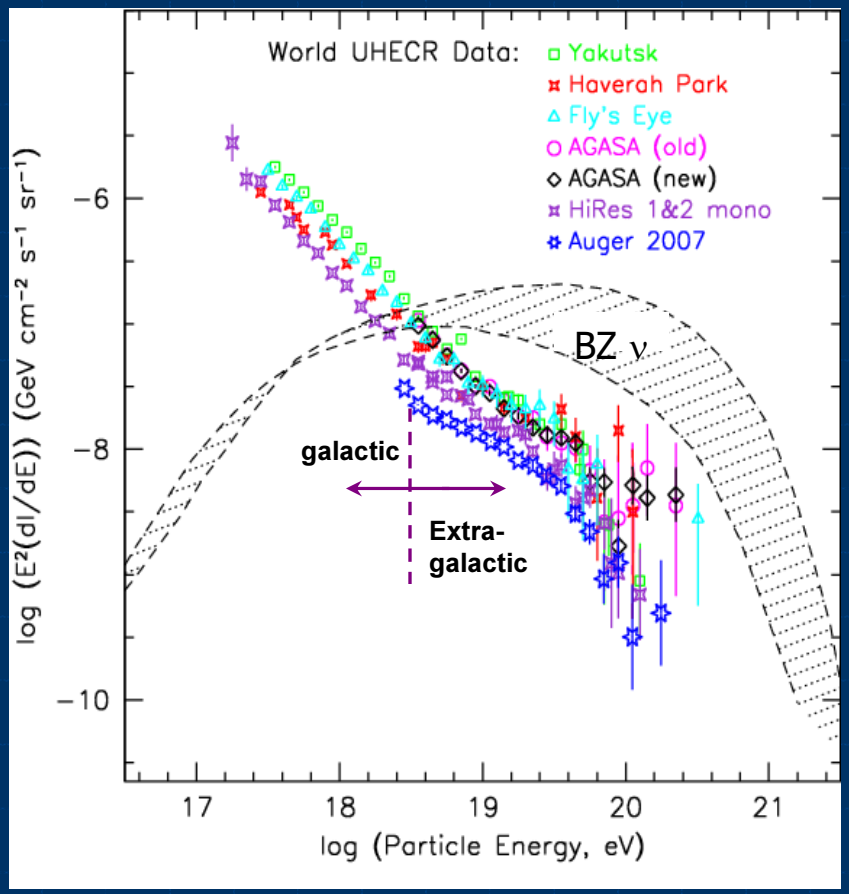
Radio Cherenkov searches for cosmogenic ultra-high energy neutrinos, & ANITA results

Peter Gorham
University of Hawaii Manoa
Department of Physics & Astronomy

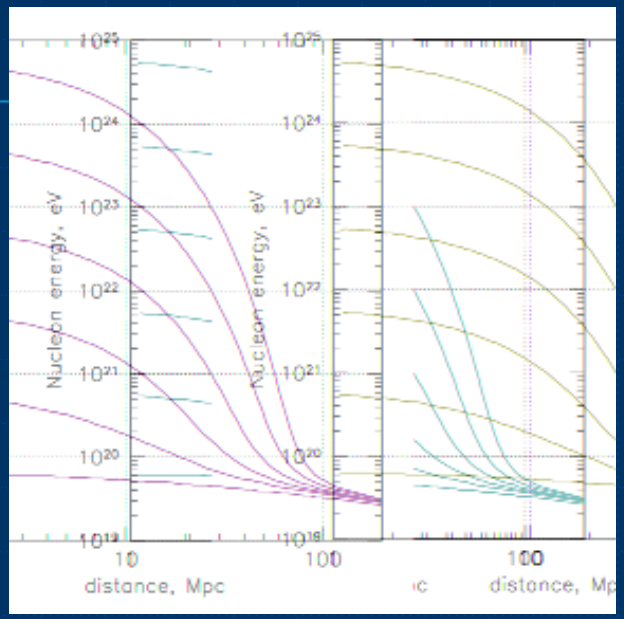
Ultra-high Energy Cosmic rays require Neutrinos

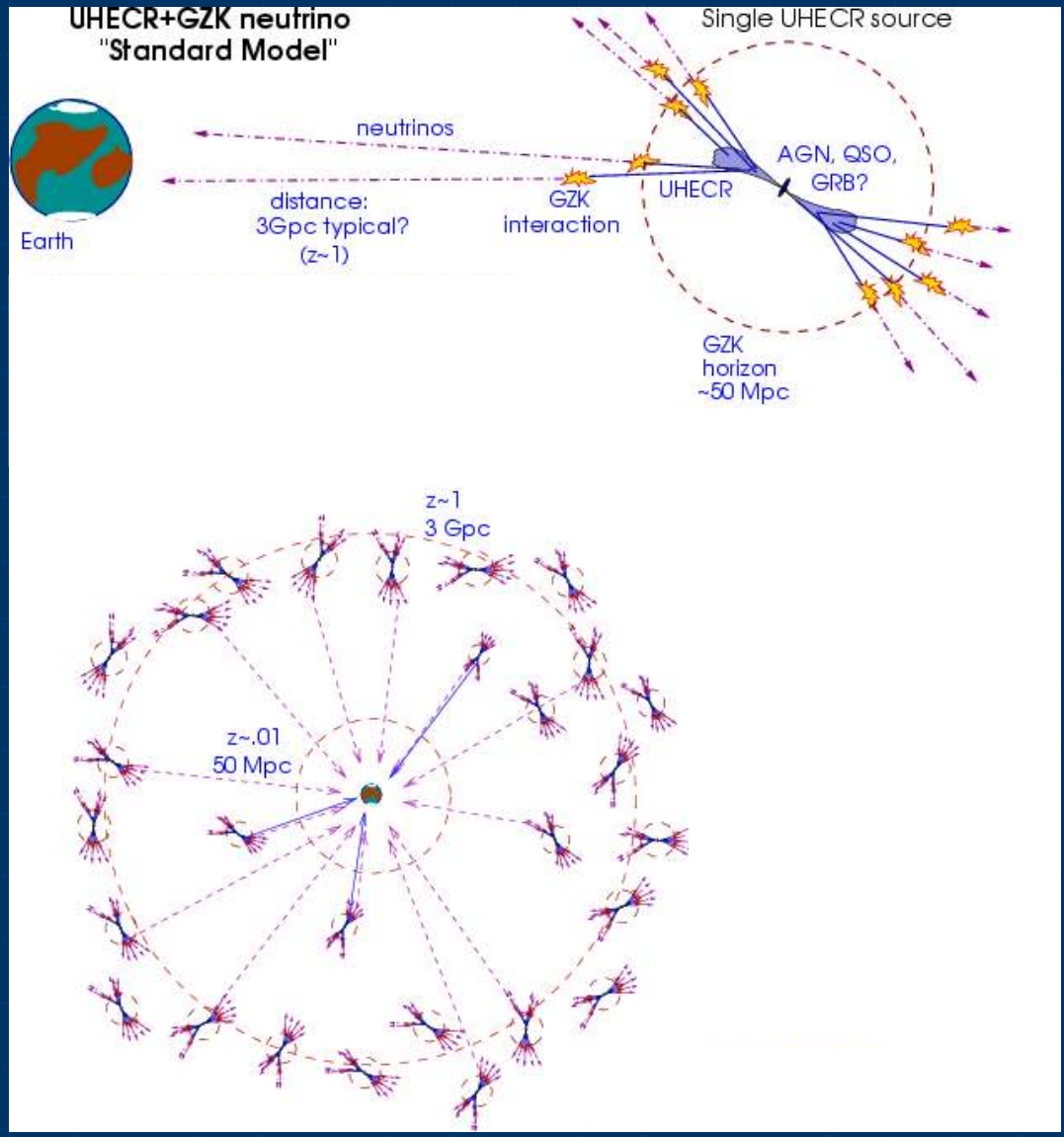
- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV, **after 40 years!**
- **A paradox**:
  - No nearby sources observed
    - Auger: yes!, HiRes: No!
  - distant sources excluded due to collisions with microwave bkg
- Neutrinos at $10^{17\text{-}19}$ eV <u>required</u>*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



* Berezinsky & Zatsepin 1970

UHECR and the "GZK horizon"

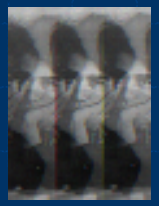




- UHECR provide only local source information
  - Universal UHECR Accelerators likely to evolve in many ways: strength, metallicity, number density, …
- BZ neutrino spectra are direct from sources at all epochs

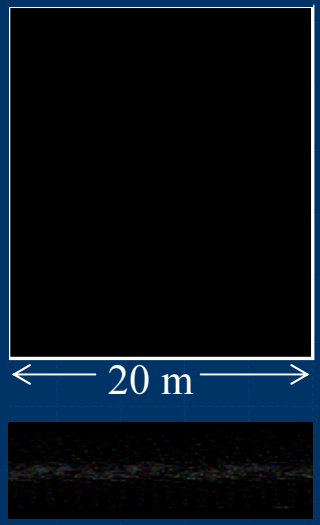
Why go after cosmogenic UHE neutrinos?

