Radio Detection of Ultra High Energy Neutrinos: ANITA and SalSA for both Astrophysics and Particle Physics

1. Background – Radio Detection
2. ANtarctic Impulsive Transient Antenna (ANITA)
3. Saltdome Shower Array (SalSA)
4. Radio Bremsstrahlung experiment (RaBID)

Gary S. Varner

University of Hawai'i

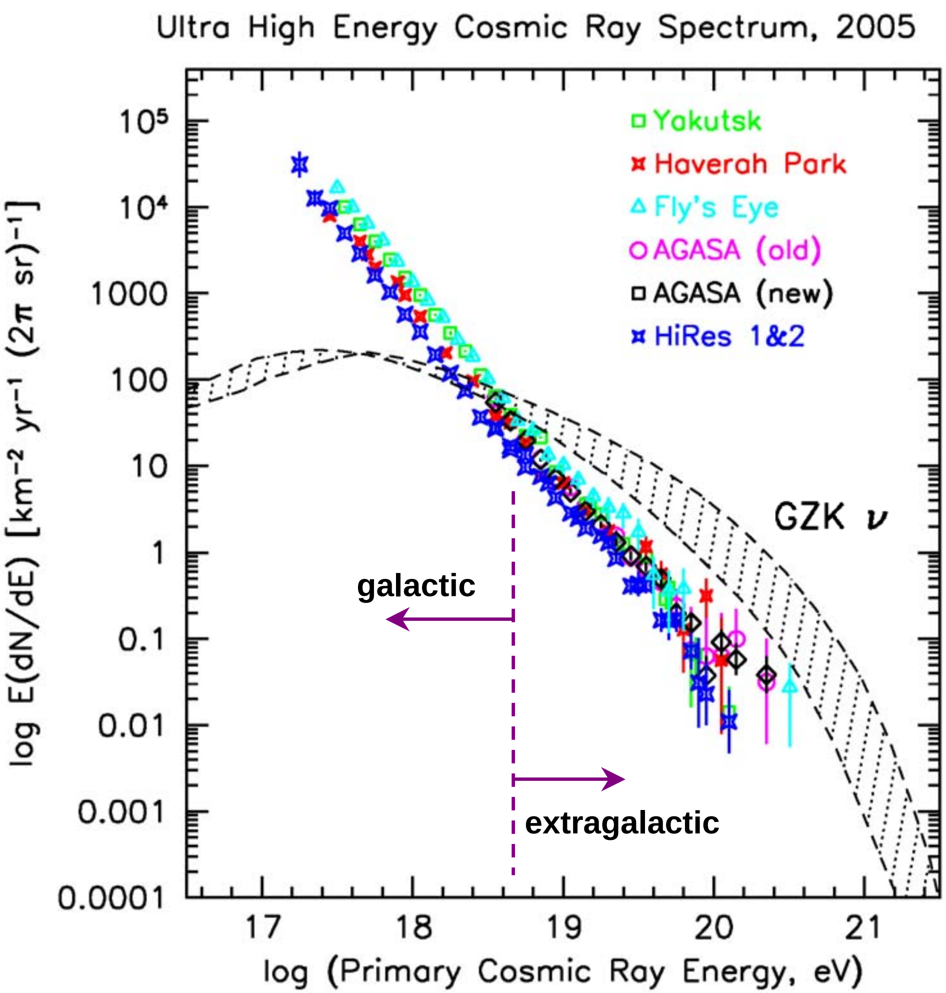
(Ultra-)High Energy Physics of Cosmic rays & Neutrinos

- Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV

- A paradox:
  - No *nearby* sources observed
  - distant sources *excluded* due to process below

- **Neutrinos** at $10^{17\text{-}19}$ eV **required** by standard-model physics

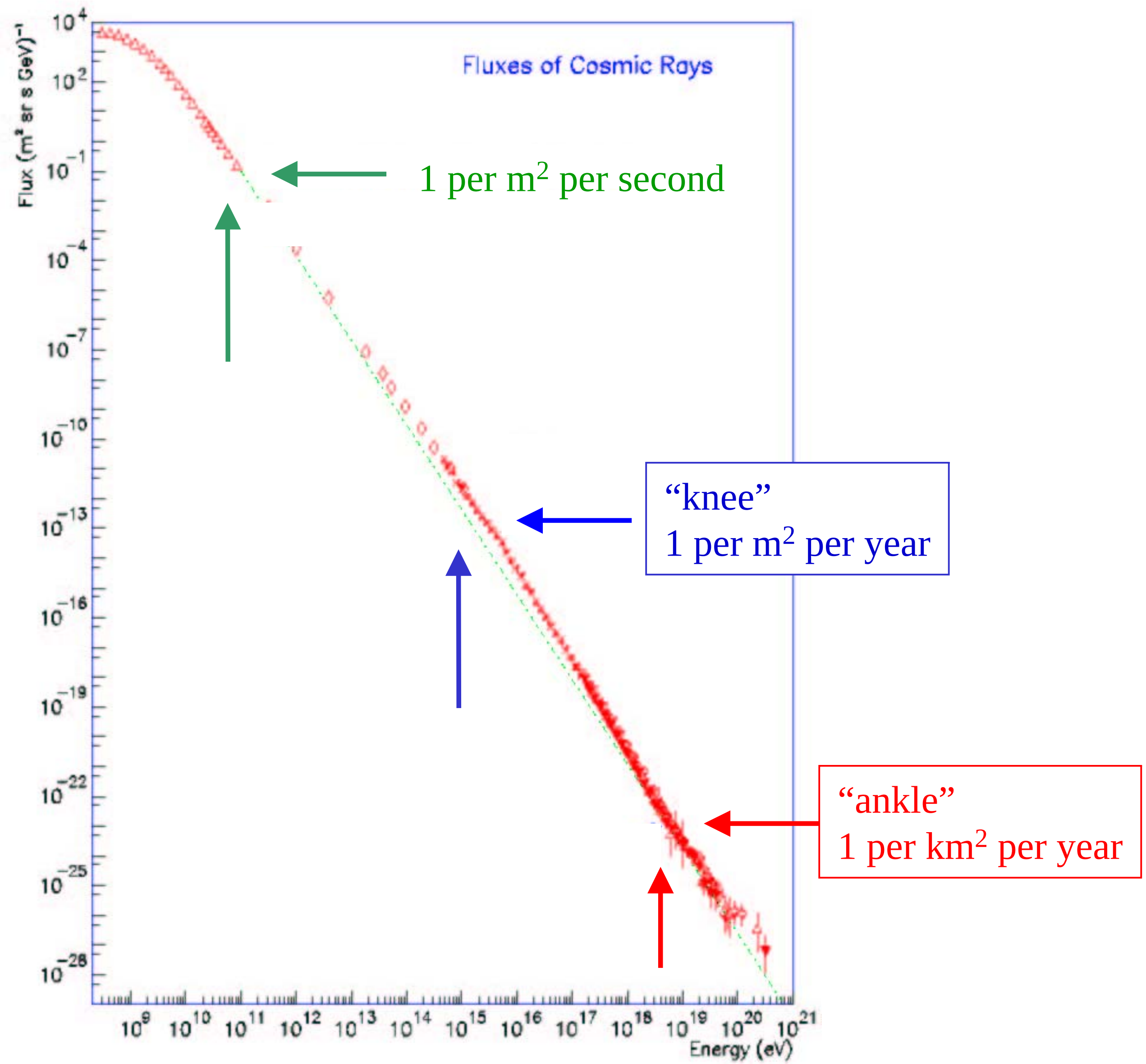
$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm} \hookrightarrow \mu\nu \hookrightarrow e\nu\nu$$



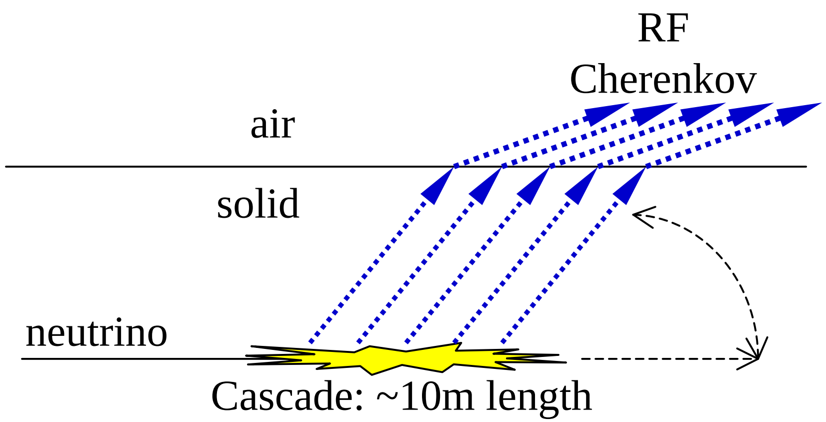
Why so Hard?? The Flux Problem

- At E>10^20…

$$\iiint_{r,\phi,\theta} dr\,d\phi\,d\theta$$



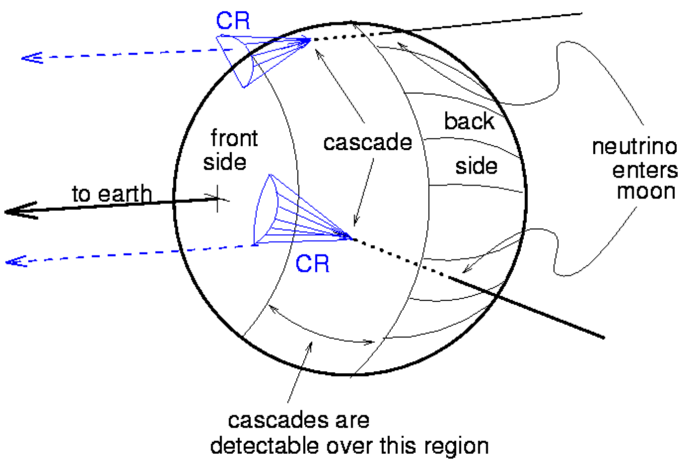
How to Observe?



1960's: Askaryan predicted that the resultant compact cascade shower (1962 JETP **14**, 144; 1965 JETP **21**, 658):

- would develop a local, relativistic net negative charge excess
- would be coherent ($P_{rf} \sim E^2$) for radio frequencies
- for high energy interactions, well above thermal noise
- detectable at a distance (via antennas)
- polarized – can tell where on the Cherenkov cone

Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)



Current Status:

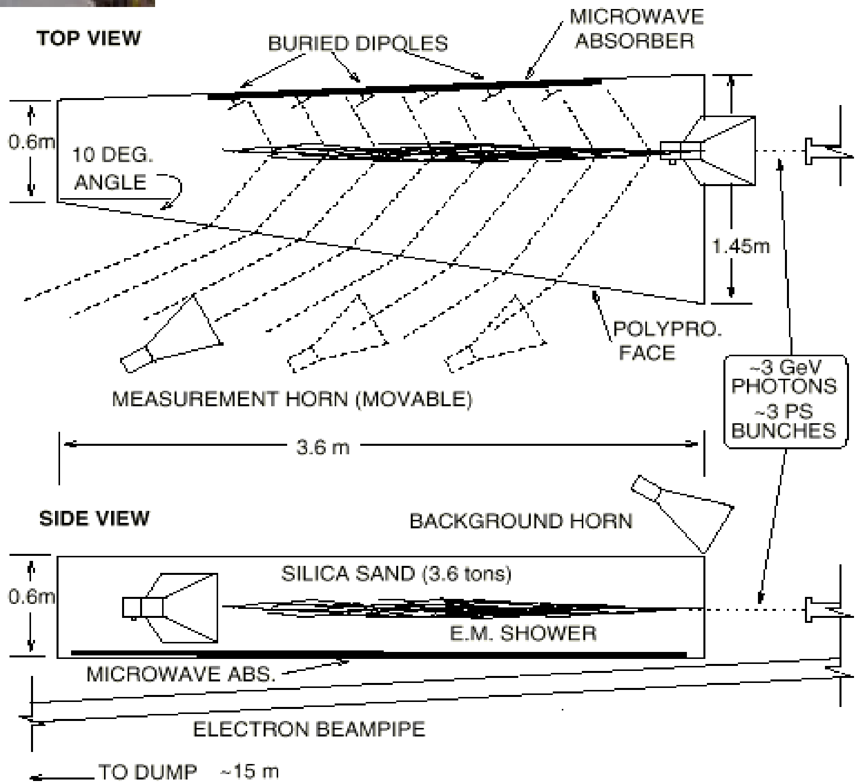
- Total of 120 hrs (clean) livetime [MER priority since August 2002]

- PRL 93:041101 (2004) limits published

- Still no events in high-threshold analysis
    - beginning to constrain highest TD models
    - low-threshold peak now diluted

- New Initiative?
    - R. Ekers (director of Australia Nat'l Telescope Facility) has solicited possible new experiment at ATCA
    - potential factor of 50 gain

Askaryan Confirmation: SLAC T444 (2000)



Saltzberg, Gorham, Walz *et al* PRL **86** 2802 (2001)

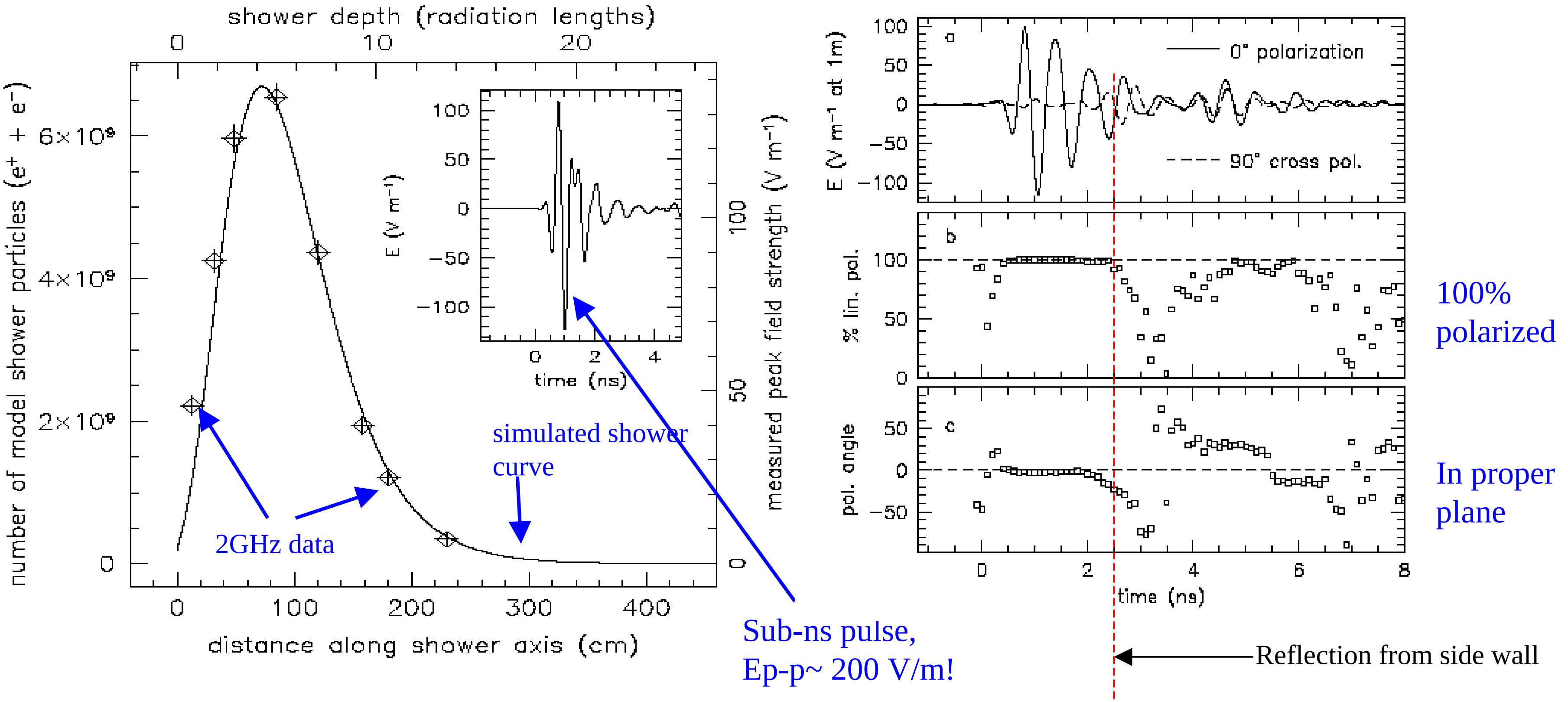
• Use 3.6 tons of silica sand, brem photons to avoid any charge entering target

==> no transition radiation

• Monitor all backgrounds carefully

• but signals were much stronger!

Shower profile observed by radio (~2GHz)

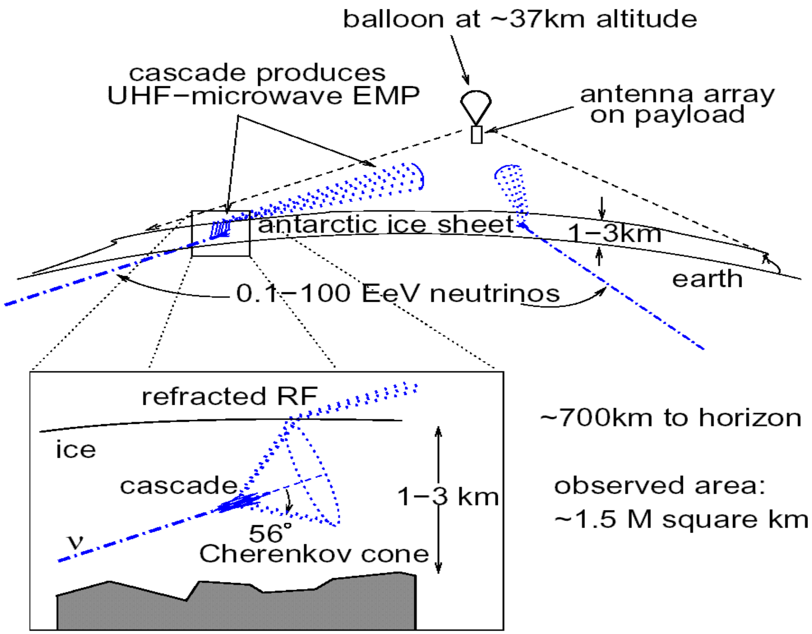


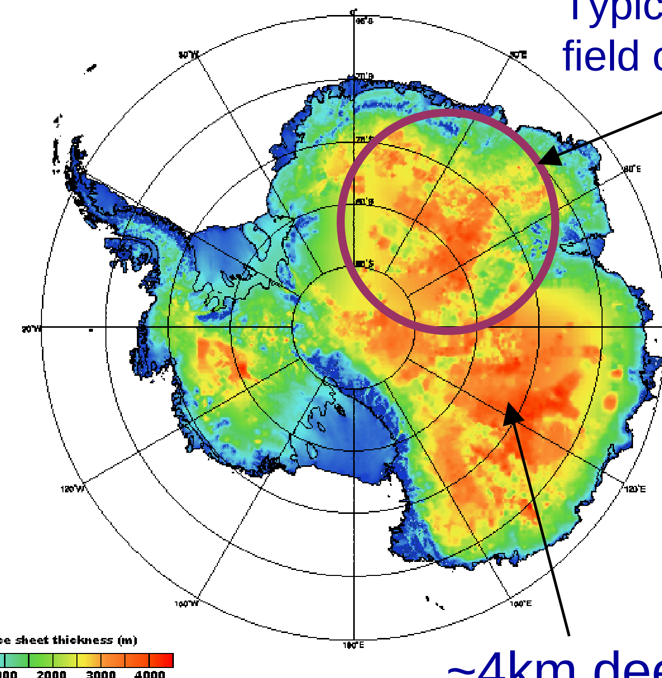
- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Polarization completely consistent with Cherenkov—can track particle source

Design for discovery of GZK ν flux

- Huge Volume of solid, RF-transparent medium: Antarctic Ice
- Broadband antennas, low noise amplifiers and high-speed digitizers to observe them
- A very high vantage point, but not too high nor too far away
- The end result: ANITA

ANITA concept

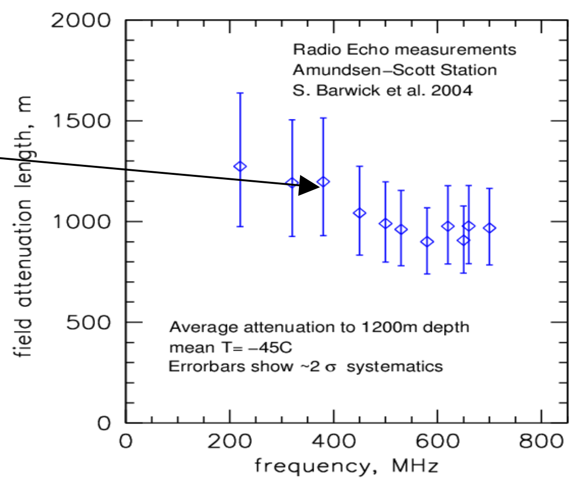




Typical balloon field of regard

~4km deep ice!

