Radio Cherenkov searches for cosmogenic ultra-high energy neutrinos, & ANITA results

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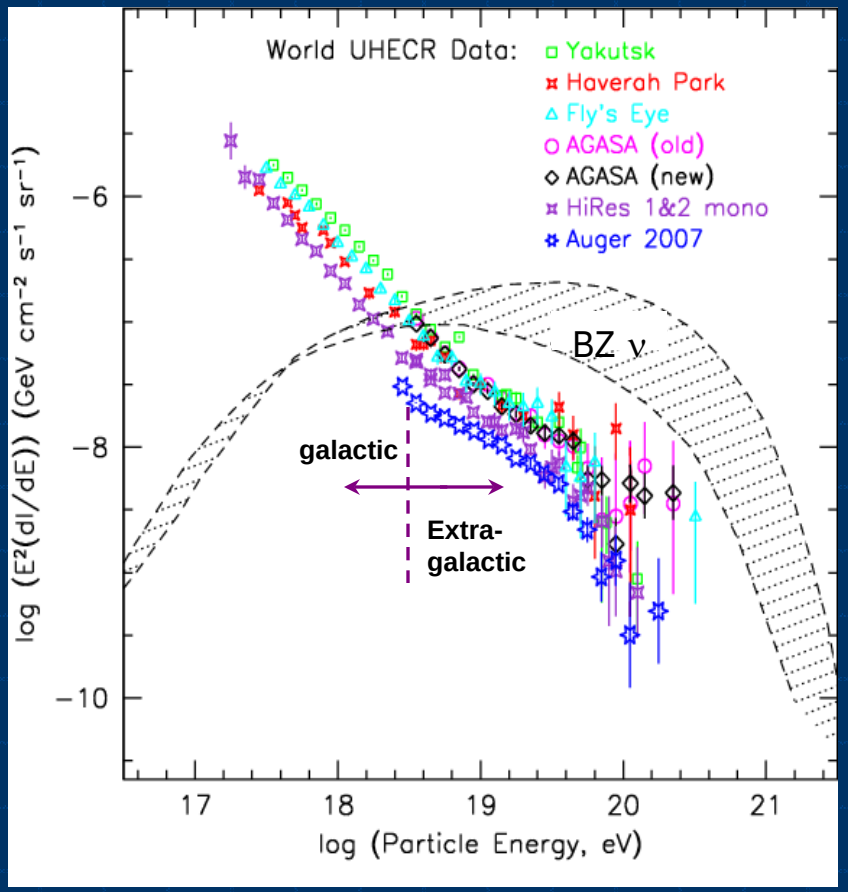
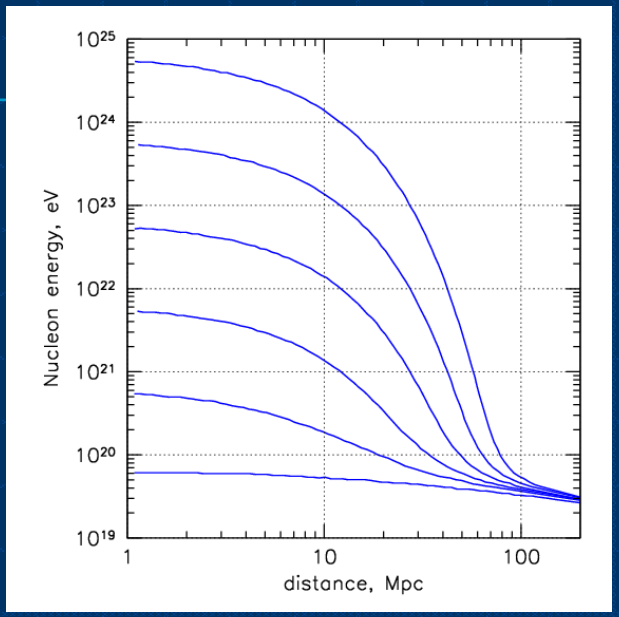
Ultra-high Energy Cosmic rays require Neutrinos

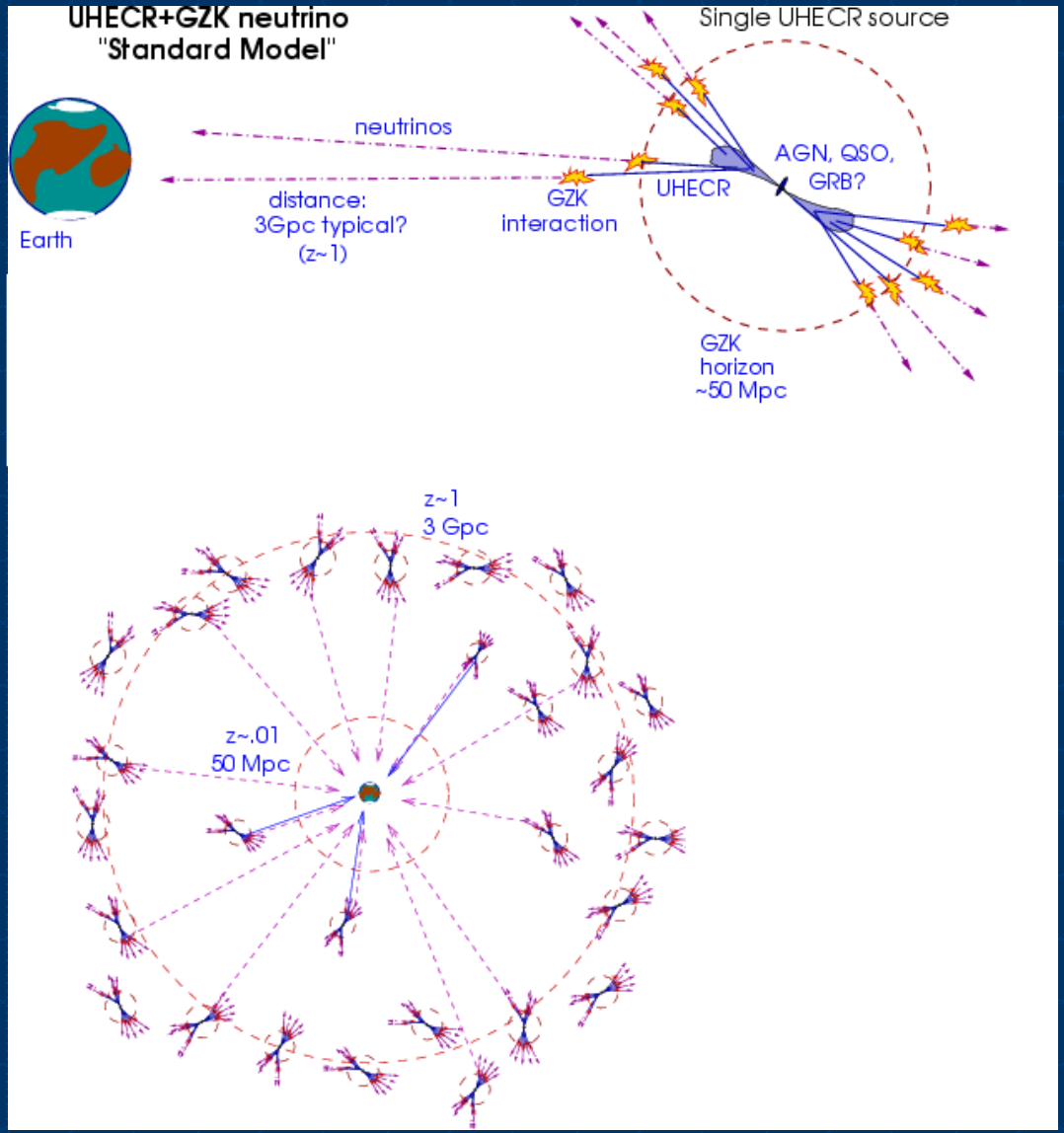
- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV, **after 40 years!**
- **A paradox**:
  - No nearby sources observed
    - Auger: yes!?, HiRes: No!
  - distant sources excluded due to collisions with microwave bkg
- Neutrinos at $10^{17\text{-}19}$ eV <u>required</u>* by standard-model physics
  - Lack of neutrinos:
    - **UHECRs all heavy nuclei?**
    - **"Just so" source spectra?**
    - **Lorentz invariance wrong?!**
    - **New physics?**



* Berezinsky & Zatsepin 1970, many others since

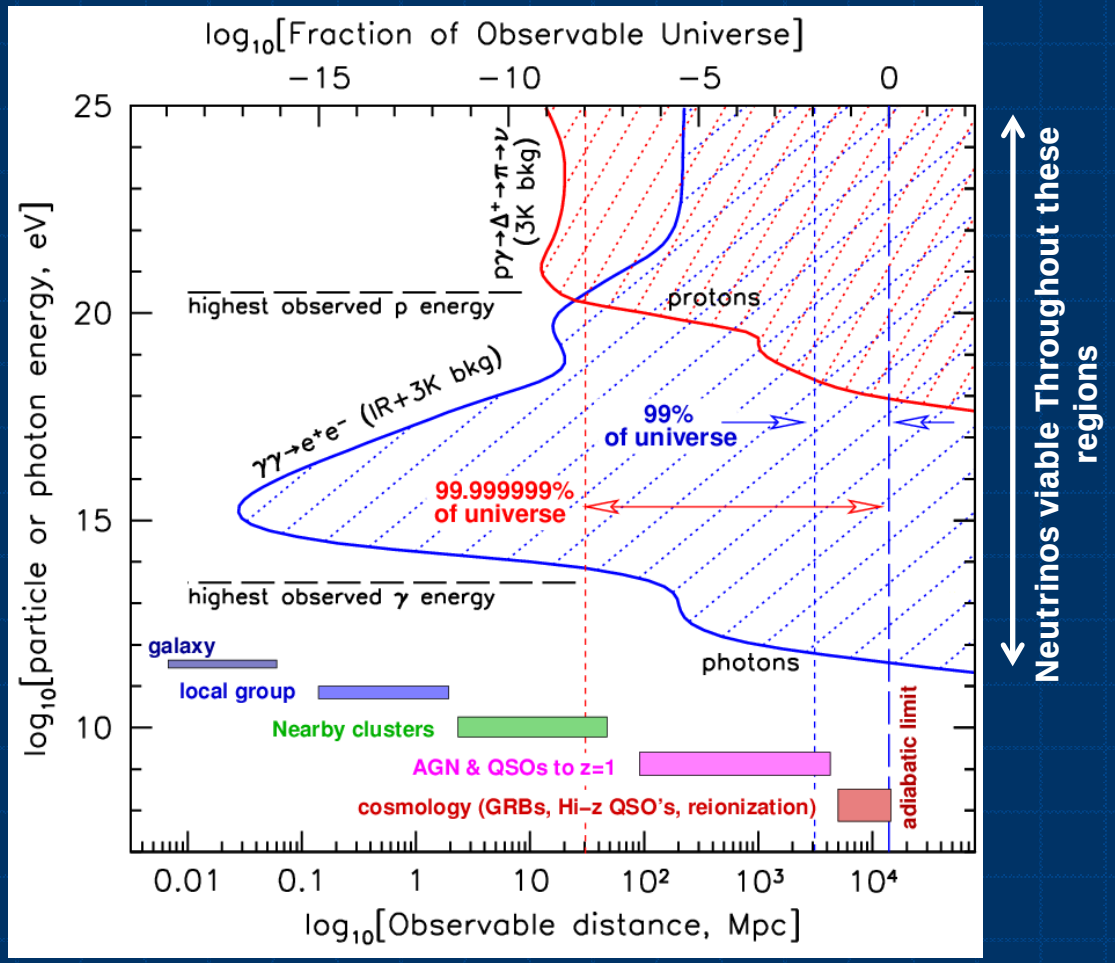
UHECR and the “GZK horizon”





- UHECR provide local source information, current epoch
  - Universal UHECR Accelerators likely to evolve in many ways: strength, metallicity, number density, ...
- BZ neutrino spectra are direct from sources at all epochs

Ultra-high Energy Neutrino Astrophysics

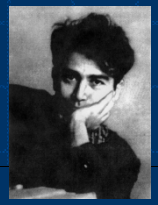


At energies above $10^{14\text{-}15}$ eV:

- Universe becomes opaque to photons beyond few tens of kpc
- CR protons, nuclei are galactic up to ~10^{18} eV, suffer GZK cutoff above that
- Neutrinos unabsorbed at all energies
- **Sources exist to at least 3×10^{20} eV**
- **Conclusion: UHE neutrinos are the only viable messenger beyond the local universe**

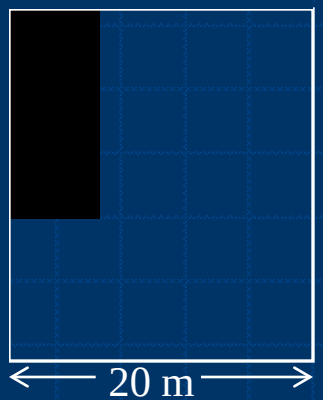
Why go after *cosmogenic* UHE neutrinos?

