Ultrahigh Energy Neutrinos: Cosmic Ghosts and How to Bust Them

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Outline

1. Why Ultrahigh Energy Neutrinos?
2. How can we look for them?
3. The first searches with a prototype (ARA)
4. Searching with a design station (ARA)
5. Novel Approach (ExaVolt Antenna)
6. Conclusions and Future

WHY ULTRAHIGH ENERGY NEUTRINOS?

What are neutrinos?

"a fermion that interacts only via the **weak subatomic force and gravity**" – Wikipedia

Neutral charge, $m_0 < 120\ \mathrm{meV}/c^2$

(No proton packs!) (Really small!)

Solar flux = ~100 trillion neutrinos per second through a human being

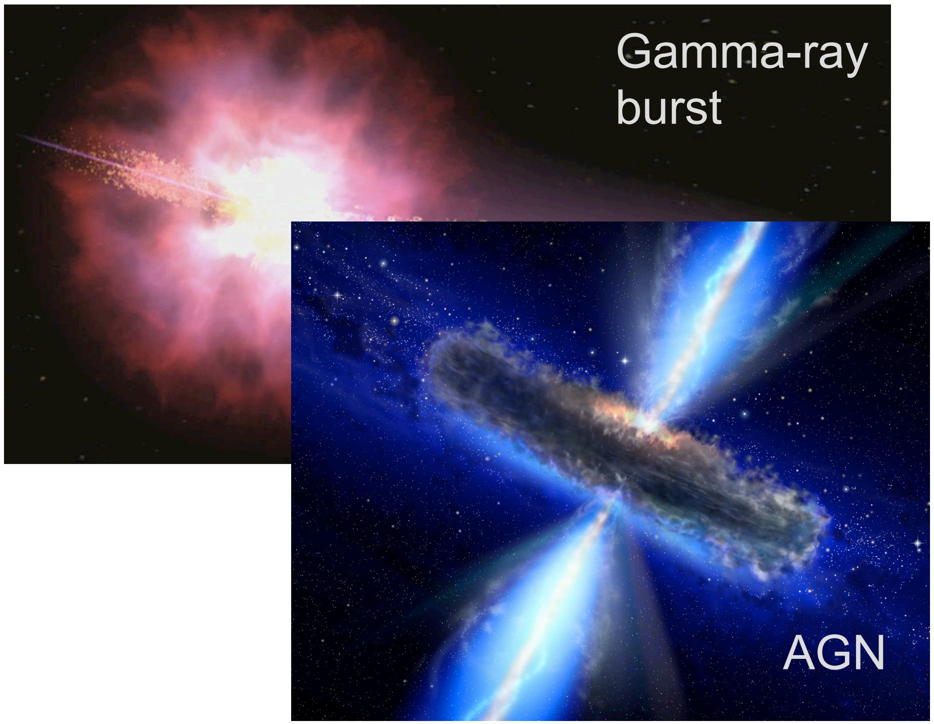
ν_e

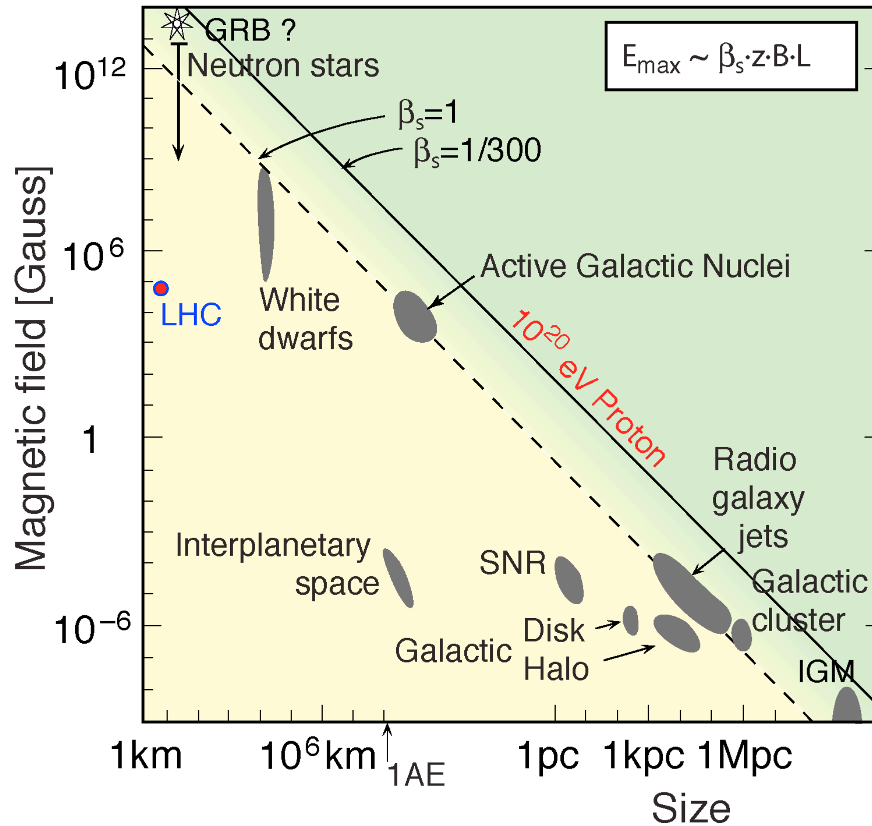
ν_μ

ν_τ

UHE Sources

How do you produce particles at E > 10^{18} eV?





Bottom-up models:

shock acceleration via E and B fields

Top-down models:

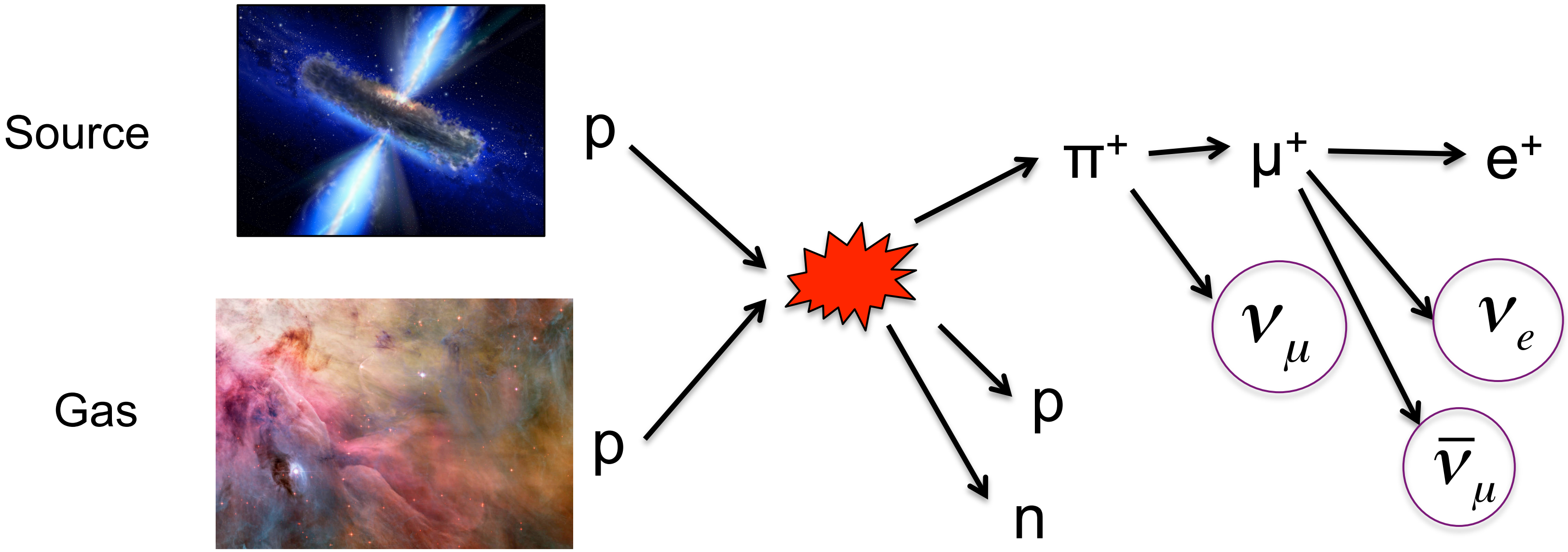
decays of ultra-heavy particles

UHE Neutrino Production?

Sources can’t accelerate neutrinos

They don’t react to magnetic fields!

But they can with protons (or heavier nuclei)



NASA, ESA and the Hubble Heritage Team

GZK Effect

Greisen-Zatsepin-Kuzmin (GZK) effect:

Cosmic rays with E > $10^{19.5}$ eV +

cosmic microwave background (CMB) photons

$$\mathbf{p} + \gamma_{\mathrm{CMB}} \rightarrow \mathbf{\Delta}^* \rightarrow \mathbf{n} + \pi^+$$

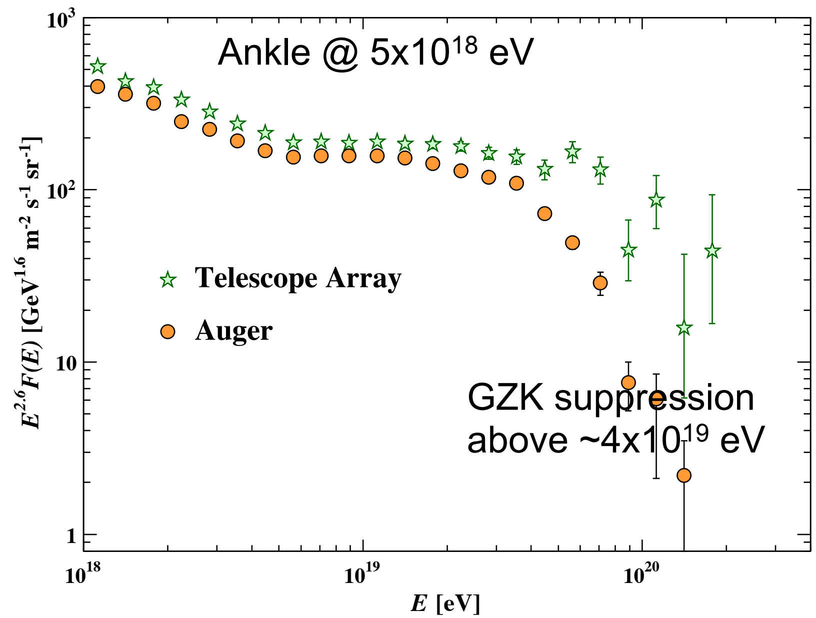
$$\mathbf{n} \rightarrow \mathbf{p} + \mathbf{e}^- + \bar{\nu}_{\mathbf{e}}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

Decreased energy!

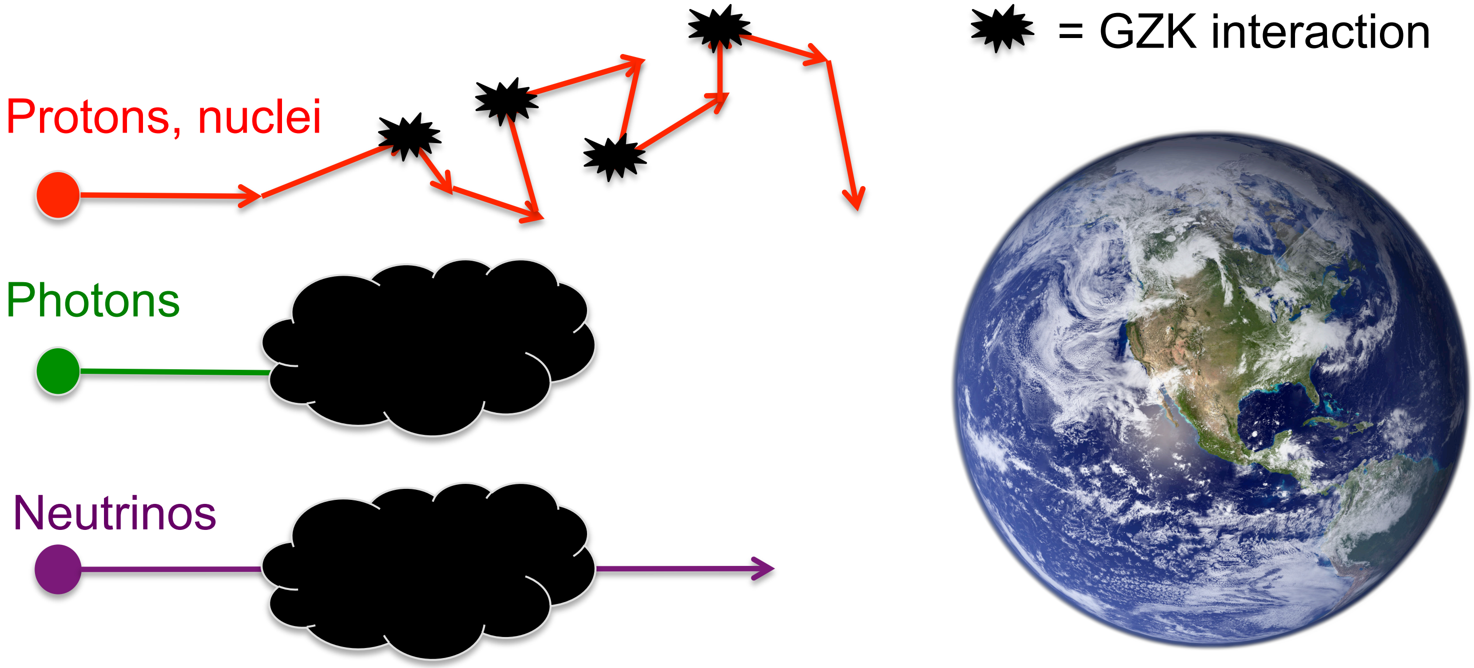
UHECR horizon = ~100 Mpc

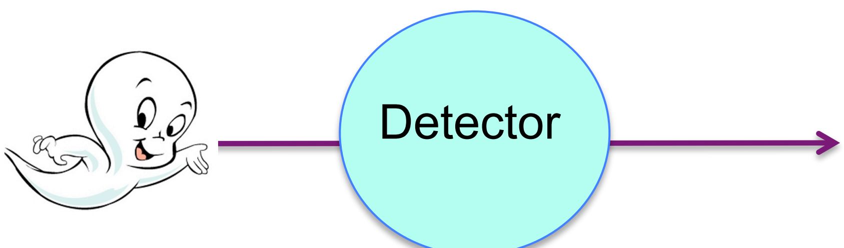


Particle Data Book, 2016

Neutrinos are the only UHE particle probes at cosmic distances!

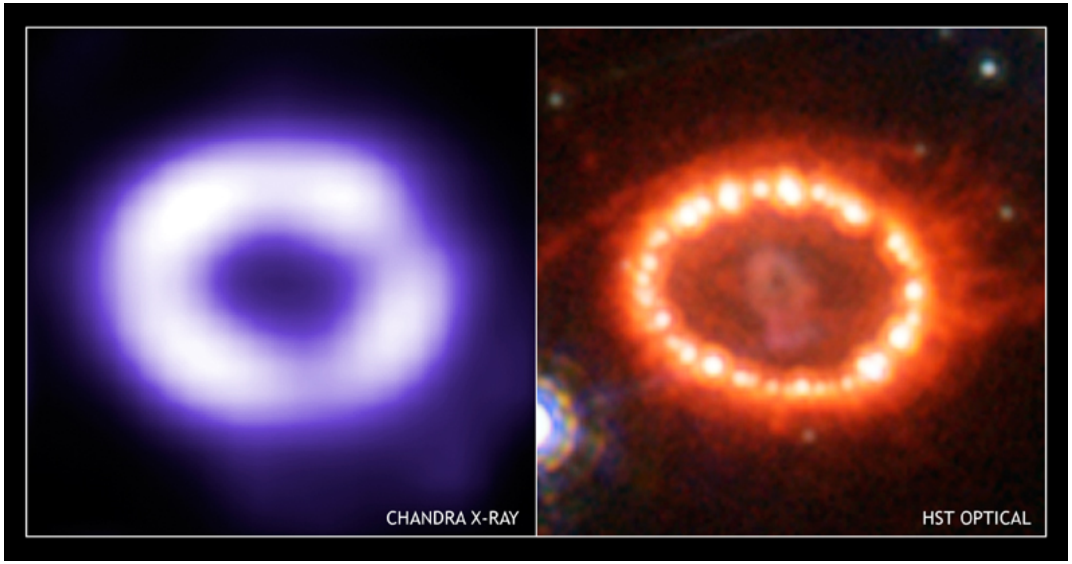
Why UHE *Neutrinos*?

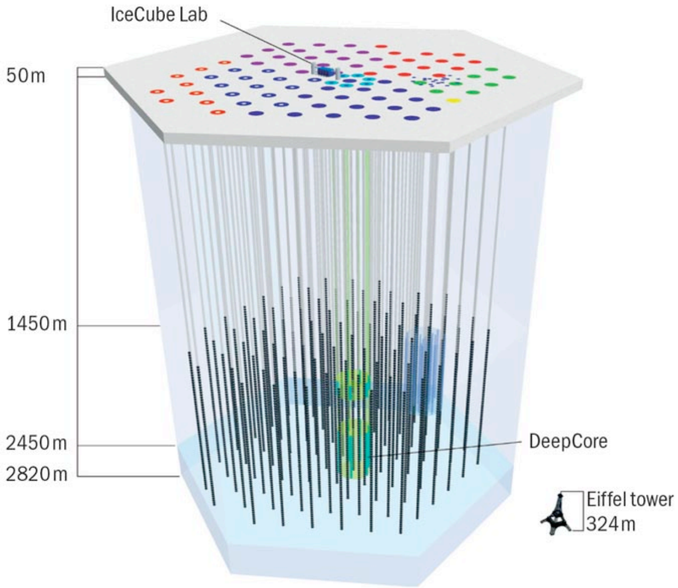




- Also low flux at Earth
- (< $1/km^3$/year/energy decade)
- Need O(100 km^3) detectors

Extrasolar Neutrinos



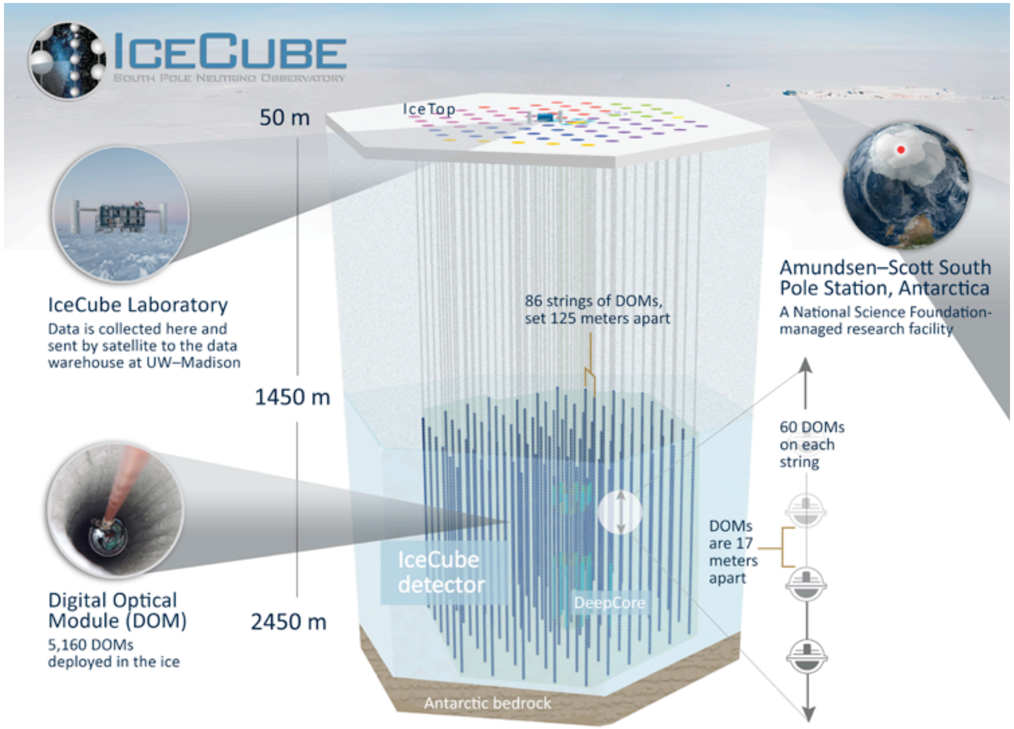


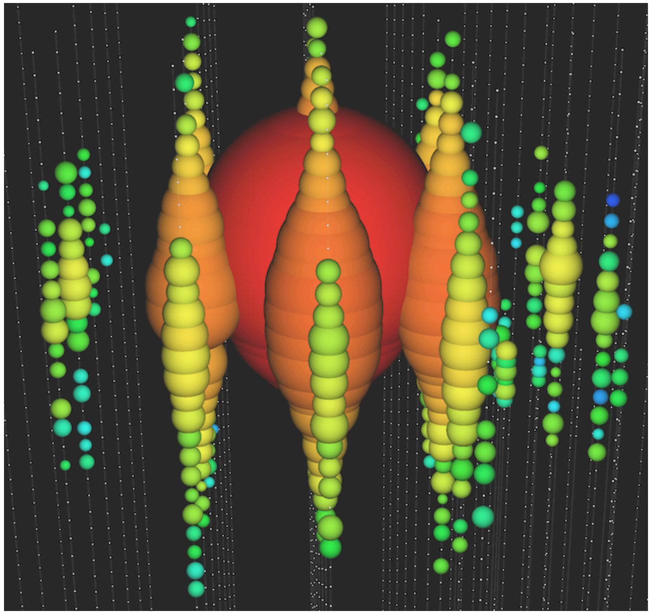
Supernova 1987A
(Credit: Chandra and HST)

IceCube
(Credit: IceCube Collaboration).

Previous detections: $E < 10^{18}$ eV
Not Ultrahigh Energy

IceCube Neutrinos





(Credit: IceCube Collaboration).