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



Effective “telescope” aperture:

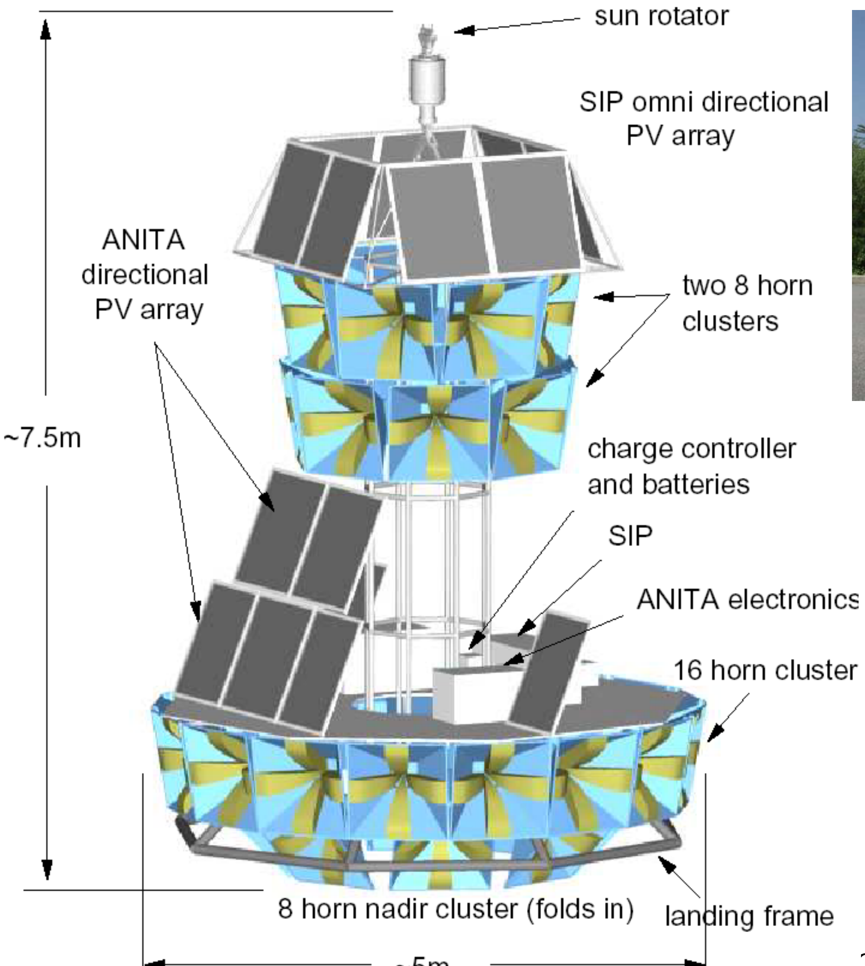
- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

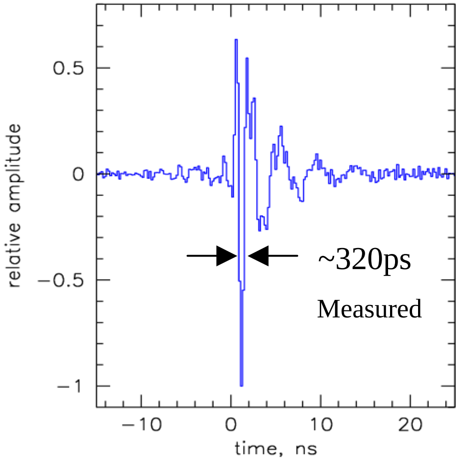
(compare to ~1 km^3 at lower E)

S.W. Barwick, J.J. Beatty, D.Z. Besson, W. R. Binns, B. Cai, J.M. Clem, A. Connolly, P.F. Dowkontt, M.A. DuVernois, D. Goldstein, P.W. Gorham, M.H. Israel, J.G. Learned, K.M. Liewer, J.T. Link, E. Lusczek, S. Matsuno, P. Miovcinovic, J. Nam, C.J. Naudet, R. Nichol, M. Rosen, D. Saltzberg, D. Seckel, A. Silvestri, G.S.Varner, F. Wu

Flight Payload Design

A radio "feedhorn array" for the Antarctica Continent





- Quad-ridged horn antennas provide superb impulse response & bandwidth (200-1200 MHz)

- Interferometry & beam gradiometry from multiple overlapped antenna measurements

ANITA Team

Peter Gorham, UH & JPL
- Optical/IR/radio astronomy
- DUMAND, UHE cosmic rays

Multi-disciplinary:combining Neutrino, High Energy, Cosmic Ray Ballooning, and Radio Physics

Steve Barwick, UCI
- AMANDA, HEAT
- HE neutrino astronomy

Jim Beatty, OSU
- HEAT, CREAM
- UHE cosmic rays

Bob Binns, WUSL
- TIGER LDB mission
- HE cosmic rays

Mike DuVernois, UM
- CREAM, Auger
- RF from air showers

Kurt Liewer, JPL
- GLUE
- DSN radio science

Chuck Naudet, JPL
- GLUE
- DSN radio science

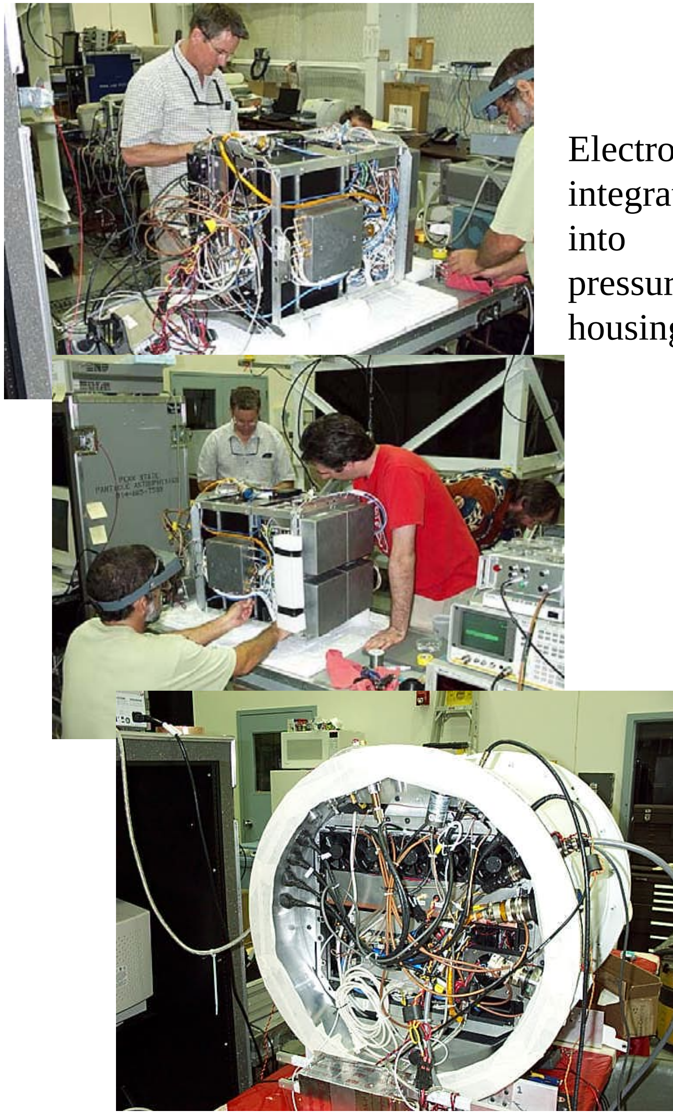
David Saltzberg, UCLA
- GLUE, radio science
- HE Particle physics

Gary Varner, UH
- HE particle physics
- Physics instrumentation

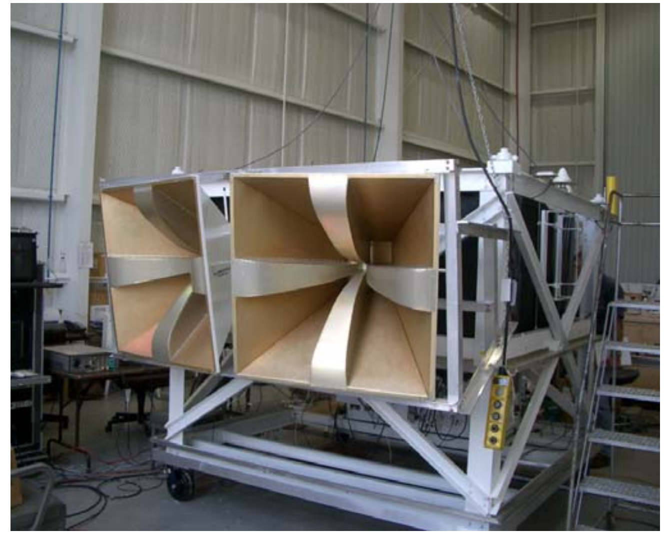
ANITA Concerns

- Ice attenuation
  - South Pole measurements
- RF background
  - ANITA-lite
- Ability to see signal in ice
  - Ground RF pulser

ANITA-lite as-built Configuration



Electronics integration into pressure housing



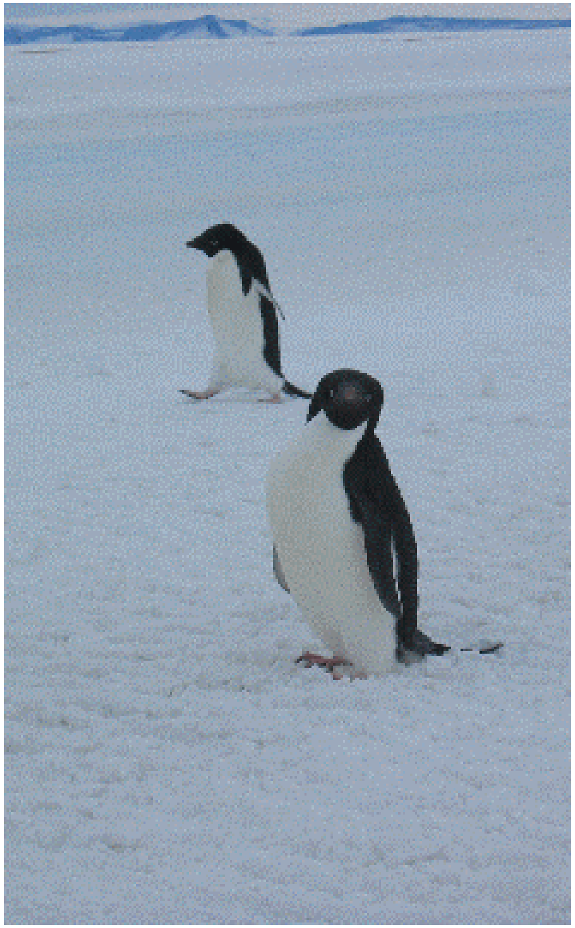
Antenna arrangement

Instrument housing under TIGER

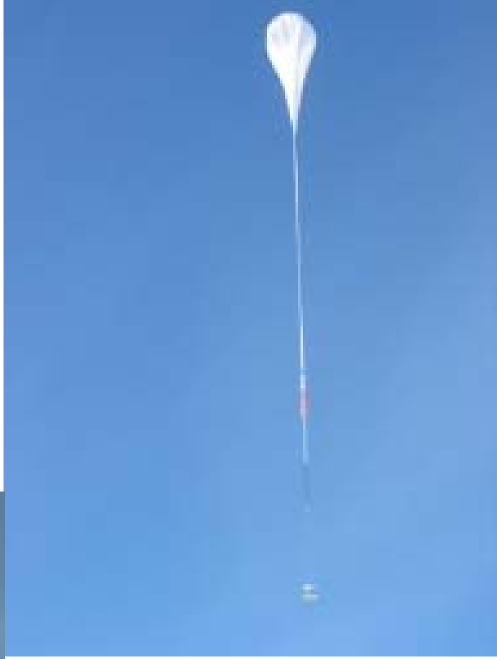
Housing, hard drive, veto antenna

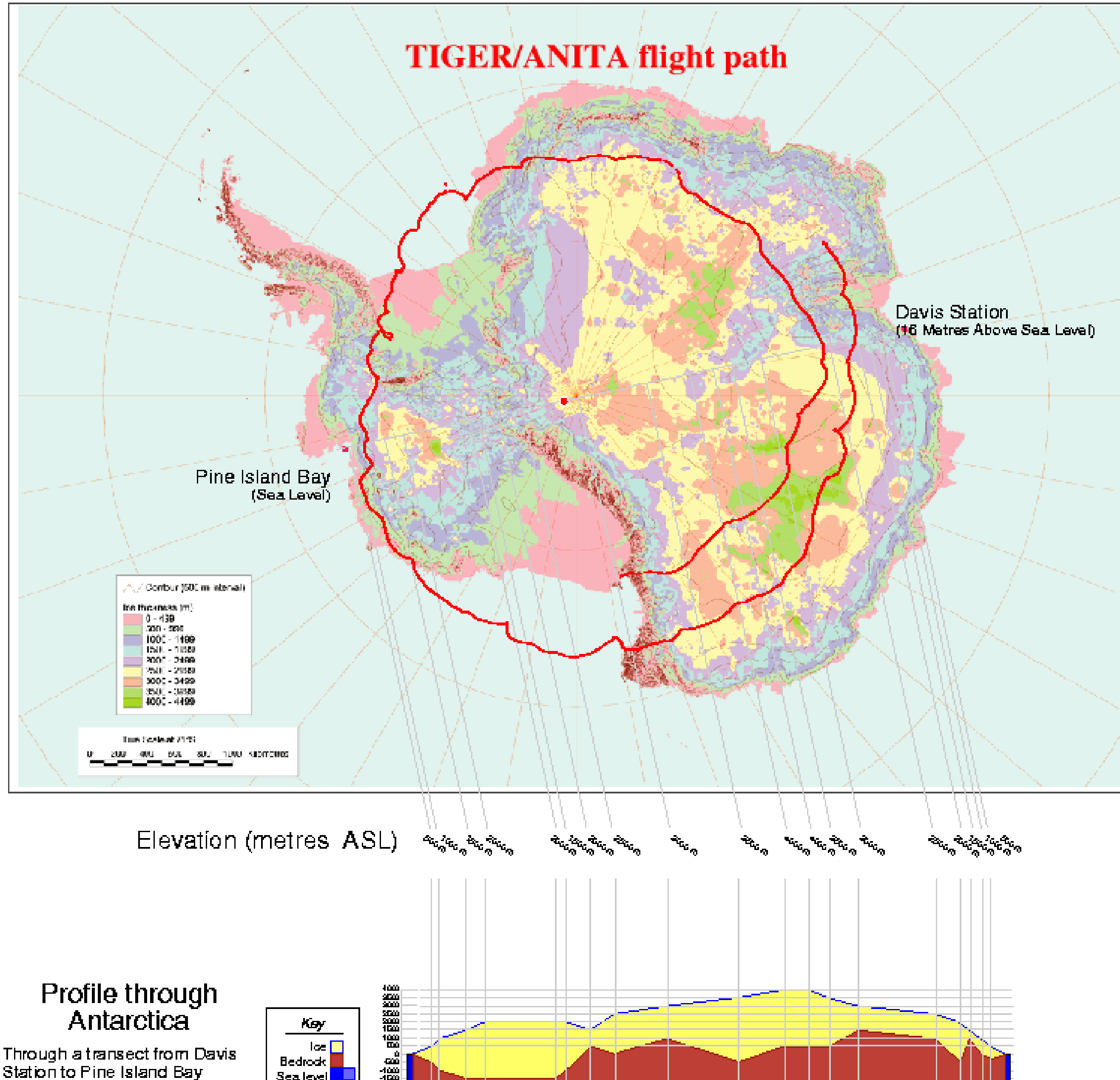
Redundant fast-recovery USB harddrive (8GB)

Pre-Launch

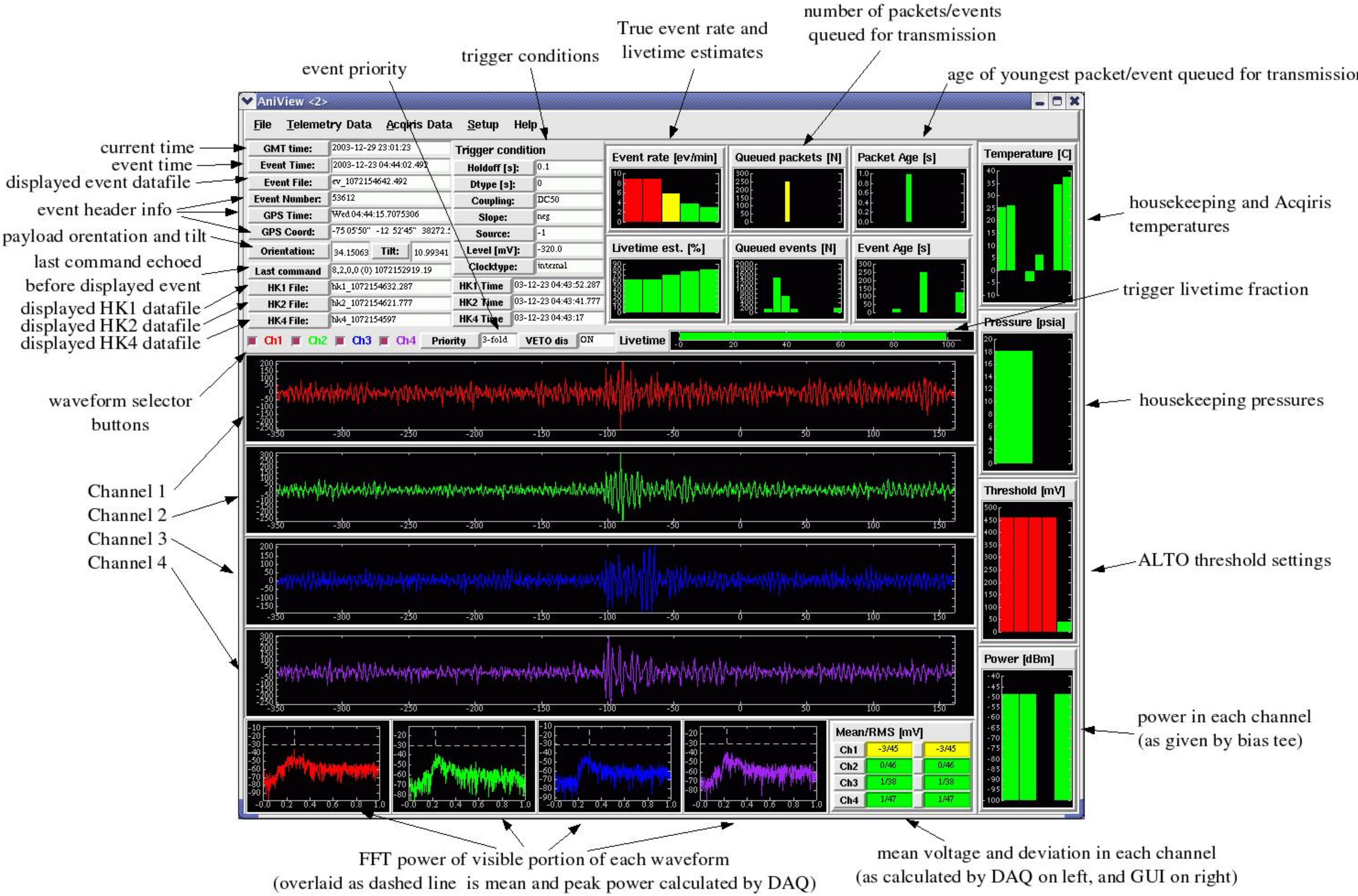


Launch!




