First Neutrino Search Results from the Askaryan Radio Array

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INTRODUCTION

GZK Process and Sources

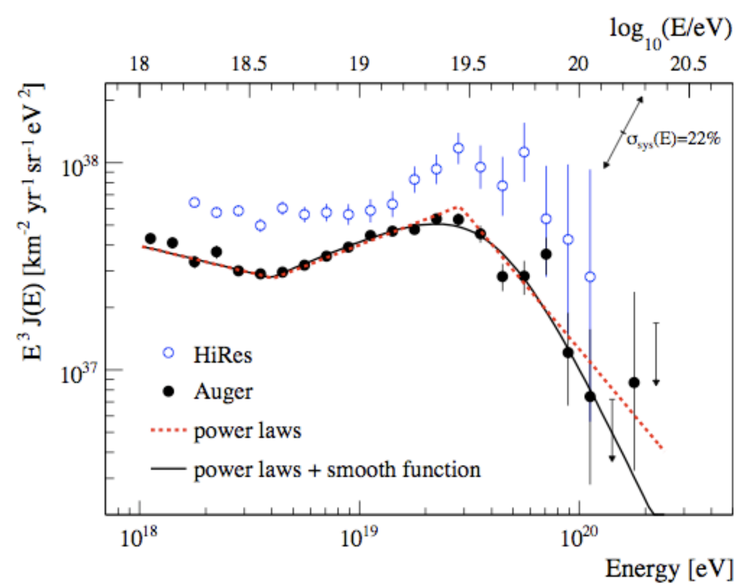
- Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays with E > $10^{19.5}$ eV interact with cosmic microwave background (CMB) photons
- Process produces BZ neutrinos, some at ultrahigh energies (UHE)
- Neutrinos are not subject to these successive interactions and happily continue on.
- UHE neutrinos could also be produced at a source location
  - If observed, will trace back to source

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

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

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

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



Large Volume Detectors

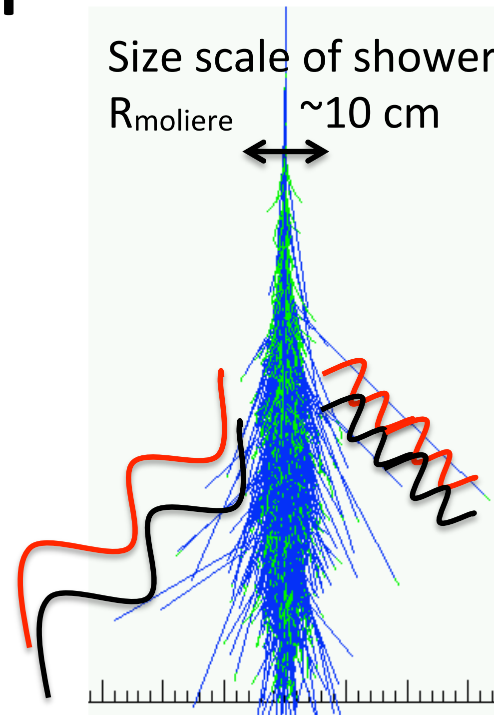
- Consider GZK models, Antarctic ice, earth shadowing, neutrino cross sections
  - Less than 1/km^3/year/energy decade

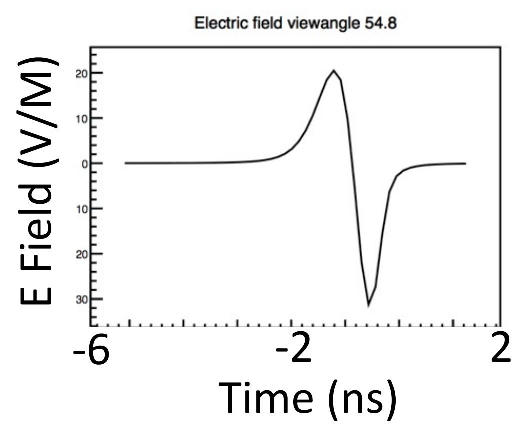
$$F \propto \frac{1}{At\Omega}$$

- 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)
- *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)

Detection technique

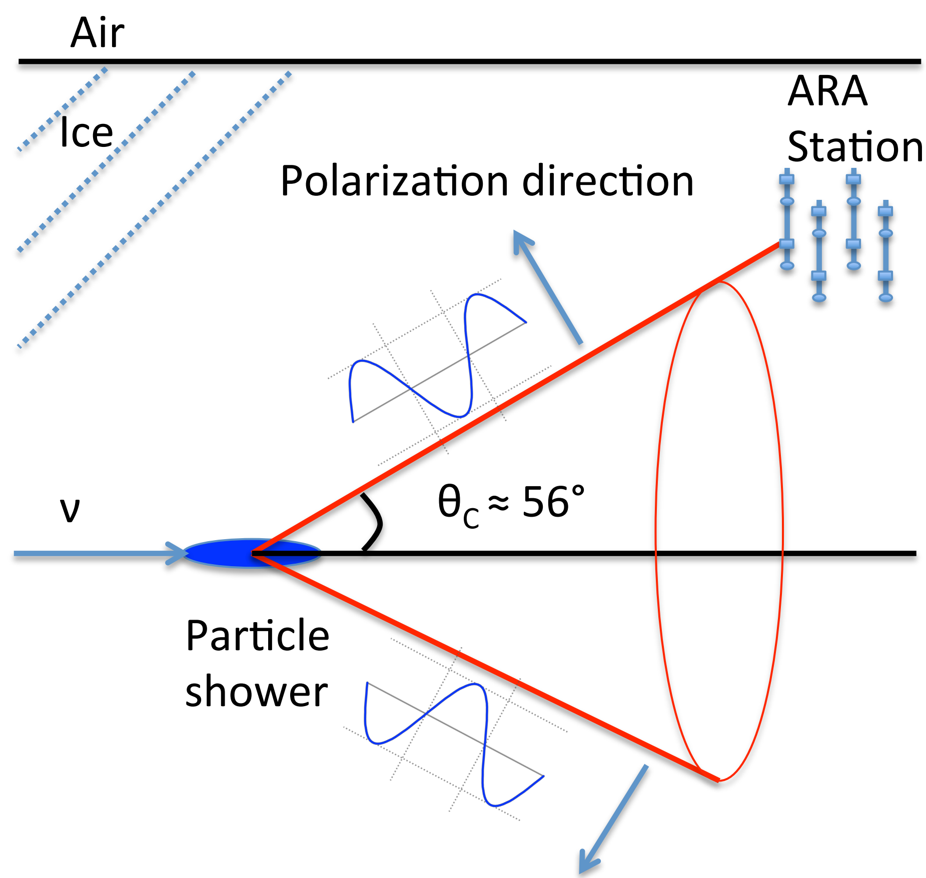
- How to get large-scale detection -
  - Brute force: make 100 IceCubes
  - Use a different approach – radio Cherenkov technique
- Coherent Cherenkov signal from net "current," instead of from individual tracks
  - A ~20% charge asymmetry develops in the shower (positrons annihilated, electrons not)
  - If $\lambda \gg R_{Moliere}$ (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





