Detection of Ultra High Energy Neutrinos via Coherent Radio Emission

1. Background – Radio Detection
2. ANtarctic Impulsive Transient Antenna (ANITA)
3. Enabling Technology (LABRADOR)
4. Particle Identification (SalSA, SND, ARIANNA)

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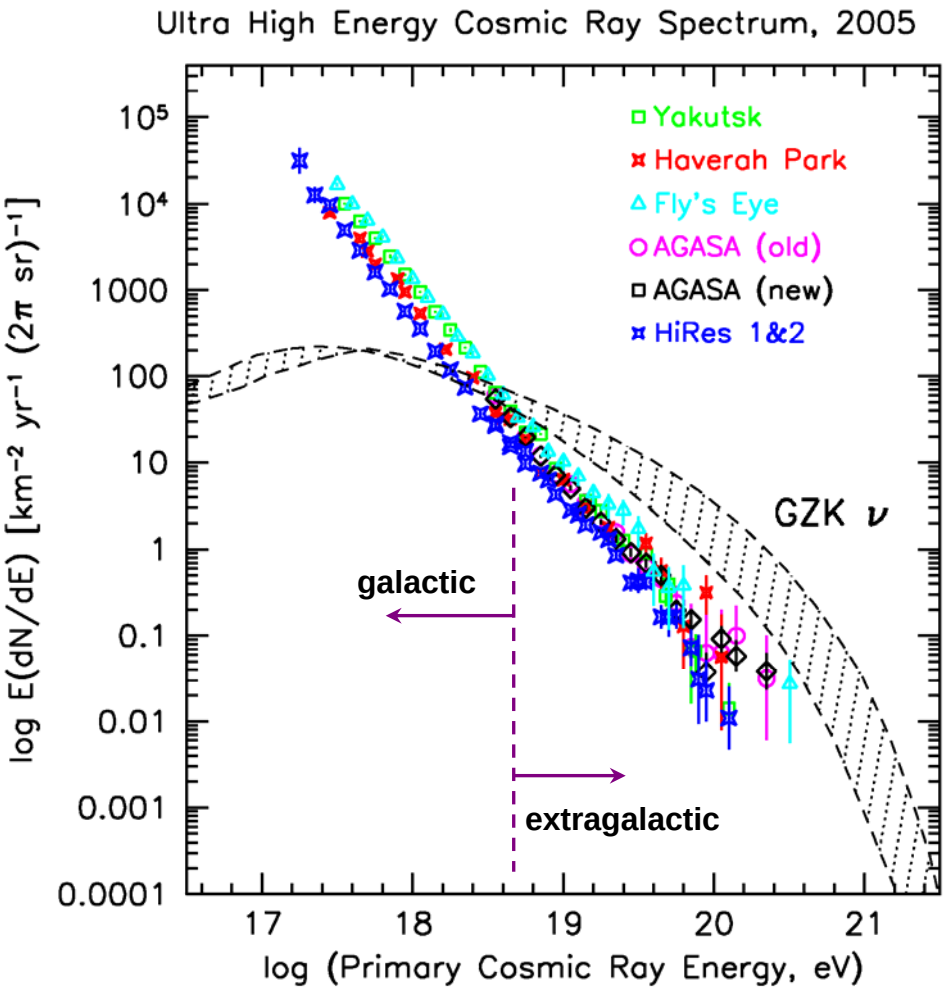
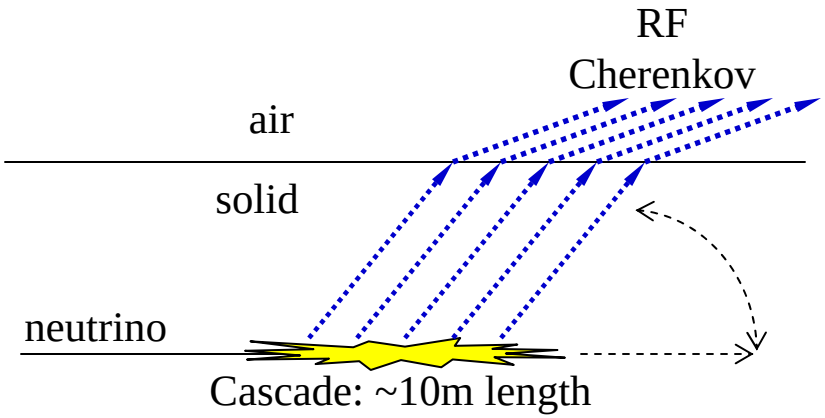
(Ultra-)High Energy Physics of Cosmic rays & Neutrinos

- 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

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



How to Observe?



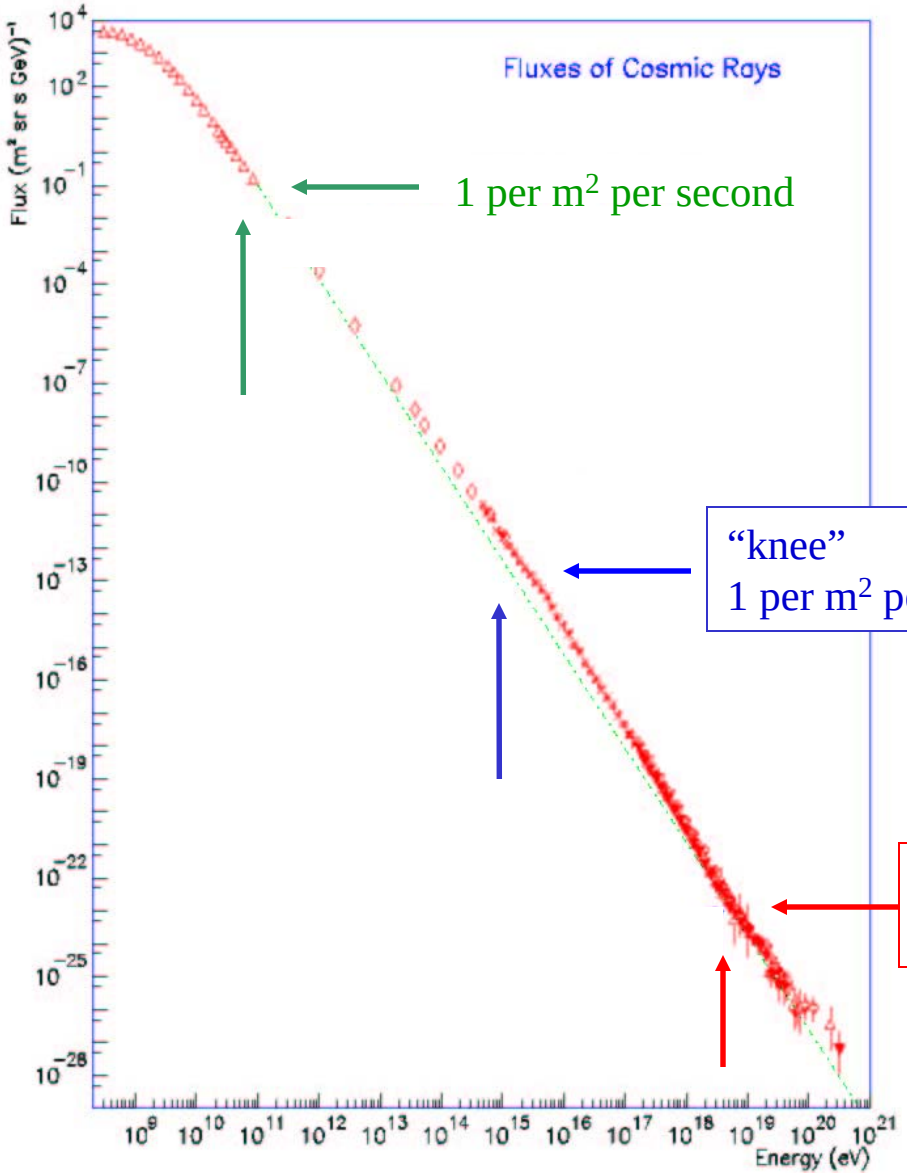
1960's: Askaryan predicted that the resultant compact cascade shower (1962 JETP **14**, 144; 1965 JETP **21**, 658):

- 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

Why so Hard?? The Flux Problem

- At E>10^20...

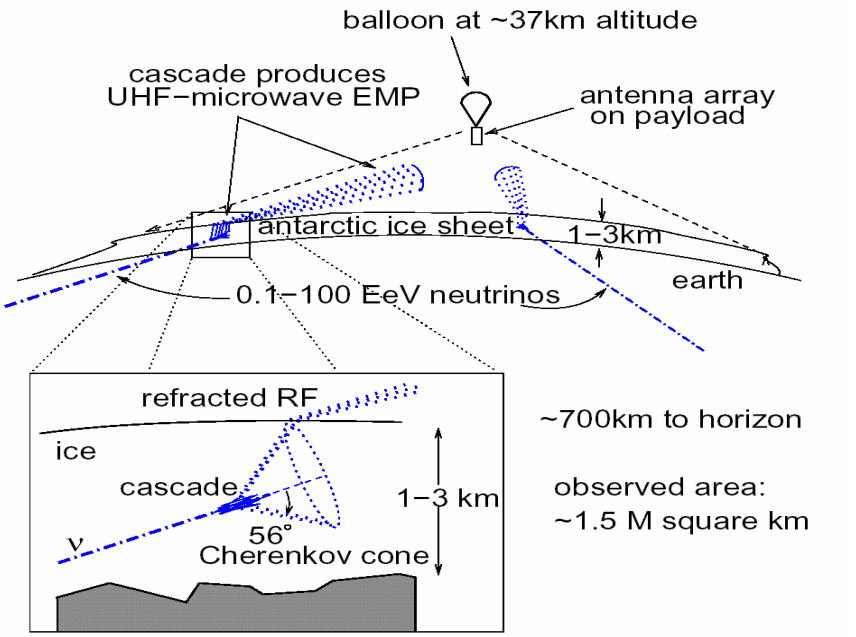
$$\iiint_{r,\phi,\theta} dr d\phi d\theta$$

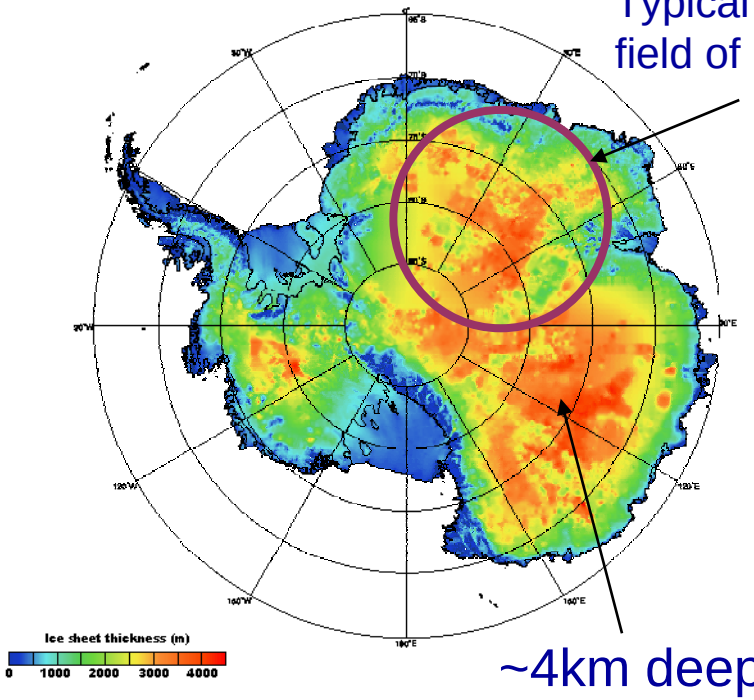


Design for discovery of GZK ν flux

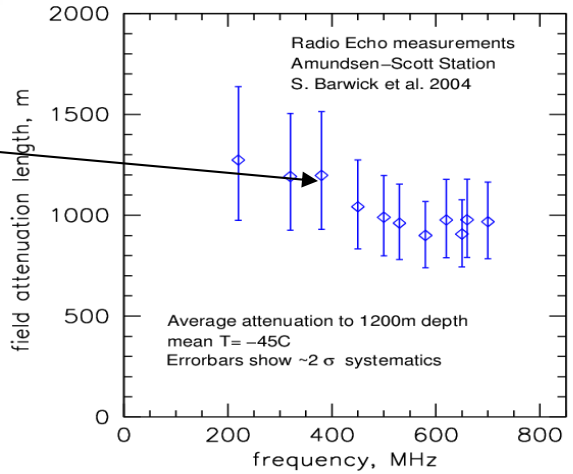
- Huge Volume of solid, RF-transparent medium: Antarctic Ice
- Broadband antennas, low noise amplifiers and high-speed digitizers to observe them
- A very high vantage point, but not too high nor too far away
- The end result: ANITA

ANITA concept





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

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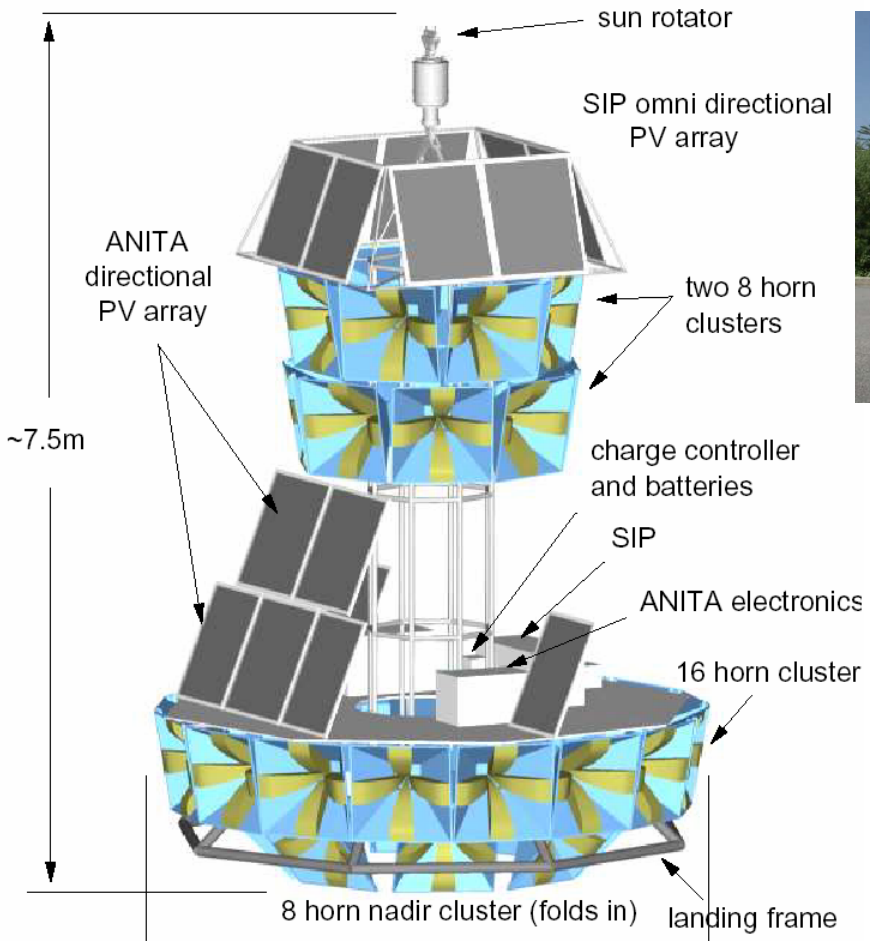
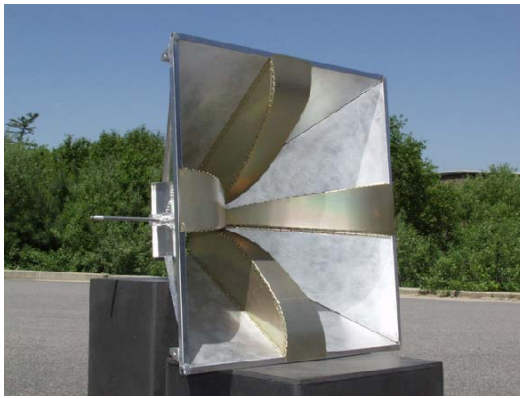
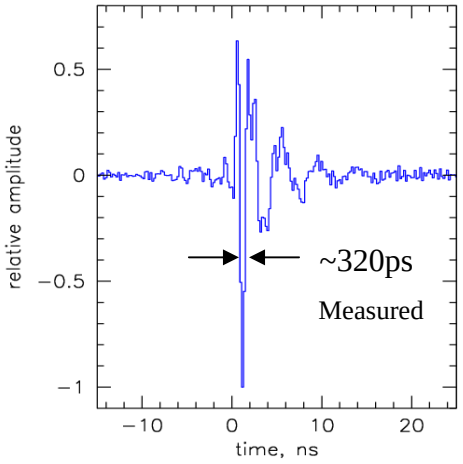
Flight Payload Design