TIGER/ANITA flight path
Davis Station
(16 Metres Above Sea Level)
Pine Island Bay
(Sea Level)
Elevation (metres ASL)
Profile through Antarctica
Through a transect from Davis Station to Pine Island Bay
Key
Ice
Bedrock
Sea level

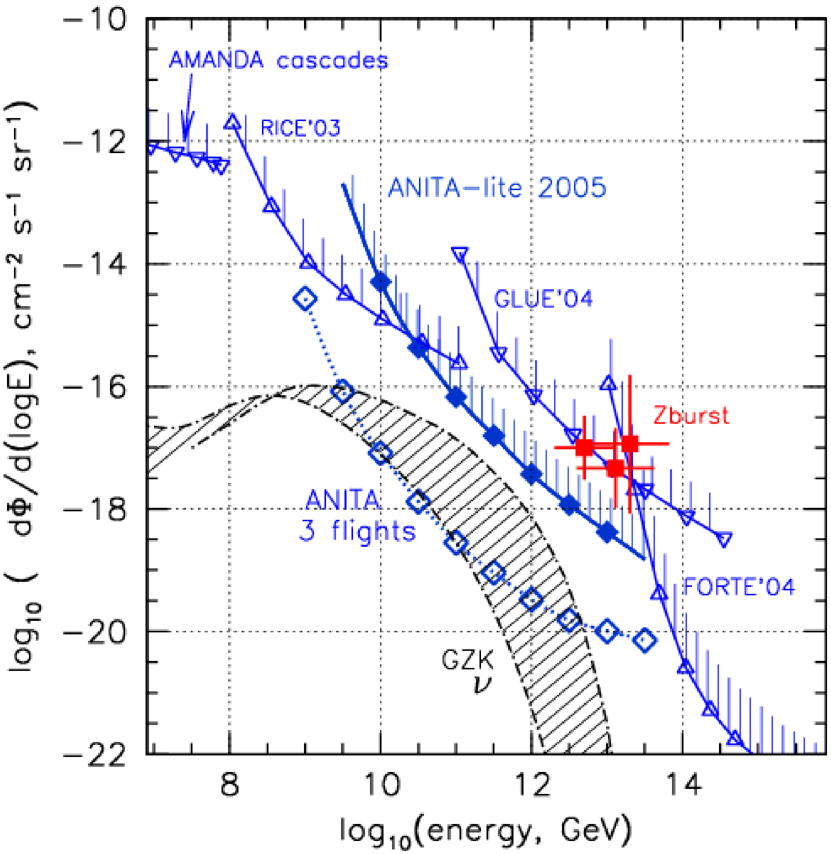
Started Feb., commission June, flew Dec.!



ANITA-Lite Operation Summary

- Power (heat) is a major issue
- 110k recorded transient events – many local (payload) induced
- Demonstrated ability to operate at thermal noise levels
- Successfully recorded test pulses (unsynchronized and GPS 1PPS)

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 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!**

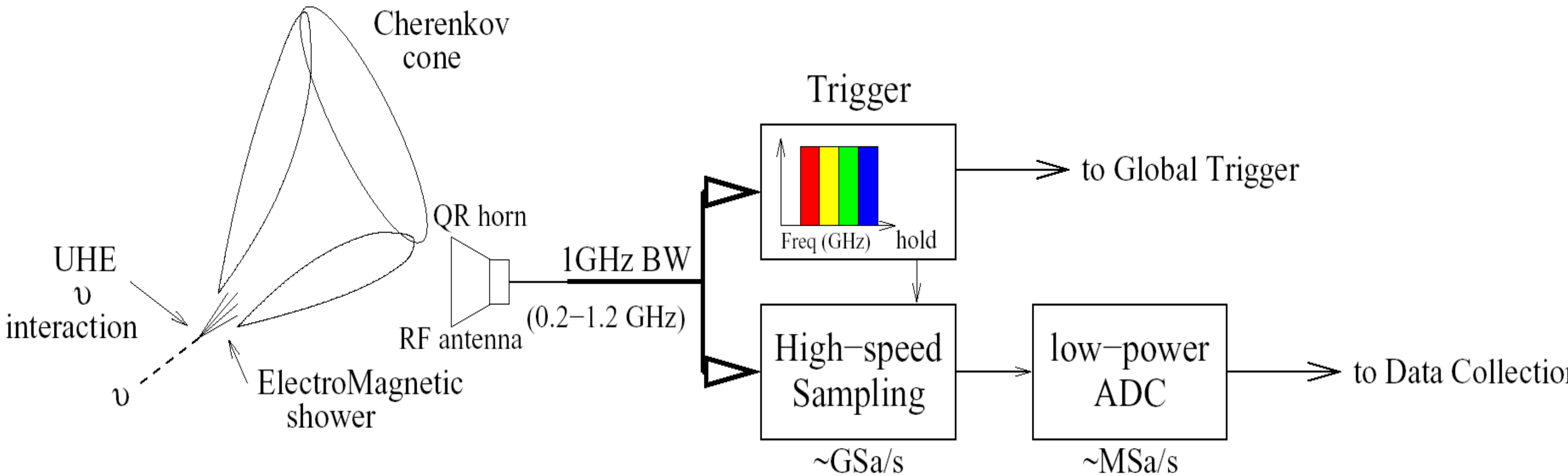
Major Hurdles

- No commercial waveform recorder solution (power/precision)

- 3σ thermal noise fluctuations occur at MHz rates (need ~2.3σ)

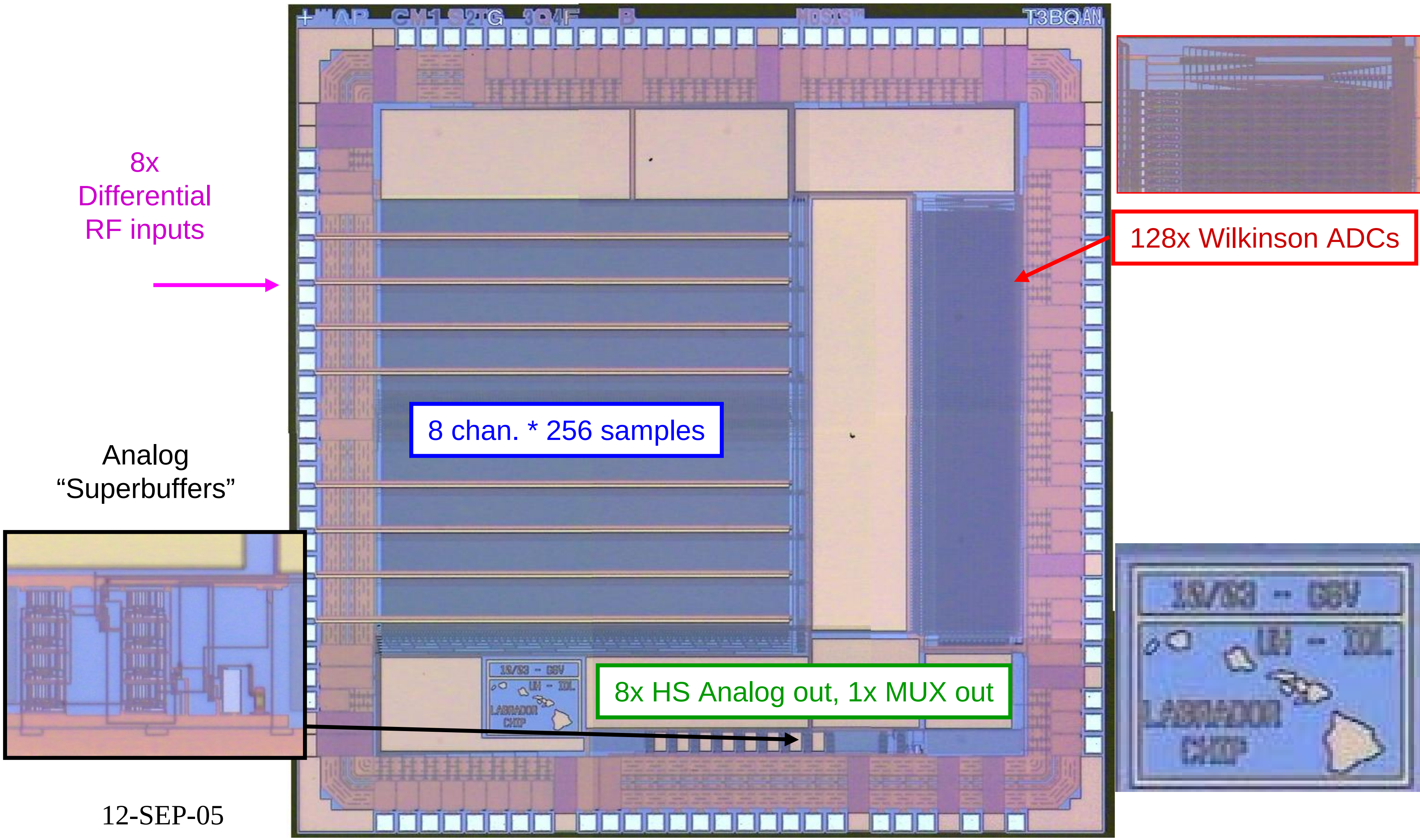
- Without being able to record or trigger efficiently, there is no experiment

Strategy: Divide and Conquer



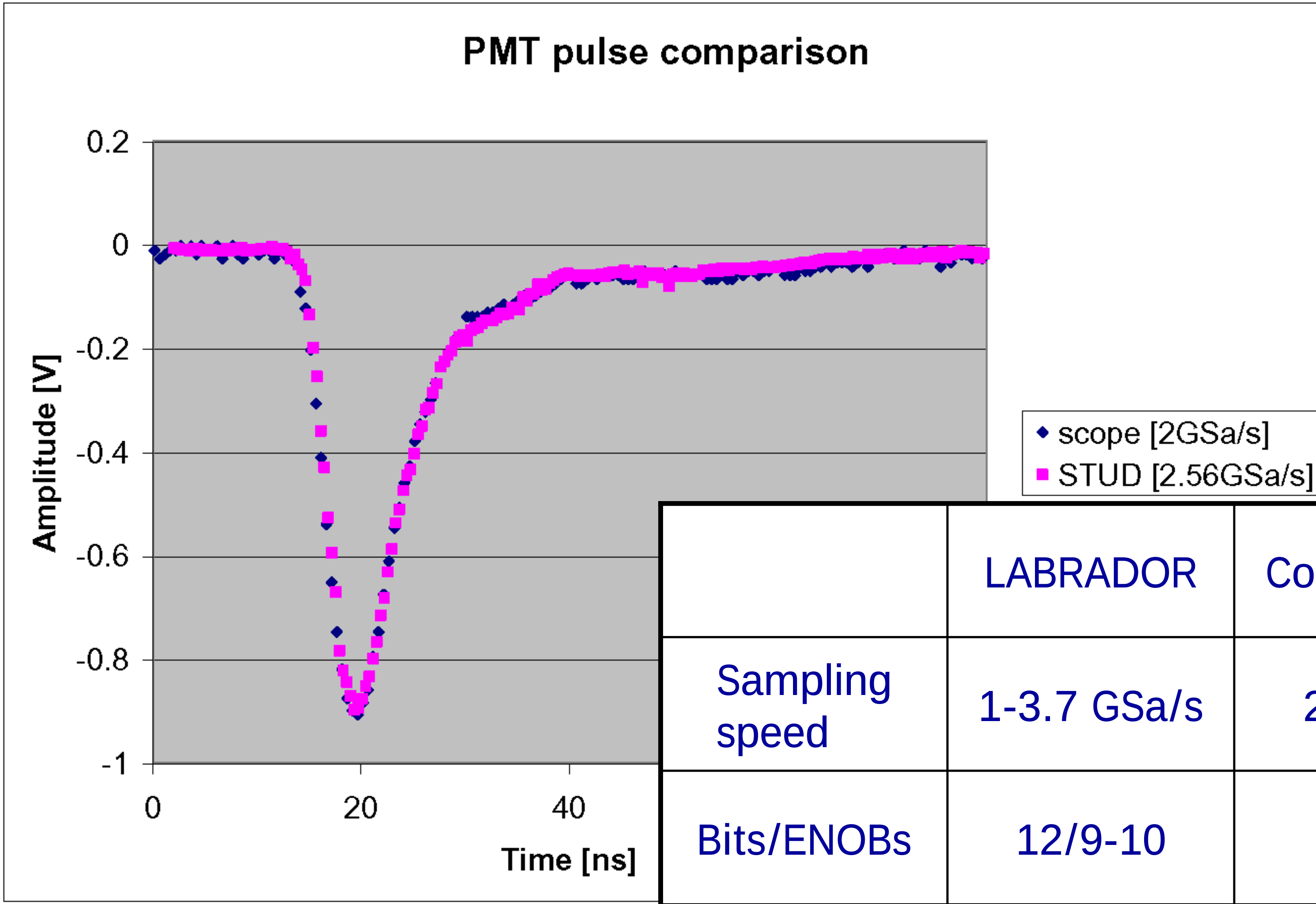
- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

LABRADOR size = $2.5mm^2$



12-SEP-05

High Speed sampling



	LABRADOR	Commercial
Sampling speed	1-3.7 GSa/s	2 GSa/s
Bits/ENOBs	12/9-10	8/7.4
Power/Chan.	<= 0.05W	5-10W

ANITA Engineering Model Payload

- Extended, heavy structure – had to prove could survive launch & recovery

ANITA EM Payload

- Successful flight from Ft. Sumner

Go for Dec. ’06 Antarctic Flight!

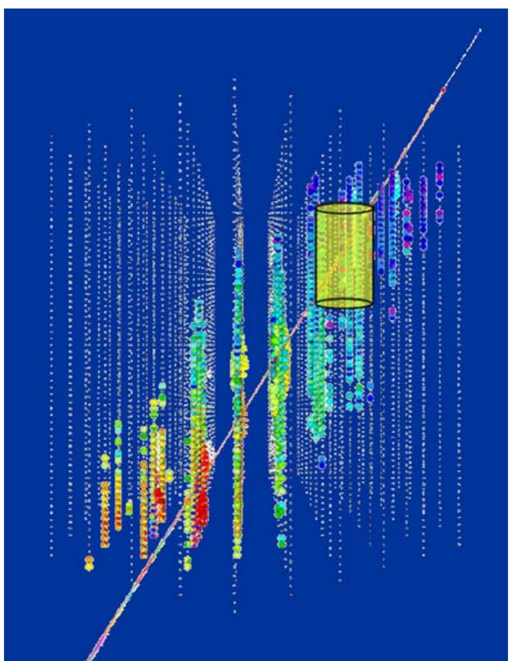
Where we might be in just 5 years...

