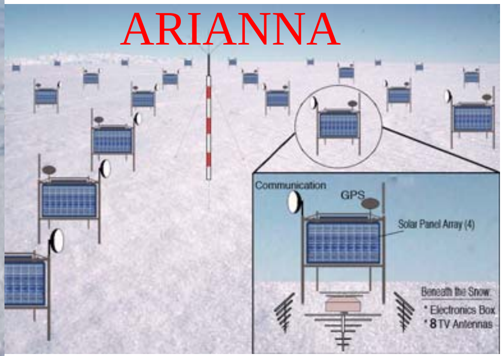
Radio Detection of UHE neutrinos


Photo courtesy Kim Palladino



Gary S. Varner
University of Hawai'i
KEK Seminar 3/13/07

Search for What Ought to Be

1. Background – Why UHE neutrinos are unique
2. Radio Detection of UHE neutrinos
3. ANtarctic Impulsive Transient Antenna (ANITA)
4. Physics with Extensive Radio Arrays
5. Tera-ton Initiatives (AURA, SalSA, ARIANNA)

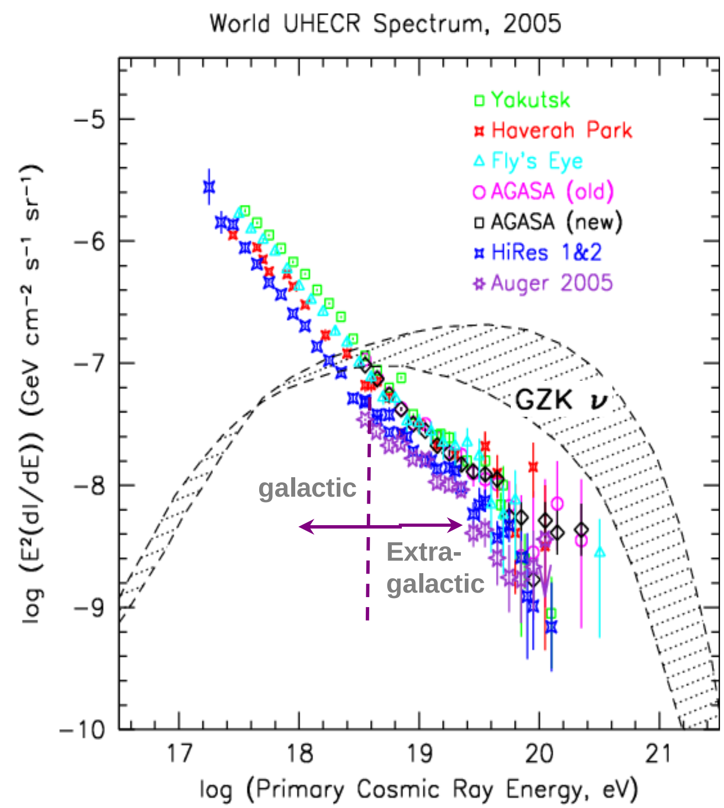
Observation of UHE Cosmic rays ➔ predict Neutrinos

- **After 40 years(!)** Neither origin nor acceleration mechanism known for cosmic rays above 10^{19} eV, A paradox:
  - No nearby sources observed
  - distant sources excluded due to collisions with microwave bkg
- Neutrinos at $10^{17\text{-}19}$ eV required by standard-model physics

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

"GZK cutoff" process

- Lack of neutrinos:
  - **UHECRs not hadrons?!**
  - **Lorentz invariance wrong?!**
  - **New physics?**



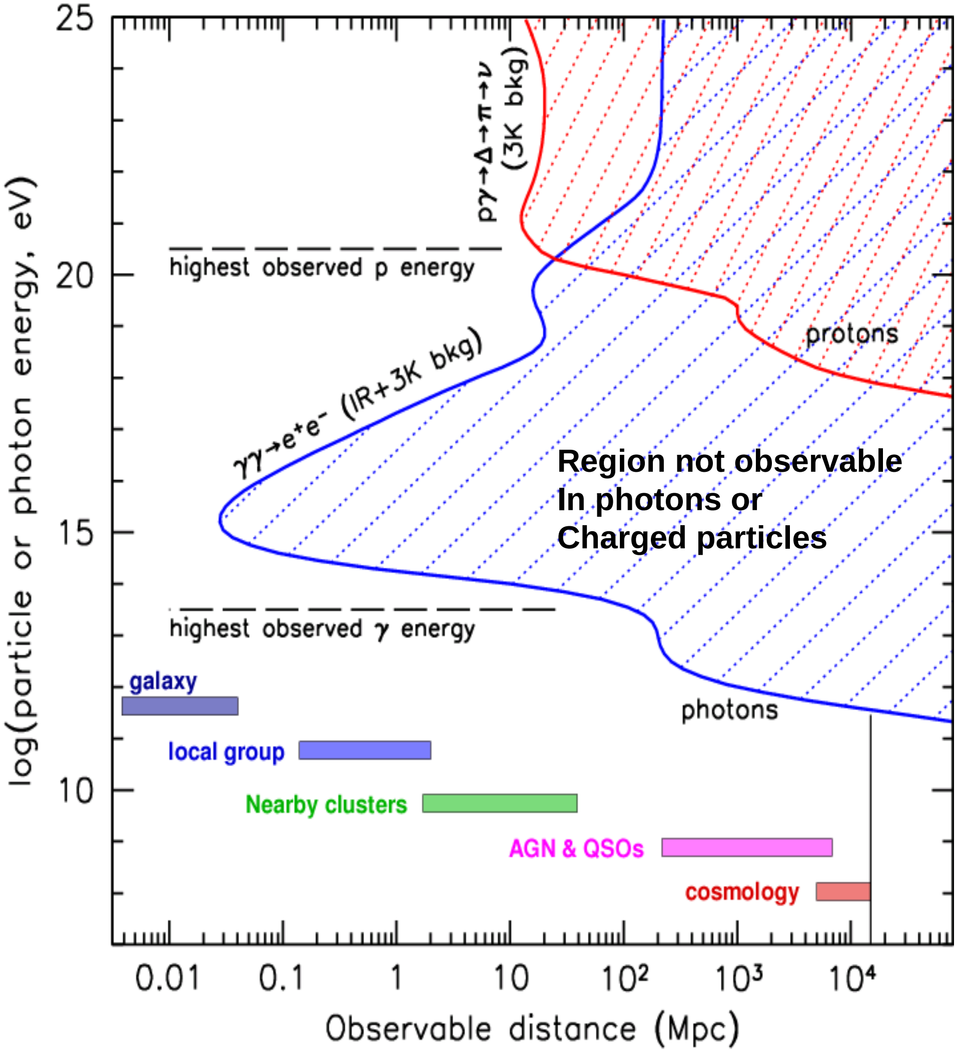
END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

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

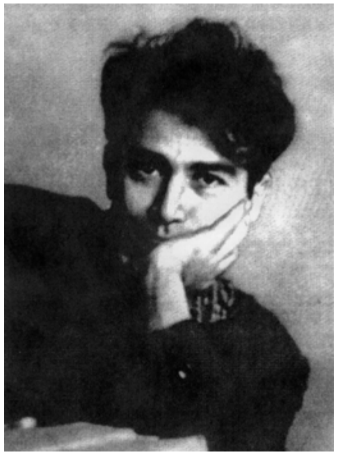
Neutrinos: The only known messengers at PeV energies and above

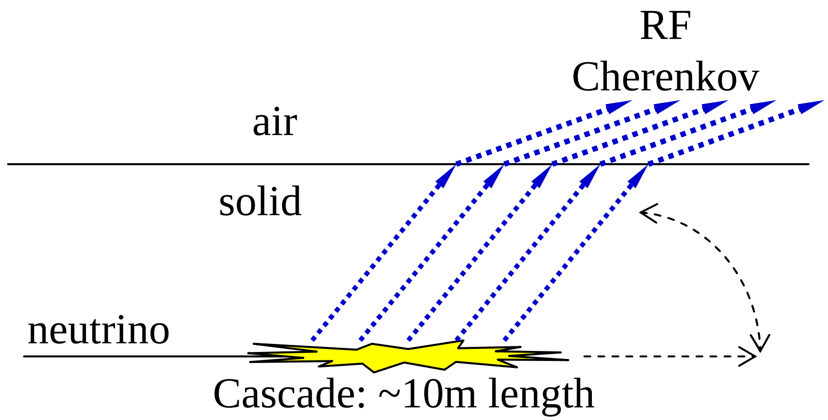
Peter Gorham [UH]



- **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**

Radio Observation in dense media



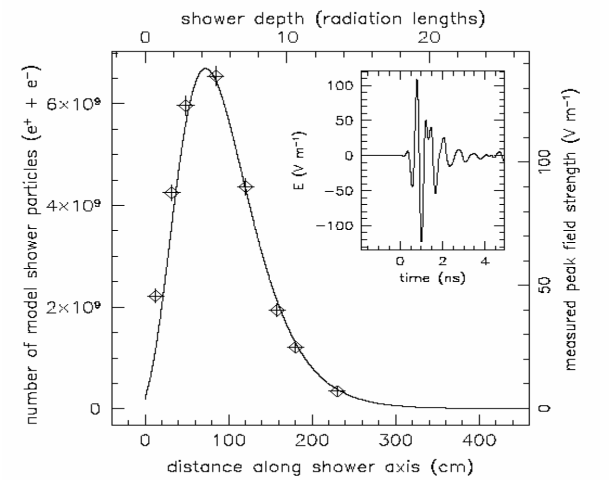


1960's: Askaryan predicted that the resultant compact cascade shower (1962 JETP **14**, 144; 1965 JETP **21**, 658):

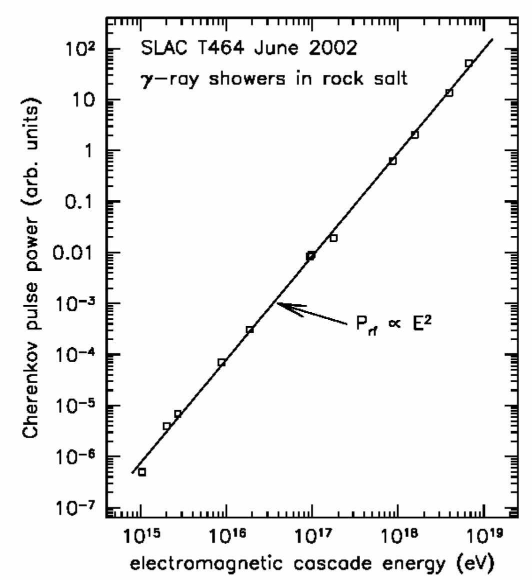
- would develop a local, relativistic net negative charge excess
- would be coherent ($P_{rf} \sim E^2$) for radio frequencies
- for high energy interactions, well above thermal noise
- detectable at a distance (via antennas)
- polarized – can tell where on the Cherenkov cone

A great idea that took a while to catch on

- **1962: G. Askaryan predicts coherent radio Cherenkov from particle showers in solid dielectrics**
  - His applications? Ultra-high energy cosmic rays & neutrinos
- **Mid-60's: Jelley & collaborators see radio impulses from high energy cosmic ray air showers**
  - **--** from geo-sychrotron emission, NOT radio Cherenkov
- **1970-2000: Askaryan's hypothesis remained unconfirmed**
- **2000-2001: Argonne & SLAC beamtests confirm strong radio Cherenkov from showers in silica sand**
- **Salt (2004) & ice (2006) also tested, all confirmed**



Saltzberg, et al PRL 2001

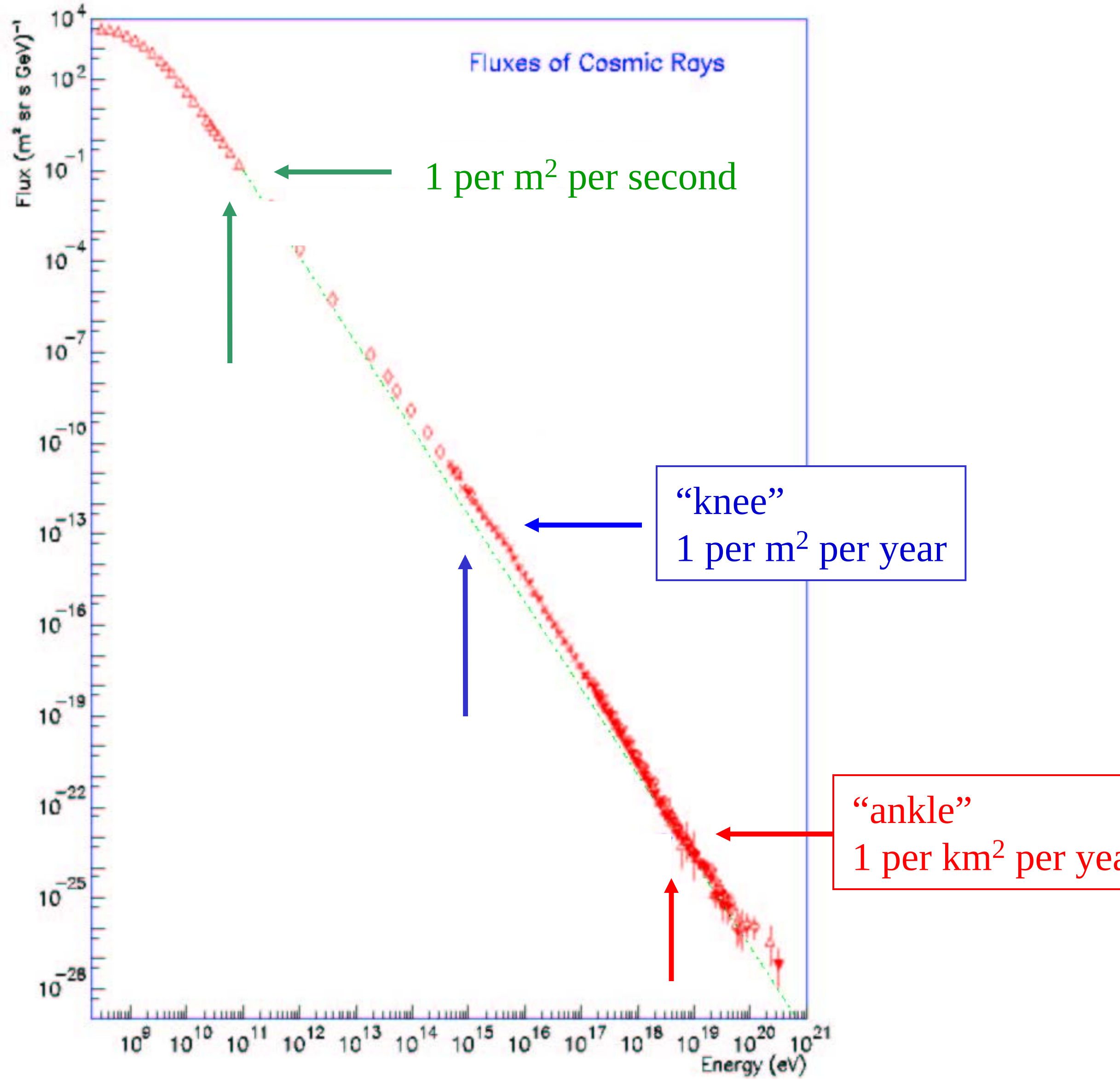


Goprham, et al PRD 2004

Why so Hard?? The Flux Problem

- At E>10^20…

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

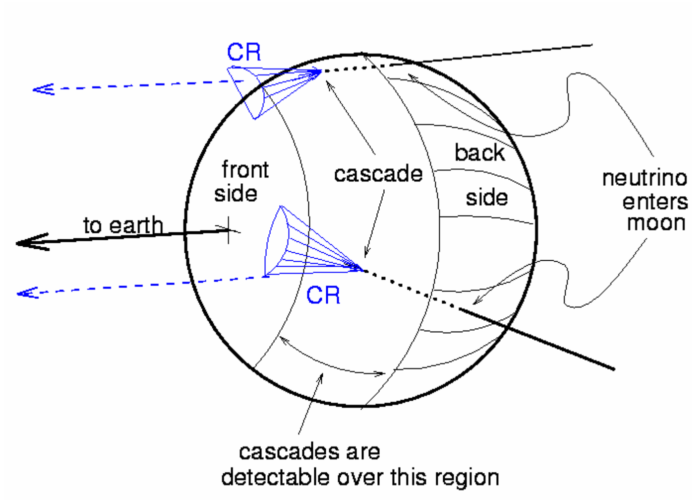


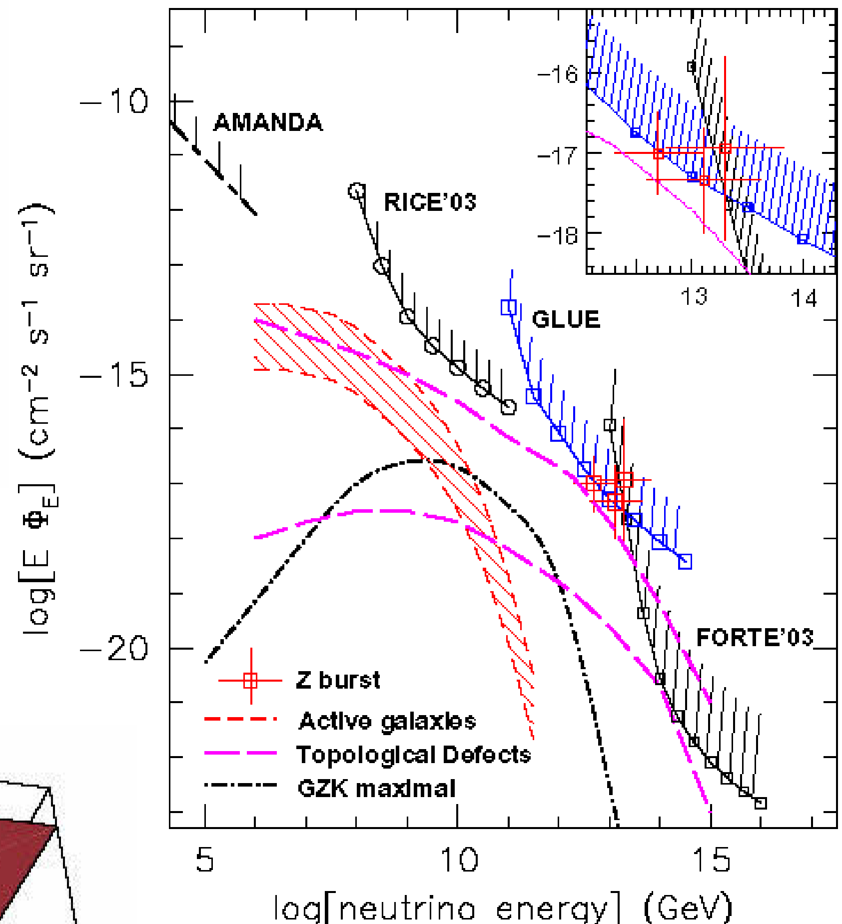
Where to Look?

- Salt
  – Salt domes
- Ice
  – In situ (RICE)
  – Overflight (FORTE , ANITA-lite)
- Silica sand
  – Lunar regolith (GLUE)

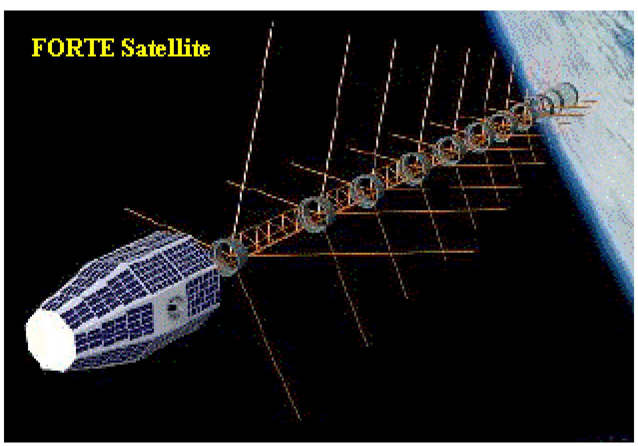
Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

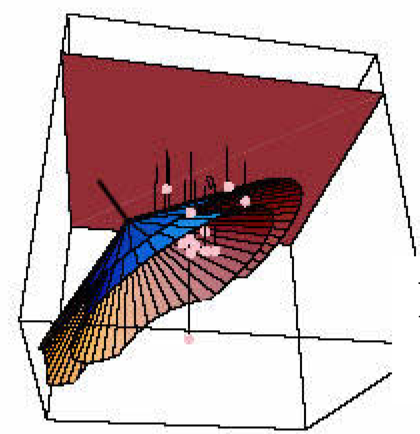
- PRL 93:041101 (2004) limits published





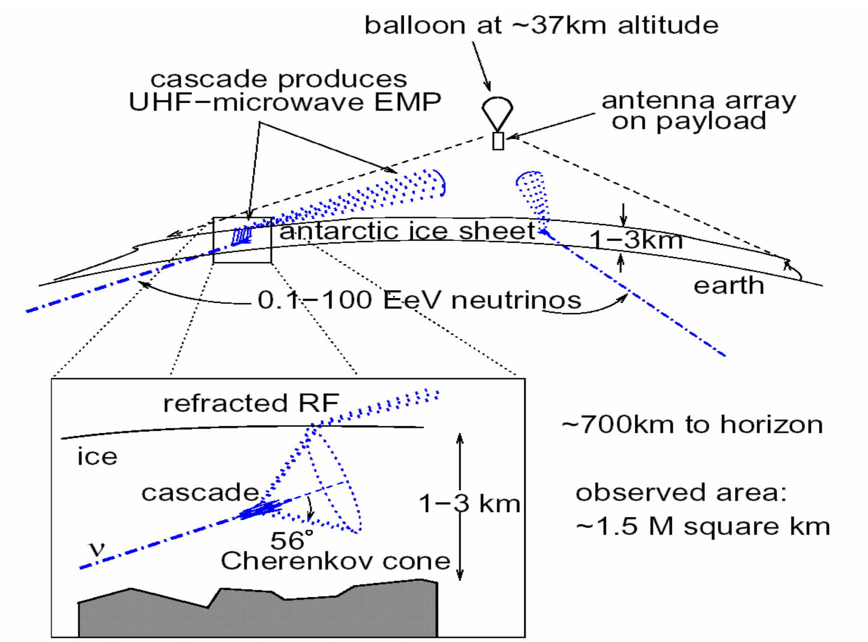
Greenland Ice

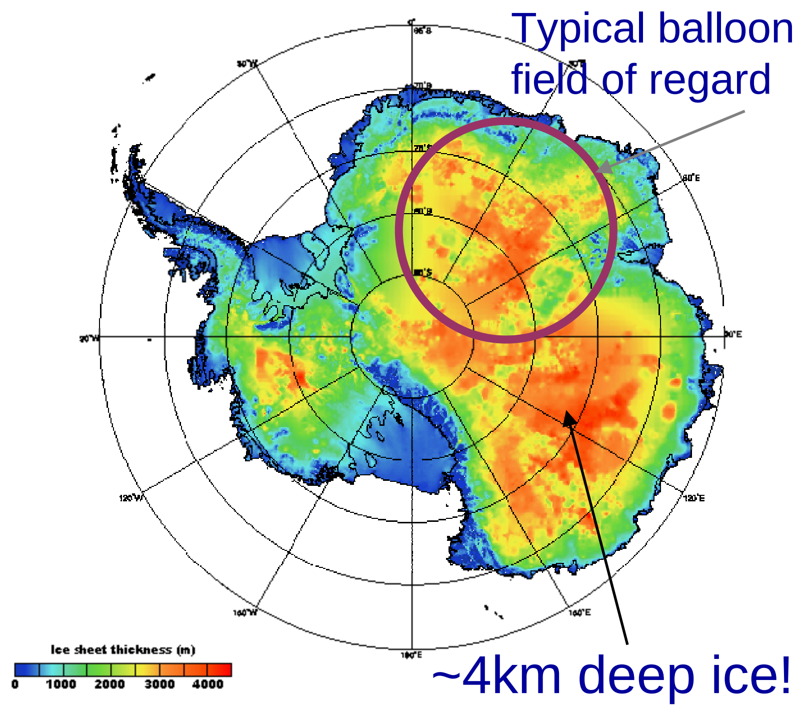




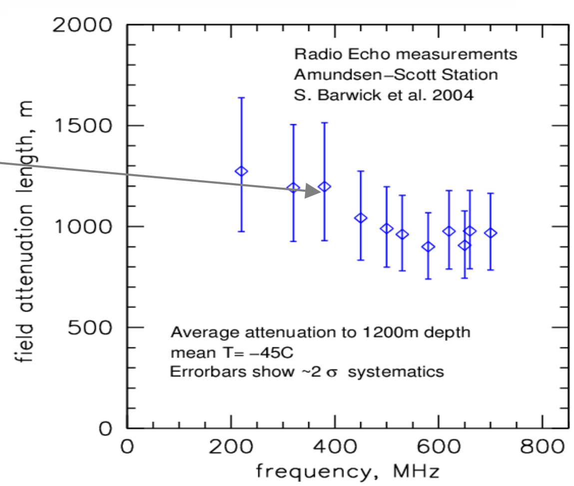
Radio Ice Experiment (RICE) @ South Pole

The ANITA Concept





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)