A radio "feedhorn array" for the Antarctica Continent







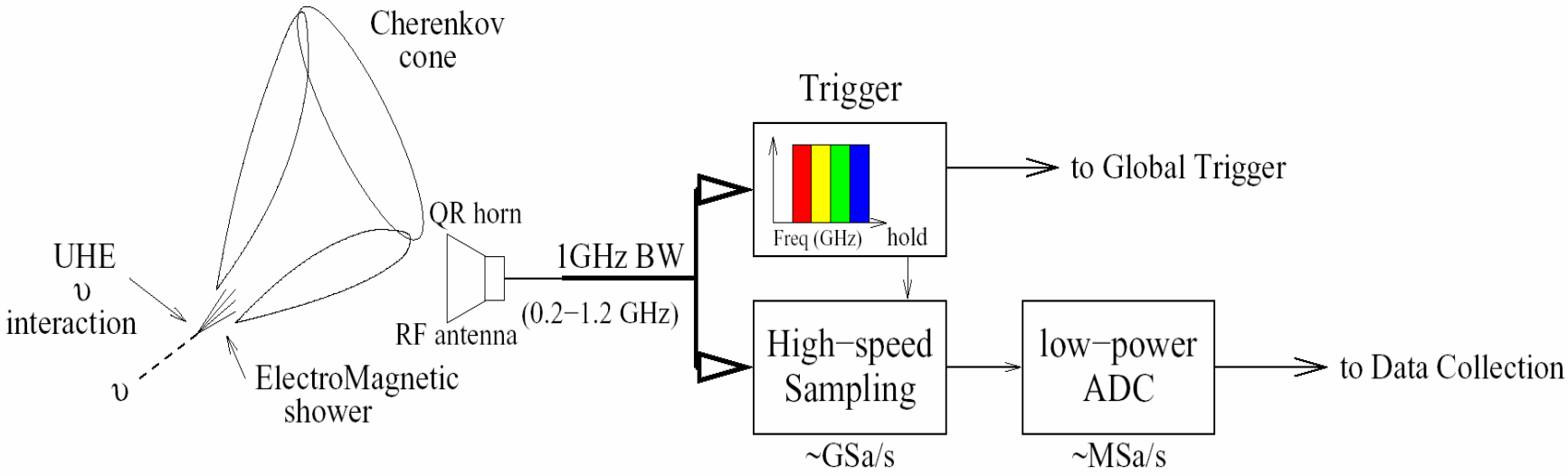
- Quad-ridged horn antennas provide superb impulse response & bandwidth (200-1200 MHz)
- Interferometry & beam gradiometry from multiple overlapped antenna measurements

Major Hurdles

- No commercial waveform recorder solution (power/resolution)
- 3σ thermal noise fluctuations occur at MHz rates (need ~2.3σ)

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

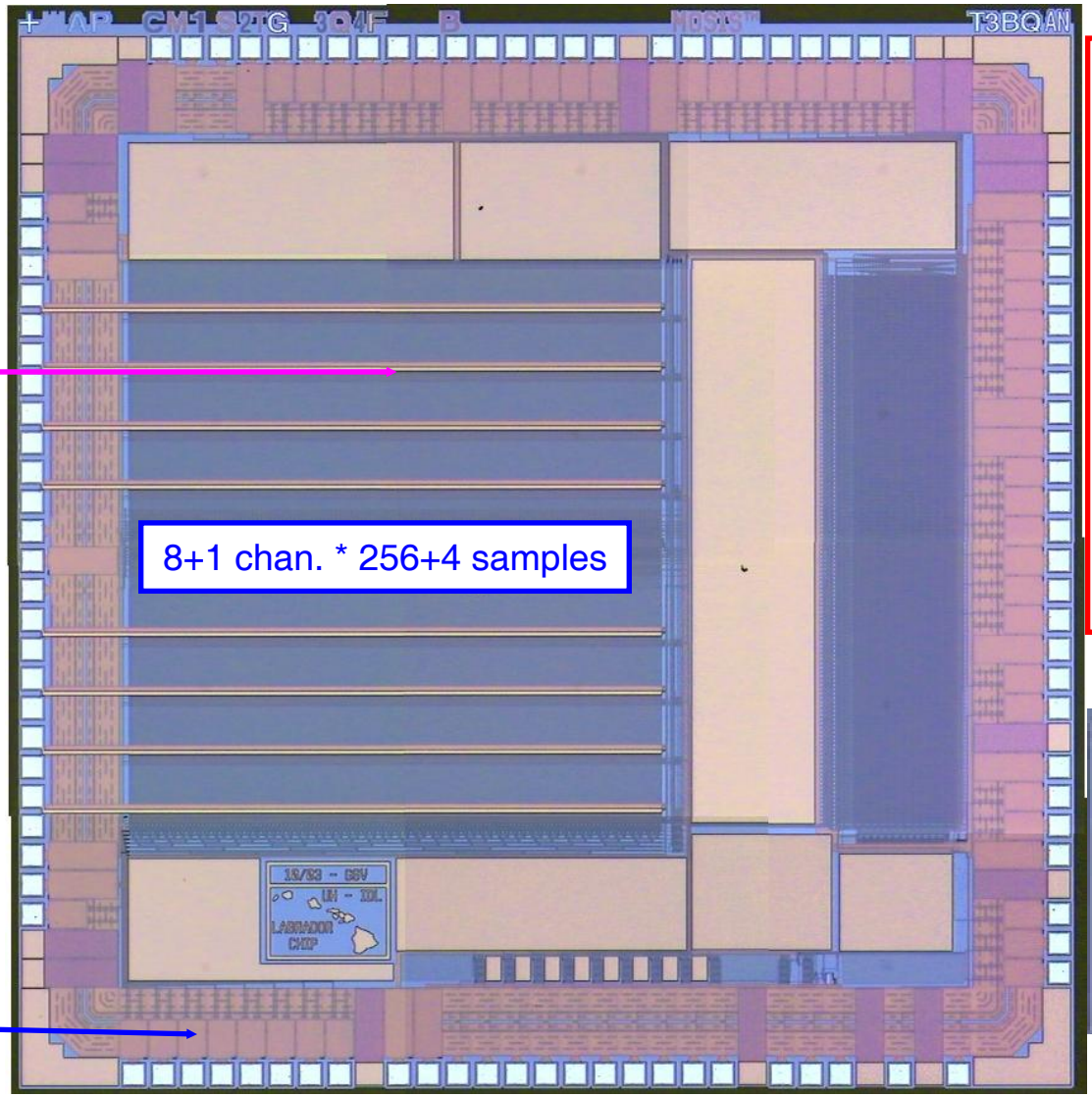
Strategy: Divide and Conquer



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

Large Analog Bandwidth Recorder and Digitizer with Ordered Readout [LABRADOR]

Straight Shot RF inputs



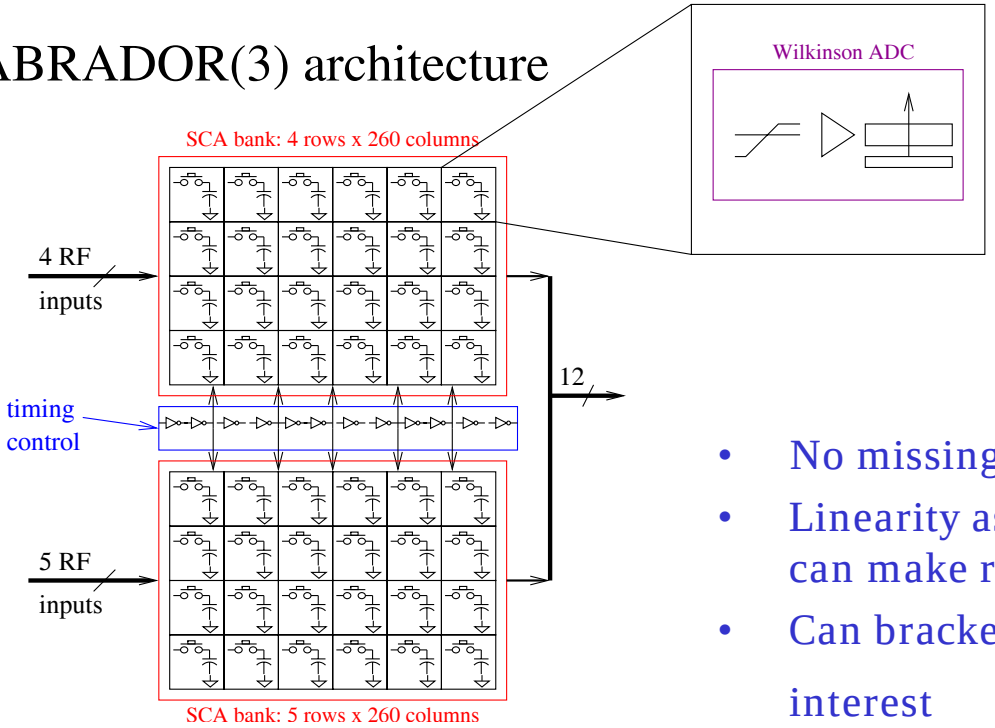
- Switched Capacitor Array (SCA)
- Massively parallel Wilkinson ADC array

- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 120μs (all 2340 samples)
- Data transfer takes 80μs
- Ready for next event in 200μs

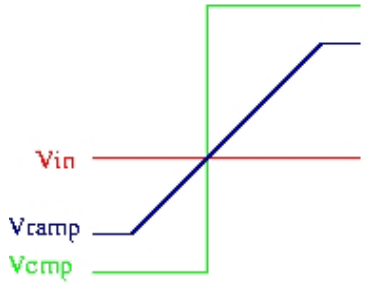
Random access:

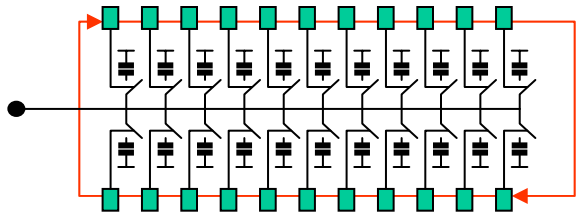
LAB3 Architecture Details

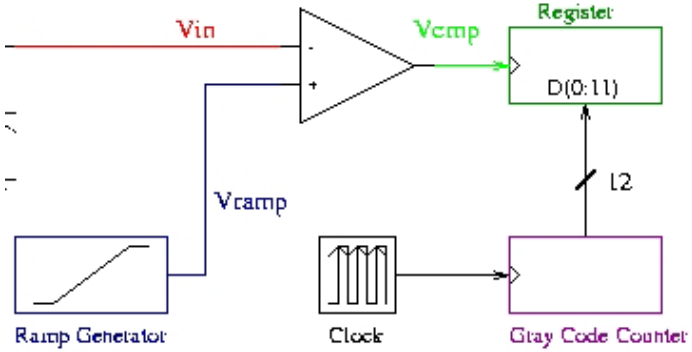
LABRADOR(3) architecture



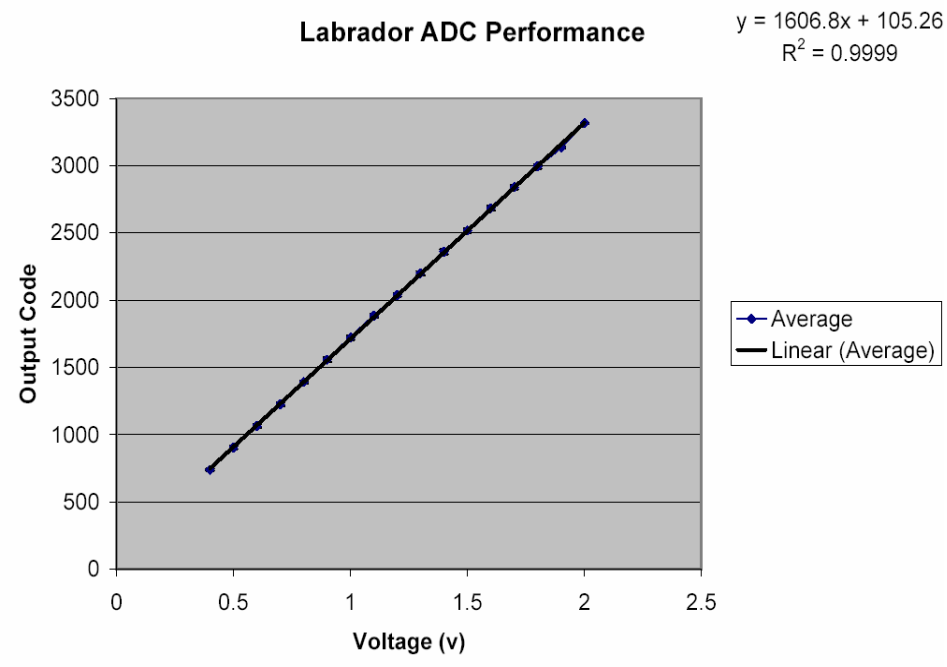
- No missing codes
- Linearity as good as can make ramp
- Can bracket range of interest

