The Askaryan Radio Array: Status, Results, and Prospects of a UHE Neutrino Detector

Carl Pfendner

Ohio State University

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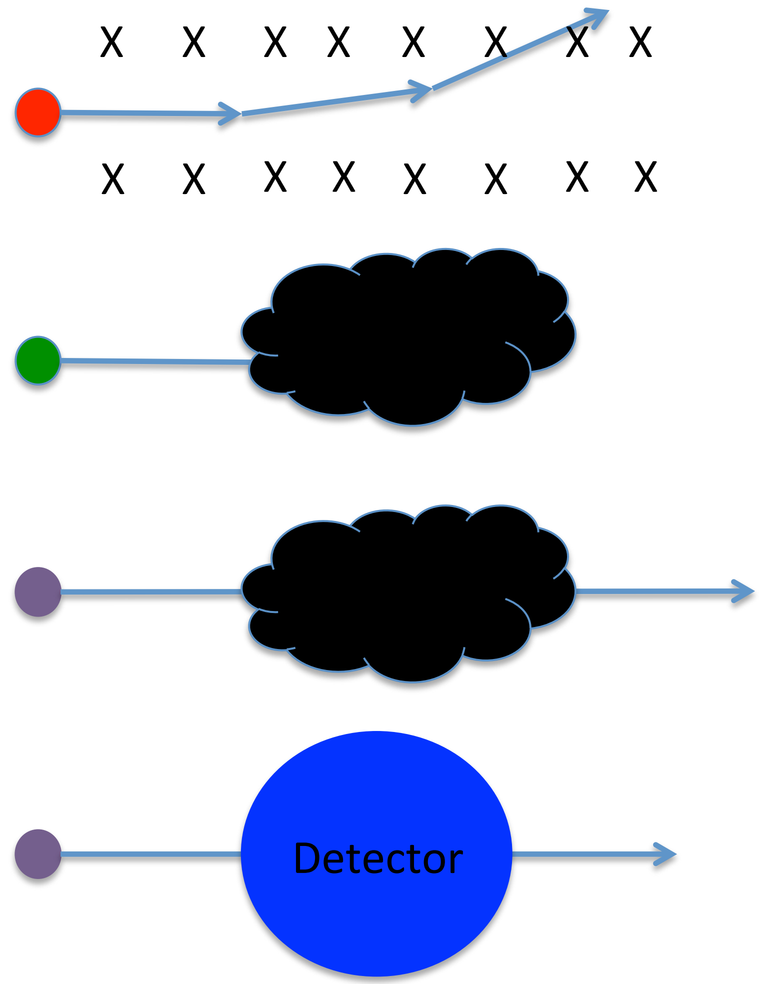
INTRODUCTION

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

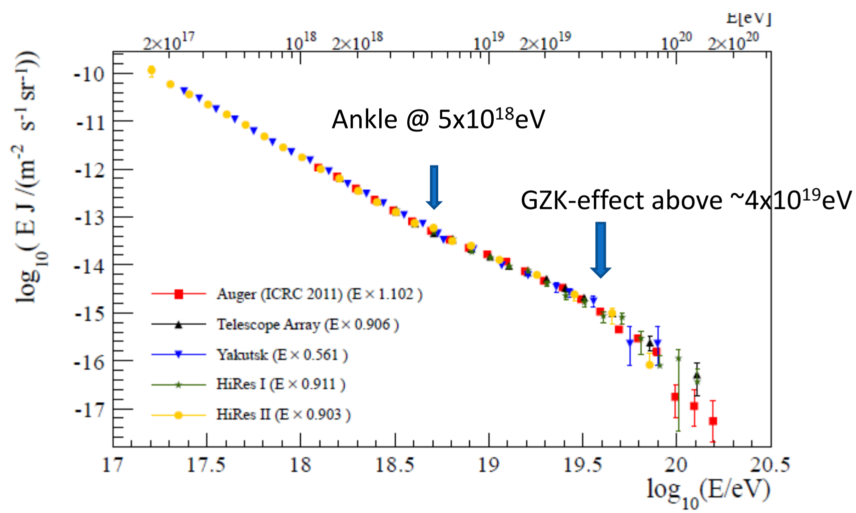
- Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays with E > $10^{19.5}$ eV interact with cosmic microwave background (CMB) photons
- Process produces BZ neutrinos, some at ultrahigh energies (UHE)
- Neutrinos happily continue on
- UHE neutrinos could also be produced at a source location
  - If observed, will trace back to source
- Low Flux at Earth
  - Less than 1/km^3/year/energy decade
  - Need large volume detectors

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

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

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

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



Proceedings of UHECR 2012

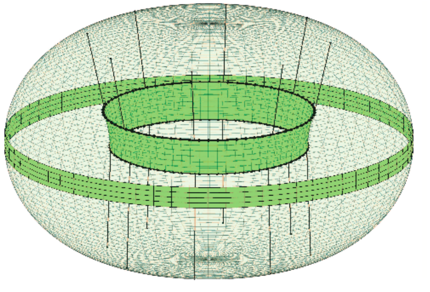
Synoptic Detectors

- 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

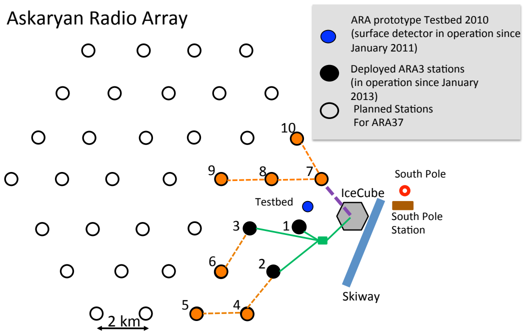


In Situ Detectors

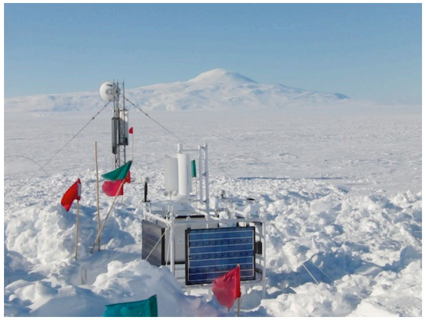
- *In situ* arrays – IceCube, HEX/NGI, RICE, ARA, ARIANNA
- Long operation time (years); smaller observable volume - O(100 km^3)
- Larger solid angle for observable signals
- Environmental problems *in situ* – measure and model environment, ice
- But better able to obtain more information about event - direction, pol., etc.
- Good as an observatory – long term stability, reaches lower energy (10^{17} eV)
- Better able to see unexpected events

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

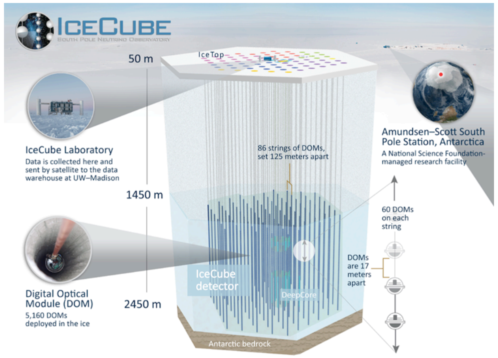
ARA



ARIANNA

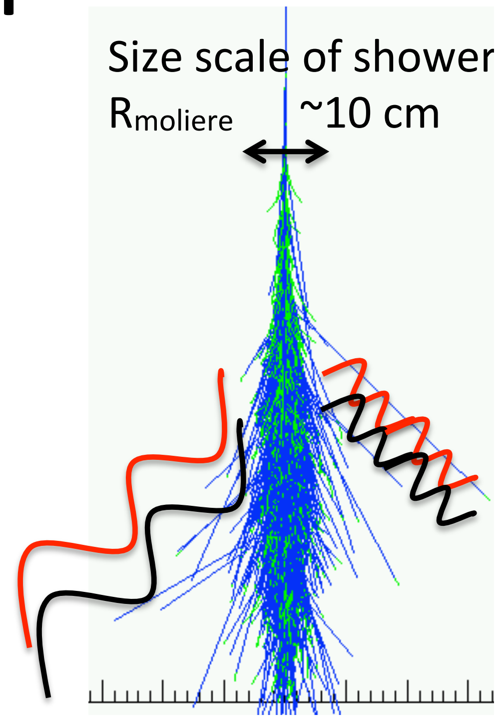


IceCube

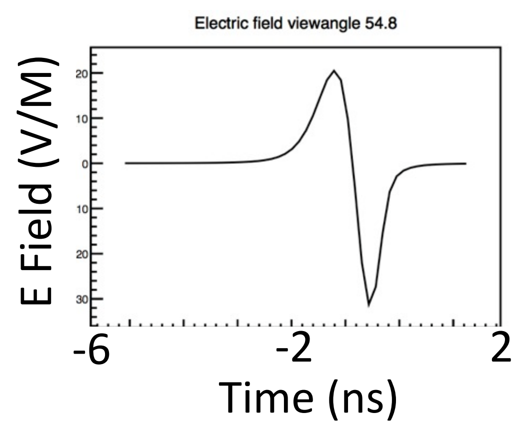


Detection technique

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

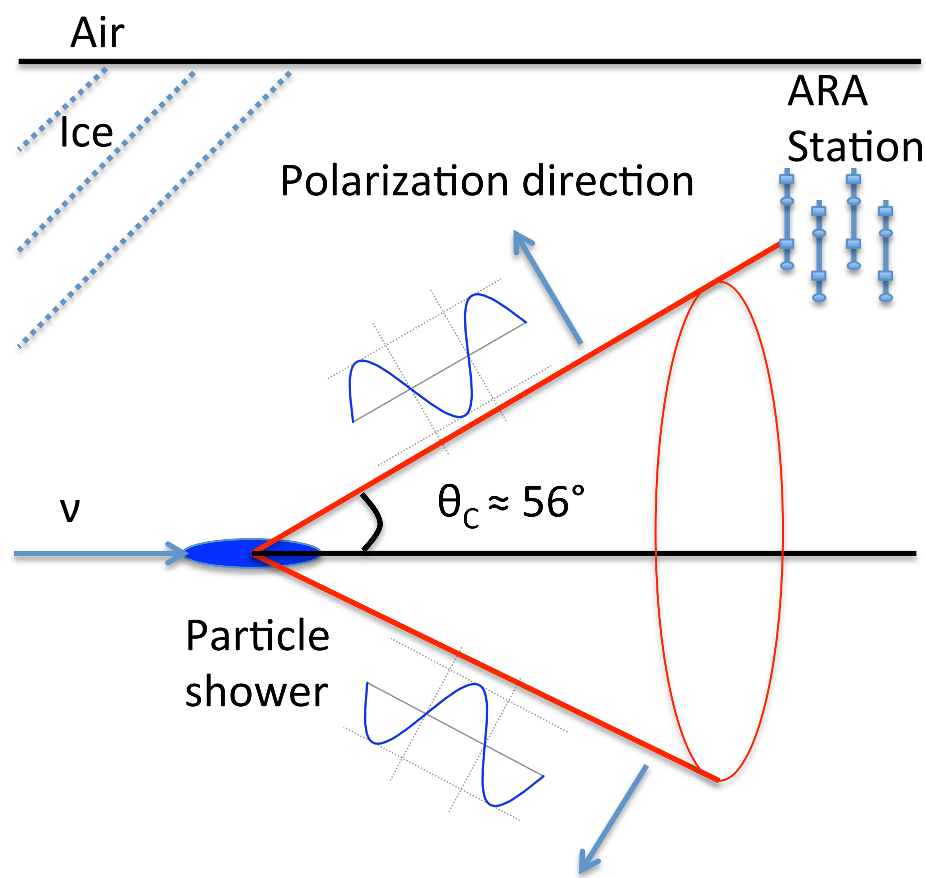


Particle shower



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



EXPERIMENT AND DETECTOR

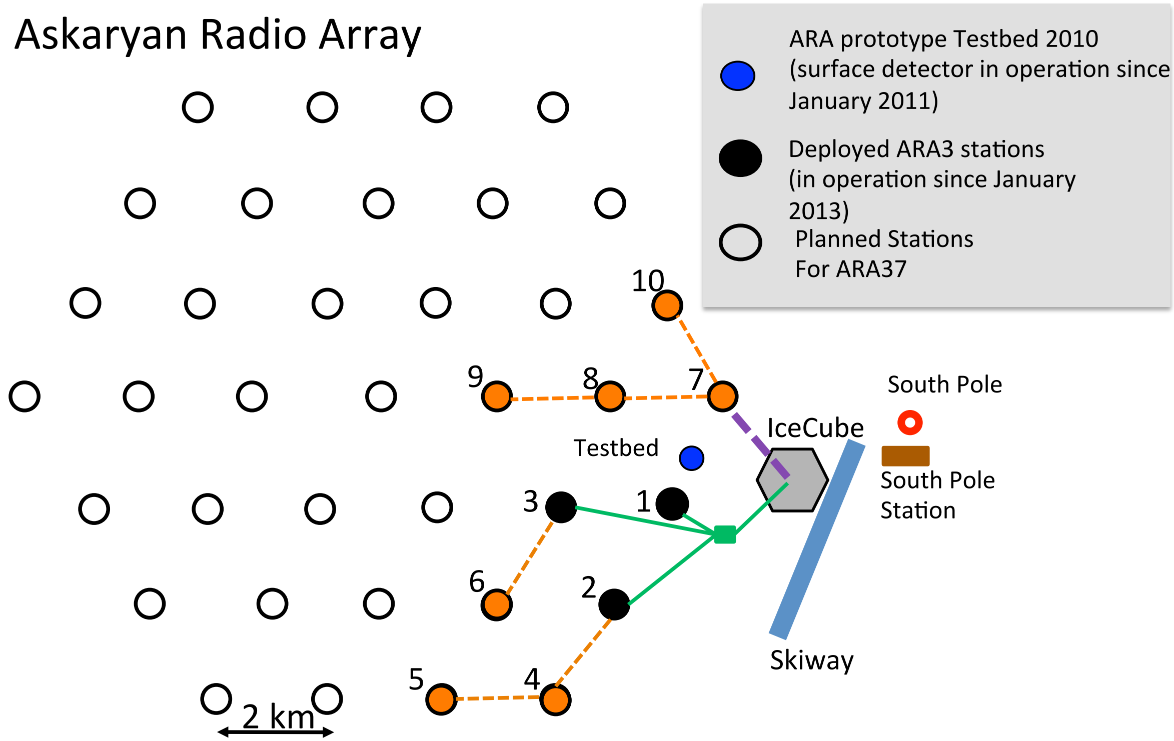
ARA Collaboration

USA:
- Ohio State University
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison

UK: University College London
Belgium: Université Libre de Bruxelles
Japan: Chiba University
Taiwan: National Taiwan University
Israel: Weizmann Institute of Science
Germany: University of Bonn
Australia: University of Adelaide

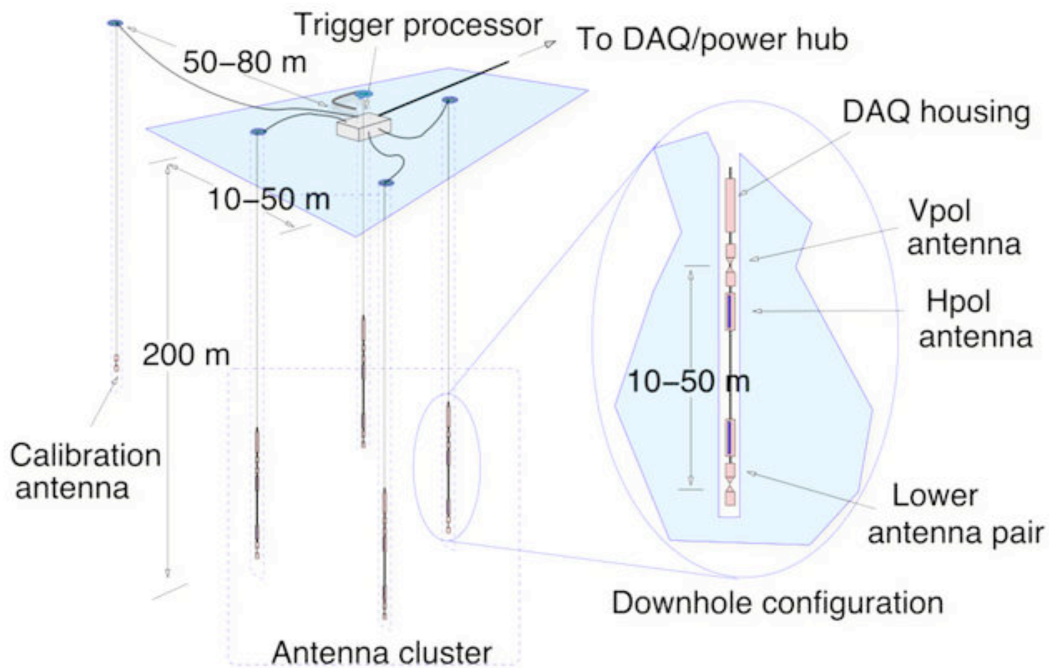
- International collaboration with 12 institutions
- ~50 authors

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



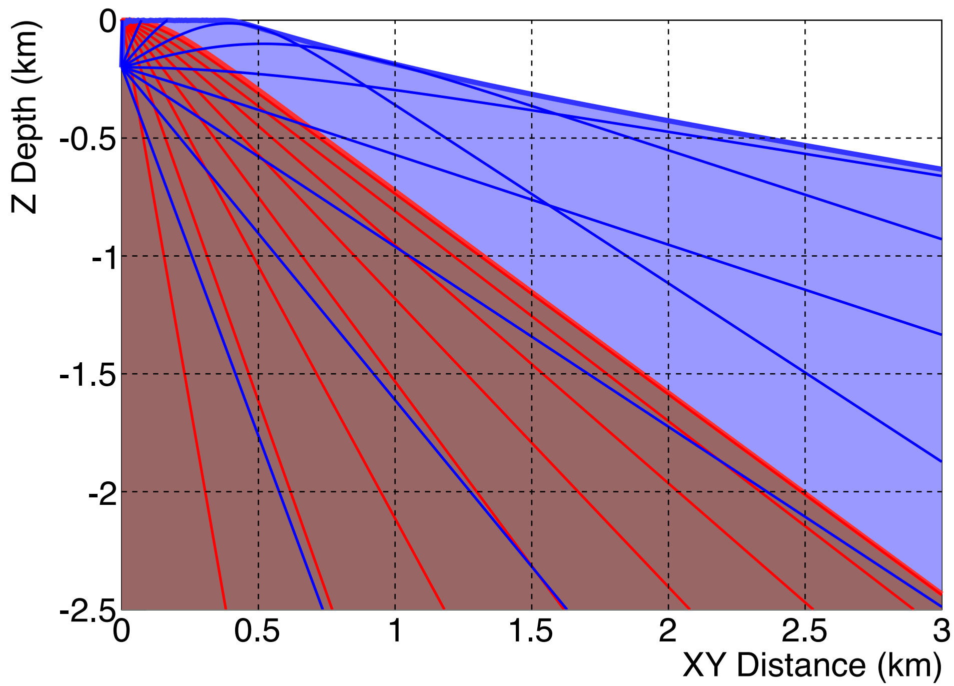
Hpol quad-slotted cylinder antenna

Vpol bicone antenna

- 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

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

Importance of Deep Deployment

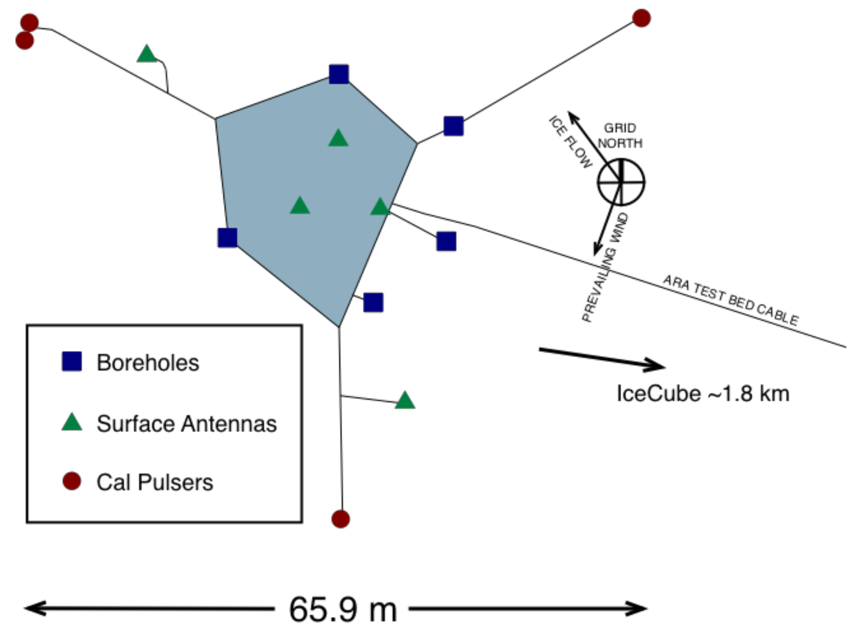


- Firn – layer of compacted snow
  - Quickly changing index of refraction (~1.35 → ~1.78 within top ~150 m of ice)
  - Causes curvature in paths of rays in ice
  - Limits viewable volume and observable neutrino incident angles
  - 30 m → 200 m depth: increases effective volume by factor of ~3.2

