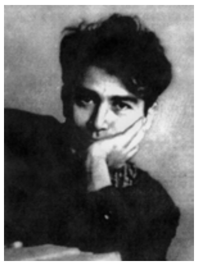
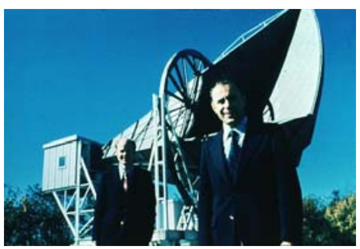
New Prospects for Detection of the Highest Energy Cosmogenic Neutrinos

Peter Gorham
University of Hawaii

Science roots: the 60's





1. 1961: First 10^{20} eV cosmic ray air shower observed
   - John Linsley, Volcano Ranch, Utah
2. 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)
4. 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

$$p, \gamma \; + \gamma(3K) \longrightarrow \text{pions, e+e-} \longrightarrow \text{GZK neutrinos}$$

"GZK cutoff " process

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

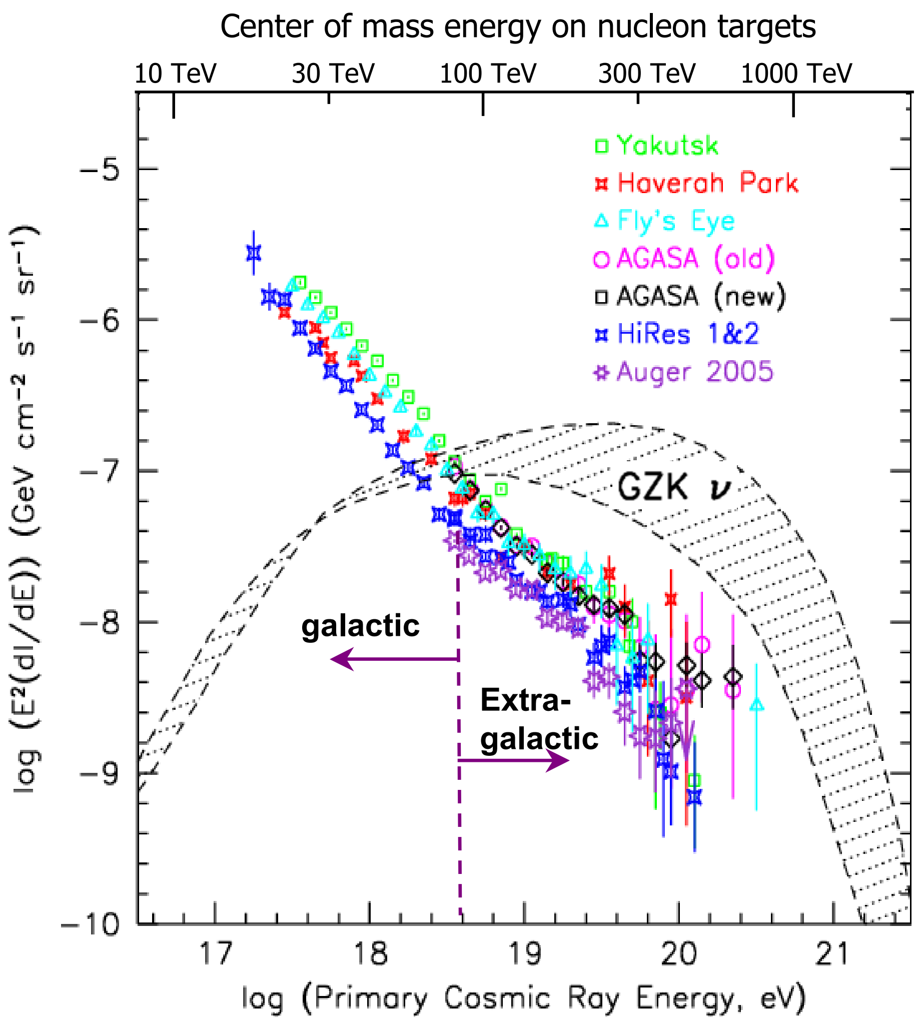
Cornell University, Ithaca, New York
(Received 1 April 1966)

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

- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV, after 40 years!

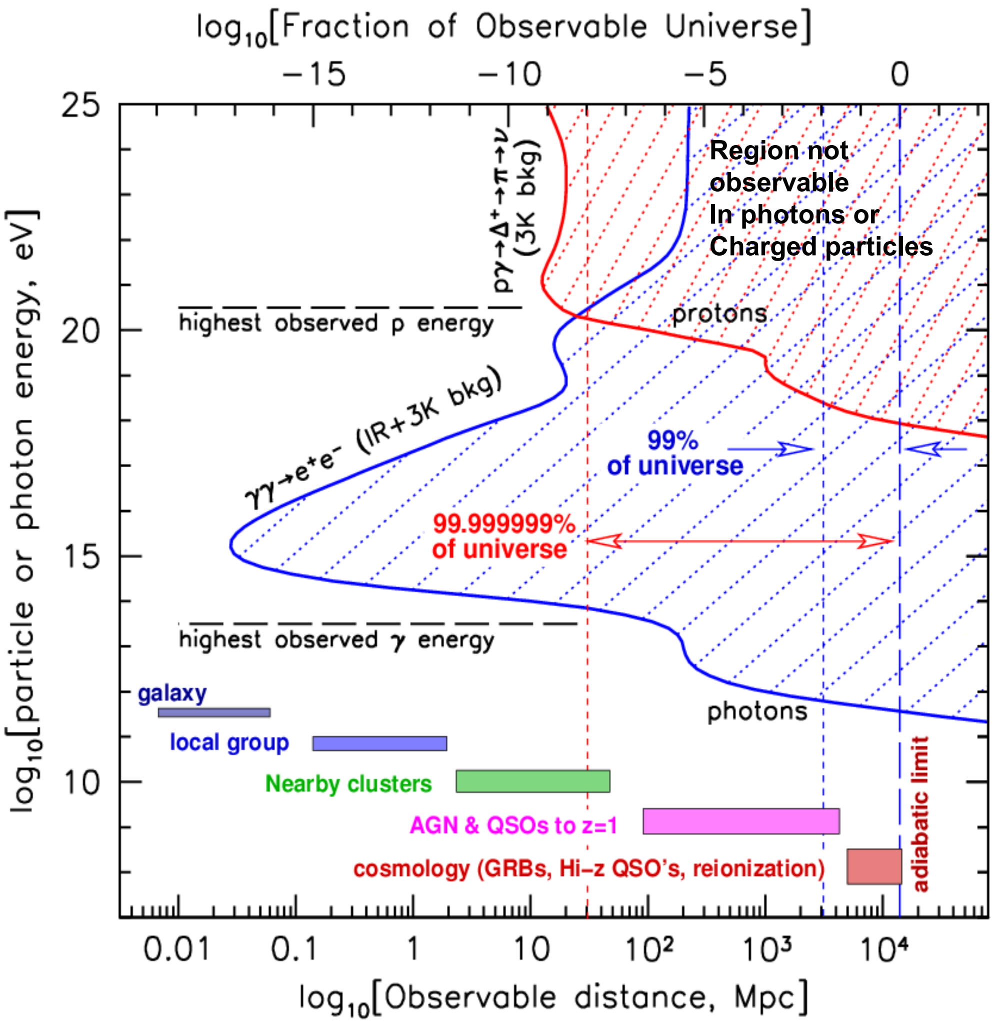
- A paradox:
  - No <u>nearby</u> sources observed
  - distant sources <u>excluded</u> due to GZK process

- **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



* Berezinsky et al. 1971.

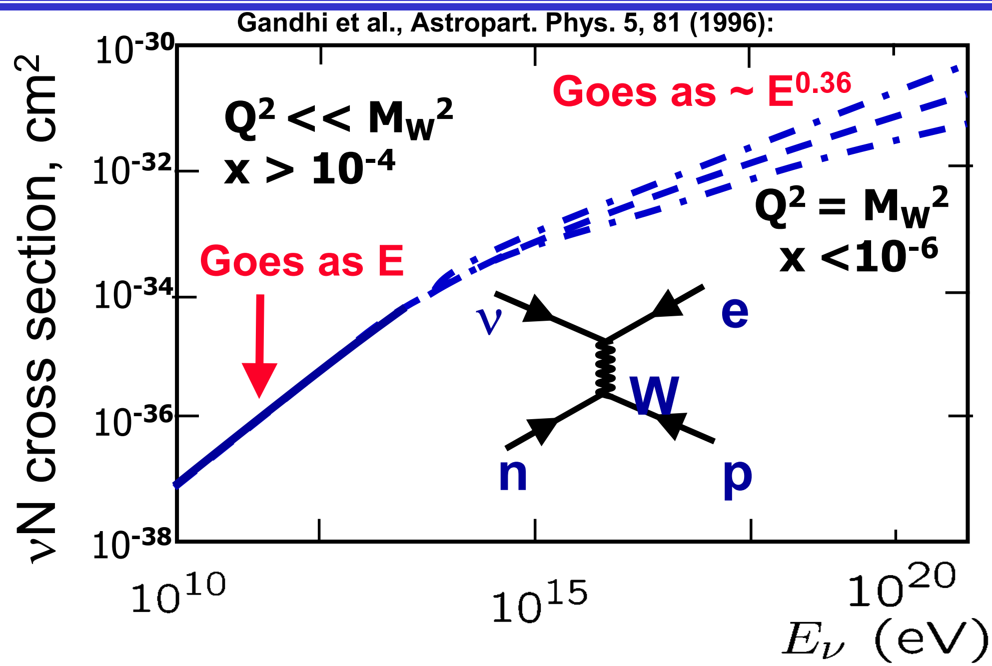
Neutrinos: The only long-range messengers at PeV energies and above