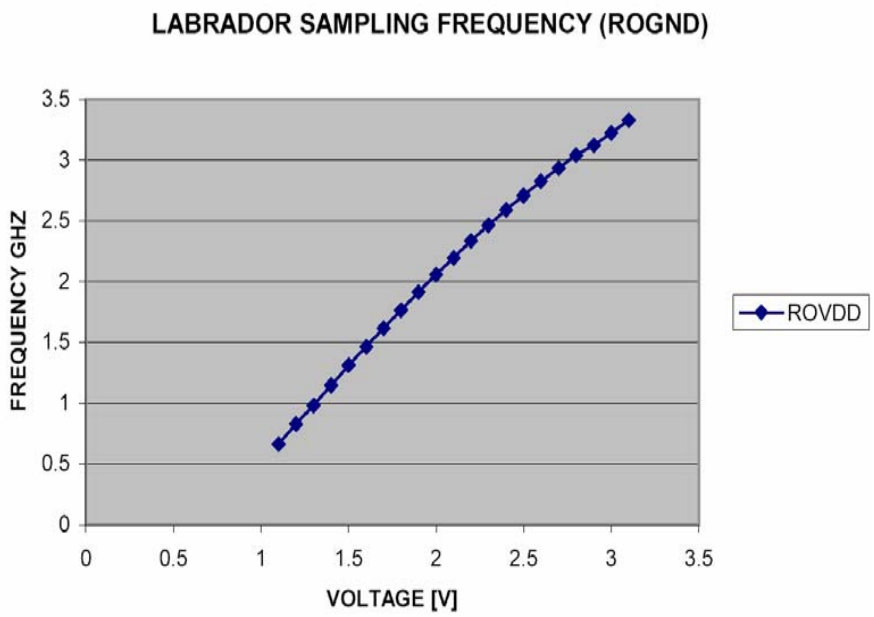






LABRADOR sampling & linearity

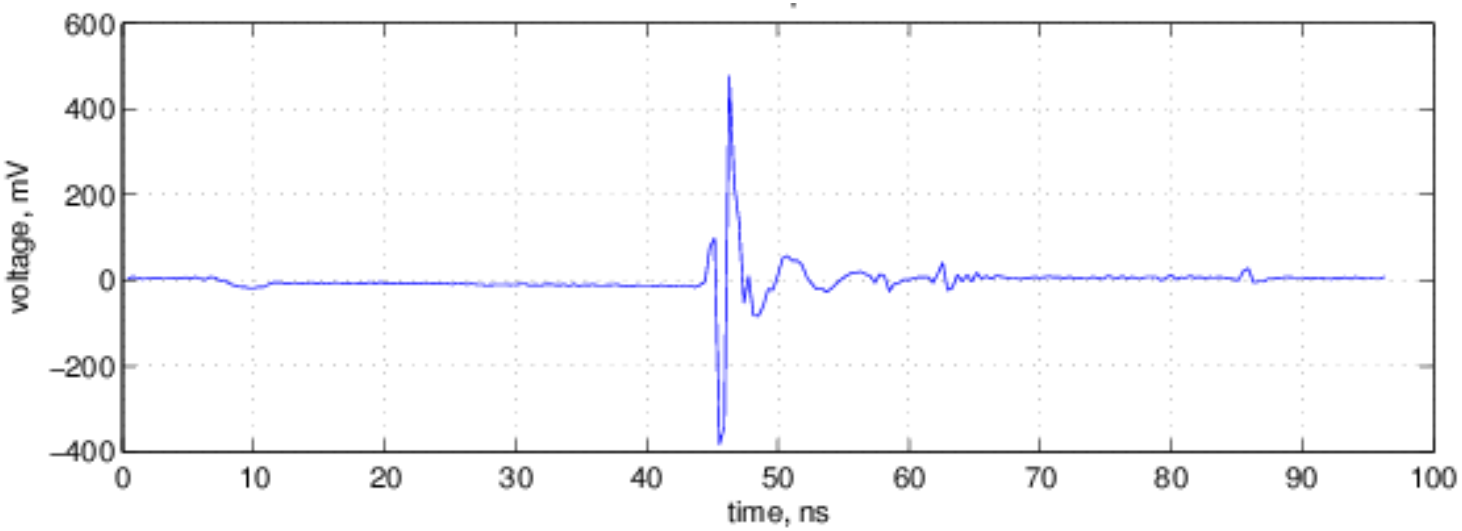




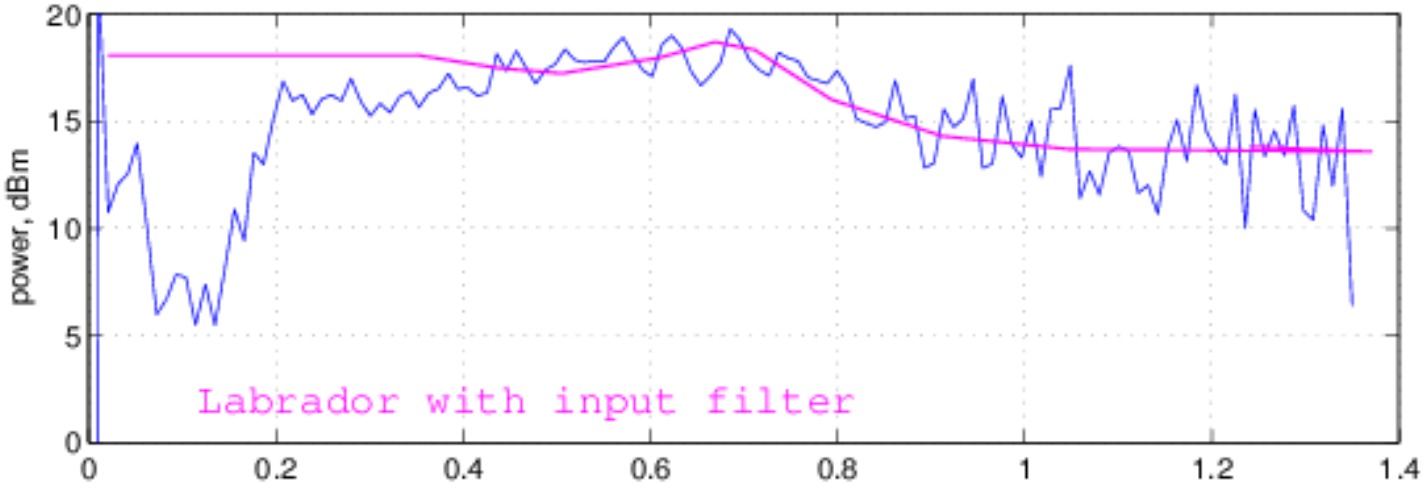
- Excellent linearity
- Sampling rates up to 4 GSa/s with voltage overdrive

Bandwidth Evaluation

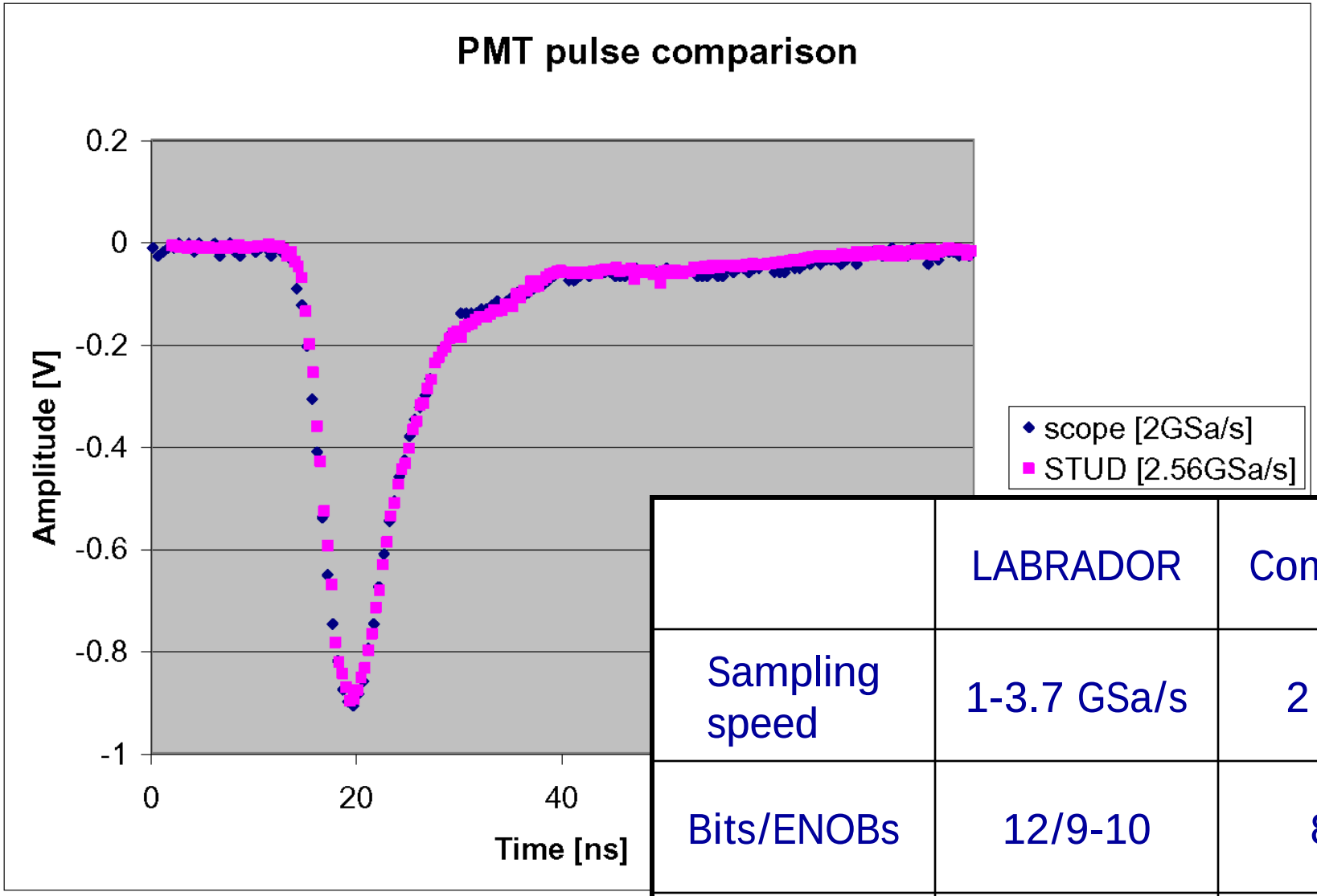
Transient Impulse



FFT Difference

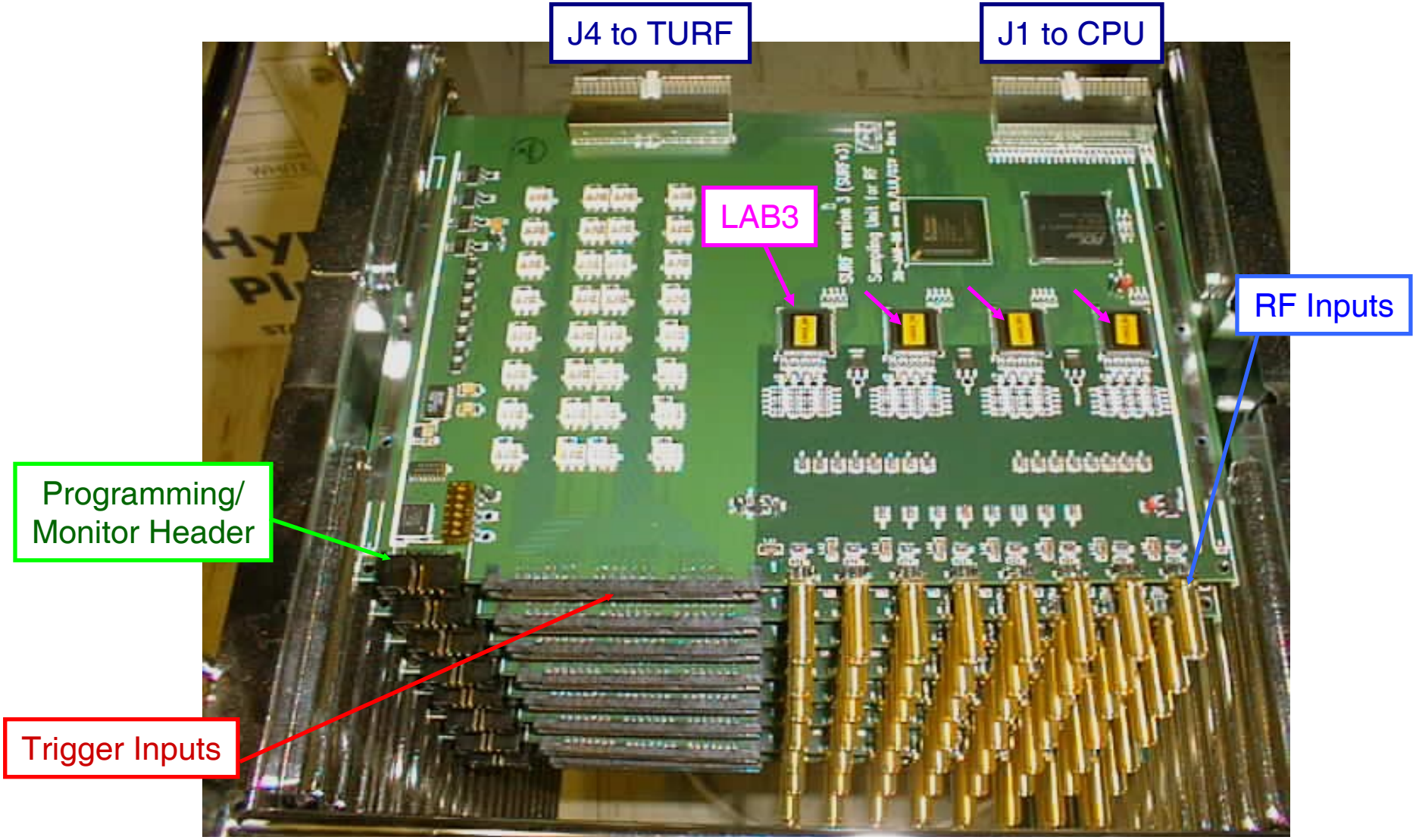


High Speed sampling



	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

SURFv3 Board



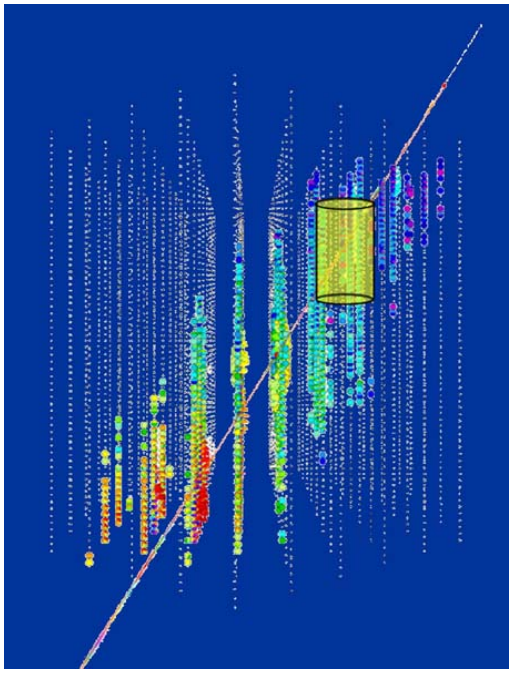
ANITA EM Payload

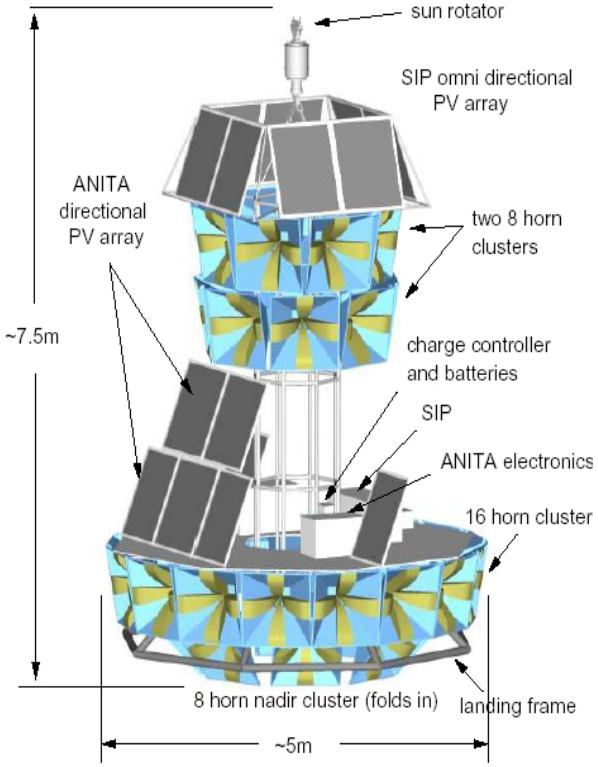
- Sept. 05 Ft. Sumner, NM flight

Go for Dec. ’06 Antarctic Flight!

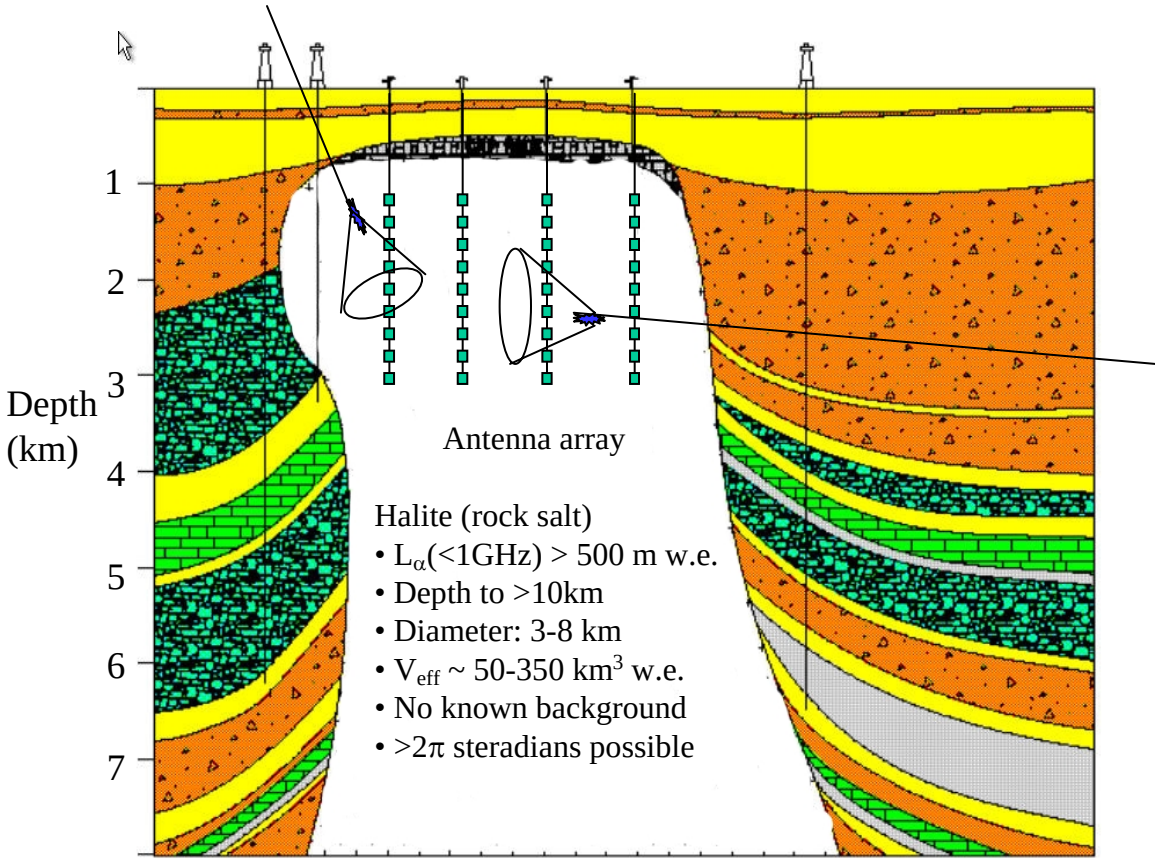
Where we might be in 5 years...