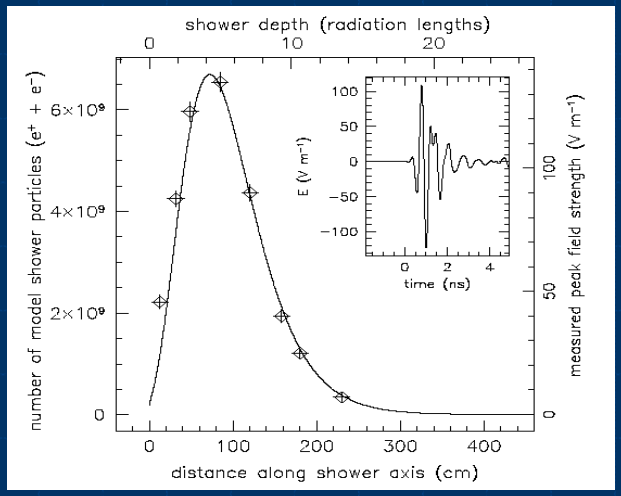
- Trace particle UHECR hyper-accelerators to very early epochs
  - Even at z~10 or more, GZK neutrino energies peak at 10-100 PeV
  - they all point back directly to the UHECR sources
- Their flux is constrained by UHECR sources, once determined
  - Can become a quasi-isotropic "test beam" of UHE neutrinos
  - ~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 IceCube**
- **→ scalable new detection method: radio Cherenkov**



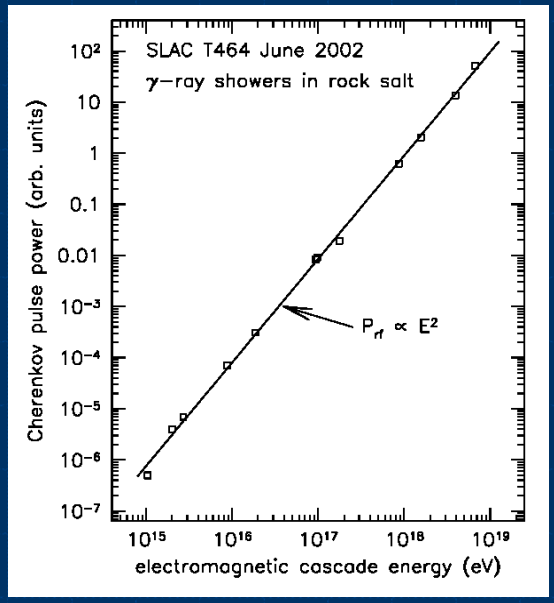
Askaryan Effect: confirmed in 2001 at SLAC

Blue: ~0.01GHz → yellow: 2GHz





Saltzberg & Gorham et al. PRL 2001



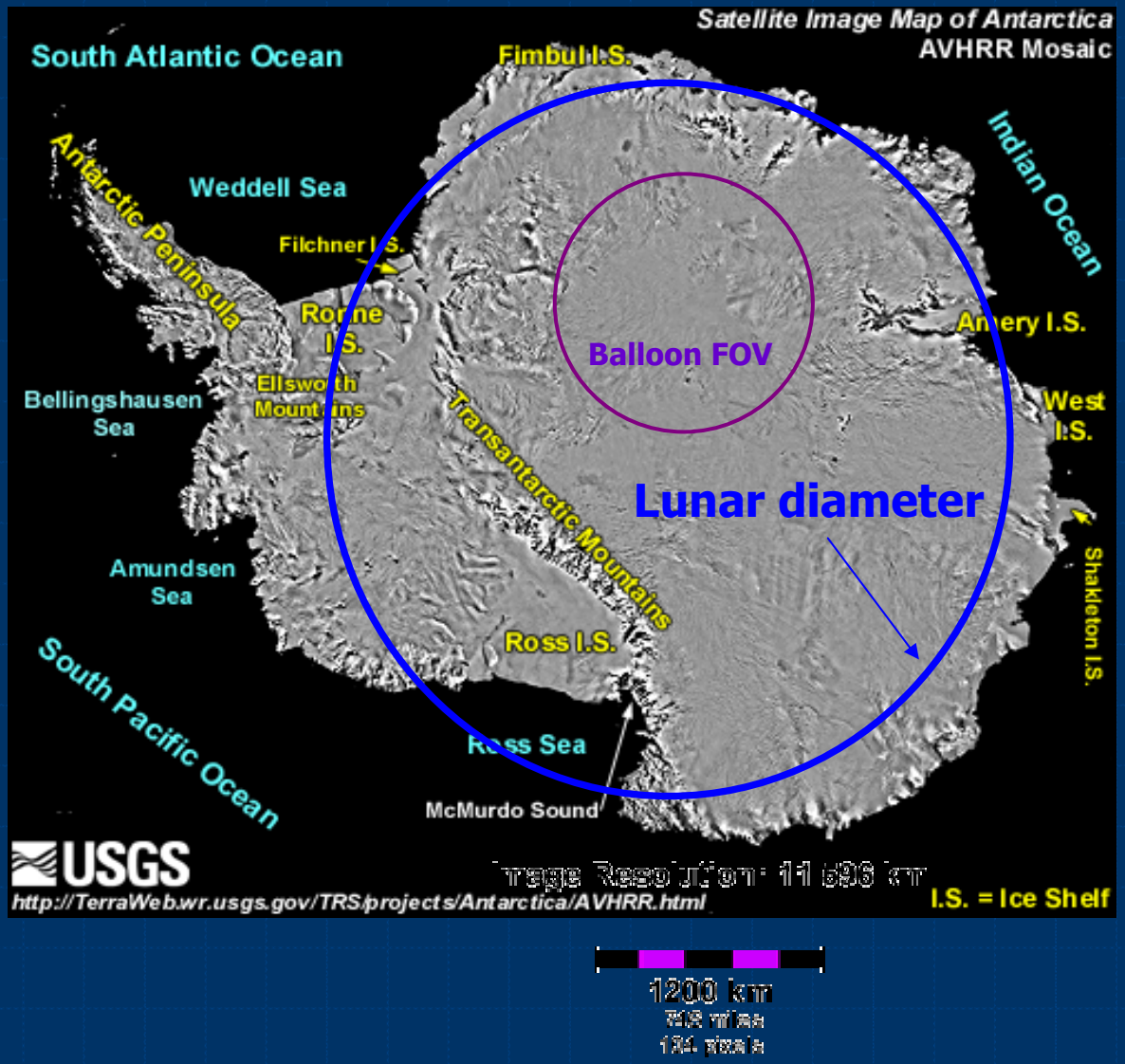
Gorham et al. PRD 2003

- 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, LOFAR, SKA … ?
- **Ice: Antarctica & Greenland**
  - Radio Ice Cherenkov Experiment (RICE) (completed 2006)
  - Fast On-orbit Recording of Transient Events (FORTE) 2004
    - DOE satellite with impulse trigger, 3.8 days obs. Of Greenland
  - **Antarctic Impulsive Transient Antenna—ANITA**
    - **ANITA-lite flew in 2003-2004, 4 channel prototype**
    - **First Full ANITA flight completed late January 2007**

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!**

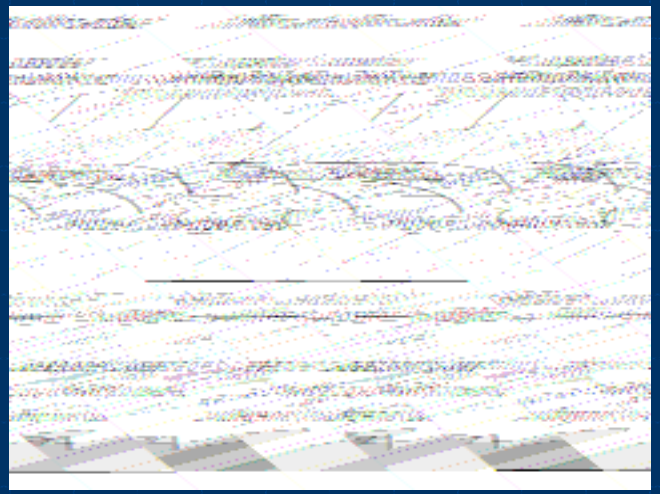
Antarctic Impulsive Transient Antenna--ANITA