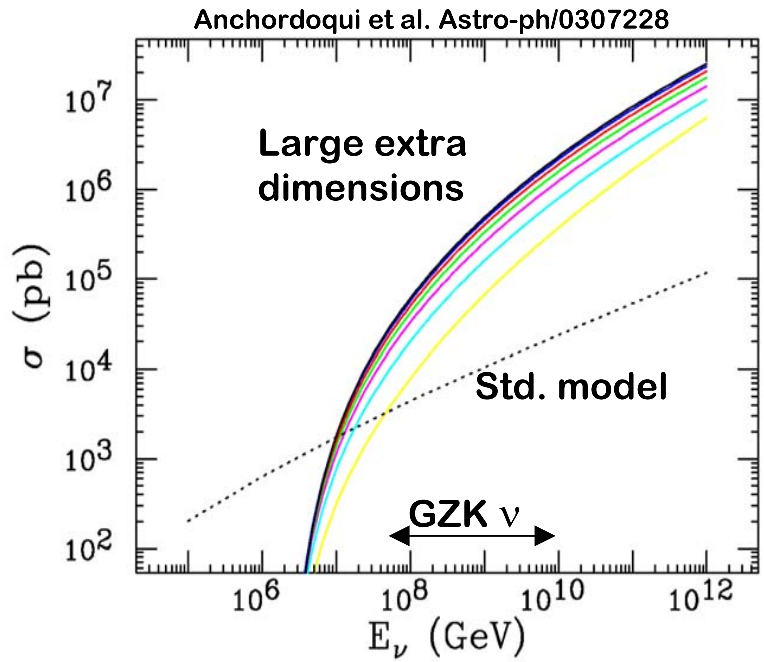


- Photons lost above 30 TeV: pair production on IR & μwave background
- Charged particles: scattered by B-fields or GZK process at all energies
- BUT: Sources known to extend to 10^9 TeV, maybe further if limited only by GZK

- => Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors

Particle Physics: Energy Frontier & Neutrinos

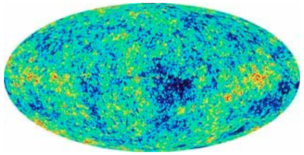




- Well-determined GZK ν spectrum becomes a useful neutrino beam
  - 10-1000 TeV center of momentum weak-interaction particle physics
  - study large extra dimensions at scales beyond reach of LHC
  - ν Lorentz factors of $\gamma = 10^{18\text{-}21}$ assuming 0.01 eV masses
- Measured flavor ratios $\nu_e:\nu_\mu:\nu_\tau$ --deviations from 1:1:1 are interesting!
  - identify non-standard physics at sources (GRBs: Kashti & Waxman astro-ph/0507599)
  - Sensitive to sterile ν admixtures & anomalous ν decays (eg. Beacom et al PRL/PRD 2003)

GZK ν Particle Astrophysics/Cosmology

- Cosmic ray sources & maximum acceleration energy
  - Most of GZK ν flux is from $z > 1$, sources several Gpc away; every GZK neutrino effectively points to a GZK cosmic ray source!
- UHECR flux vs. redshift to $z = 15\text{-}20$, eg. WMAP early bright phase, re-ionization



- Independent sensitivity to dark energy density
  - GZK Source function depends on Ω_Λ, probes larger range of z than other tracers
- Exotic (eg. Top-down) sources; GUT-scale decaying relics or topological defects

What is needed for a GZK ν detector?

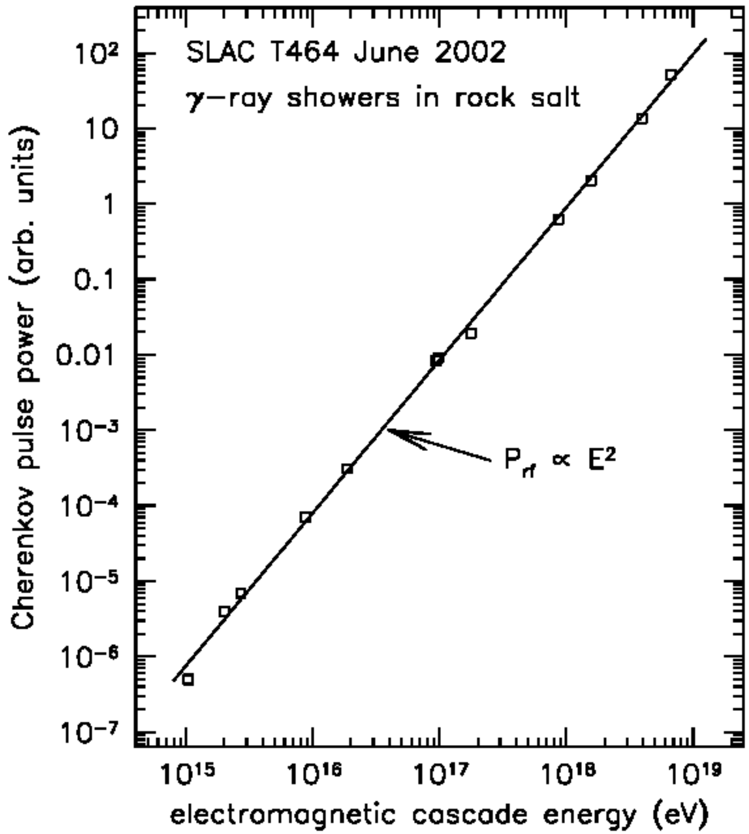
- Standard model GZK ν flux: <1 per km^2 per day over 2π sr
  - Interaction probability per km of water = 0.2%
  - Derived rate of order 0.5 event per year per cubic km of water or ice

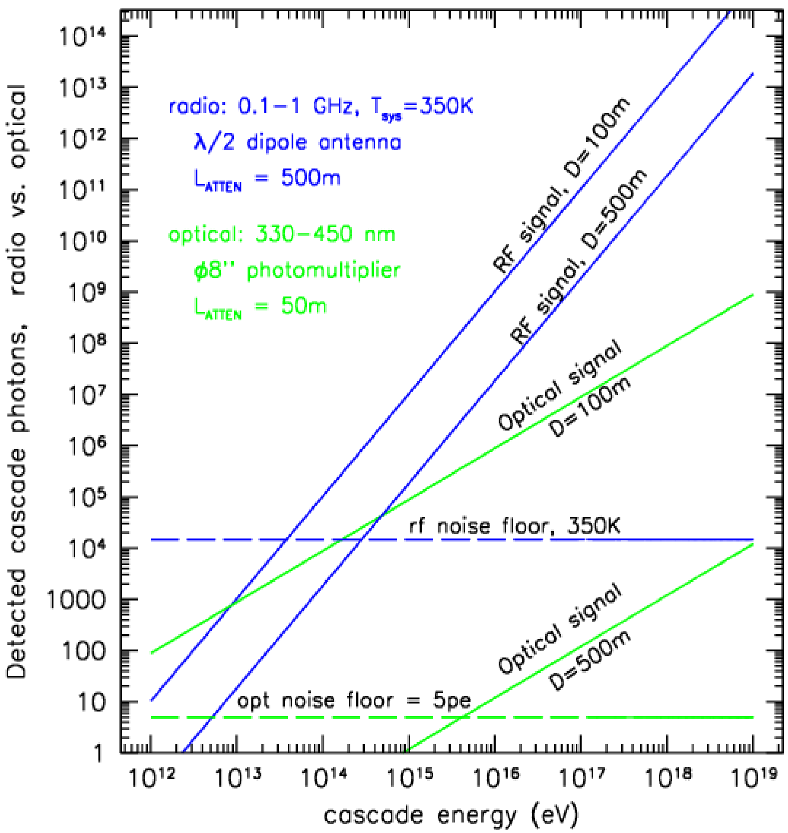
➔ A teraton (1000 km^3 sr) target is required!

Problem: how to scale up from current water Cherenkov detectors

- One solution: Askaryan effect: coherent radio Cherenkov emission
  - Particle showers in solid dielectrics yield strong radio impulses
  - Neutrinos can shower in many radio-clear media: air, ice, rock-salt, etc.
  - Economy of scale for radio (antenna array + receivers) is very competitive for hypergiant detectors

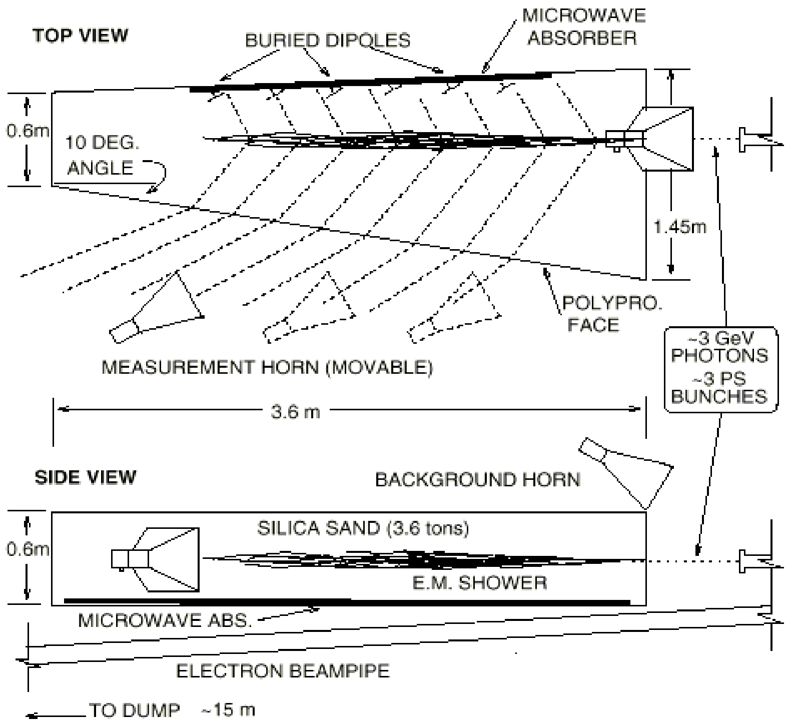
Radio vs. optical Cherenkov detection

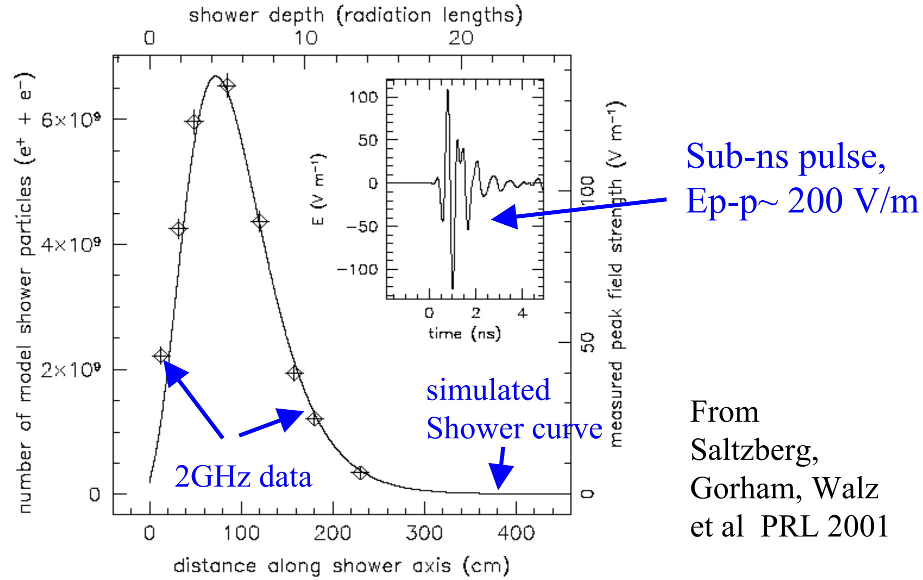




- RF signal grows quadratically with shower energy, dominates above PeV
- Both RF & optical have high SNR at E>PeV, but transmissivity of target materials (ice, salt, etc.) is much higher in RF ==> RF owns HE regime