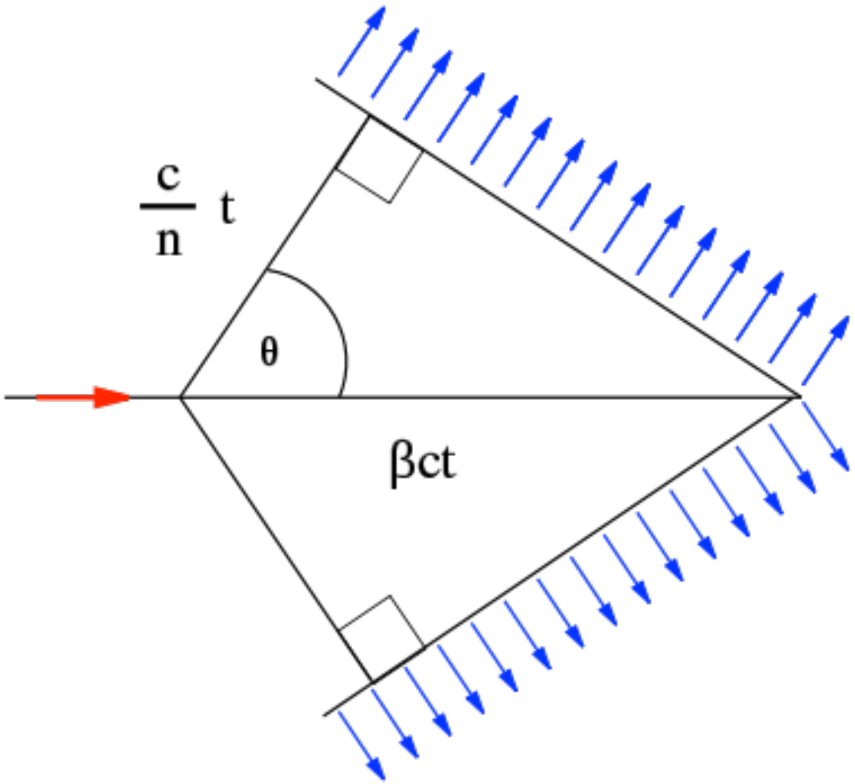
Dawn of neutrino astronomy!

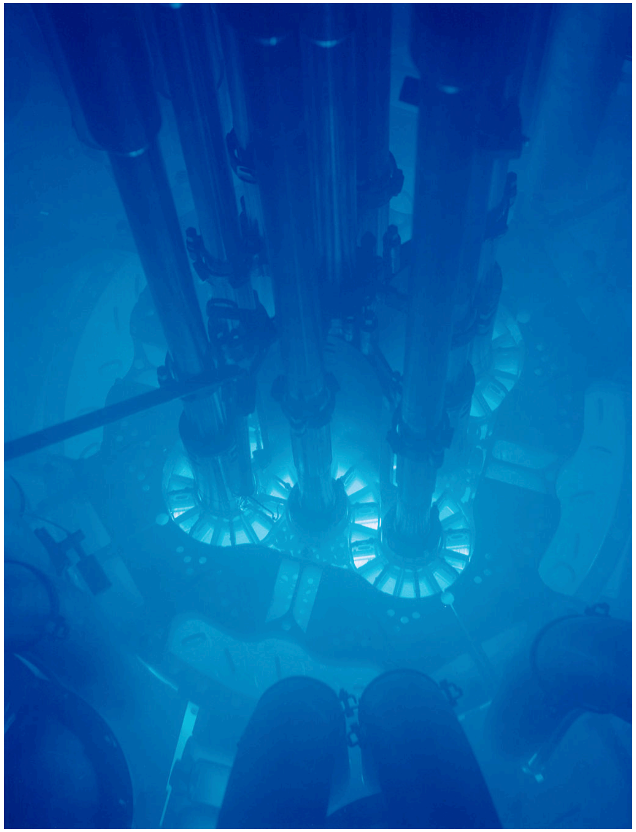
First events above 10^{15} eV

Reconstruct energy, direction

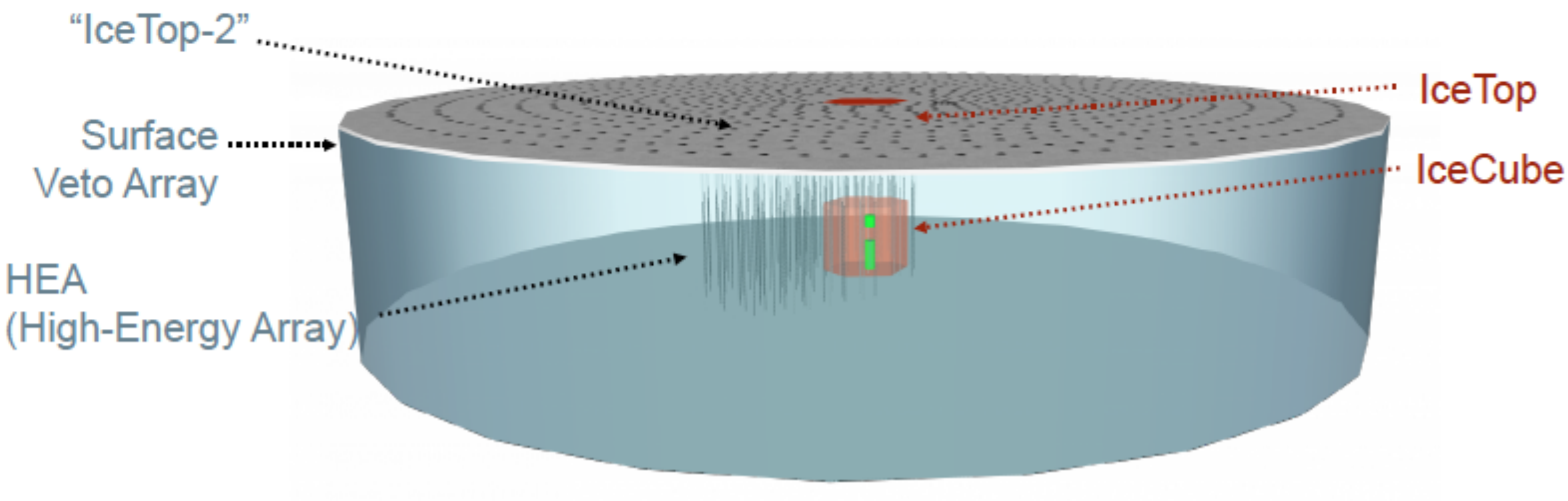
Cherenkov Radiation

Charged particle travelling through a dense dielectric medium with v > c/n





IceCube Gen2



(Proceedings of ISVHECRI 2016)

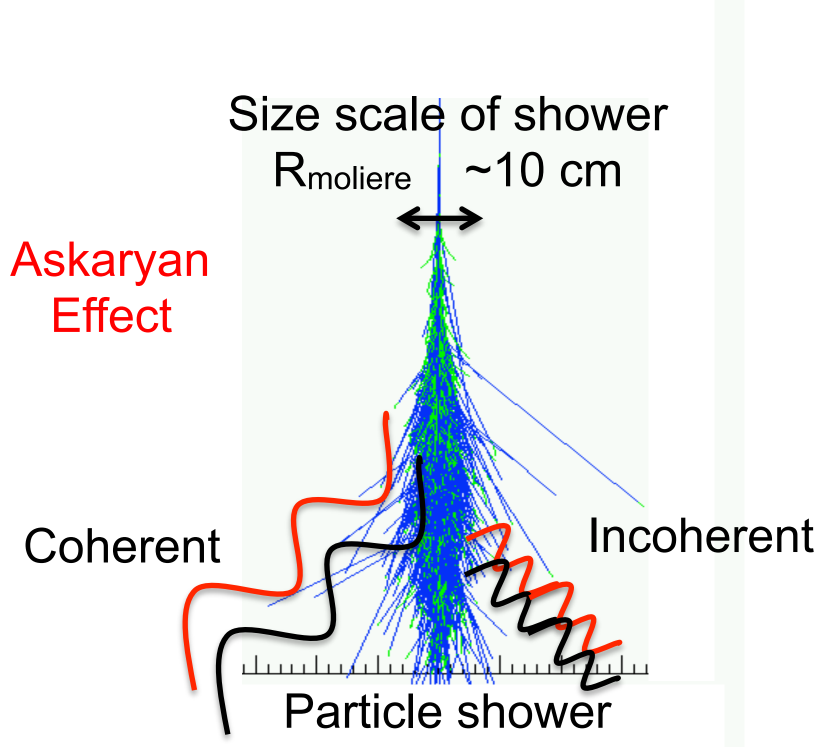
IceCube Gen2: 10X larger array

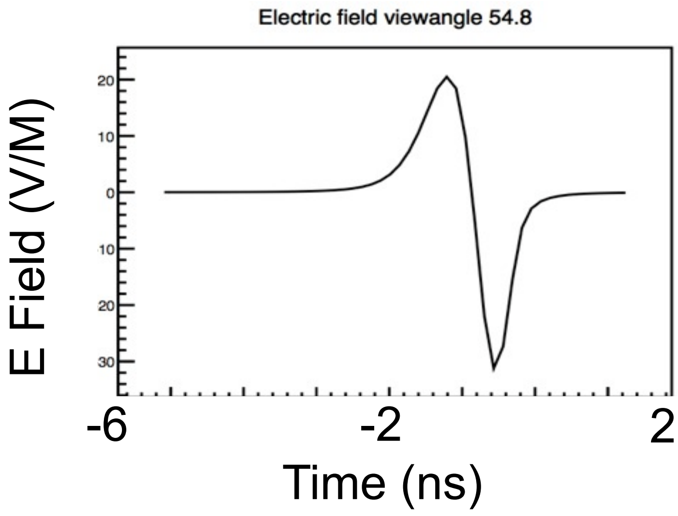
Increased sensitivity at $E > 10^{18}$ eV

Detection Technique

How do you bust UHE neutrinos (very low flux)?

1. Build the same things but bigger
2. Try a different detection technique – Radio!



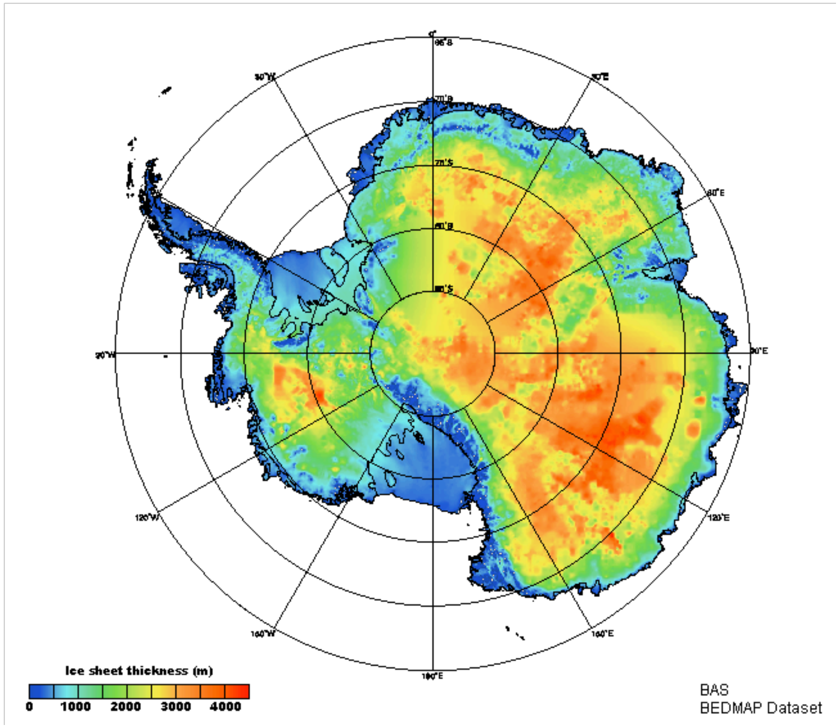


Where?

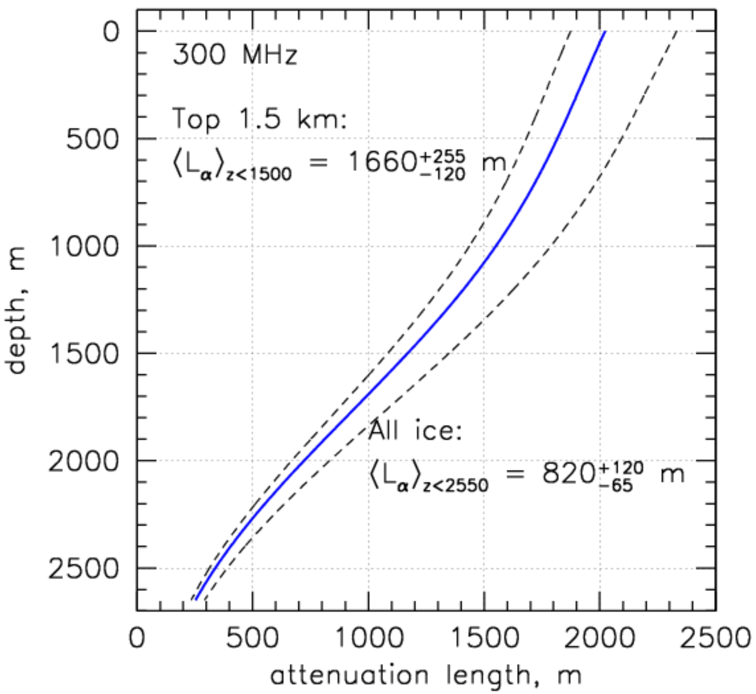
Observed in Air, Salt, Sand, Ice

Ice: large volumes naturally occurring

Long (~1 km) attenuation lengths, Infrastructure

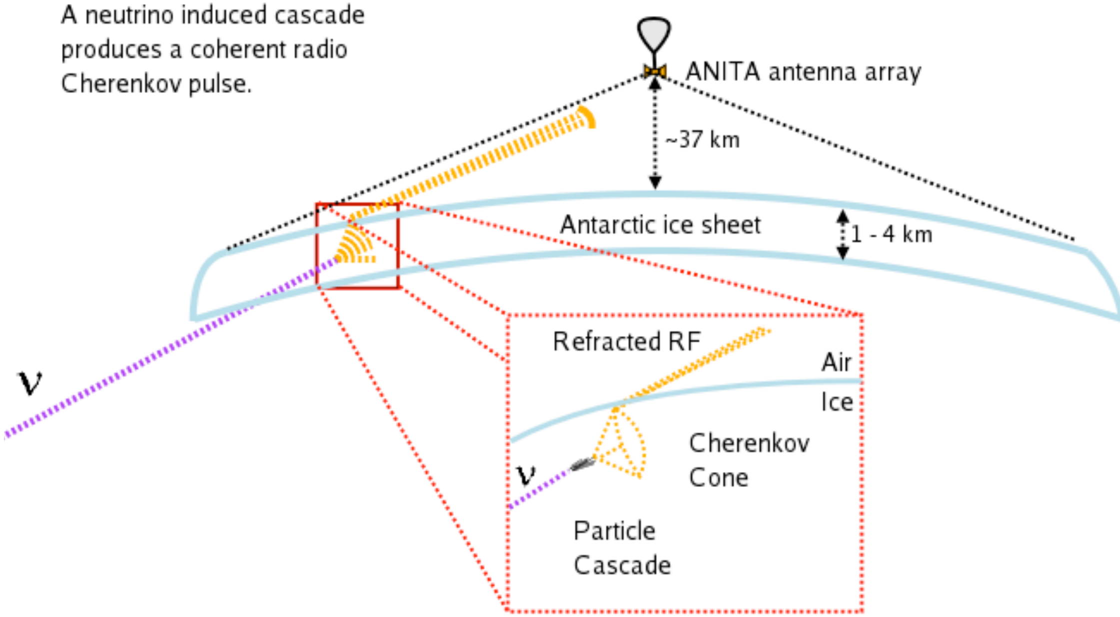


Credit: BEDMAP



DETECTORS

Synoptic Detectors

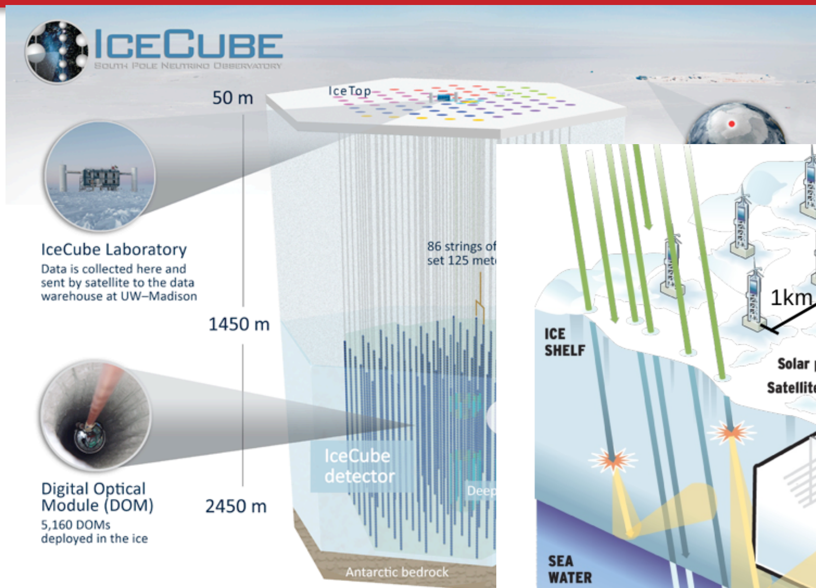


(Credit: ANITA collaboration)

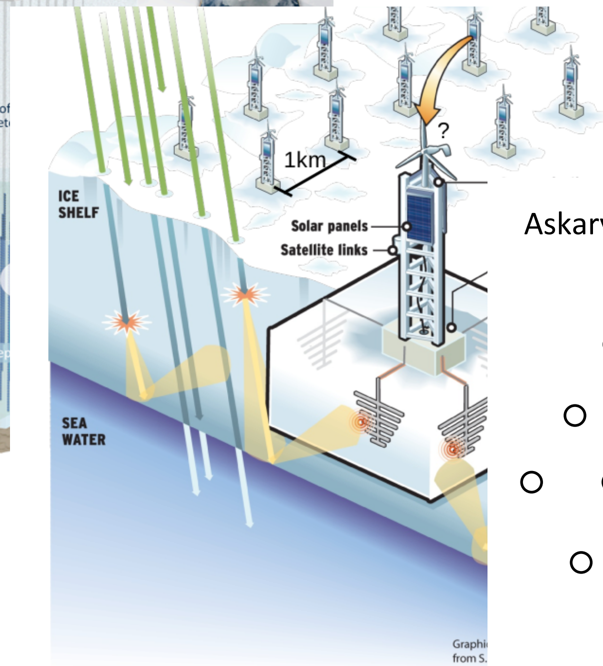
Antarctic Impulsive Transient Antenna (ANITA)

4 flights, O(10^6 km^3), 30-40 day flight time

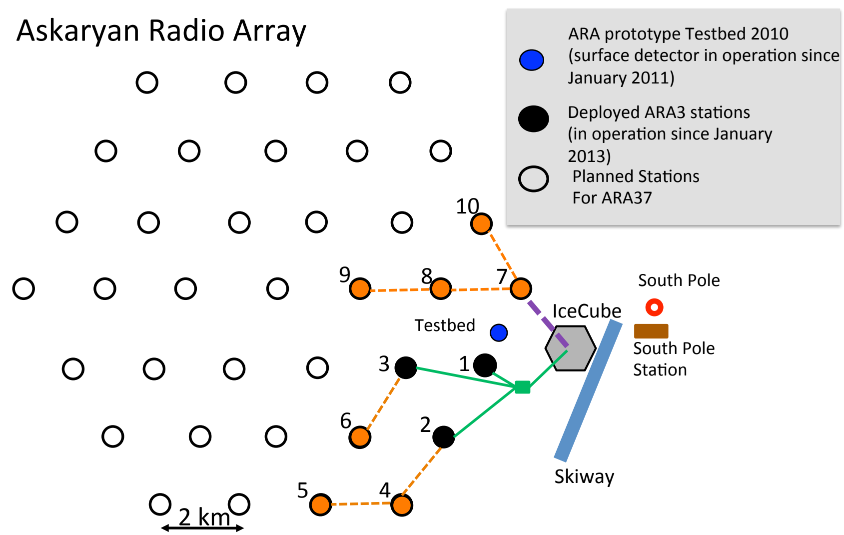
In Situ Detectors



IceCube



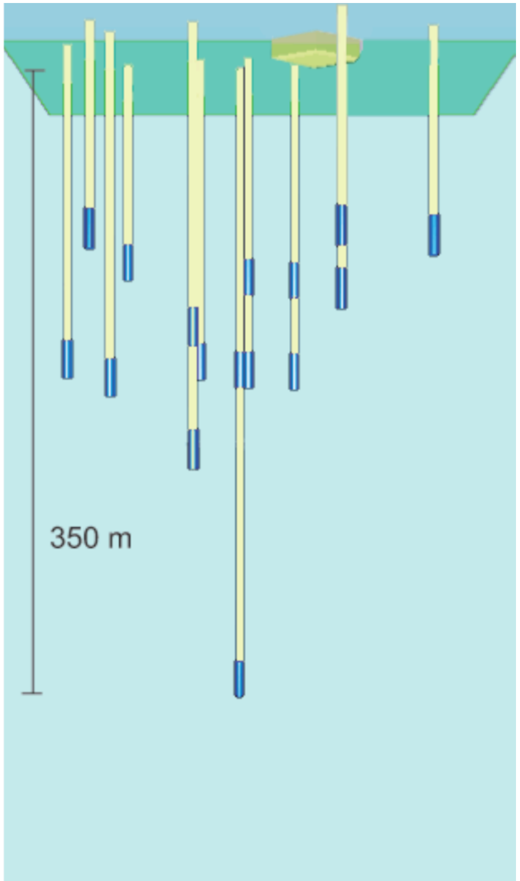
ARIANNA



ARA

Permanent observatory, O(100 km^3)

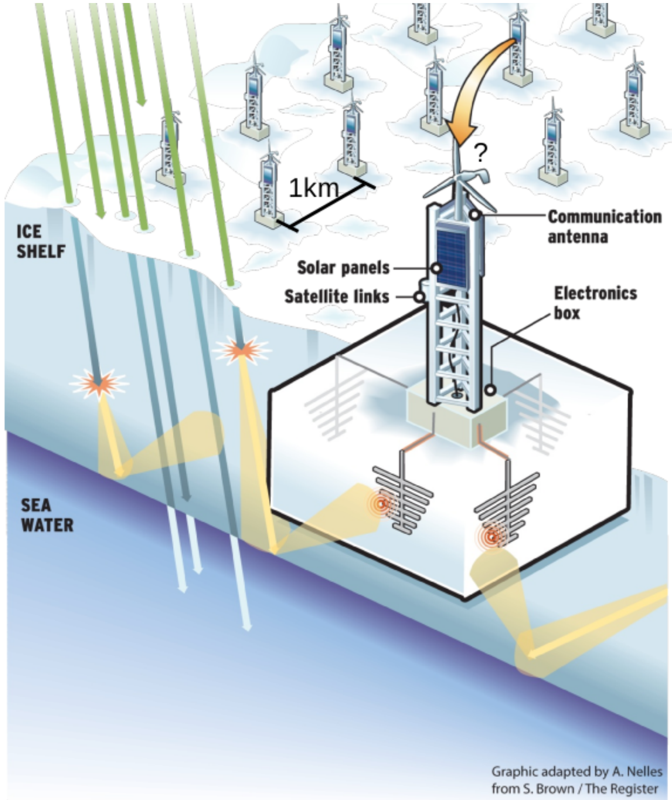
RICE



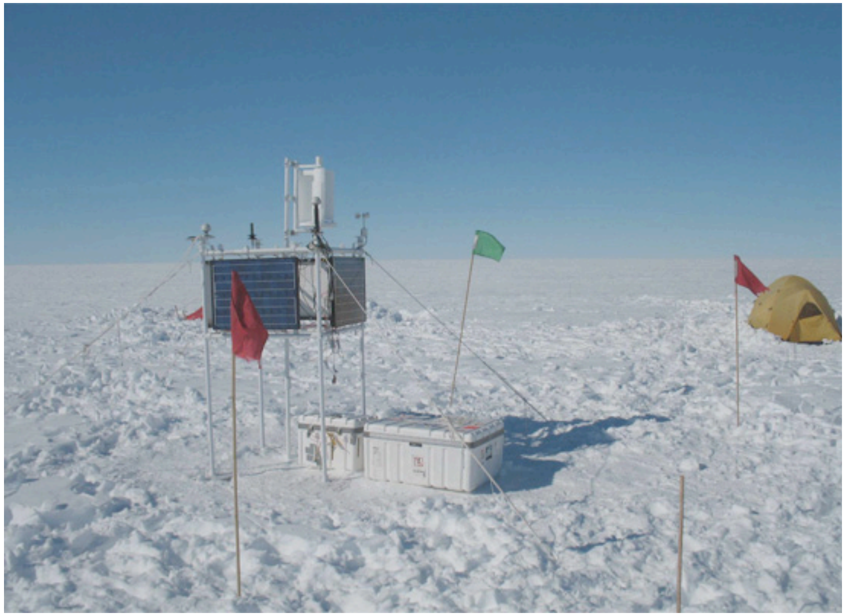
Kravchenko et al, 2011

- "Radio Ice Cherenkov Experiment"
- Radio antennas deployed along AMANDA strings
- Proof of concept
- First in-situ detector
- Early constraints at UHE