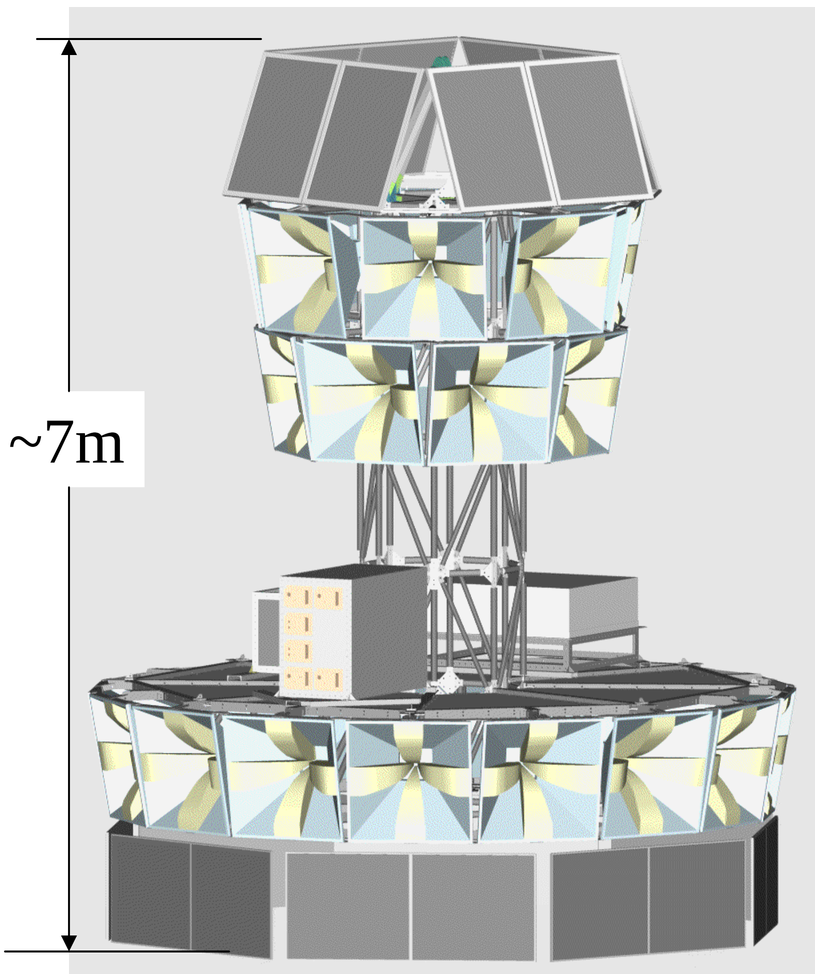
ANITA

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

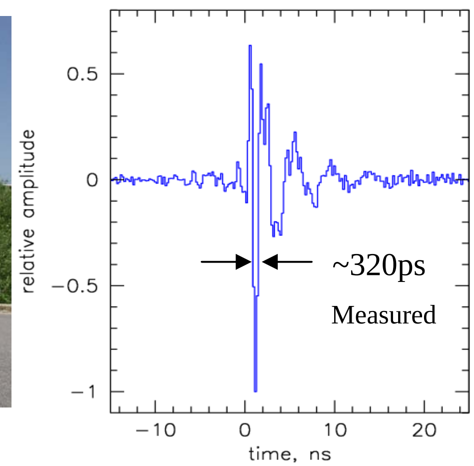
UNIVERSITY OF HAWAII AT MANOA
THE OHIO STATE UNIVERSITY
UCIrvine University of California, Irvine
1851 150 YEARS 2001
NASA
JPL Jet Propulsion Laboratory California Institute of Technology
NATIONAL SCIENTIFIC BALLOON FACILITY
UCLA
Washington University in St.Louis

Flight Payload Design

A radio "feedhorn array" for the Antarctica Continent



Gondola design: Marc Rosen



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

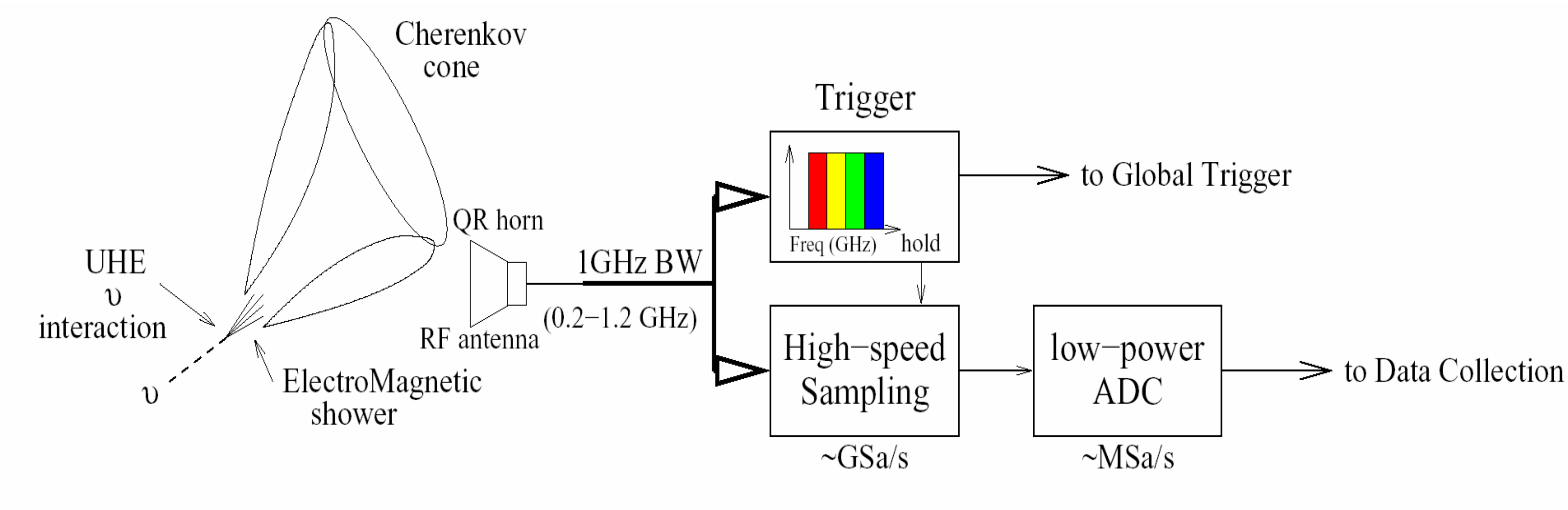
- Interferometry & beam gradiometry from multiple overlapped antenna measurements

Major Hurdles

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

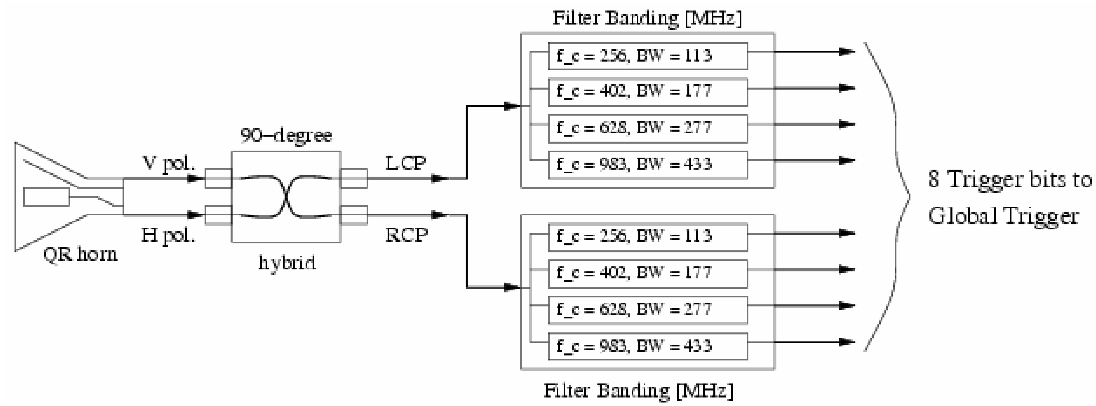
- Without being able to record or trigger efficiently, there is no experiment

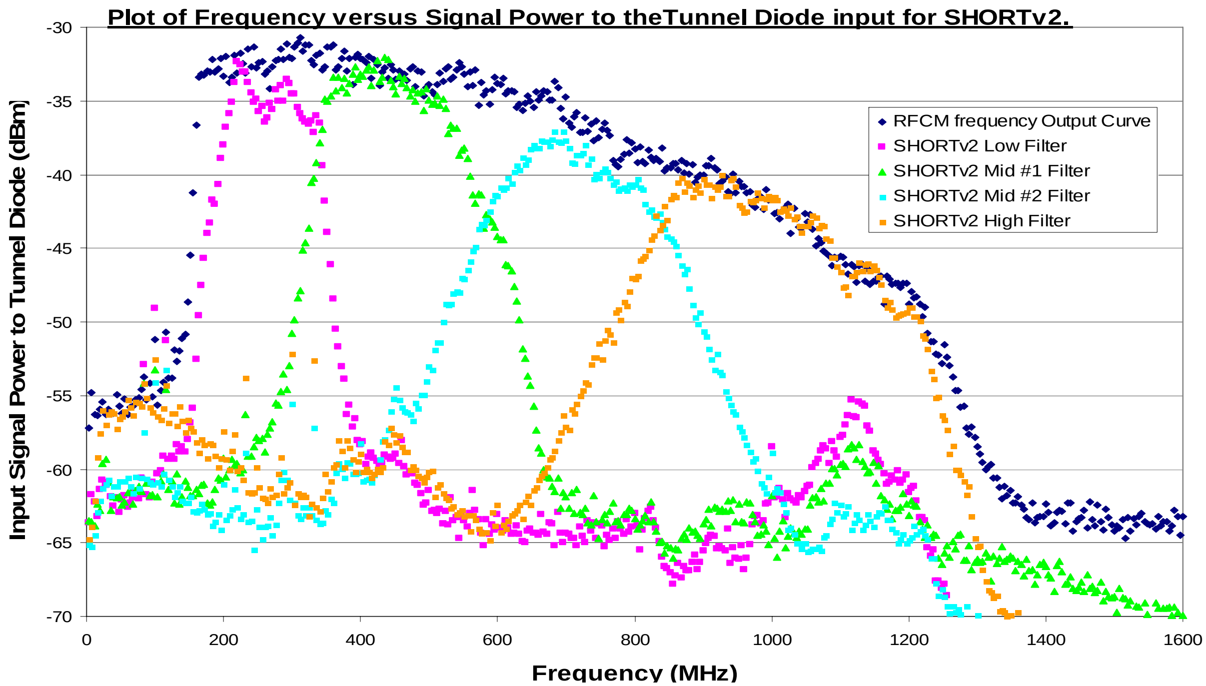
Strategy: Divide and Conquer



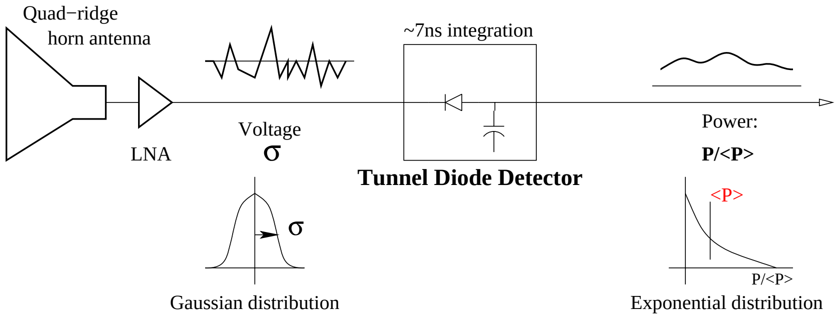
- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

ANITA Level 1 – 3 of 8 Antenna

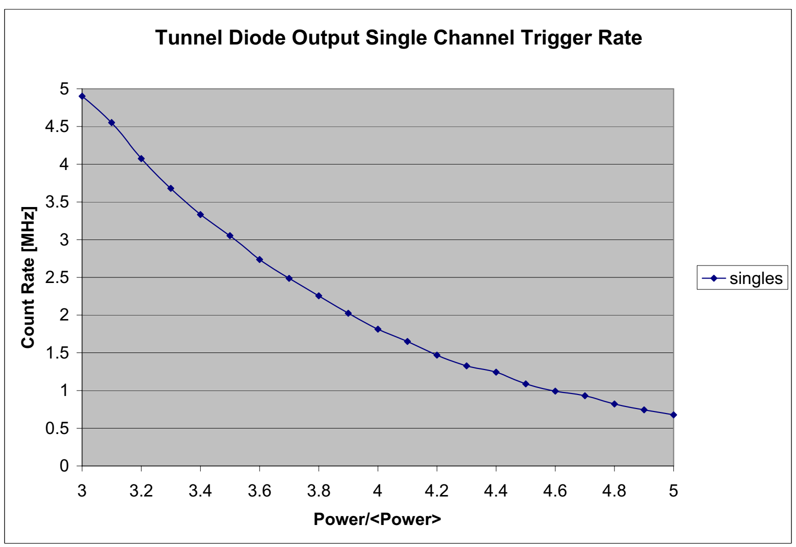


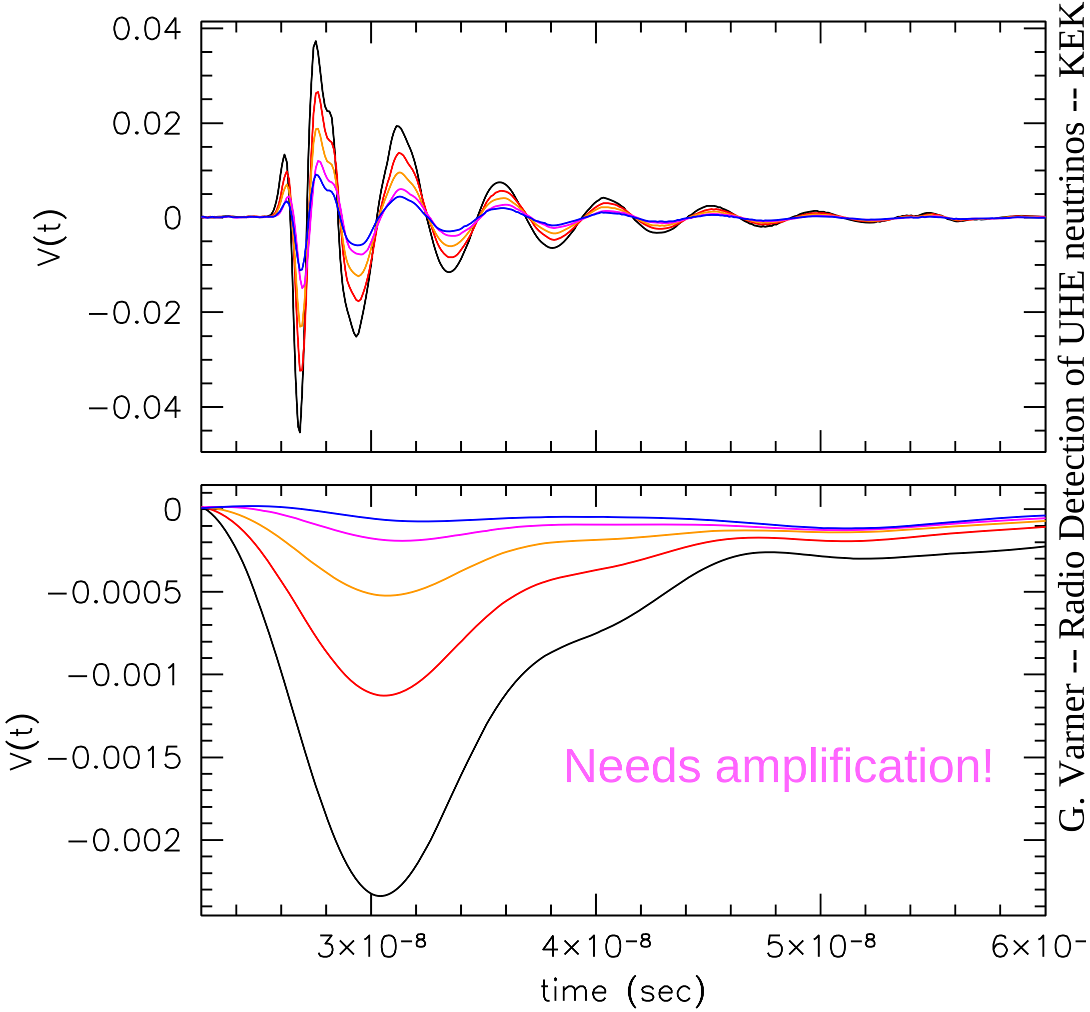


Diode detector Response

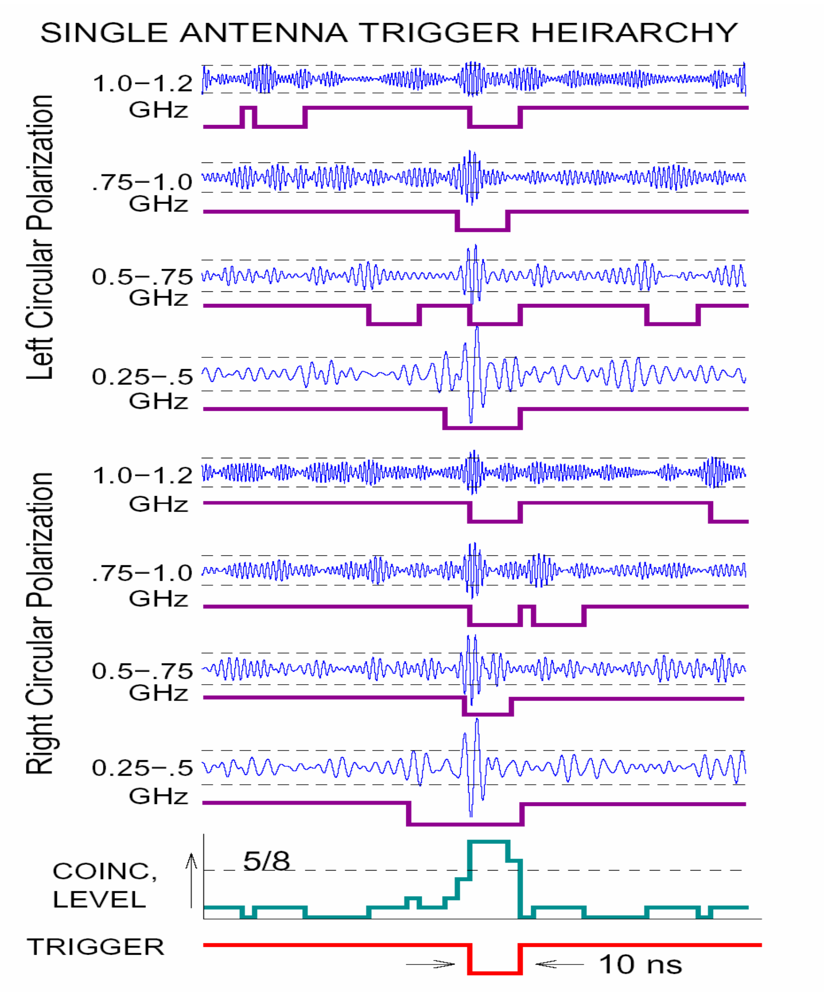


2.3σ ~= 3.9 P/<P>



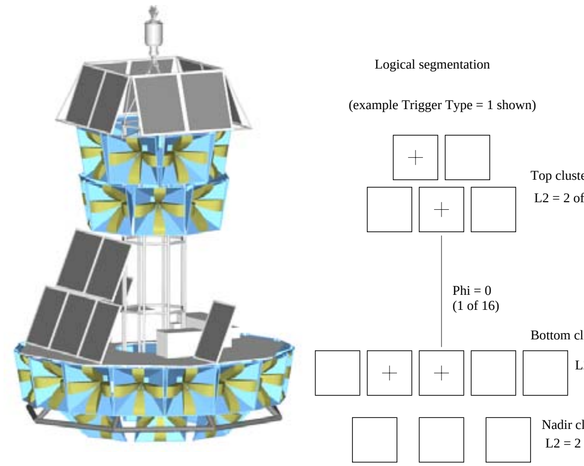


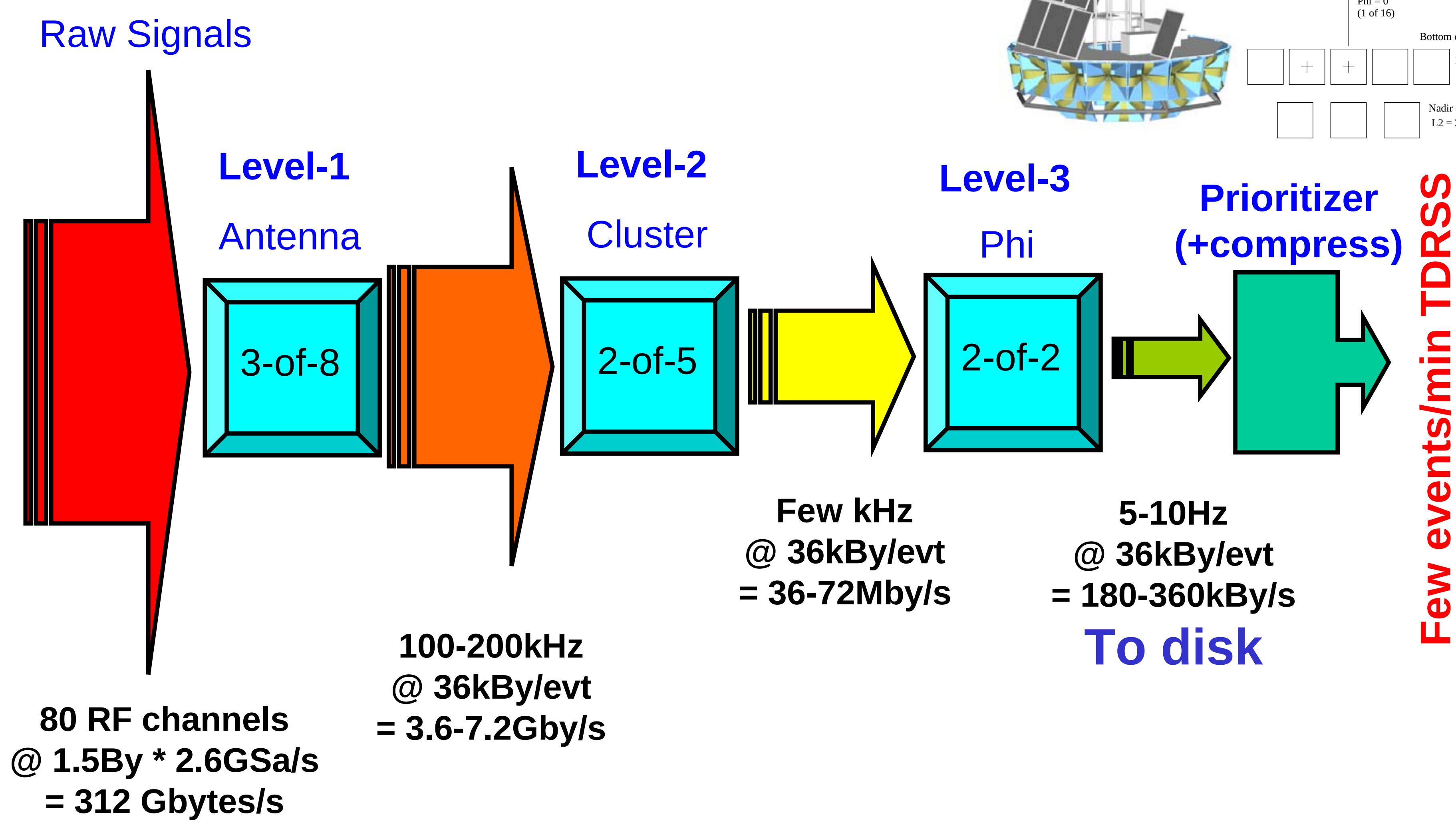
ANITA local trigger



- Multi-band triggering essential to ANITA sensitivity
- Methods proven by FORTE, GLUE experiments
- Exploits statistical properties of thermal noise vs. linear polarization for signal
- Signal: most or all bands;
- noise: random
- all 8 shown here -- 3 of 8 is found to be enough