Askaryan Effect: SLAC T444 (2000)



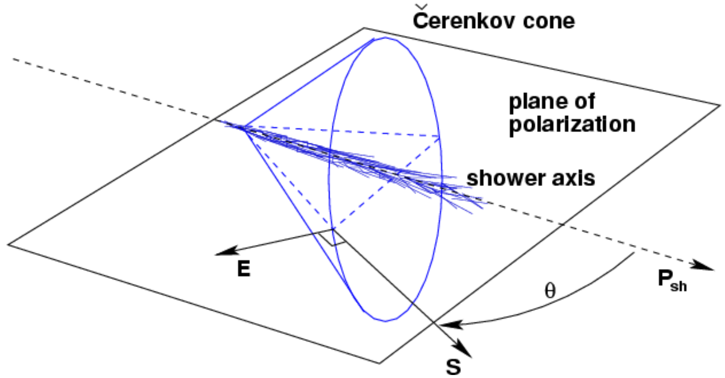


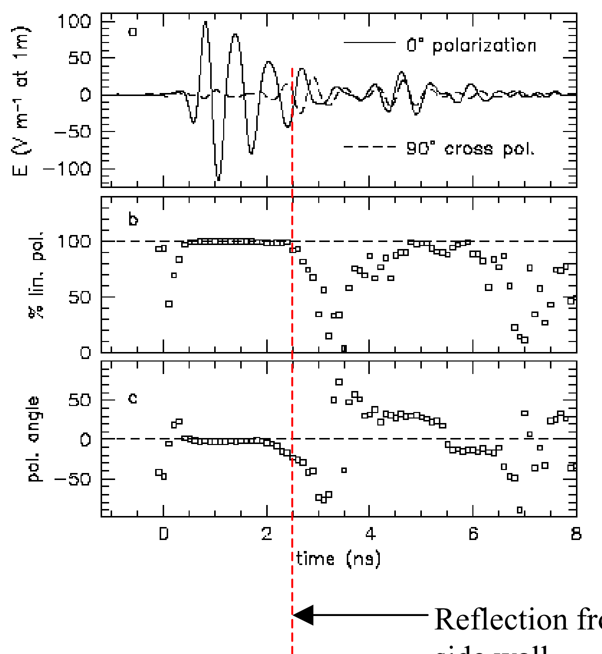
From Saltzberg, Gorham, Walz et al PRL 2001

- 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!

Cherenkov polarization tracking

Emission 100% linearly polarized in plane of shower





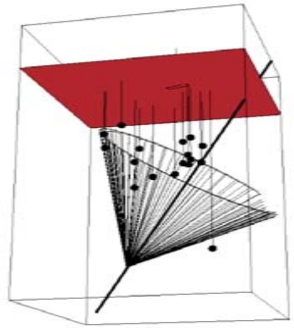
100% polarized

In proper plane

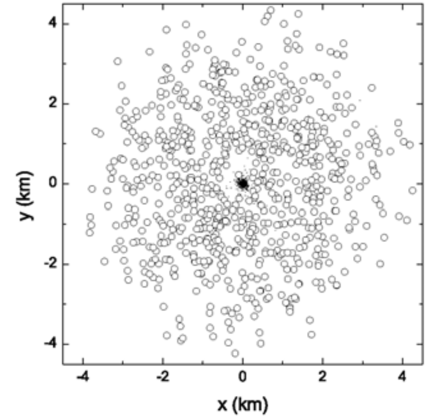
Reflection from side wall

- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone will measure different projected plane of E, S
- Intersection of these planes defines shower track

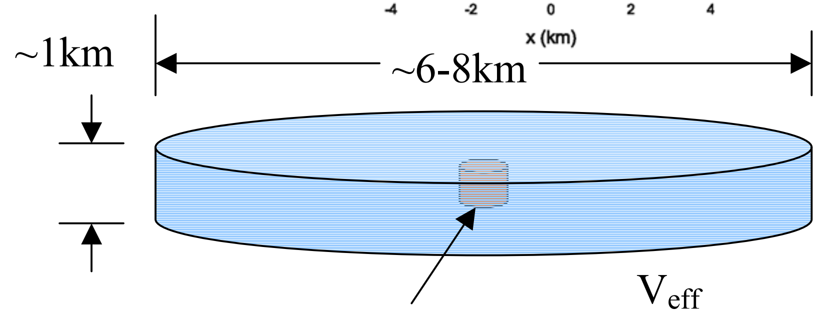
Radio Ice Cherenkov Experiment (RICE)



~1 EeV
Monte Carlo
Event vertices

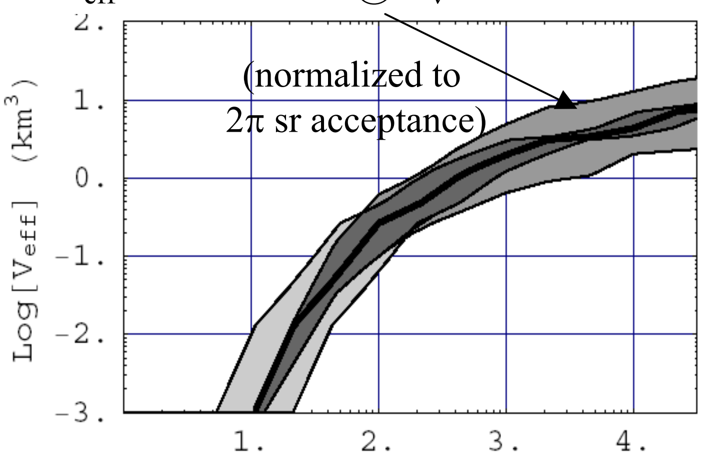


RICE: testbed array of antennas embedded in 100-350m of ice above the AMANDA optical Cherenkov neutrino telescope at S. Pole--in operation since about 1998



RICE fiducial V ~100m radius

$V_{eff}\,\Omega \sim 3\ km^3\ sr\ @\ E_\nu \sim 1\text{-}2\ EeV$



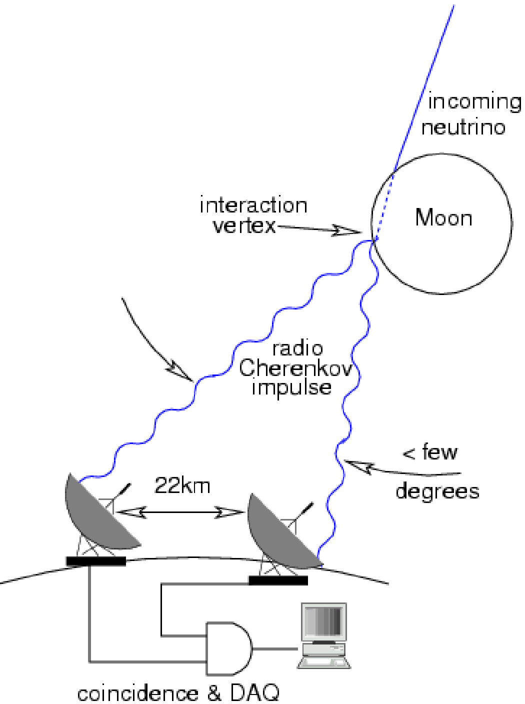
$\text{Log}\ (E_{shower}, \text{PeV}) \sim 0.2\ E_\nu$

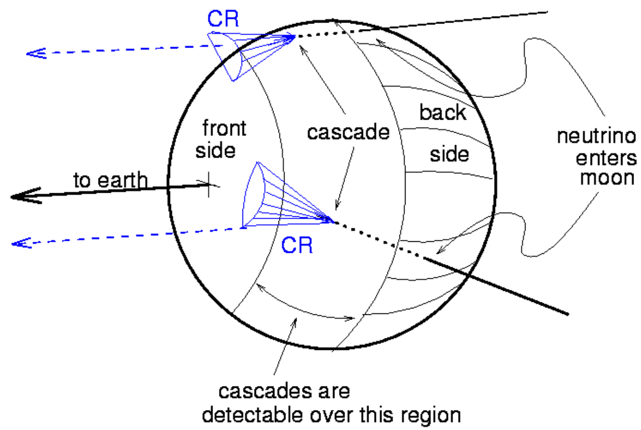
- Large >EeV effective volume based on ice transparency:
  - L_{atten} ~ 1km at 300 MHz
- Best current limits in PeV-EeV energy range

Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)-- A ZeV example…

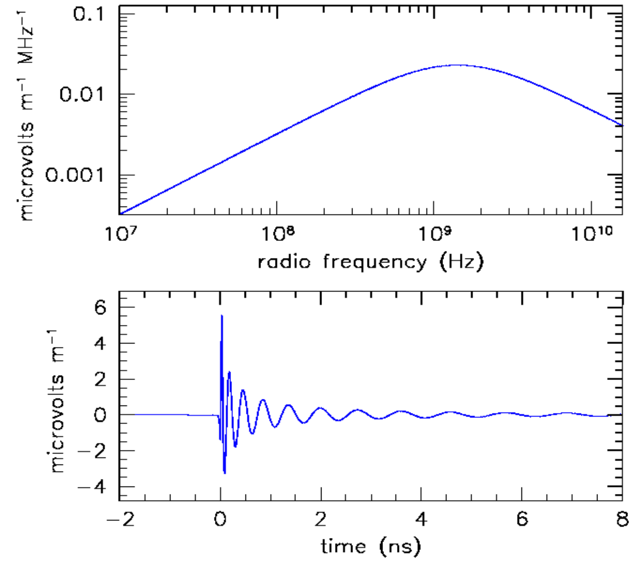
- Used NASA Deep Space Network antennas to search for Askaryan pulses from neutrinos interacting in lunar regolith
- Used coincidence to beat RF interference
- Askaryan suggested the moon; I. Zheleznykh ('88) showed we don't have to go there with antennas
- Hankins & Ekers did first experiment with Parkes in 1996

