Ultrahigh Energy Neutrino Radio Frequency Detectors

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June 25, 2014

GZK Process and Sources

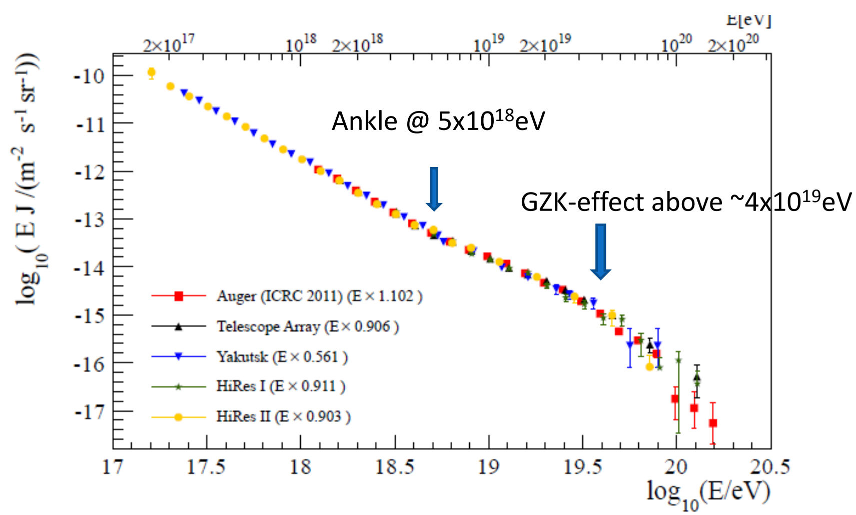
- Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays with $E > 10^{19.5}$ eV interact with cosmic microwave background (CMB) photons
- Process produces neutrinos, some at ultrahigh energies (UHE)
- Neutrinos are not subject to these successive interactions and happily continue on.
- UHE neutrinos could also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

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

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

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

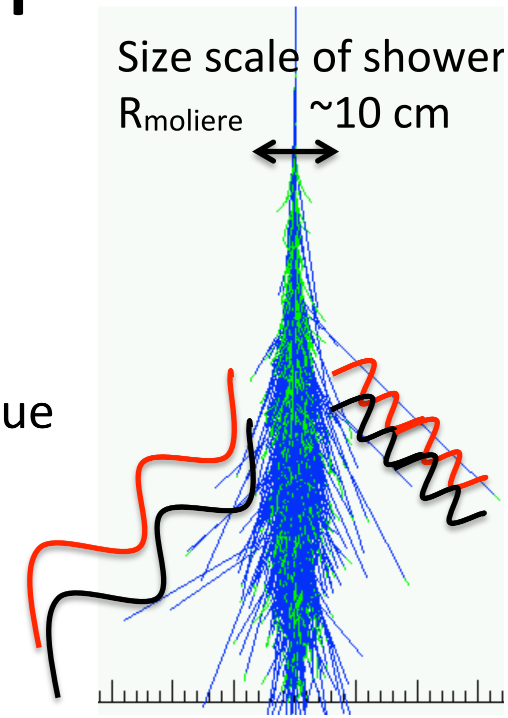
$$\mu^{+} \rightarrow \mathbf{e}^{+} \bar{\nu}_{\mu} \nu_{\mathbf{e}}$$

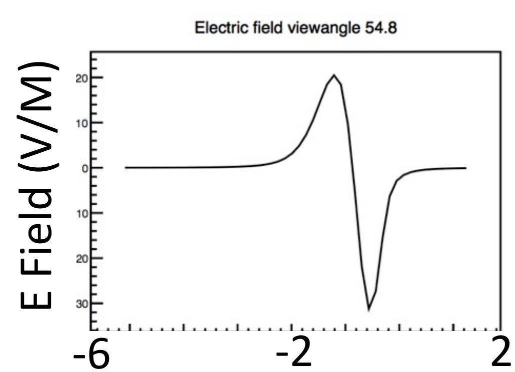


Proceedings of UHECR 2012

Detection technique

- Consider GZK models, Antarctic ice, earth shadowing, neutrino cross sections
  - Less than 1/km^3/year/energy decade
- 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 $\lambda >> R_{Moliere}$ (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





Large Volume Detectors

- Mostly using ice as a target
- Synoptic – balloons
  - Large target volume - O(10^6 km^3); short flight time 30-40 days
  - More limited viewing angles → less solid angle
  - Requires stronger signal, sensitive to higher energies
  - Must be reconstructed after flight and "landing"
  - Good as a "discovery" instrument for highest energies (>10^{20} eV)

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

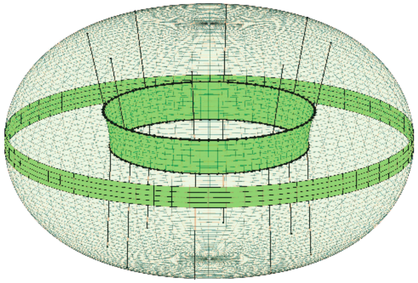
- *In situ* arrays
  - Long operation time (years); smaller observable volume - O(100 km^3)
  - Larger solid angle for observable signals
  - Environmental problems *in situ* – measure and model environment, ice
  - But better able to obtain more information about event - direction, pol., etc.
  - Good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

Detectors Built and In Progress

Synoptic

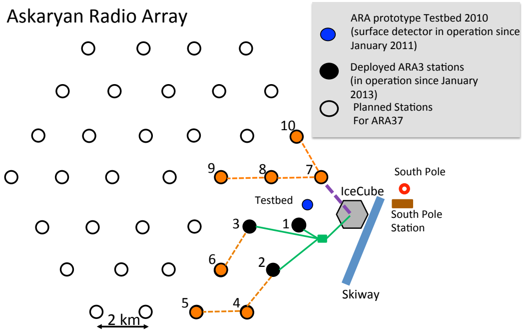
ANITA

EVA

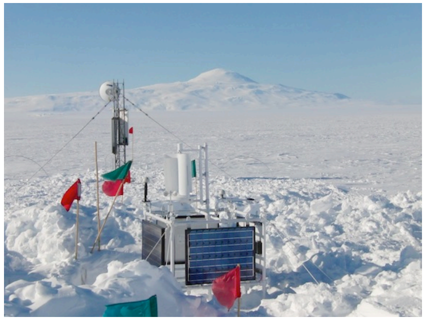


In situ

ARA



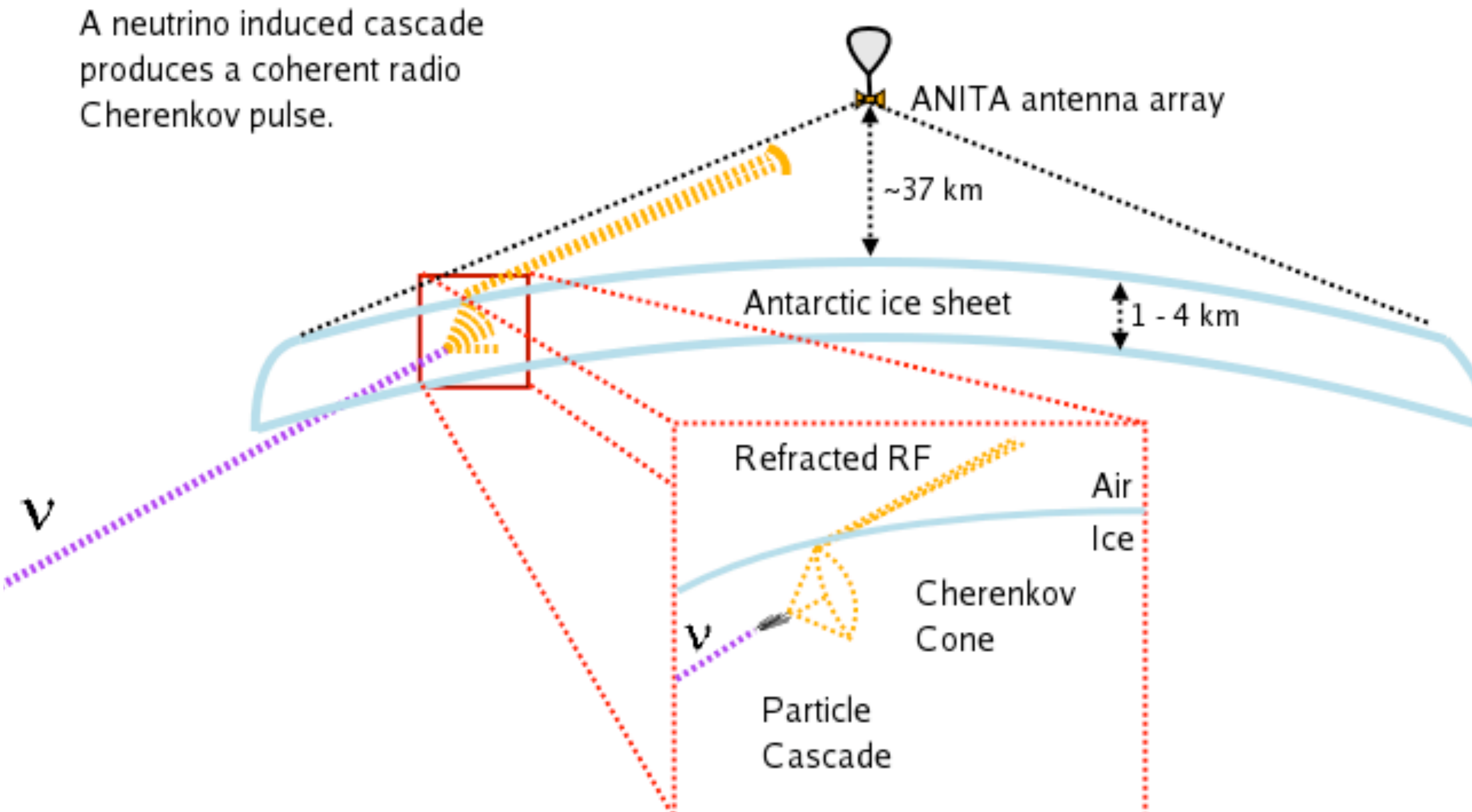
ARIANNA



GNO

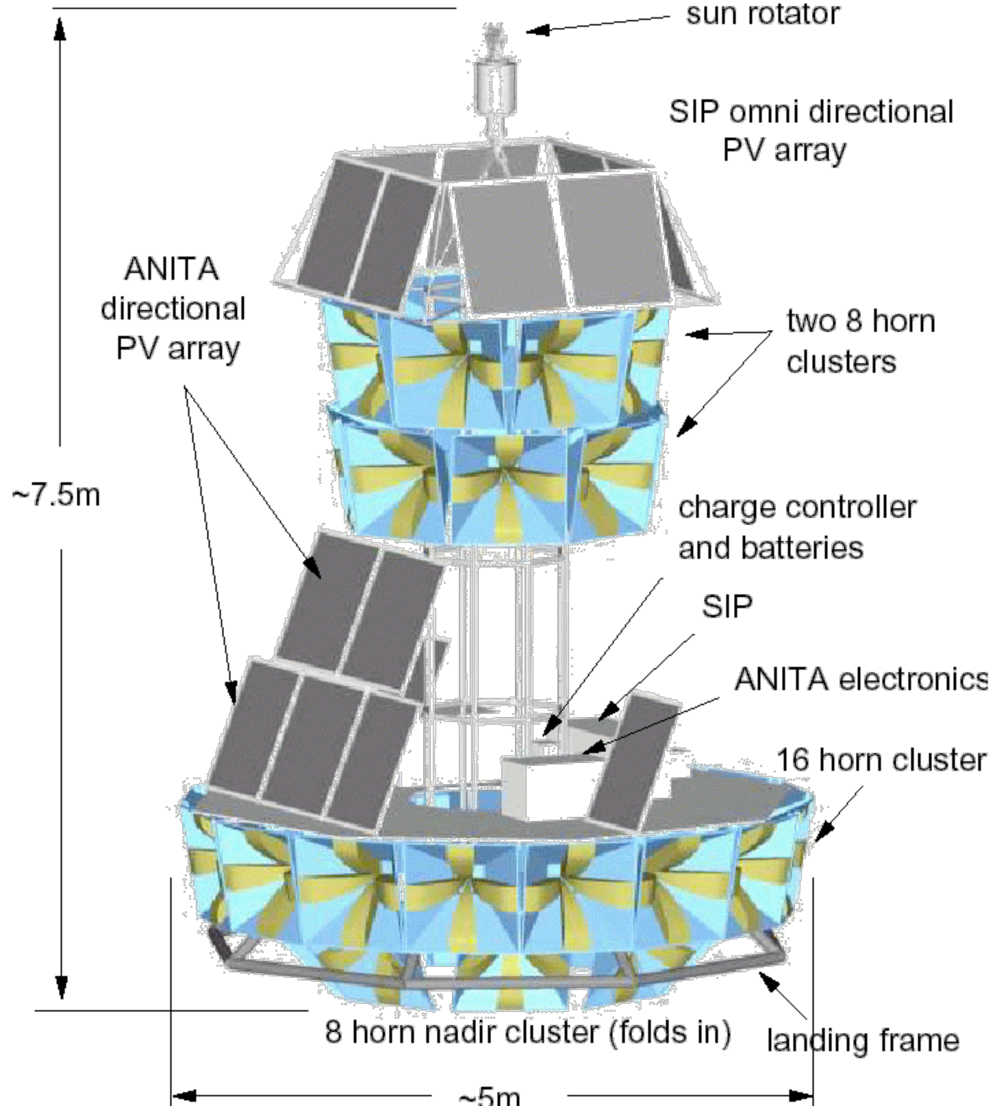
Antarctic Impulsive Transient Antenna (ANITA) Concept