ARIANNA



(Source: ARIANNA Collaboration)

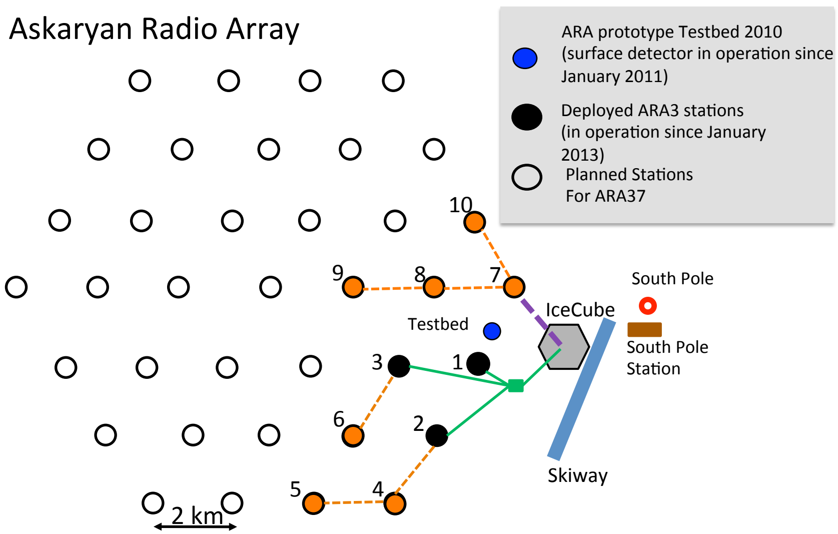


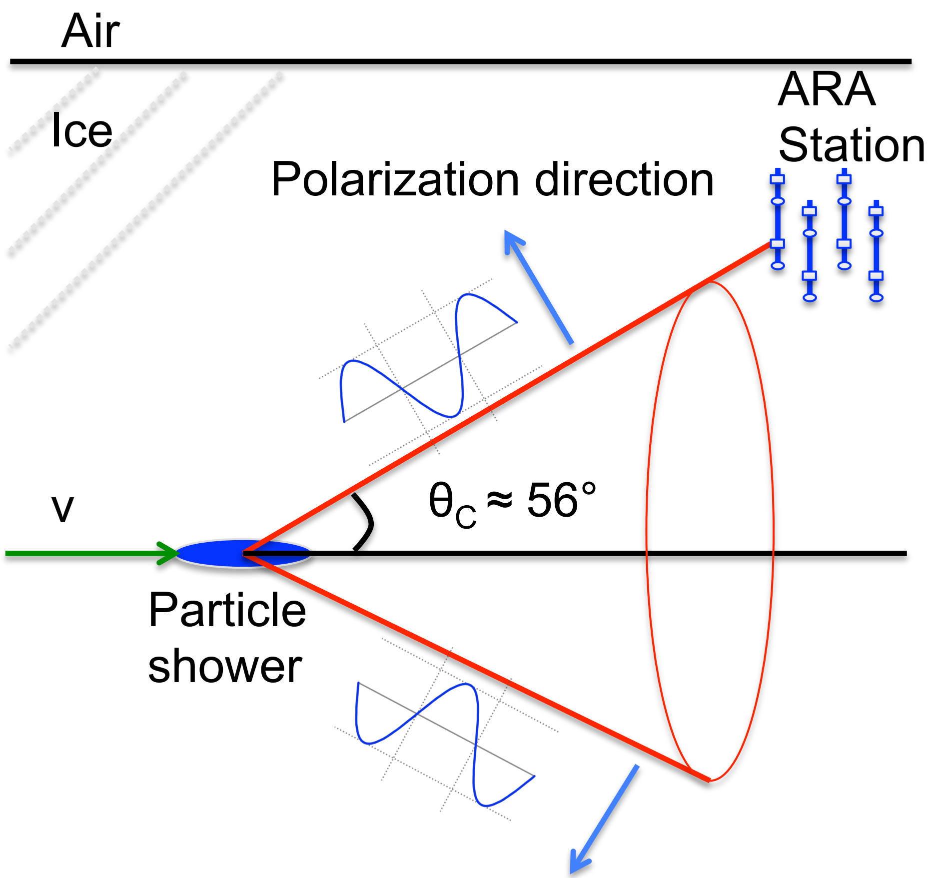
(Photo by Spencer Klein/LBNL)

Surface deployed stations at Ross Ice Shelf

Have already observed cosmic rays

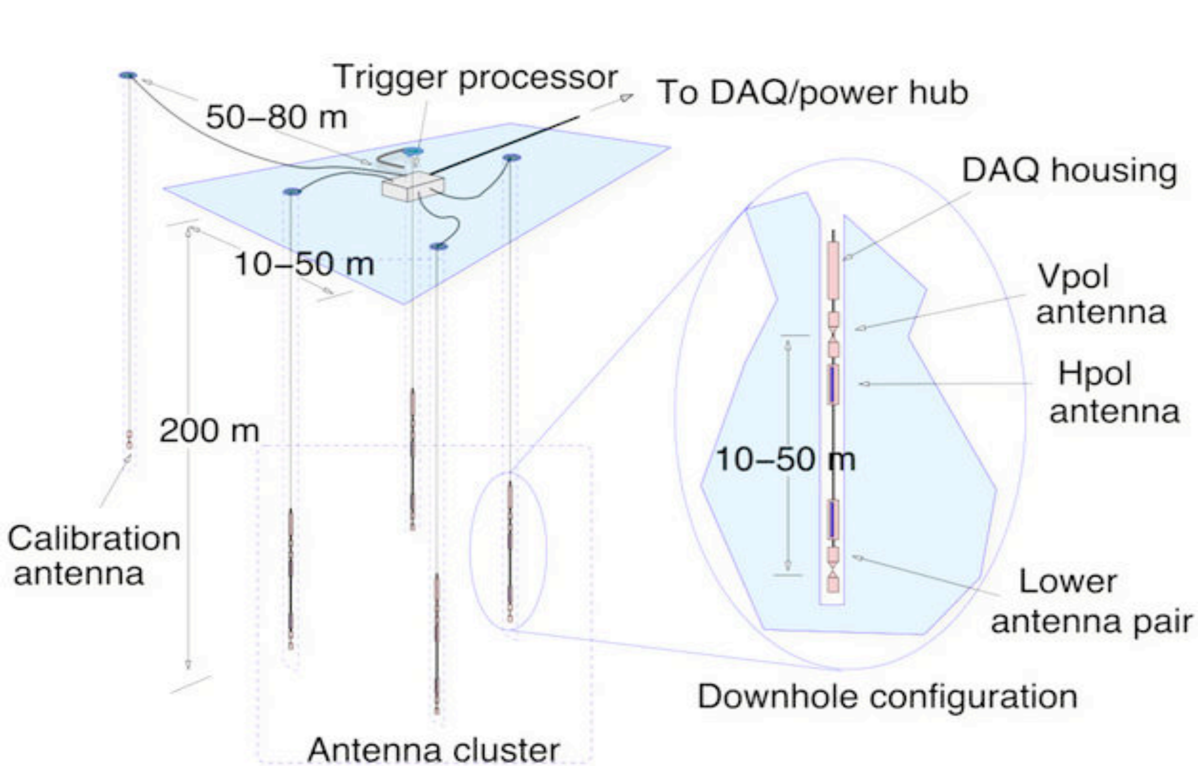
ARA Concept





Askaryan Radio Array (ARA)

Station Design

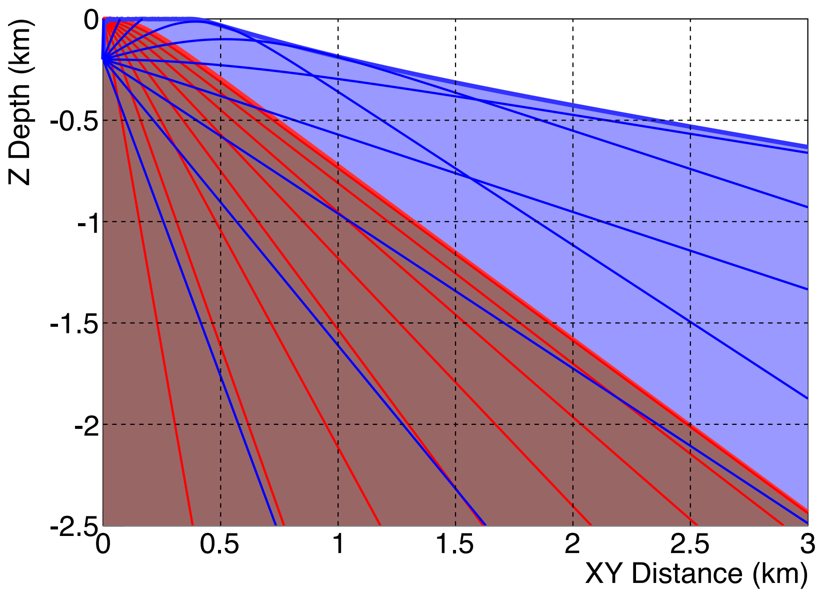


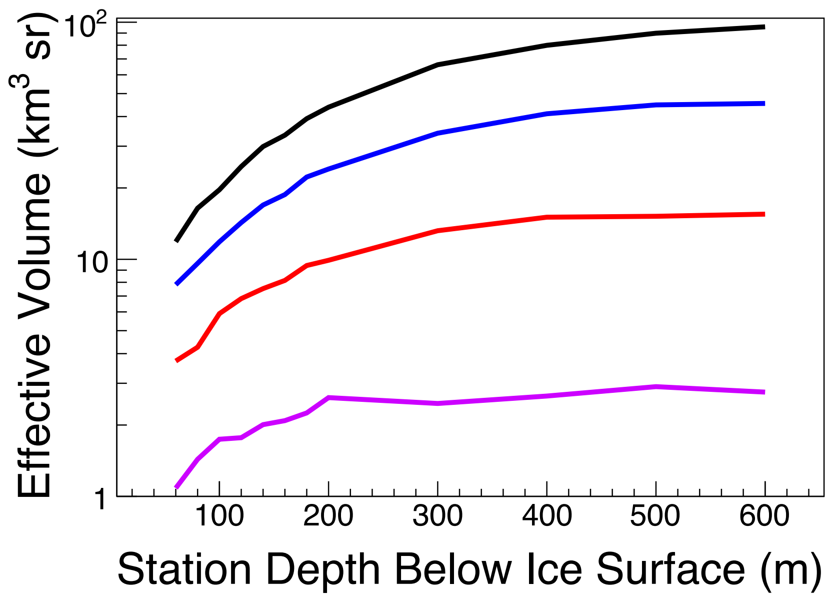
Hpol quad-slotted cylinder antenna

Vpol bicone antenna

16 Deep antennas: 4 strings of 2 Hpol + 2 Vpol

Deep Deployment

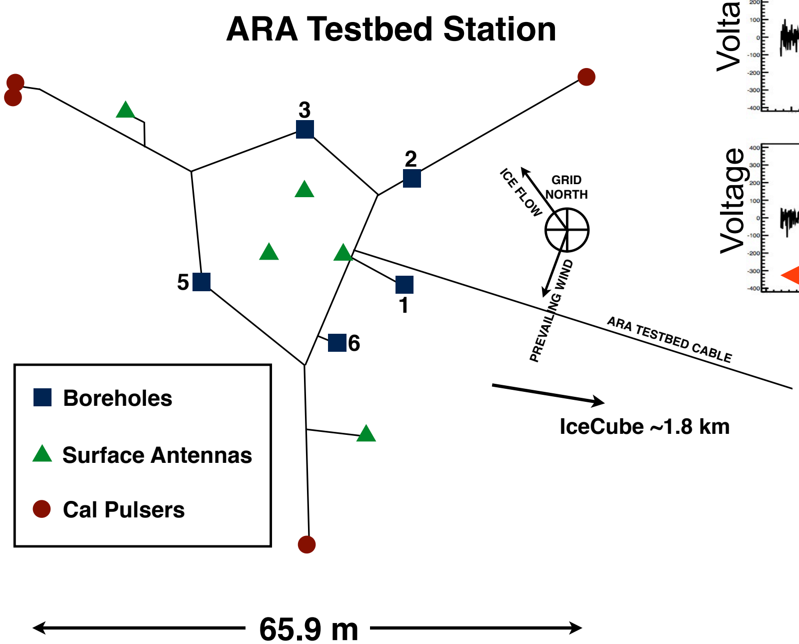


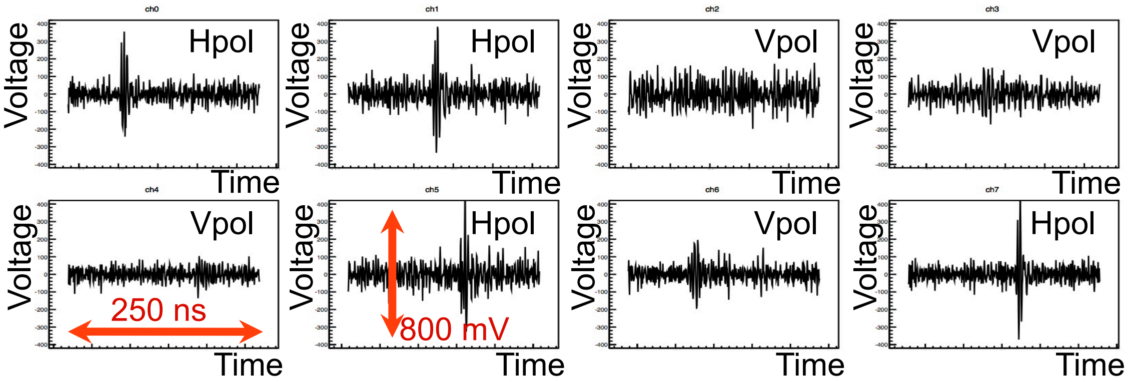


- Firn – layer of compacted snow
  - Changing index of refraction
    - (~1.35 → ~1.78 within top ~150 m of ice)
  - Causes curvature in paths of rays in ice?
  - New measurements may suggest otherwise – ongoing investigation

ANALYSIS: ARA TESTBED

Testbed Station





Calibration pulser event waveform from 8 deep antennas in Testbed

Data: January 2011 – December 2012

- First ARA neutrino searches carried out with Testbed station data
    - Diffuse: Astropart. Phys. 70, 2015, 62–80, arxiv:1404.5285
    - GRB: Astropart.Phys. 88 (2017) 7-16, arxiv:1507.00100

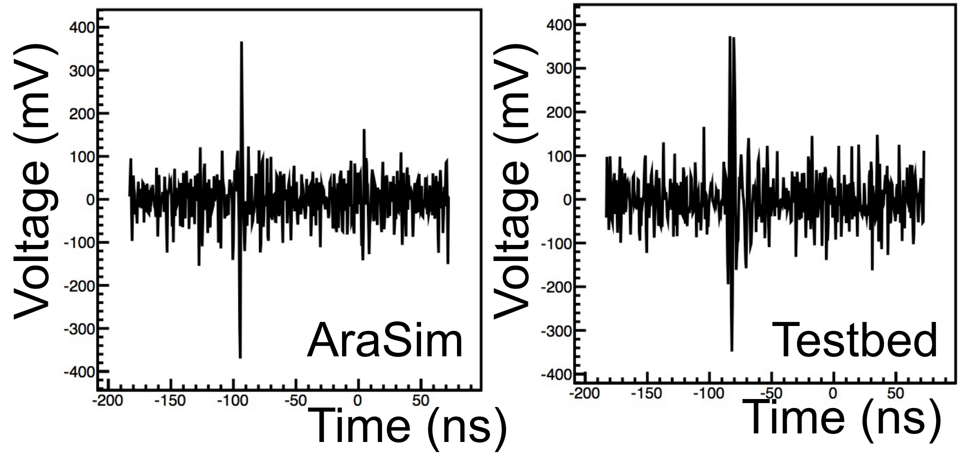
Simulation

End-to-end simulation

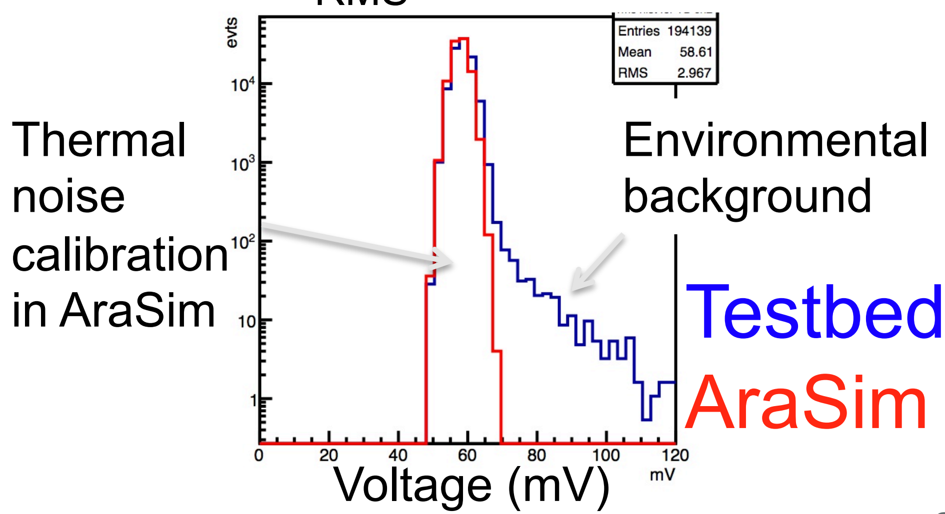
Includes:

- Parameterized shower
- Index of refraction model
- Calibrated noise simulation
- Antenna and electronics
- responses
- Trigger model
- Event output in data format (first time for a young field!)

Calibration pulser event waveforms



V_{RMS} Distribution

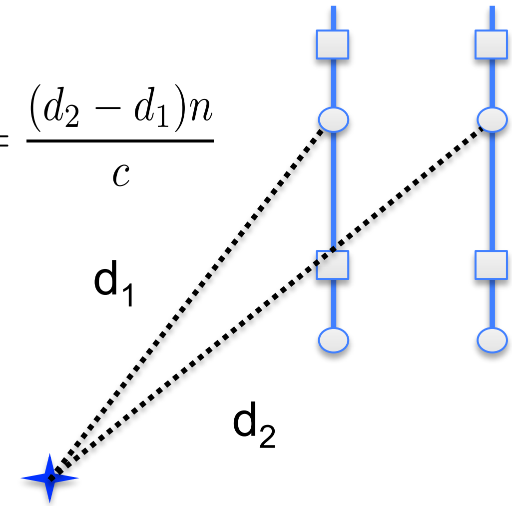


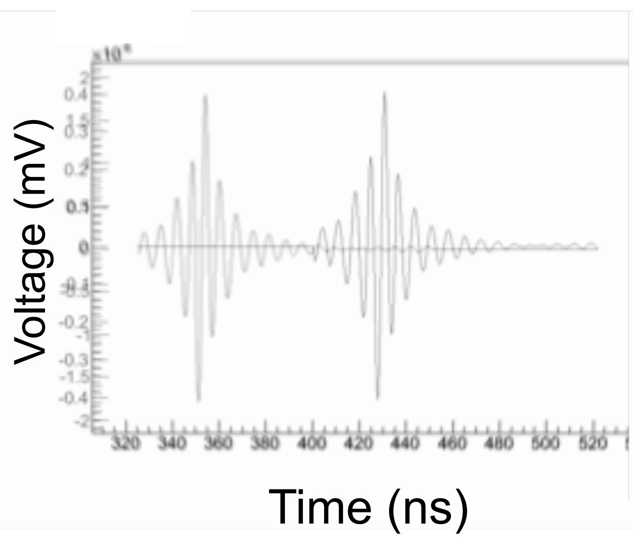
Interferometry

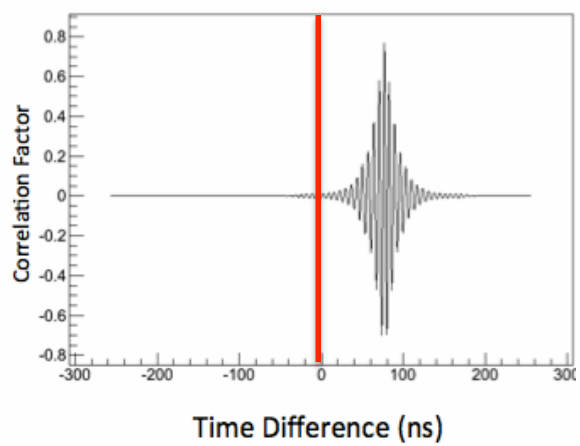
Timing delays between antennas → directional reconstruction

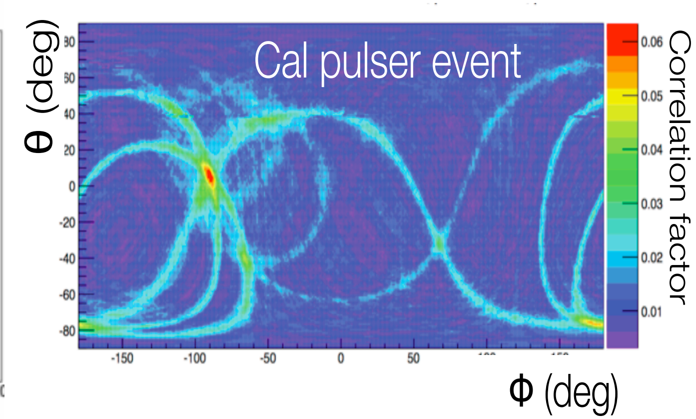
Sum up correlation map all pairs of antennas → reconstruction direction

$$\Delta t = \frac{(d_2 - d_1)n}{c}$$









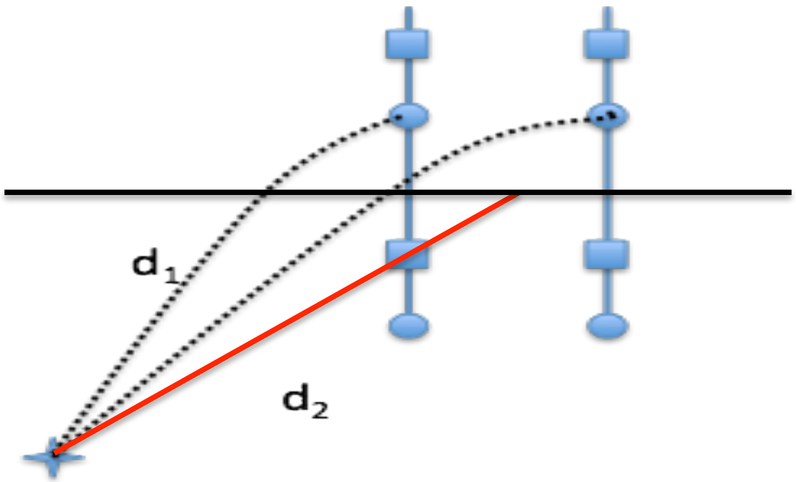
Reconstruction Quality Cut

Ray-traced timings for maps (first time!)

