UH HEPG Particle Astrophysics: Radio Detection of High Energy Particles

1. GZK neutrinos revisited, update
2. ANITA update
3. Saltdome Shower array R&D
4. Radio Bremsstrahlung experiment (RaBID)

Prof. P. Gorham, Prof. J. Learned, Prof. G. Varner+ (presenter)

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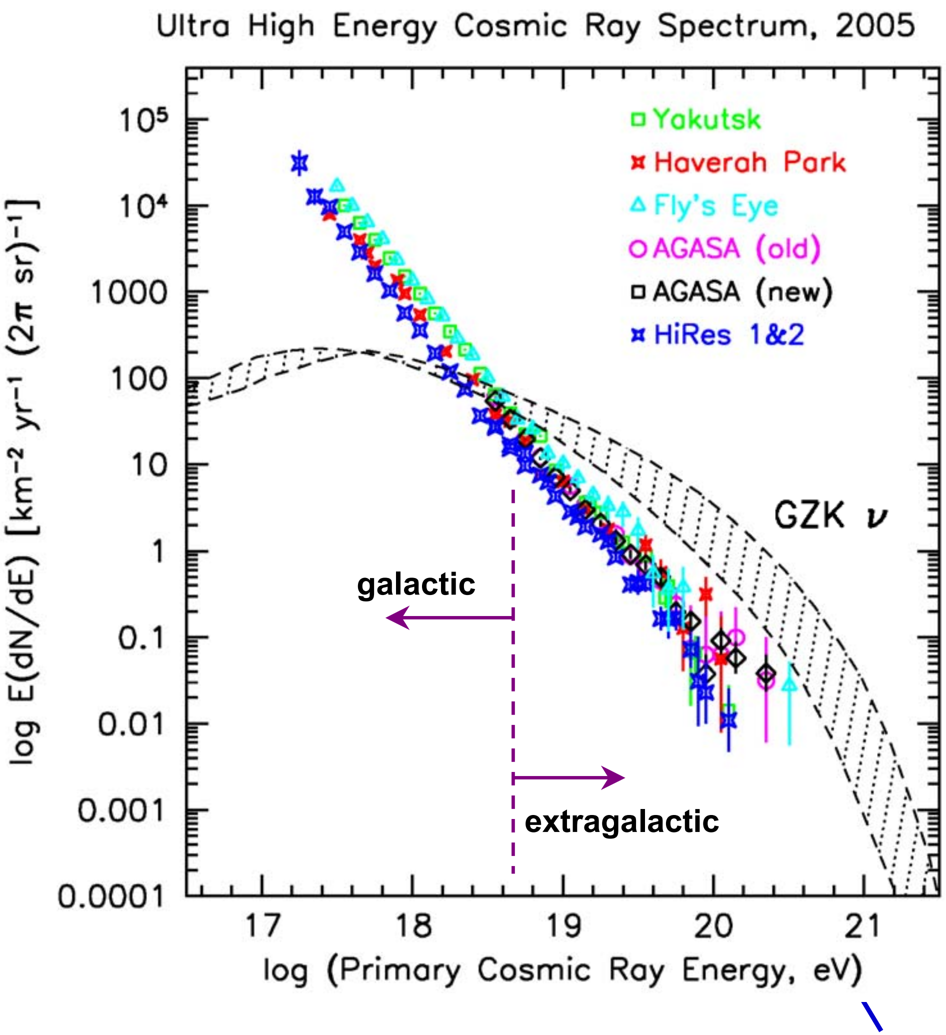
* New group members

+New faculty!

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

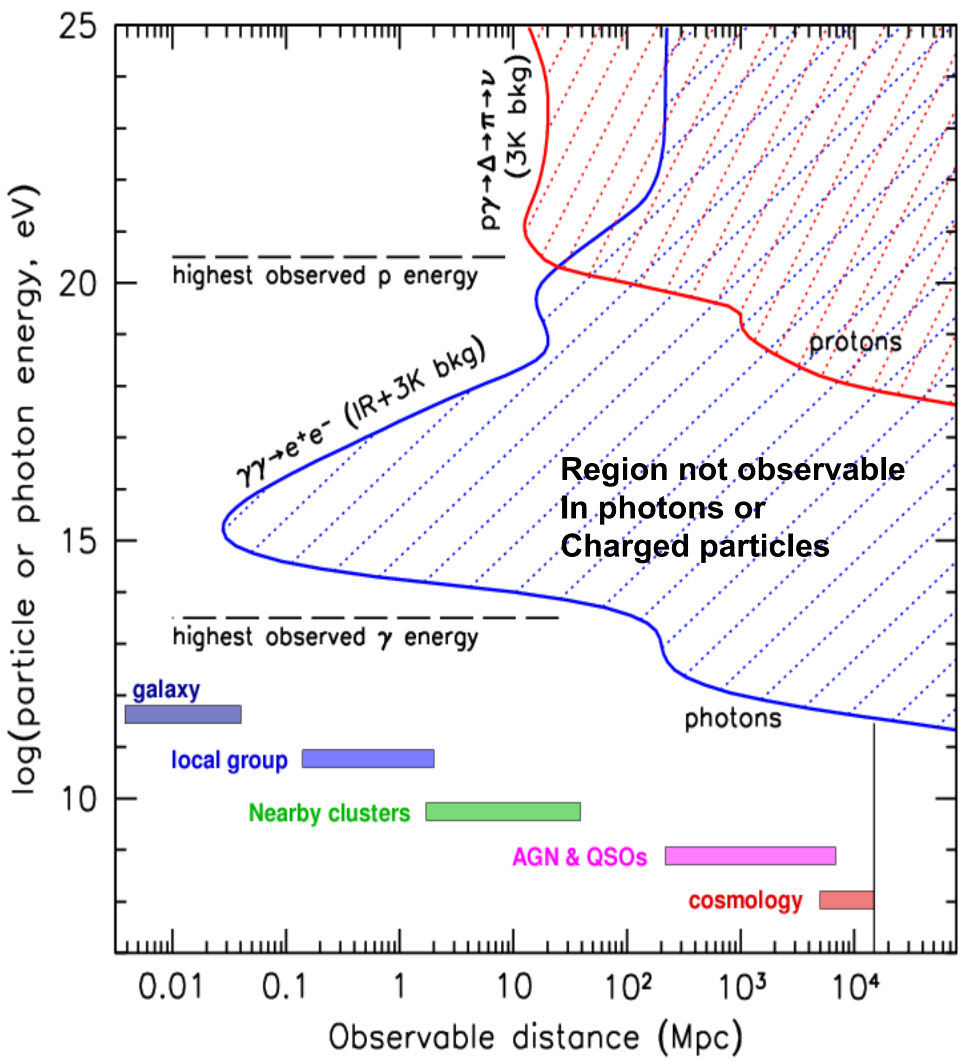
- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV
- A paradox:
  - No *nearby* sources observed
  - distant sources *excluded* due to GZK process
- **Neutrinos** at $10^{17\text{-}19}$ eV **required** by standard-model physics* through the GZK process--observing them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

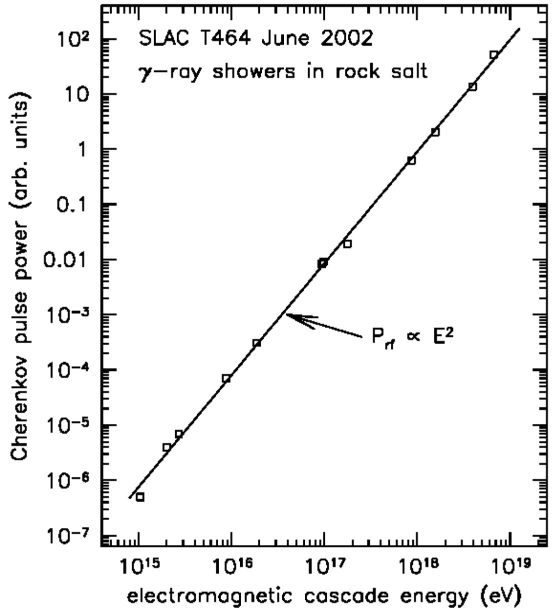
What is needed for a GZK ν detector?

- 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

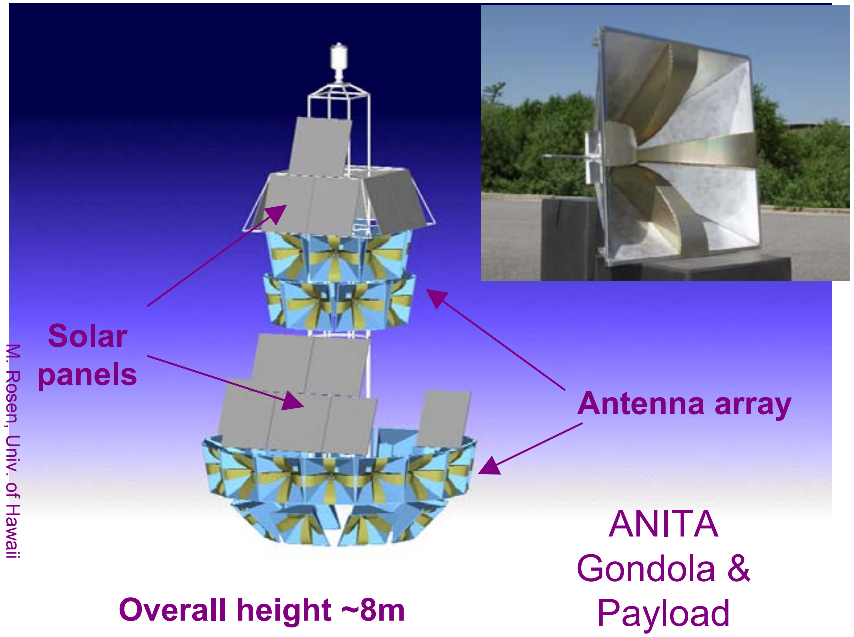
- **One solution: exploit the Askaryan effect: coherent radio Cherenkov emission**
  - Particle showers in solid dielectric media yield strong, coherent radio pulses
  - Neutrinos can shower in many radio-clear media: air, ice, rock-salt, etc.
  - Economy of scale for a radio detector (antenna array + receivers) is very competitive for giant detectors



Design for discovery of GZK ν flux

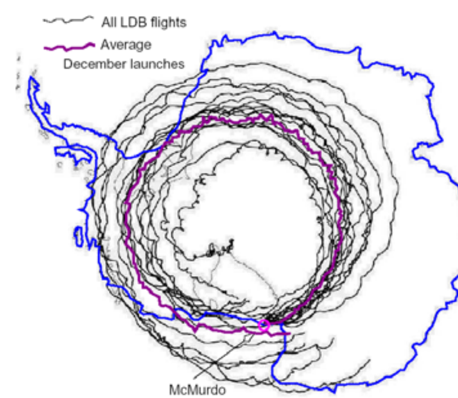
- Huge Volume of solid medium: Antarctic Ice
- Broadband antennas & low noise amplifiers to watch it
- A very high vantage point, but not too high or too far away
- The end result: ANITA

Antarctic Impulsive Transient Antenna

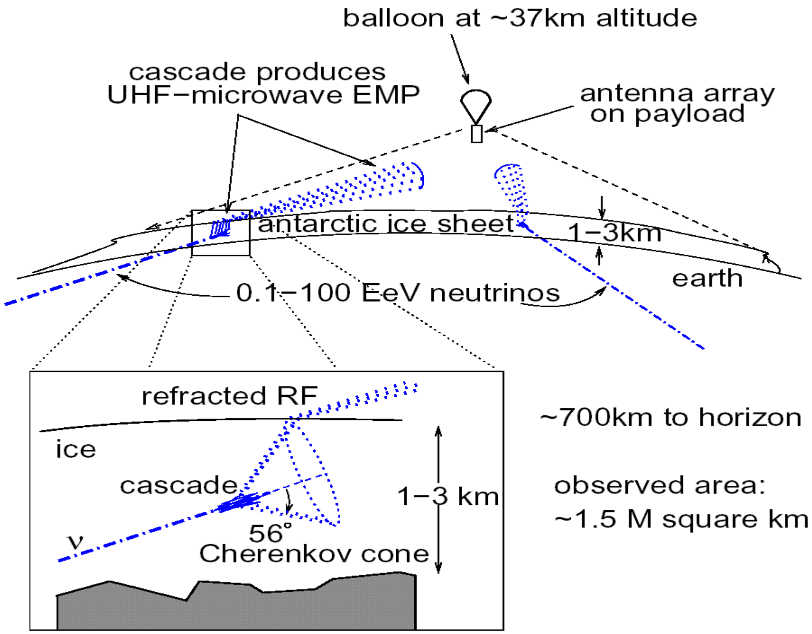


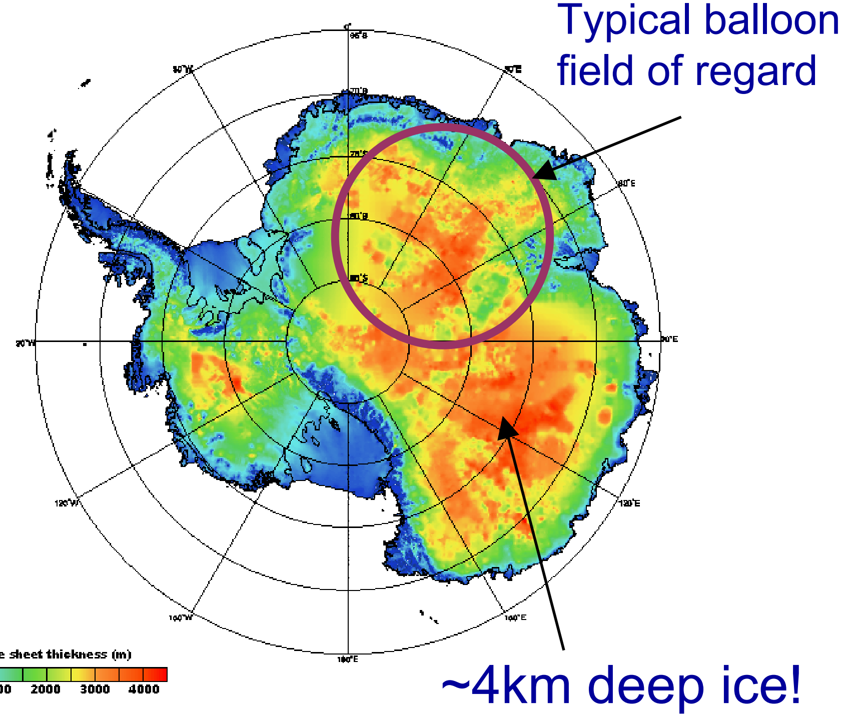
Instantaneous balloon field of view

- ANITA: First in line of ALL high energy neutrino detectors for cosmogenic (GZK) neutrino detection
- first flight: December 2006