- Synoptic balloon-borne detector



ANITA Design

- Payload consists of an array of quad-ridge horn antennas
- Antennas aimed down 10° to view ice rather than sky
- 2.6 GHz data sampling and fast triggering electronics
  - Signal bandwidth = 150-1000 MHz

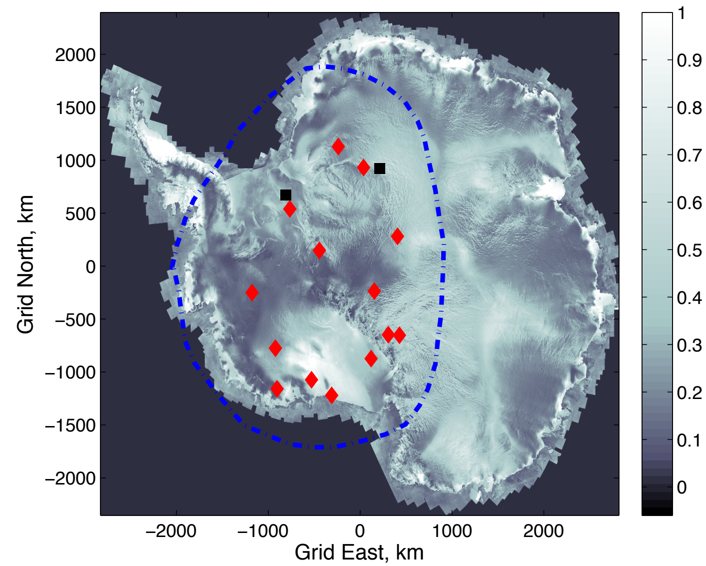


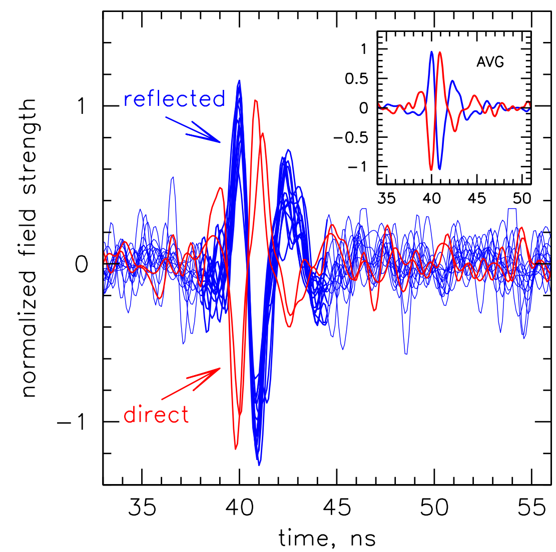
ANITA Flights and Differences

- ANITA-I – flew austral summer 2006-2007
  - 18 days good livetime, cosmic ray events observed
- ANITA-II – flew austral summer 2008-2009
  - Added 8 antennas over ANITA-I, optimized trigger
  - Lower noise amplification, directional mask
  - No h-pol trigger
- ANITA-III - planned for 2014-2015 pole season
  - Integration taking place now
  - Added 8 new antennas over ANITA-II
  - Improved trigger mechanism – coherent sum trigger – causal timing
  - Optimized for neutrinos and cosmic rays

ANITA Results

- ANITA-I observed radio signals from 16 cosmic ray showers
  - Radio signals produced by geomagnetic effects
  - Majority of events reflected from the ice surface
  - Some direct events
- No neutrinos but placed competitive limits above 1 EeV
- See next talk by Harm Schoorlemmer for ANITA updates

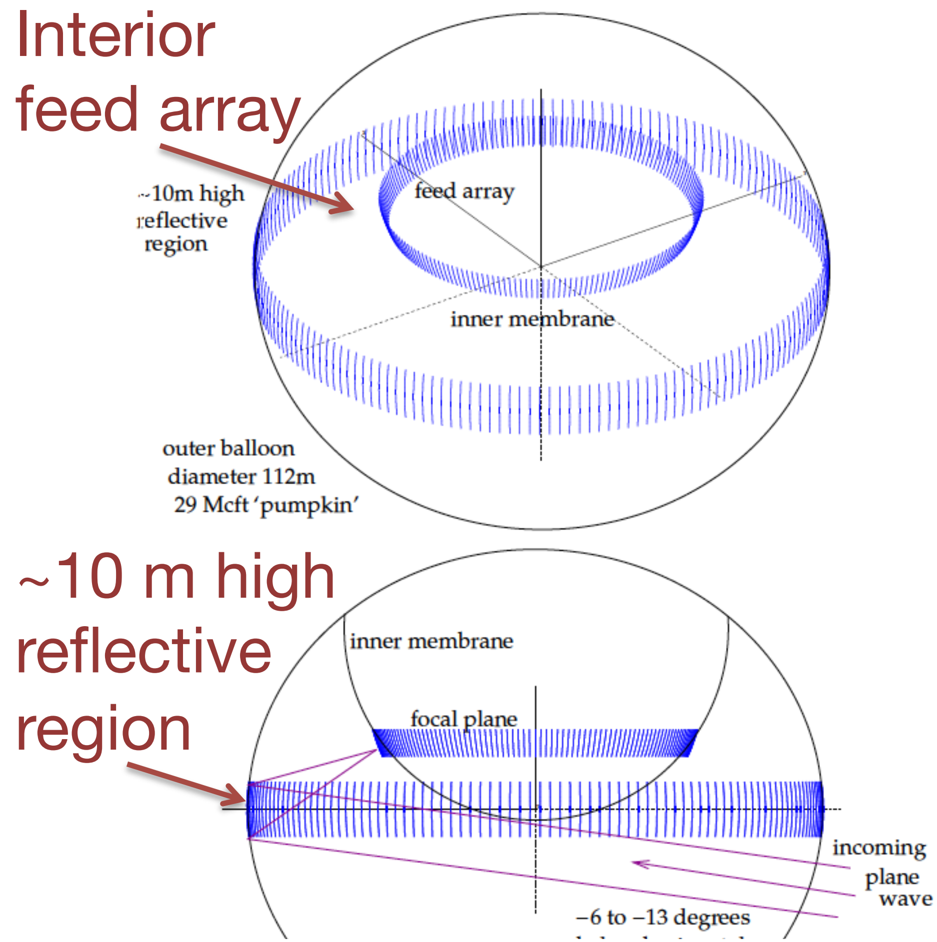




S. Hoover *et al.*

ExaVolt Antenna (EVA) concept

- Design balloon to be a part of the detector
  - Put reflector on exterior to focus signal inwards
- Would be the world’s largest aperture airborne telescope
  - 1000’s of square meters
  - 150-600 MHz ($\lambda_{air} \approx 0.5\text{-}2$ m)
- 100X increase in sensitivity to radio signals
- Currently under development with 3 year NASA engineering study

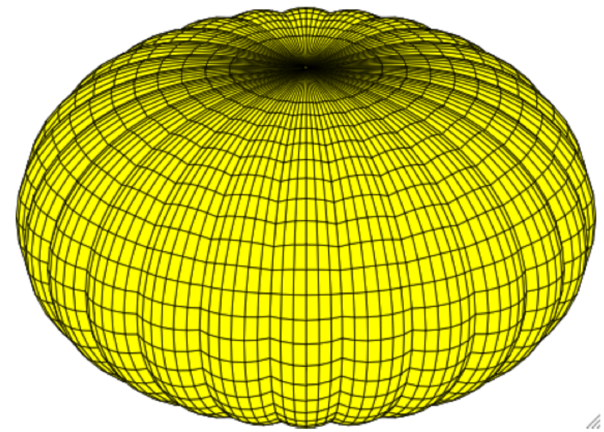


incoming plane wave at -6 to -13 degrees below horizontal

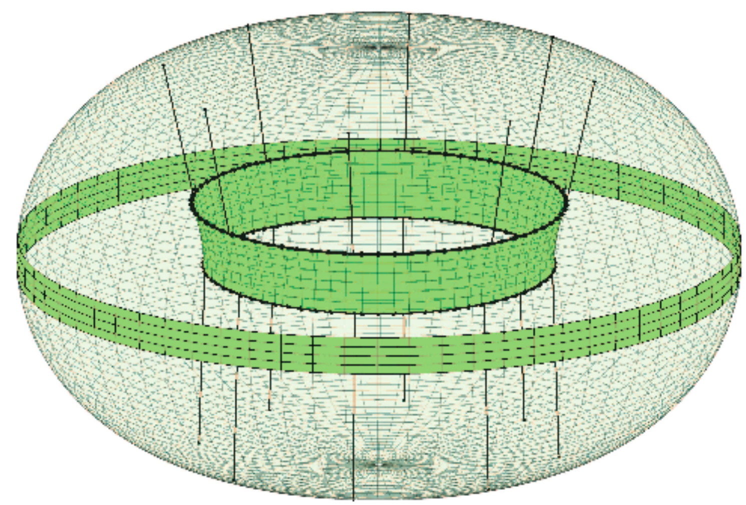
P. W. Gorham et al., 2011.

EVA Design

- Use a super pressure balloon (SPB) instead of standard zero pressure balloon
  - Maintains relatively consistent lobed geometry (like a pumpkin)
- Feed array on suspended surface within balloon
  - 3m high, 5 rows of total 1200 feed antennas
- Planned 1:20 scale hang test at Wallops Flight facility later this year



Gorham *et al.* 2011)