GLUE geometry & effective target volume



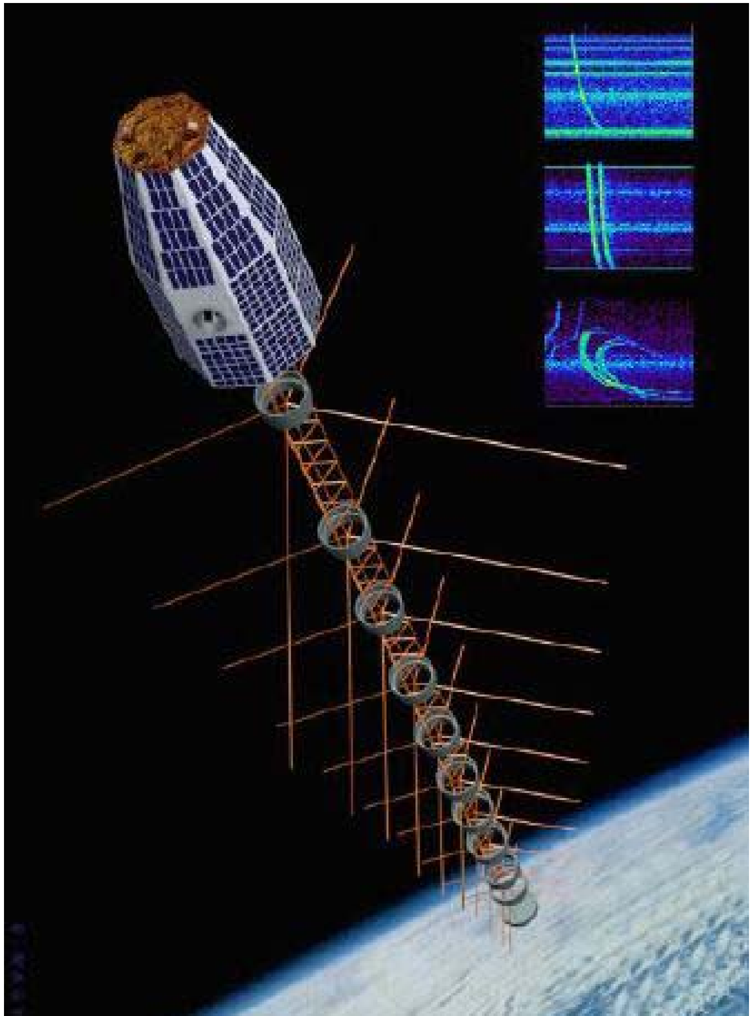


RF pulse spectrum & shape



- Effective target volume: 30% of 20M km^2 lunar surface down to of order 10 m depth
- ~100,000 cubic km water equivalent!!
- Experiment completed in 2003 with 120hrs of total livetime (PRL 2004)--no candidates yet seen, but threshold was 100 EeV or more

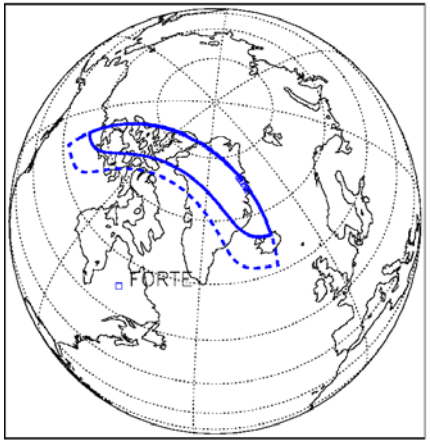
FORTE: An accidental space-based EHE neutrino detector

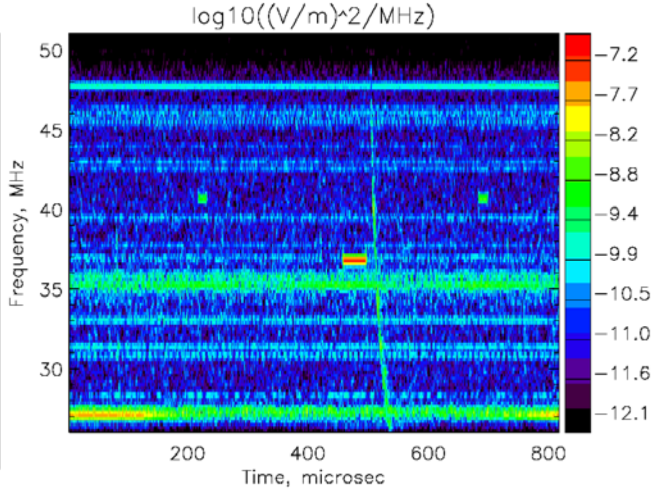


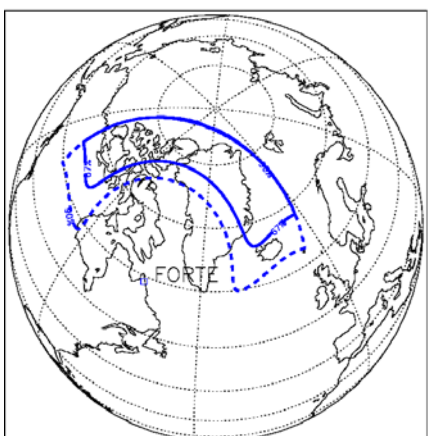
Fast On-orbit Recording of Transient Events

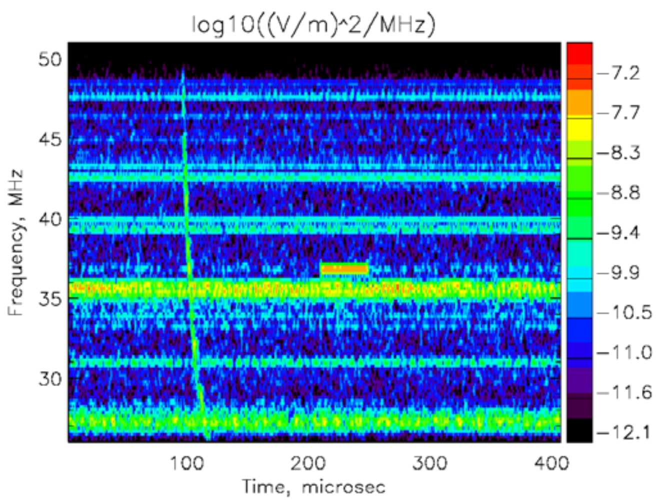
- Pegasus launch in mid-1997, 800km orbit
  - Testbed for nuclear verification sensing
  - US DOE funded, LANL/Sandia ops
  - Scientific program in lightning & related atmospheric discharges
- 30-300 MHz (VHF) frequency range
  - ~3M impulsive triggers recorded (End of mission in 2003)
- FORTE data used in 2003 to set first limits on UHE neutrinos in the $10^{22\text{-}24}$ eV energy range

FORTE: Search for neutrino candidate events from Greenland ice sheet (N. Lehtinen et al., PRD 2004)



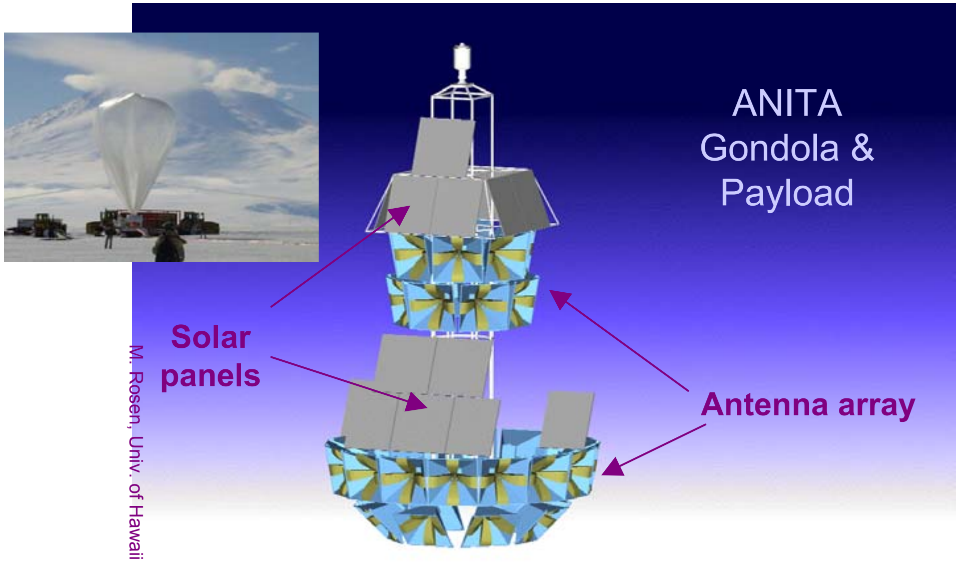




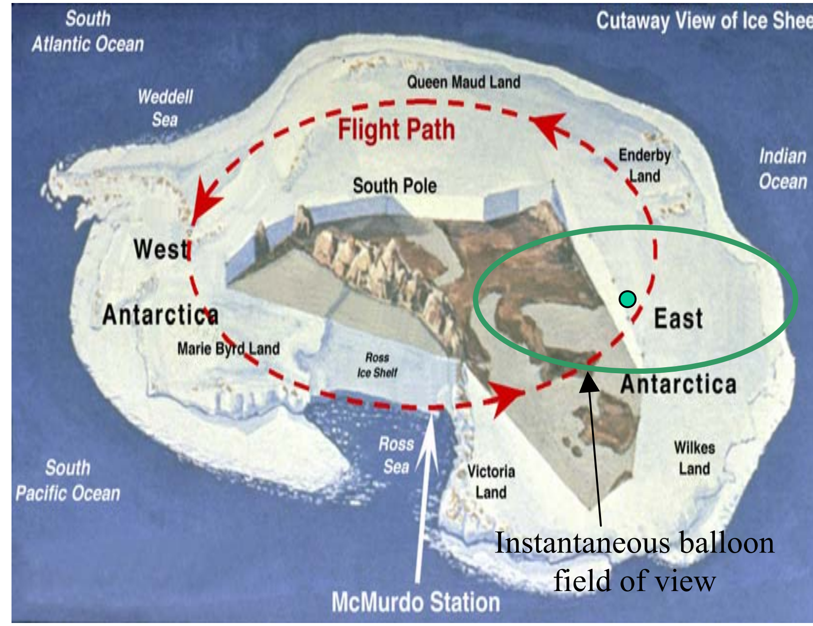


- 3.8 days total livetime over Greenland
  - Not designed for high efficiency
- Threshold high: $10^{22.5}$ eV
- Plots: frequency vs. time
  - Strong CW signals (earth transmitters) = horizonal bands
  - Impulses cross entire band, curvature due to ionospheric dispersion
- 1 candidate survives out of ~2500 initial events
  - Require high polarization, non-lightning, geolocation consistent w/ ice origin