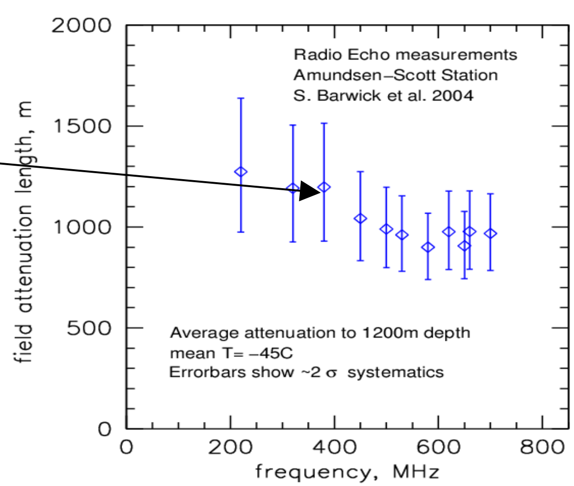


ANITA concept





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



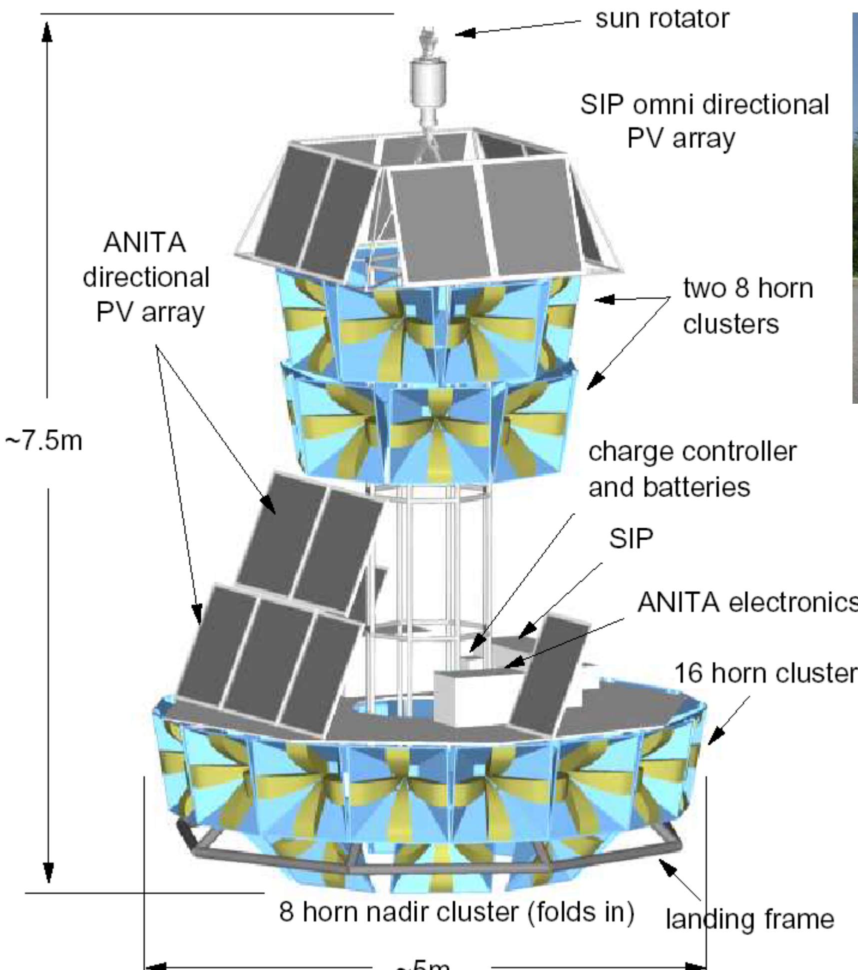
Effective "telescope" aperture:

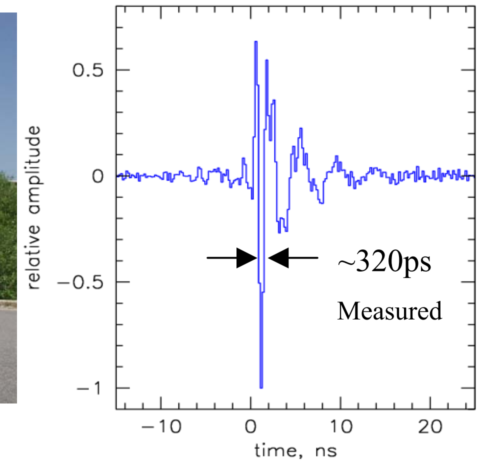
- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

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

Flight Payload Design

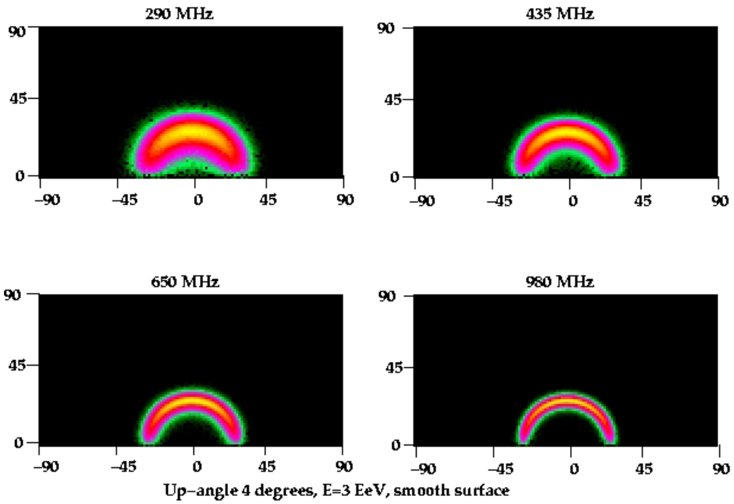
A radio "feedhorn array" for the Antarctica Continent

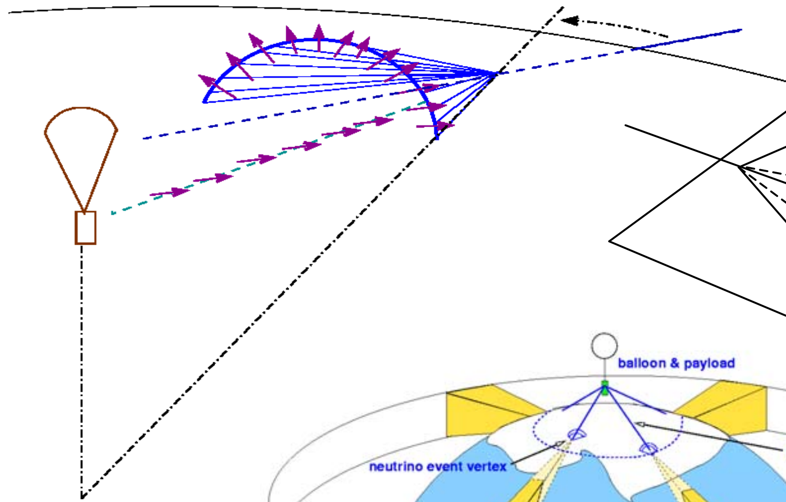


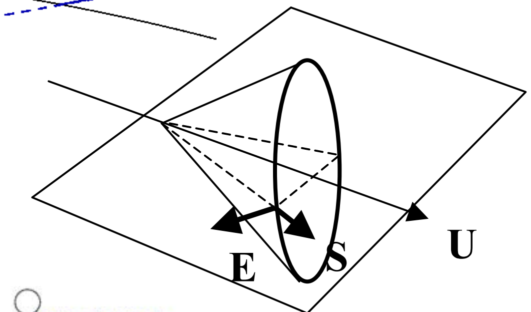


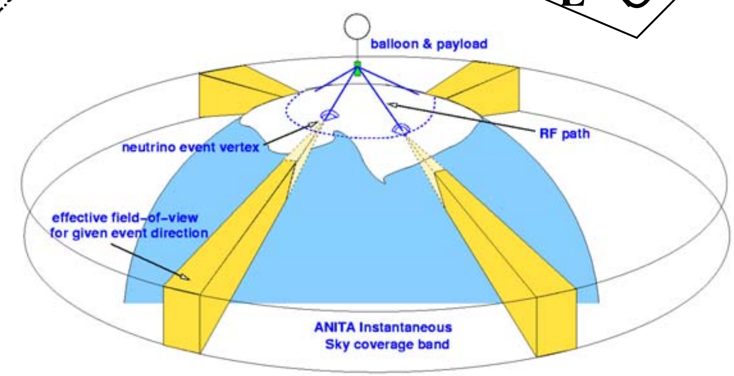
- Quad-ridged horn antennas provide superb impulse response & bandwidth
- Interferometry & beam gradiometry from multiple overlapped antenna measurements

