Radio Detection of GZK Neutrino Interactions in Dense Media

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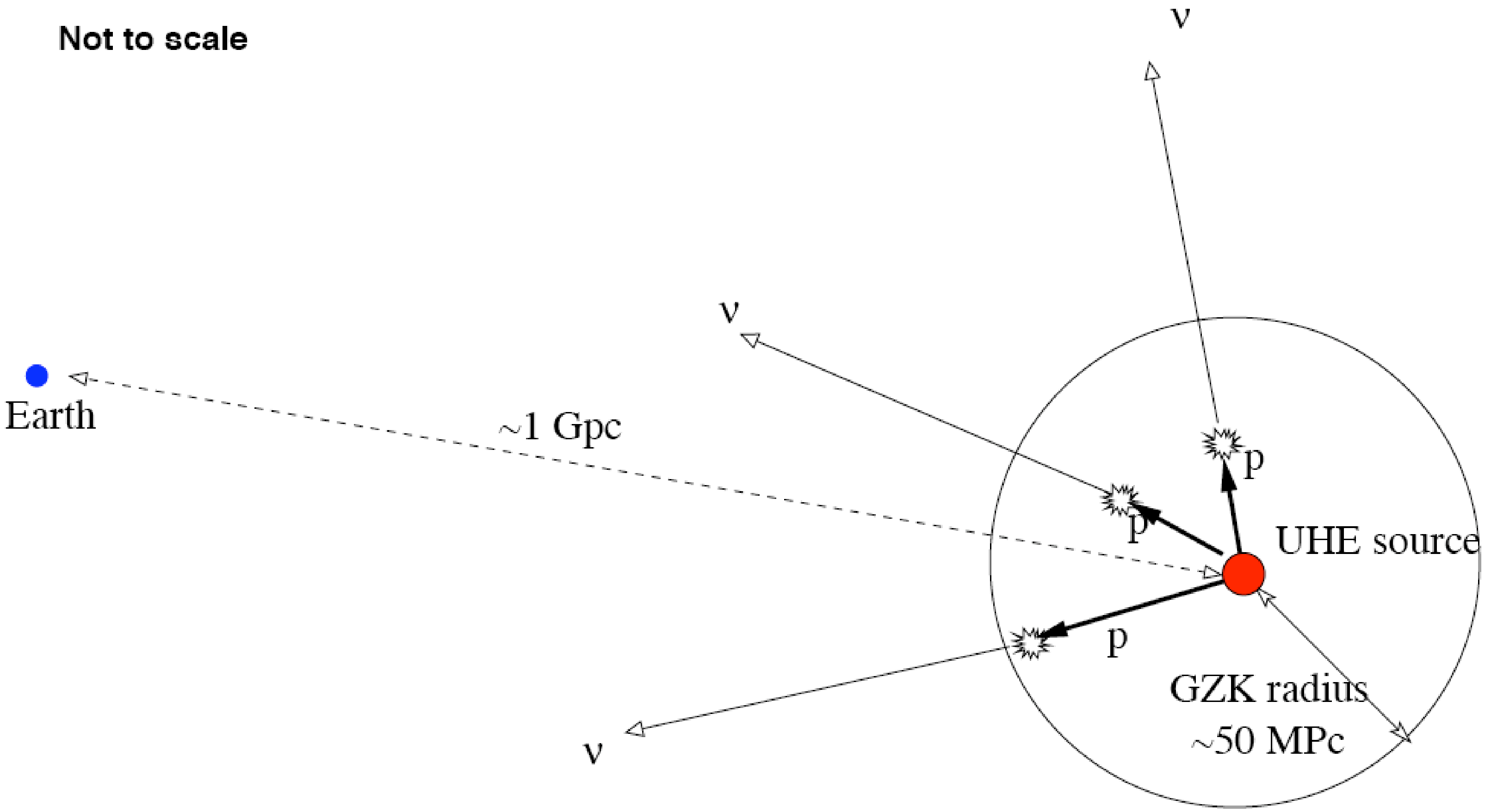
Outline

- Origin of GZK Neutrinos
- Physics of the Askaryan Effect
- Observations of the Askaryan Effect at Accelerators
- The Antarctic Ice Sheet as a Neutrino Detector
  - ANITA
  - ARIANNA

Distant UHECR Sources as Neutrino Sources



The Askaryan Effect

- Electromagnetic cascades result in an evolving population of electrons, positrons, and photons as showers develop.
  - Positrons are depleted by in-flight annihilation.
  - Additional electrons are upscattered from the medium.
  - The net effect is a negative charge excess (~20%) in the shower moving relativistically.
- Dominant RF mechanism in solids (ice, salt).
- *Coherent* Cherenkov Radiation
  at long wavelengths!

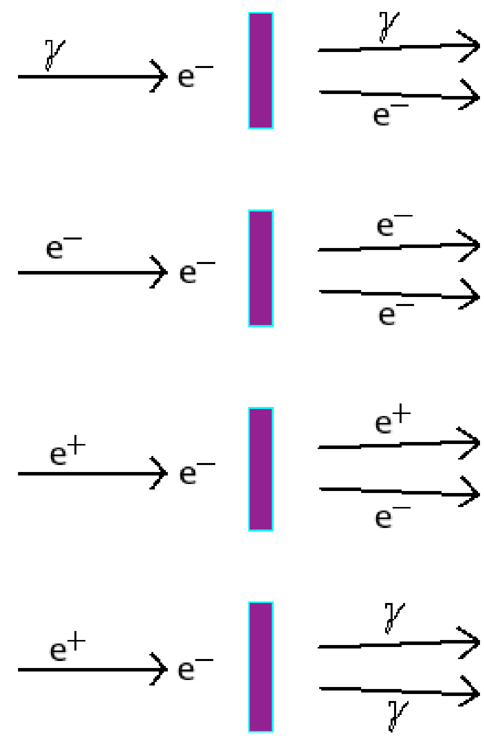
Askaryan effect: charge asymmetry

Compton scattering

Möller scattering

Bhabha scattering

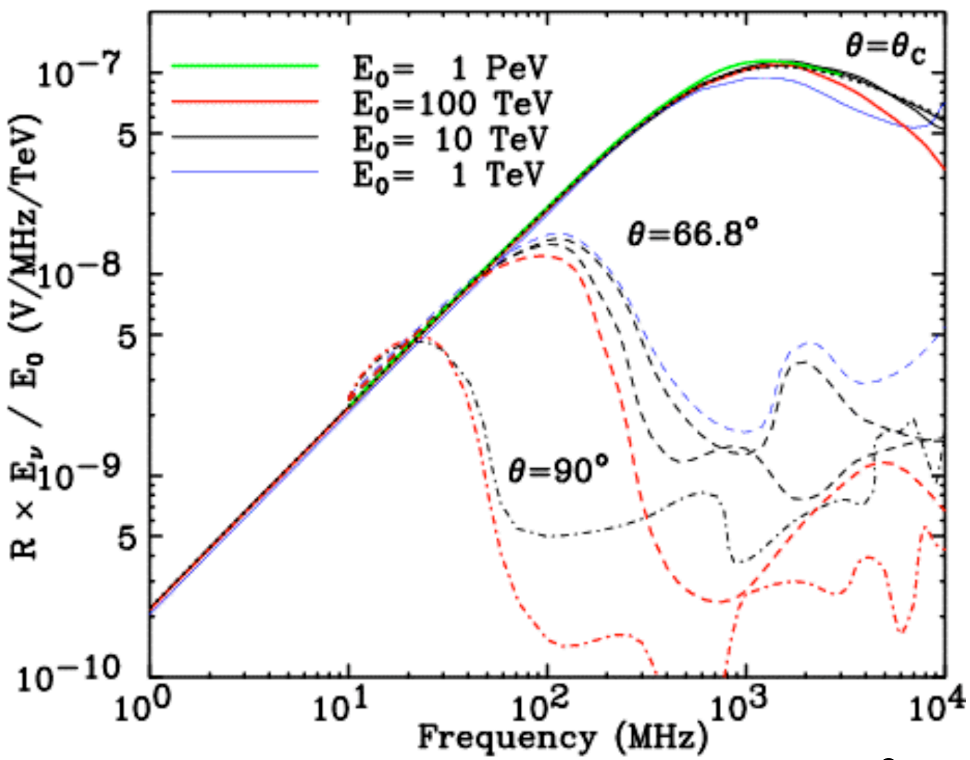
pair annihilation



- Shower particles collide with electrons in the medium to give the shower an overall negative charge.
- Askaryan: pair annihilation would produce a charge asymmetry of $(N_- - N_+) / (N_- + N_+) \approx 5\%$.

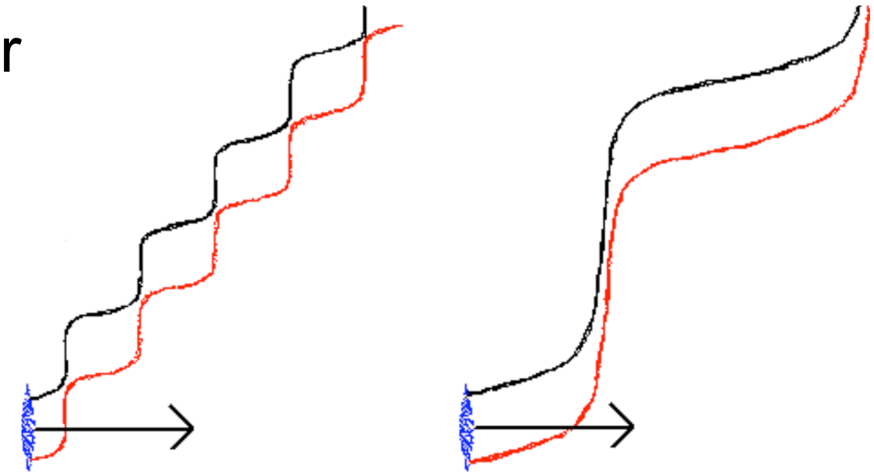
Zas-Halzen-Stanev (ZHS) simulation

- $(N_- - N_+) / (N_- + N_+) \approx 20\%$
- 60% of Askaryan effect due to Compton scattering, 30% due to Bhabha/Möller scattering, 10% due to pair annihilation
- Coherence lost above ~2 GHz in ice



Askaryan effect: coherent Cherenkov light

At wavelengths much greater than the shower radius, Cherenkov light adds coherently from all excess electrons.