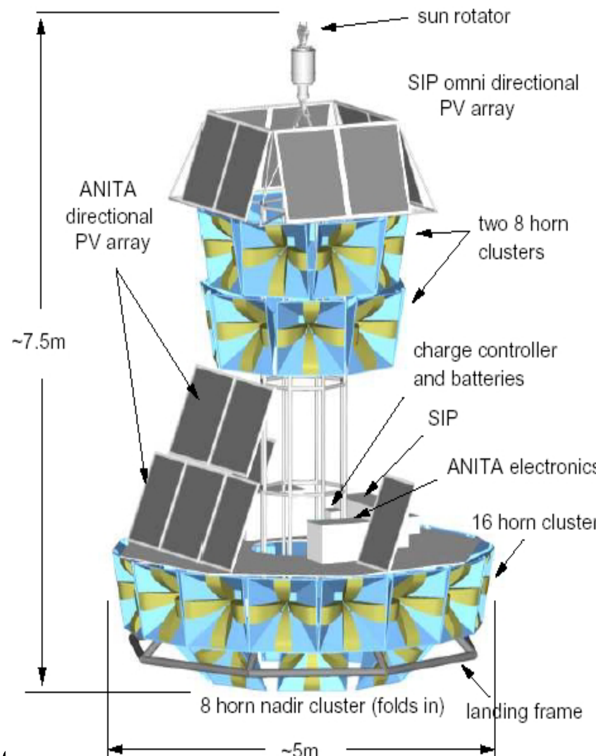
- <u>IceCube</u>
  - Discovery of bottom-up sources
  - Discovery of ~ 3 GZK neutrinos

- <u>ANITA:</u>

  Discovery of ~10 GZK neutrinos

- <u>Auger</u>
  - Discovery of a few GZK neutrinos





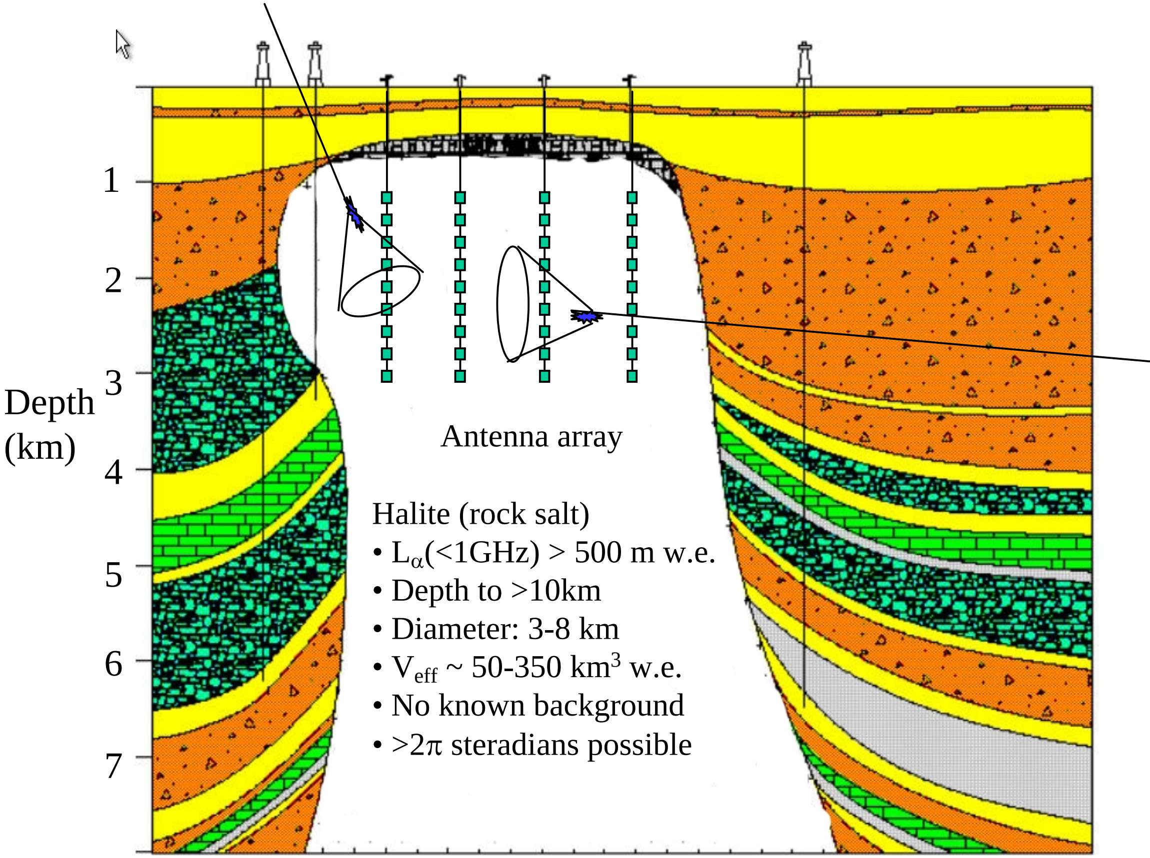
What is needed for a GZK ν detector?

- 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 detectors

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.**

SALSA Collaboration

University of Delaware

University of Hawaii

University of Minnesota

U.C.L.A.

S.L.A.C. and Stanford University

Louisiana State University

Washington University

University of Kansas

UC Berkeley and LBNL

University of Utah

Endeavour Corporation

Deutsches Elektronen Synchrotron (Germany)

UT Austin

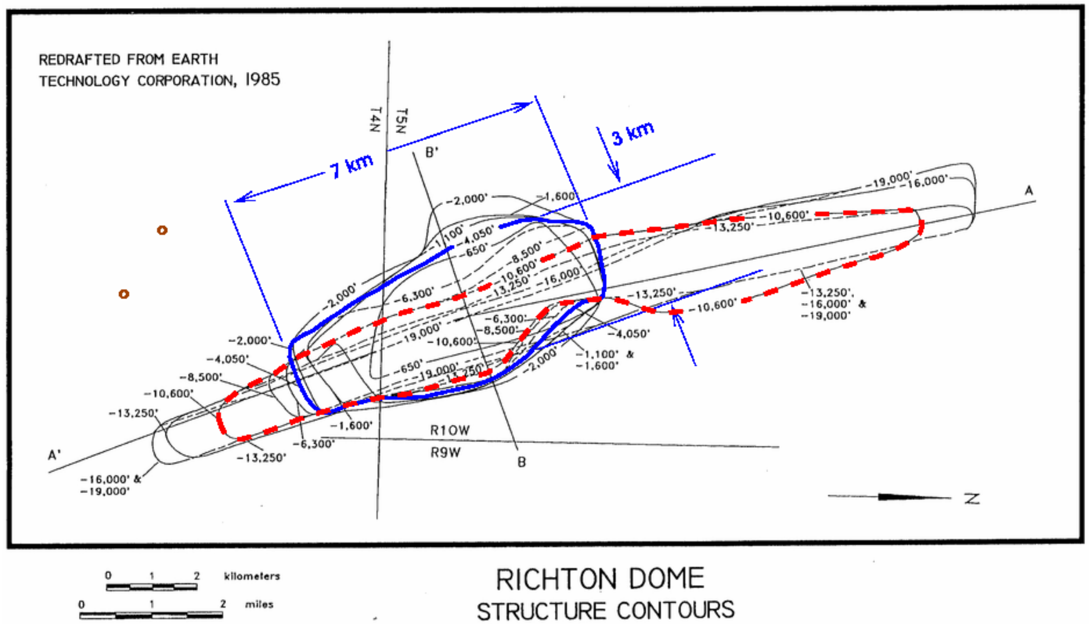
Kernfysisch Versneller Instituut (Netherlands)

Ohio State Univesity

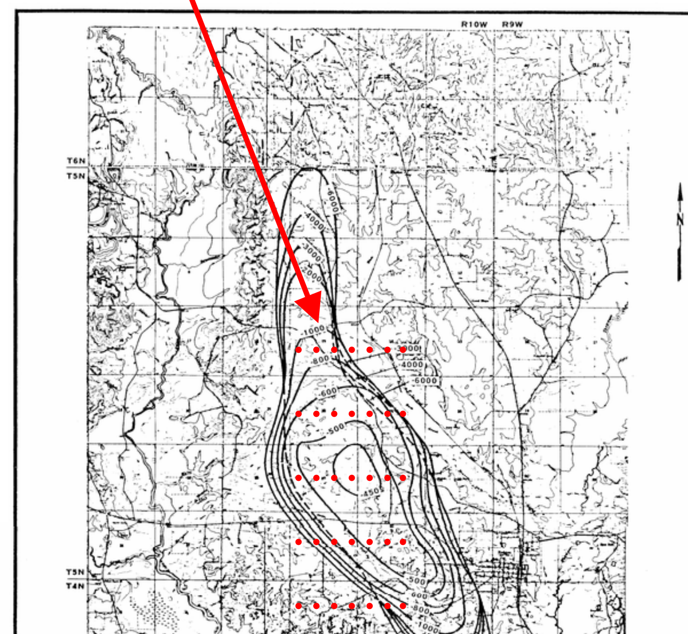
UC Irvine

e.g. Richton Dome (MS)

Array of bore holes using standard oil drilling techniques

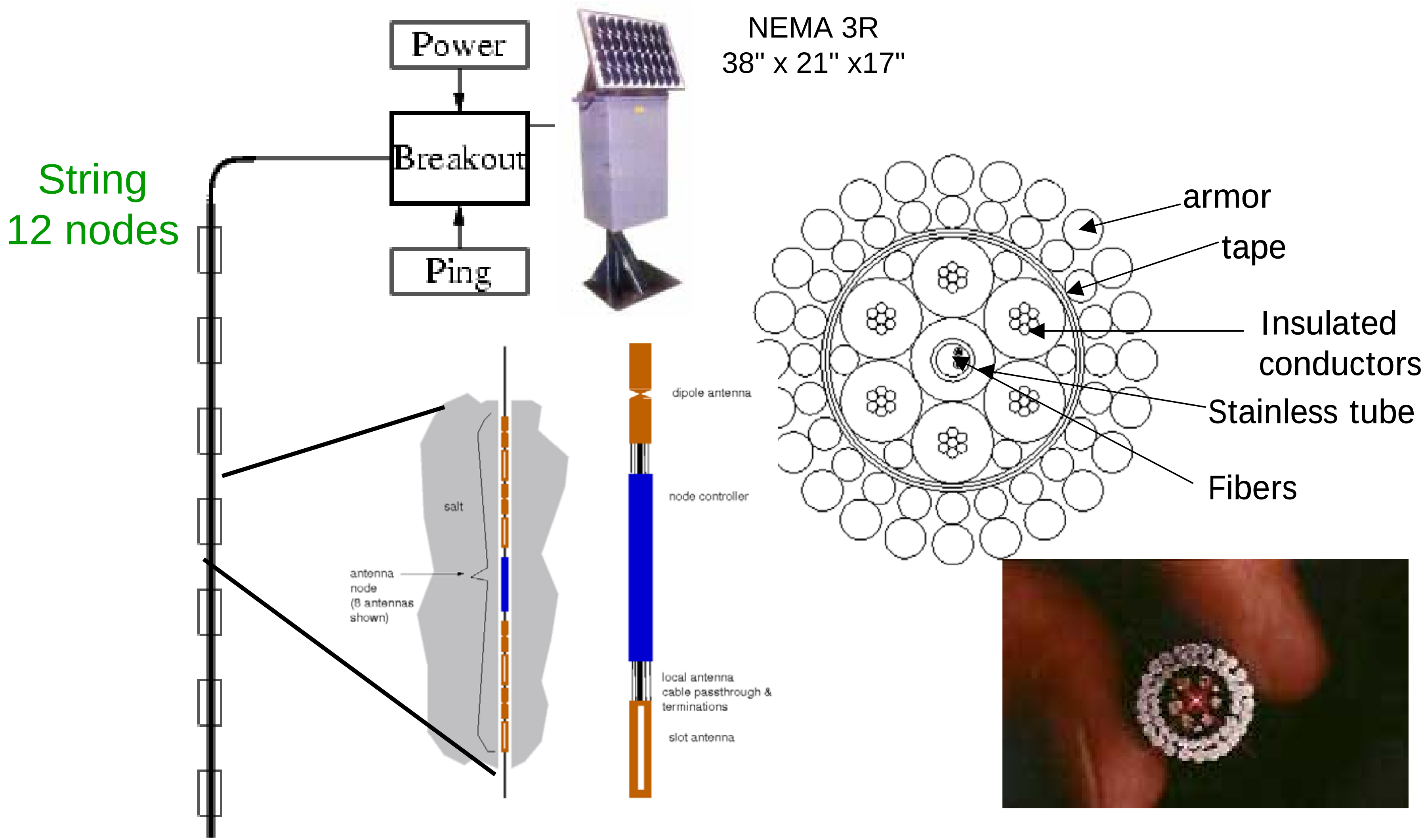


RICHTON DOME
STRUCTURE CONTOURS
TOP OF SALT MODEL



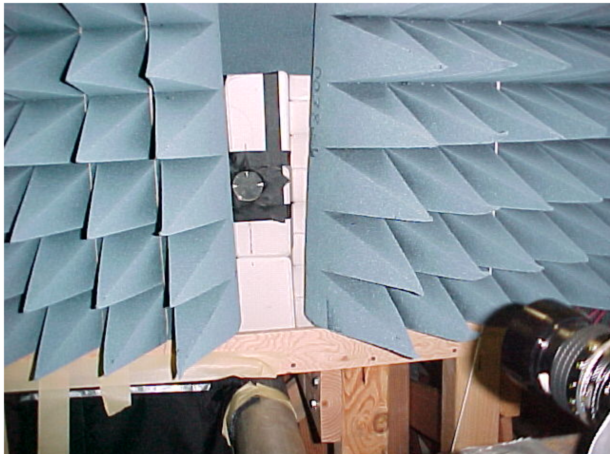
- Richton Dome has excellent seismic, gravity & direct drilling measurements of salt body
- Among the largest of all Gulf coast domes

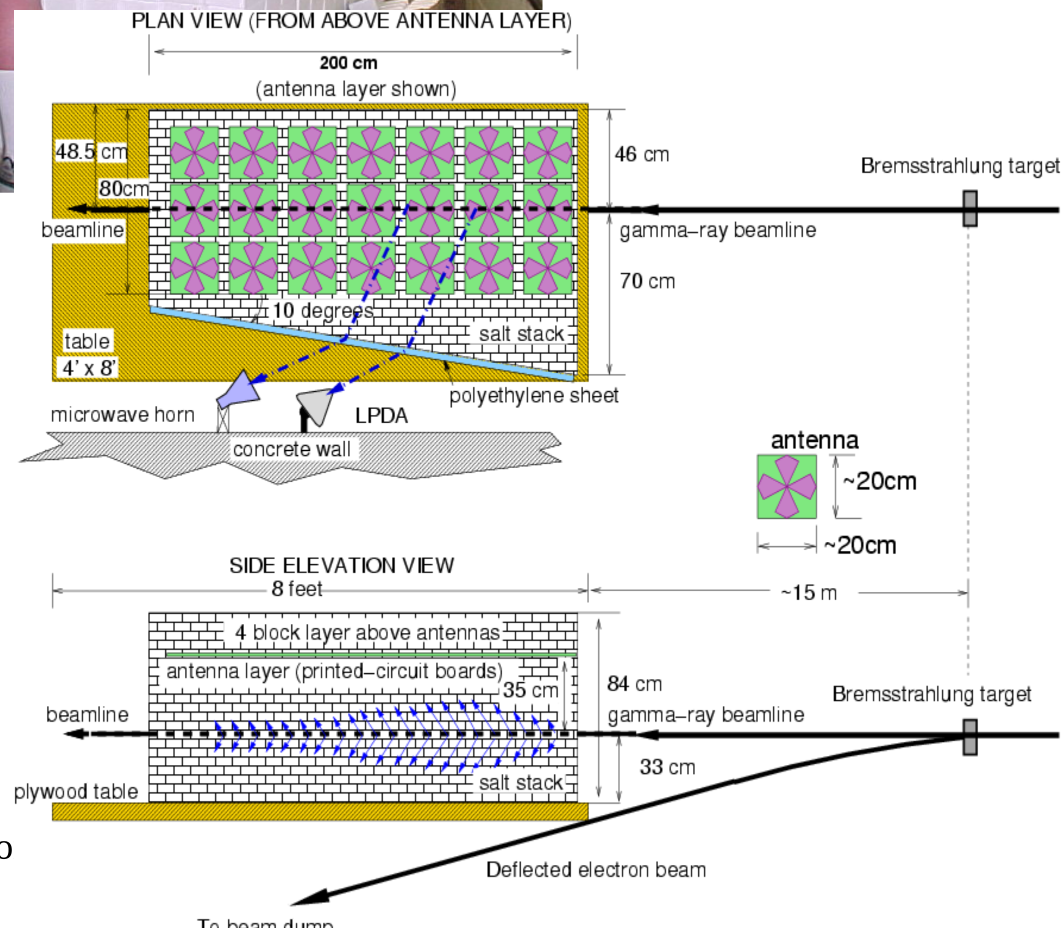
Basic string architecture



Node = 12 antennas and center housing

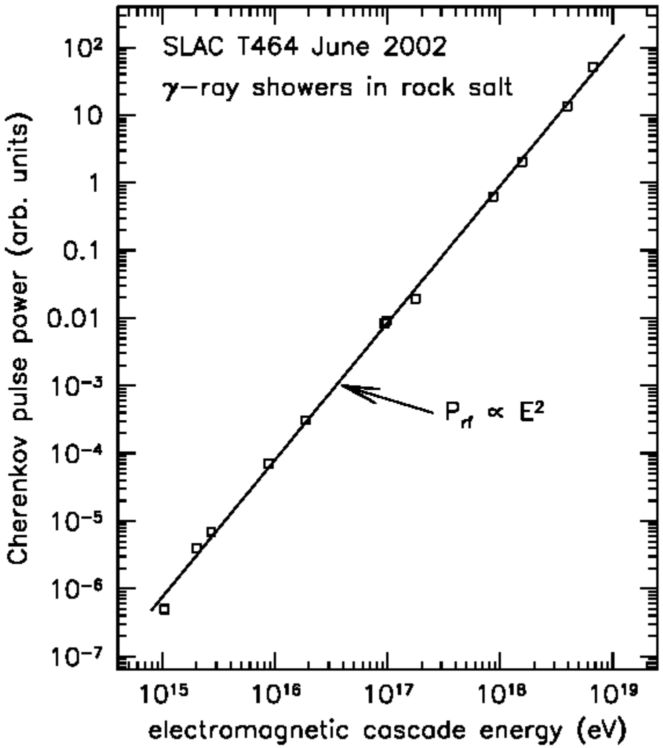
Askaryan in Salt: SLAC T460

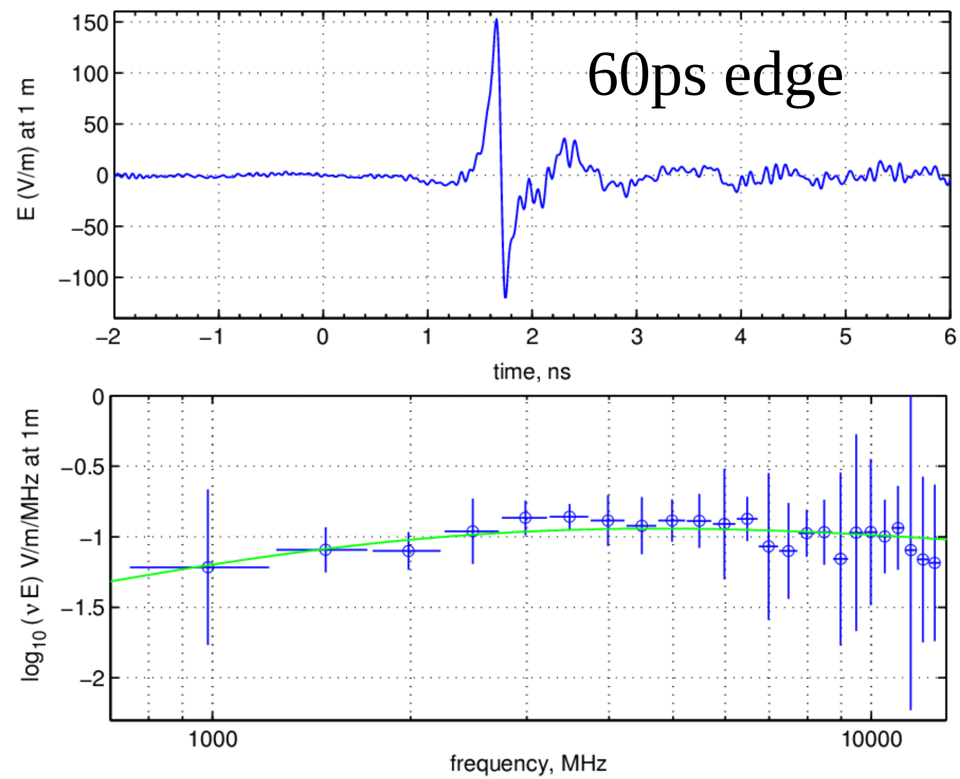




- Target: 6 tons of Morton brick salt
- Provide shower volume and embedded antenna matrix
- Antennas sample 21 grid-points along shower, dual polarization