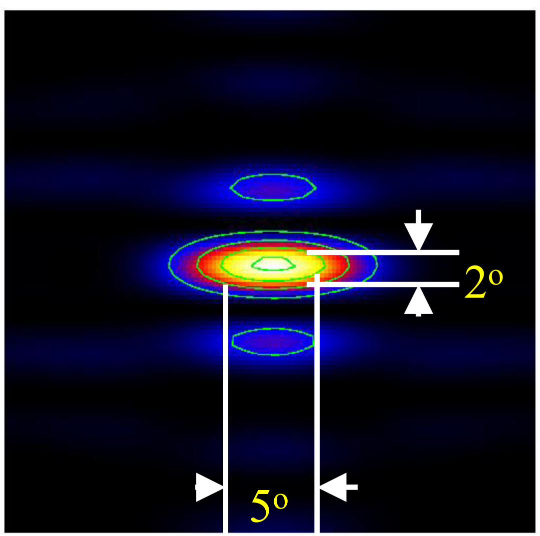
ANITA as a neutrino telescope







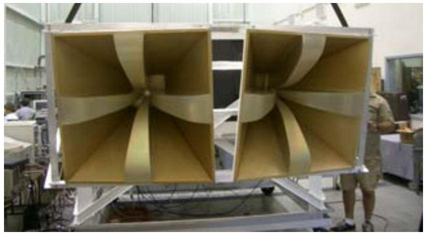


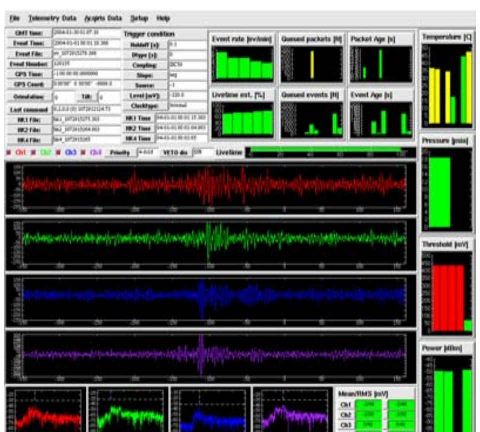


- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse

- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

ANITA-lite Prototype flight

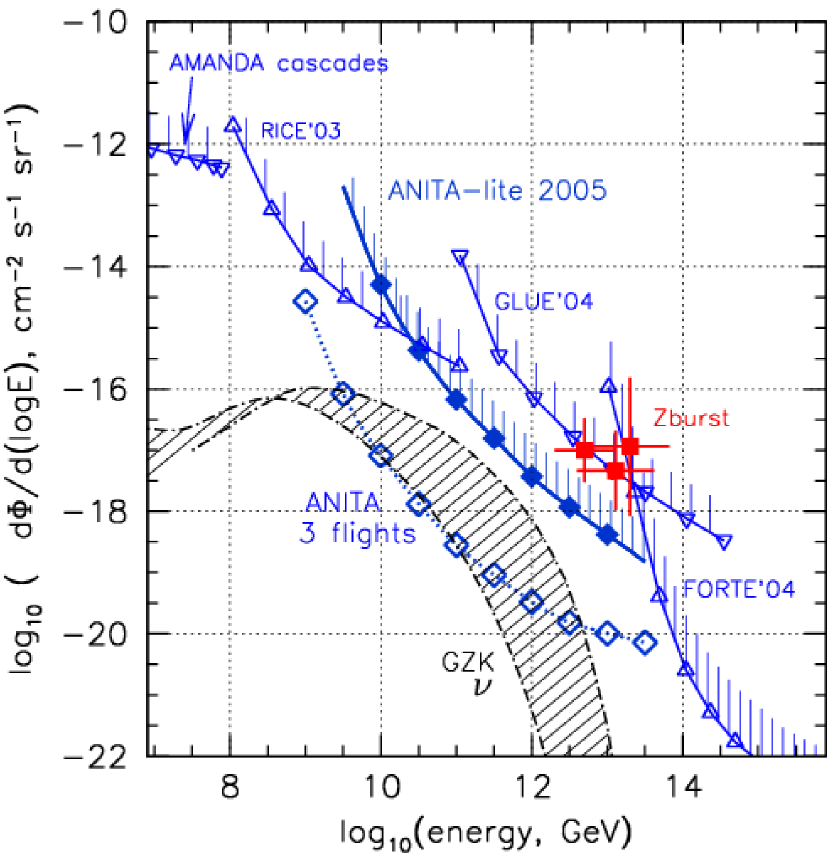




- Piggyback Mission of Opportunity on the 03-04 TIGER* flight, completed mid-January 04
- ANITA prototypes & off-the-shelf hardware used
  - 2 dual-pol. ANITA antennas w/ low-noise amps
  - 4 channels at 1 GHz RF bandwidth, 2 GHz sampling
- 18.4 days flight time, 40% net livetime due to slow (4sec per 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 & 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 (UH & UCI)
- **Z-burst model ($\nu\nu$ annihilation --> UHECR) strongly excluded: we expect 20-30 events, see none**

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

ANITA Engineering Model Payload

- **Ft. Sumner hangar webcam**
- **Lower truss section ~16′ diameter**
- **EM flight August 26th**
- **Full payload Antarctic flight in Dec. 2006**

- August 22, 2005: Gondola nearing completion for flight this week

Saltdome Shower Array:

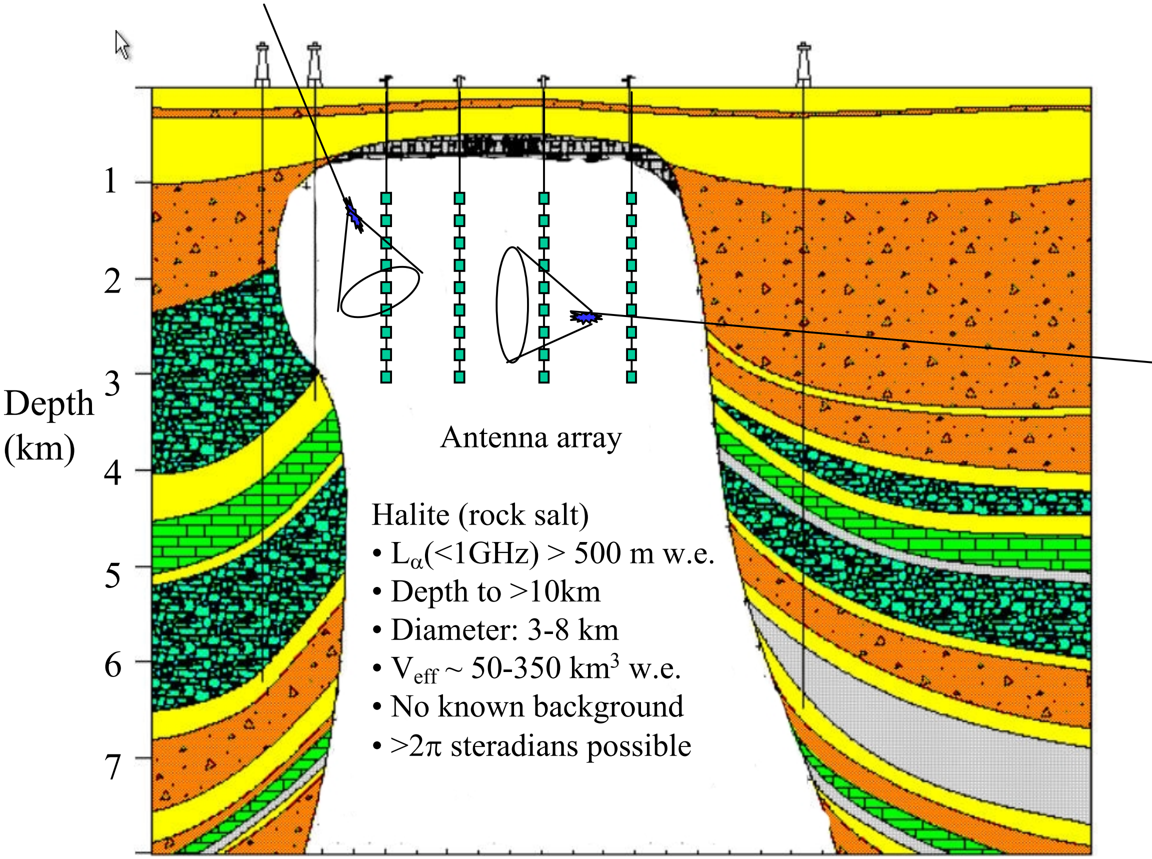
- Goal: Precision HEP and Particle Astrophysics with GZK neutrinos

- Publication of Final T460 Askaryan-in-salt analysis (PRD 2005) & full SalSA simulations

- Significant hardware design & development

- Site selection studies: Richton & Vacherie salt domes

Saltdome Shower Array (SalSA) concept



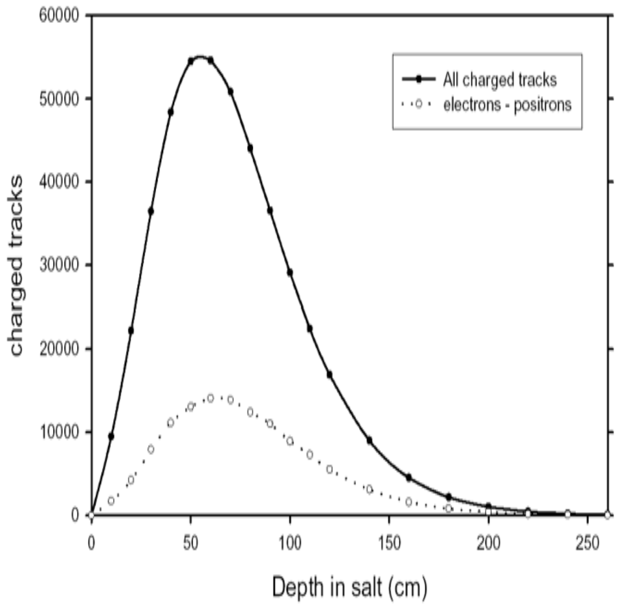
- Rock salt can have extremely low RF loss, as radio-clear as Antarctic ice
- ~2.4 times as dense as ice
- typical: **50-100 km^3** water equivalent in top ~3.5km =>**300-600 km^3 sr w.e.**

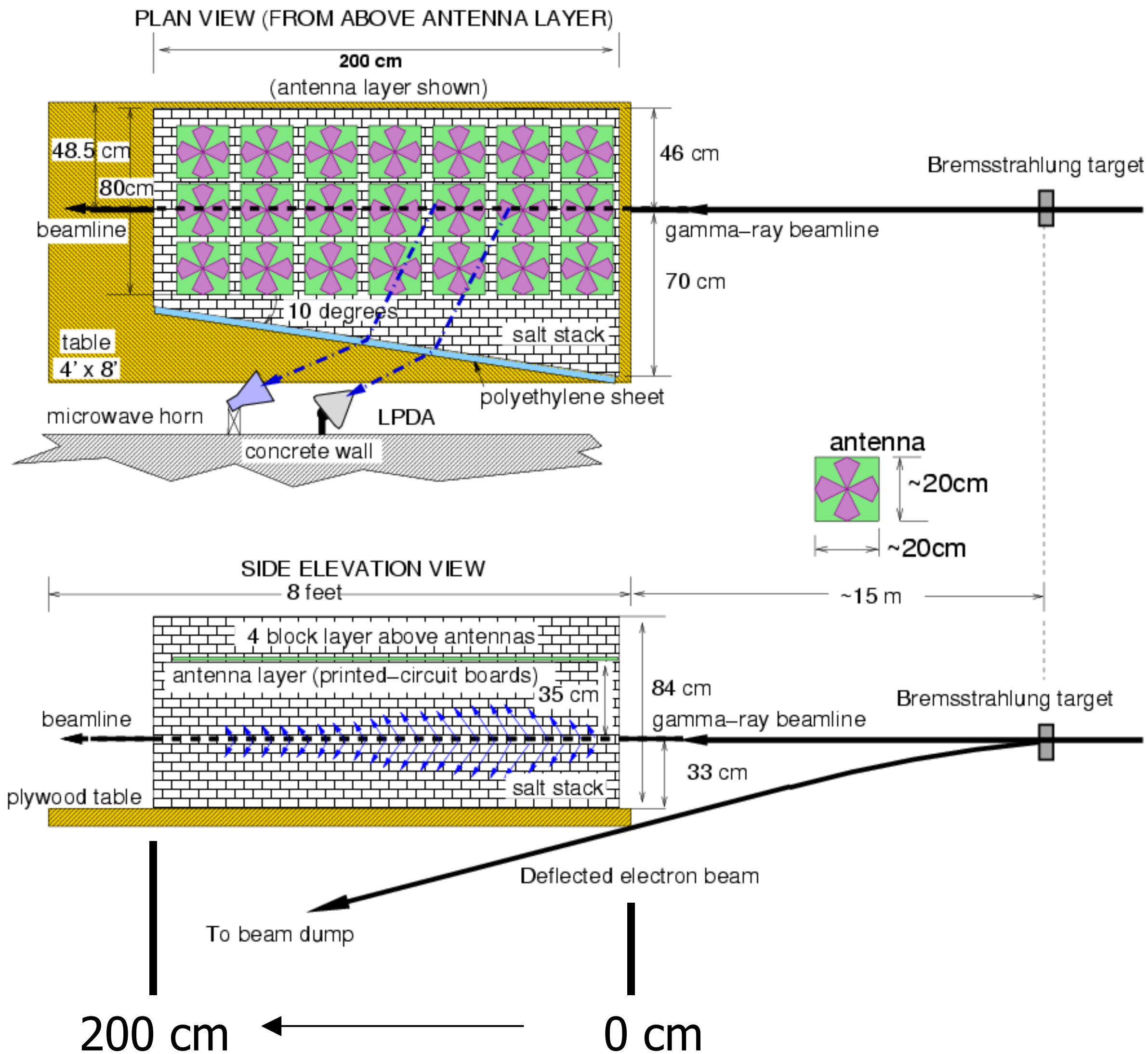
T460 rock-salt target

- 4lb high-purity synthetic rock-salt bricks (density=2.07)
- + some filler from local grocery store…

- Beam exit point shown above
- Depth ~ 15 radiation lengths
  - good indicator of transverse size of shower!

