Antarctic Impulsive Transient Antenna

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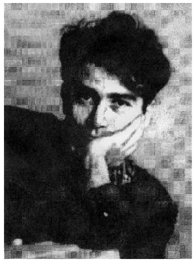
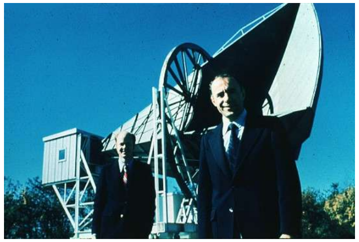
(for the ANITA collaboration)

Outline

- History, GZK cutoff, & neutrinos
- The Askaryan effect
- Radio Antarctica
- ANITA prototype: ANITA-lite
- Plans & prospects

Science roots: the 60's





Four crucial events from the 1960's

- **1961: First 10^{20} eV cosmic ray air shower observed**
  - John Linsley, Volcano Ranch, Utah
- **1962: G. Askaryan predicts coherent radio Cherenkov from showers**
  - His applications? Ultra-high energy cosmic rays & neutrinos

3. **1965: Penzias & Wilson discover the 3K echo of the Big Bang**
  - (while looking for bird dung in their radio antenna)

- **1966: Cosmic ray spectral cutoff at $10^{19.5}$ eV predicted**
  - K. Greisen (US) & Zatsepin & Kuzmin (Russia), independently
  - Cosmic ray spectrum *must end* close to ~10^{20} eV

$p, \gamma + \gamma(3K) \longrightarrow$ pions, e+e- $\downarrow$ GZK neutrinos

"GZK cutoff " process

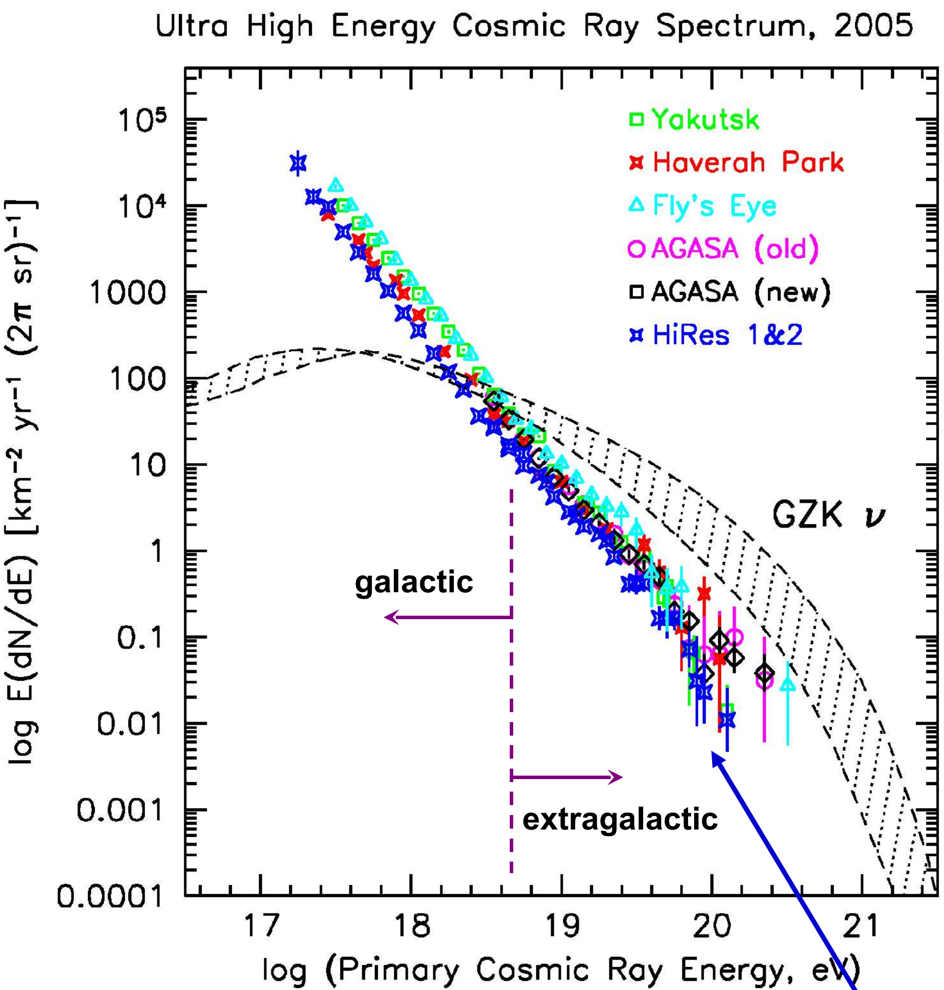
END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

(Ultra-)High Energy Physics of Cosmic rays & Neutrinos

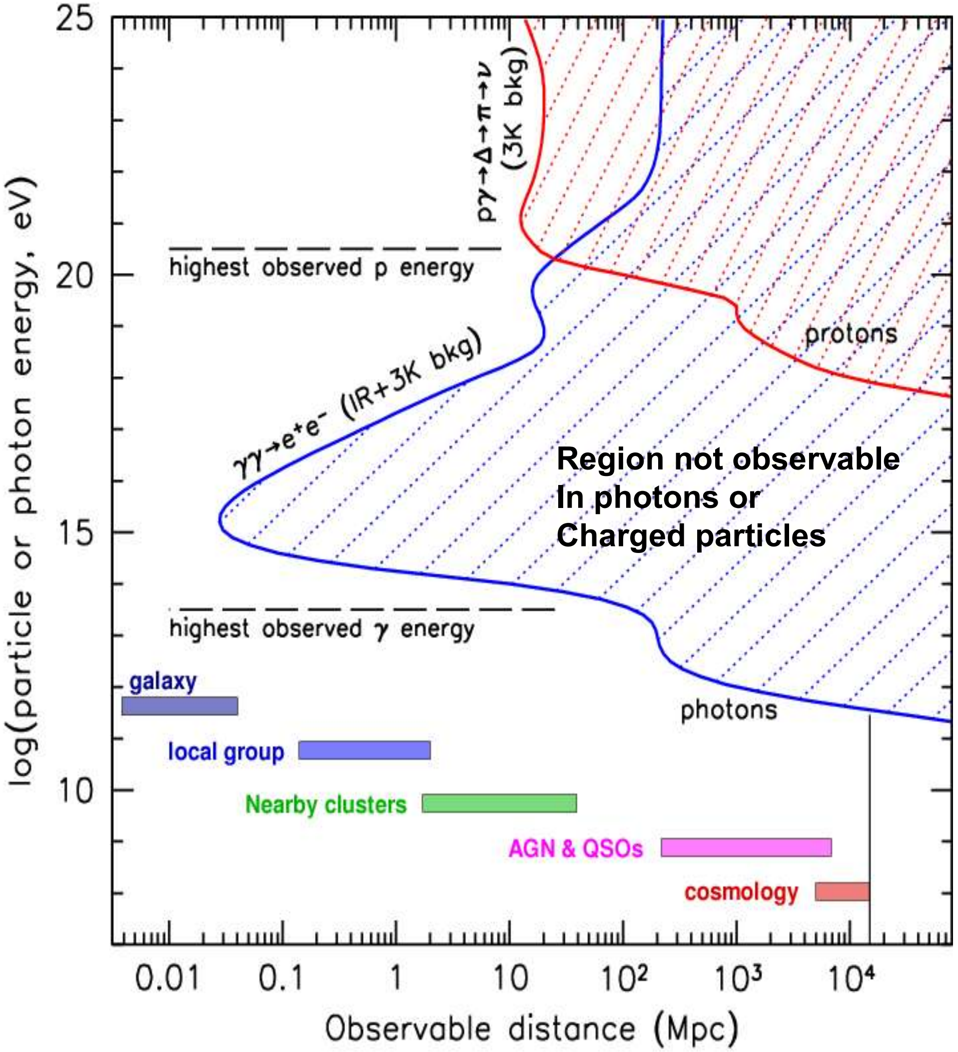
- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV
- A paradox:
  - No *nearby* sources observed
  - distant sources *excluded* due to GZK process
- **Neutrinos** at $10^{17\text{-}19}$ eV **required** by standard-model physics* through the GZK process--observing them is crucial to resolving the GZK paradox



10^7 times Tevatron

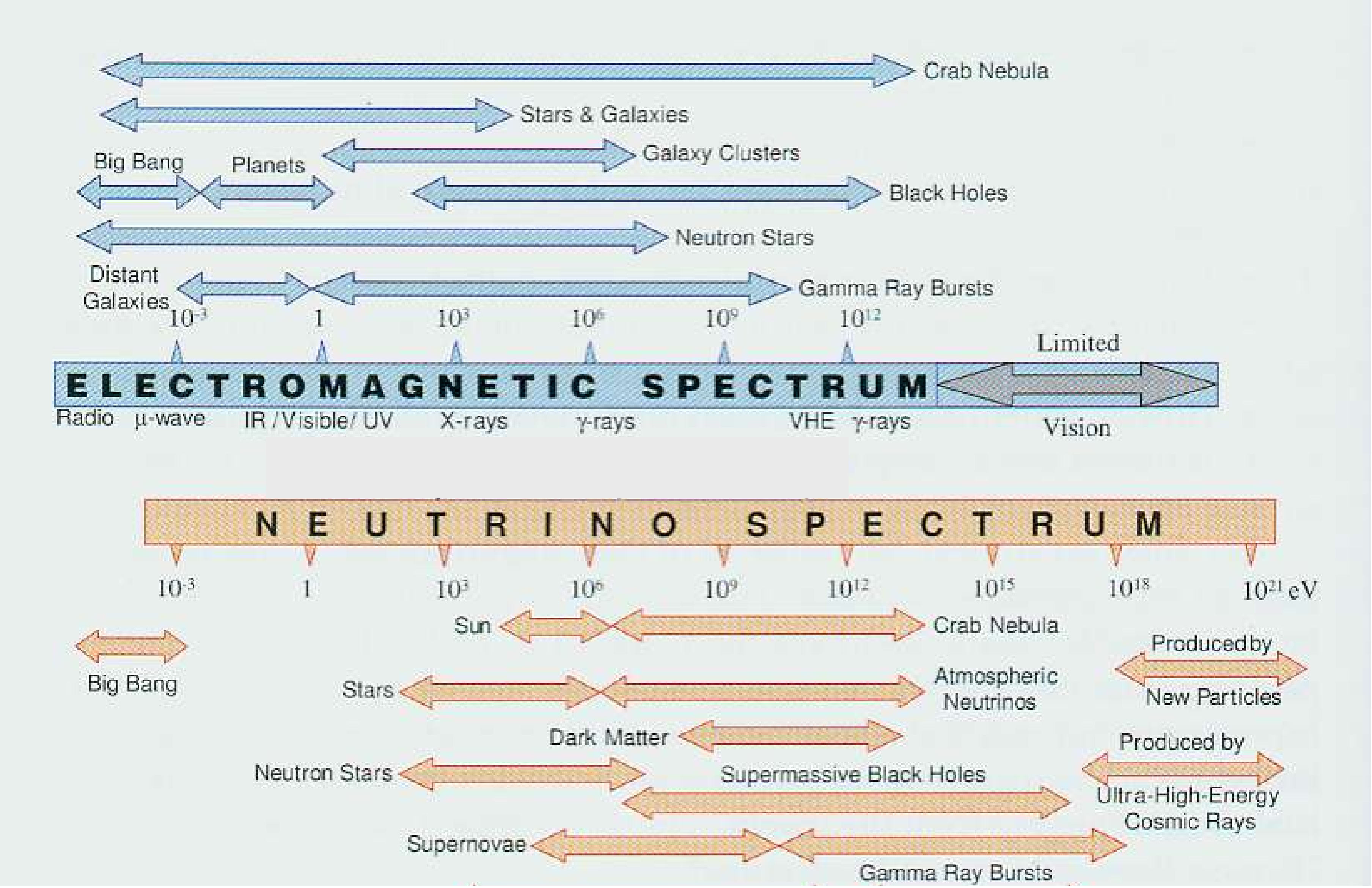
* Berezinsky et al. 1971.