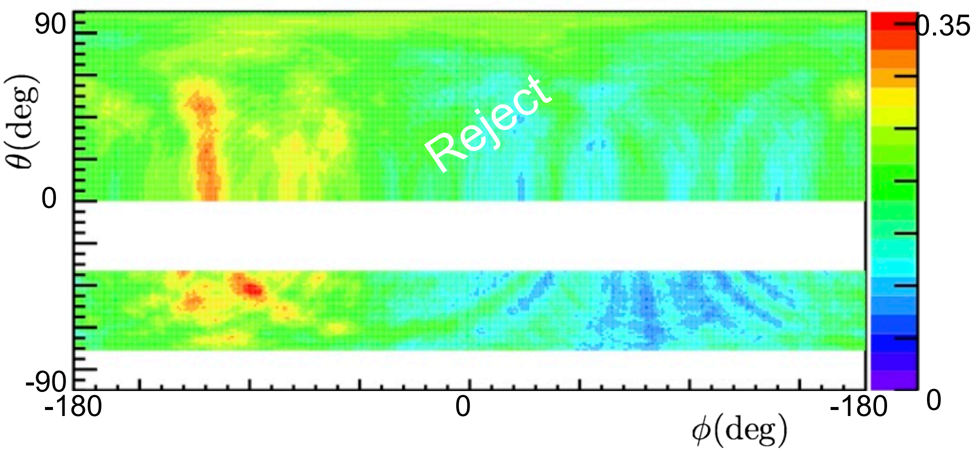
One reconstruction map (30m vs 3 km, vpol and hpol) to be of good quality

- well-defined - small area around peak
- unique peak – small ratio of area of rest of map to the peak

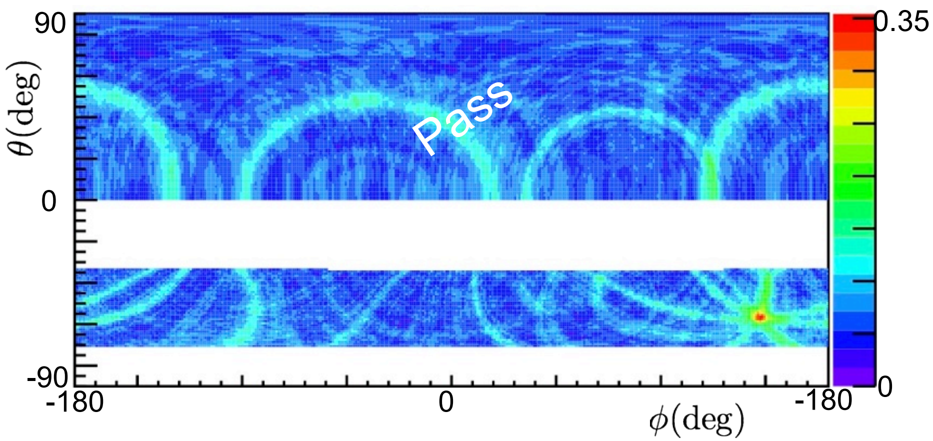
Rejects ~95% of noise-dominated events after initial quality cuts



Known background event reconstruction map example



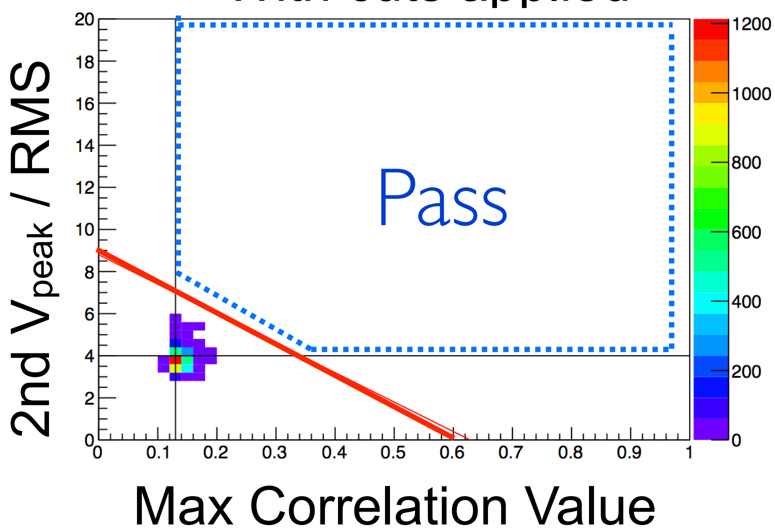
Simulated ν event reconstruction map example



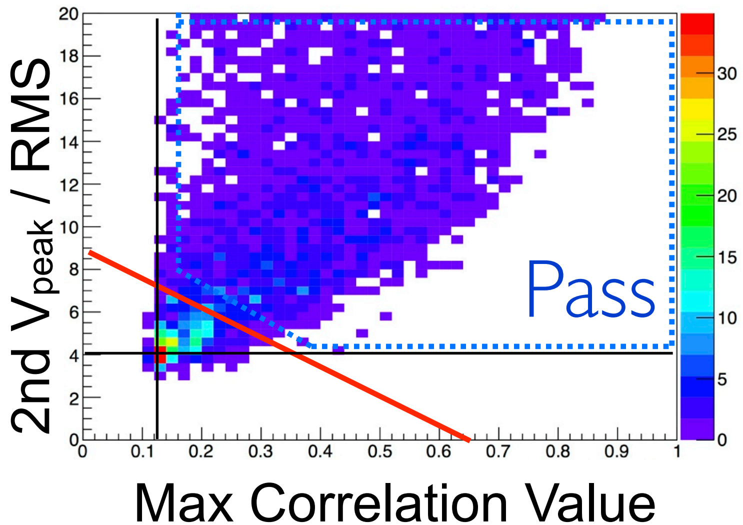
Peak/Correlation Cut

- Impulsive event: correlation between signal strength and map correlation value from reconstruction

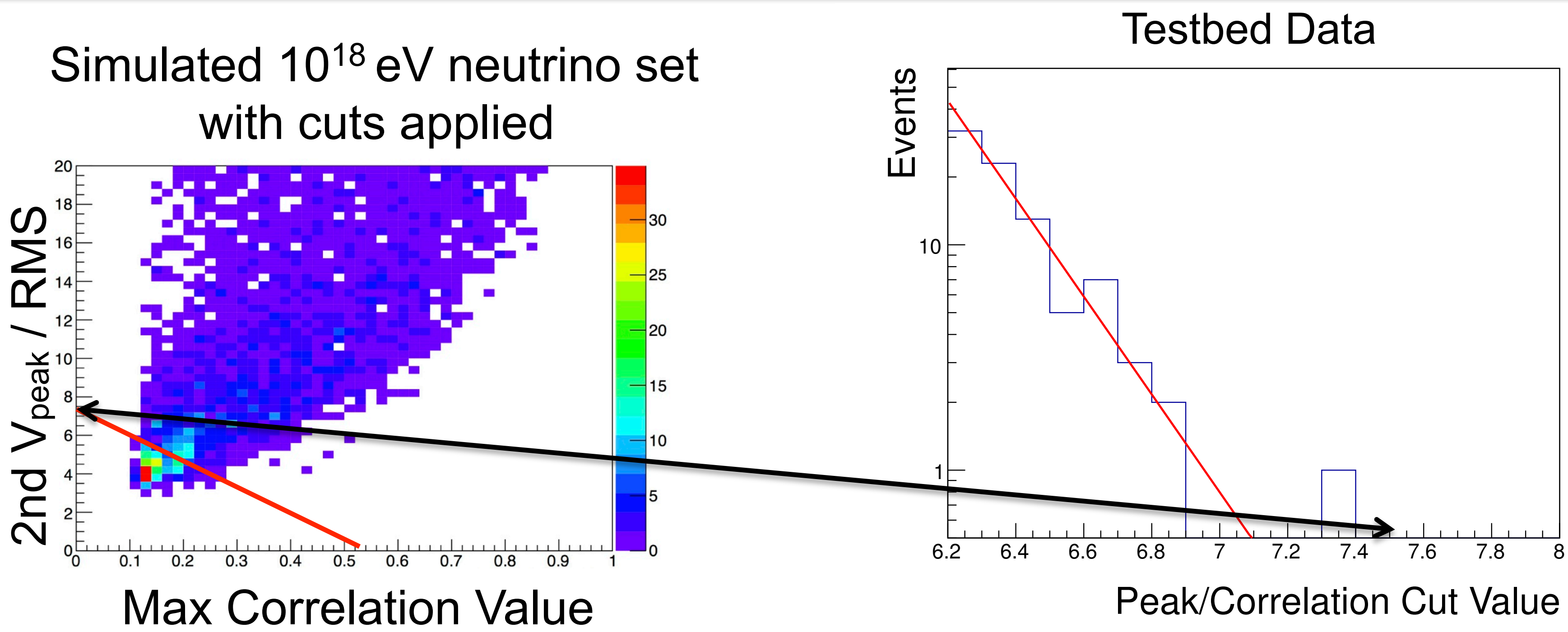
Testbed 10% data set
With cuts applied



Simulated 10^{18} eV ν set
with cuts applied



Optimization

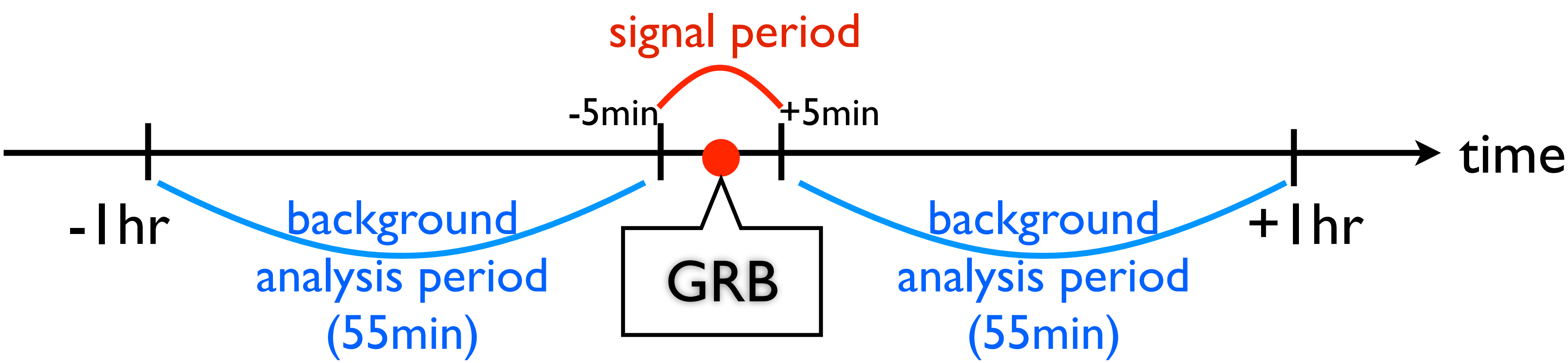


- Optimize the cut parameters for best limit:
  - Extrapolate to get expected background
  - S_{upper} is the 90% confidence limit on the signal for an expected background

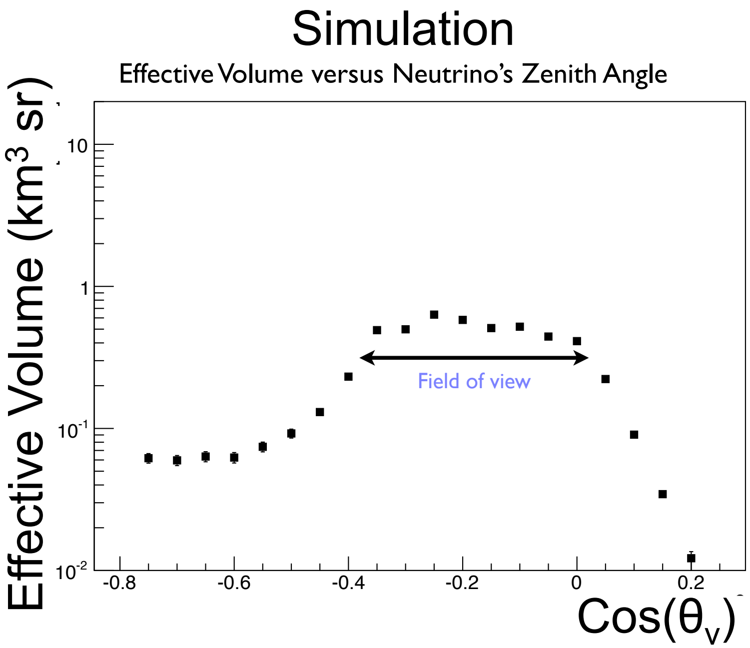
$$R = \frac{N_{passed,sim}}{S_{upper}}$$

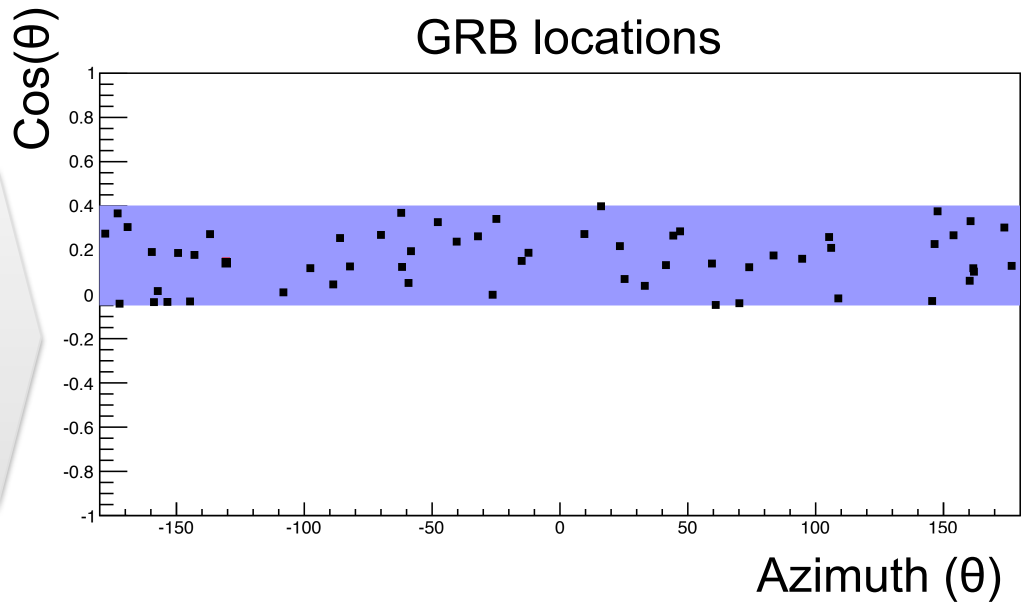
Testbed GRB analysis

- Adapt method to search for events coincident with known Gamma Ray Bursts
  - Stricter requirements in time → relaxation of event quality cuts
  - Timing technique adapted from ANITA (arxiv: 1102.3206)

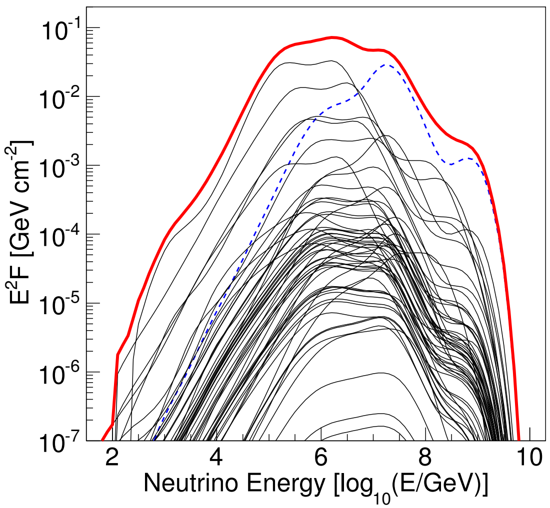


GRB Selection





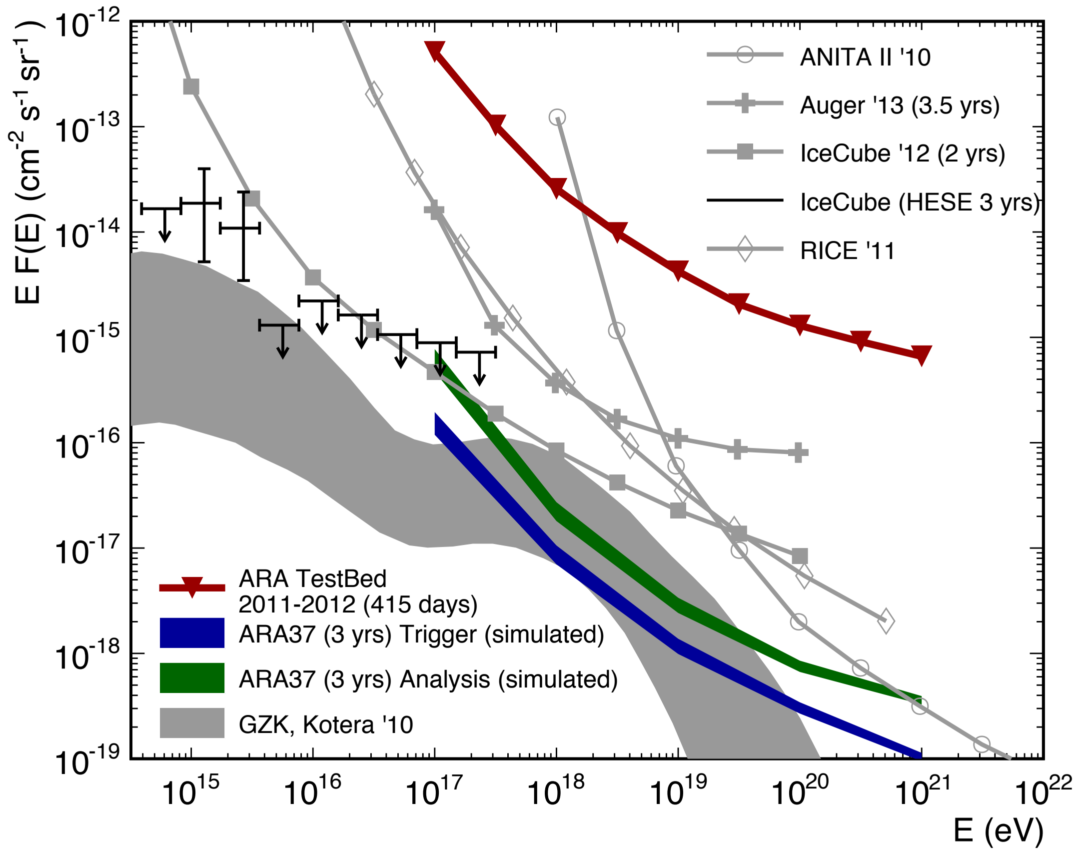
- Selected 57 GRBs based on livetime and geometric acceptance
- Find fluences for each GRB from NeuCosmA simulation (collaborated with M. Bustamante)
- Tune cuts based on modeled neutrino fluence including GRB-dependent flavors (first time!)