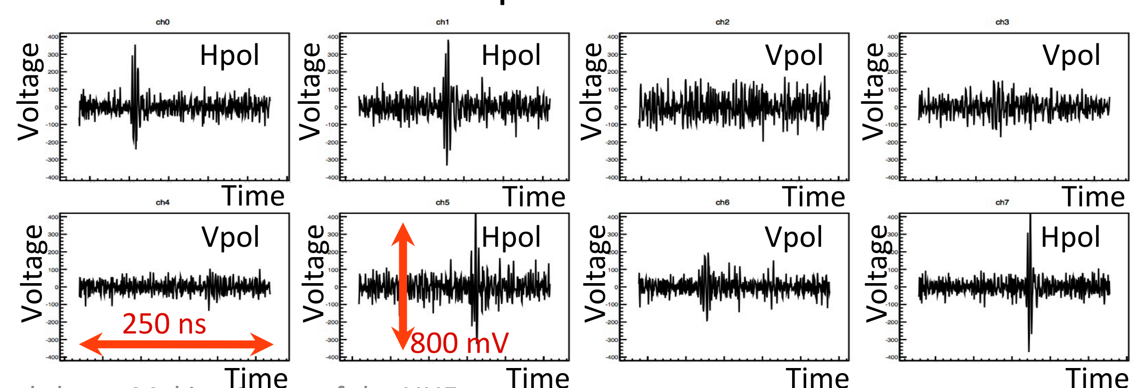
ANALYSIS STATUS I: TESTBED

Testbed Analysis

- Total 16 antennas, 8 borehole antennas at 150 MHz to 850 MHz
- Maximum depth of antennas ~ 30 m
- 3 sets of calibration pulsers
  - Each set has a Vpol and an Hpol pulser
- First ARA neutrino searches carried out with Testbed station data



Calibration pulser event waveform from 8 deep antennas in Testbed

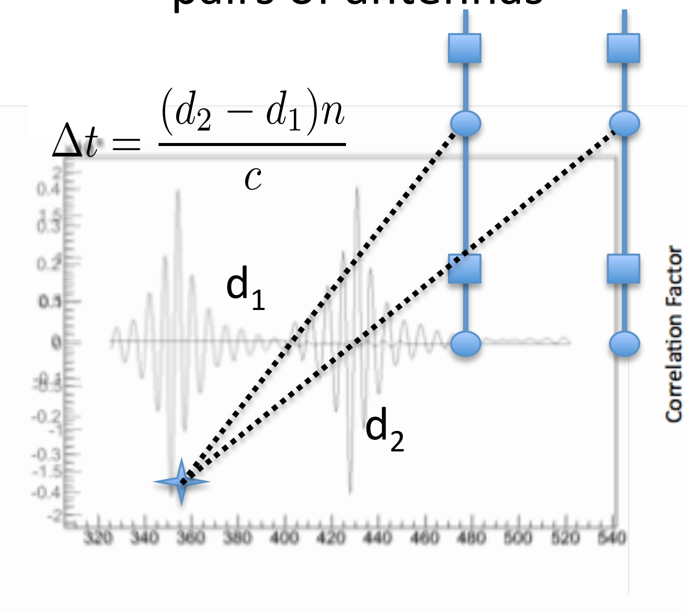


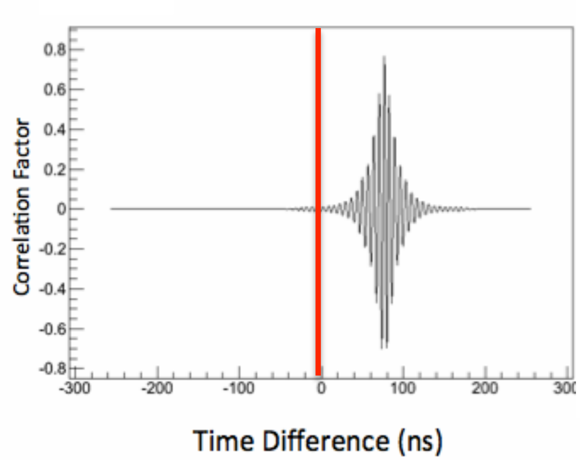
ARA – Testbed Neutrino Analysis

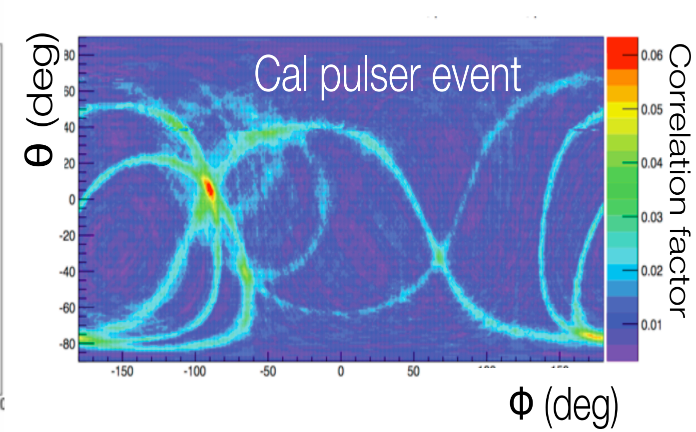
- Standard ARA blinding protocol – examine 10% of data to characterize backgrounds and tune cuts
  - Thermal Noise
  - Continuous wave (CW)
  - Anthropogenic impulsive background
- 3 analyses – ~330 million events
  - Concentrate on 2 comparable analyses covering 2011-2012
- Interferometric Map (IM) Analysis
  - stage 1: Feb-Jun 2012; stage 2: Jan 2011-Dec 2012
  - Interferometric reconstruction from ray-traced cross-correlation map
  - Optimized cuts for background rejection and signal retention
- Coherently Summed Waveform (CSW) Analysis – Jan 2011 - Dec 2012
  - Uses least-squares fit to a source location
  - Examines the coherently summed waveform for power
- Template analysis – Identify similar waveforms, Based on RICE heritage

Interferometric Map

- Impulsive waveform – ~1-10 ns time scale
- Correlation factor - Convolution of the two waveforms including a timing offset
- Only Vpol-to-Vpol comparison and Hpol-to-Hpol comparison
- Calculate timing delays for all angles of approach
- Sample correlation plot at these delays
- Many positions will produce the same timing delays for a pair of antennas
- Solution: Use more antennas - Add up all the correlation values from all the pairs of antennas

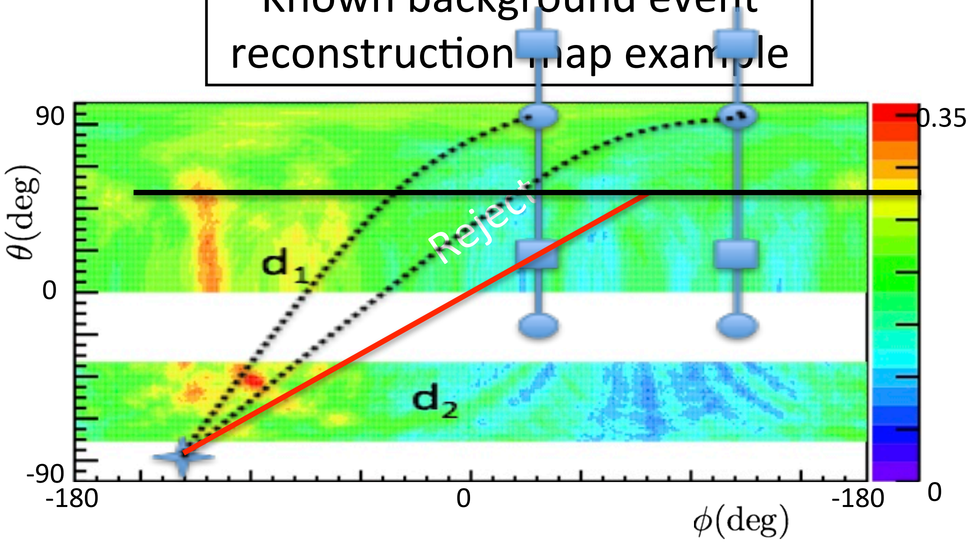




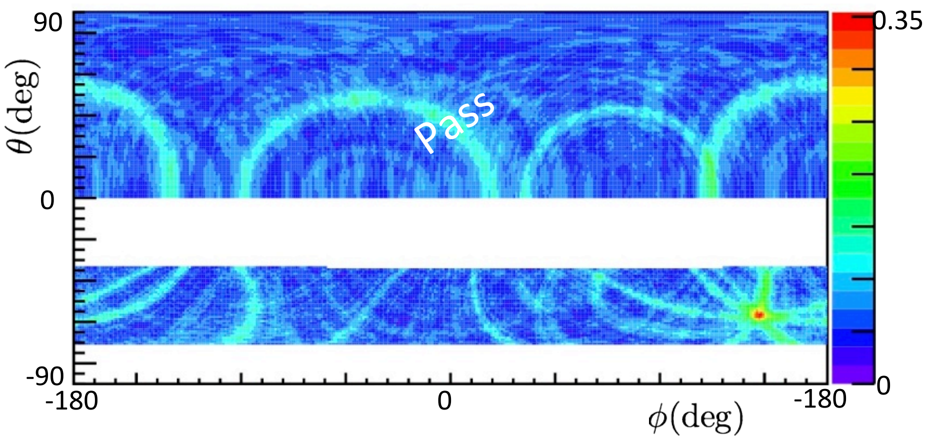


IM analysis - Reconstruction Quality Cut

Known background event reconstruction map example



Simulated ν event reconstruction map example

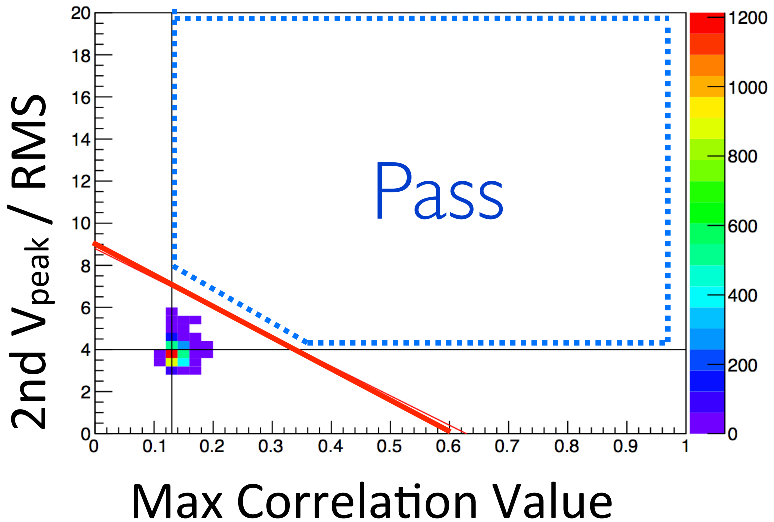


- Reconstruction based on timing from ray-tracing
  - Use 30 m and 3 km maps in Hpol and Vpol
- Requires at least one reconstruction map to be of good quality
  - 1 deg^2 < Area of 85% contour surrounding the peak < 50 deg^2
  - Total 85% contour peak area < 1.5 x Area of 85% contour surrounding the 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

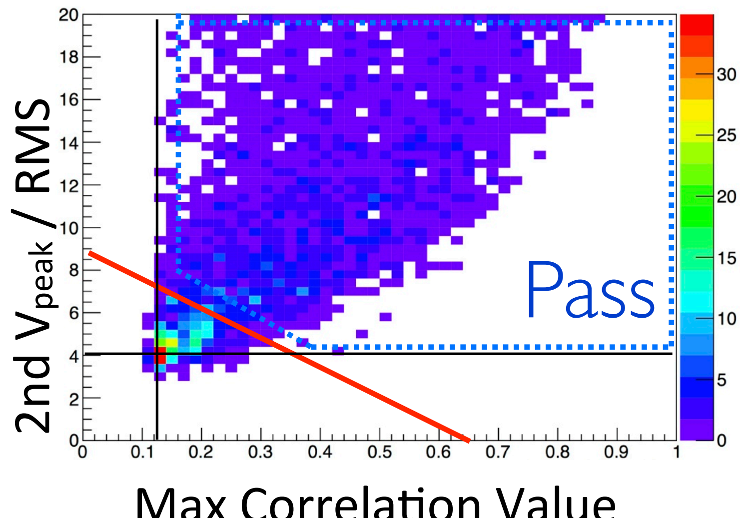
2nd V_{peak} / Correlation Cut

- Other cuts : Data Quality cut, Down cut, CW cut, Delta delay cut, Gradient cut, Geometry cuts (clustering, South Pole, Calibration Pulser), periods of known increased activity at South Pole
- Expect a correlation between V_{peak}/RMS 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
- We optimized the cut for best limit on maximal Kotera *et al*. model
- As a last cut, this rejects 22% of Kotera neutrino flux

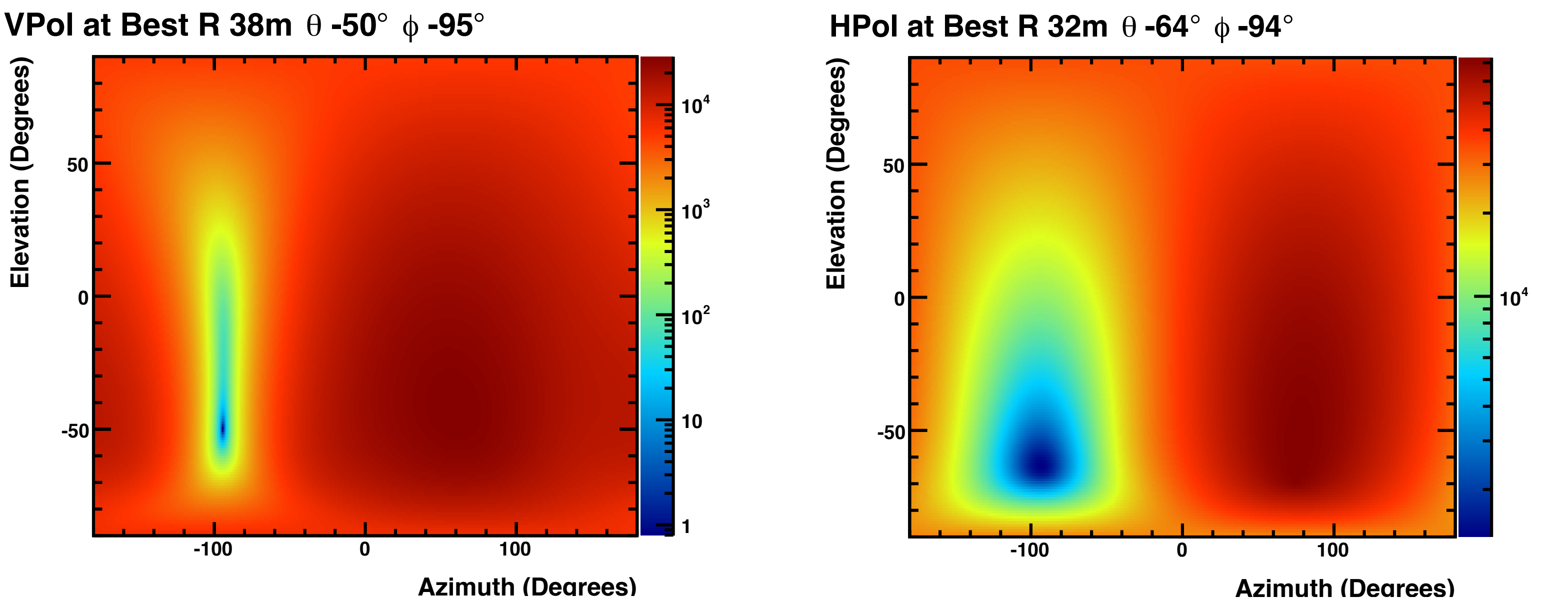
Testbed 10% data set after cuts applied



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

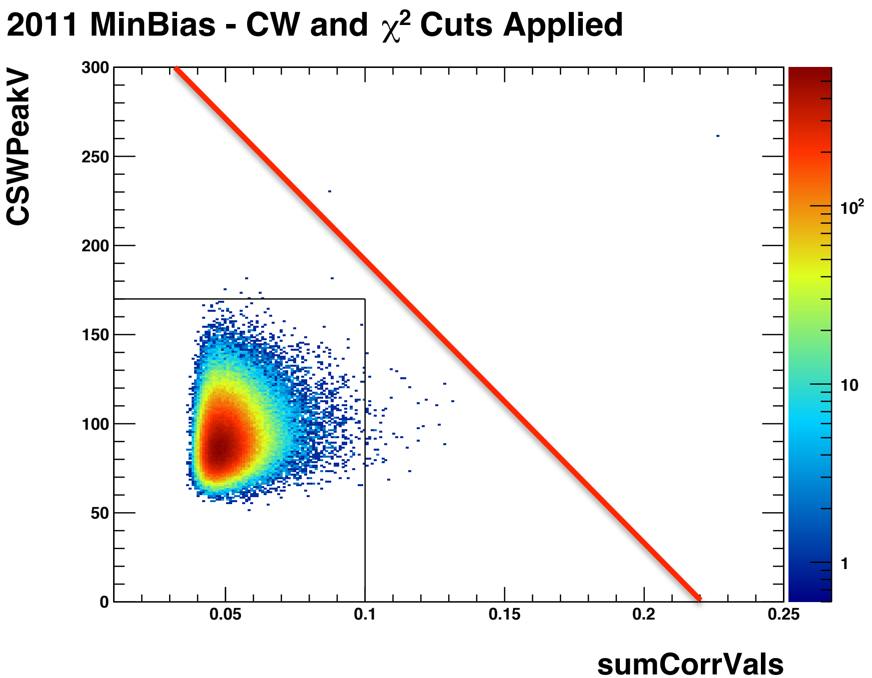


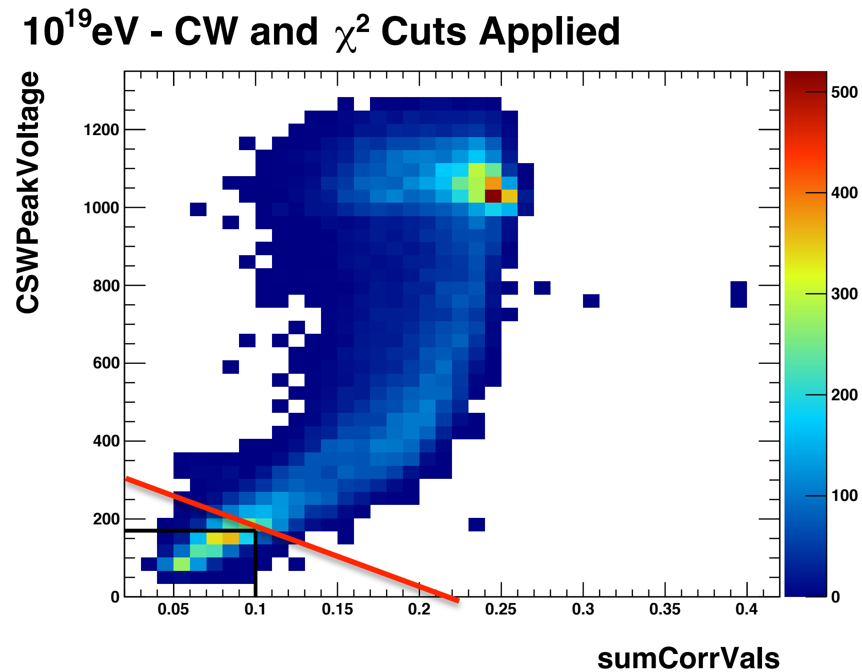
CSW Analysis Reconstruction



- Obtain coherently summed waveform (CSW):
  - Iteratively find the best correlation between a waveform and the CSW; obtains set of delays with best correlation
- Compare delays used to make the CSW to delays expected from putative source positions: minimize $\chi^2 = \Sigma(T_{expected} - T_{observed})^2$
- Cut events with $\chi^2 > 2$.
- Also cut events with excess CW power

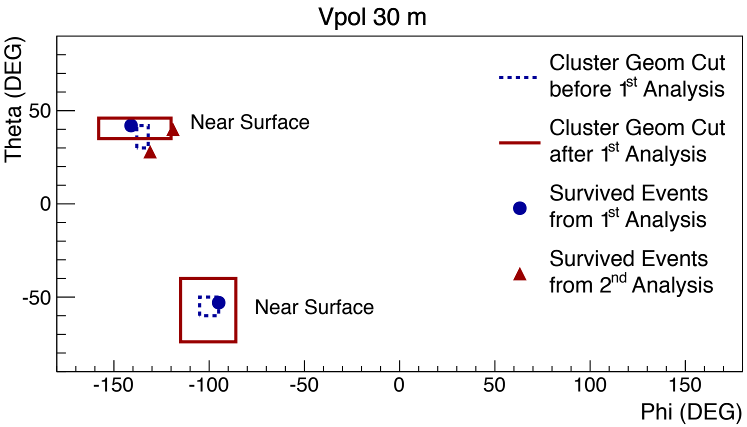
CSW - “Powherence” Cut

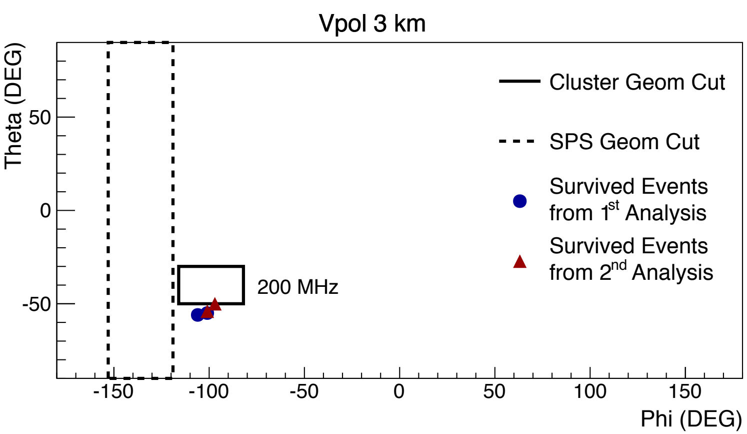


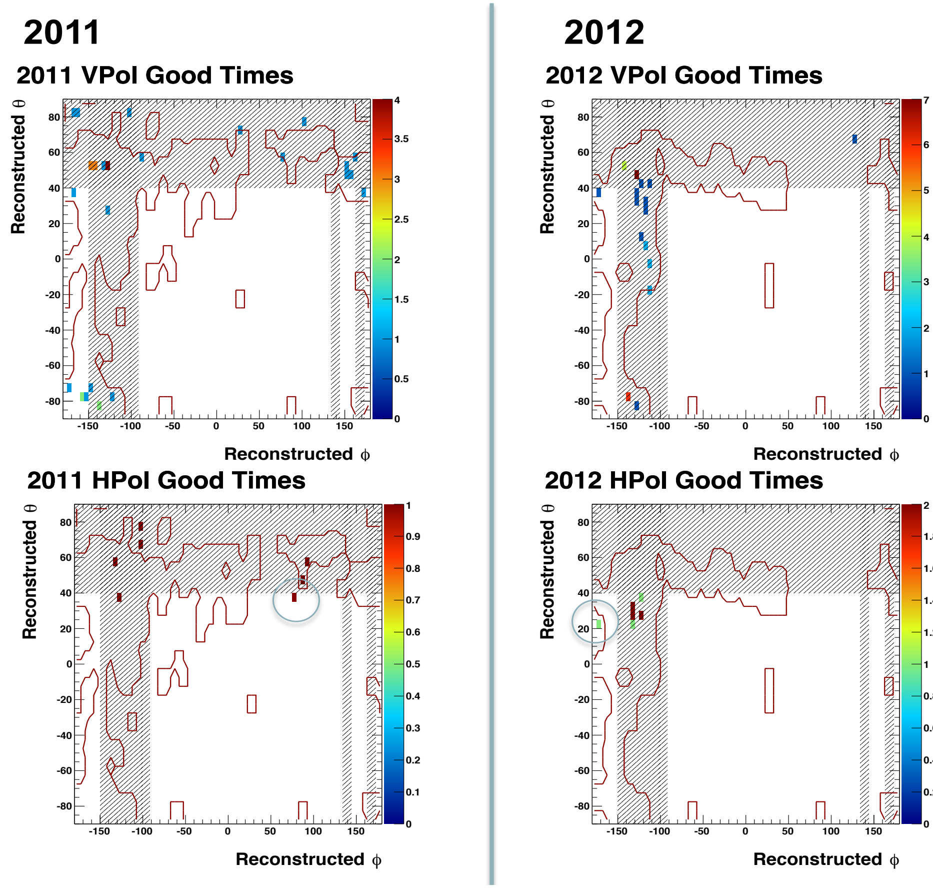


- Linear combination of:
  - peak power of the CSW
  - sum of the maximum correlation values of antennas with the CSW of the remaining antennas
- Expect impulsive events to separate out from noise, CW