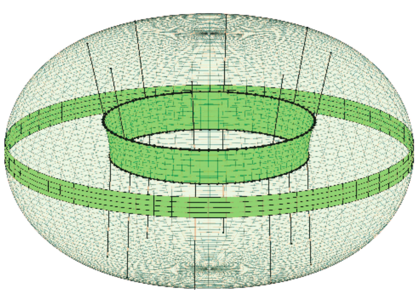
outer balloon diameter
112 m, 29 Mft^3

Detectors Built and In Progress

Synoptic

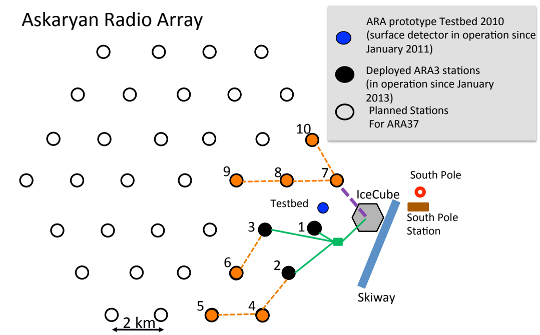
ANITA

EVA

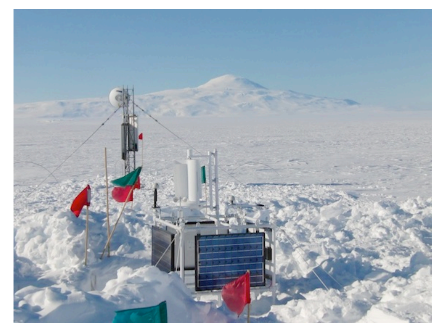


In situ

ARA



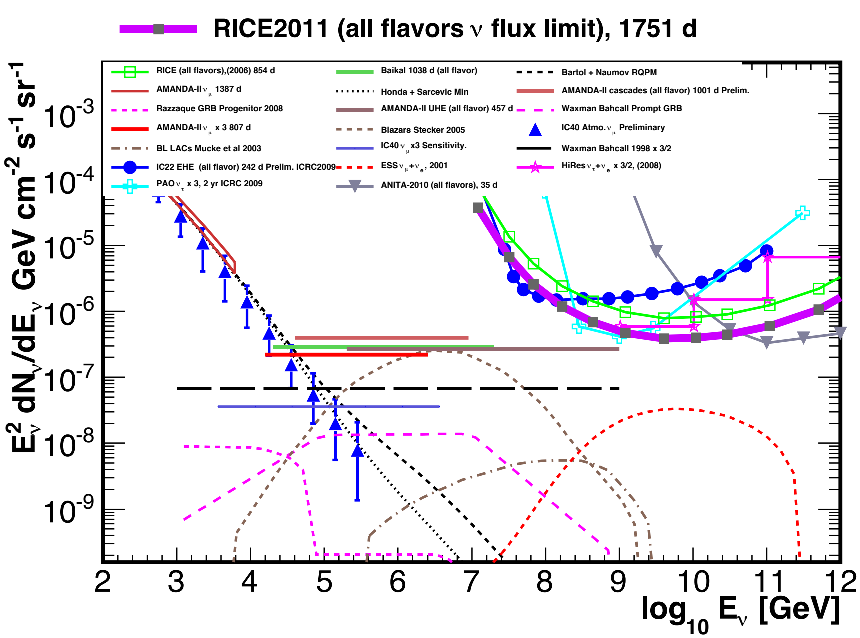
ARIANNA

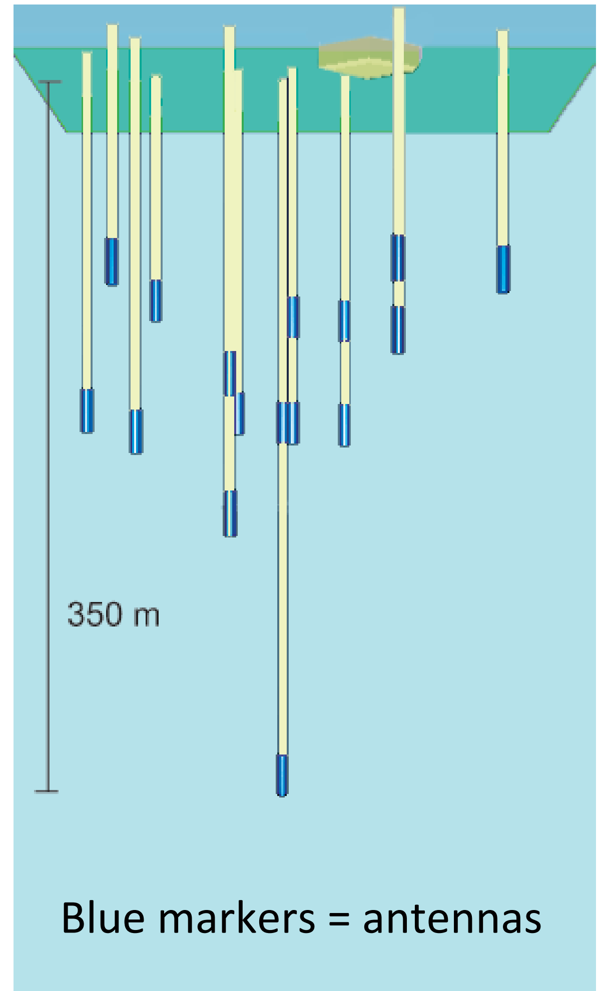


GNO

Radio Ice Cherenkov Experiment (RICE)

- Antennas deployed in AMANDA boreholes
- First in situ radio Cherenkov array
- Placed competitive limits on UHE neutrino flux
  - Kravchenko *et al.*, 2011
  - arXiv:1106.1164

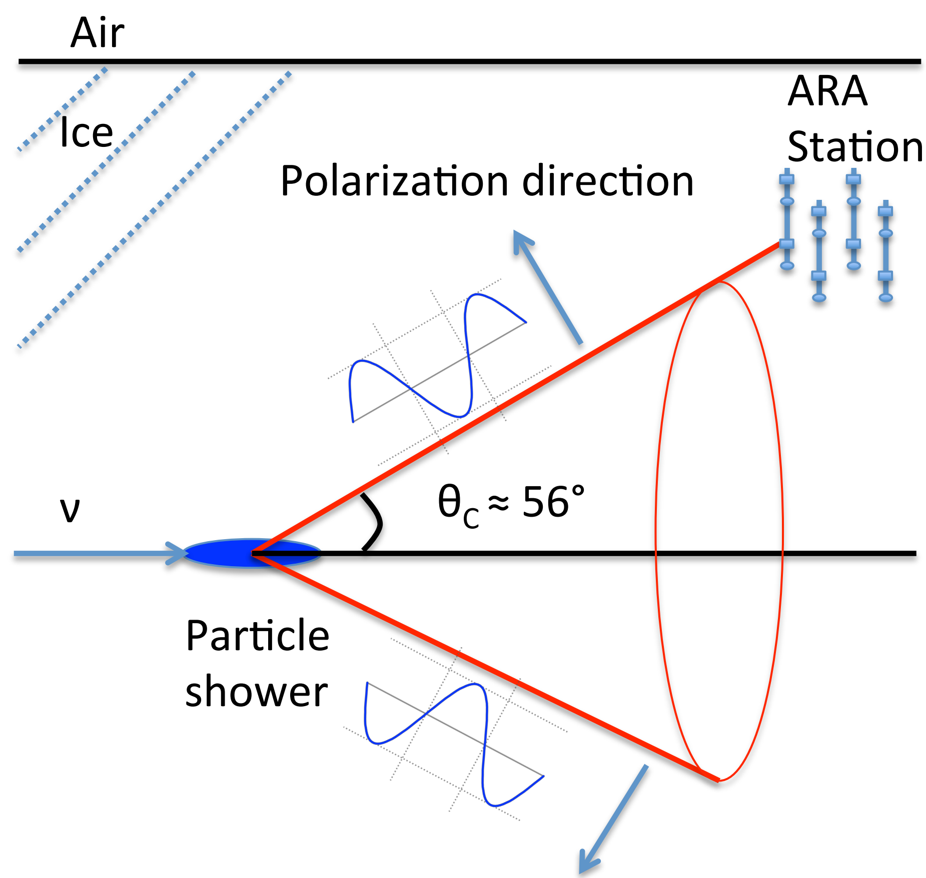




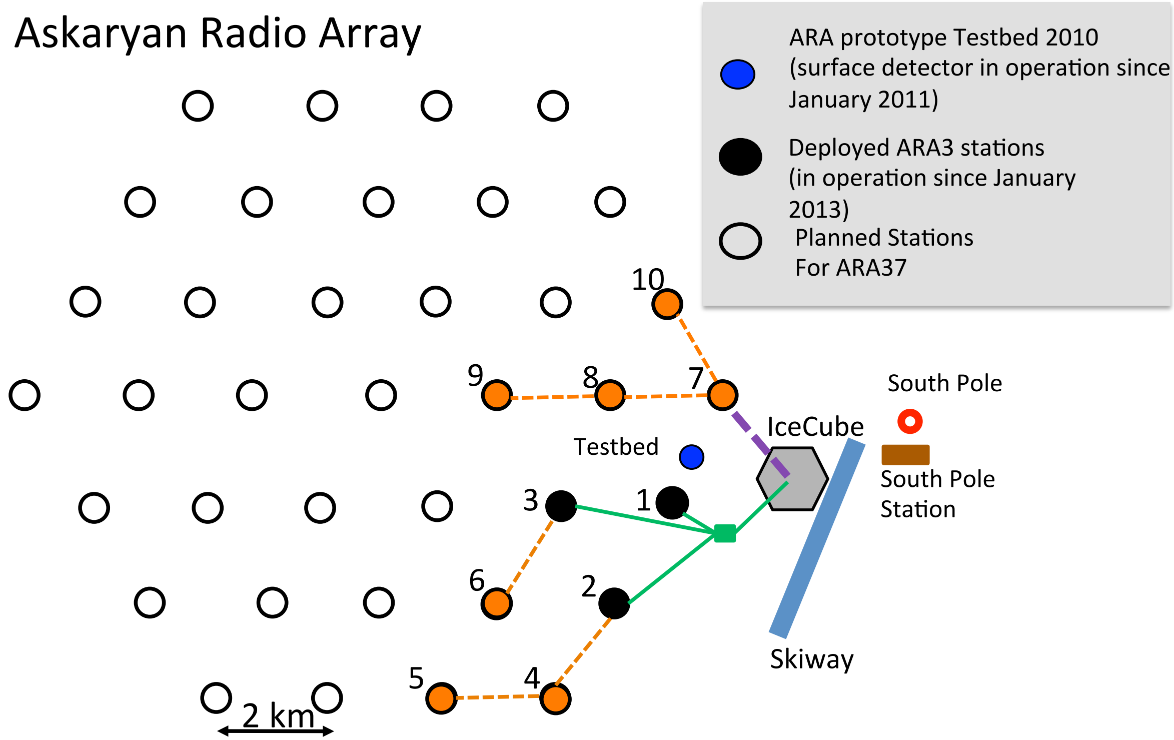
I Kravchenko *et al, 2011*

Askaryan Radio Array (ARA) 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

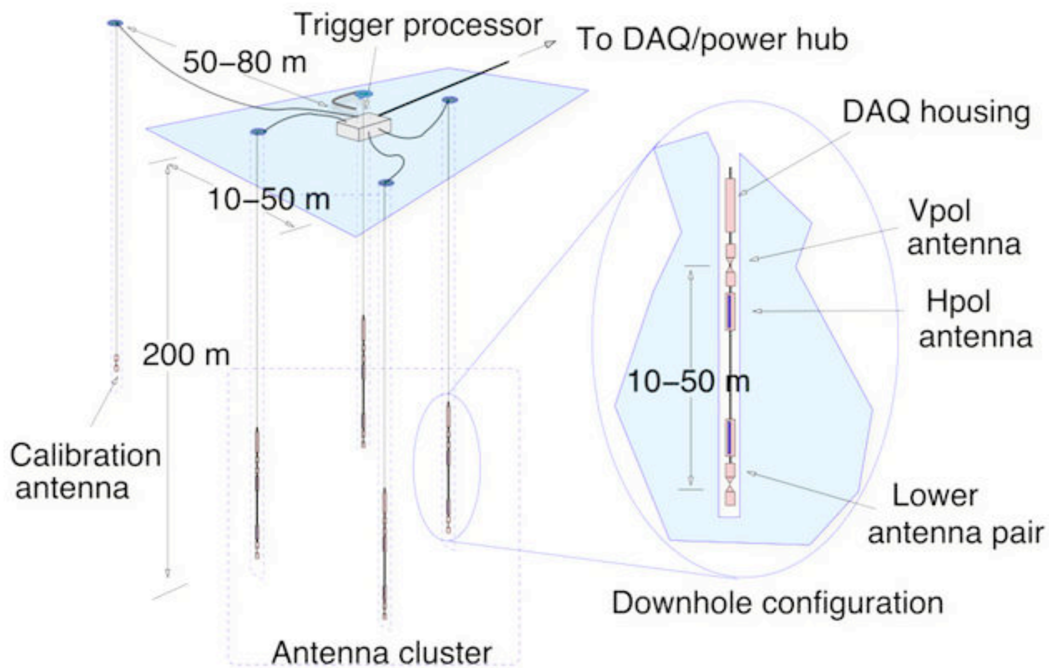


ARA layout



- Each station is independent detector
- 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