Neutrinos: The only known messengers at PeV energies and above



- **Photons lost above 30 TeV:** pair production on IR & μwave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- Sources extend to 10^9 TeV !
- => Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors
- To **guarantee** EeV neutrino detection, **design for the GZK neutrino flux**

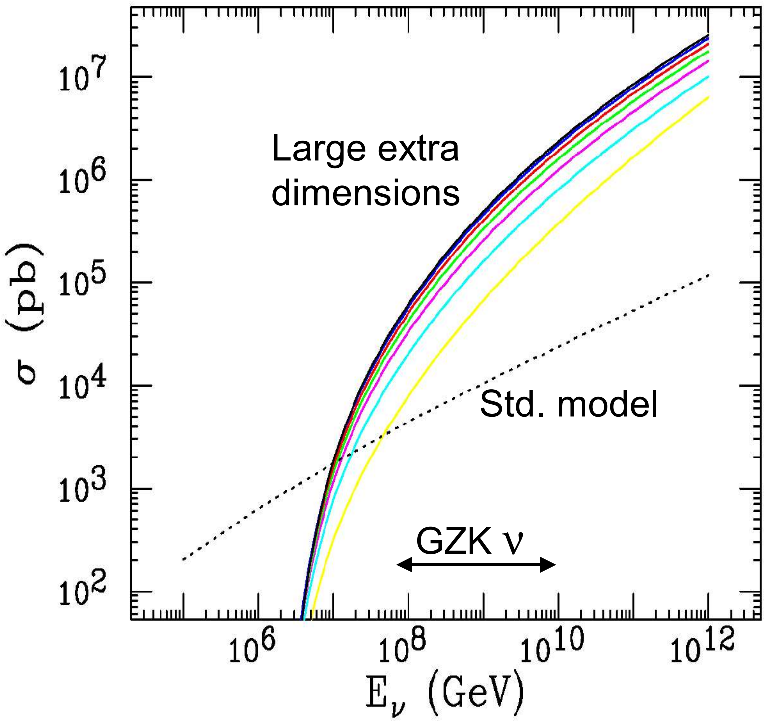
More Neutrino Propaganda



Particle Physics: Energy Frontier & Neutrinos

- Well-determined GZK ν spectrum becomes a useful beam
  - 10-300 TeV center of momentum particle physics
  - study large extra dimensions at scales beyond reach of LHC
  - ν Lorentz factors of γ=$10^{18\text{-}21}$!

- Measured flavor ratios ν_e:ν_μ:ν_τ
  - identify non-standard physics at source
  - Sensitive to sterile ν admixtures & anomalous ν decays



Anchordoqui et al. Astro-ph/0307228

GZK ν Particle Astrophysics/Cosmology

- Cosmic ray E_{max}, the maximum acceleration energy
- UHECR flux vs. redshift to z = 15-20 (eg. WMAP early bright phase,)
- Independent sensitivity to dark energy density
- Exotic (eg. Top-down) sources; GUT-scale decaying relics

What is needed for a GZK ν detector?

- Standard model GZK ν flux: <1 per km^2 per day over 2π sr

- Interaction probability per km of water = 0.2%

- Derived rate of order 0.5 event per year per cubic km of water or ice

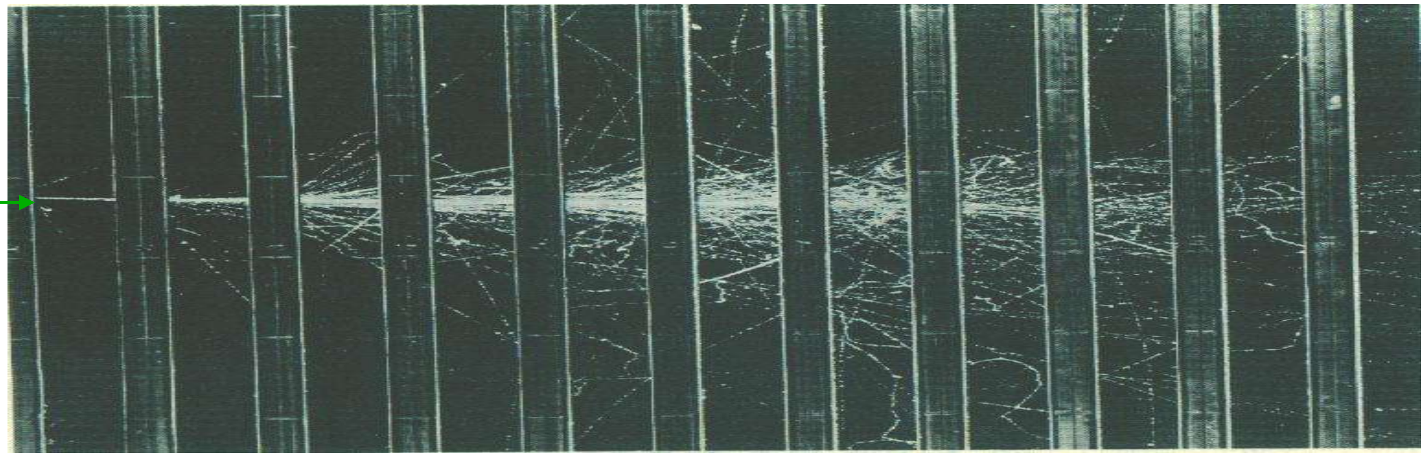
  ➔ **A teraton (1000 km^3 sr) target is required!**

- **Problem: how to scale up from current water Cerenkov detectors**

The Askaryan Effect

- In 1962 Gurgen Askaryan hypothesized coherent radio transmission from high energy showers in dielectric media.

UHE e^-



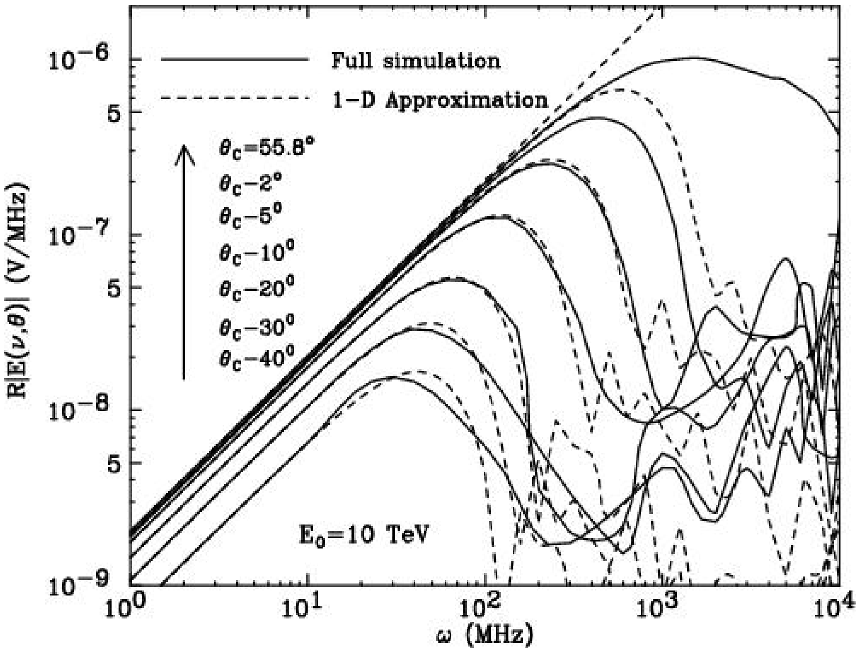
- A negative charge excess (~20%) develops:
  - Compton scattering: $\gamma + e^-(\text{at rest}) \rightarrow \gamma + e^-$
  - Positron Annihilation: $e^+ + e^-(\text{at rest}) \rightarrow \gamma + \gamma$
- Excess moving $v > c/n$ in matter
  - Cerenkov Radiation: $dP \propto \nu \, d\nu$
- If $\lambda > R \rightarrow$ Coherent emission $P \sim E_{SH}^2$

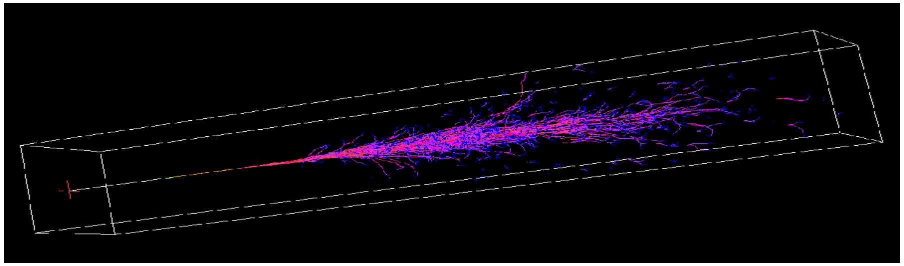
Shower with macroscopic size:

$R_{Moliere} \approx 10$ cm

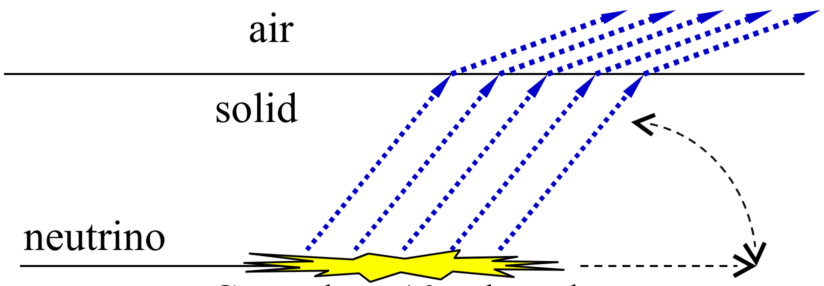
$L \sim$ meters

More on Askaryan Effect



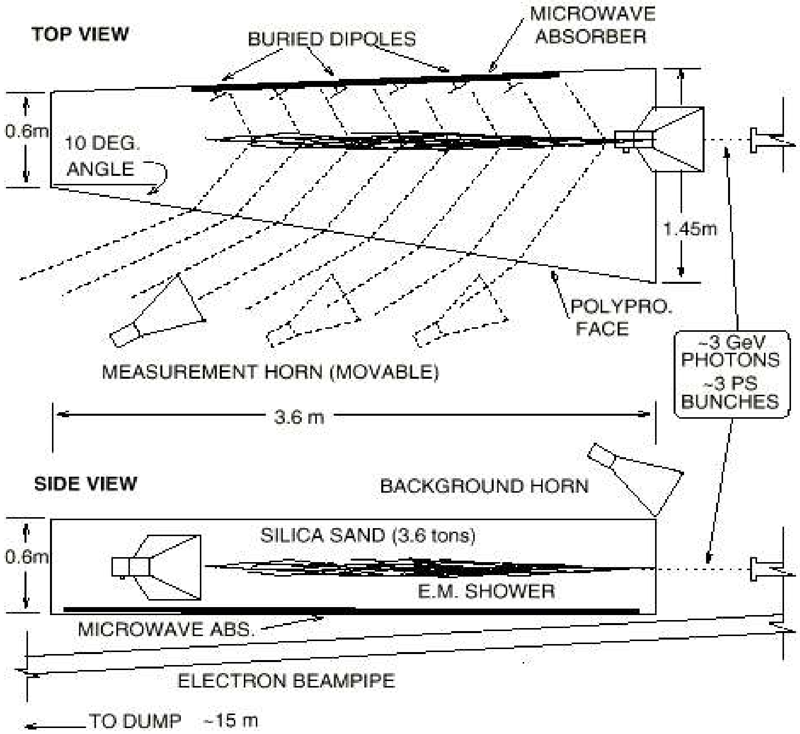


- **Ice**: n = 1.78 in radio,
  - $\cos^{-1}(1/n) = 56^o$
- **Halite (rock salt):** n=2.45 in radio,
  - $\cos^{-1}(1/n) = 66^o$
- RF Cerenkov cone: propagates through solid, refracts at interface