Diffuse Results

First diffuse limits from ARA Testbed

Projected sensitivity of 37-station array extends to GZK flux models



GRB Results

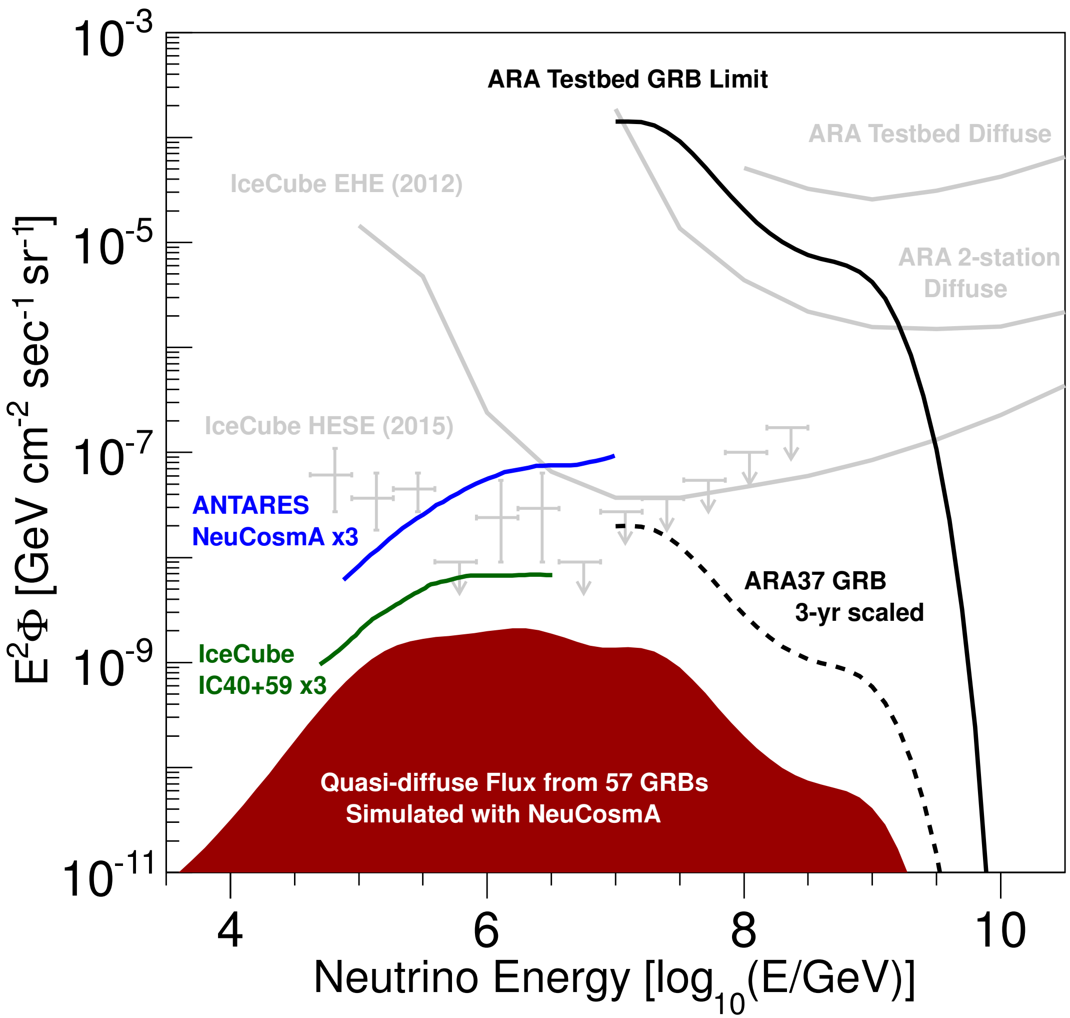
First quasi-diffuse flux limit above 10^{16} eV

First time expected GRB-dependent flavor ratios were included in the limit determination

Further improvements expected:

- Directional constraints
- Trigger improvements
- Analysis efficiency

(Astropart.Phys. 88 (2017) 7-16, arxiv:1507.00100)



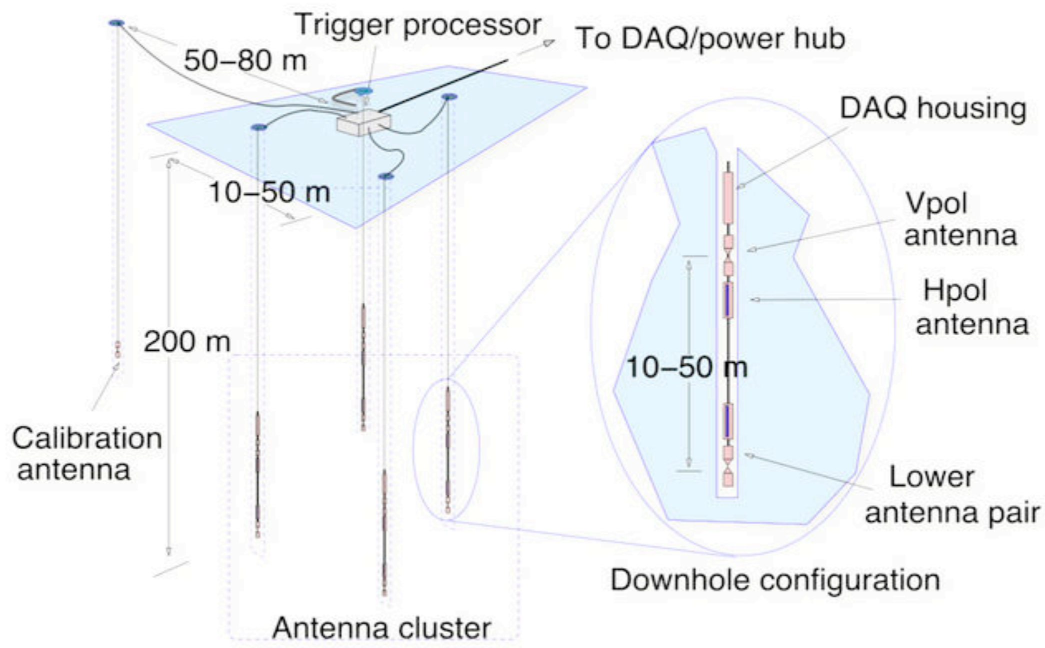
ANALYSIS: DEEP STATIONS

Analysis

First efforts: 10 months of data from 2 deep stations from 2013

Improvements in data quality:

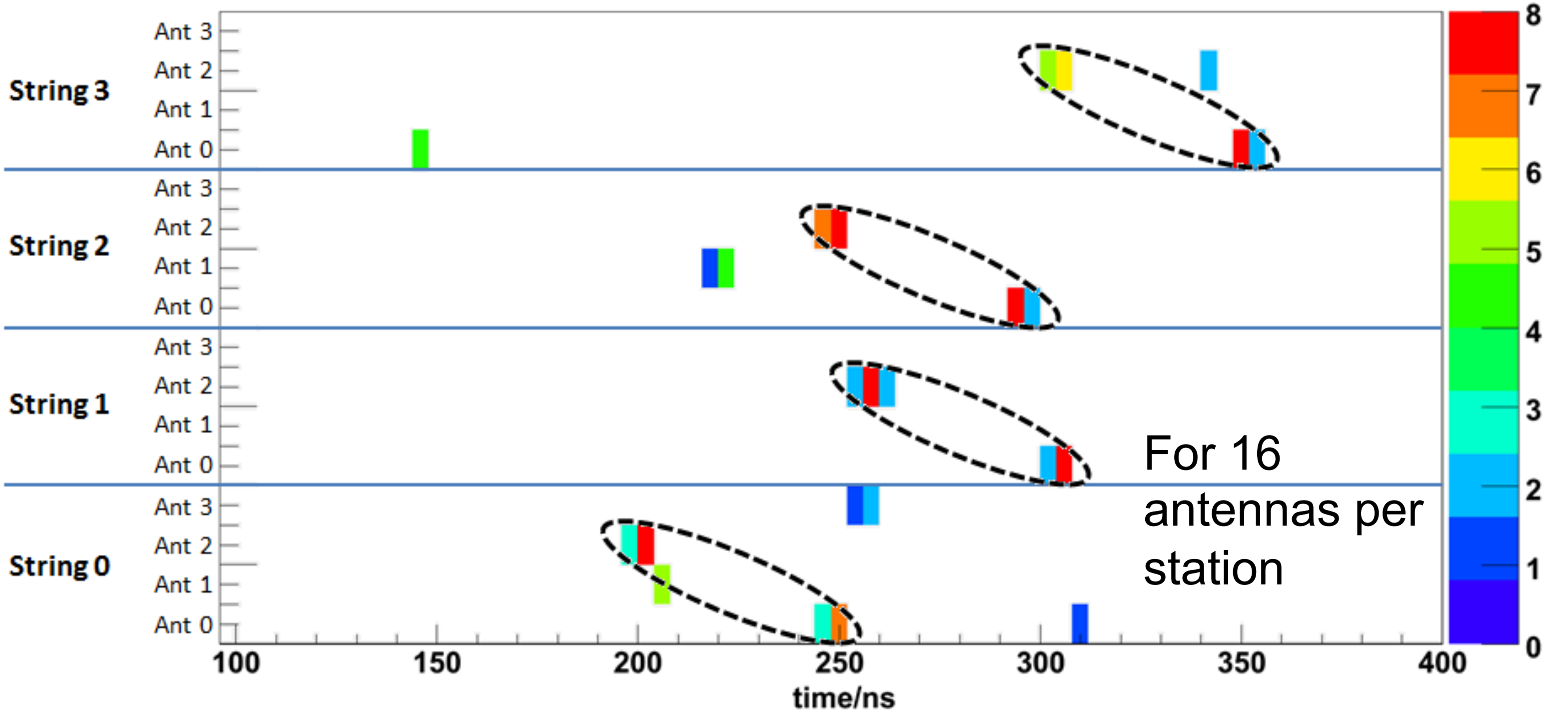
- Further from South Pole
- More antennas
- Effective volume
  3X over Testbed Analysis
- Efficiency
  ~10% → ~60%



Noise filtering

5 Hz thermal noise trigger rate (~300 million events per year per station)
→ Needs to be reduced before applying sophisticated algorithms

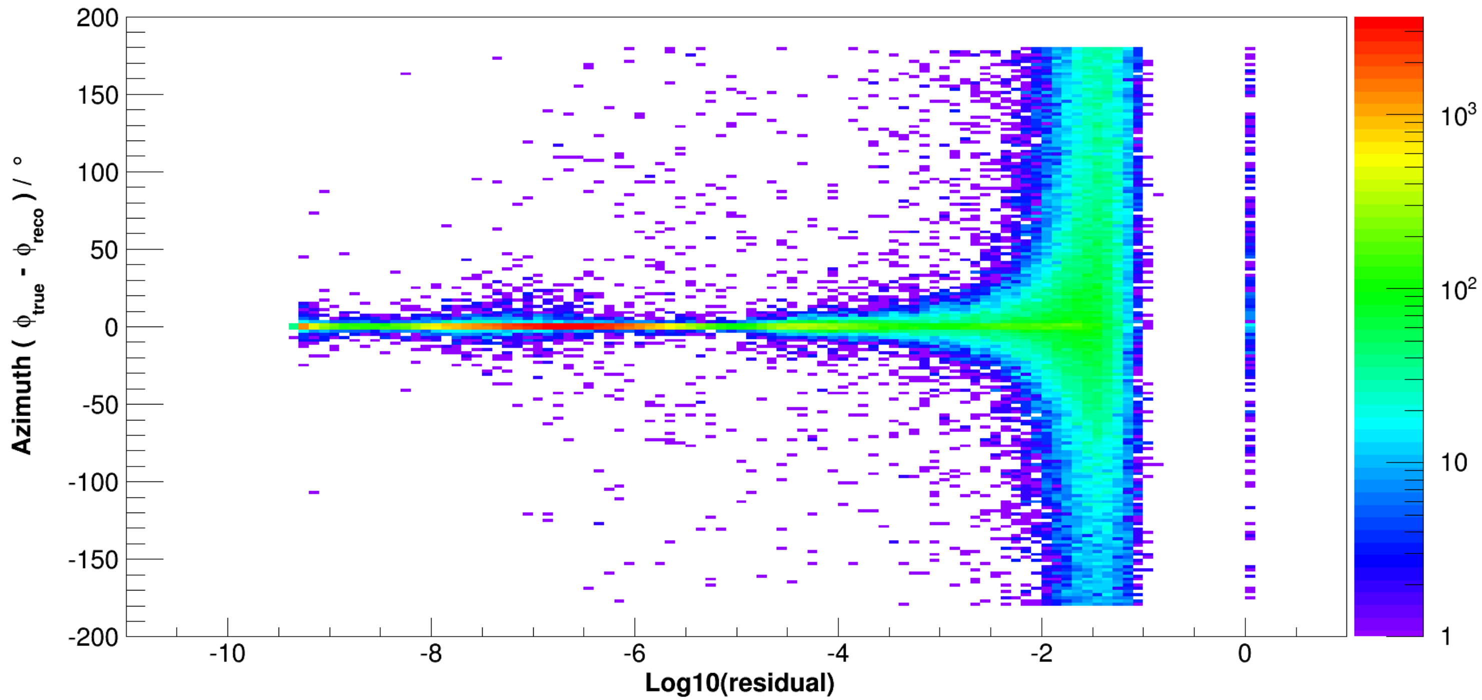
- Time Sequence Quality Parameter – "boosted" hit count with agreements in timing
- >99% efficient against thermal noise



Reconstruction

- Reconstruct interaction position with linear algebra
  - Matrix inversion
- Main quality criterion is residual

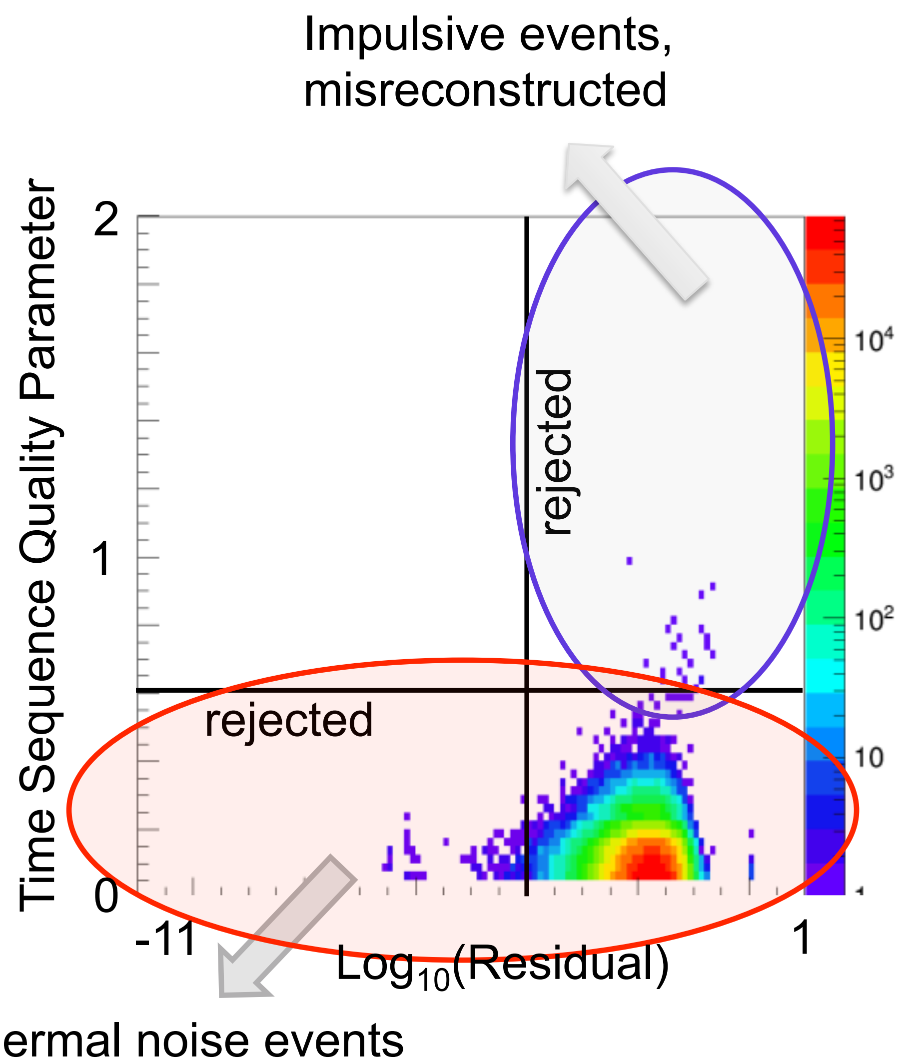
Reconstruction error vs residual:



Background rejection

Strategy:

- Use 10% burn sample
- Estimate angular cuts
  - Calibration pulsers, surface
- Apply time sequence and reconstruction residual cuts

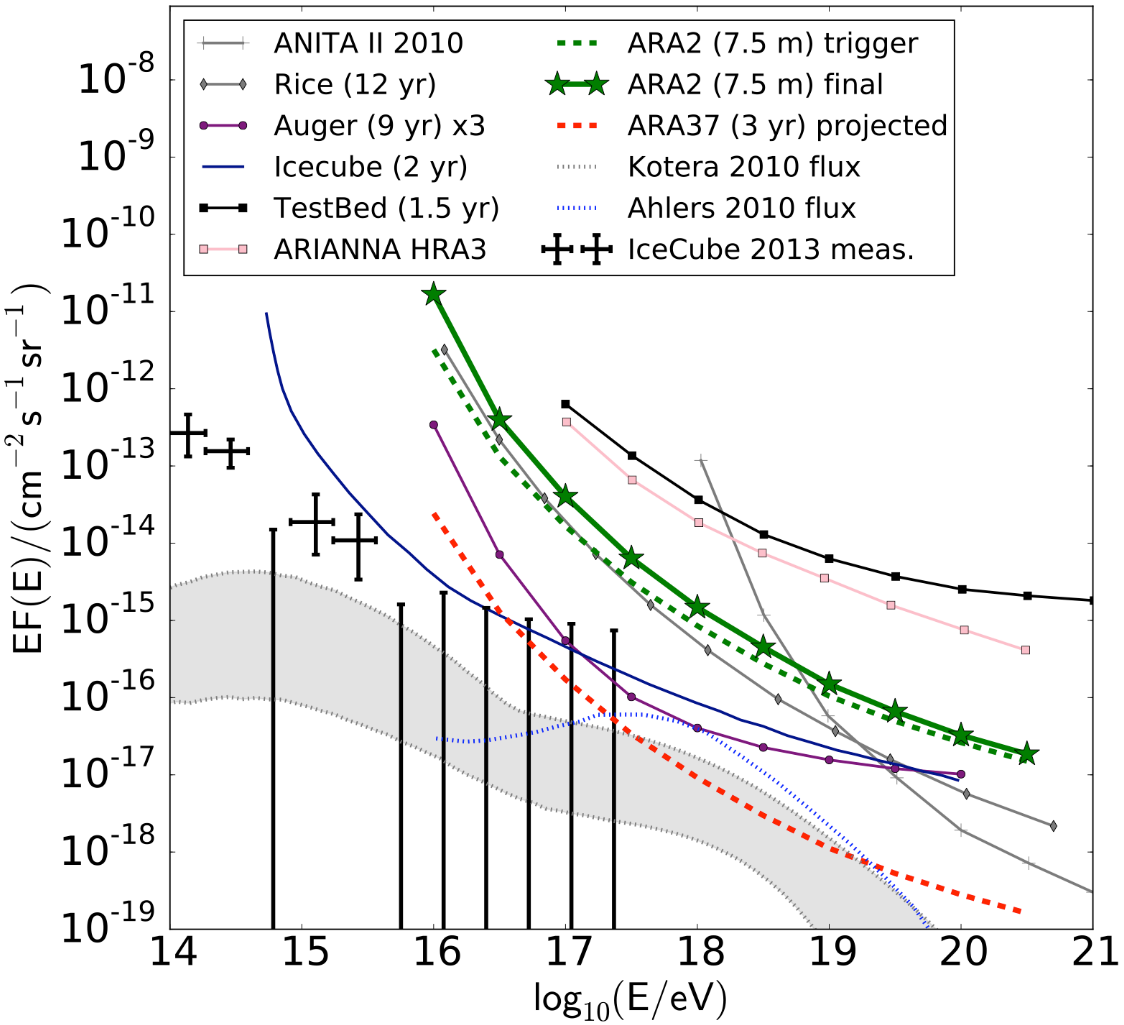


Results – 2 Stations

No candidates found

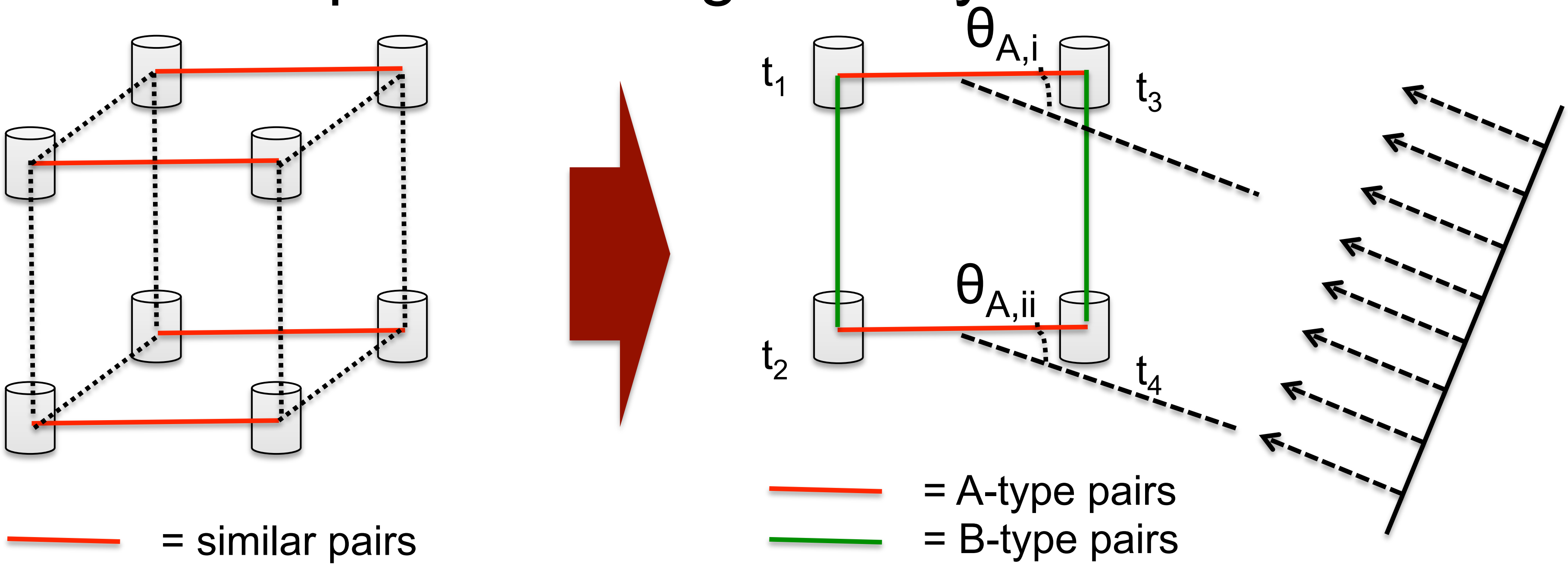
Improvements over Testbed

- Analysis efficiency (~6X)
- Effective volume (~3-10X)