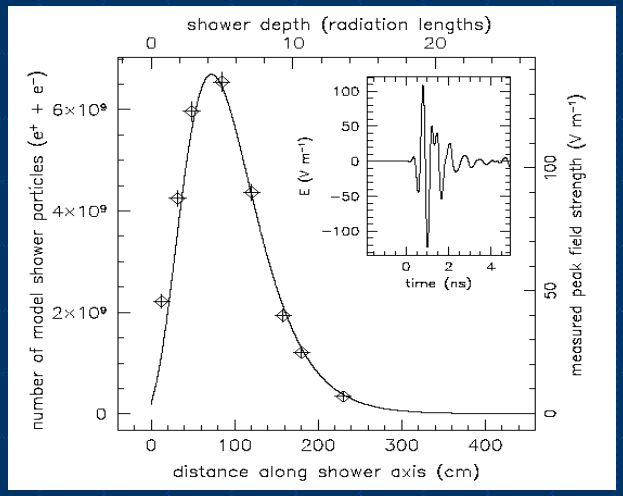
- Trace particle UHECR hyper-accelerators to very early epochs
  - Even at z~10 or more, GZK neutrino energies peak at 10-100 PeV
  - they all point back directly to the UHECR sources
- Their flux is constrained by UHECR sources, once determined
  - Can become a quasi-isotropic “test beam” of UHE neutrinos
  - ~100-1000 TeV center-of-momentum-frame energies on nucleons
- Flavor Oscillations! (who ordered that?)
  - A new kind of messenger, unlike photons—surprises await
  - Flavor ratios encode source information, even new physics
- **Proper detector scale: 1 km^3 ? No, try ~ 1000 km^3**
- **Cannot easily scale up optical IceCube**
- **→ scalable new detection method: radio Cherenkov**



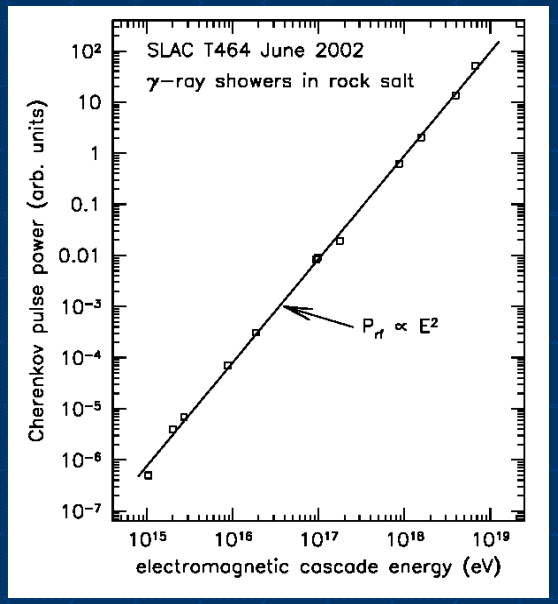
Askaryan Effect: confirmed in 2001 at SLAC

Blue: ~0.01GHz → yellow: 2GHz





Saltzberg & Gorham et al. PRL 2001



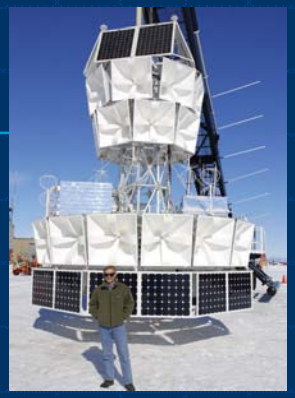
Gorham et al. PRD 2003

- Coherent radio emission from excess negative charge in an EM shower
  - e- upscattered into shower, e+ annihilated → 20% -ve asymmetry
- "Shower" is actually a thin disk of HE particles
  - A few mm thick and few cm wide in solids
- At radio wavelengths longer than ~10-20 cm:
  - **appears as a single charge of $Z \sim 10^8$ → $Z^2 = 10^{16}$ x single e-**

Askaryan effect: experiments

- **Lunar, with ground-based dishes:**
  - Parkes 64m dish: Hankins, Ekers, O'Sullivan 1996 (first suggested by Zkeleznyk & Dagkesamanski, Neutrino '88 Boston)
  - GLUE: Goldstone Lunar Ultra-high energy neutrino expt. 1998-2002, 120 hrs with 70m+34 m radio dishes
  - 64m Kalyazin telescope, Russia, 2003-2005
  - More to come: Westerbork, EVLA, LOFAR, SKA, and **SPACE-BASED** ?
- **Ice: Antarctica & Greenland**
  - Radio Ice Cherenkov Experiment (RICE) (completed 2006)
    - Constrained highest GZK neutrino models
  - Fast On-orbit Recording of Transient Events (FORTE) 2004
    - DOE satellite with impulse trigger, 3.8 days obs. Of Greenland, ➔ UHE limits >1e21 eV
  - **Antarctic Impulsive Transient Antenna—ANITA**
    - **ANITA-lite flew in 2003-2004, 4 channel prototype**
    - **First Full ANITA flight completed late January 2007**
    - **ANITA-2 now completed, January 2009**
  - **Future: ARA (eg, super-RICE), EeVA, others…**

Antarctic Impulsive Transient Antenna--ANITA

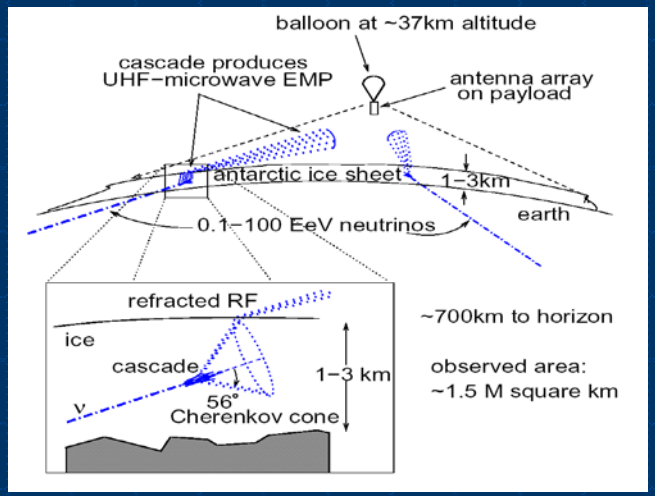


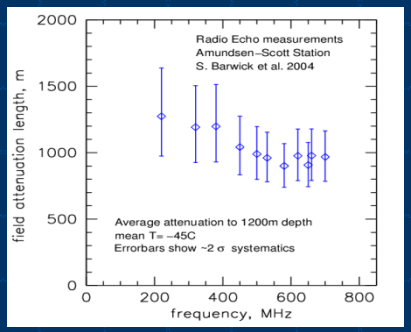
ANITA Gondola & Payload

Overall height ~8m

- NASA start in 2003, 1st launch in '06-07, 2nd in '08-09 baseline 10 day mission, got 35 + 31 days total
- Ultra-broadband antenna array, views 1.5 M km^2 of ice sheet looking for Askaryan impulses, Δf ~ 0.2-1.2GHz

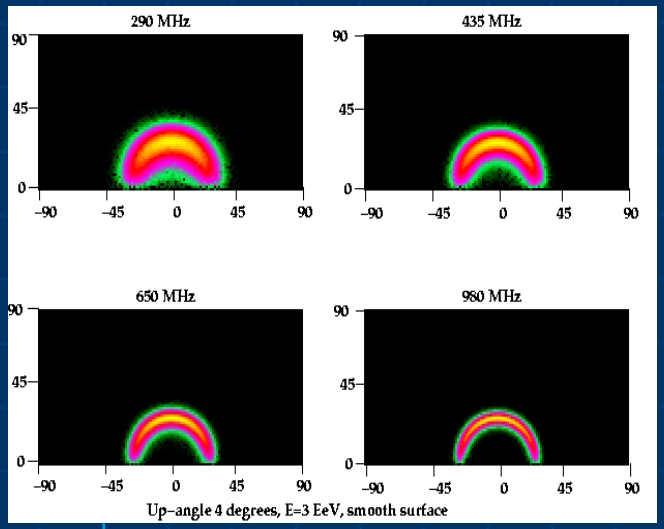
ANITA-1 collaboration P. Gorham (PI, UH Manoa), S. Barwick, D. Goldstein, F. Wu, UCI; J. Beatty, K. Palladino, B. Mercurio OSU, D. Besson, KU; W. Binns, P. Dowkonnt M. Israel, Wash. U. St. Louis, C. Chen, C. Hast, K. Reil, D. Walz, SLAC; J. Clem, D. Seckel, U Del., M. DuVernois, U. Minn., K. Liewer & C. Naudet, JPL/NASA; R. Nichol, A. Connolly, UC London, D. Saltzberg, A. Goodhue, S. Hoover UCLA, G. Varner, J. Learned, S. Matsuno, P. Allison, A. Romero-Wolf, J. Kowalski, C. Miki, UH Manoa, P. Chen, J. Nam, Y. Wang, NTU.