RF Coherence vs. energy & frequency

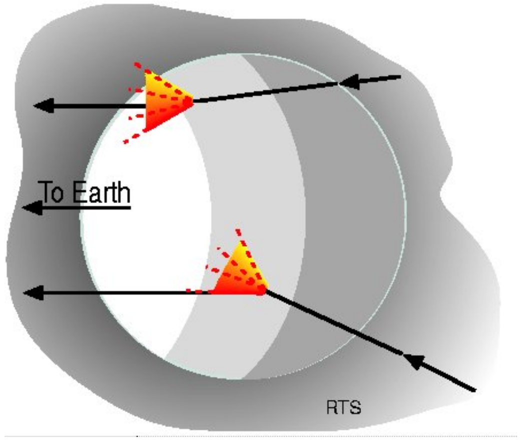




- **Much wider energy range covered than previously: 1PeV up to 10 EeV**
- **Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power**
- **Differs from actual EeV showers only in leading interactions==> radio emission almost unaffected**

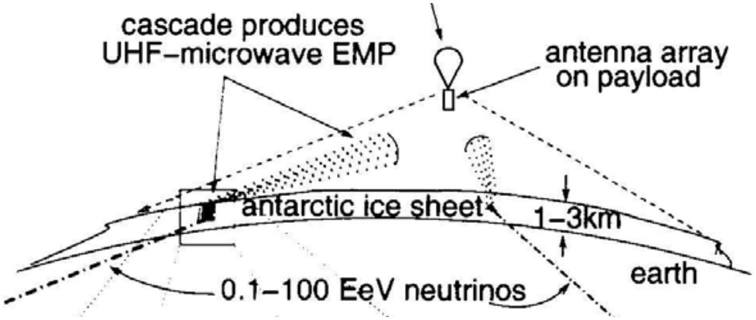
Taking as input

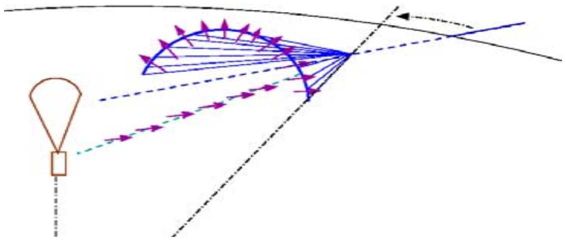
- Currently on <u>third generation</u> of several independently developed simulations

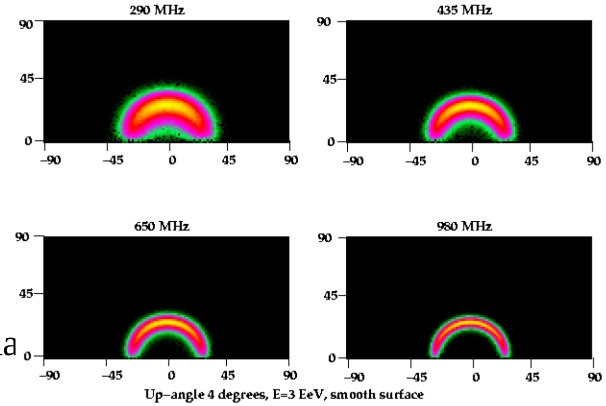


  – GLUE (Goldstone)

  – ANITA (Antarctic Impulsive Transient Antenna)

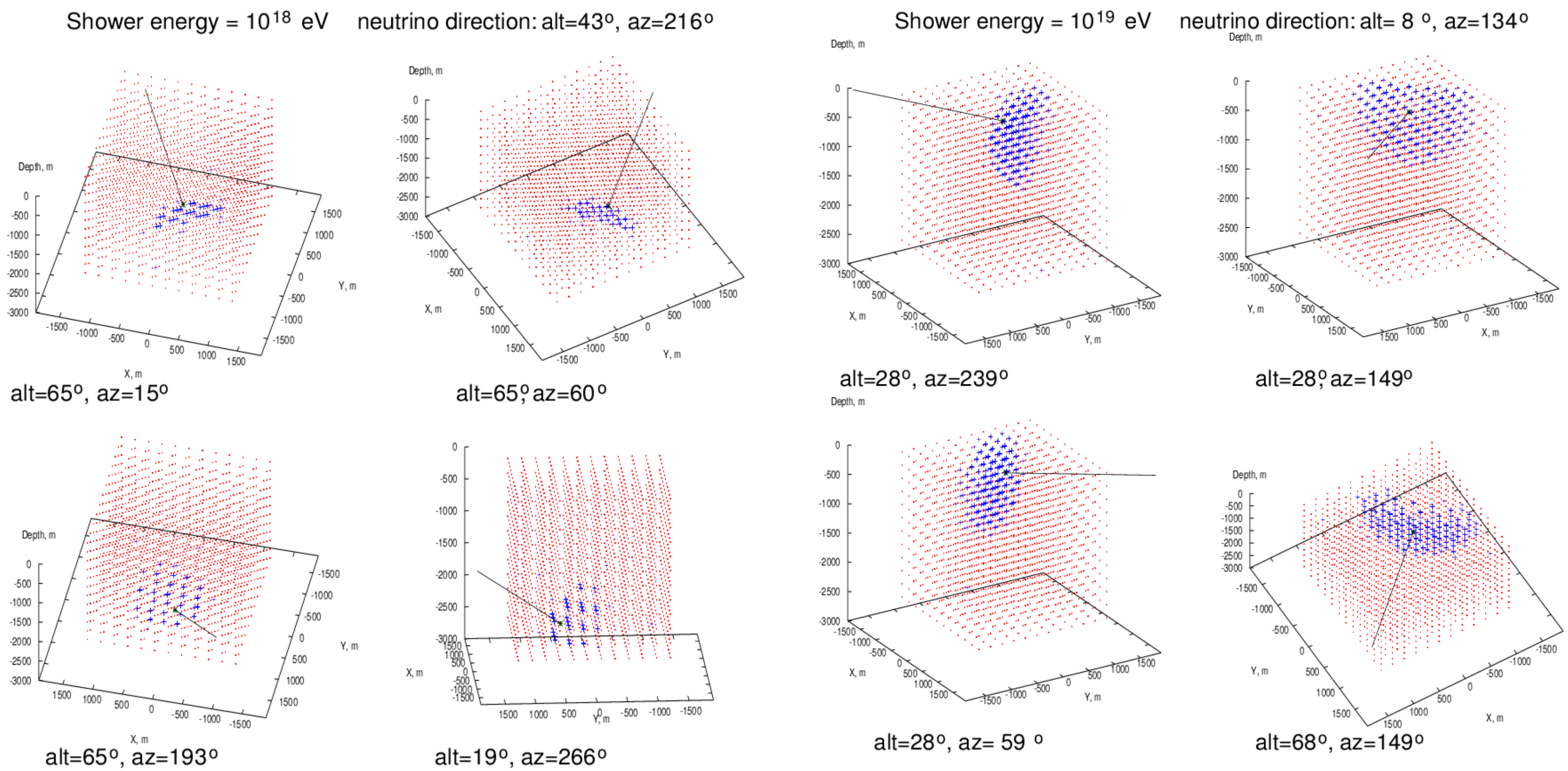






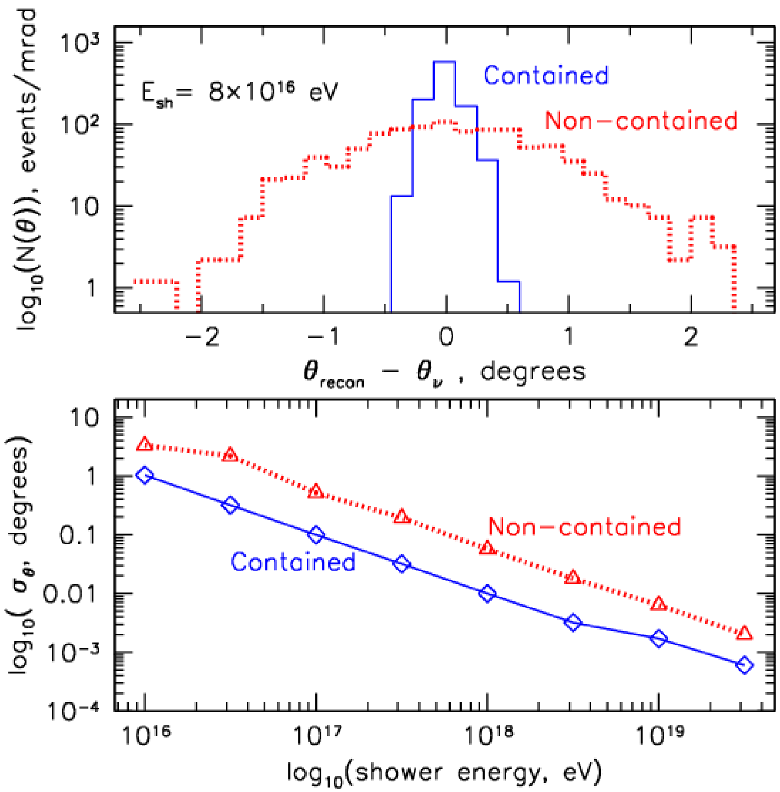
  – ➔ SALSA simulations…

SalSA simulations



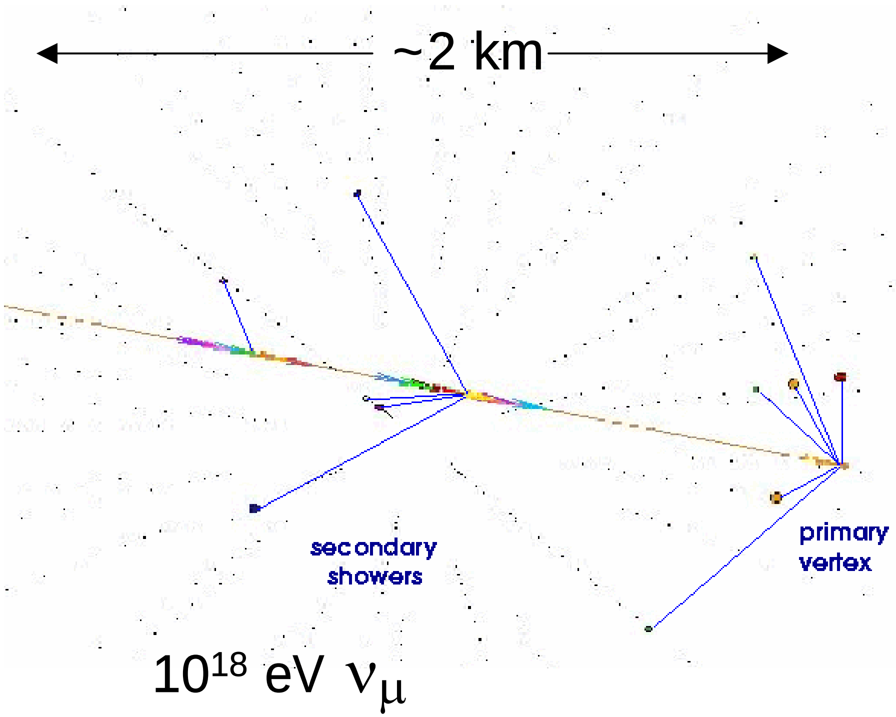
- A 2.5 km^3 array with 225 m spacing, 12^2=144 strings, 12^3=1728 antenna nodes, 12 antennas per node, dual polarization ==> **$V_{eff}\,\Omega$ = 380 km^3 sr w.e. at 1 EeV**
- Threshold <10^{17} eV, few 100s antennas hit at 1 EeV, >1000 hits at 10 EeV
- **Rate: at least 20 events per year from rock-bottom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

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!

Neutrino Flavor/Current ID



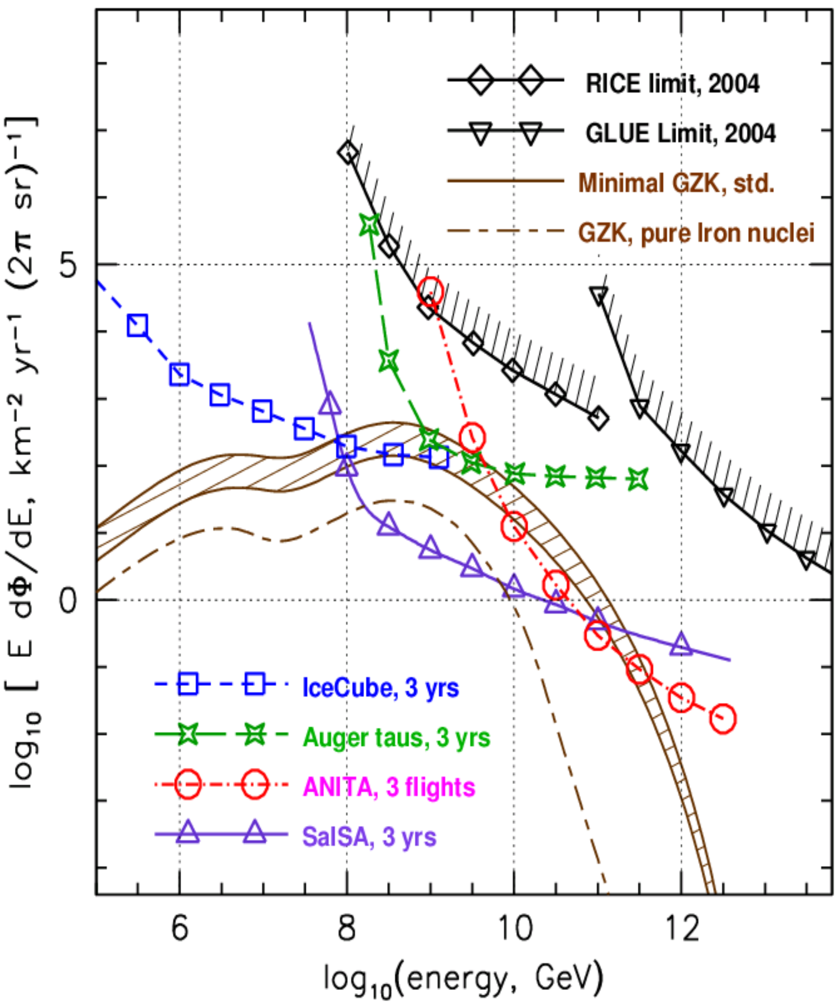
	Charged current (SM: 80%)	Neutral current (SM: 20%)
e	25% hadronic + 75% EM shower at primary vertex; LPM on EM shower	Single hadronic shower at vertex
μ	25% hadronic at primary, 2ndary lepton showers, mainly EM	Single hadronic shower at vertex
τ	25% hadronic at vertex, 2ndary lepton showers, mainly hadronic	Single hadronic shower at vertex

- Charged/neutral current & flavor ID possible on subset of SalSA events
- At least 20% of GZK CC events will get first order flavor ID
- Detailed studies in process – looks very promising

SalSA Physics Menu

- Astro-physics
  - Detection/observation of HE ν sources
- Cross-section
  - Test with precision SM well above LHC cm energies
  - Deep inelastic ν-n probing → high energy ν "beam"
- Particle ID
  - 1:1:1 ?
  - CC/NC ratio ?
- Others?

Existing Neutrino Limits and Potential Future Sensitivity

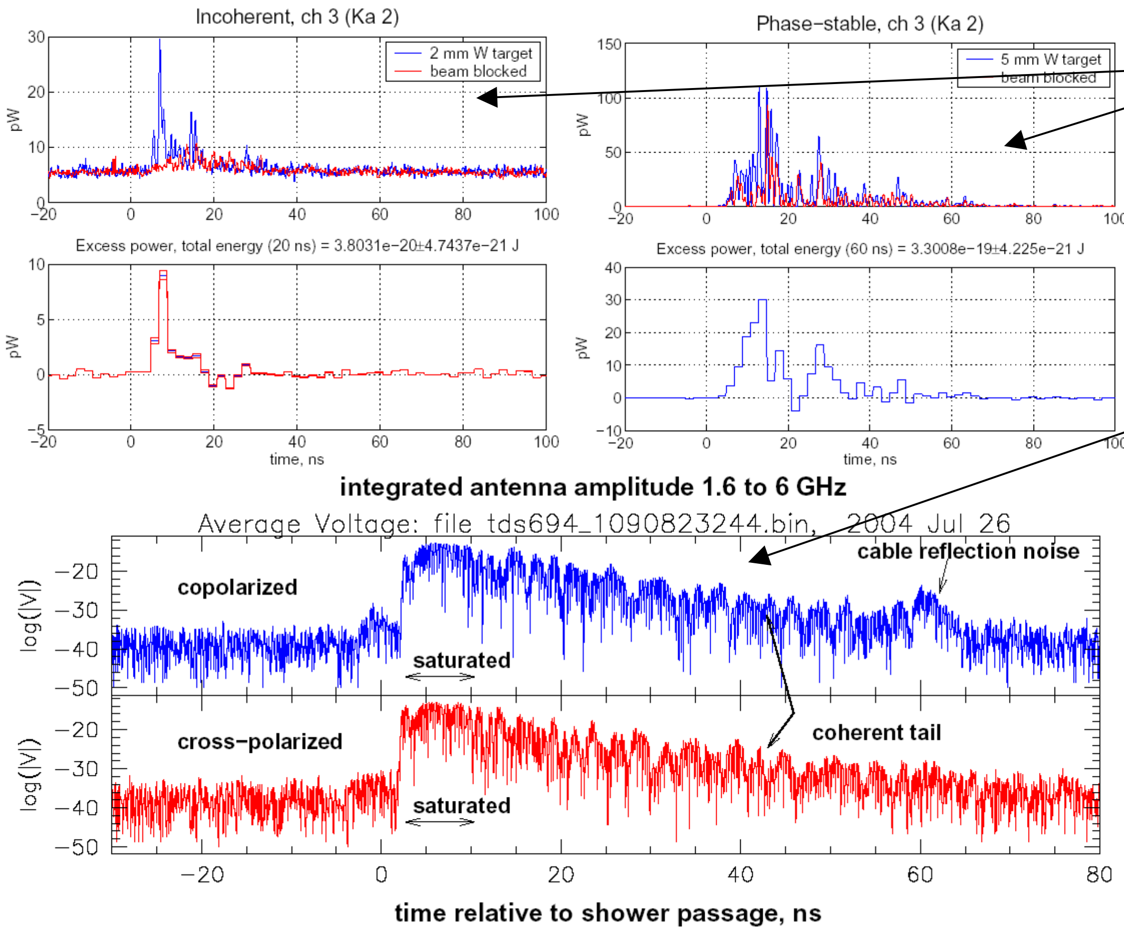


- RICE limits for 3500 hours livetime
- GLUE limits ~120 hours livetime
- ANITA sensitivity, 45 days total:
  - ~5 to 30 GZK neutrinos
- IceCube: high energy cascades
  - ~1.5-3 GZK events in 3 years
- Auger: Tau neutrino decay events
  - ~1 GZK event per year?
- **SalSA sensitivity, 3 yrs live**
  - **60-230 GZK neutrino events**