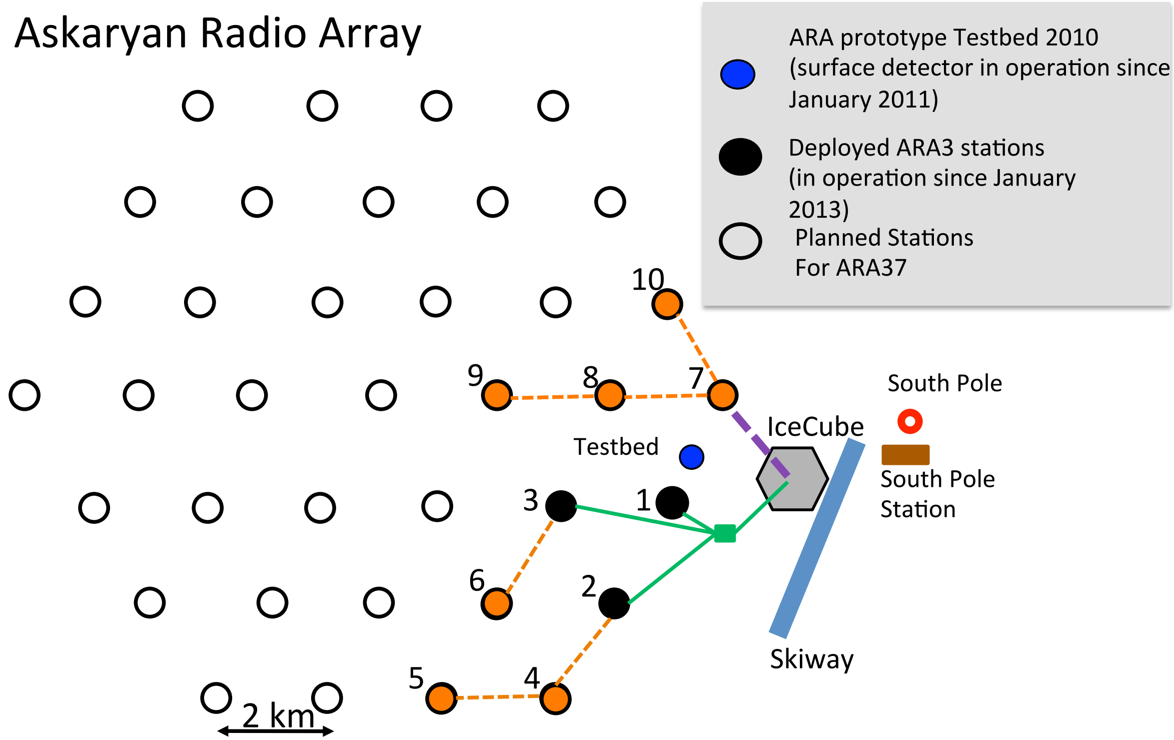
Detector Concept

- 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



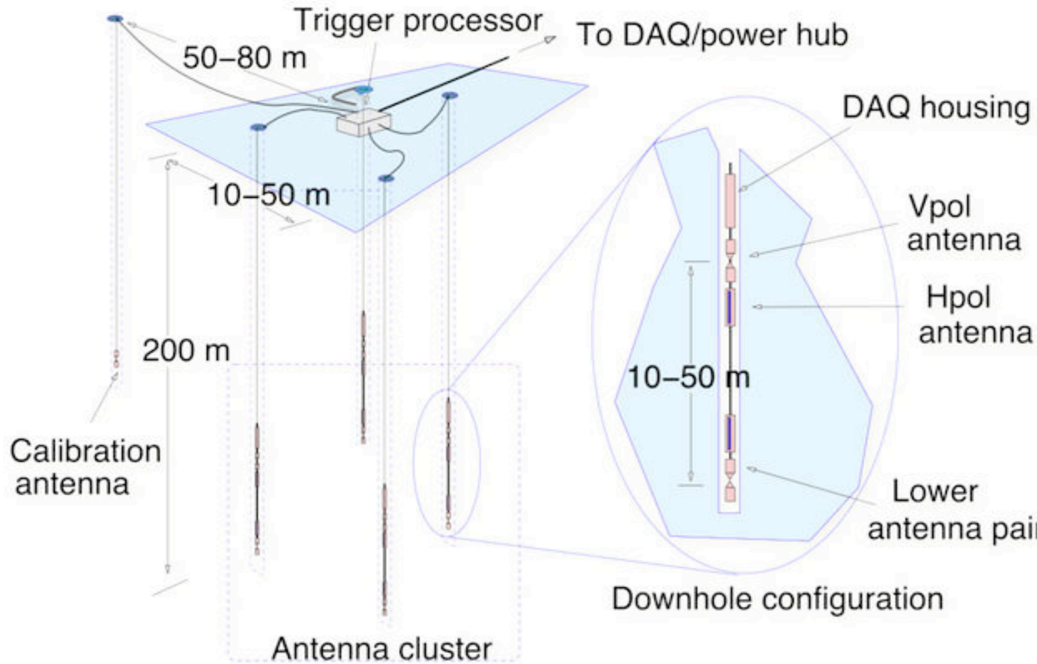
EXPERIMENT AND DETECTOR

ARA 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



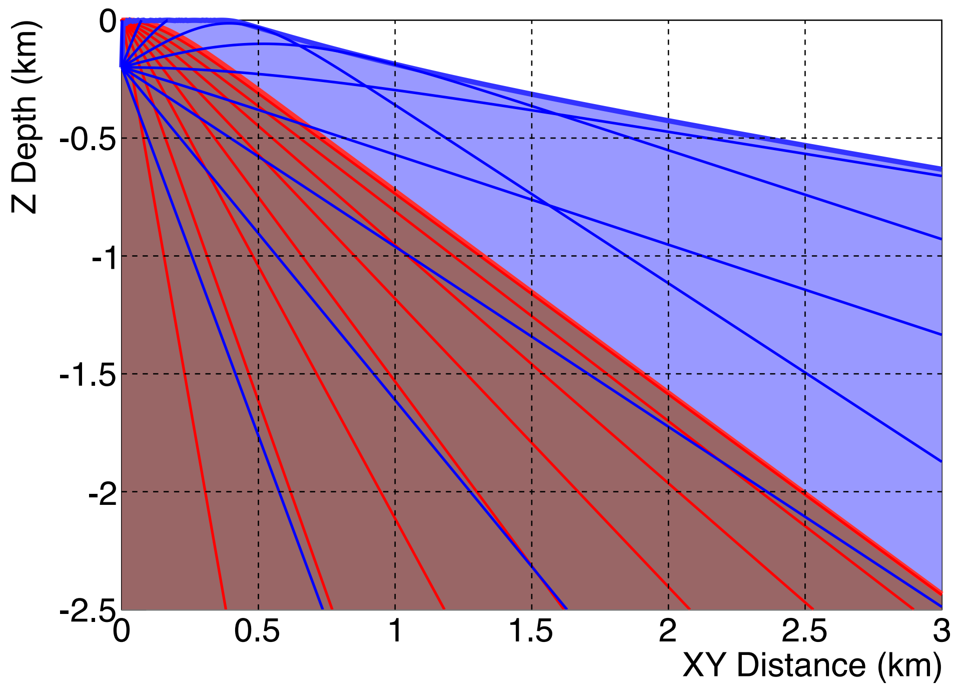
Hpol quad-slotted cylinder antenna

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

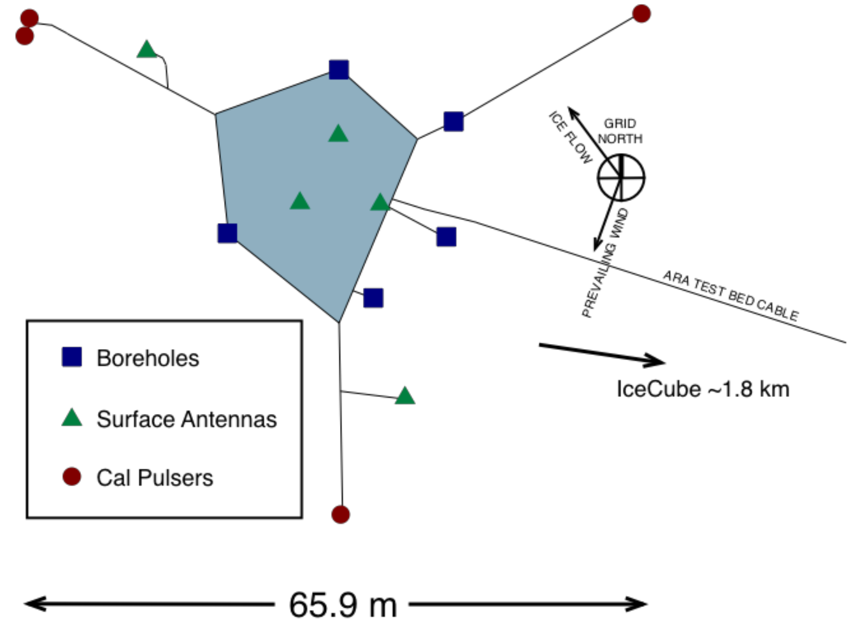


- Firn – layer of compacted snow
  - Quickly changing index of refraction (~1.35 → ~1.78 within top ~150 m of ice)
  - Causes curvature in paths of rays in ice
  - Limits viewable volume and observable neutrino incident angles
  - 30 m → 200 m depth: increases effective volume by factor of ~3.2