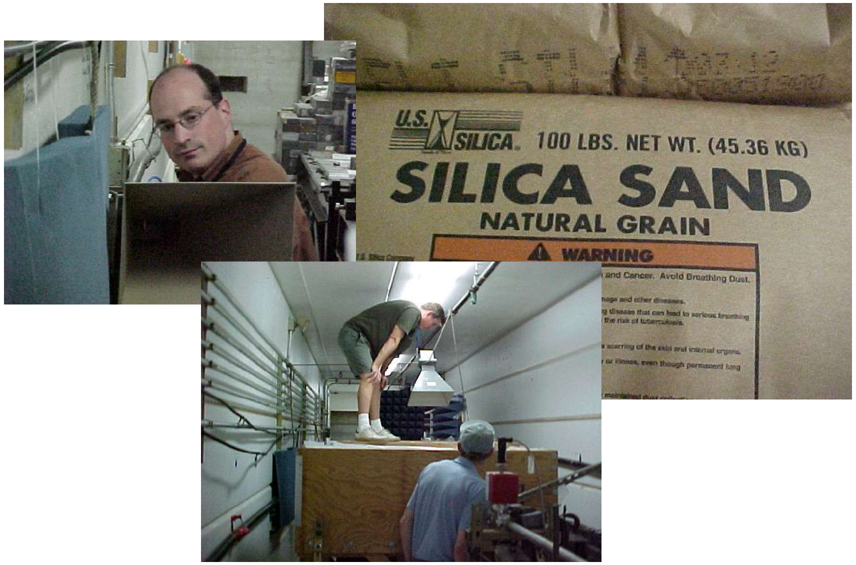


- Linearly polarized plane wave
- Field strength increases with frequency (Cerenkov) until coherence begins to be lost
  - In ice the peak frequency occurs at ~ 2 GHz

Askaryan Confirmation: SLAC T444 (2000)

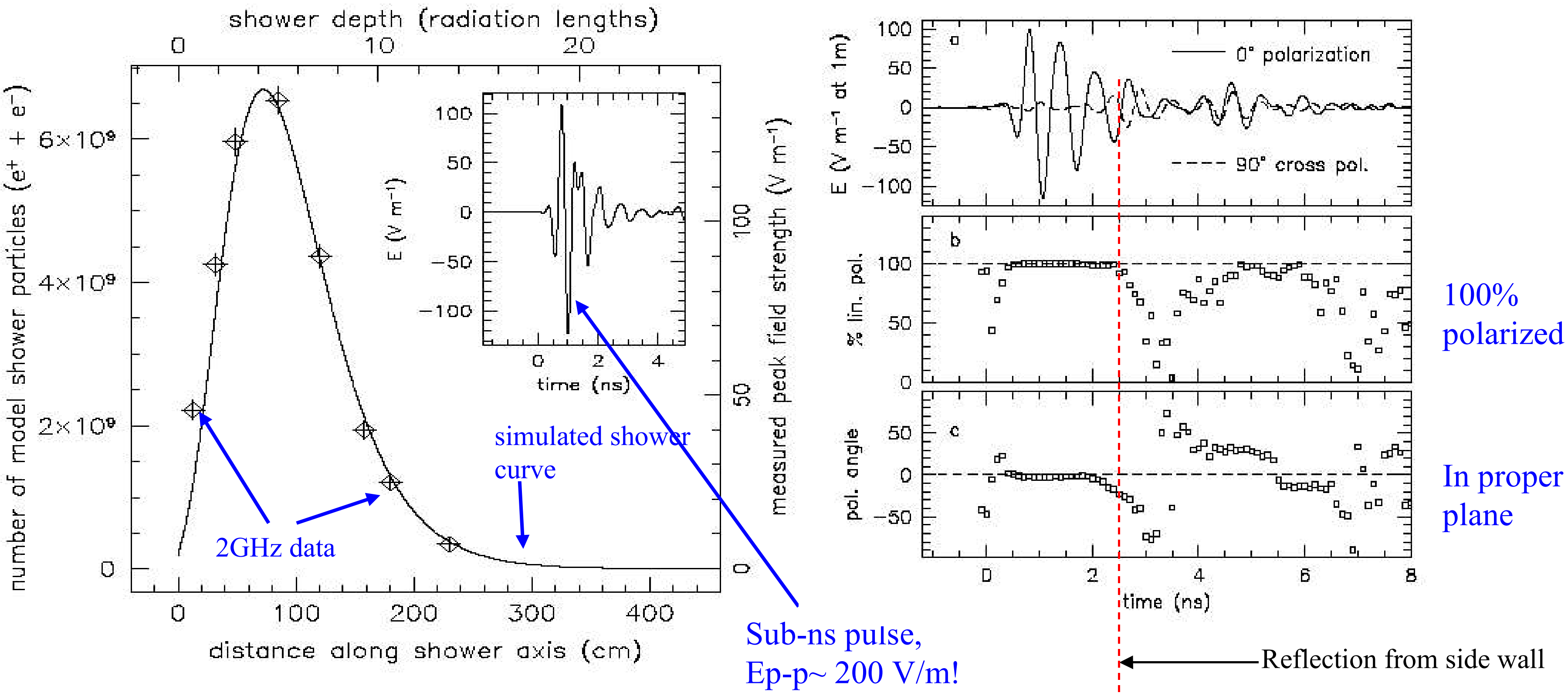


From Saltzberg, Gorham, Walz et al PRL 2001



- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> avoid RF transition radiation
- RF backgrounds carefully monitored
  - but signals were much stronger!

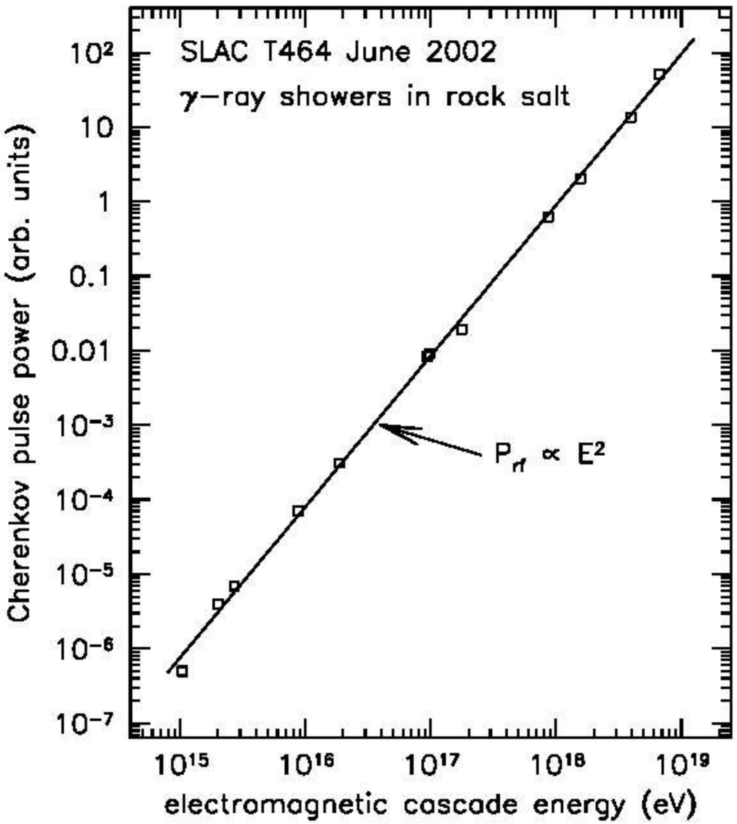
Shower profile observed by radio@2GHz



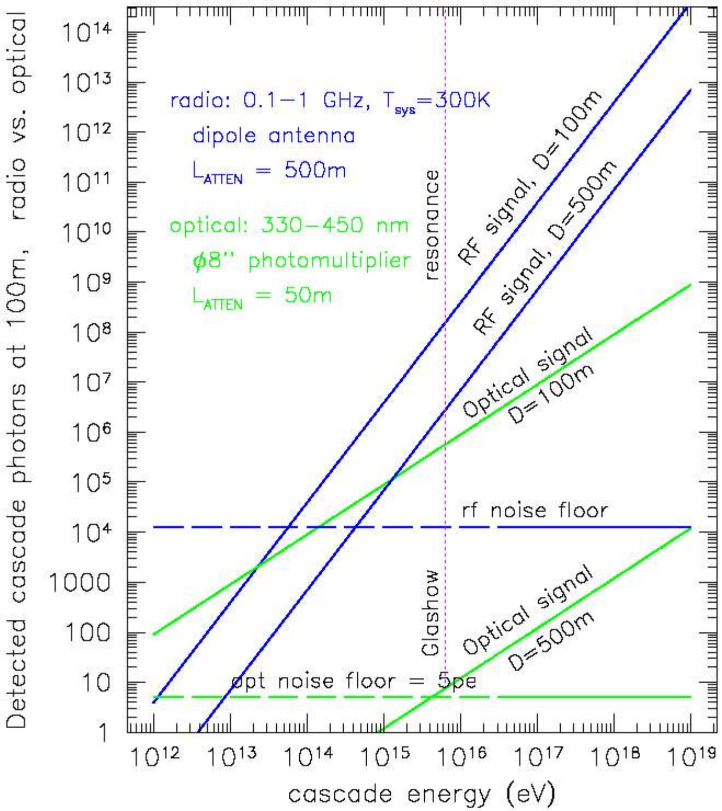
- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- **Polarization** completely consistent with Cerenkov—**can track particle source**

Where does Askaryan win?