- IceCube
  - Discovery of bottom-up sources
  - Discovery of ~ 3 GZK neutrinos
- ANITA:
  Discovery of ~10 GZK neutrinos
- Auger
  - Discovery of a few GZK neutrinos



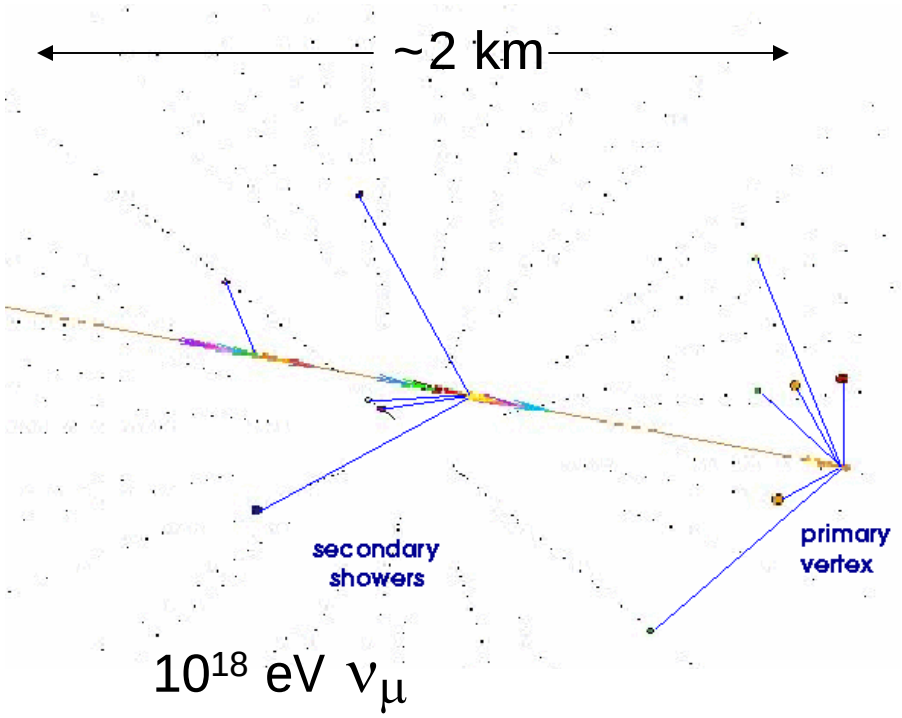


Saltdome Shower Array (SalSA) concept



- Rock salt can have extremely low RF loss, as radio-clear as Antarctic ice
- ~2.4 times as dense as ice
- typical: **50-100 km³** water equivalent in top ~3.5km =>**300-600 km³ sr w.e.**

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

Summary

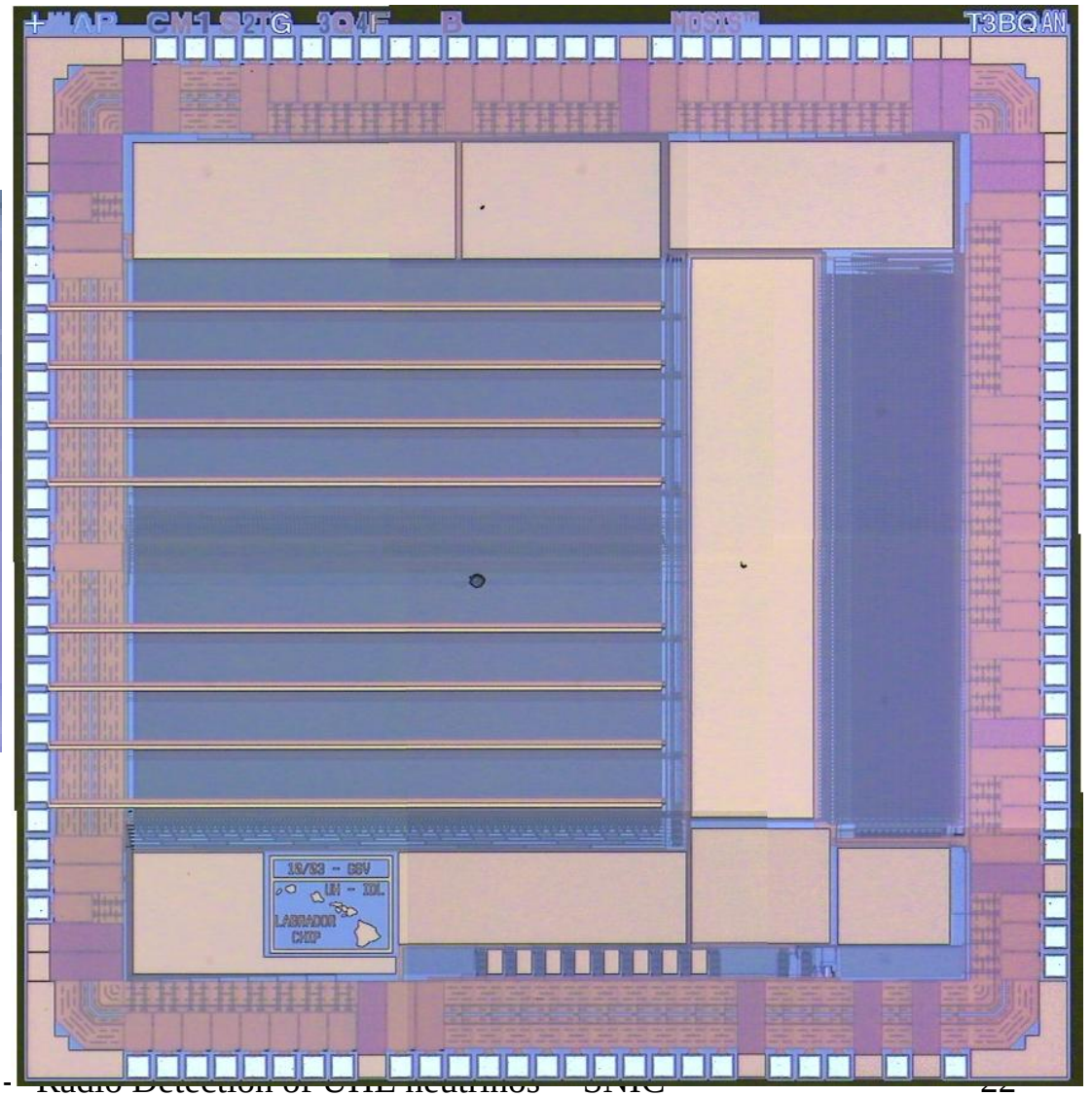
Radio Detection may well win the race to detect GZK neutrinos:

- ANITA first experiment to probe the "guaranteed" GZK flux
  - Calibration run in End Station A in June
  - First flight 2006/2007 Antarctic campaign

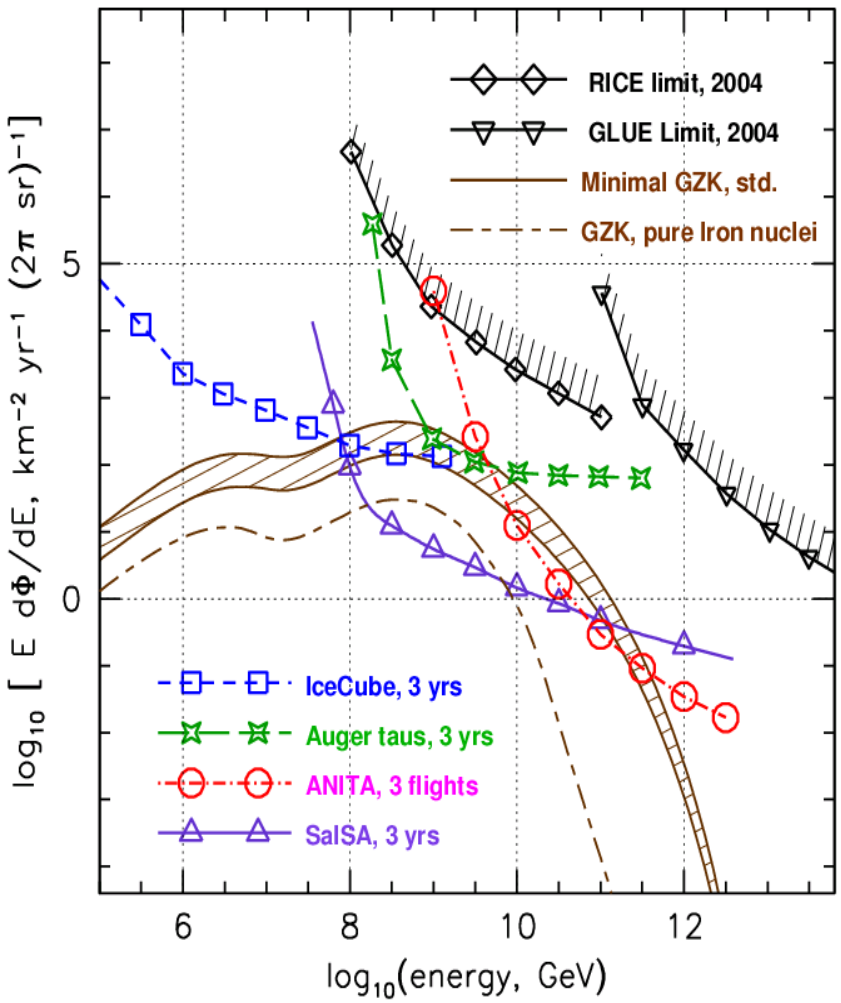
- LABRADOR technology enables low-cost, extensive terrestrial arrays
  - SalSA very attractive, but for drilling
  - SND Salt Neutrino Detector (Salt mine planar array)
  - ARIANNA (Ross Ice Shelf planar array)
  - Precision timing readout of APDs (e.g. focusing DIRC)

Just catching the wave -- Stay tuned!

Back-up slides



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**

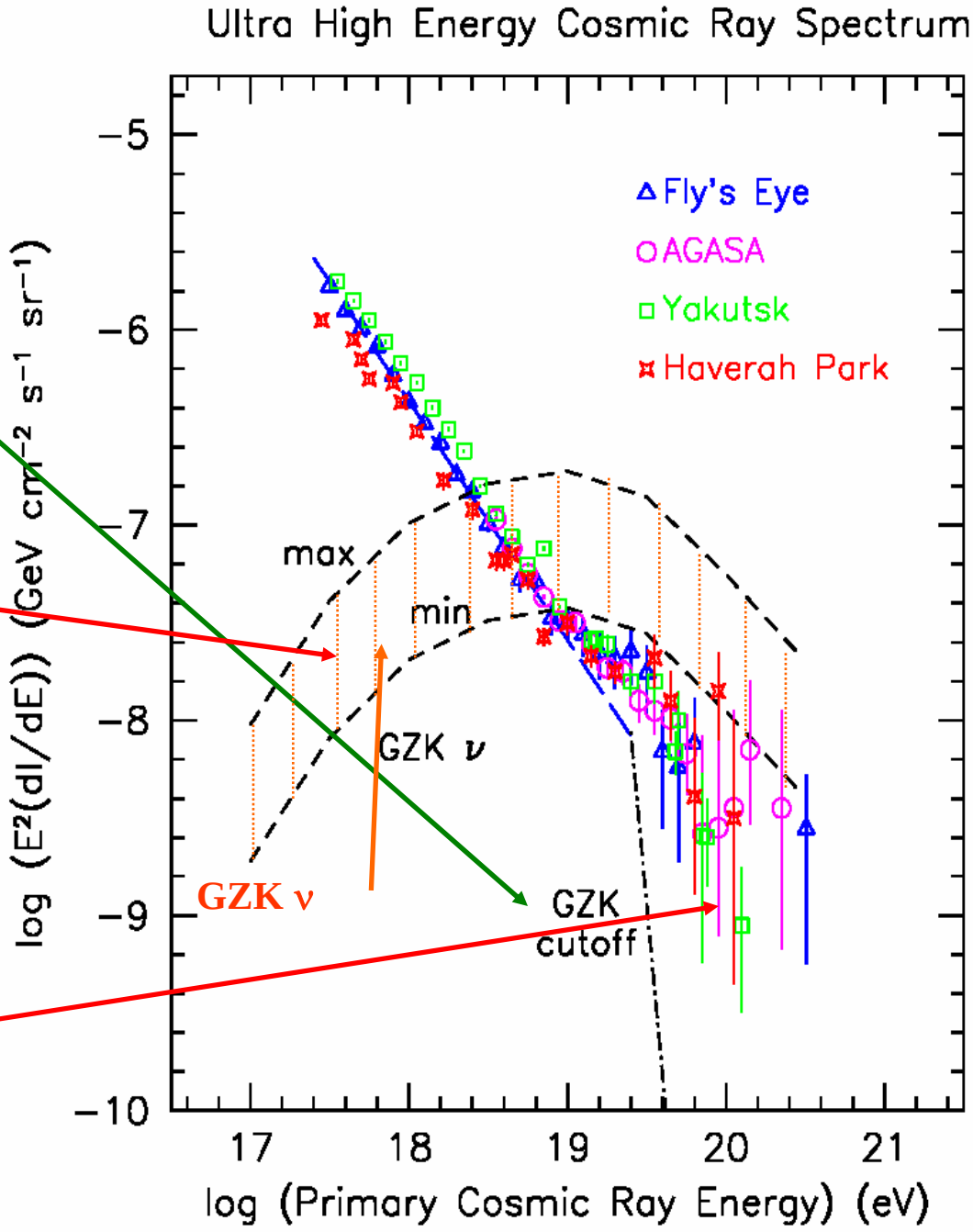
Expectations:

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

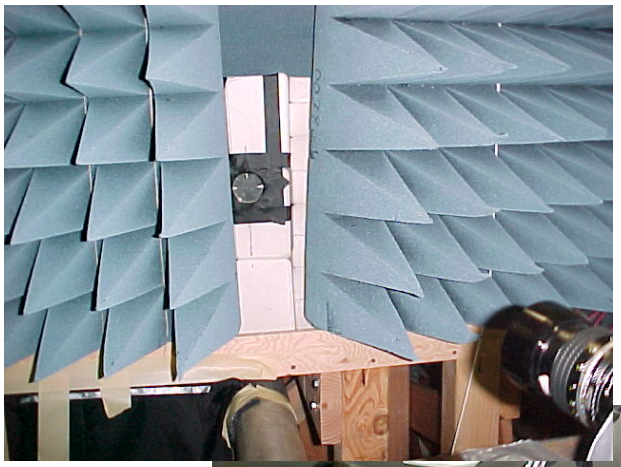
$p * \gamma \rightarrow \Delta \rightarrow n + \pi \rightarrow \nu$

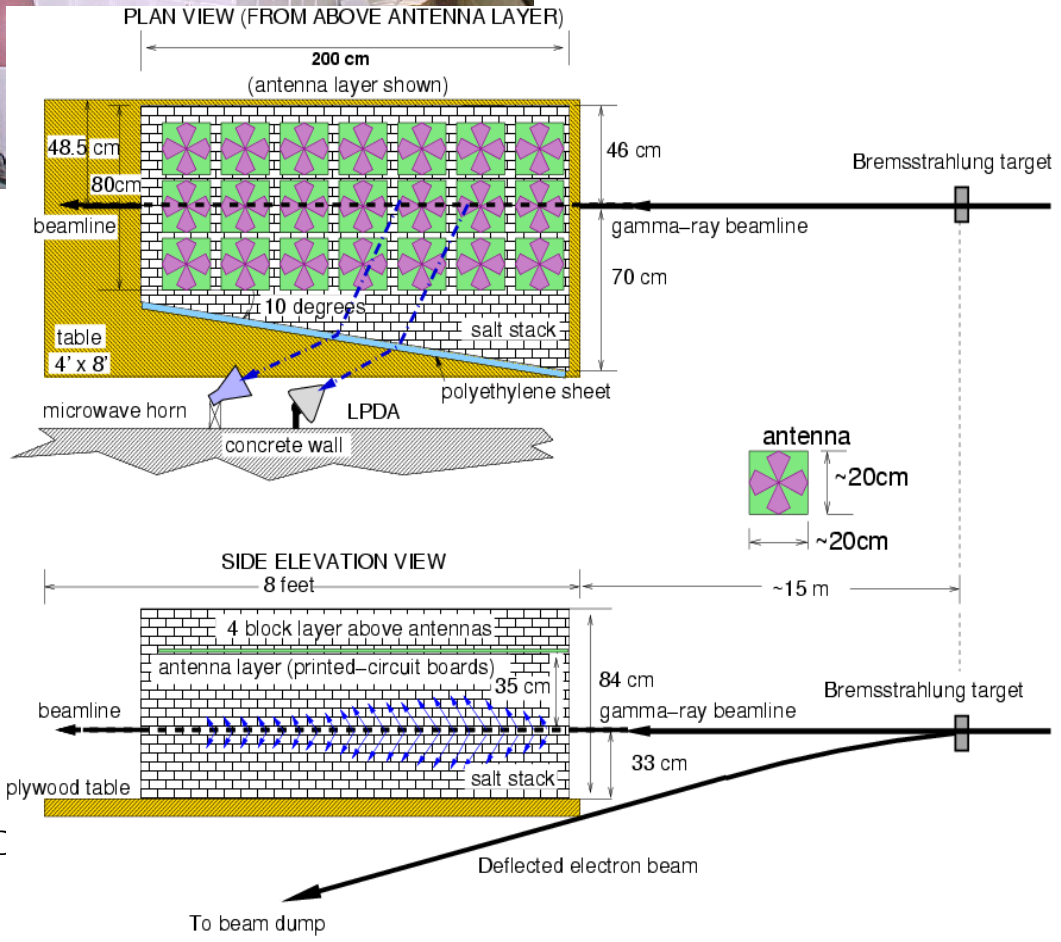
2. These interactions produce a corresponding neutrino flux