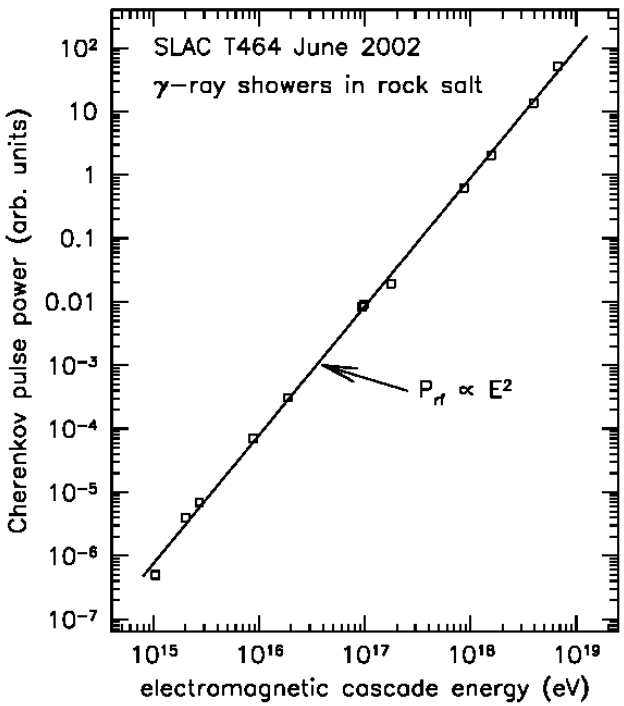
Detector layout; EGS simulation

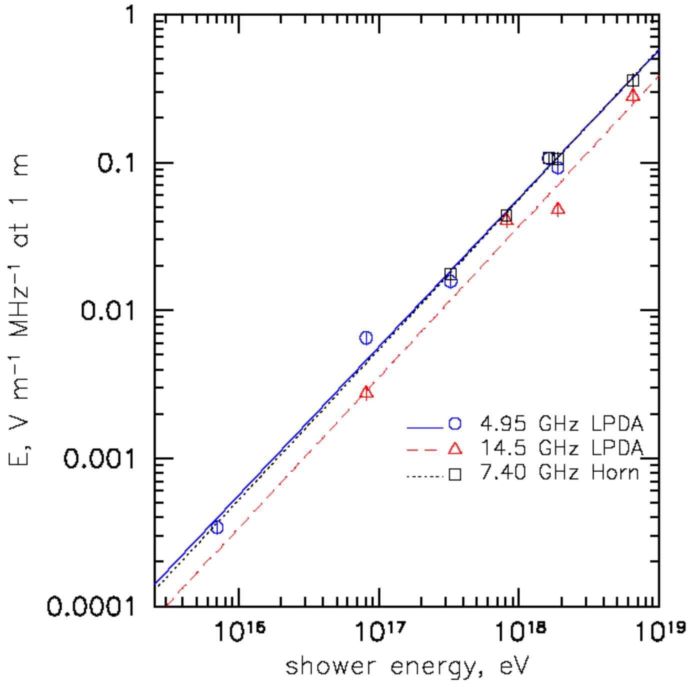




- Salt block target
- Contained about 98% of shower as per Electron-Gamma Shower (EGS) simulation

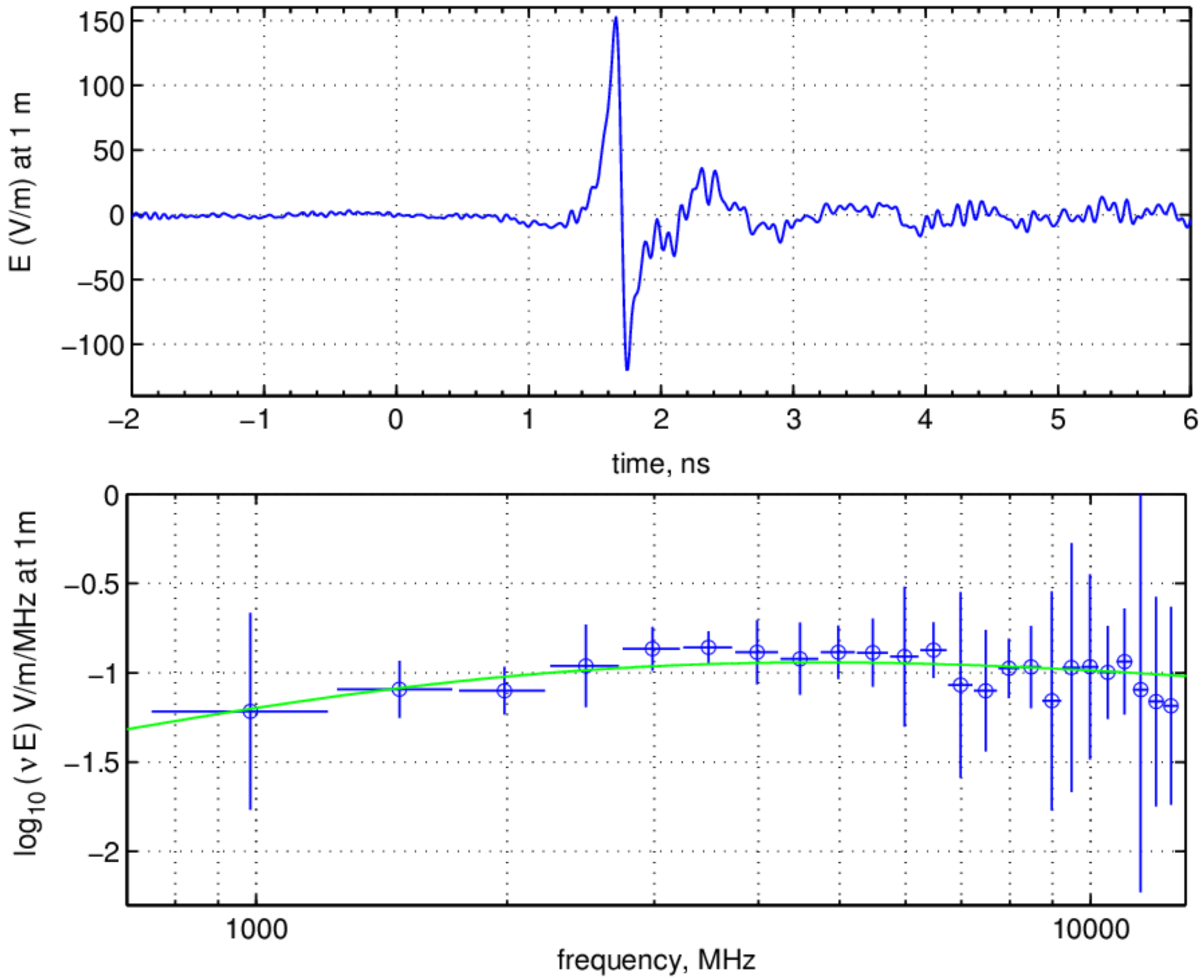
RF Coherence vs. energy & frequency





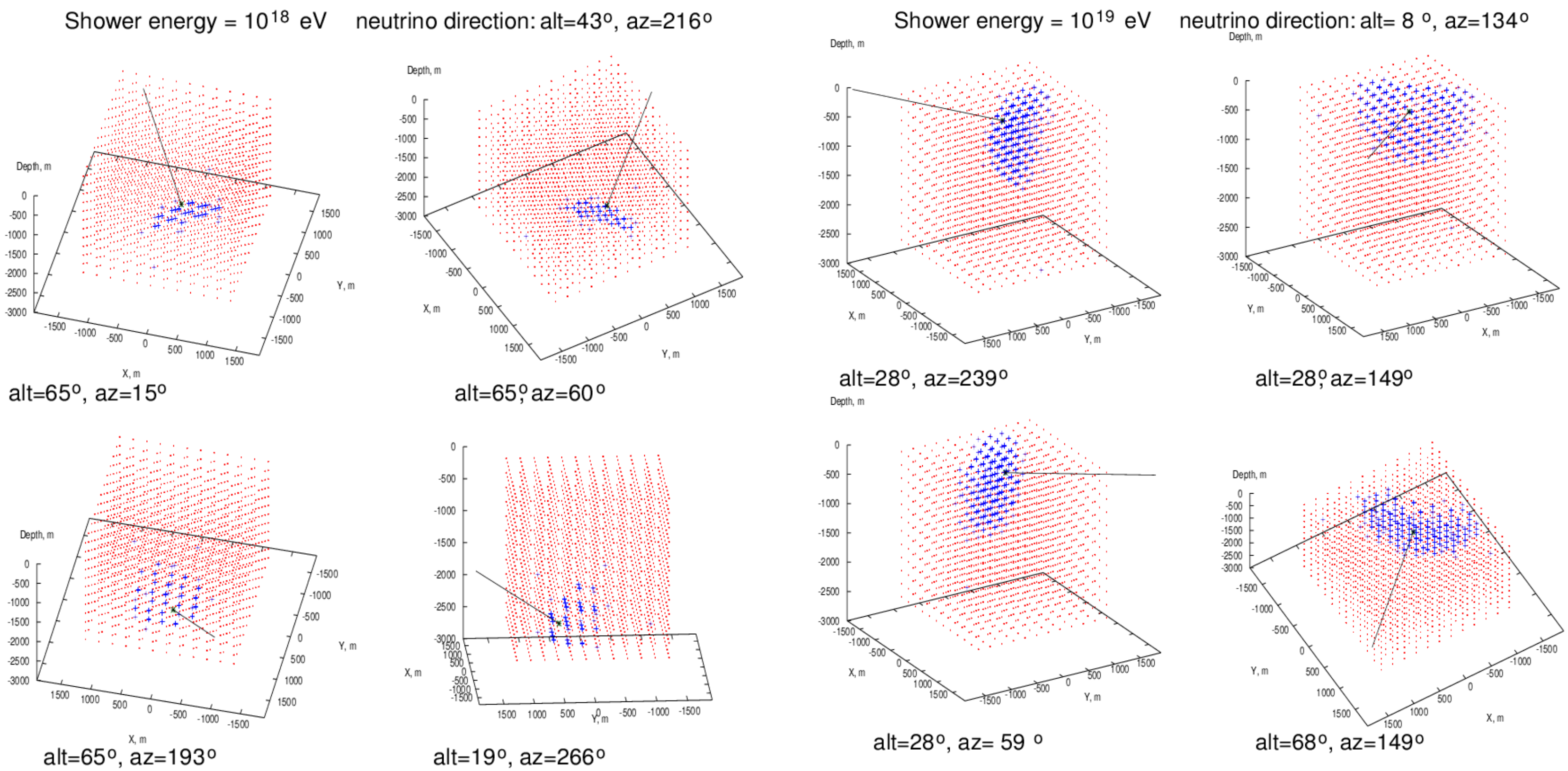
- **Much wider energy range covered than previously: 1PeV up to 10 EeV**
- **Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power**
- **Differs from actual EeV showers only in leading interactions==> radio emission almost unaffected**

Ultra-wideband data on Askaryan pulse



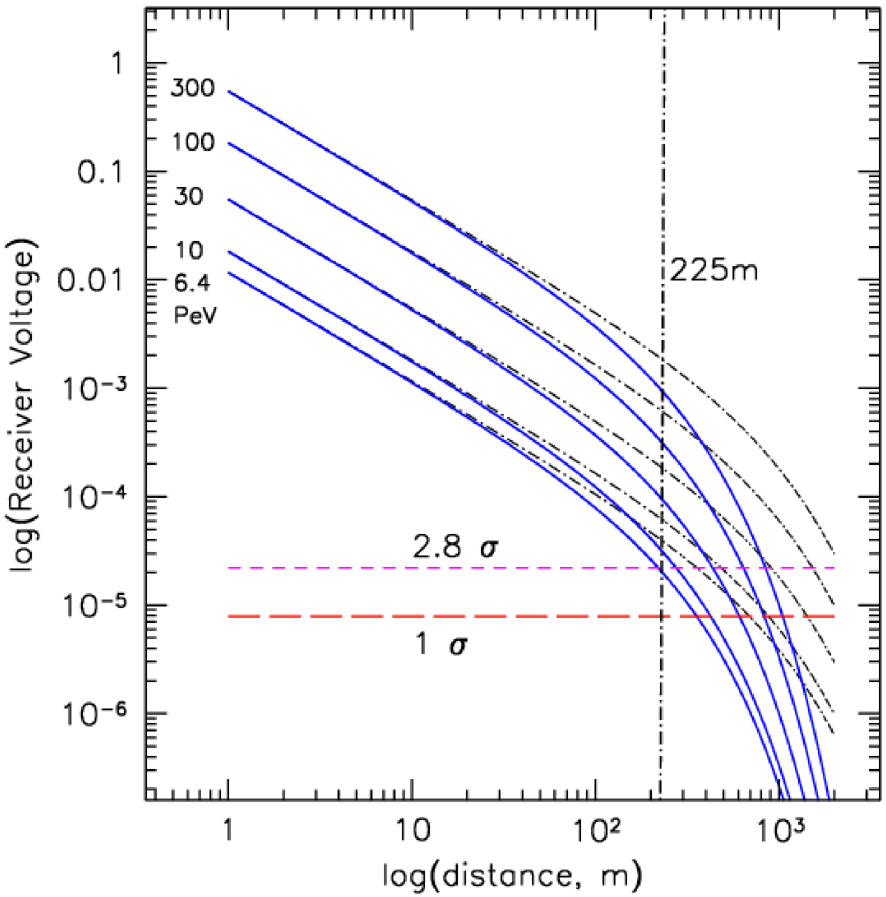
- 2000 & 2002 SLAC Experiments confirm extreme coherence of Askaryan radio pulse
- 60 picosecond pulse widths measured for salt showers
- Flat spectrum radio emission extends well into microwave regime

SalSA simulations



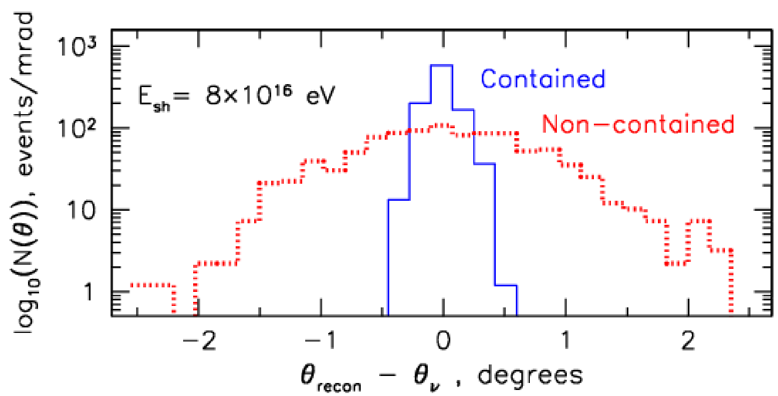
- A 2.5 km^3 array with 225 m spacing, 12^2=144 strings, 12^3=1728 antenna nodes, 12 antennas per node, dual polarization ==> **$V_{eff}\,\Omega$ = 380 km^3 sr w.e. at 1 EeV**
- Threshold <10^{17} eV, few 100s antennas hit at 1 EeV, >1000 hits at 10 EeV
- **Rate: at least 20 events per year from rock-bottom minimal GZK predictions**