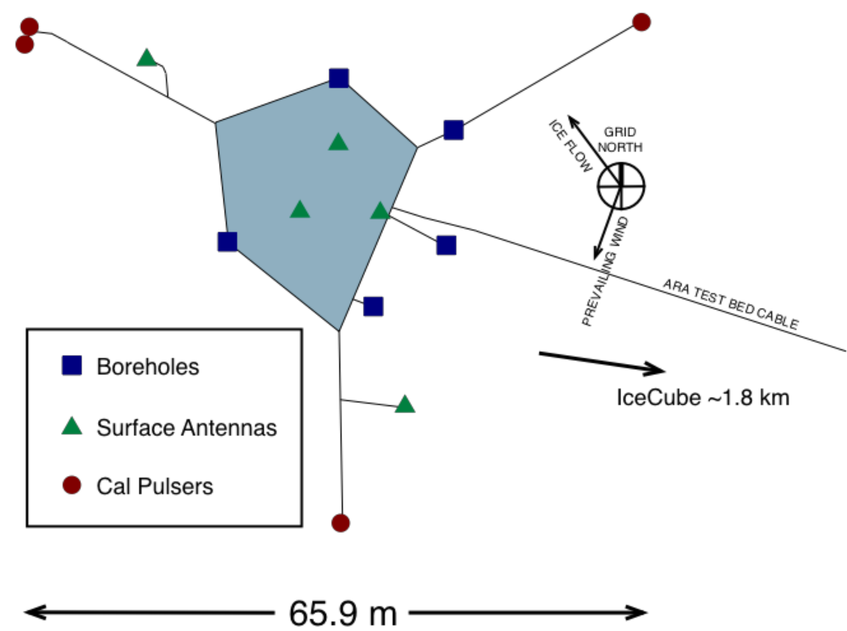
Vpol bicone antenna

- 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
- 3.2 GSamples/Sec → ~1° resolution of shower reconstruction direction

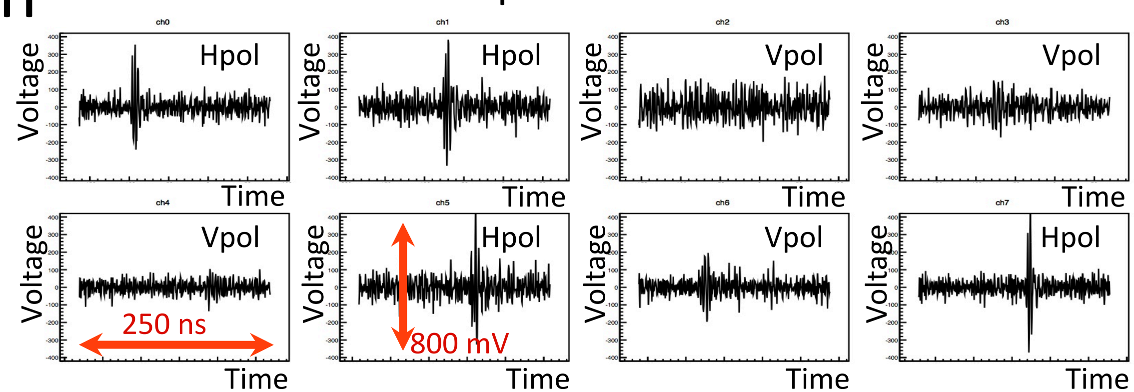
- Bandwidth: 150-850 MHz
- Azimuthal symmetry, dipole at low frequencies

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 on Testbed station data
  - Event selection performed with timing, signal strength data

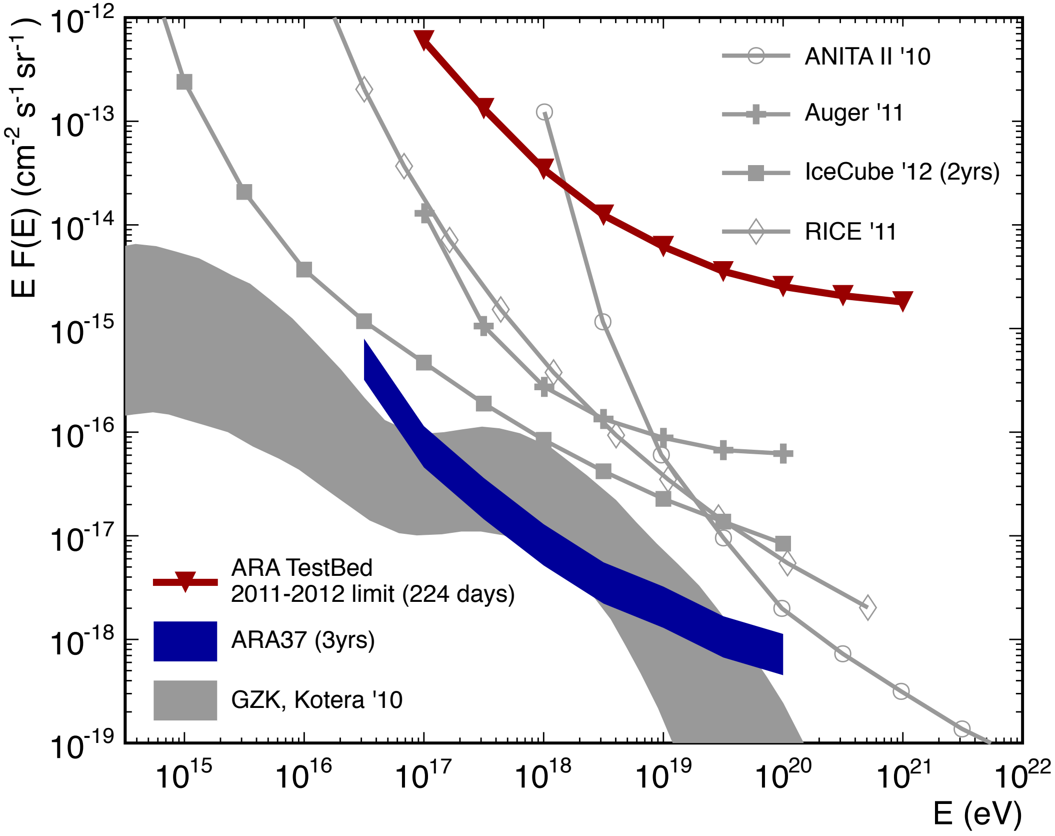


Calibration pulser event waveform from 8 deep antennas in Testbed



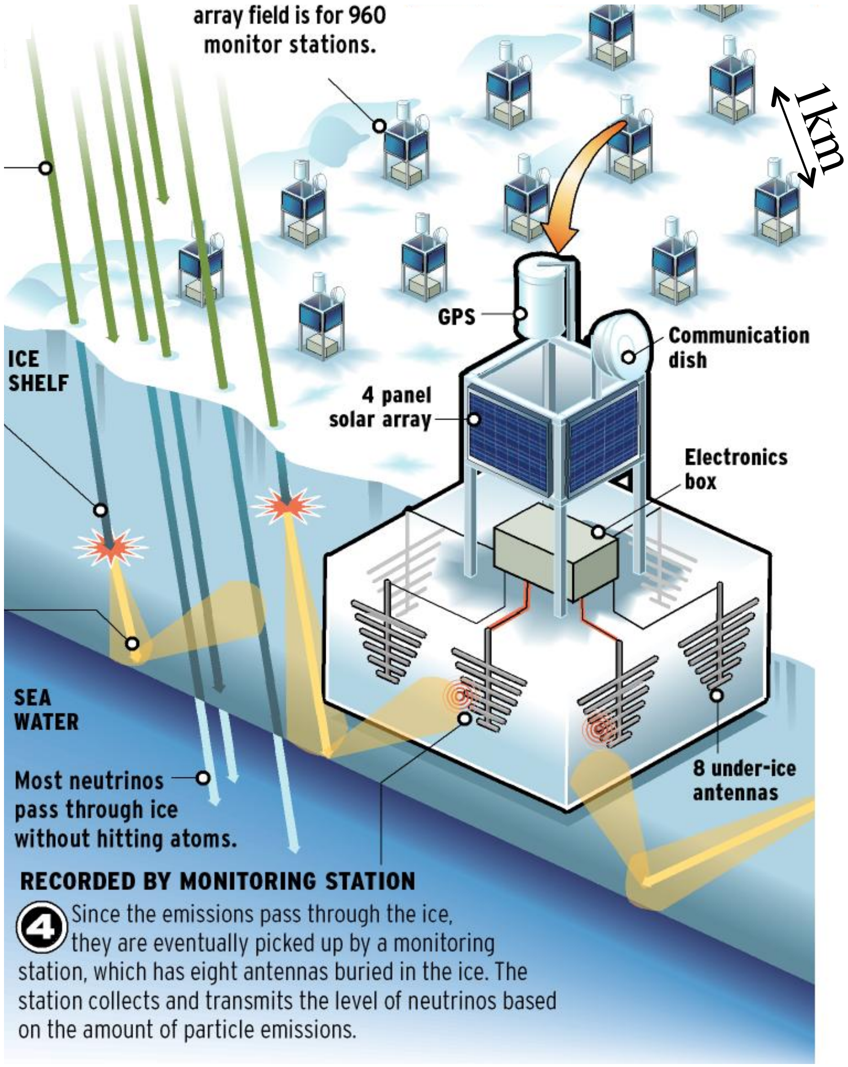
Sensitivity

- First limits from ARA Testbed found – no neutrino candidates
  - (see arXiv:1404.5285)
- Two separate analyses performed on 2011-2012 data
  - Limits comparable
- Projected sensitivity of expanded array extends to GZK flux models
- Analysis being expanded to deeper design-type stations – 1 year of data



ARIANNA

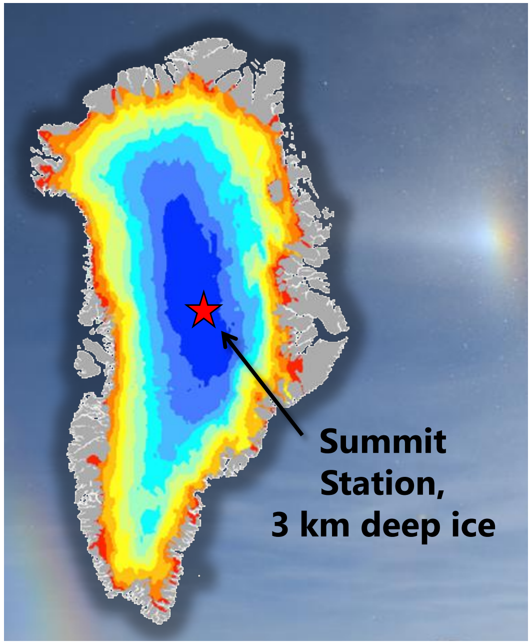
- Array of antennas on the surface of Ross Ice Shelf in Antarctica
  - Antennas buried just under the ice surface
- Radio Cherenkov signals reflected from the bottom of the ice sheet
  - Could potentially see more "down-going" events
  - Relies on detailed knowledge of ice sheet
- Planned deployment of 1 hexagon (7 stations)
  - to be completed this year
  - ~960 total planned stations
- Prototype station description
  - arXiv:1005.5193
- Site tests - Time domain response
  - arXiv:1406.0820, 2014



From OC Register 2012

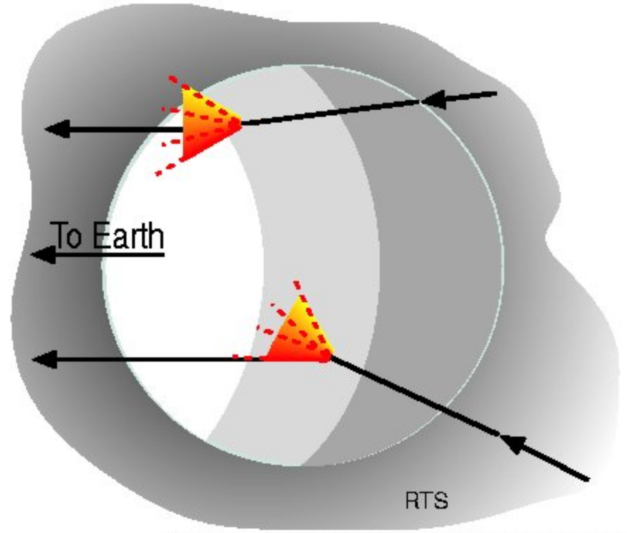
Greenland Neutrino Observatory (GNO)

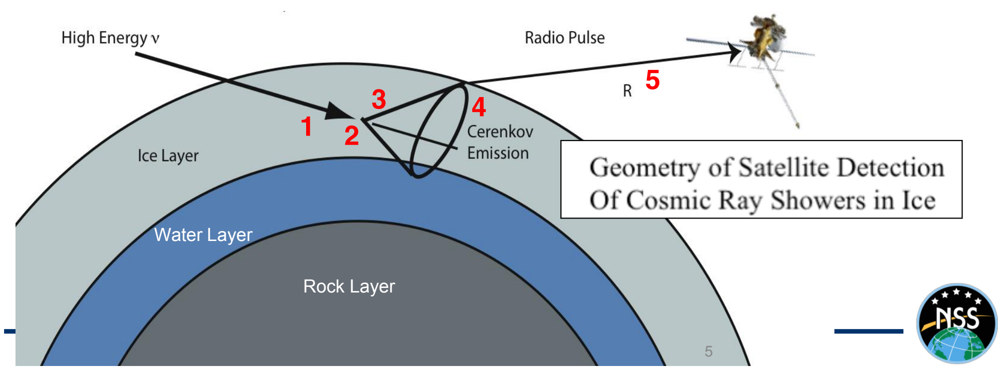
- Exploratory work for a proposed radio neutrino detector
- Site – Summit Station, Greenland
  - Year-round NSF research Station
  - 10 months of sunlight
  - Access by C-130s, annual overland traverse, direct flights from NY
  - Plans for expanded "Isi" station
- Ice – 3km deep,
  - 997+/-150 m attenuation length
- Deploy testbed in spring 2015
  - 8 hpol, 8 vpol antennas
  - Hardware in development