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



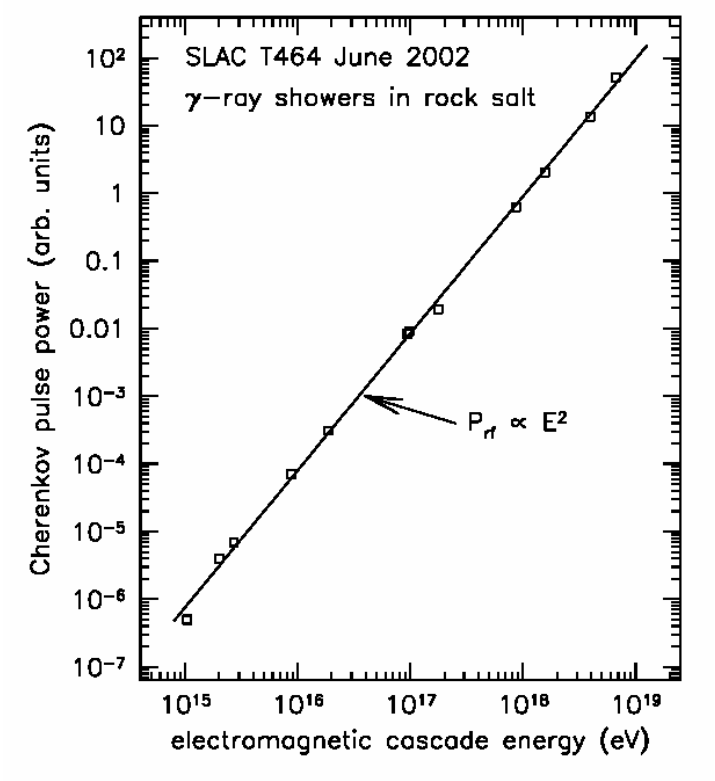
Askaryan in Salt: SLAC T460

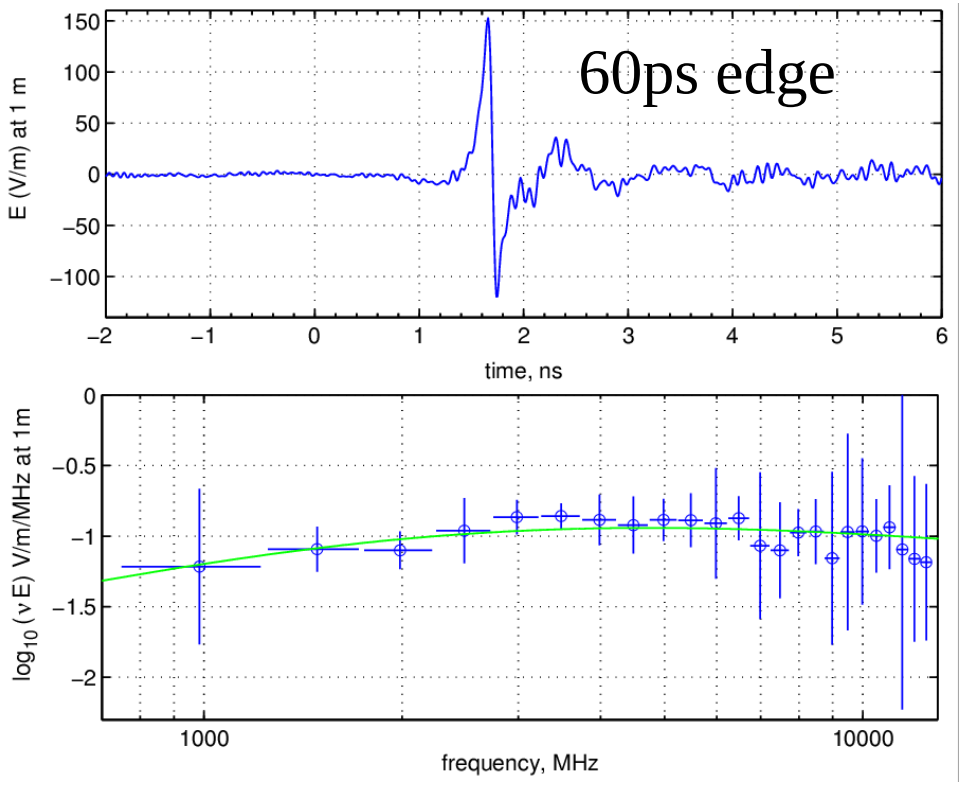




- Target: 6 tons of Morton brick salt
- Provide shower volume and embedded antenna matrix
- Antennas sample 21 grid-points along shower, dual polarization

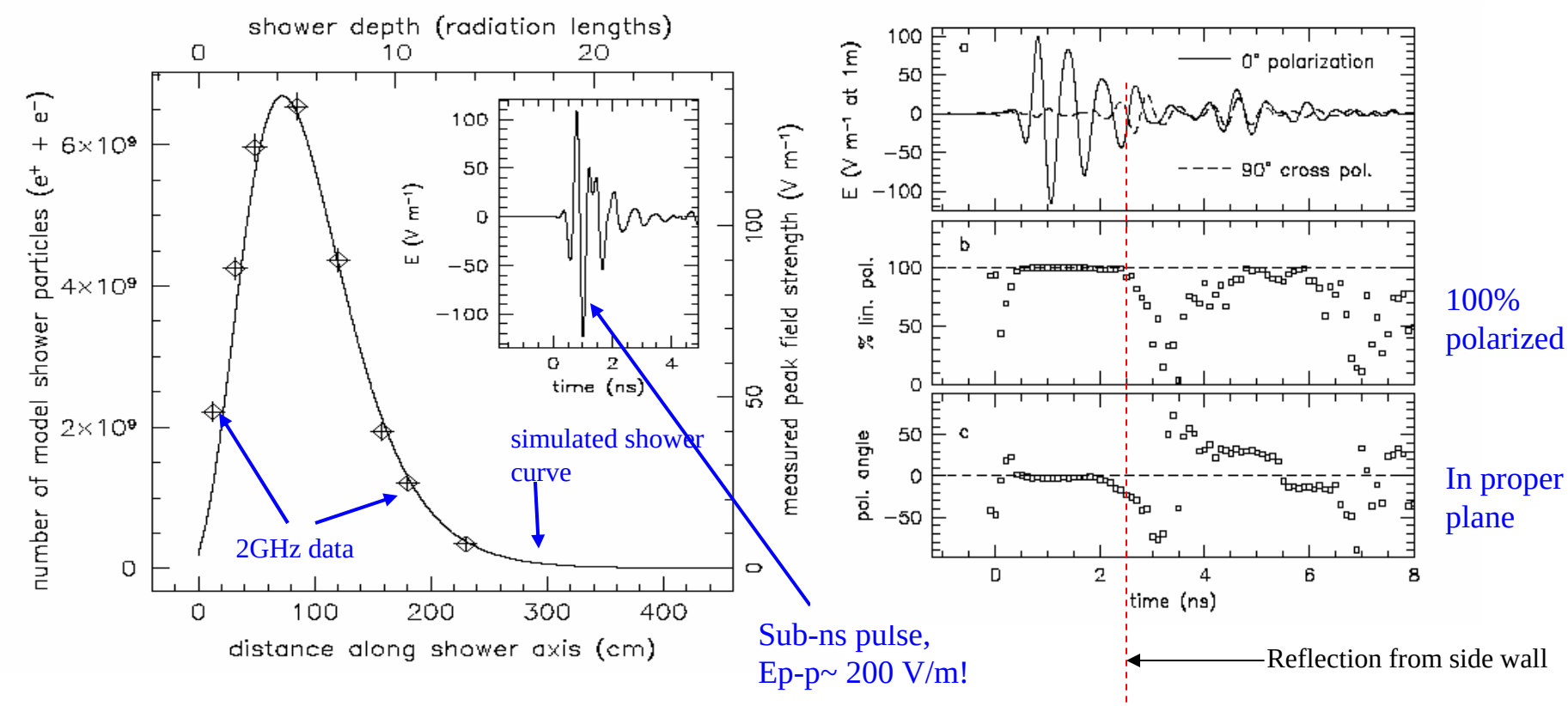
RF Coherence vs. energy & frequency





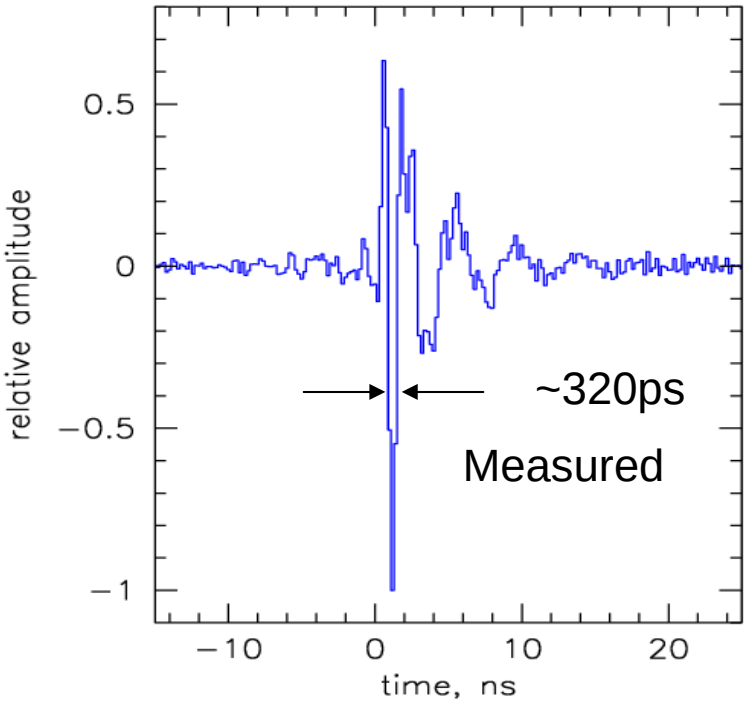
- **Much wider energy range covered than previously: 1PeV up to 10 EeV**
- **Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power**
- **Differs from actual EeV showers only in leading interactions= = > radio emission almost unaffected**

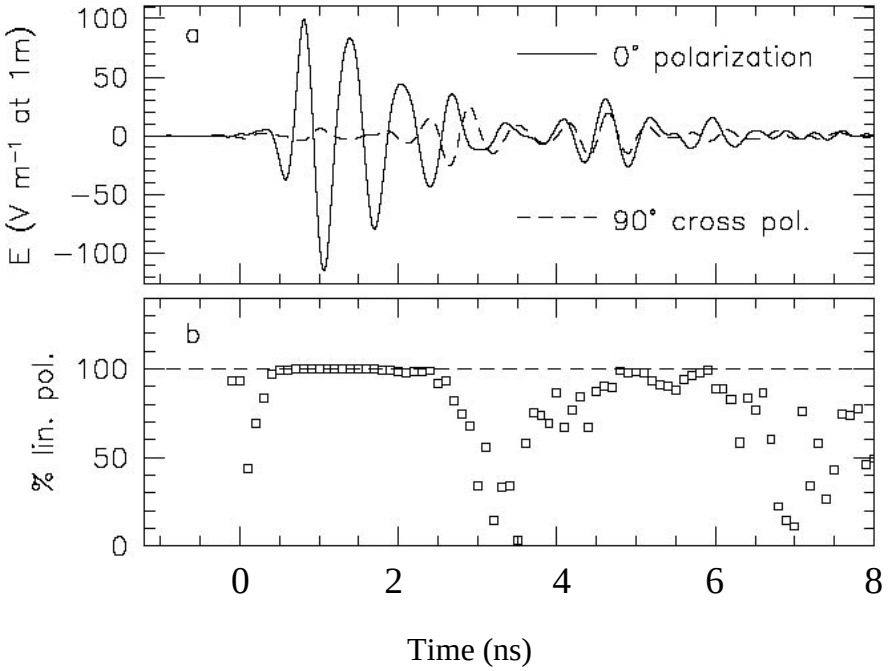
Shower profile observed by radio (~2GHz)



- 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

Askaryan Signature

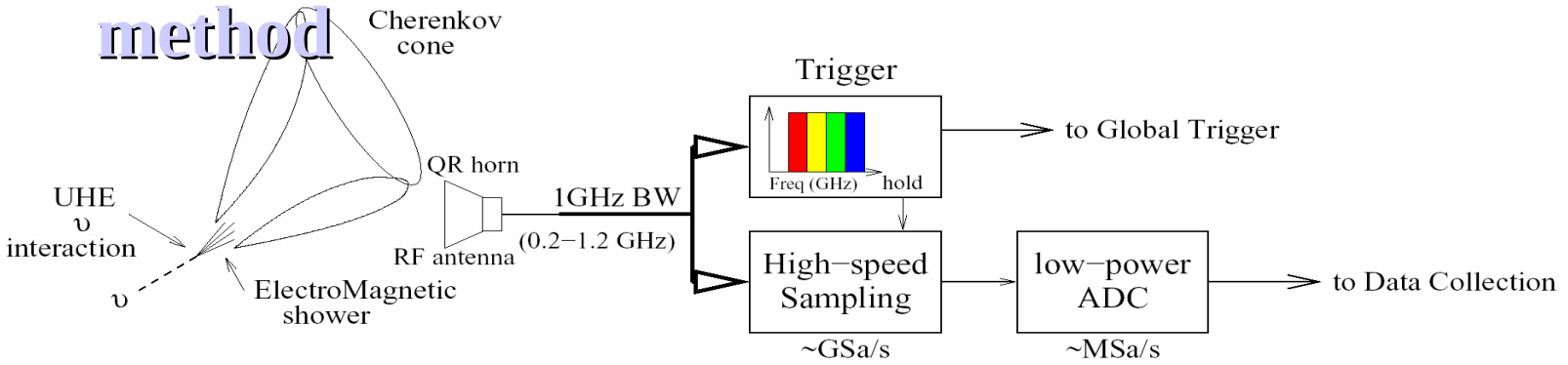




- Significant signal power at large frequencies
- Strong linear polarization (near 100%)

