The Abdus Salam
International Centre for Theoretical Physics

United Nations
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2246-26

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Results in ultra-high energy particle detection in Antarctica

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Radio Cherenkov Search for Cosmogenic Ultra-High Energy Neutrinos: ANITA and ARA

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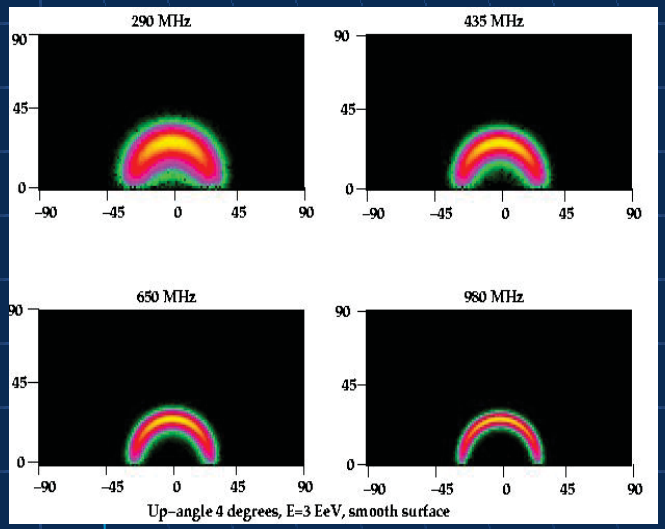
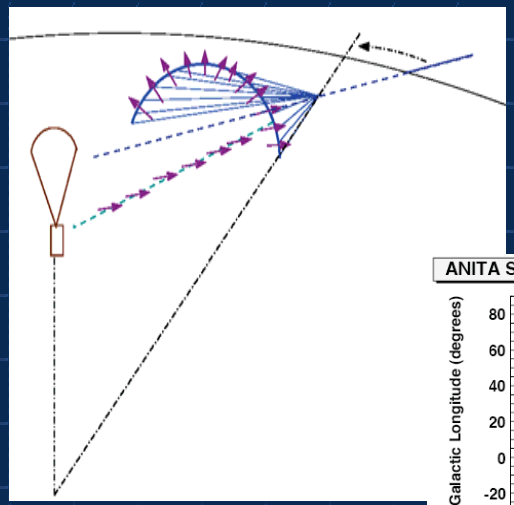
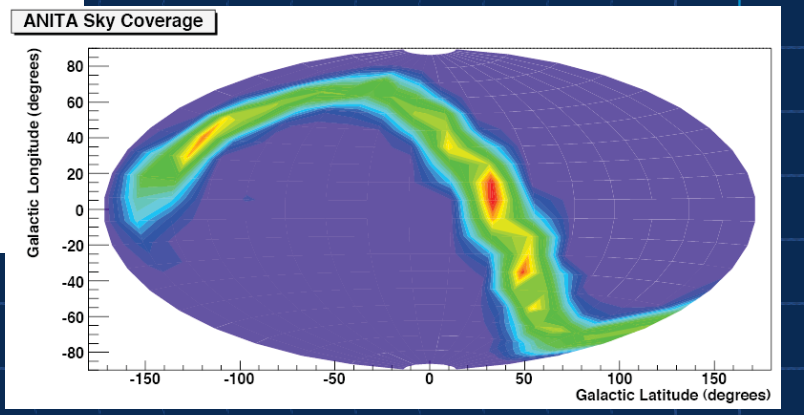
KIPAC, SLAC, Stanford University

For ANITA & ARA collaborators at Univ. Hawaii, UCLA, National Taiwan University, SLAC, JPL, Univ. Kansas, Washington Univ. St Louis, Ohio State Univ., Univ. of Delaware, Univ. College London, Univ. Wisconsin, Madison, Univ. Maryland

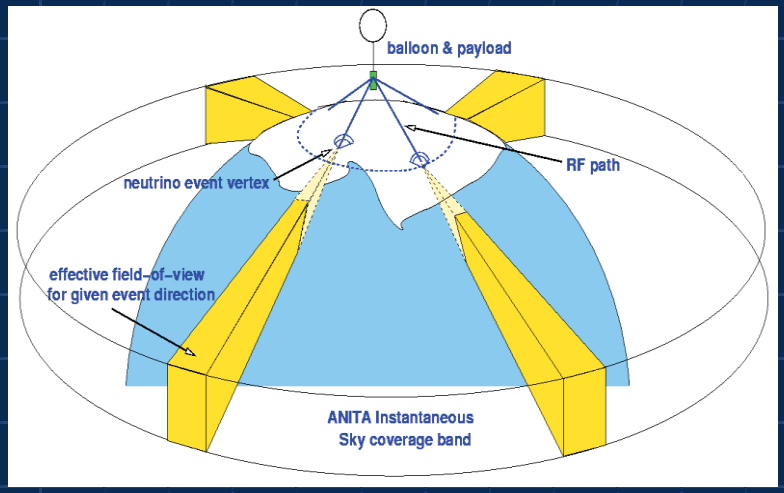
ANITA as a neutrino radio telescope





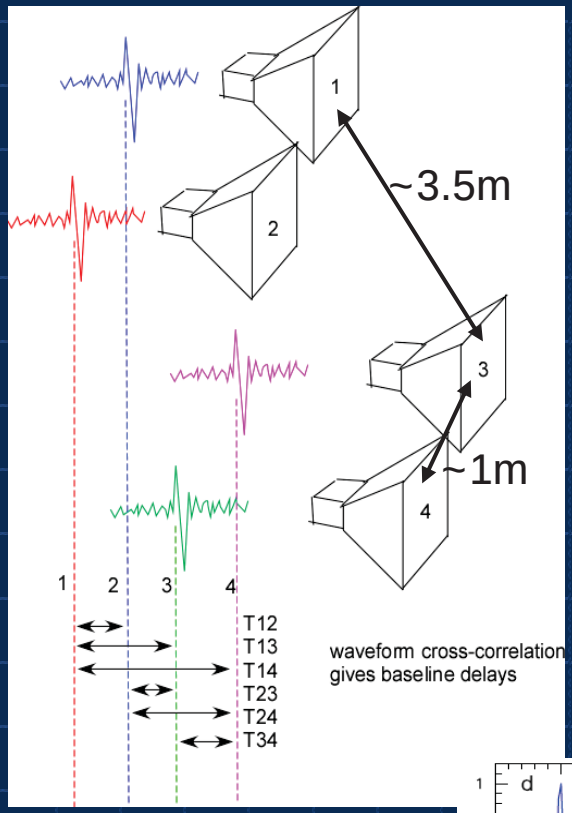


Brian Mercurio & Chris Williams, OSU

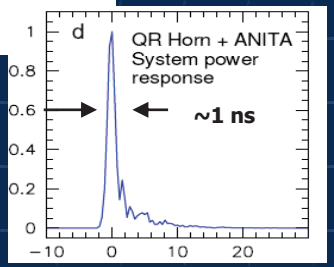


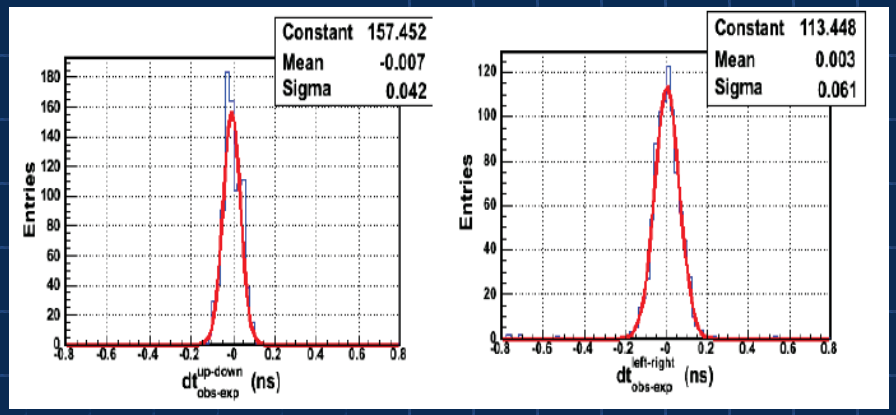
- Pulse-phase interferometer (<30-60 ps timing) gives intrinsic resolution of <0.3° elevation by ~1° azimuth for **arrival direction of radio pulse**
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~5-7° in azimuth by observed **polarization angle of detected impulse**

Pulse phase interferometry



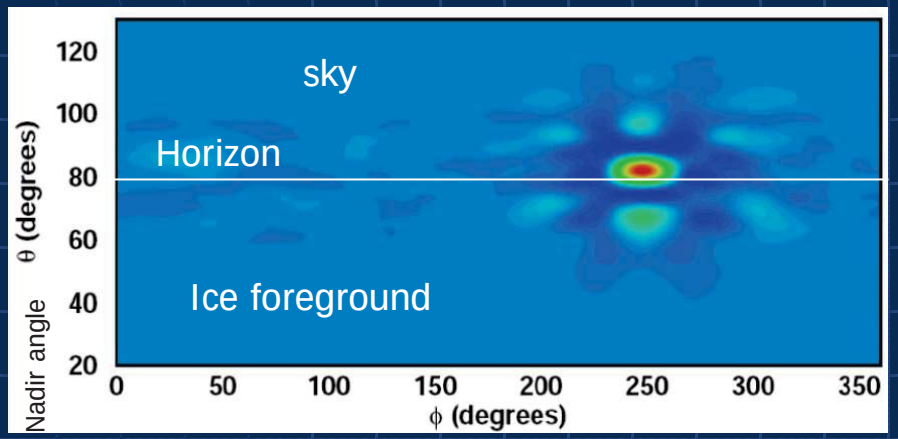
0.2-1.2 GHz bandwidth
➔ 1 ns impulses





JiWoo Nam, NTU

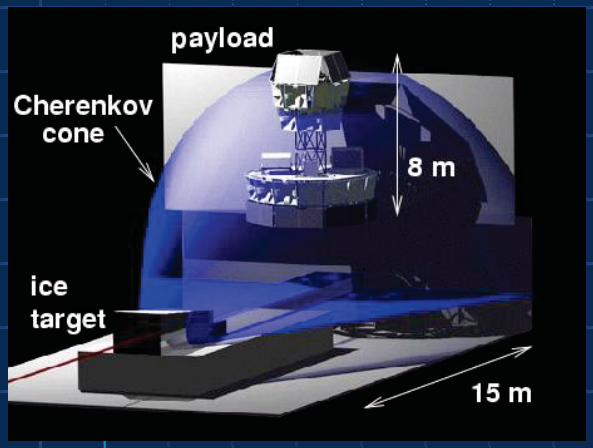
- RF Waveform samplers (G. Varner, UHM)
  - Provide 10 bits, 2.6 Gsamples/sec for 80 channels
- Waveform cross-correlation delay precision determines angular resolution
  - ~30-40 ps (~1 cm) vertical at SNR~5σ
  - ~60-80 ps (2-3cm) horizontal (due to DAQ clock jitter)



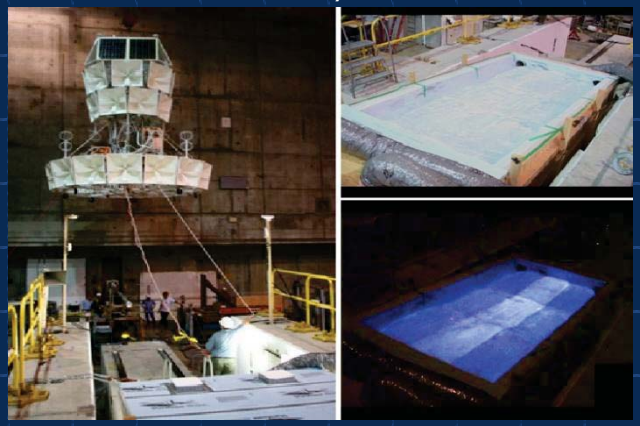
Andrew Romero-Wolf, UHM

End result: map of instantaneous radio intensity, Method pioneered by UH student Romero-Wolf!