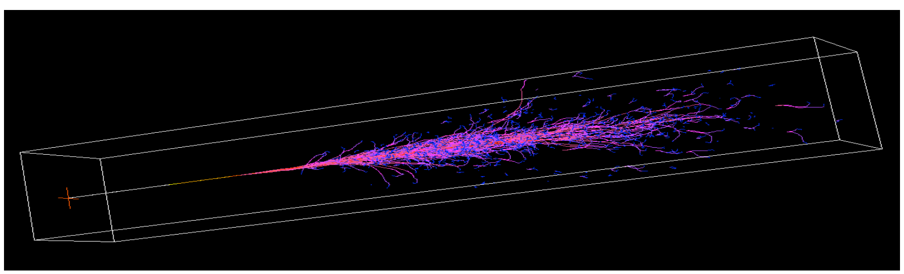


- $|\vec{E}| \propto$ charge excess $\propto$ $(N_- + N_+)$ $\propto$ shower energy
- Cherenkov pulse power $\propto$ $|\vec{E}|^2$ $\propto$ (shower energy)^2
- At smaller wavelengths, Cherenkov light experiences destructive interference from electrons at different parts of the shower.
- prefer a high density medium
- possible radio detection of showers in halite, marble, granite, and ice

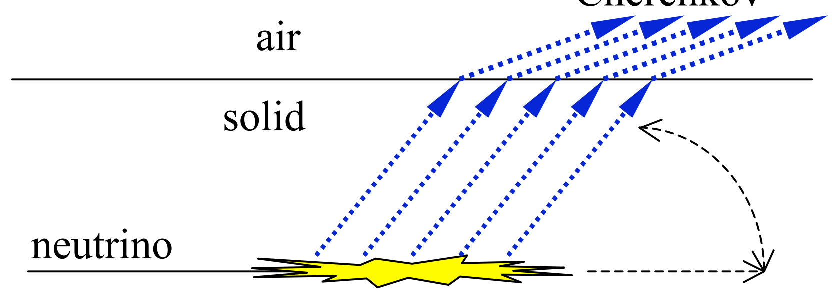
Showers in solid media

Simulation: in rock salt, 0.2-1GHz, 1EeV cascade

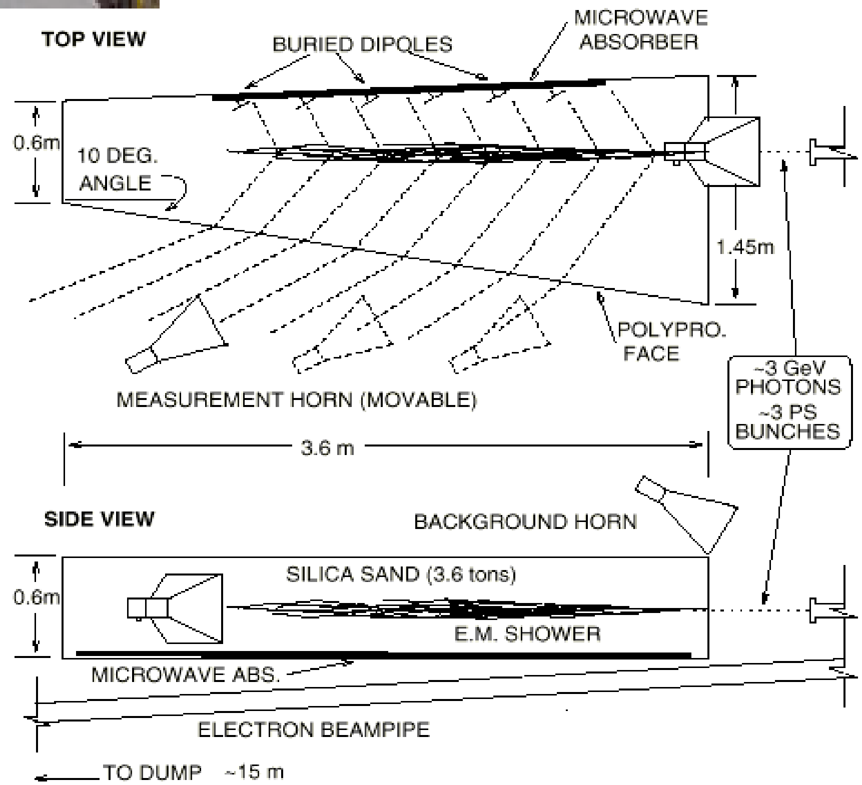
20 m

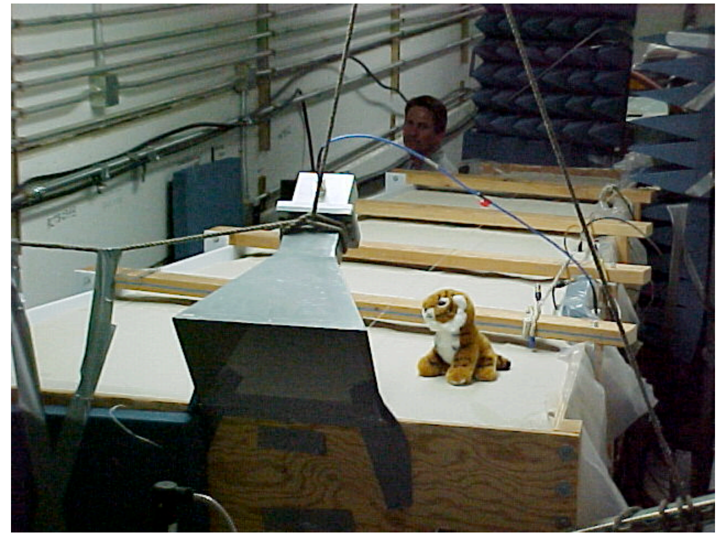


- Ice: n = 1.78,
  - $\cos^{-1}(1/n) = 53^{o}$
- **Halite (rock salt): n=2.45,**
  - $\cos^{-1}(1/n) = 66^{o}$
- **RF Cherenkov cone: propagates through solid, refracts at interfaces**



Askaryan Confirmation: SLAC T444 (2000)

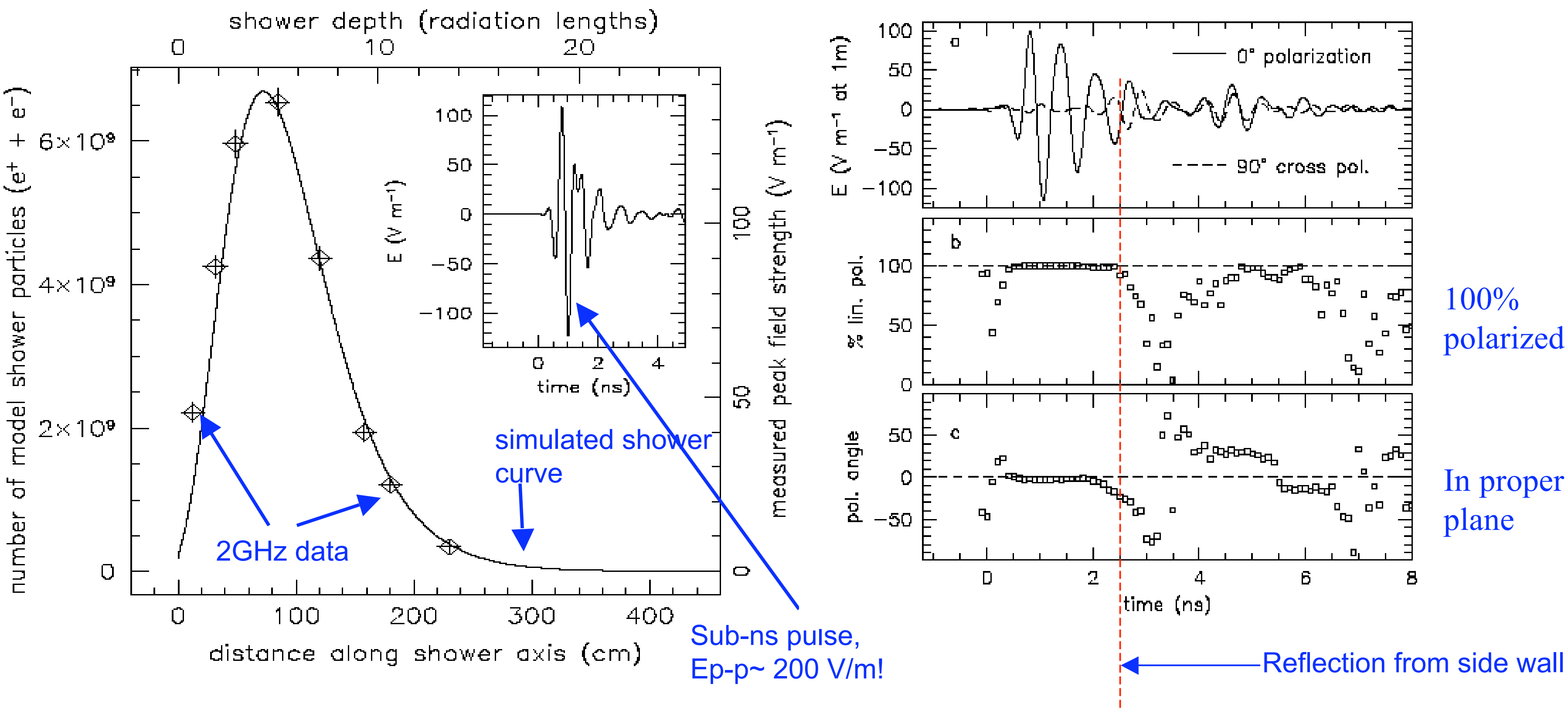




From Saltzberg, Gorham, Walz et al. PRL 2001

- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  - ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!

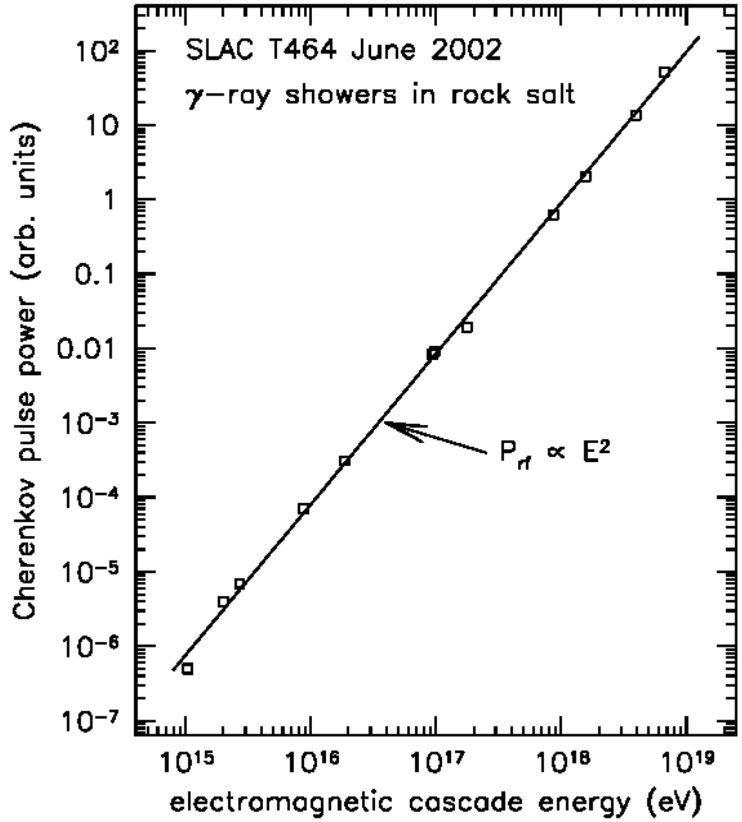
Shower profile observed by radio (~2GHz)



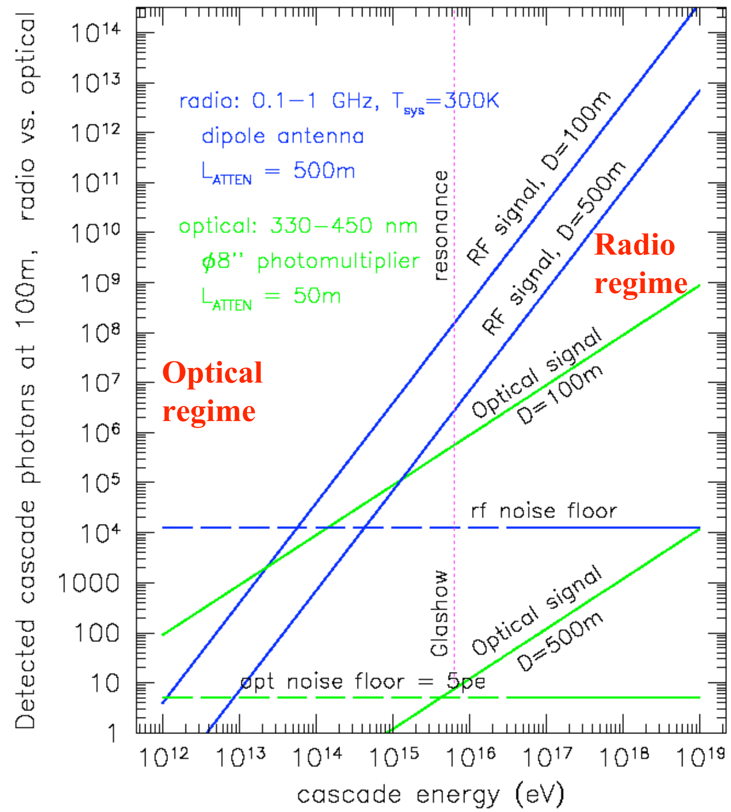
- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- **Polarization** completely consistent with Cherenkov—**can track particle source**