Trigger/Digitizer Specifications

ANITA trigger & digitizer uses a proven dual-track method

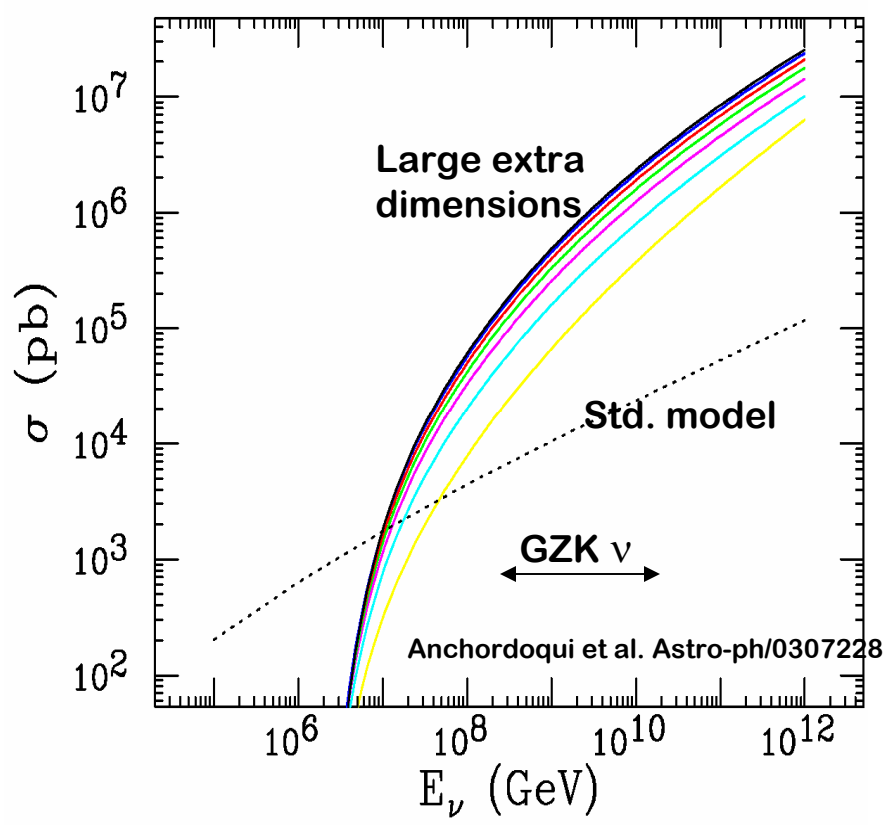


- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

	parameter	quantity	comments
Sampling	# of RF channels	80	32 top; 32 bottom; 8 monitor; 8 veto
	Sampling rate	2.6 GSa/s	> Nyquist
	Sample resolution	> 9 bits	3 bits noise + dynamic range
	Samples per window	260	100ns time window
	# of Sample buffers	4	multi-hit + extended window
	Power/channel	< 1W	excluding LNA, triggering
Trigger	# of Trigger bands	4	0.2-0.4; 0.4-0.65; 0.65-0.88; 0.88-1.2GHz
	# of Trigger channels	8	per antenna (4bands x RCP,LCP)
	Trigger threshold	<= 2.3σ	operation down to ~300K thermal noise
	Accidental trigger rate	< 5Hz	at target Trigger threshold
	Level2 Trigger latency	~50ns	to issue Hold signal

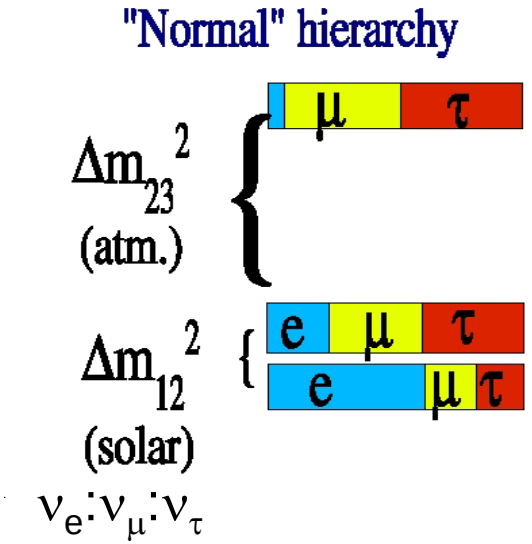
Particle Physics: Energy Frontier

- 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

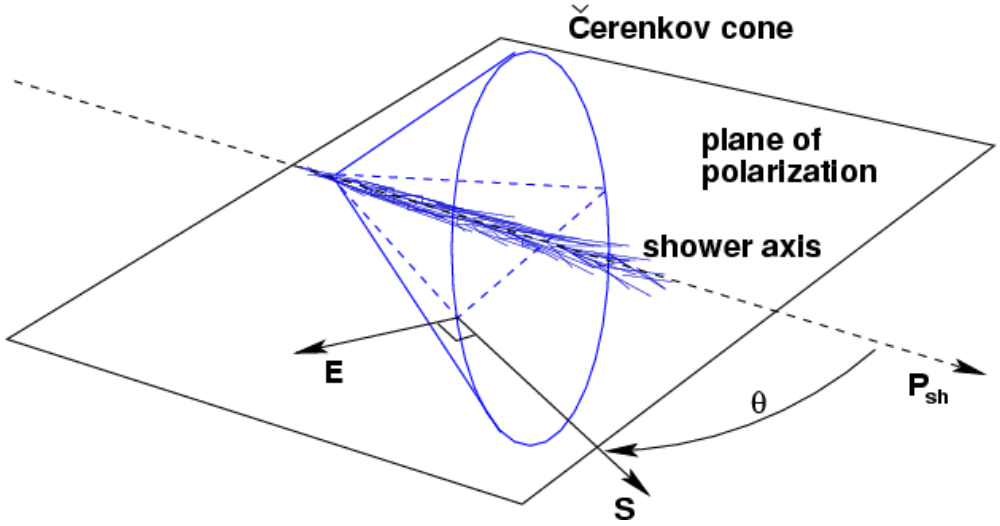
- GZK neutrinos are the "longest baseline" neutrino experiment:
  - Longest L/E (proper time) for: sterile ν admixtures & anomalous ν decays
    - SUN: L/E ~ 30 m/eV
    - GZK: L/E ~ 10^9 m/eV
- Measured flavor ratios of $\nu_e:\nu_\mu:\nu_\tau$ can identify non-standard physics at source



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

Neutrino decay leaves a strong imprint on flavor ratios at Earth

Cherenkov polarization tracking

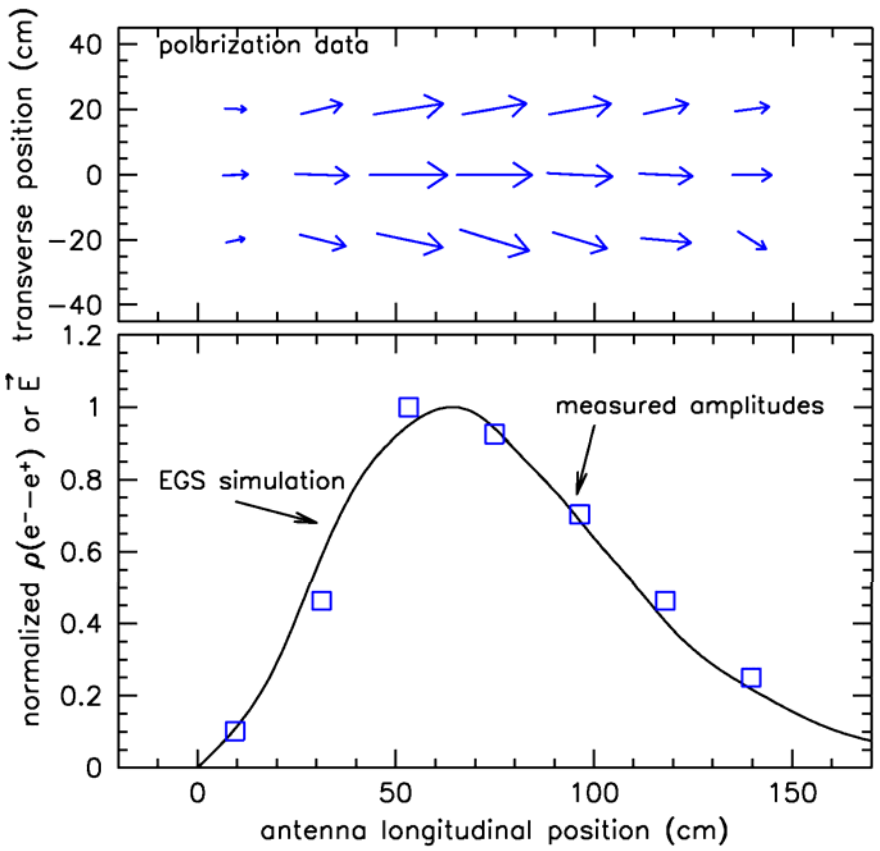


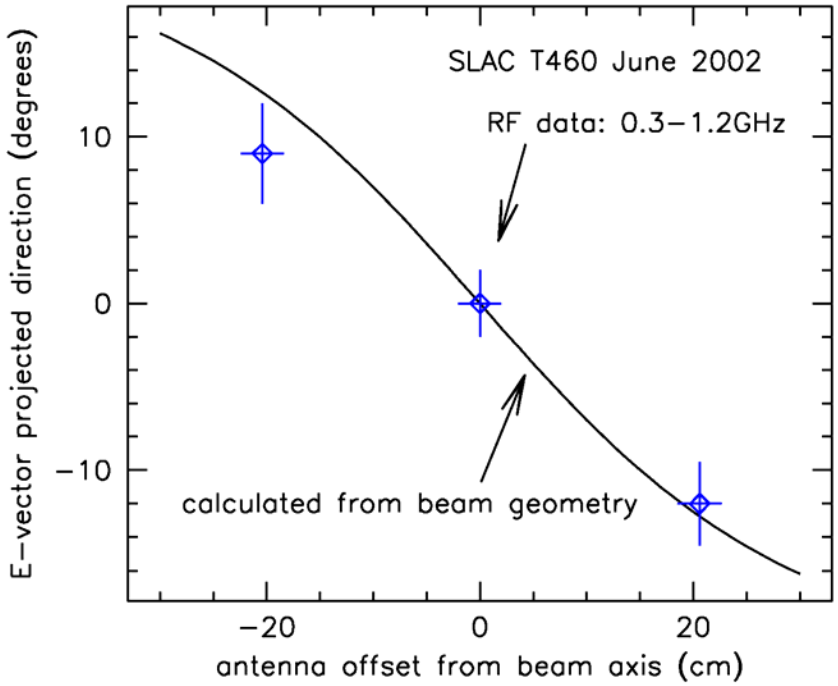
- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - **Intersection of these planes defines shower track**

Cherenkov radiation predictions:

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

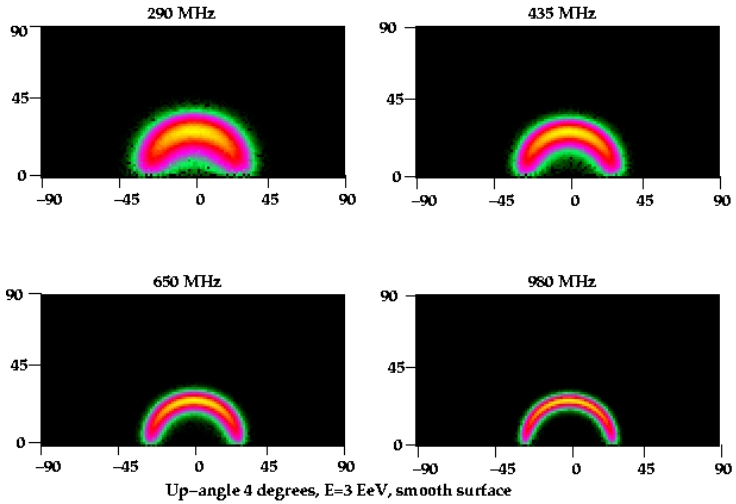
Polarization tracking

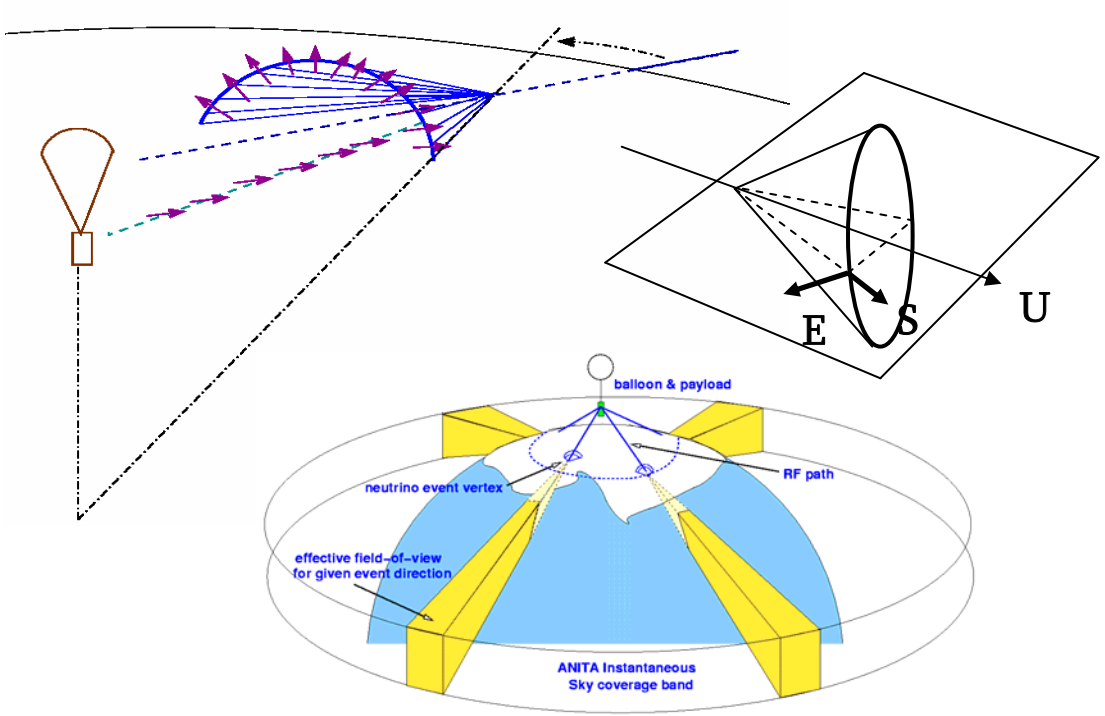


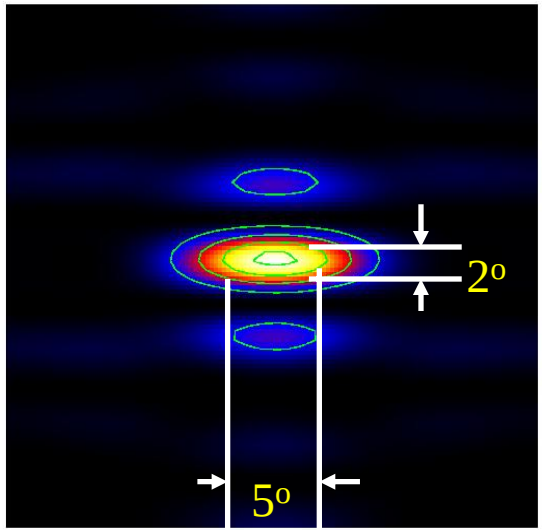


- Measured with dual-polarization embedded bowtie antenna array in salt

ANITA as a neutrino telescope

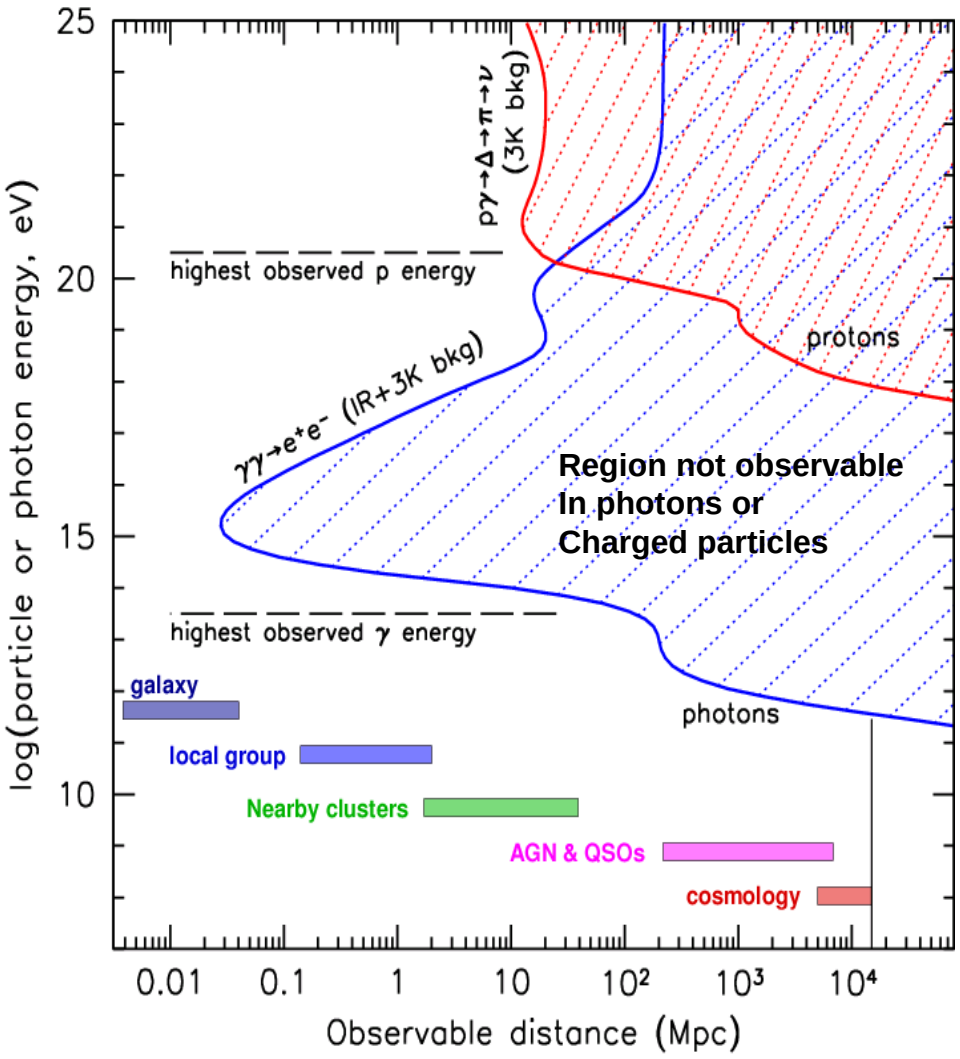






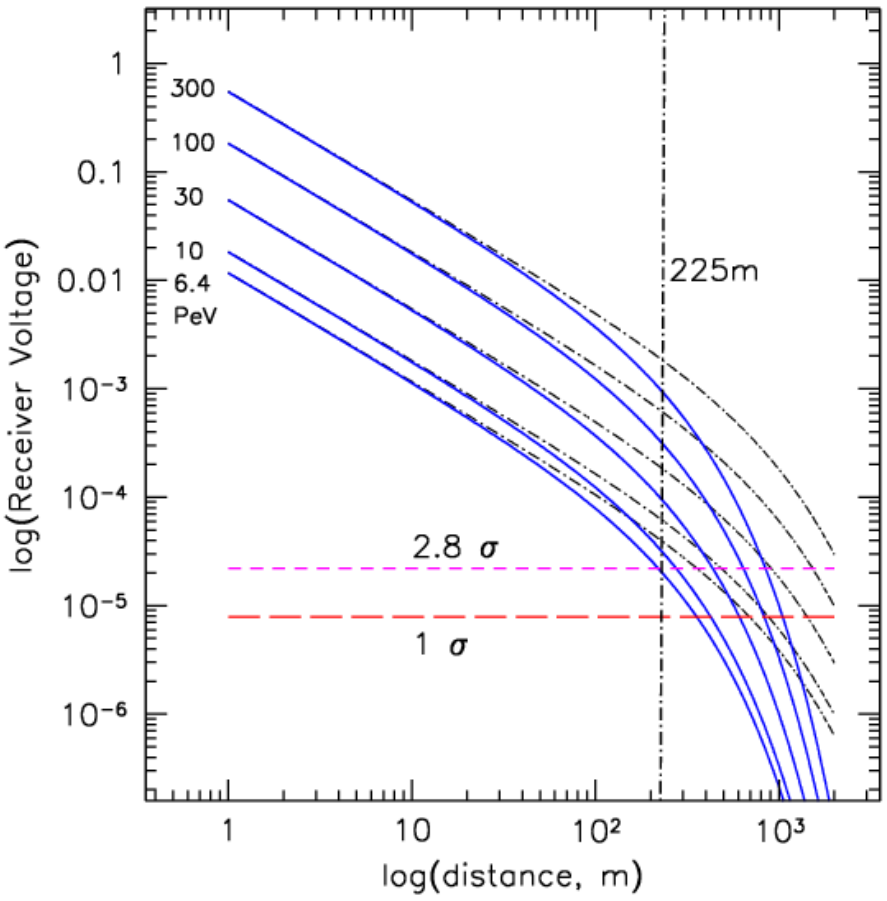
- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

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**

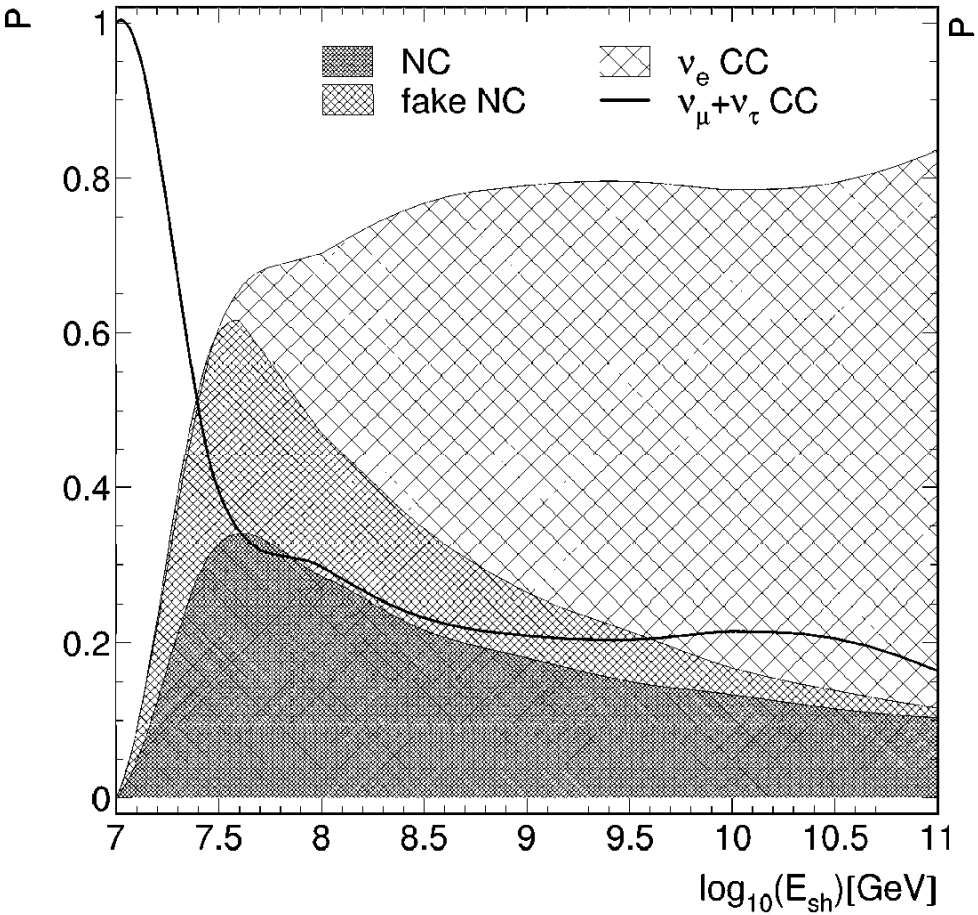
Estimated SalSA Energy threshold

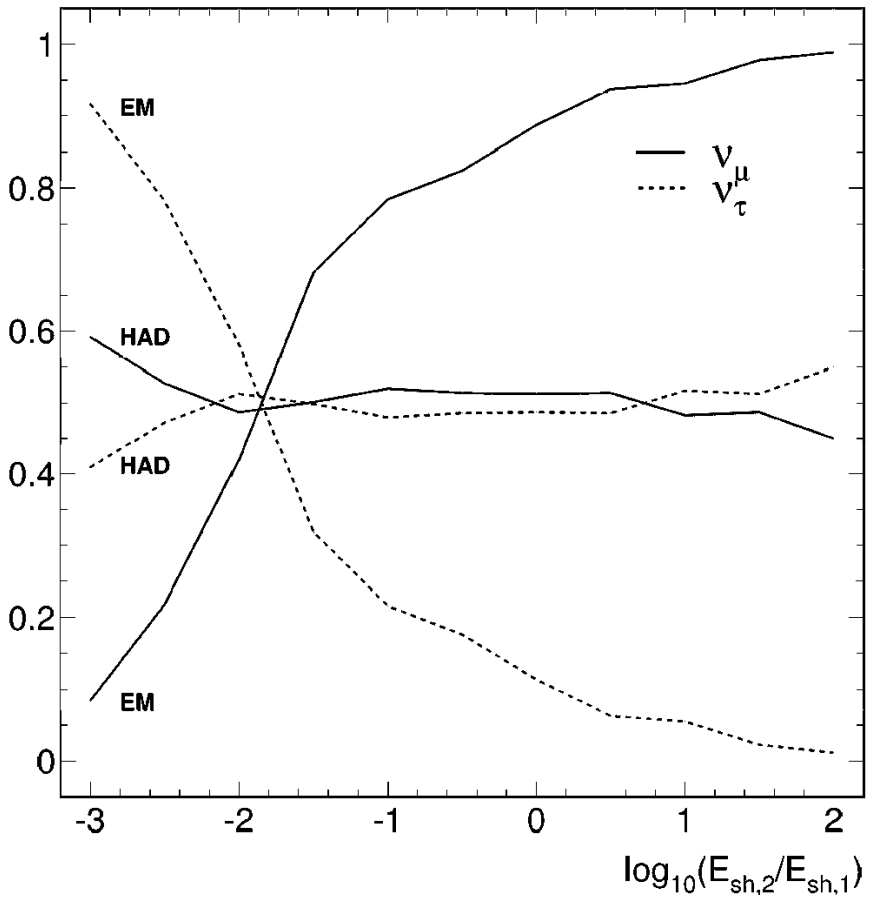


- Ethr < 300 PeV (3 x 10^{18} eV) best for full GZK spectral measurement
- Threshold depends on average distance to nearest detector and local antenna trigger voltage above thermal noise
  - Vnoise = k T Δf
  - Tsys = Tsalt+Tamp = 450K
  - Δf of order 200 MHz
- 225 m spacing gives 30 PeV
- Margin of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

Interaction/PID

Ped Miocinovic (UH)





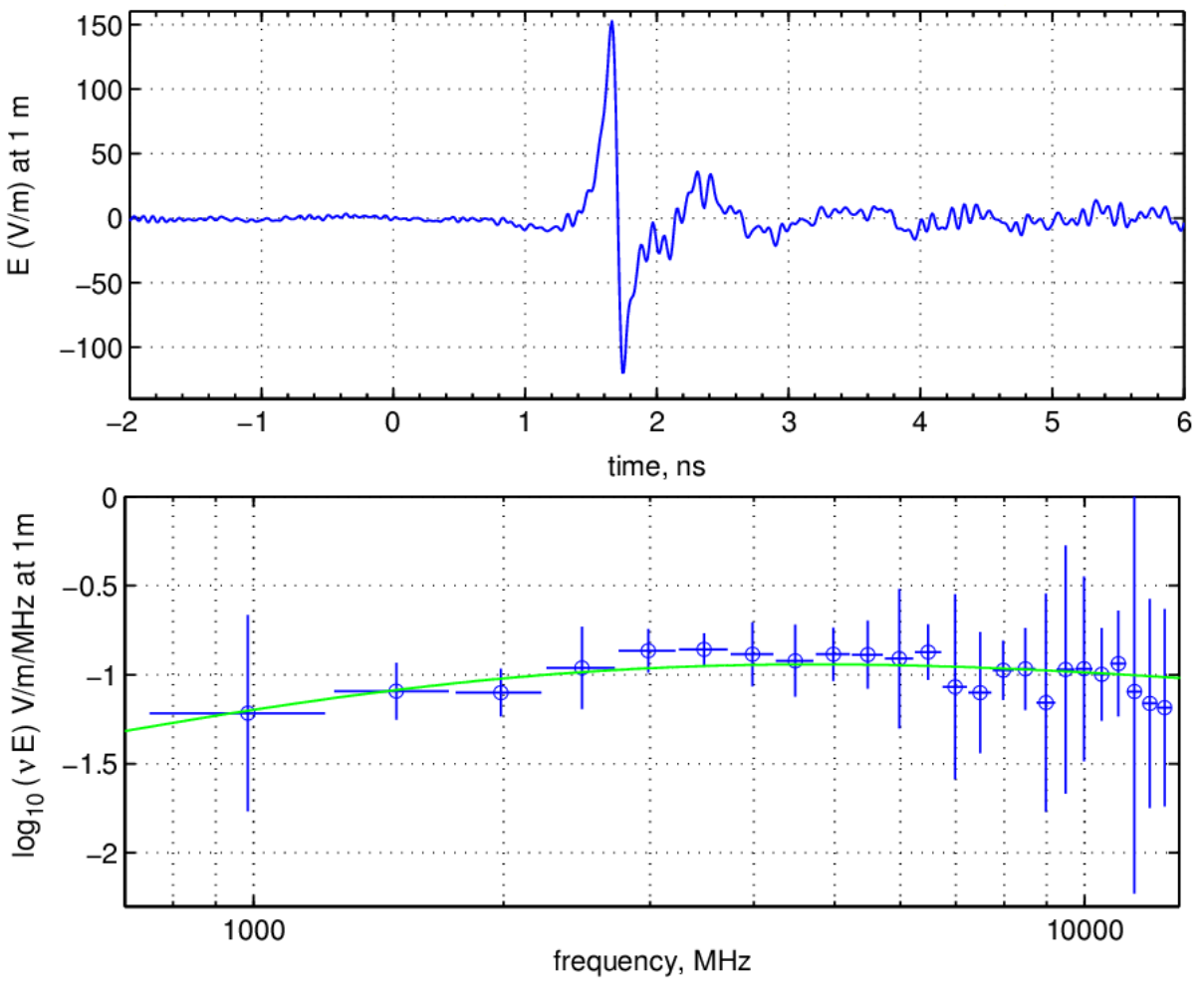
T460 rock-salt target

2cm

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

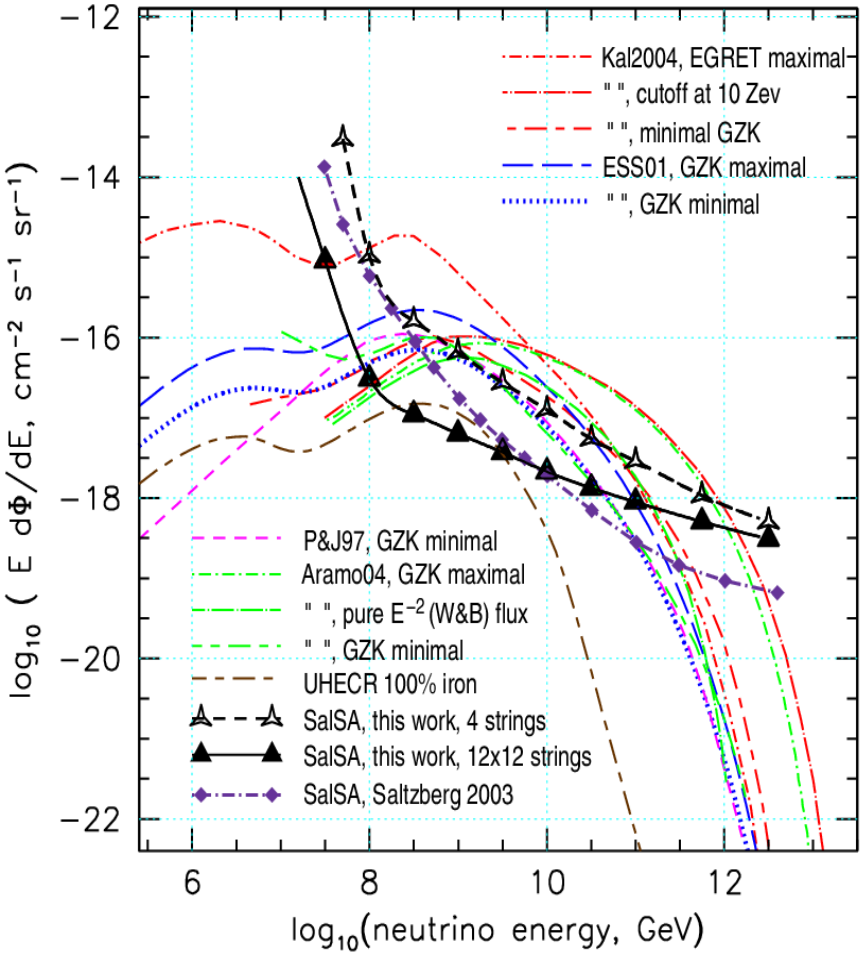
- Beam exit point shown above
- Depth ~ 15 radiation lengths
  - Shows some deposits from spallation, good indicator of transverse size of shower!

