The Askaryan Radio Array:

A Radio-Based Ultrahigh Energy Neutrino Detector at the South Pole

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Contents

INTRODUCTION

Cosmic Messengers

Cosmic rays

Charged - subject to magnetic deflection

Lose energy to GZK

Gamma rays and other photons

Attenuation

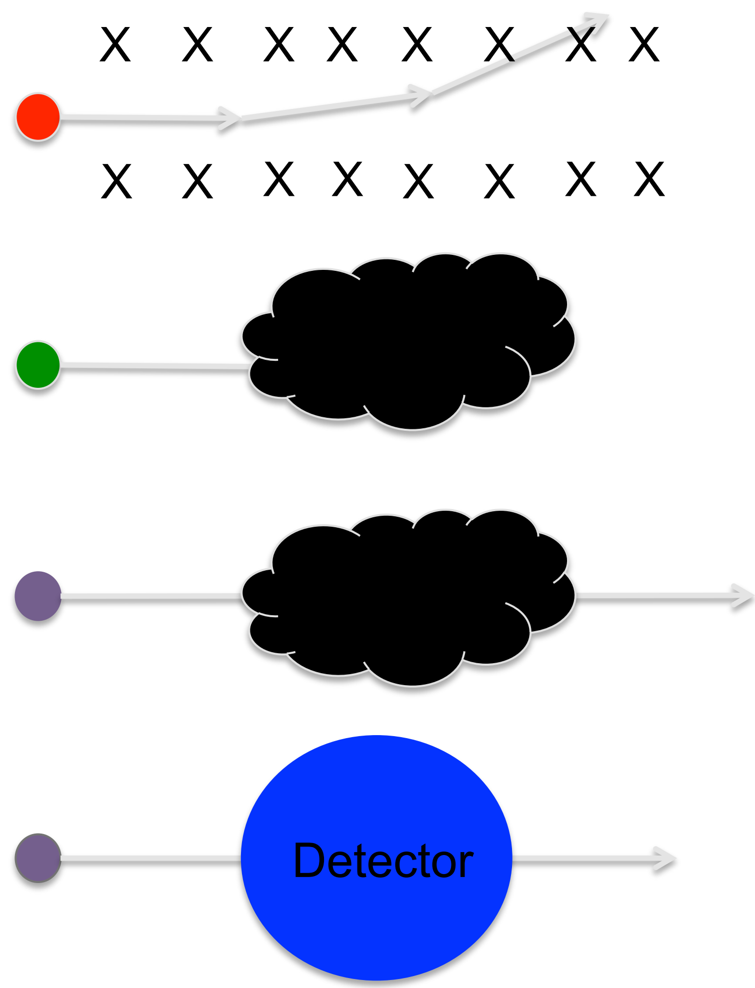
Neutrinos

No attenuation or deflection

Weakly interacting - difficult to observe

Only extraterrestrial sources

- Sun, Supernova 1987A
- new IceCube events



GZK Process and Sources

Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays with E > $10^{19.5}$ eV interact with cosmic microwave background (CMB) photons

Process produces BZ neutrinos, some at ultrahigh energies (UHE)

Neutrinos happily continue on

UHE neutrinos could also be produced at a source location

If observed, will trace back to source

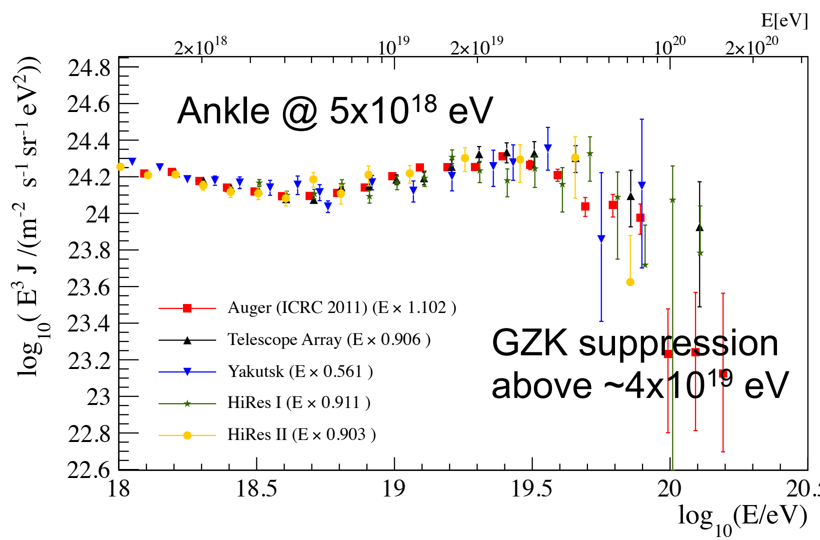
- Low flux at Earth
  - Less than 1/km^3/year/energy decade
  - Need large volume detectors

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

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

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

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



Proceedings of UHECR 2012

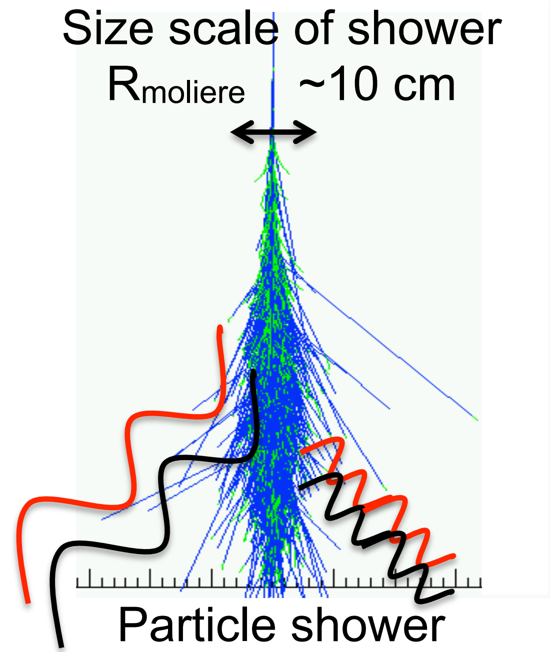
Detection Technique

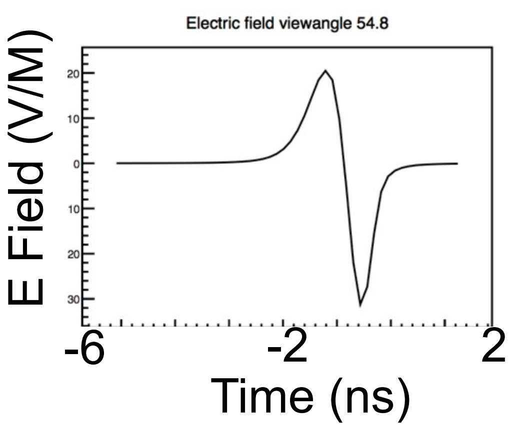
How to get large-scale detection -
- Brute force: make 100X IceCube
- Use a different approach – radio Cherenkov technique

Coherent Cherenkov signal from net "current," instead of from individual tracks
- In dense medium, a ~20% charge asymmetry develops in the shower (positrons annihilated, electrons not)
- If λ >> $R_{Moliere}$ (radial size scale) → Coherent Emission
- Hypothesized by Gurgen Askaryan, 1962
- Effect observed in ice, water, salt
- Impulsive bipolar signal

Ice: Long (~1 km) attenuation lengths in 0.1-1 GHz → large observable volume

Where is there a lot of ice? Antarctica!





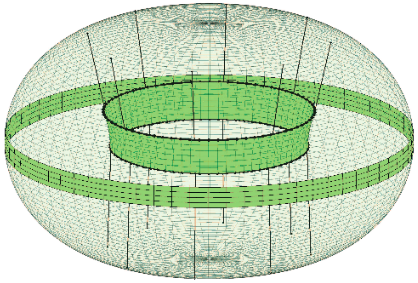
Synoptic Detectors

- Synoptic – balloons, satellites – ANITA, EVA, PRIDE
- Large target volume - O(10^6 km^3); short flight time 30-40 days
- More limited viewing angles → less solid angle
- Must be reconstructed after flight and "landing"
- Good as a "discovery" instrument for highest energies (>10^{20} eV)

$$F \propto \frac{1}{At\Omega}$$

ANITA

EVA



In Situ Detectors

In situ arrays – IceCube, HEX/NGI, RICE, ARA, ARIANNA

Long operation time (years); smaller observable volume - O(100 km^3)

Larger solid angle for observable signals

Environmental problems *in situ* – measure and model environment, ice

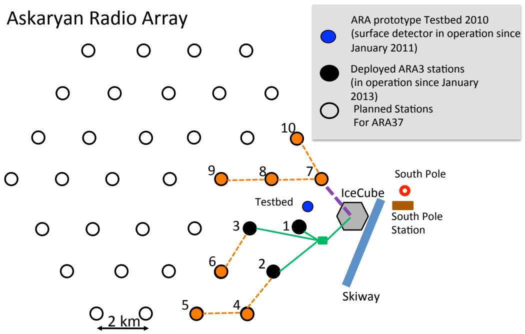
But better able to obtain more information about event - direction, pol., etc.

Good as an observatory – long term stability, reaches lower energy (10^{17} eV)

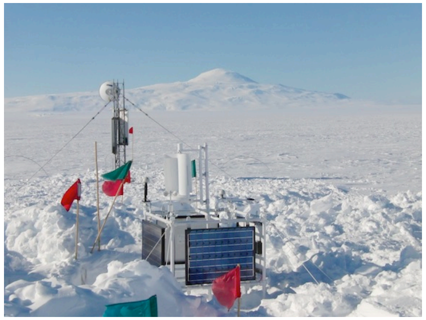
Better able to see unexpected events?