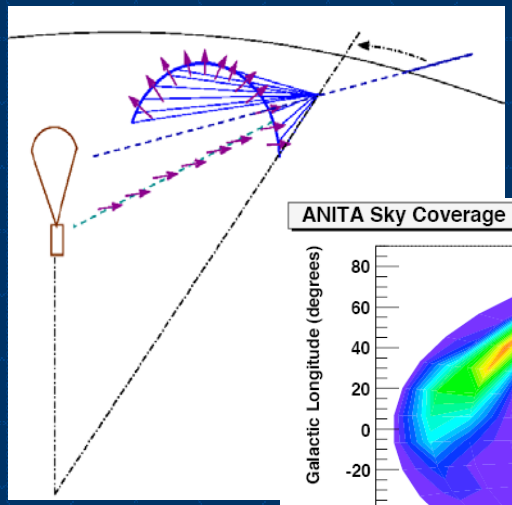


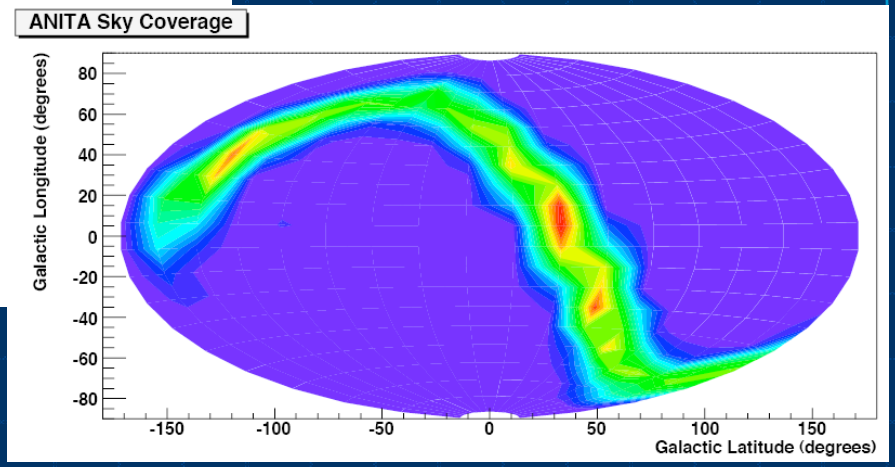


Ice RF clarity:
1.2 km(!) attenuation Length @ 300 MHz

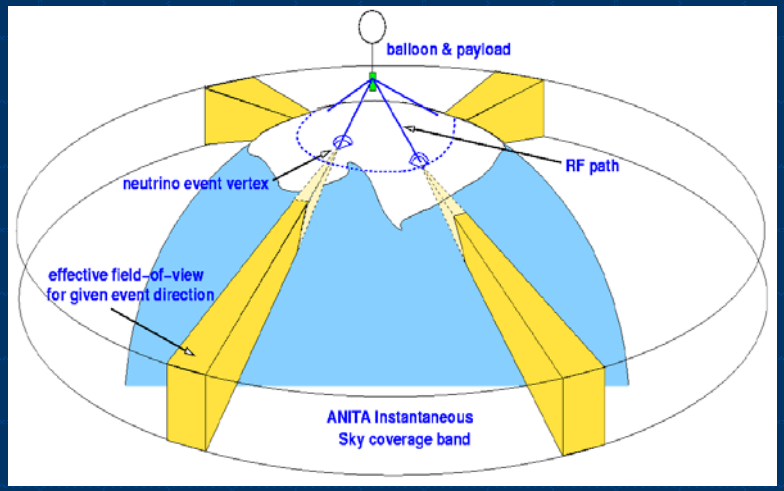
ANITA as a neutrino radio telescope





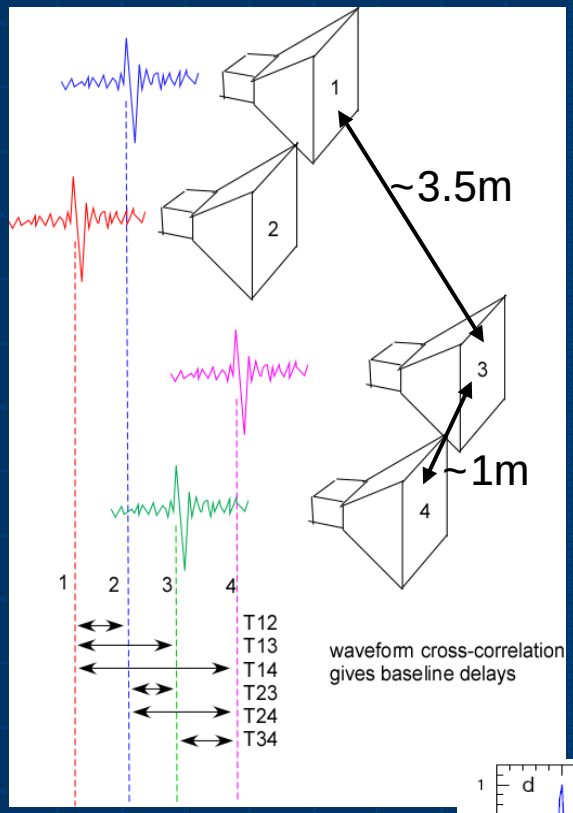


Brian Mercurio & Chris Williams, OSU

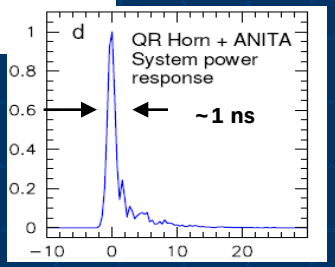


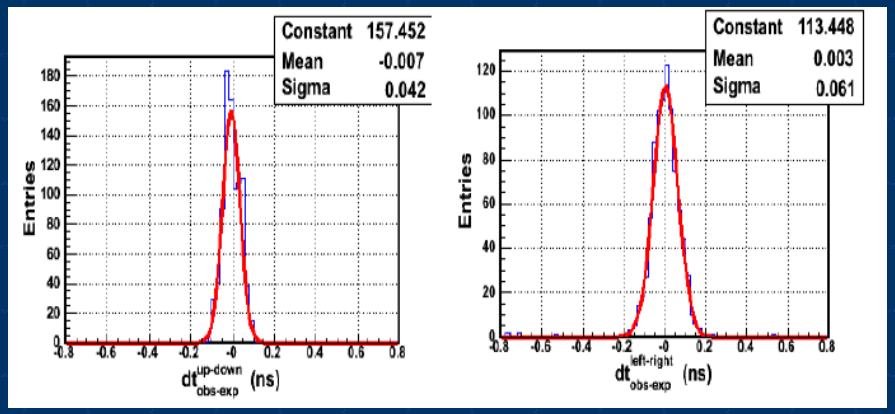
- Pulse-phase interferometer (<30-60 ps timing) gives intrinsic resolution of <0.3° elevation by ~1° azimuth for **arrival direction of radio pulse**
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~5-7° in azimuth by observed **polarization angle of detected impulse**

Pulse phase interferometry



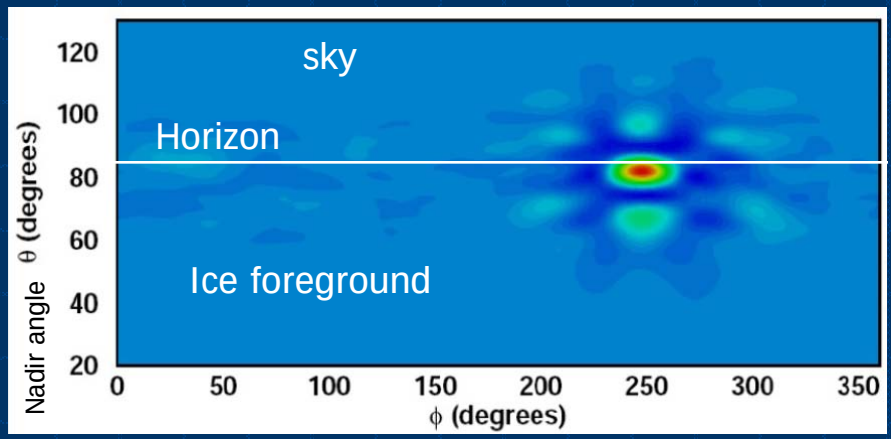
0.2-1.2 GHz bandwidth
➔ 1 ns impulses





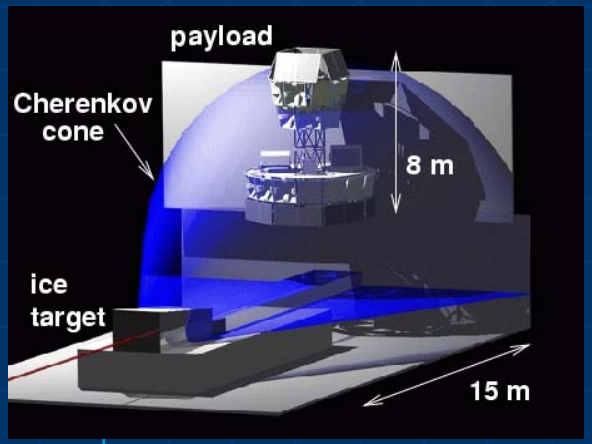
JiWoo Nam, NTU

- 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 vertical at SNR~5σ
  - ~60-80 ps horizontal (due to DAQ clock alignment errors)

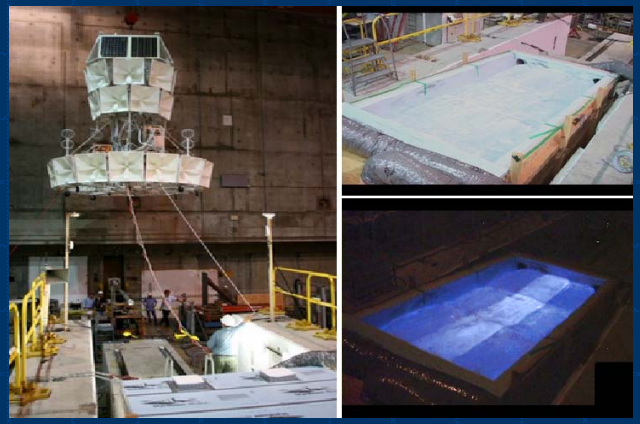


Andrew Romero-Wolf, UHM

June 2006, SLAC T486: “Little Antarctica”

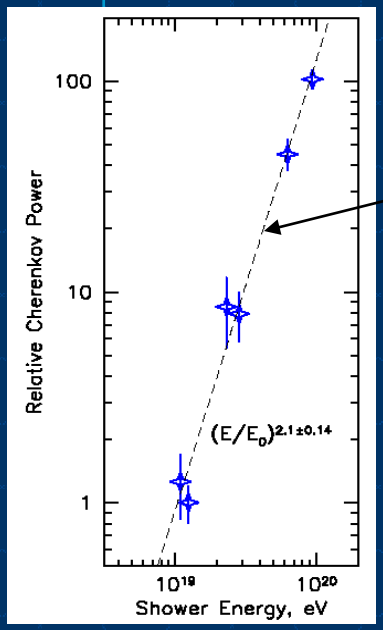


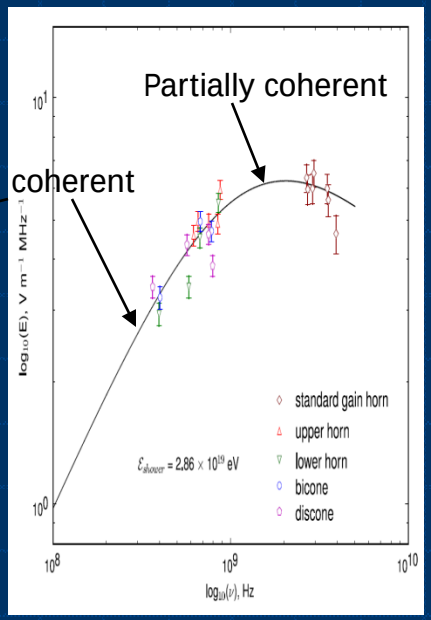
End Station A, SLAC

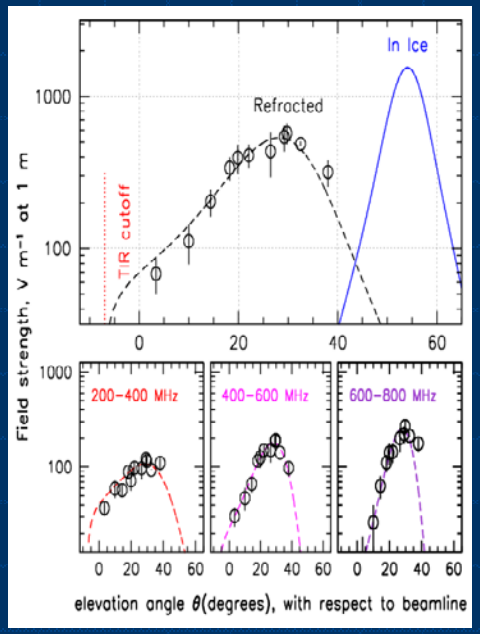


Thanks to P. Chen, C. Hast, SLAC

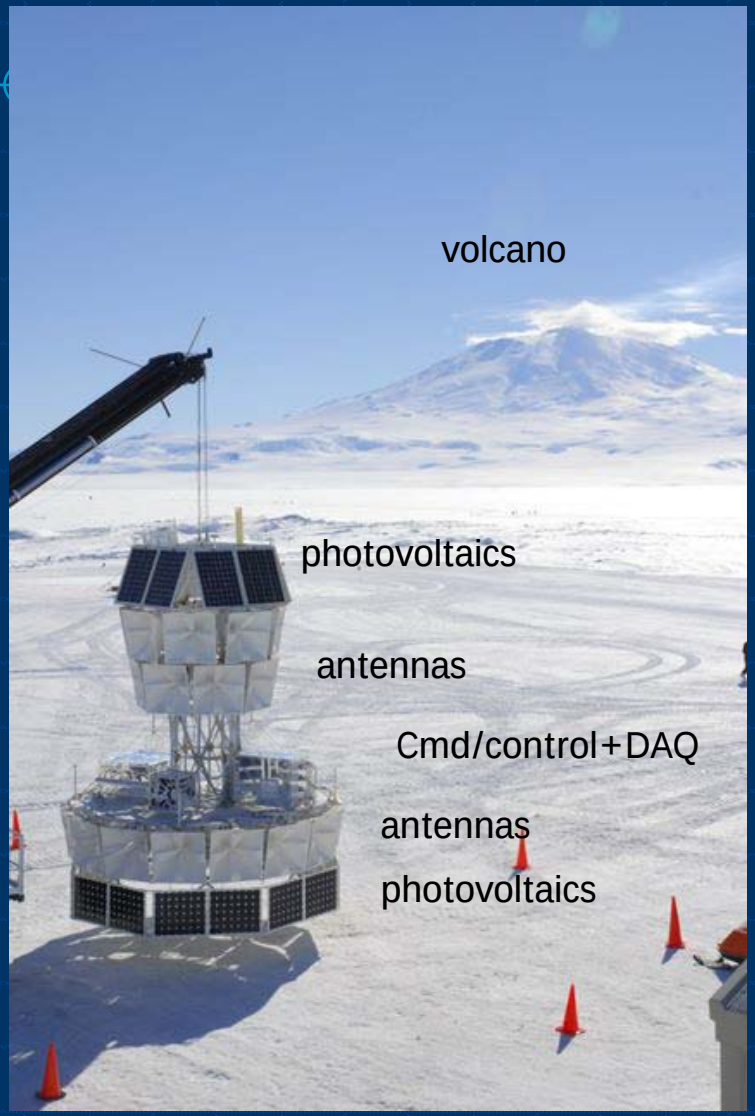
- **SLAC e^- showers with composite energy same as UHE neutrinos**
  - **$10^{8\text{-}9}$ x 28 GeV $= 2.8 \times 10^{19}$ eV**
- **Coherent radio power, consistent with theory**
- **1st direct observation of radio Cherenkov cone**