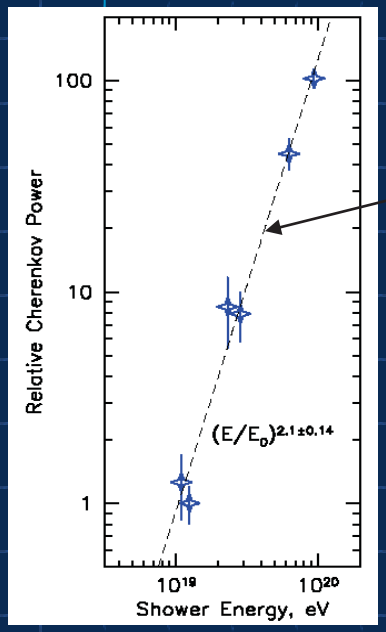
June 2006, SLAC T486: "Little Antarctica"

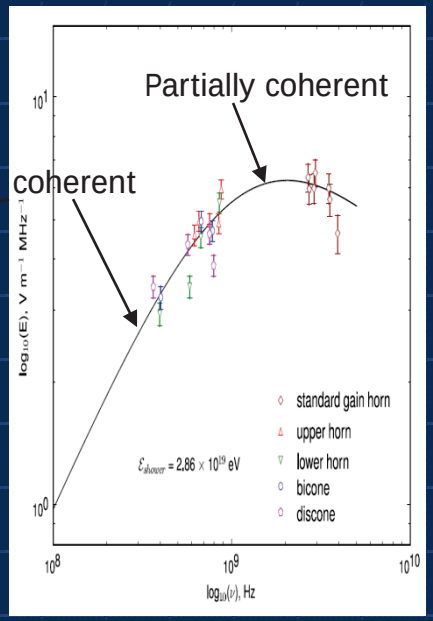


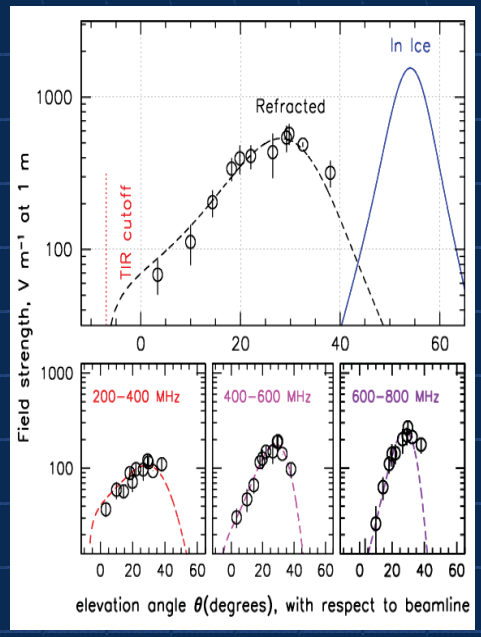
End Station A, SLAC



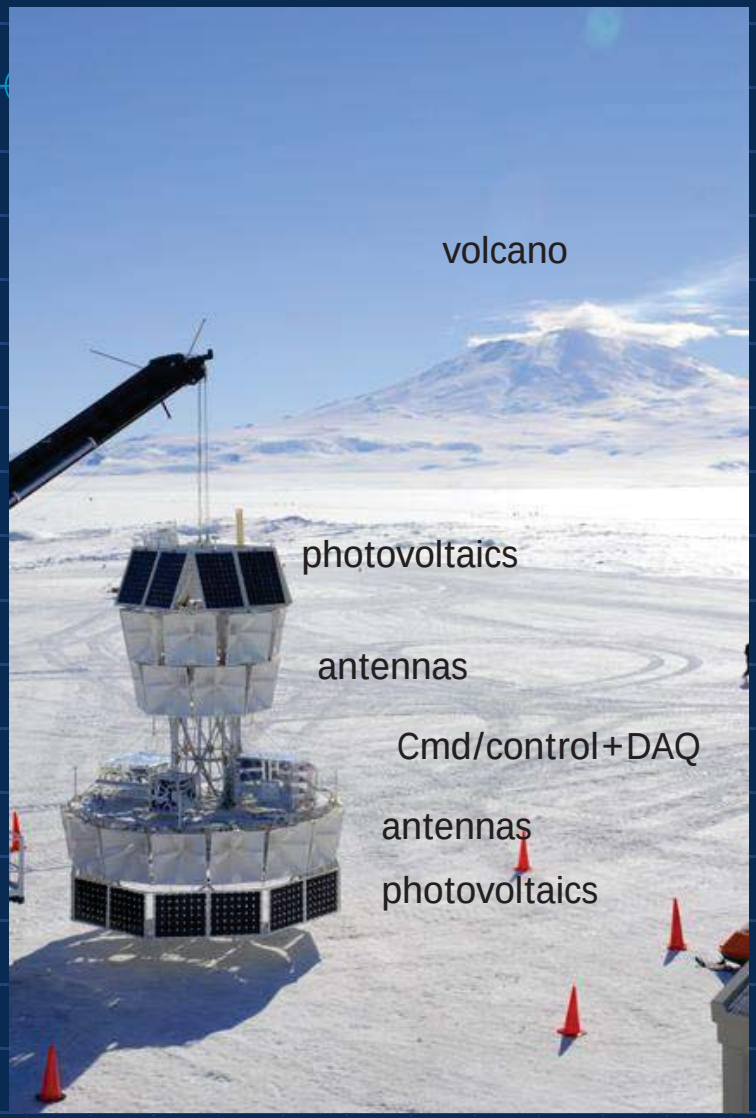
- **SLAC e⁻ showers with composite energy same as UHE neutrinos**
  - **10^9 x 28 GeV =2.8 x 10^{19} eV**
- **Coherent radio power, consistent with theory**
- **1st direct observation of radio Cherenkov cone**







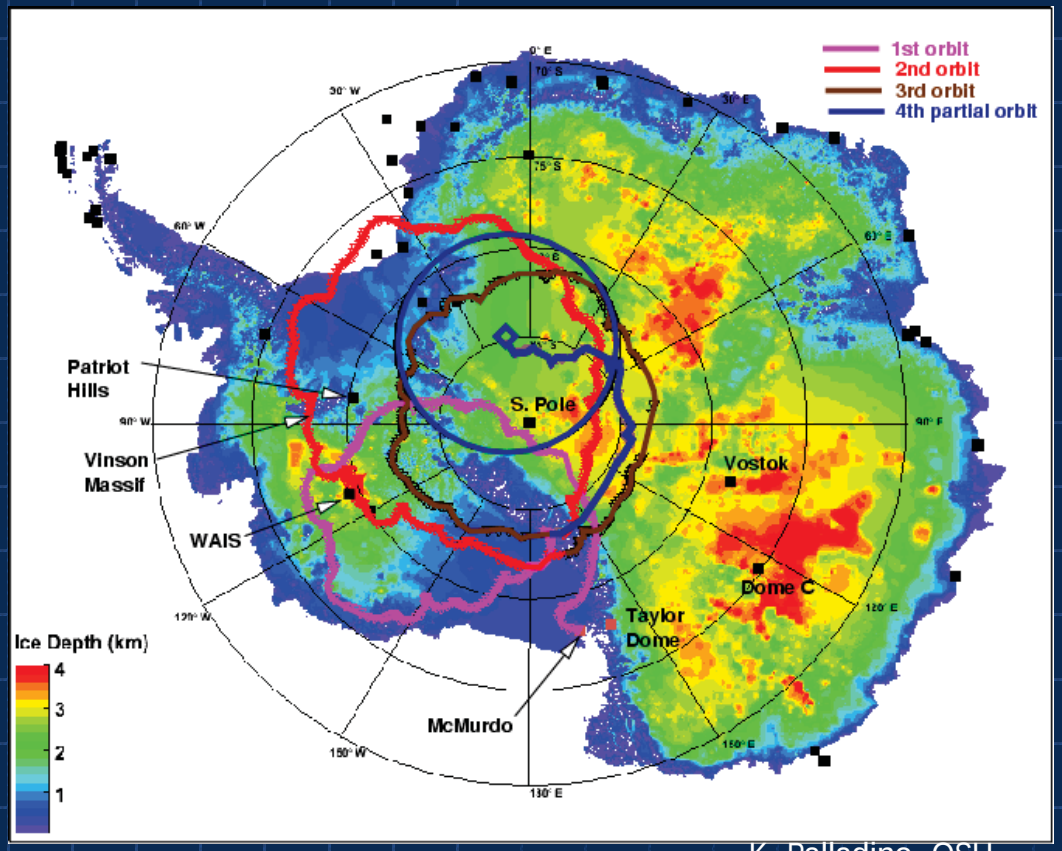
Pre-launch rollout



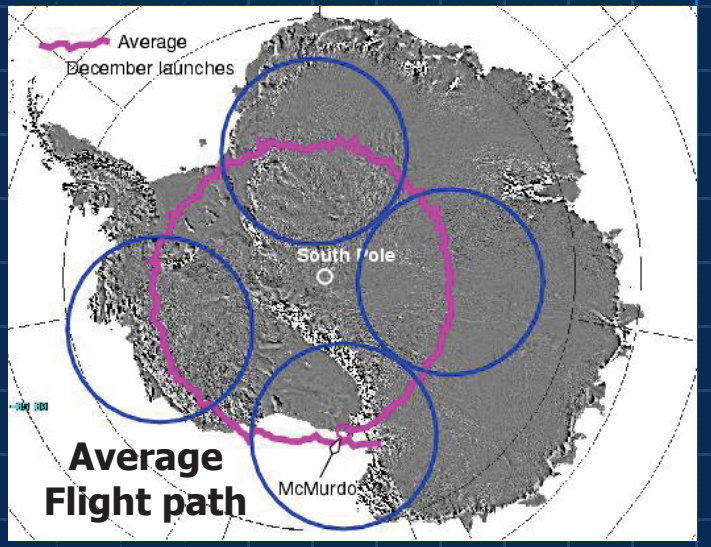
- Launch from ~80m deep Ross Ice Shelf (floats on Ross Sea)
- ~8 miles from McMurdo Station
- Affords flat, stable 1-mile diameter launch pad

Photos: J. Kowalski

ANITA-I flight path

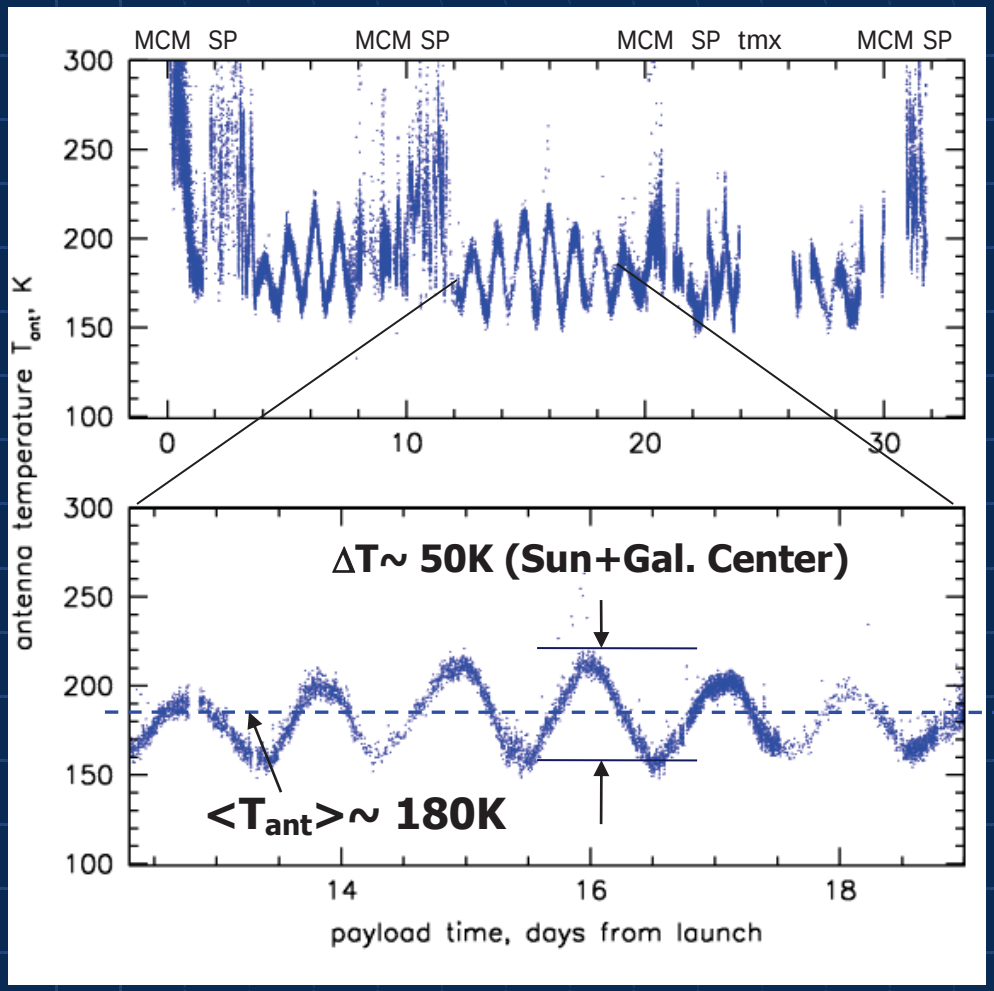


K. Palladino, OSU



- 35 days, 3.5 orbits, but anomalous Polar Vortex conditions
- Stayed much further "west" than average
- In view of radio noise from stations (S. Pole & McM) ~50% of time
- But still achieved 18 days of good livetime at ~1.2km average depth of ice