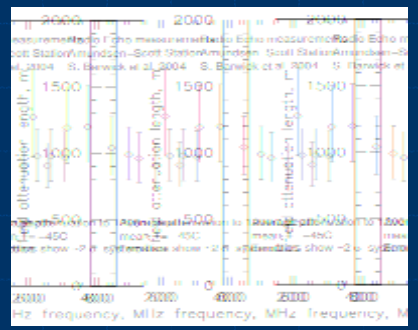
ANITA Gondola & Payload

Overall height ~8m

- NASA start in 2003, launch in '06-07, baseline 10 day mission, got 35 days total
- Ultra-broadband antenna array, views 1.5 M km^2 of ice sheet looking for Askaryan impulses, $\Delta f \sim 0.2$-1.2GHz

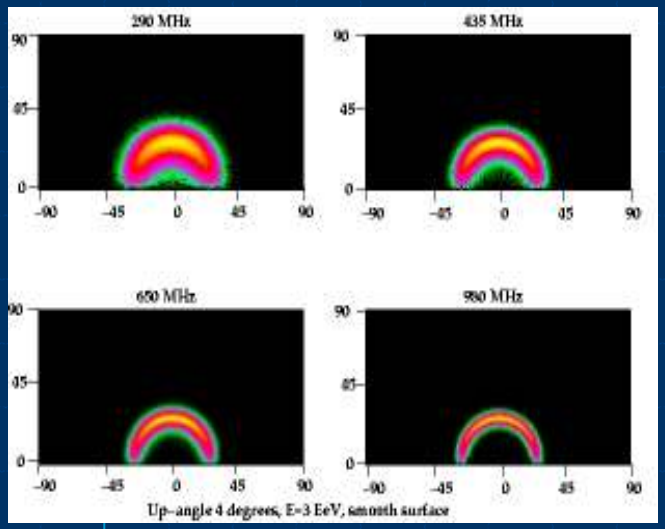
ANITA-1 collaboration P. Gorham (PI, UH Manoa), S. Barwick, D. Goldstein, F. Wu, UCI; J. Beatty, K. Palladino, B. Mercurio OSU, D. Besson, KU; W. Binns, P. Dowkonnt M. Israel, Wash. U. St. Louis, C. Chen, C. Hast, K. Reil, D. Walz, SLAC; J. Clem, D. Seckel, U Del., M. DuVernois, U. Minn., K. Liewer & 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.

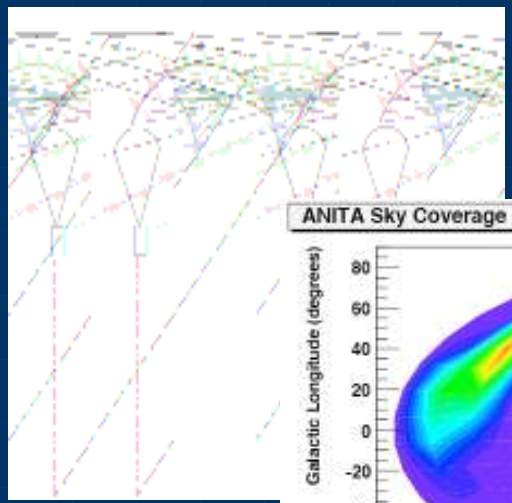


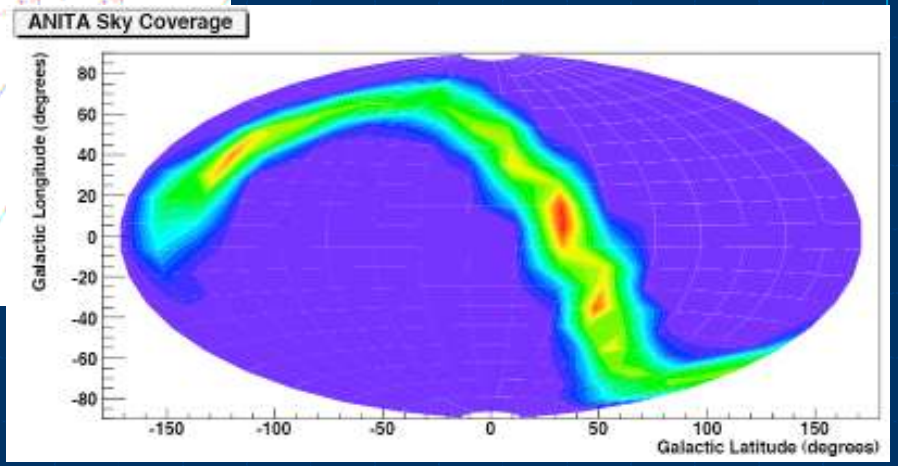


Ice RF clarity:
1.2 km(!) attenuation Length @ 300 MHz

ANITA as a neutrino radio telescope



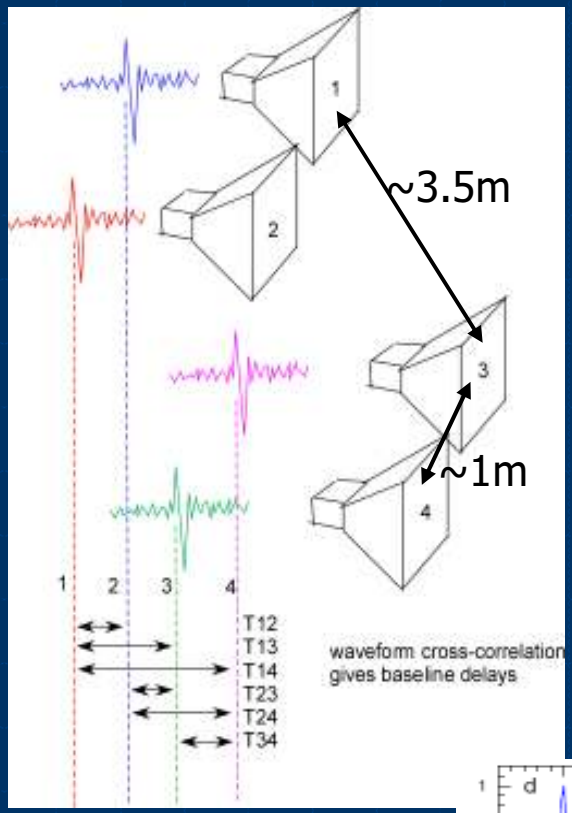




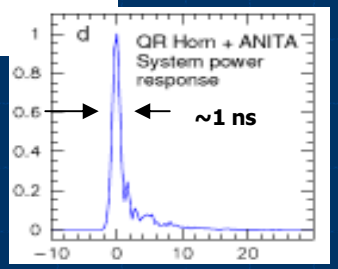
Brian Mercurio & Chris Williams, OSU

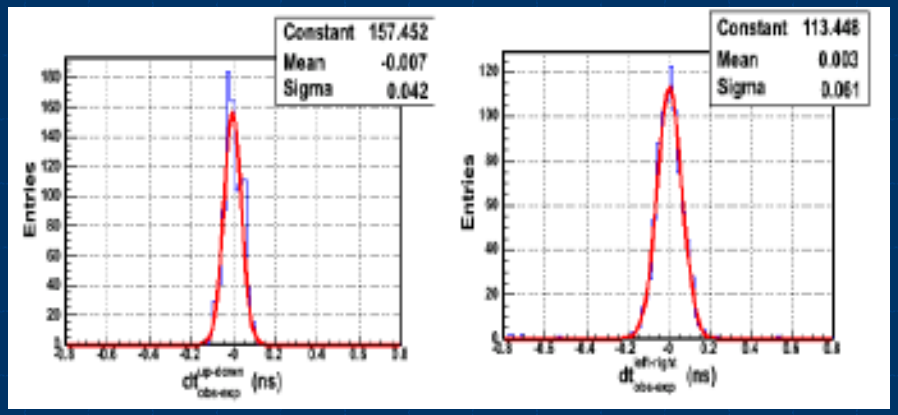
- Pulse-phase interferometer (<40-60 ps timing) gives intrinsic resolution of <0.3° elevation by ~1° azimuth for **arrival direction of radio pulse**
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by observed **polarization angle of detected impulse**