Radio Bremsstrahlung

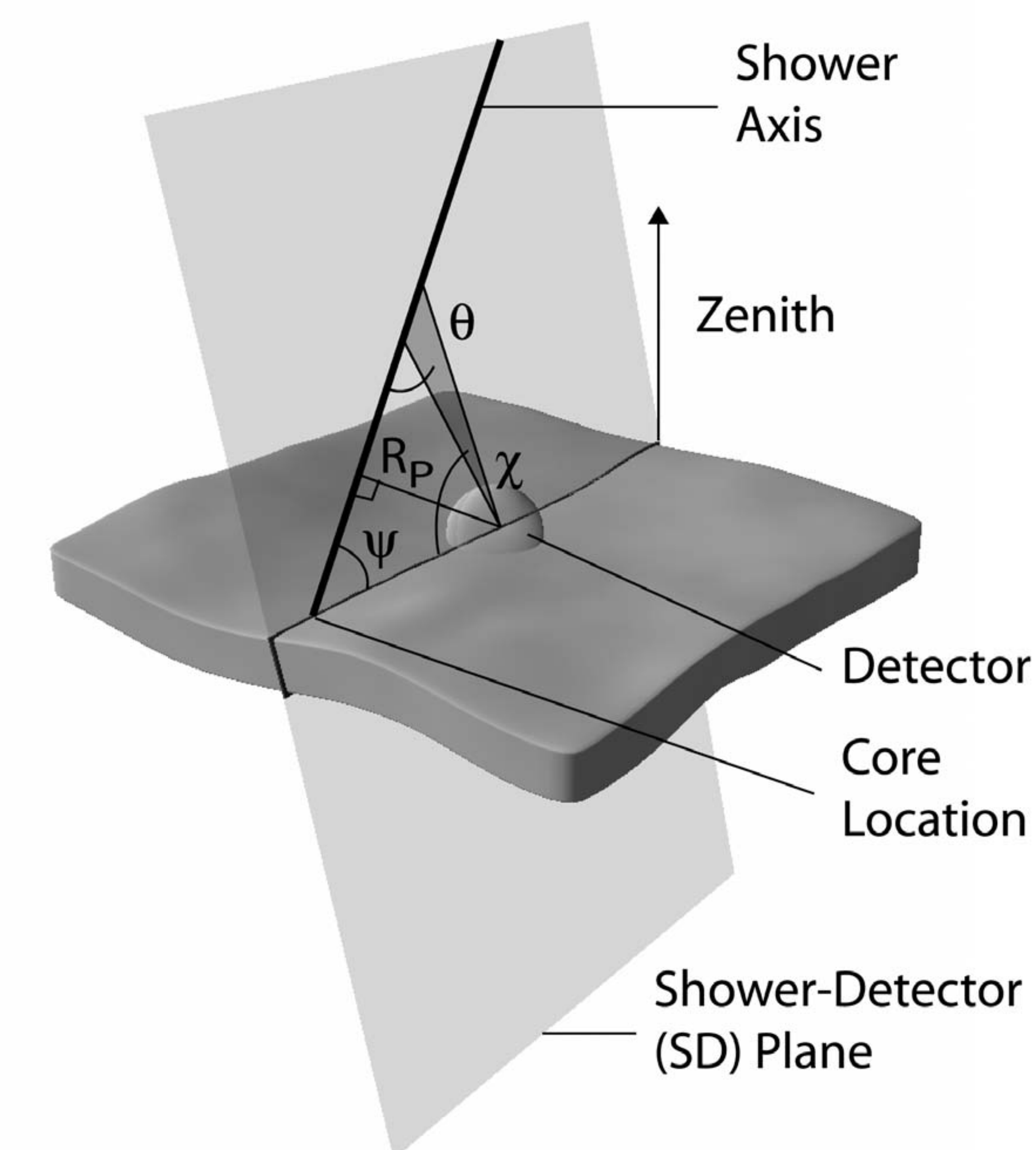
- “Radio fluorescence-equivalent” detection of ultra-high energy cosmic ray air showers
- Could provide 100% duty-cycle alternative to N2 fluorescence detection (<10% duty cycle typical)
- Two accelerator experiments: Argonne Wakefield Accelerator (2002) & SLAC-T471 (summer 2004) indicate stronger-than-expected 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

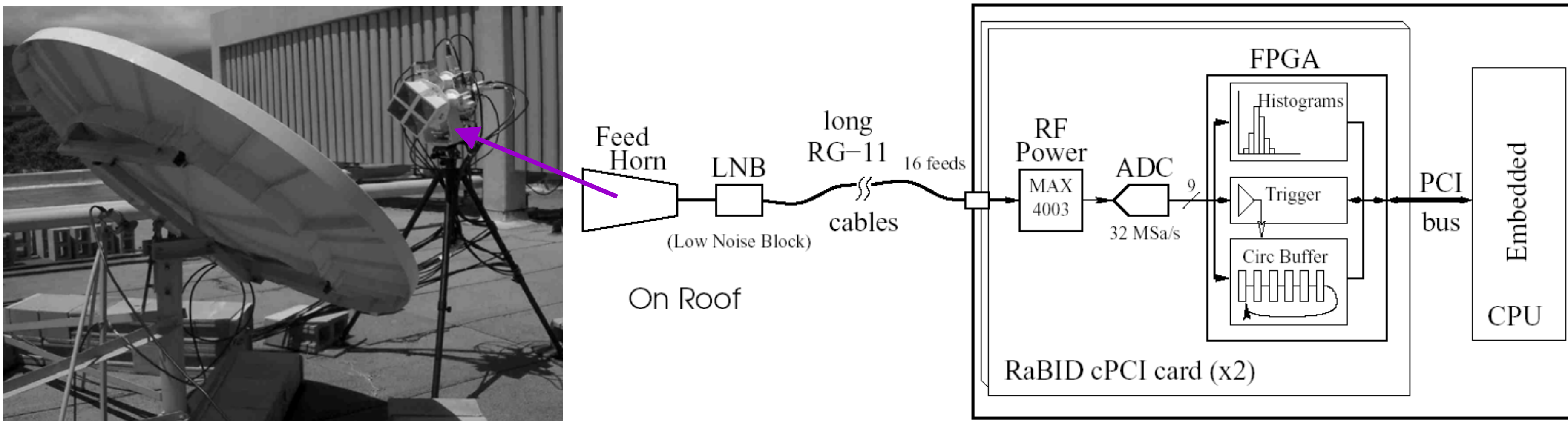


- Top: AWA signals strong, but high backgrounds
- Bottom: SLAC
- T471 signals were free of backgrounds, strong, and mostly coherent!
- Stimulated Emission? Plasma resonance?

RaBID Detection scheme

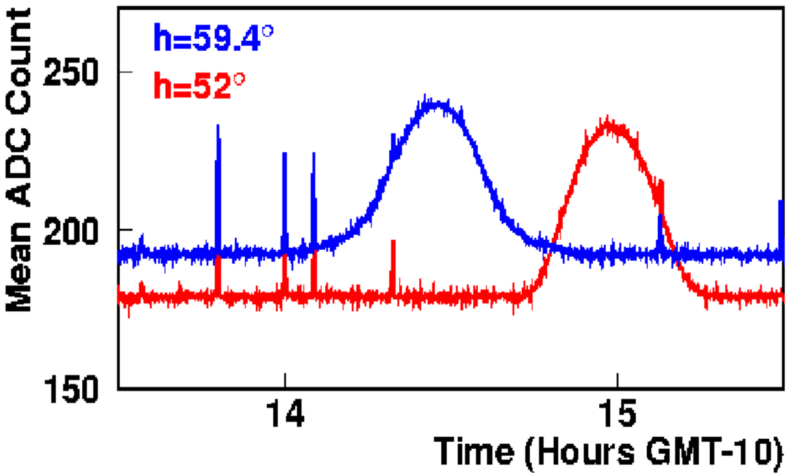


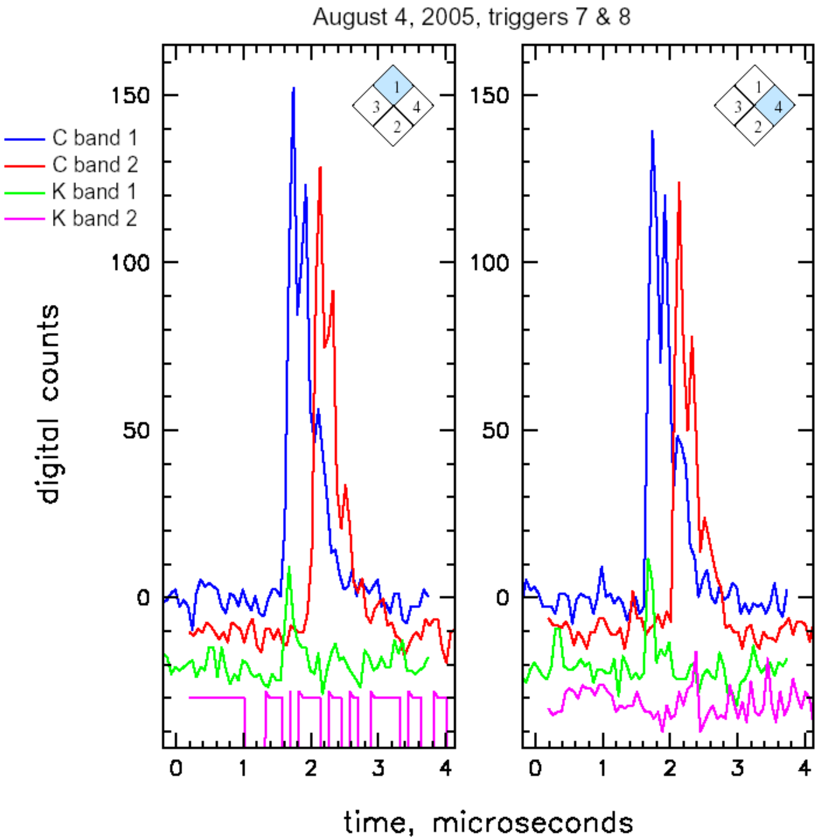
Next step: try it on real air showers



- Based on commercial sat-TV, wireless & cellular technology to keep cost low (<$10K per station)
- "All weather" design
- Can be external triggered (coincidence with large ground array)

Data from RaBID





- Solar scan at 4GHz

- Triggered event, sequential in 2-different feedhorns, at both 4 & 12 GHz
- After local check – operate in coincidence with ground array

Summary

Radio Detection may well win the race to detect GZK neutrinos:

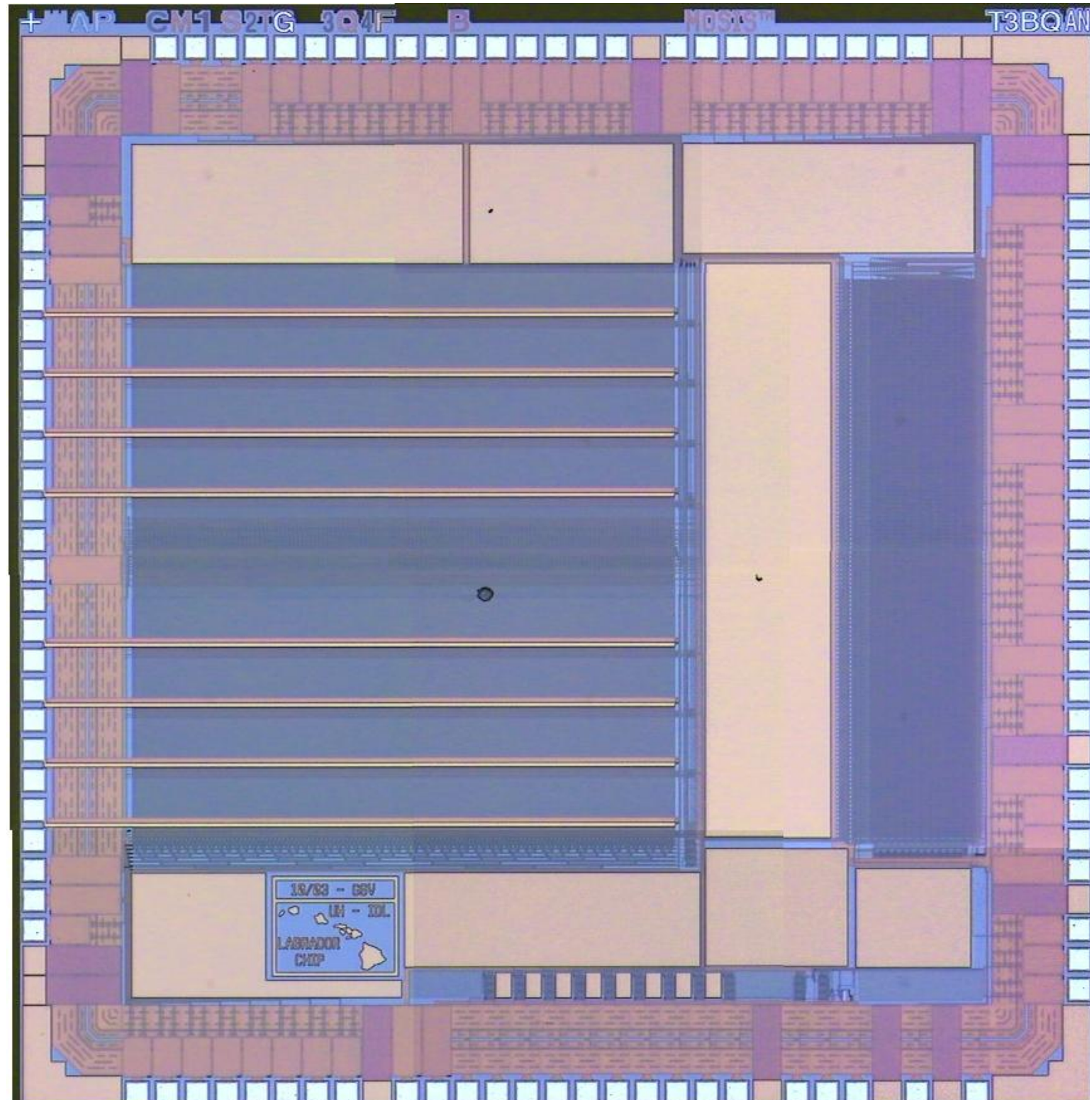
- GLUE, FORTE limits now widely accepted in community

- ANITA has the earliest shot at constraints (or detection) of the GZK flux
  - Successful proto flight 2003/4; Engineering flight 2 weeks ago
  - First flight 2006/2007 season

- SalSA may be the most cost-effective GZK neutrino telescope
  - Test array deployment in 2005/2006
  - UHE neutrino beam opens particle physics options

Just catching the wave -- Stay tuned!

Back-up slides



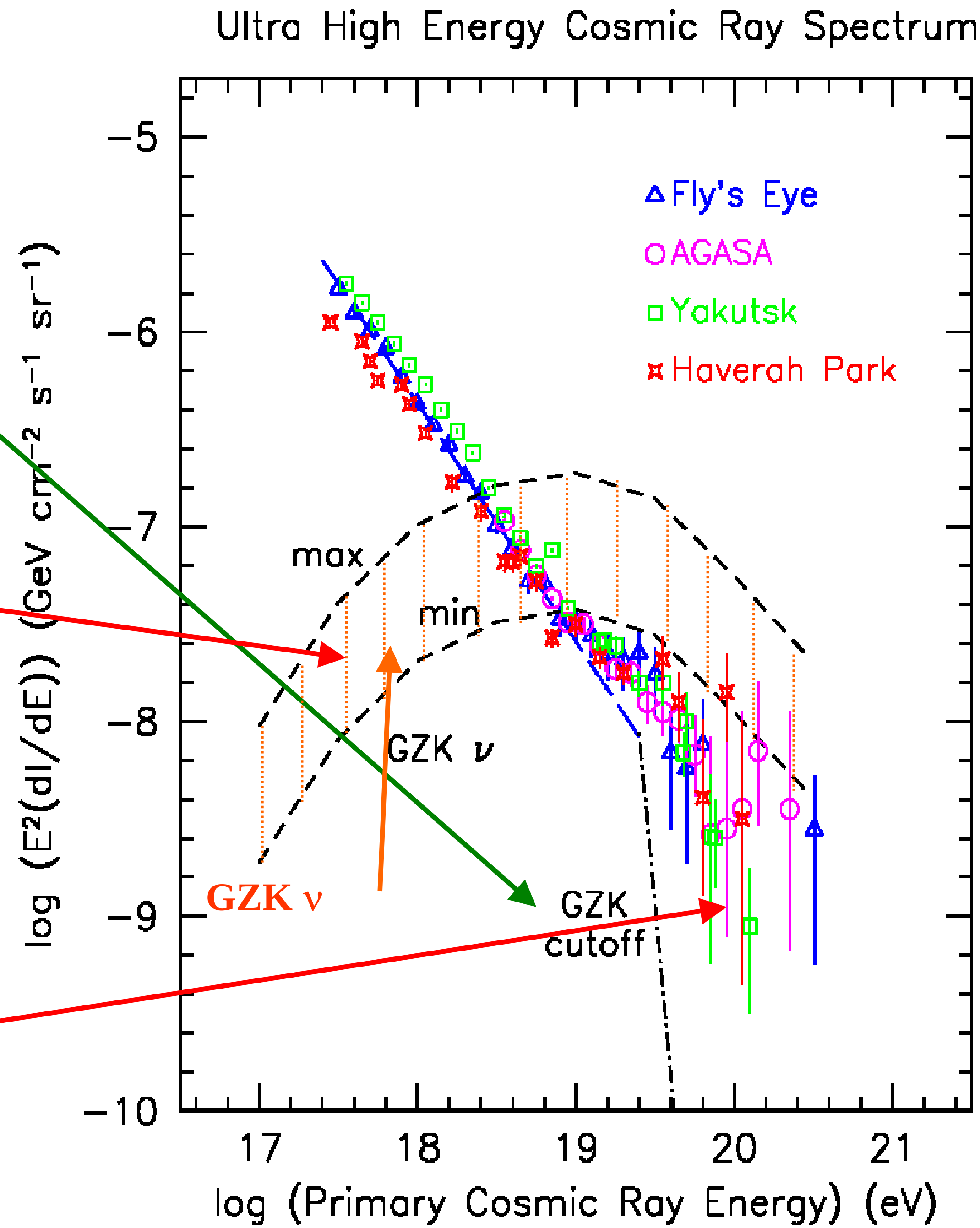
Expectations:

1. Greisen, Zatsepin, Kuzmin (GZK) calculated a cutoff:

$p * \gamma \rightarrow \Delta \rightarrow n + \pi \rightarrow \nu$

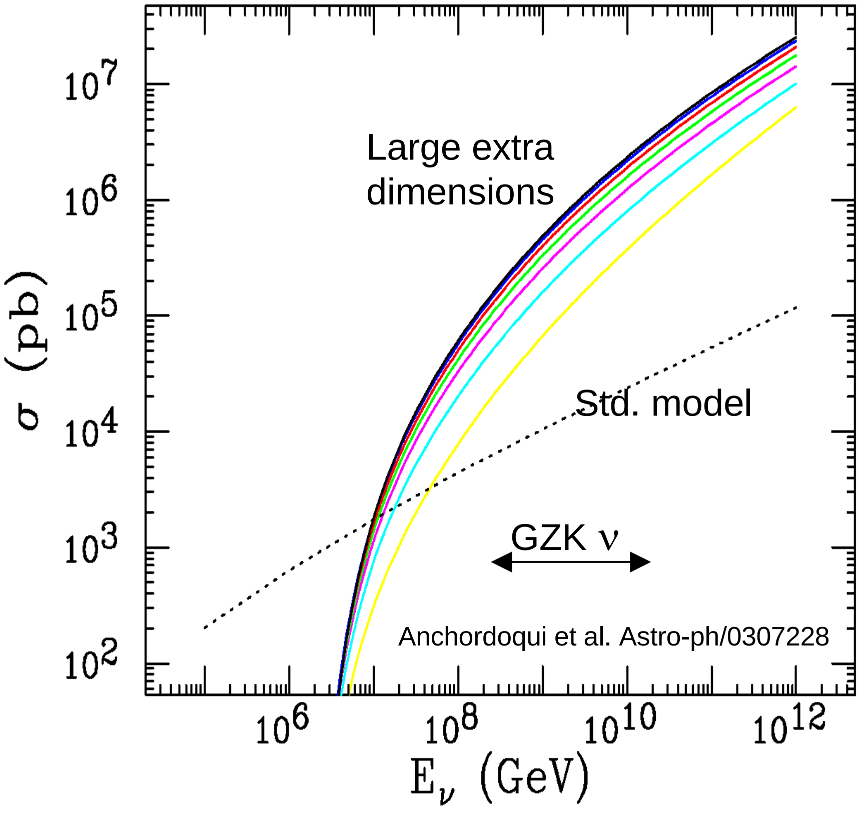
2. These interactions produce a corresponding neutrino flux

3. Provides a handle on what is going on for these “extra-GZK” events



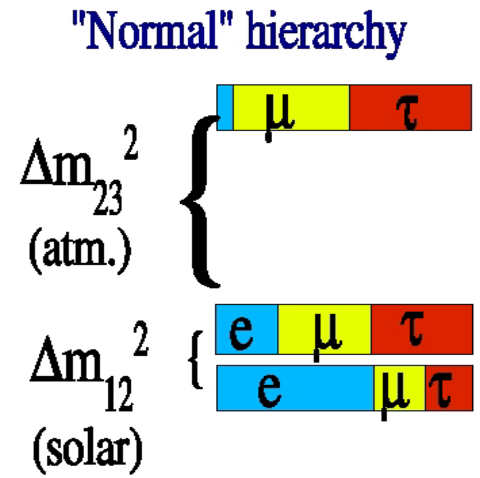
Particle Physics: Energy Frontier

- GZK ν spectrum is an energy-frontier beam:
  - up to 300 TeV center of momentum particle physics
  - Search for large extra dimensions and micro-black-hole production at scales beyond reach of LHC
  - ν Lorentz factors of $\gamma=10^{18\text{-}21}$



Particle Physics: Neutrinos

- GZK neutrinos are the "longest baseline" neutrino experiment:
  - Longest L/E (proper time) for: sterile ν admixtures & anomalous ν decays
    - SUN: L/E ~ 30 m/eV
    - GZK: L/E ~ 10^9 m/eV
- Measured flavor ratios of ν_e:ν_μ:ν_τ can identify non-standard physics at source

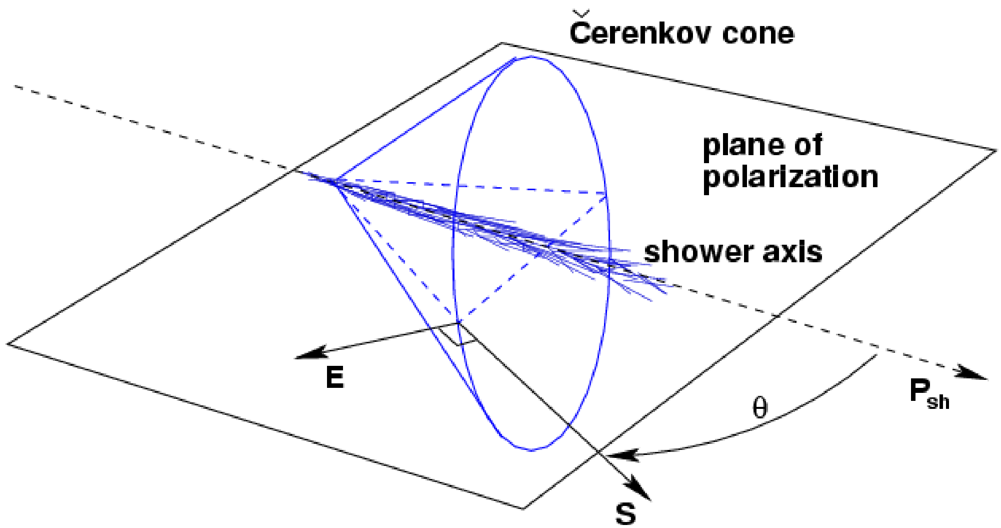


ν_e:ν_μ:ν_τ

(1:1:1)! (5-6):1:1

Neutrino decay leaves a strong imprint on flavor ratios at Earth

Cherenkov polarization tracking

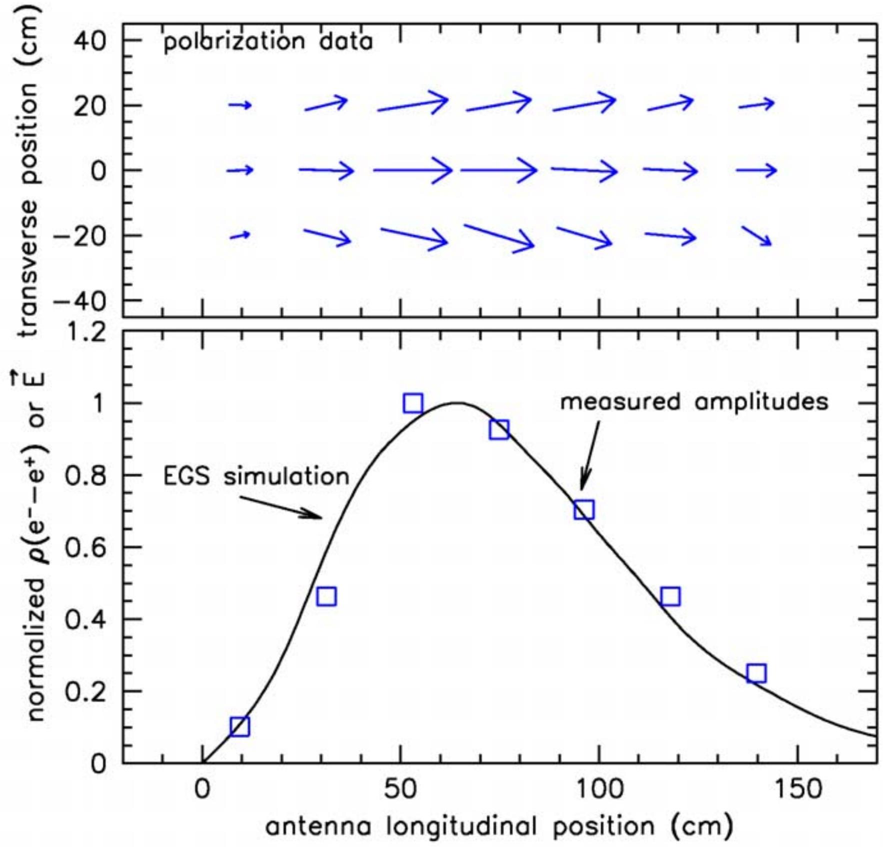


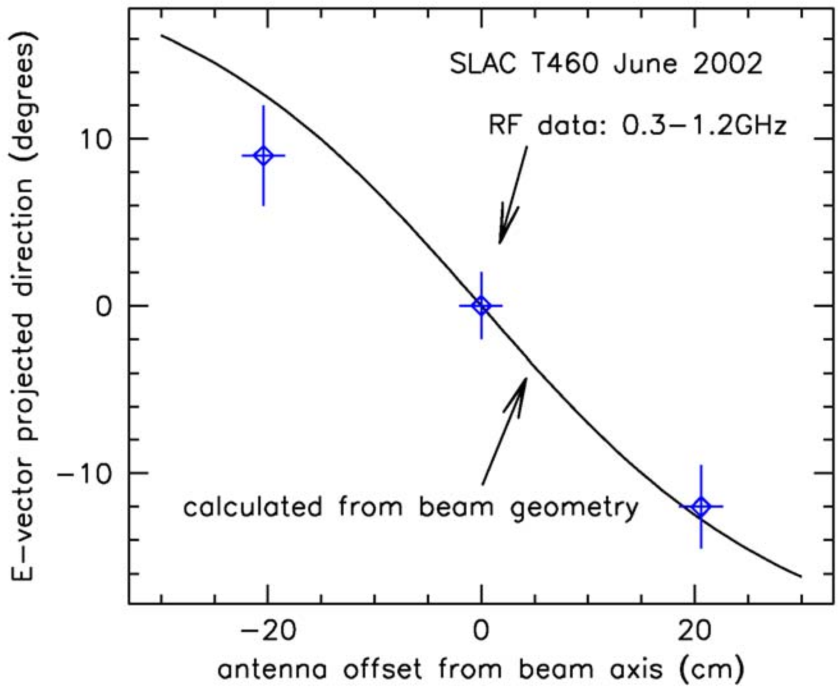
- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - **Intersection of these planes defines shower track**

Cherenkov radiation predictions:

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

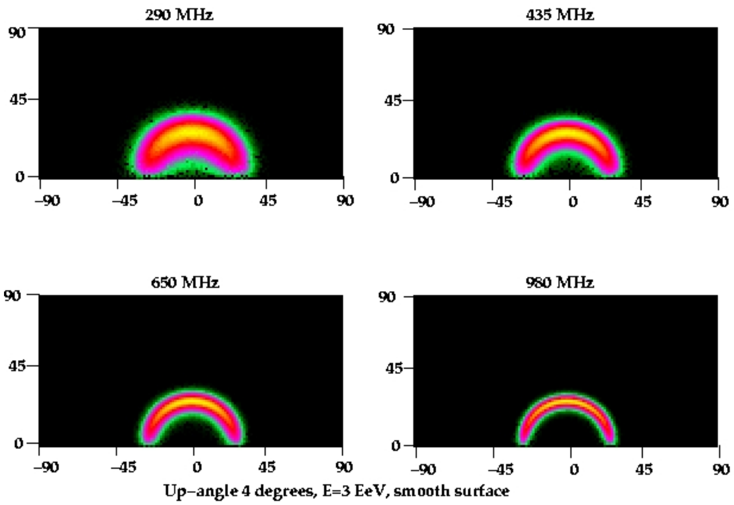
Polarization tracking

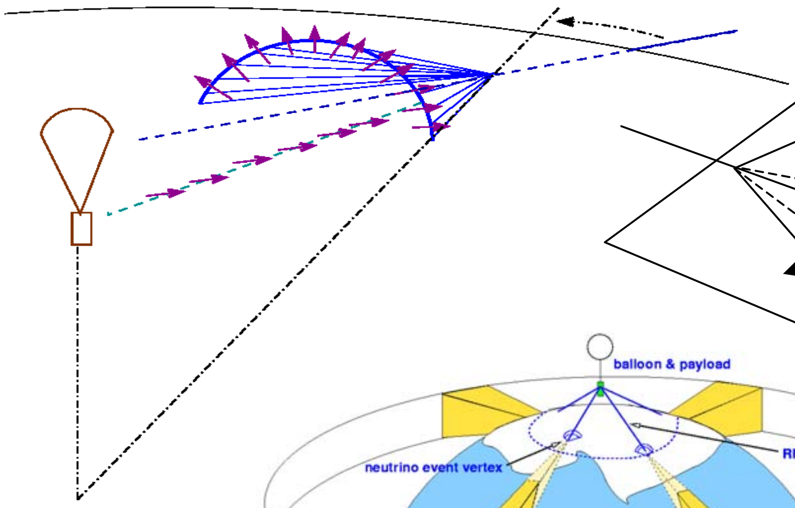


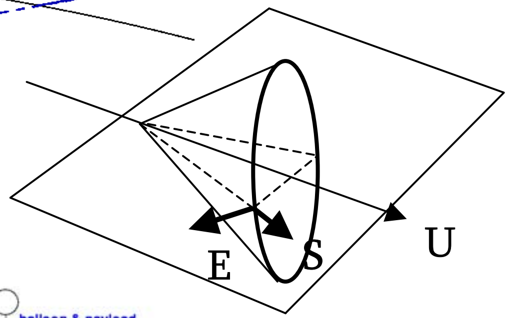


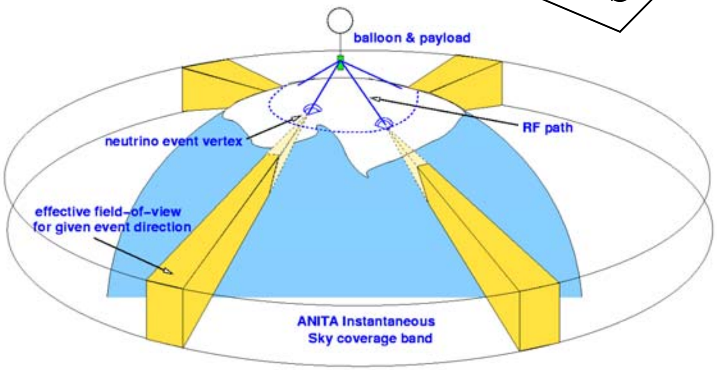
- Measured with dual-polarization embedded bowtie antenna array in salt

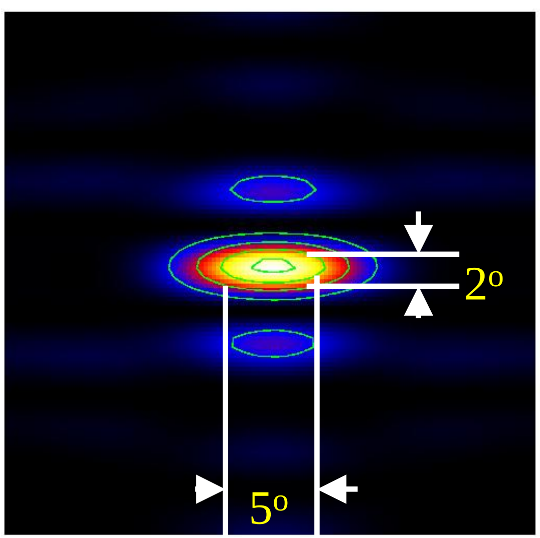
ANITA as a neutrino telescope







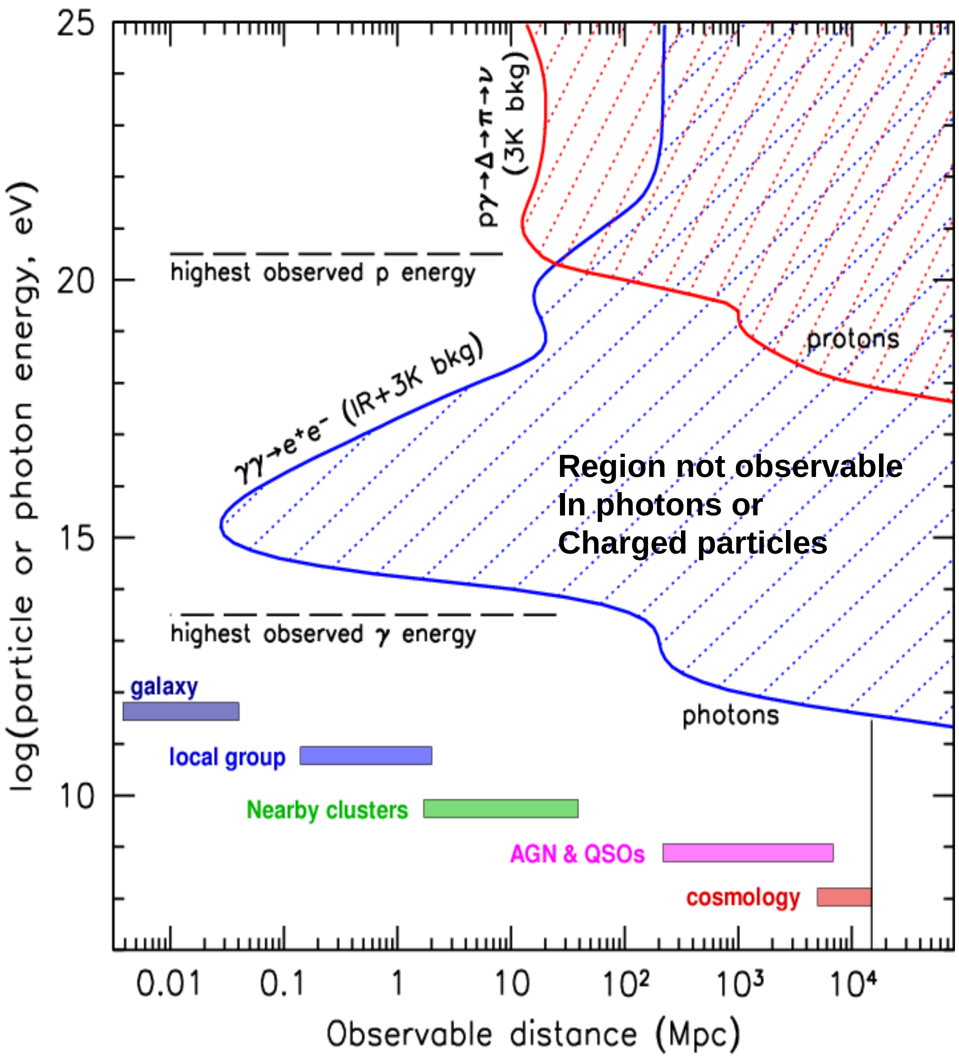




- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1º elevation by ~1º azimuth for **arrival direction** of radio pulse