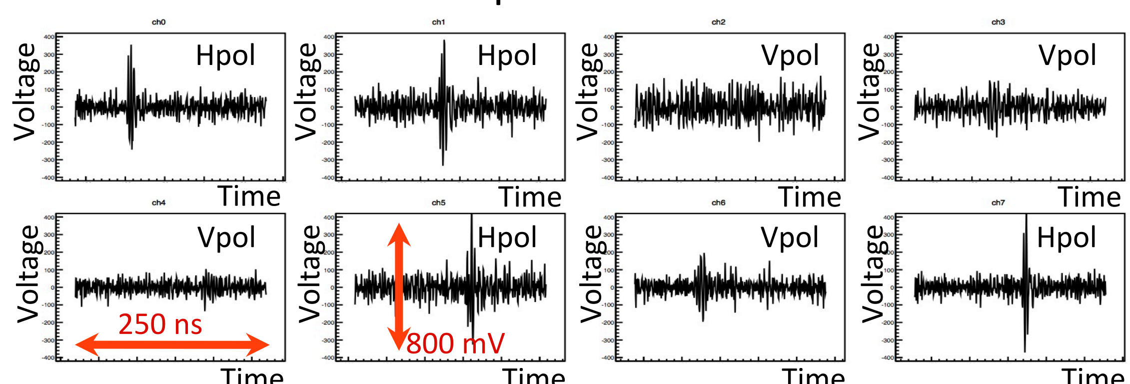
ANALYSIS STATUS I: TESTBED

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



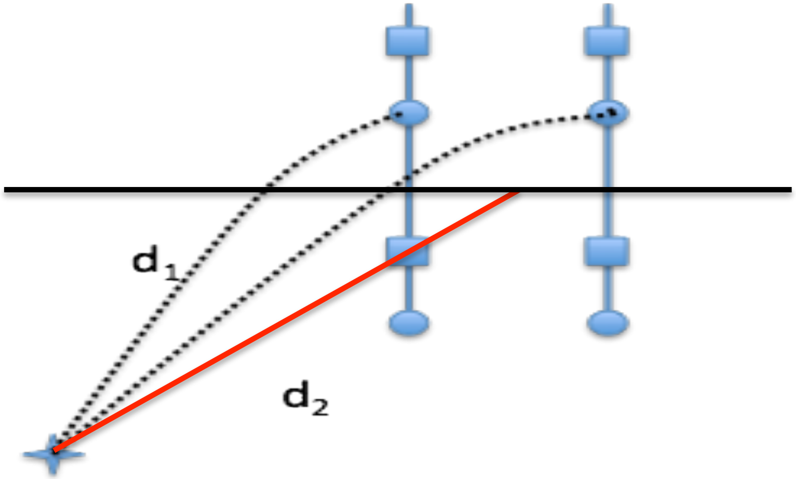
Calibration pulser event waveform from 8 deep antennas in Testbed



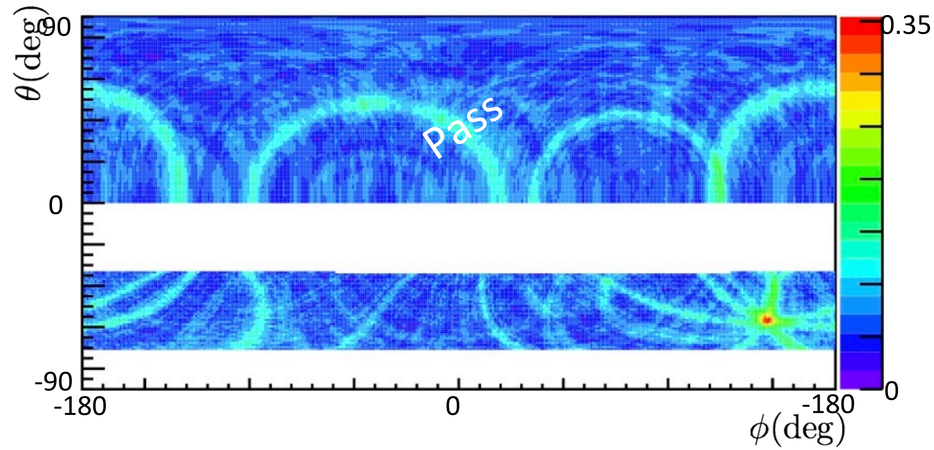
ARA – Testbed Neutrino Analysis

- 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

IM analysis - Reconstruction Quality Cut



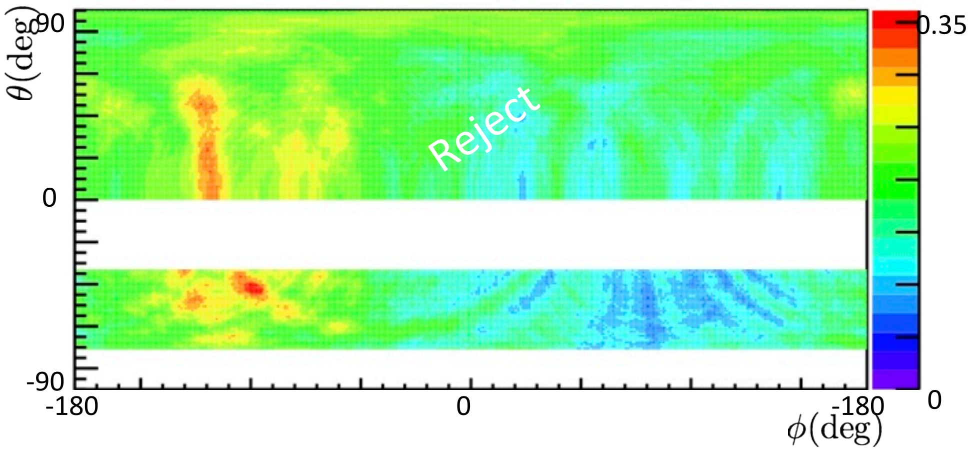
Simulated ν event reconstruction map example



- 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

IM analysis - Reconstruction Quality Cut

Known background event reconstruction map example



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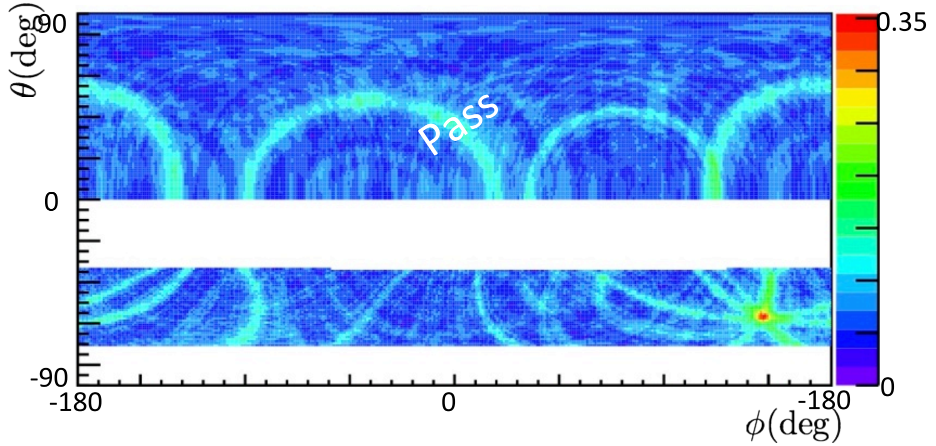

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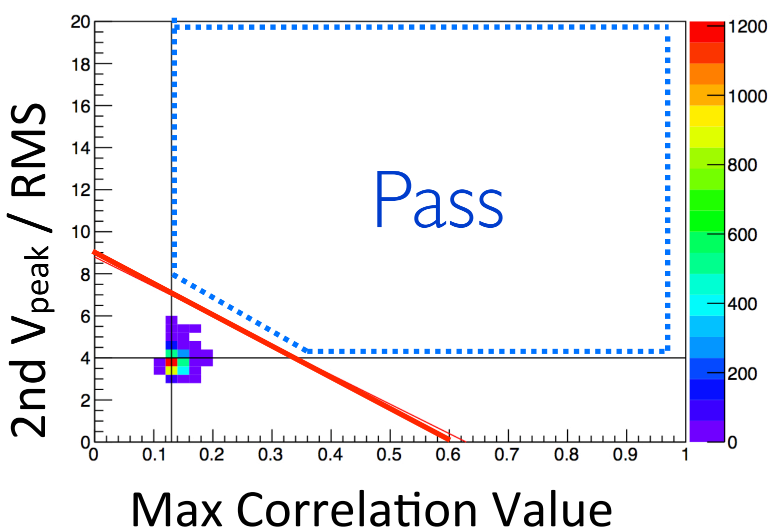
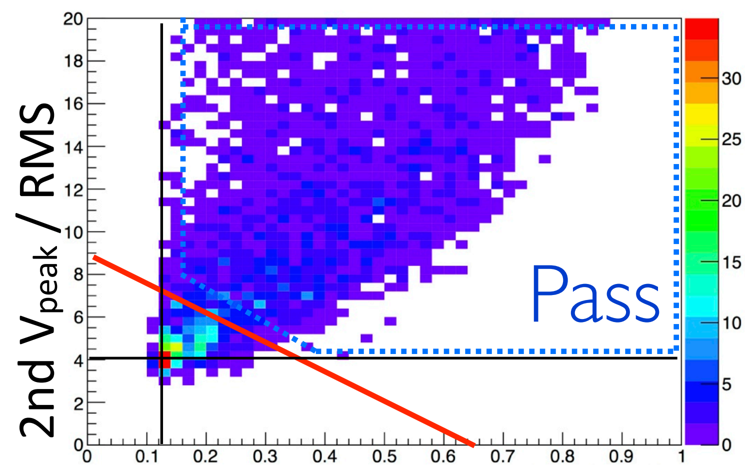
2nd V_{peak} / Correlation Cut