Pulse phase interferometry



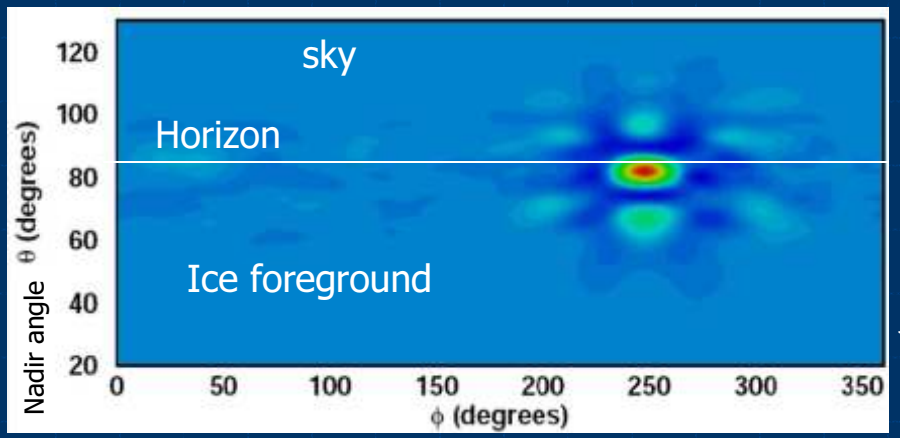
0.2-1.2 GHz bandwidth
➔ 1 ns impulses





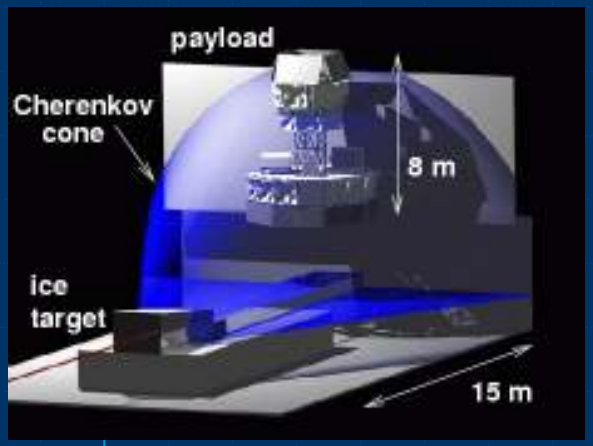
JiWoo Nam, NTU

- 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

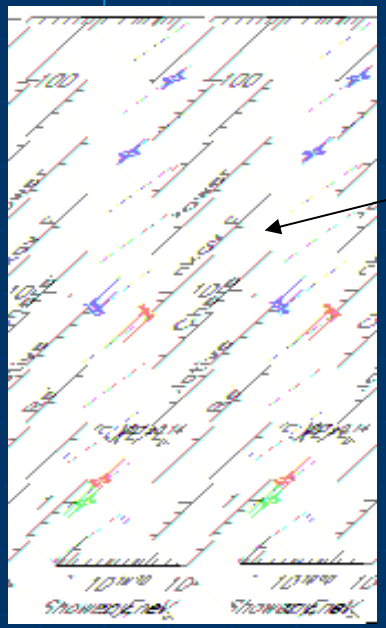
June 2006, SLAC T486: "Little Antarctica"

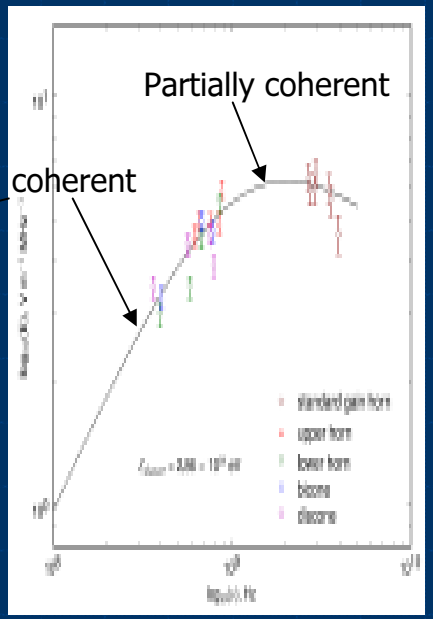


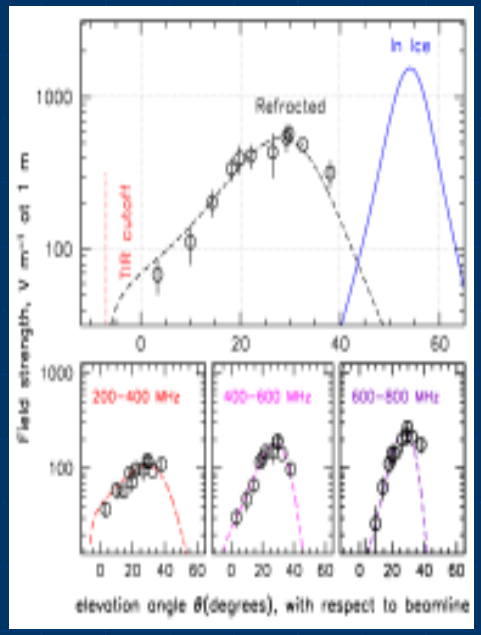
End Station A, SLAC

Thanks to P. Chen, C. Hast, SLAC

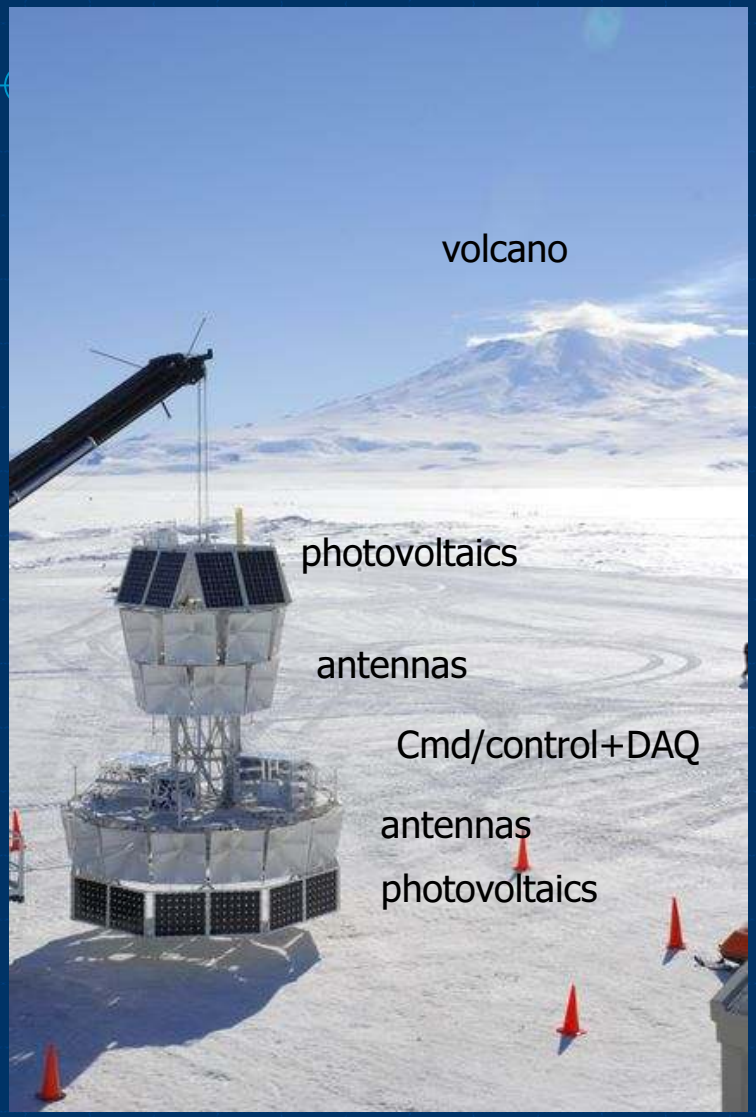
- **SLAC e^- showers with composite energy same as UHE neutrinos**
  - **$10^{8\text{-}9}$ x 28 GeV =2.8 x 10^{19} eV**
- **Coherent radio power, consistent with theory**
- **1st direct observation of radio Cherenkov cone**







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 Launch: December 15, 2006

K. Palladino & D. Saltzberg

Photos: J. Kowalski

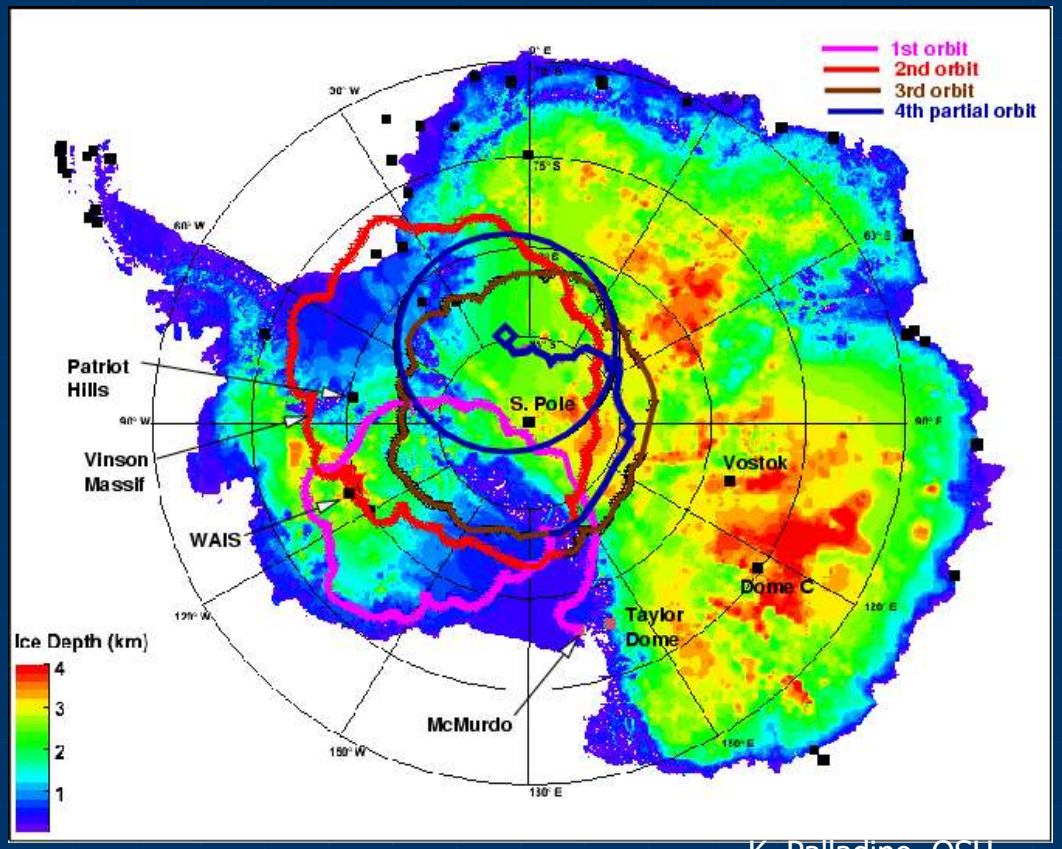
- ANITA at float (123Kft)
  - See through amateur telescope from the South Pole
  - Size of the Rose Bowl (really!)
  - (thanks to James Roth)