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

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**

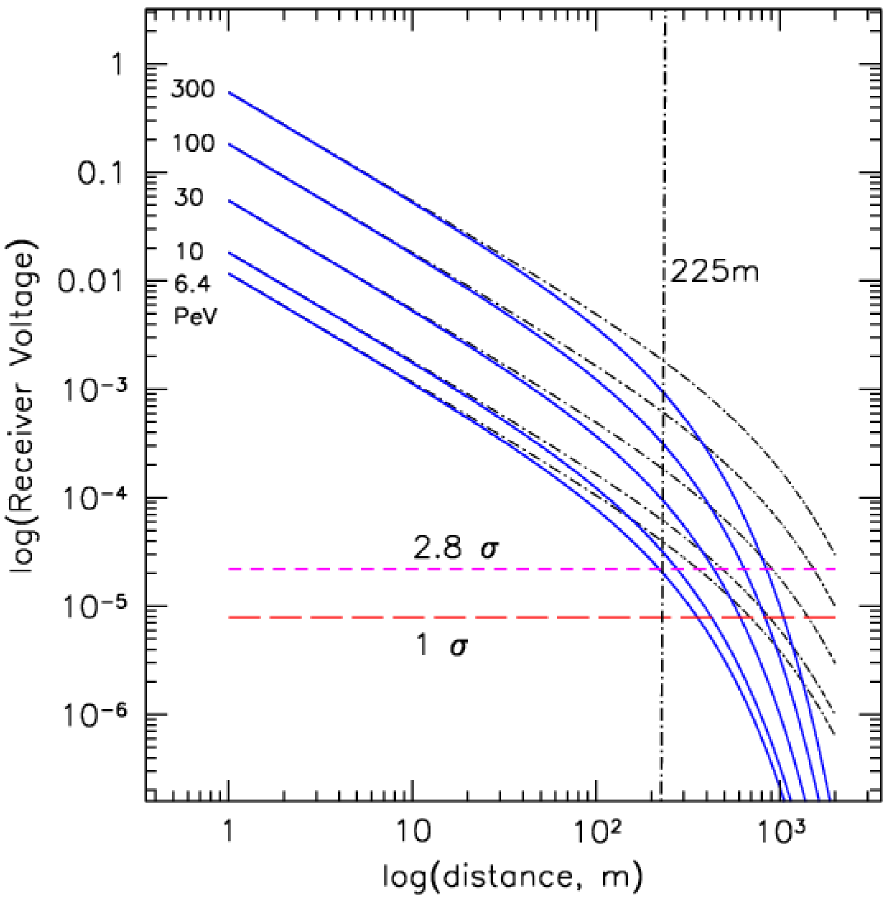
The Z-burst model

- 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

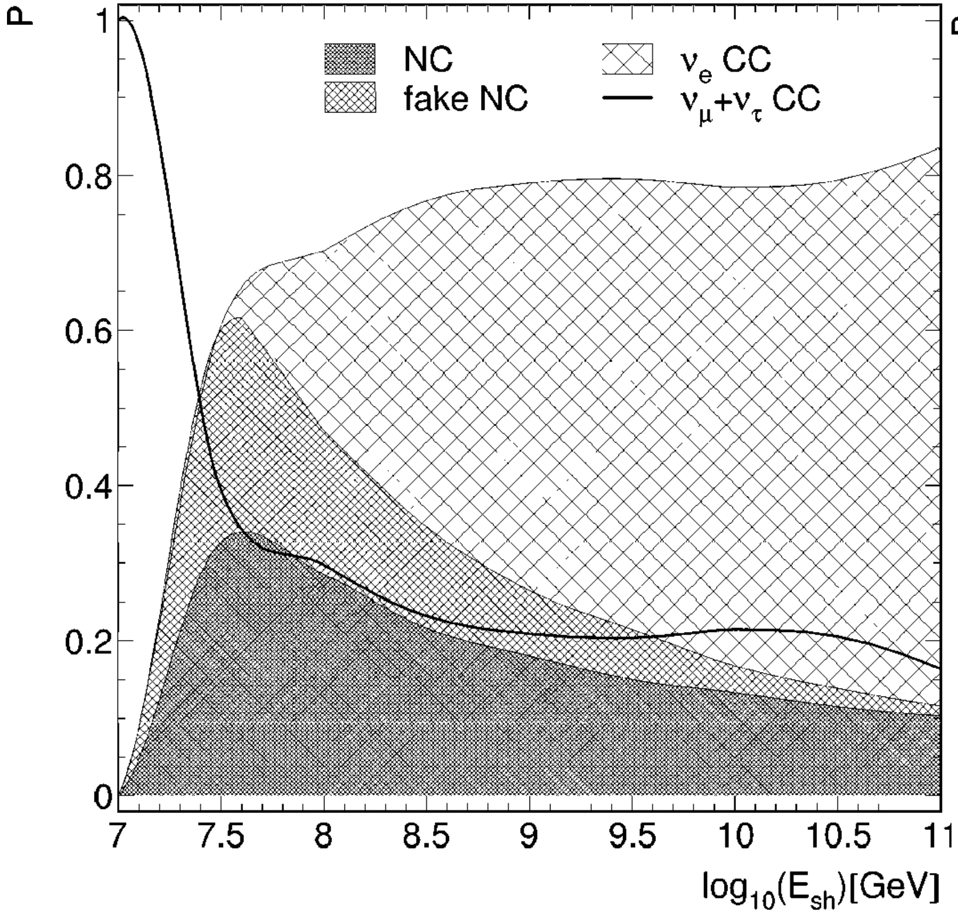
Estimated SalSA Energy threshold

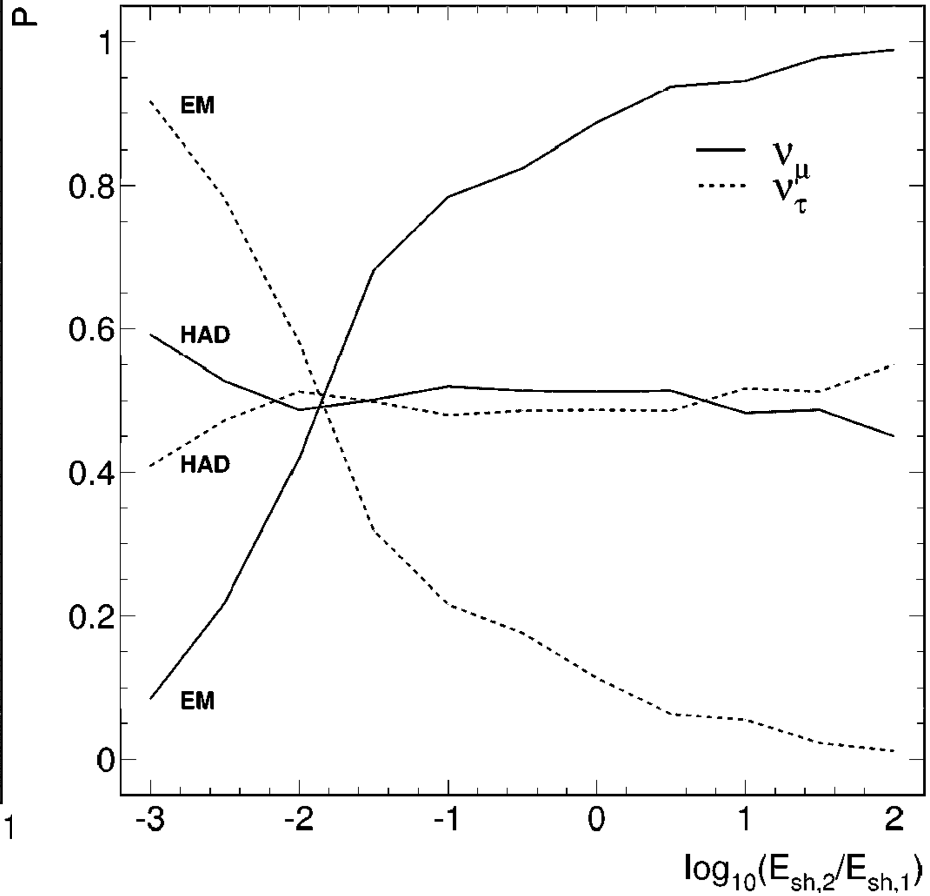


- Ethr < 300 PeV (3 x 10^{18} eV) best for full GZK spectral measurement
- Threshold depends on average distance to nearest detector and local antenna trigger voltage above thermal noise
  - Vnoise = k T Δf
  - Tsys = Tsalt+Tamp = 450K
  - Δf of order 200 MHz
- 225 m spacing gives 30 PeV
- Margin of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

Interaction/PID

Ped Miocinovic (UH)





T460 rock-salt target

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

- Beam exit point shown above
- Depth ~ 15 radiation lengths
  - Shows some deposits from spallation, good indicator of transverse size of shower!

GEISER Data flow

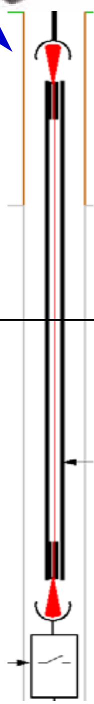
(Giga-bit Ethernet Instrumentation for SalSA Electronics Readout)

- 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

Digital Cell system for data collection

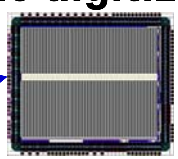
Trigger packets sent via FM/local radio

64kb/event
1.6kHz (100baseT)
16kHz (Gbit Ethernet)



Central control & Global Trigger station

asic digitizer



antennas

RF in Continuous

Hold event if >2.4σ

Internal FPGA: Logic, Buffer

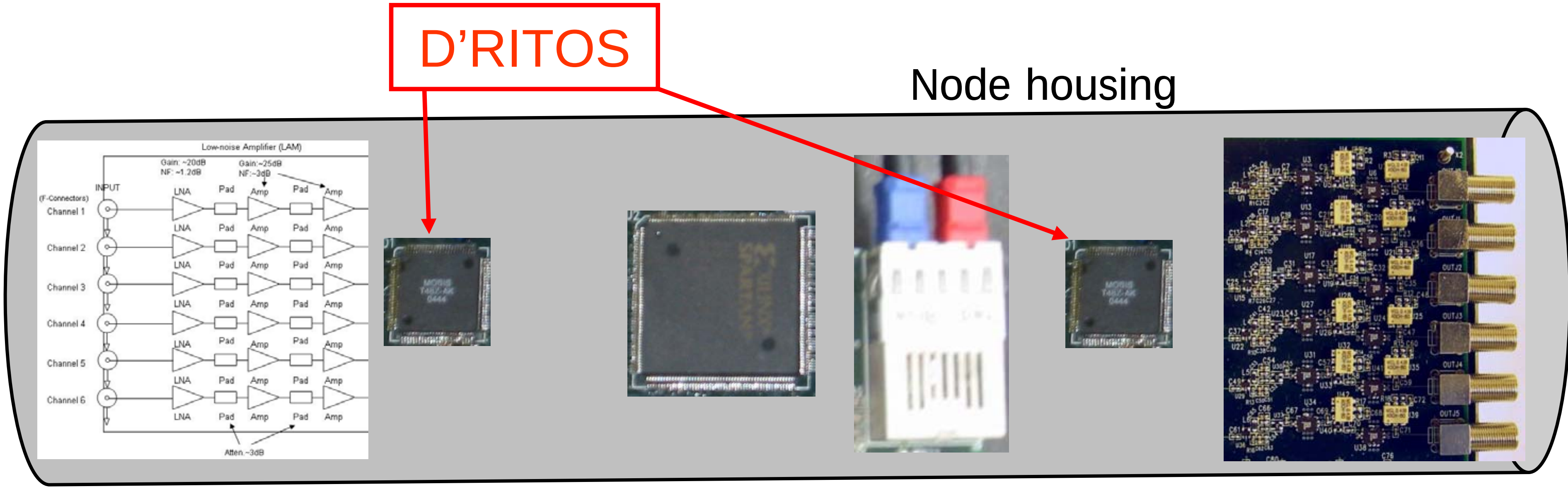
In salt

Node/String Time stamps

Event request

Final Data Transfer

SalSA Node-controller readout board architecture



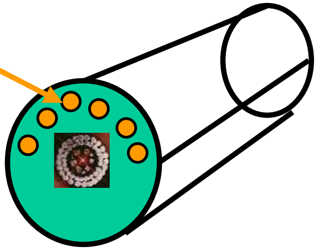
LNA, 2nd-stage amps (one each end)

Trigger, bi-directional fiber-link

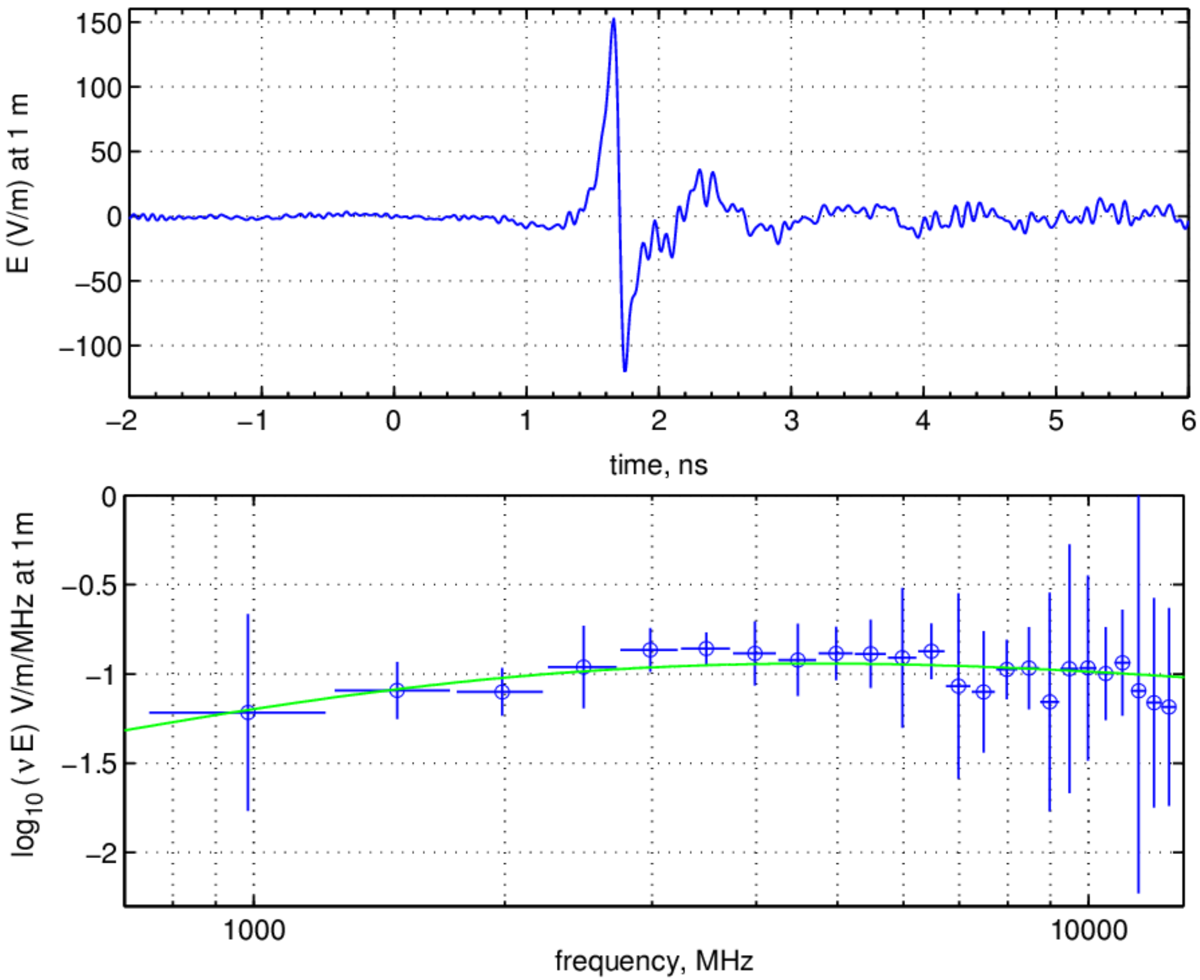
LNA, 2nd-stage amps (other end)

Typical 4" coring bit

RF connectors

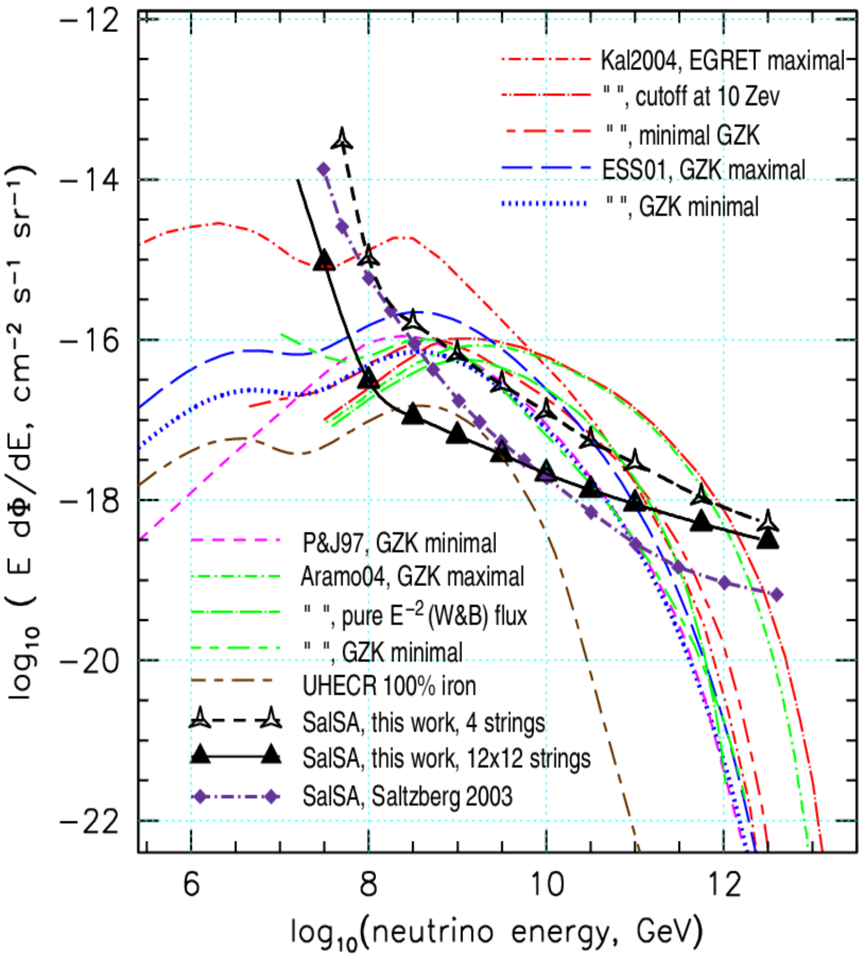


Ultra-wideband data on Askaryan pulse



- 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

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!**