Coherence

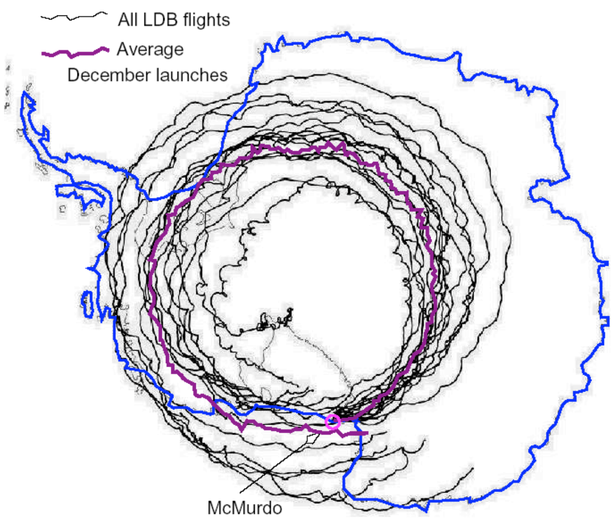
Huge dynamic range, E-field linearity

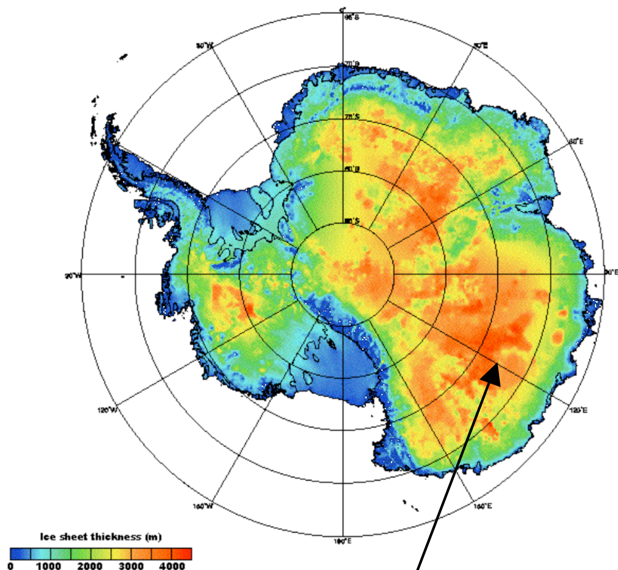


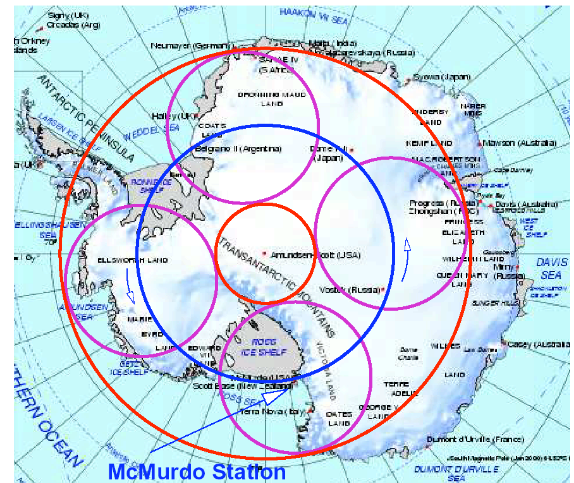
SNR dominant at E >10 PeV

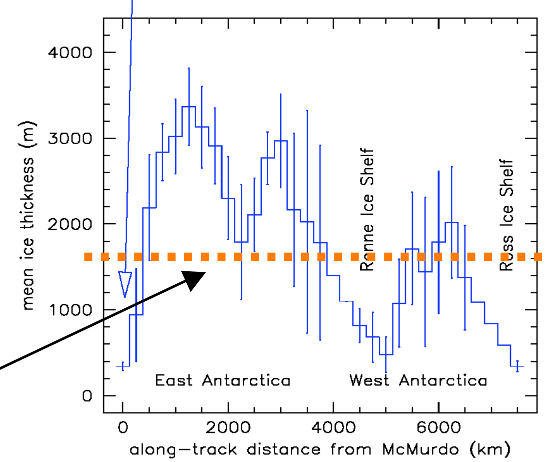


The Antarctic Ice Sheet





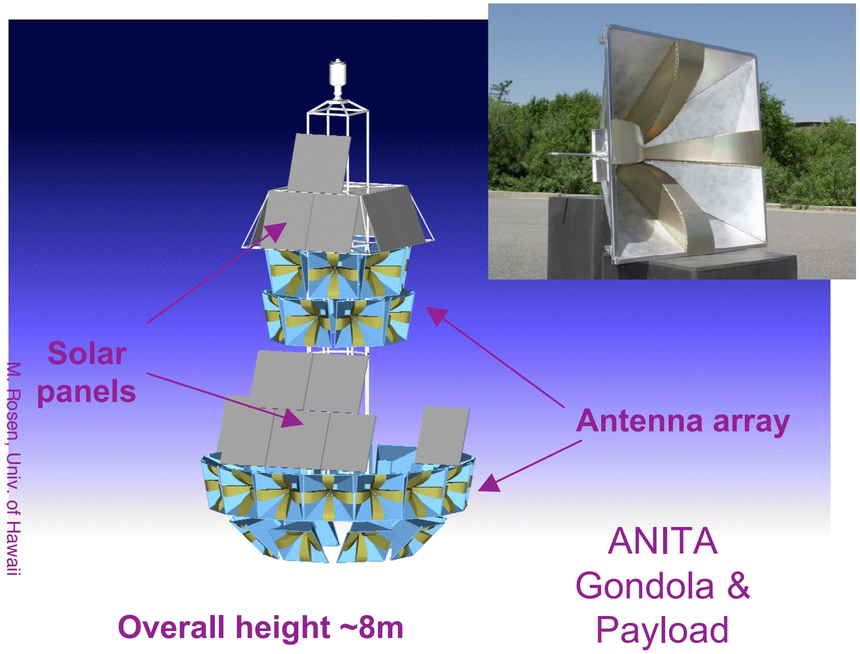


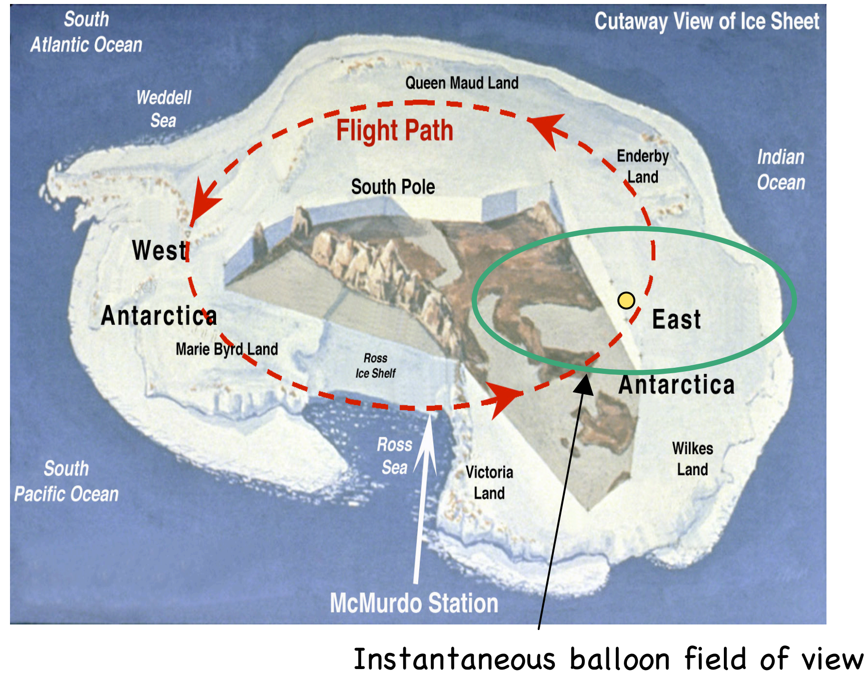


~4km deep!

~1500m avg

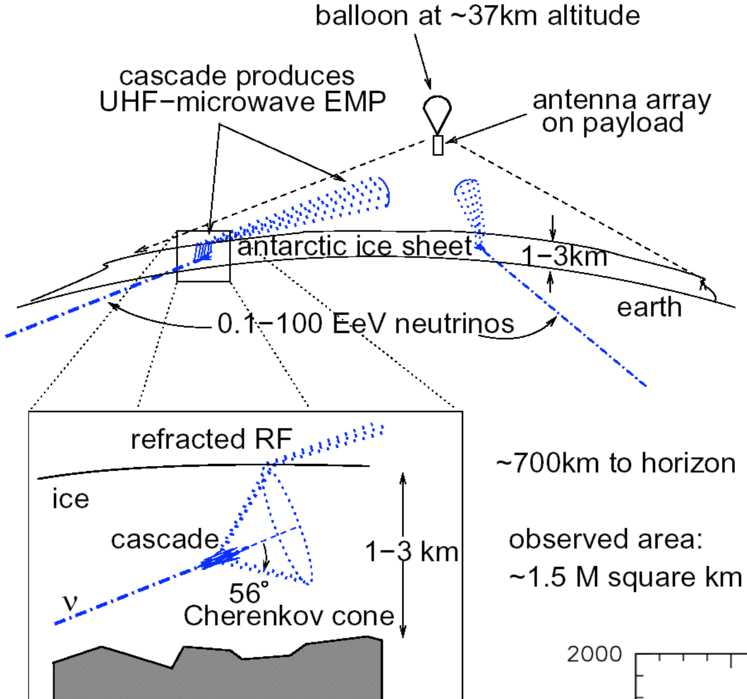
Antarctic Impulsive Transient Antenna

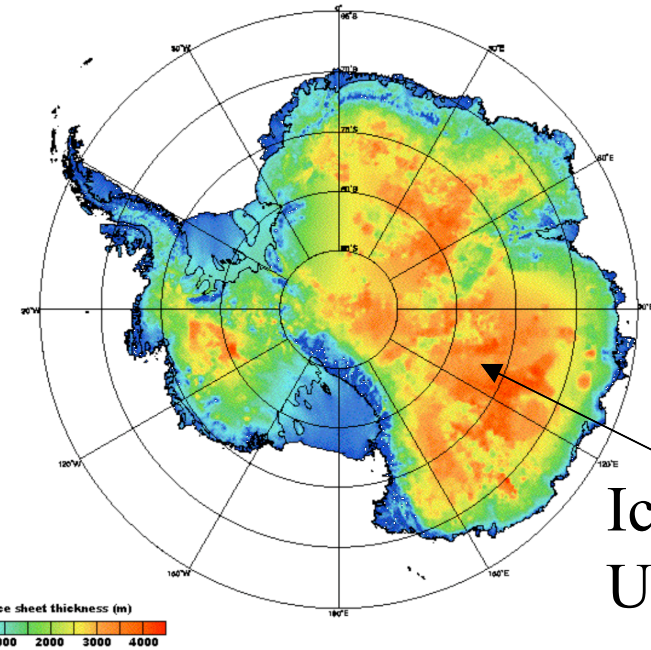




- **ANITA Goal: Pathfinding mission for ultra-high energy ν**
- NASA SR&T start early in 2003, Background survey 2003-2004, systems test flight 2005, first science flight of full payload 2006-2007
- UH (Gorham, Hebert, Learned, Link, Matsuno, Miocinovic, Rosen, Varner), UCI (Barwick, D. Goldstein), JPL (Liewer, Naudet), Ohio State (Beatty, Mercurio, Nichol, Palladino), U. Del. (Seckel, Clem), UCLA (Saltzberg, Connolly, Goodhue, Hoover), U.Minn. (DuVernois), Univ. Kansas (Besson), SLAC (Chen,Field,Hast,Reil,Walz), Washington U. St. Louis (Binns, Dowkontt, Israel, Olevitch)

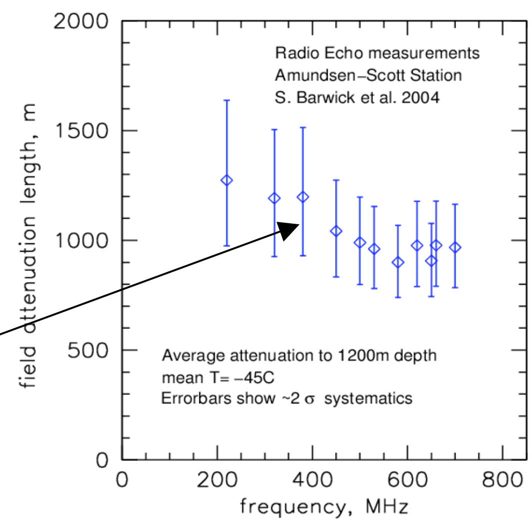
ANITA concept & basis





Ice thickness:
Up to 4km!