Landing…~360 miles from South Pole

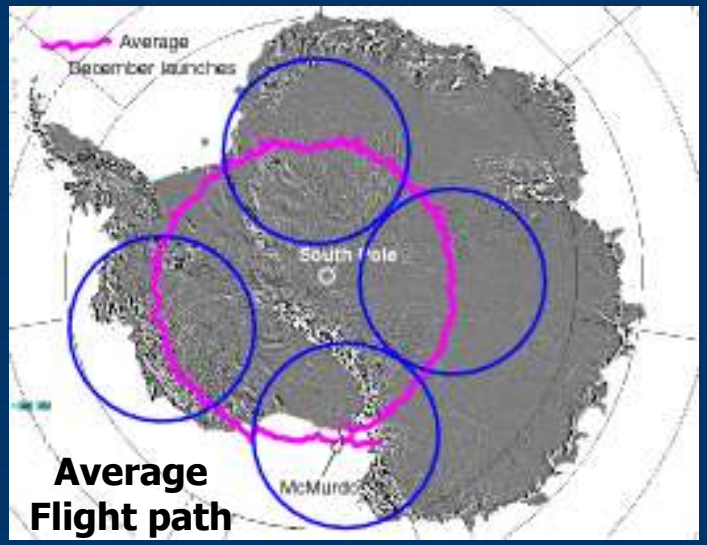
Photos: D. Braun

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

ANITA flight path

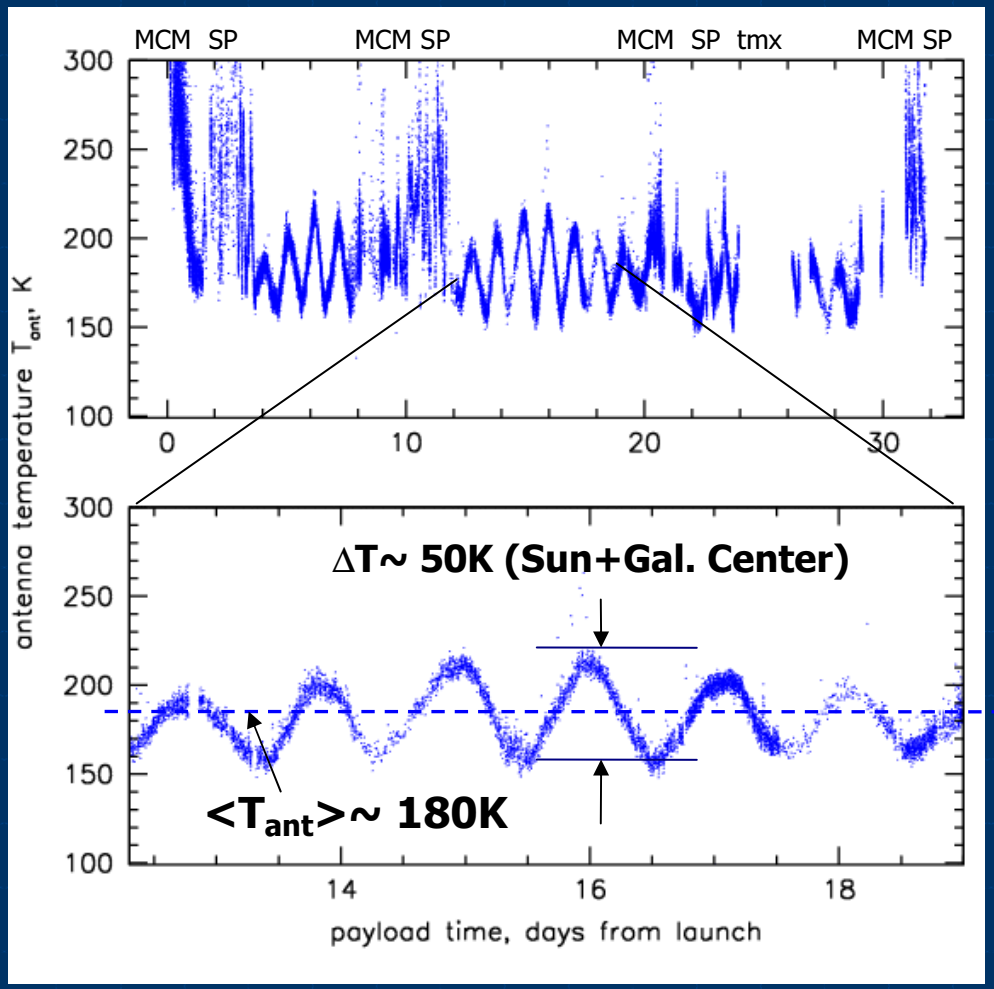


K. Palladino, OSU



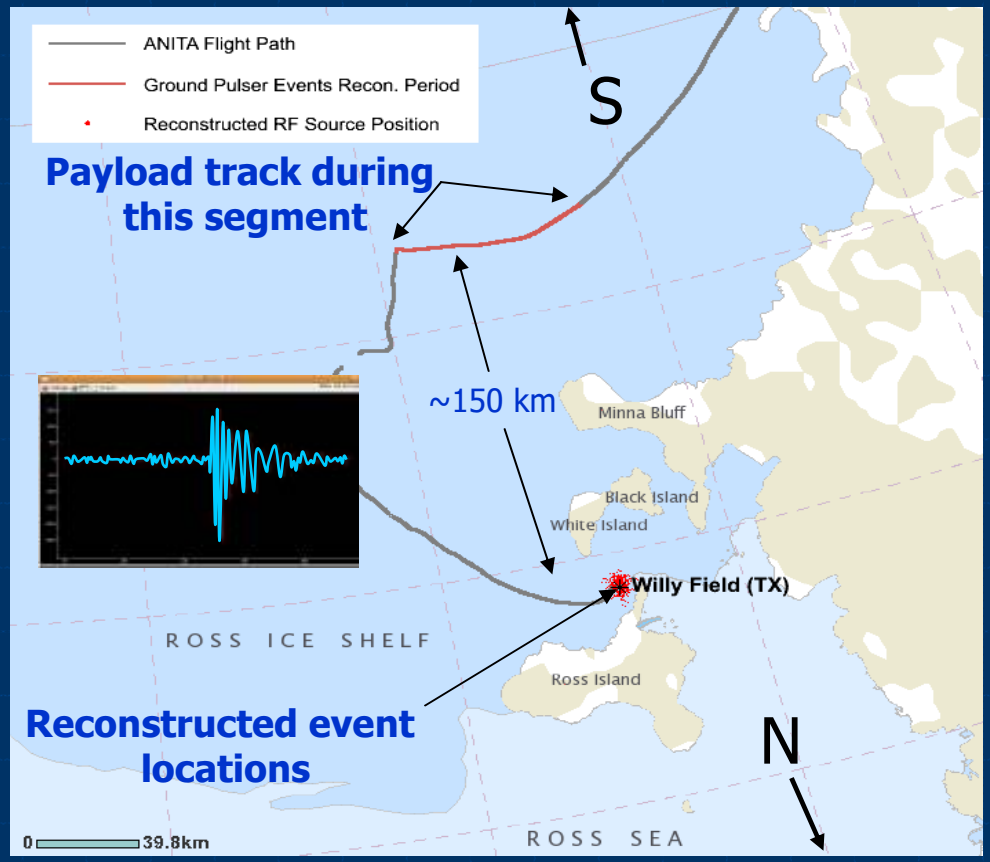
- 35 days, 3.5 orbits, but anomalous Polar Vortex conditions
- Stayed much further "west" than average
- In view of radio noise from stations (S. Pole & MCM) ~50% of time
- But still achieved 18 days of good livetime at ~1.2km average depth of ice