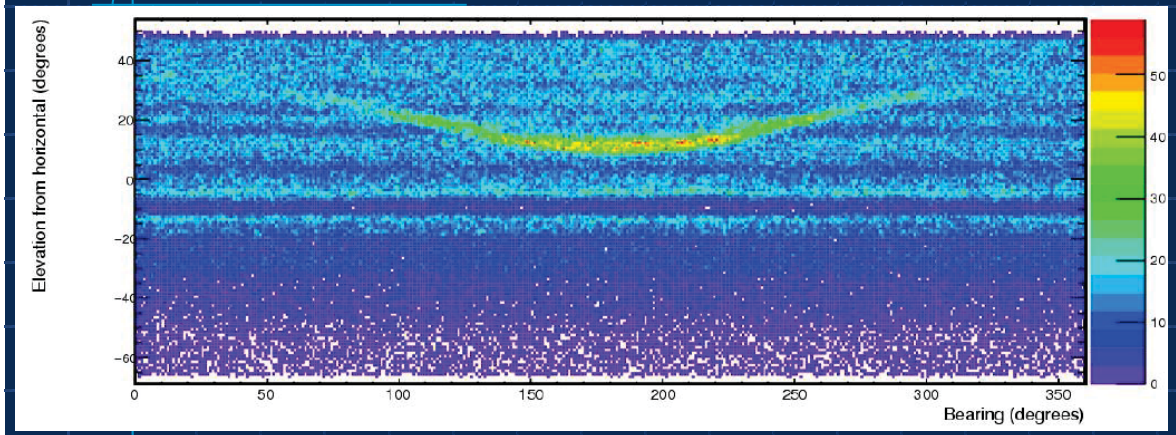
Flight sensitivity snapshot



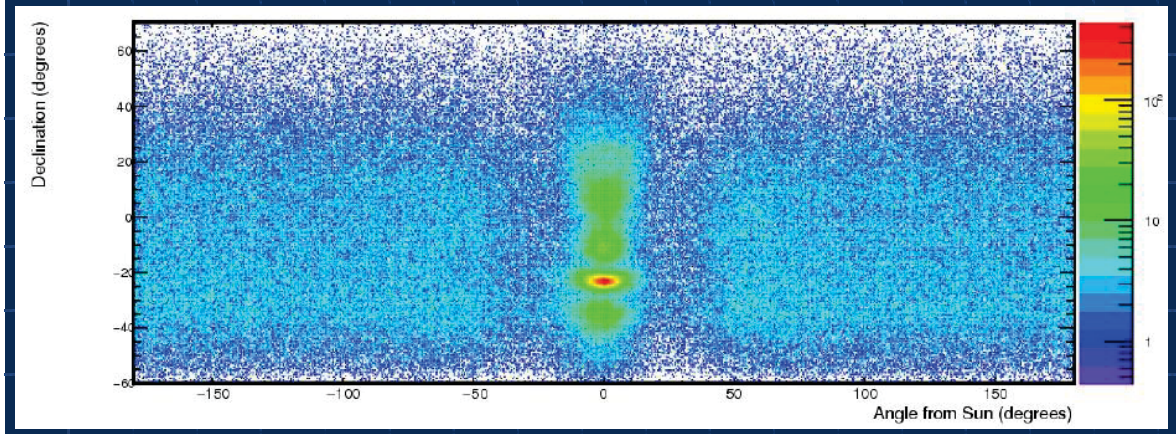
- ANITA sensitivity floor defined by thermal (kT) noise from ice+sky+rcvr
  - T_{rcvr} ~140K
  - T_{ice} ~ 230K
  - T_{sky} ~ 20-80K
- Thermal noise floor seen intermittently throughout the flight—but punctuated by station noise
  - South Pole and McMurdo stations!
- Still a significant fraction (~50-60%) of time with pristine conditions

Solar Sensitivity calibration

Elevation-azimuth coordinates



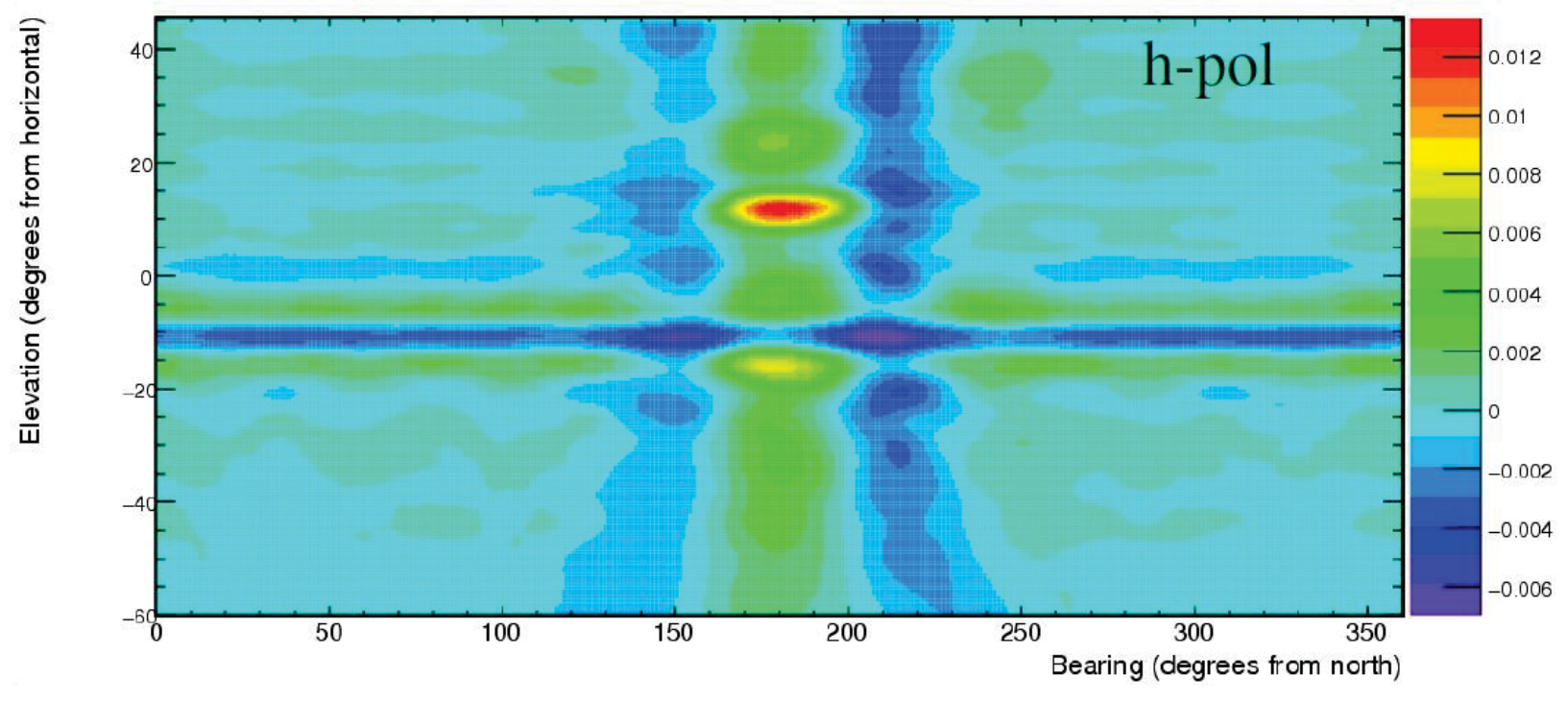
Heliocentric coordinates



Images from S. Hoover, UCLA

- ANITA (~3-5m cluster) interferometric images of the radio sun
  - Flight averages shown here
- Sun detection required about 200 sec of thermal noise data
- Provides 1st-order absolute calibration of antenna noise, beam response, event timing
- Note also horizon (and its sidelobes) at -6 degrees!

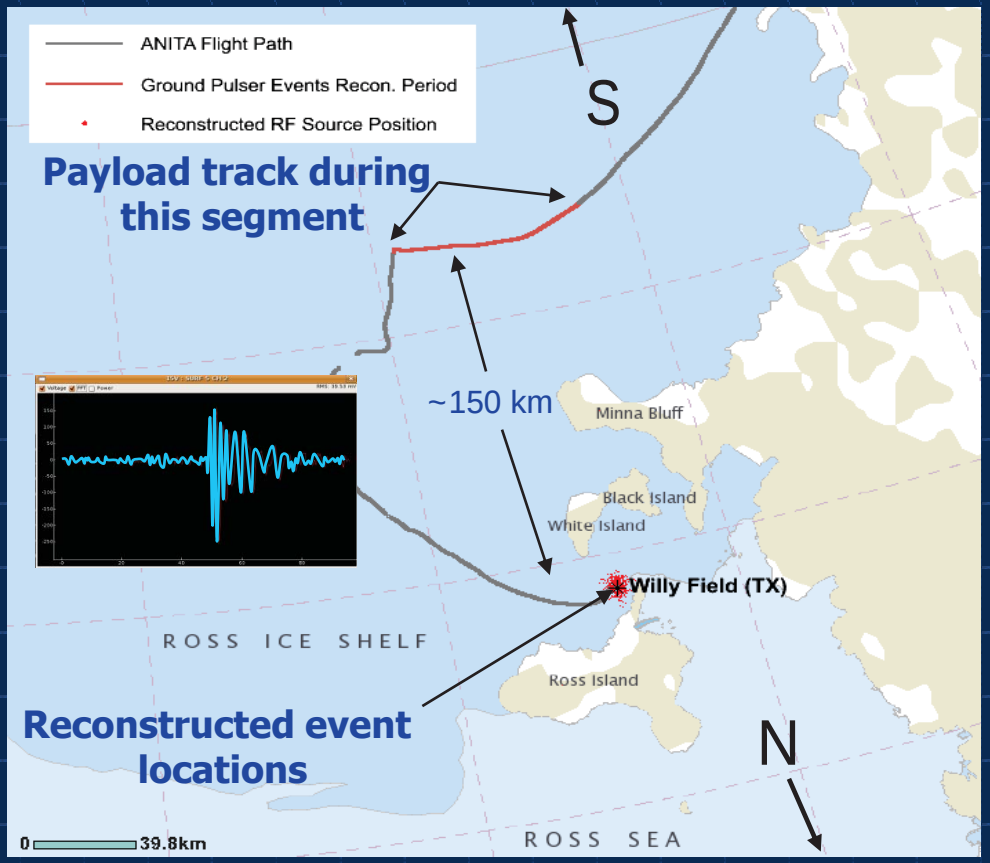
Solar reflection



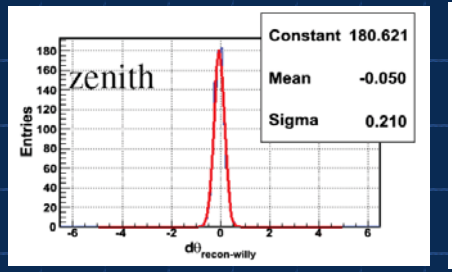
S. Hoover, UCLA

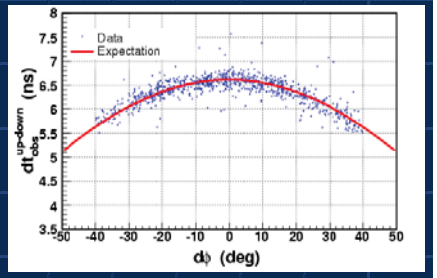
- Higher SNR imaging of the reflected sun in Hpol near Brewster angle
  - Reveals ice surface reflection & Fresnel diffraction pattern of horizon (resolved out by inteferometer)
  - Reflection coefficient confirms relatively smooth ice surface

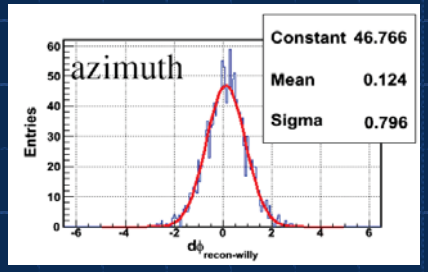
ANITA geo-location of borehole cal events

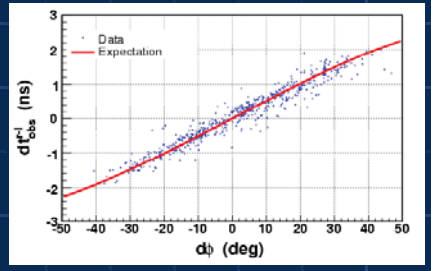


- Expect ~ $c\Delta\tau/2D$ altitude & azimuth
- $\Delta\tau$ ~ 40-60 ps, D ~ 1m (horizontal) to 3 m (vertical)
- Altitude: 0.21º observed, 0.3º expected
- Azimuth: 0.8º observed, 1.7º expected
- Multiple baselines improve constraints
- Pulse-phase interferometry works well!