Ice RF clarity:
~1km(!) atten.
length

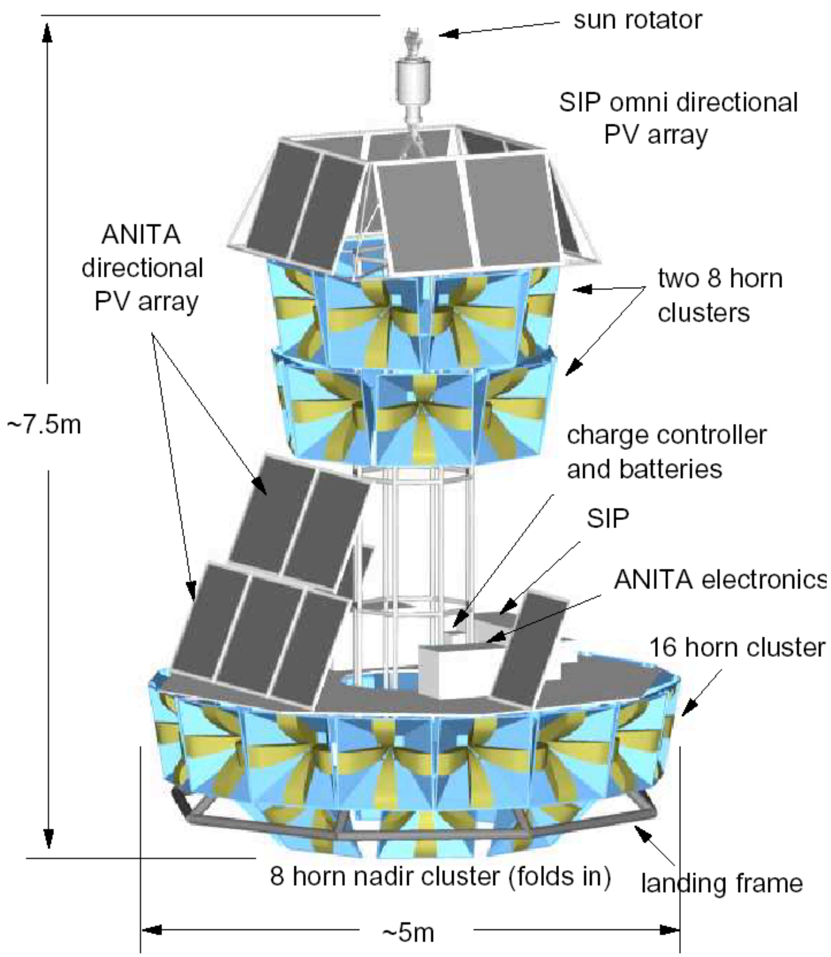


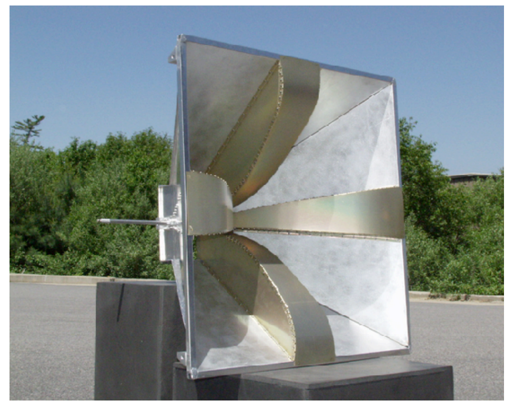
Effective “telescope” aperture (km^3 sr):

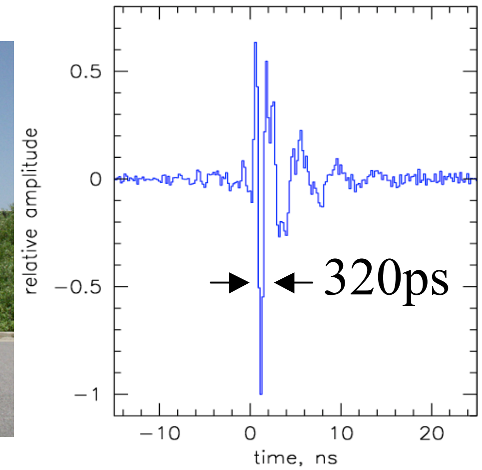
- ~250 @ 10^{18} eV
- ~10^4 @ 10^{19} eV