Flight sensitivity snapshot

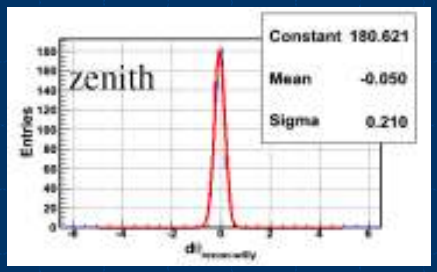


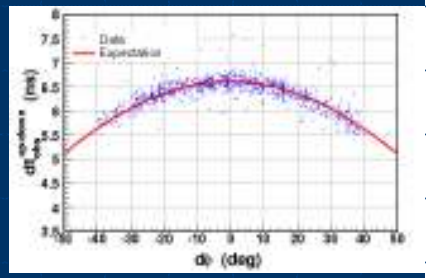
- ANITA sensitivity floor defined by thermal (kT) noise from ice+sky+rcvr
  - T_{rcvr} ~140K
  - T_{ice} ~ 230K
  - T_{sky} ~ 20-80K
- Thermal noise floor seen intermittently throughout of flight—but punctuated by station noise
  - South Pole and McMurdo stations!
- Still a significant fraction (~50-60%)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

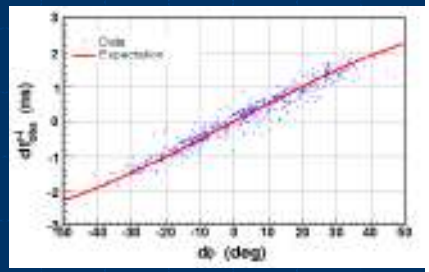
ANITA geo-location of borehole cal events



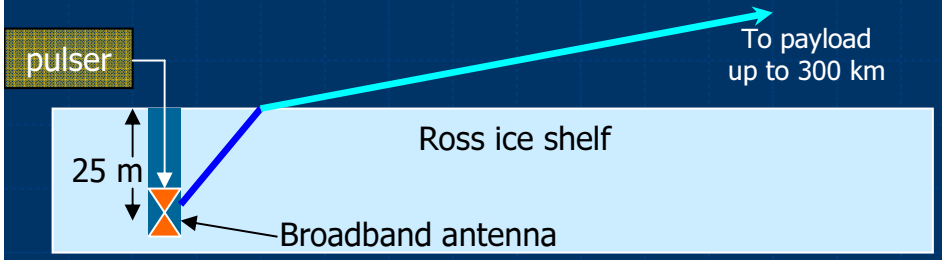
- Expect ~ $c\Delta\tau/2D$ altitude & azimuth
- $\Delta\tau$ ~ 40-60 ps, D ~ 1m (horizontal) to 3 m (vertical)
- Altitude: 0.21° observed, 0.3° expected
- Azimuth: 0.8° observed, 1.7° expected
- Multiple baselines improve constraints
- Pulse-phase interferometry works well!