Clustering – IM, CSW







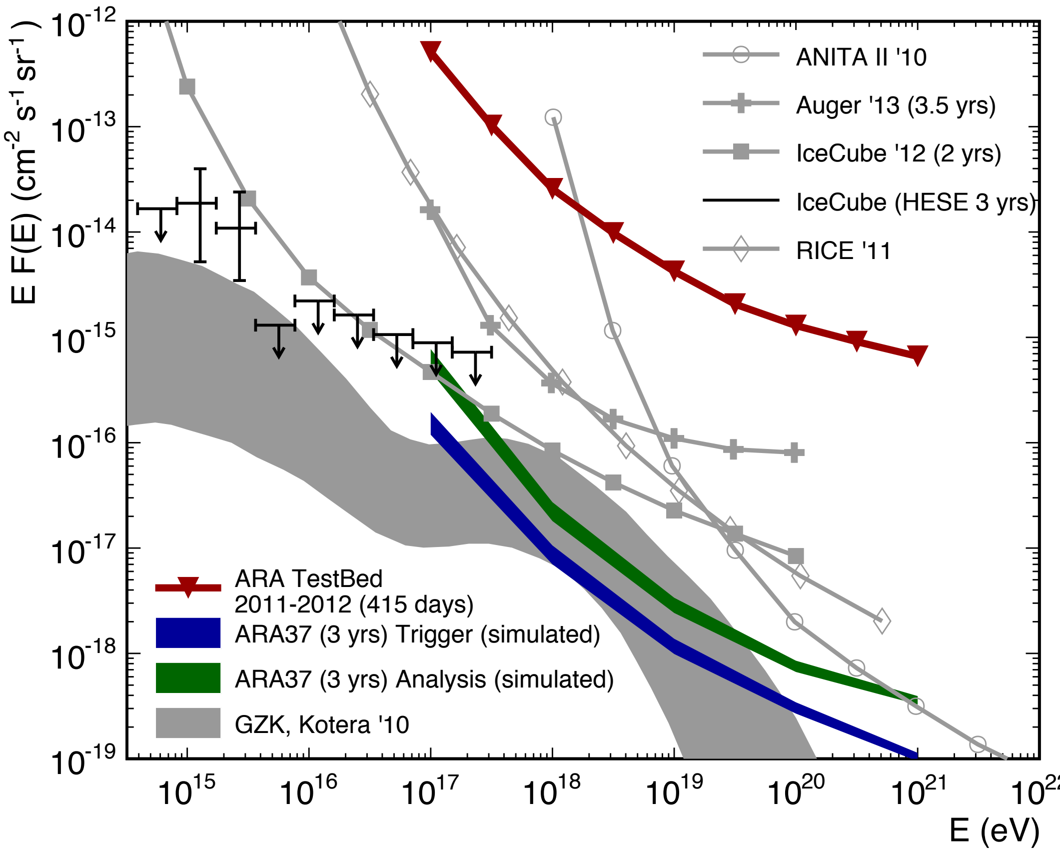
- Both analyses reject events reconstructing to a location where an excess of events can be found
- Also reject South Pole phi range and require reconstruction in the ice

Analysis Results

- Interferometric Map Analysis
  - Stage 1: 3 events passed cuts
    - Known background event types, adjusted the gradient and clustering geometric cuts to better match those types
  - Stage 2: 2 events passed cuts
    - Also known backgrounds, slightly expanded clustering geometry cuts to reject the events (5% change in rejected area)
- Coherently Summed Waveform Analysis: 1 event passed cuts
  - CW event with two carrier frequencies, non-impulsive
- No neutrino candidates

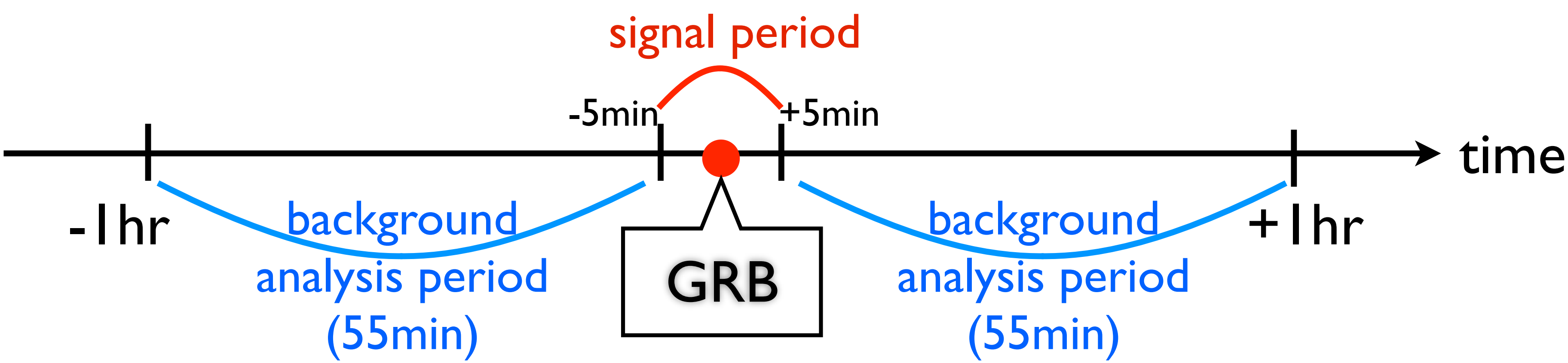
Sensitivity

- First diffuse limits from ARA Testbed found
  - see [arXiv:1404.5285]
  - Accepted by Astropart. Phys.
- Limits comparable for the two 2011-2012 analyses
- Projected sensitivity of 37-station array extends to GZK flux models

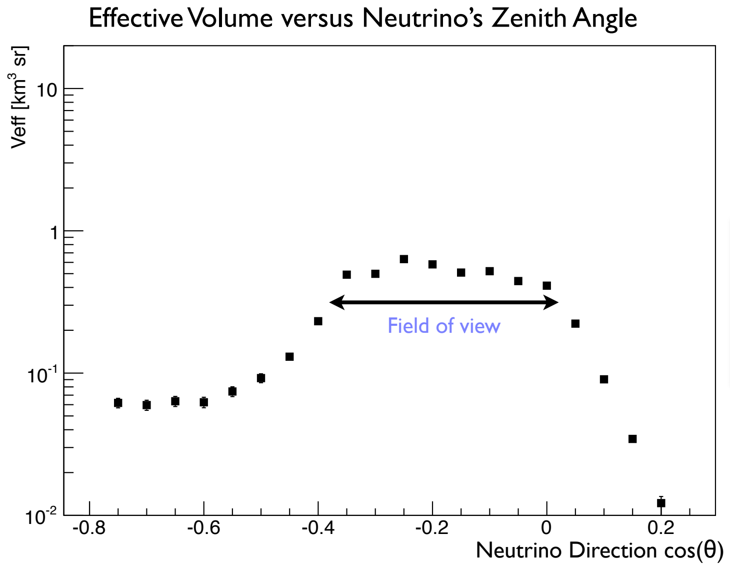


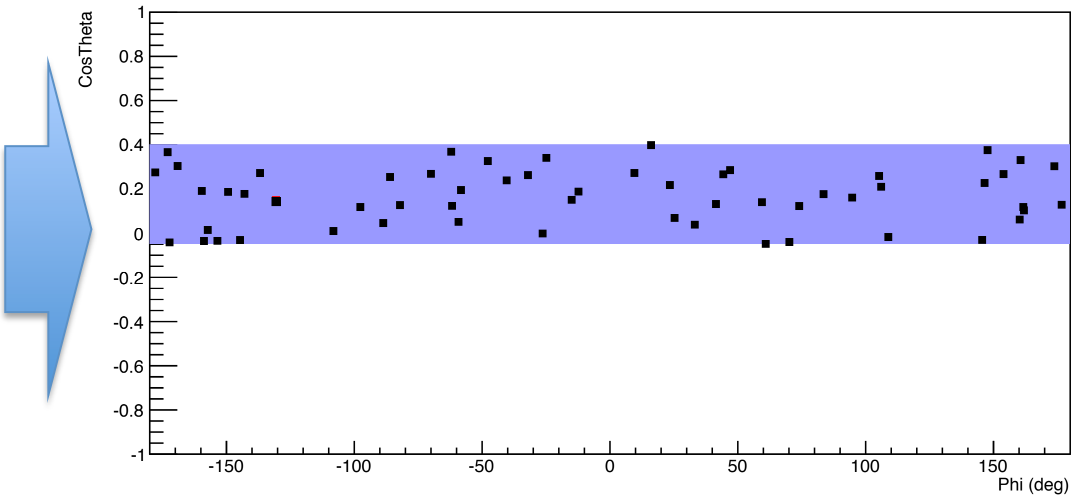
Testbed GRB analysis

- Adapt the Interferometric Map Analysis techniques 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% data sets → 90%
  - 1: Background estimation - only blue period
  - 2: Signal search - +/- 5 minutes around GRB event time

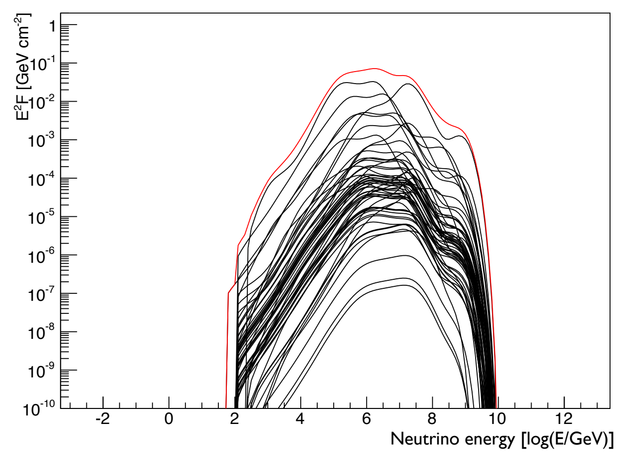


GRB Selection



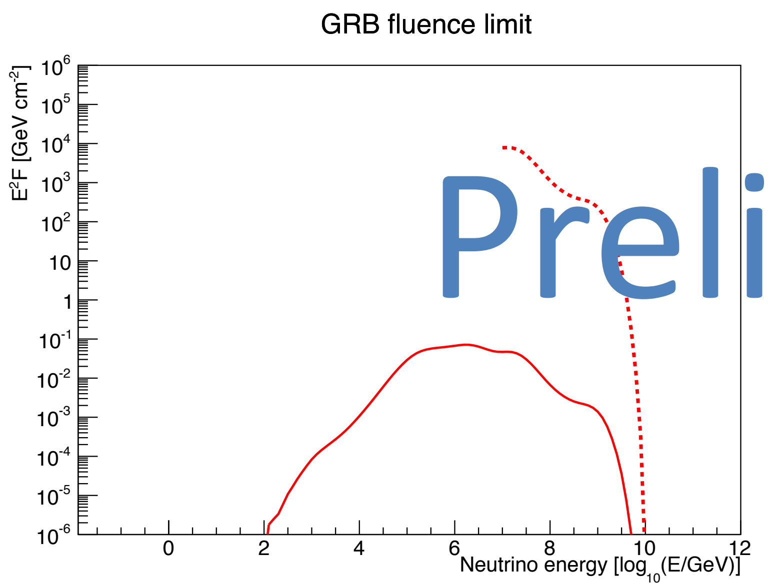


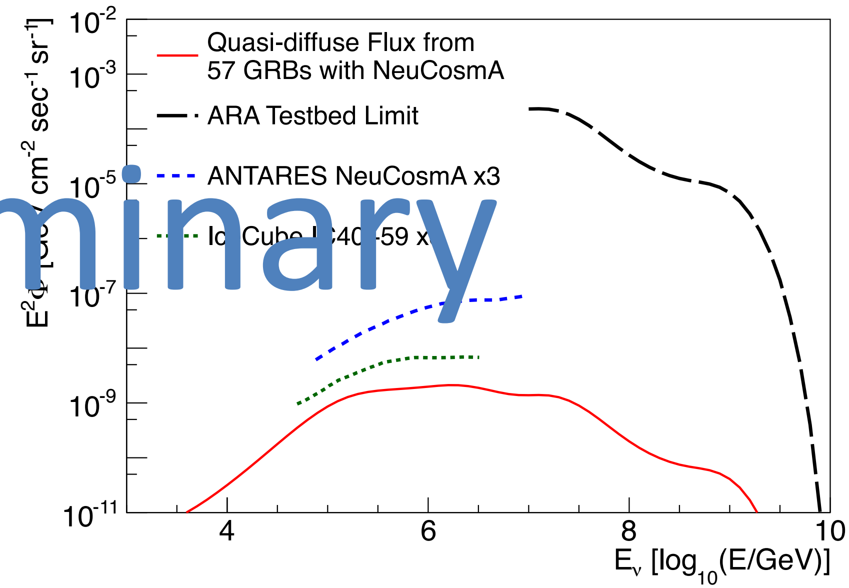
- Selected 57 GRBs based on livetime and geometric acceptance
- Get fluences for each GRB from NeuCosmA simulation and overall
- Tune cuts based on modeled neutrino fluence
- Relaxed Reconstruction Quality, Peak vs CC, Delay Difference cuts



Preliminary Results

- Stage 1 (background period unblinding):
  - Expected background events: 1.166
  - 1 event survived
- Stage 2 (signal period unblinding):
  - Expected background: 0.106, Expected neutrinos: 1.47e-5
  - 0 events survived
- One of the first quasi-diffuse flux limit above 10^{16} eV

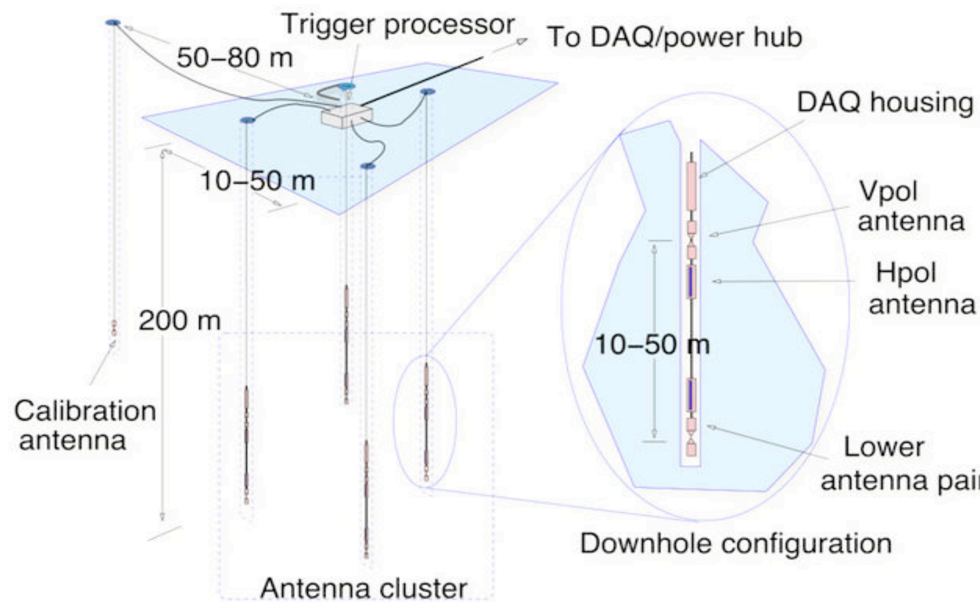




ANALYSIS STATUS II: DEEP STATIONS

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 Station
  – Effective volume
    - 3X over Testbed
  – Analysis efficiency
    - ~10% → ~60%



Noise filtering

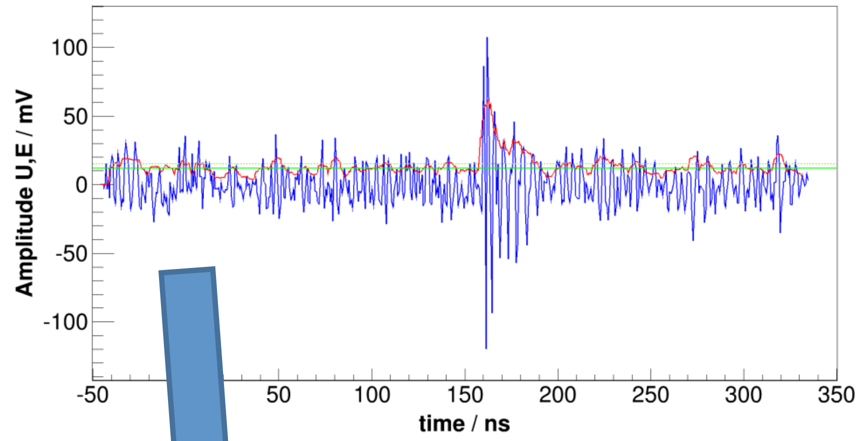
5 Hz thermal noise trigger rate
→ Needs to be reduced before applying sophisticated algorithms

Time sequence algorithm:

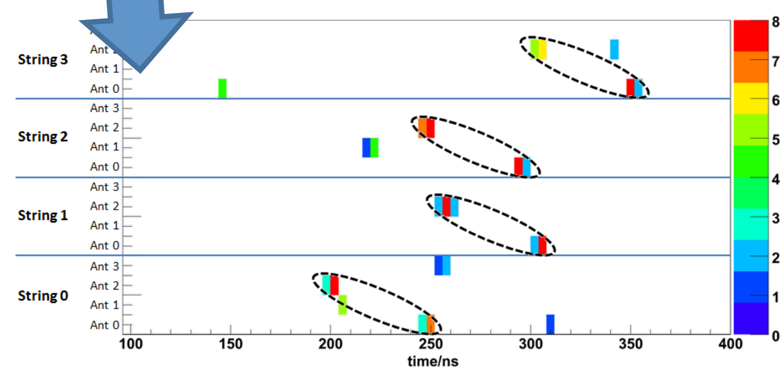
- Boosted hit count
- Simple algorithm (possible usage as trigger)

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

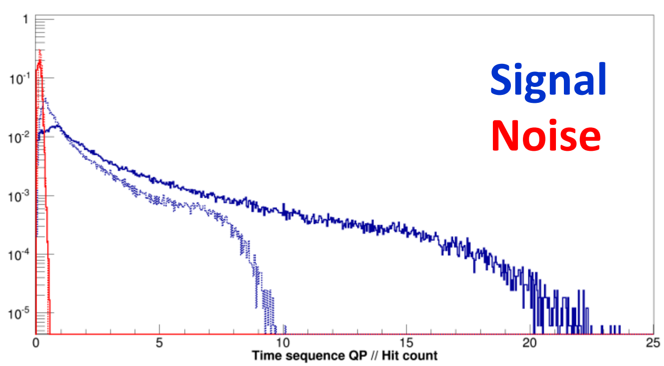
→ ***quality parameter (similarity to wavefront)x(hit count)***



For 16 antennas per station



Quality Parameter for simulated neutrinos

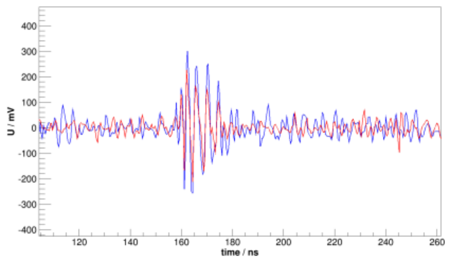


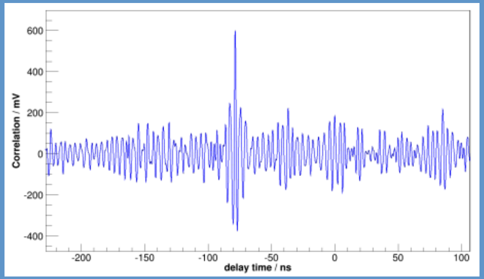
Vertex reconstruction

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

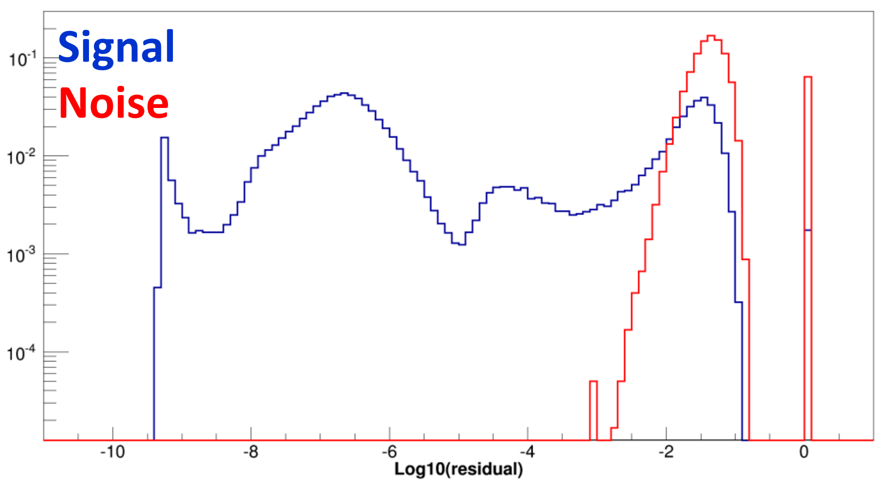
Vertex reconstruction: quality criterion