Antarctic Impulsive Transient Antenna--ANITA

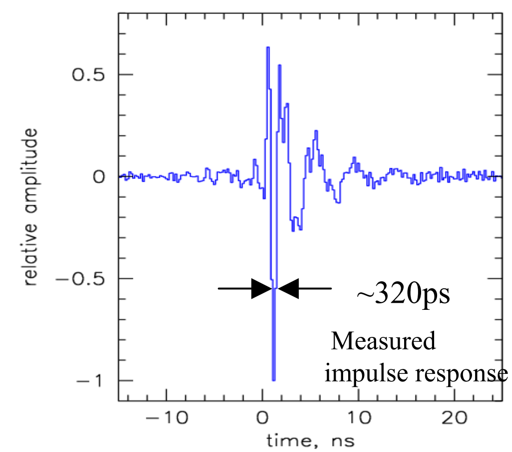


Overall height ~8m

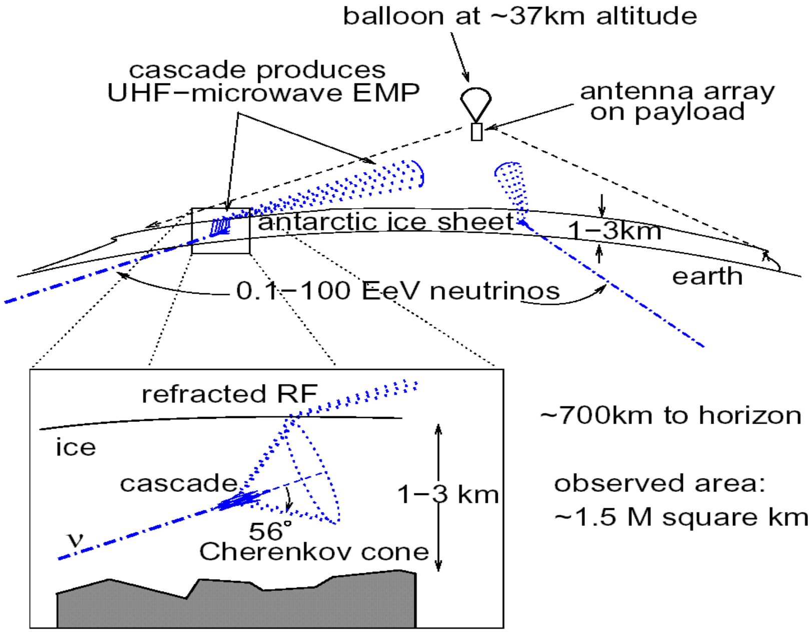


- NASA start in 2003, first LDB launch in '06-07
- Ultra-broadband antenna array, views large portion of ice sheet looking for Askaryan impulses

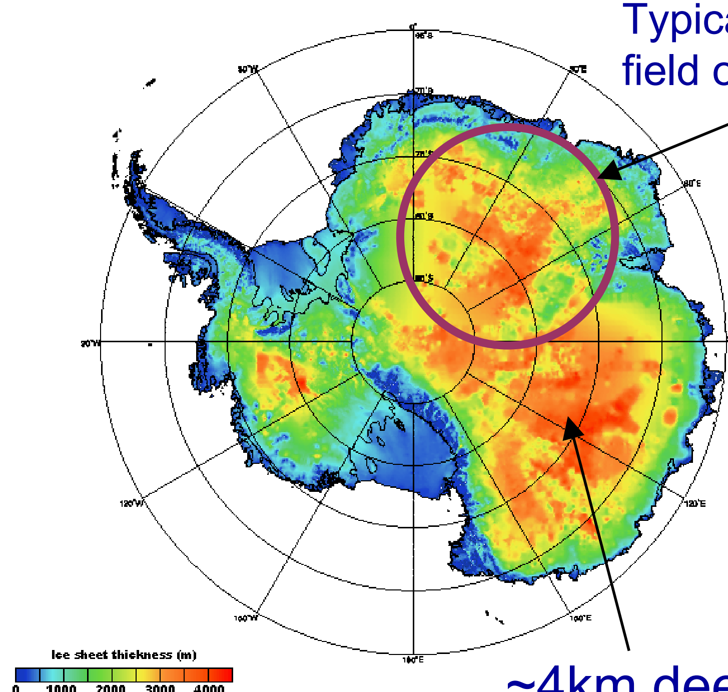
Quad-ridged-horn dual-pol antenna



ANITA concept

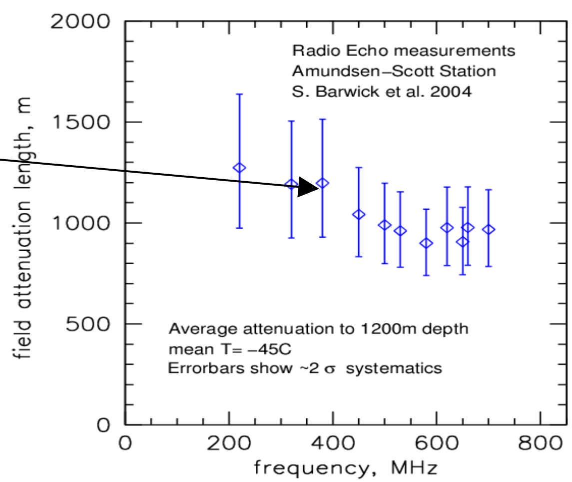


Typical balloon field of regard



~4km deep ice!

Ice RF clarity: 1.2 km(!) attenuation length

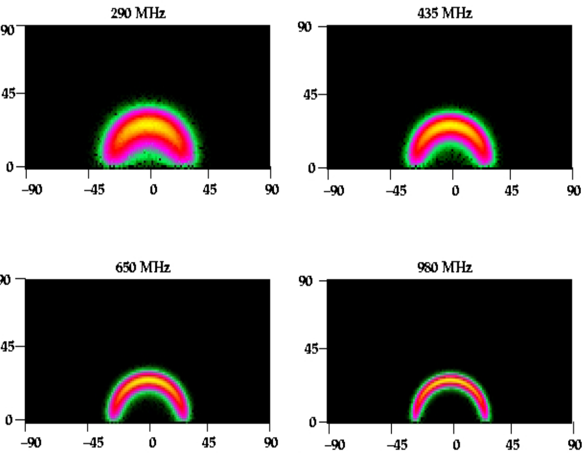


Effective "telescope" aperture:

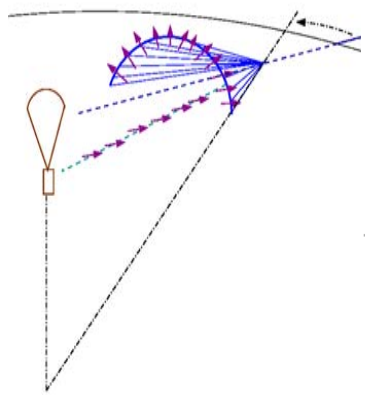
- ~250 km^3 sr @ $10^{18.5}$ eV
- ~10^4 @ km^3 sr 10^{19} eV

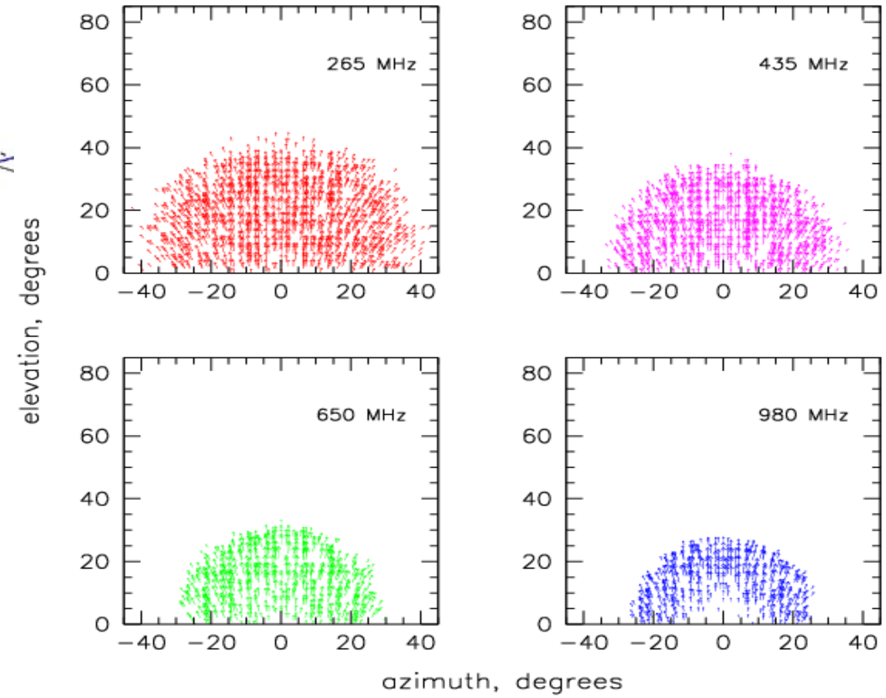
Area of Antarctica ~ area of Moon!