- 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

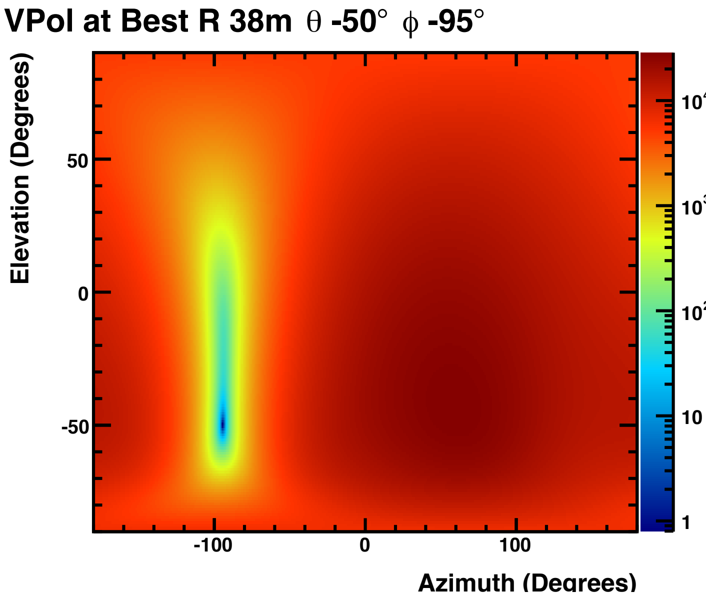


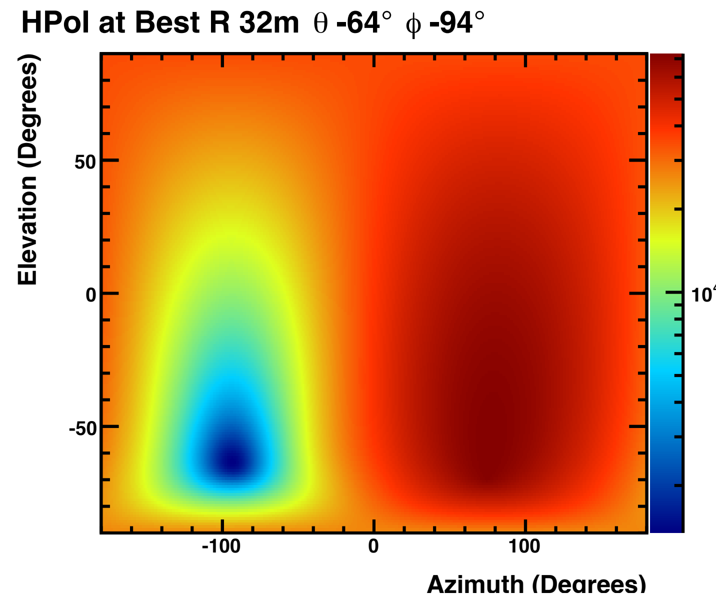
Simulated 10^{18}eV ν set with cuts applied



Max Correlation Value

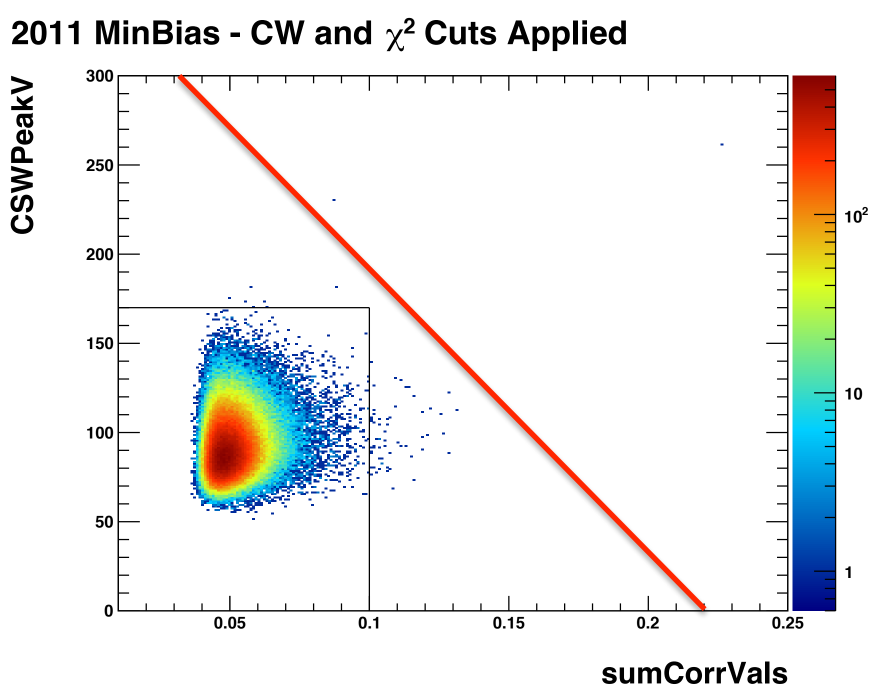
CSW Analysis Reconstruction

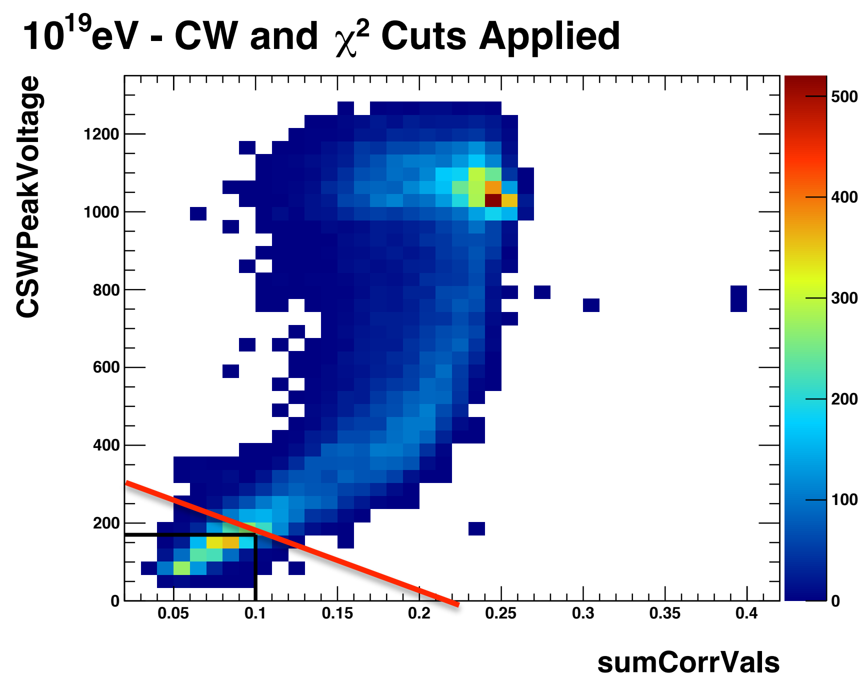




- Obtain coherently summed waveform (CSW):
  - Iteratively find the best correlation between a waveform and the CSW; obtains set of delays with best correlation
- Compare delays used to make the CSW to delays expected from putative source positions: minimize $\chi^2 = \Sigma(T_{expected} - T_{observed})^2$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