Main quality criterion is residual:

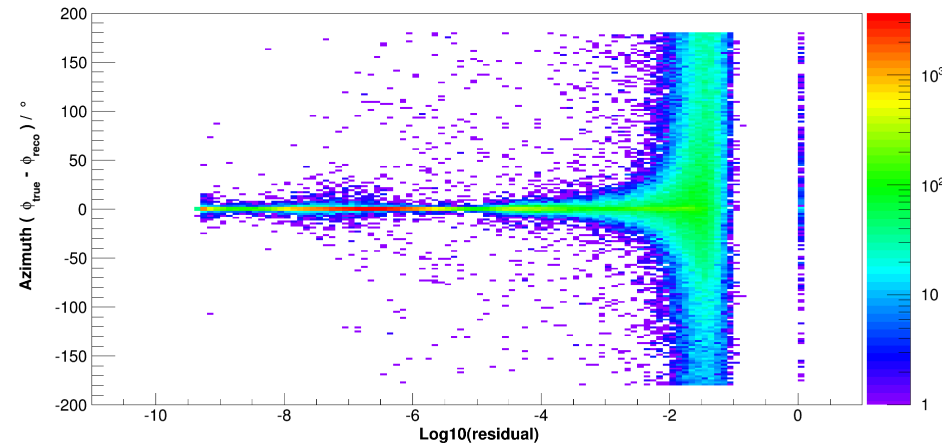
$$res = \left| \frac{\vec{b}}{|\vec{b}|} - \frac{\mathbf{A}\cdot\vec{v}}{|\mathbf{A}\cdot\vec{v}|} \right|^2 \cdot \frac{1}{N_{chp}}.$$

Require a minimum correlation value to be included as a pair

Residual for signal and noise



Reconstruction error vs residual:

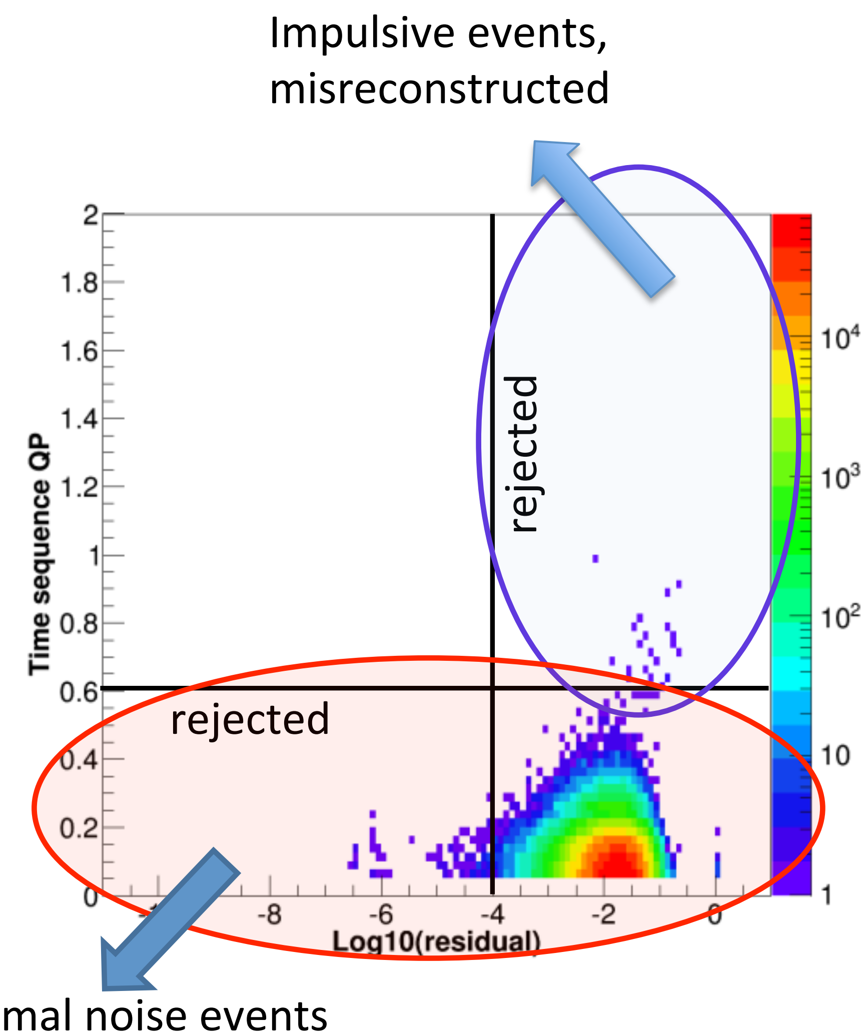


Other quality criteria are applied to further clean out bad reconstructions

Neutrino identification = Background rejection

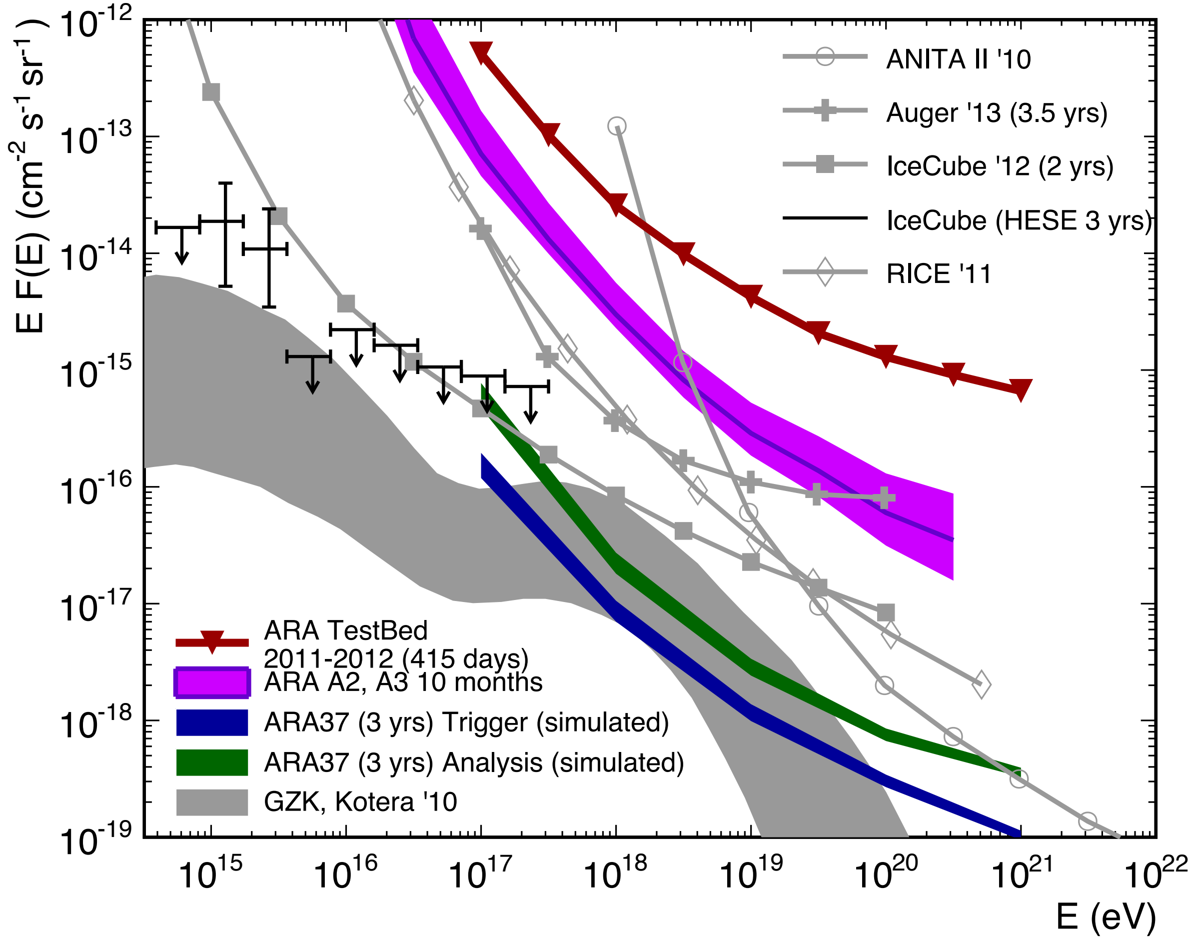
Strategy:

- 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**



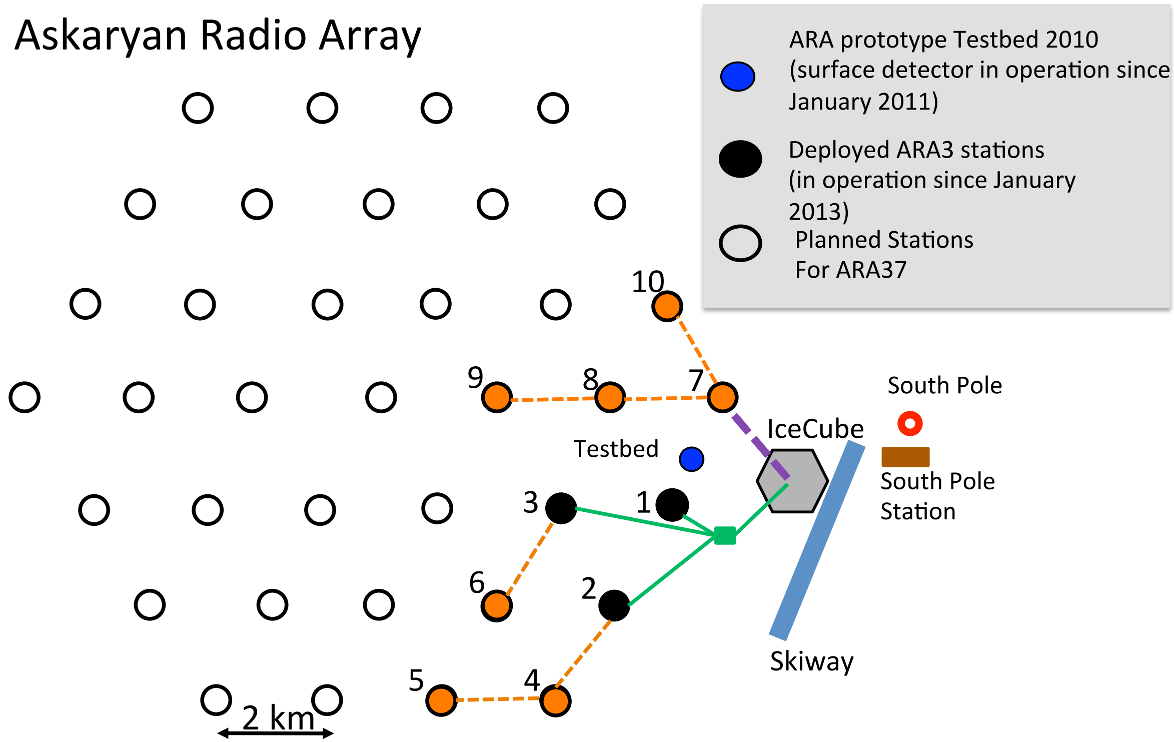
Preliminary Results – 2 Stations

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



PROSPECTS AND FUTURE CAPABILITIES

Future Expansion



- Expansion of array will increase sensitivity
- Improvements in station electronics and analysis techniques
  - Have yielded improvements in sensitivity already

Improvements up to ARA37

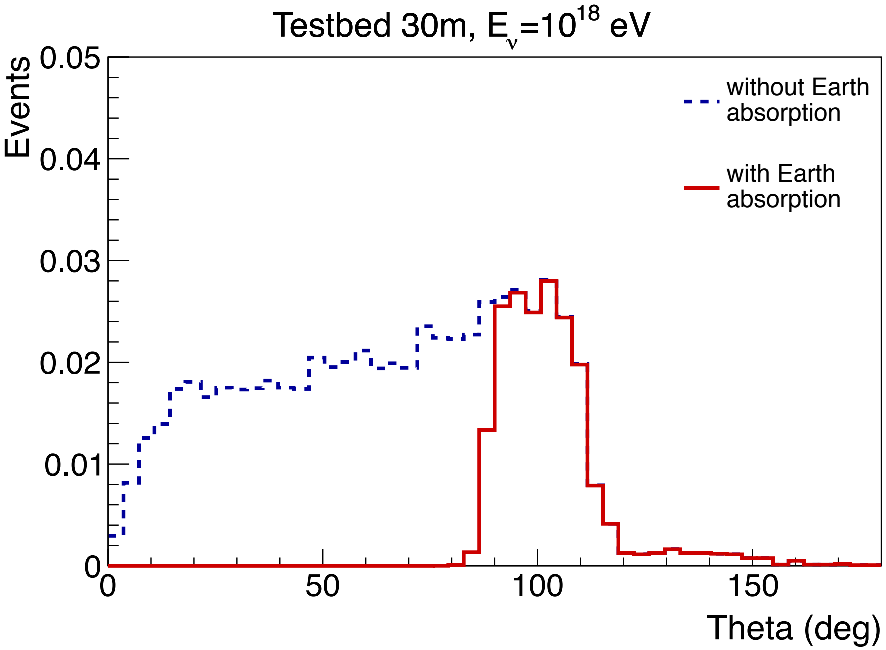
Simulated Improvements at 10^{18} eV	$A\Omega_{eff}$ [$km^2 sr$]	Accumulative factor	
Testbed Analysis	1.5E-4	1	A
Testbed Trigger	1.5E-3	10	B
ARA One-station Trigger	4.1E-3	28	
ARA37 Trigger	1.3E-1	900	

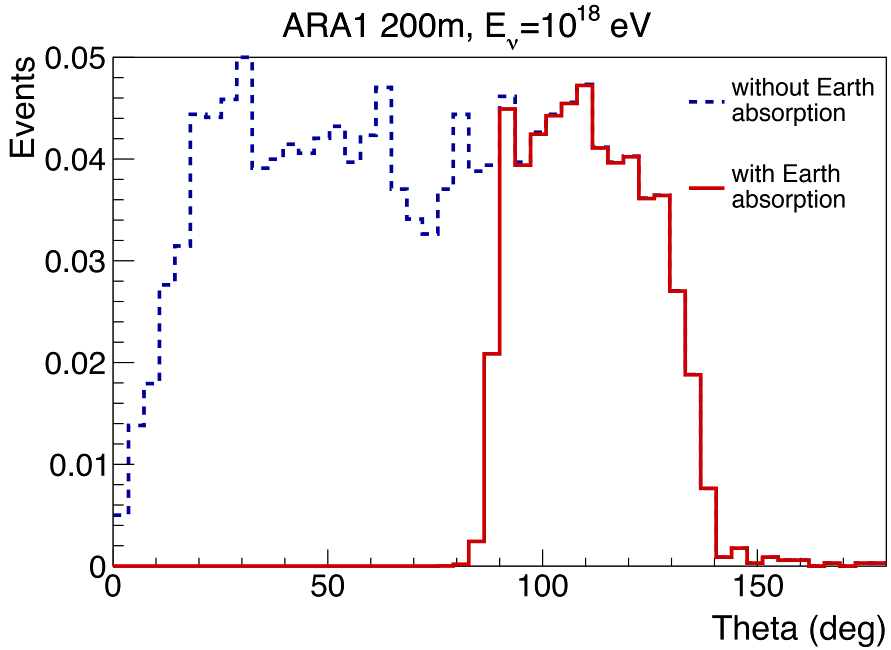
- Improvement in a number of areas - 2 basic types
  - A: Analysis level – 10% for Testbed → 60% for A2/3
  - B: Trigger level - deeper stations, station design

Analysis Improvements (TB → A2/3)

- Improvements on Testbed analysis technique alone
  - Further from South Pole Station
    - Less noisy, geometric rejection region can be smaller
  - Not taking data during IceCube drilling period
    - Less noise, no noisy-time cuts
  - Removal of pattern recognition cuts for "strange" repeating events found only in Testbed
  - Removal of redundant cuts
  - Improves efficiency from 10% → 40%
- A2/3 analysis uses simplified set of cuts with higher efficiency on simulated neutrinos
  - Improvements in reconstruction method
  - 40% → 60% efficiency

Trigger Level Improvements

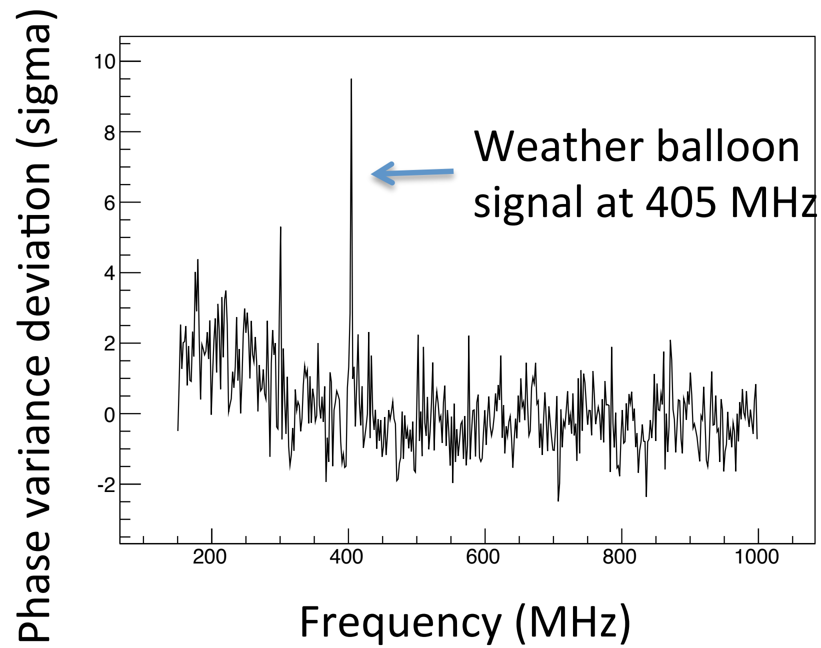




- Shallow Testbed station → deeper stations
  - Decreased shadow region (see slide 13)
  - Acceptance from a greater range of inclined showers
- Currently working on trigger design improvements
  - Currently use a simple coincidence trigger (N hits above threshold within X nanosecond window)
  - Possible improvements: Pattern trigger, two triggers

Future Improvements

- Reconstruction methods
  - Account for index of refraction and reflection, speed
- Better identification of anthropogenic signals from South Pole – less critical for deeper stations
  - Improve livetime and event selection during active season
- Improved CW removal
  - Developing phase variance technique for filter instead of cutting outright
- Improved trigger
  - require causal time sequence with respect to known geometry



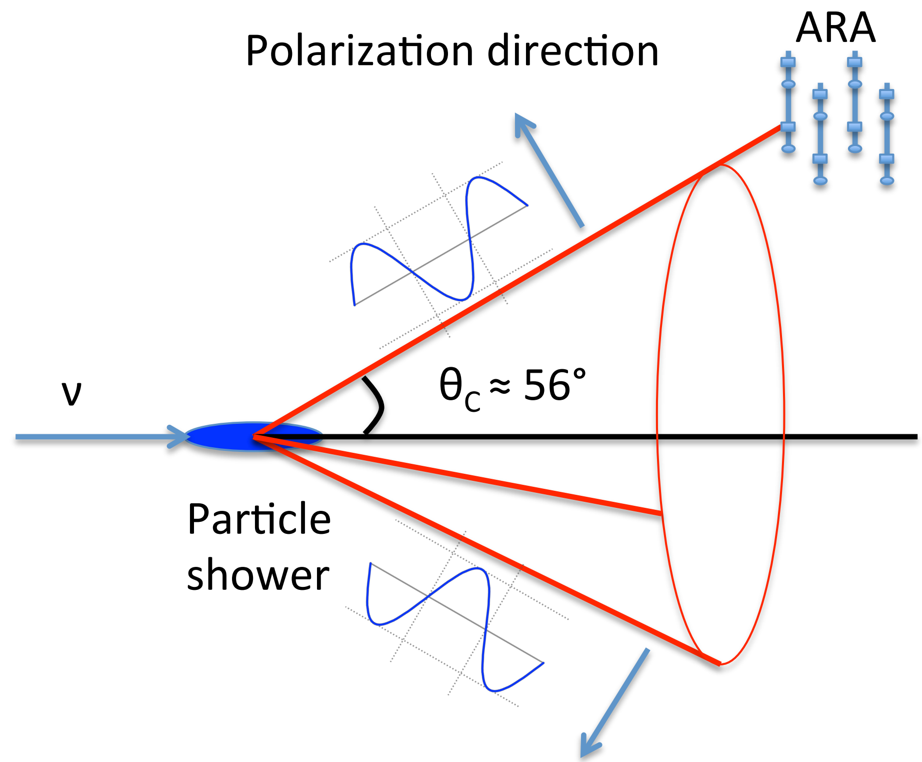
PROSPECTS FOR EXTRACTING NEUTRINO INFORMATION

Observables

- What information about the neutrino do we want to extract?
  - Energy, pointing direction, flavor
- How do we get there?
  - received radio signals → information about neutrino
  - Must interpret the radio signal
    - relative timing, shape, amplitude, polarization
  - Need refined modeling of radio Cherenkov signal
    - Shower emission model, ice model, LPM effect

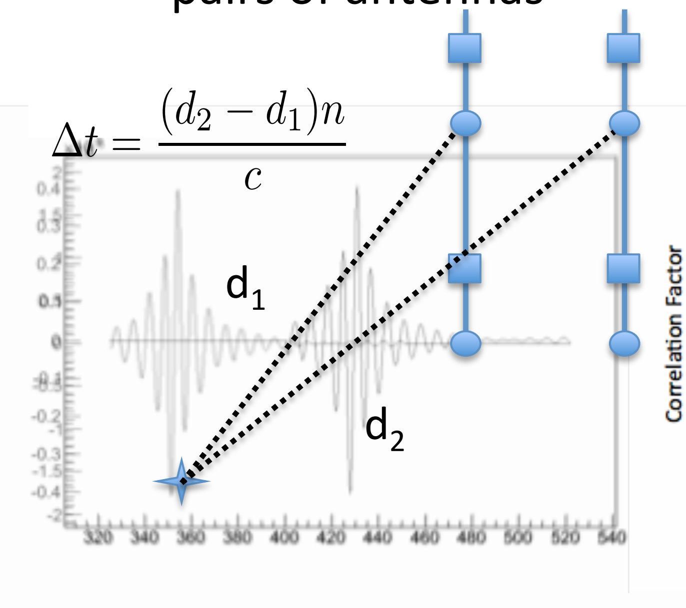
Pointing Direction

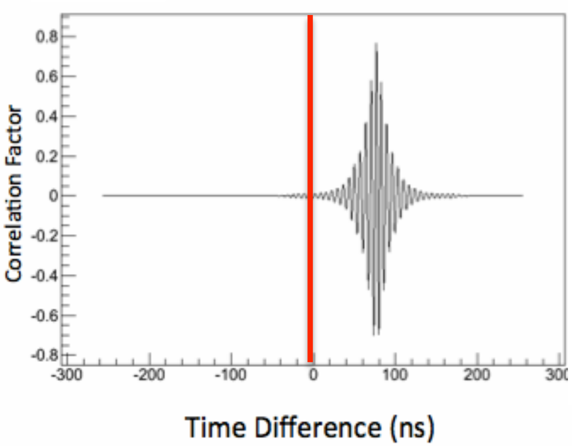
- Want to trace events back to a point in the sky
  - Source? Diffuse?
- Pointing direction of incoming neutrino needs
  - Reconstructed position
  - Polarization
  - Known Cherenkov angle (~56°)
- Cherenkov ring depends on direction of shower/incident neutrino
- Rejection of known sources and clusters of events
  - South Pole Station, weather balloons, etc.