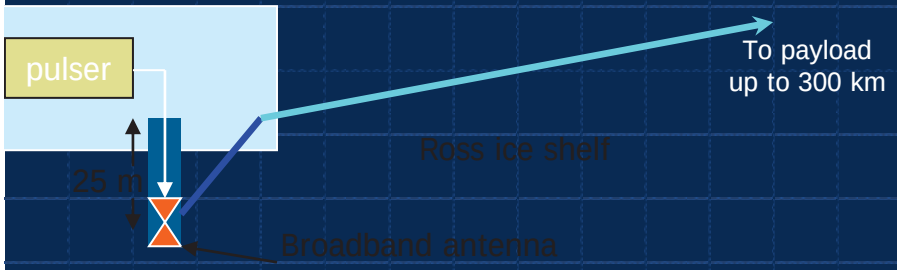




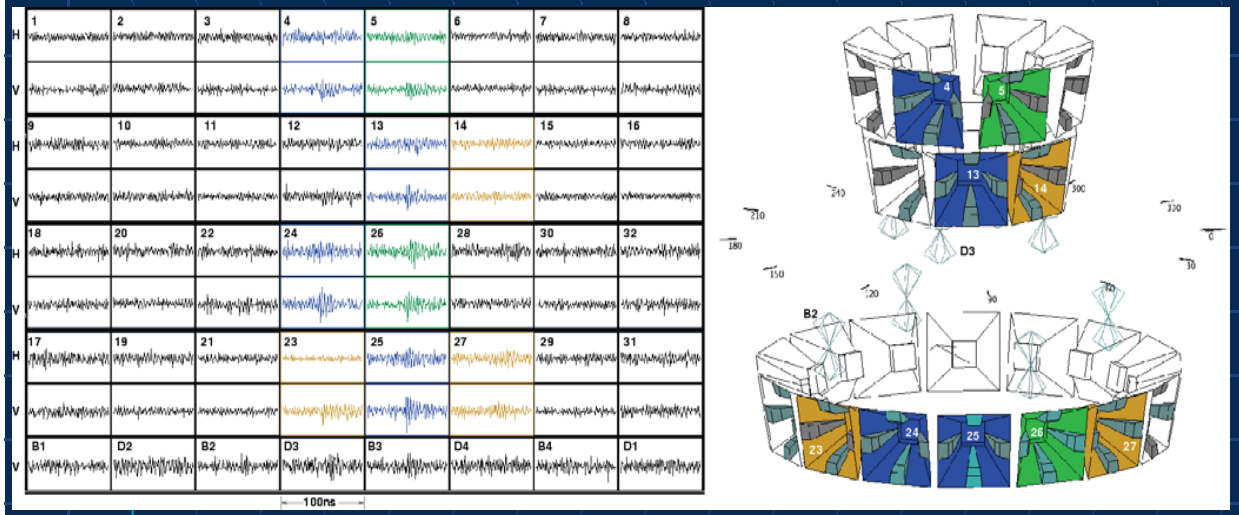


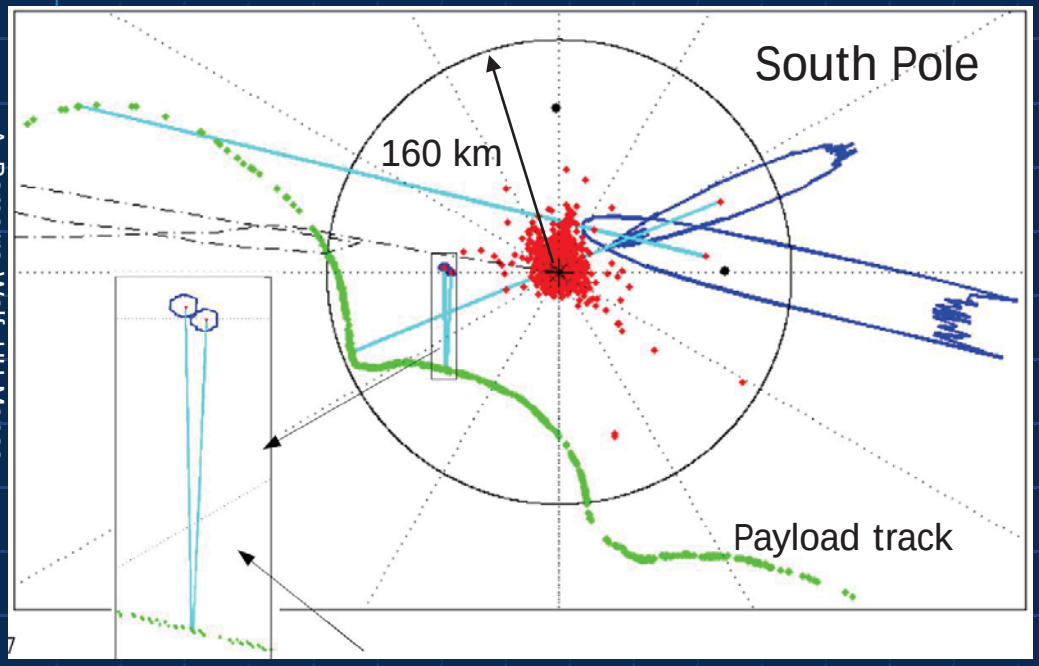


Thanks to JiWoo Nam, NTU



Event reconstruction & analysis

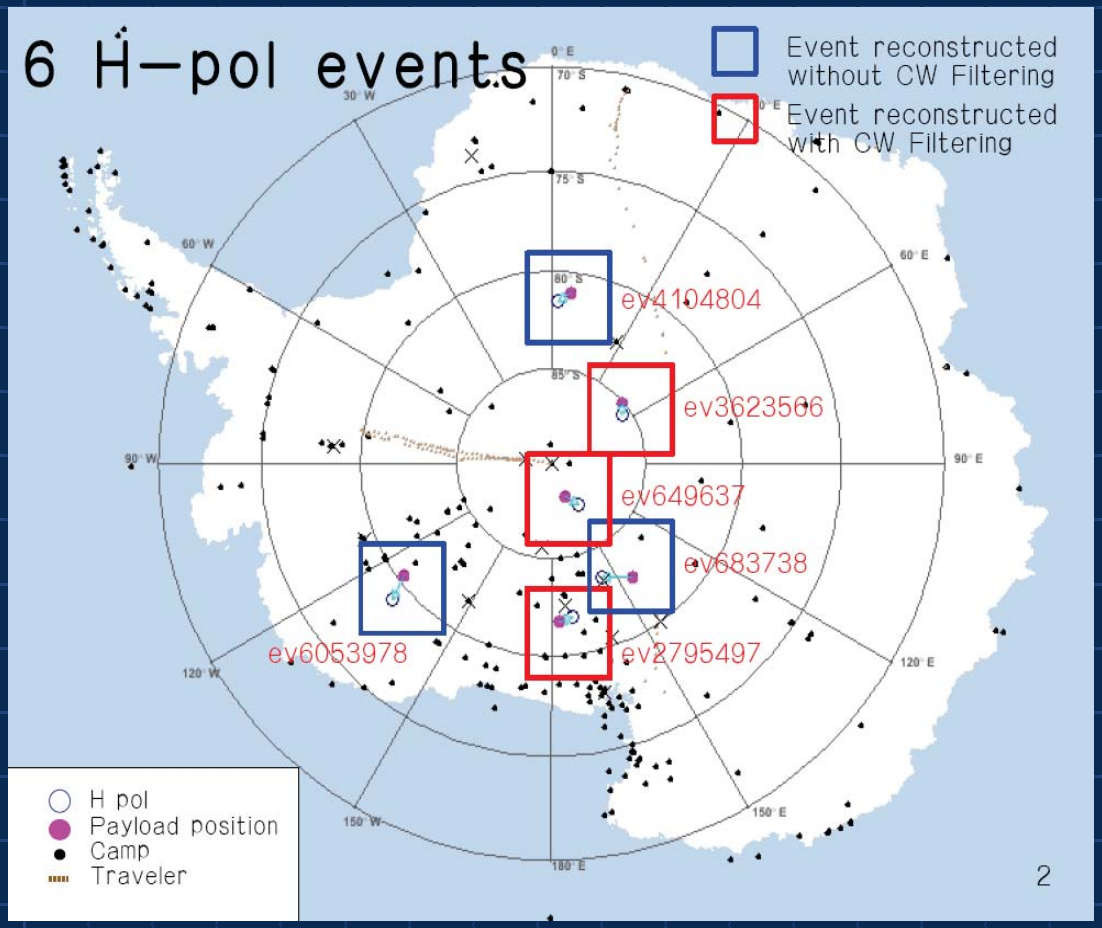




A. Romerro-Wolf, UH Manoa

- Raw data: RF plane-wave lights up one side of payload
- Waveform correlator (offline) gives 30-60ps timing
- Reconstruct ground position & error ellipse
- If <3σ from camp or any other event, reject
- South pole EMI, calibrated borehole pulser at MCM used to calibrate timing & statistical behavior

Initial unblinded higher-threshold event set

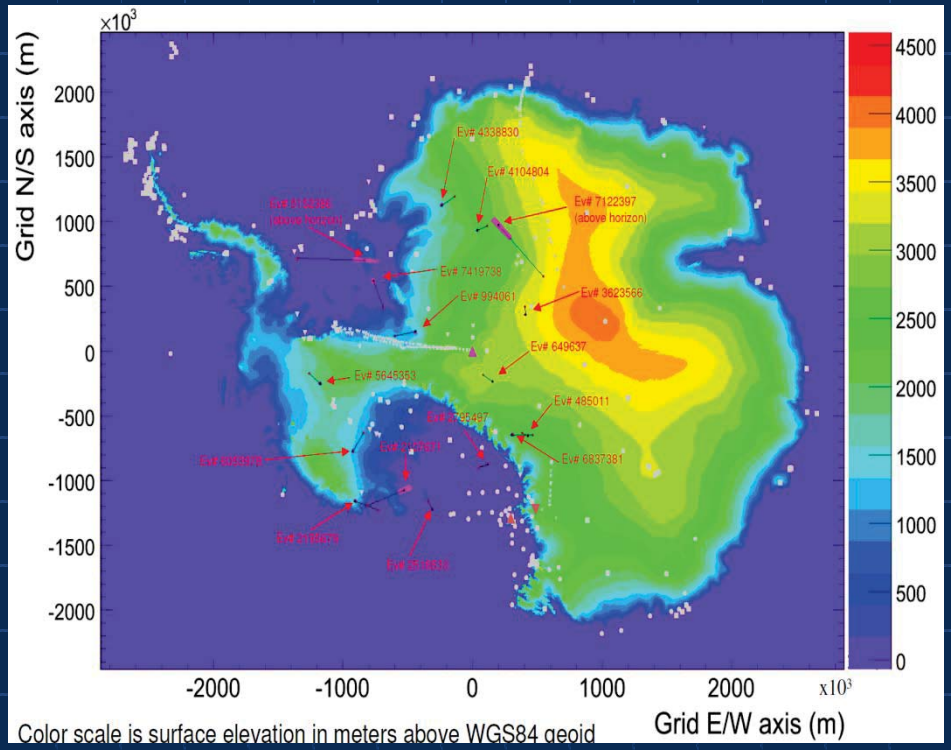


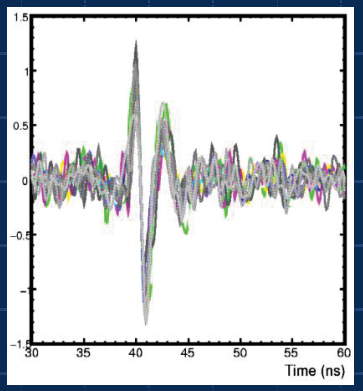
Jiwoo Nam, NTU, first discovered these events unexpectedly

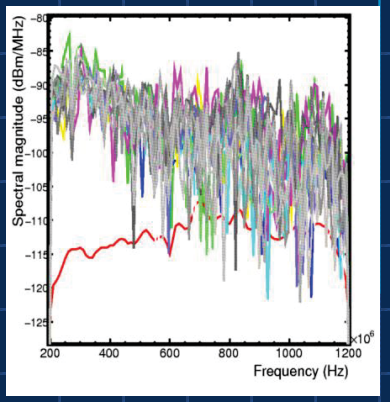
- ~19K events (9.6K Vpol & 10K Hpol) are impulsive & reconstruct to Antarctic ice locations
- Exclude all repeating locations (H,V,H+V)
- Exclude single events within ~50km from known sites
- After cluster+camp rejection:
  - 0 V-polarized (no askaryan-like signals➔ no neutrinos)
  - 6 H-polarized events left

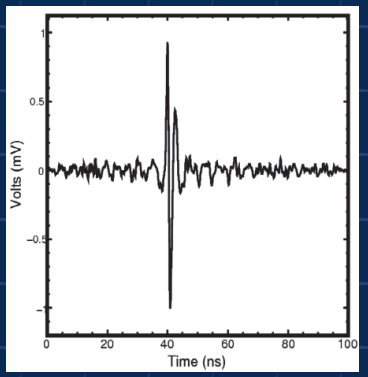
"camp" = any man-made installation, active or not
- most are inactive, many may be gone in fact
- but exposed metals could discharge

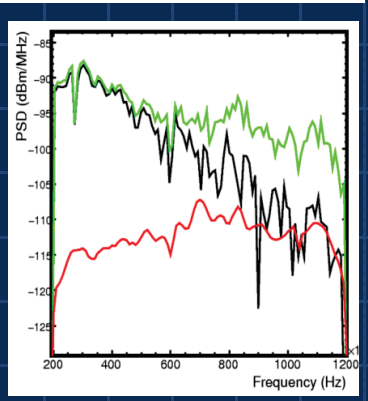
ANITA-I lower threshold analysis







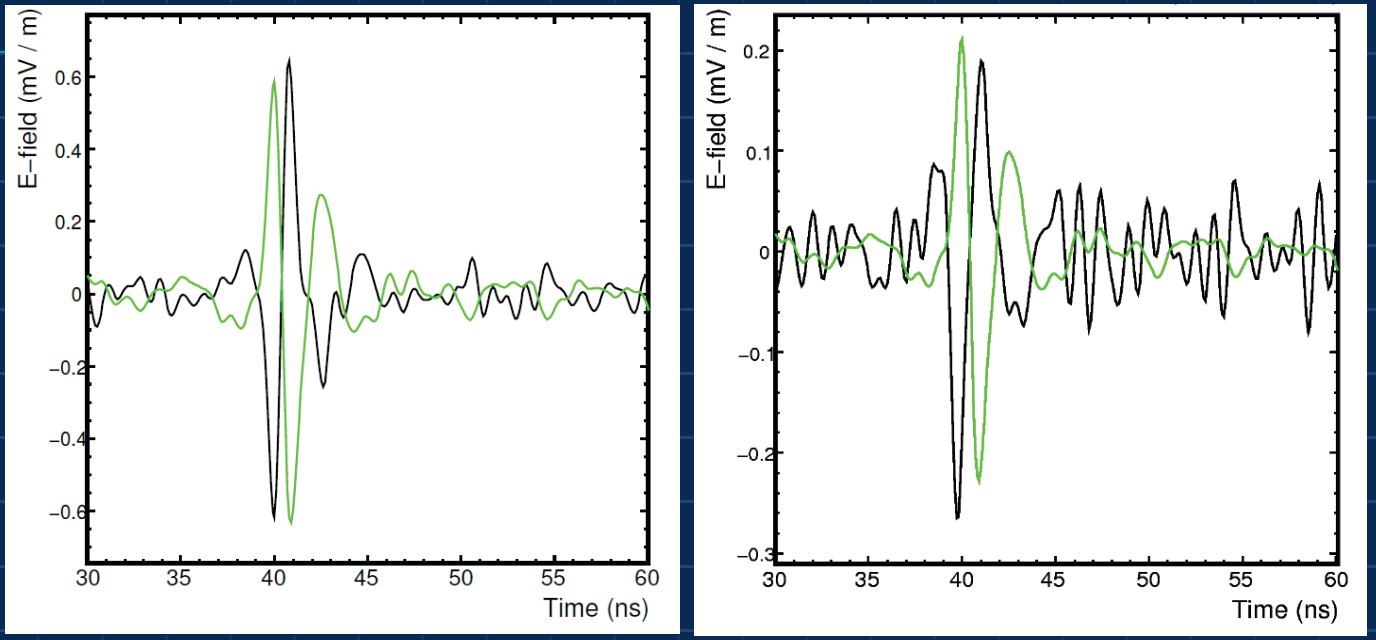




Stephen Hoover UCLA

- Independent deeper analysis done at UCLA
- Detected: **no neutrino candidates**, all of original 6 Hpol events, **+10 more**
- Hpol events: good coherence, not like any anthropogenic signals, low-frequency-dominated

2 of 16 Hpol events were unusual...