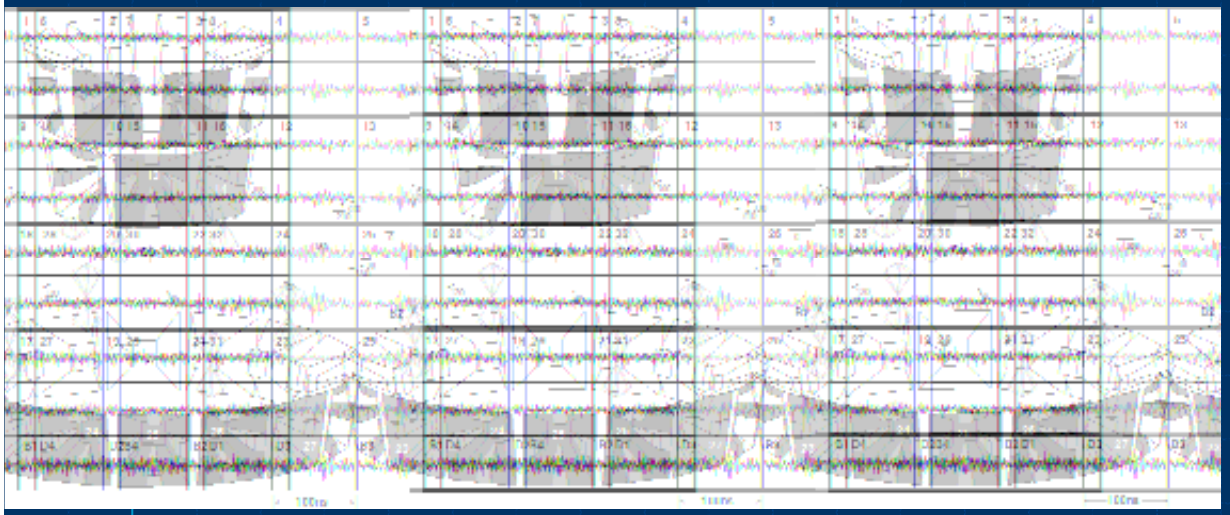


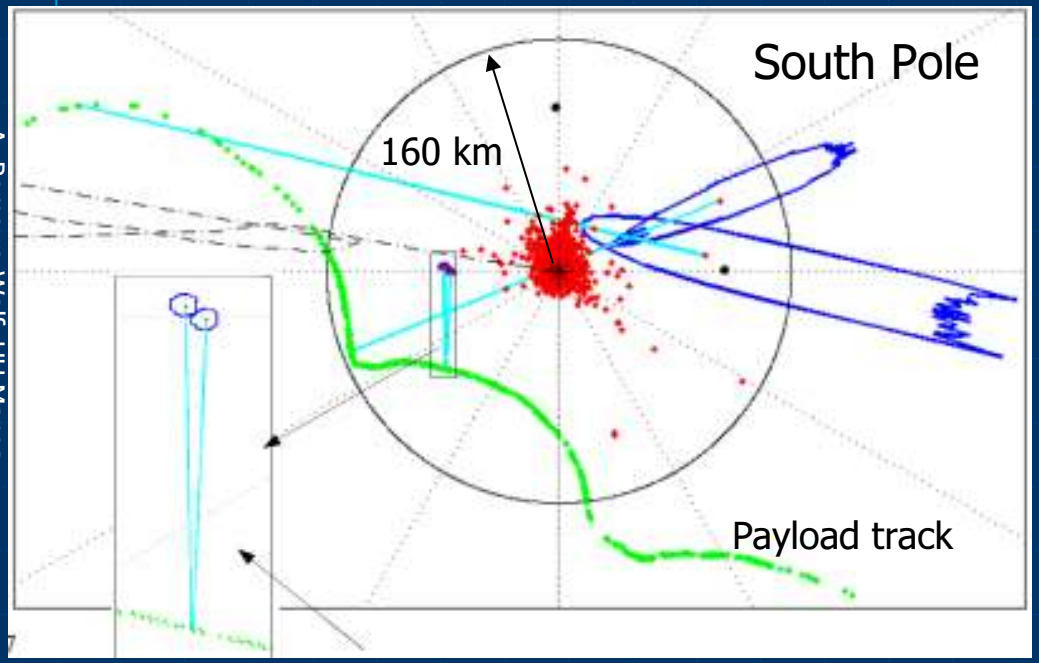


Thanks to JiWoo Nam, NTU



Event reconstruction & analysis

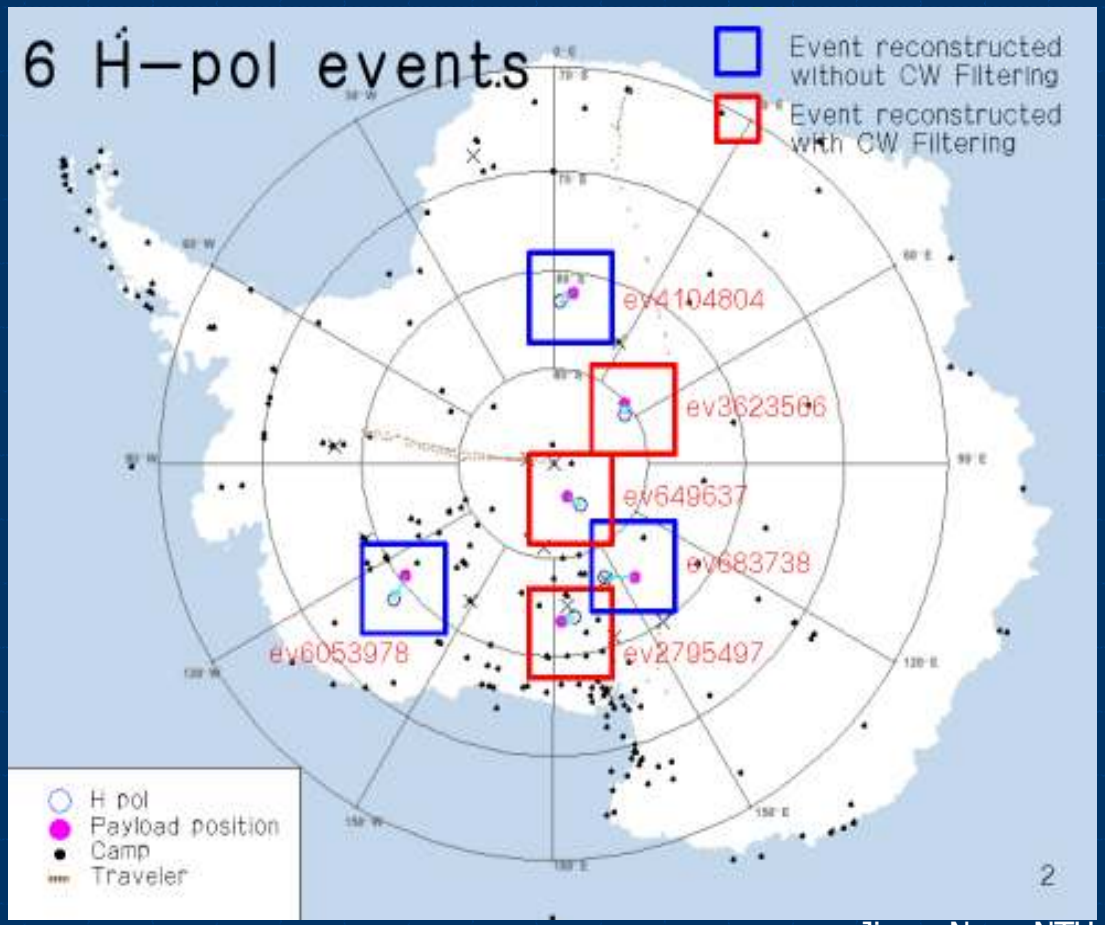




A. Romerro-Wolf, UH Manoa

- Raw data: RF plane-wave lights up one side of payload
- Waveform corrletor (offline) gives 40-60ps timing
- Reconstruct ground position & error ellipse
- If $<3\sigma$ 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

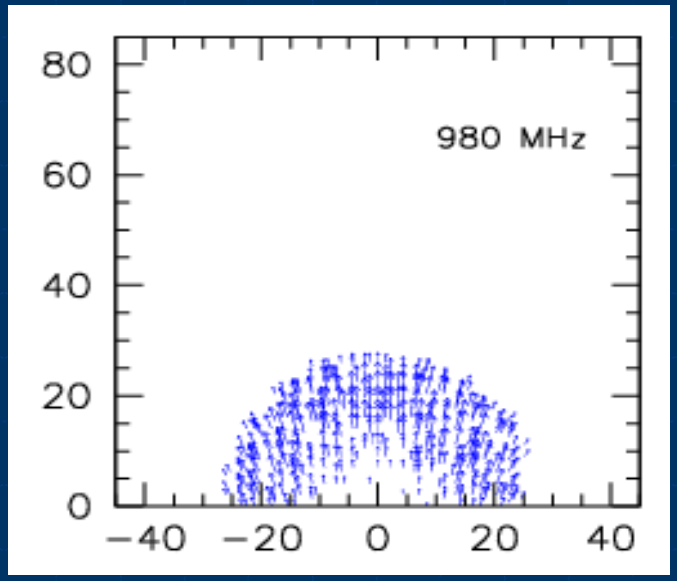


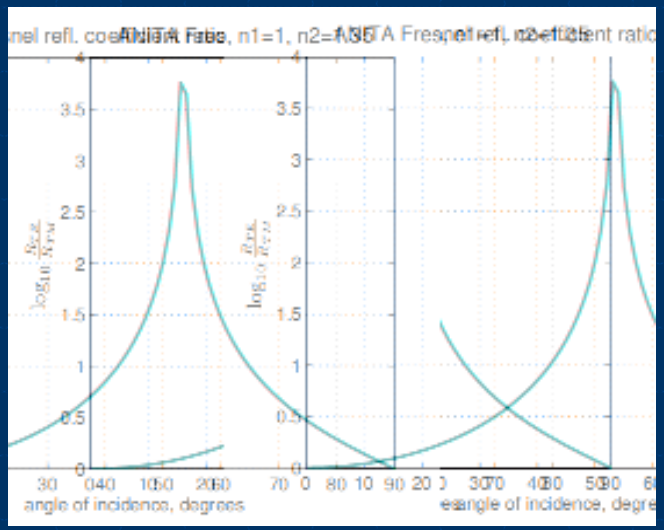
Jiwoo Nam, NTU

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

- ~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

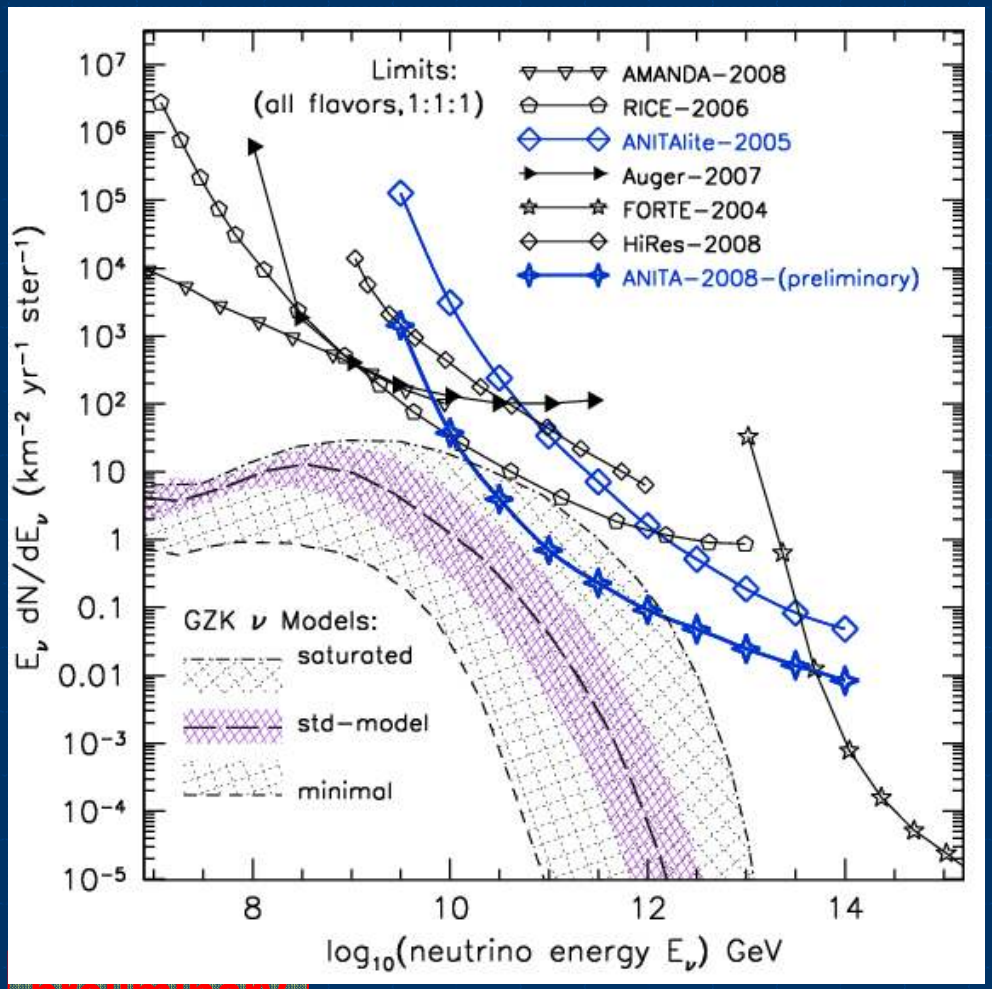
Horizontal Polarization??





- 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

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 (scheduled for Dec. 2008 flight) should reach std-model range

Preliminary lower threshold analysis

Full Data Set.....~8,000,000 events

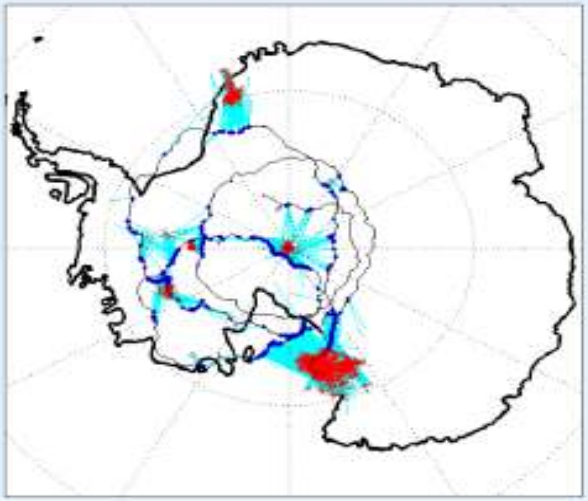
Figure of Merit Cut in Directional Fitting.....69,249 events
(quality of timing alignment)

Misreconstruction Rejection.....45,023 events
(Pointing Consistency Check
with Global Interferometric Image)

Projection onto Antarctica.....44,914 events
Not all events point below the horizon.