- Huge dynamic range



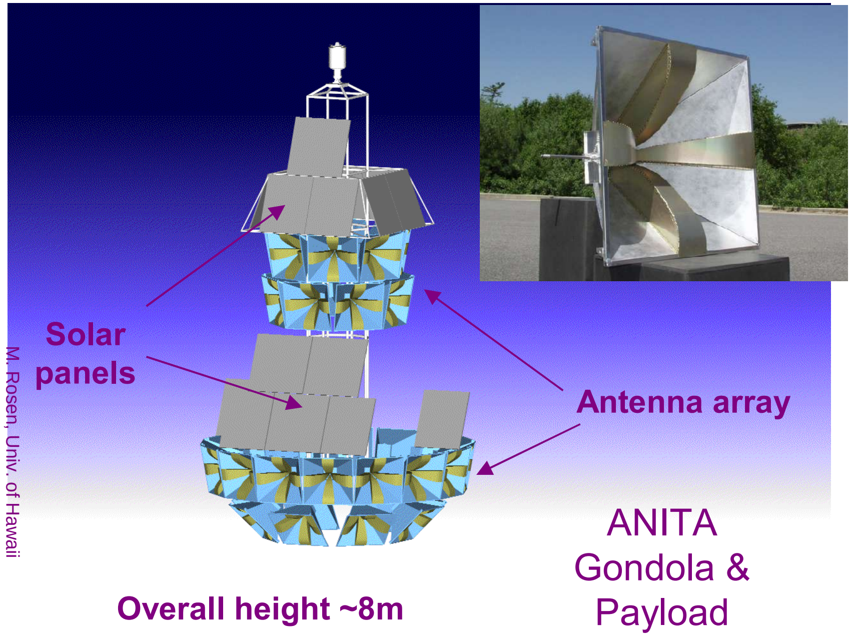
- SNR dominant for E > 10 PeV

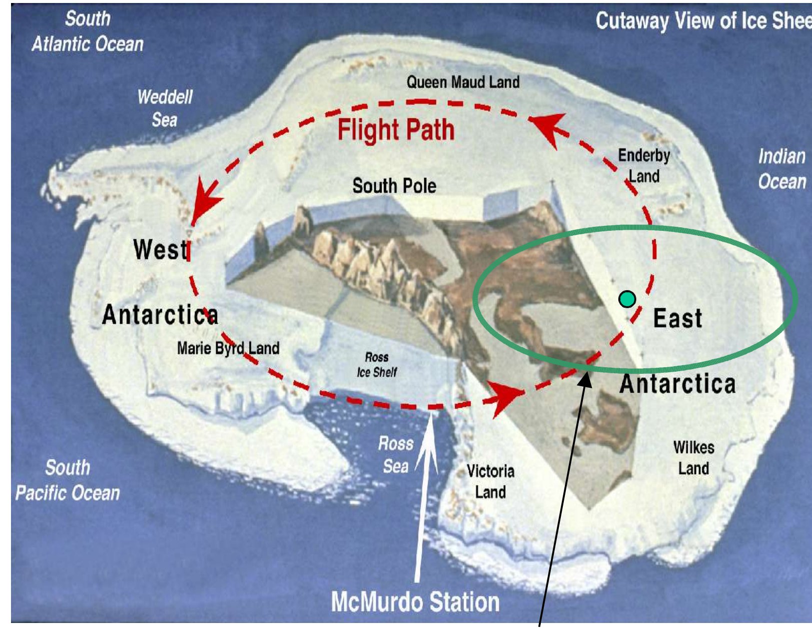


Design for GZK ν flux

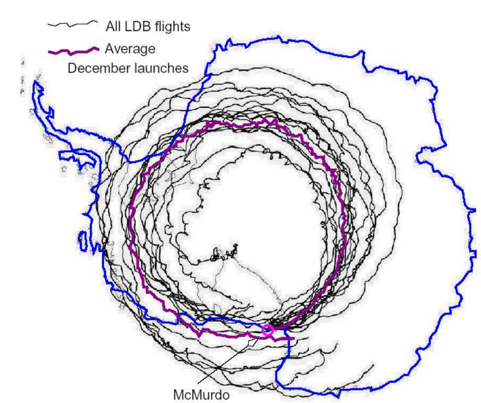
- Huge Volume of solid medium: Antarctic Ice
- Broadband antennas & low noise amplifiers to watch it
- A very high vantage point, but not too high or too far away
- The end result: ANITA

Antarctic Impulsive Transient Antenna





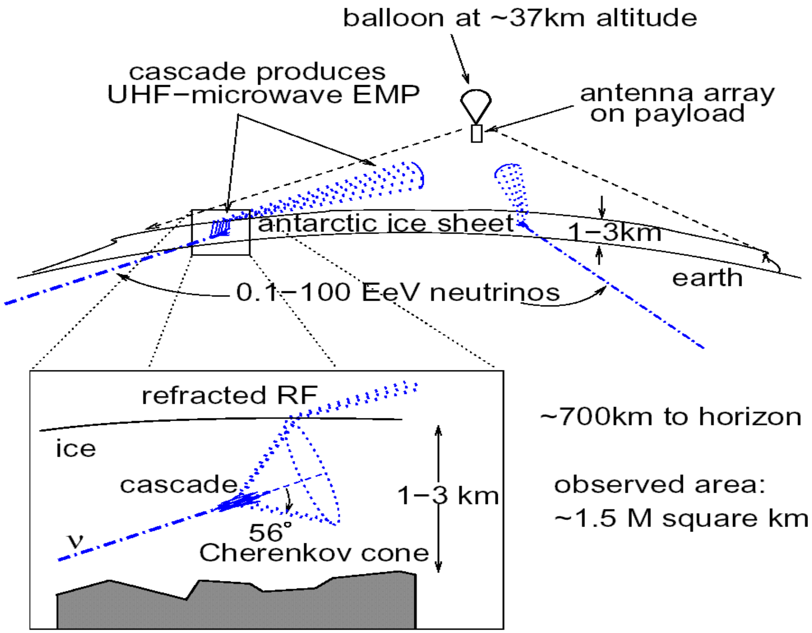
Instantaneous balloon field of view

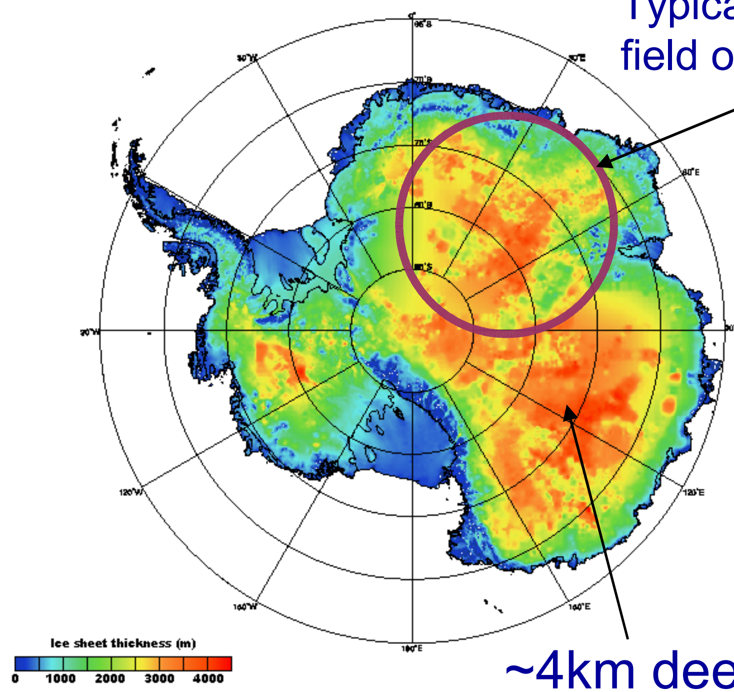


- NASA SR&T start in 2003
- launch in ‘06-07, every two years after

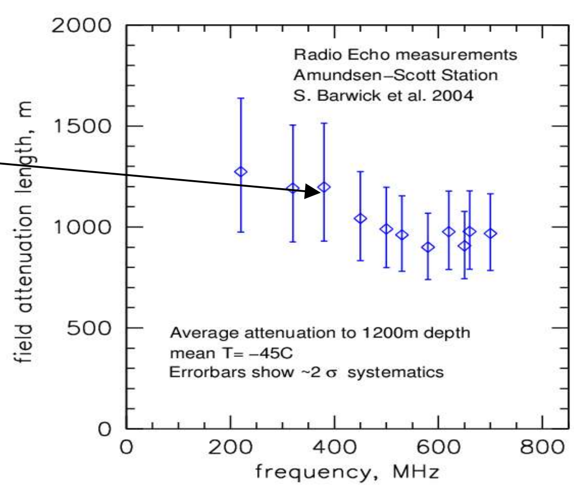
- UH (P. Gorham, C. Hebert, J. Learned, J. Link, S. Matsuno, P. Miocinovic, M. Rosen, B. Stokes, G. Varner), UCI (S. Barwick, J. Nam), JPL (K. Liewer, C. Naudet), Ohio State U. (J. Beatty, B. Mercurio, R. Nichol, K. Palladino), U. Del. (D. Seckel, J. Clem), UCLA (D. Saltzberg, A. Connolly), U.Minn. (M. DuVernois), Univ. Kansas (D. Besson)

ANITA concept





Ice RF clarity: ~1.2km(!) attenuation length

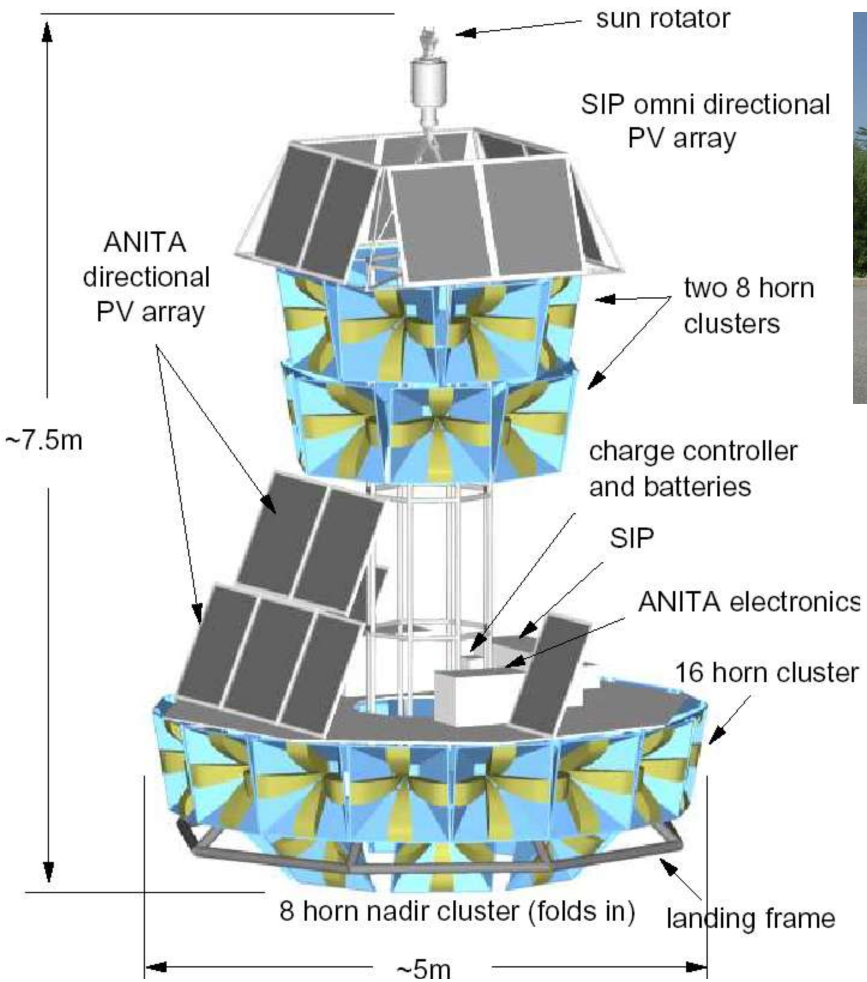


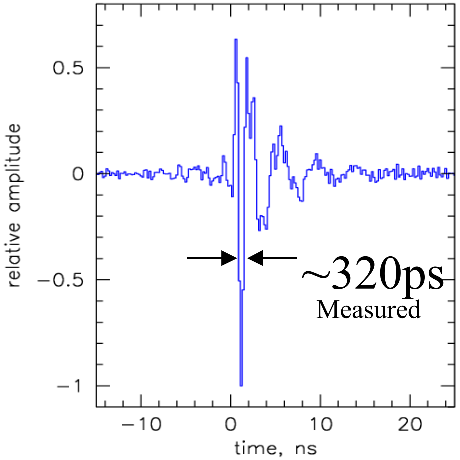
Effective "telescope" aperture:

- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

(compare to ~1 km^3 at lower E)