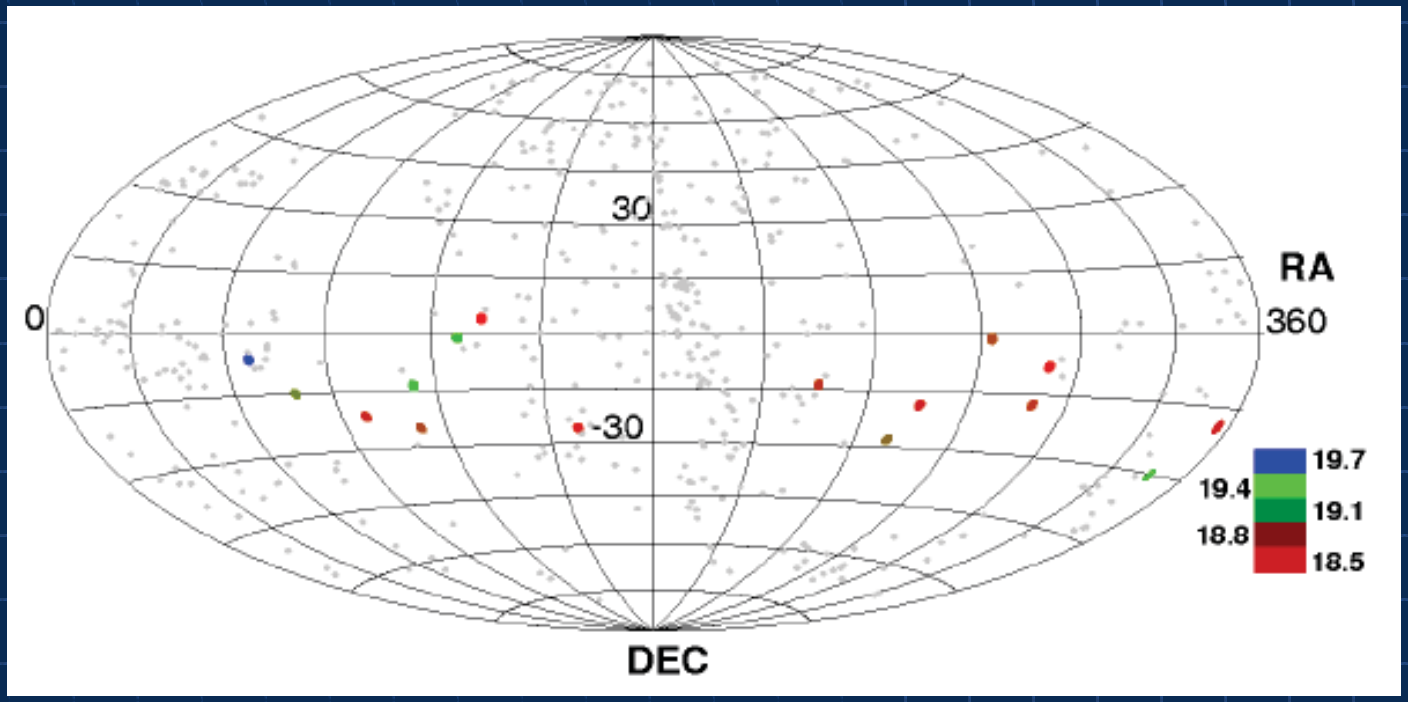


Images from S. Hoover, UCLA

- Both of these impulses were seen from directions above the horizon, but below the horizontal
- Green: average of 14 events with same-sign
- Black: above-horizon events: phase is 180 degree inverted!
  - Reflections cause phase inversion → are these the direct signals of the same process as the 14 others?

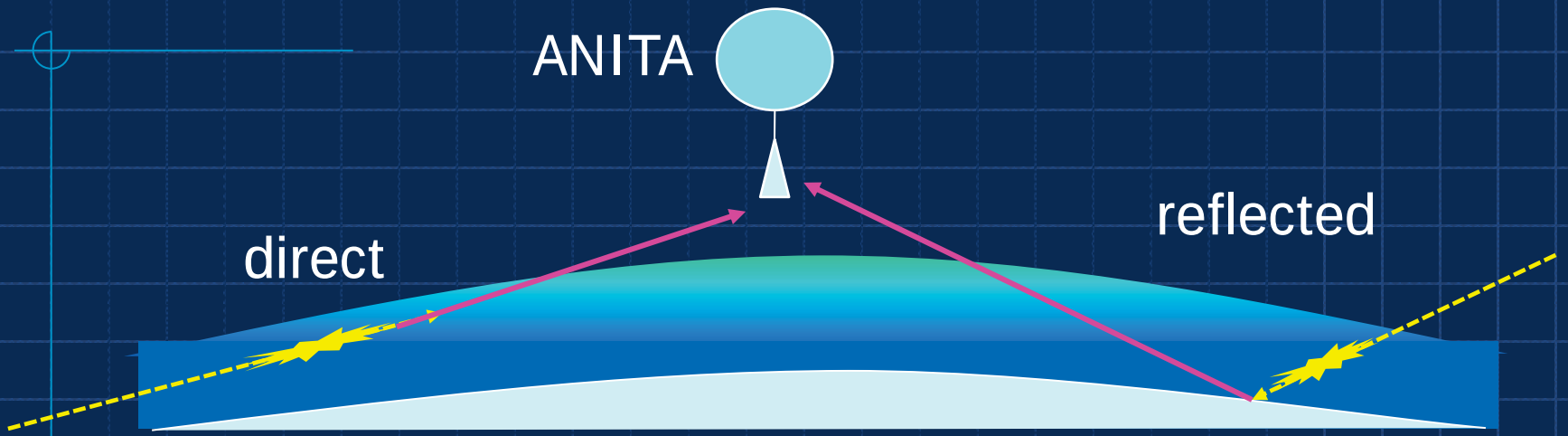
Energy scale, directions

- Data-driven Bayesian max likelihood fitter
  - Allow radio intensity & angular parameters to float within model priors
  - Results: energy scale is lowered, but with large asymmetric errors



$$\langle E \rangle = 1.5^{+2}_{-0.4} \times 10^{19}\ \text{eV}$$

ANITA as a UHECR telescope?

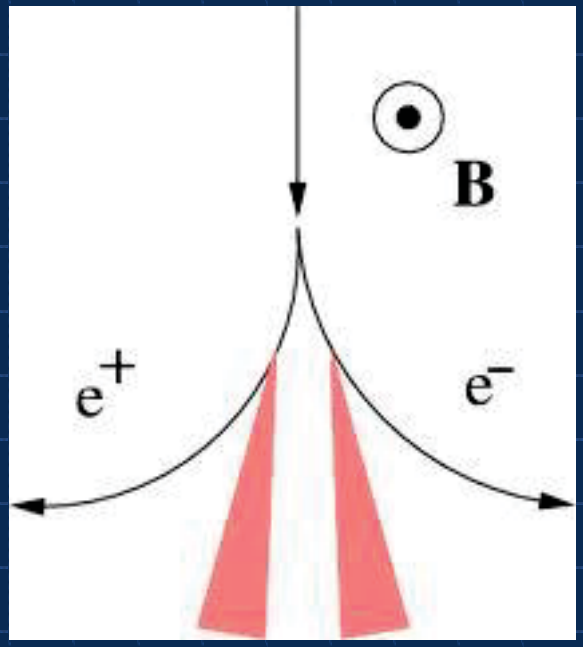


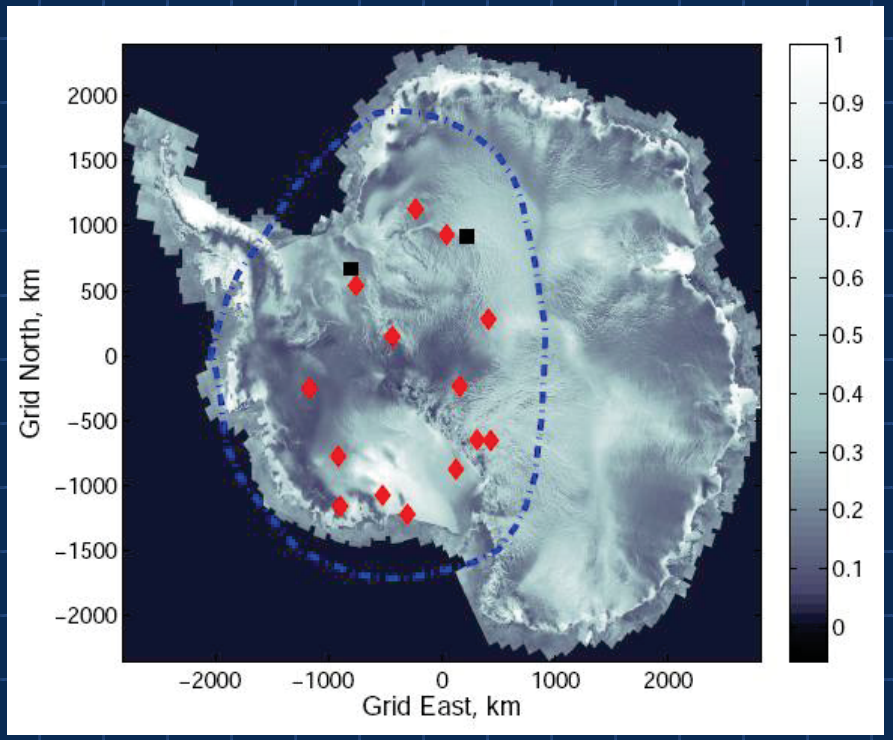
- If hypothesis of UHECR radio signals is correct, direct events have much less acceptance than reflected
  - Reflected events can come from a wide range of angles
  - Direct events have only a narrow stripe near the horizon
- UHECR energy spectrum well-measured, so test this with a simulation

ANITA-I Summary

Live Days	17.3
Antennas	32
Quality Events	8.2M

- Geosynchrotron radiation induced by UHECR air shower at Pole is horizontally polarized.