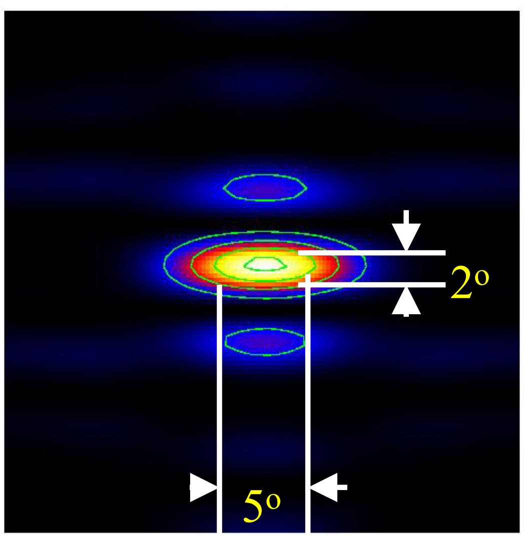
ANITA as a neutrino telescope



Up-angle 4 degrees, E=3 EeV, smooth surface

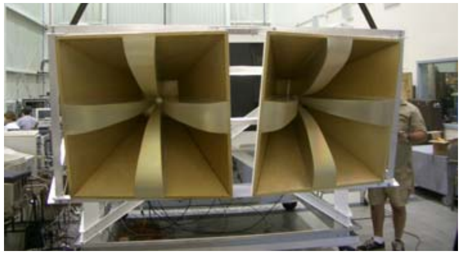






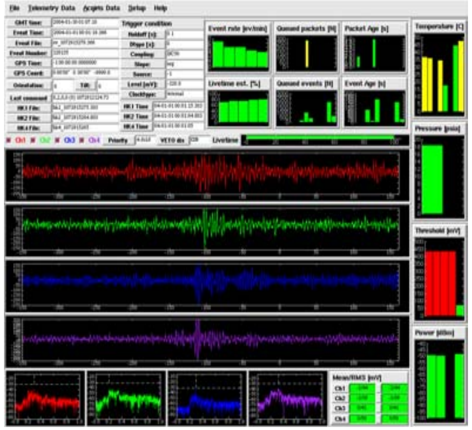
- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival** direction of radio pulse
- Neutrino direction constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

ANITA-lite Prototype flight 2004



- Piggyback Mission of Opportunity on the 03-04 TIGER* flight, completed mid-January 04

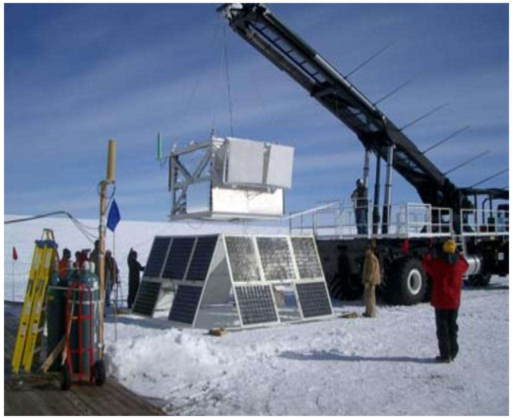
- ANITA prototypes & off-the-shelf hardware used
  - 2 dual-pol. ANITA antennas w/ low-noise amps
  - 4 channels at 1 GHz RF bandwidth, 2 GHz sampling



- 18.4 days flight time, 40% net livetime due to slow (4sec per event) GPS time readout

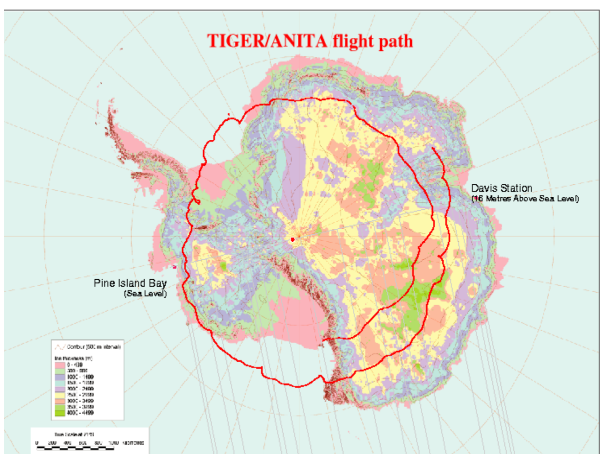
*Trans-Iron Galactic Element Recorder

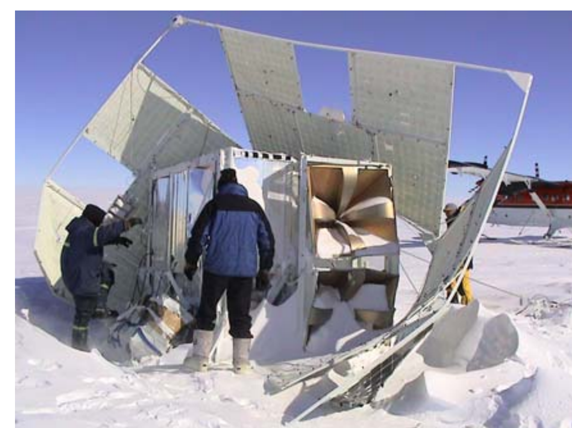
TIGER/ANITA-lite launch…



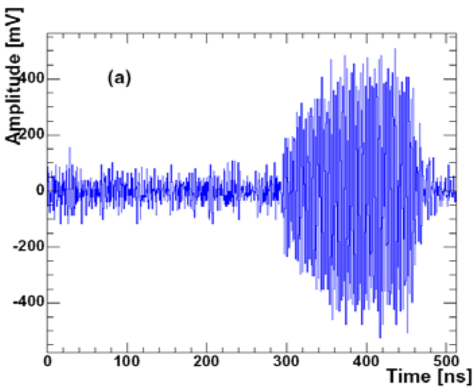
….flight…

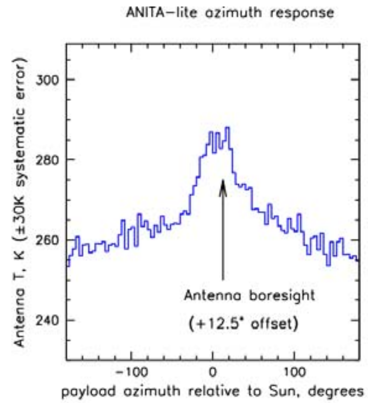
… & landing!

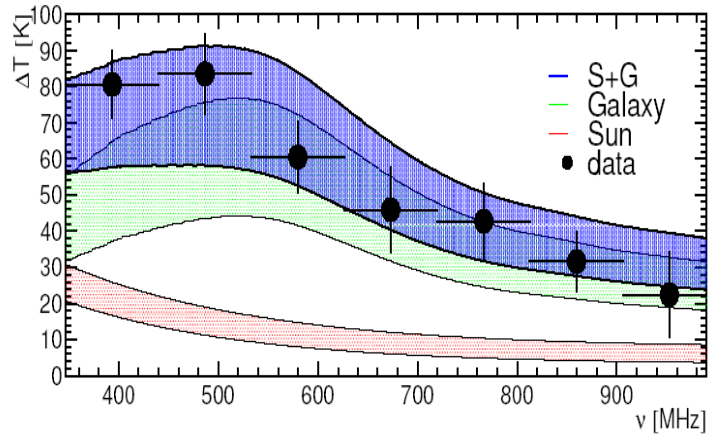




ANITA-lite sensitivity calibration



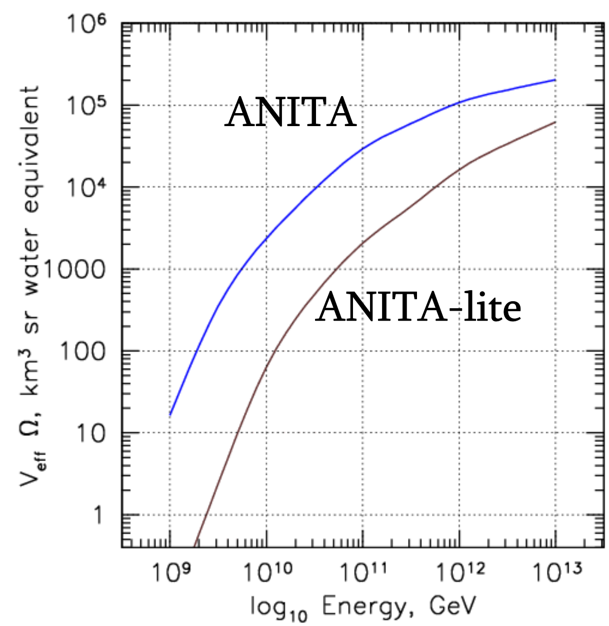




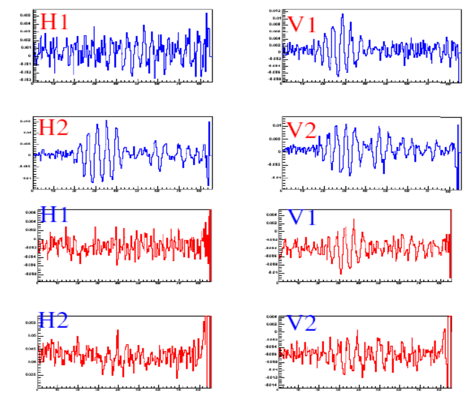
- Ground RF pulser used with GPS synch out to 200-300 km from McMurdo station

- Galactic Center & solar thermal & non-thermal RF emission provided realtime antenna sensitivity, along with onboard noise diodes for gain calibration

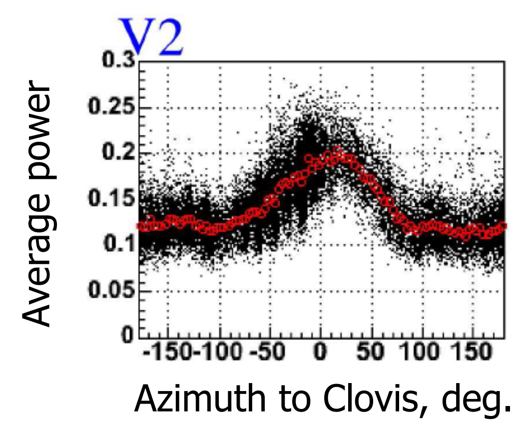
- Aperture estimate by Monte-Carlo using ice thickness data & balloon trajectory