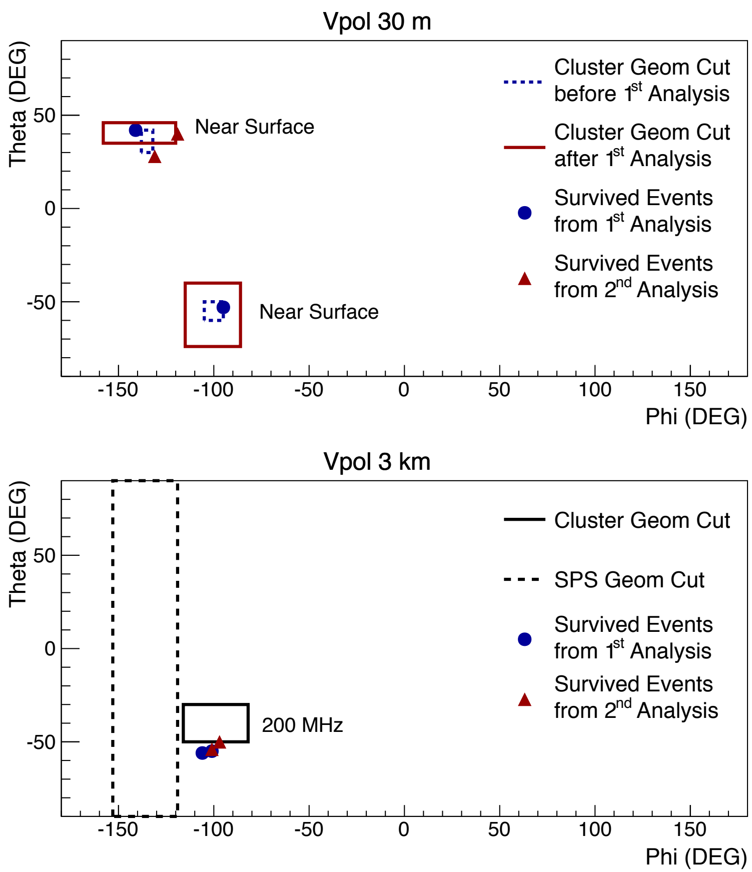
CSW - “Powherence” Cut

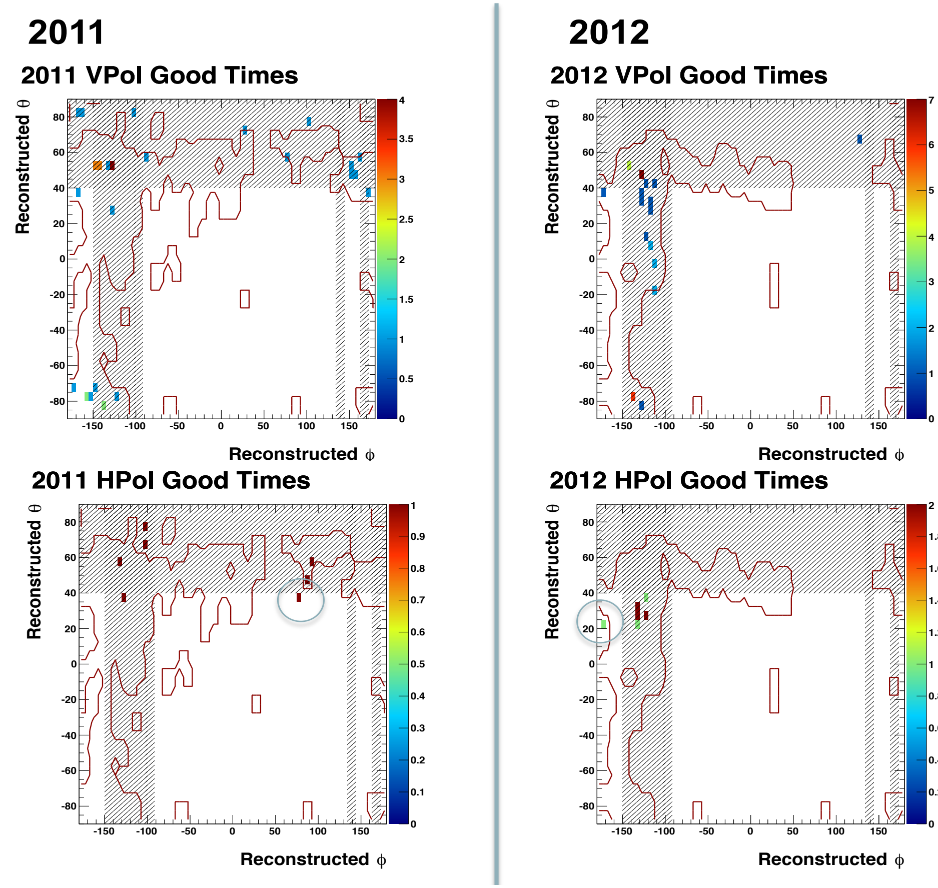




- Linear combination of:
  - peak power of the CSW
  - sum of the maximum correlation values of antennas with the CSW of the remaining antennas
- Expect impulsive events to separate out from noise, CW

Clustering – IM, CSW





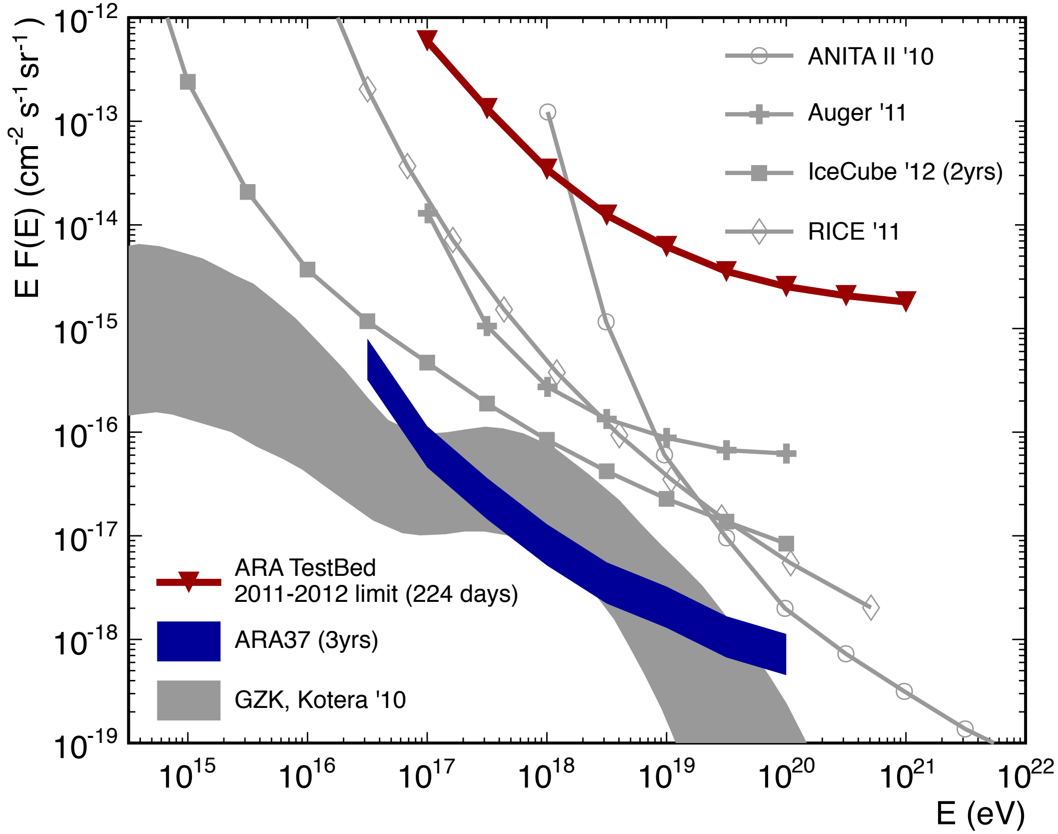
- Both analyses reject events reconstructing to a location where an excess of events can be found
- Also reject South Pole phi range and require reconstruction in the ice