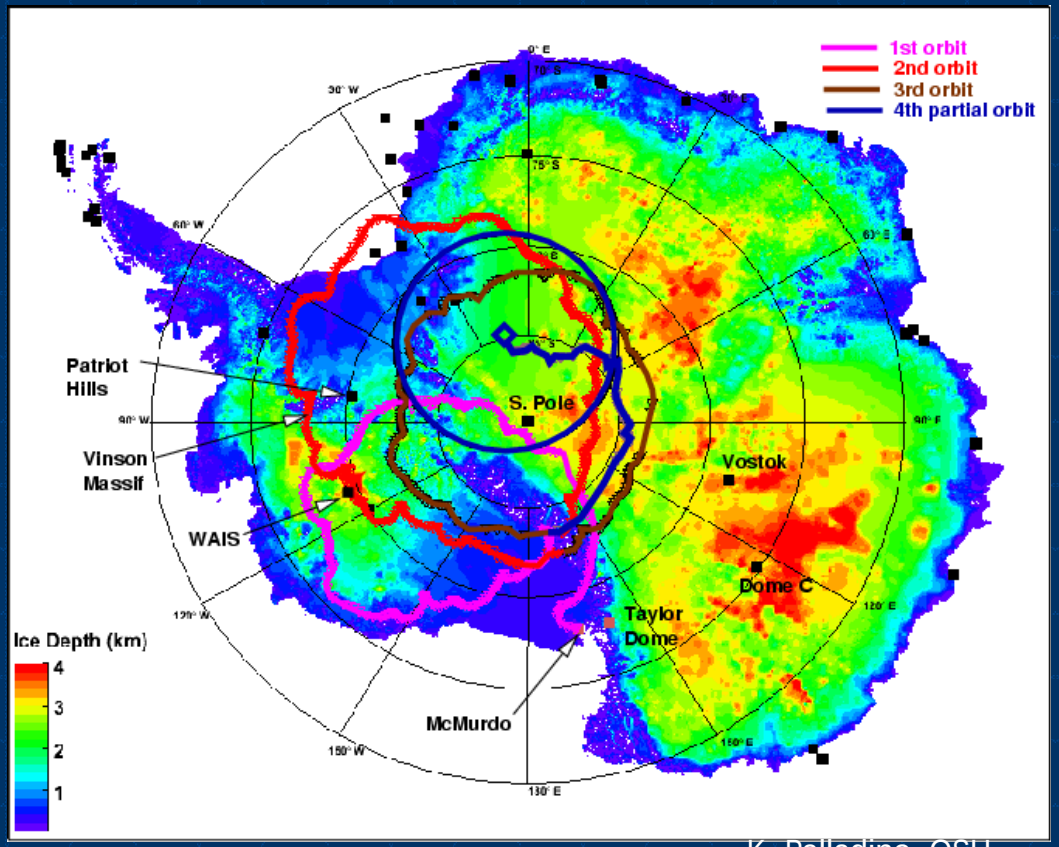
Pre-launch rollout

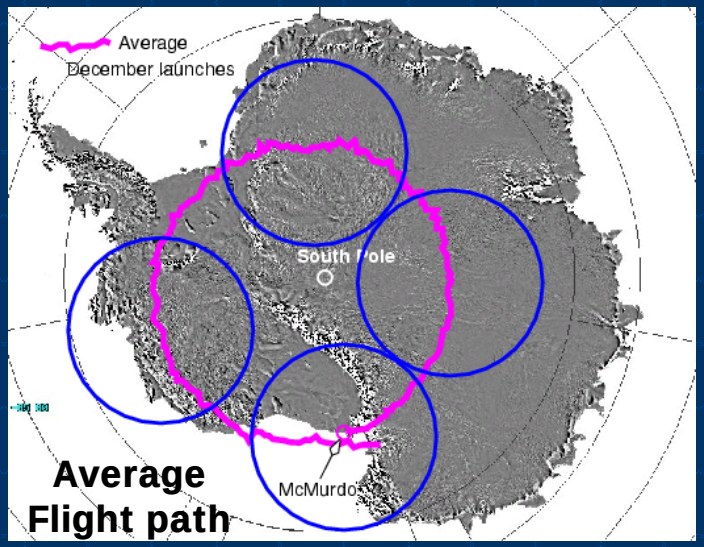


Photos: J. Kowalski

- Launch from ~80m deep Ross ice shelf (floats on Ross sea)
- ~8 miles from McMurdo station
- Affords flat, stable 1-mile diameter launch pad

ANITA-1 flight path

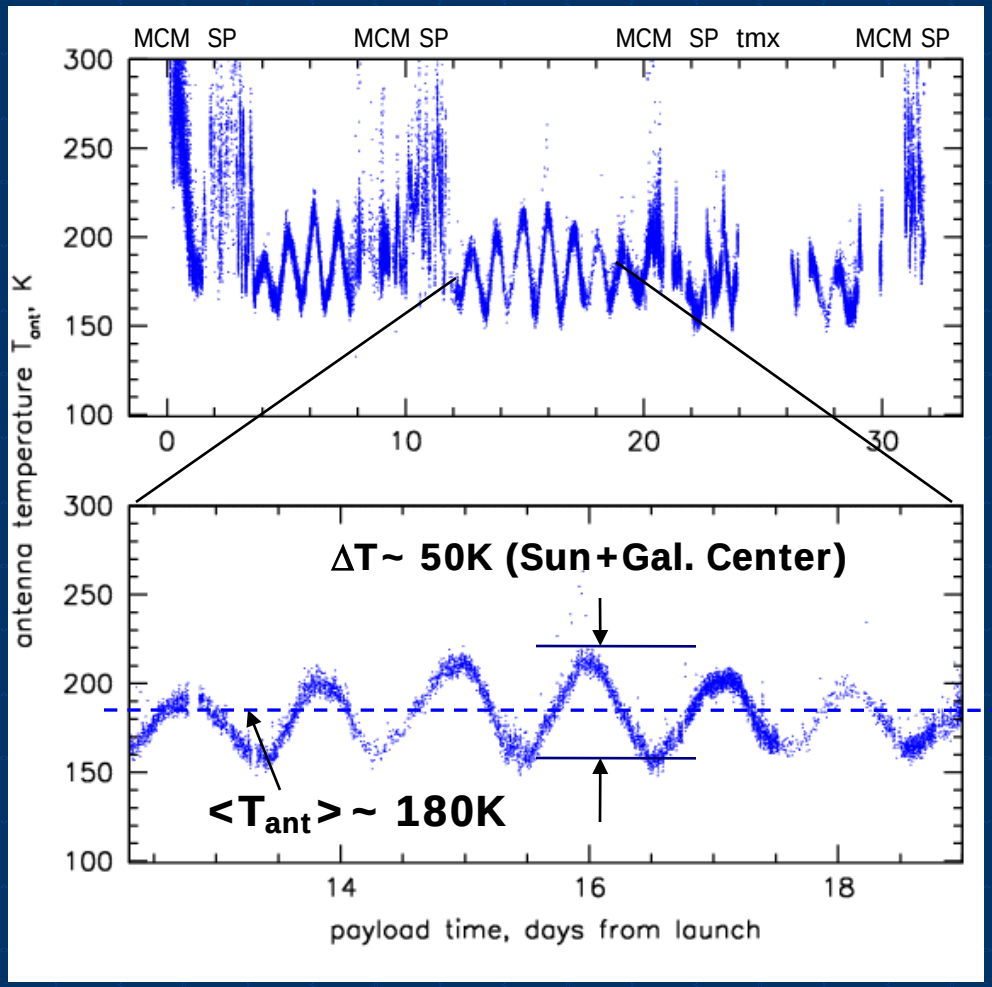




K. Palladino, OSU

- 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

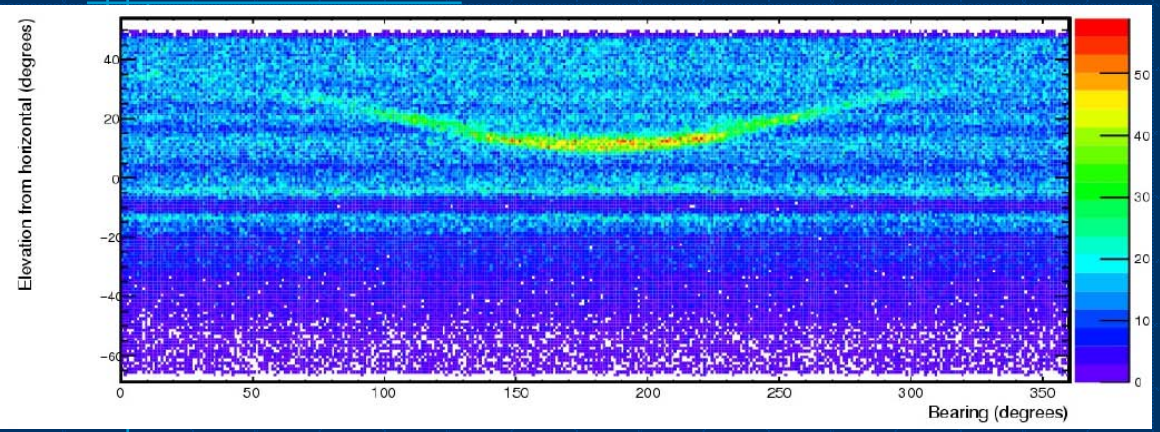
Flight sensitivity snapshot



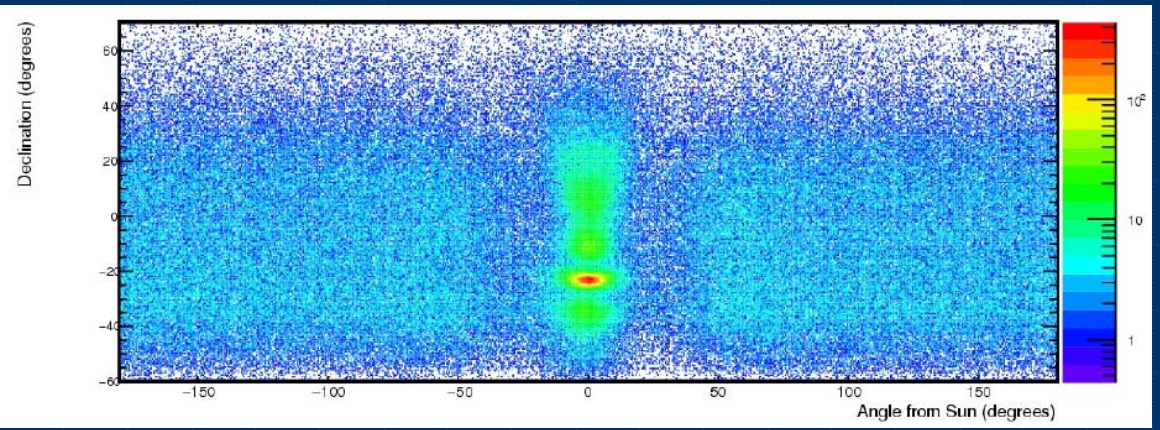
- ANITA sensitivity floor defined by thermal (kT) noise from ice+sky+rcvr
  - T_{rcvr} ~140K
  - T_{ice} ~ 230K
  - T_{sky} ~ 20-80K
- Thermal noise floor seen intermittently throughout of flight—but punctuated by station noise
  - South Pole and McMurdo stations!
- Still a significant fraction (~50-60%)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

Solar Sensitivity calibration

Elevation-azimuth coordinates



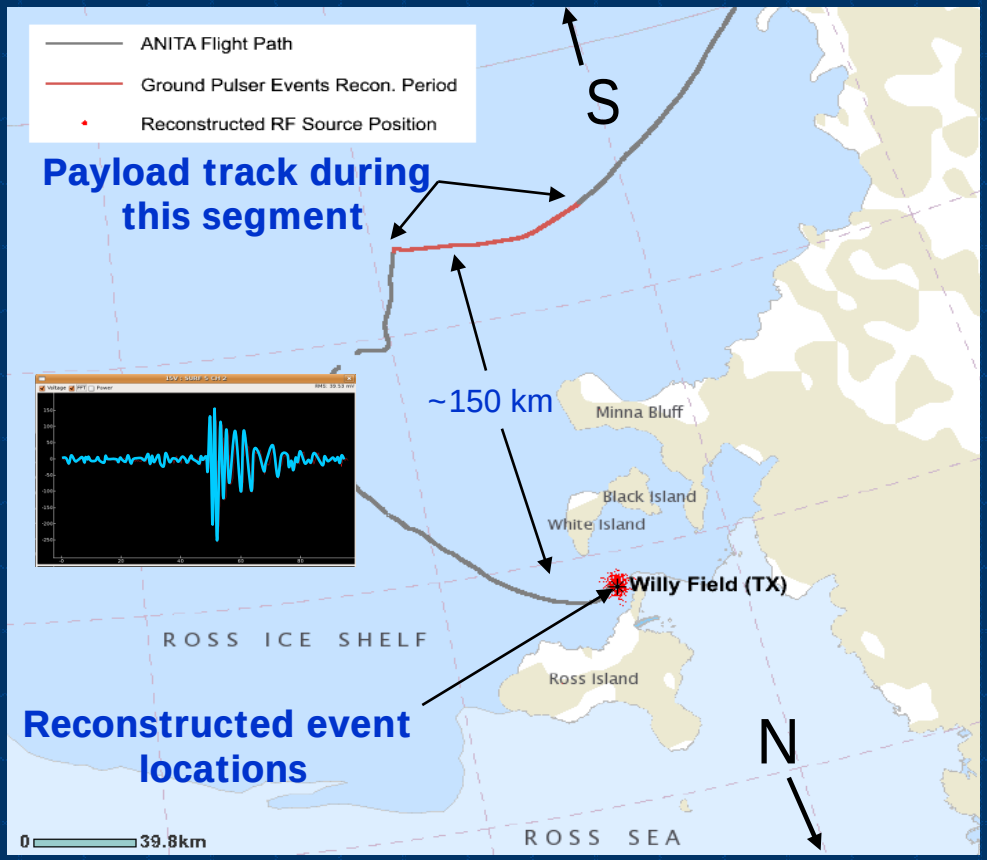
Heliocentric coordinates



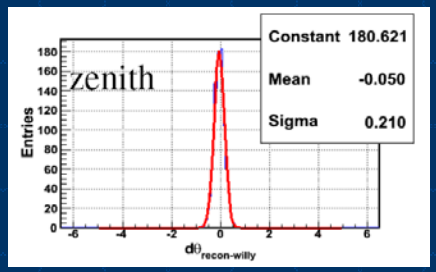
Images from S. Hoover, UCLA

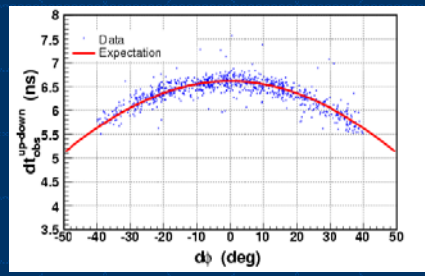
- ANITA (~3-5m cluster) interferometric images of the radio sun
  - Flight averages shown here
- Sun detection required about 200 sec of thermal noise data
- Provides 1st-order absolute calibration of antenna noise, beam response, event timing
- Note also horizon (and its sidelobes) at -6 degrees!