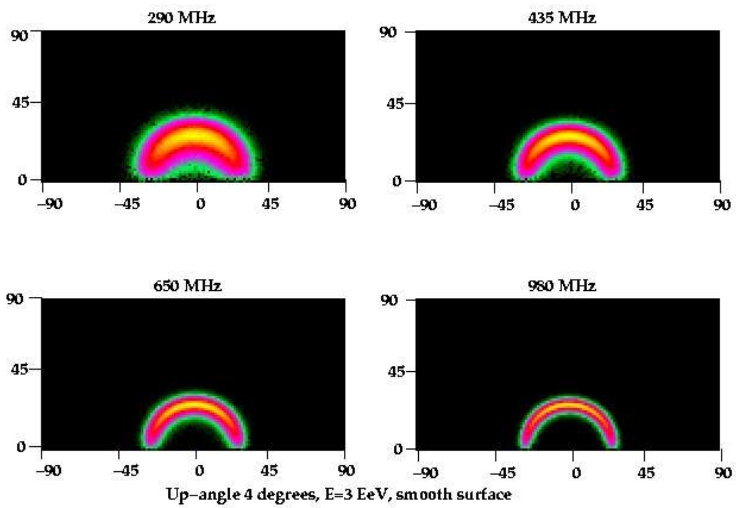
Flight Payload Design

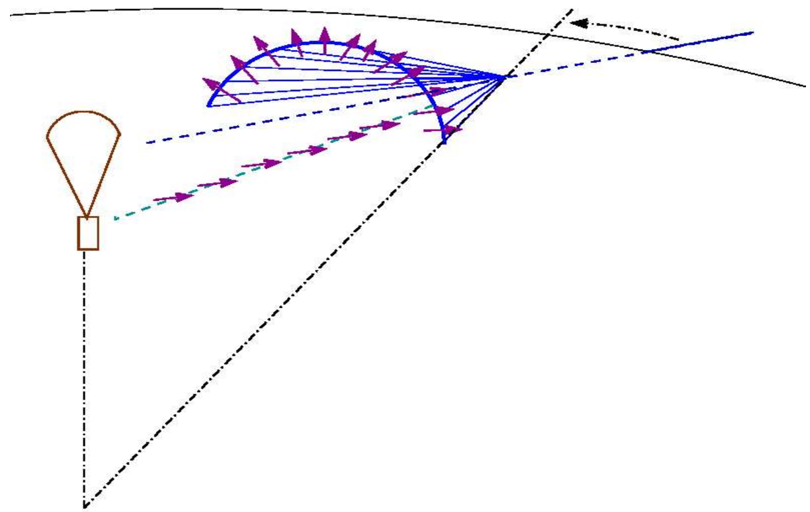


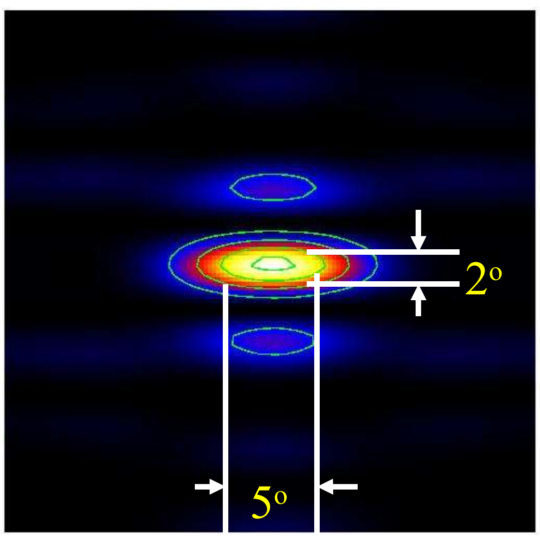


- Quad-ridged horn antennas provide superb impulse response & bandwidth
- Interferometry & beam gradiometry from multiple overlapped antenna measurements

ANITA as a neutrino telescope

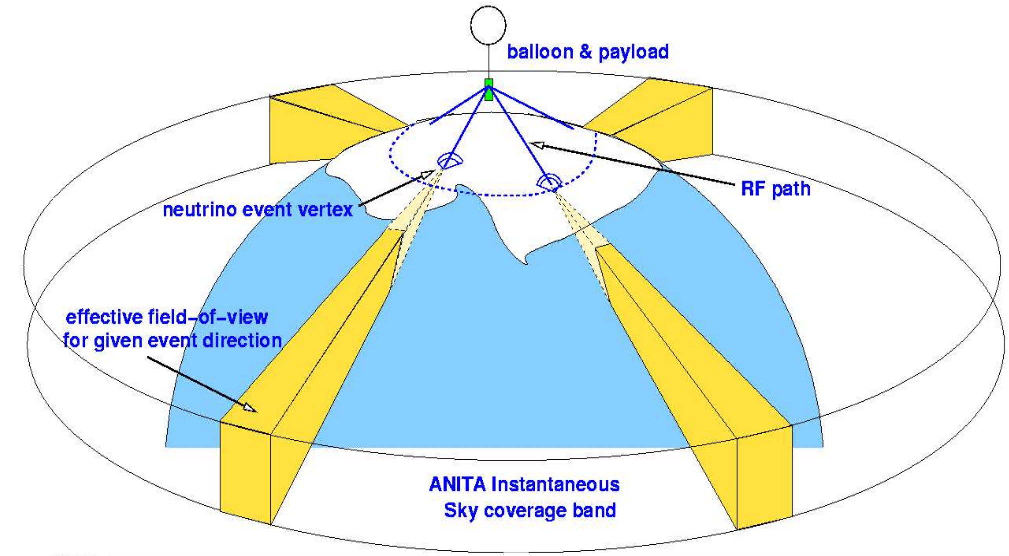


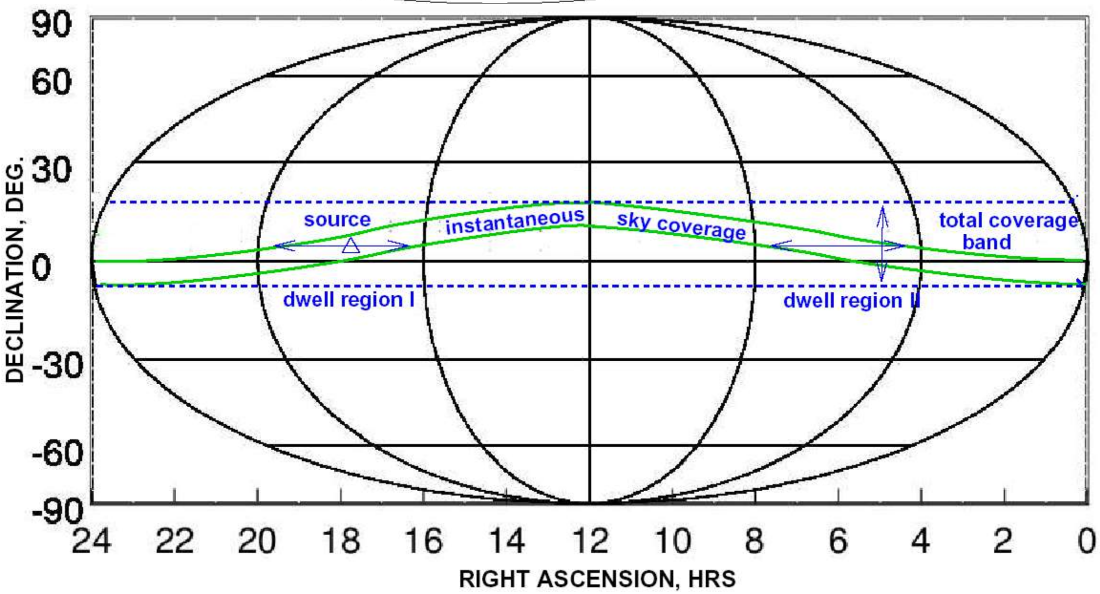


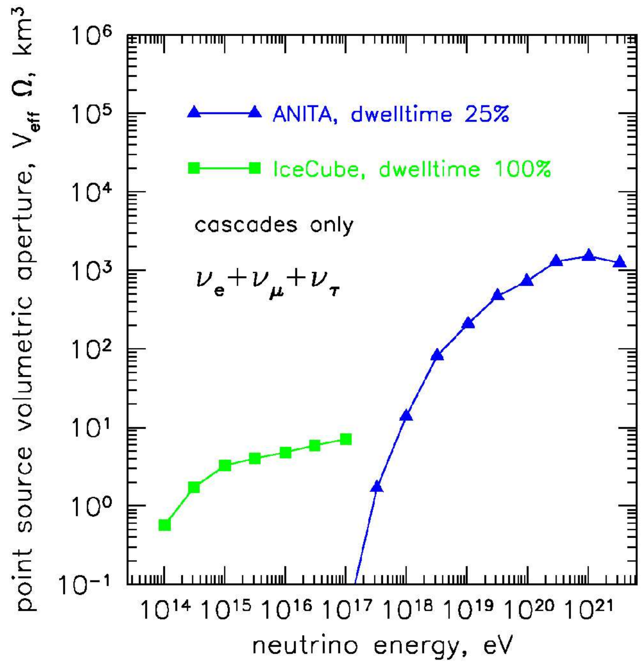


- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

Sky Coverage







- The aperture for point sources is less than that for diffuse sources due to beam size and dwell time.

ANITA as a Calorimeter

- The observed voltage V_{obs} is proportional to the neutrino energy E_ν:

$$V_{obs} \sim E_\nu \, y \, h_{eff} \, R^{-1} \exp\left(-\frac{\beta^2}{2\sigma_{\beta^2}} - \alpha d \right)$$

y is the fraction of neutrino energy in the cascade

h_{eff} is the effective height of the antenna (gain)

R is the range to the cascade

Gaussian in β from observer position on Cerenkov cone

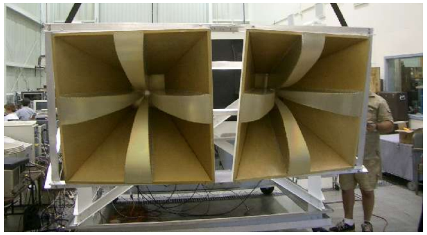
(estimated from RF spectrum)

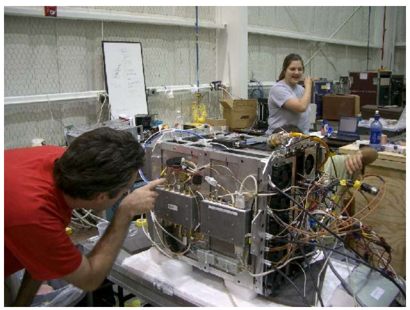
Exponential is attenuation in ice at depth *d*.