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

ANITA Payload Design

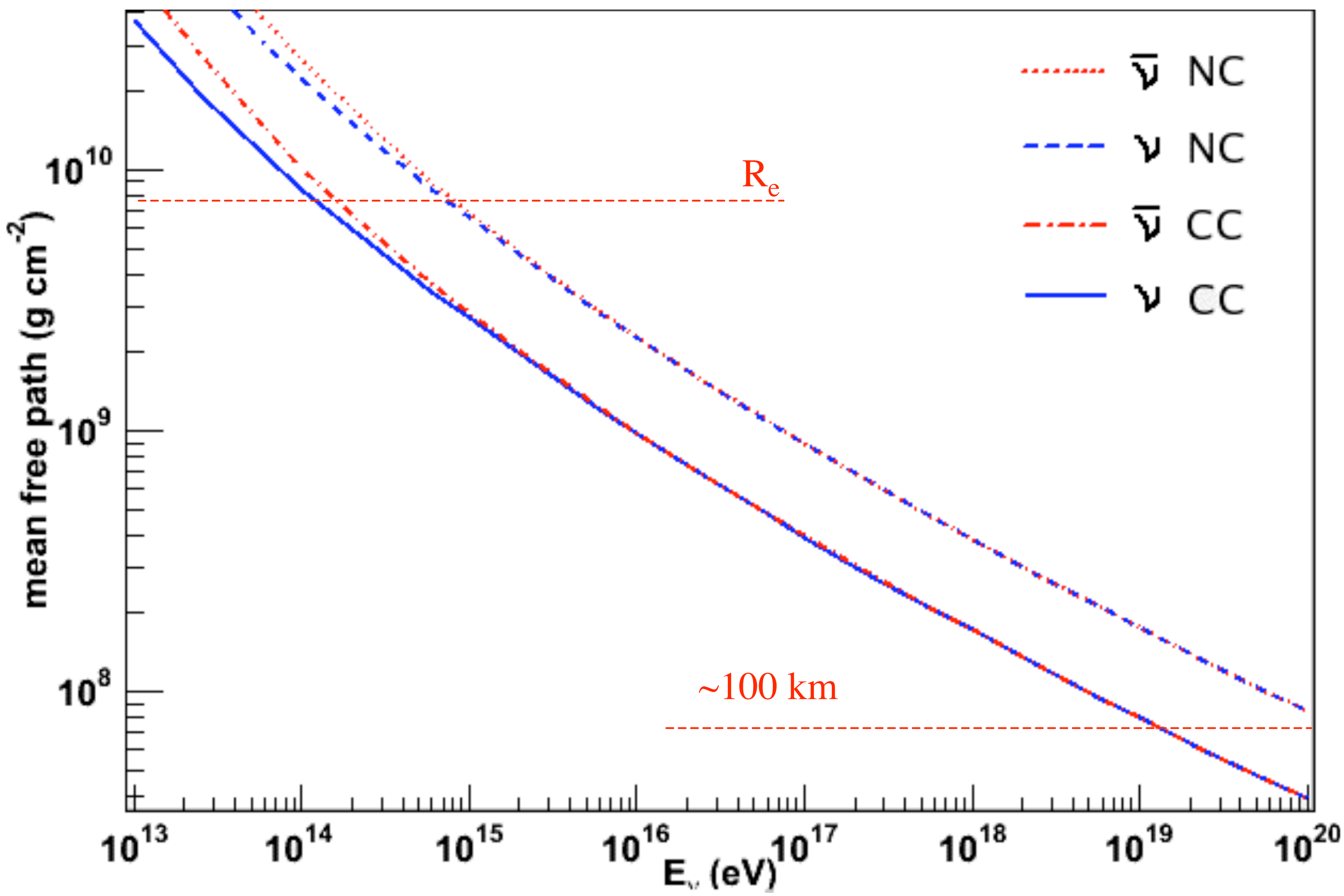




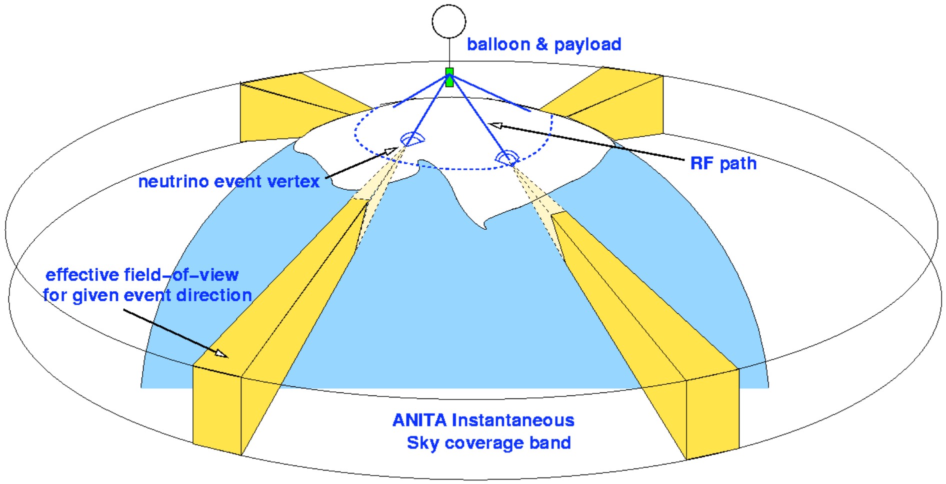


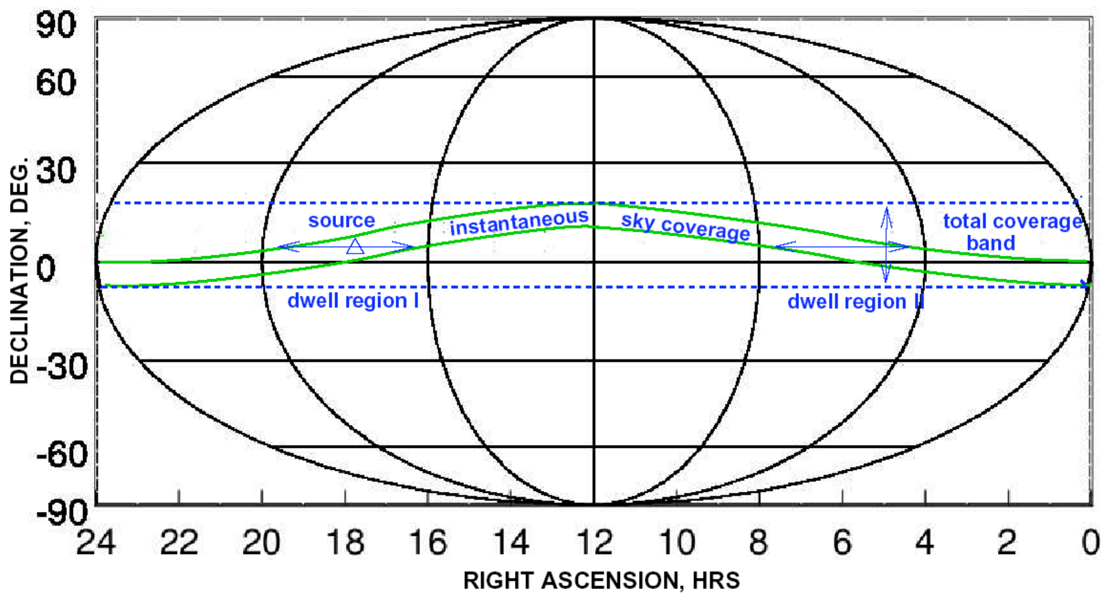
- Quad-ridged horn antennas provide superb impulse response & bandwidth
- Interferometry/beam gradiometry from multiple overlapped antenna measurements
- Cherenkov polarization tracking possible

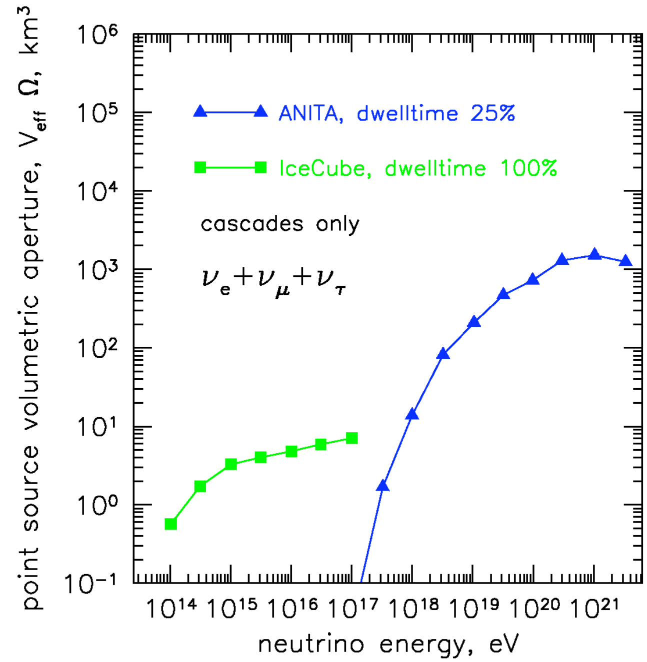
Neutrino interactions



Sky Coverage and Angular Resolution



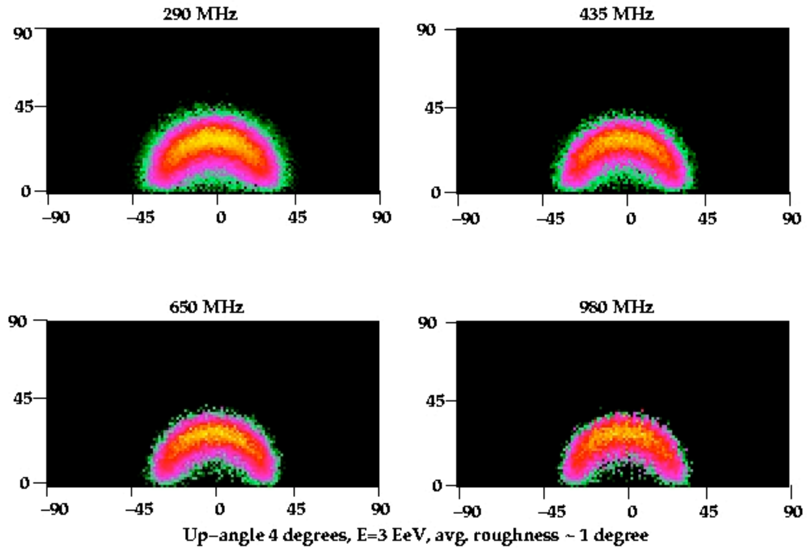


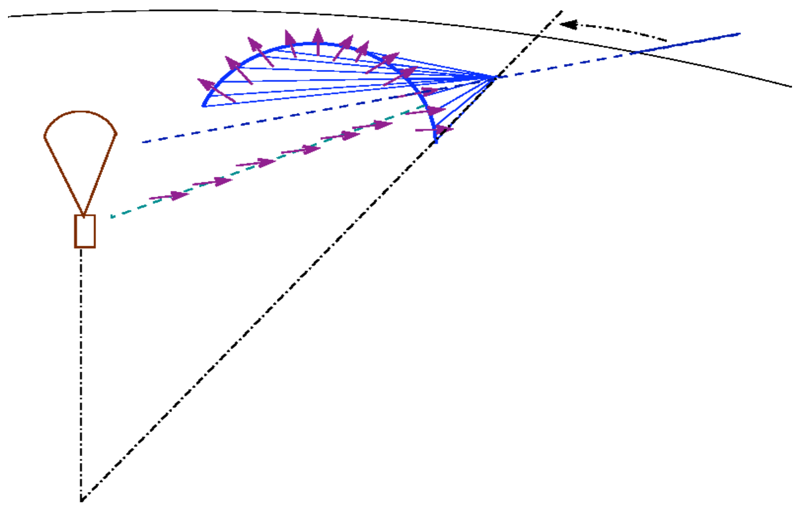


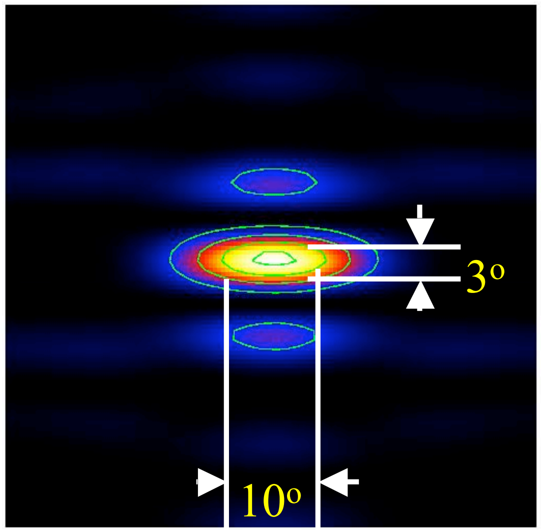
The aperture for point sources differs from that for diffuse fluxes due to:

- beam size
- duty cycle (dwell time)

ANITA as a neutrino telescope







- Pulse-phase interferometer gives intrinsic beamsize of ~3° elevation by ~10° azimuth for **arrival direction of radio pulse**
- **Neutrino direction** constrained to ~1-2° in elevation by earth absorption, and by 3-5° in azimuth by polarization angle

ANITA-lite EMI balloon survey

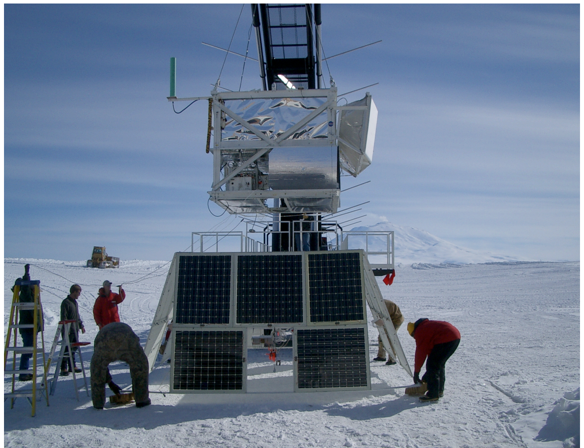
NASA provided a piggyback Mission of Opportunity for ANITA on the 2003-2004 Trans-Iron Galactic Element Recorder (TIGER) flight, completed in mid-January 2004…

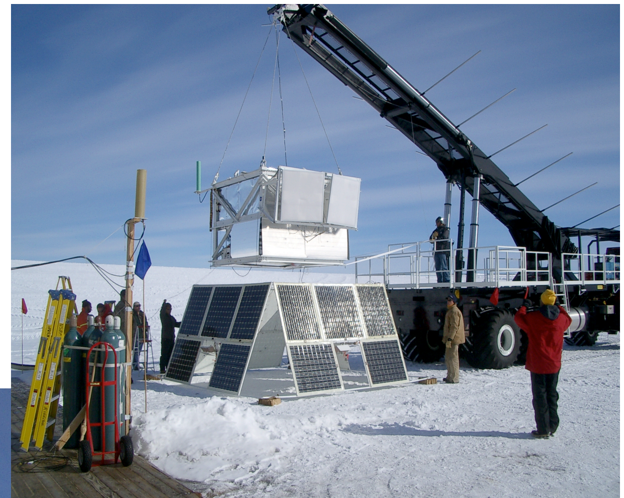
- ANITA-lite flew ANITA prototypes & OTS hardware
  - 2 dual polarization quad-ridge horns (prototype ANITA antennas)
  - 4 channels total at 2 GHz sampling, 1 GHz bandwidth

- Measured ambient RF interference & thermal noise
- 18 days flight time, 130K transient events recorded
- External drive recovered w/ 80% of data
  - 20% just out of cold storage, due to delayed instrument recovery
- Results look excellent for ANITA so far…