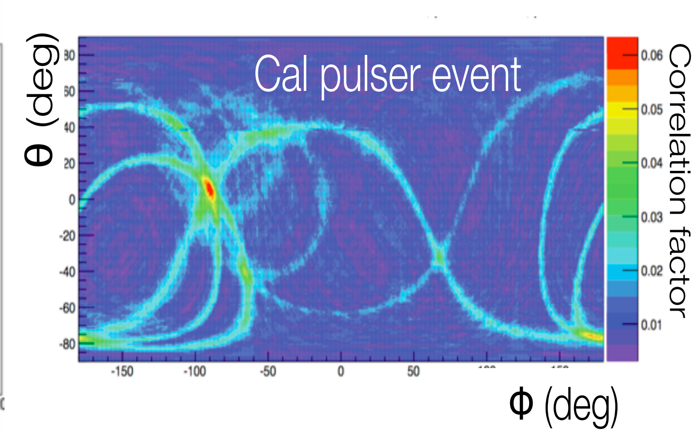


Position Reconstruction

- Impulsive waveform – ~1-10 ns time scale
- Correlation factor - Convolution of the two waveforms including a timing offset
- Only Vpol-to-Vpol comparison and Hpol-to-Hpol comparison
- Calculate timing delays for all angles of approach
- Sample correlation plot at these delays
- Many positions will produce the same timing delays for a pair of antennas
- Solution: Use more antennas - Add up all the correlation values from all the pairs of antennas

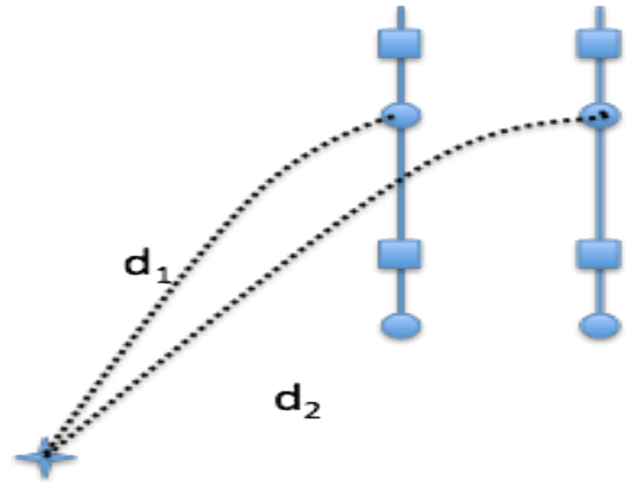


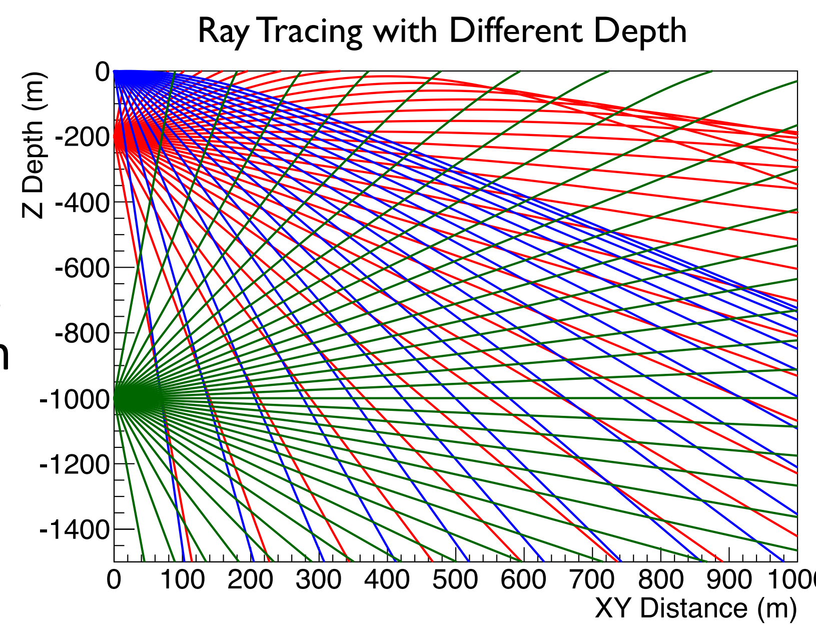




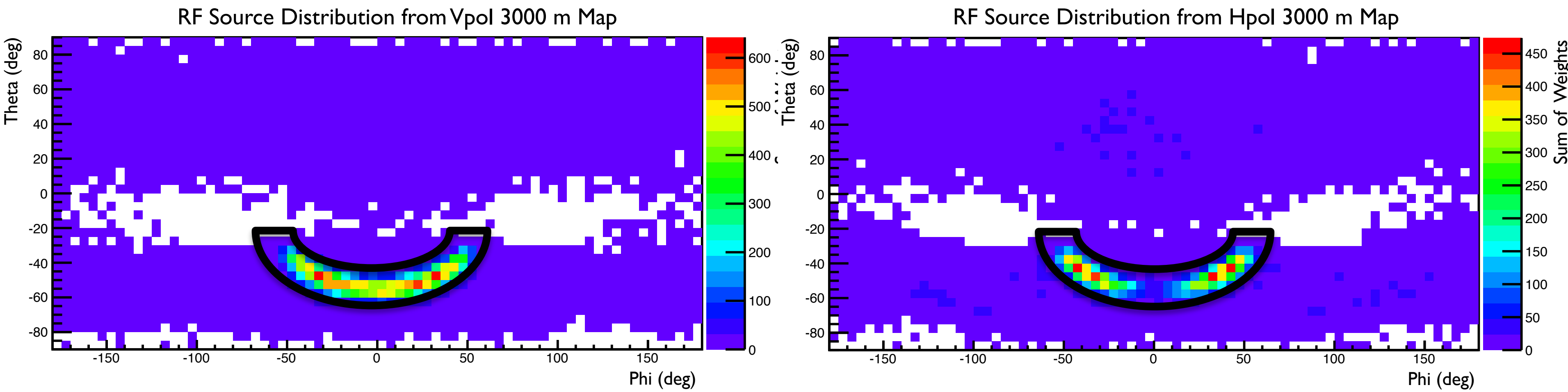
Concerns for Reconstruction

- Anything that affects timing delays will affect the correlation map
- The index of refraction of the ice
  - The values themselves
  - How they change in the ice
    - First 150 m “firn” – rapidly changing n
    - Changing n -> Snell’s law
    - Curvature in path
    - Some areas excluded
- Electronics delays - measure them
- Use calibration pulser, surface pulsers, ICL pulser to get additional timing information
- Geometric assumptions - plane-wave vs spherical vs other (ray tracing)
- Also noise over the signal can severely wash out the correlation

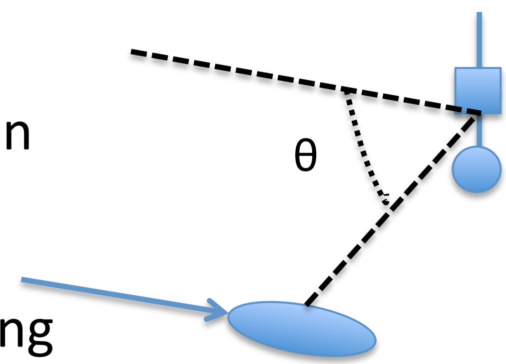




Find the Incoming Direction?



- Reconstruction direction rotated so that the neutrino incoming direction is at (0,0)
- Useful to restrict the possible source direction
- Compare events to particular astrophysical events (GRBs, etc.)
- Add polarization information, narrow incoming direction even further

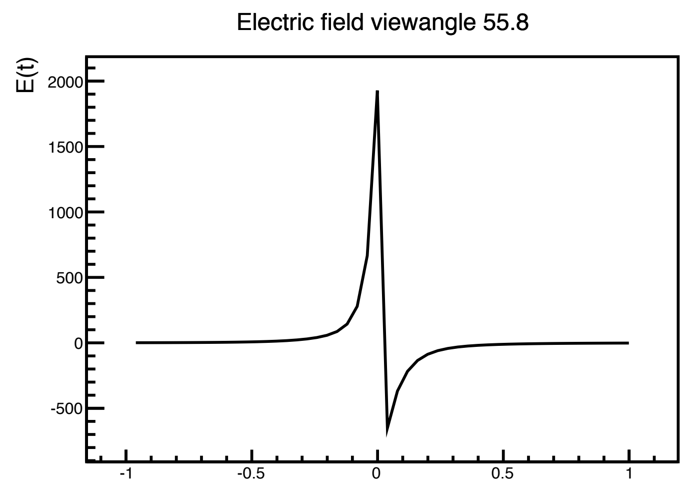


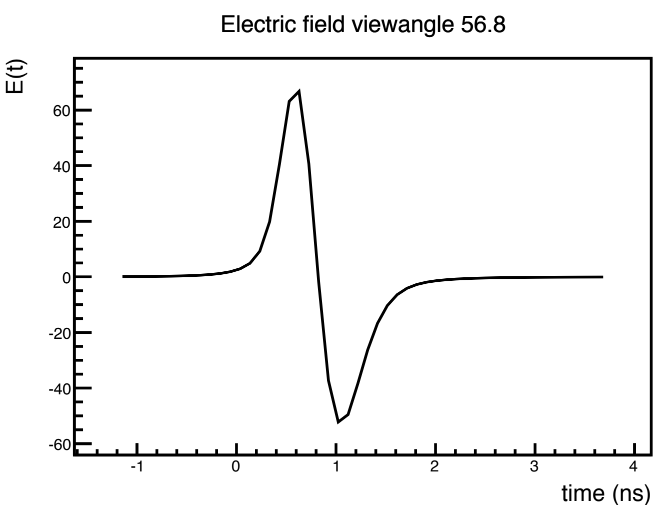
Energy of Primary

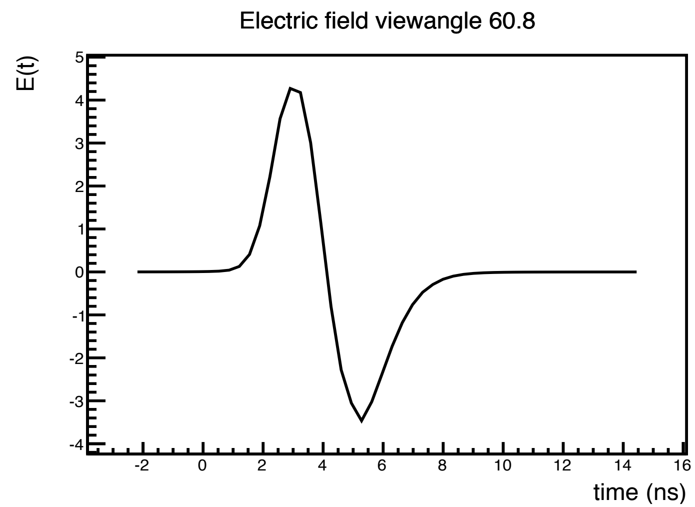
- Primary → shower development → viewing angle → received radio signal
- Energy reconstruction will depend on
  - Signal strength, signal shape
  - Position reconstruction
- Shape and amplitude of the signal depend on
  - Energy of primary – proportional to charge in shower
  - Charge excess profile of particle shower
  - Deviation from Cherenkov angle
    - Also dependent on ice model

Cherenkov angle

- Viewing angle relative to the Cherenkov angle changes the shape and magnitude of the signal
  - Faster signal at Cherenkov angle
  - Can also be examined in frequency domain

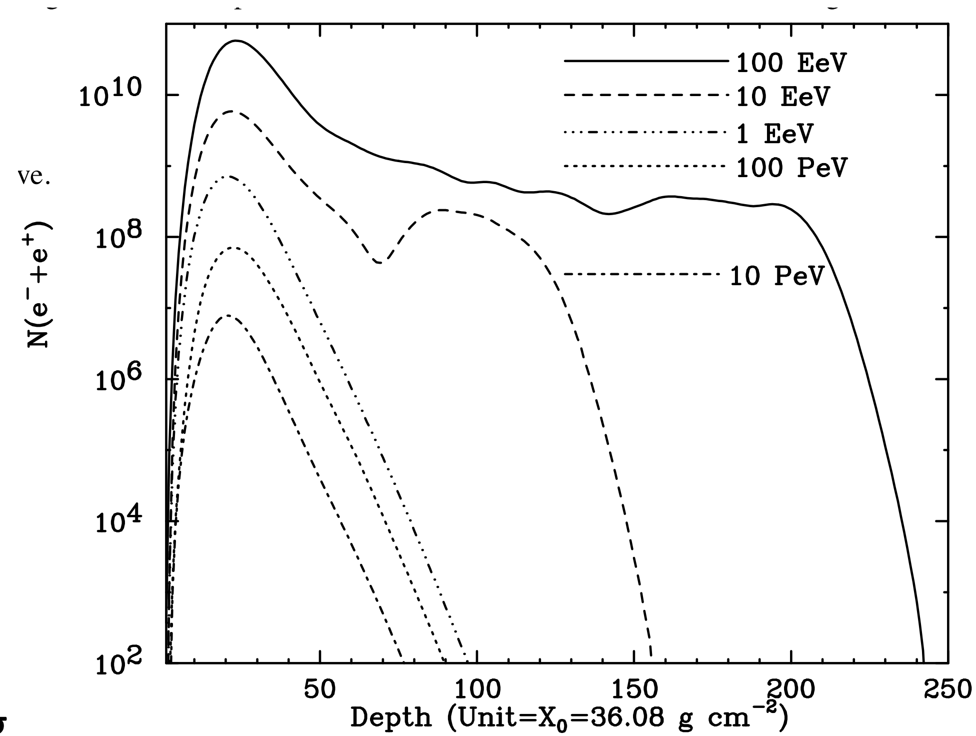






LPM effect

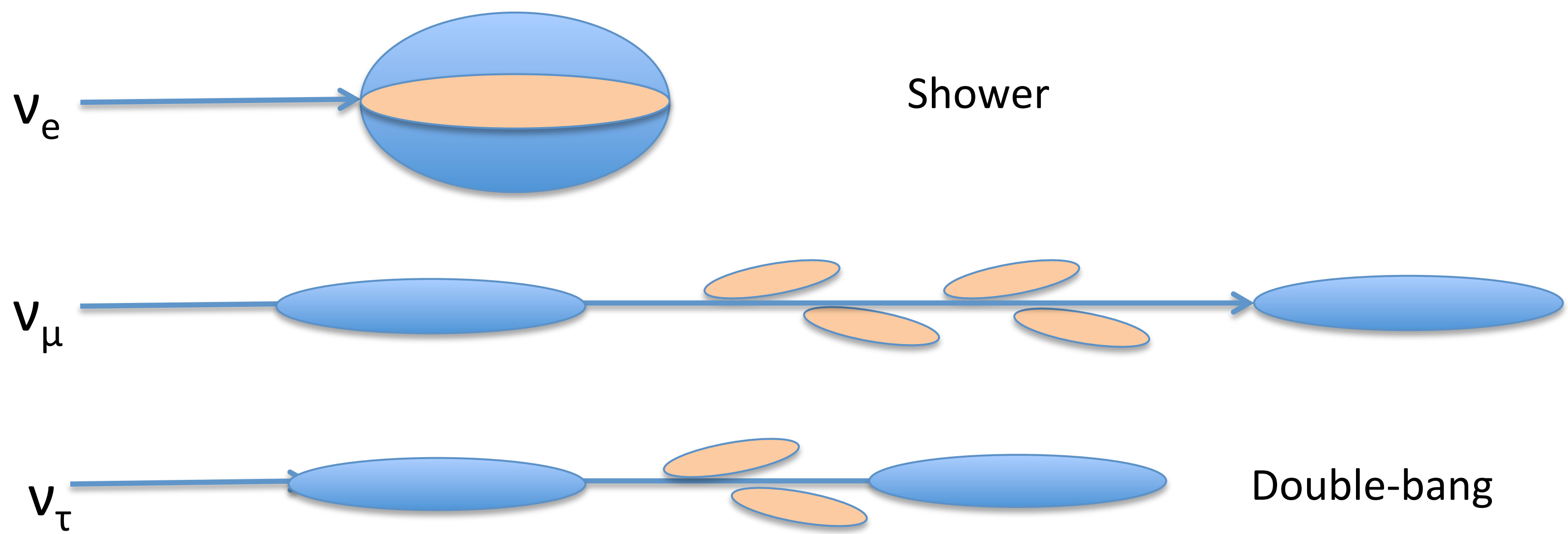
- At sufficiently high energies, interaction length increases dramatically
- Hadronic showers
  - For E_ν > 1 EeV, LPM effect becomes important
- Electromagnetic showers
  - $E_{LPM,E\text{-}M}$ = 2.4 PeV
  - EeV neutrinos will show lengthening of shower profiles
- Shower profile → charge excess profile → radio signal
- Developing models for including LPM effect in radio pulse profile



J. Alvarez-Muniz and E. Zas, ICRC 1999, arXiv:astro-ph/9906347

Flavor determination

- ν_e produces prompt hadronic and electromagnetic showers
- ν_μ and ν_τ produce initial hadronic shower, stochastic losses, final hadronic shower, different lengths for produced μ and τ
- Each shower produces a radio Cherenkov signal
  - For ν_μ and ν_τ, multiple radio pulses with observable delays
  - Useful to have a large array for this
    - One station is not likely to see both bangs because of directed Cherenkov emission
- Analyses of ANITA data look for repeated triggers with short delays for magnetic monopoles too (Phys.Rev.D83:023513,2011)



Summary

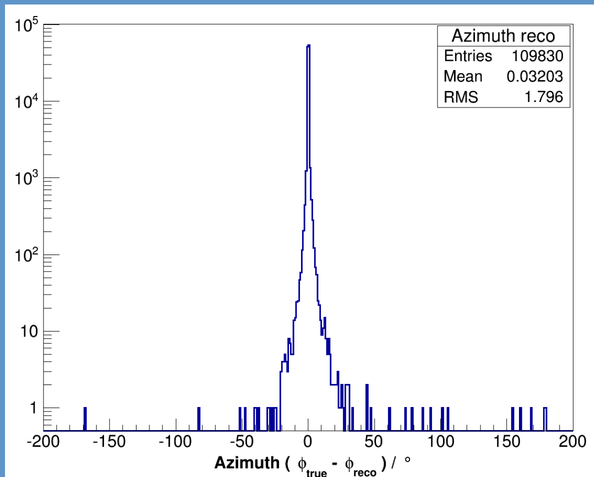
- ARA is continuing to be built
- First limits from Testbed analysis
  - Diffuse flux: arXiv:1404.5285, accepted in *Astropart. Phys.*
  - GRB flux: quasi-diffuse limits above 10^{16} eV
    - Publication in preparation
- Deep stations:
  - Preliminary diffuse limit from 2 stations
    - Publication in preparation
- Deep stations see marked improvement in sensitivity
  - Deeper station, more antennas, better quality data
  - Improved (2nd generation) analysis techniques
  - Expect even more refined analysis and trigger in future
- Capable of extracting information about neutrino
  - pointing direction – some additional work,
  - energy – lots of additional systematics to study
  - flavor (?) – shower type (CC/NC), possibility of seeing a double bang

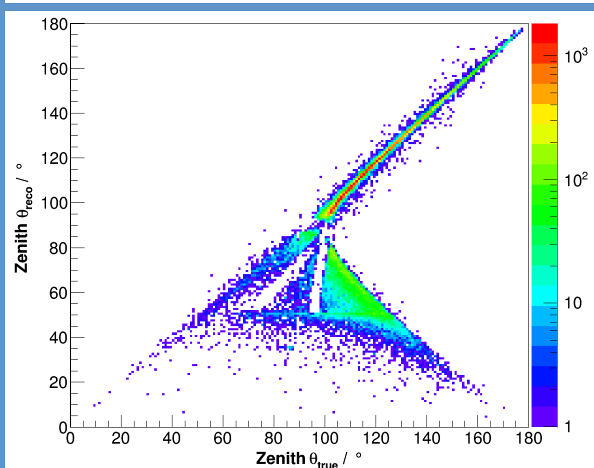
Questions?