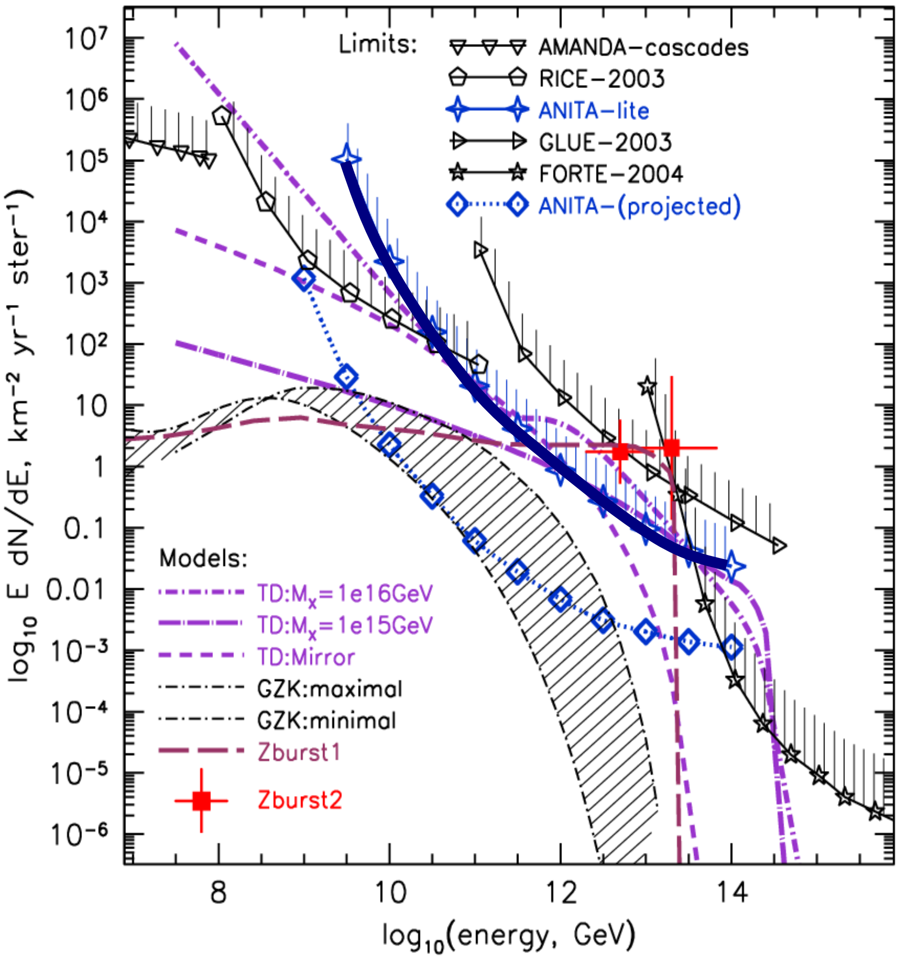
ANITA Engineering Flight, August 2005



- August 29,2005, Ft. Sumner New Mexico
  - All subsystems represented (two dual-pol. antennas only, to limit landing damage)
  - 8 m tall Gondola performed perfectly
  - No science possible due to EMI (Cannon AFB in nearby Clovis), but waveform recording worked well
  - Full ANITA payload now cleared for Antarctica



Current Limits & projections



Strongest limits: all radio

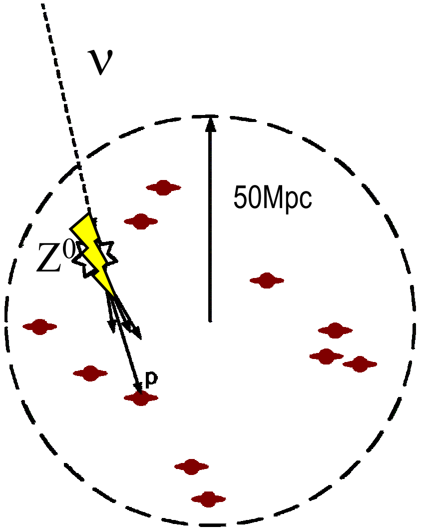
- RICE limits for 3500 hours livetime
- GLUE limits 120 hours livetime
- FORTE limits on 3.8 days of livetime

- ANITA-lite: 18.4 days of data, net 40% livetime with 60% analysis efficiency for detection
  - No candidates survive
  - Z-burst UHECR model ($\nu\nu$ annihilation -->hadrons) excluded:
    - we expect 6-50 events, see none
  - Highest Toplogical defect models also excluded

- 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 $\nu + 1.9\text{K}\ \bar{\nu} \longrightarrow Z_0$ produces a dip in a cosmic neutrino source spectrum with a location dependent on the ν mass ,
  - *IF one has a source of 10^{23} eV neutrinos!*



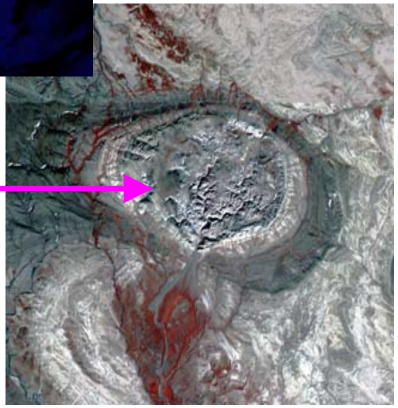
- More recently: Z_0 decay into hadron secondaries gives 10^{20+} eV protons to explain any super-GZK particles, again
  - *IF there is an appropriate source of neutrinos at super-mega-GZK energies*
- (Many authors including Weiler have explored this revived version)

- The Z-burst proposal had the virtue of solving three completely unrelated (and very difficult) problems at once:
  - relic neutrino detection AND ~~super-GZK cosmic rays~~ AND neutrino mass
  - ==> " Nobel^3 " physics…. ? (No, but Nobel^2 still possible!)

