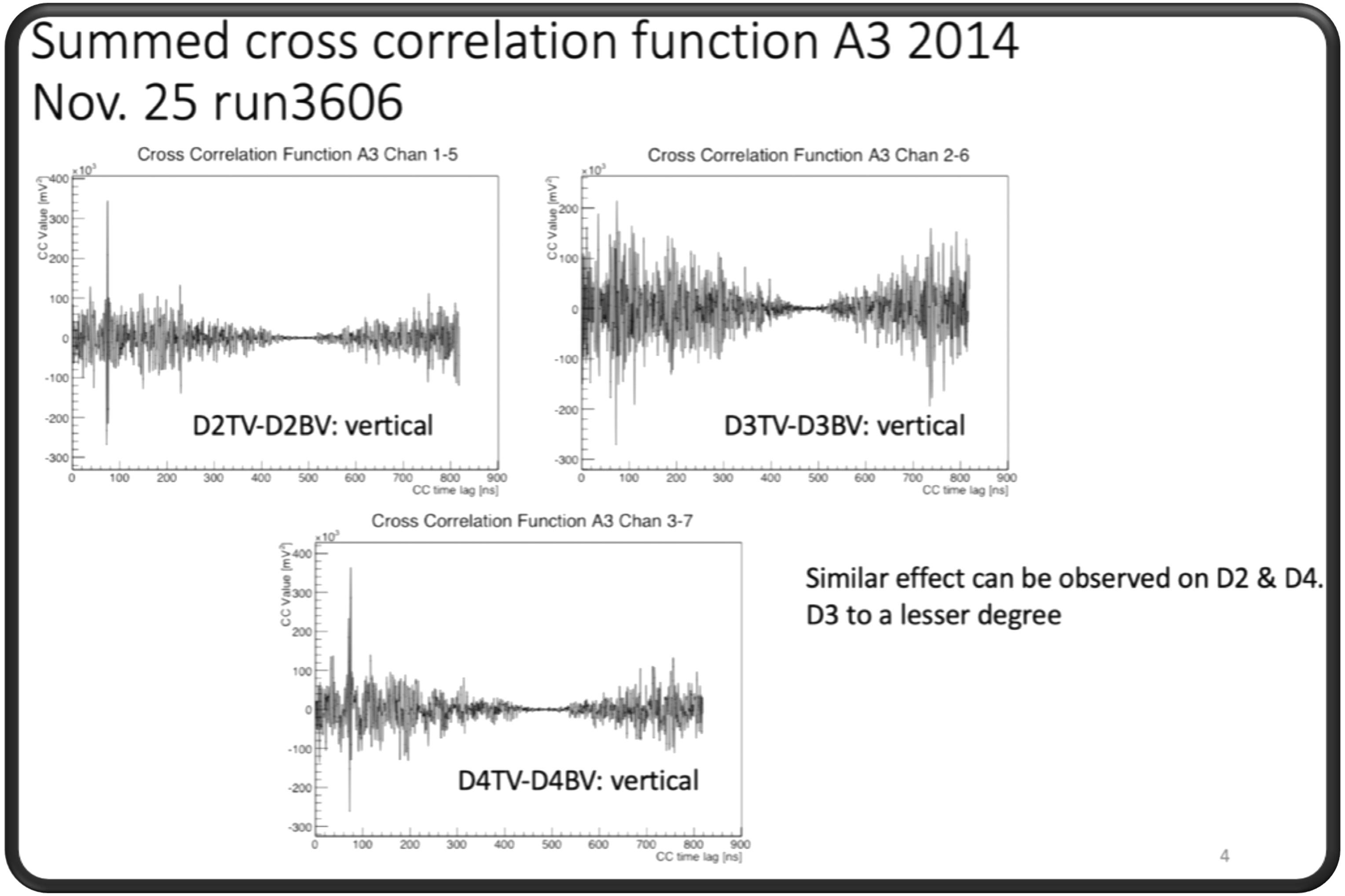


$$D \sin\theta = \frac{c}{n}\Delta t$$

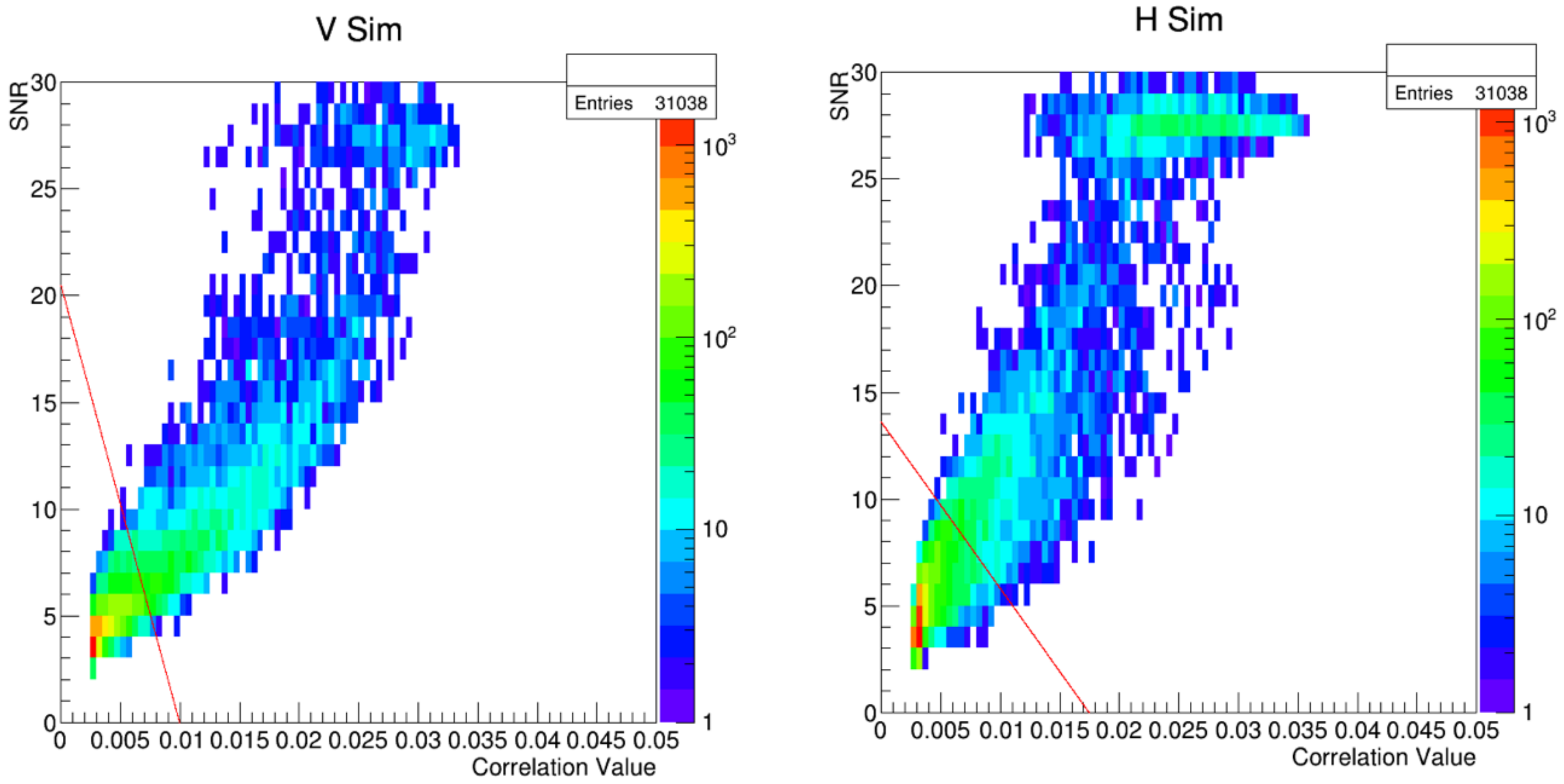
Theta Anisotropy