$$F \propto \frac{1}{At\Omega}$$

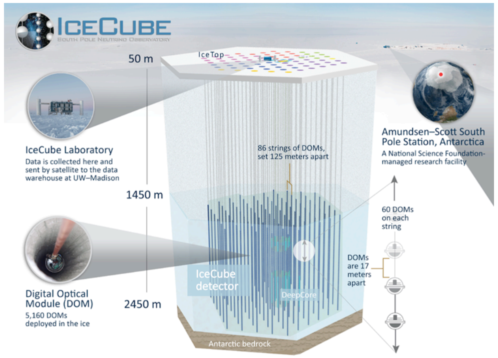
ARA



ARIANNA

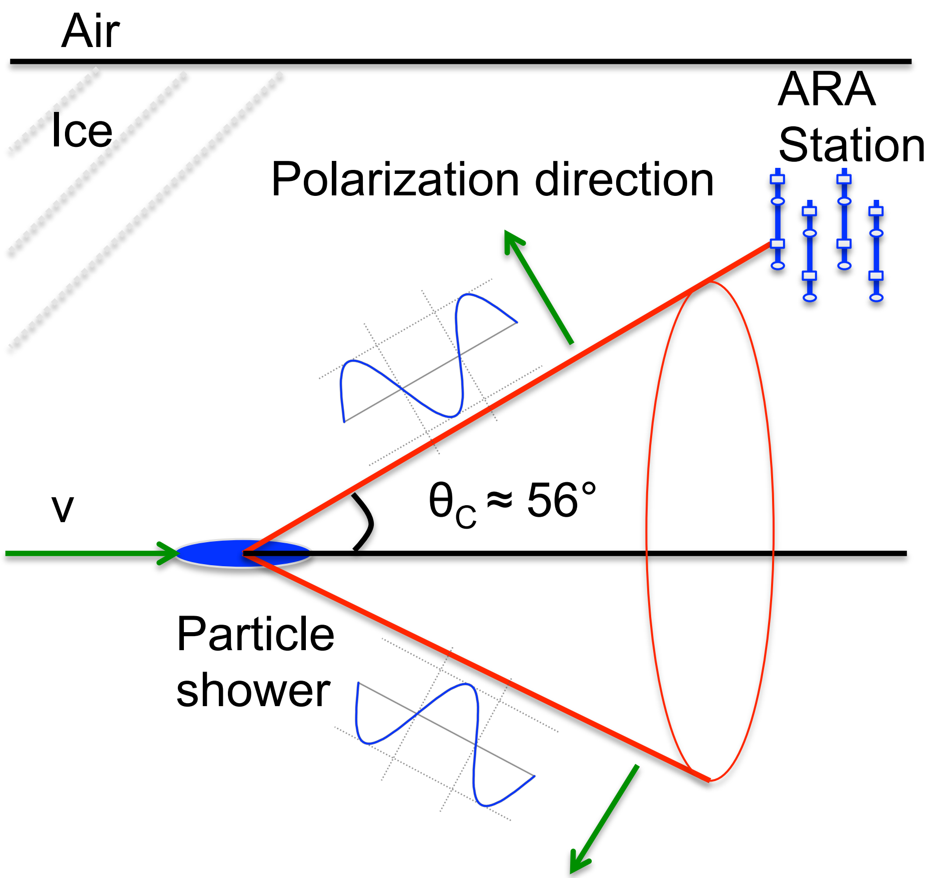


IceCube



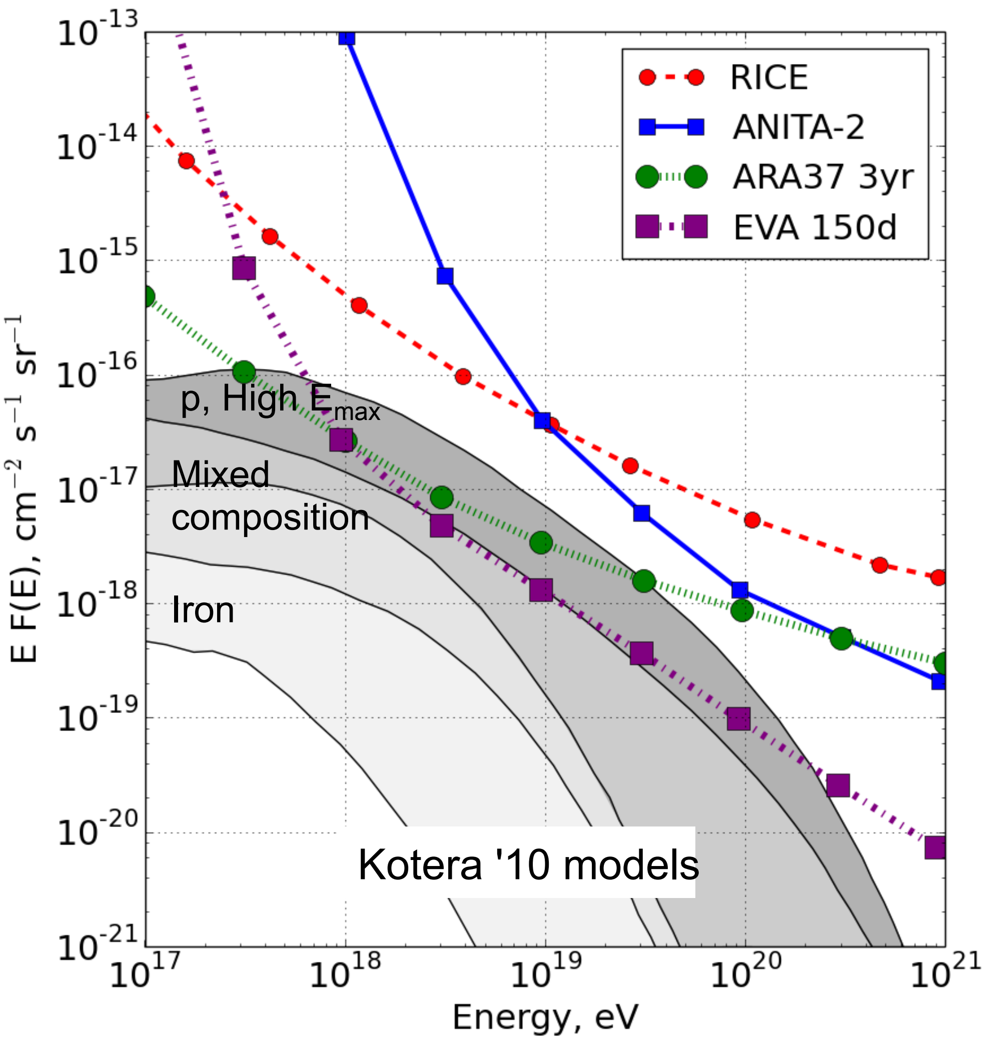
Detector Concept

- Place antennas in ice to observe the radio signals
- Delays in arrival times used for reconstruction
- 3-D array design for each station
  - Varying baseline directions – not localized to 1 plane
  - Good reconstruction in arrival direction from surrounding ice volume
- Observation angle determines the coherence of the signal and thus frequency content



In-ice vs. Balloons

- In-ice antennas:
  - lower energy threshold.
  - Reduced visible volume.
- Balloon-borne antennas:
  - Higher energy threshold.
  - Increased visible volume.



ARA Collaboration

International collaboration with 13 institutions

~50 authors

USA:
- Ohio State University
- University of Chicago
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison
- California Polytechnic State University, San Luis Opisbo

UK: University College London

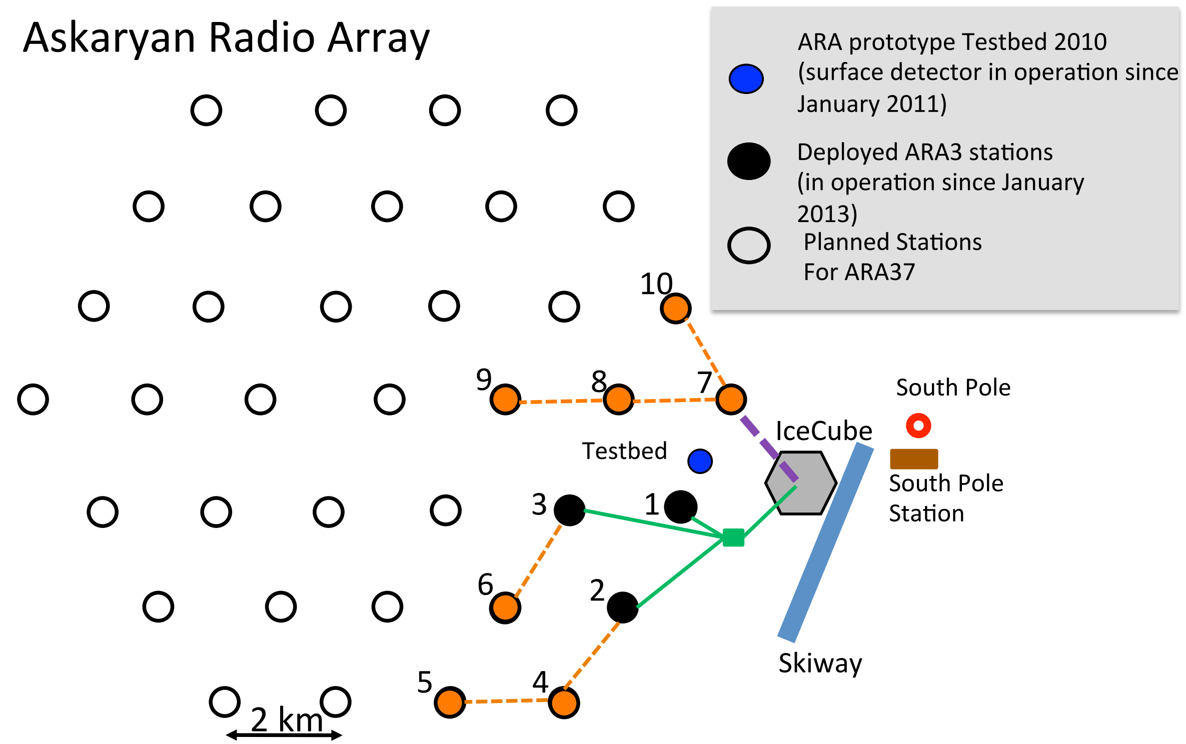
Belgium: Université Libre de Bruxelles

Japan: Chiba University

Taiwan: National Taiwan University

Israel: Weizmann Institute of Science

ARA layout



Currently installed: 3 design stations + 1 shallow prototype Testbed

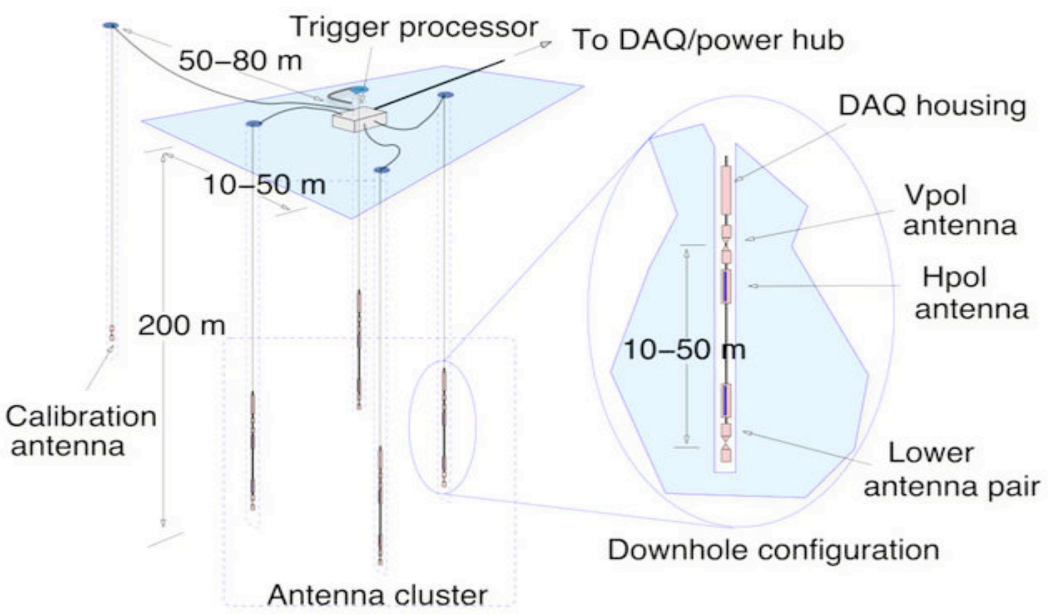
Installation dates: Testbed 2010-2011 @ 30 m depth;

A1 2011-2012 @ 100m depth; A2 and A3 2012-2013 @ 200 m depth

Next installation phase: 7 more stations for ARA10

Total planned – 37 stations viewing ~ 100 km^2 of surface area

Station Design



Hpol quad-slotted cylinder antenna

Vpol bicone antenna

- Bandwidth: 150-850 MHz
- Azimuthal symmetry, dipole at low frequencies

4 strings with 4 antennas each

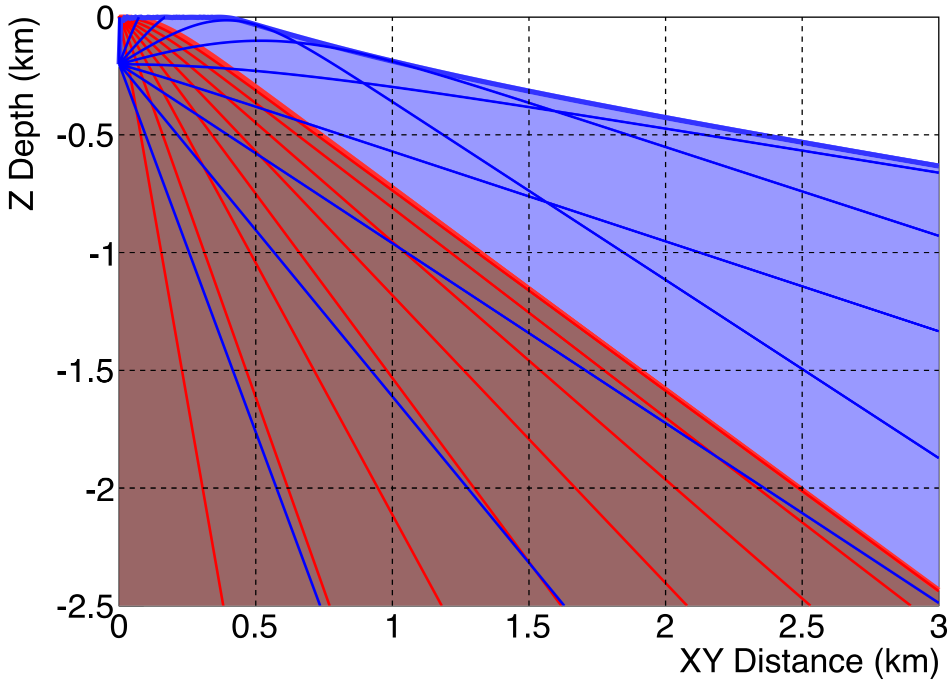
2 pairs (upper and lower) of 1 Vpol and 1Hpol antenna