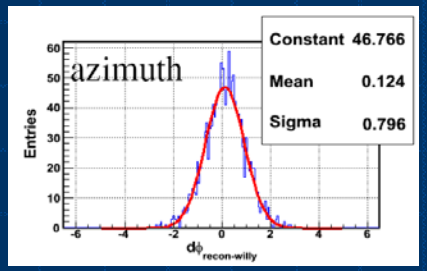
ANITA geo-location of borehole cal events

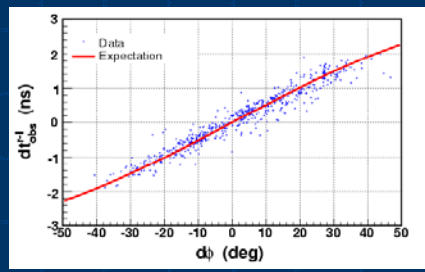


- Expect ~ $c\Delta\tau/2D$ altitude & azimuth
- $\Delta\tau$ ~ 40-60 ps, D ~ 1m (horizontal) to 3 m (vertical)
- Altitude: 0.21° observed, 0.3° expected
- Azimuth: 0.8° observed, 1.7° expected
- Multiple baselines improve constraints
- Pulse-phase interferometry works well!

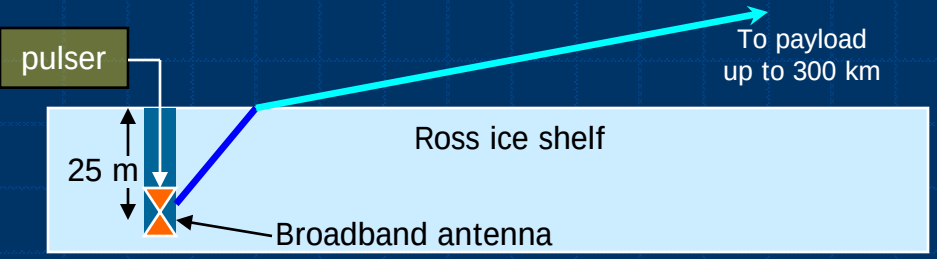




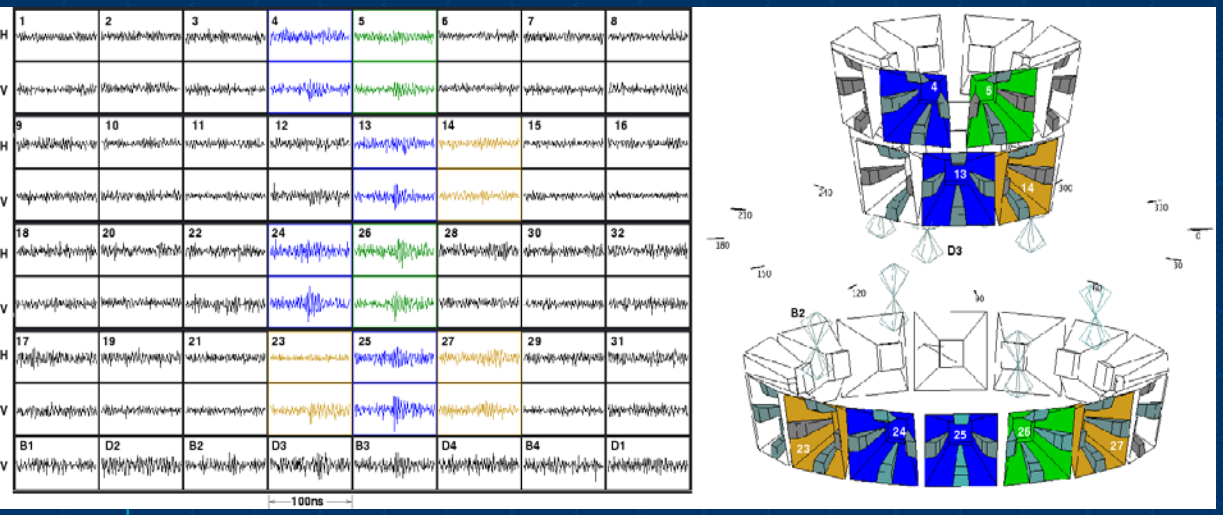


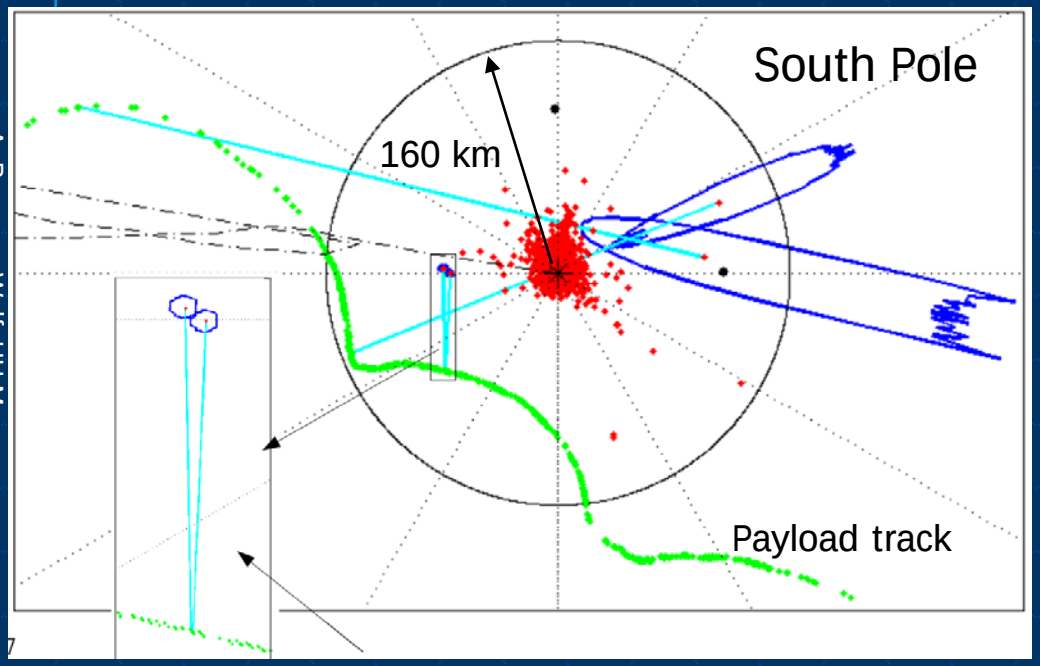


Thanks to JiWoo Nam, NTU



Event reconstruction & analysis

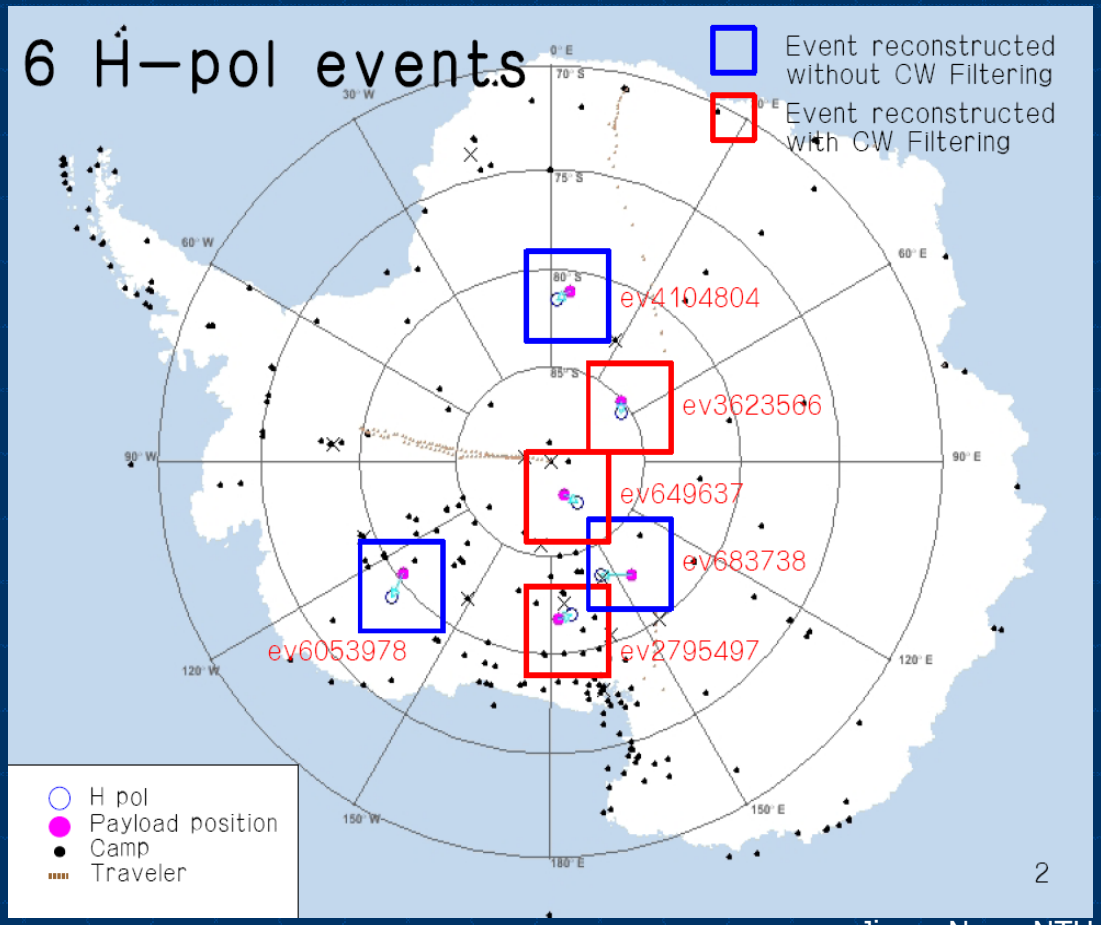




- Raw data: RF plane-wave lights up one side of payload
- Waveform corrletor (offline) gives 30-60ps timing
- Reconstruct ground position & error ellipse
- If <3σ from camp or any other event, reject
- South pole EMI, calibrated borehole pulser at MCM used to calibrate timing & statistical behavior