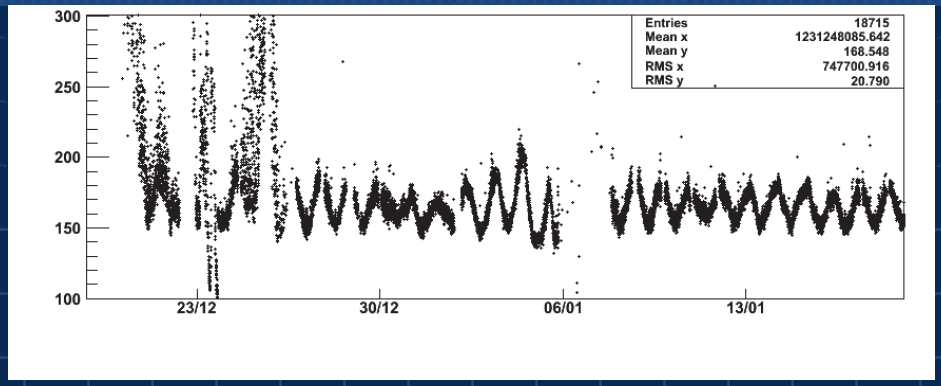


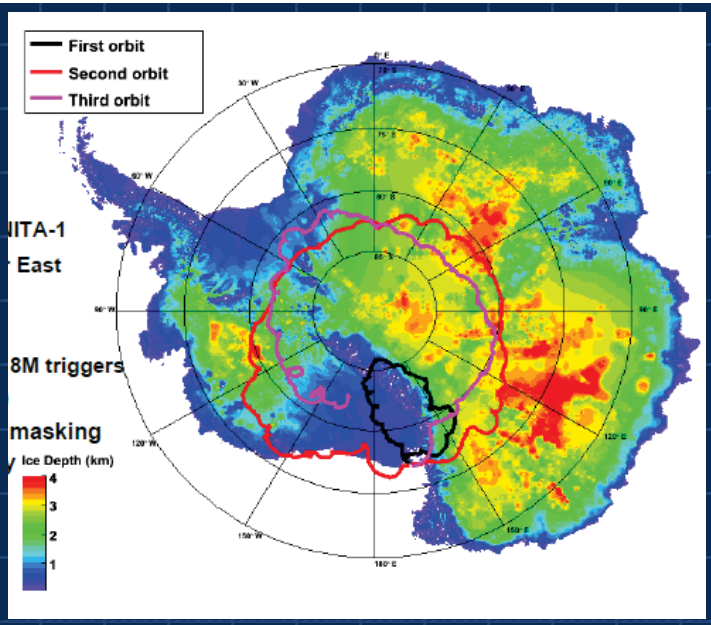


H-pol Events	16
V-pol Events	0

ANITA-II launch Dec. 2008

ANITA-II

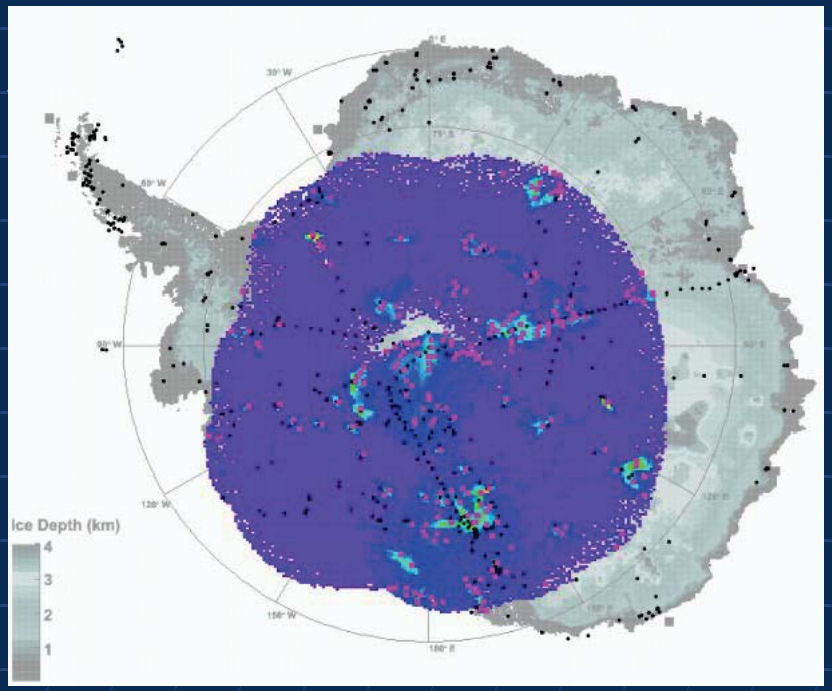


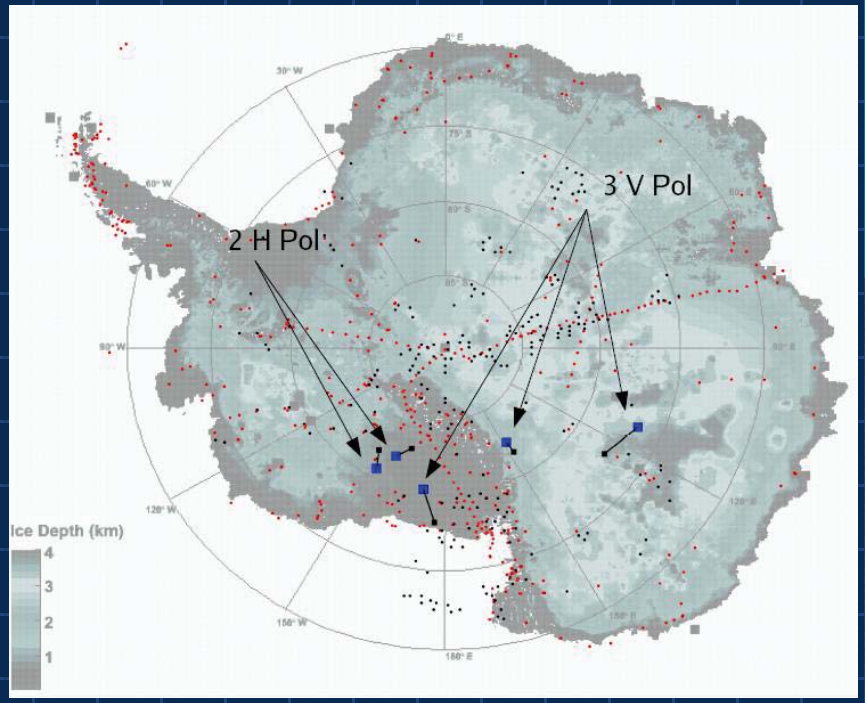


- ANITA-II: 31 days at float, >70% in radio-quiet conditions
- Collected 3x as much data as ANITA-I
- Angular resolution ~50% better
  - Less ice "lost" to camp peripheries

- Predicted sensitivity increase verified by in-flight calibration (pulsers + cosmic srcs)

ANITA-II analysis

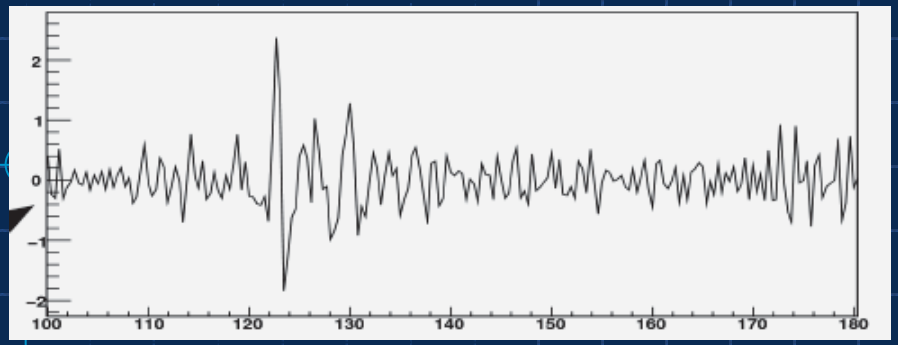


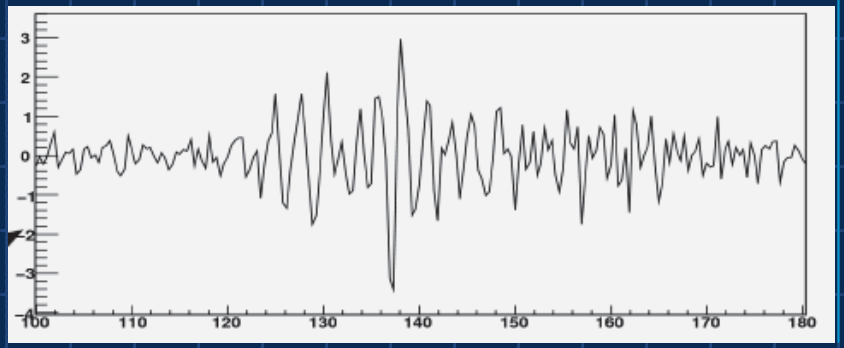


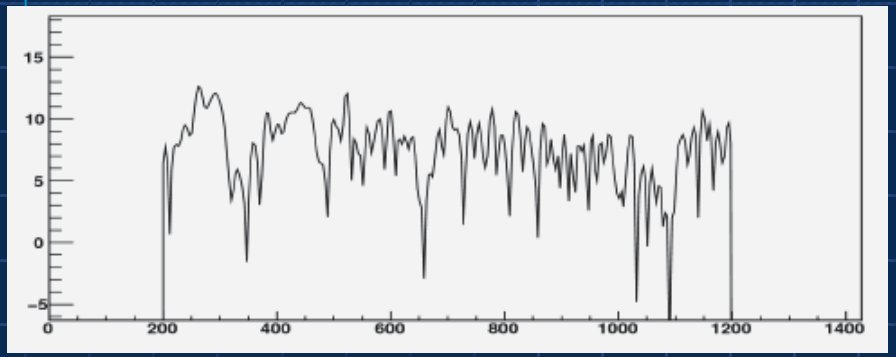
Images from Abby Vieregg, UCLA

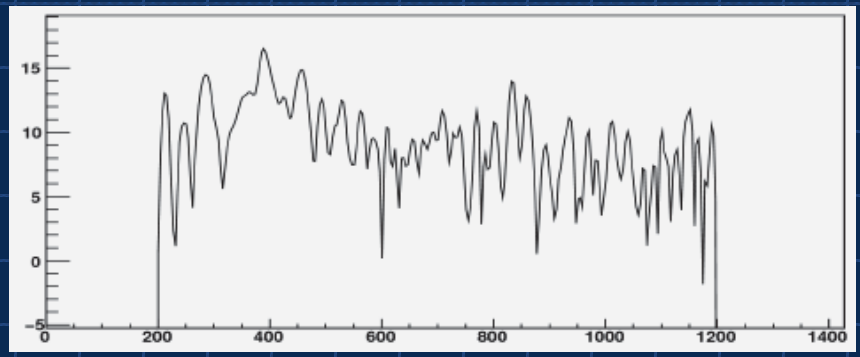
- Left: map of background RF intensity for ANITA-II, with "quiet" ice (pure thermal) in violet, 'hotspots' in light blue, camps,traverses, flight paths ==black dots
  - Everything not consistent with thermal gets effectively excluded from search region
  - (Methodology of map on left another A. Romero-Wolf invention!)
- Right: final sample after unblinding: 2 Hpol, 3 Vpol (but where are the UHECRs??)
  - **Trigger tuned for max neutrino sensitivity at the expense of cosmic rays – before we knew we were a UHECR telescope! (will do better next flight)**

Survivors





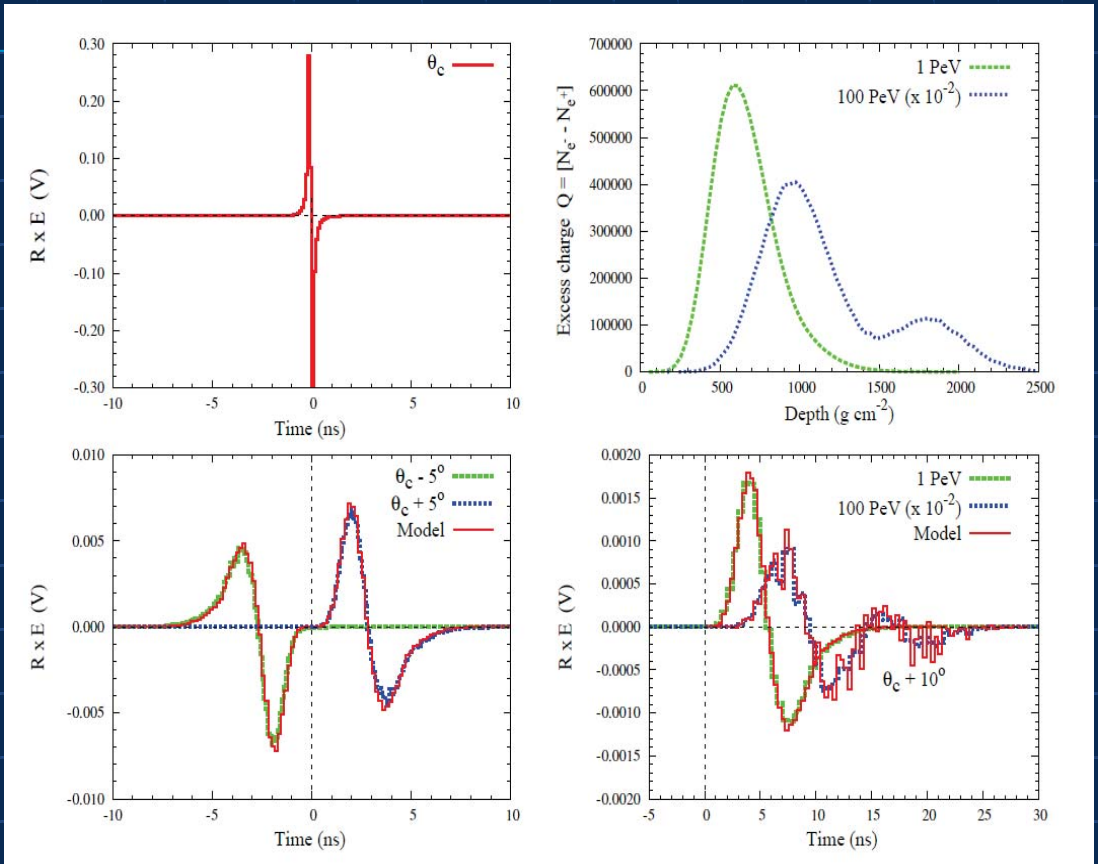




Images from Abby Vieregg, UCLA

- 1 of 3 Vpol survivors had sub-threshold partners
  - Anything that repeats cannot be a neutrino!
- Two remaining events: highly Vpol (>80%), flat spectrum, not near any camps, consistent neutrino simulations