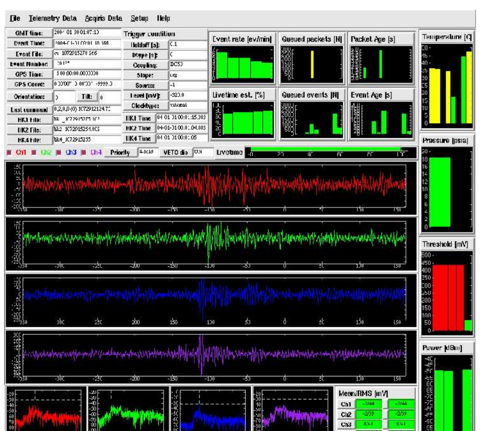
(estimated from RF spectrum and polarization effects)

Gives: $\Delta E_\nu / E_\nu \sim 1.9$ (60% of which is intrinsic from y)

ANITA-lite Prototype flight



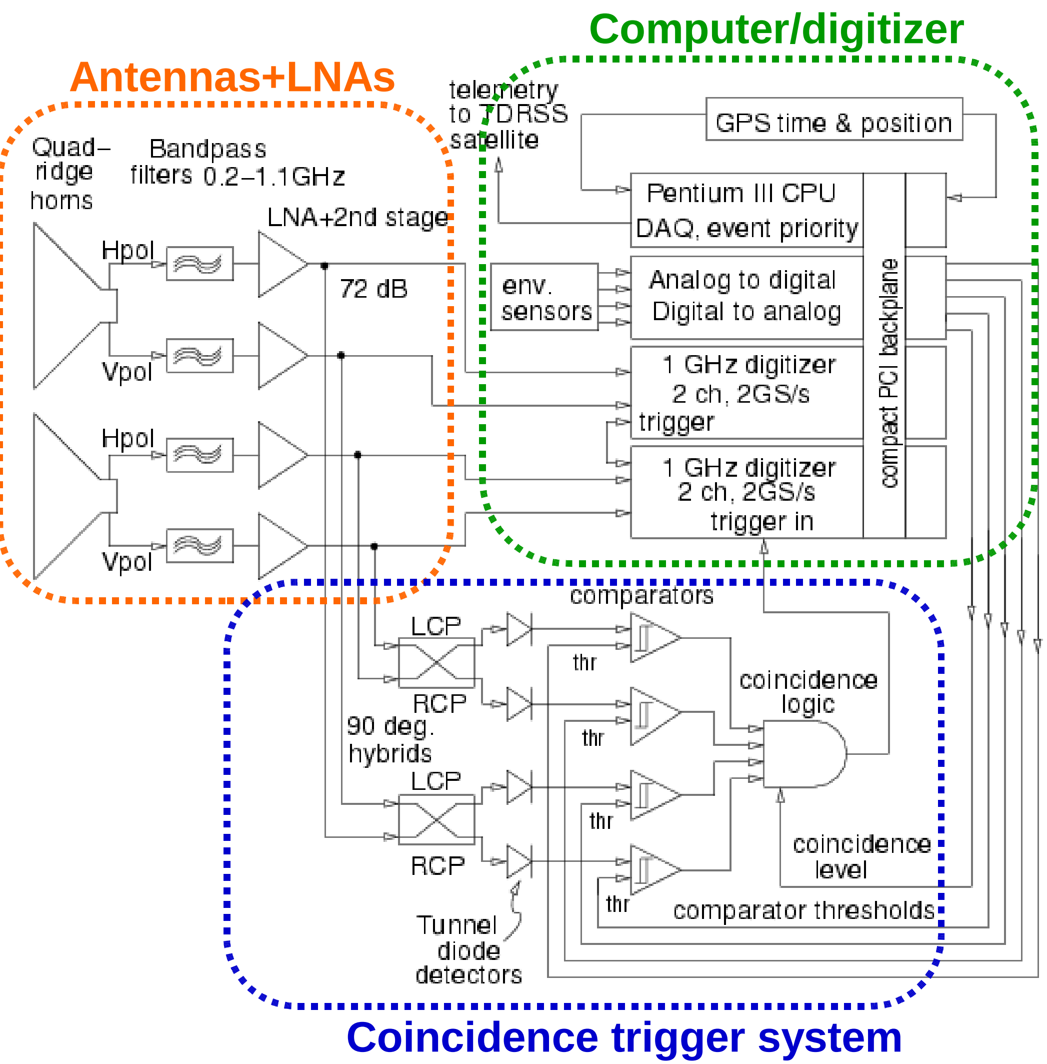




- Piggyback Mission of Opportunity on the 03-04 TIGER* flight, completed mid-January 04
- ANITA prototypes & off-the-shelf hardware used
  - 2 dual-pol. ANITA antennas w/ low-noise amps
  - 4 channels at 1 GHz RF bandwidth, 2 GHz sampling
- 18.4 days flight time, 40% net livetime due to slow (4sec per event) GPS time readout
- “Heartbeat” event rate of several per minute, with~100K events recorded:
  - payload generated EMI + thermal noise + calibration triggers + forced/timeout triggers

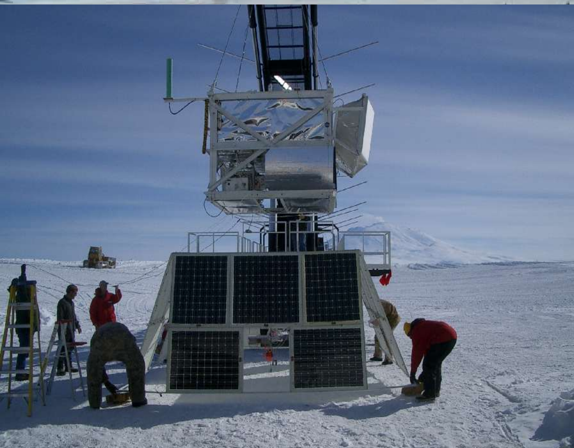
*Trans-Iron Galactic Element Recorder

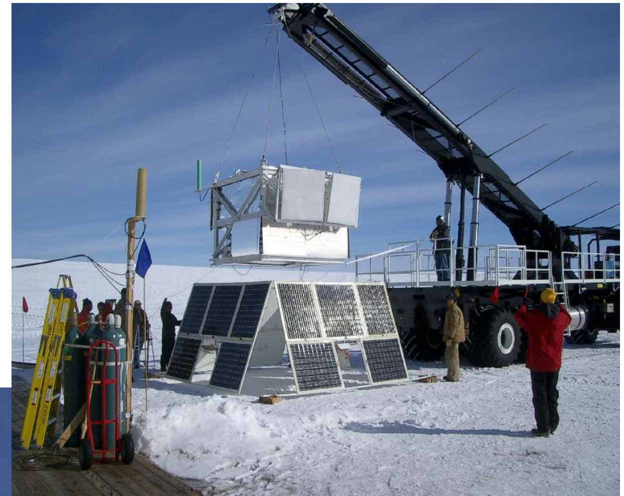
ANITA-lite instrument



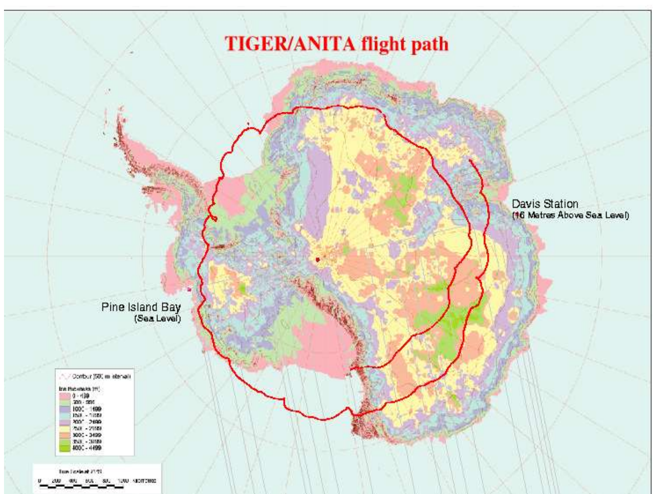
- Dual horns into bandpass filters & LNAs 200-1100 MHz
- Split signal into trigger path & digitizer path
- Use Circular polarization since radio Cherenkov is pure linear (thus equal LCP & RCP)
- Standard HEP coincidence logic

TIGER/ANITA-lite launch

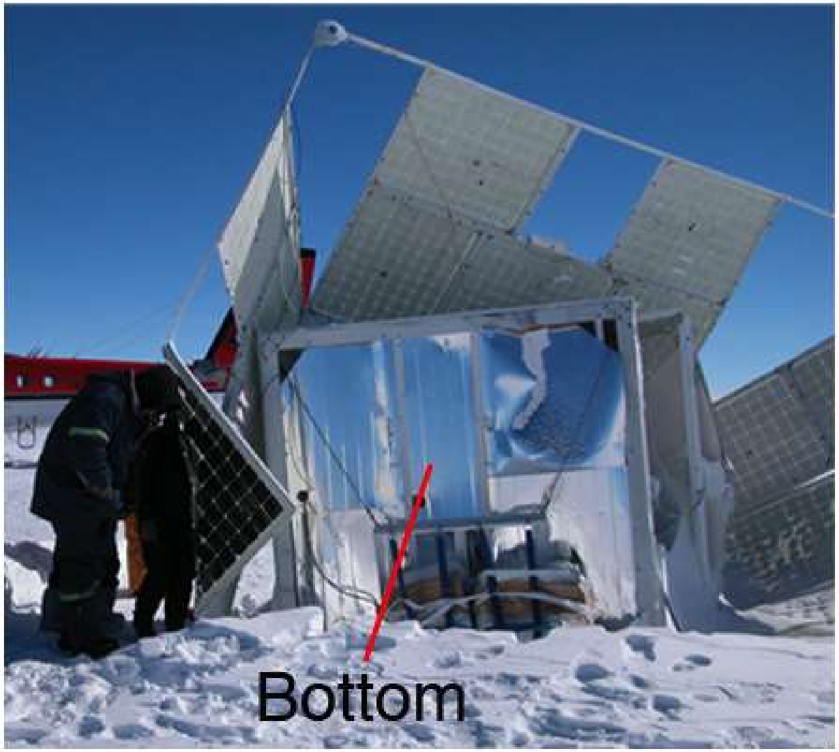




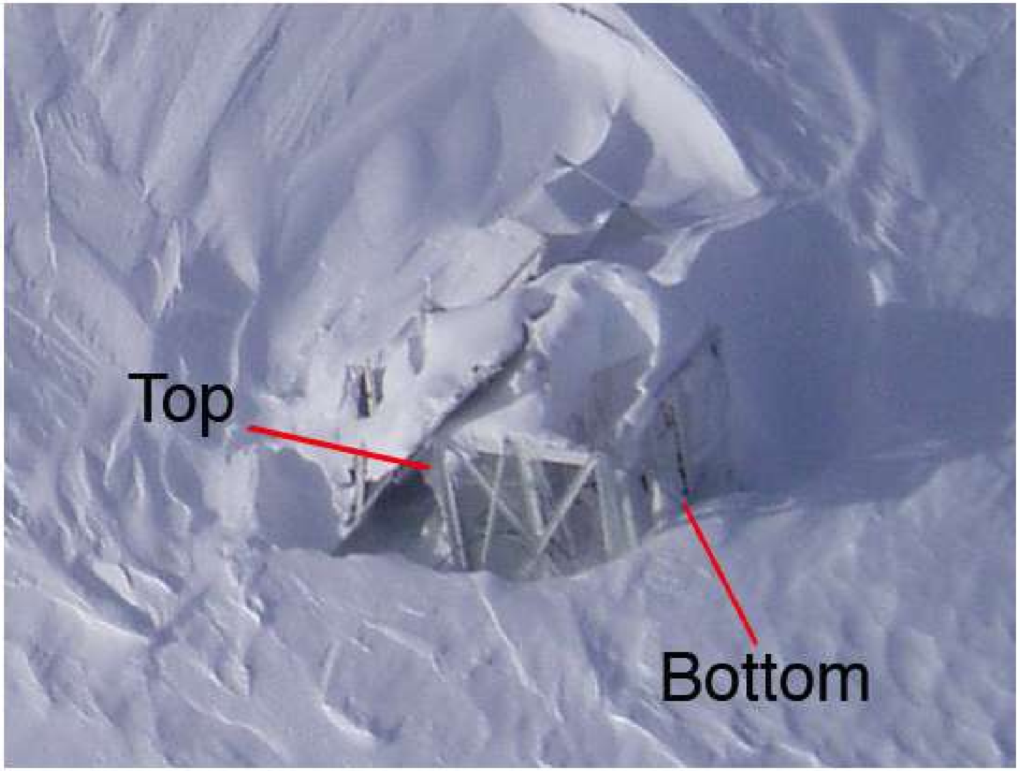
…& Landing


TIGER/ANITA flight path
Davis Station
(16 Metres Above Sea Level)
Pine Island Bay
(Sea Level)

Still There...