Extraterrestrial Searches

- Use moon as giant target
  - Use radio arrays to search for UHE neutrino and CR radio signals from moon
    - Goldstone Lunar UHE Neutrino Search (GLUE)
    - NuMoon at Westerbork Radio telescope (WRST), LOFAR
    - Square Kilometer Array (SKA)
- Use outer planet lunar ice as large target
  - Passive Radio Ice Depth Experiment (PRIDE)
  - Build satellite to orbit objects like Europa, Enceladus





From ARENA 2014 talks

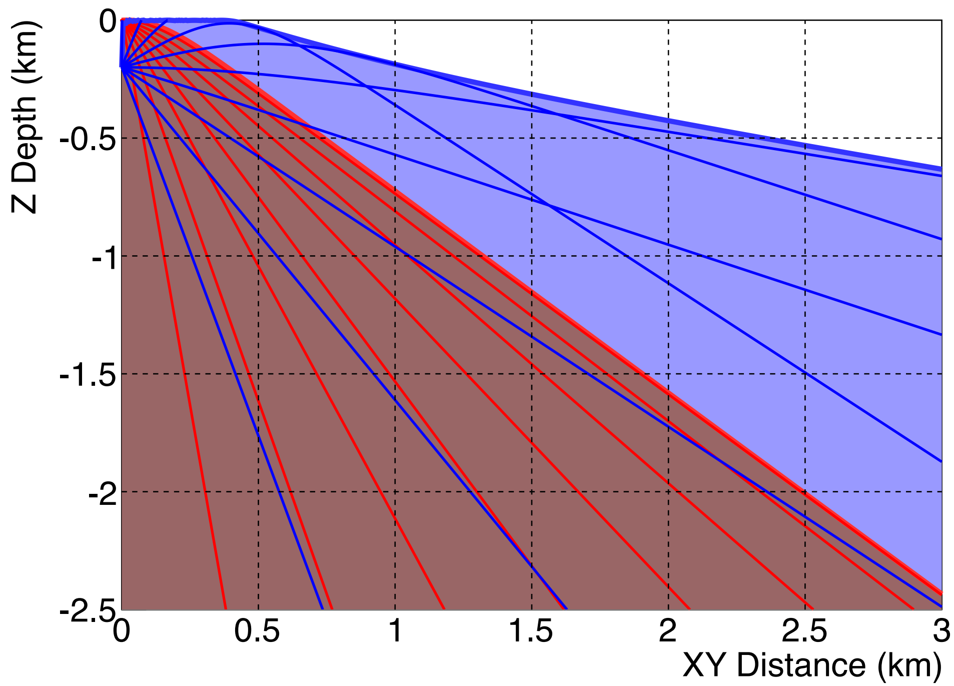
Summary

- Want to build a large-scale UHE neutrino observatory
  - RF detectors are promising advances in the field
- Synoptic experiments have flown already
  - ANITA-I, ANITA-II
  - More planned: ANITA-III, EVA
- *In situ* arrays deployed: RICE, ARA3
  - More being built with some data already analyzed
    - ARA37, ARIANNA, GNO

Questions?

- Backup slides

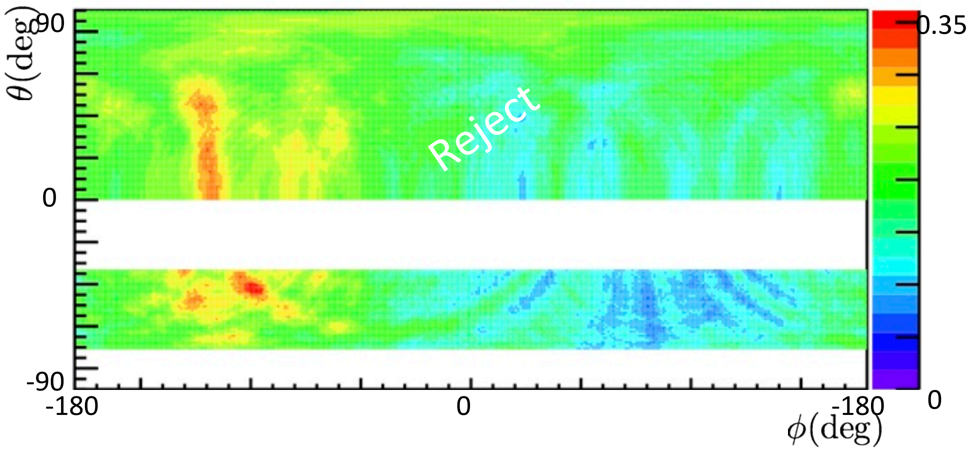
Importance of Deep Deployment



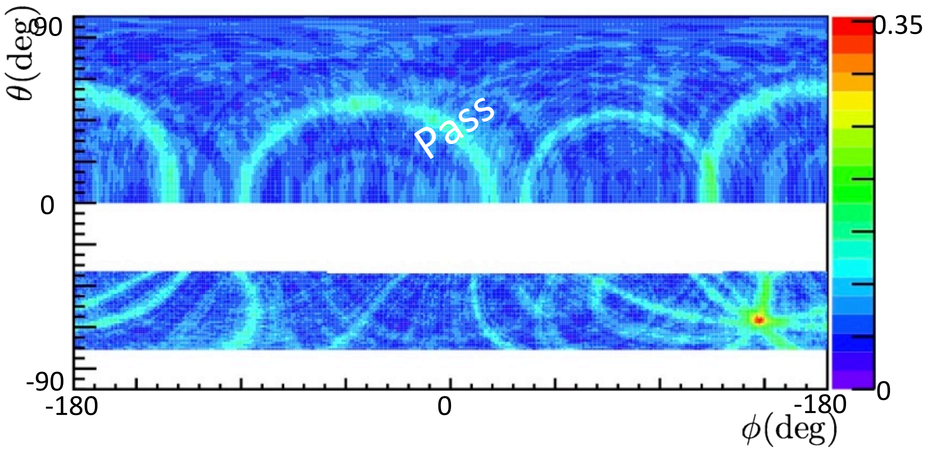
- Firn – layer of compacted snow
  - Quickly changing index of refraction (~1.35 → ~1.78 within top ~150 m of ice)
  - Causes curvature in paths of rays in ice
  - Limits viewable volume and observable neutrino incident angles
  - 30 m → 200 m depth: increases effective volume by factor of ~3.2
- Cost-benefit analysis
  - Ice closer to surface is colder, longer attenuation length
  - Drill to lower depths to gain effective volume vs money and time to drill further

OSU analysis - Reconstruction Quality Cut

Known background event reconstruction map example



Simulated ν event reconstruction map example

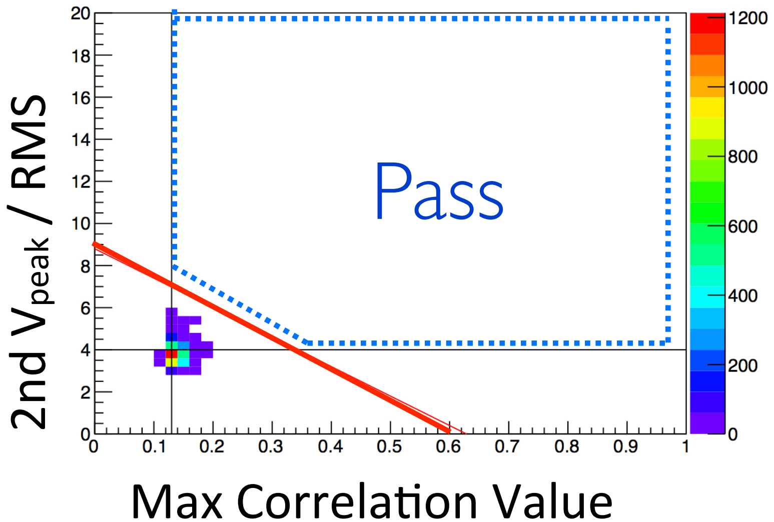


- Reconstruction based on timing from ray-tracing – use 30 m and 3 km maps in Hpol and Vpol
- Requires at least one reconstruction map to be of good quality
  - 1 deg^2 < Area of 85% contour surrounding the peak < 50 deg^2
  - Total 85% contour peak area < 1.5 x Area of 85% contour surrounding the peak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