A. Romerro-Wolf, UH Manoa

Initial unblinded higher-threshold event set

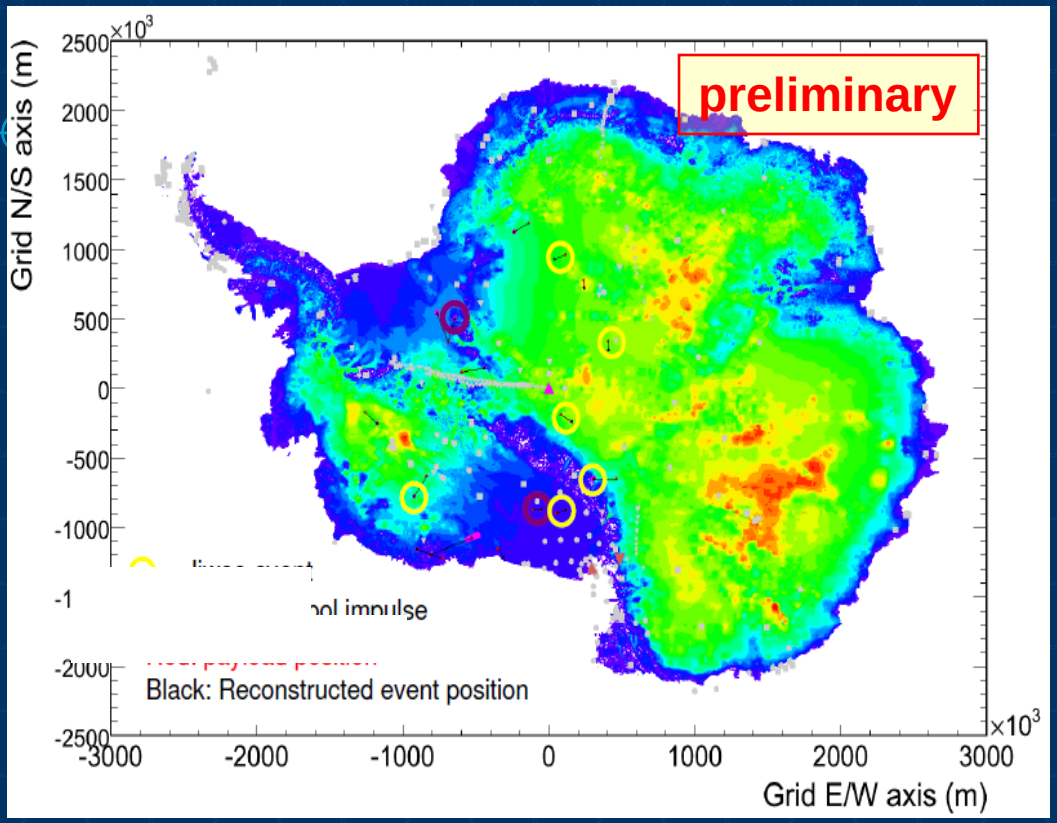


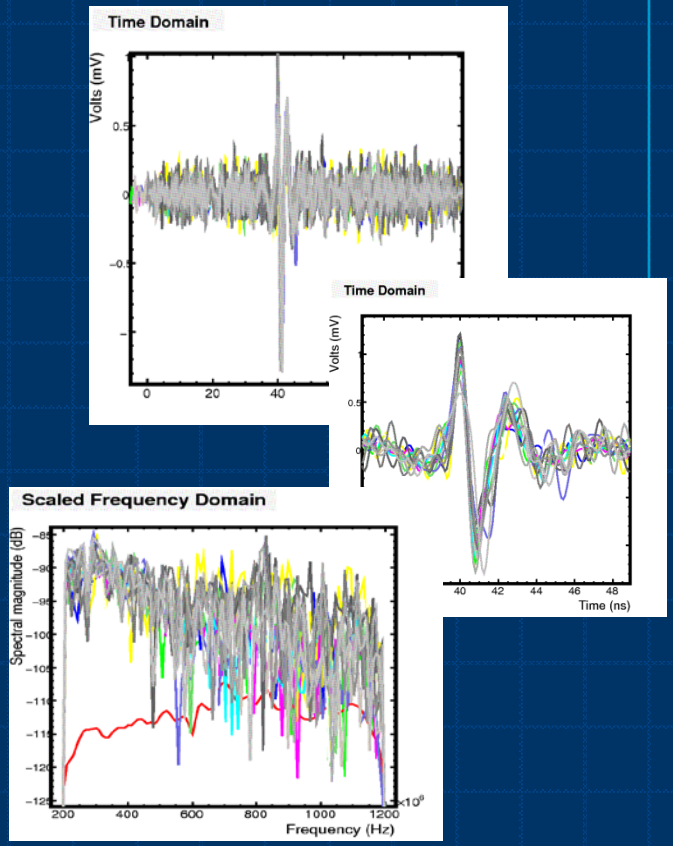
Jiwoo Nam, NTU

- ~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-1 lower threshold analysis

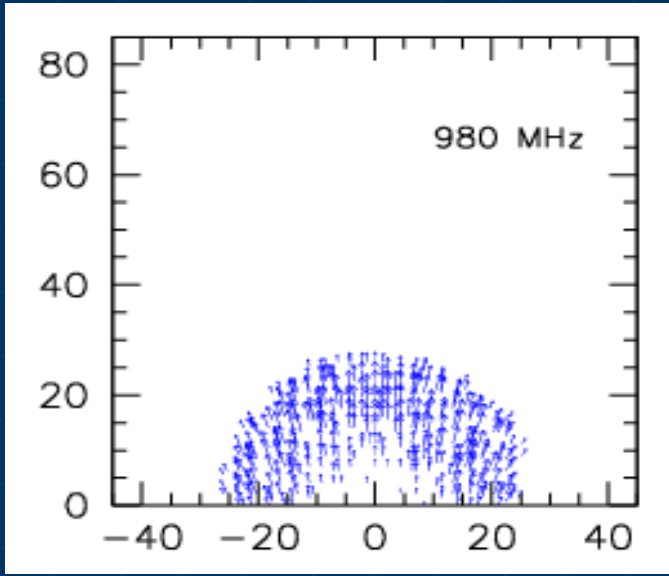


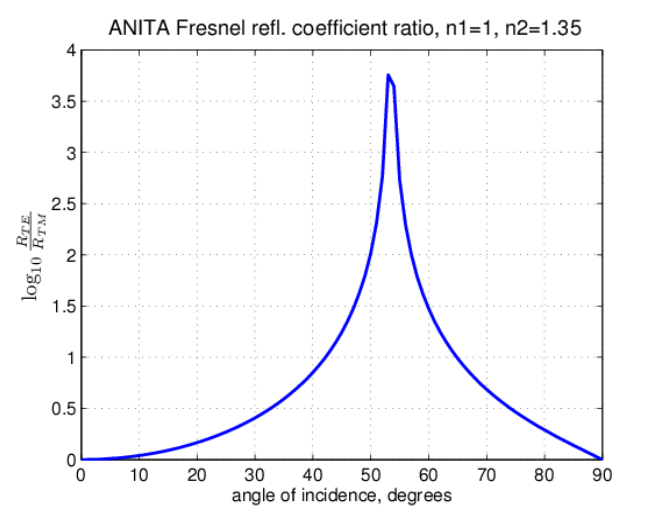


Stephen Hoover UCLA

- Independent deeper analysis done at UCLA
- Detected: **no neutrino candidates**, all of original 6 Hpol events, **+8 more**
- Hpol events: good coherence, not like any anthropogenic signals, low-frequency-dominated

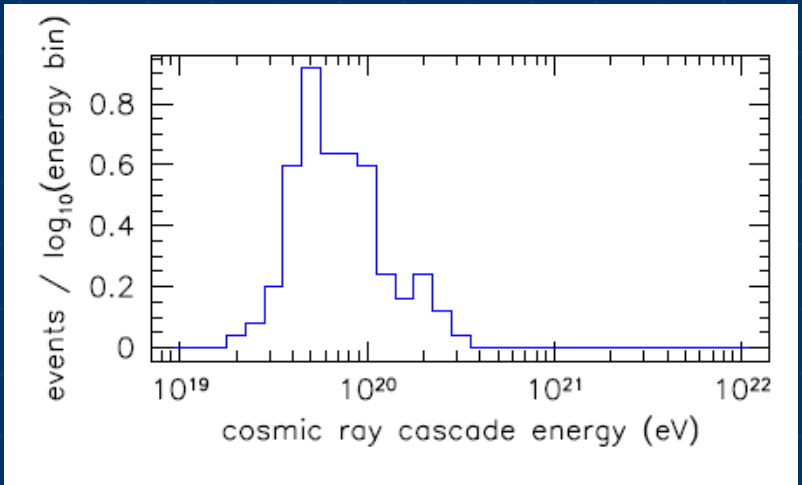
Horizontal Polarization??

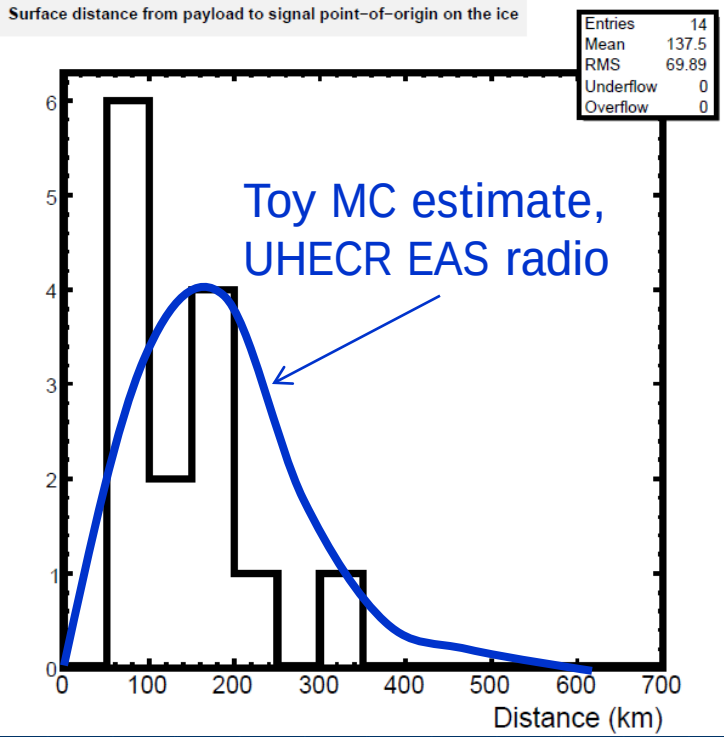




- Askaryan (eg, neutrino) signals strongly favor vertical polarization
  - Only top quadrant of Cherenkov "clock-face" escapes TIR at surface
  - Fresnel coefficient transmits more Vpol (TM) than Hpol (TE)
- Reflections from above-the-horizon sources tend to strongly favor horizontal polarization
- R_{TE}/R_{TM} > 3:1 over most of ANITA acceptance
- ➔ Hpol events cannot be neutrino candidates but could be
  - Air shower radio (geo-synchrotron)
  - Solid-state relays on satellites

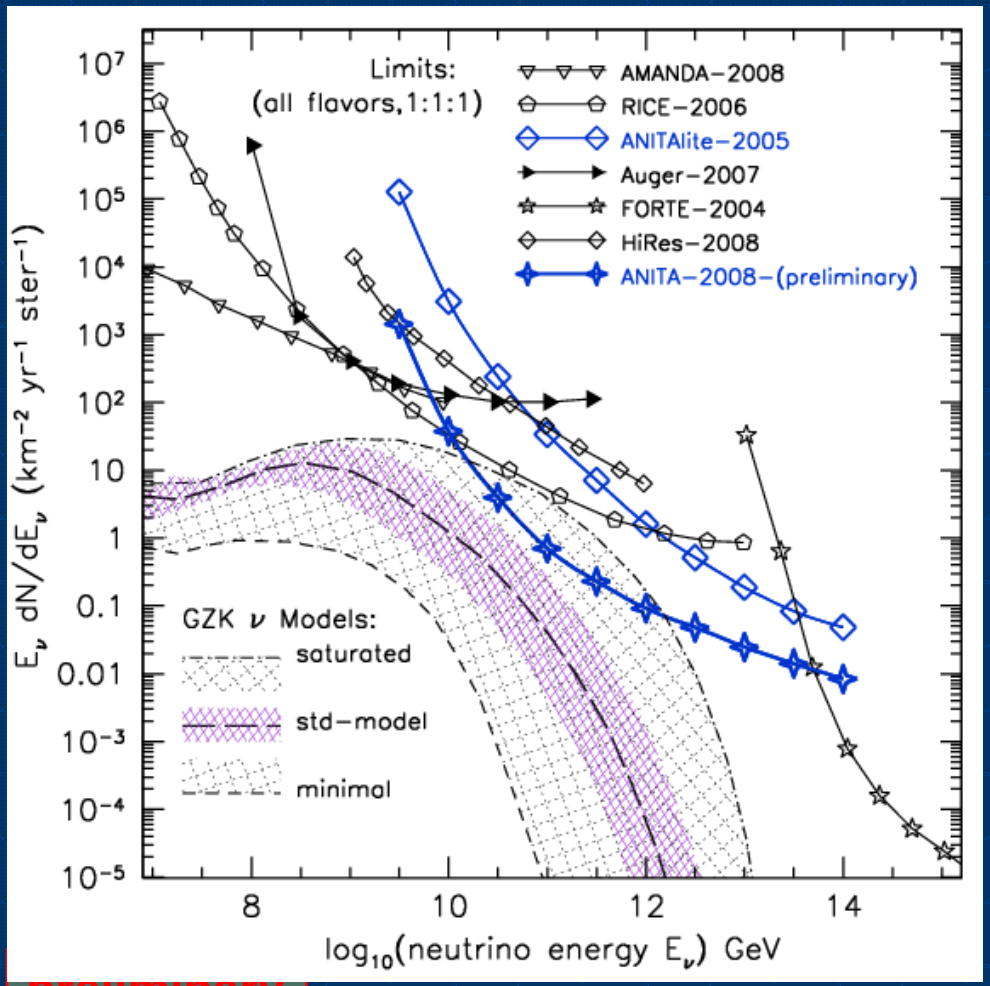
ANITA as a UHECR telescope?





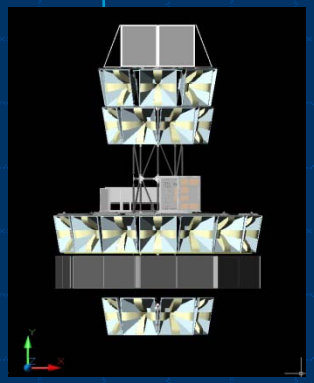
- Toy Monte Carlo: if EAS radio emission has a partially coherent tail → 1 GHz (eg. Data from 1960's), ANITA would see it
- Acceptance is comparable to Auger: ~10-15K km^2 sr at 10^{20} eV
- But time exposure far less than Auger, & no good energy cal
- Virtue: it proves ANITA was sensitive to UHE neutrinos as well!