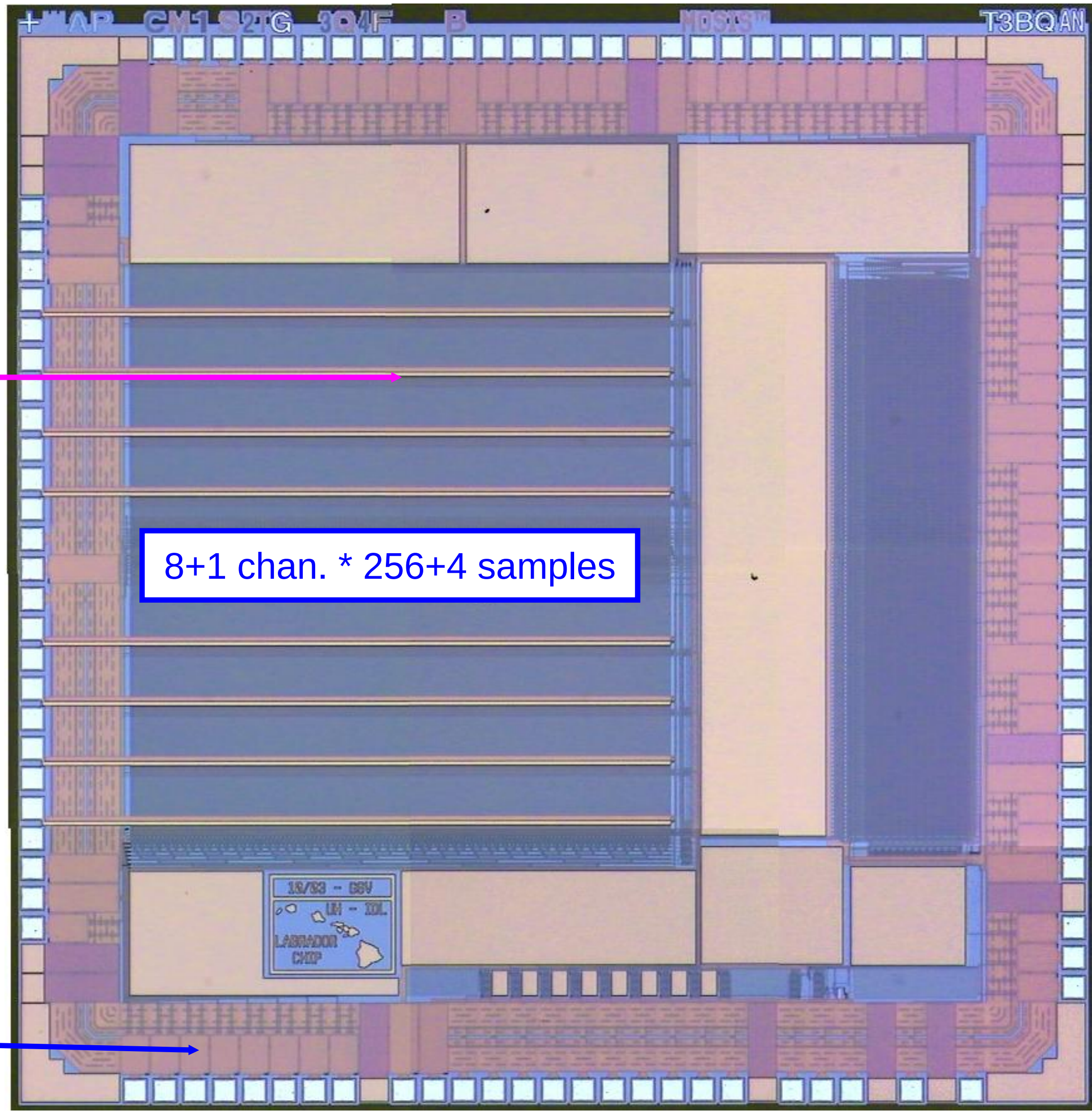
Trigger Reduction





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

Straight
Shot
RF inputs



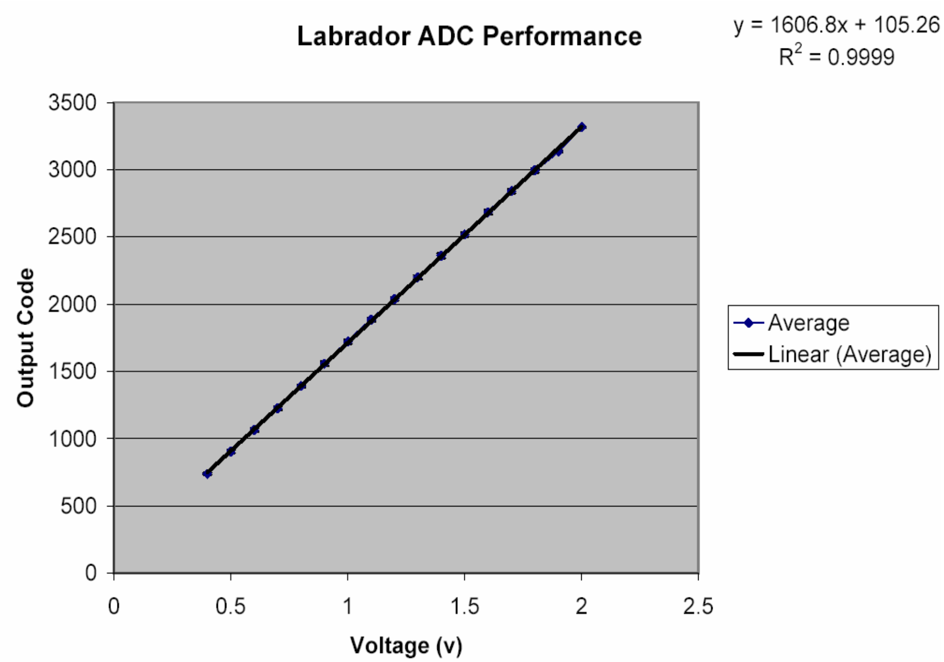
- Switched Capacitor Array (SCA)
- Massively parallel Wilkinson ADC array

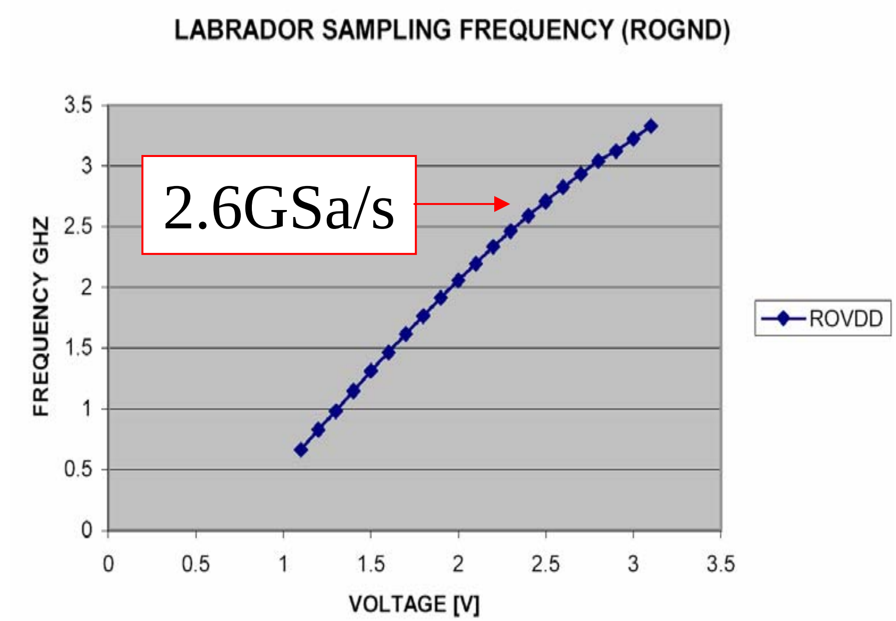
Random access:

- 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

LABRADOR sampling & linearity

12-bit ADC

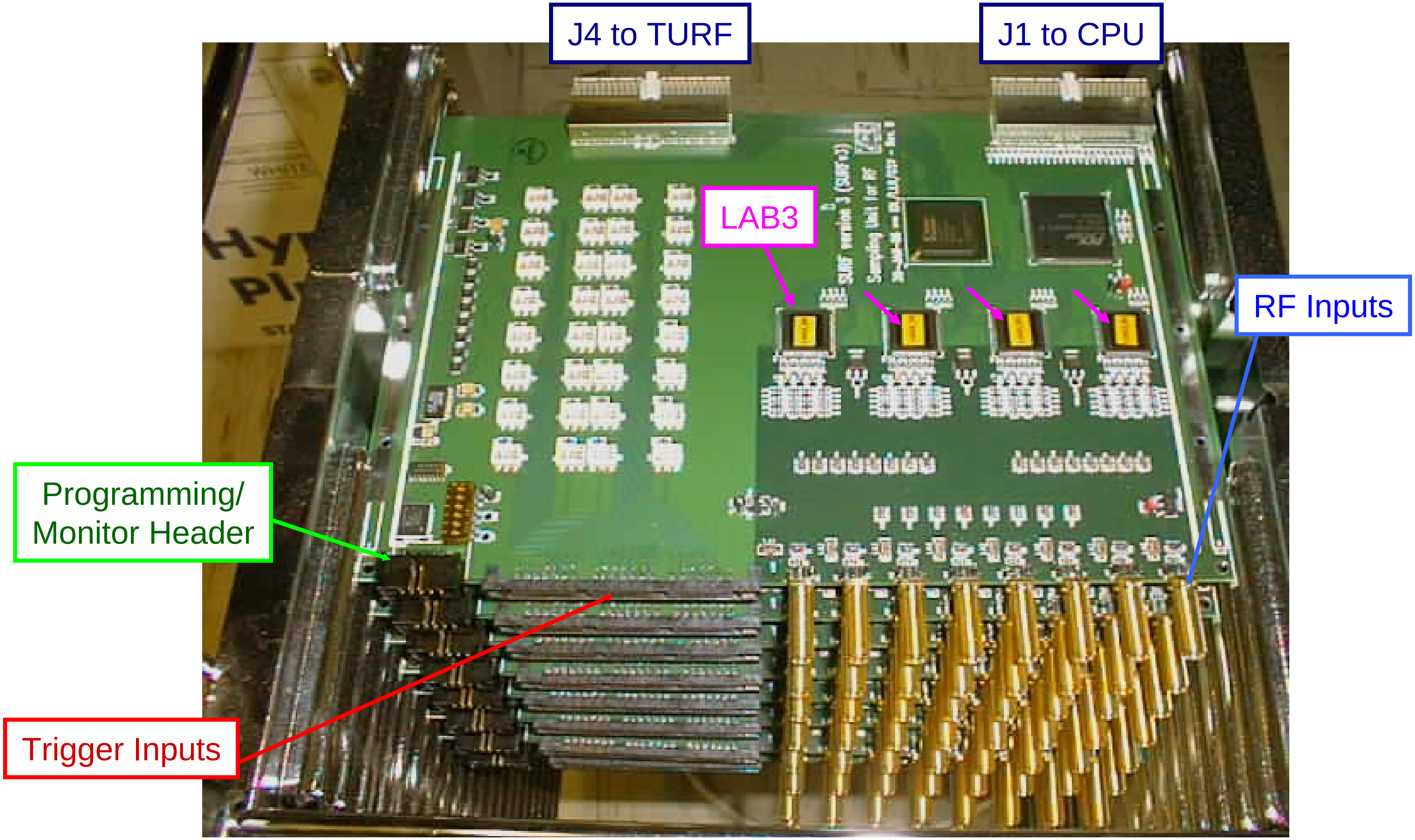




- Excellent linearity
- Sampling rates up to 4 GSa/s with voltage overdrive

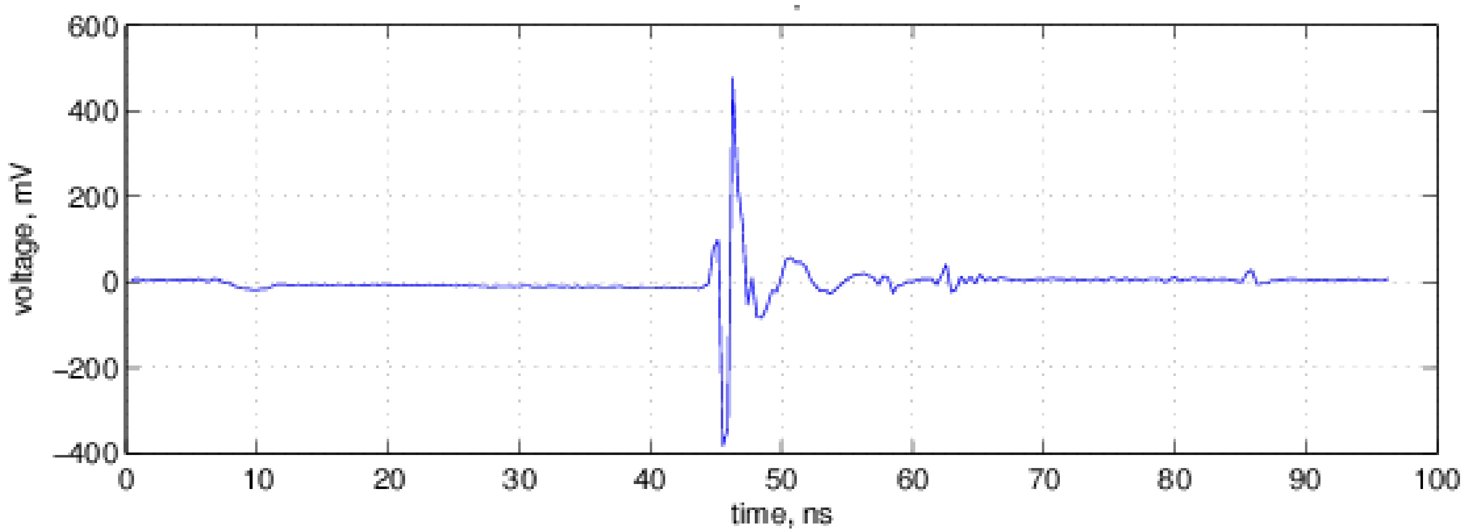
SURFv3 Board

(SURF = Sampling Unit for RF)
(TURF = Trigger Unit for RF)

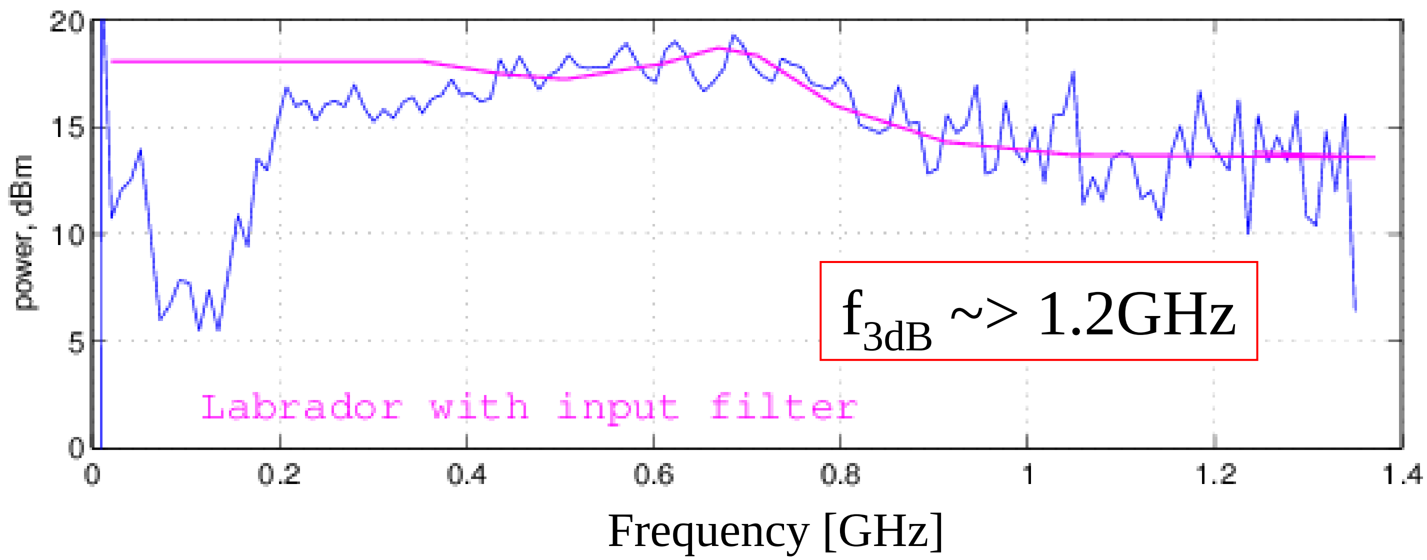


Bandwidth Evaluation

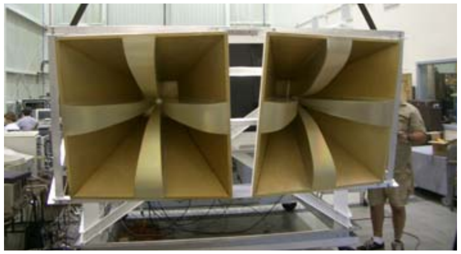
Transient Impulse

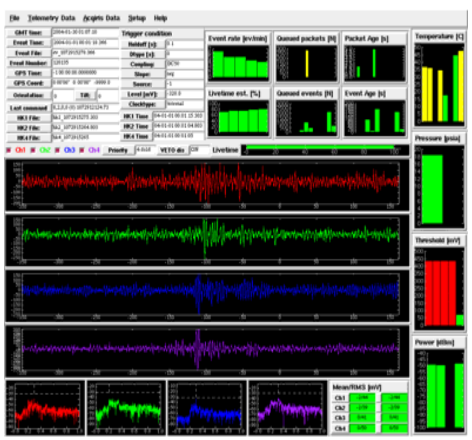


FFT Difference



ANITA-lite Prototype flight 2004





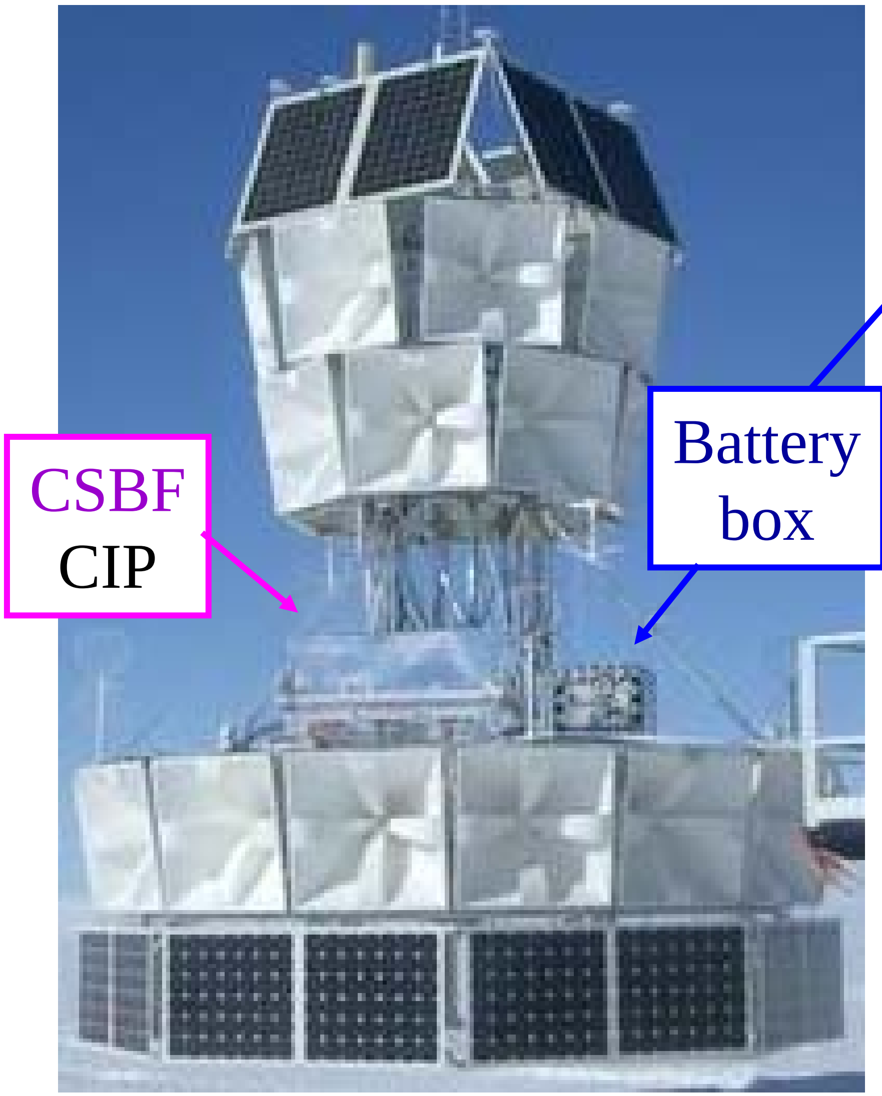
- Piggyback Mission of Opportunity on the 03-04 TIGER* flight, completed mid-January 04
- EMI Survey of Antarctic continent
  - 2 dual-pol. ANITA antennas w/ low-noise amps
  - 4 channels at 1 GHz RF bandwidth, 2 GHz sampling
- 18.4 days flight time, set the best current limits on UHE neutrino fluxes
- Paved the way for a full-scale ANITA payload

*Trans-Iron Galactic Element Recorder

ANITA Payload Assembly

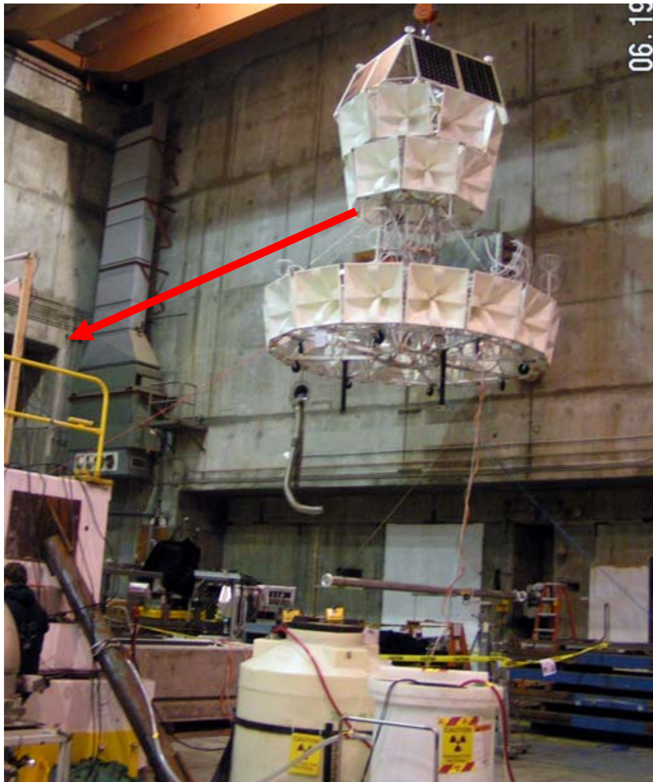
- (Engineering payload)

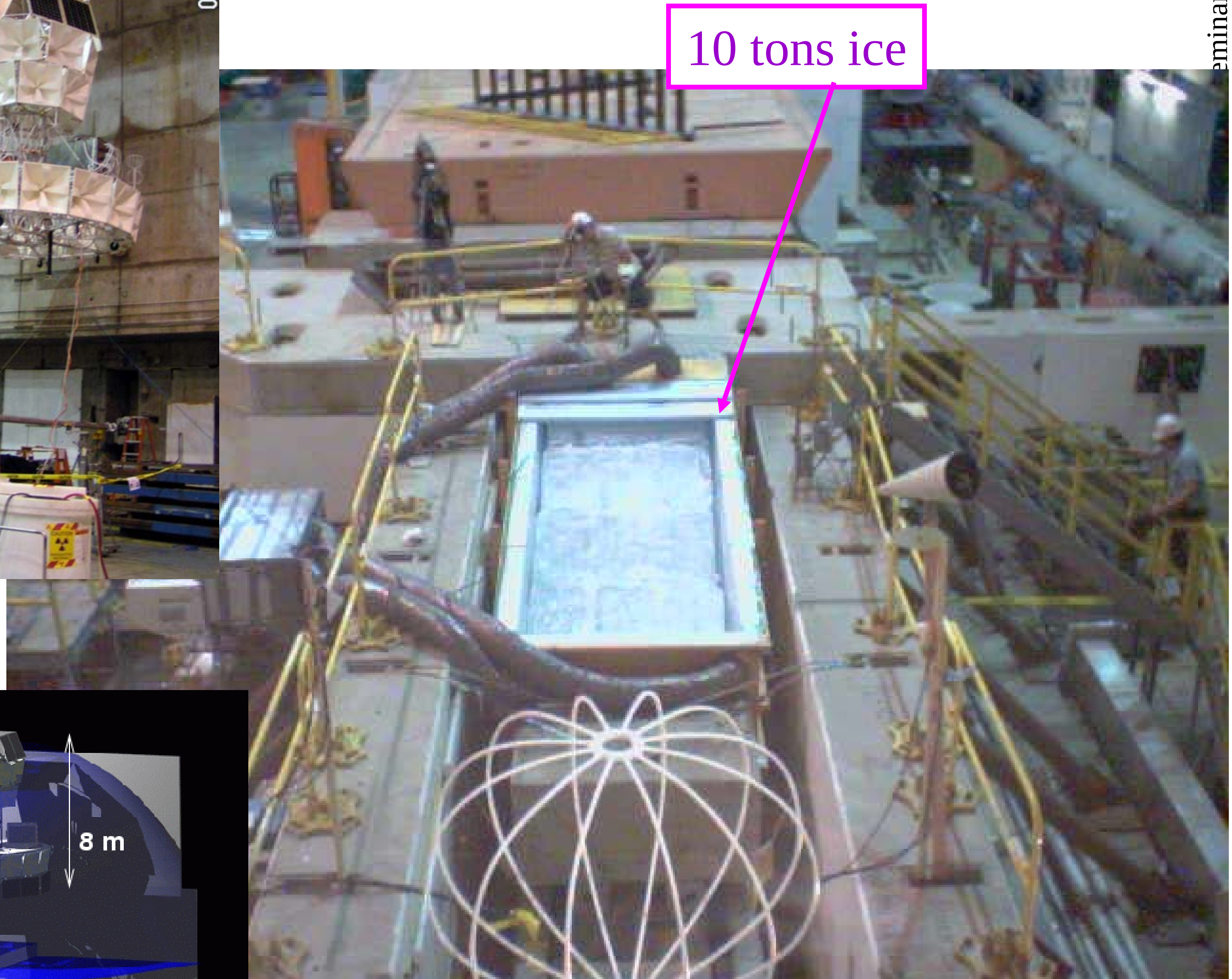
Key Instrument pieces

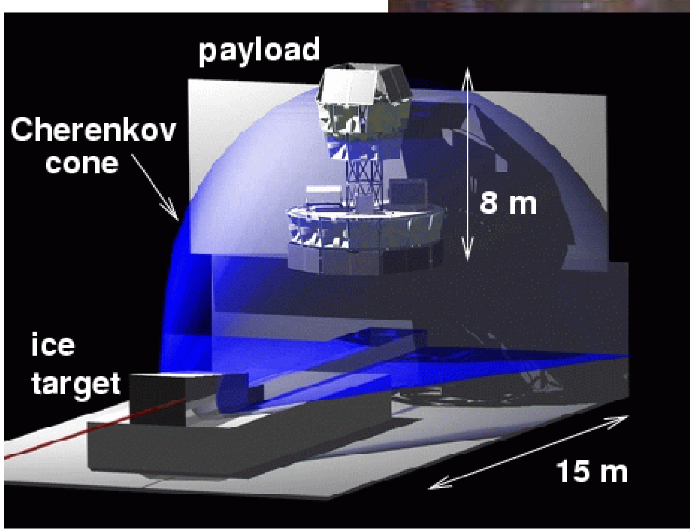


T-486 [Ice!] ANITA on the End Station A beamline (June 2006)