2 Calibration pulser antennas @ receiver antenna depth

4 fat dipole antennas at surface for cosmic ray identification

Deployed 200m deep in ice – minimize effect of firn layer

Deep Deployment



Firn – layer of compacted snow

- Quickly changing index of refraction (~1.35 → ~1.78 within top ~150 m of ice)
- Causes curvature in paths of rays in ice
- Limits viewable volume and observable neutrino incident angles
- 30 m → 200 m depth: increases effective volume by factor of ~3.2

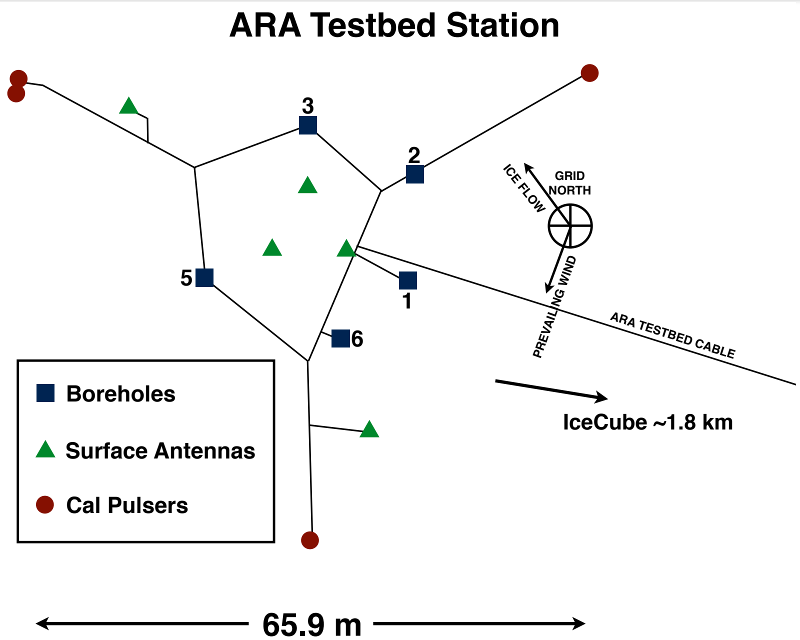
ANALYSIS: TESTBED

Background Rejection

- 2 basic types of noise
  - CW
  - Thermal
    - Characterized by (semi-)random fluctuations from surrounding environment
- ARA trigger – based on tunnel diode output
  - Acts as a few-ns power integrator
  - Trigger rides a threshold determined by the thermal noise level
  - 100’s of millions of events – almost all thermal noise
- How to reject these signals efficiently?
  - For analysis cuts
  - For filtering before transmission to the North

Testbed Station

- Total 16 antennas, 8 borehole antennas at 150 MHz to 850 MHz
- Maximum depth of antennas ~ 30 m
- 3 sets (Vpol + Hpol) of calibration pulsers
- Deployed 2010-2011
- Ran for 2 years (2011 – 2012)
  - Not intended for long-term operation

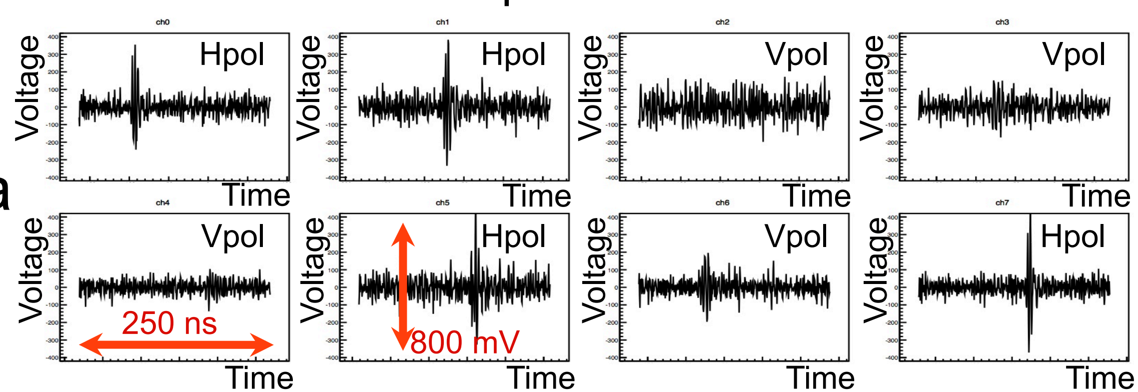


- First ARA neutrino searches carried out with Testbed station data

Diffuse: arxiv:1404.5285

GRB: arxiv:1507.00100

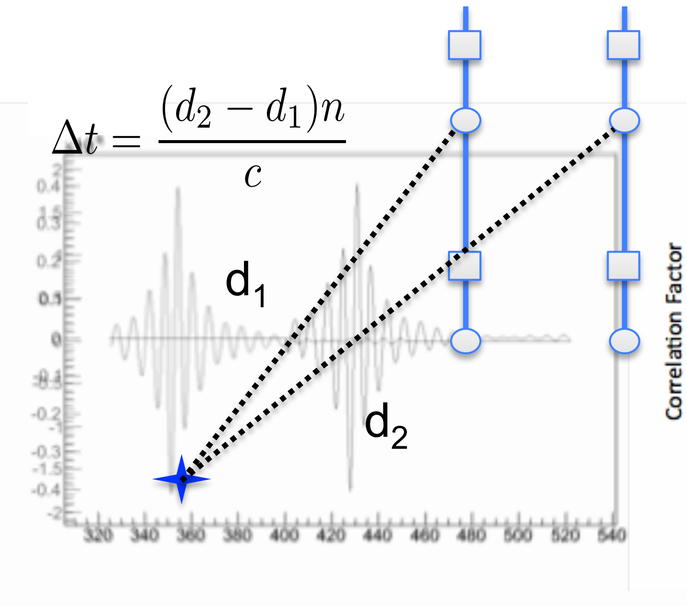
Calibration pulser event waveform from 8 deep antennas in Testbed

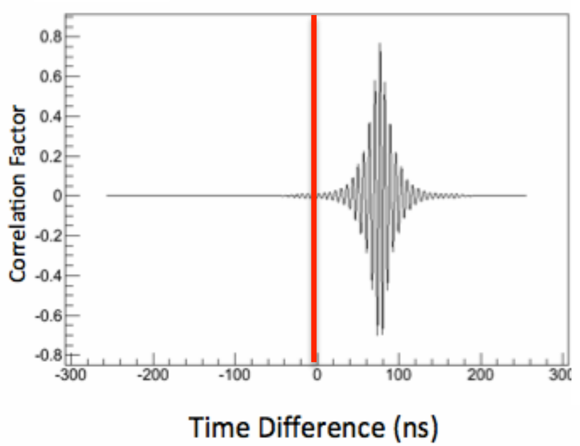


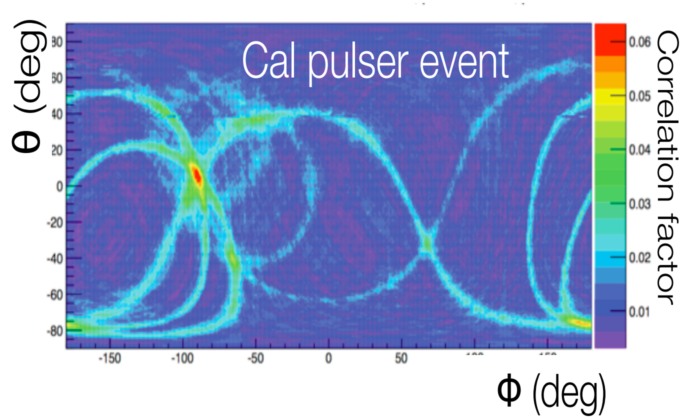
Testbed Analysis

Adapted interferometric technique from diffuse search for GRB search

1. Impulsive waveform – ~1-10 ns time scale
2. Correlation factor - Convolution of the two waveforms including a timing offset
3. Calculate timing delays for all angles of approach
4. Sample correlation plot at these delays
5. Create a map for all pairs of antennas and the correlation

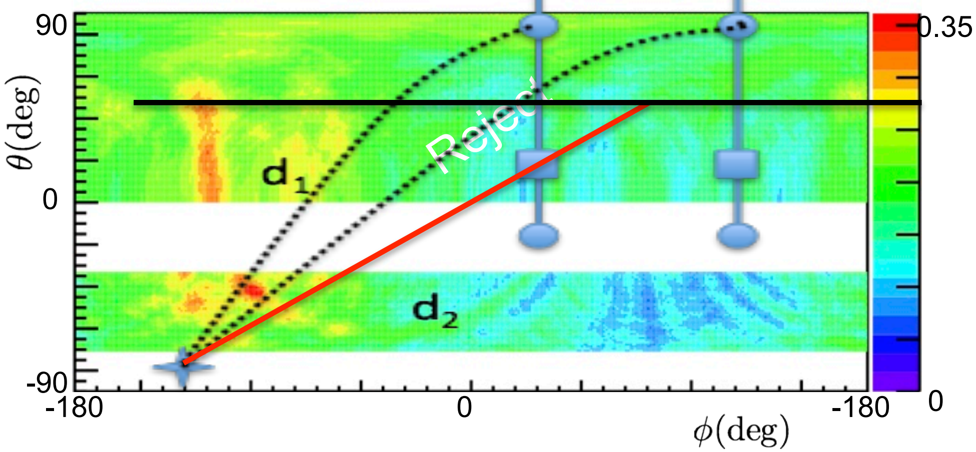




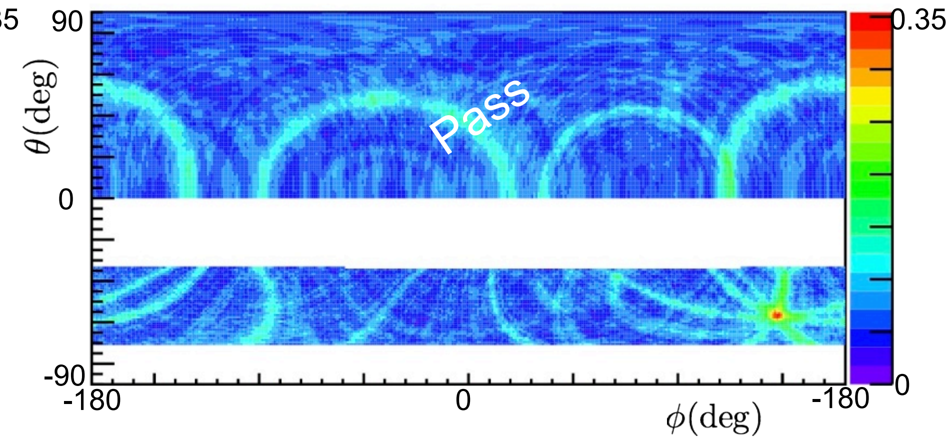


Reconstruction Quality Cut

Known background event reconstruction map example



Simulated ν event reconstruction map example

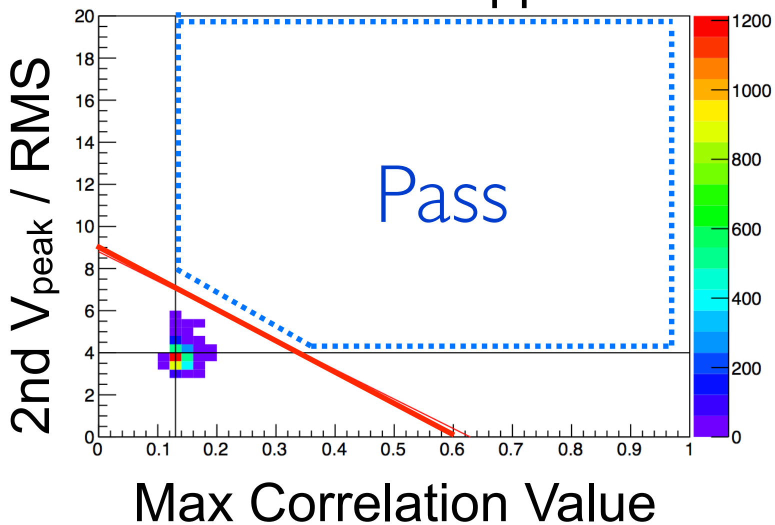


- Rejected thermal noise by requiring strong reconstruction map peak that is unique
- Reconstruction based on timing from ray-tracing
  - Use 30 m and 3 km maps in Hpol and Vpol
- Requires at least one reconstruction map to be of good quality
  - 1 deg^2 < Area of 85% contour surrounding the peak < 70 deg^2
  - Total 85% contour peak area < 16.2 x Area of 85% contour surrounding the peak
- Depending on the polarizations which pass the cut, the event is separated into Vpol and/or Hpol channels
- Rejects ~95% of noise-dominated events after initial quality cuts