Where we are after the ANITA-1 flight...



- GZK neutrino "envelope" contains nearly all cosmogenic neutrino models proposed to date (from Berezinsky's mirror matter at high end, to pure iron UHECR at low end)
- ANITA-1 has begun to constrain highest, less likely models
- ANITA-2 (Flight completed in January 2009) will begin to probe "standard model" range
- ANITA-2 Unblinding expected within a month

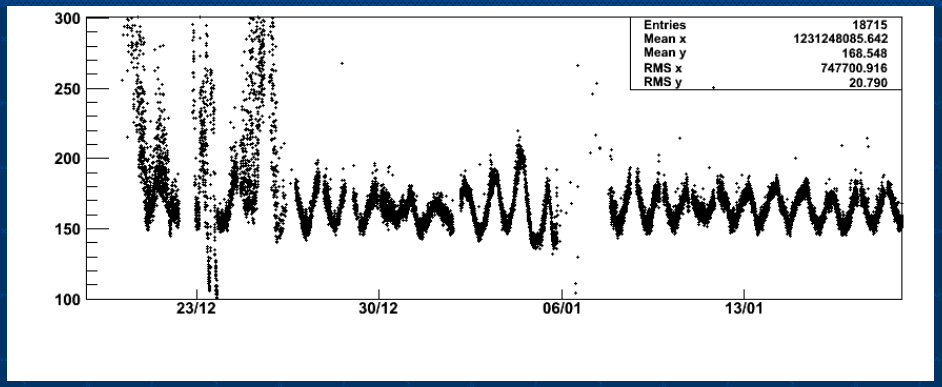
ANITA 2 (2008-2009) improvements

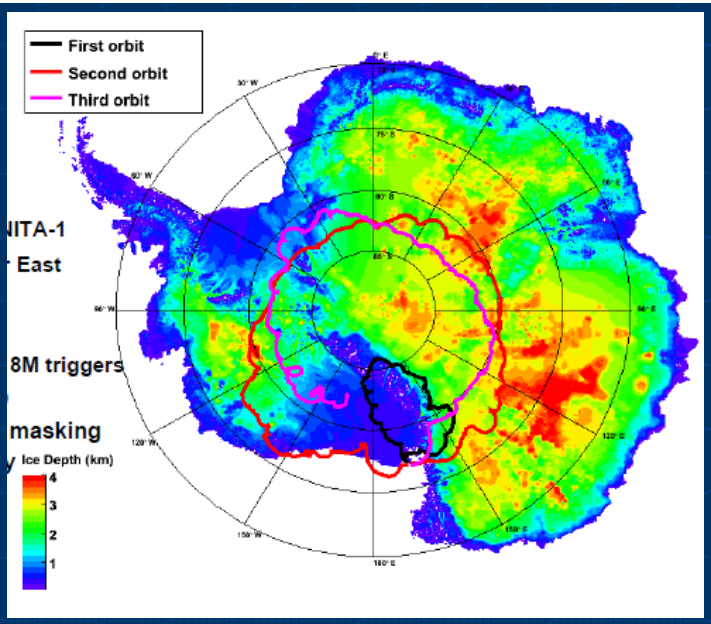


- **Improve system temperature by 40K (new front end)**
- Improve efficiency ~20%
  - active direction mask for trigger to blank out direction of camps & stations
- Improve trigger sensitivity by ~30% (Vpol-based trigger)
- Drop-down antenna ring: ~30% sensitivity increase
- ➔ Net improvement:
  - Factor of ~1.7 in energy threshold (Tsys+trigger+drop-down)
  - ANITA gains as ~ E_{thr}^{-2} ➔ 1.7^2 = factor of 3 in event rate increase
  - 30% in exposure for better flight trajectory & direction mask
  - 40% improvement in livetime possible
  - **3 x 1.3 x 1.4 = factor of >5 in neutrino event rate**

ANITA-2 launch Dec. 2008

ANITA-II

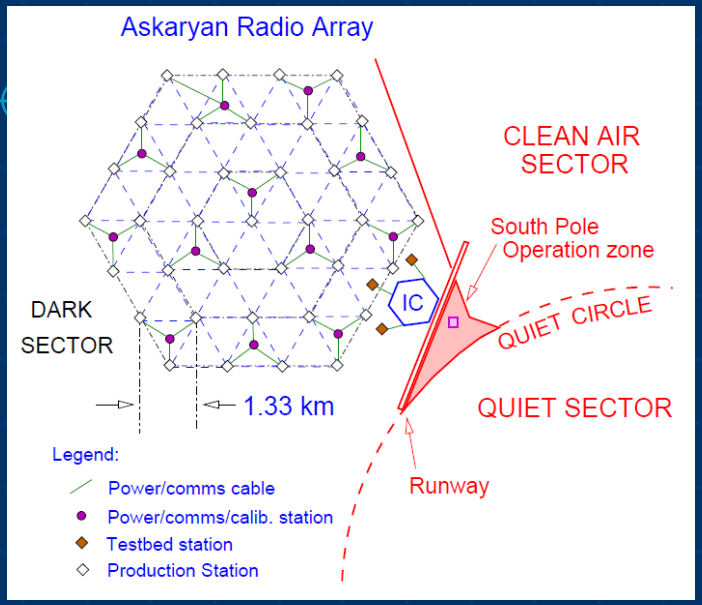




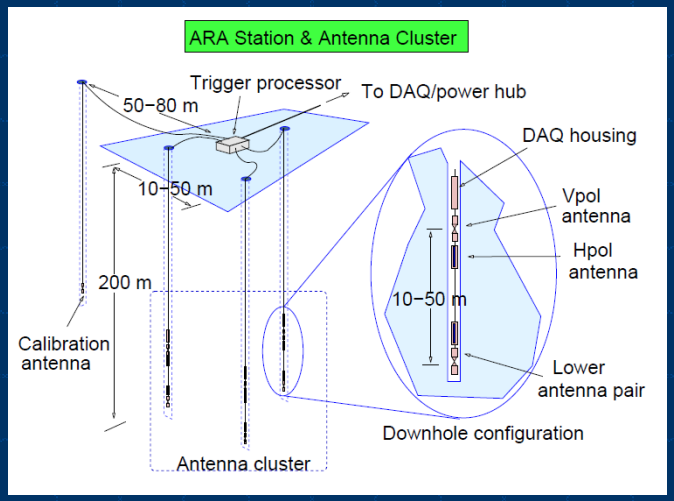
- ANITA-II: 31 days at float, >70% in radio-quiet conditions
- Collected 3x as much data as ANITA-1
- Angular resolution ~50% better
  - Less ice “lost” to camp peripheries

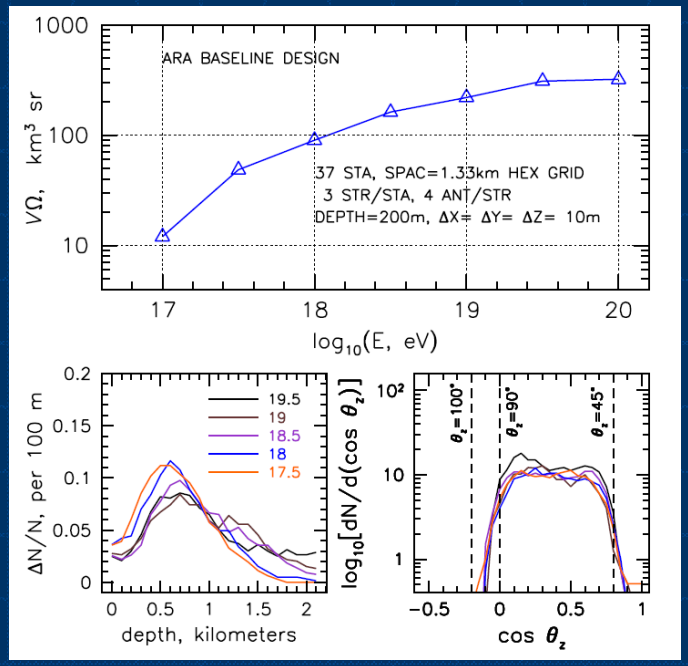
- Expect to realize most or all of predicted sensitivity increase

Askaryan Radio Array (ARA)



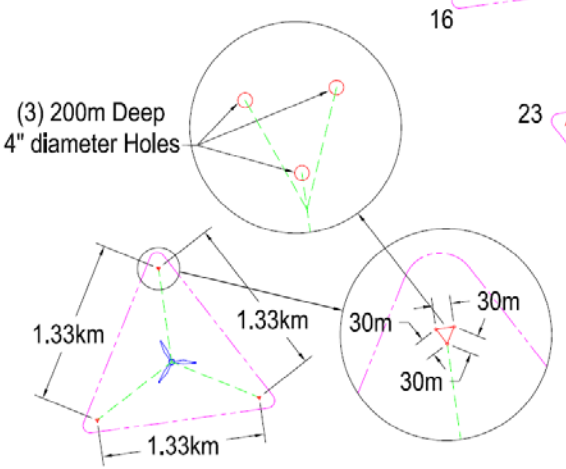
- NSF MRI proposal Aug. 09
- US: Wisconsin , Maryland, Hawaii, Kansas, Delaware & others
- UK, German, Belgian, Dutch, & Taiwan support as well
- Low Cost ~80 km^2 radio Cherenkov array at SP
- Goal: establish the cosmogenic neutrino flux



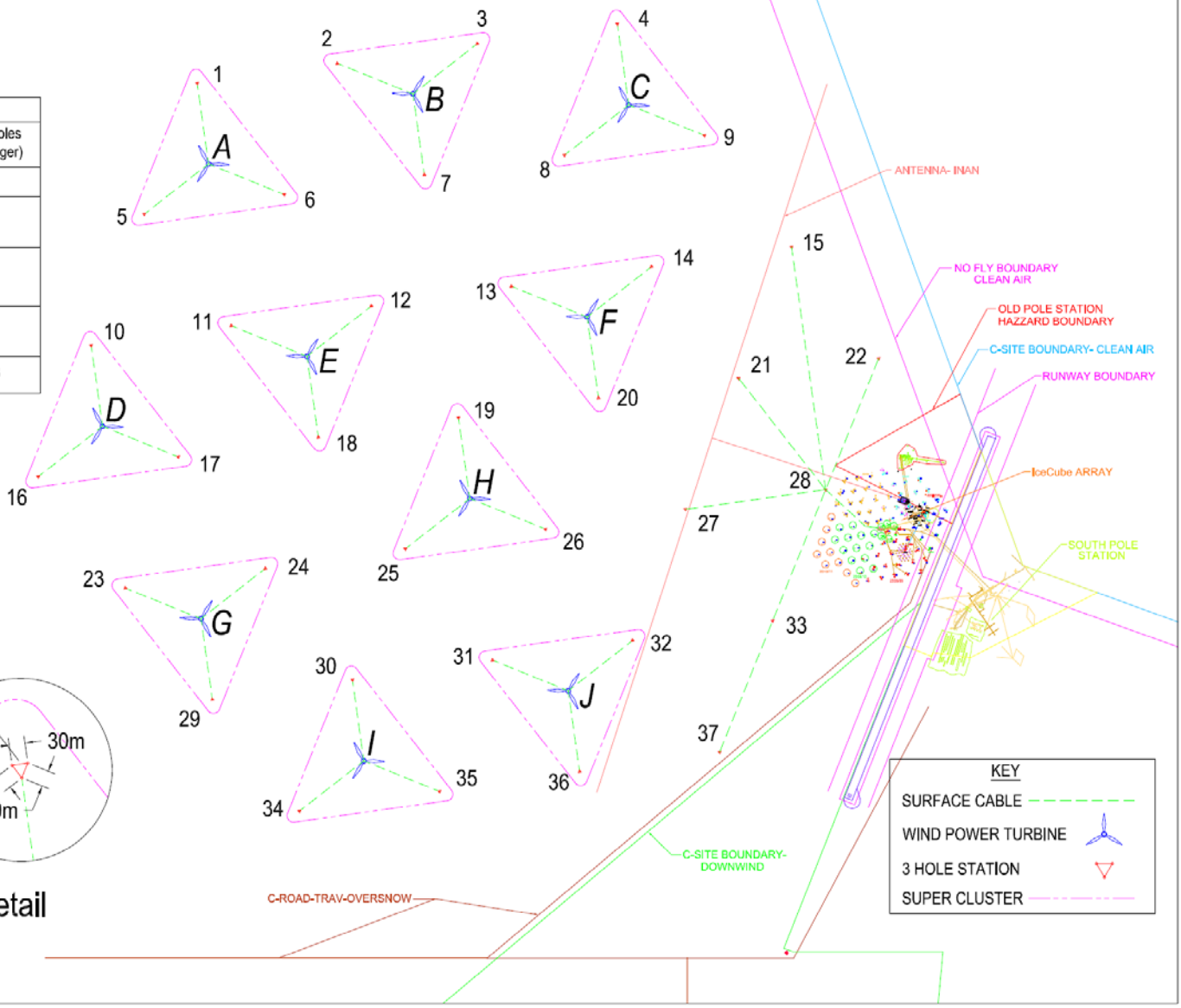


Drill Table				
Drill Season	Station Numbers	Super Cluster I.D.	Total Stations	Total Holes (with pinger)
11/12	27,28,33,37		4	13
12/13	2,3,4,7,8,9,13, 14,15,20,21,22	B,C,F	12	40
13/14	19,23,24,25,26,29, 30,31,32,34,35,36	G,H,I,J	12	40
14/15	1,5,6,10,11,12,16, 17,18	A,D,E	9	30
Total		10	37	123