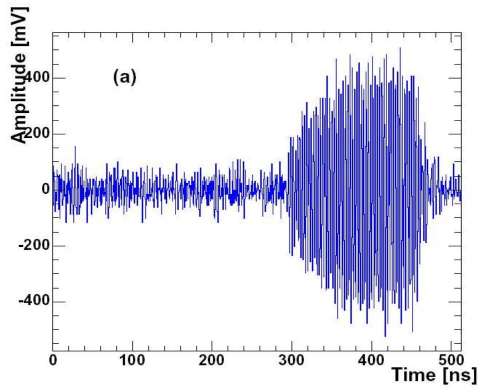


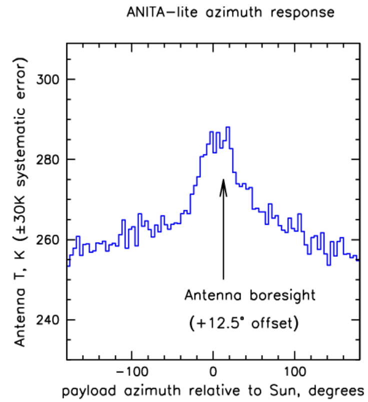
January 2004

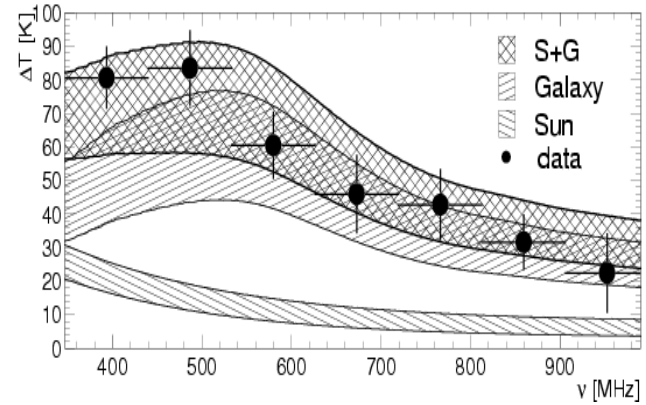


February 2005

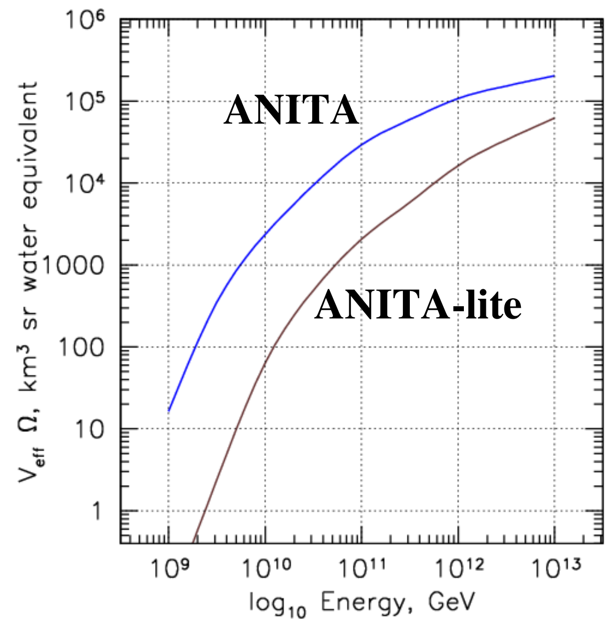
ANITA-lite sensitivity calibration



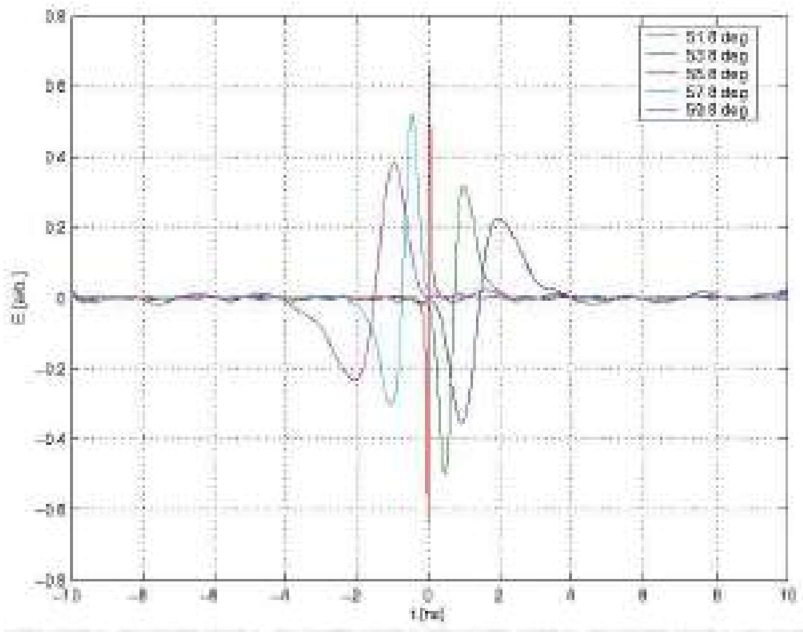




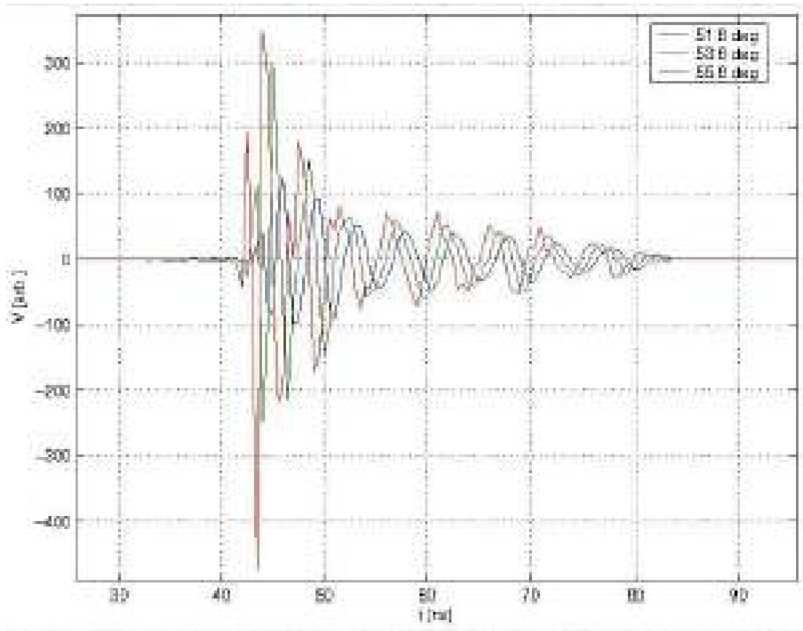
- Ground RF pulser used with GPS synch out to 200-300 km from McMurdo station
- Galactic Center & solar thermal & non-thermal RF emission provided realtime antenna sensitivity, along with onboard noise diodes for gain calibration
- Aperture estimate by Monte-Carlo using ice thickness data & balloon trajectory