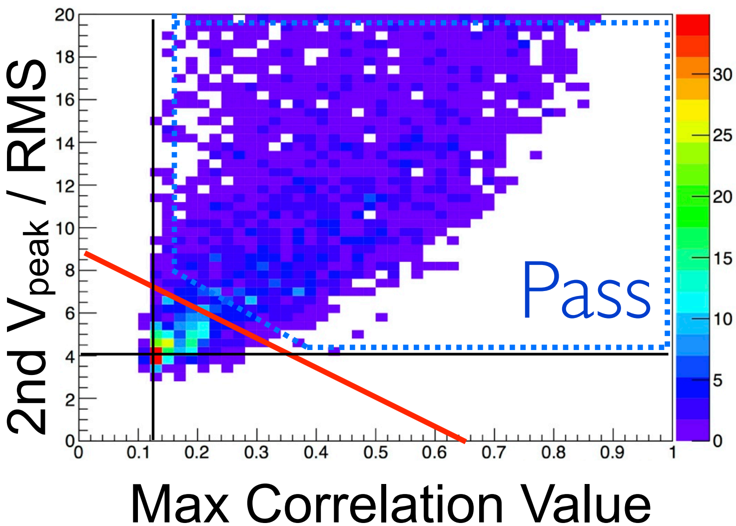
Peak/Correlation Cut

- Expect a correlation between signal strength from waveform and correlation value from reconstruction map for an impulsive event
- After removing known background events with other cuts, use this relation to get background estimation
  - Other cuts made: most reject specific anthropogenic signals

Testbed 10% data set
With cuts applied

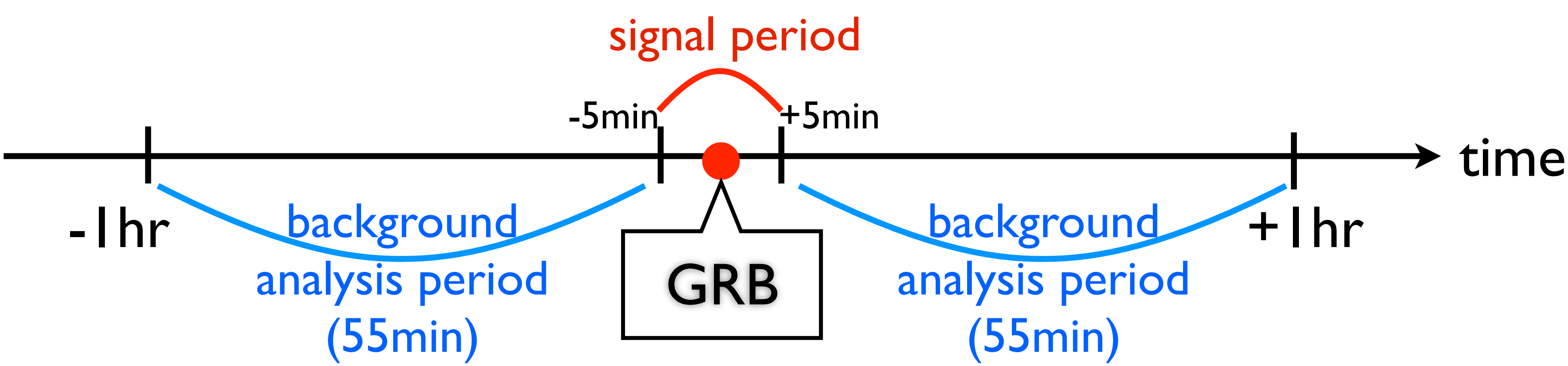


Simulated 10^{18} eV ν set
with cuts applied

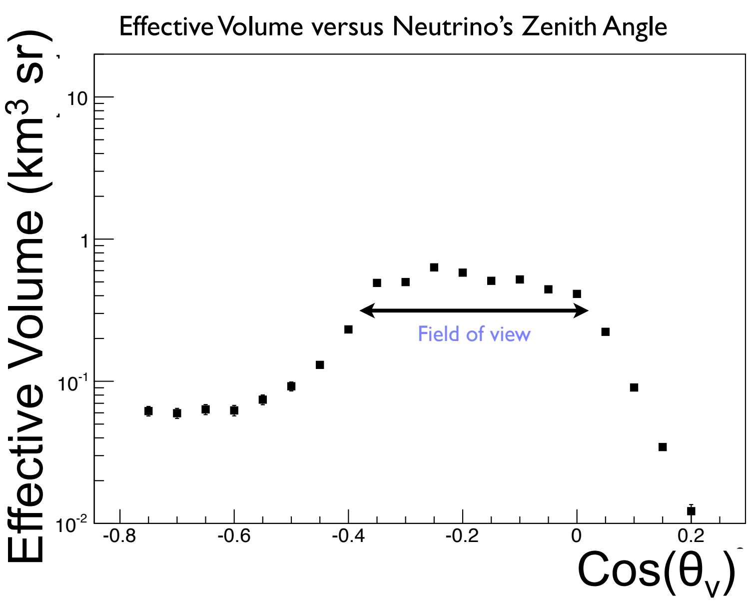


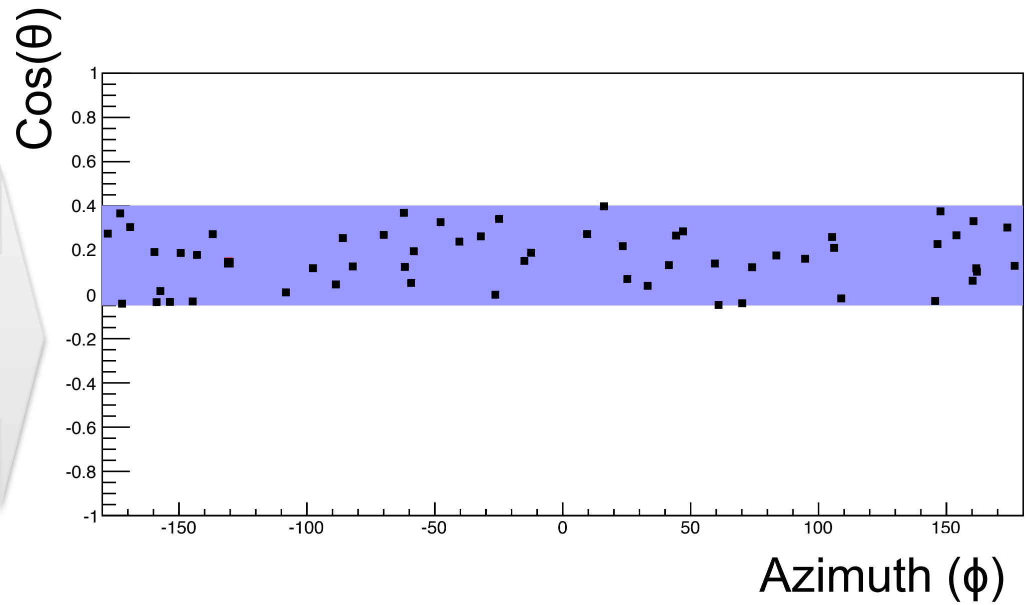
Testbed GRB analysis

- Adapt the above techniques from the Testbed diffuse neutrino search (arxiv:1404.5285) to search for events coincident with known Gamma Ray Bursts
  - Stricter requirements in time → relaxation of cut values
- 2 unblinding stages
  - Tune cuts on 10% of data in the background estimation window
  - 1: Check remaining 90% in background estimation window
  - 2: Signal search – 100% of data +/- 5 minutes around GRB event
  - Timing technique adapted from ANITA (arxiv: 1102.3206)

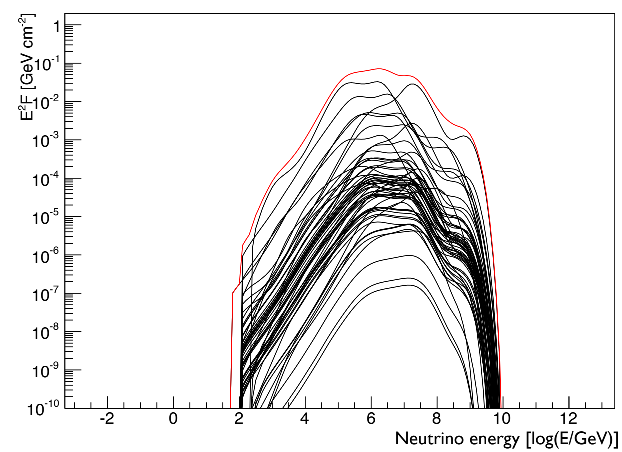


GRB Selection



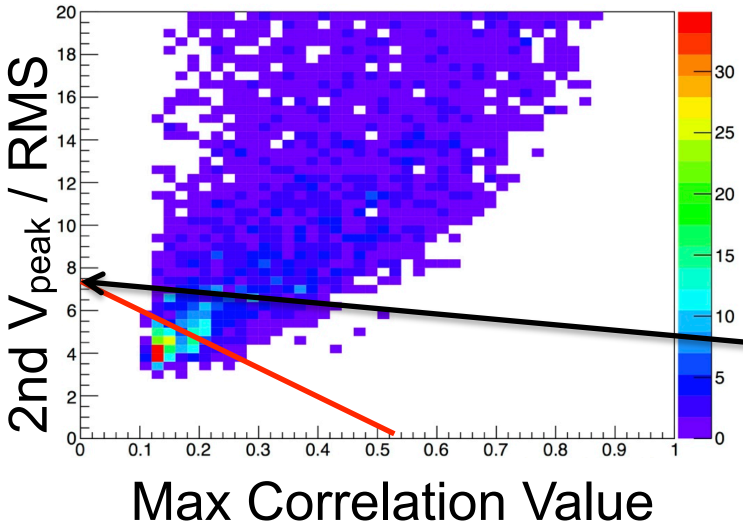


- Selected 57 GRBs based on livetime and geometric acceptance
- Get fluences for each GRB from NeuCosmA simulation and then total
- Tune cuts based on modeled neutrino fluence