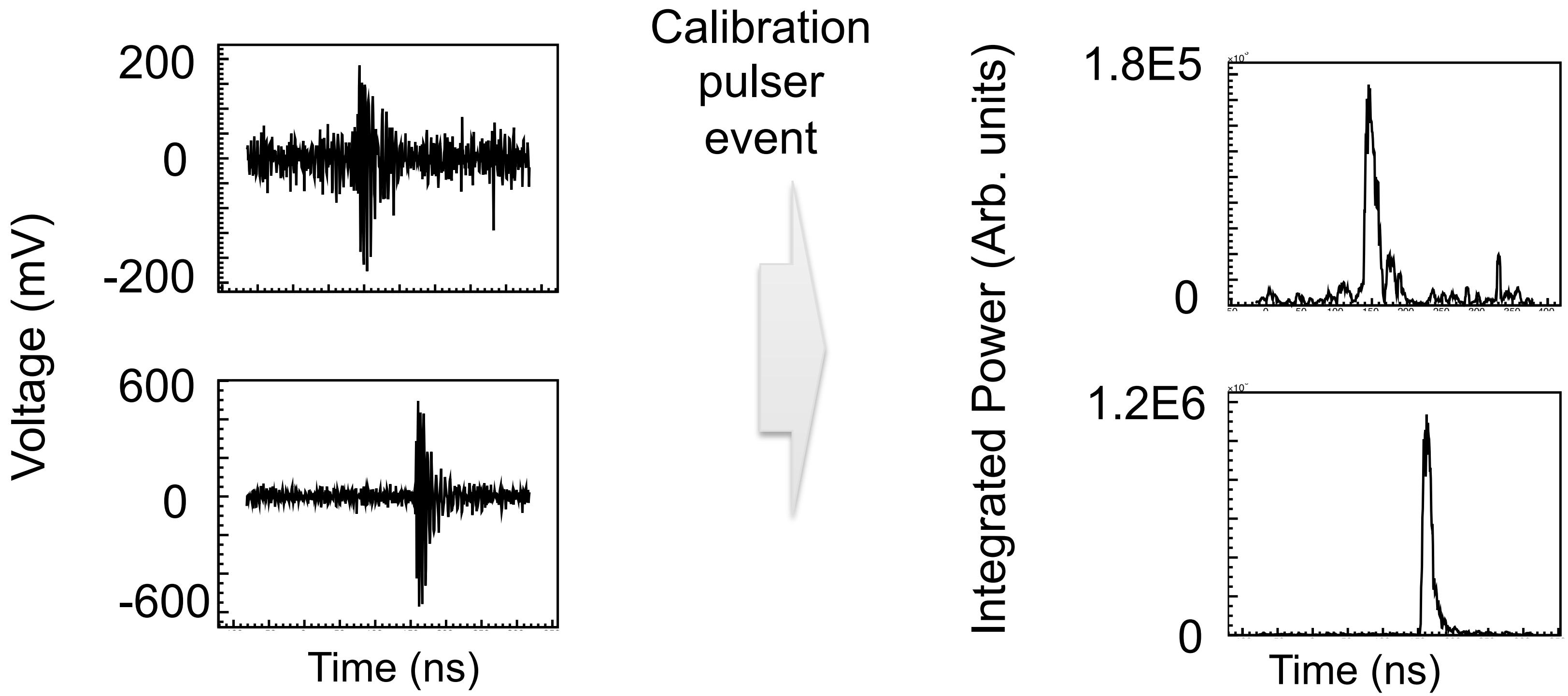


ARA Filter Technique

- Interferometry = computationally complex
- Filter >99% of noise before reconstruction
- Deep stations have regular geometry
- Assume plane-wave geometry

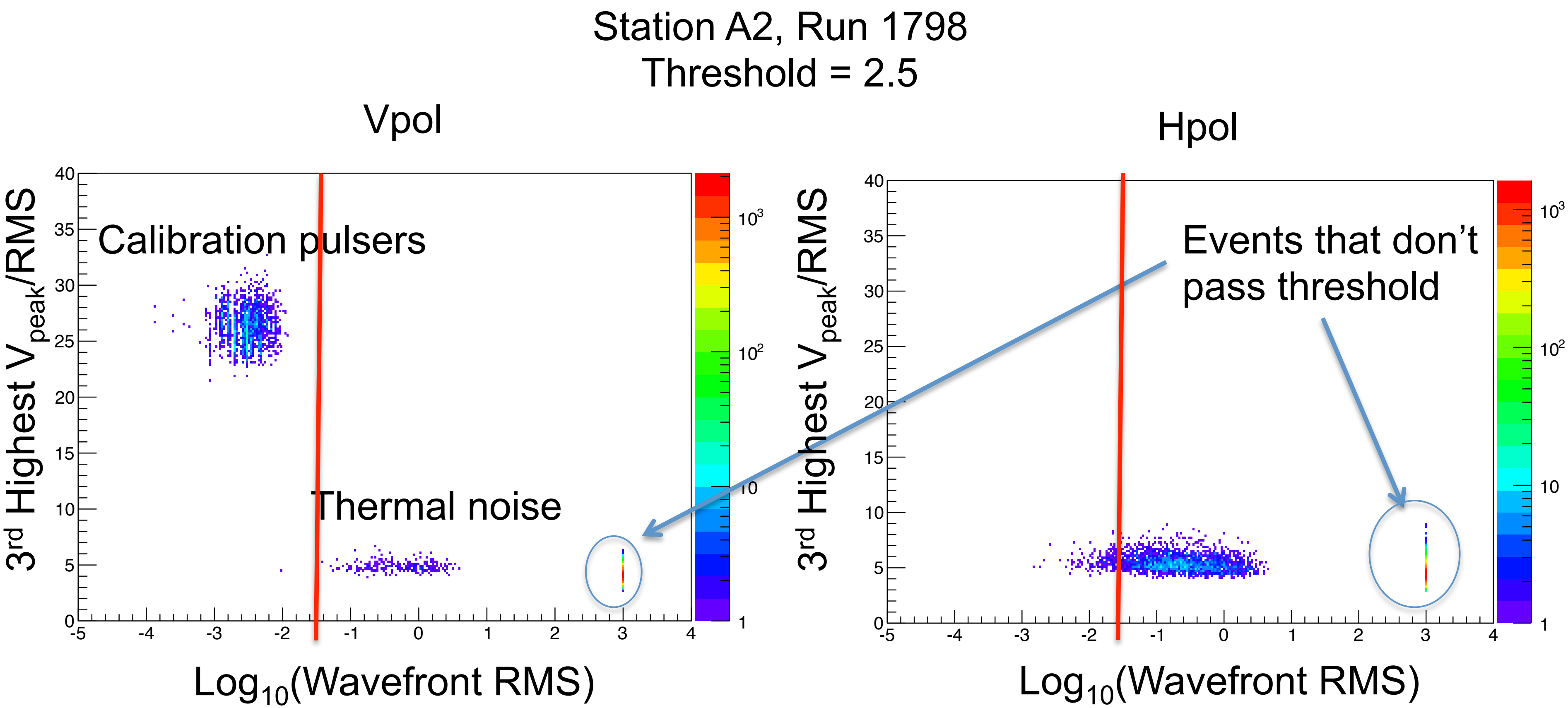


Wavefront Similarity



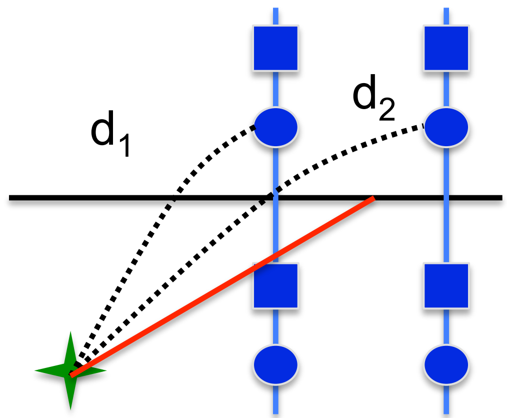
- Decrease noise fluctuations, use an integrated power window of 5 ns
- Two highest peaks → potential "hit times" for that channel
- Find how well the delays between similar pairs agree
- Use RMS of delays between pairs – "Wavefront RMS"

Preliminary Results - Data

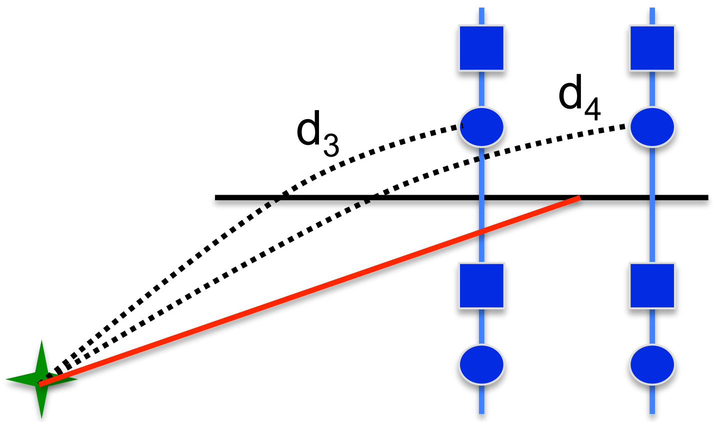


- More event pass threshold in Hpol antennas
  - use separate thresholds for Vpol and Hpol

Radial Interferometry

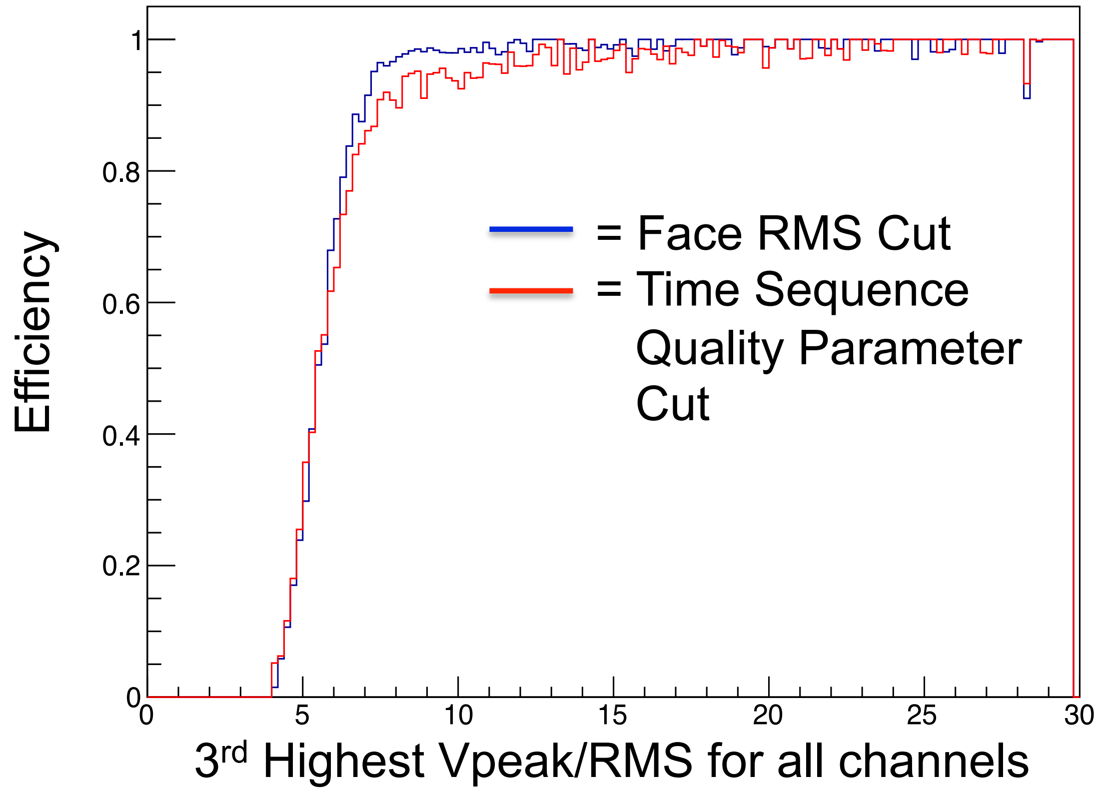


VS



- Arrival times depend on path through ice
- Curvature will change those times
- Solution: maps for different radii + find best map
- Could improve reconstruction accuracy and cuts

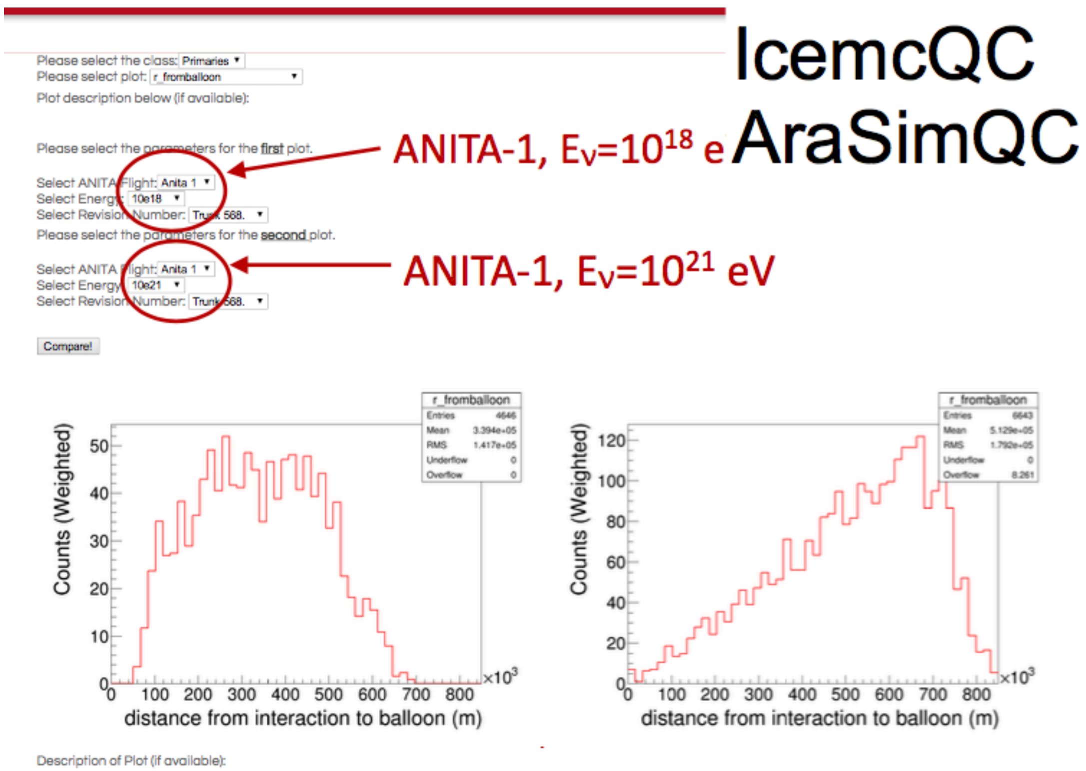
Efficiency



- Same noise rejection, improvement in efficiency vs SNR
- Expect further improvements from:
  - Full optimization of cuts
  - Improved reconstruction based – remove noise contribution on maps

AraSimQC/IcemcQC

- Simulation Monitoring Tool – ARA and ANITA
- Helps us identify the effect of changes to simulation code
- Quickly bring up results of different configurations

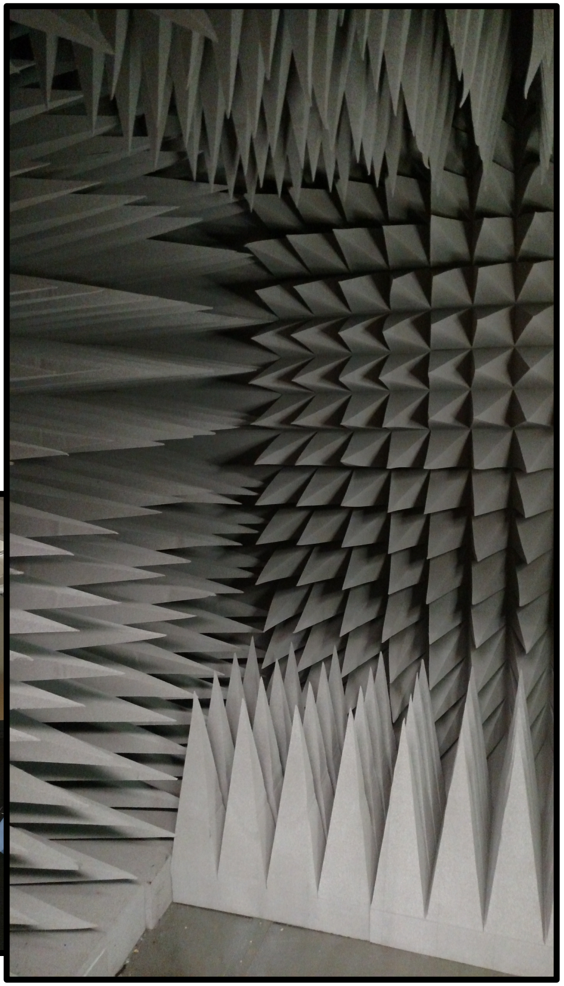


Facilities

Prototyping Electronics

Cold-testing

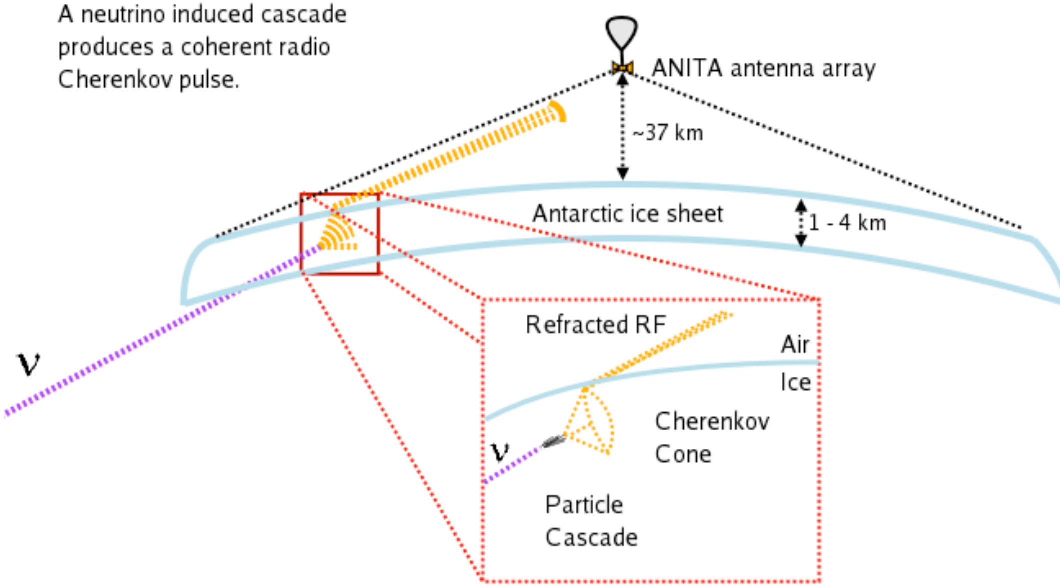
RF-quiet testing

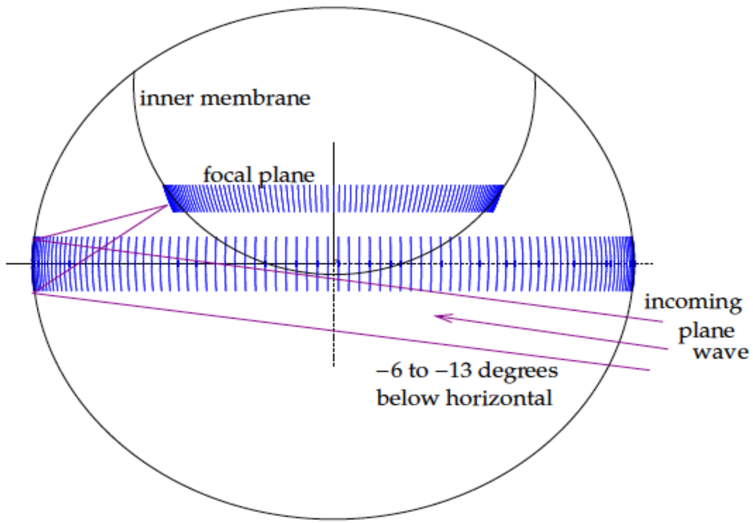


CART (CCAPP Antarctic Radio Testing facility)

EXAVOLT ANTENNA (EVA)

ExaVolt Antenna (EVA)

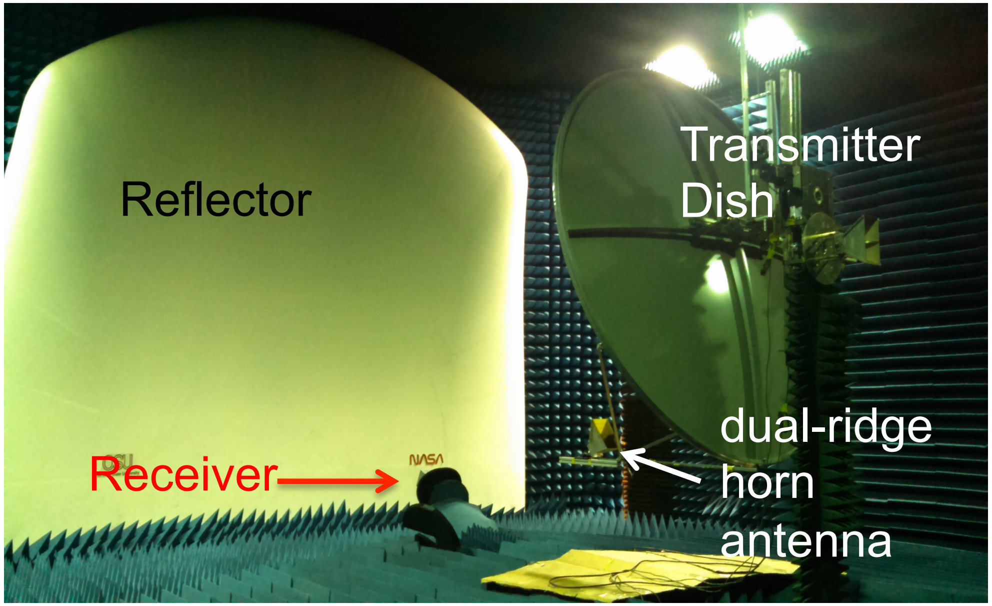




- Idea for a next generation synoptic detector (e.g. ANITA)
- Balloon above ice observes interactions from ~100 km away
- Use balloon surface as part of antenna
- Aim to improve gain to achieve better sensitivity

1:20 Scale Hang Test

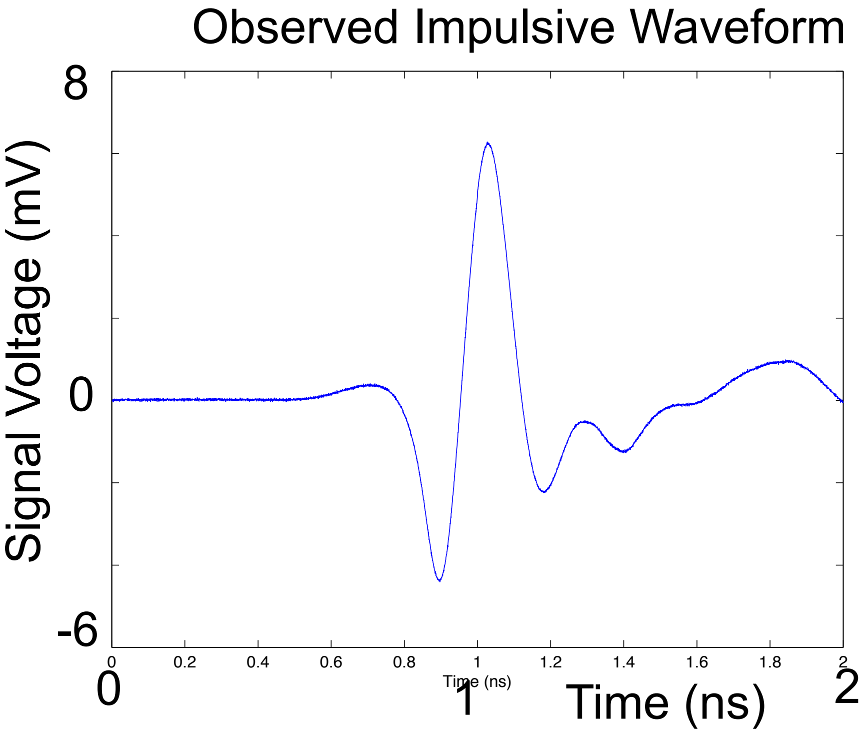
Wallops Flight Facility, September 2014



- Assembled impulsive signal transmitter to test 1:20 EVA
- Tested and characterized using facilities at the OSU ElectroSciences Lab (ESL)
- Worked with U Hawaii, GWU, NASA's JPL