Backup Slides

Reconstruction results

Simulated neutrinos

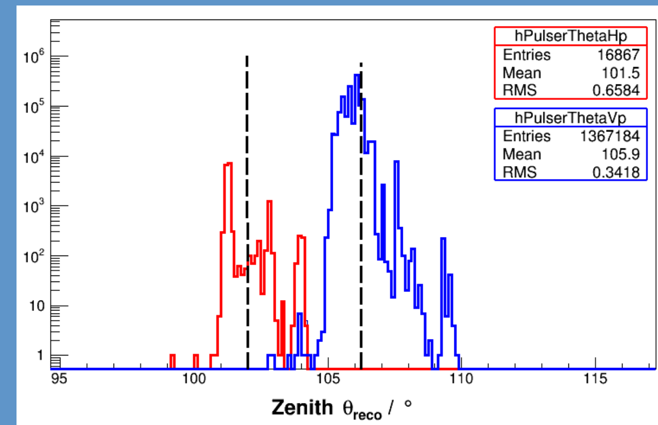


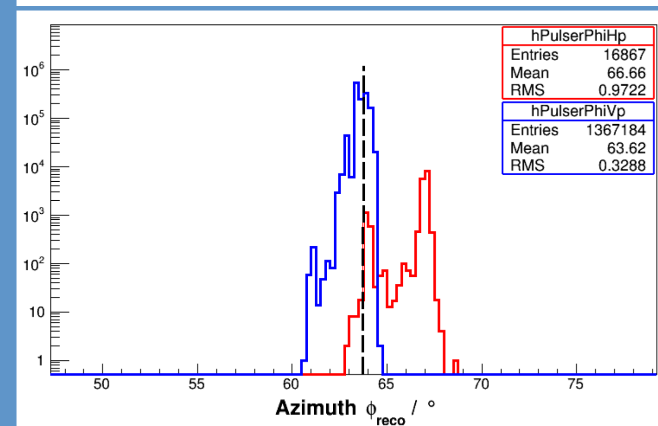


Can not handle surface reflections

This causes efficiency loss

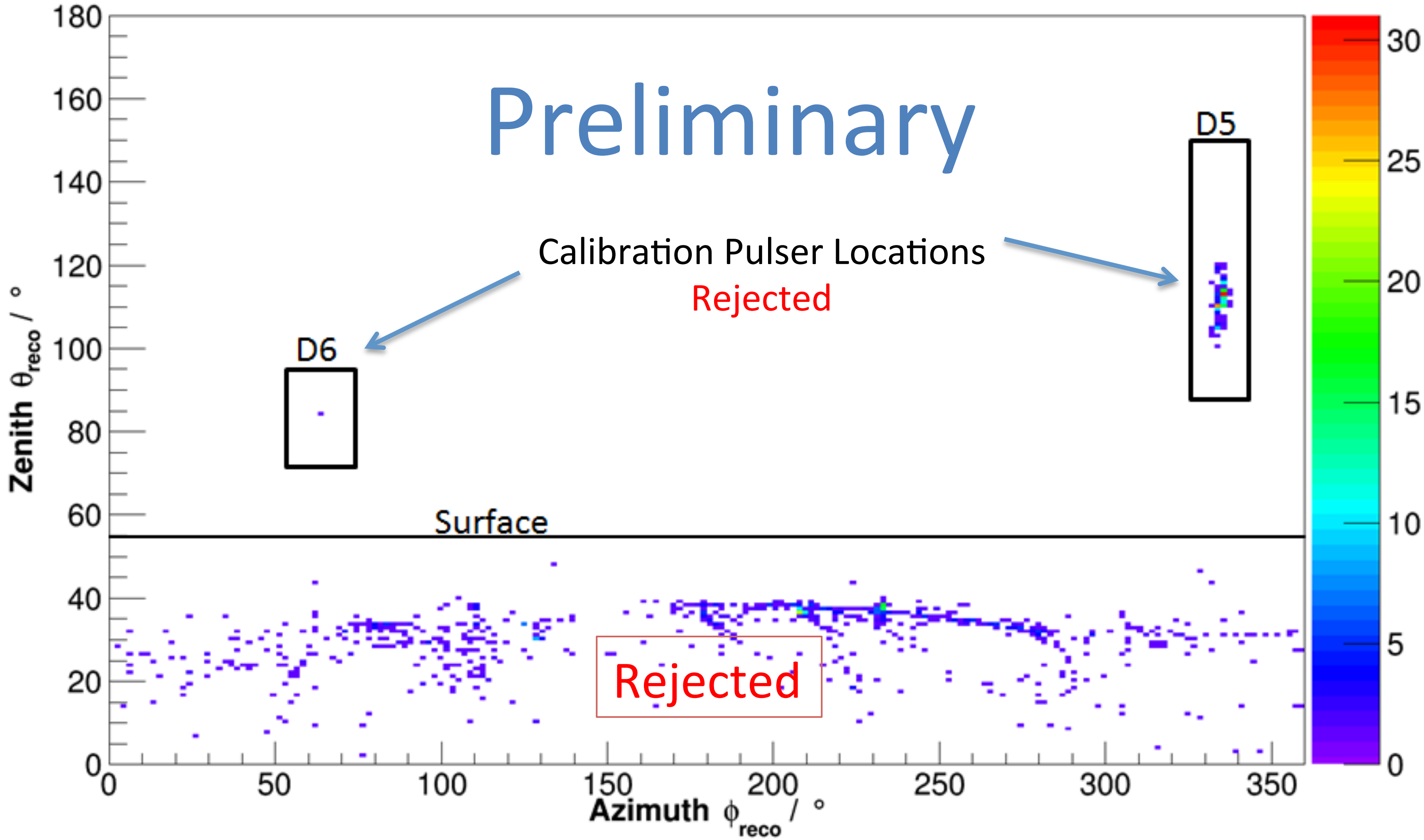
Calibration source: distance 40m





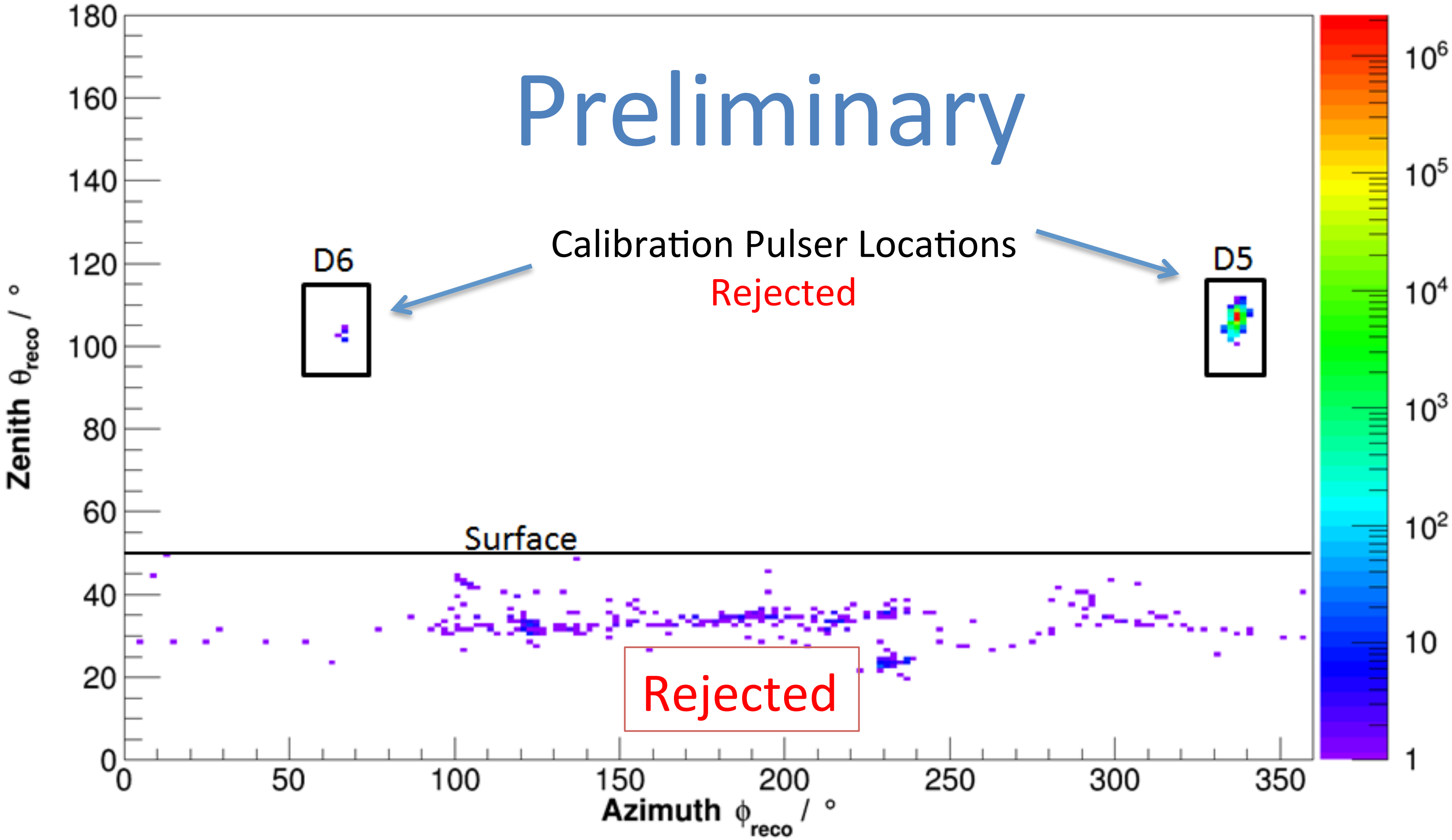
RMS < 1°

Skymap A02



Preliminary
Calibration Pulser Locations
Rejected
D5
D6
Surface
Rejected
Zenith θ_{reco} / °
Azimuth ϕ_{reco} / °
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
30
25
20
15
10
5
0

Skymap A03



Preliminary
Calibration Pulser Locations
Rejected
D6
D5
Surface
Rejected
Zenith θ_{reco} / °
Azimuth ϕ_{reco} / °
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
10^6
10^5
10^4
10^3
10^2
10
1

ARA Collaboration

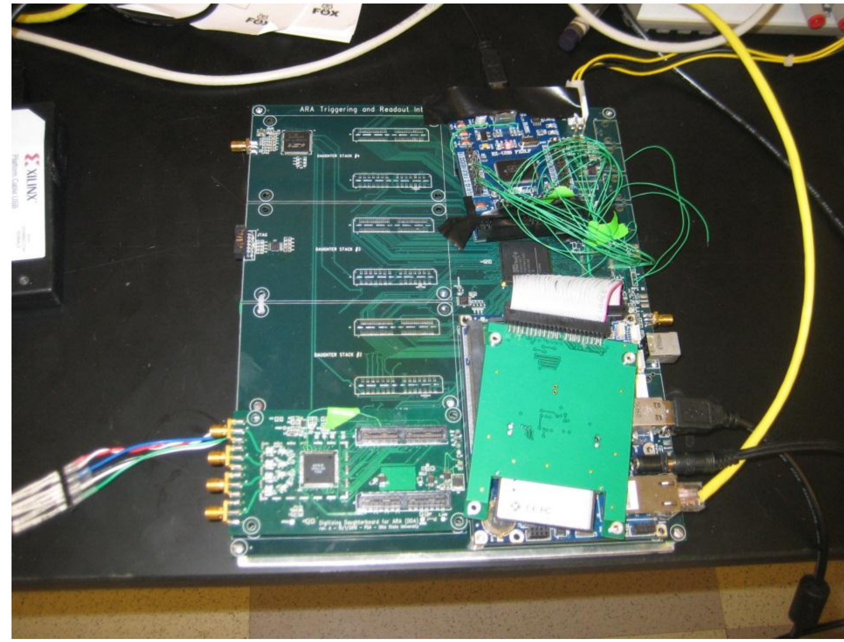
USA:
- Ohio State University
- University of Delaware
- University of Kansas
- University of Maryland
- University of Nebraska
- University of Wisconsin – Madison

UK: University College London
Belgium: Université Libre de Bruxelles
Japan: Chiba University
Taiwan: National Taiwan University
Israel: Weizmann Institute of Science
Germany: University of Bonn
Australia: University of Adelaide

- International collaboration with 12 institutions
- ~50 authors

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

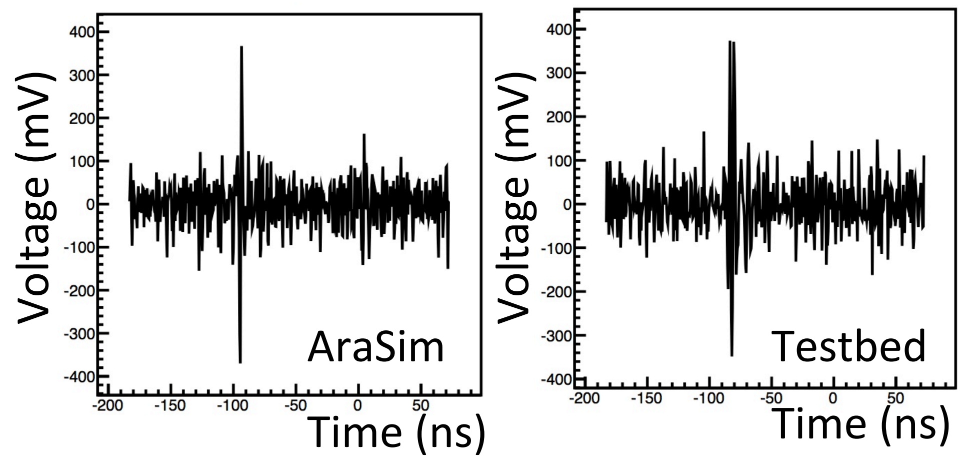


- Notch filter at 450 MHz removes communications signals
- LNA for each antenna improves received signal strength above background

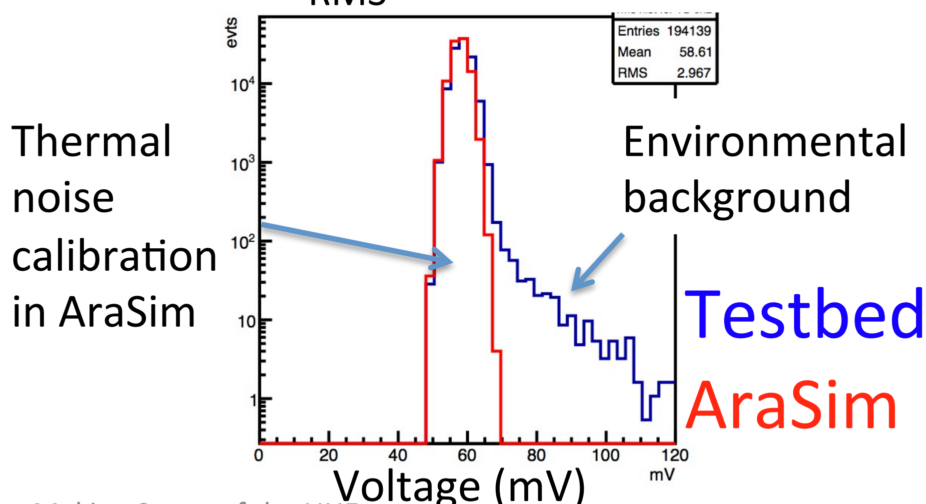
AraSim

- Official collaboration Monte Carlo simulation package for assessing sensitivity and general use
- Writes simulated events in data format for direct comparison
- Simulates full trigger and signal chain for neutrino events detected by ARA stations
- Uses parameterized shower signal
- Takes into account
  - Index of refraction model
  - Calibrated noise simulation
  - Antenna and electronics responses
  - Trigger model

Calibration pulser event waveforms



V_{RMS} Distribution



Passed Events Table from 2011-2012 TestBed Data

	Total	Quality Cut	Reco. Qual
Events	~330,000,000	157,019,347	3,265,047

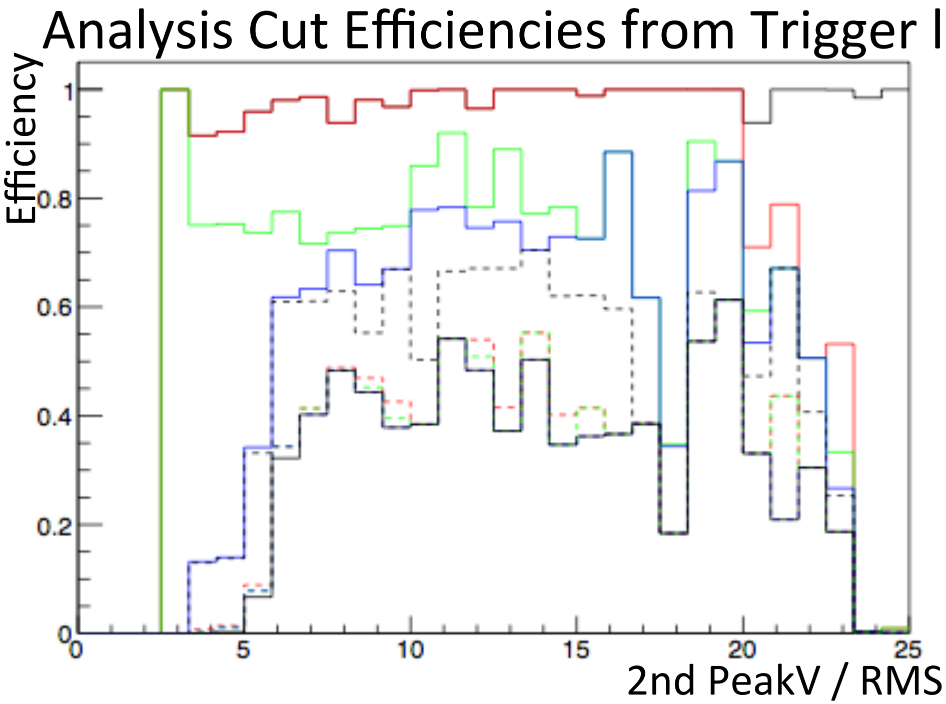
Vpol channel

	Pass Events
Reco.Qual Vpol	1,839,348
NoisyTime	1,354,670
Geom Cuts	1,122,083
Gradient Cut	1,120,713
Delta Delay	178,796
CW	177,944
Down	16,894
Rcut	0

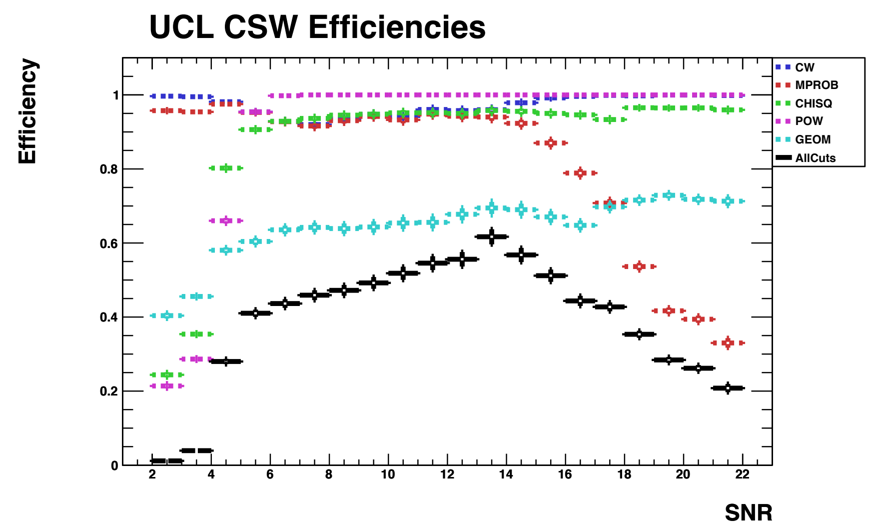
Hpol channel

	Pass Events
Reco.Qual Hpol	1,443,303
NoisyTime	1,095,497
Geom Cuts	904,099
Gradient Cut	903,036
Delta Delay	145,196
CW	142,581
Down	19,394
Rcut	0