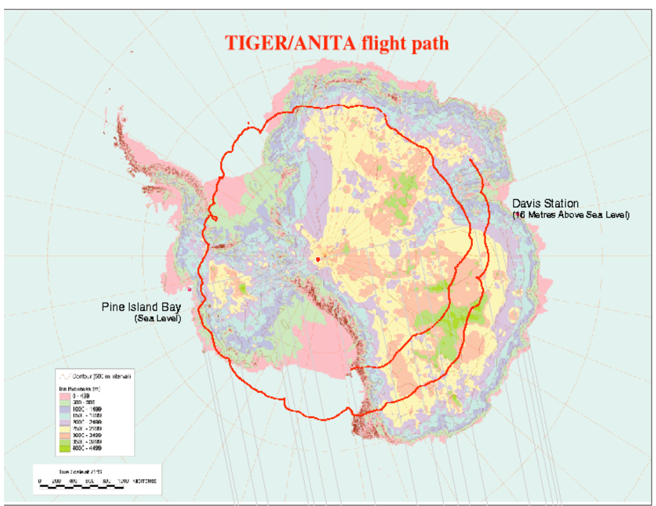
ANITA-lite in Antarctica

TIGER/ANITA-lite launch

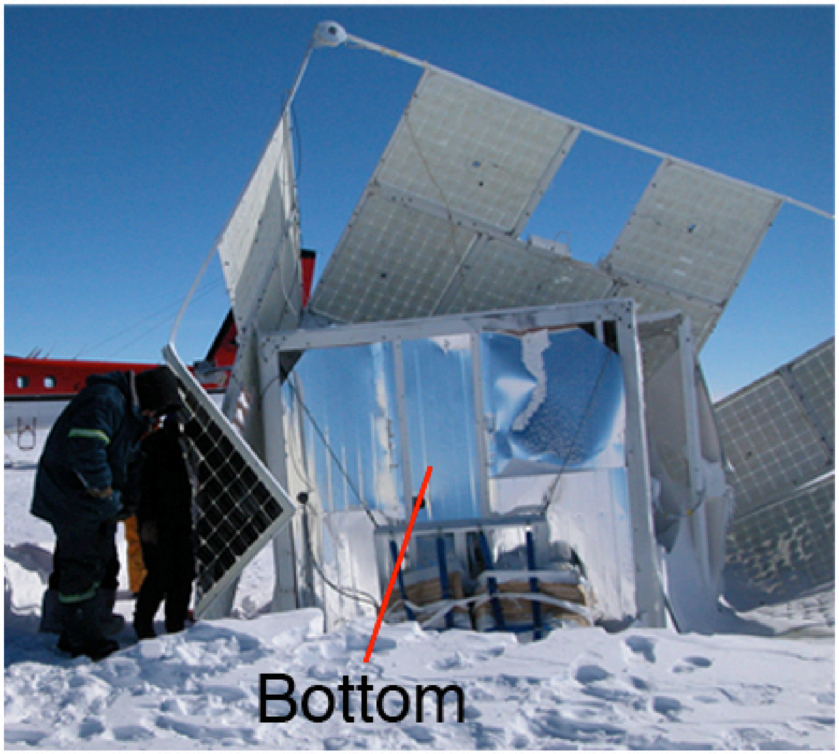




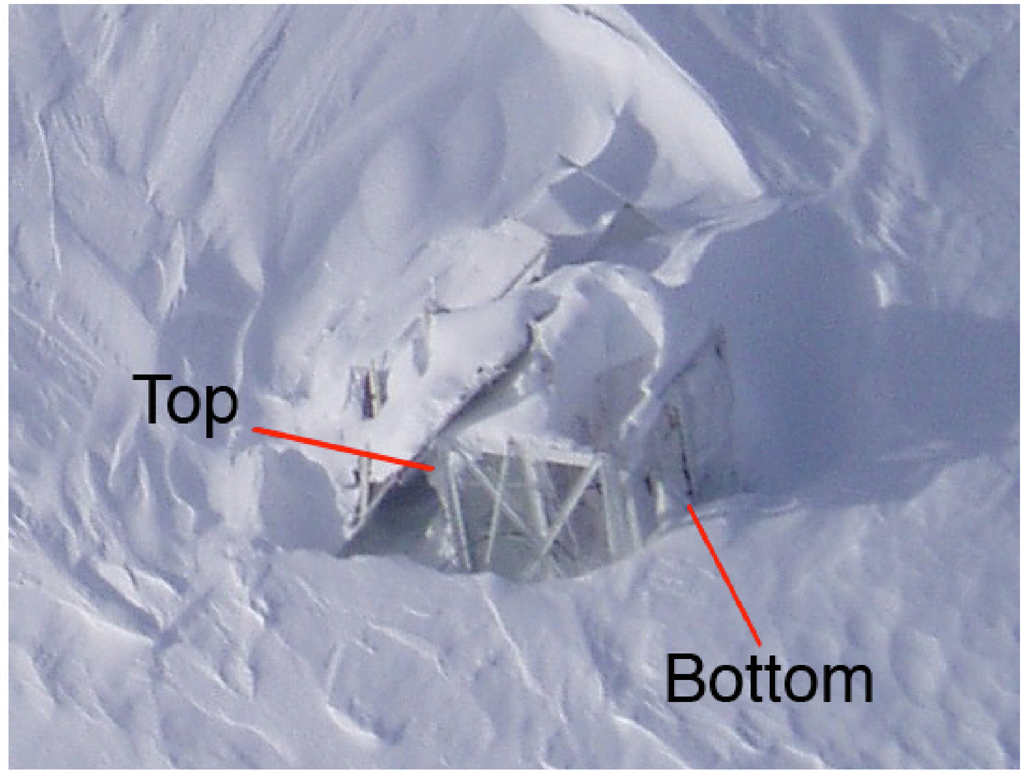
...& Landing


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

Still there a year later (recovered 2006)

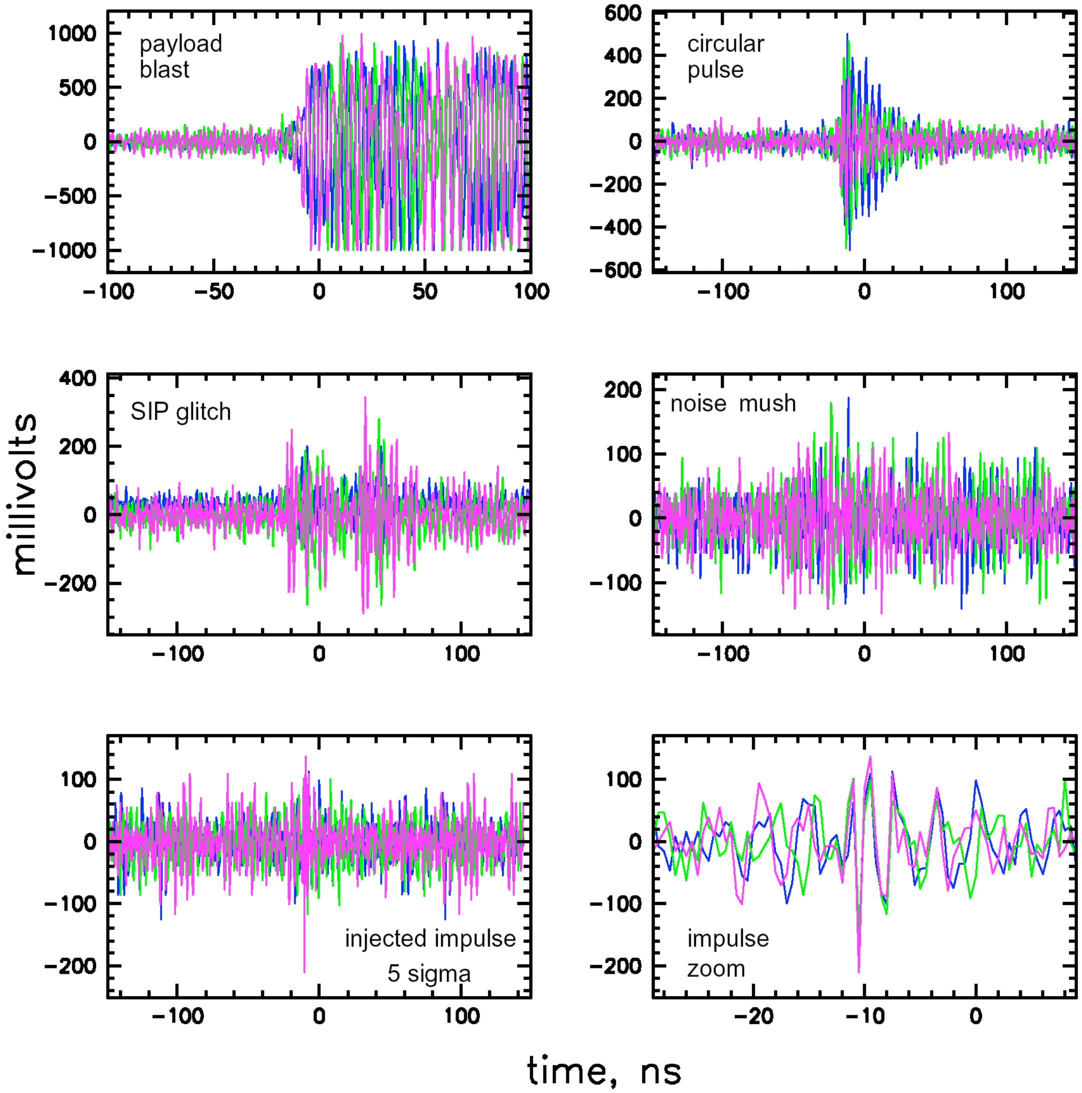


January 2004



February 2005

ANITA-lite impulse analysis



Dominated by payload local noise

Circularly polarized impulses (TDRSS relay turn-on?) are closest to true impulses (but not)

Glitches from balloon support package (charge controller MOSFETS)

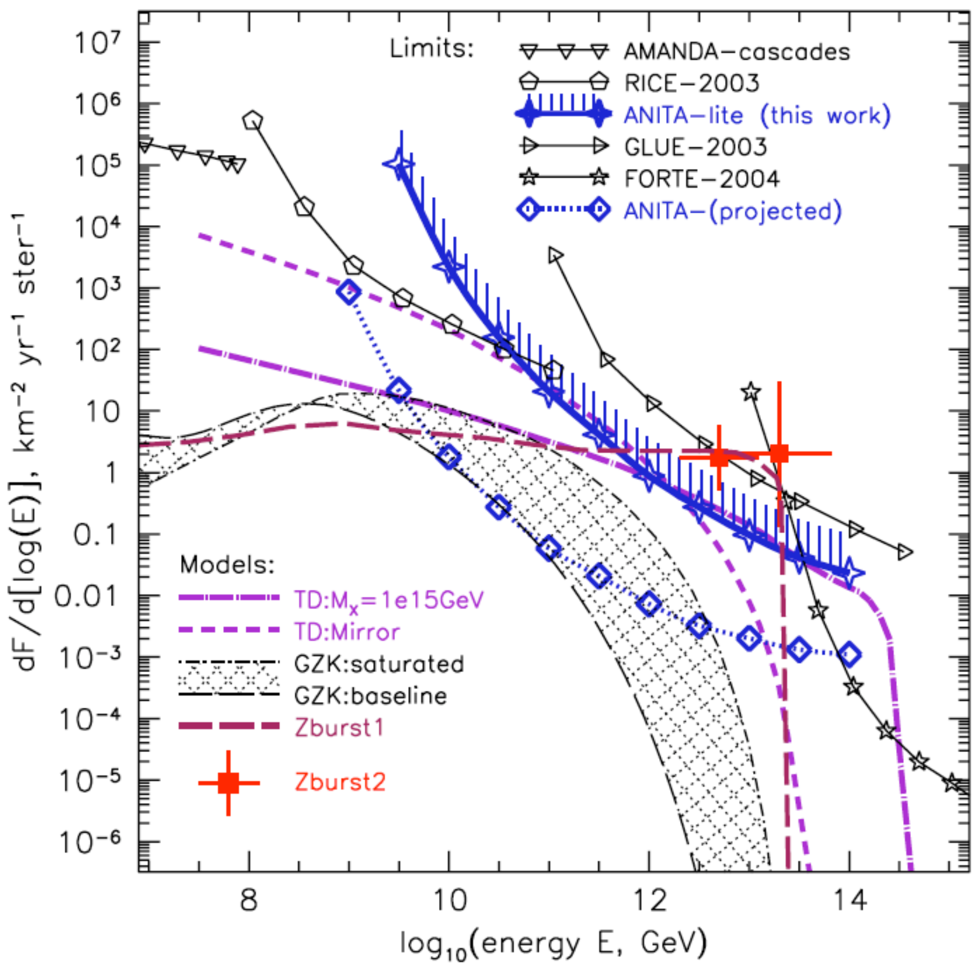
Injected 3 and 5 sigma signals (overlain on actual thermal noise) used to test algorithm efficiency

Accidental rate: 3-fold, 5 sigma:

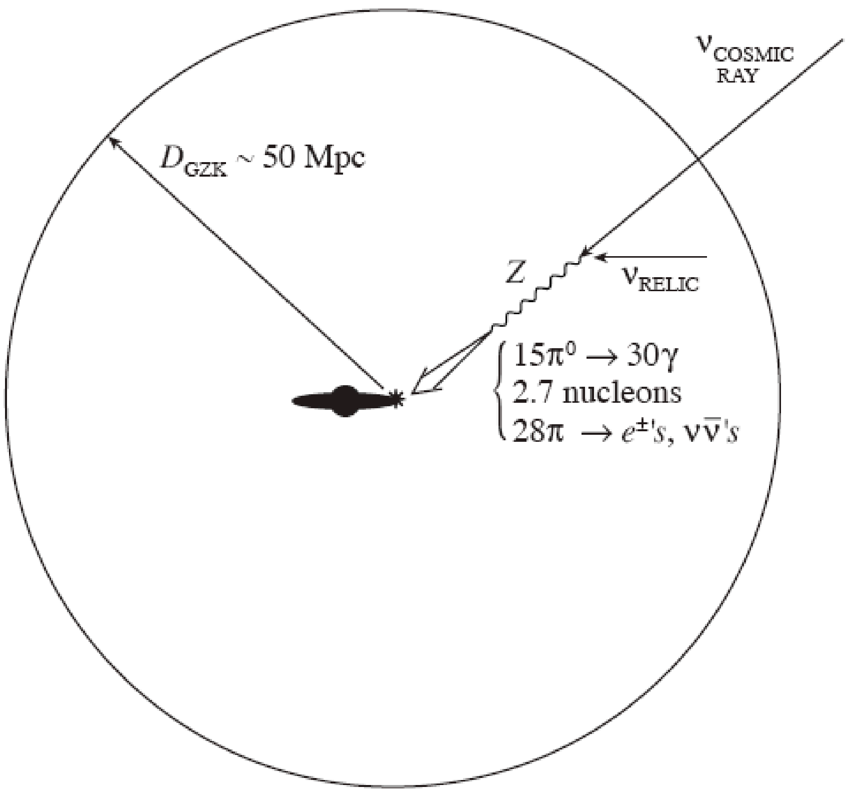
- < 1 per week

In 7days livetime:
no background events survive;
70% efficiency for detecting simulated Askaryan pulses

ANITA-lite Limits



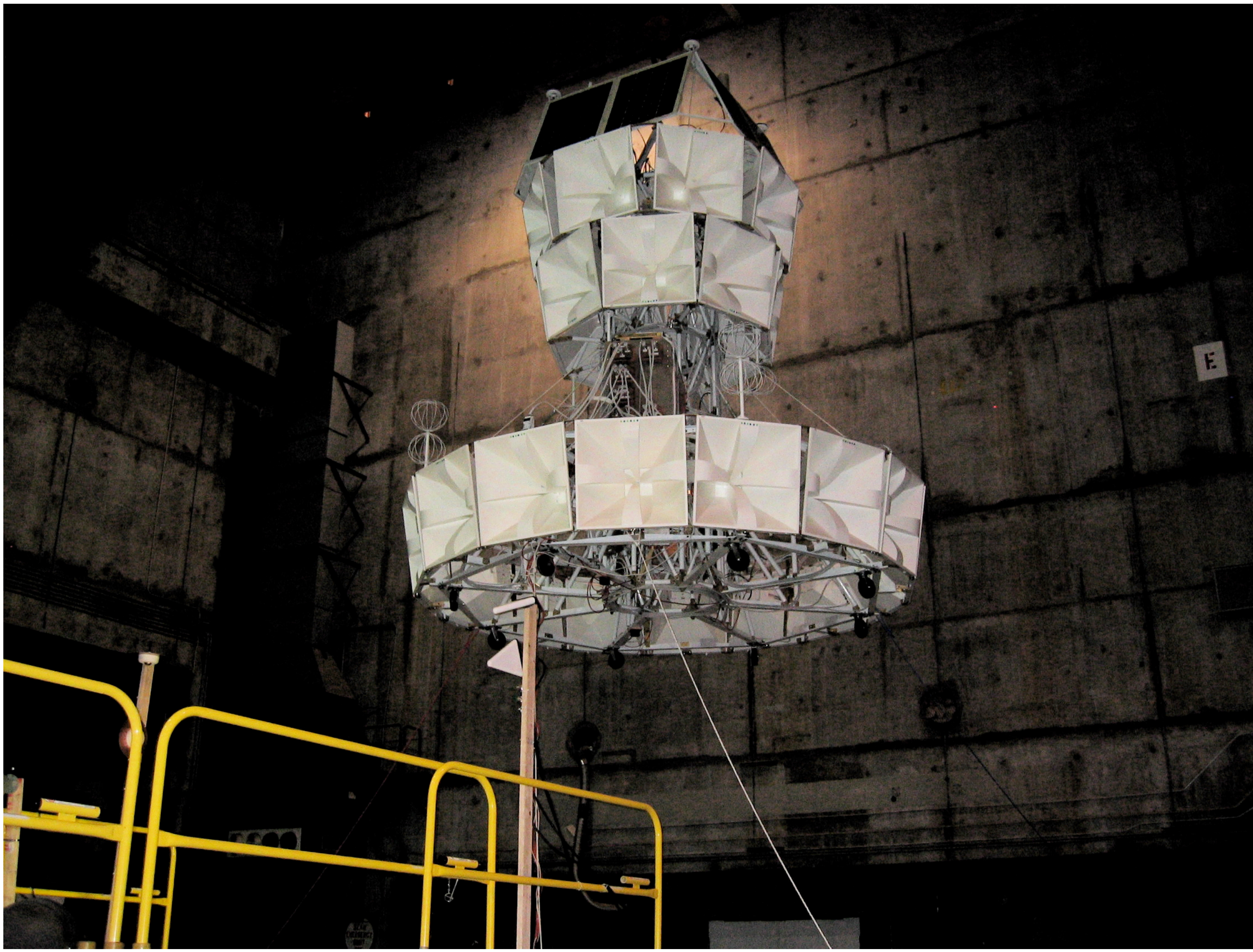
Z-bursts



Weiler, 1999

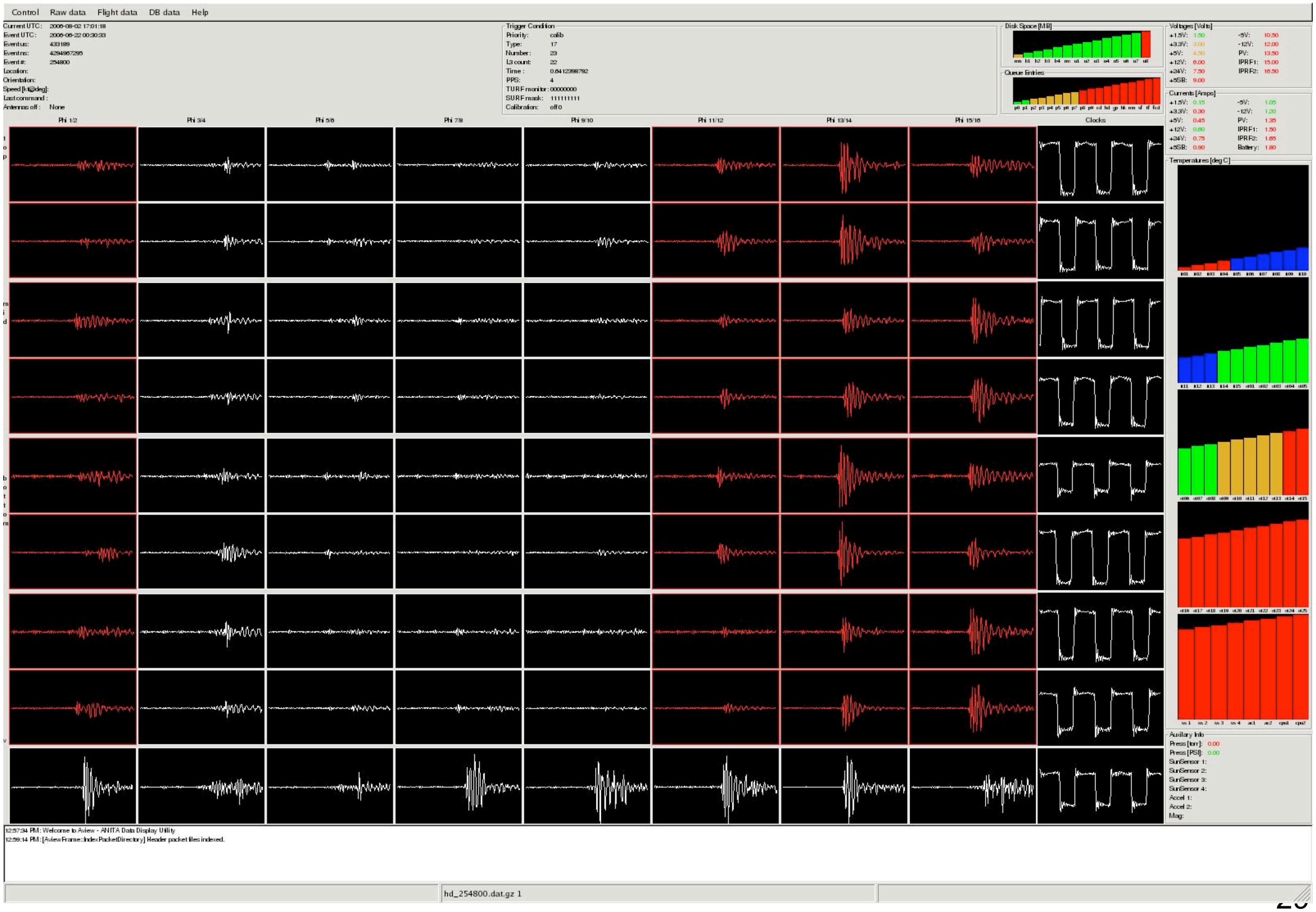
- Original idea, proposed as a method of Big Bang relic neutrino detection via resonant annihilation (T. Weiler PRL 1986):
  - 10^{23} eV ν + 1.9K $\nu \to Z_0$ produces a dip in a cosmic neutrino source spectrum, *IF one has a source of 10^{23} eV neutrinos*
- More recently: Z_0 decay into hadron secondaries 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 at SLAC Endstation A