1:20 Scale Hang Test

Wallops Flight Facility, September 2014



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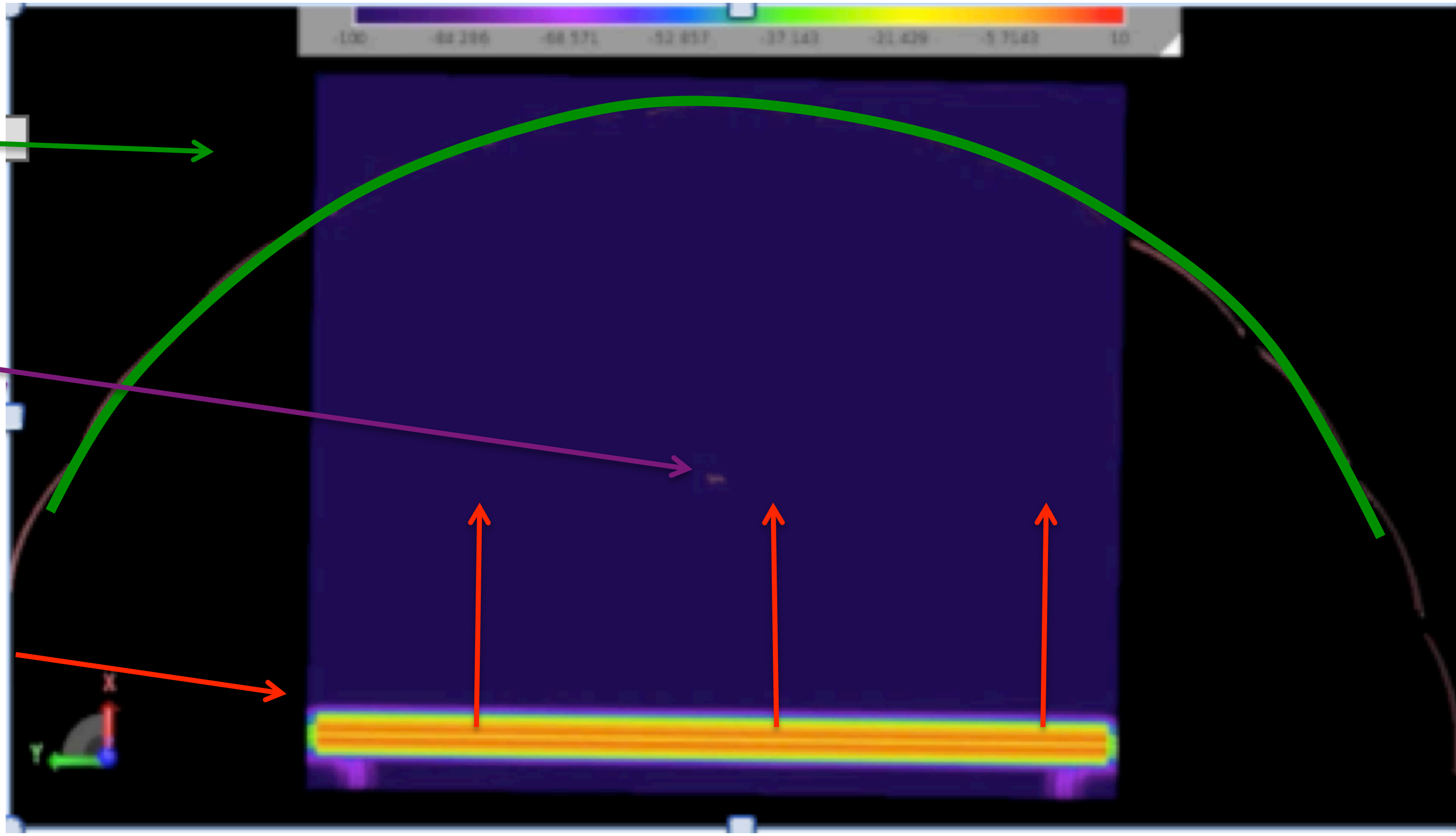
Hang Test Simulation

Reflective Balloon Surface

Receiver Antenna

Incoming plane wave (propagation direction)



Time-domain simulation using XFdtd

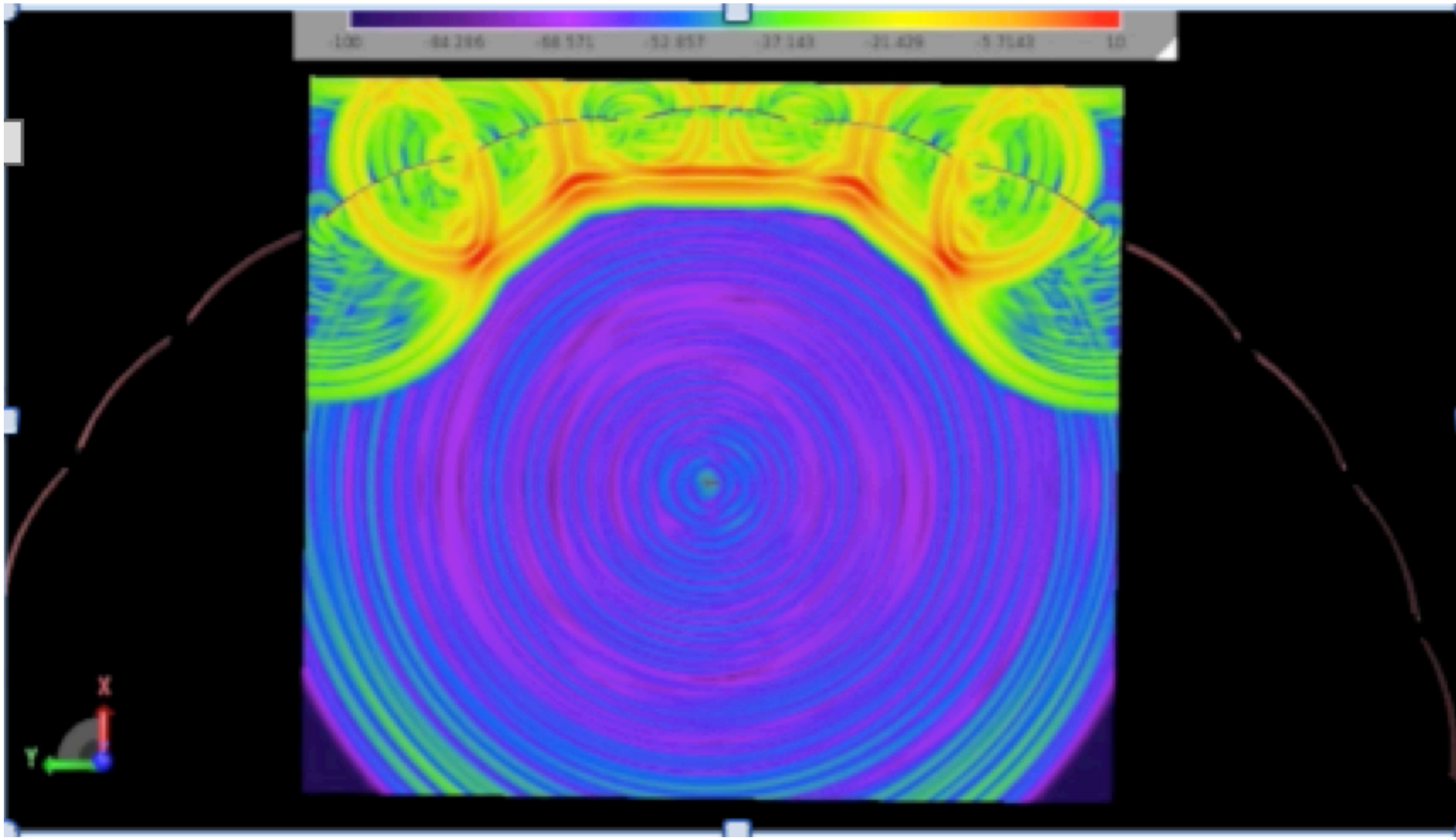
THE OHIO STATE UNIVERSITY

Hang Test Simulation

Reflective Balloon Surface

Receiver Antenna

Incoming plane wave (propagation direction)



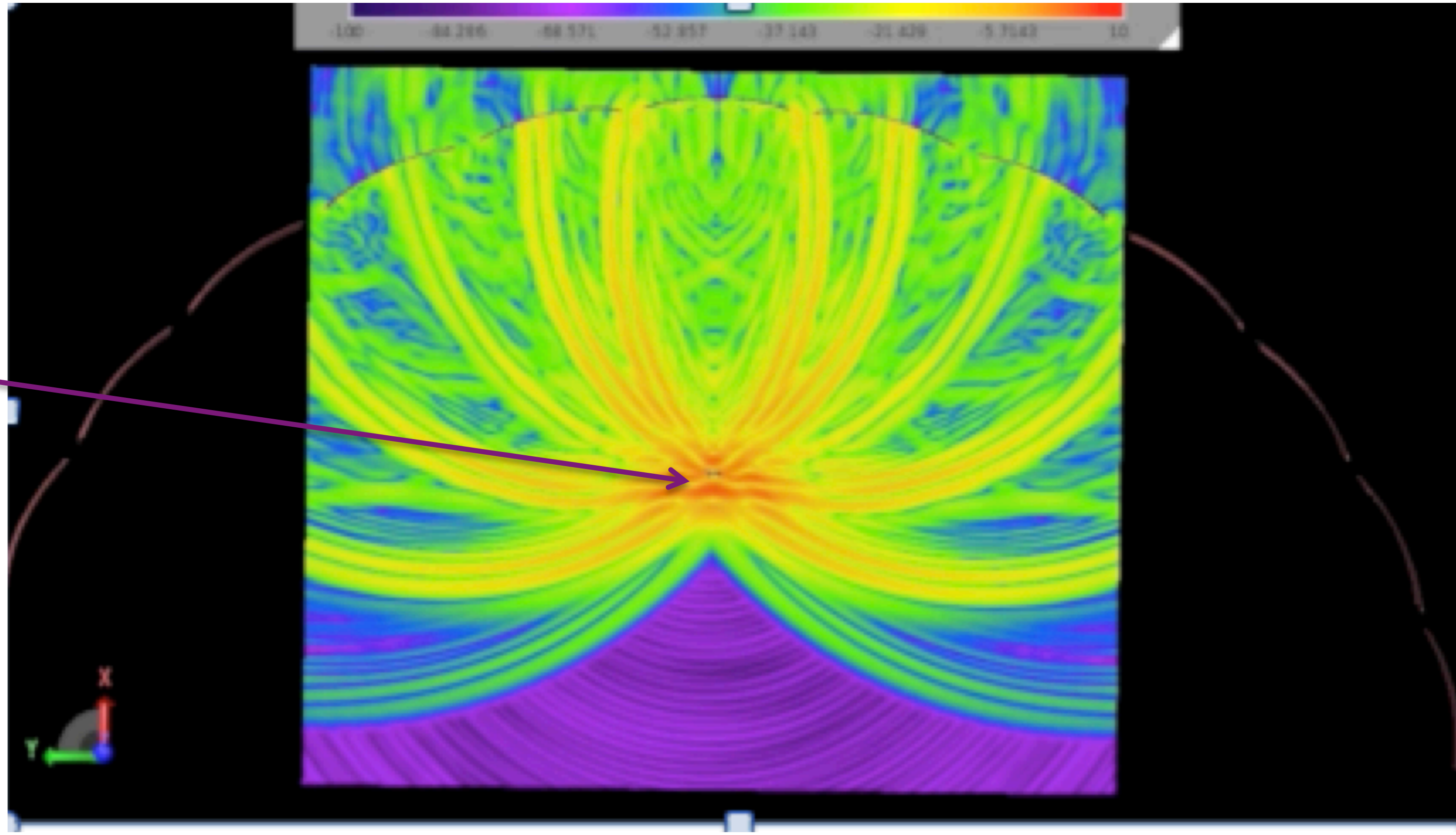
Time-domain simulation using XFdtd

Hang Test Simulation

Reflective Balloon Surface

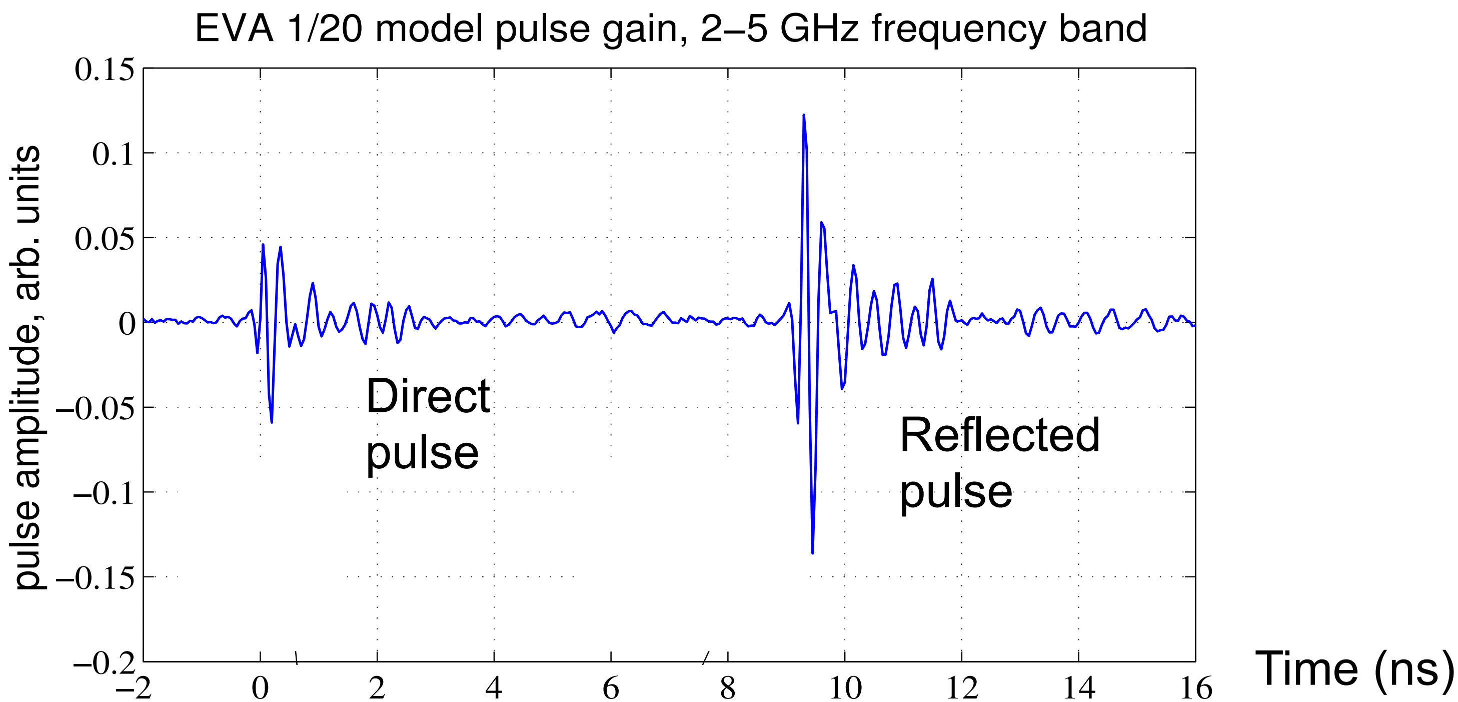
Receiver Antenna

Incoming plane wave (propagation direction)



Time-domain simulation using XFdtd

Hang Test Results



- Data: increased gain (~11.4 dBi), coherent pulse
- XF7 simulation predicts 10.0 dBi
- EVA concept is credible: consistent within ~2 dBi
- Full-scale detector predictions >24 dBi: needed to reach target sensitivity

dBi = decibels above isotropic

CONCLUSIONS

Future

Radio detection of UHE neutrinos

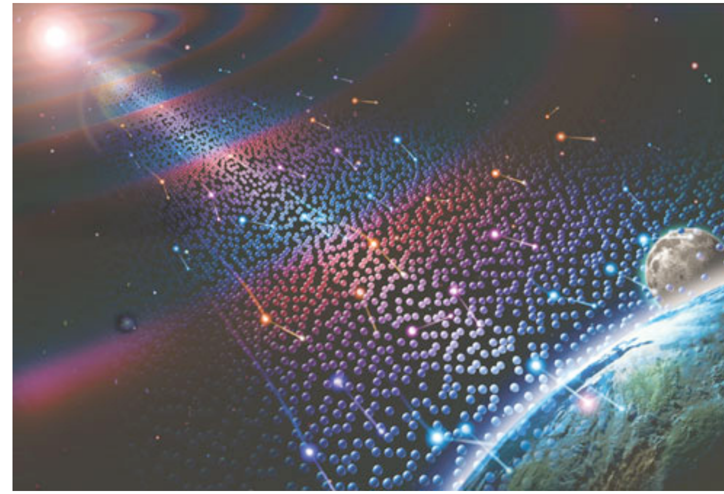
- Can reach ultra-low fluxes expected
- Cost-effective (~ $8 Million for ARA37)

Collaboration between ARIANNA and ARA

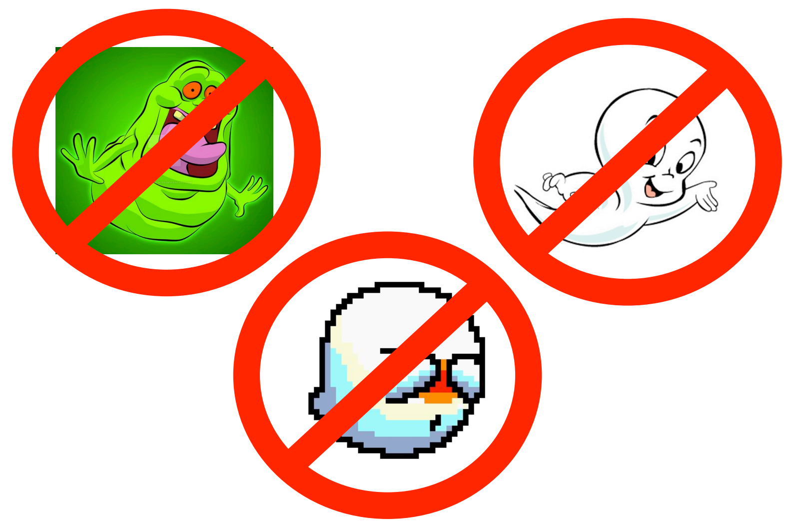
- In-Ice simulation improvements
  - Framework, ice model, radio signal model
- Developing consensus for the field

Conclusions

- Beginning of Neutrino Astronomy! – IceCube
- UHE neutrino astrophysics
  - developing field
  - exciting insights into the nature of UHE sources!
- Expect to detect (bust) a UHE neutrino (ghost) in the next several years!
- Needs expansion of current detectors and innovative new designs to reach low flux



Source: Jovian Archive



Questions?

® Sony Pictures

BACKUP SLIDES

CHEAPR

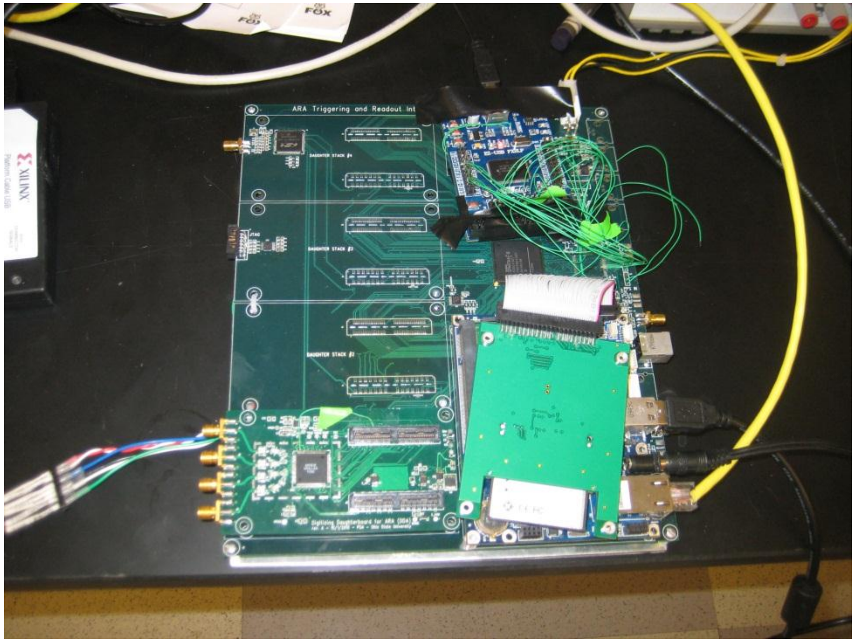
Computing in High Energy Astroparticle Research (CHEAPR 2016)

Workshop devoted to how to use machine learning to identify Askaryan radio pulses

http://ccapp.osu.edu/workshops/CHEAPR2016/workshop.html

Electronics

- 3.2 Gigasamples/sec rate
- Trigger –
  - Tunnel diode acts as a power integrator over few ns time scale
  - Requires 3 excursions of tunnel diode output above threshold within 110 ns in antennas of same polarization (3/8)
  - Threshold automatically adjusted to maintain steady global trigger rate
- 12-bit digitization
- 400 ns output waveform



- Notch filter at 450 MHz removes communications signals
- LNA for each antenna improves received signal strength above background

Optimized Cut Values

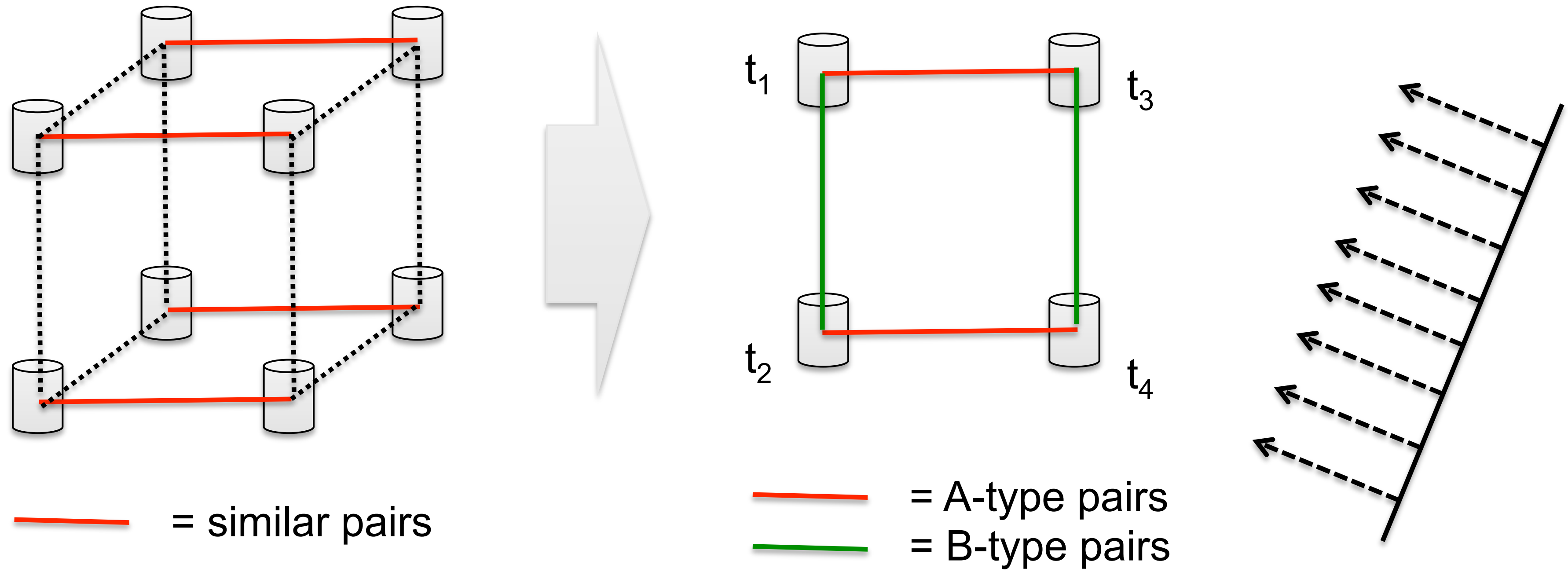
- All optimized cut parameters relaxed for GRB neutrino search when compared with diffuse neutrino search
- Factor of 2.4 improvement in efficiency against a simulated GRB flux

Cut	**Reconstruction Quality Cut**		**Peak/Correlation Cut**
Parameter	A_{peak}	A_{peak}/A_{total}	Peak/Correlation Cut Value
Diffuse Neutrino Search	50 deg^2	1.5	8.8
GRB Neutrino Search	70 deg^2	16.2	7.5

Filter-level Algorithm

- 100's of millions of events – too many to efficiently use complex reconstruction methods
  - Need < 0.1% thermal acceptance to be efficient
- Can we create an adaptable, efficient filter-level algorithm
- Goals:
  - Computationally simple
  - Easily differentiates between signal and noise
  - Decrease volume of data to then use more computationally intensive techniques (ray-tracing, etc)
  - Single understandable output
  - Easily optimizable
- Ultimate goal is a deep station analysis of current data
  - Perhaps use algorithm as a trigger or filter to the North?