Slide from MYL

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



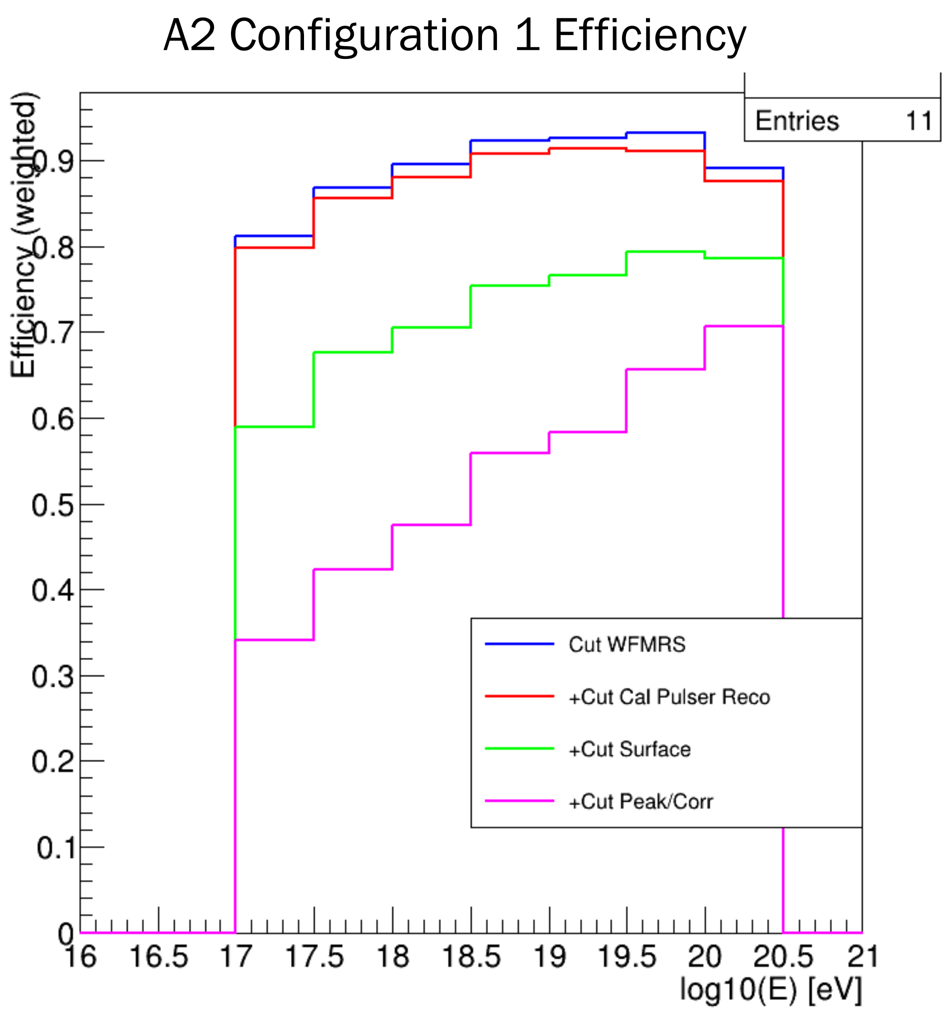
H vs V Comparison