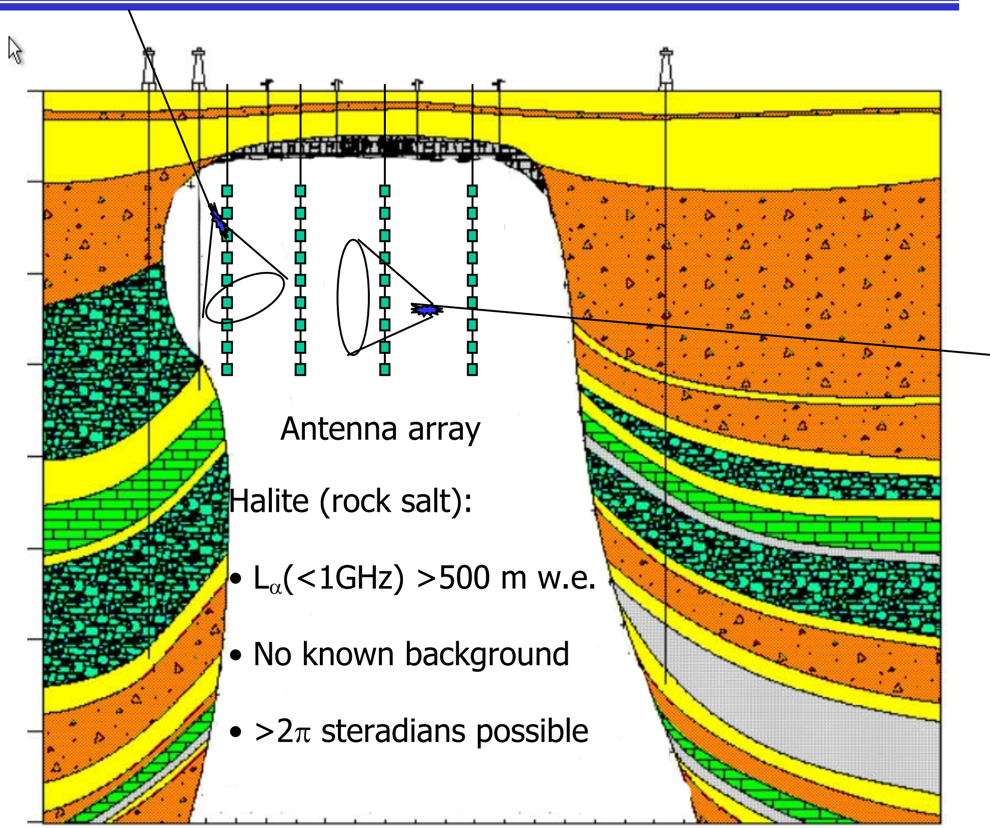
Saltdome Shower Array (SalSA) concept

Salt domes: found throughout the world

Qeshm Island, Hormuz strait, Iran, 7km diameter



Isacksen salt dome, Ellef Ringnes Island, Canada 8 by 5km

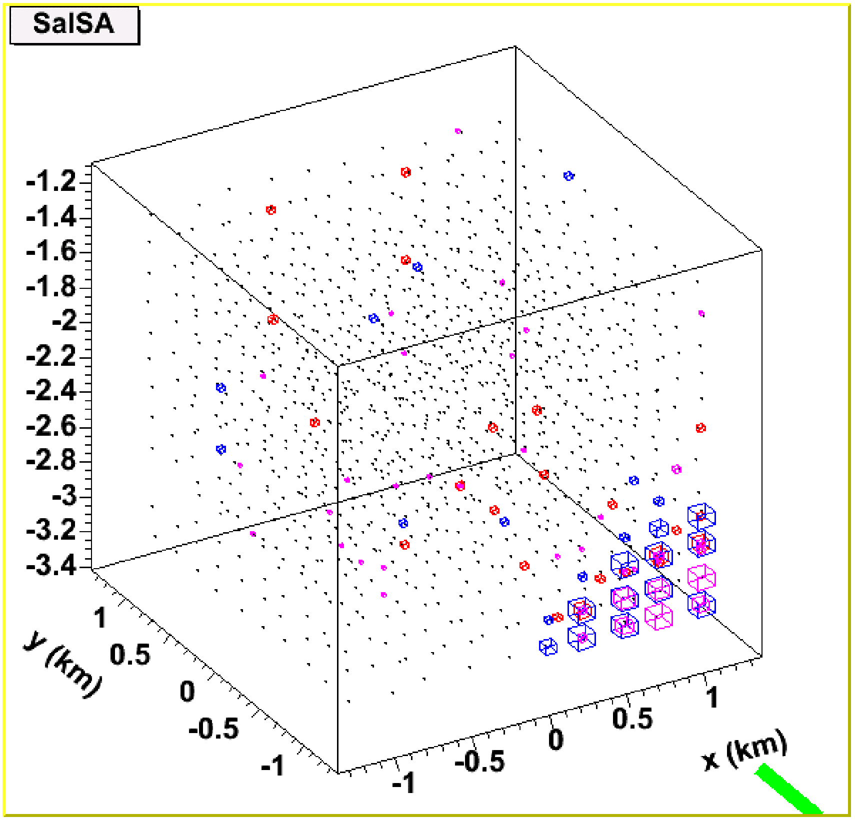


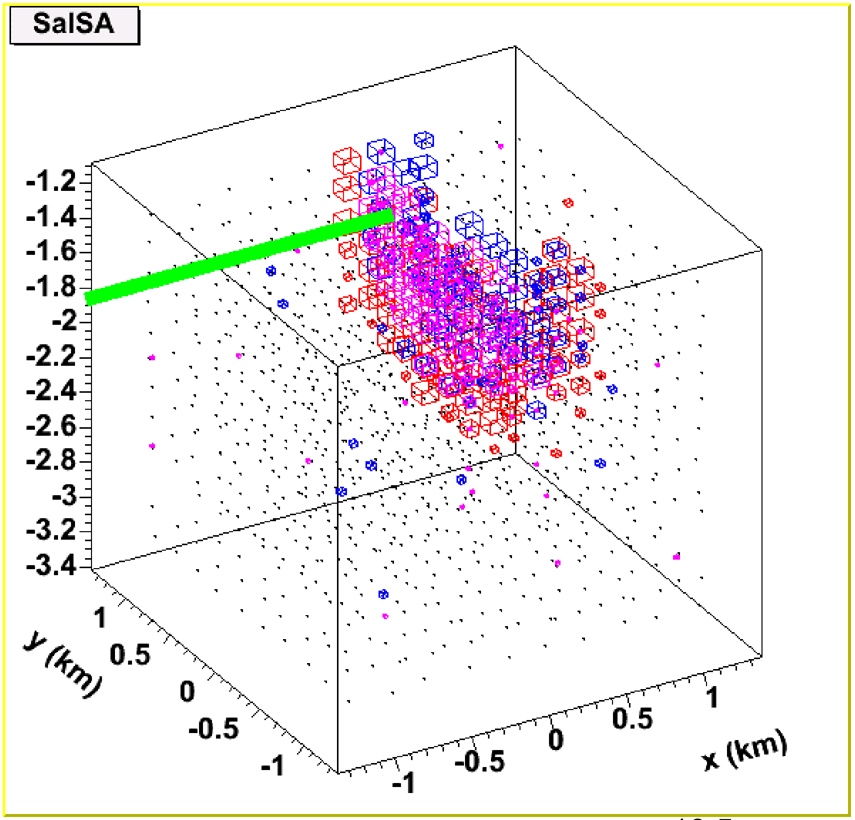
- Pure Rock salt: density of 2.2 g/cc, extremely low RF loss
- typical: 50-100 km^3 water equivalent mass (1g/cc) in top ~3.5km

➡ Up to 300-600 km^3 steradians water equivalent per salt dome

SalSA Events

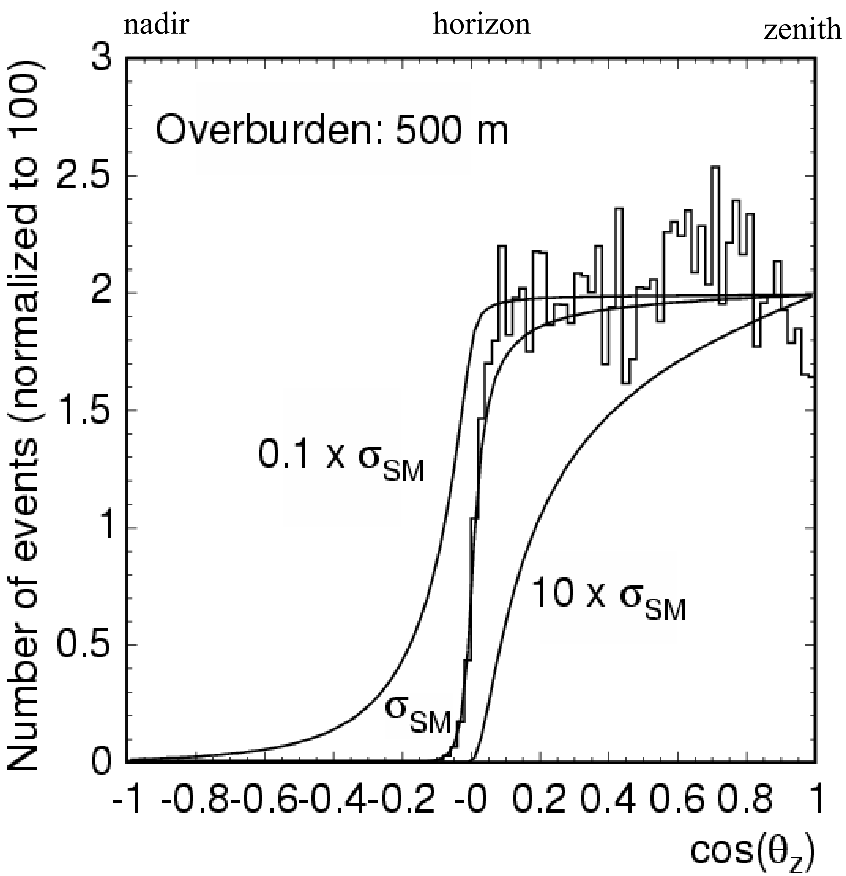
K. Reil (SLAC) simulation, 10x10 strings in 2.5 km3
12 clusters of 12 antennas each per string



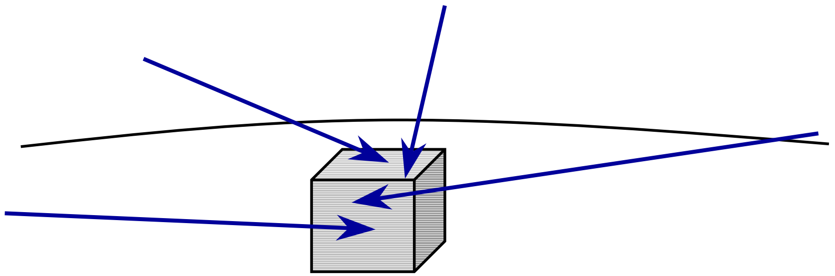


SalSA_{100} $E=10^{18.5}$eV

High energy neutrino cross section

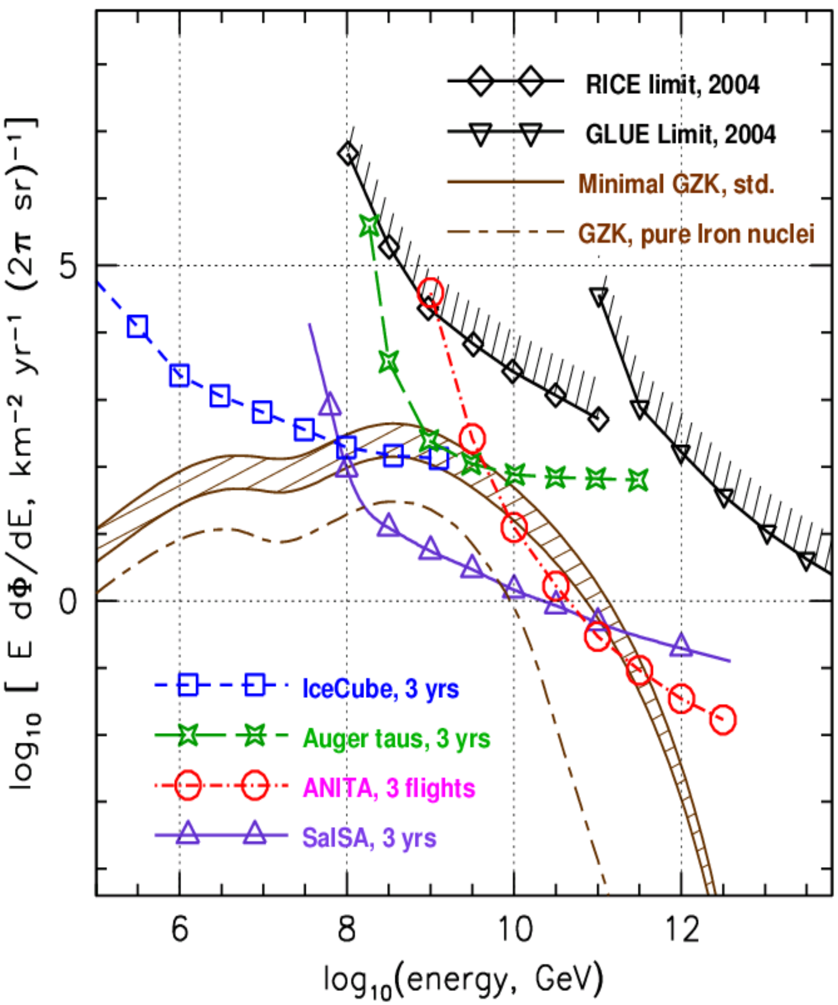


From A. Connolly, D. Saltzberg UCLA



- Embedded neutrino detectors measure model-independent cross section by fitting for interaction length in known overburden (eg. Alvarez-Muniz et al. PRD 65, 2002)
- Requires only an isotropic or otherwise known source intensity distribution--as expected for EeV cosmogenic neutrinos
- SalSA_{100} gets $\Delta\sigma/\sigma \sim 30\%$ for 100 events
- Factor of 2 better than current theory

Existing Neutrino Limits and Future Sensitivity



- RICE limits for 3500 hours livetime
- GLUE limits 120 hours livetime
- ANITA sensitivity, 45 days total:
  - ~5 to 30 GZK neutrinos
- IceCube: high energy cascades
  - ~1.5-3 GZK events in 3 years
- Auger: tau neutrino decay events
  - ~1 GZK event per year?
- SalSA sensitivity, 3 yrs live
  - 70-230 GZK neutrino events

Summary

- Radio Cherenkov detection of cosmogenic neutrinos almost certain within 5 years!

- Rich potential for particle physics/ particle astrophysics

- Next generation ring imaging Cherenkov detectors (eg. SalSA) can begin to do particle physics cosmogenic neutrinos
  - 10-1000 TeV CM weak (or strong?!) interactions