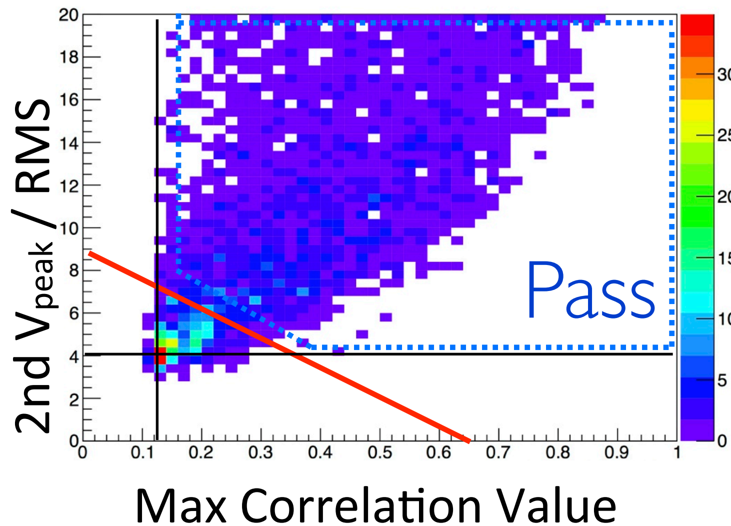
2nd V_{peak} / Correlation Cut

- 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

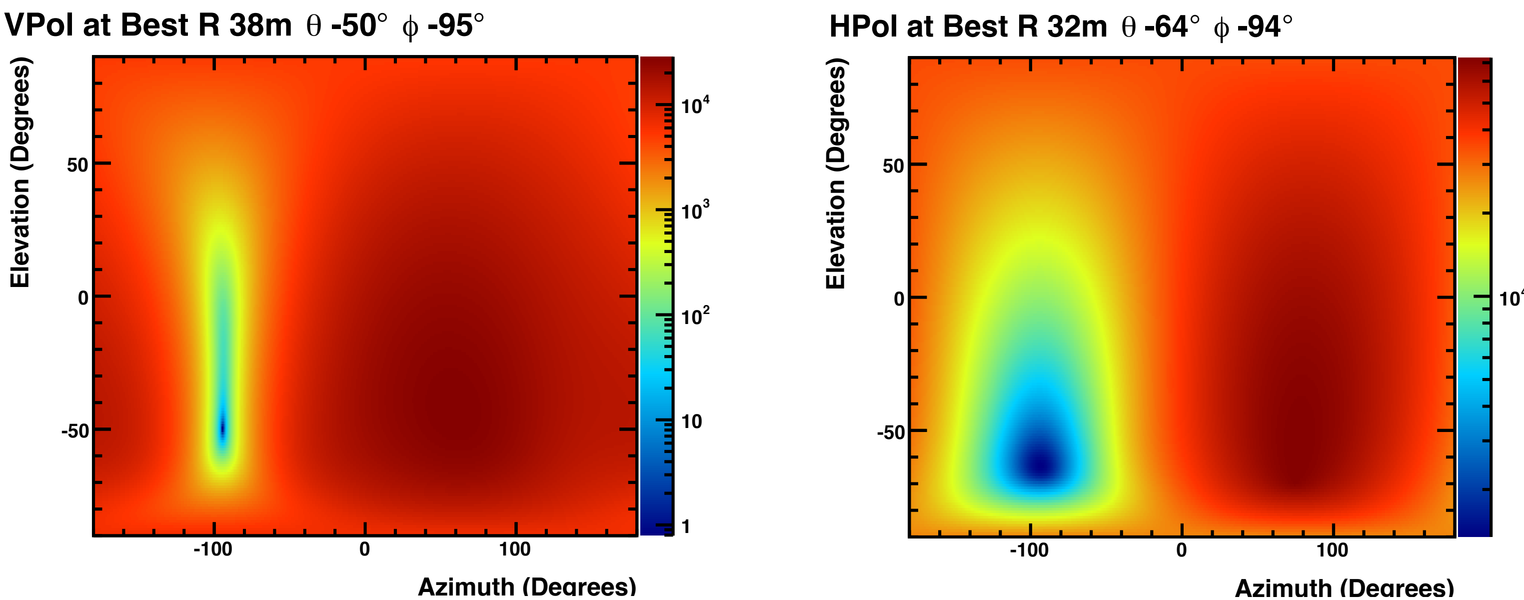
Testbed 10% data set after cuts applied



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

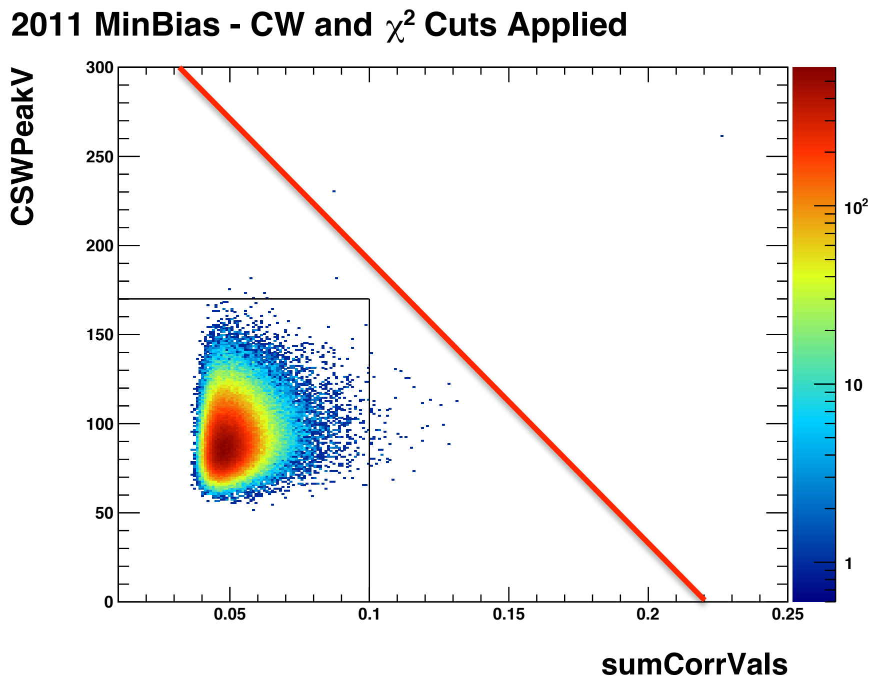


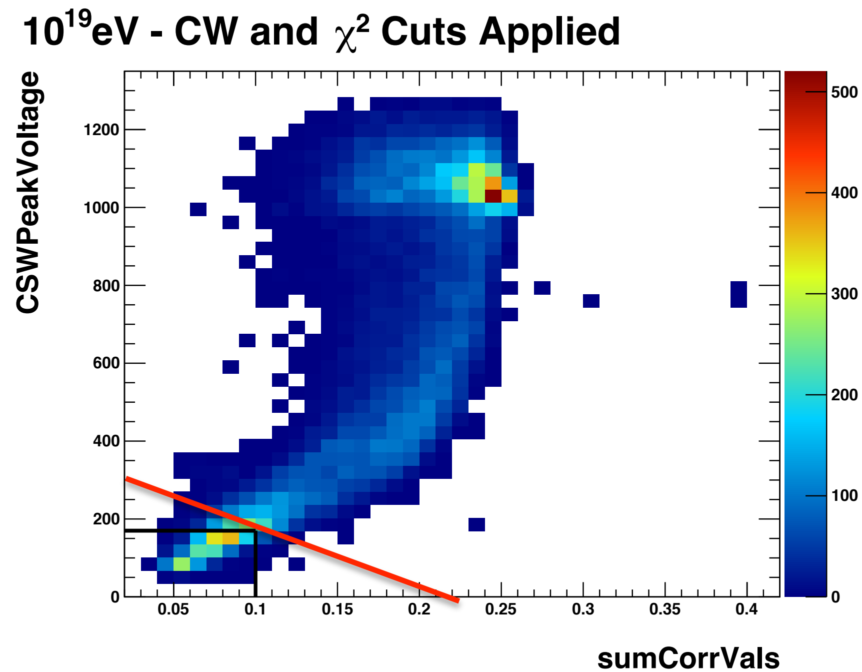
UCL Analysis Reconstruction



- 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

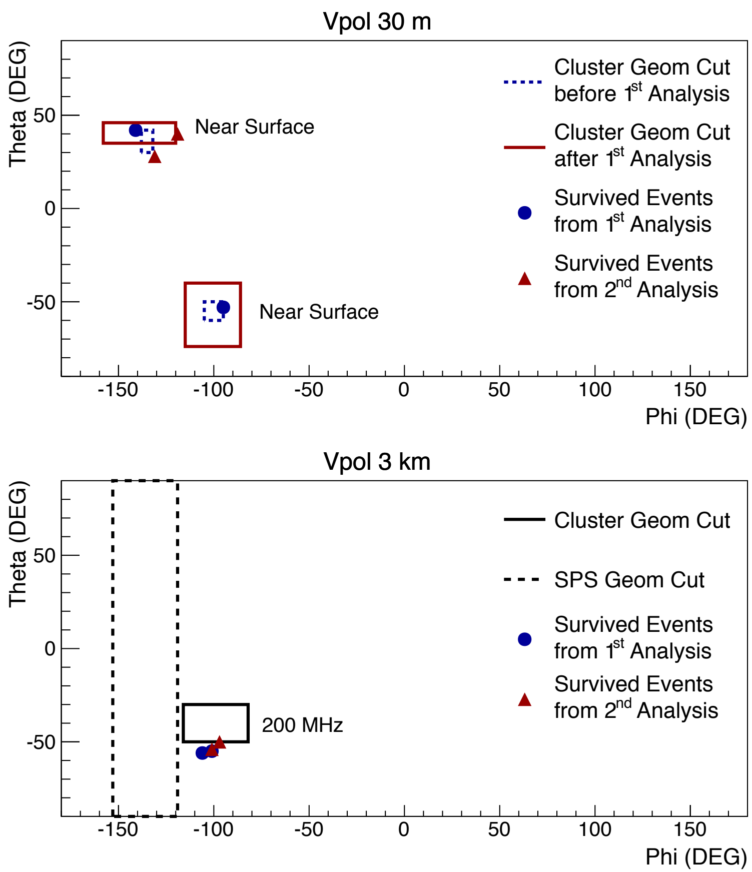
UCL - “Powherence” Cut

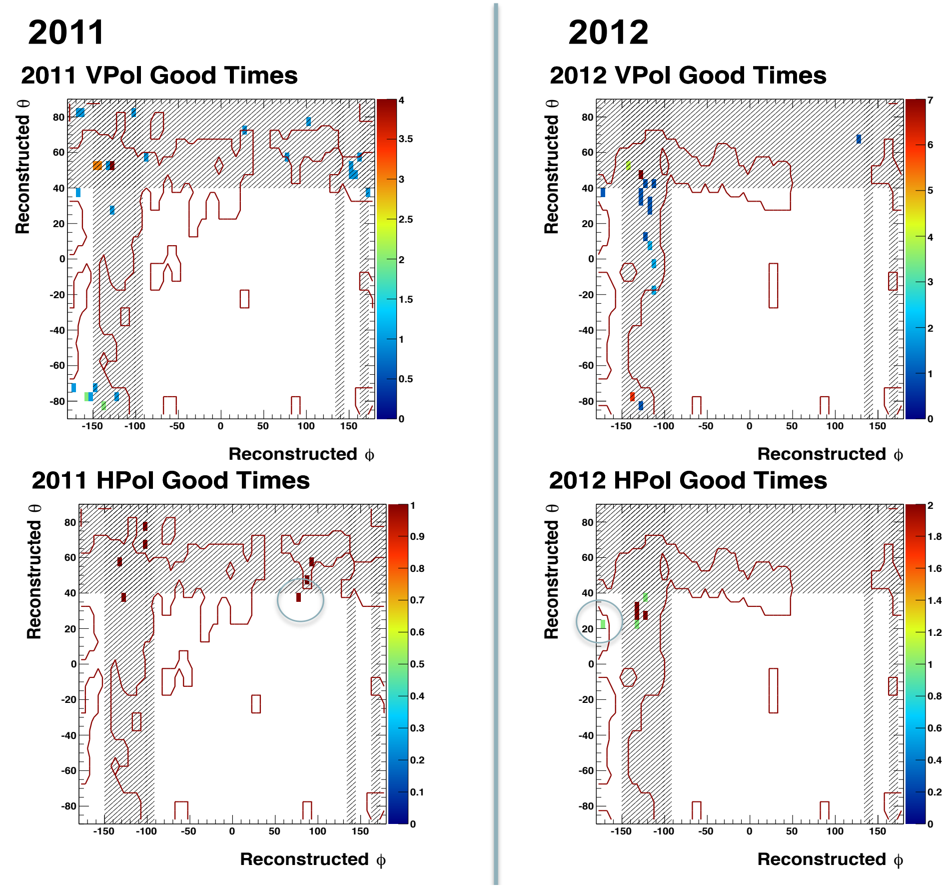




- Linear combination of:
  - peak power of the CSW
  - sum of the maximum correlation values of antennas with the CSW of the remaining antennas
- Expect impulsive events to separate out from noise, CW

Clustering - OSU, UCL



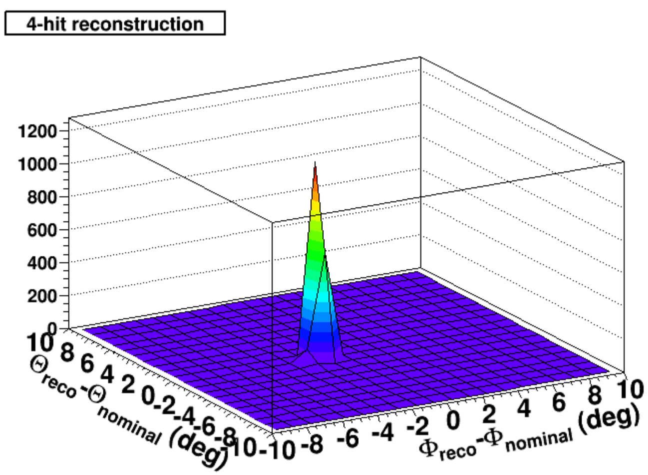


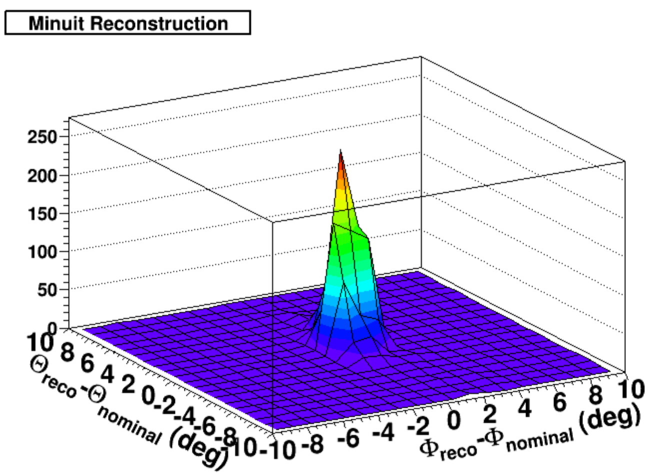
- Both analyses reject events reconstruction to a location where an excess of events can be found
- Also reject South Pole phi range and require reconstruction in the ice