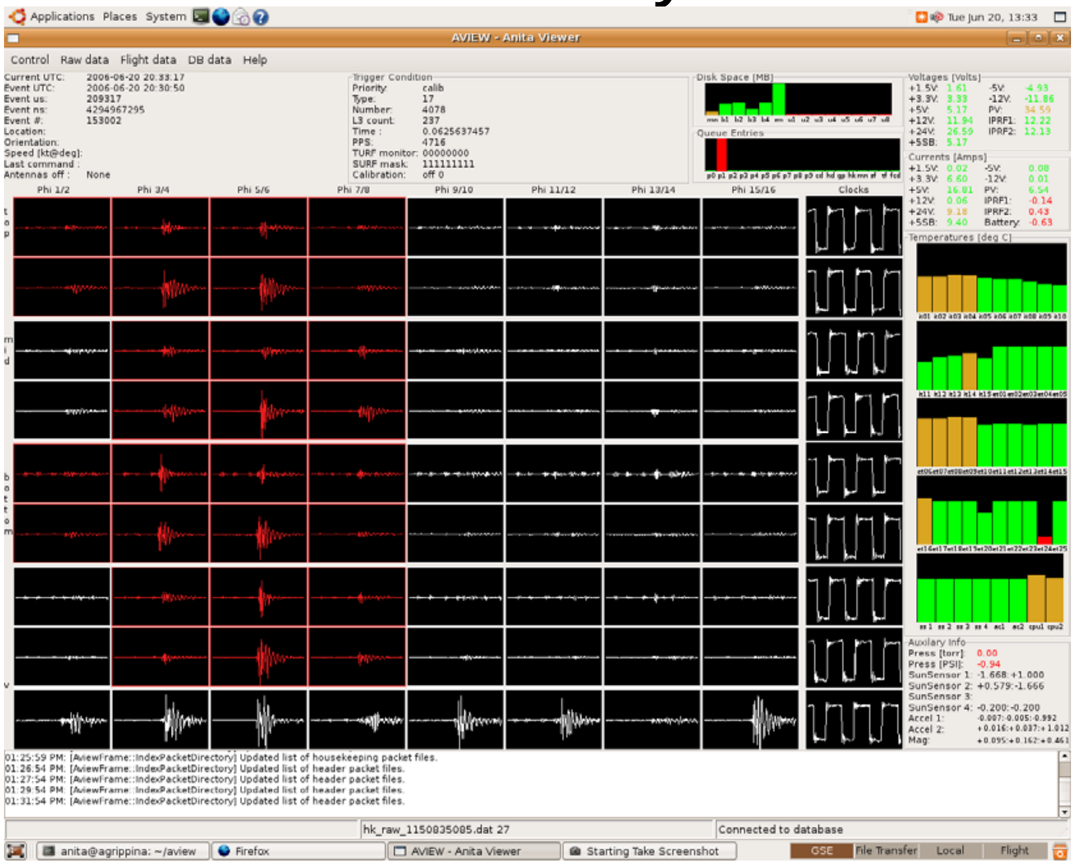
- 32 QR horns
- 4 discones
- 4 bicones
- 8 monitor antennas
- 72 (288) channels RF digitizer & 256 channels trigger (self-triggered)
- Ethernet/LOS Tx only

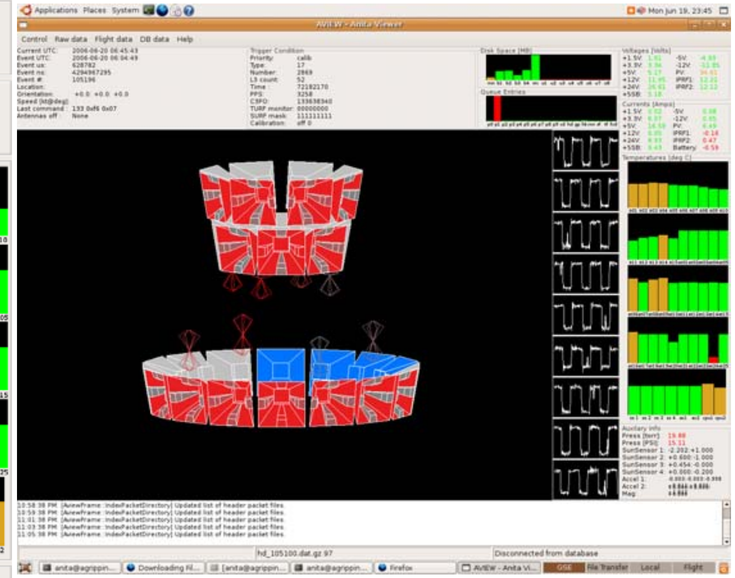


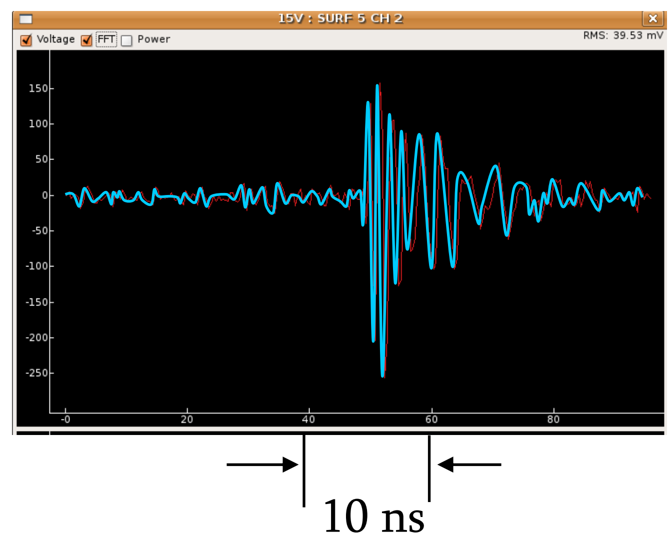

10 tons ice


payload
Cherenkov cone
8 m
ice target
15 m

Askaryan effect in ice





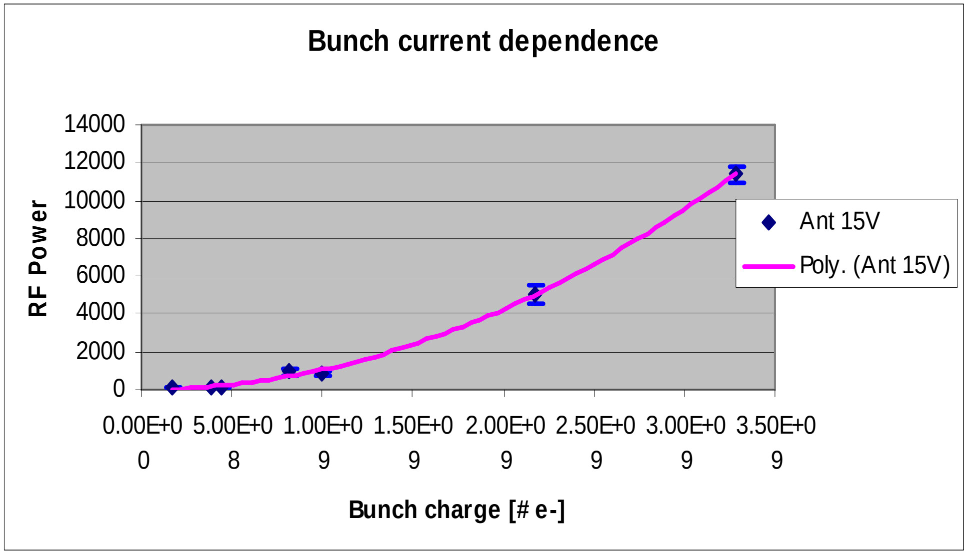


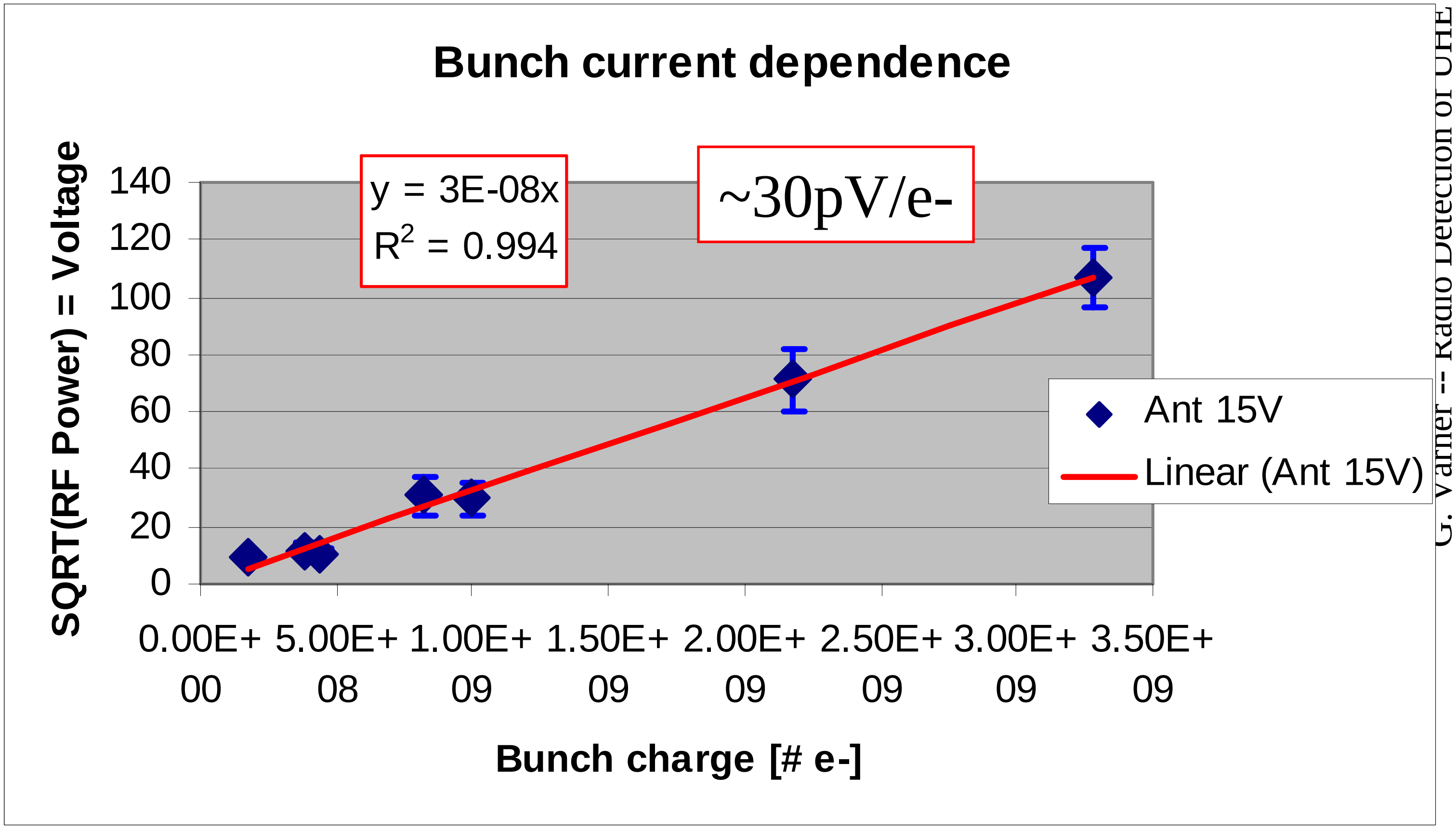
- **Impulses are band-limited, highly polarized, as expected**
- **Very strong--need 20dB 'pads' on inputs--signals are +95dB compared to Antarctic neutrino signals, since we are much closer**

Askaryan Coherence

$P \sim E^2$

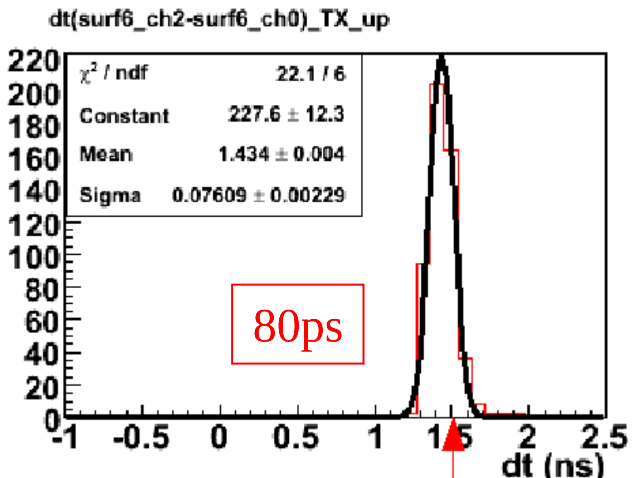
$E = 20GeV\ e- * bunch\ q$



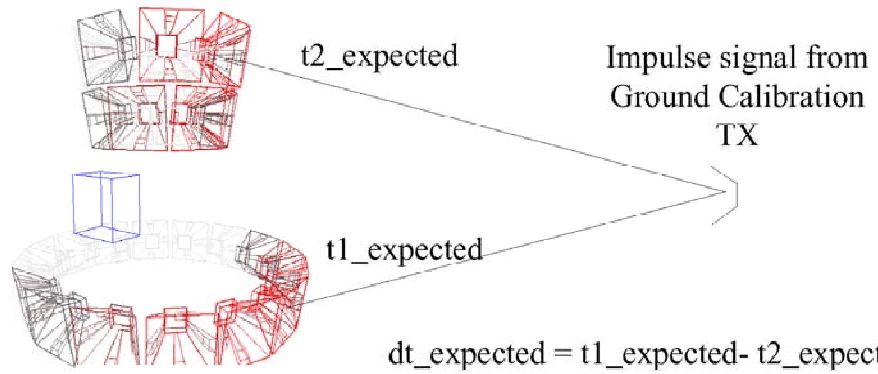


Timing vs Angle (with Impulse Calibration Radio Signal)

TX Up
by 1.56 m



expected time delay

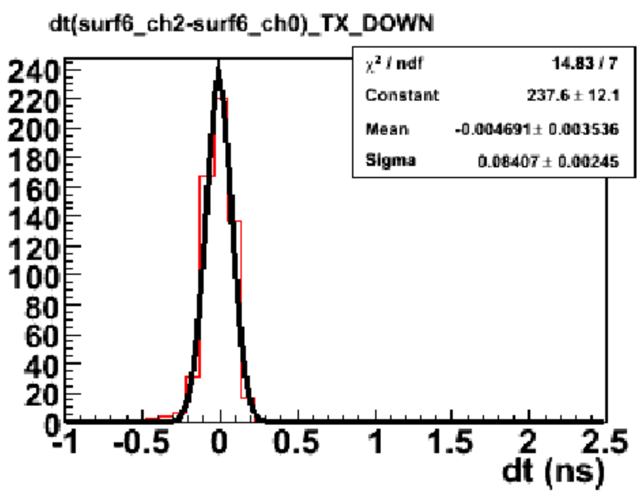


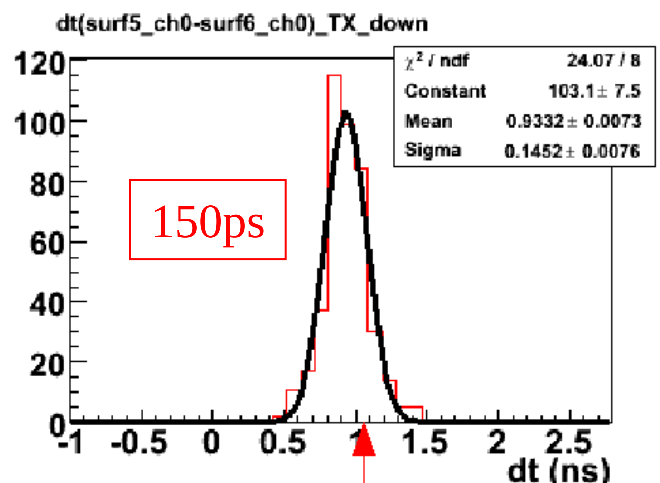
dt_expected = t1_expected- t2_expected

dt = dt_observation - dt_expected

Vertical Angle
Dependency

TX Down



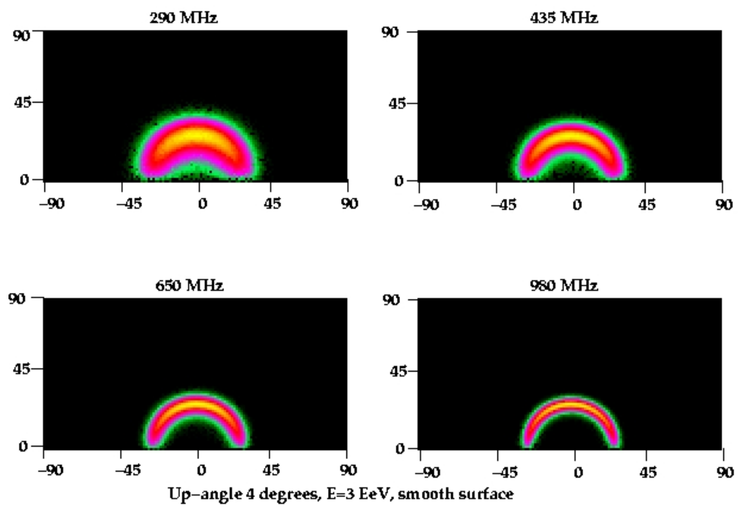


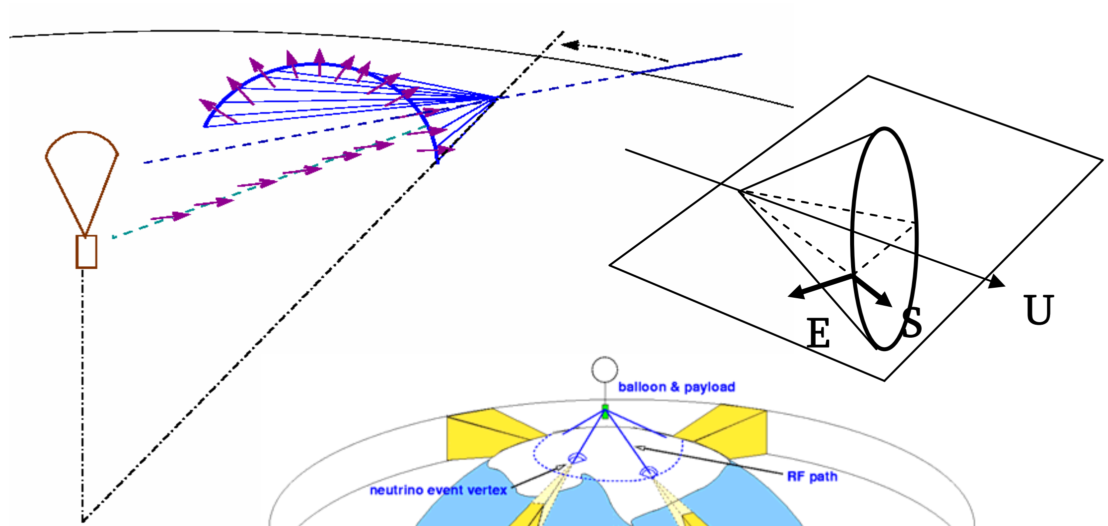
expected time delay

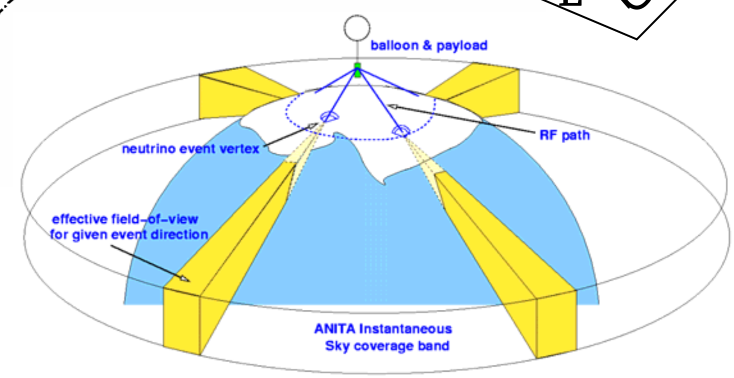
Jiwoo Nam
UC Irvine

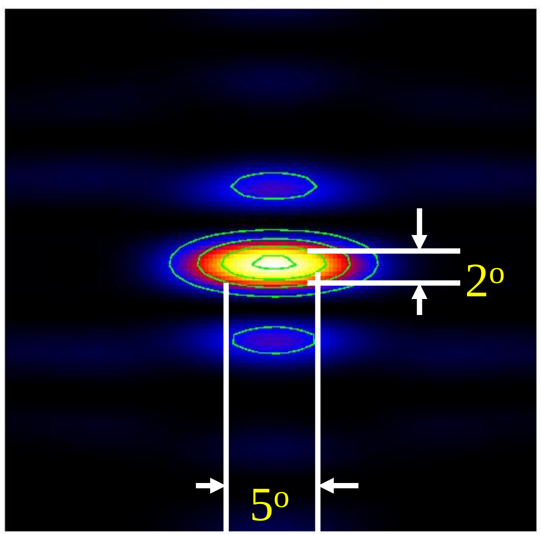
Face to TX ← Horizontal Angle Dependency → Off by 1 Antenna

ANITA as a neutrino telescope



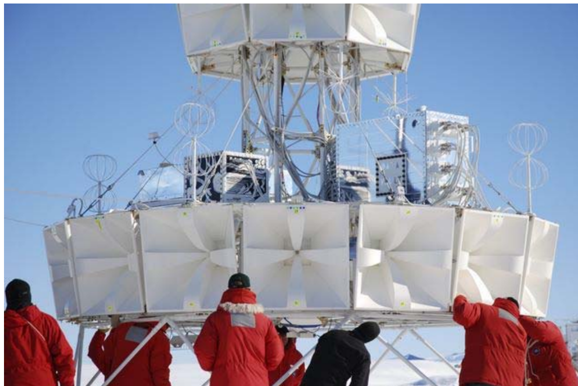






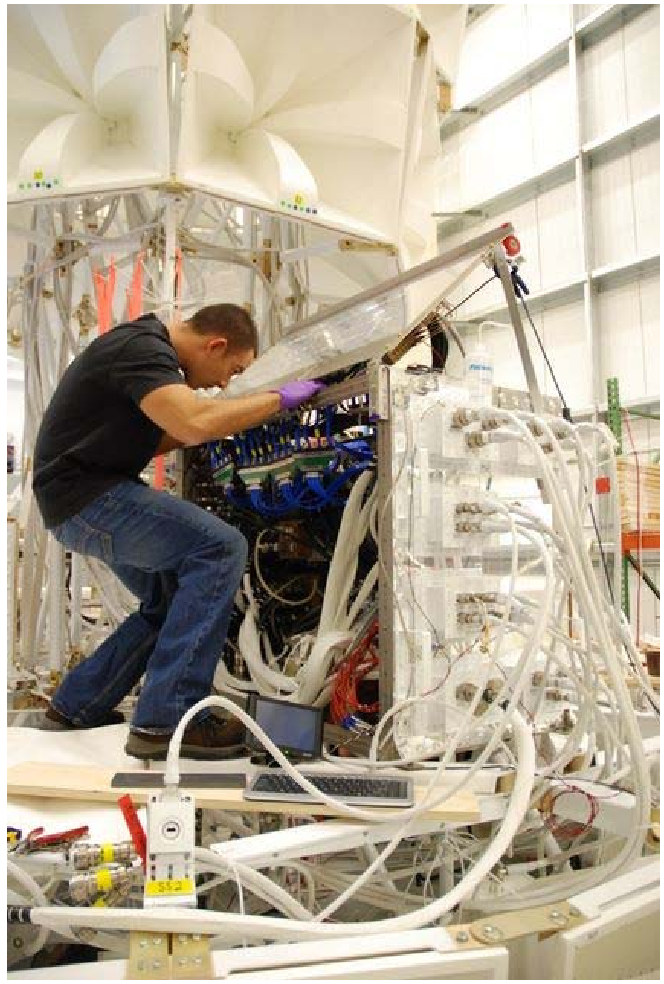
- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