CABLE NOTE: 17.5km of Surface Cables From ICL to 7 Stations

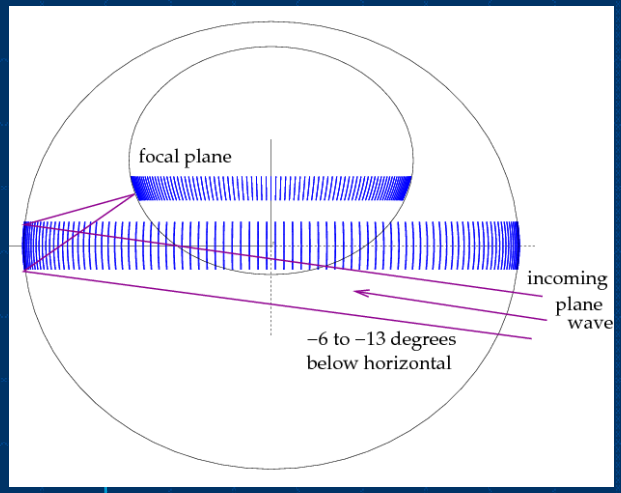


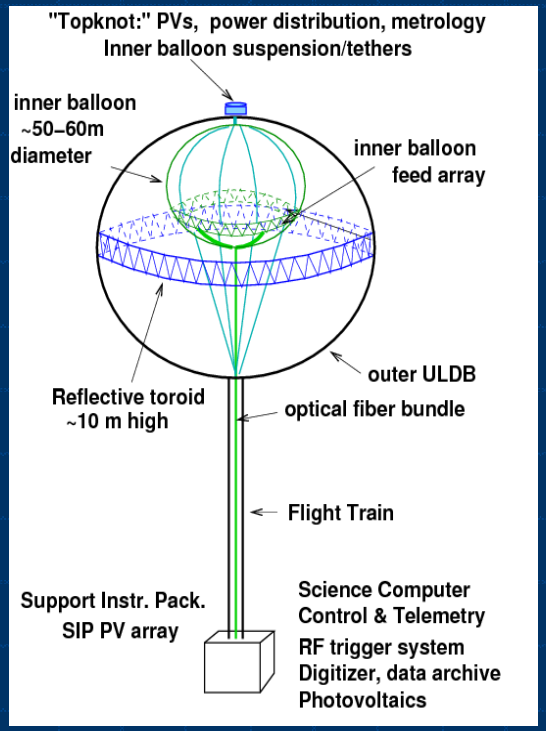
Super Cluster Detail



EeVA: ExaVolt Antenna, a NASA ULDB Mission

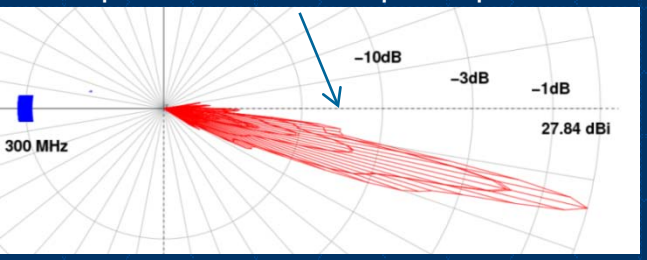
A toroidal balloon-surface reflector as a neutrino telescope



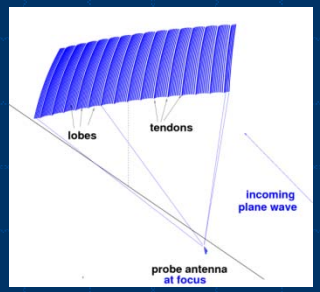


- Toroidal ~10 m high reflective band
- Inner balloon or membrane supports feed array
- Effective collecting area for any direction >100 m^2, but aberrations reduce gain
- **ULDB necessary** for stable shape
- Antenna modeling gives ~27 dBi net gain—achieves goal

Polar plot of elevation response pattern

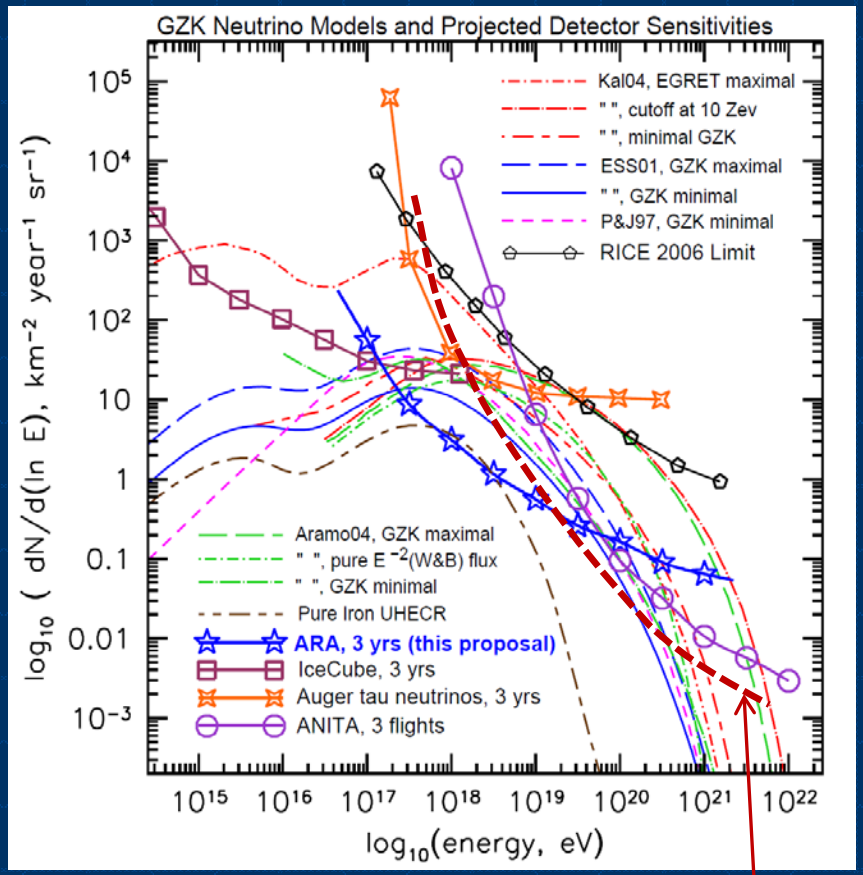


Numerical Electromagnetics NEC2 model
(includes ULDB shape and surface)



EeVA improves a factor of ~100 on existing ANITA-1 BZ neutrino limits

Compiled limits & future sensitivity

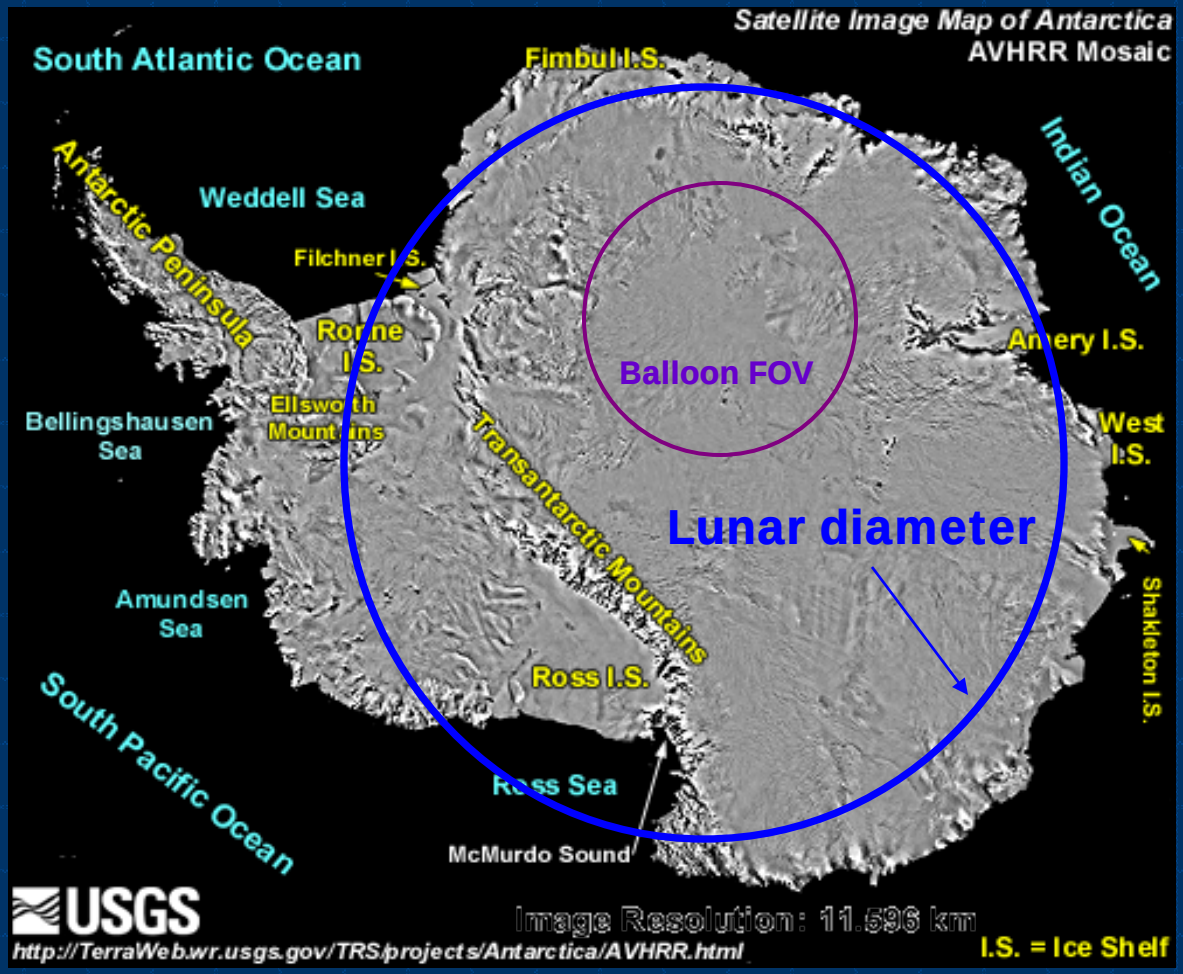


- Highest BZ models now excluded, RICE + ANITA-1
- Near term: ANITA-2,3 should probe “standard model” range
- Future: Exavolt Antenna will continue NASA’s sole neutrino astronomy initiative
- Askaryan Radio Array: will engender a new phase of precision measurements

Summary

- Askaryan's hypothesis about coherent radio Cherenkov from UHE showers is now proven solid
- Cosmogenic neutrino flux (the 'guaranteed' neutrinos) within reach
- ANITA-1 has come close to detection, source evolution constraints forthcoming
- ANITA-2 will soon begin to dig deeper into GZK model space
- Future initiatives abound: we are going to see these neutrinos soon!

Moon vs. Antarctica...

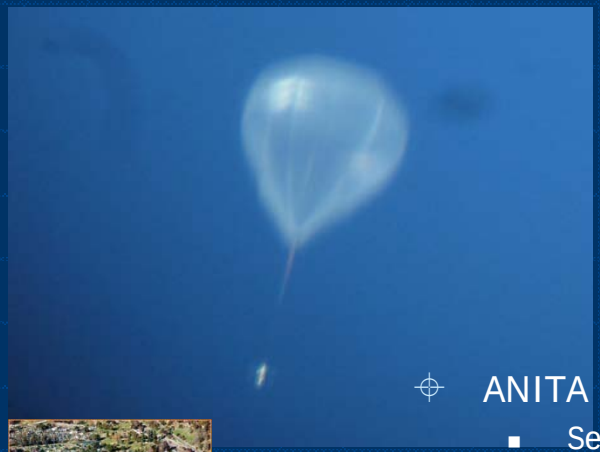


- Area of Antarctica ~ visible area of Moon
- Antarctic ice:
  - Latten ~ >1200 m at 400 MHz
  - Depth ~ 3 km
- Lunar Regolith:
  - Latten ~ 20-30 m at 400 MHz
  - Depth ~ few tens of m to bedrock
- **Conclusion: at GZK neutrino energies, Antarctica wins!**

ANITA-1 Launch: December 15, 2006

K. Palladino & D. Saltzberg

Photos: J. Kowalski



- ANITA at float (123Kft)
  - See through amateur telescope from the South Pole
  - Size of the Rose Bowl (really!)
  - (thanks to James Roth)

Landing...~360 miles from South Pole

Photos: D. Braun

- Ouch! Chute did not release after landing, payload dragged ~1 mile
- BUT: DAQ & data OK → success