Planar Signal Wavefront



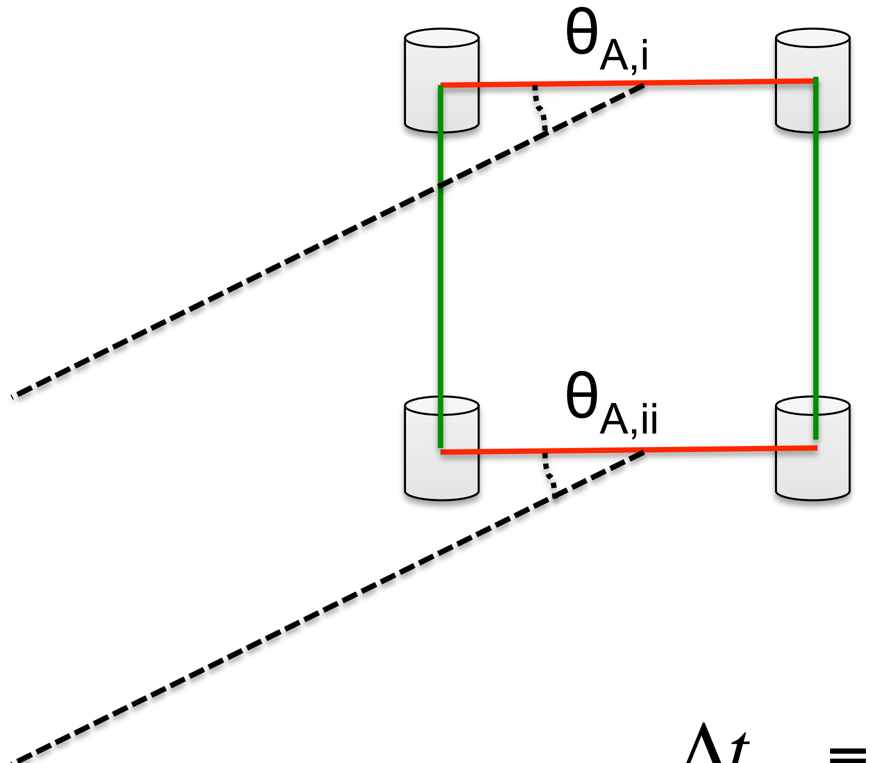
$\Delta t_{A,i} = t_3 - t_1$

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

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

- Divide array into faces
- Difficult to directly compare timing from different sets of pair-types – what to do?

Angle of Incidence



$$\Delta t_{A,i} = \frac{n}{c}\cos\left(\theta_{A,i}\right)\Delta d_{A,i}$$

- Use the angle from the baseline
- Comparable between different pair types

$$\cos\left(\theta_{A,i}\right) = \frac{c\Delta t_{A,i}}{n\Delta d_{A,i}}$$

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

Angular Variation - RMS

- Similar time differences → small variation
  - Find the "RMS" around their average

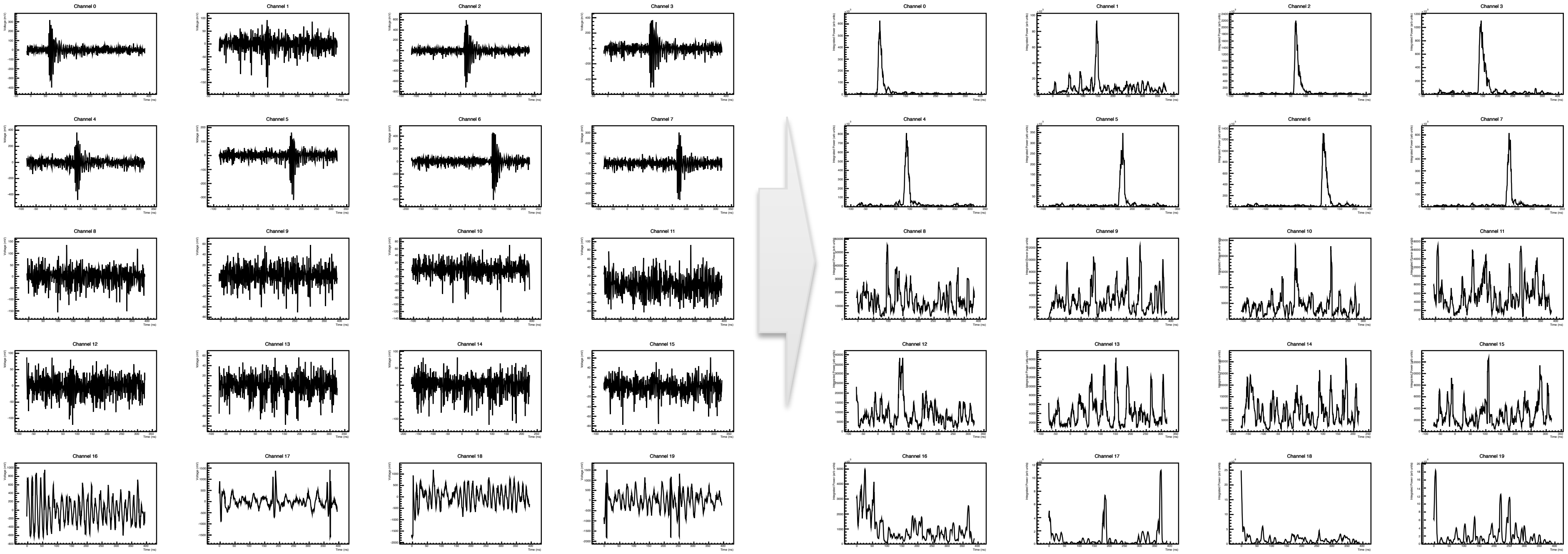
$$\overline{\cos\left(\theta_A\right)} = \frac{\cos\left(\theta_{A,i}\right) + \cos\left(\theta_{A,ii}\right)}{2}$$

$$\mathrm{RMS}\left(\cos(\theta_A)\right) = \sqrt{\frac{\left(\cos\left(\theta_{A,i}\right) - \overline{\cos\left(\theta_A\right)}\right)^2 + \left(\cos\left(\theta_{A,ii}\right) - \overline{\cos\left(\theta_A\right)}\right)^2}{2}} = \sqrt{\frac{\left(\frac{c\Delta t_{A,i}}{n\Delta d_{A,i}} - \overline{\frac{c\Delta t_A}{n\Delta d_A}}\right)^2 + \left(\frac{c\Delta t_{A,ii}}{n\Delta d_{A,ii}} - \overline{\frac{c\Delta t_A}{n\Delta d_A}}\right)^2}{2}}$$

- RMS(cos(θ)) < 0.1 if the arrival directions agree
- Also corrects for differences in baseline lengths

Find "hit times"

Calibration pulser event



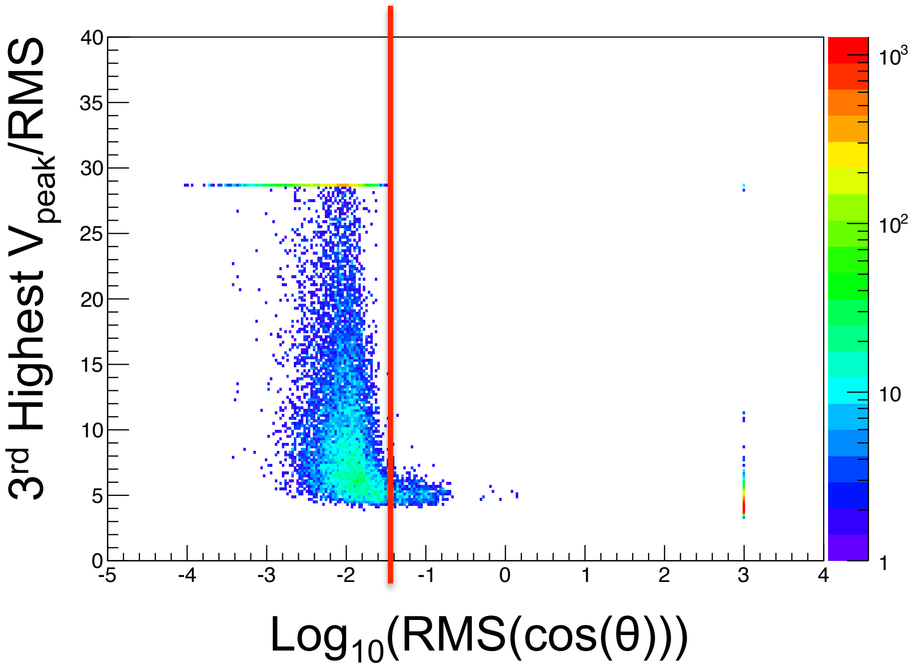
- To decrease noise fluctuations, scan an integrated power window of 5 ns
- Find the two highest peaks, use these as "hit times" for that channel
- Apply a threshold:

$$\frac{\mathrm{RMS}(5\text{ ns around the peak})}{\mathrm{RMS}(\mathrm{waveform})} > \mathrm{Threshold}$$

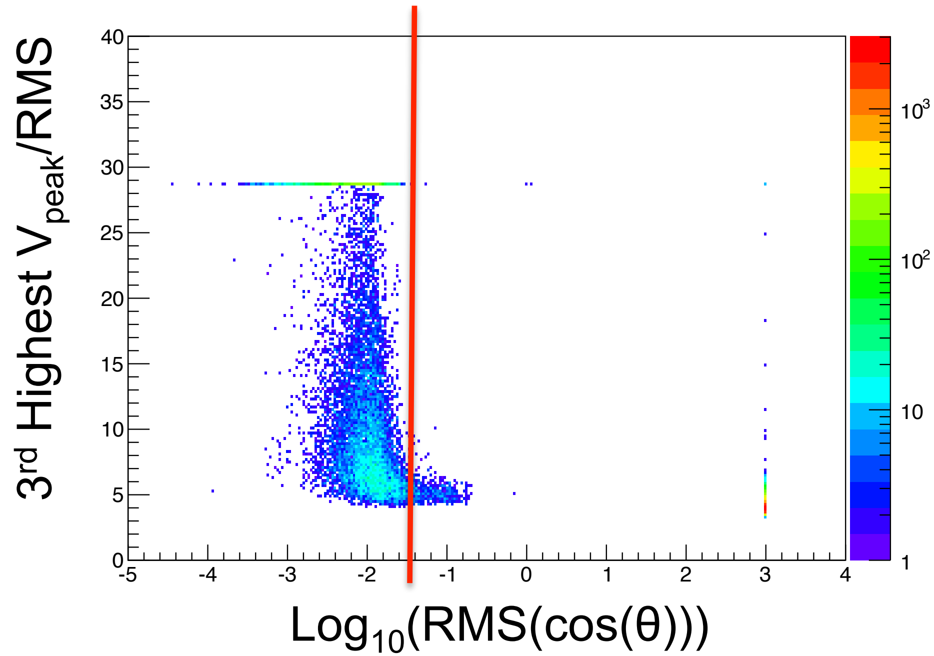
- Find the face with the timing that agrees best with incoming signal (lowest face RMS)

Preliminary Results - Simulation

Vpol



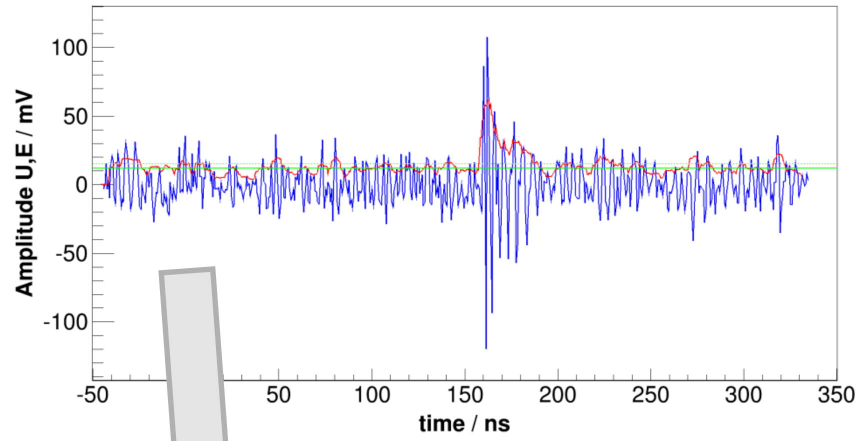
Hpol



- Simulated 10^{19} eV neutrino events generated with AraSim simulation package
- Good separation at high signal strength
- Reasonable separation at lower signal strength
- Noise starts to dominate over low SNR signals – difficult to reconstruct anyway

Noise filtering

5 Hz thermal noise trigger rate
→ Needs to be reduced before applying sophisticated algorithms



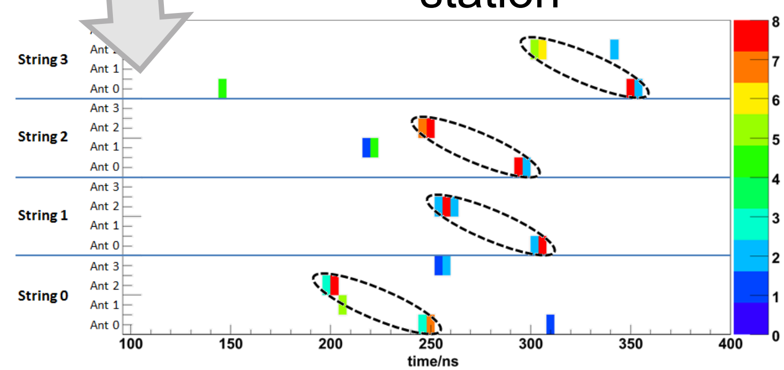
Time sequence algorithm:

- Boosted hit count
- Simple algorithm (possible usage as trigger)

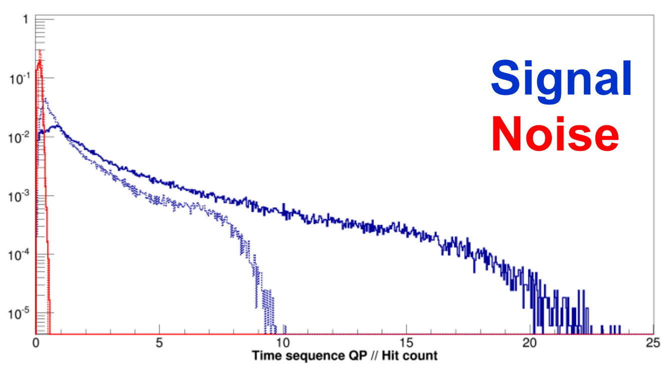
1. Generate hit pattern with threshold on energy envelope (red line)
2. Check hit pattern on conformity with incoming plane wave

→ ***quality parameter (similarity to wavefront)x(hit count)***

For 16 antennas per station



Quality Parameter for simulated neutrinos



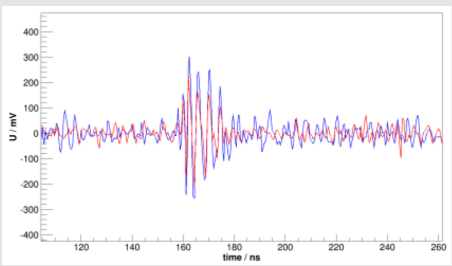
Vertex reconstruction

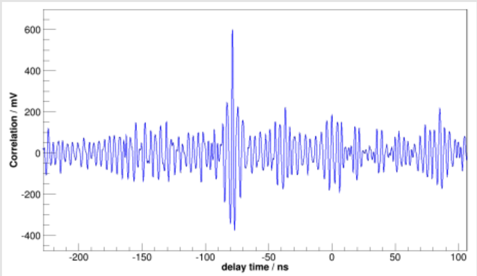
We need:

- Angular reconstruction of vertices, to distinguish neutrinos from other sources

The algorithm:

1. Determine time differences





2. Select good antenna pairs, based on correlation amplitude

3. Set up and solve system of linear equations

Signal arrival time from positions:

$$c^2(t_v - t_i)^2 = (x_v - x_i)^2 + (y_v - y_i)^2 + (z_v - z_i)^2$$

Use difference between antennas & reorder:

$$\boldsymbol{x_v} \cdot 2x_{ij} + \boldsymbol{y_v} \cdot 2y_{ij} + \boldsymbol{z_v} \cdot 2z_{ij} - \boldsymbol{t_{v,ref}} \cdot 2c^2 dt_{ij} = r_i^2 - r_j^2 - c^2(dt_{i,ref}^2 - dt_{j,ref}^2).$$

This can be represented by:

$$\mathbf{A}\vec{v} = \vec{b},$$

Solve with matrix inversion tools

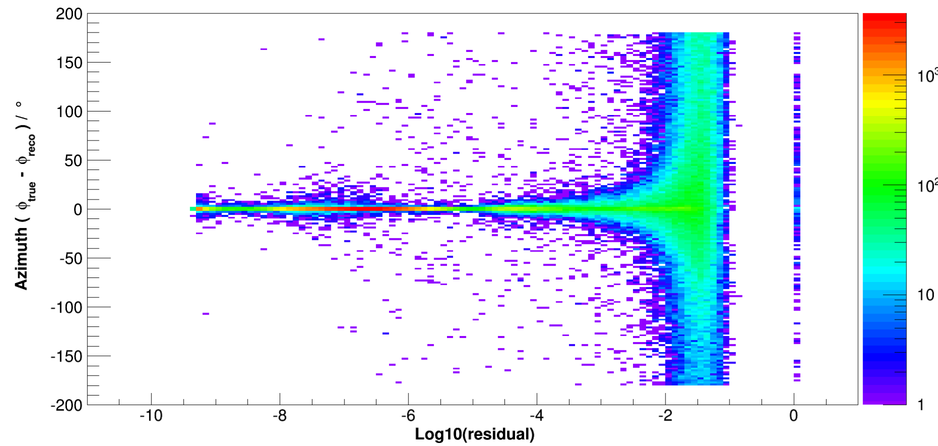
Quality Criterion

Main quality criterion is residual:

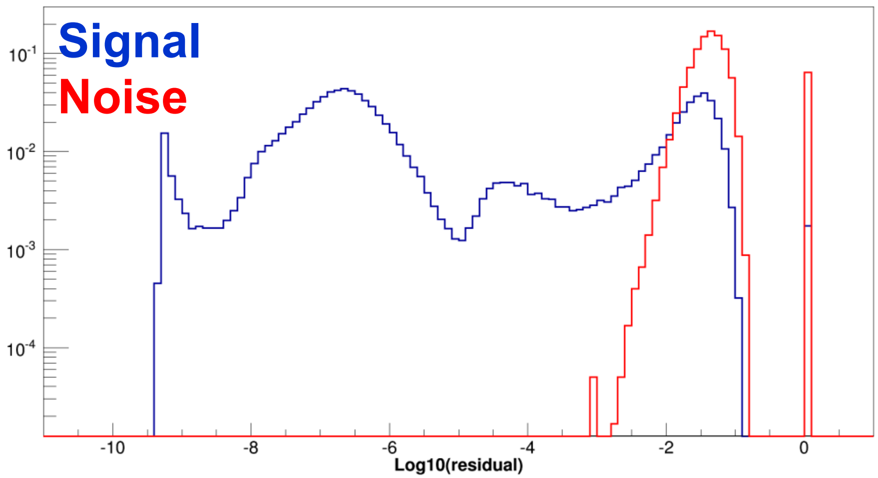
$$res = \left| \frac{\vec{b}}{|\vec{b}|} - \frac{\mathbf{A}\cdot\vec{v}}{|\mathbf{A}\cdot\vec{v}|} \right|^2 \cdot \frac{1}{N_{chp}}.$$

Require a minimum correlation value to be included as a pair

Reconstruction error vs residual:



Residual for signal and noise



Other quality criteria are applied to further clean out bad reconstructions

Background rejection

Strategy:

- Use 10% burn sample
- Estimate appropriate angular cuts
    - Calibration pulsers, surface
- Look only at events outside the angular cut region
  → Leftover events are not correlated to known signals, need to be rejected by other cuts: QP, residual
- **Final cuts at QP=0.6, Log10(residual)=-4**
- Estimated background:
    - **0.009+/- 0.010 ARA02**
    - **0.011 +/- 0.015 ARA03**