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

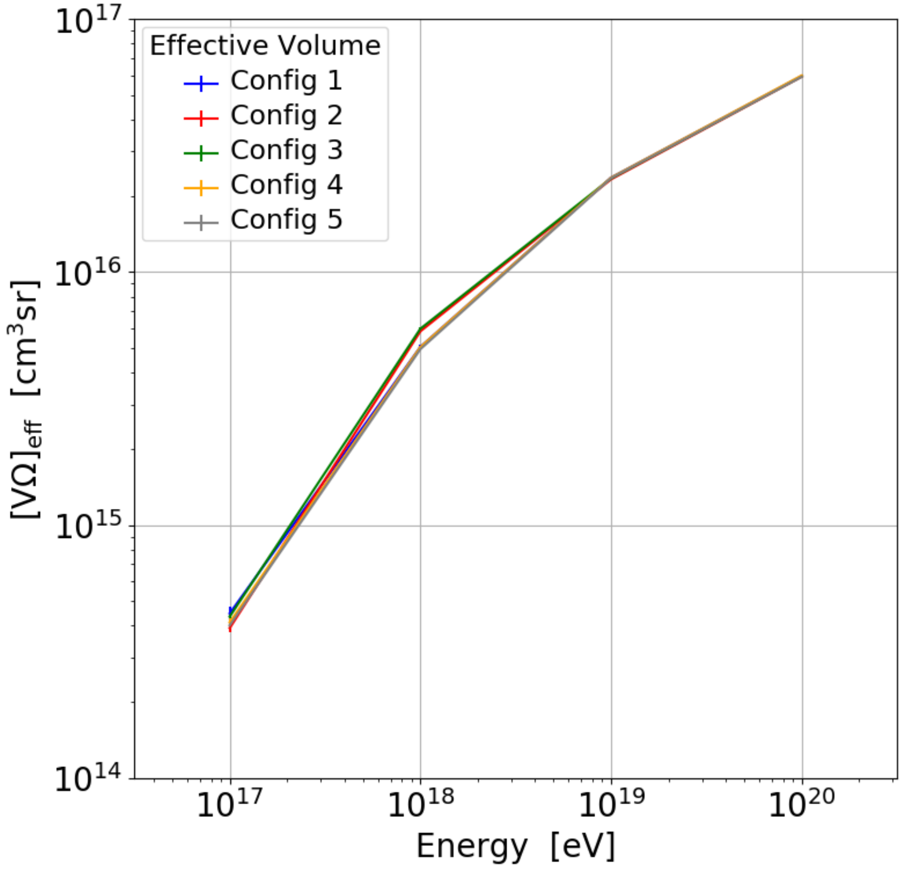
- Compute effective volume at trigger level from simulation