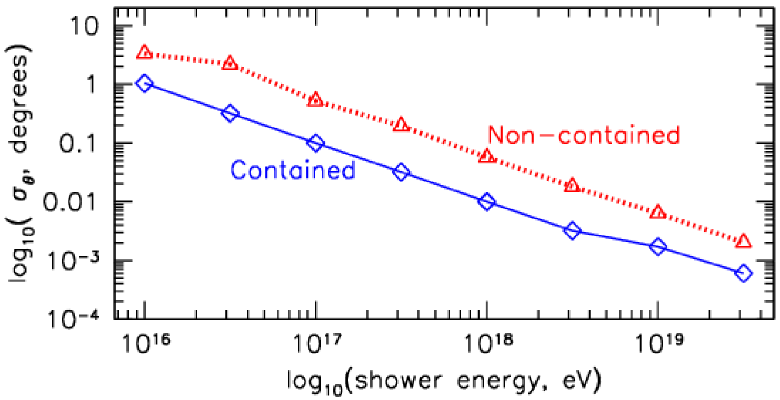
Estimated SalSA Energy threshold



- Ethr < 300 PeV (3 x 10^{18} eV) best for full GZK spectral measurement
- Threshold depends on average distance to nearest detector and local antenna trigger voltage above thermal noise
  - Vnoise = k T Δf
  - Tsys = Tsalt+Tamp = 450K
  - Δf of order 200 MHz
- 225 m spacing gives 30 PeV
- Margin of at least 10x for GZK neutrino energies

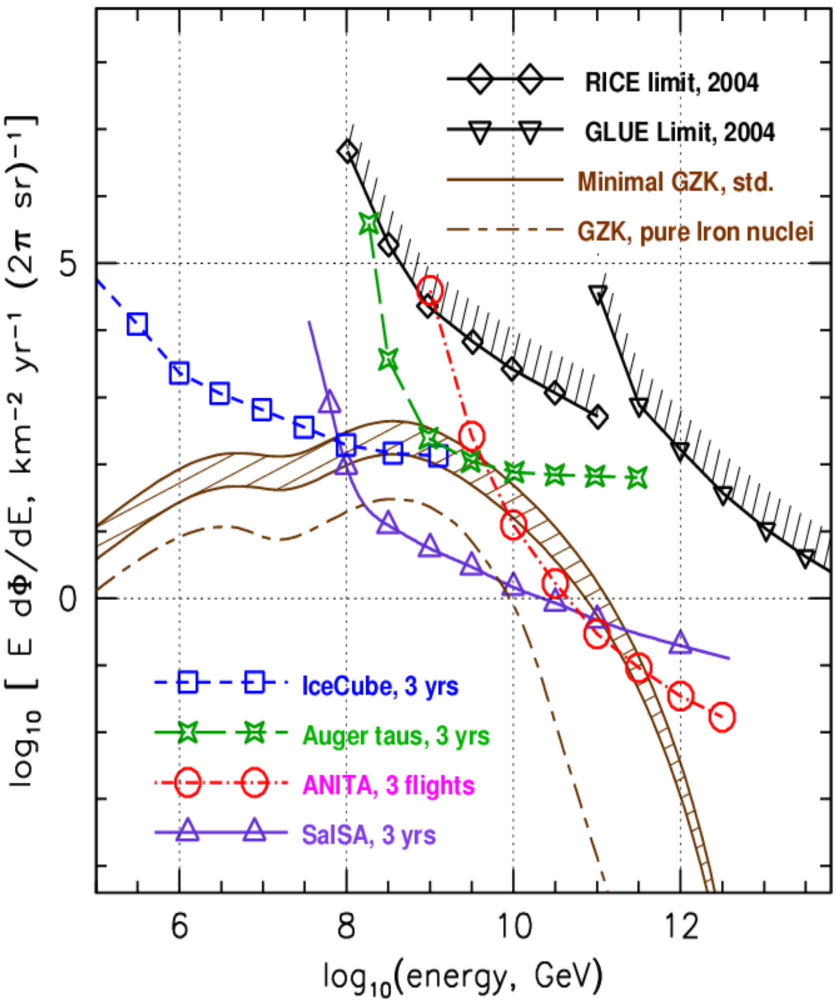
Angular resolution





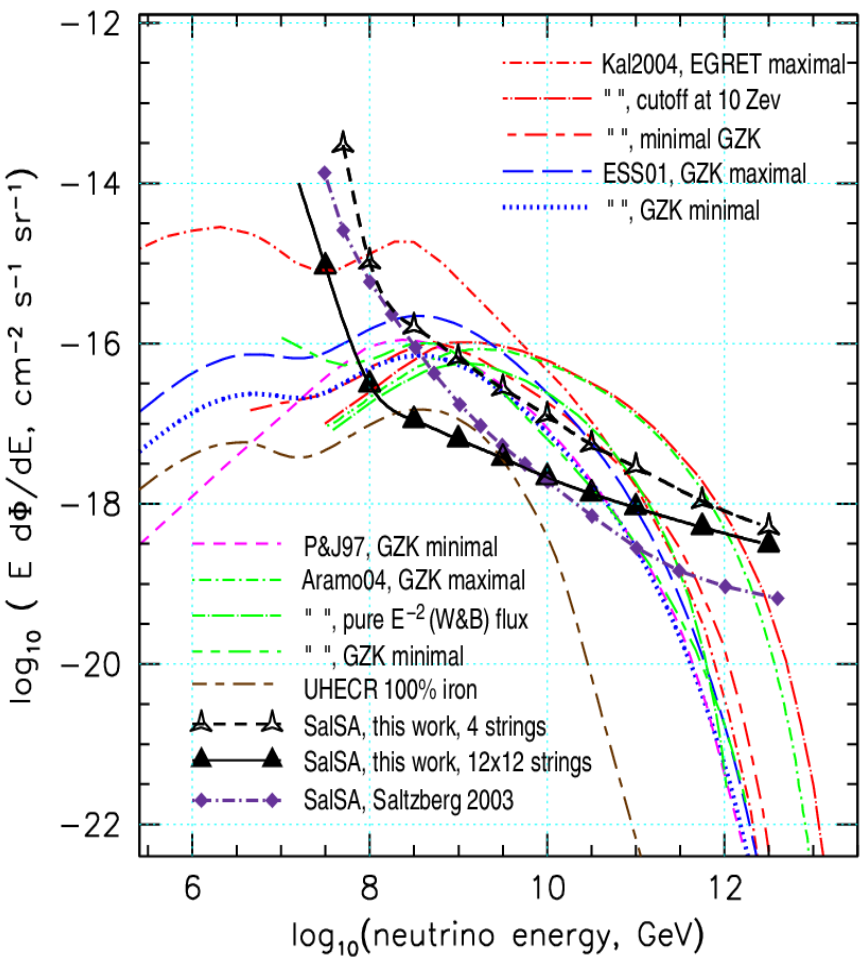
- Of order 1 degree angular resolution required for neutrino cross section measurements
- Studied in detail for 12x12 string array, using Chi-squared minimization
- For GZK energies:
  - 0.1° achieved for contained events--inside the array
  - 1° achieved for external events, parallel to face, 250 m outside of array (partial Cherenkov cone seen)
- Polarization information + unscattered Cherenkov cone leads to excellent angular resolution!

Existing Neutrino Limits and Potential Future Sensitivity



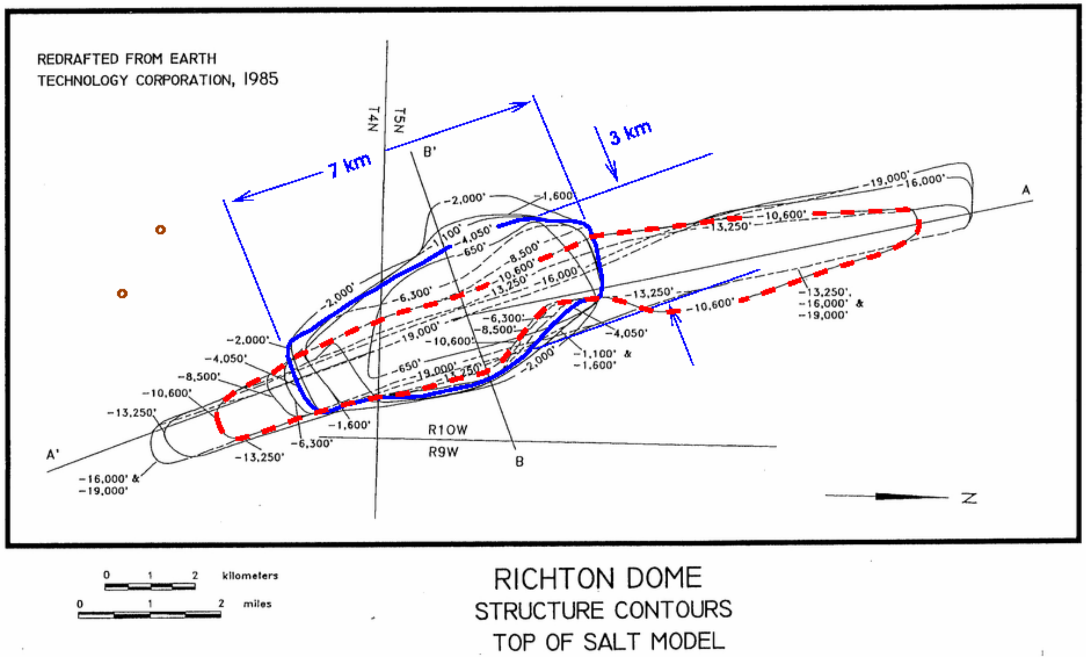
- RICE limits for 3500 hours livetime
- GLUE limits ~120 hours livetime
- ANITA sensitivity, 45 days total:
  - ~5 to 30 GZK neutrinos
- IceCube: high energy cascades
  - ~1.5-3 GZK events in 3 years
- Auger: Tau neutrino decay events
  - ~1 GZK event per year?
- **SalSA sensitivity, 3 yrs live**
  -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

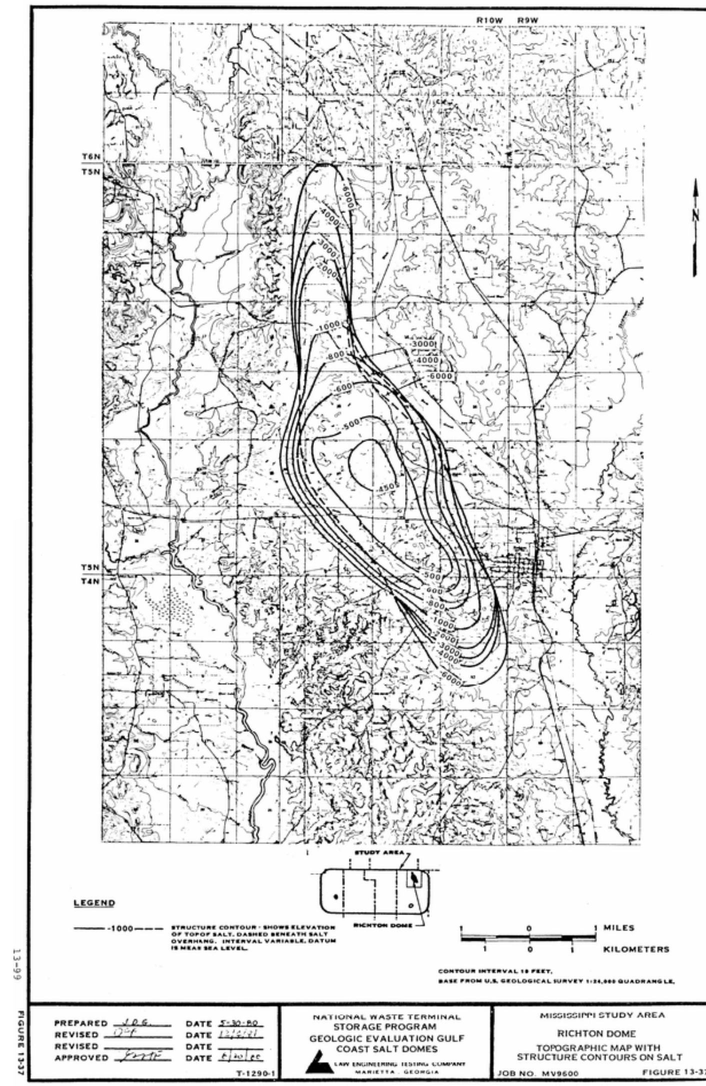
GZK neutrino sensitivity details, 1 yr



- 2 independent MC calculations: UCLA & UH
- UCLA: Saltzberg 2002 SPIE; also 2005 Nobel symposium
  - Simplified 10x10 strings, 10 antenna nodes per string
  - Did not truncate dome, so high energies extended
- UH: Gorham et al. PRD 2005
  - 12x12 strings, 12 nodes with realistic trigger sims
  - **Even 4-string array sees GZK events in 1 year!**

Richton Dome





- Richton Dome has excellent seismic, gravity & direct drilling measurements of salt body
- Among the largest of all Gulf coast domes