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

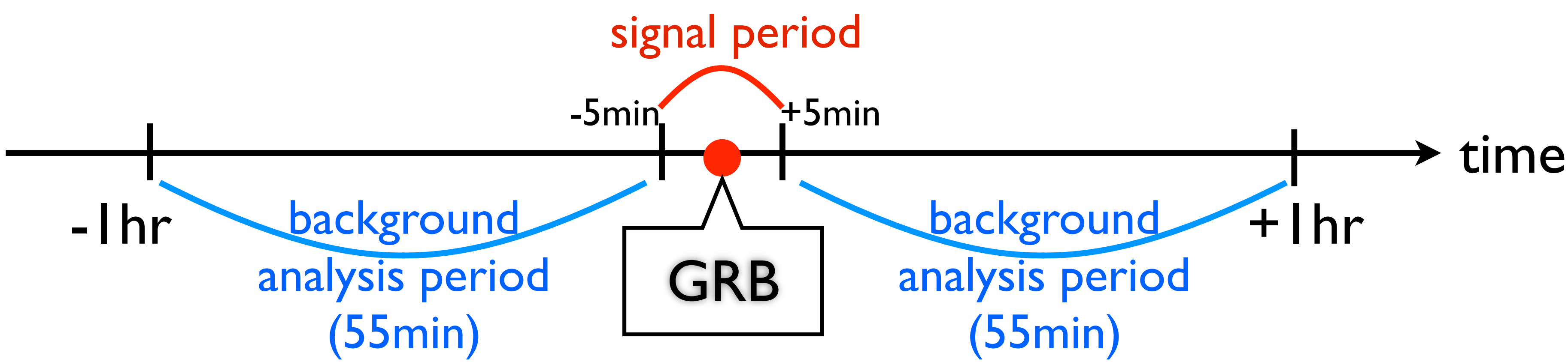
Sensitivity

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

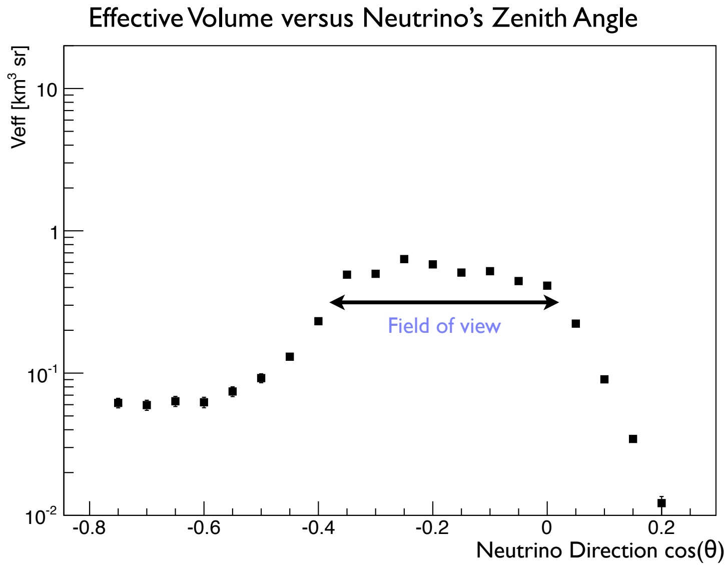


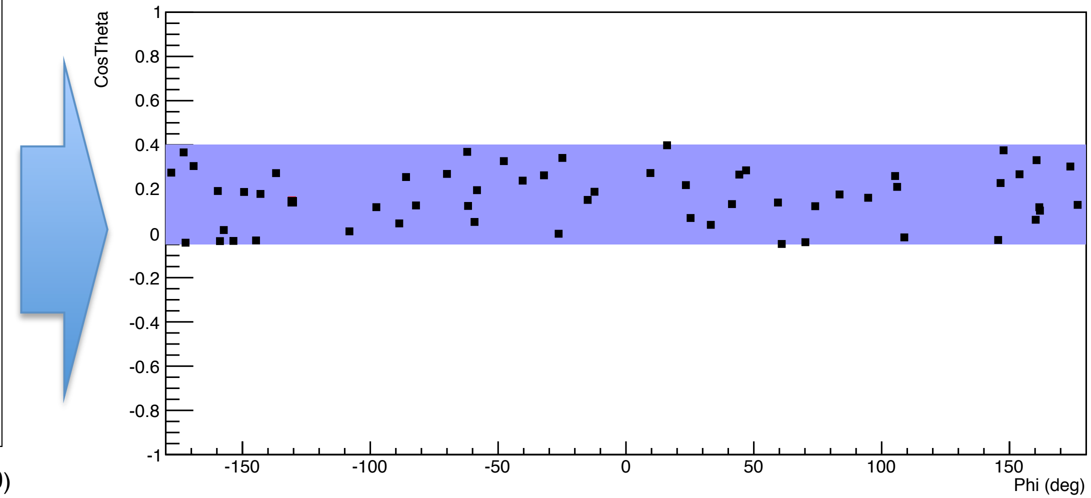
Testbed GRB analysis

- 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

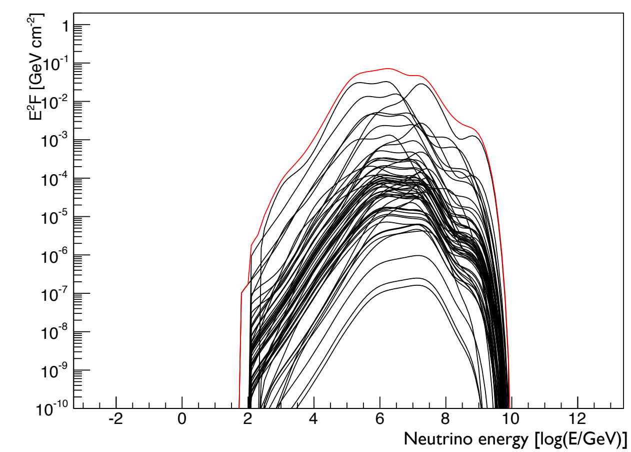


GRB Selection



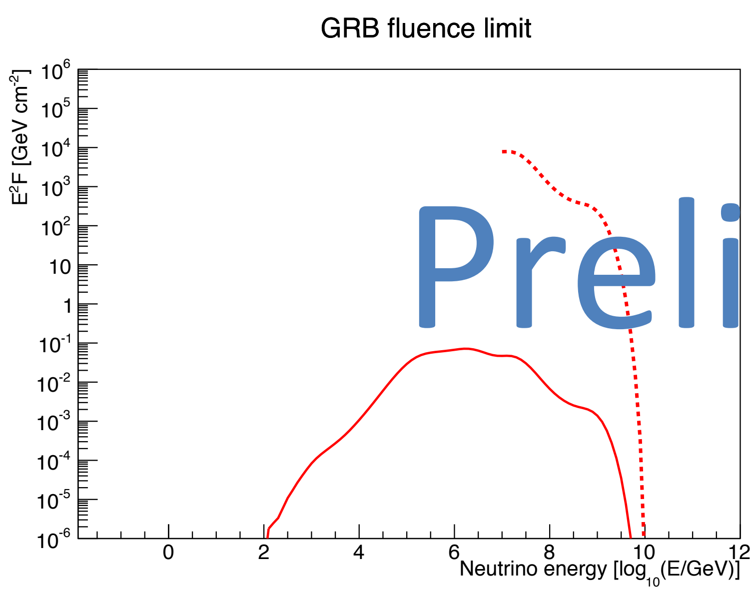


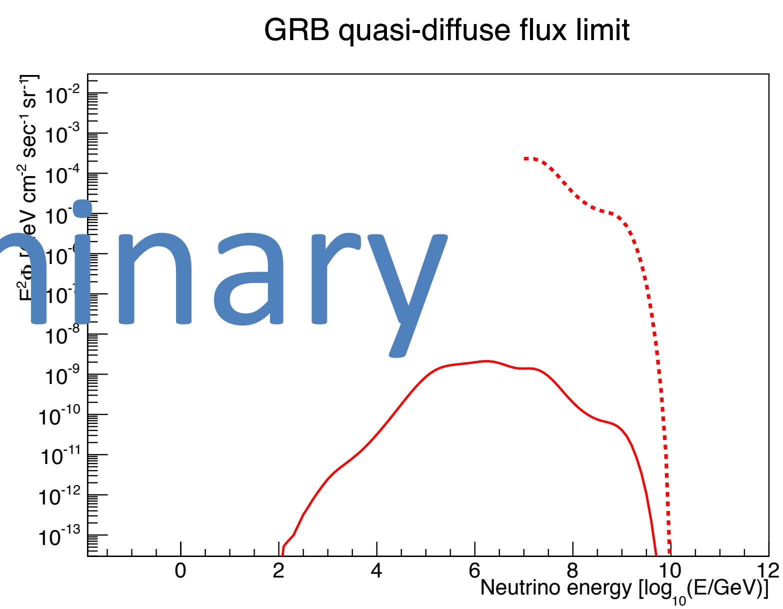
- Selected 57 GRBs based on livetime and geometric acceptance
- Get fluences for each GRB from NeuCosmA simulation and overall
- Tune cuts based on modeled neutrino fluence
- Relaxed Reconstruction Quality, Peak vs CC, Delay Difference cuts