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



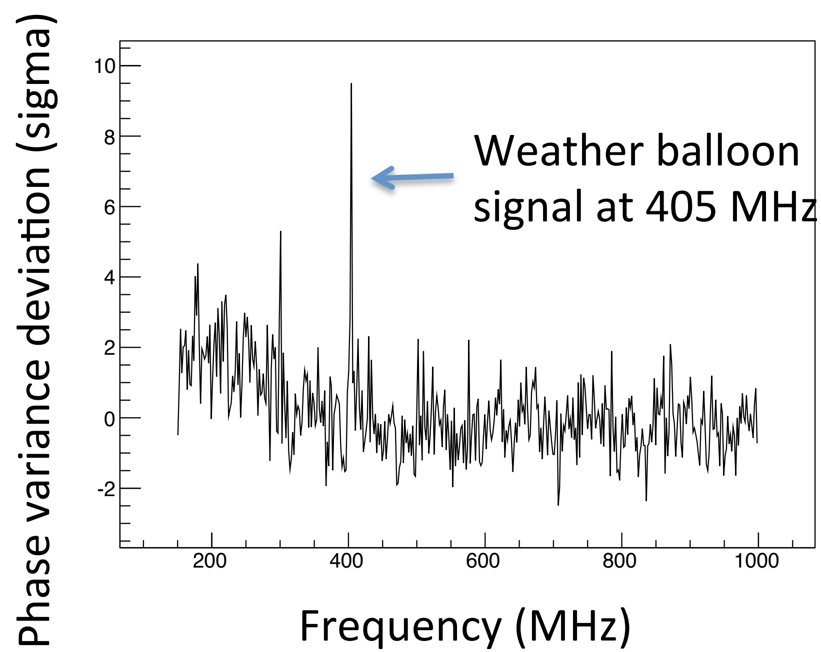


Analysis Results

- OSU 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)
- UCL analysis: 1 event passed cuts
  - CW event with two carrier frequencies, non-impulsive
- KU analysis: 1 event passed cuts
  - Consistent with calibration pulser event, misidentified by template matching
- No neutrino candidates

Future Improvements

- Reconstruction methods
  - Account for index of refraction and reflection
  - Reconstruction quality parameters
- Better identification of anthropogenic signals from South Pole
  - 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



Passed Events Table from 2011-2012 TestBed Data

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

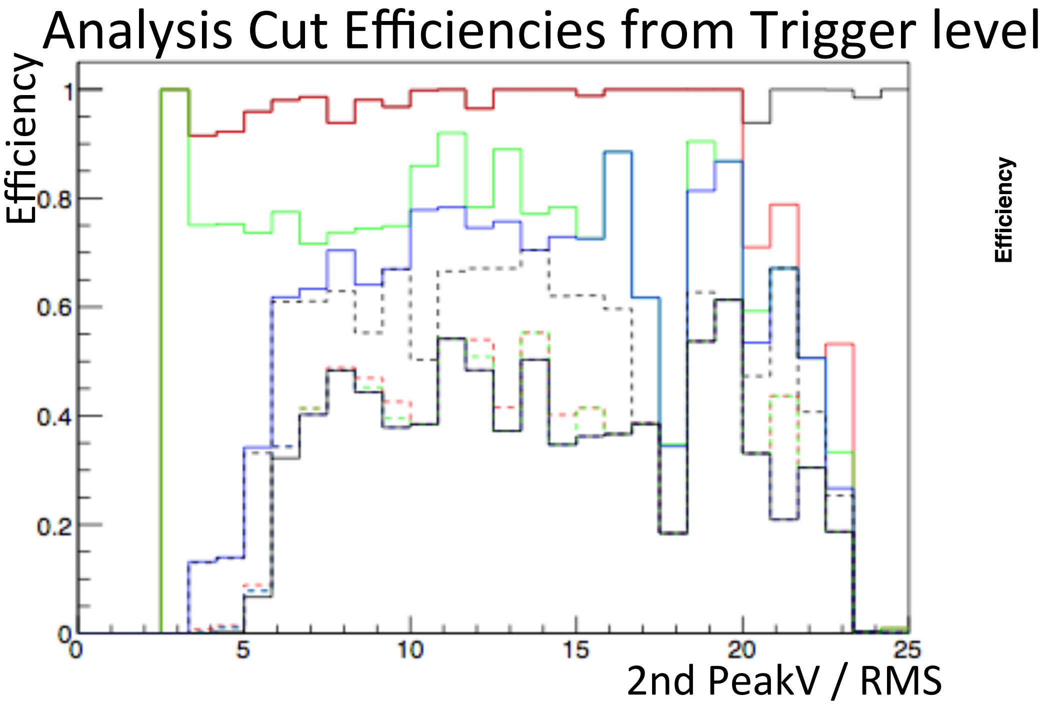
Vpol channel

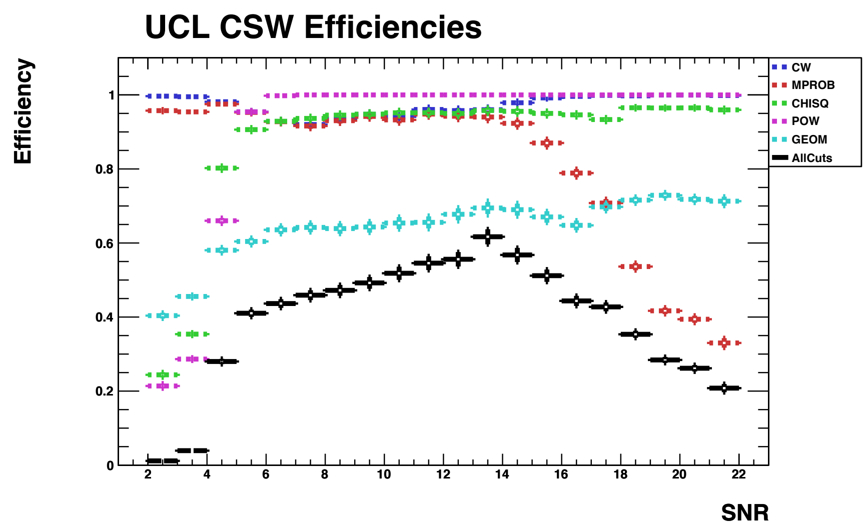
	Pass Events
Reco.Qual Vpol	1,839,348
NoisyTime	1,354,670
Geom Cuts	1,122,083
Gradient Cut	1,120,713
Delta Delay	178,796
CW	177,944
Down	16,894
Rcut	0

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

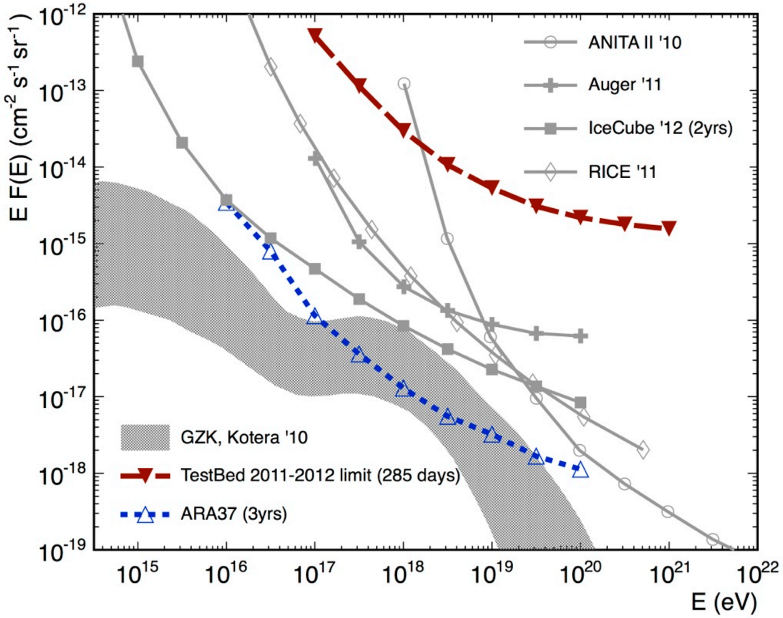




OSU

UCL

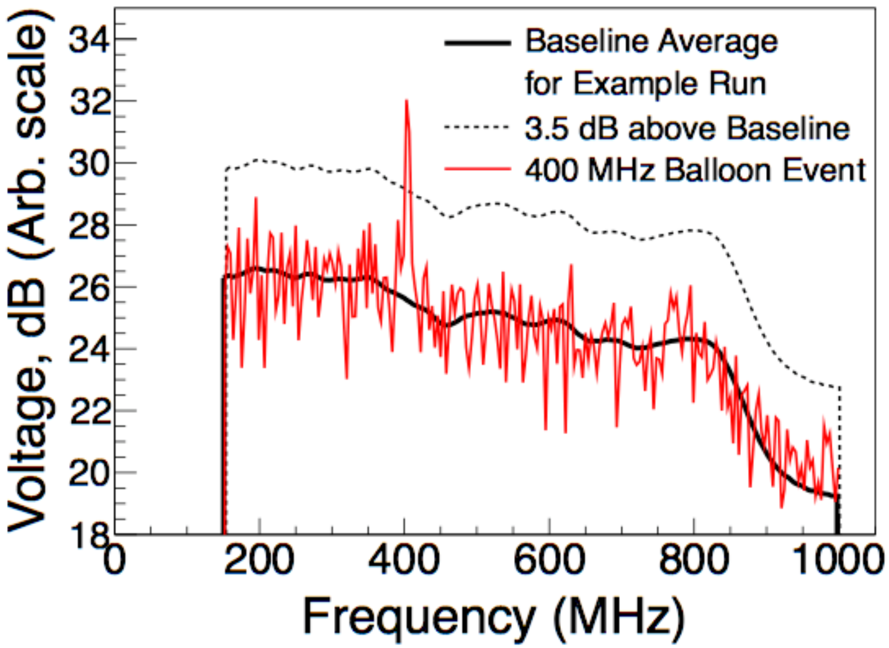
Neutrino Limit from 2011-2012 Testbed Data

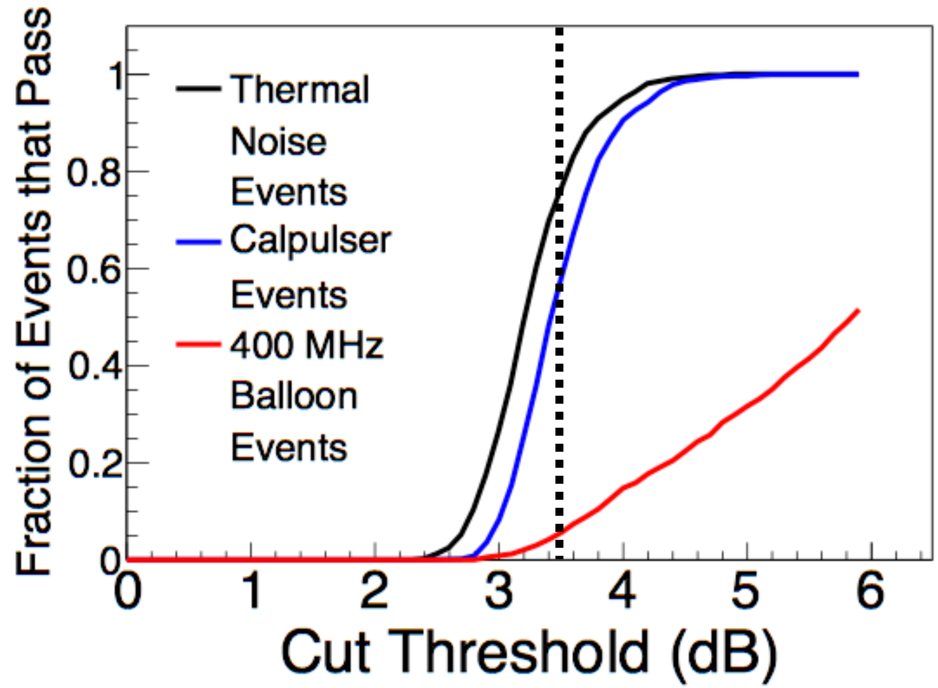


	Effective Area at 10^{19} eV [km^{2}sr]	Accumulative Factor from Testbed Analysis
Testbed Analysis	7.37E-04	1
Testbed Trigger	4.08E-03	6
ARA one station Trigger	1.70E-02	23
ARA two stations Trigger	2.98E-02	40
ARA 37 Trigger	4.04E-01	550