Vacherie Salt dome, LA

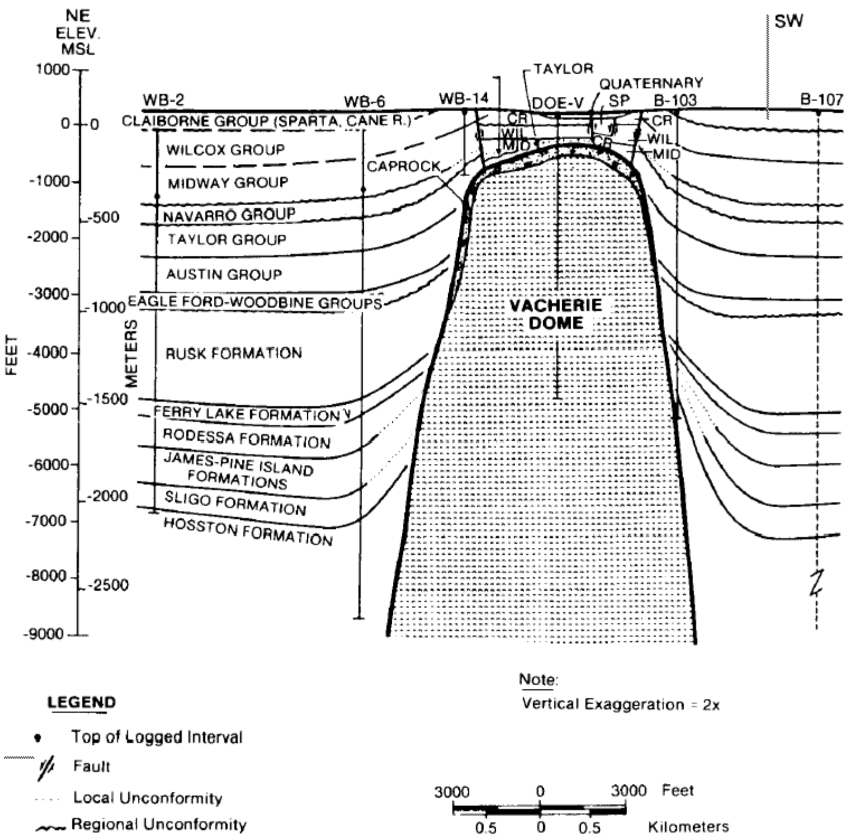


Figure 8. Northeast-southwest geologic section of Vacherie Salt Dome. From Law Engineering Testing Company (1981).

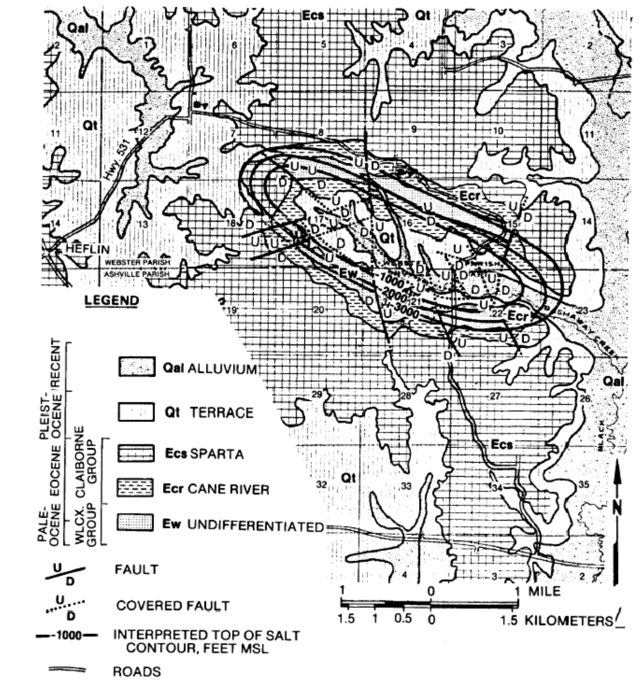
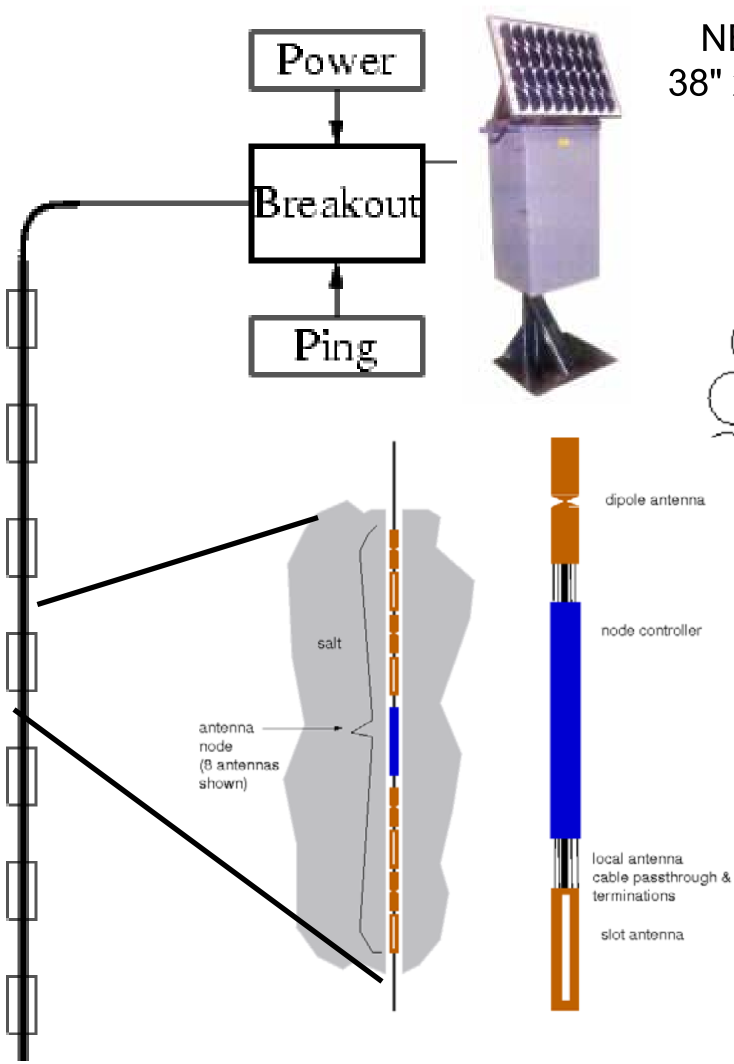


Figure 7. Geologic map of Vacherie Salt Dome. From Law Engineering Testing Company (1981).

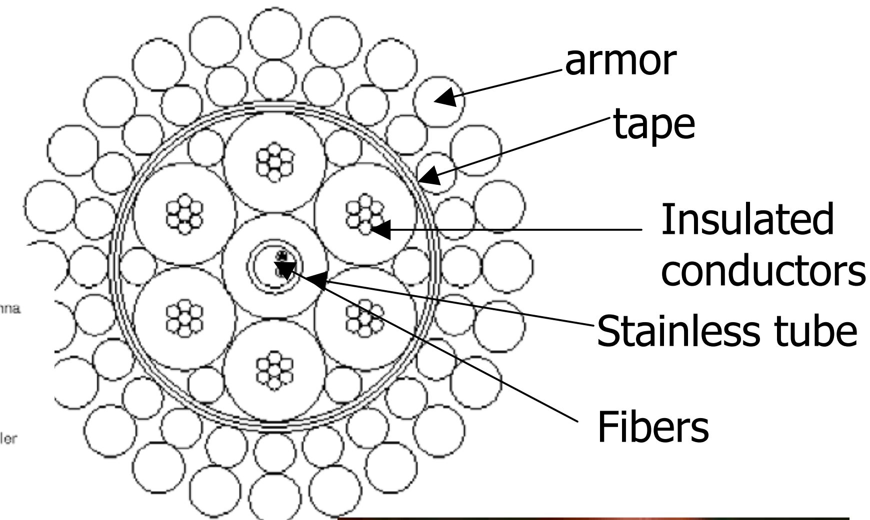
- 2500’ core analyzed by DOE in 80’s
- Salt extremely dry (25ppm brine)
- Low economic usage, no oil or gas

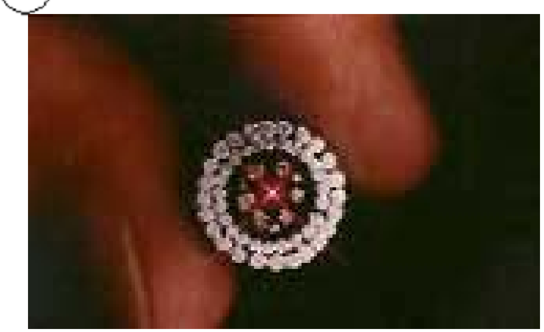
Basic string architecture

String
12 nodes



NEMA 3R
38" x 21" x17"





Node = 12 antennas
and center housing

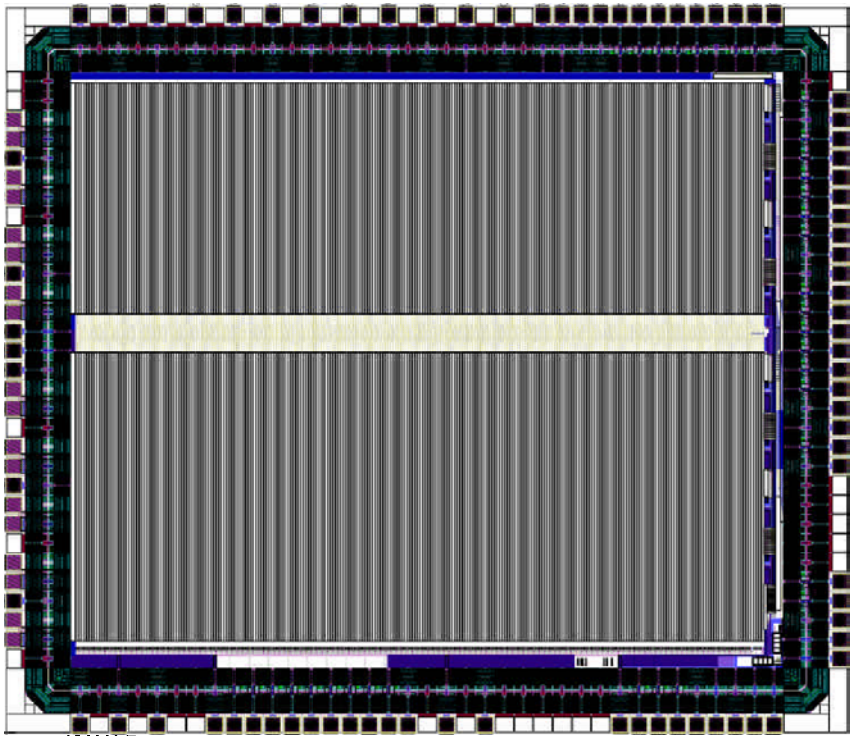
In hole digitization

Digitizer n' Readout, In-situ Transient Observation in Salt [D'RITOS]

To avoid several watts per channel for a commercial Gsample/s digitizer:

- Use analog storage of GHz-rate samples (SCA) in ring-buffer
- Separate logic decides if signal is present at ~2-3σ level
- Issue a "hold," then "digitize" and read out with low-power ADCs

3rd generation switched-capacitor array (SCA) architecture (Varner)