Nov. 2006, Antarctica: Putting it together

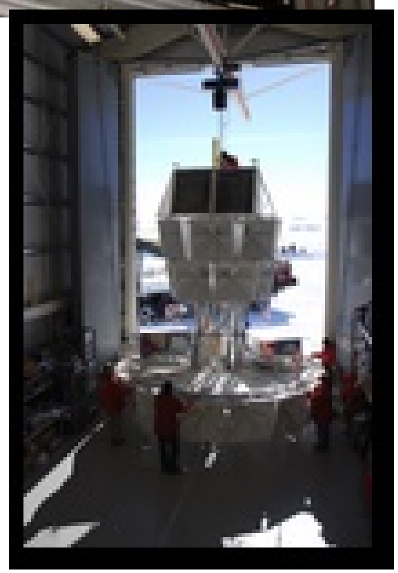


- The Long Duration Balloon Base at Williams field
  - ~7 miles out on Ross Ice shelf, smooth, flat ice, 80m deep
- a first-class field operation, run by NASA's Columbia Scientific Balloon Facility (Palestine Texas)

Life in Payload Bay 1



- Barely fit out door
- Room dropped 45C in 30 s
- 4-5 hours to recharge
- Go outside to warm up



ANITA "hangtest," Sunday 12/3/06

- Final pre-flight checkout
- Payload is ready for launch
- 3 Payloads in queue (BLAST, BSI)

- Few hundred Giga-bytes of Redundant Storage
  - Solid-state drives
  - External USB drives
  - Large HD (pressurized)
- 2x GPS (+1 CSBF)
- Diff. GPS, magnetometer and sunsensors
- TDRSS, Iridium phone (via NASA CIP)

Launch: December 15, 2007
(after almost 2 agonizing weeks of waiting)

- A flawless launch
  - CSBF truly professional
  - After day after day after day of false starts, we were really ready to go

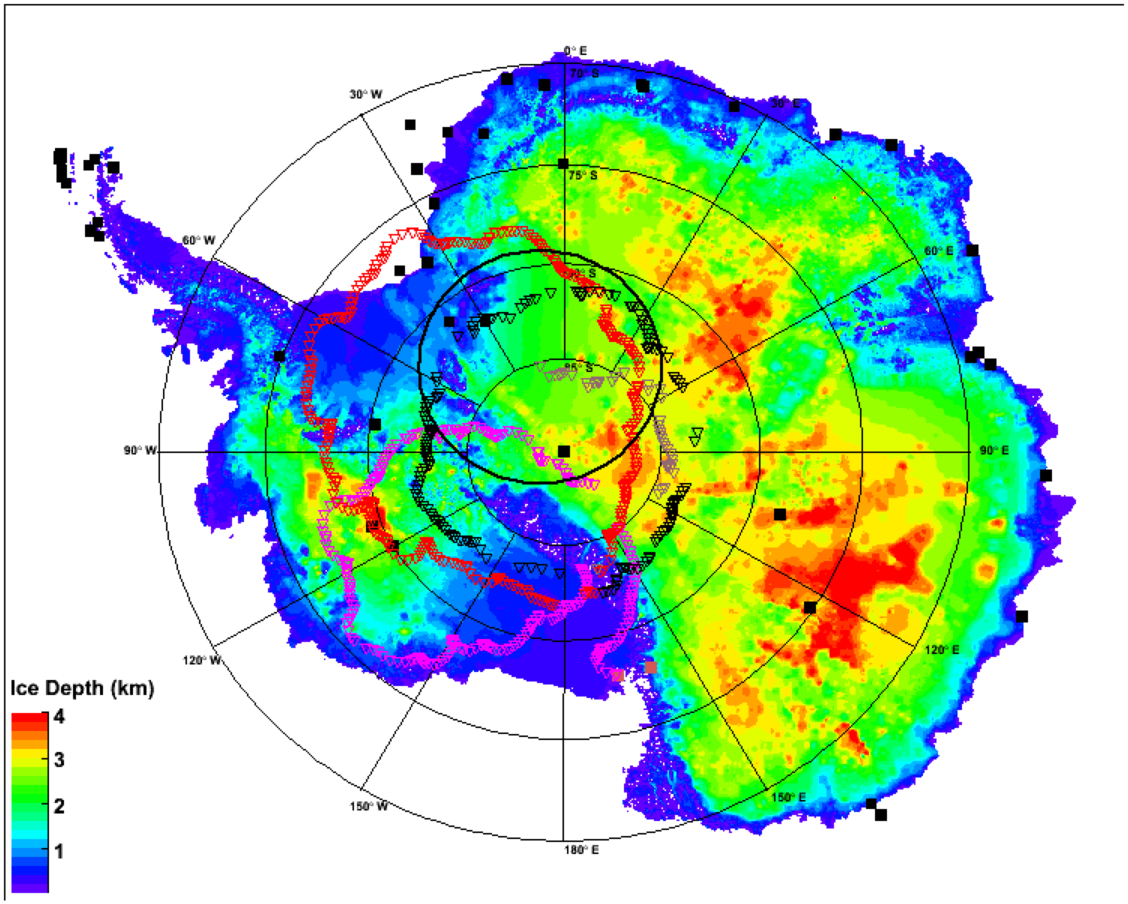
Visiting South Pole Station

- ANITA at float (123Kft)
  - Seen through amateur telescope from the South Pole
  - Size of the Rose Bowl!
  - (thanks to James Roth)

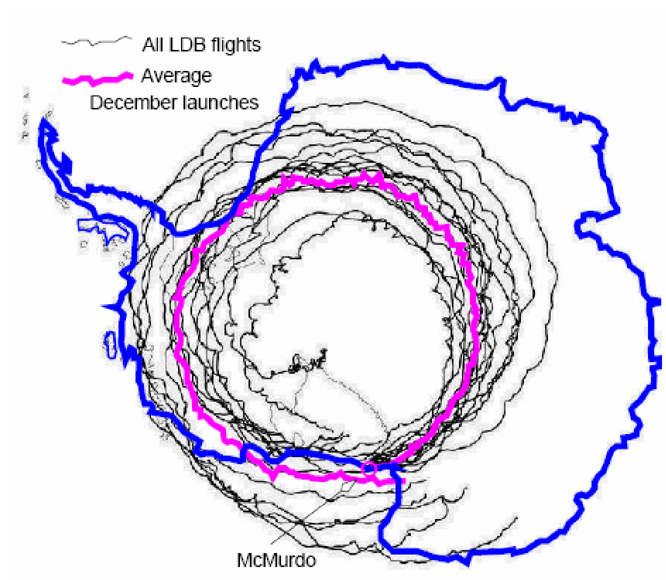
After 35 days landing…~360 miles from S.Pole

- Ouch!
- What a drag…
- But instrument & data OK

ANITA flight path

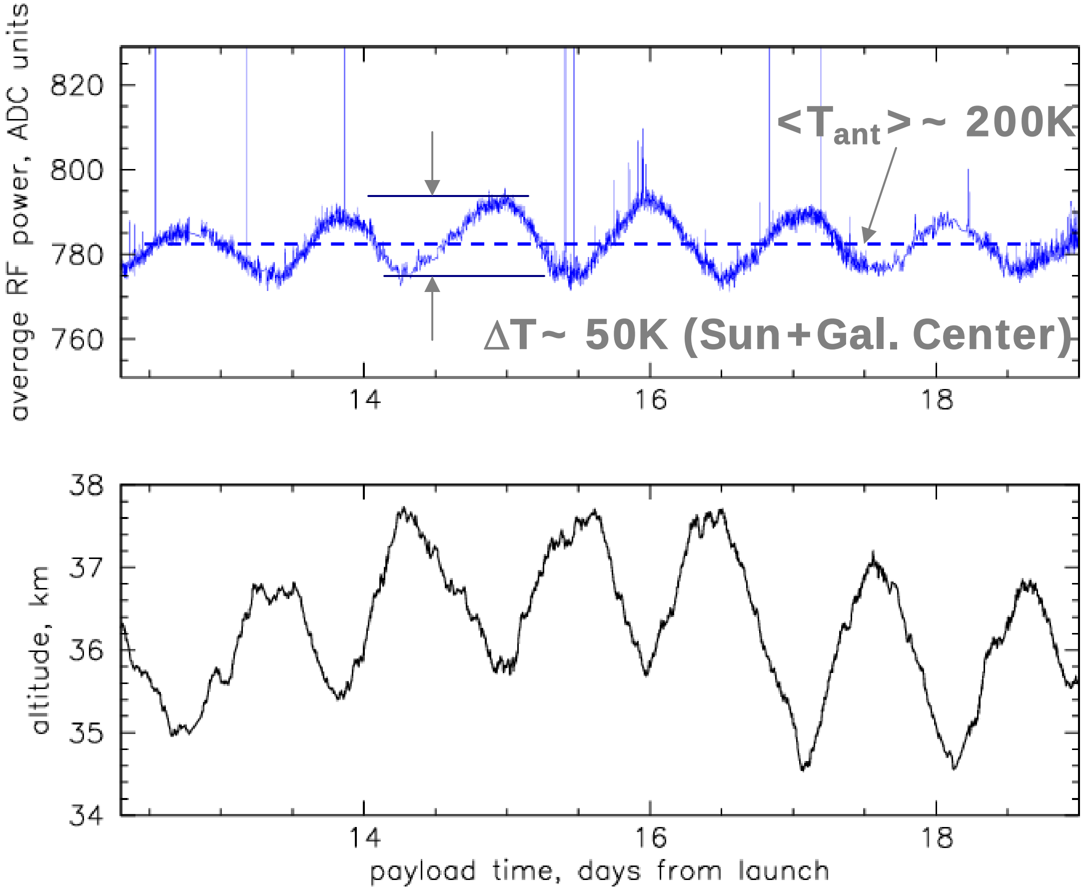


- 35 days, 3.5 orbits
- Anomalous Polar Vortex conditions
- Stayed much further "west" than average
- In view of stations (Pole & MCM) ~30% of time



About 8.2M Triggered Events logged

Flight sensitivity snapshot (preliminary)



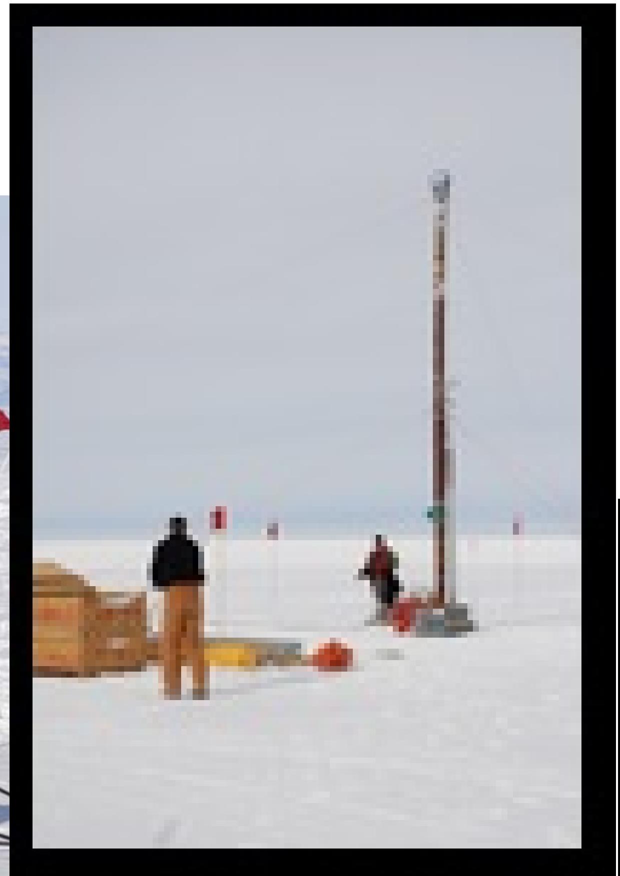
- ANITA sensitivity floor defined by thermal (kT) noise from ice + sky
- Thermal noise floor seen throughout most of flight—but punctuated by station & satellite noise
- Significant fraction (>40%) of time with pristine conditions

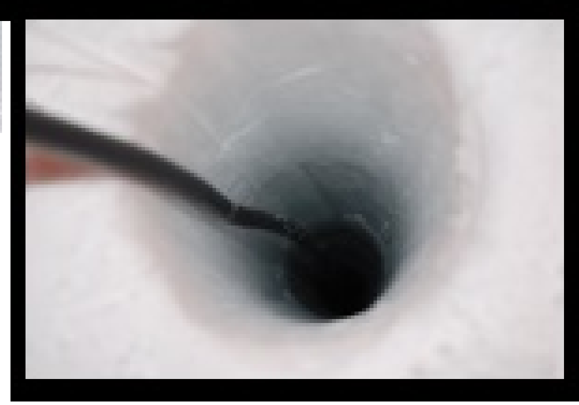
•T anti-correlated to altitude:
- higher altitude at higher sun angle
- sun+GC higher ➔ farther off main antenna beam

Quiet, but are we sensitive?

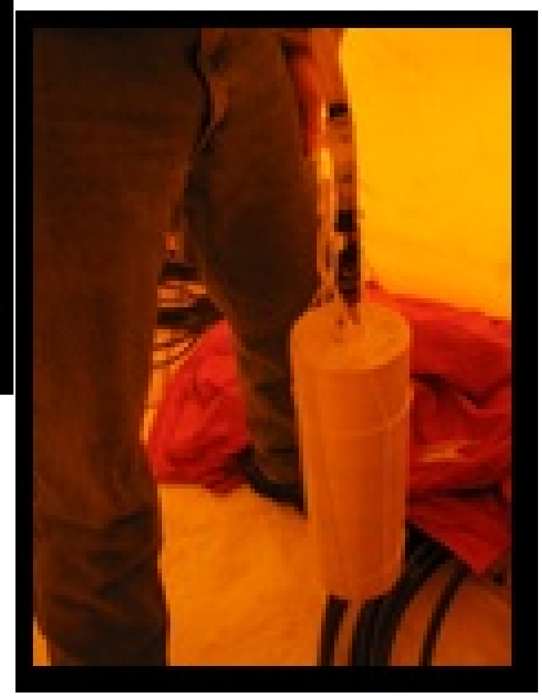
Ground pulser

- Ice 80m thick and messy



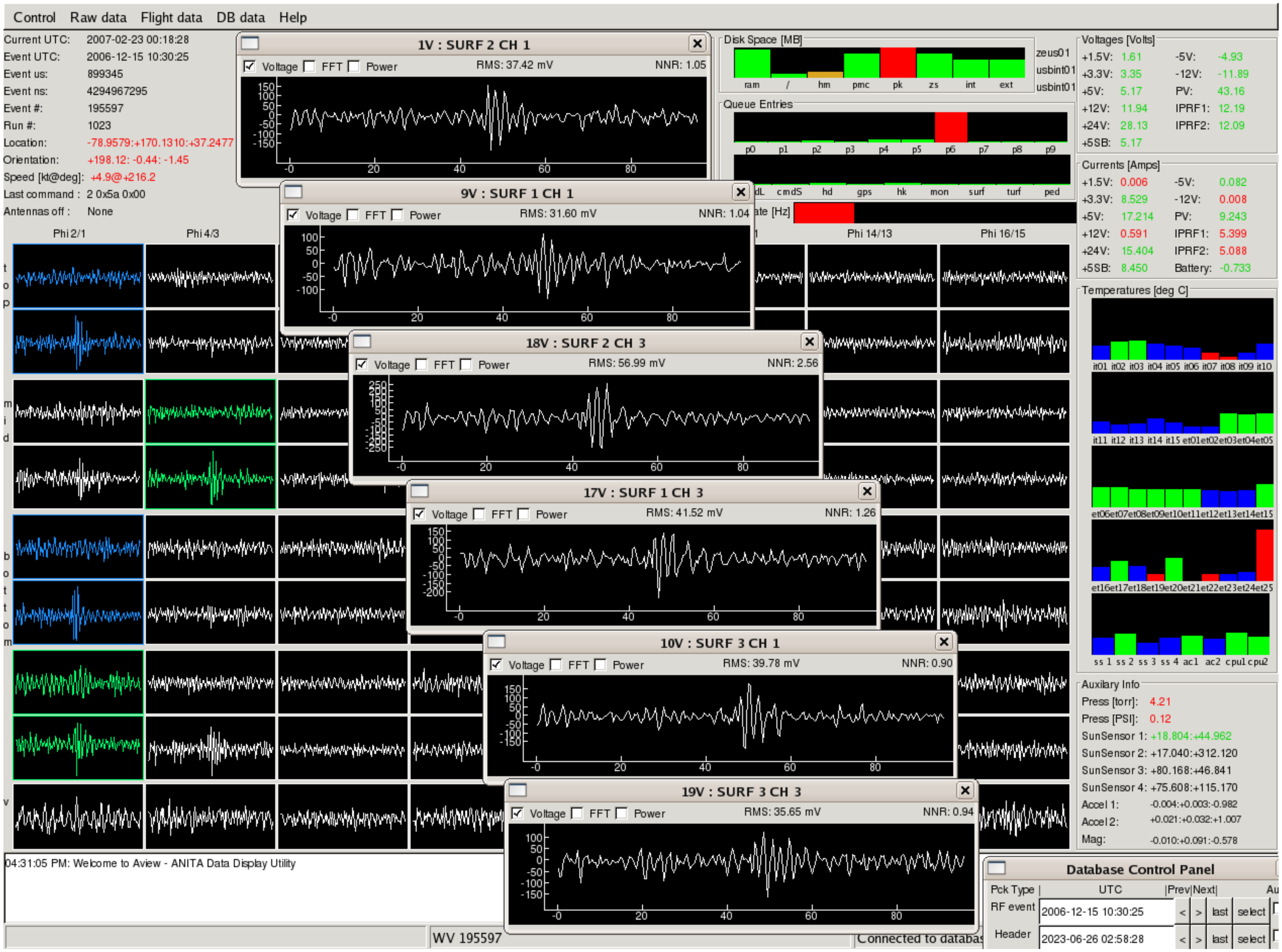


Bore hole pulser



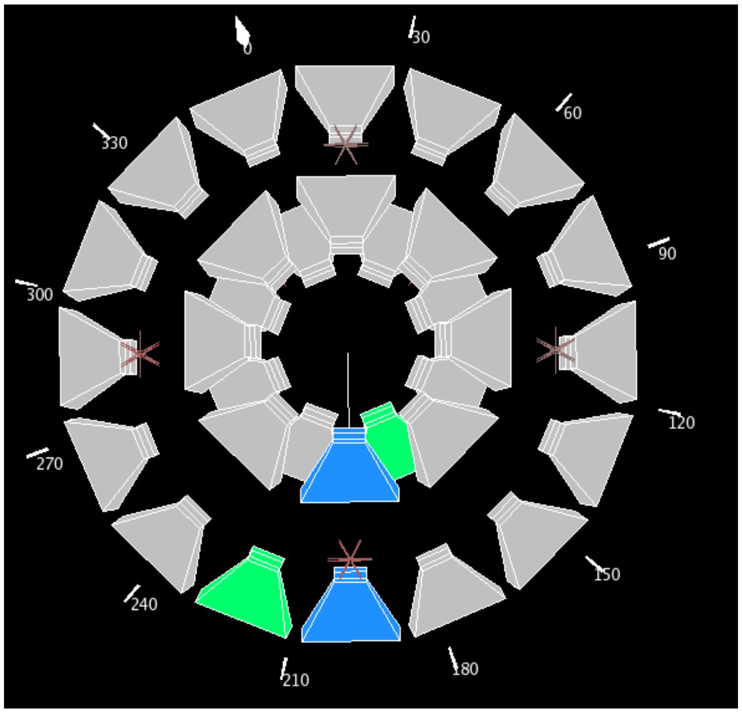
Dipole

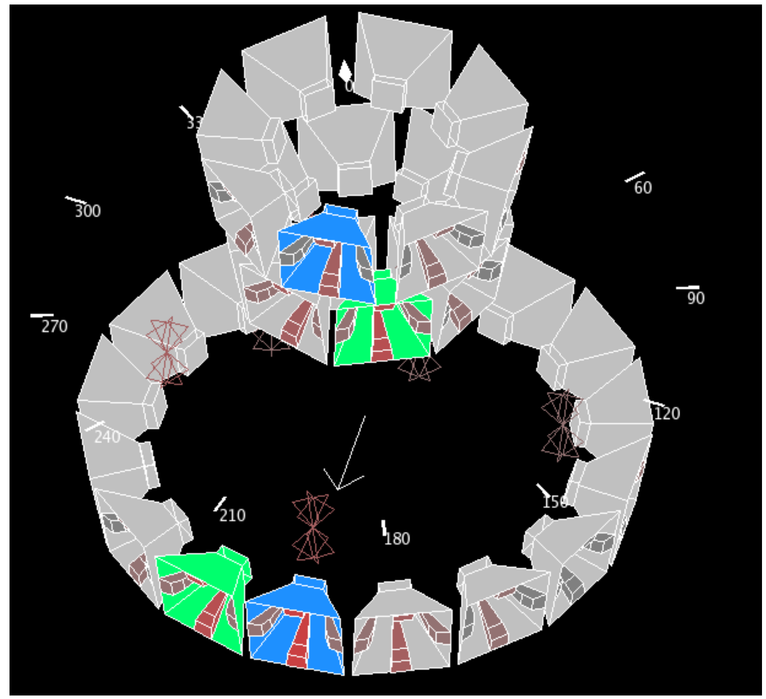
Validation data: borehole pulser



- RF Impulses from borehole antenna at Williams field
- Detected at payload out to 300-400 km, consistent with expected sensitivity
- Will allow trigger & pointing calibration

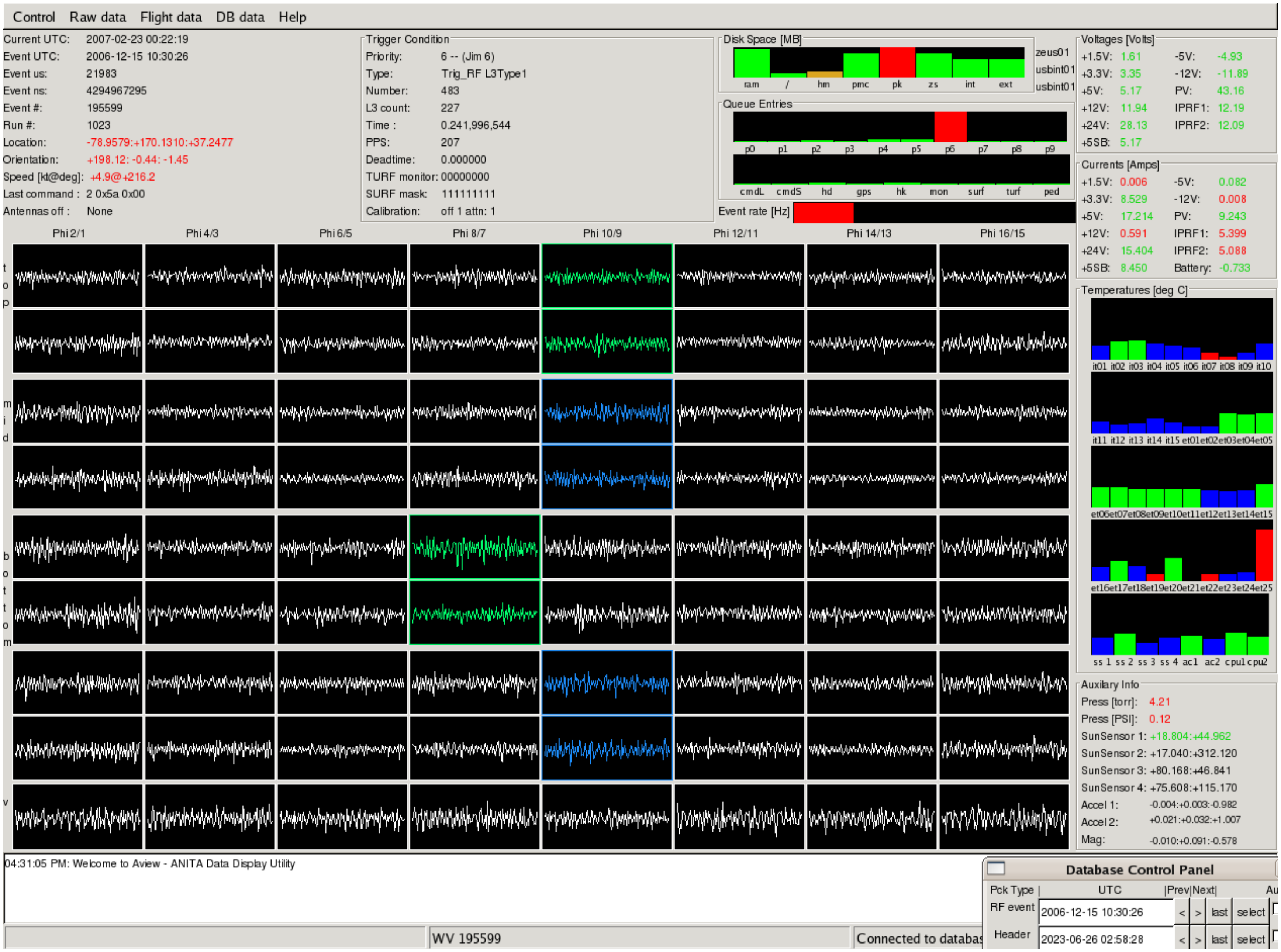
Trigger pattern, borehole pulser



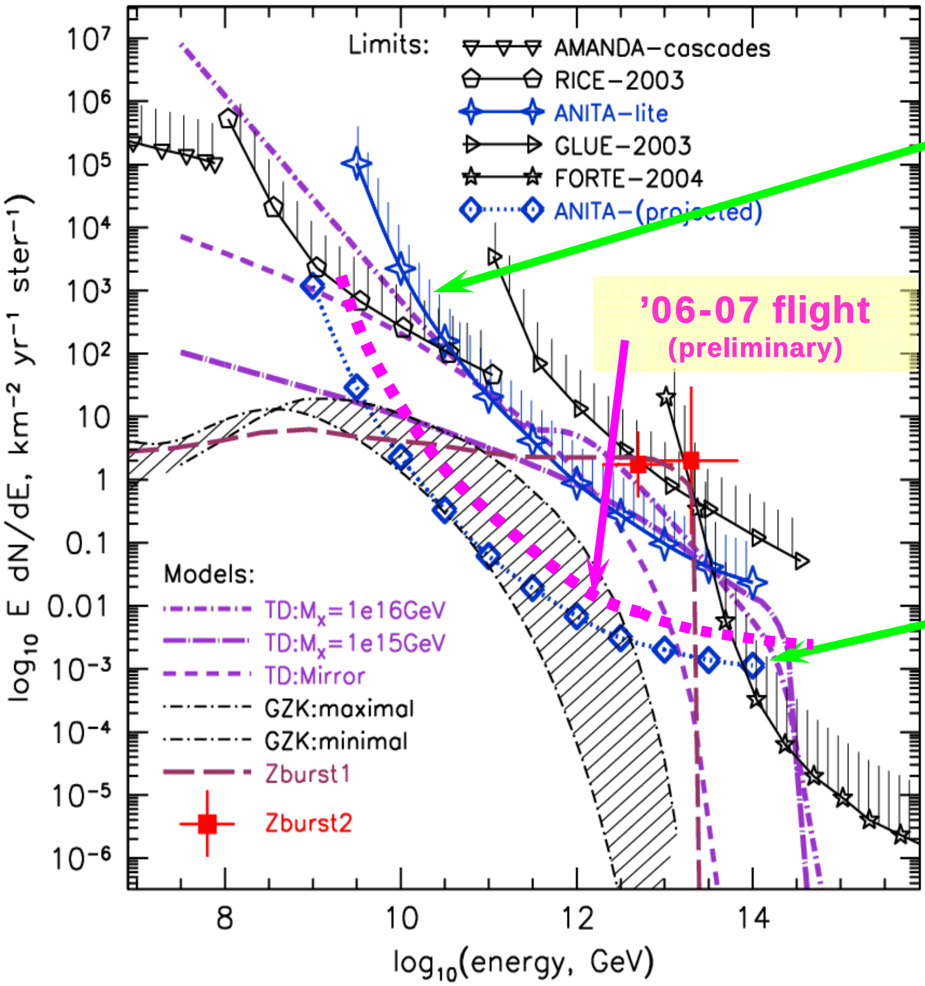


- Trigger pattern requires L2 from 2-of-3 L1 (3-of-8) in both upper and lower 16-antenna rings for same phi sector
- Negligible accidentals, but ~4-5Hz from thermal noise
  - But Thermal noise is incoherent in spatial & temporal character