Ultra-wideband data on Askaryan pulse



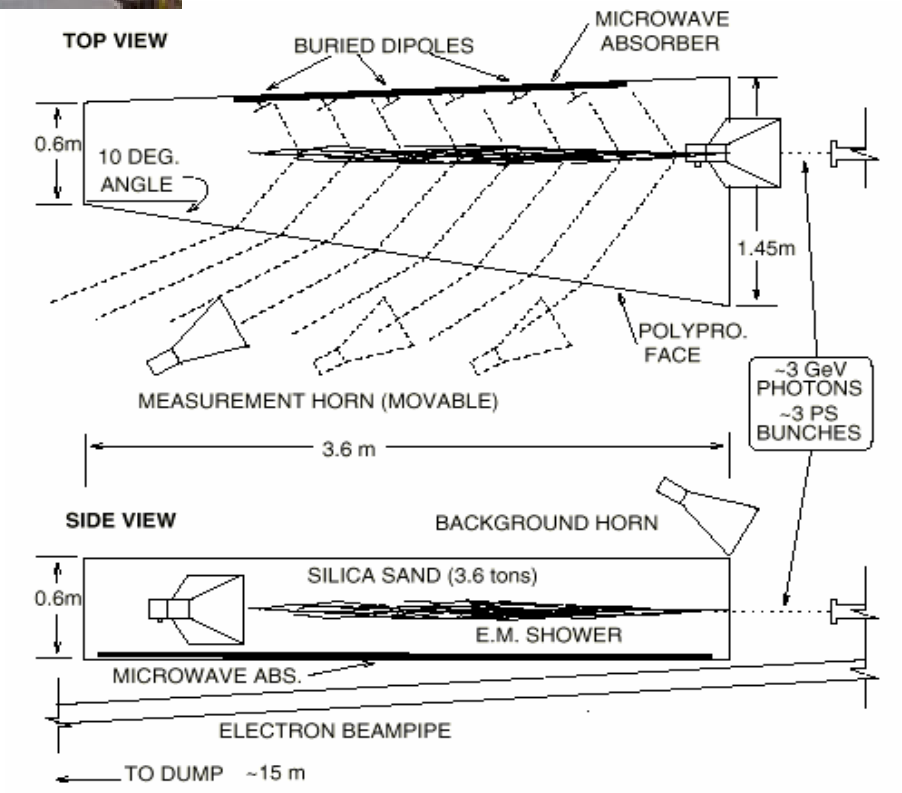
- 2000 & 2002 SLAC Experiments confirm extreme coherence of Askaryan radio pulse
- 60 picosecond pulse widths measured for salt showers
- Flat spectrum radio emission extends well into microwave regime

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!**

Askaryan Confirmation: SLAC T444 (2000)



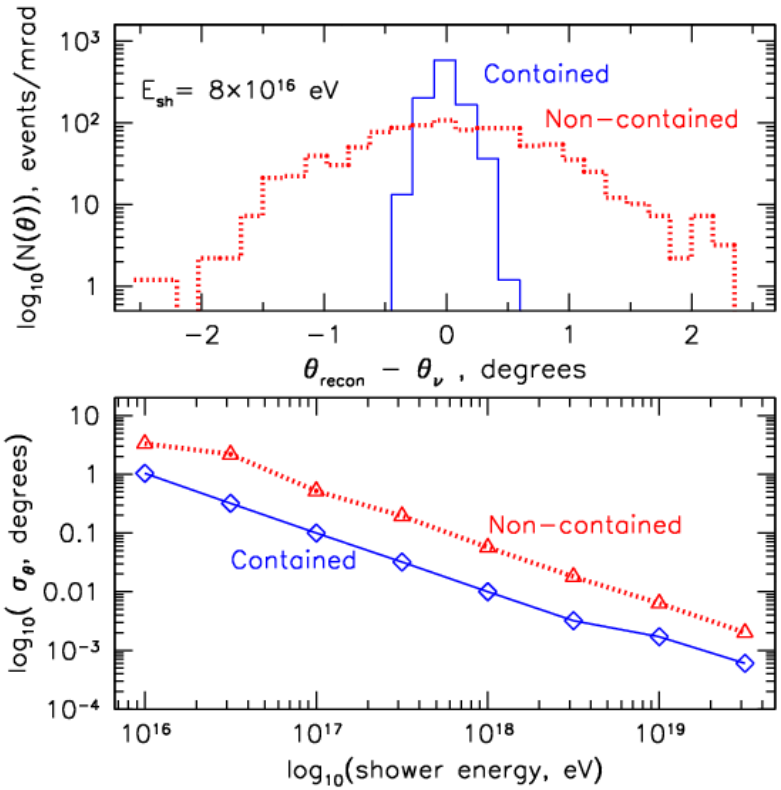
Saltzberg, Gorham, Walz *et al* PRL **86** 2802 (2001)

- 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!

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?

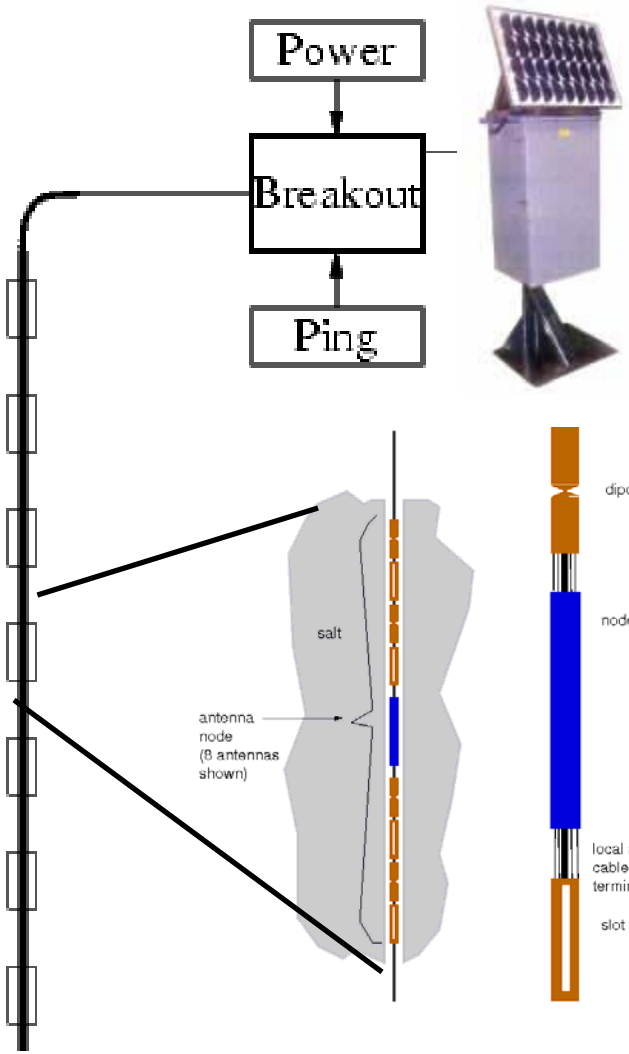
Angular resolution



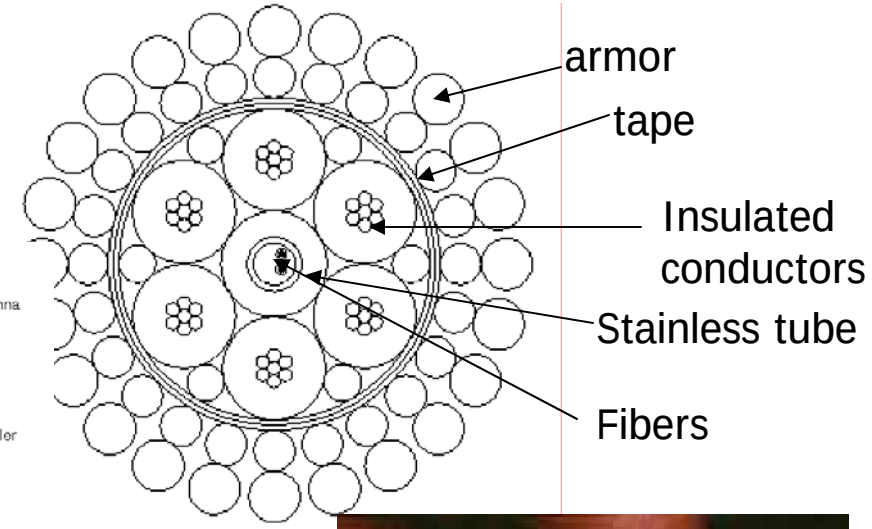
- Of order 1 degree angular resolution required for neutrino cross section measurements
- Studied in detail for 12x12 string array, using Chi-squared minimization
- For GZK energies:
  - 0.1º achieved for contained events-- inside the array
  - 1º achieved for external events, parallel to face, 250 m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

Basic string architecture

String
12 nodes



NEMA 3R
38" x 21" x17"



Node = 12 antennas
and center housing

GEISER Data flow

(Giga-bit Ethernet Instrumentation for SalSA Electronics Readout)

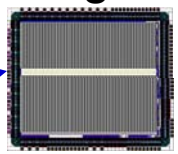
- GEISER approach:
  - Digitize the “mud” in downhole
  - ‘Pan for gold’ at the surface
- Node/string time stamps
  - Allow global trigger
  - Initiate full array data dump

Digital Cell system for data collection

Trigger packets sent via FM/local radio

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

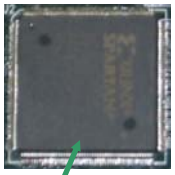
asic digitizer



antennas

RF in Continuous

Hold event if >2.4σ



Internal FPGA: Logic, Buffer

In salt

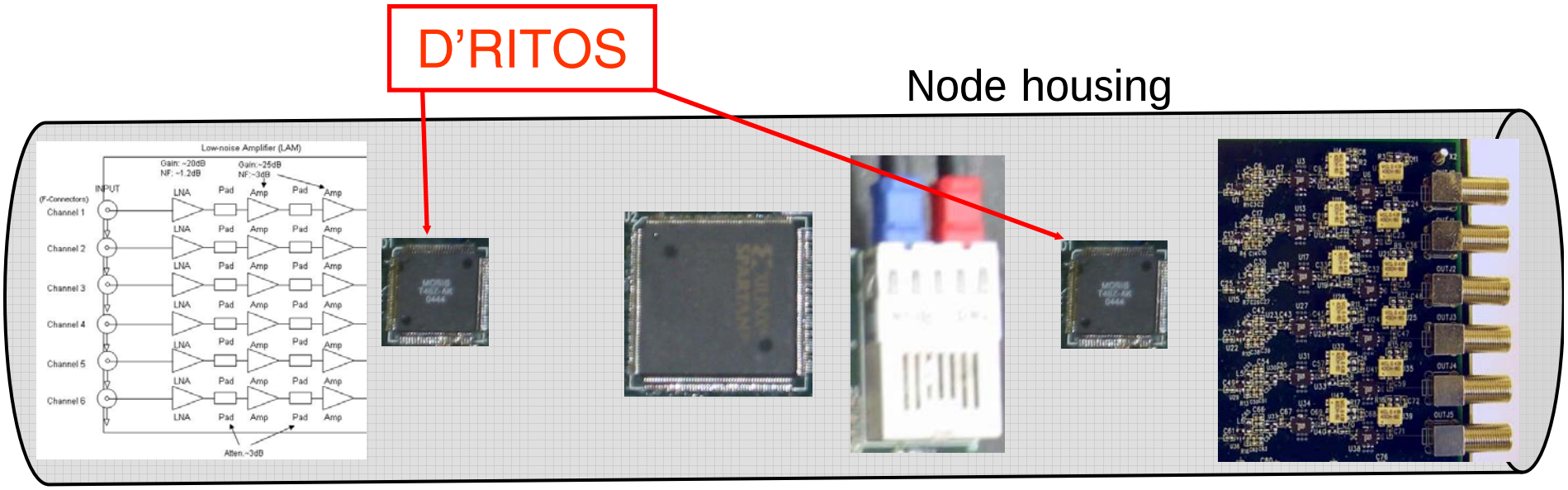
Central control & Global Trigger station

Node/String Time stamps

Event request

Final Data Transfer

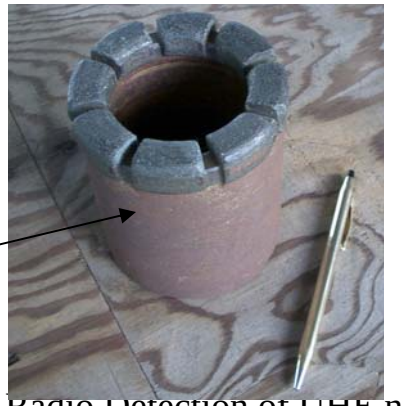
SalSA Node-controller readout board architecture



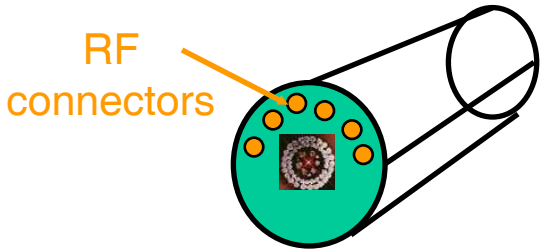
LNA, 2nd-stage amps (one each end)

Trigger, bi-directional fiber-link

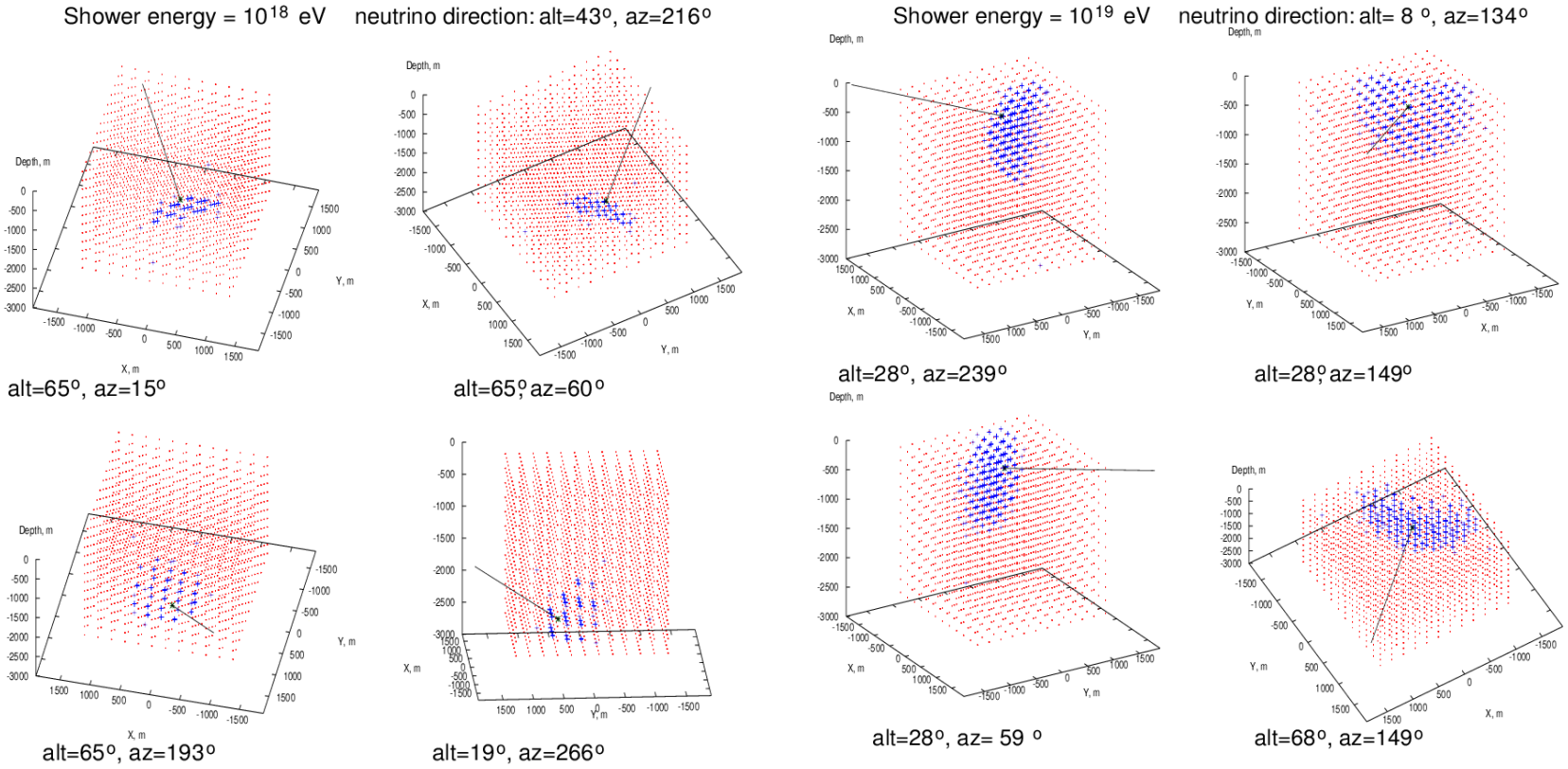
LNA, 2nd-stage amps (other end)



Typical 4" coring bit



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**