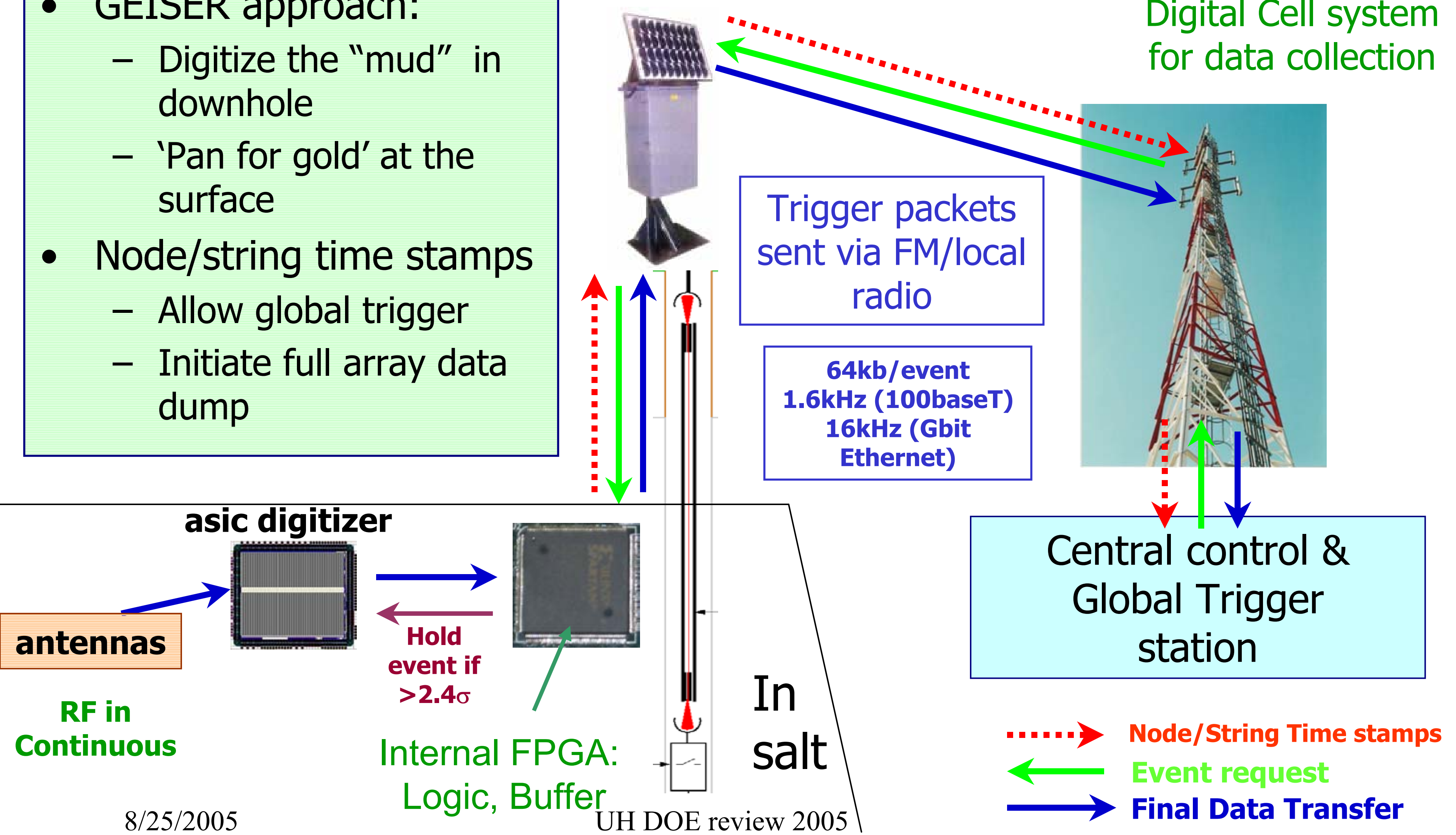


0.25μ CMOS process

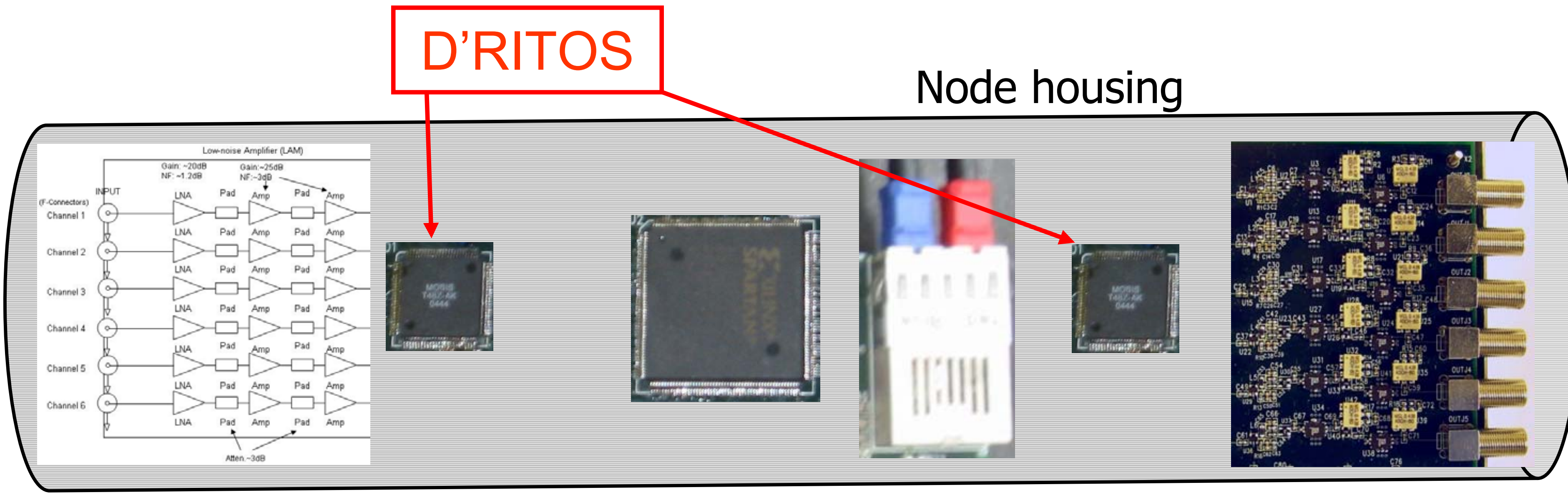
GEISER Data flow

(Giga-bit Ethernet Instrumentation for SalSA Electronics Readout)

- GEISER approach:
  - Digitize the "mud" in downhole
  - 'Pan for gold' at the surface
- Node/string time stamps
  - Allow global trigger
  - Initiate full array data dump



SalSA Node-controller readout board architecture



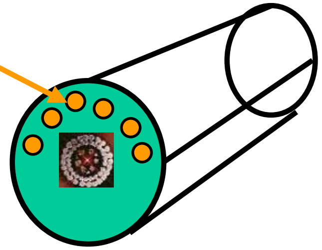
LNA, 2nd-stage amps (one each end)

Trigger, bi-directional fiber-link

LNA, 2nd-stage amps (other end)

Typical 4" coring bit

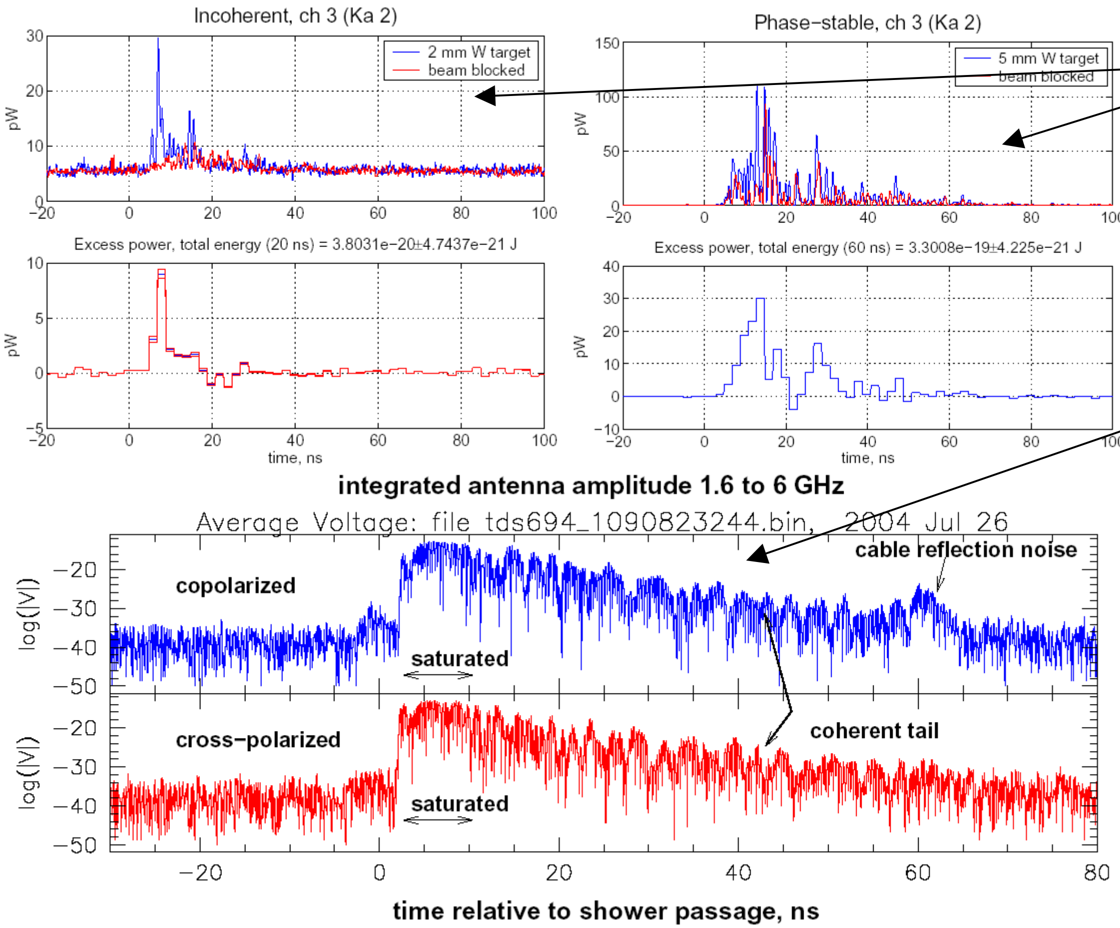
RF connectors



Radio Bremsstrahlung

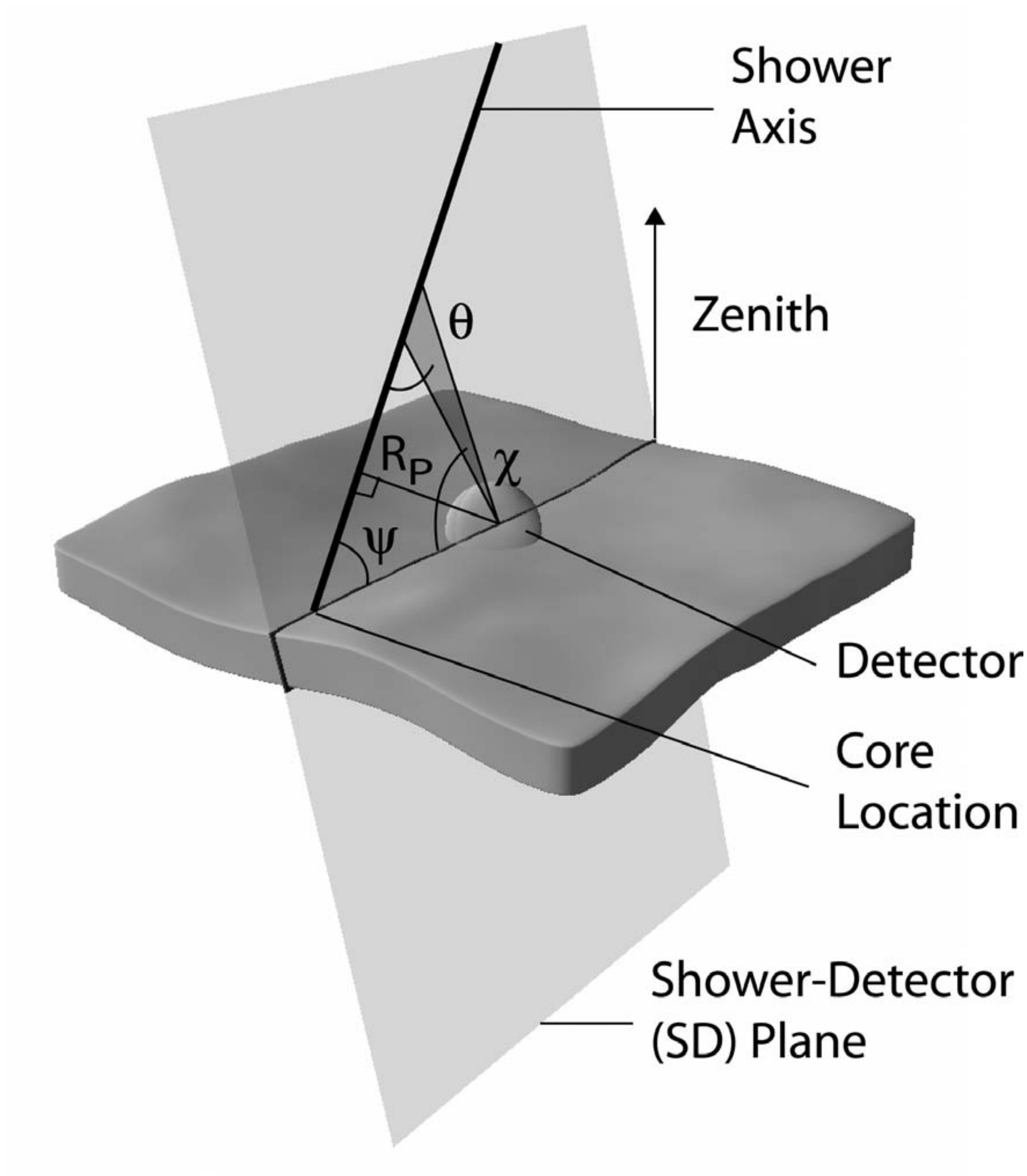
- "Radio fluorescence-equivalent" detection of ultra-high energy cosmic ray air showers
- Could provide 100% duty-cycle alternative to N2 fluorescence detection (<10% duty cycle typical)
- Two accelerator experiments: Argonne Wakefield Accelerator (2002) & SLAC-T471 (summer 2004) indicate stronger-than-expected microwave emission for 20-50ns after shower passage
- Radio Bremsstrahlung Impulse Detector (RaBID): 2005 experiment to verify for UHE real air showers