Cut Efficiencies

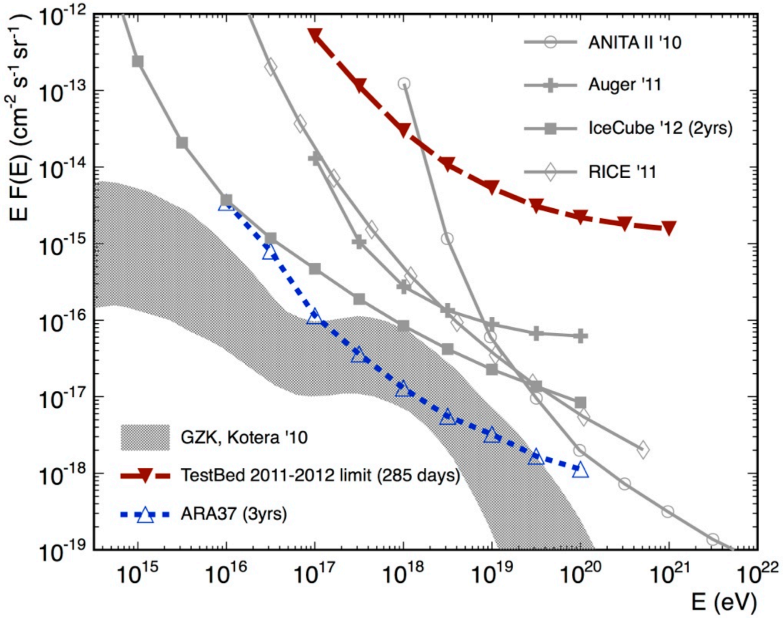


IM



CSW

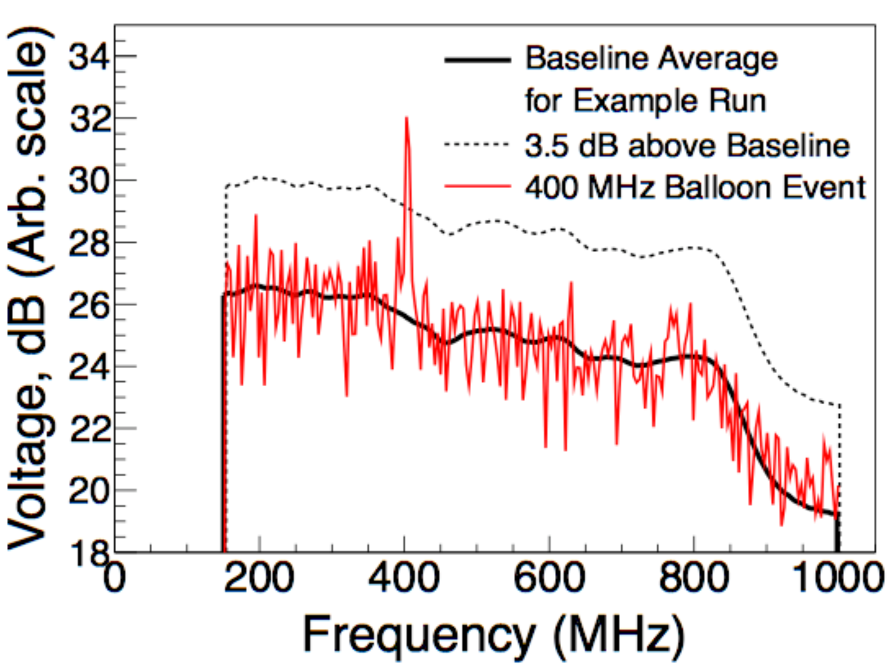
Neutrino Limit from 2011-2012 Testbed Data

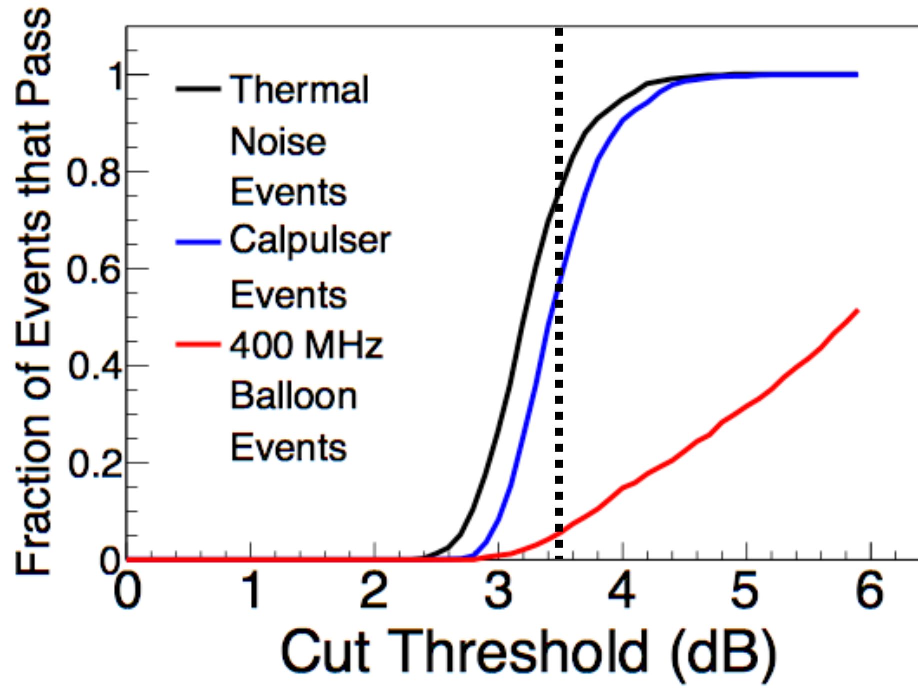


	Effective Area at 10^{19} eV [km^{2}sr]	Accumulative Factor from Testbed Analysis
Testbed Analysis	7.37E-04	1
Testbed Trigger	4.08E-03	6
ARA one station Trigger	1.70E-02	23
ARA two stations Trigger	2.98E-02	40
ARA 37 Trigger	4.04E-01	550

- After finalizing all the cuts, we looked at remaining 90% of data
- ~ 0.06 expected thermal background events and ~ 0.02 neutrino events from 1.5 years of Kotera flux from TestBed
- Analysis cut efficiency on Kotera model ~ 40% for V_{peak}/RMS from 7 to 20
- From first 2012 4 months analysis, we had 3 survived events and from 2011-2012 analysis, we had 2 survived events (total livetime ~ 285 days)
- Both survived events are anthropogenic backgrounds (rejected by modifying geometric cuts)
- Zero neutrino candidate event

Rejecting CW Background





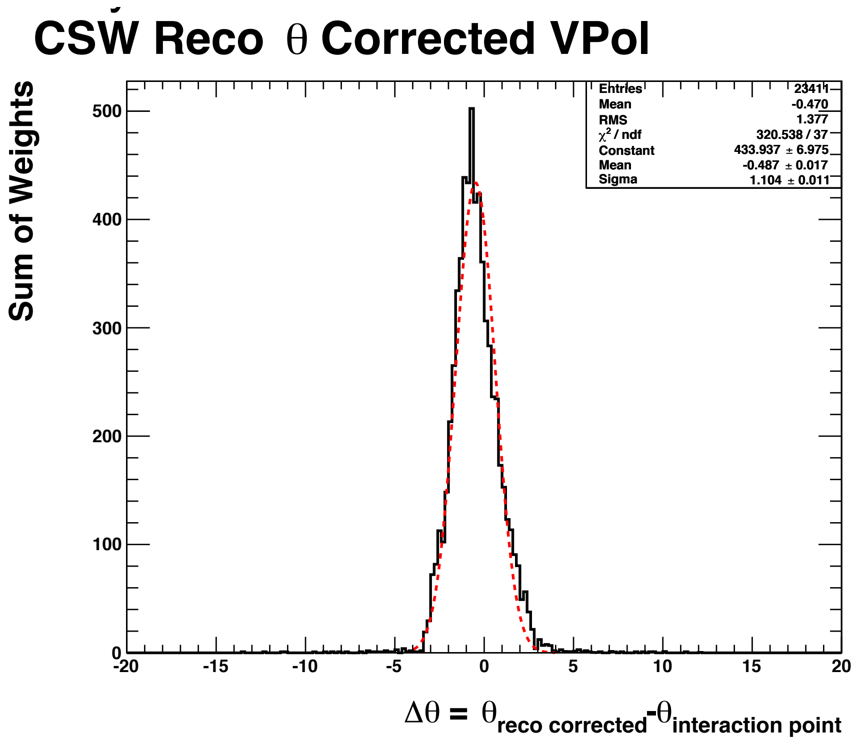
- Design cut based on ANITA experience
- Make average spectrum for each run (1 run = 18000 evts ~ 30 minutes)
- Reject events whose Fourier transformed voltage waveform exceeds 3.5 dB baseline anywhere in frequency space
- Will optimize the cut using AraSim and 10% not blinded testbed data

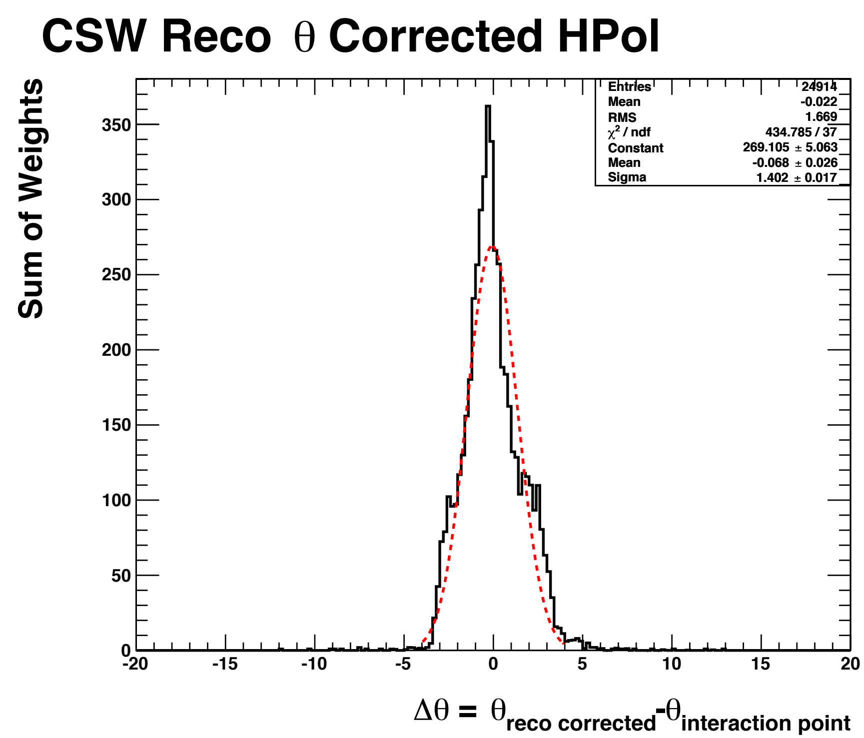
Event Cut Table (IM)

Total	3.3E8					
Cut	Number passing (either polarization)					
Event Qual.	1.6E8					
Recon. Qual.	3.3E6					
	VPol			HPol		
		Rejected			Rejected	
	In sequence	as last cut	as first cut	In sequence	as last cut	as first cut
Recon. Qual.	1.8E6			1.4E6		
SP Active Period	1.4E6	125	4.9E5	1.1E6	13	3.5E5
Deadtime < 0.9	1.4E6	0	3.2E4	1.1E6	0	9.2E3
Saturation	1.4E6	0	1.4E4	1.1E6	0	618
Geometric, except SP	1.3E6	7	9.9E4	1.0E6	0	4.6E4
SP Geometric	1.1E6	0	2.9E5	9.0E5	1	2.0E5
Gradient	1.1E6	0	1.4E4	9.0E5	0	4.6E3
Delay Difference	1.8E5	0	1.5E6	1.5E5	0	1.2E6
CW	1.8E5	0	1.3E4	1.4E5	1	3.4E4
Down	1.7E4	15	1.6E6	1.9E4	1	1.2E6
V_{peak}/Corr	**0**	1.7E4	1.8E6	**0**	1.9E4	1.4E6

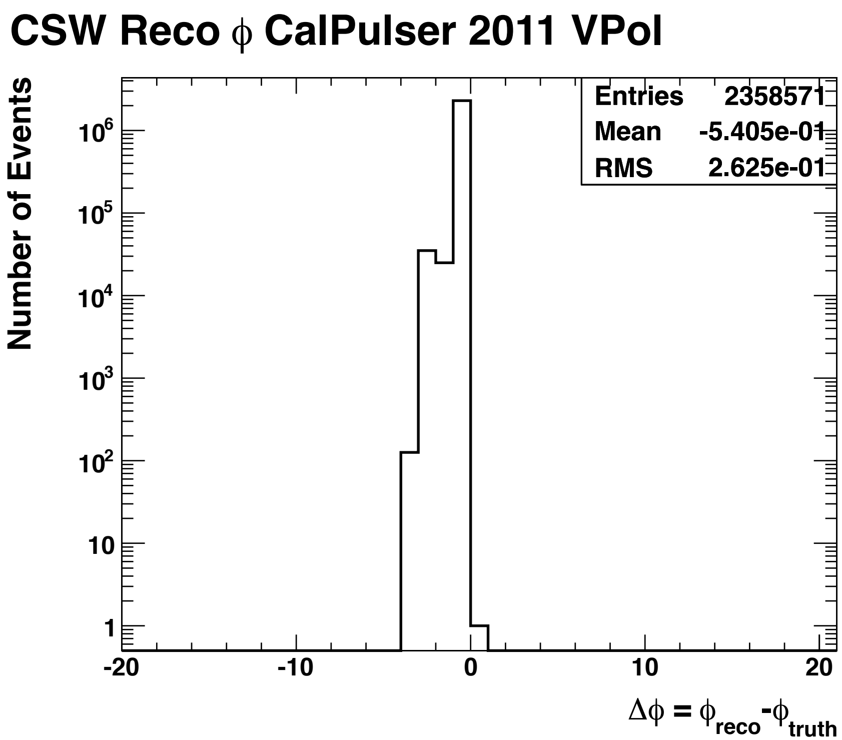
Table 2: This table summarizes the number of events passing each cut in the Interferometric Map Analysis, in Phase 2 (2011-2012, excluding Feb.-June 2012). We list how many events each cut rejects as a last cut, and how many are rejected by each cut if it is the first cut. After the Event Quality and Reconstruction Quality Cuts are applied, VPol

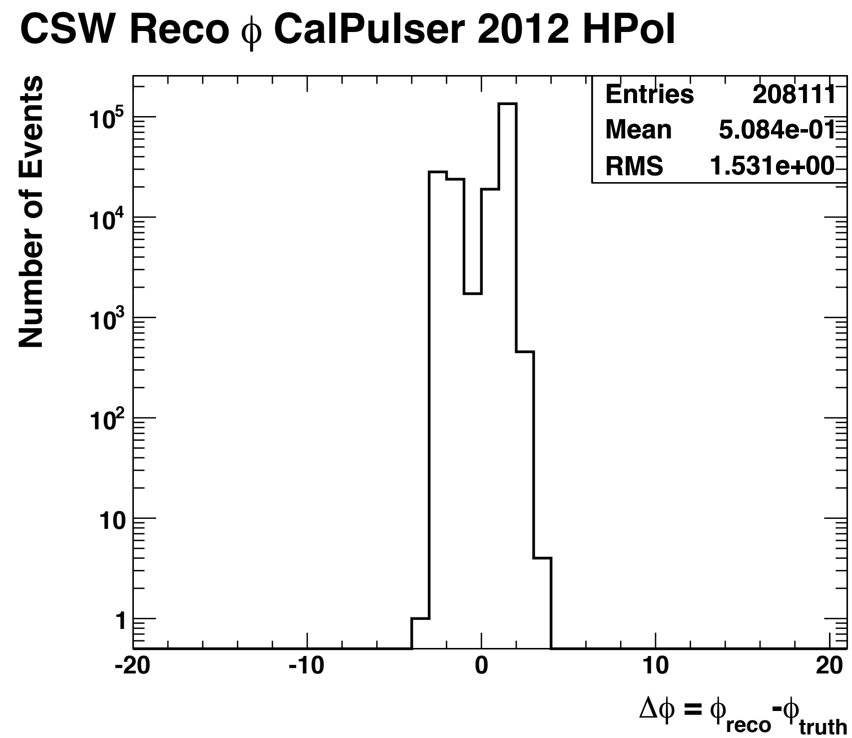
Reconstruction Error - Simulation



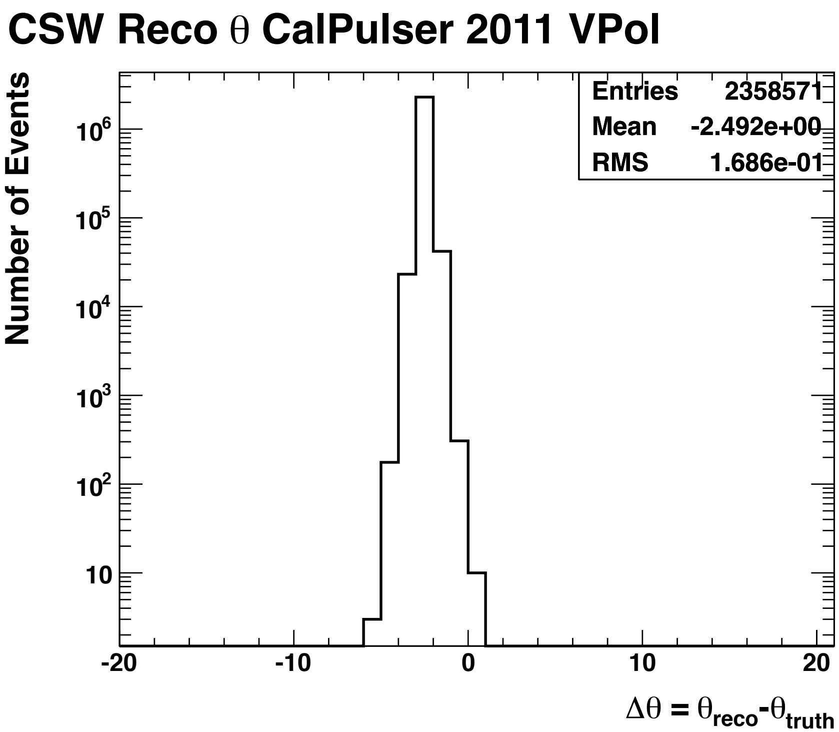


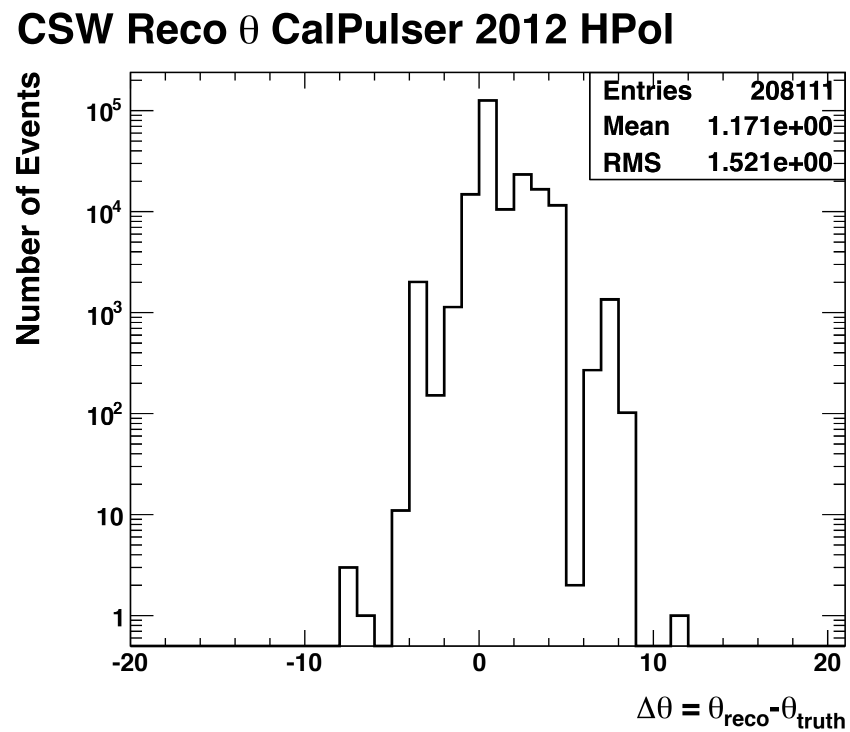
Reconstruction - Calpulser





Reconstruction - Calpulser





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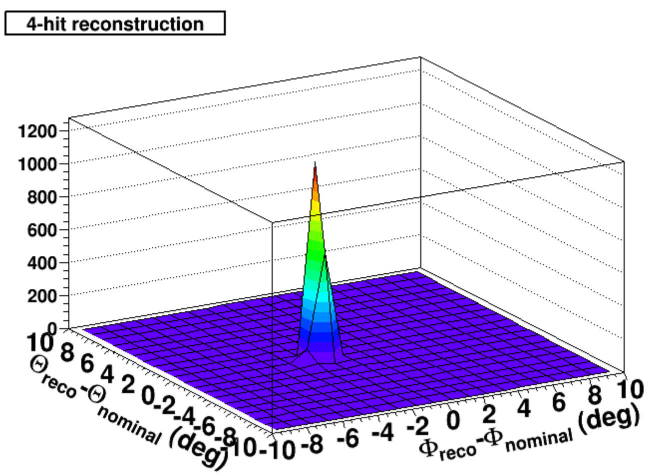
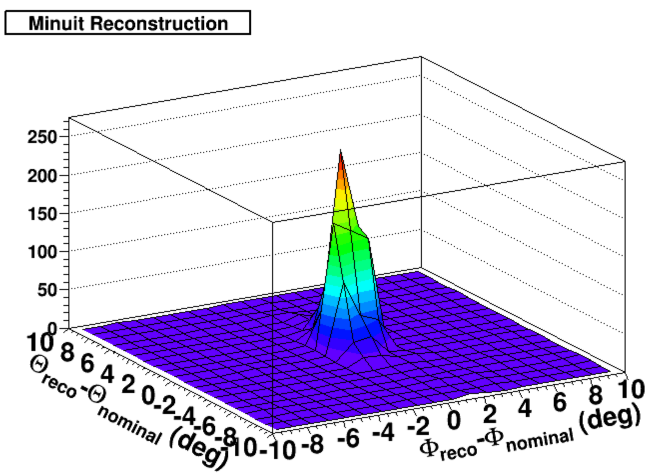
KU Analysis – Template-based

Initial Requirements:
CW filter
4 antennas have peaks in excess of
6X RMS
Minimum waveform power requirement
well-reconstructed single source vertex
non-pulser reconstruction location

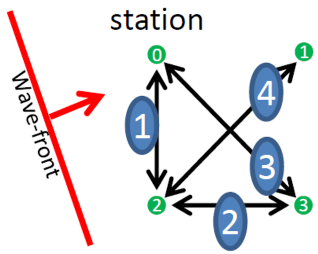
- Template matching: take remaining events and find the cross correlation between the events
  - If events have high CC, they are alike and are thus rejected