- 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





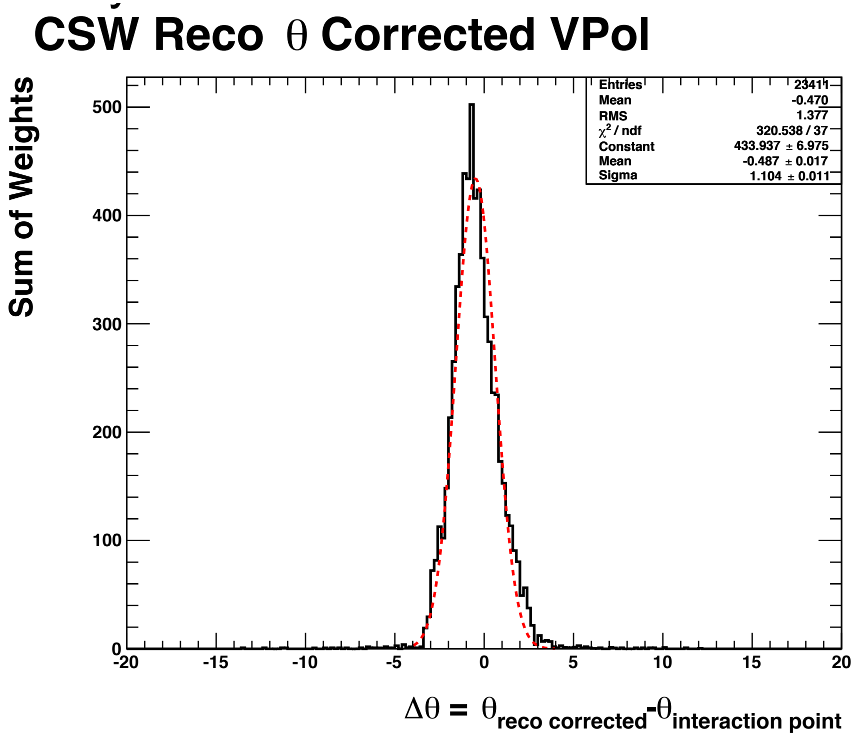
- Design cut based on ANITA experience
- Make average spectrum for each run (1 run = 18000 evts ~ 30 minutes)
- Reject events whose Fourier transformed voltage waveform exceeds 3.5 dB baseline anywhere in frequency space
- Will optimize the cut using AraSim and 10% not blinded testbed data

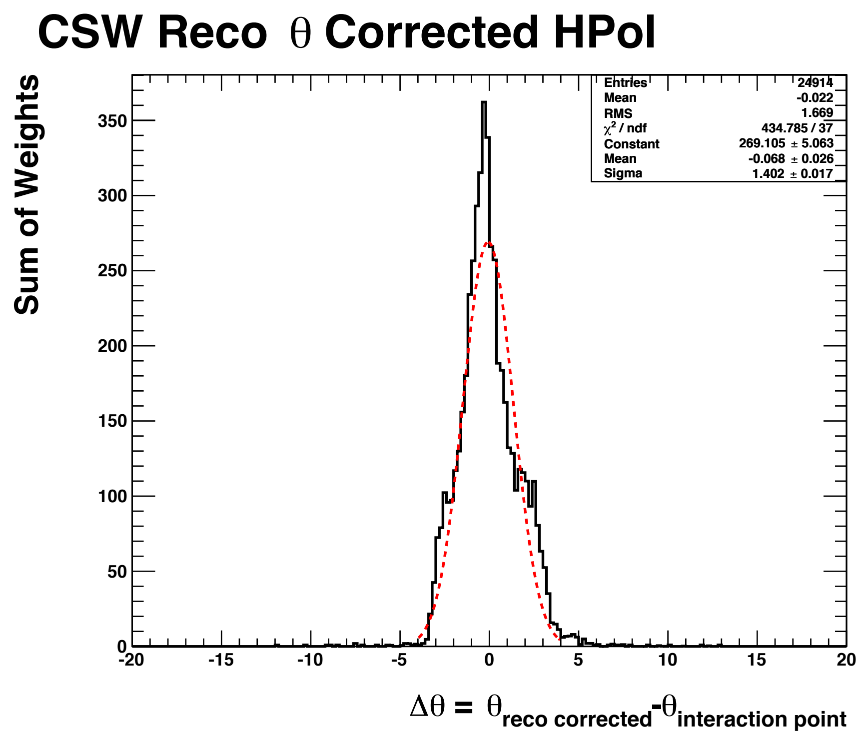
Event Cut Table (OSU)

Total	3.3E8					
Cut	Number passing (either polarization)					
Event Qual.	1.6E8					
Recon. Qual.	3.3E6					
	VPol			HPol		
	In sequence	Rejected as last cut	Rejected as first cut	In sequence	Rejected as last cut	Rejected 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

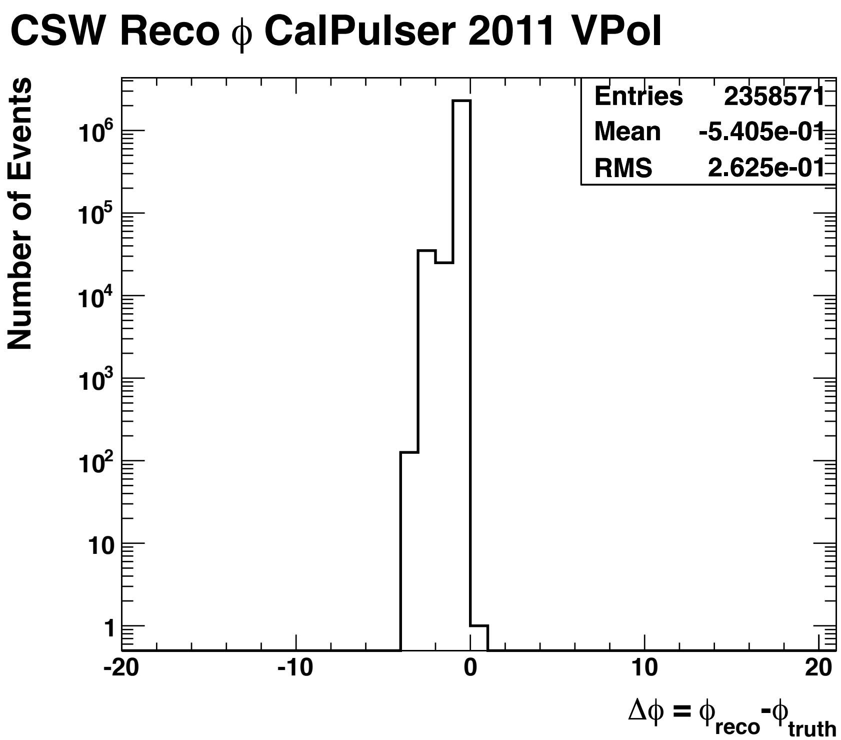
Table 2: This table summarizes the number of events passing each cut in the Interferometric Map Analysis, in Phase 2 (2011-2012, excluding Feb.-June 2012). We list how many events each cut rejects as a last cut, and how many are rejected by each cut if it is the first cut. After the Event Quality and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

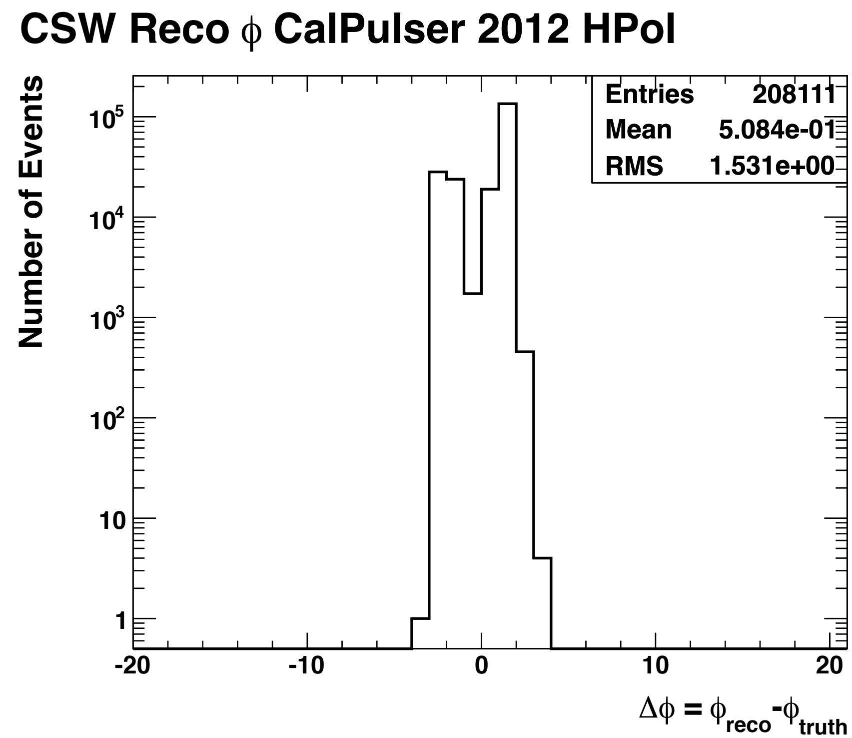
Reconstruction Error - Simulation



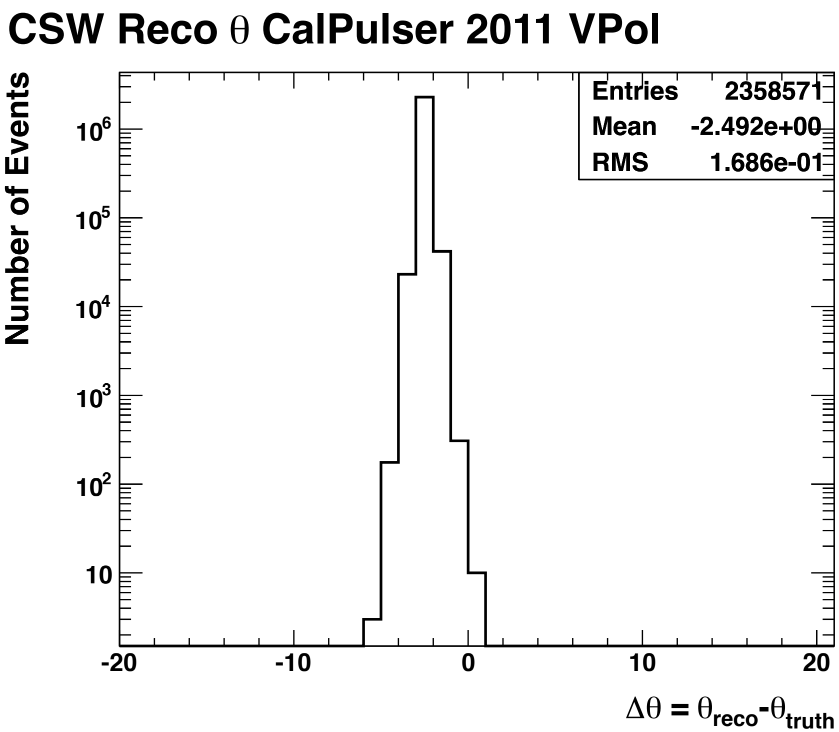


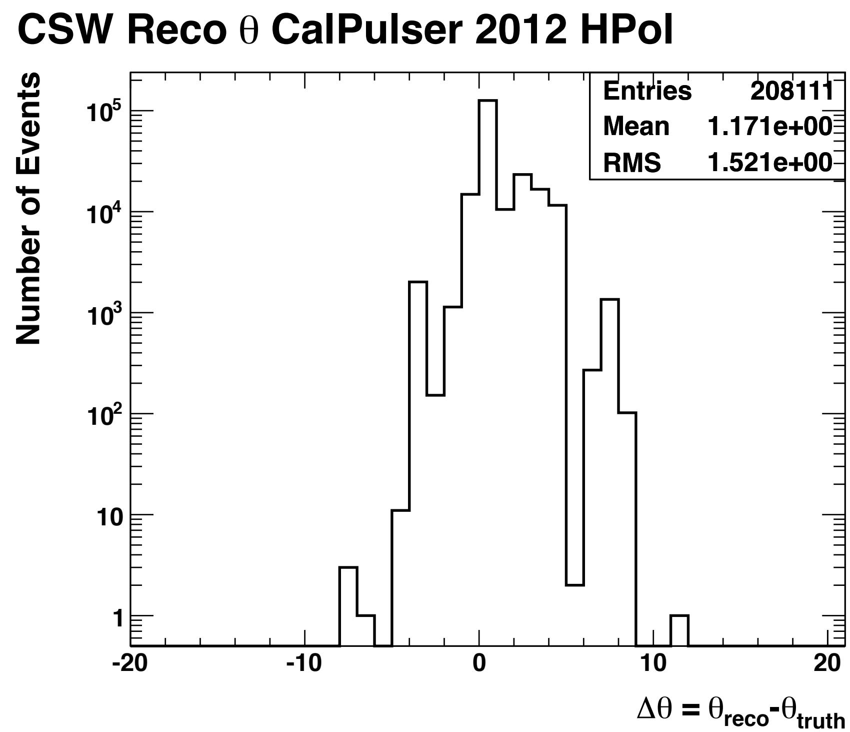
Reconstruction - Calpulser





Reconstruction - Calpulser





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