99.99+% of triggers: incoherent thermal noise



ANITA's potential science impact



Strongest limits: all radio

- **ANITA-lite**: 18.4 days of data, net 40% livetime with 60% analysis efficiency for detection
  - Z-burst UHECR model ($\nu\nu$ annihilation -->hadrons) excluded:
    - expect 6-50 events, see none
  - Highest Toplogical defect models also excluded
- **ANITA projected sensitivity (3 flights):**
  - ν_e ν_μ ν_τ included, full-mixing assumed
  - 45 days exposure at 67% efficiency assumed
  - We are roughly within a factor of 2 with 1st flight

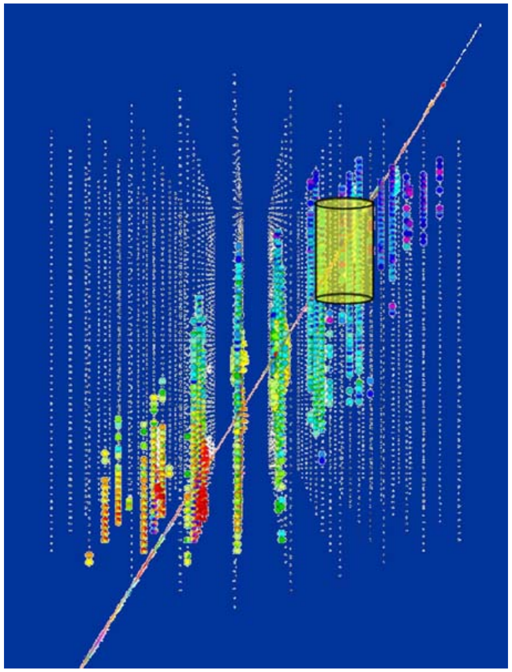
ANITA Plans

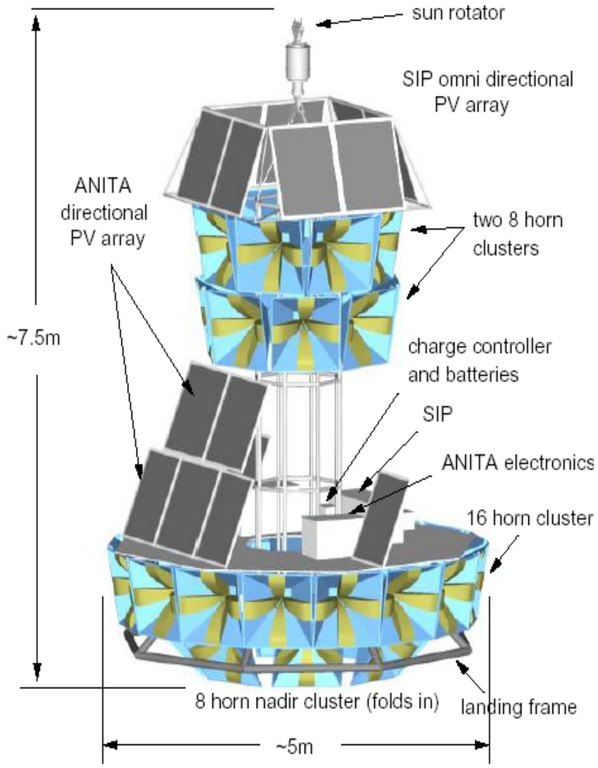
- ANITA may have first glimpse of the ultra-high energy neutrino universe already on disk
  - Data disks returned from Antarctica a couple of weeks ago
- Two independent blind analyses just getting started
  - Preliminary results by late summer?
- ANITA proposed to fly again in 2008

In Antarctica, everything has to be recycled!

A first peek over the next few years...

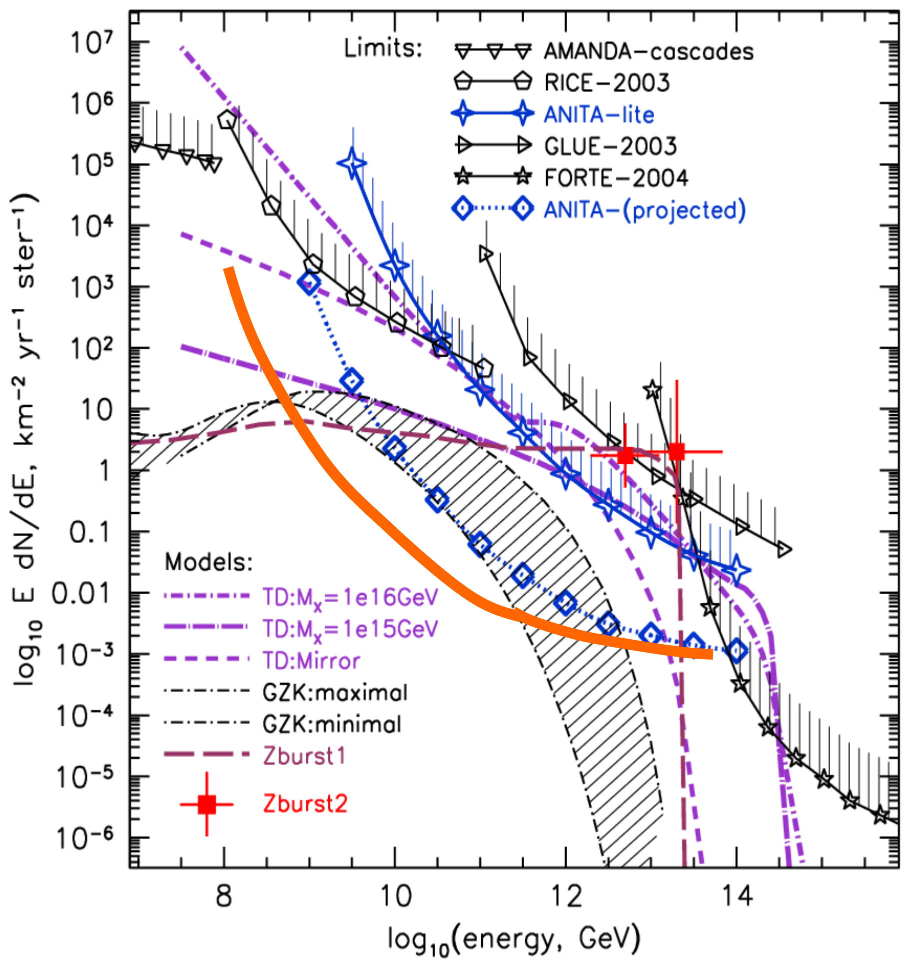
- <u>IceCube</u>
  - Discovery of bottom-up sources
  - Discovery of ~ 3 GZK neutrinos
- <u>ANITA:</u>
  Discovery of ~10 GZK neutrinos
- <u>Auger</u>
  - Discovery of a few GZK neutrinos





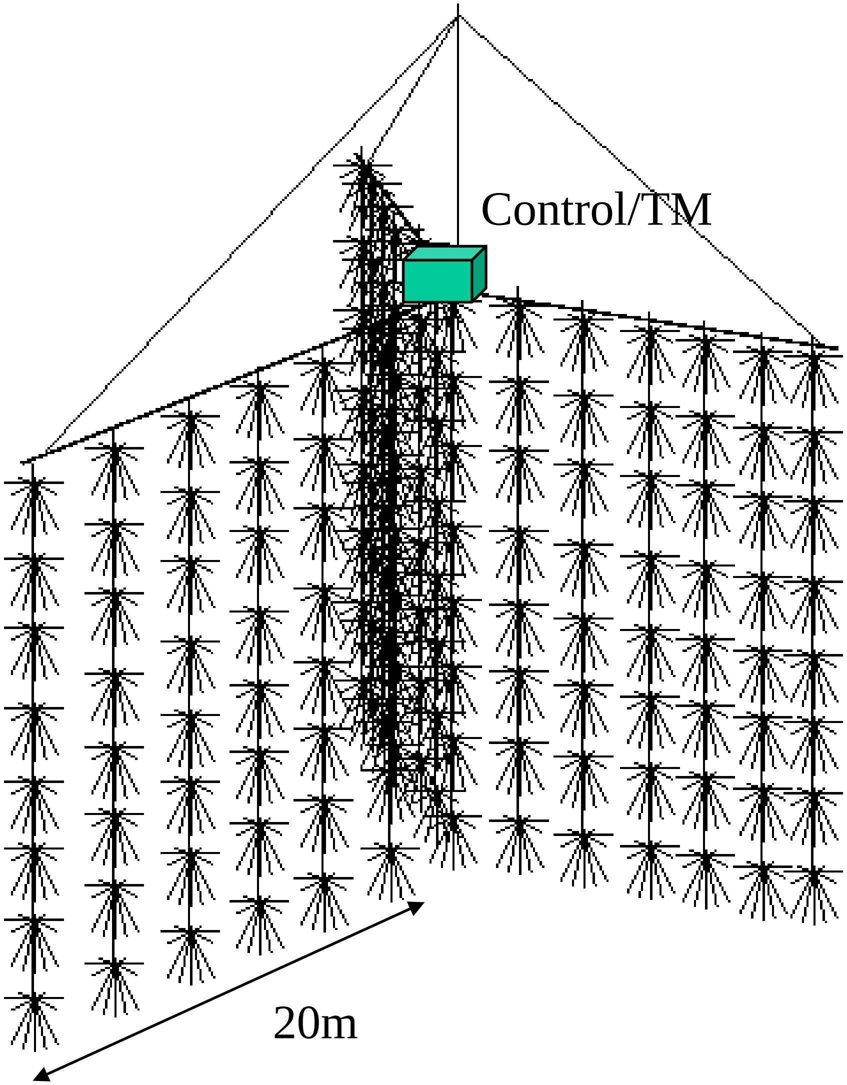
Requirement for compelling science

- Difficult to increase effective volume -- we are already seeing all of Antarctica we can
  - Projected ANITA sensitivity (2-3 flights) just barely constrains model space
  - Larger Veff moves curve down
  - Small # of events at best
- To improve: need to lower energy threshold
  - Lower Ethresh moves curve to the right
  - Gain nearly quadratically in event rates



Peter Gorham - UH

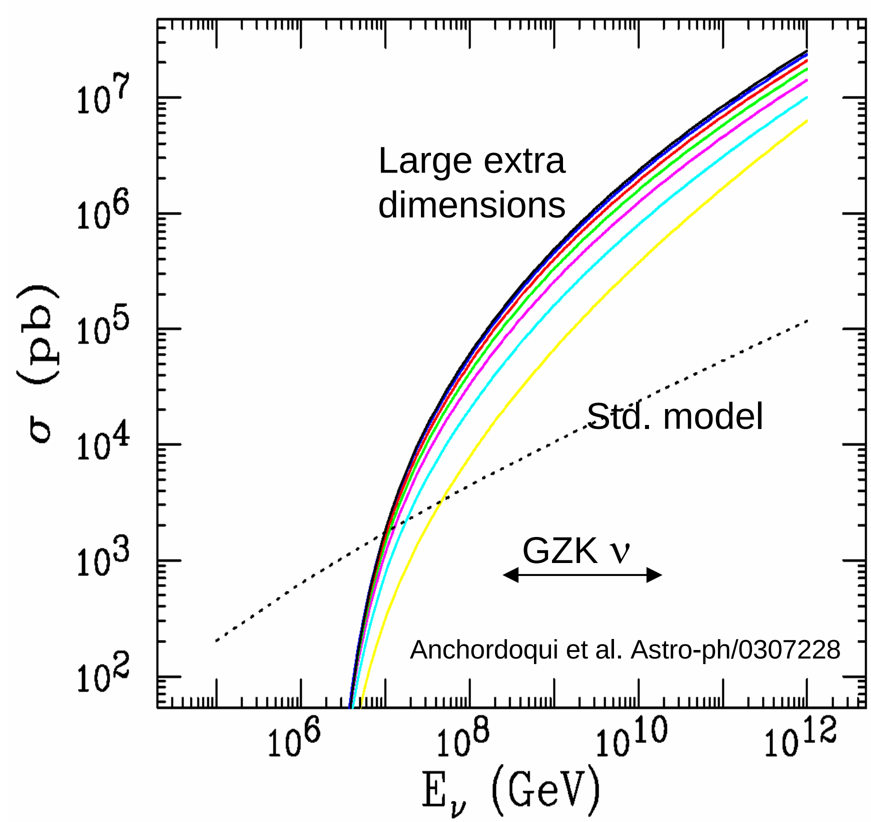
ANITA II (MidEx)



- To get 10x lower Ethresh: we need factor of ~100 in antenna area
  - Implies of order 400 m^2
- Use large suspened array of antennas with cylindrical symmetry
  - ~5 string x 16 antennas per triangle arm
  - deployable discone antennas shown
  - deployable “venetian blind” of printed-circuit antennas is probably better)
- Each antenna cluster has local PV LNA, digitizer
- Digital signals sent to central processor
- Digital beamforming for triggers

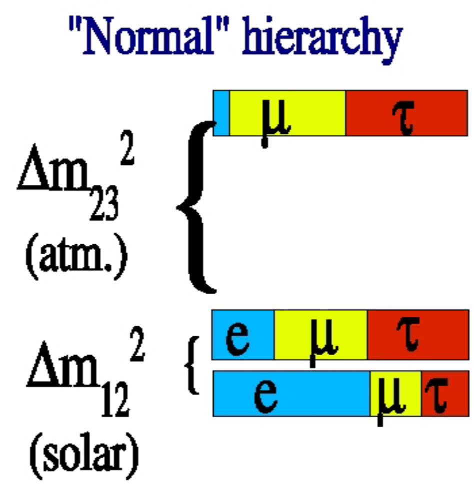
Particle Physics: Energy Frontier

- 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 $\gamma=10^{18-21}$



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

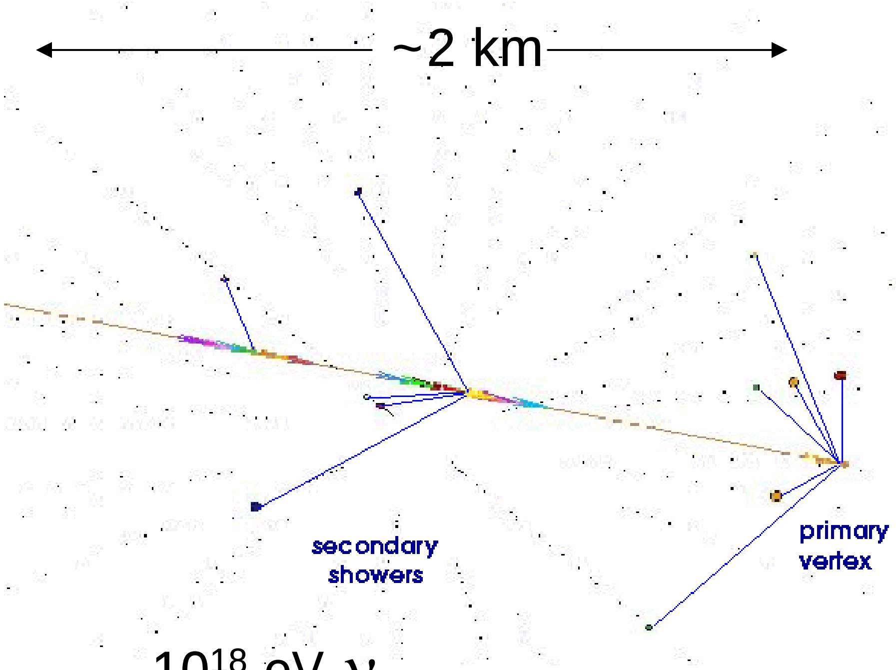


$\nu_e:\nu_\mu:\nu_\tau$

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

Neutrino decay leaves a strong imprint on flavor ratios at Earth

Particle ID – subthreshold detection



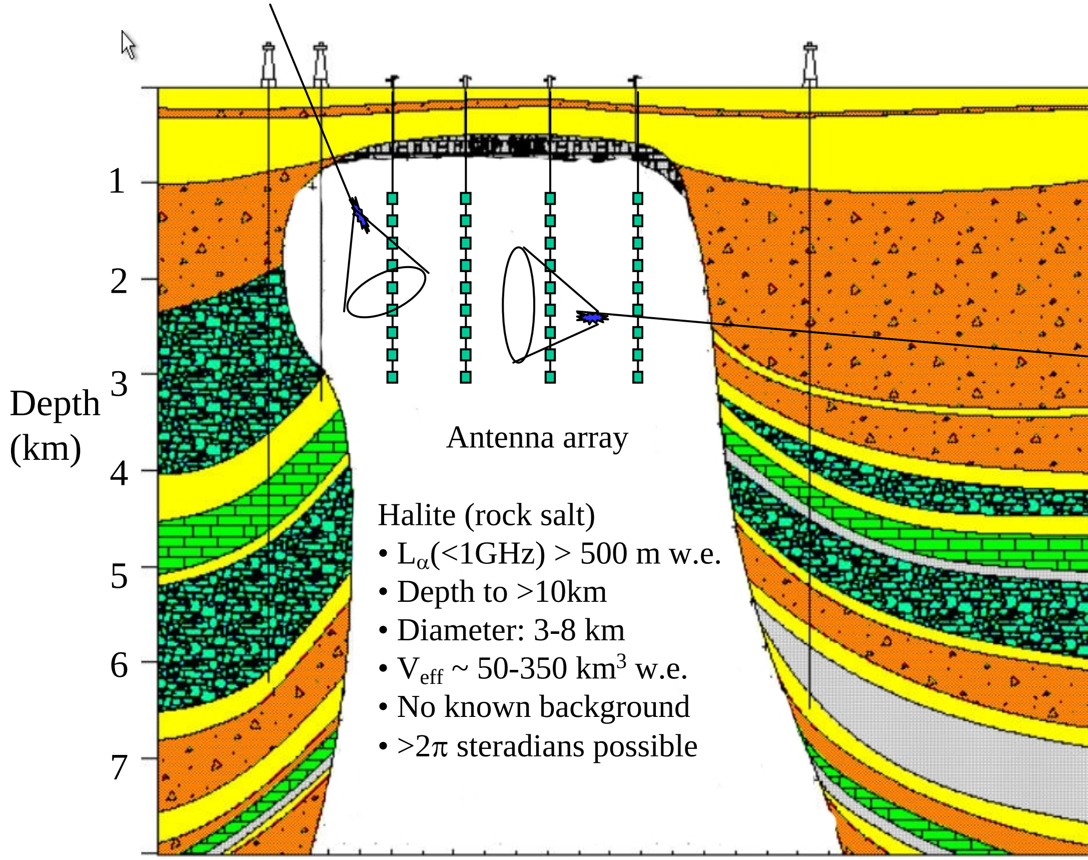
	Charged current (SM: 80%)	Neutral current (SM: 20%)
e	25% hadronic + 75% EM shower at primary vertex; LPM on EM shower	Single hadronic shower at vertex
μ	25% hadronic at primary, 2ndary lepton showers, mainly EM	Single hadronic shower at vertex
τ	25% hadronic at vertex, 2ndary lepton showers, mainly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

- Charged/neutral current & flavor ID enhanced with subthreshold samples
- Coincidence with optical (lower E threshold [PeV])
- Phased array – can push well down into the noise
- Challenge: for multi-k antenna array, multi-Terasamples/s

Tera-ton Detector 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 ?