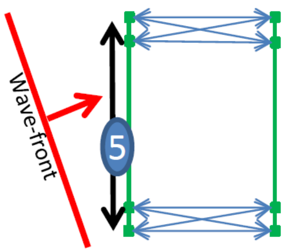


Noise filtering

Top-view on ARA station

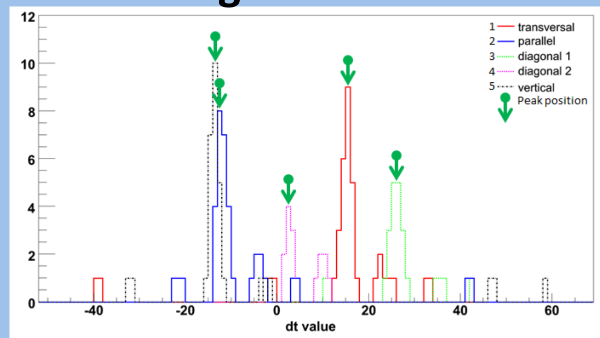


Side-view

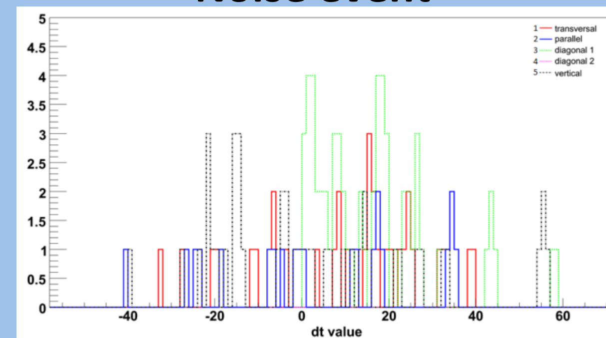


Histogram projected time differences

Signal event



Noise event

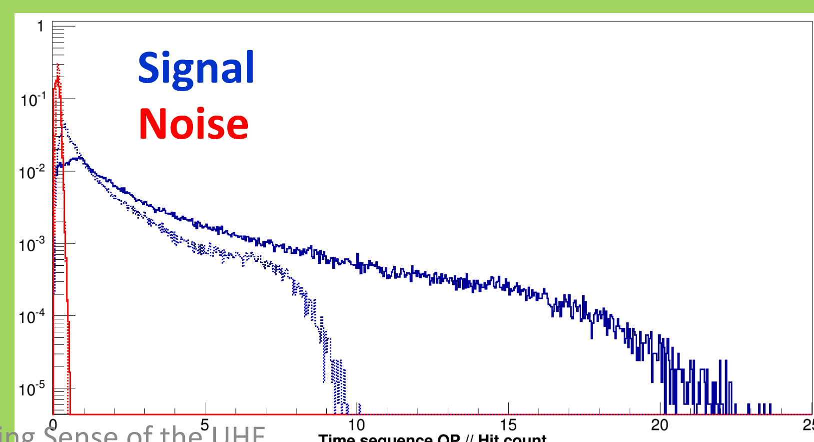


Quality Parameter: Sum of peak maxima

Result on simulated neutrino events and noise (solid lines)

Compared to simple hit count (dashed lines)

Normalized on 99% noise cut



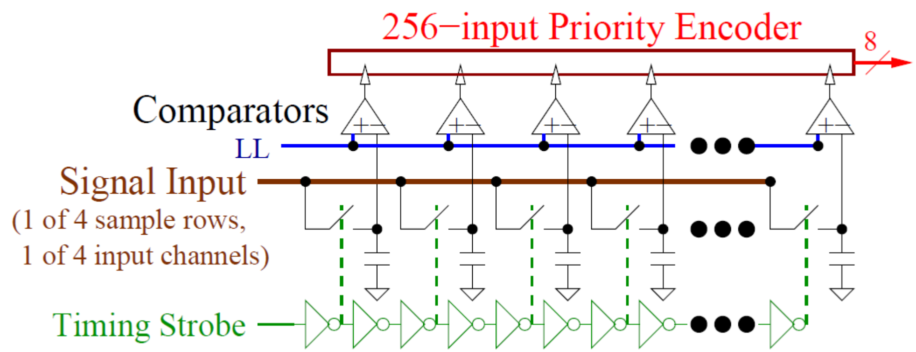
IRS2 calibration

Sample timing:

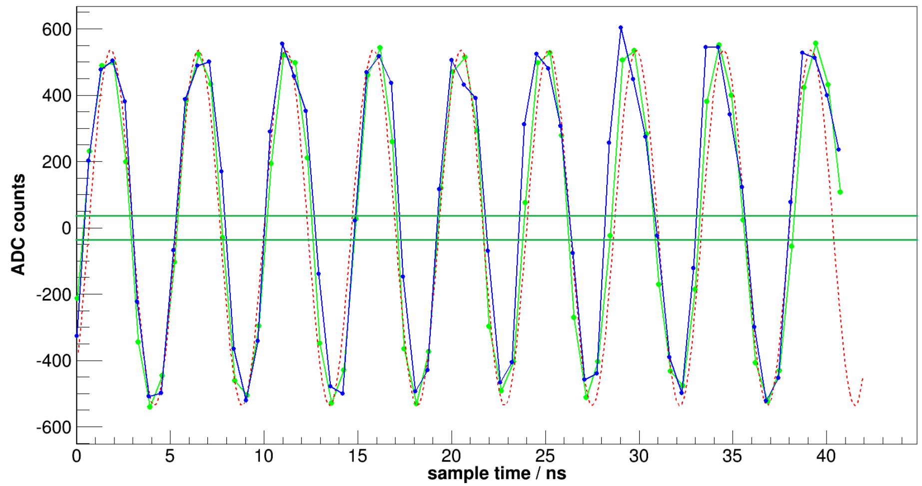
- Sampling with Switched Capacitor Array
- Average speed can be tuned up to 4 GS/s

We need:

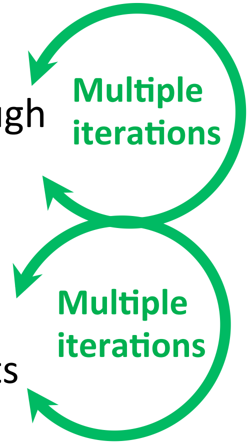
- calibration of average speed
- Calibration of singe delay elements (128 per channel)



Use sine wave inputs for calibration



- Correct average speed through fit frequency
- Correct timing for individual samples at **+/- 30 ADC** counts



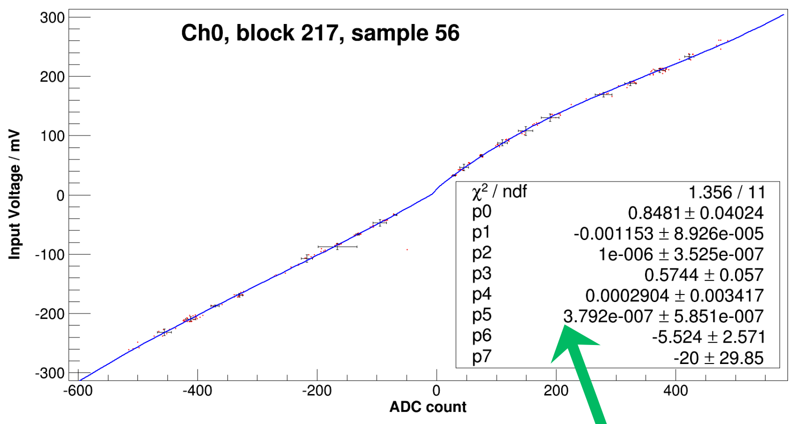
IRS2 calibration

Sample voltage:

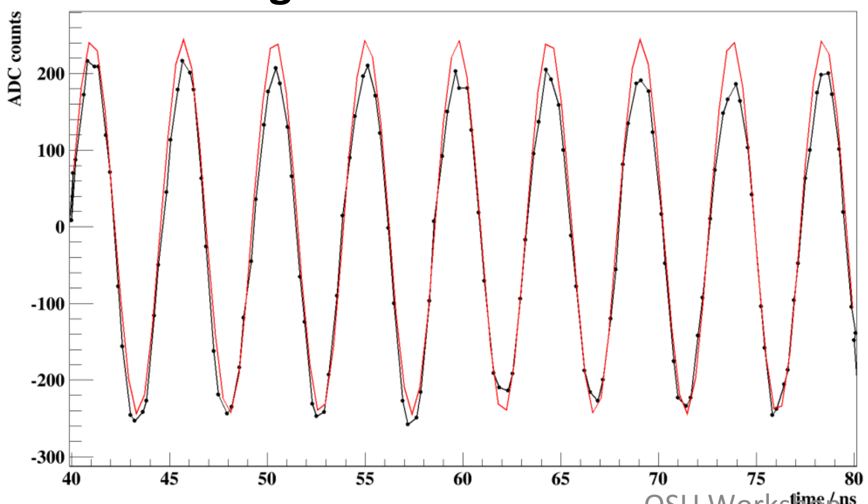
- Samples are stored on 32768 buffer elements / channel
- Digitized via Wilkinson method

We need:

- ADC to voltage conversion for the full sampling chain of each buffer element
- 1.3 M calibrations →Needs to be automated

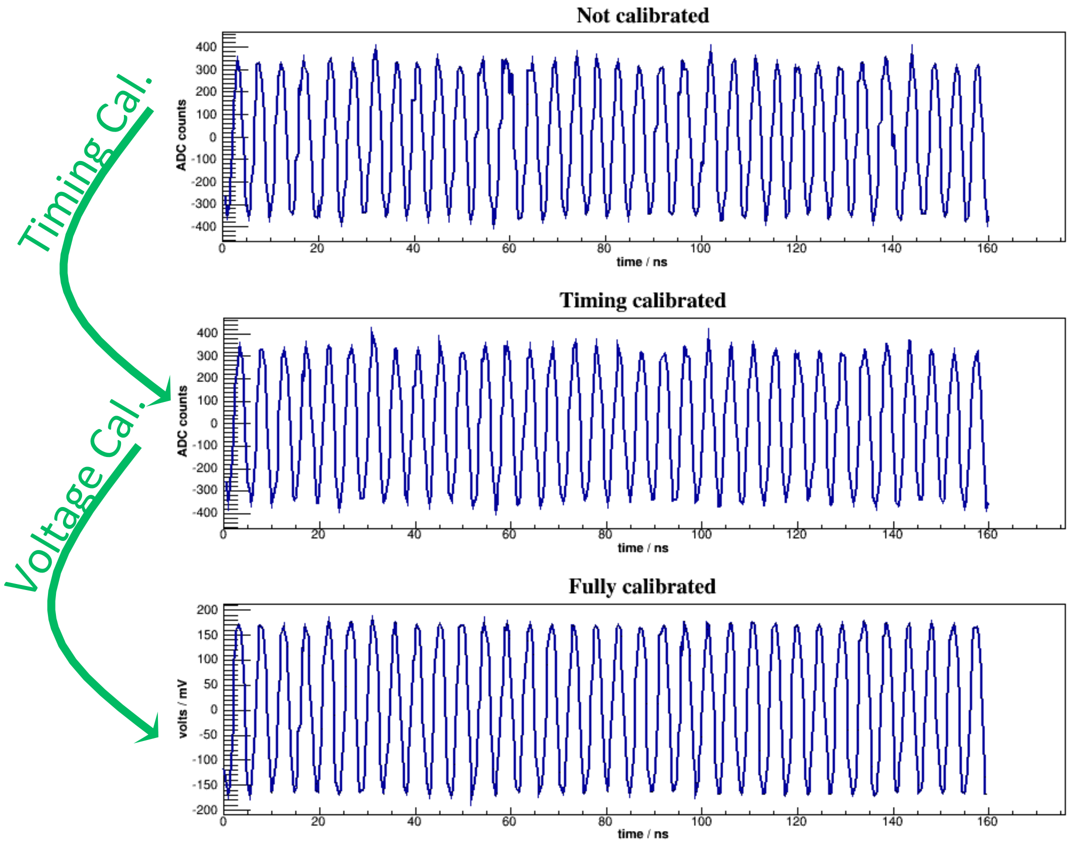


Use timing calibrated sine waves

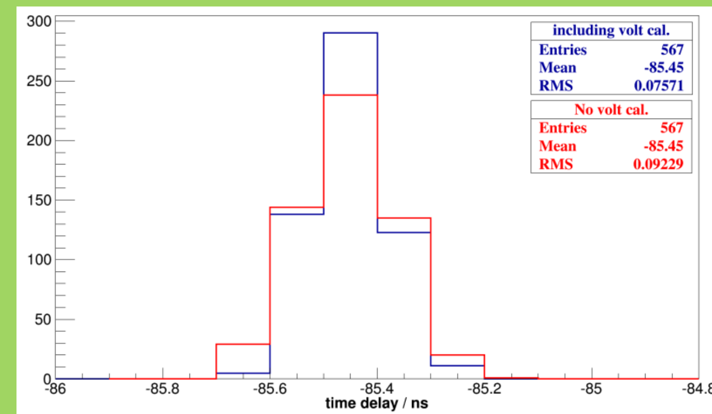


- Fit waveform with 2 X nominal input amplitude
- take calibration data for samples at peak values:
  Amplitude of fit, ADC counts
- Fit the resulting curve (multiple times with random seed)

Results



Check cross correlation



Timing precision: ~100 ps

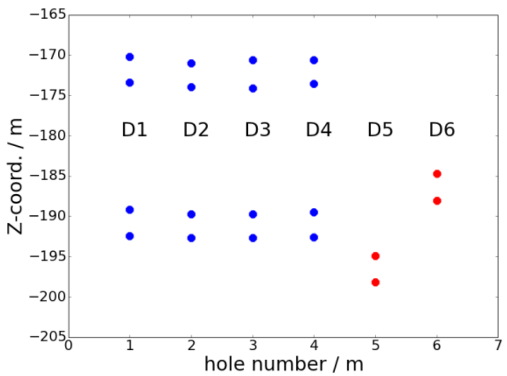
Further calibrations:

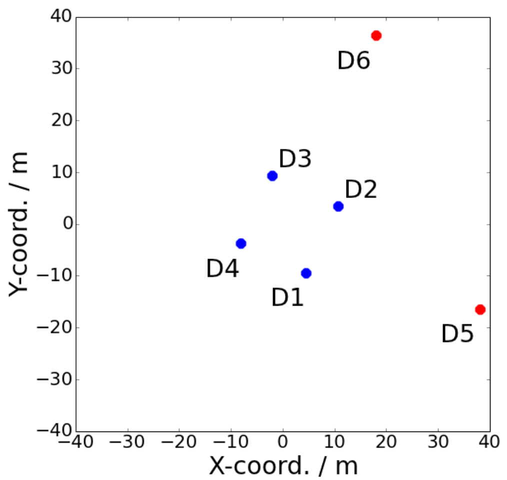
- Temperature: No dependence found
- Frequency response: Not enough information

Unsolved problems:

- Asymmetry in voltage
- Non linearity in voltage
- Slope dependence in timing
- (Frequency response)

Geometrical calibration





4 calibration sources per station (D5, D6)

→ 28 independent equations **from time differences dt**

→ 80 unknowns

→Need initial assumptions:

strings are perfectly vertical,

internal structure and time delays are perfectly known

Fitting

- String X,Y,Z position
  + relative cable delay

Reference: One string and one pulser

→ **17 fitted parameters per station (added as corrections)**

$$\chi^2 = \sum \left[c^2 (dt^2_{k,i,ref} - dt^2_{k,j,ref}) + x_k \cdot 2x_{ij} + y_k \cdot 2y_{ij} + z_k \cdot 2z_{ij} - t_{k,ref} \cdot 2c^2 dt_{k,i,j} - r_i^2 + r_j^2 \right]$$

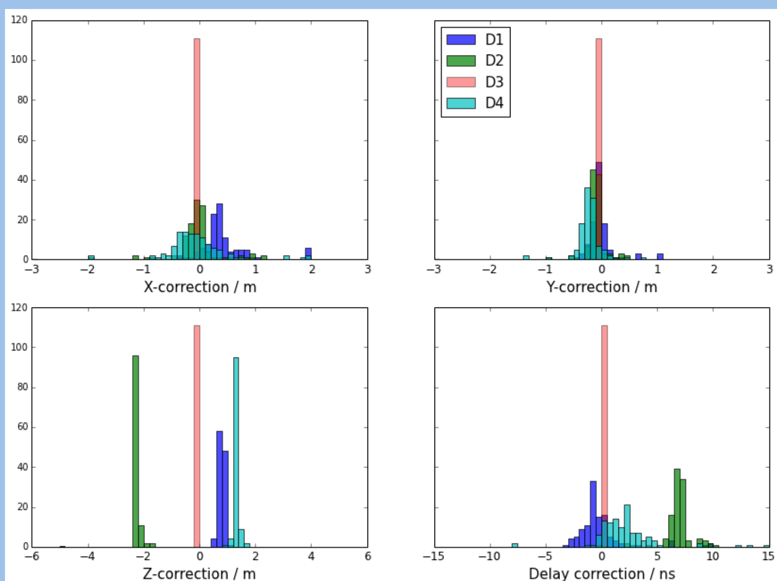
k = calibration source

ref = reference string

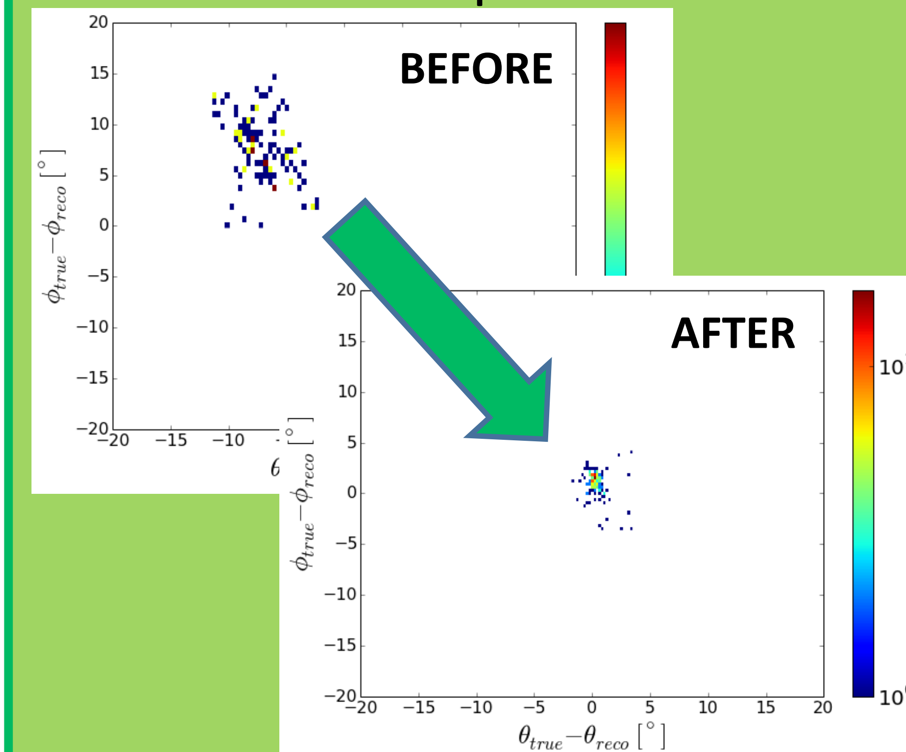
i,j = measurement antennas

Geometry calibration

Fit result ARA03



Cross check: ICL roof pulser reconstruction

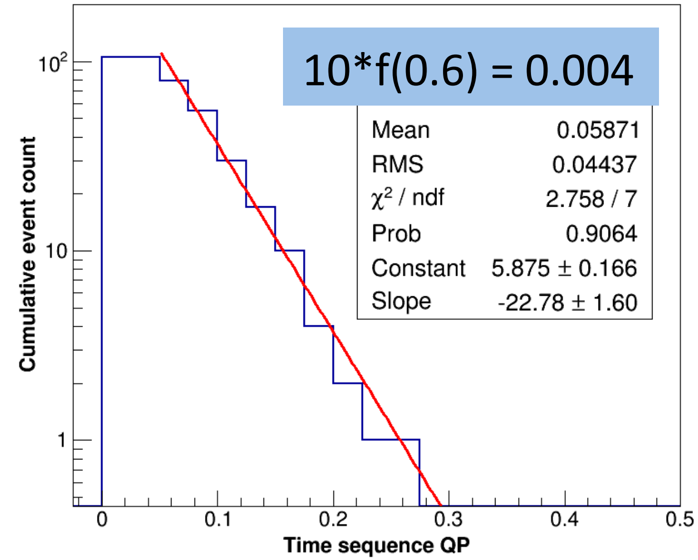


Background estimation

Iterative search, to have the sum of all backgrounds <<1

- Each cut produces background: Estimated by fit to cumulative distribution
- For QP: 10*f(0.6)
- For Residual: Perturb timings and repeat reconstruction 10 times to get an extrapolation
- For angular cuts: Same as residual

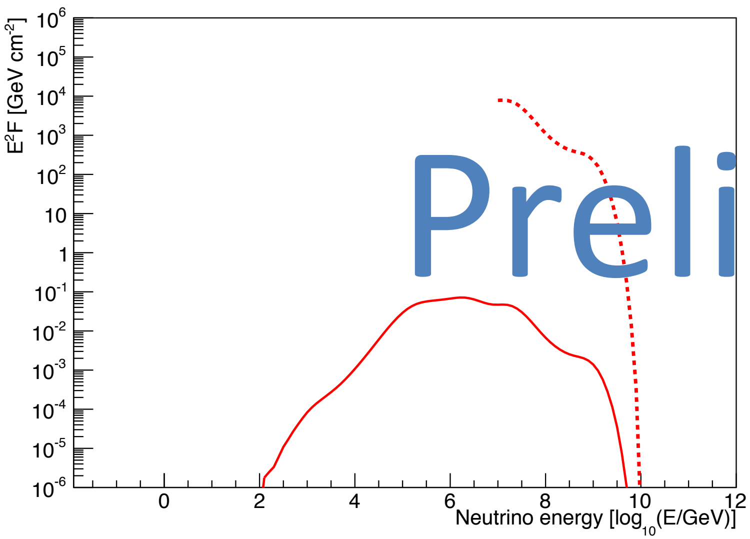
Time sequence QP cut example:



Preliminary Results

- Stage 1 (background period unblinding):
  - Expected background events: 1.166
  - 1 event survived
- Stage 2 (signal period unblinding):
  - Expected background: 0.106, Expected neutrinos: 1.47e-5
  - 0 events survived
- First quasi-diffuse flux limit above 10^{16} eV

GRB fluence limit



GRB quasi-diffuse flux limit