Event Clustering Rejection.....14 events
Discard events whose 3σ projected error
ellipses overlap.

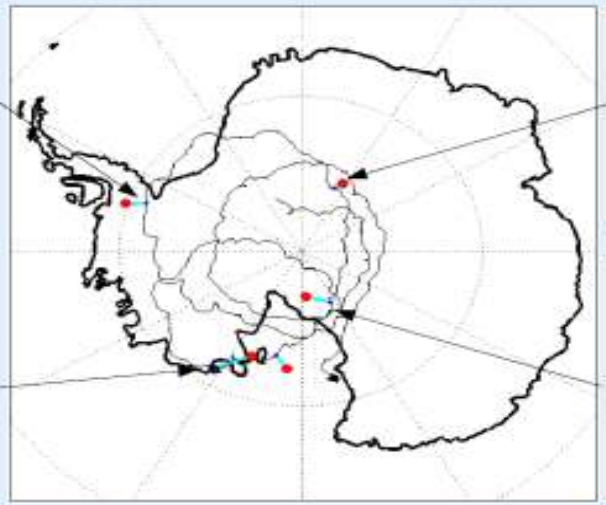
Narrow Band Source Rejection.....5 events
Check for reconstruction and pointing
consistency when bands of common
CW background are filtered out.

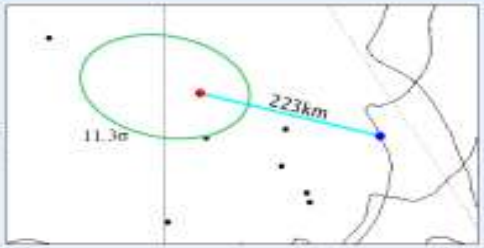


Left: A map of all 44,914 even
that project onto the Antarctic
continent. Regions of human
activity show a clear
concentration of events.

Bottom: Maps of the 5 remaini
events with cataloged position
of bases and traverses.

Legend
- Payload Position
- Connecting Line
- Reconstructed Event Position
- ANITA Flight Path
- Known Base
- Automated Weather Station
- Traverses

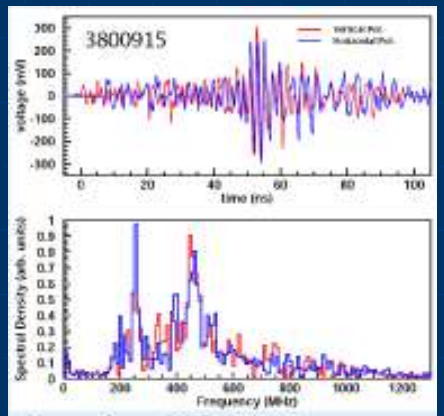




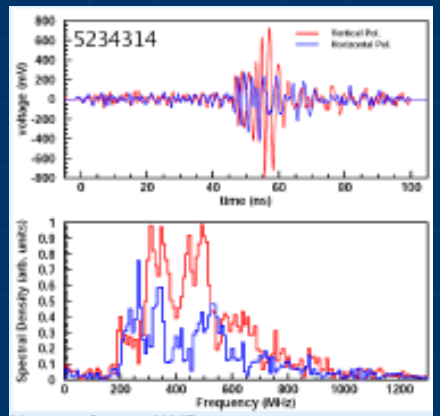
preliminary

Andres Romero-Wolf UH Manoa

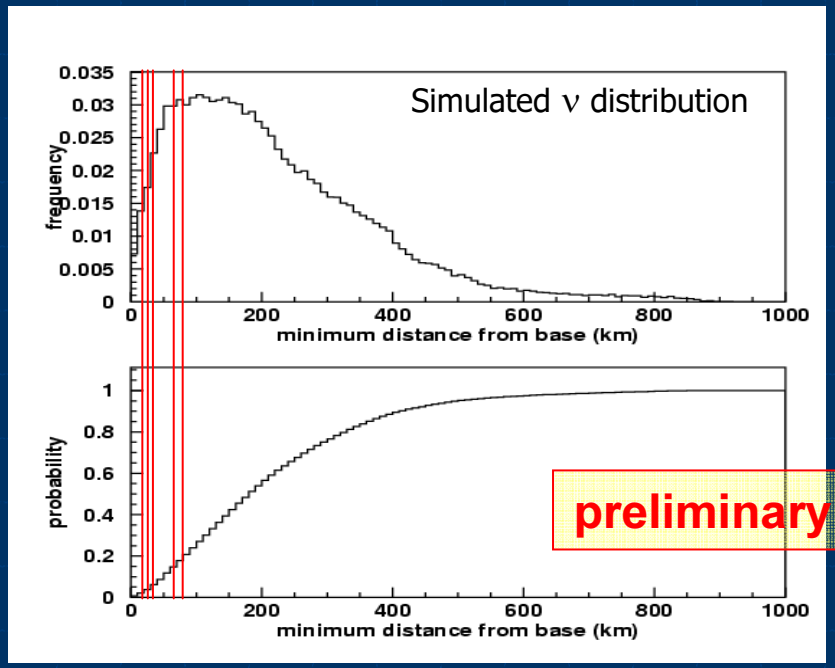
Remaining events

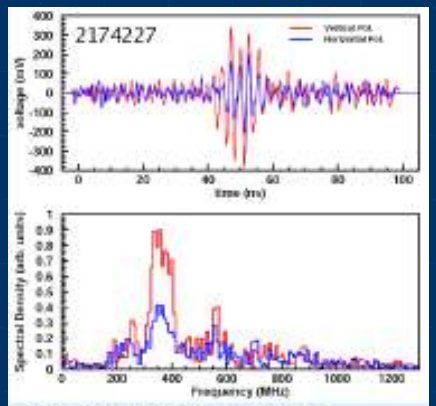


Nearest base: AWS
Distance of Event to Base: 19.6km
Angular distance to base: 10σ

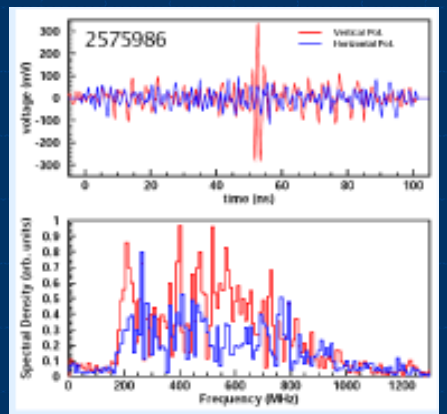


Nearest base: AWS
Distance of Event to Base: 22km
Angular distance to base: 4.4σ

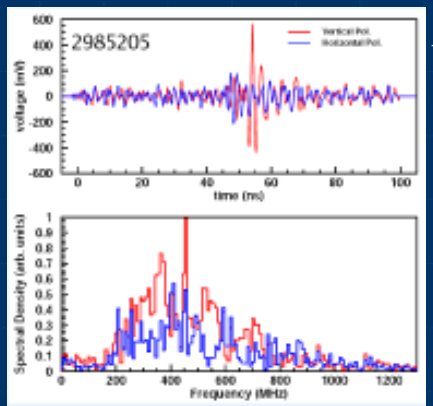




Nearest base: Camp Wisconsin
Distance of Event to Base: 75km
Angular distance to base: 4.8σ



Nearest base: Martha I and II AWS
Distance of Event to Base: 34km
Angular distance to base: 6.9σ

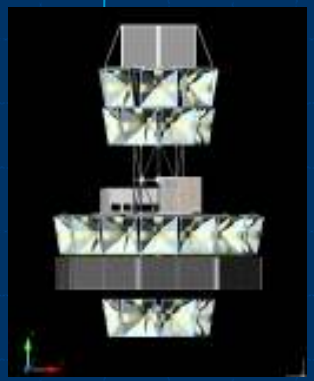


Nearest base: McGregor Glacier Hut
Distance of Event to Base: 65km
Angular distance to base: 11.3σ

- Population consistent with neutrinos?
  - $\sim 10^{-5}$ joint probability➔must be base-related in part
  - RF analysis will probably reject 2-3 of these

Andres Romero-Wolf UH Manoa

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**

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 will be significant, first glimpse still possible
- ANITA-2, 2008: will begin to dig deep into GZK model space