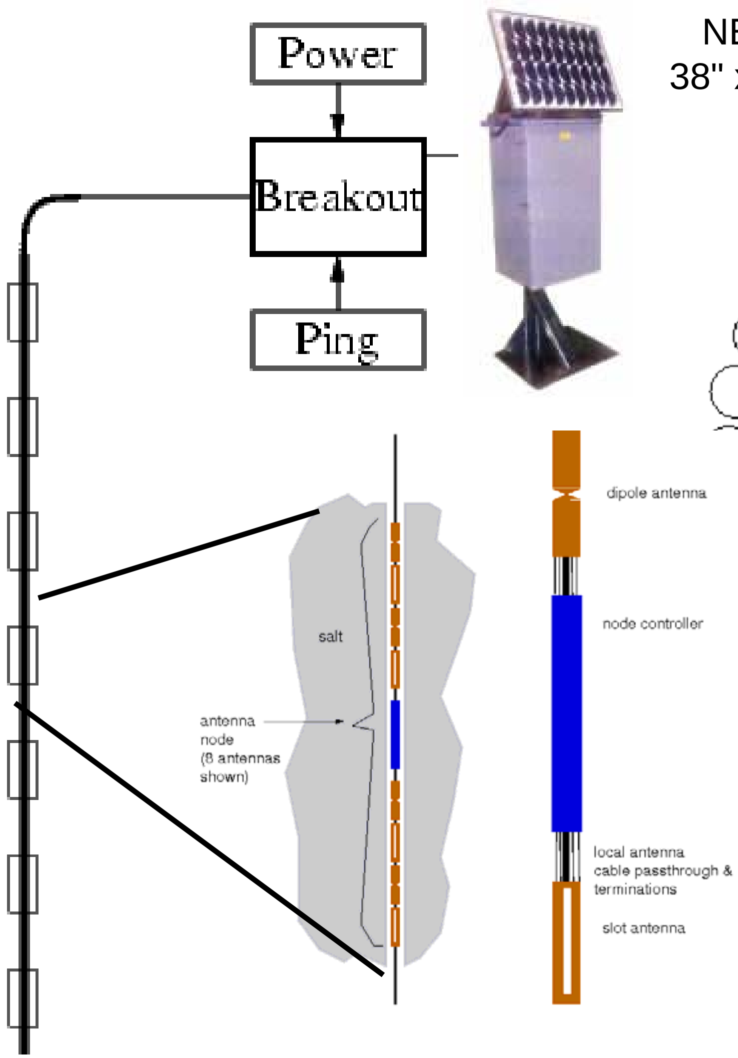
Saltdome Shower Array (SalSA) concept



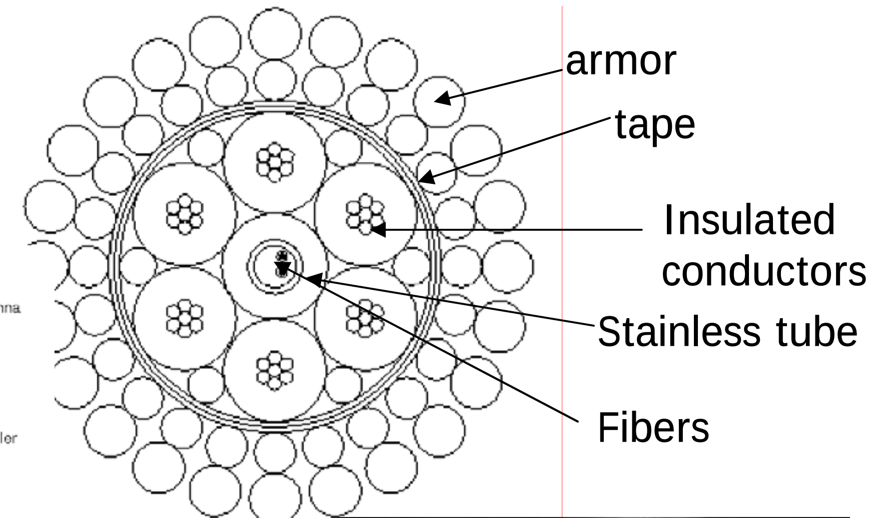
- Rock salt can have extremely low RF loss, as radio-clear as Antarctic ice
- ~2.4 times as dense as ice
- typical: **50-100 km^3** water equivalent in top ~3.5km =>**300-600 km^3 sr w.e.**

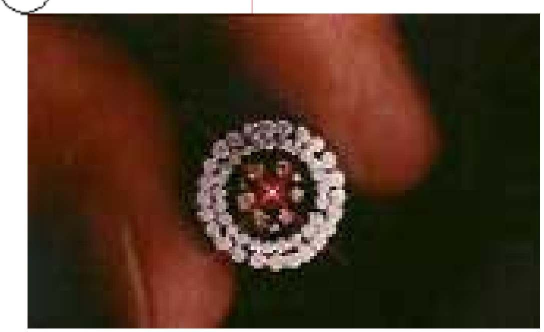
Basic string architecture

String
12 nodes



NEMA 3R
38" x 21" x17"



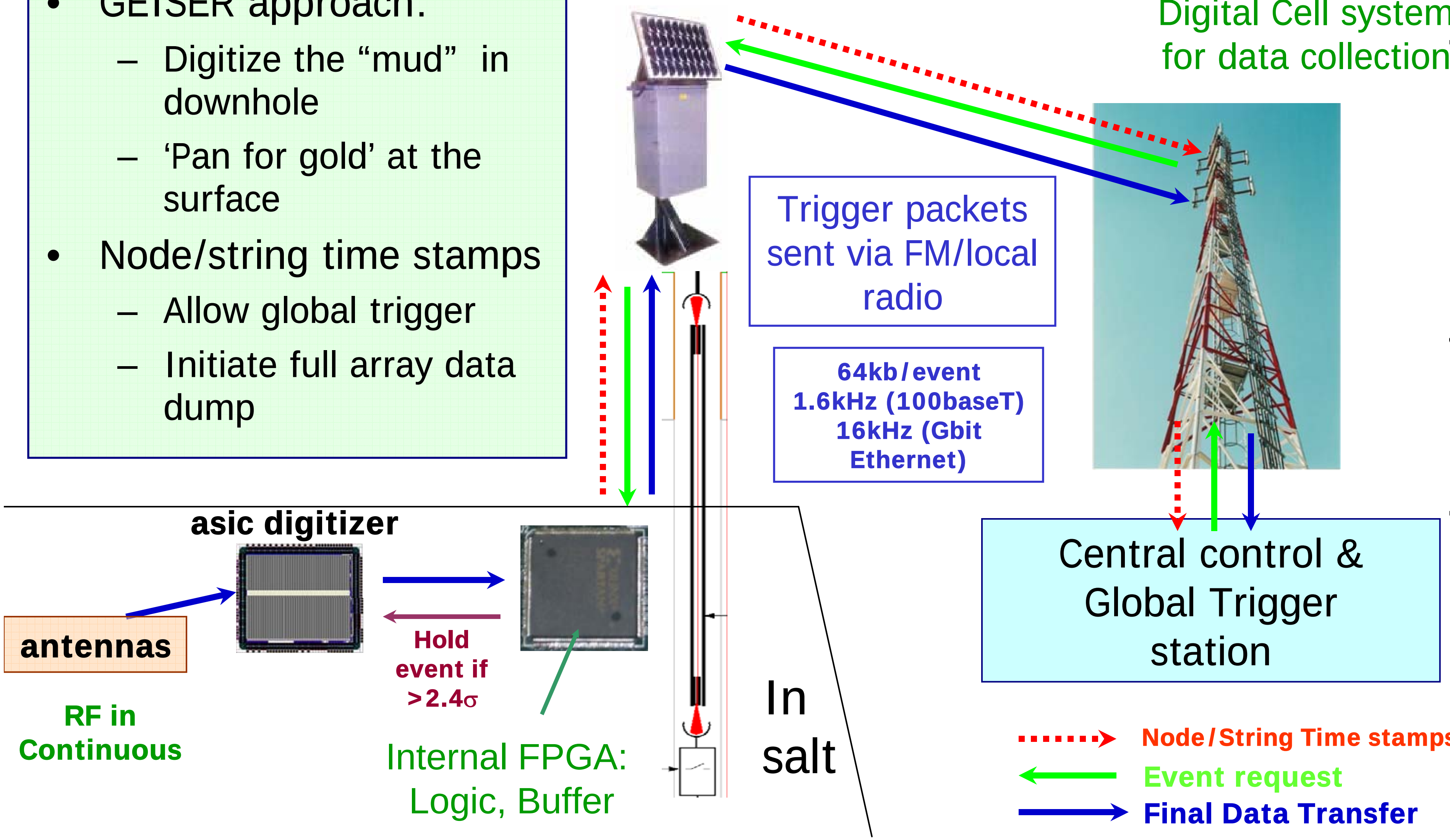


Node = 12 antennas
and center housing

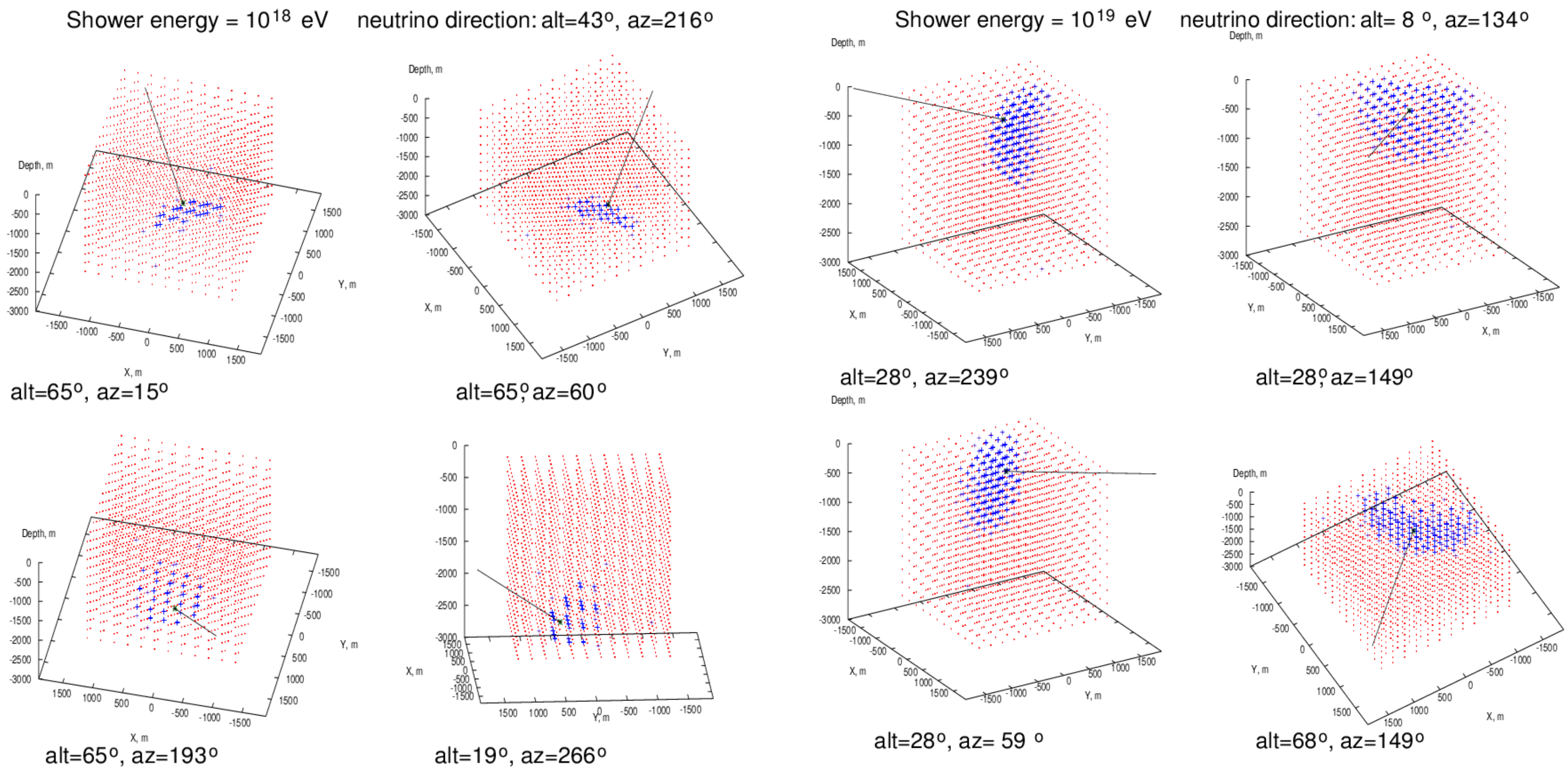
GEISER Data flow [NIM A554 (2005) 437-443]

(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

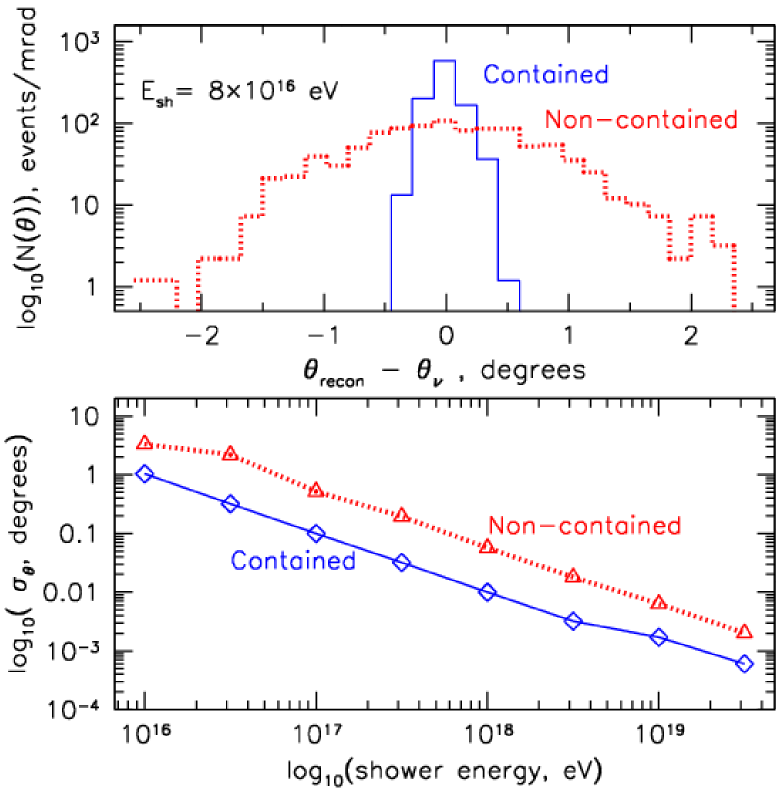


SalSA simulations



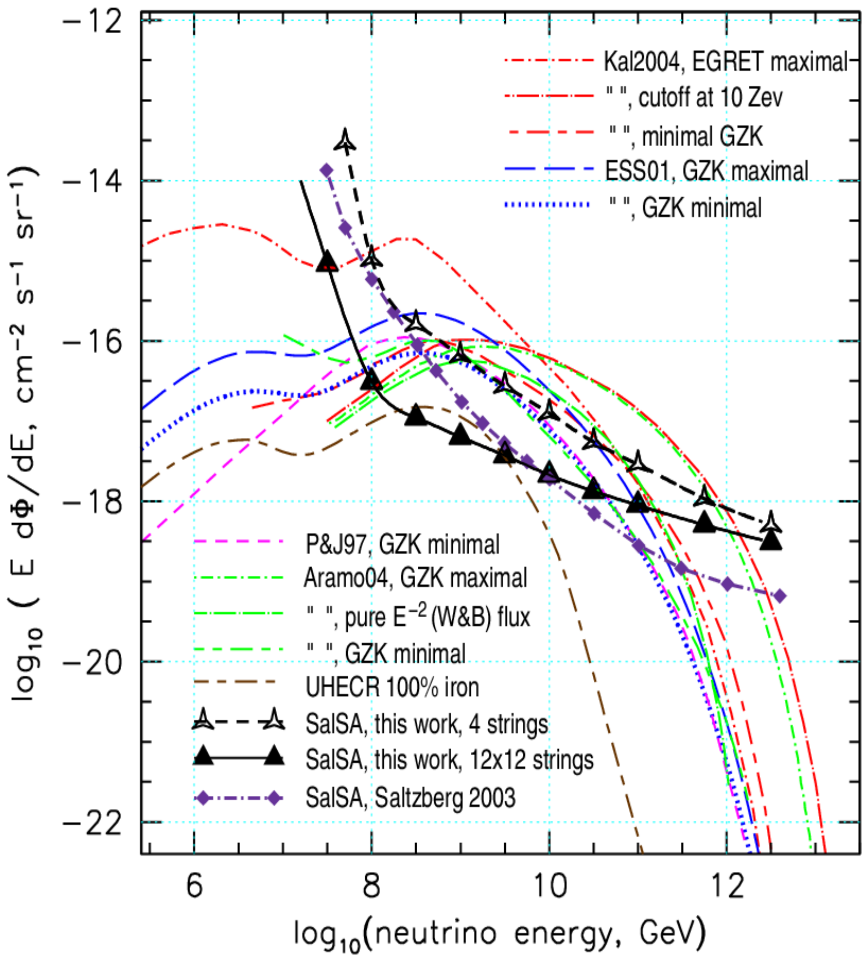
- A 2.5 km^3 array with 225 m spacing, 12^2=144 strings, 12^3=1728 antenna nodes, 12 antennas per node, dual polarization ==> **$V_{eff}\,\Omega$ = 380 km^3 sr w.e. at 1 EeV**
- Threshold <10^{17} eV, few 100s antennas hit at 1 EeV, >1000 hits at 10 EeV
- **Rate: at least 20 events per year from rock-bottom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

GZK neutrino sensitivity details, 1 yr

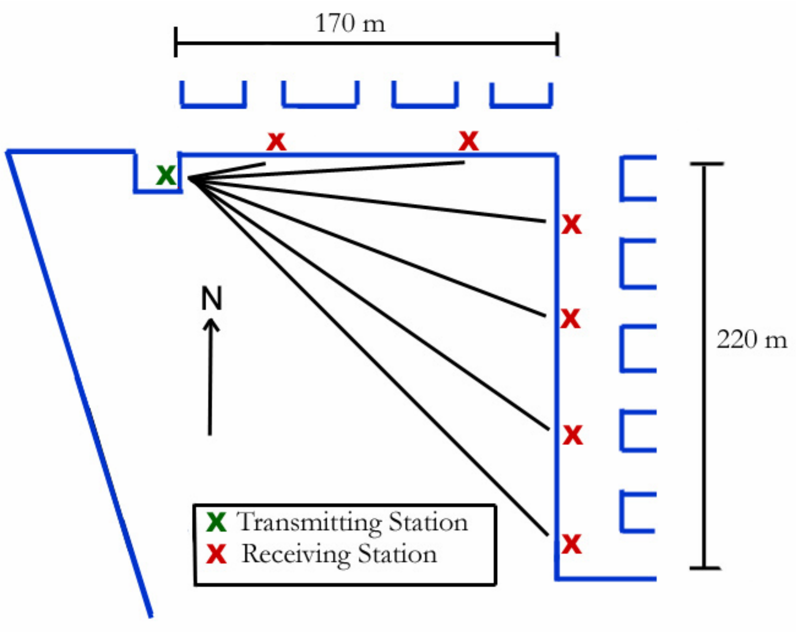


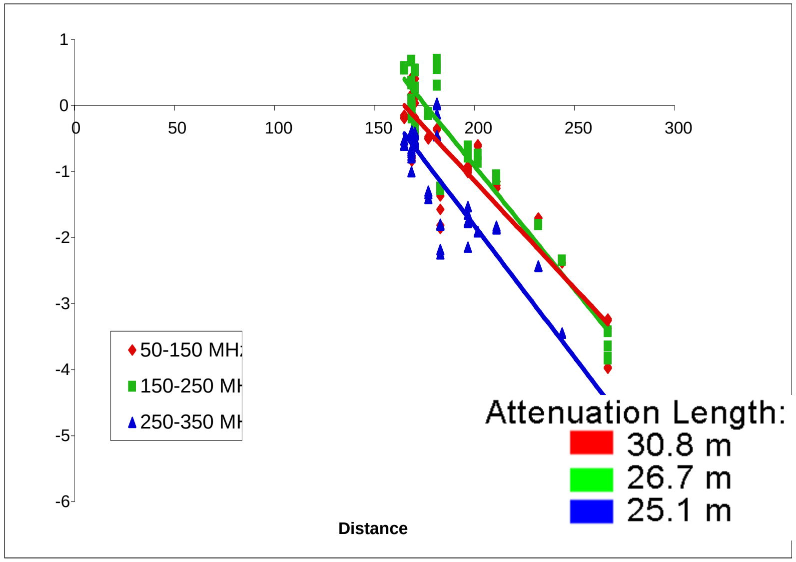
- 2 independent MC calculations: UCLA & UH
- UCLA: Saltzberg 2002 SPIE; also 2005 Nobel symposium
  - Simplified 10x10 strings, 10 antenna nodes per string
  - Did not truncate dome, so high energies extended
- UH: Gorham et al. PRD 2005
  - 12x12 strings, 12 nodes with realistic trigger sims
  - **Even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

"Rock bottom" min. of 20 events/year

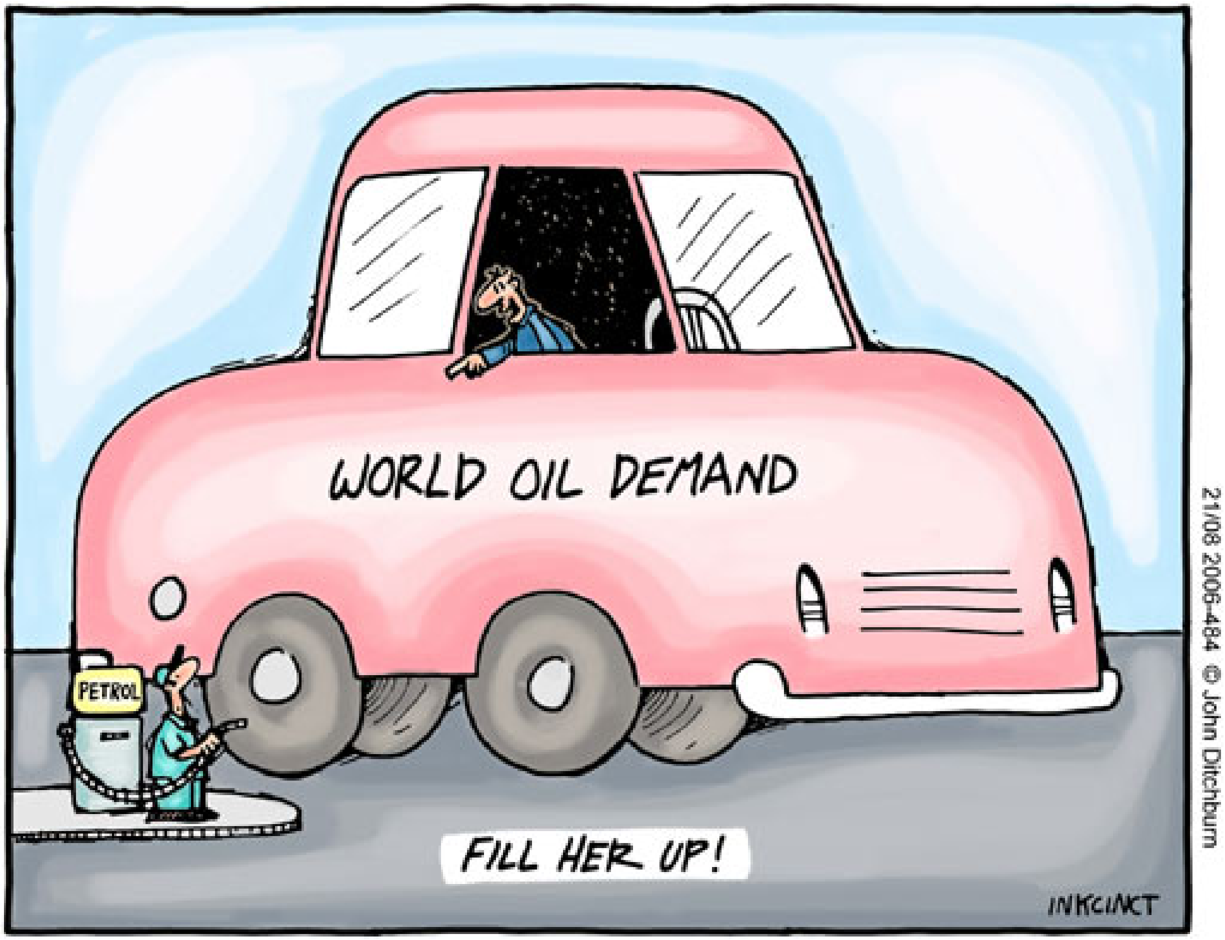
Cote Blanc Measurements

Amy Connolly and Abby Goodhue





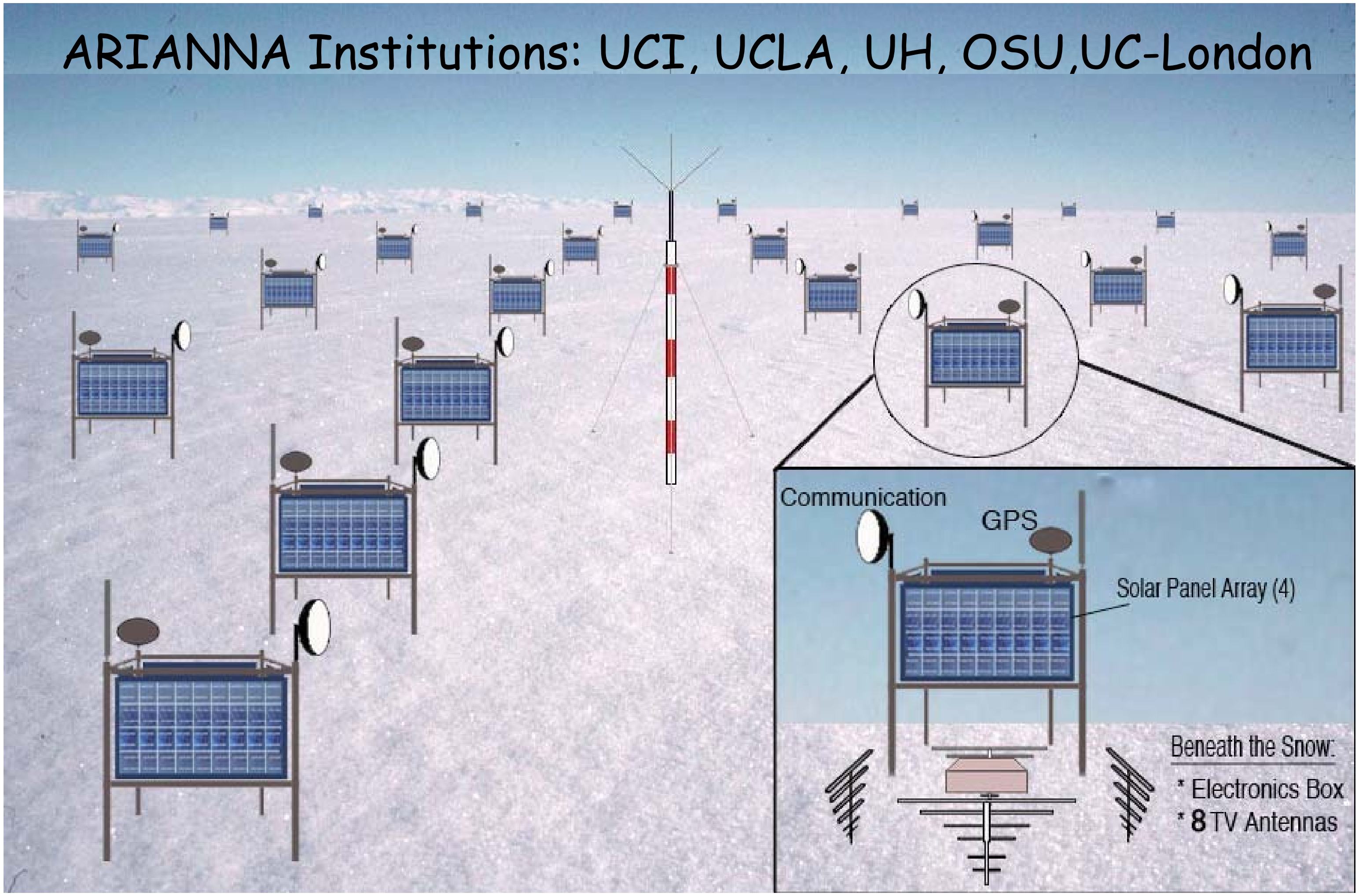
Hubbard's Peak?