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

- 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

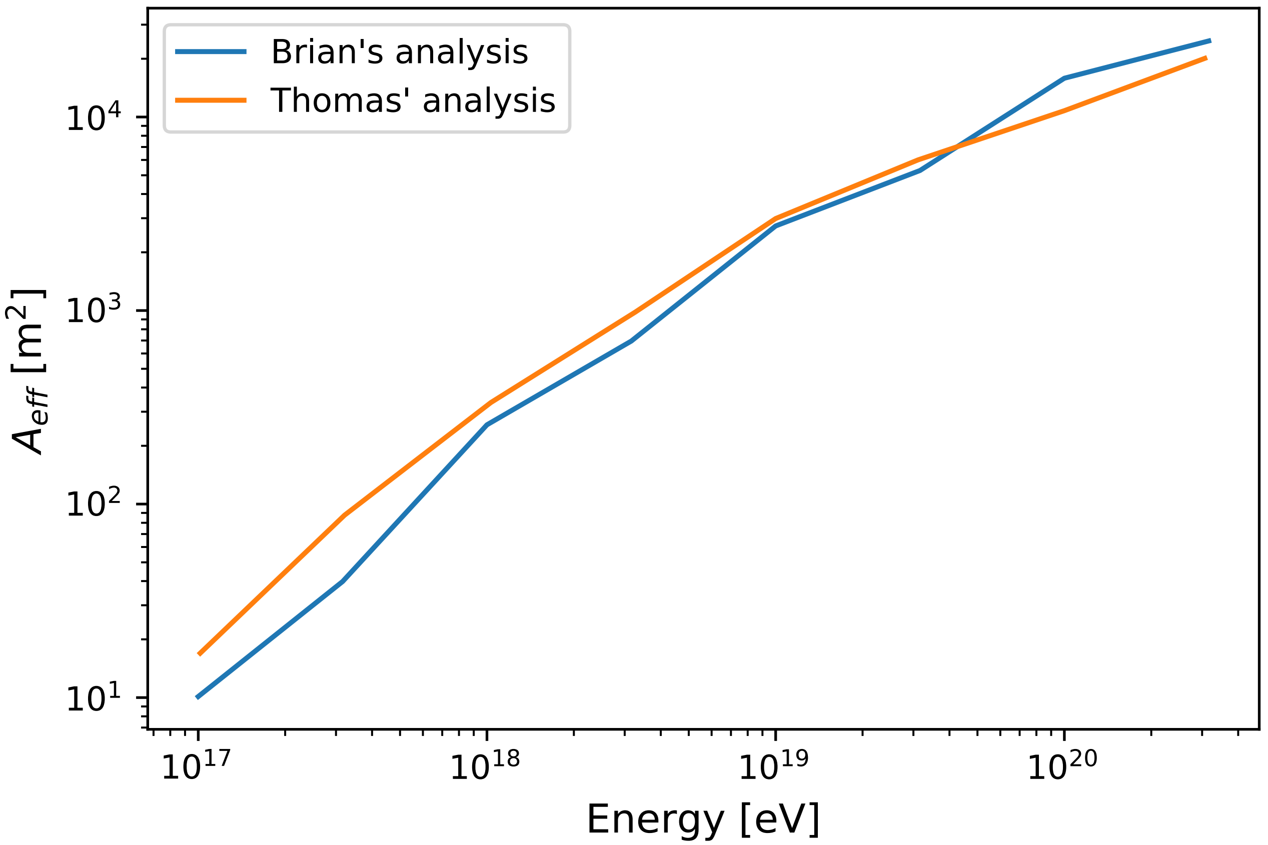
- Compute 90% UL on the maximum size the flux, $EF(E)$, can be in an energy bin E_i