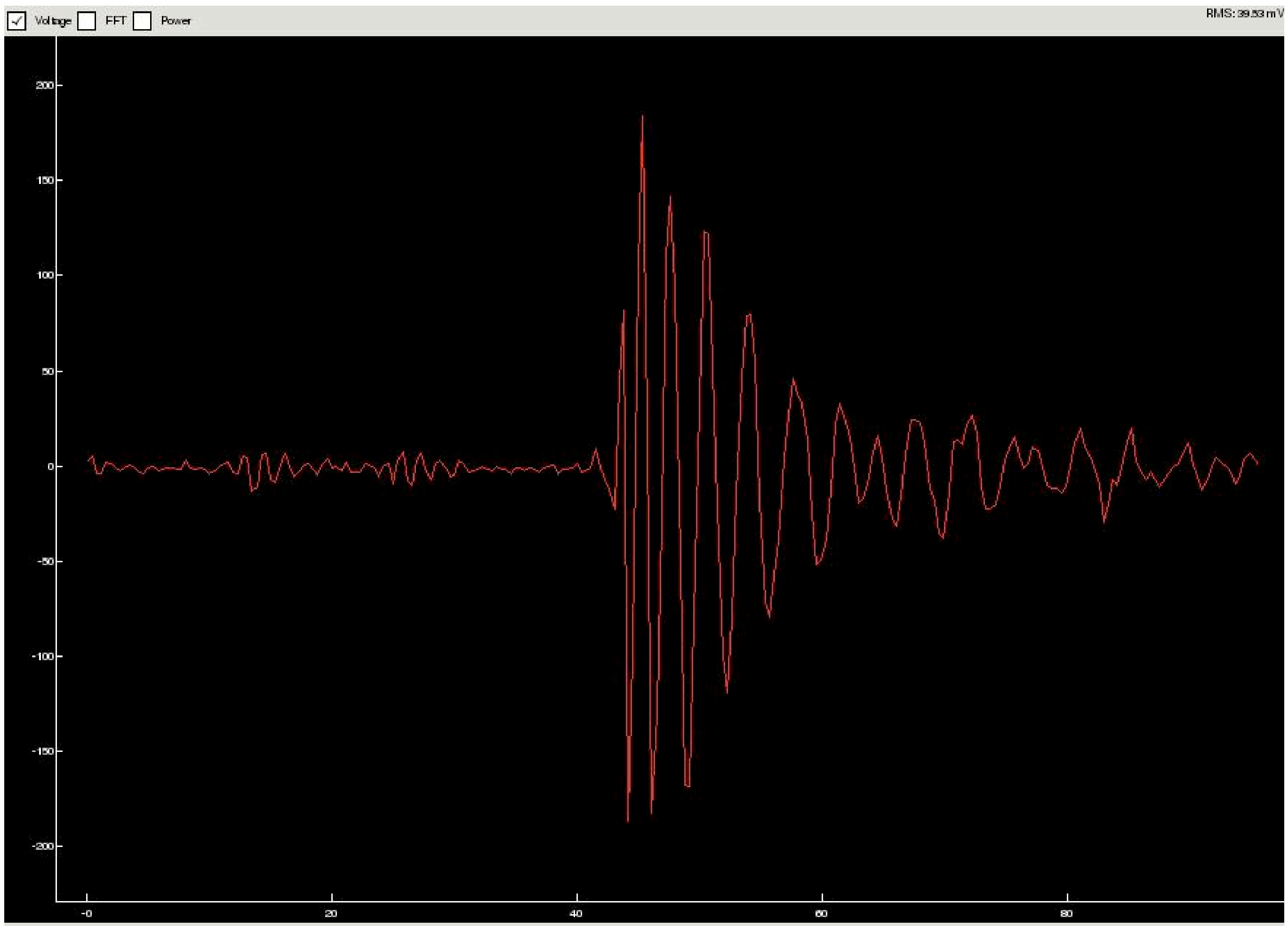


Optical Cherenkov Emission

ANITA at SLAC



Askaryan Pulse from Ice

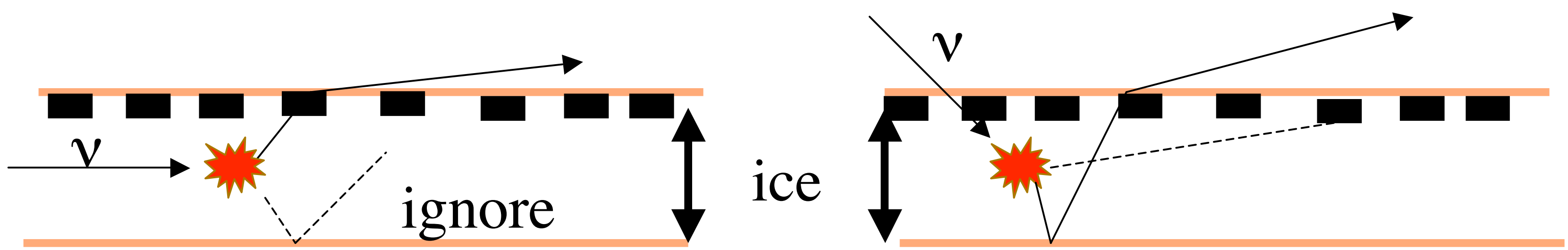


ANITA is on its way to the ice

After a successful full-system checkout, the instrument has been disassembled and is on its way to Antarctica.

The flight is scheduled for December 2006.

Reflected and Direct Events

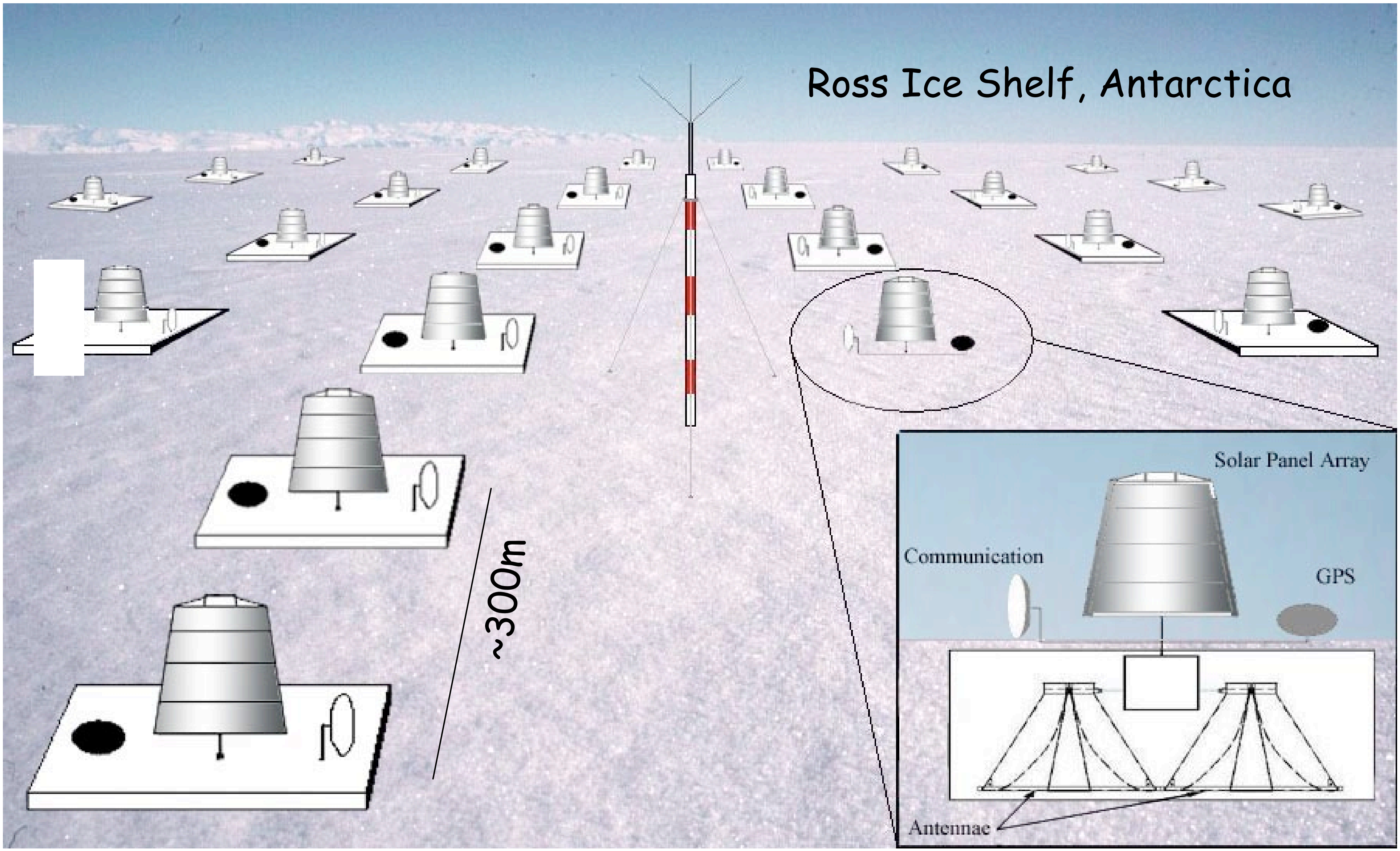


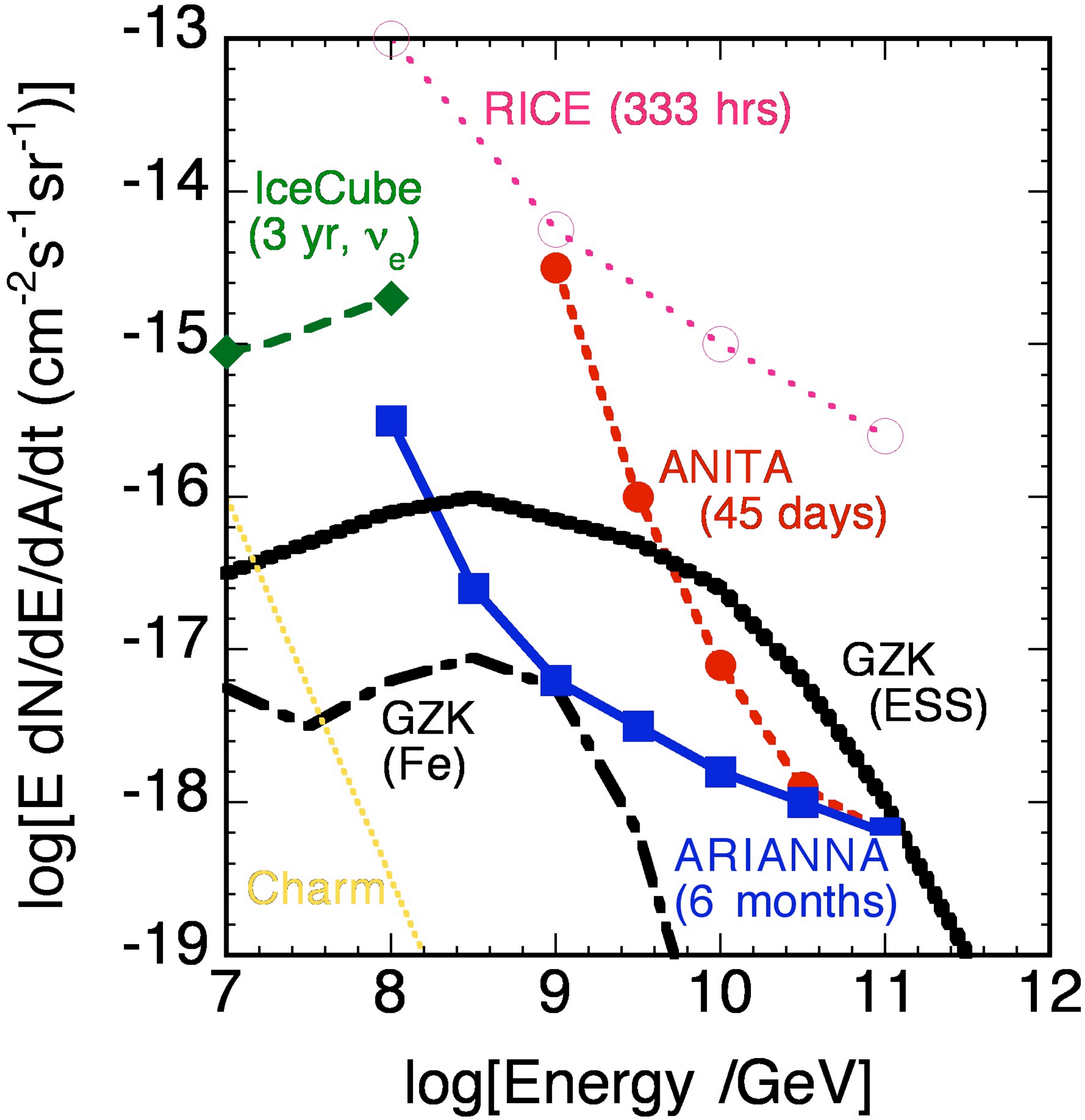
Direct

Reflected
(much greater solid angle)

S. Barwick et al.,
in preparation

ARIANNA Concept
100 x 100 station array





RICE (333 hrs)
IceCube
(3 yr, ν_e)
ANITA
(45 days)
GZK
(ESS)
GZK
(Fe)
ARIANNA
(6 months)
Charm
-13
-14
-15
-16
-17
-18
-19
7
8
9
10
11
12
log[E dN/dE/dA/dt (cm^{-2}s^{-1}sr^{-1})]
log[Energy /GeV]

[redacted]