AWA 2002 & SLAC T471

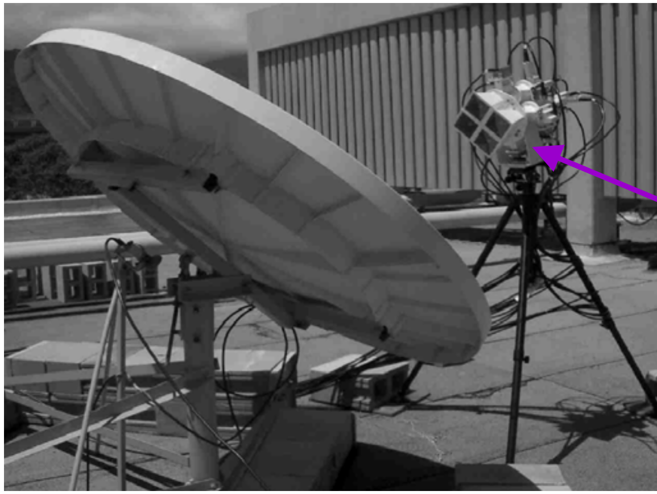


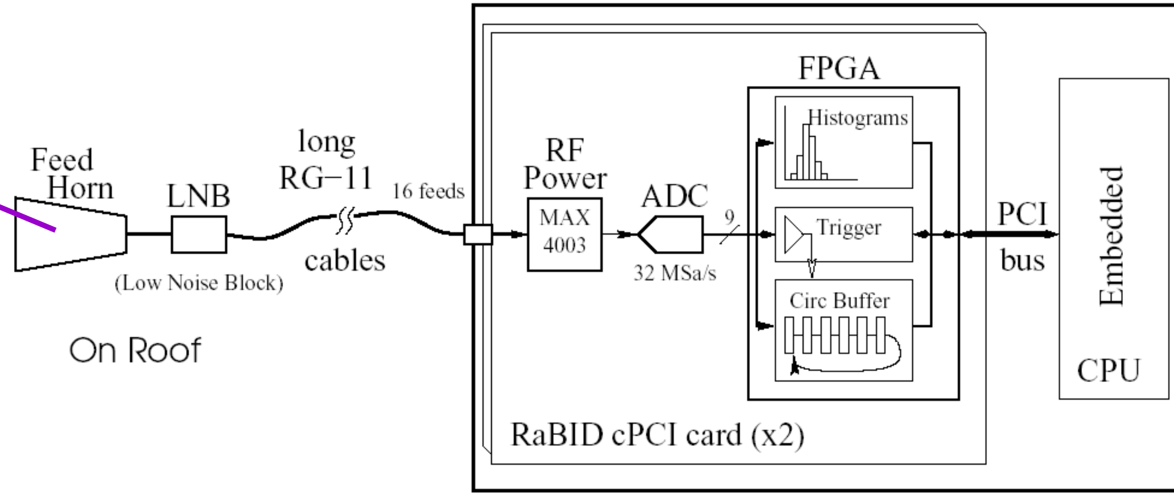
- Top: AWA signals strong, but high backgrounds
- Bottom: SLAC
- T471 signals were free of backgrounds, strong, and mostly coherent!
- Stimulated Emission? Plasma resonance?

RaBID Detection scheme



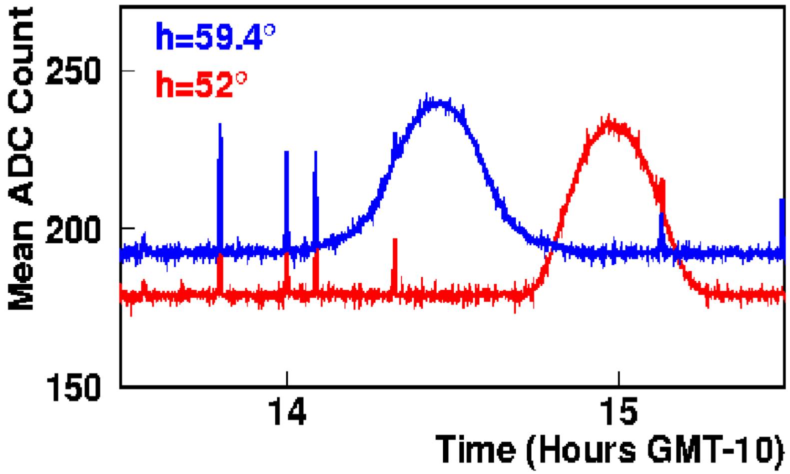
Next step: try it on real air showers



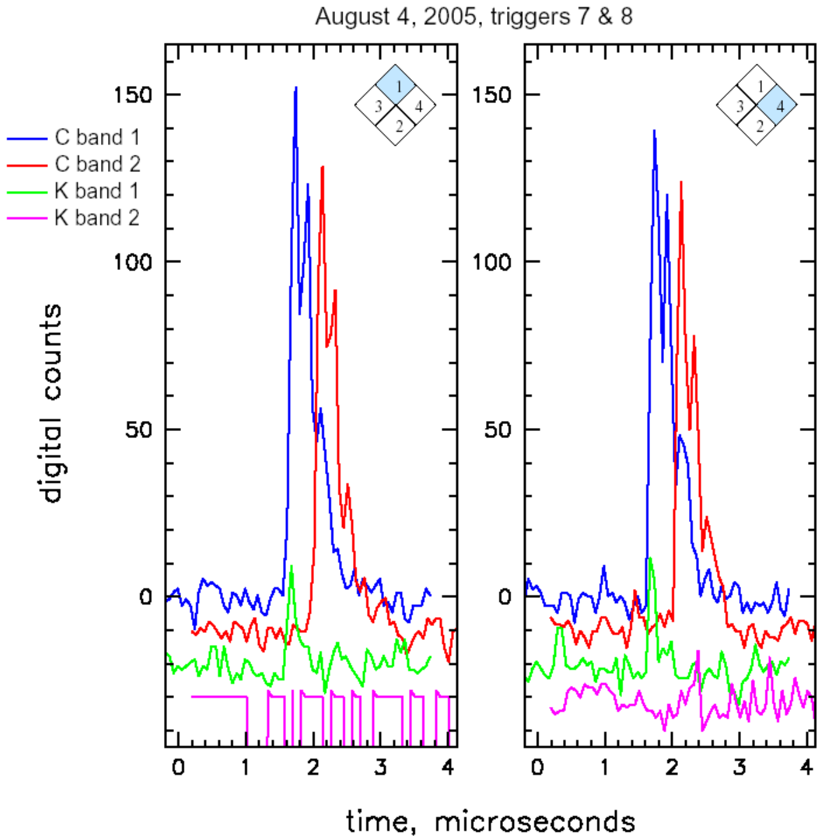


- G. Varner designed custom compact-PCI DAQ system
- 12 microwave channels on two cPCI boards
- Based on commercial sat-TV, wireless & cellular technology to keep cost low (<$10K per station)

Data from RaBID



- Solar scan at 4GHz



- Triggered event, sequential in 2-different feedhorns, at both 4 & 10 GHz (feed-1 10GHz data dropped out here)

RaBID status & plans

- Single-dish prototype already operational on Watanabe roof
- B. Stokes/M. Chasse developing Monte Carlo, firmware, & analysis software
- Proposal to NSF Small Grants For Exploratory Research (SGER) to be submitted this week
  - 4-dish system to be deployed at the Telescope Array in Utah
  - Will get shower trigger from TA ground & N2Fl array
- UH prototype can still set first limits or achieve detection if NSF declines support this year

Summary

UH Radio detection group is a world leader!

ANITA is setting the pace for UHE/GZK neutrino detectors

SalSA: Has the Potential to bridge HEP to Particle Astro like no other detector

RaBID: new directions & possibilities for radio detection

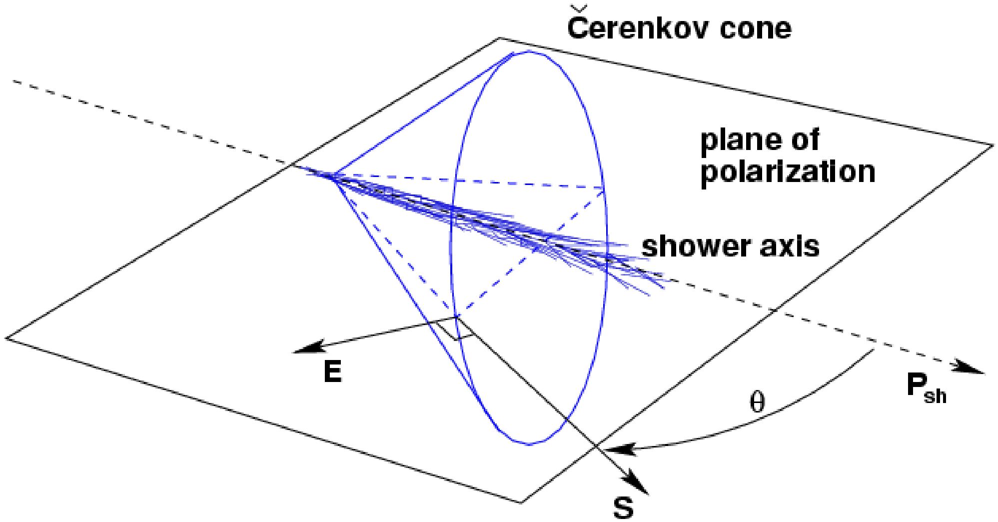
The Z-burst model

- 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 Tom 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 direct ν mass
  - ==> " N^3 " physics….(Nobel^3 ?), no more!

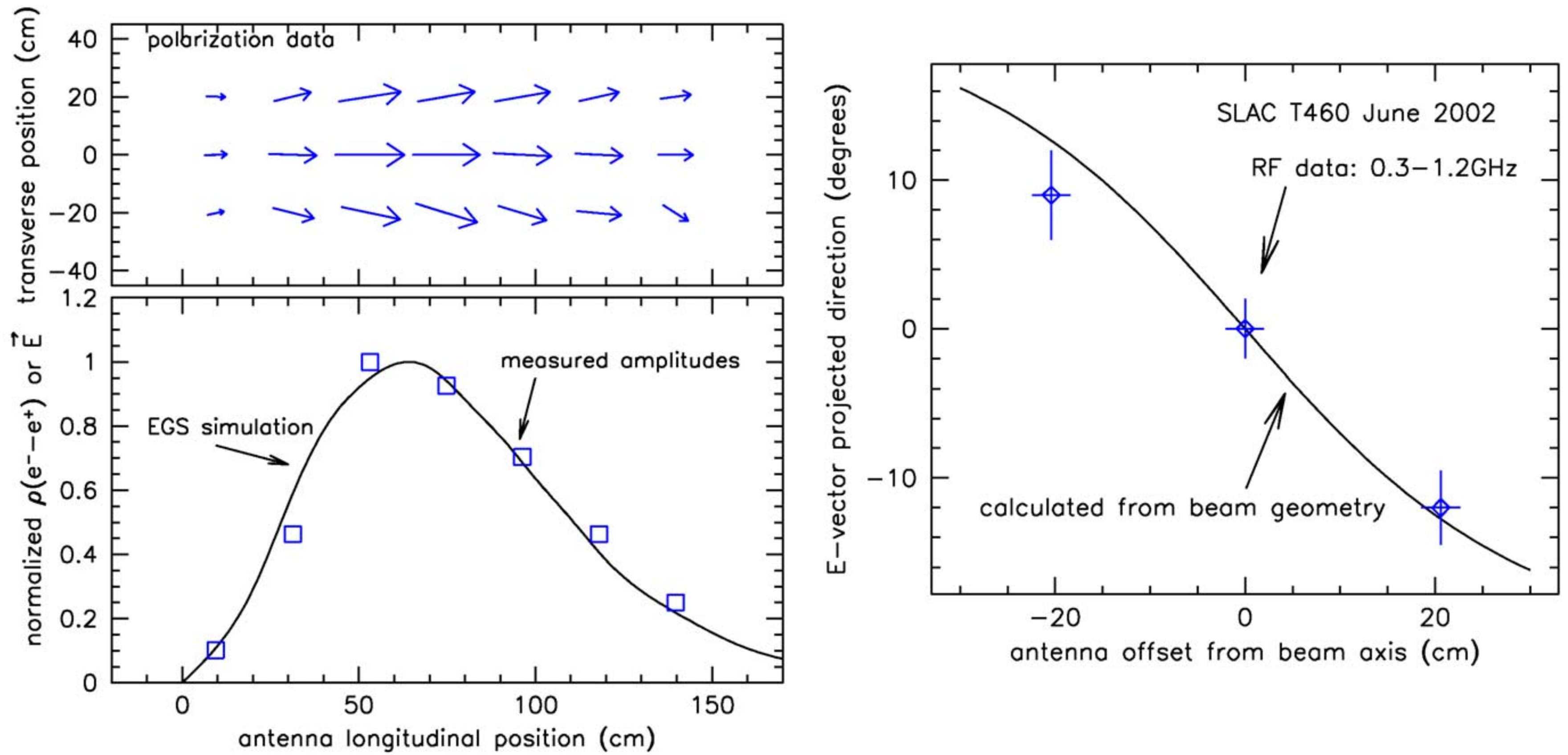
Cherenkov polarization tracking



- 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**

Cherenkov radiation predictions:
- 100% linearly polarized
- plane of polarization aligned with plane containing Poynting vector **S** and particle/cascade velocity **U**

Polarization tracking



- Measured with dual-polarization embedded bowtie antenna array in salt