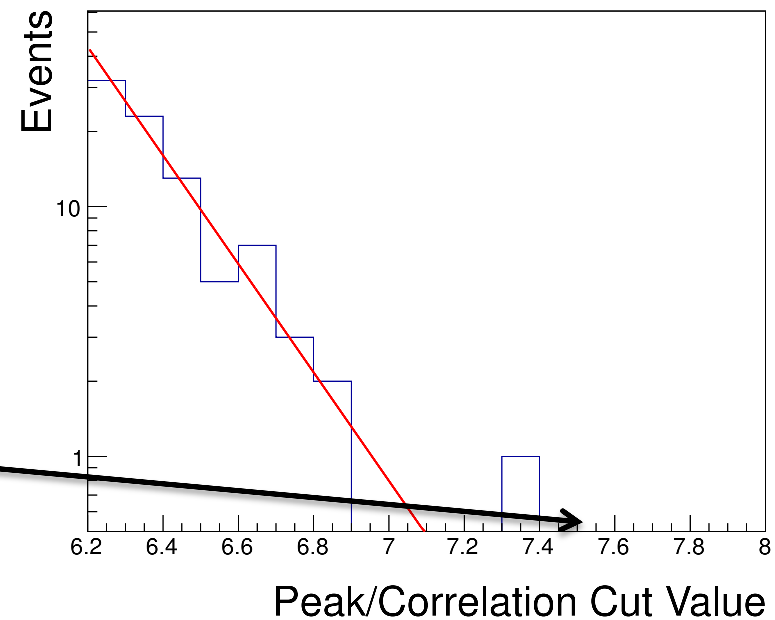


Optimization

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



Testbed Data



- Optimize the cut parameters:
  - Fit the background distribution with an exponential
  - Integrate extrapolation to get expected background
  - S_{upper} is the 90% confidence limit on the signal for an expected background
  - $N_{passed,sim}$ is the weighted number of passed simulated neutrinos from an expected flux
  - Maximize R to optimize for best limit

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

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
- Another cut for rejecting CW was removed

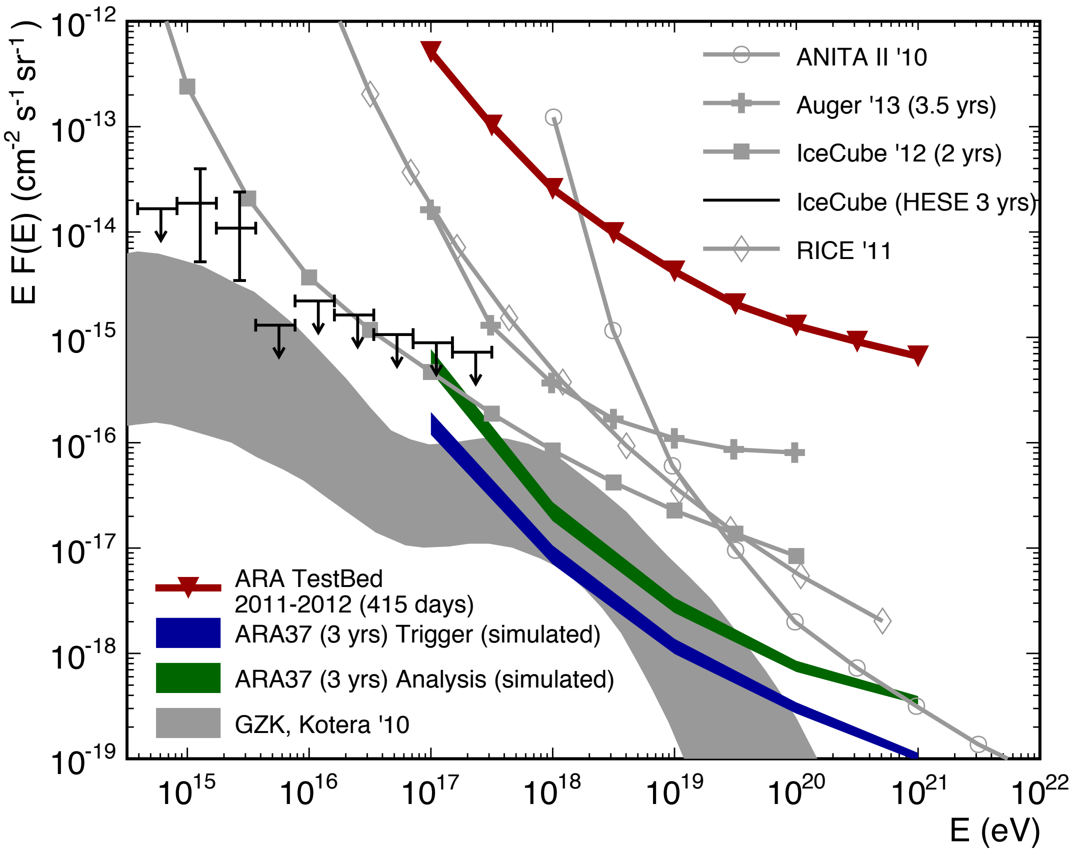
Cut	Reconstruction Quality Cut		Peak/Correlation Cut
Parameter	A_{peak}	A_{peak}/A_{total}	Peak/Correlation Cut Value
Diffuse Neutrino Search	50 deg^2	1.5	8.8
GRB Neutrino Search	70 deg^2	16.2	7.5

Sensitivity

First diffuse limits from ARA Testbed found

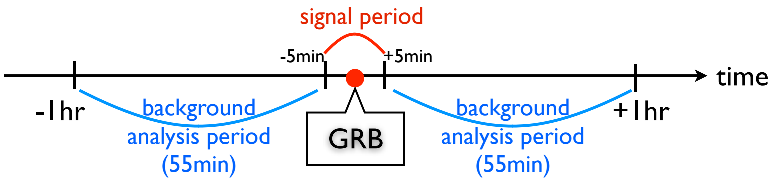
- see arXiv:1404.5285 (Astropart. Phys. 70, 2015, 62–80)

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



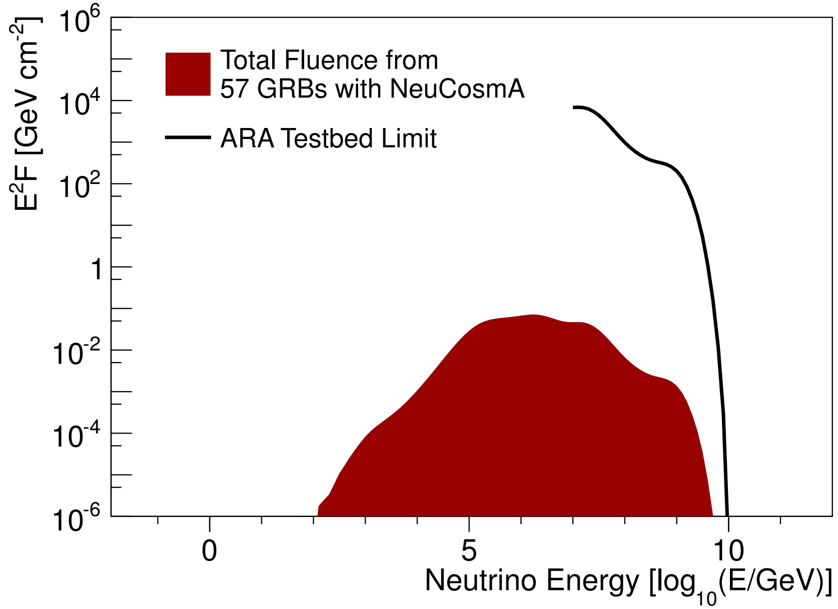
Preliminary Results

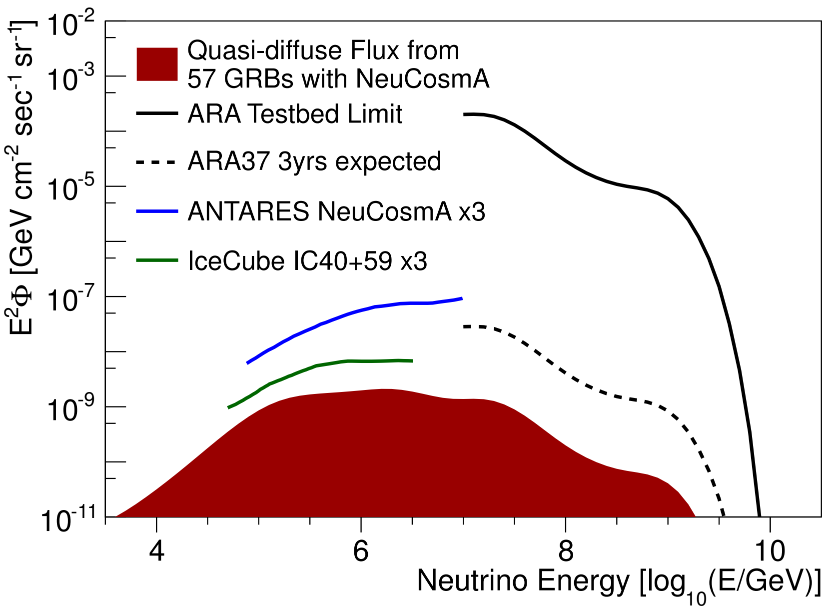
Stage 1 (90% background period unblinding):
- Expected background events: 0.7
- 2 events survived



Stage 2 (signal period unblinding):
- Expected background: 0.07, Expected neutrinos: 1.7e-5
- 0 events survived

First quasi-diffuse flux limit above 10^{16} eV (arxiv:1507.00100)





ANALYSIS: DEEP STATIONS

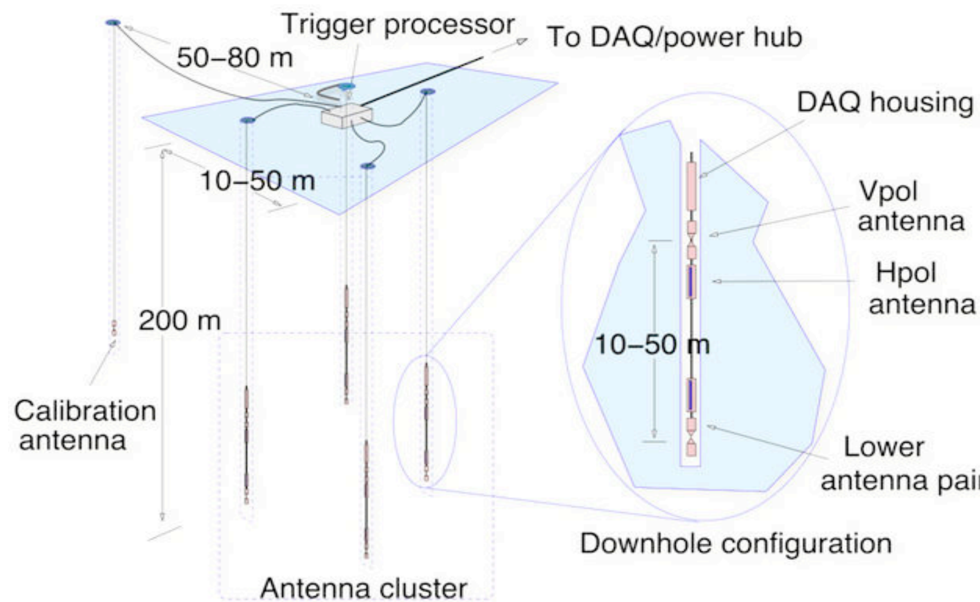
Deep Station Analysis

First efforts to examine data from 10 months of data from 2 design stations at 200 m depth