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

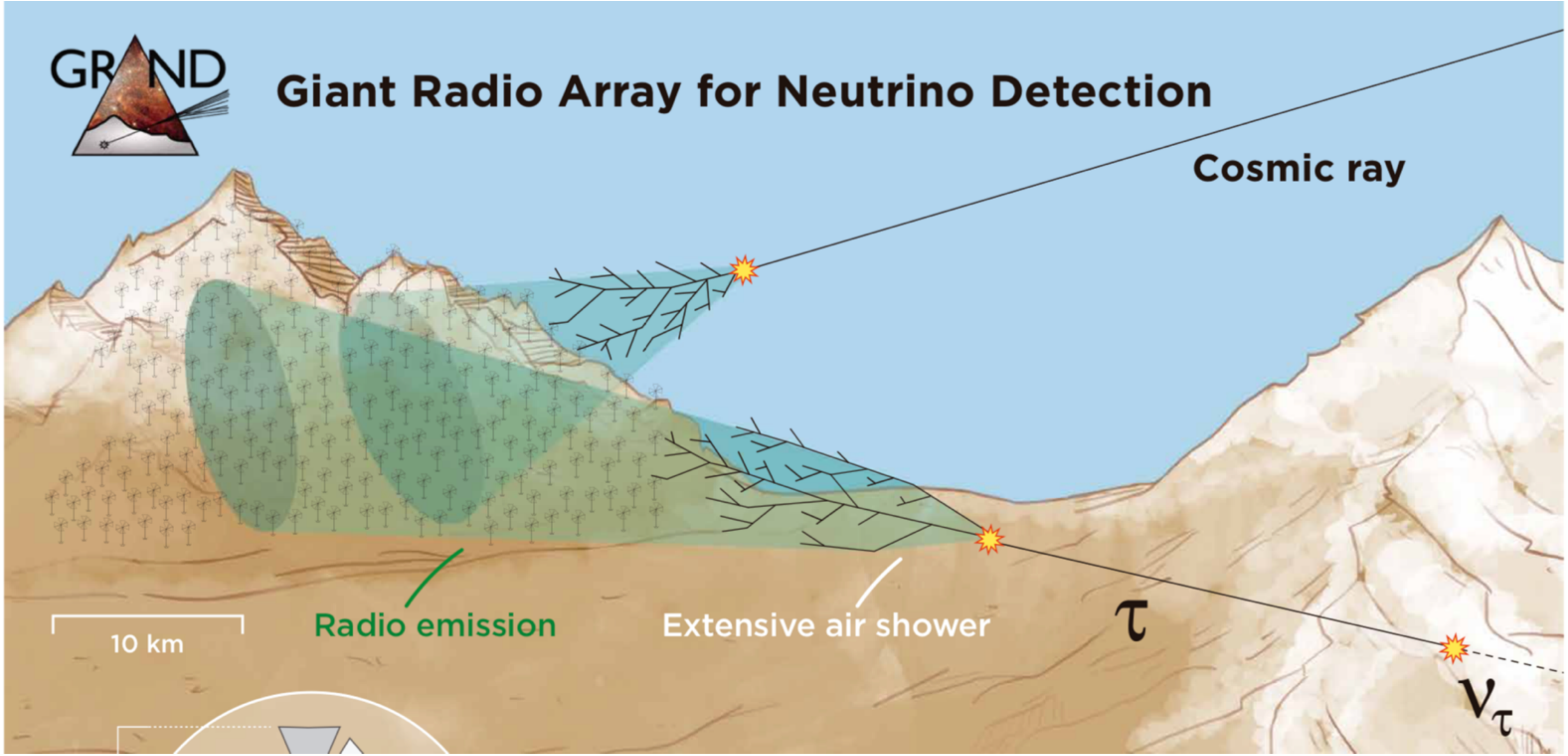
V_{eff} Comparison

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

- The discrepancy is under study



Future Radio Instruments



See arXiv 1810.09994