Simulated Response to Askaryan Pulse

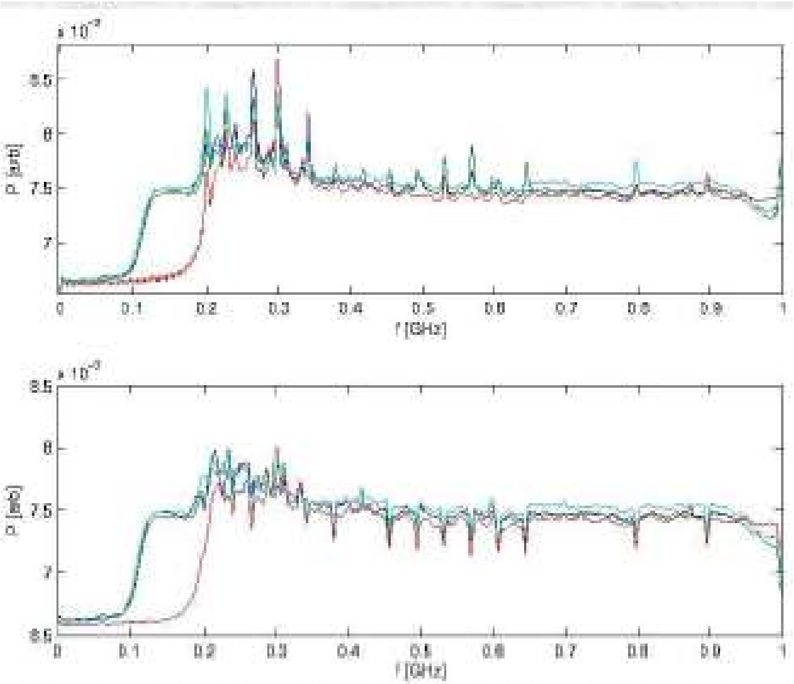


Simulated Askaryan pulses at various angles near the Cerenkov cone



Simulated Askaryan pulses convolved with ANITA-lite instrument response

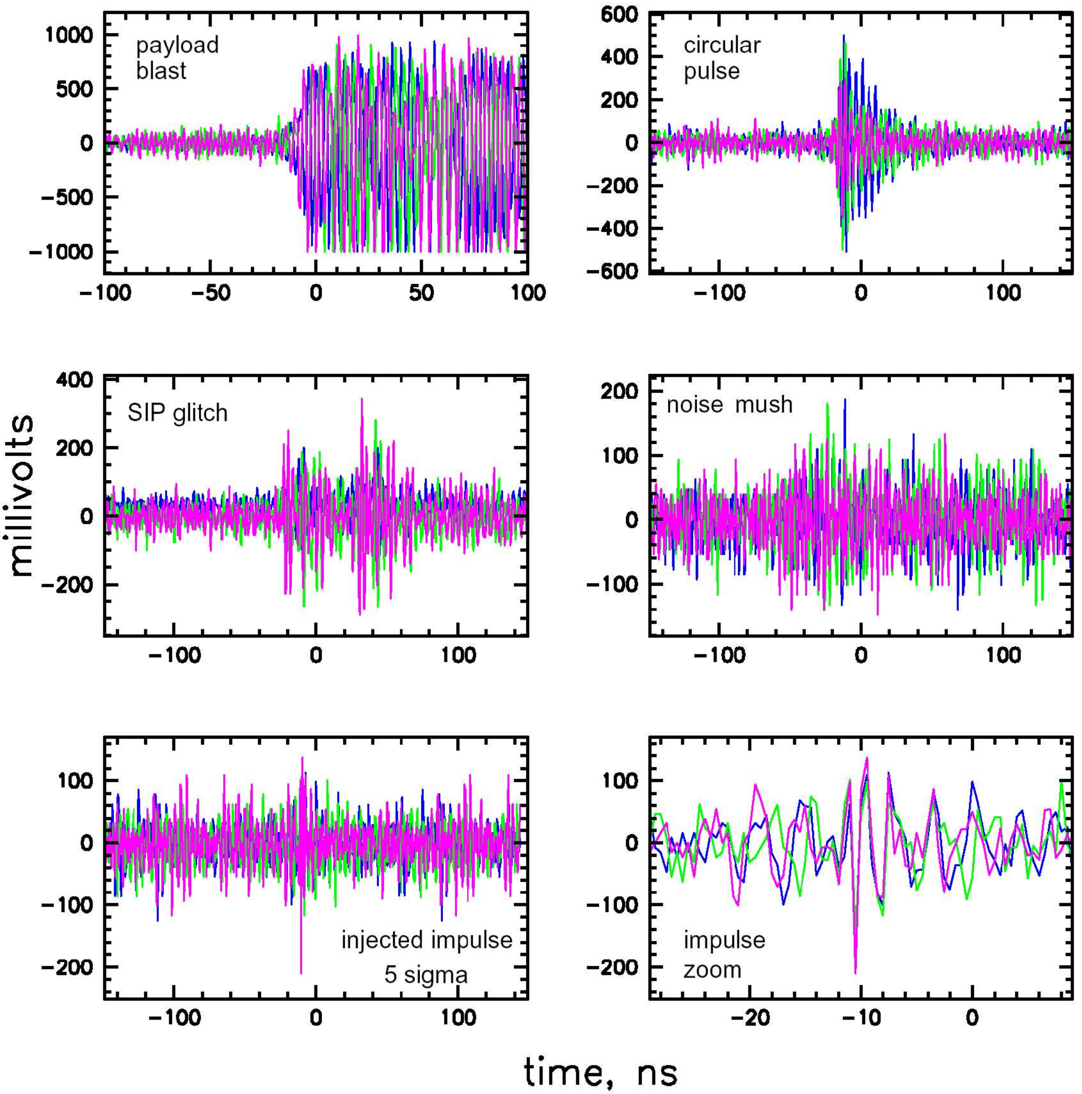
Data Selection



- Use 2 Mhz wide notch filters to remove narrowband payload noise.
- Analyse trace both with and without a 400 Mhz high pass filter

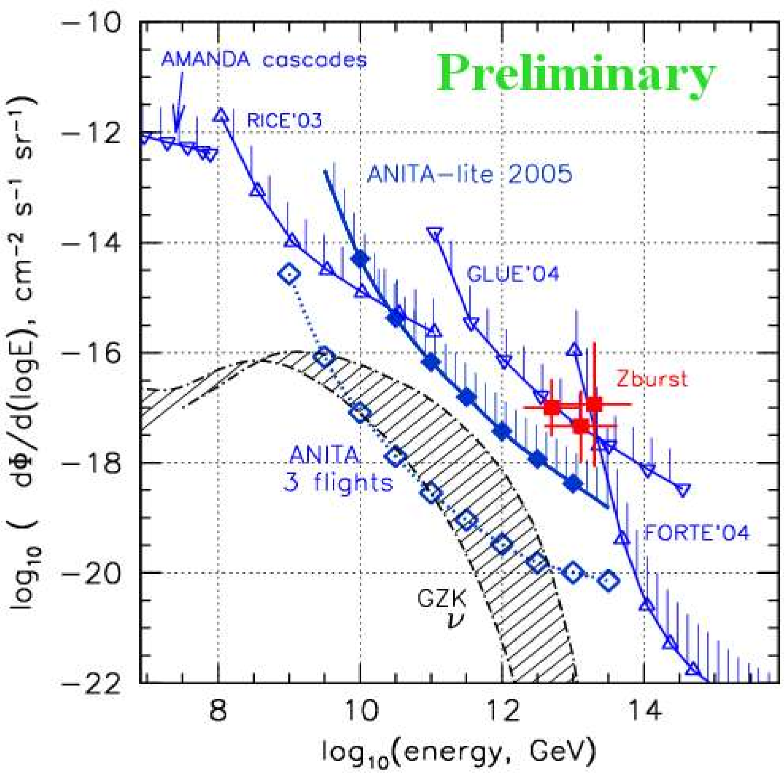
- Apply a matched filter optimized for response to simulated Askaryan pulses.
- Demand (for each channel)
  - SNR not degraded by matched filter, both with and without the 400 Mhz highpass filter.
  - Peak signal timing insensitive to application of matched filter.
  - For pulses that satisfy these requirements, demand that the peaks
    - are within 1ns in same antenna
    - within 5.5ns in different antennas.

ANITA-lite impulse analysis



- **Dominated by payload local noise**
- **Circularly polarized impulses** (TDRSS relay turn-on?)
- **Glitches** from balloon support package (charge controller MOSFETS)
- **Injected Cherenkov signals** (overlain on actual thermal noise) used to test algorithm efficiency
- **Accidental rate**: 3-fold, 5 sigma:
  - Of order 1 per week, but still not phase coherent

Anita-lite & other limits & projections



- **RICE** limits for 3500 hours livetime in embedded South Pole array
- **GLUE** limits ~120 hours livetime, Lunar regolith observations
- **FORTE** limits on 3 days of satellite observations of Greenland ice sheet

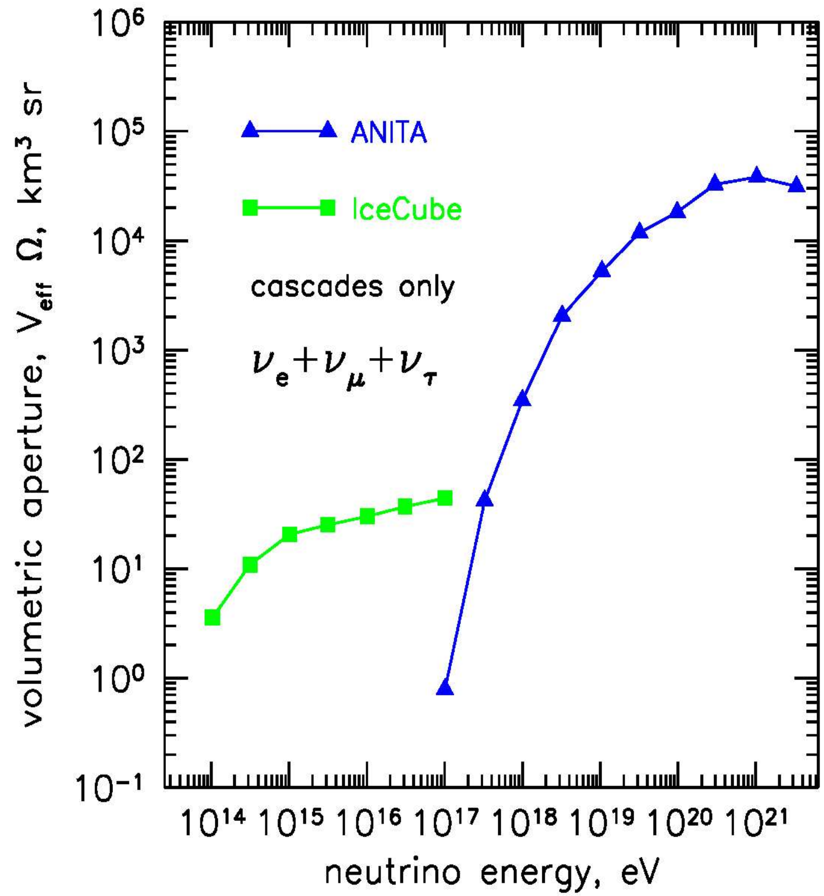
- **ANITA-lite**: 18.4 days of data, net 40% livetime with 60% analysis efficiency for detection
- Ice coverage & average depths included
- No candidates survive impulse cuts in 2 independent analyses
- Z-burst model ($\nu\nu$ annihilation --> UHECR) strongly excluded: we expect 20-30 events, see none
- Large extra dimensions: No limit yet
  - MC modeling is more complicated than expected

- **ANITA projected sensitivity:**
  - ν_e ν_μ ν_τ included, full-mixing assumed
  - **1.5-2.5 orders of magnitude gain!**

The Z-burst model

- Original idea, proposed as a method of Big-bang relic neutrino detection via resonant annihilation (T. Weiler PRL 1986):
  - 10^{23} eV ν + 1.9K $\bar{\nu} \longrightarrow Z_0$ produces a dip in a cosmic neutrino source spectrum, *IF one has a source of 10^{23} eV neutrinos*
- More recently: Z_0 decay into hadron secondaries gives 10^{20+} eV protons to explain any super-GZK particles, again *IF there is an appropriate source of neutrinos at super-mega-GZK energies*
  - (Many authors including Weiler have explored this revived version)
- The Z-burst proposal has the virtue of solving two completely unrelated (and very difficult) problems at once: relic neutrino detection AND super-GZK cosmic rays

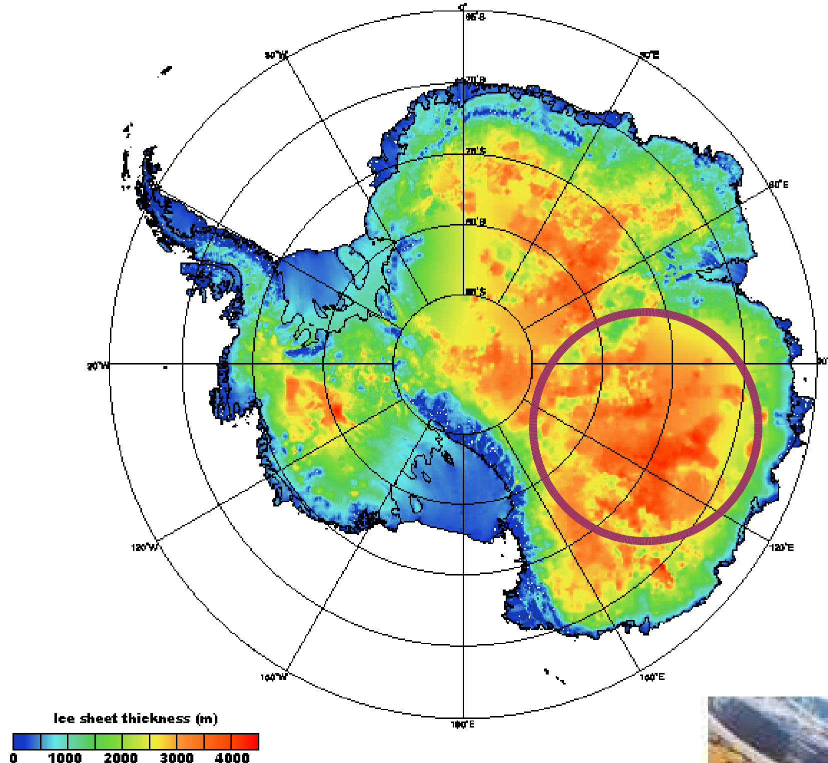
ANITA & IceCube

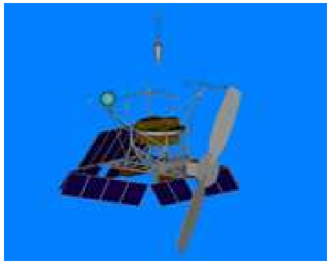


- Different energy regime, very complementary
- IceCube designed for TeV to PeV sources, with some reach to EeV energies
- ANITA “turns on” only for EeV-ZeV sources--GZK neutrinos

For the future: Antarctic station-keeping payload?

- ANITA could greatly improve duty cycle if payload could keep station above <u>east Antarctica</u>
  - ~3-4 km ice depth, least anthropogenic activity
- Either tethered airship at ~80Kft (wind minimum) or station-keeping balloon possible
- With lightweighting of antenna arrays, other possibilities (eg. High altitude UAV aircraft) also possible





Summary

- Radio Cherenkov Detection of GZK neutrinos is well on the way toward first 'light' in 2006-2007
- ANITA-lite: a strong proof-of-concept for ANITA, with some physics thrown in as well
- Antarctica is an unmatched resource for physics and astrophysics…