Improvements in

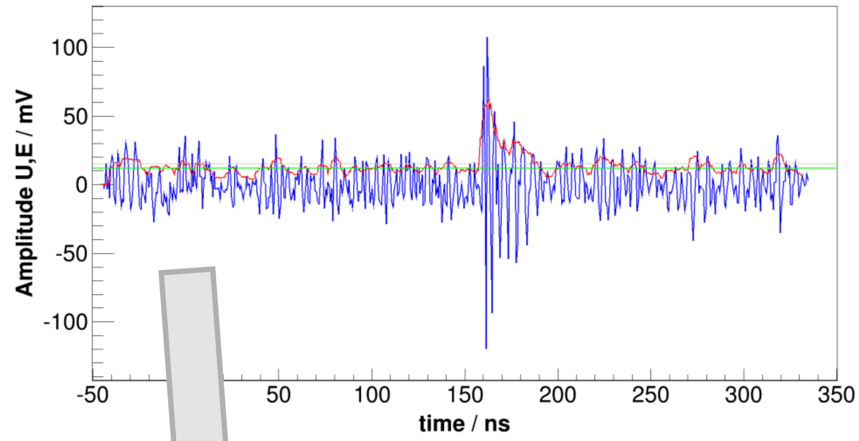
Data quality

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



Noise filtering

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



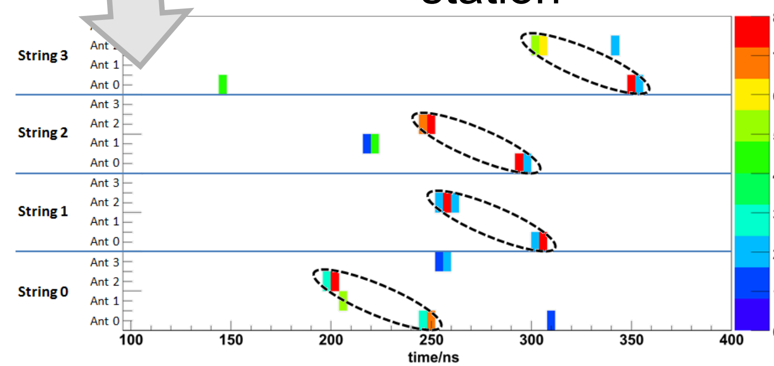
Time sequence algorithm:

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

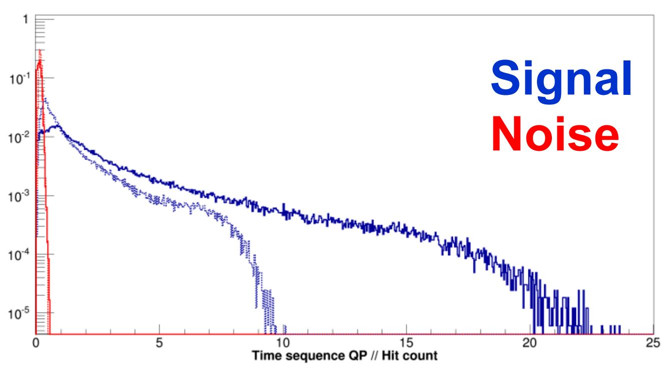
1. Generate hit pattern with threshold on energy envelope (red line)
2. Check hit pattern on conformity with incoming plane wave

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

For 16 antennas per station



Quality Parameter for simulated neutrinos



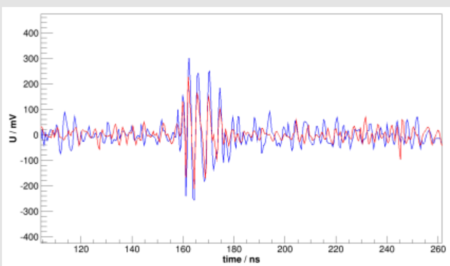
Vertex reconstruction

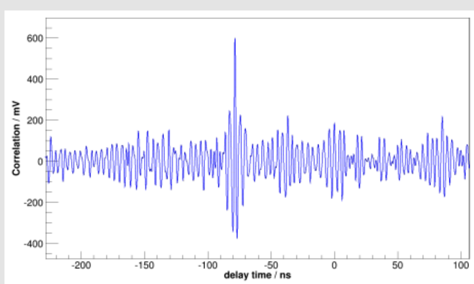
We need:

- 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

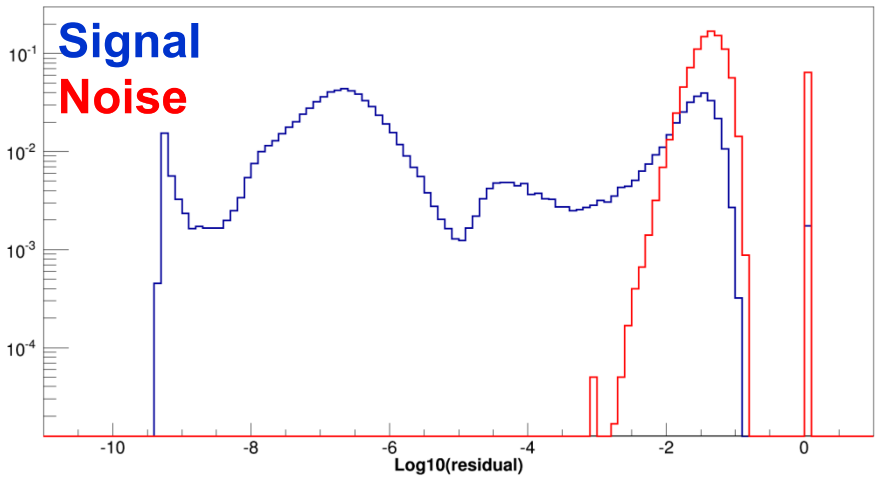
Quality Criterion

Main quality criterion is residual:

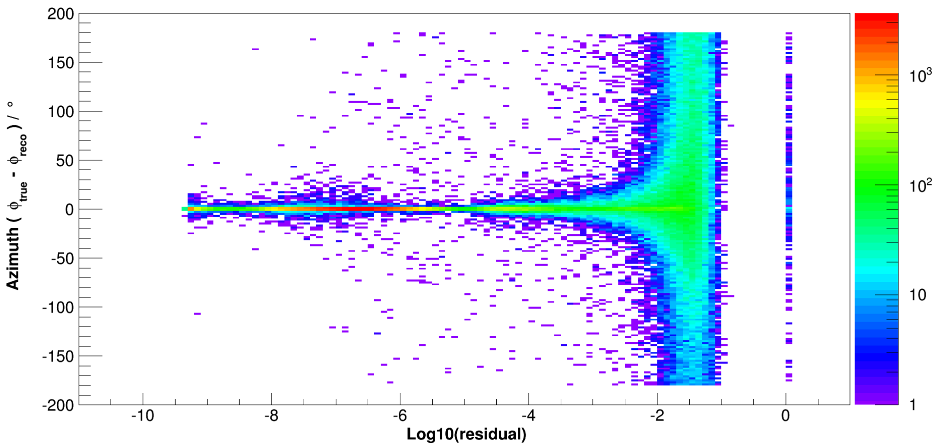
$$res = \left| \frac{\vec{b}}{|\vec{b}|} - \frac{\mathbf{A}\cdot\vec{v}}{|\mathbf{A}\cdot\vec{v}|} \right|^2 \cdot \frac{1}{N_{chp}}.$$

Require a minimum correlation value to be included as a pair

Residual for signal and noise



Reconstruction error vs residual:

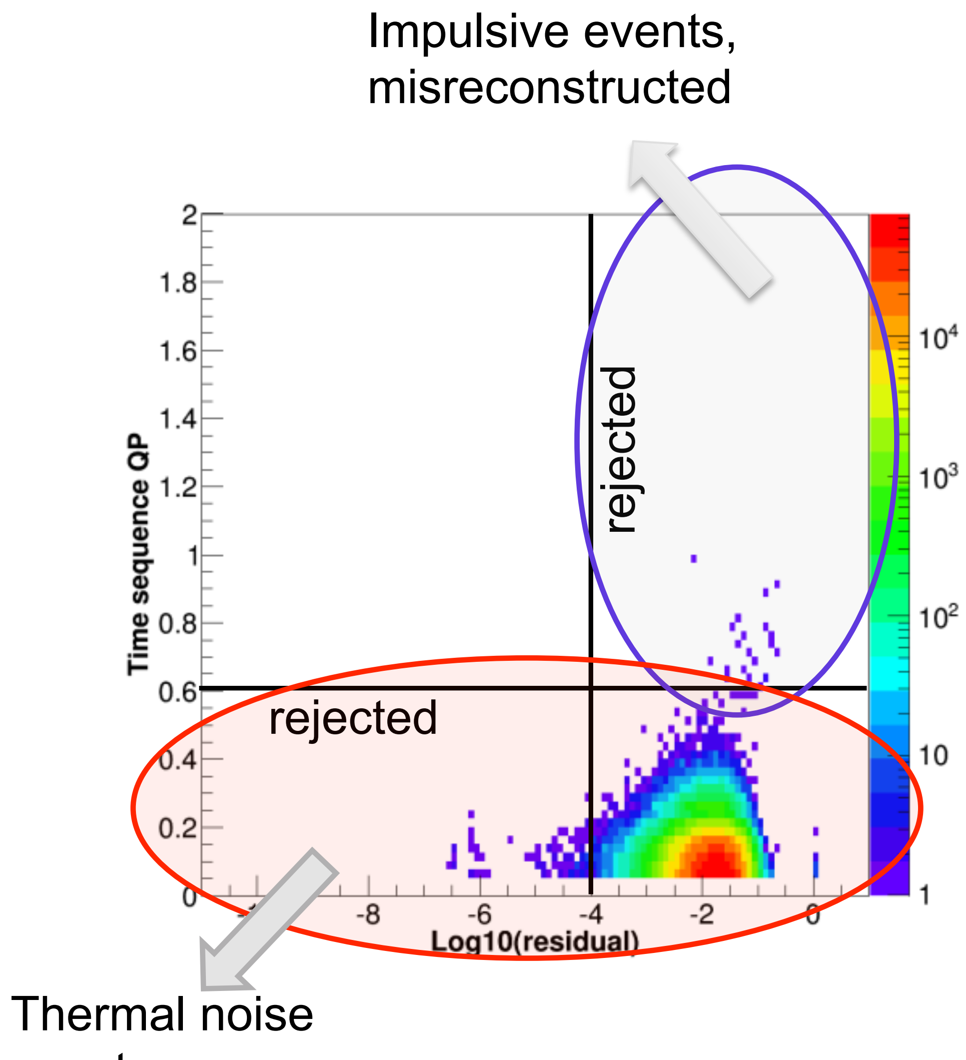


Other quality criteria are applied to further clean out bad reconstructions

Background rejection

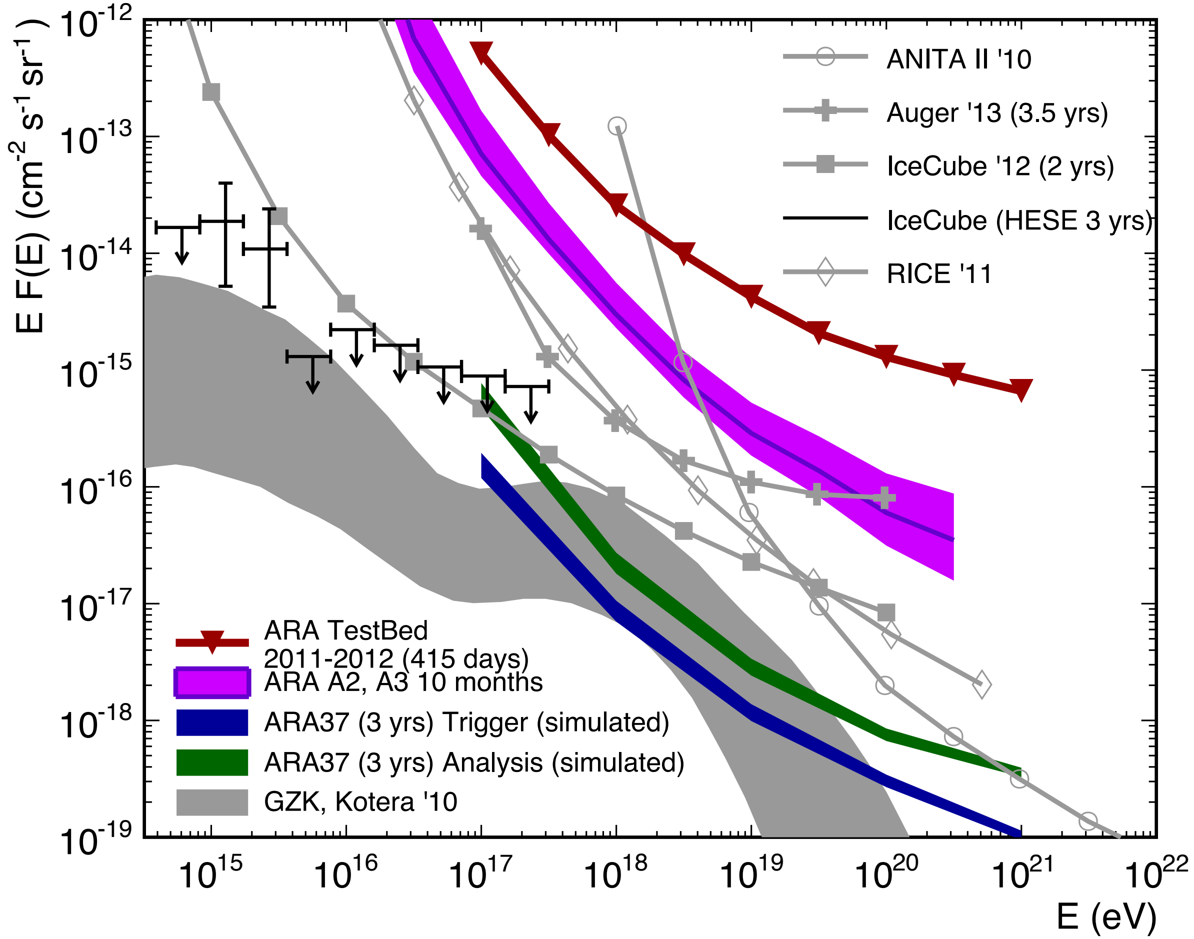
Strategy:

- 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**



Results – 2 Stations

- Expected events = 0.103 (Ahlers 2010)
- No candidates found
- Limit with systematics shown in violet band
- Considerable improvement
  - analysis efficiency
  - effective volume

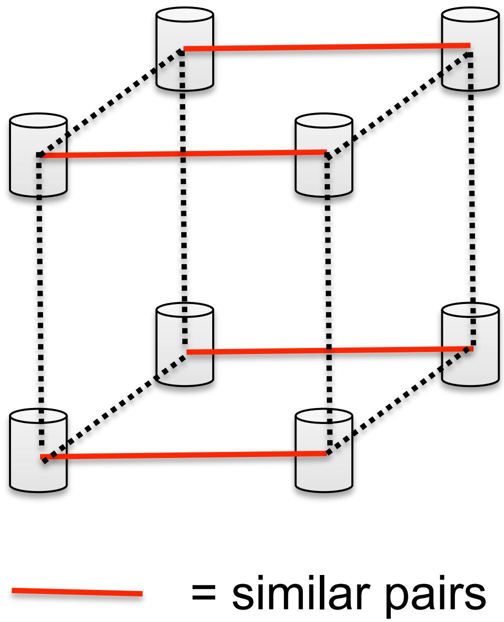


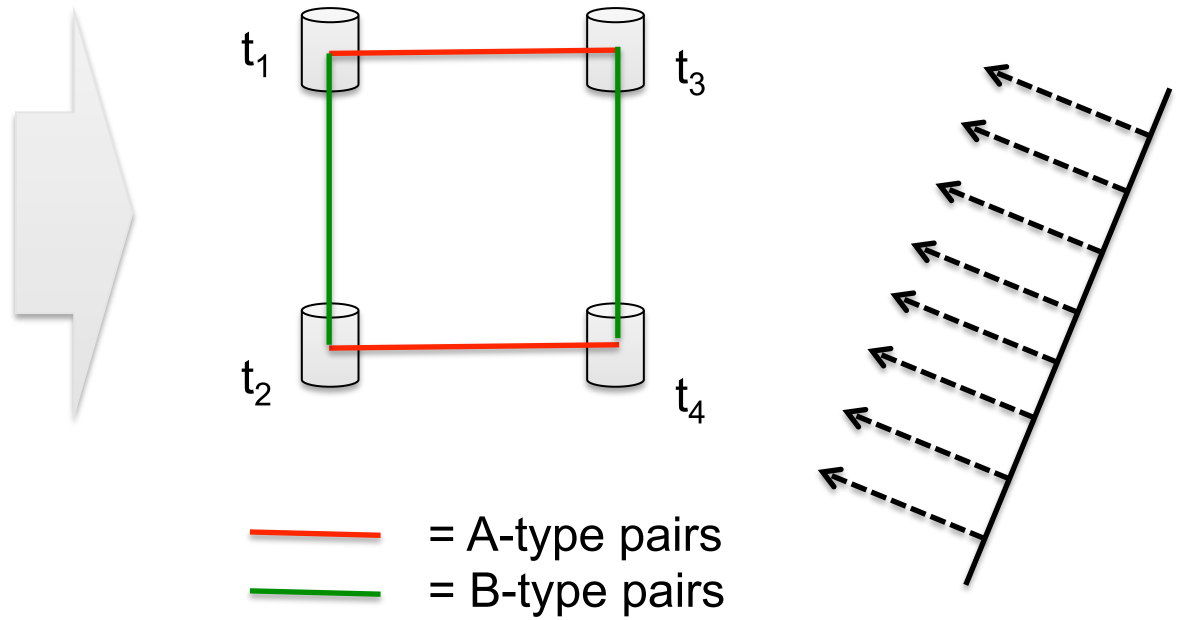
FURTHER ANALYSIS WORK

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





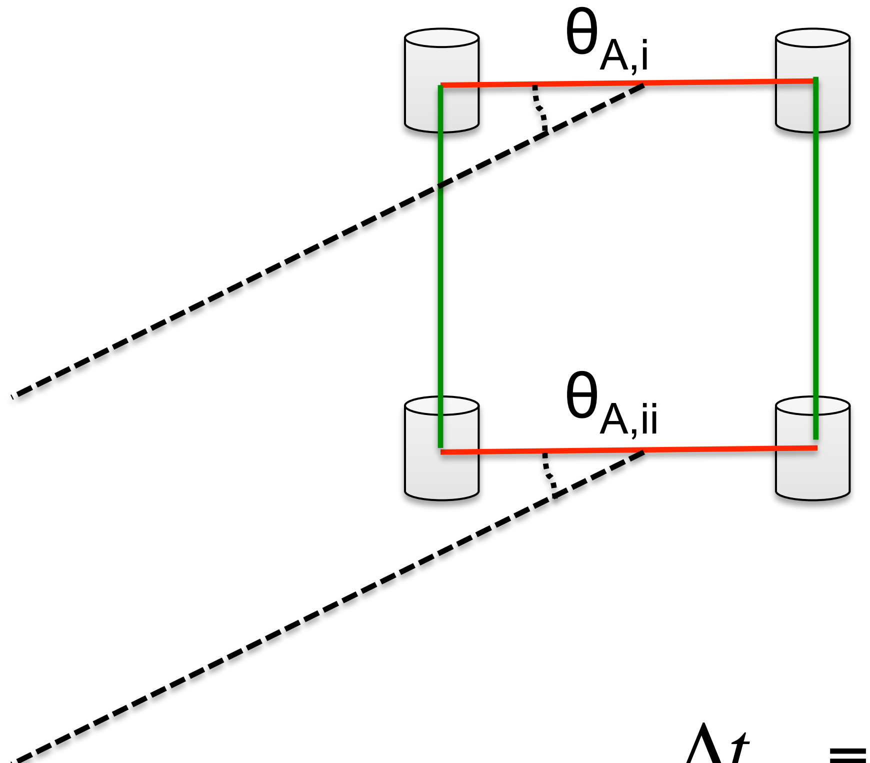
$\Delta t_{A,i} = t_3 - t_1$

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

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

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

Angle of Incidence



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

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

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

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

Angular Variation - RMS

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

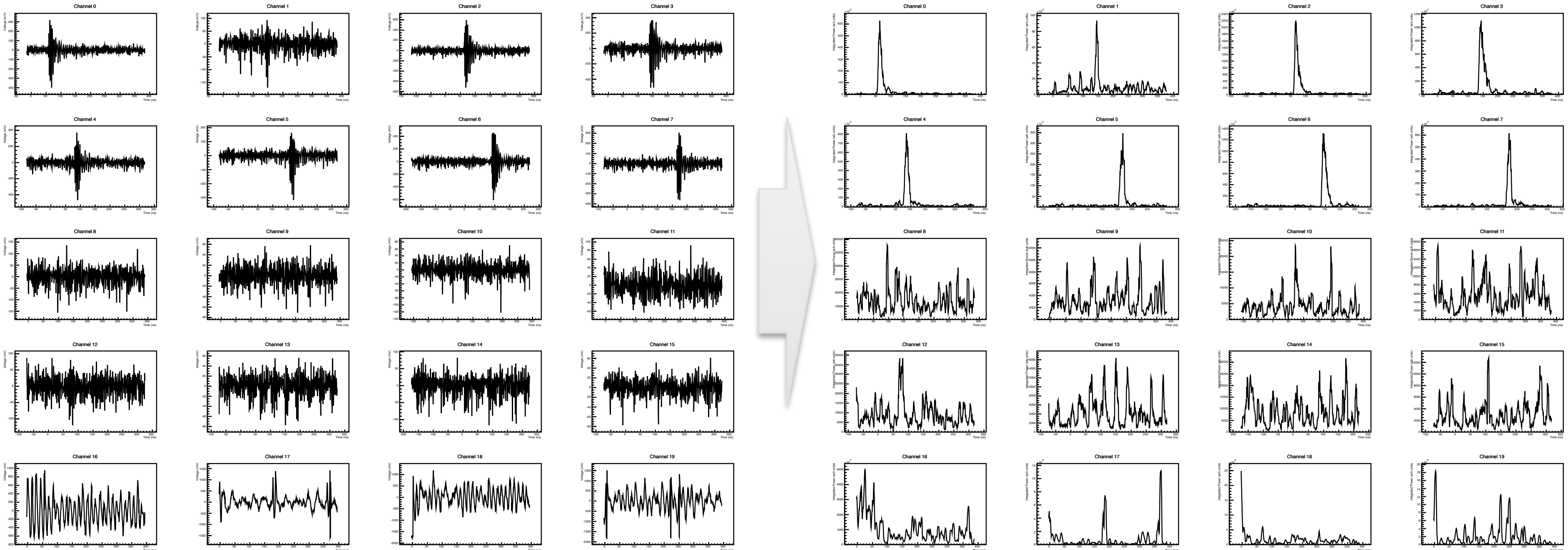
$$\overline{\cos(\theta_A)} = \frac{\cos(\theta_{A,i}) + \cos(\theta_{A,ii})}{2}$$

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

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

Find “hit times”

Calibration pulser event



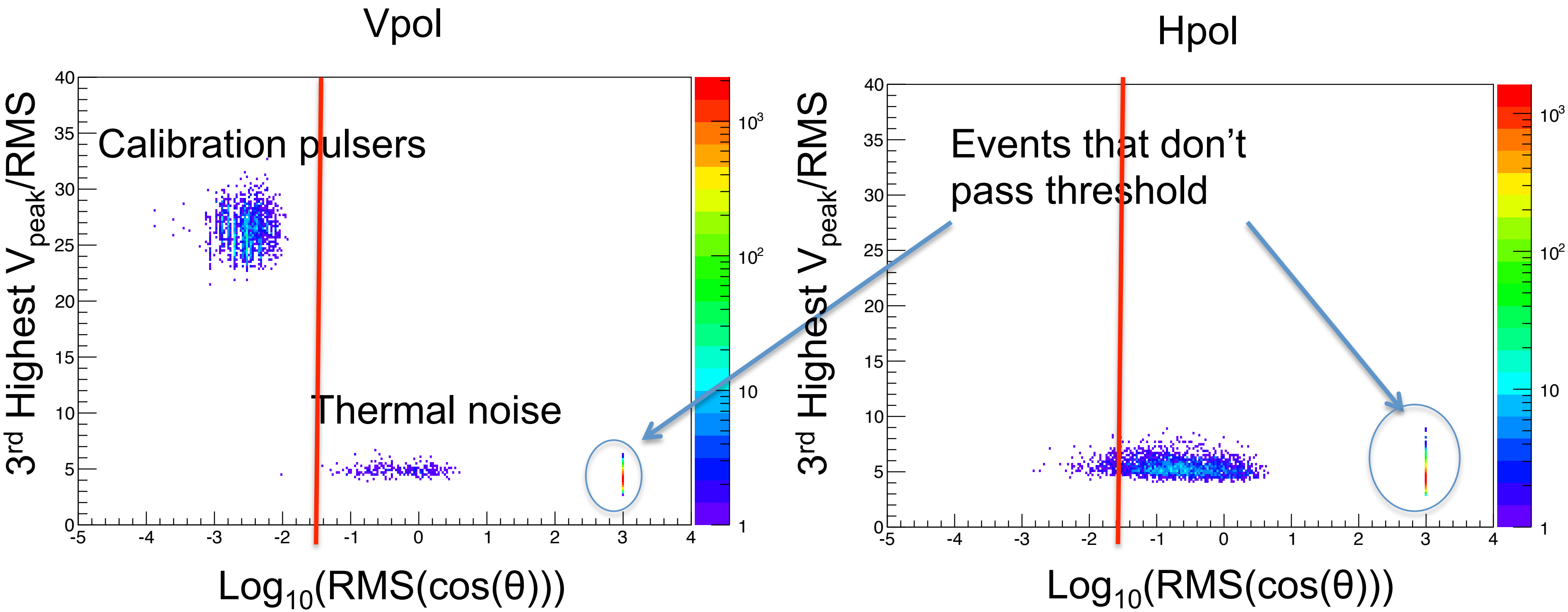
- To decrease noise fluctuations, scan an integrated power window of 5 ns
- Find the two highest peaks, use these as “hit times” for that channel
- Apply a threshold:

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

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

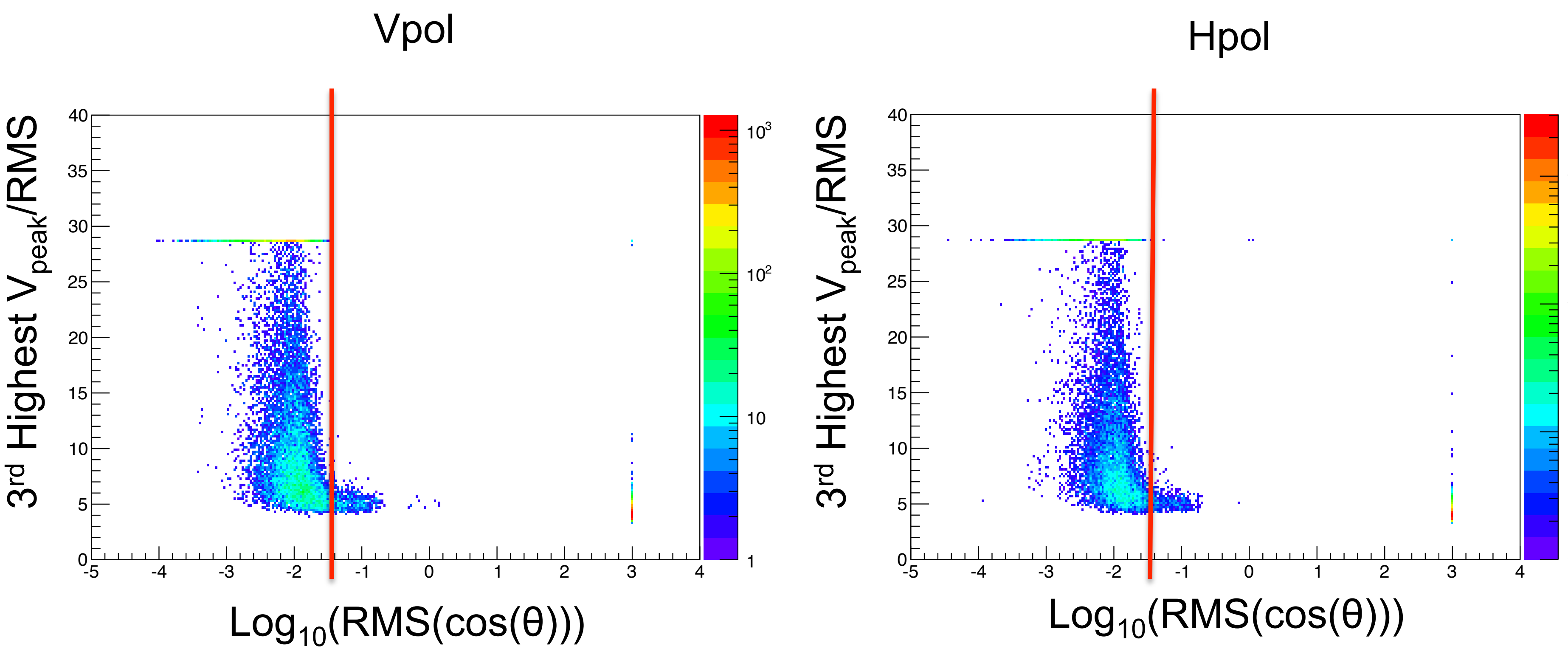
Preliminary Results - Data

Station A2, Run 1798
Threshold = 2.5



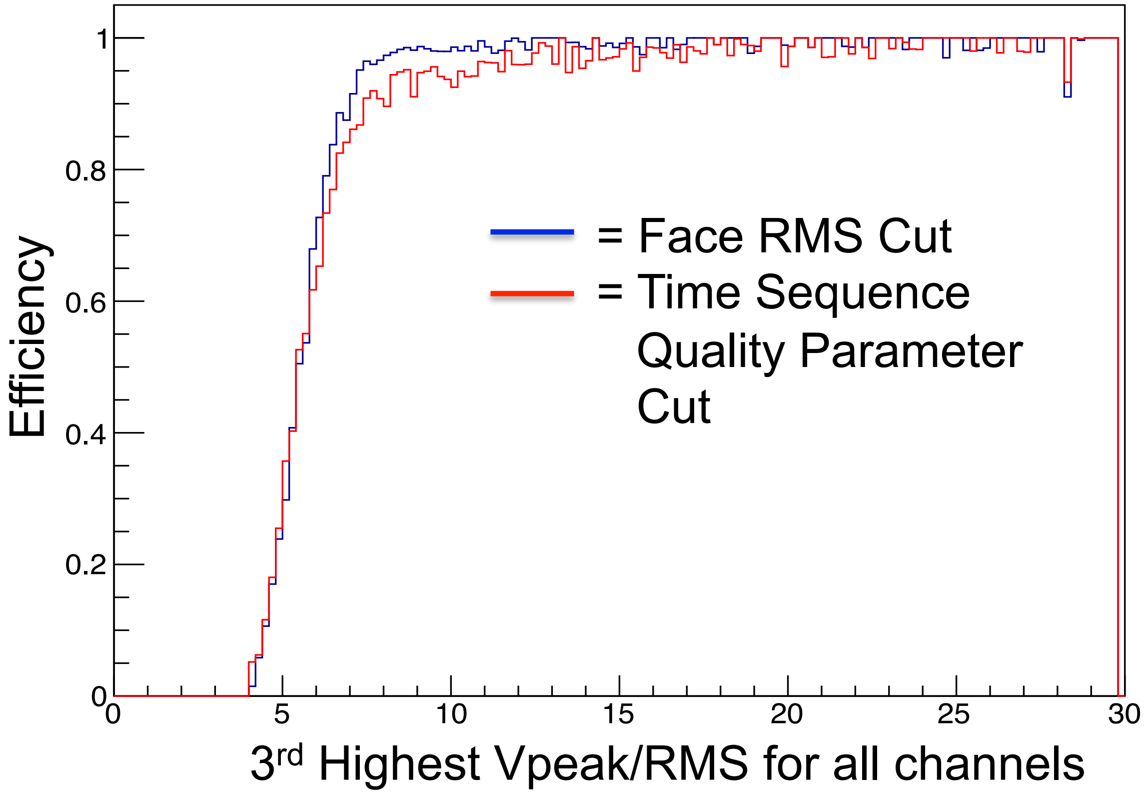
- More event pass threshold in Hpol antennas
  - use separate thresholds for Vpol and Hpol

Preliminary Results - Simulation



- 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

Efficiency



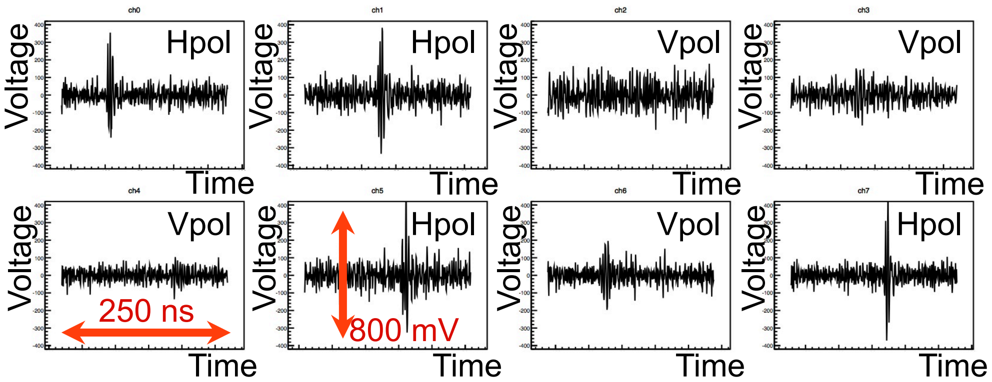
Vpol thresh = 2.5
Hpol thresh = 2.9
$\text{Log}_{10}(\text{RMS}(\cos(\theta))) < -1.5$

Time Sequence Quality Parameter > 0.6
(value used in 2013 A2/3 analysis, described by Kael in earlier talk)

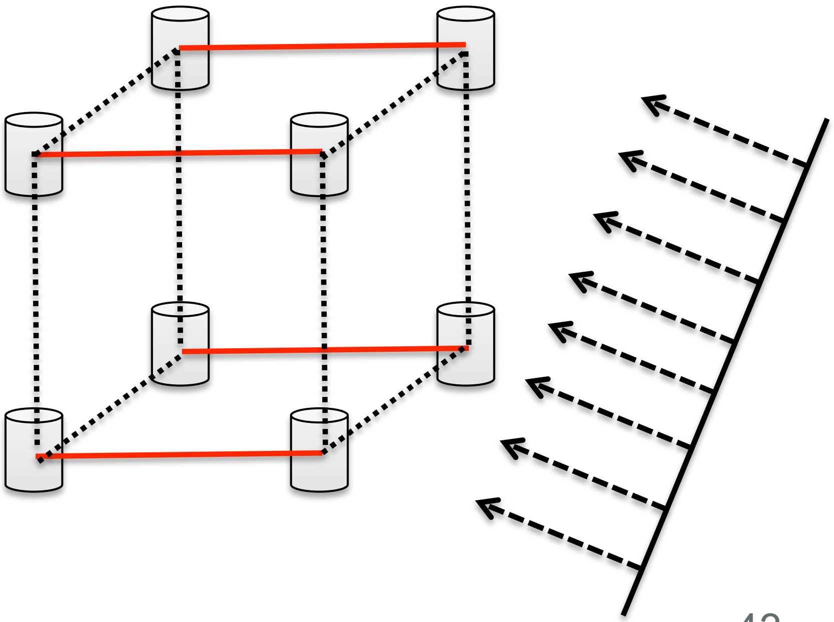
- Data RF events - Face RMS efficiency = 0.08 %, TSQP = 0.08 %
- Simulation - Face RMS efficiency = 83.1%, TSQP efficiency = 81.6%
- Currently filter algorithms comparable
- Face RMS not optimized, may improve even more

Feature Types

- Single channel - waveform
  - Signal strength
  - Signal shape
  - Spectrum



- Between channels
  - Relative arrival times
  - Spectral similarities
  - Correlation map



Conclusions

- ARA is a ultrahigh energy neutrino detector being built at the South Pole

- **Prototype Testbed station**
- Asymmetrical layout
- Completed diffuse neutrino search
  - Optimized cuts
  - Projected limit for ARA37
- Completed GRB neutrino search - quasi-diffuse flux limit above 10^{16} eV
  - Limiting background search window → cut relaxation

- **Deep Stations**
- Analysis of 10 months of data complete – diffuse neutrino flux limit
- Further analysis work ongoing
- Assess potential for future work using machine learning

Questions?