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

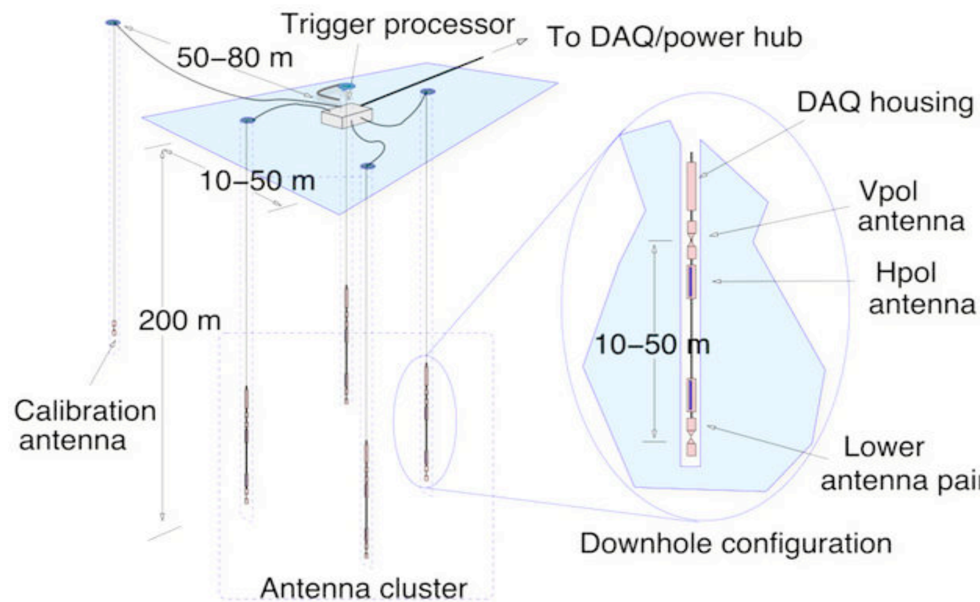




ANALYSIS STATUS II: DEEP STATIONS

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



Noise filtering

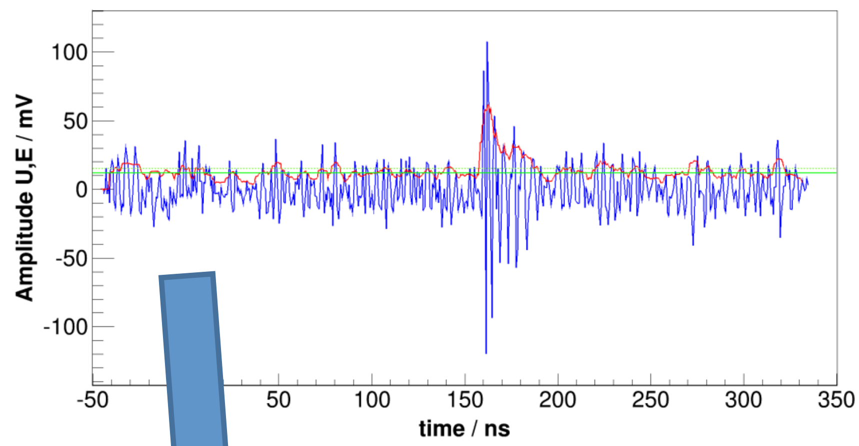
5 Hz thermal noise trigger rate
→ Needs to be reduced before applying sophisticated algorithms

Time sequence algorithm:

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

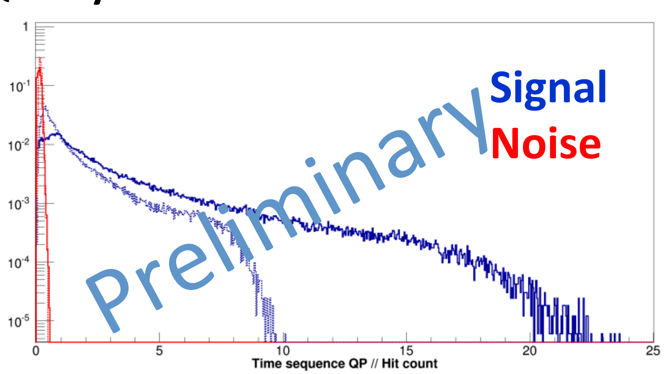
1. Generate hit pattern with threshold on energy envelope (red line)
2. Check hit pattern on conformity with incoming plane wave

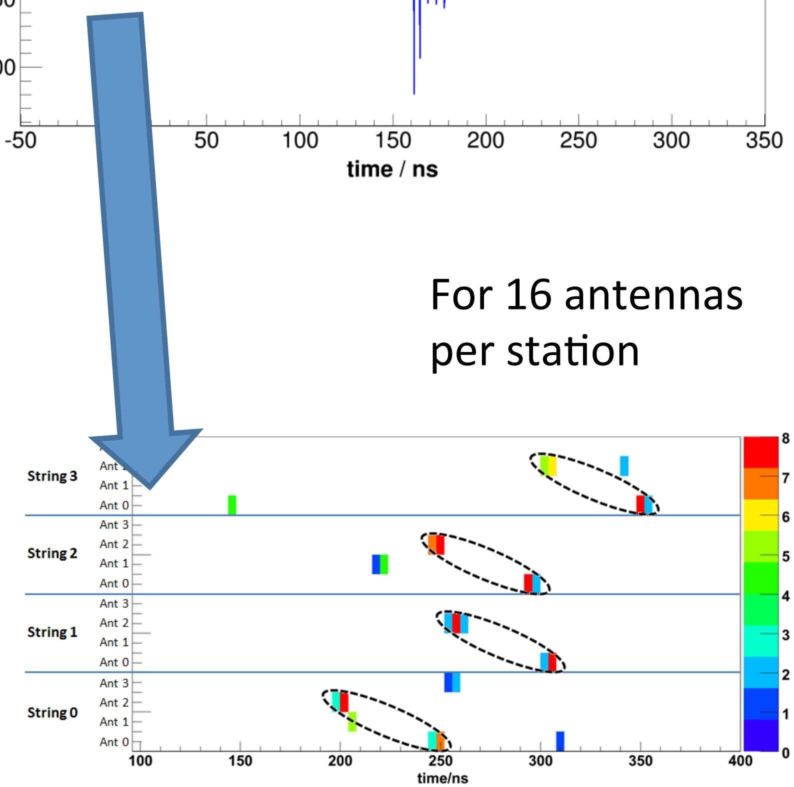
→ ***quality parameter (similarity to wavefront)x(hit count)***



For 16 antennas per station

Quality Parameter for simulated neutrinos





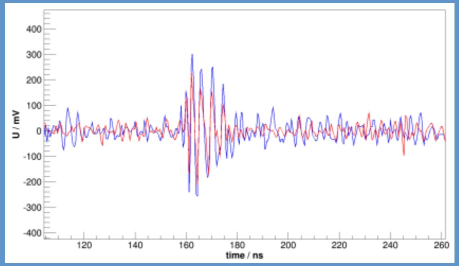
Vertex reconstruction

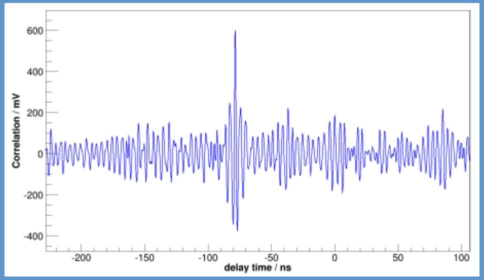
We need:

- 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

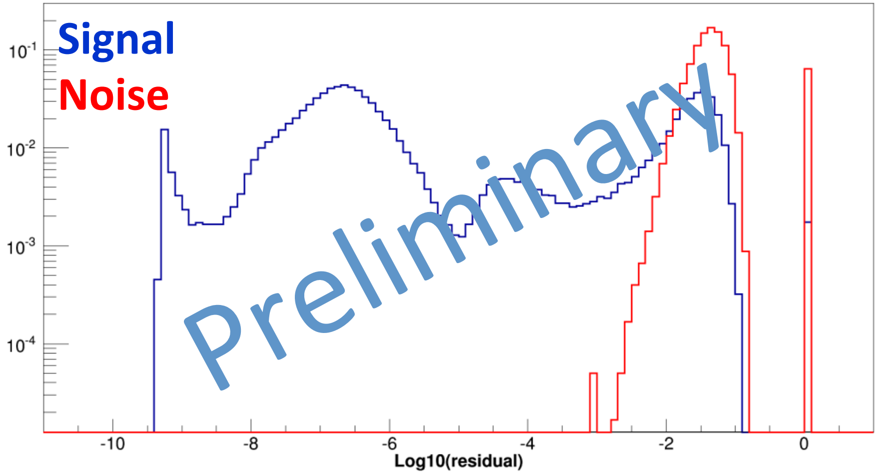
Vertex reconstruction: quality criterion

Main quality criterion is residual:

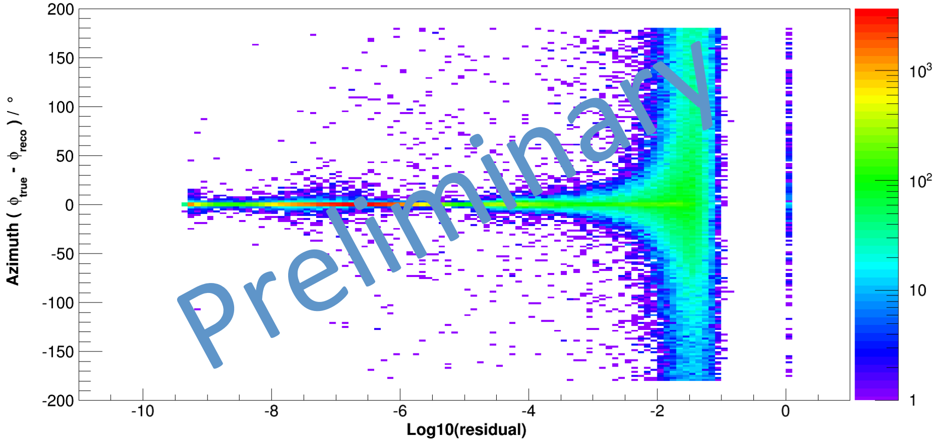
$$res = \left| \frac{\vec{b}}{|\vec{b}|} - \frac{\mathbf{A}\cdot\vec{v}}{|\mathbf{A}\cdot\vec{v}|} \right|^2 \cdot \frac{1}{N_{chp}}.$$

Require a minimum correlation value to be included as a pair

Residual for signal and noise



Reconstruction error vs residual:

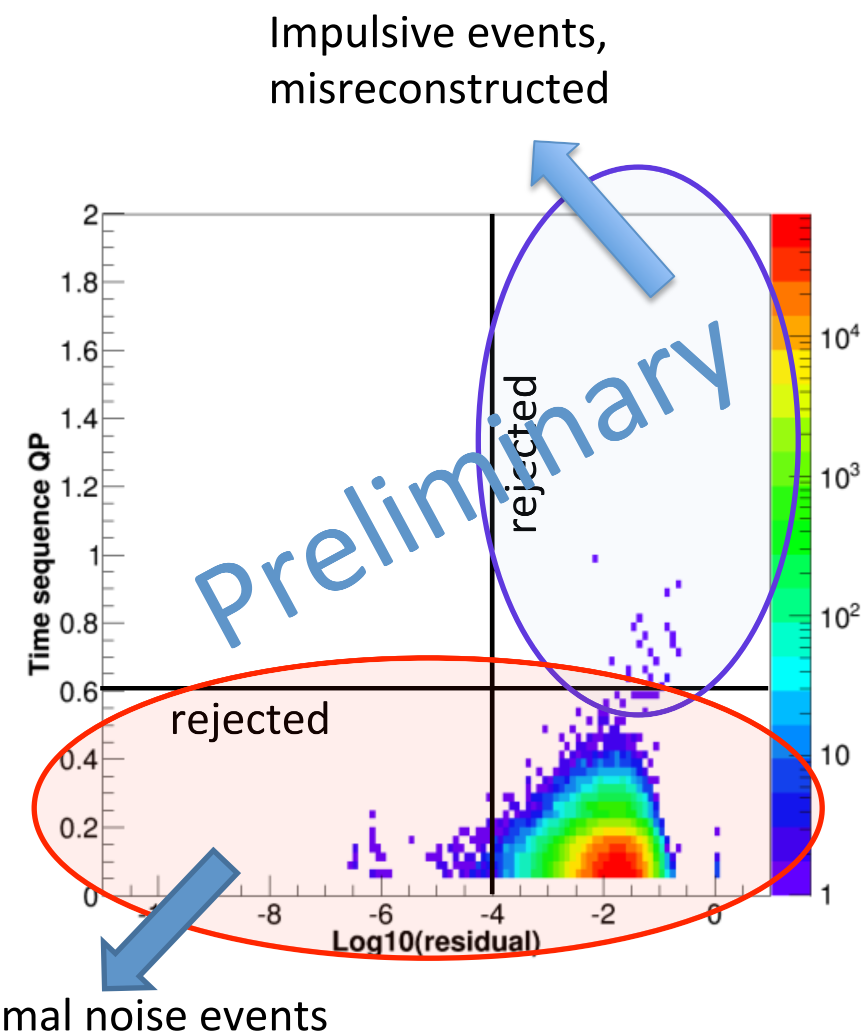


Other quality criteria are applied to further clean out bad reconstructions

Neutrino identification = Background rejection

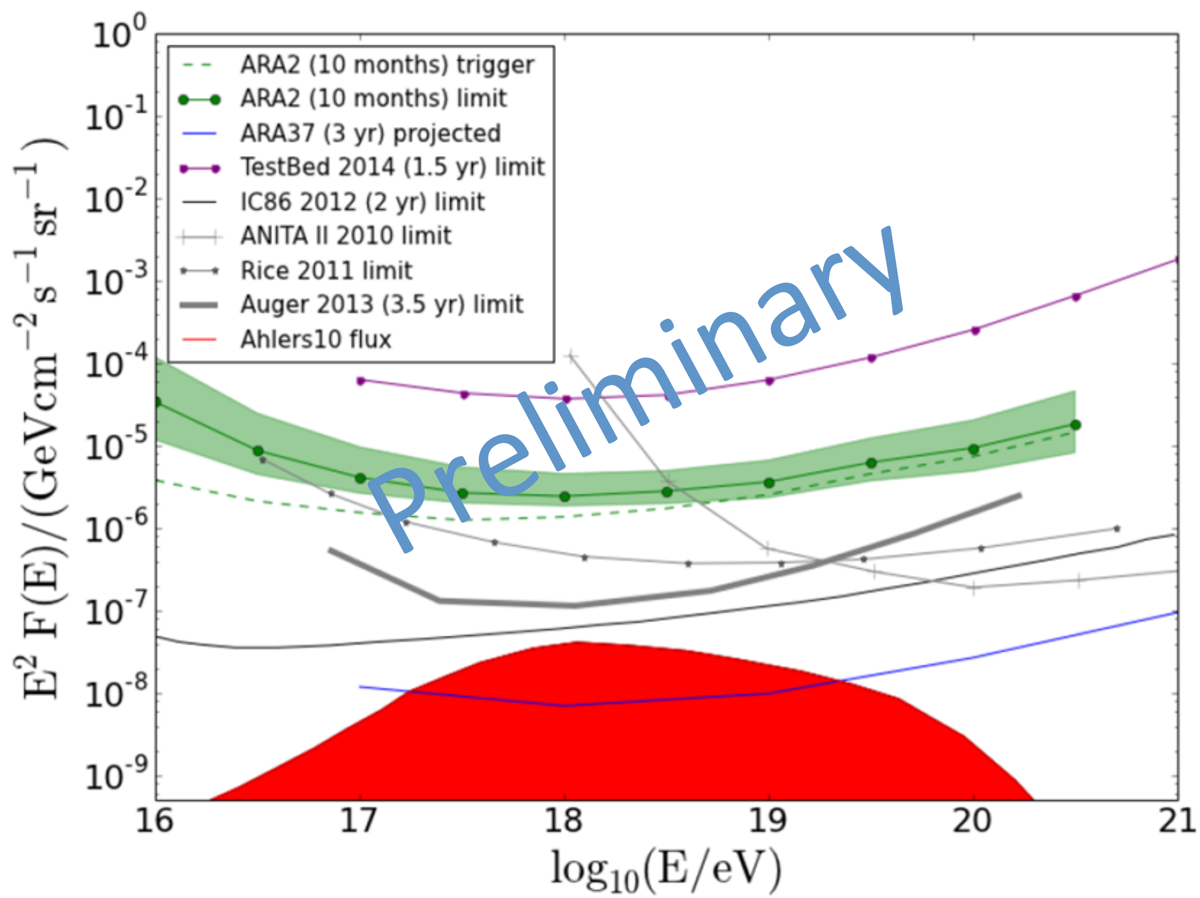
Strategy:

- 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 green band
- Considerable improvement
  - analysis efficiency
  - effective volume



Summary

- ARA is continuing to be built
- First limits from Testbed analysis
  - Diffuse flux: arXiv:1404.5285, submitted to *Astropart. Phys.*
  - GRB flux: first quasi-diffuse limits above 10^{16} eV
    - Publication in preparation
- Deep stations:
  - Preliminary diffuse limits from 2 stations
    - Publication in preparation
- Deep stations see marked improvement in sensitivity
  - Deeper station, more antennas, better quality data
  - Improved (2^{nd} generation) analysis techniques
  - Expect even more refined analysis and trigger in future