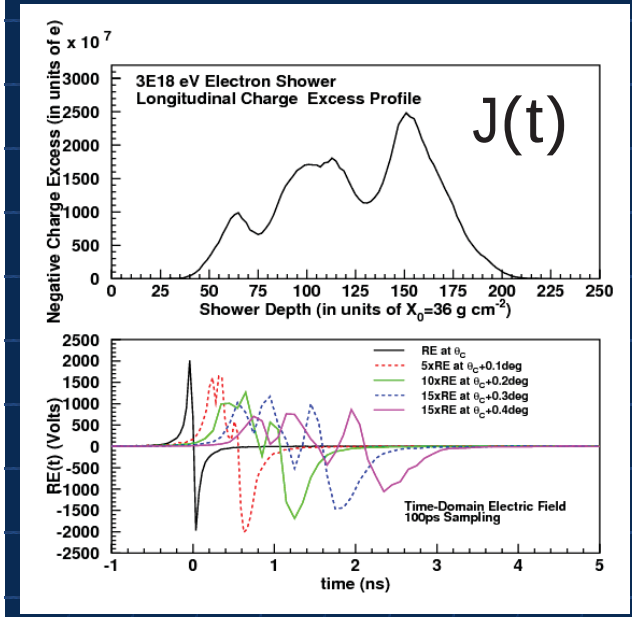
Shower to waveform mapping

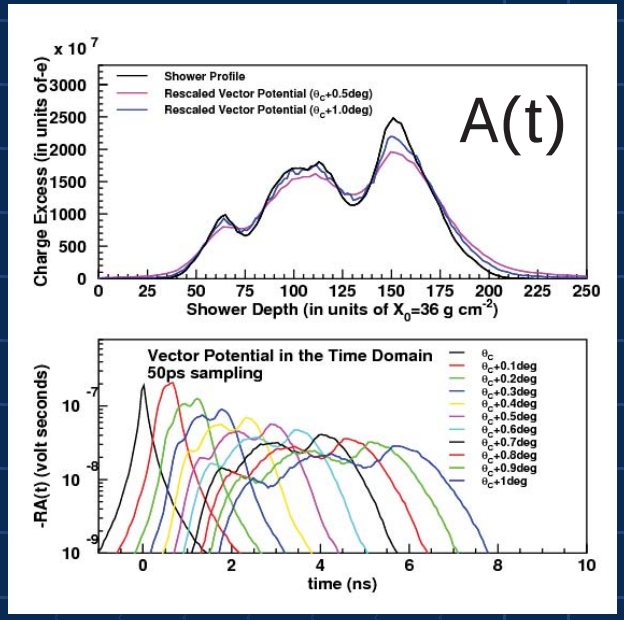


Alvarez-Muniz, Romero-wolf, Zas, arXiv 1002.3873 2010

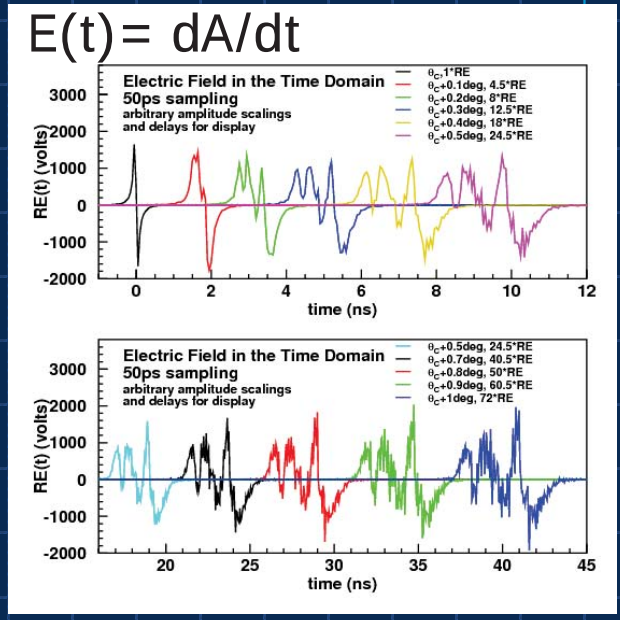
- Time domain waveform off the Cherenkov angle:
  - Vector potential *A* maps shower current to far-field
  - Electric field: determined from time derivative of A
- Waveforms (phase & amplitude) encode interaction!

Shower to waveforms (2)





E(t)= dA/dt



- A. Romero-Wolf (UH), working with Alvarez-Muniz & Zas
  - New formalism for inverting waveforms to determine shower properties
  - Waveform shape at the sub-ns level encodes the intrinsic shower profile
  - LPM showers can produce very "ratty" pulse shapes – but these are the highest percentage of showers that trigger near threshold
  - Underlines potential importance of good waveform sampling

ANITA-II results summary

TABLE I: Event totals vs. analysis cuts and estimated signal efficiencies for the ANITA-II data set

Cut requirement	passed:	Vpol	Hpol	Efficiency (ESS)
(0) Hardware-Trigger		~ 26.7M	~ 26.7M	
(1) Quality Event		~ 21.2M	~ 21.2M	1.00
(2) Reconstructed Event		271,824	48,898	0.93
(3) Event-isolated		15	7	0.718
(4) Not Payload Noise		12	7	1.00
(5) Not Misreconstruction		9 or 10	4	1.00
(6) Hot Spot-isolated		4 or 5	3	0.957
(7) Camp-isolated		2 or 3	3	0.930
Total Efficiency				0.592

TABLE II: Expected numbers of events N_ν from several UHE Cosmogenic neutrino models, and confidence level for exclusion by ANITA-II observations.

Model & references	predicted N_ν	**CL,%**
Baseline models		
Protheroe & Johnson 1996 [22]	0.49	19
Engel, Seckel, Stanev 2001 [11]	0.28	14
Stanev 2006 [?]	0.29	14
Barger, Huber, & Marfatia 2006 [30]	0.89	29
Berezinsky 2005 [?]	0.61	22
Strong source evolution models		
Engel, Seckel, Stanev 2001 [11]	0.87	29
Aramo *et al.* 2005 [27]	2.2	62
Berezinsky 2005 [?]	4.67	92
Barger, Huber, & Marfatia 2006 [30]	2.8	73
Yuksel & Kistler 2007 [29]	1.44	44
Models that saturate all bounds:		
Yoshida *et al.* 1997 [?]	25	> 99.999
Aramo *et al.* 2005 [27]	15.6	99.999
Waxman-Bahcall fluxes:		
Waxman, Bahcall 1999, evolved sources [12]	1.37	42
Waxman, Bahcall 1999, standard [12]	0.49	19

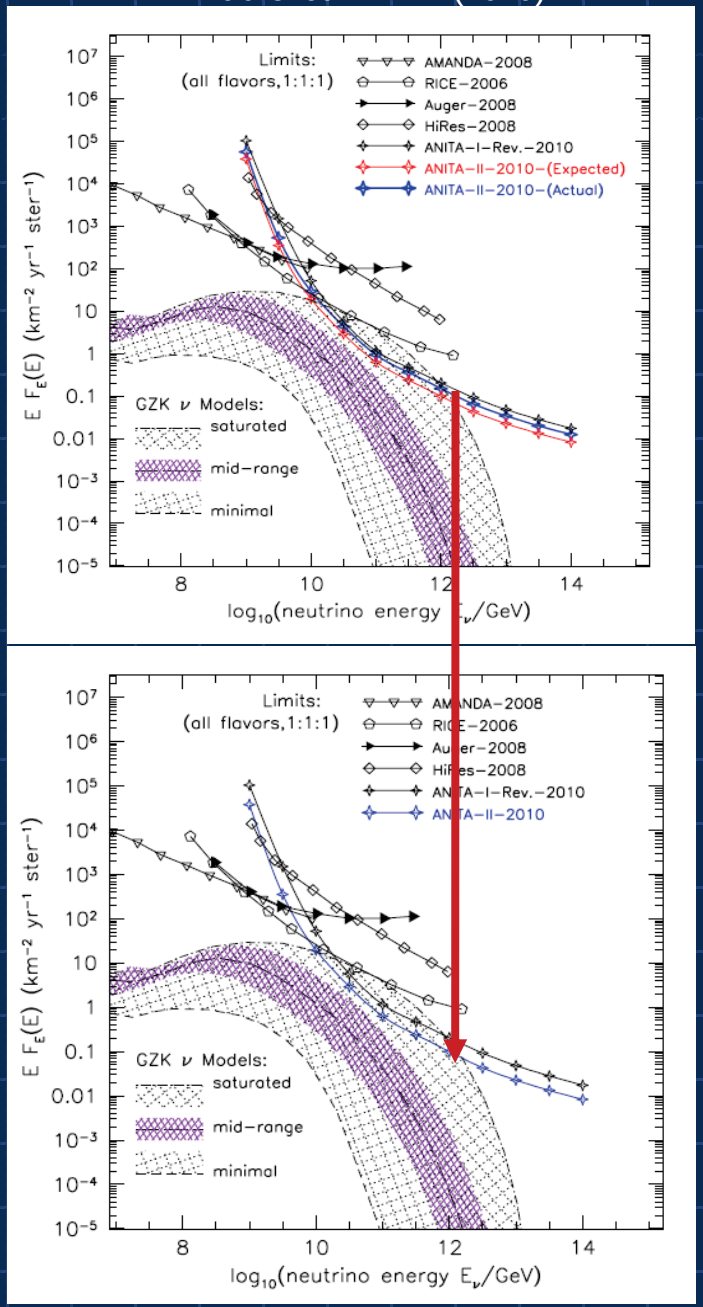
- Results summary: expected 1 bkg event, saw 3 events
  - 1 of 3 is demonstrable anthropogenic, published 2 in 2010 (PRD)
  - NTU student Ruo-Yu Shang found out that 1 of 2 was a fake, Taylor Dome event. Result: 3 → 2 → 1 (PRD Erratum 2011)
- GZK models predict 0.3 up to 25 events (1-2 events for some mainstream models)

ANITA-II Summary

- Candidate event appears to have similar distributions as simulated neutrinos
- After eliminating the false event, the actual and the expected are now the same.
- Current effort: Reanalyze data with improved cuts

H-pol Events	3
V-pol Events	2 → 1

Published in PRD (2010)



Beyond ANITA-II:

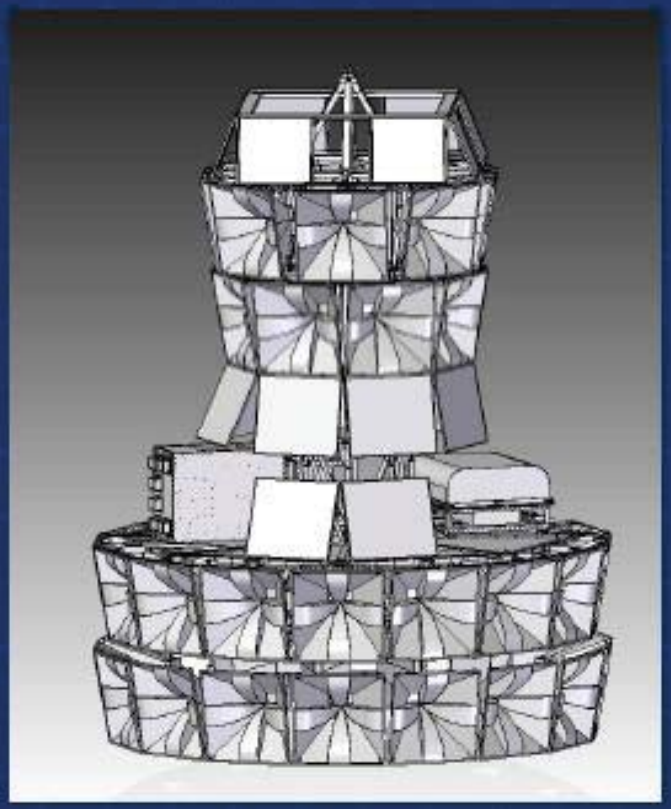
ANITA-III

- Approved to fly in 2013-2014 Austral summer
- Optimized to search for BOTH UHE neutrinos (~3-5 times more sensitive over ANITA-II) AND UHECR (~O(100))

ARA37

- Joint force by scientists from IceCube and ANITA to bring radio Cherenkov back on ground
- Initial approval under NSF MRI in 2009 for constructing 9 stations with deployment of 3. The 1st, the ARA Test-bed, developed by UH, was deployed in 2010-2011. The 2nd and the first formal station, ARA-1, constructed by NTU, will be deployed in 2011-2012 winter.
- Full-scaled ARA37 proposal submitted to NSF in June 2011.Taiwan has pledged to contribute 9, or ¼ of 37 stations.

Additional antennas



- Additional Seaveys:
  - Fixed ring where old PV array was, total will be 48 == 96 channels
  - 12 SURFs required, 48 (?) SHORTS
- PVs: either in discrete locations on upper section or as a drop-down skirt array like original

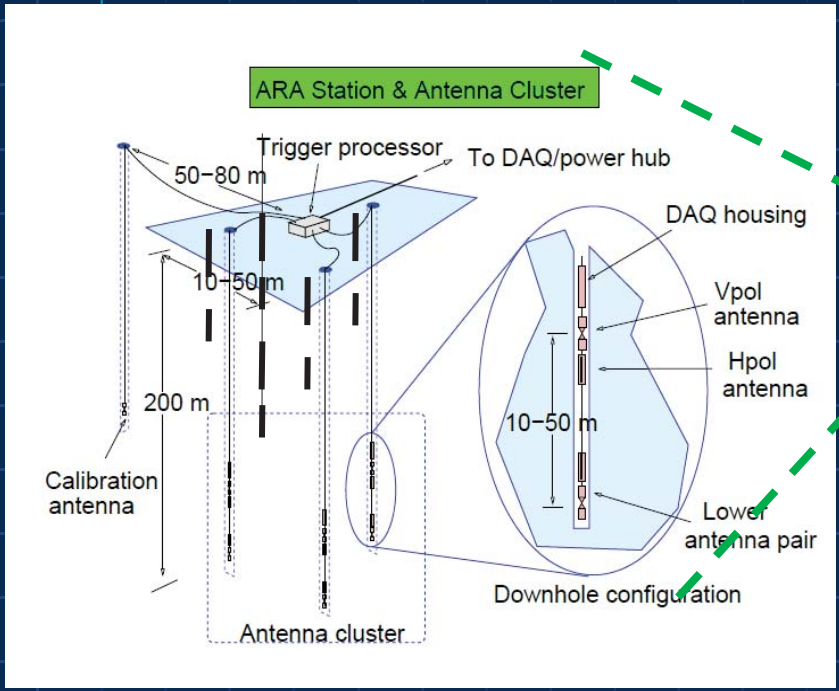
ARA (Askaryan Radio Array)

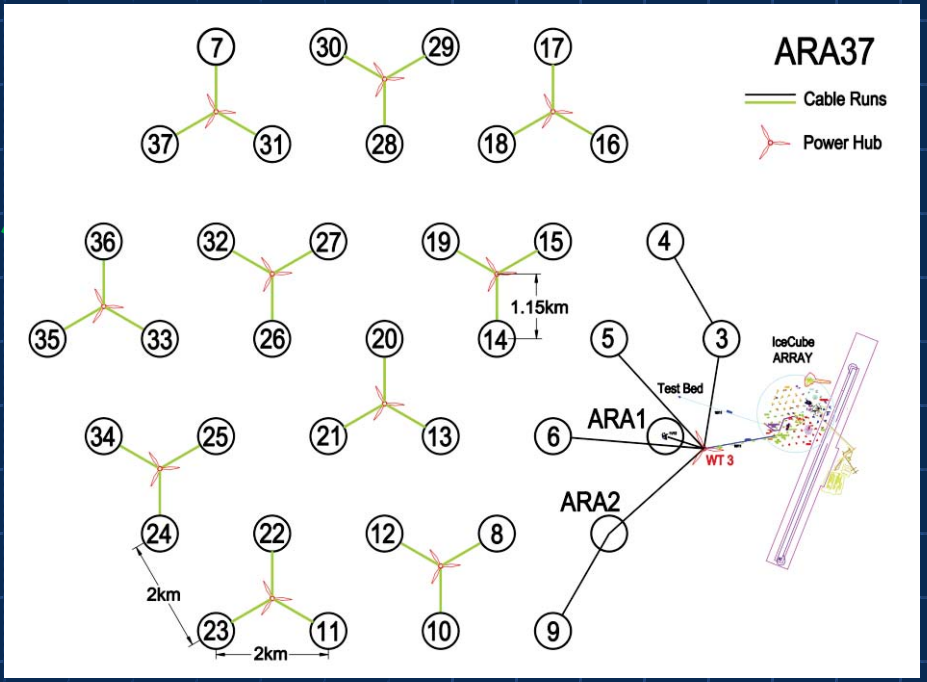
37 4-string, 16-antenna stations covering 100km^2 w. 3-5 v/yr

(Taiwan team will contribute 9 stations, or ¼ of ARA.)

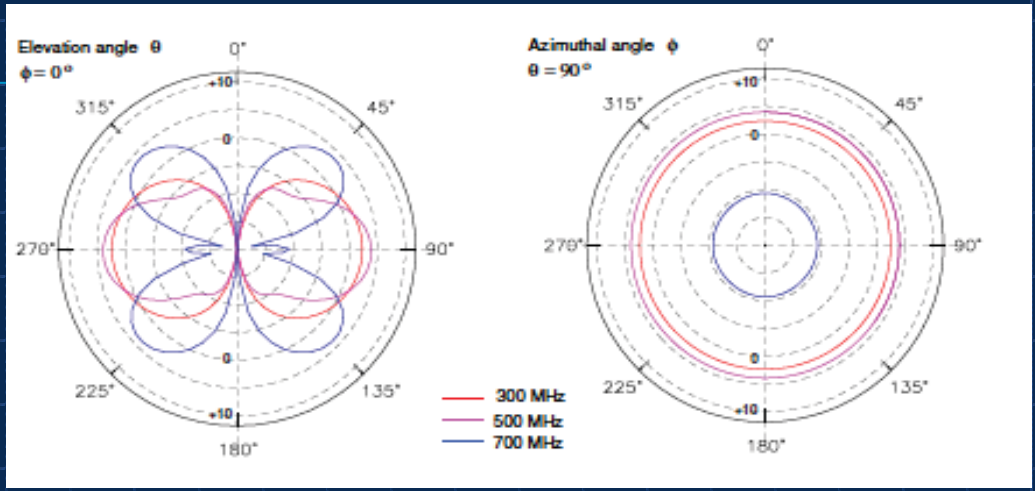
Angular resolution: ~ 6°,

Energy resolution: dominated by Bjorken y --> ΔE/E ~ 1 @ 3x10^{18} eV





ARA Test-bed antennas



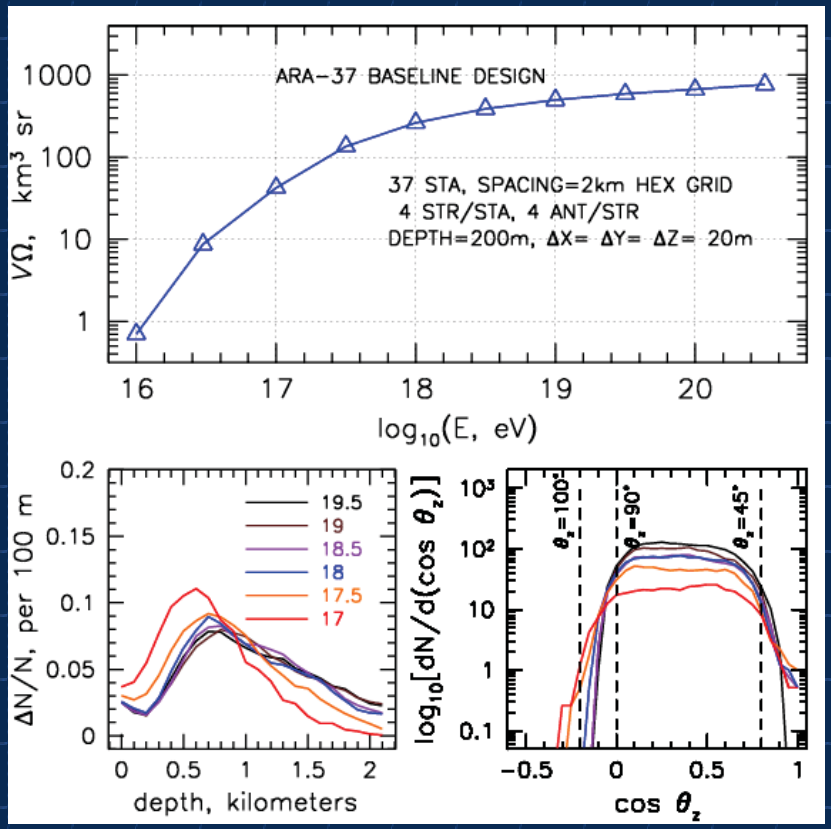
P. Gorham, UH

Wire-frame bicone Vpol antennas

Bowtie-slotted-cylinder Hpol antennas

ARA Test-Bed Deployment (10-11 winter)

P. Allison et al. [ARA Coll.], arXiv: 1105.2854



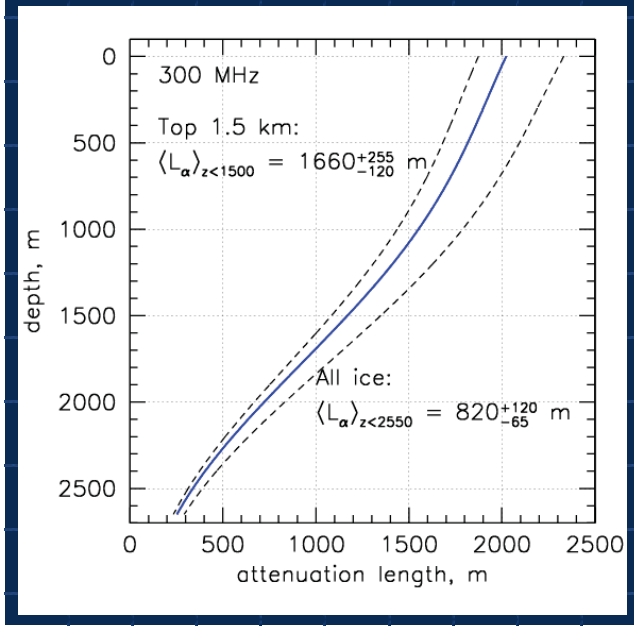
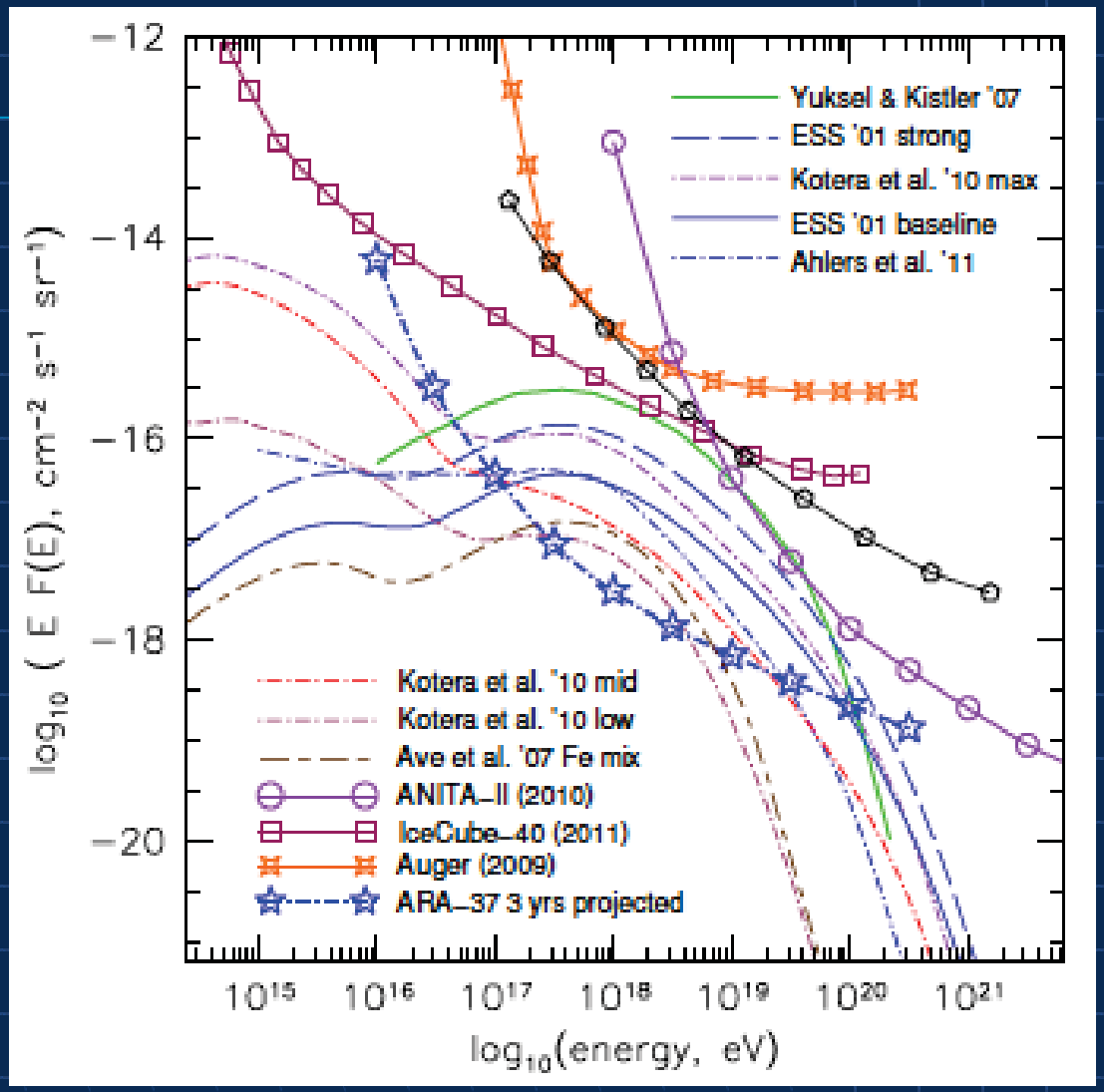


FIG. 25: Top (large pane): Simulated neutrino volumetric acceptance (km^3 sr water equivalent) for the ARA instrument baseline design. Bottom left: Depth distribution of simulated events for different neutrino energies, showing the contribution of deep ice down to 2 km or more at the higher energies. Bottom right: zenith angle distribution of detected neutrino arrival directions for a range of neutrino energies. Events are detected over a range from $\sim 45^\circ$ above the horizon to $\sim 5^\circ$ below it.

ARA37 3-year projection



Summary

- Major accomplishments by ANITA-I,-II:
  - ANITA-I: Found 16 UHECR in serendipity
  - ANITA-II: Found 1 candidate UHE neutrino event in 2010; Re-analysis on-going
- Beyond ANITA-II:
  - ANITA-III: Optimized to detect both UHE neutrinos and UHECR. To fly in 1.5 year (2012)
  - ARA-37: Ground-based antenna array at the Pole.

    37 stations covering 100 km^2 (2012-2015); expected yield 3-5 v per year.

    Test-bed + drilling + wind turbine tests in 2010-2011 winter.

    ARA-1 to be deployed this coming winter.