"If we don't change course, we'll end up where we're headed"

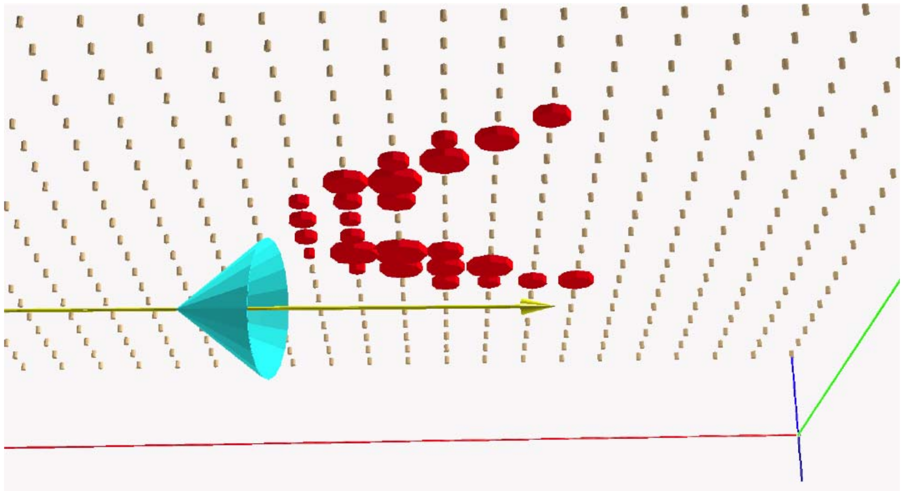
-- Chinese Proverb

ARIANNA - A New Concept for Neutrino Detection

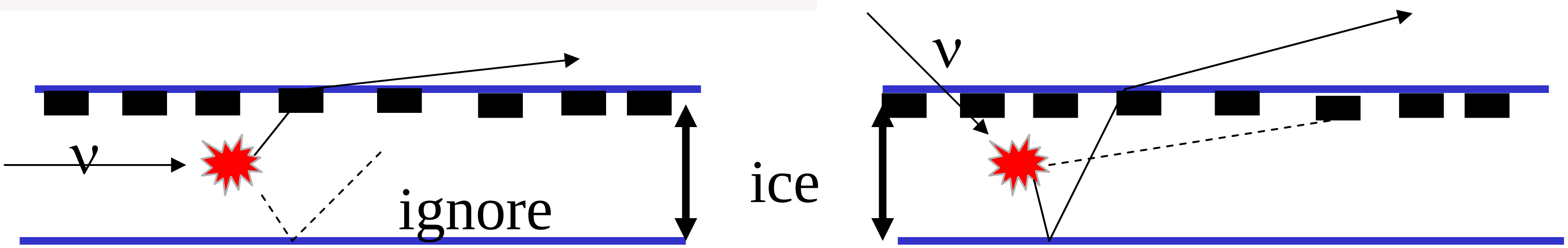


Satellite Image of Victoria Land and Ross Ice Shelf

Reflected and Direct Events



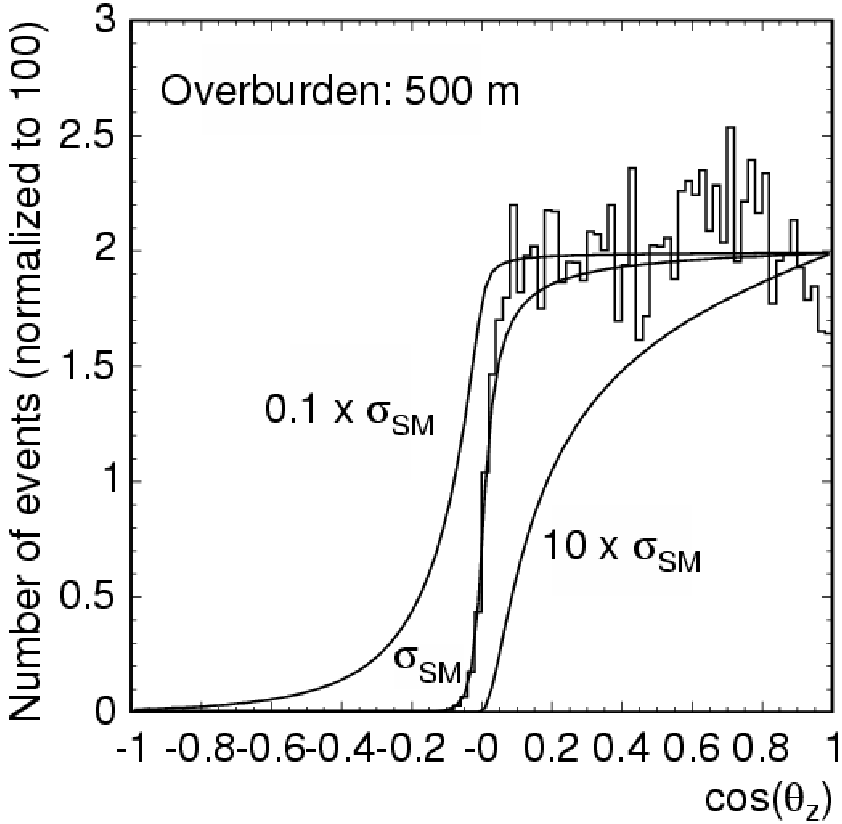
S. Barwick, 3rd NOVE Workshop (Venice, 2006)

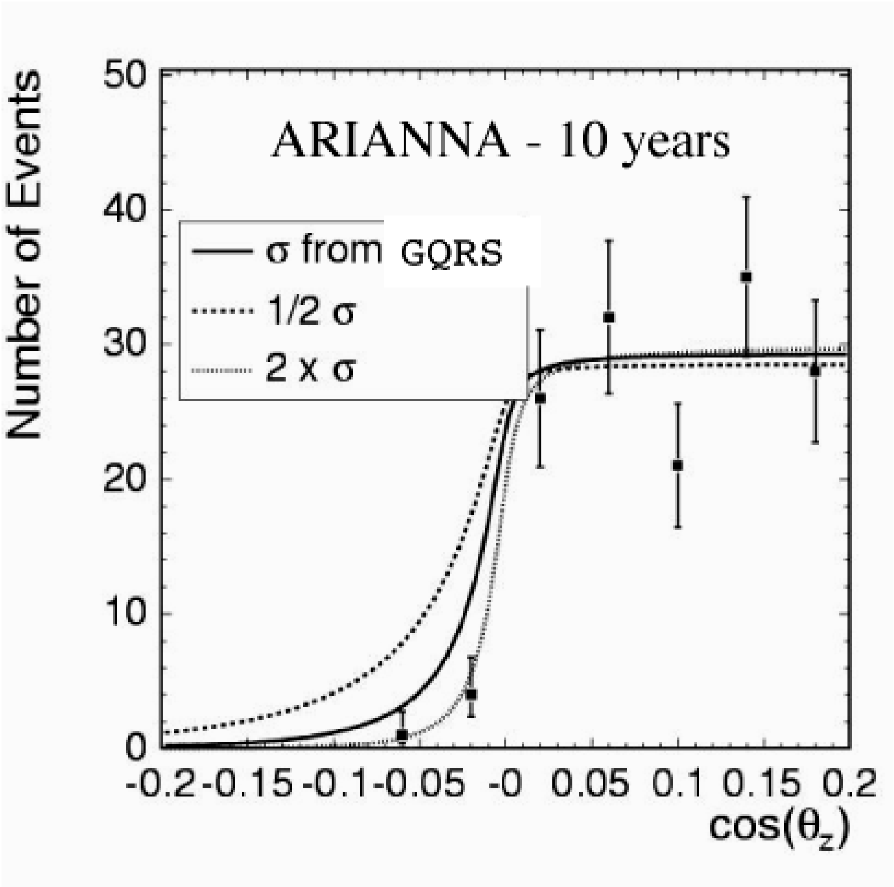


Direct

Reflected (much greater solid angle)

Testing SM Cross-section

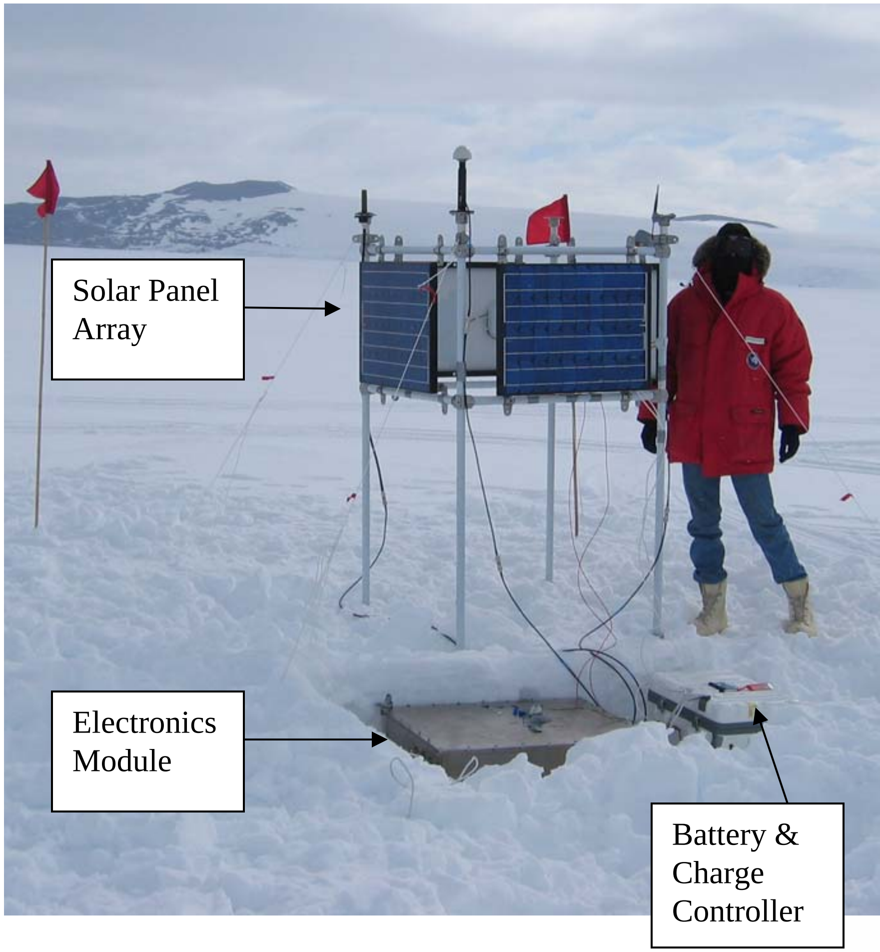




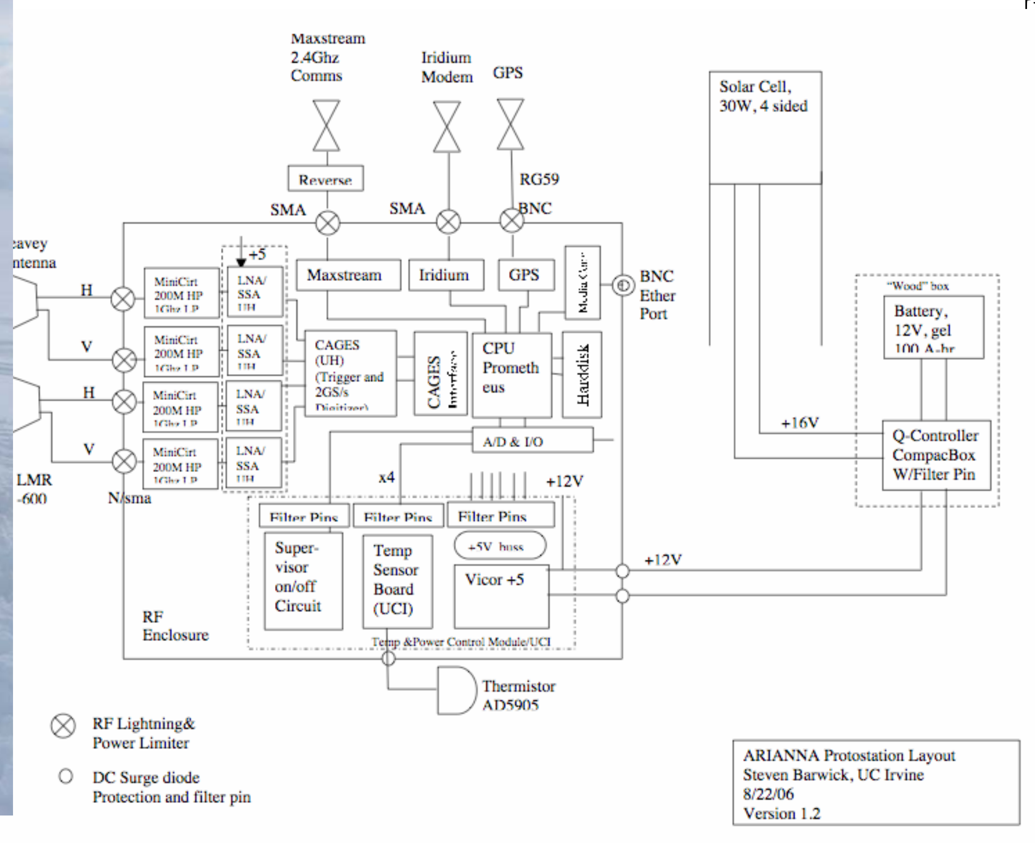
[A. Connolly]

100 events: measure L_{int} = 400 km ± 33%

Protostation



Block Diagram of Electronics

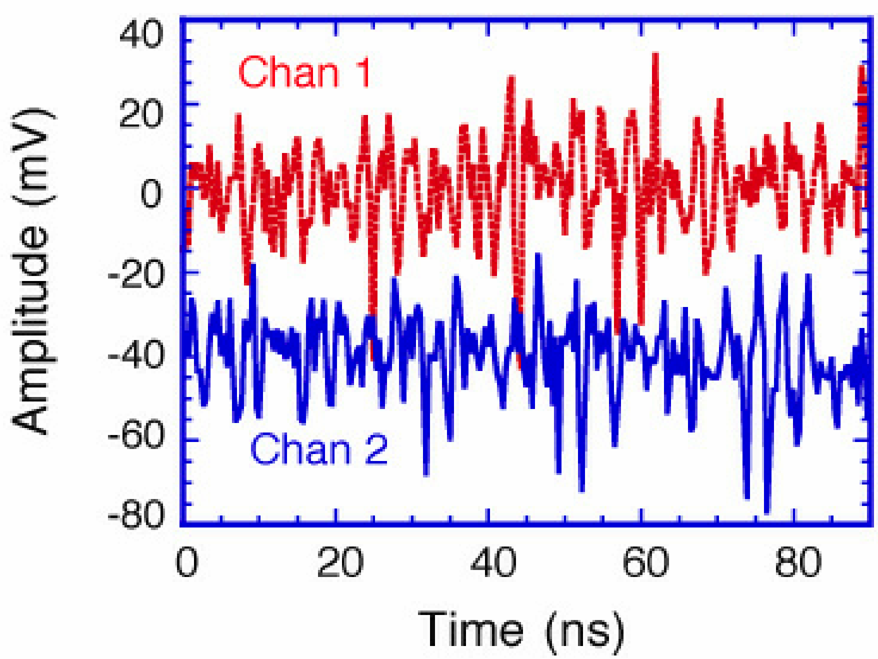


ANITA & AUGER technology

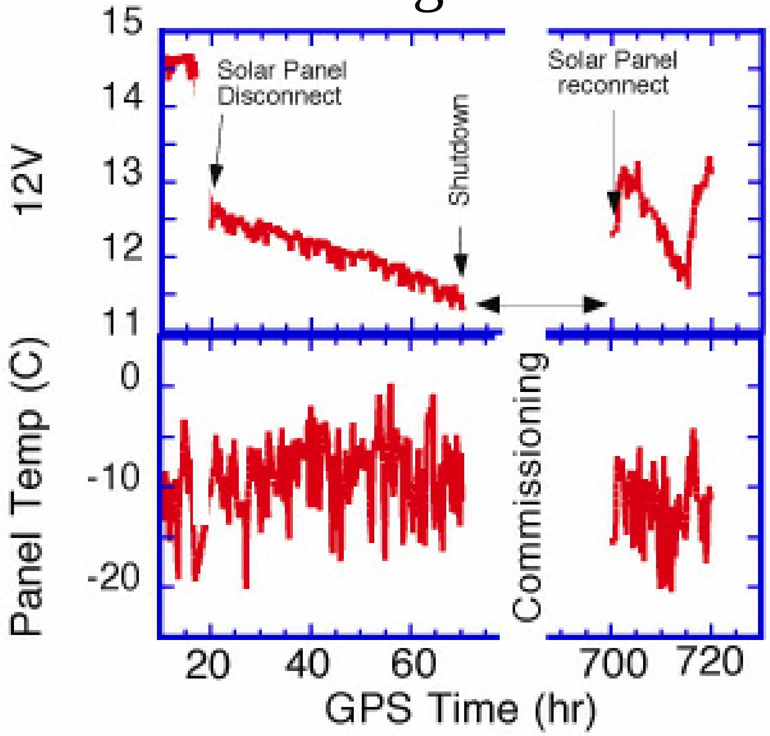
Will run over the winter, test “awakening” on its own

Data Taking – Test "wake up"

Thermal Noise



Long Winter



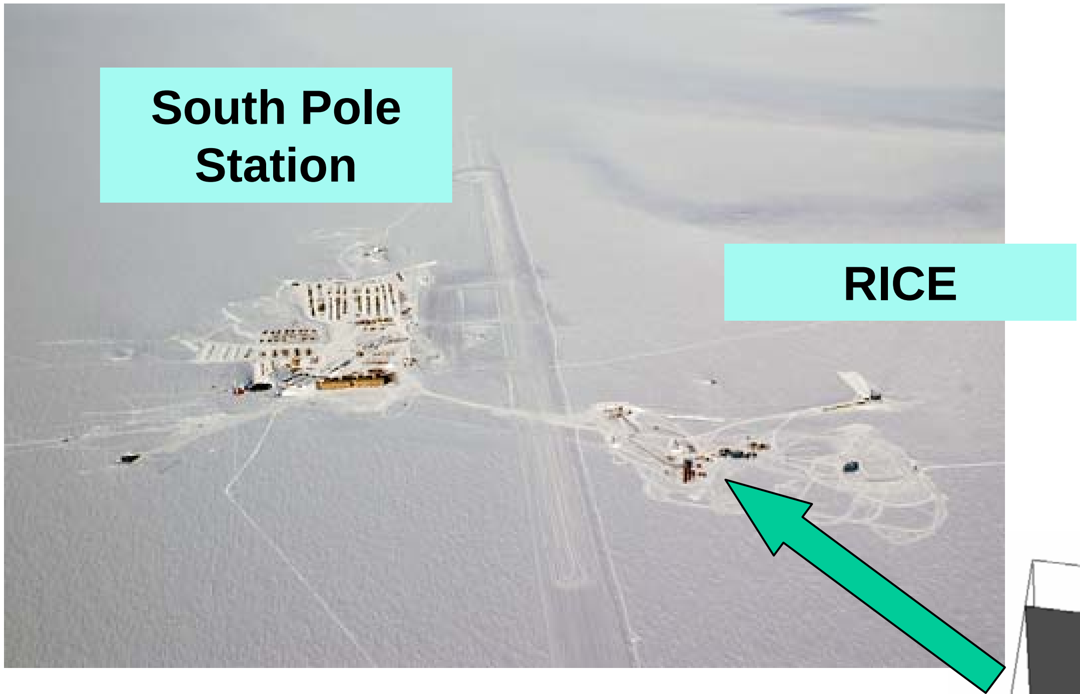
AURA

(Askaryan Under-ice Radio Array)

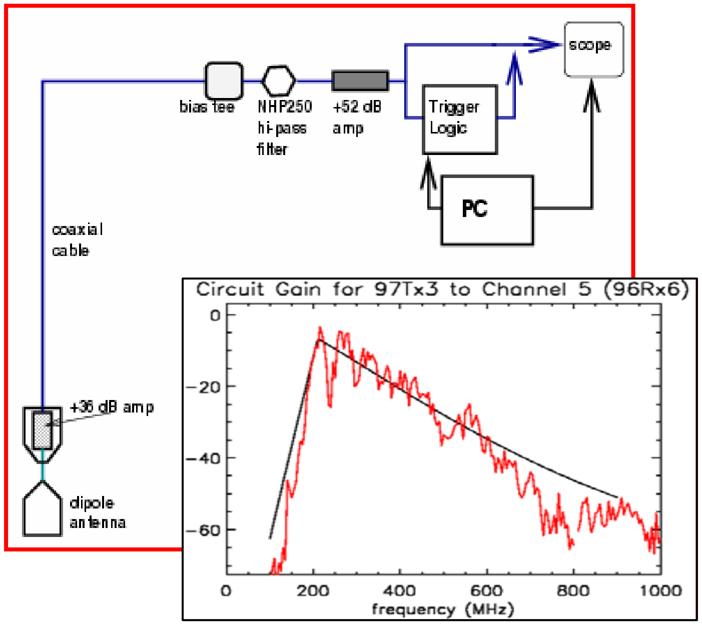
A Successor to RICE and Prelude to a 10-km scale Neutrino Detector

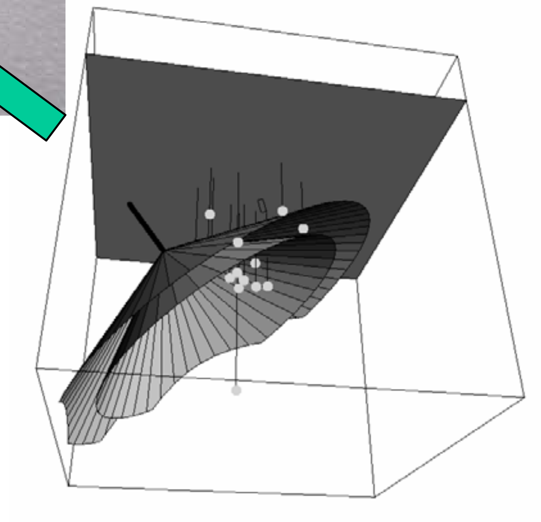
RICE started late ’90’s

- Deployed with AMANDA
- Challenging EMI backgrounds

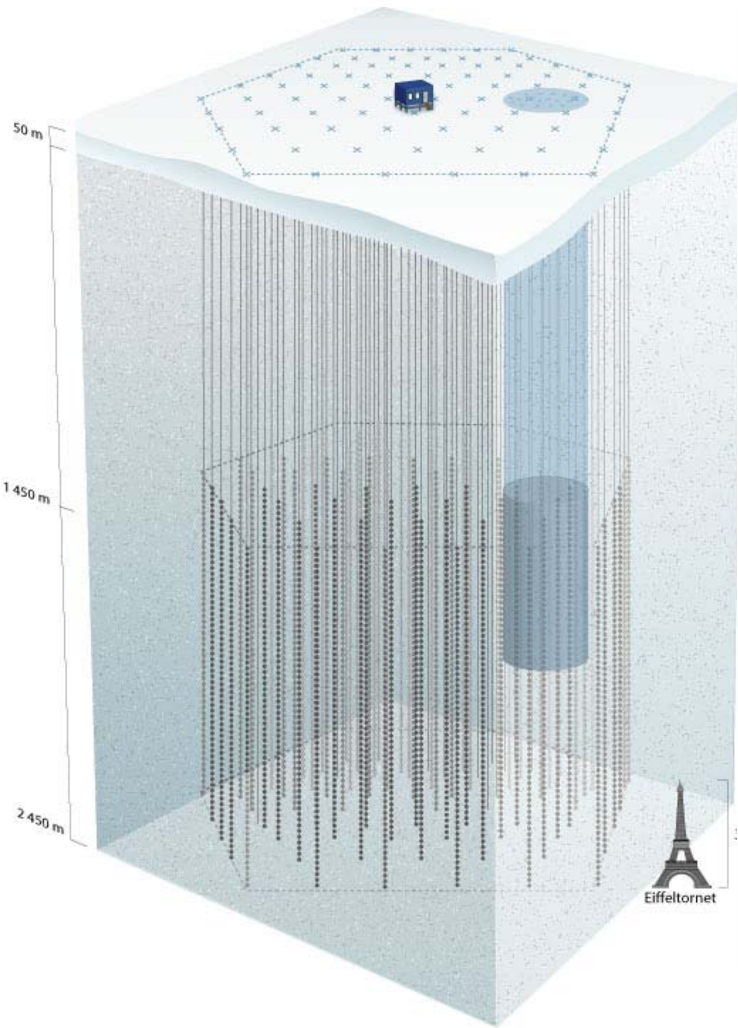


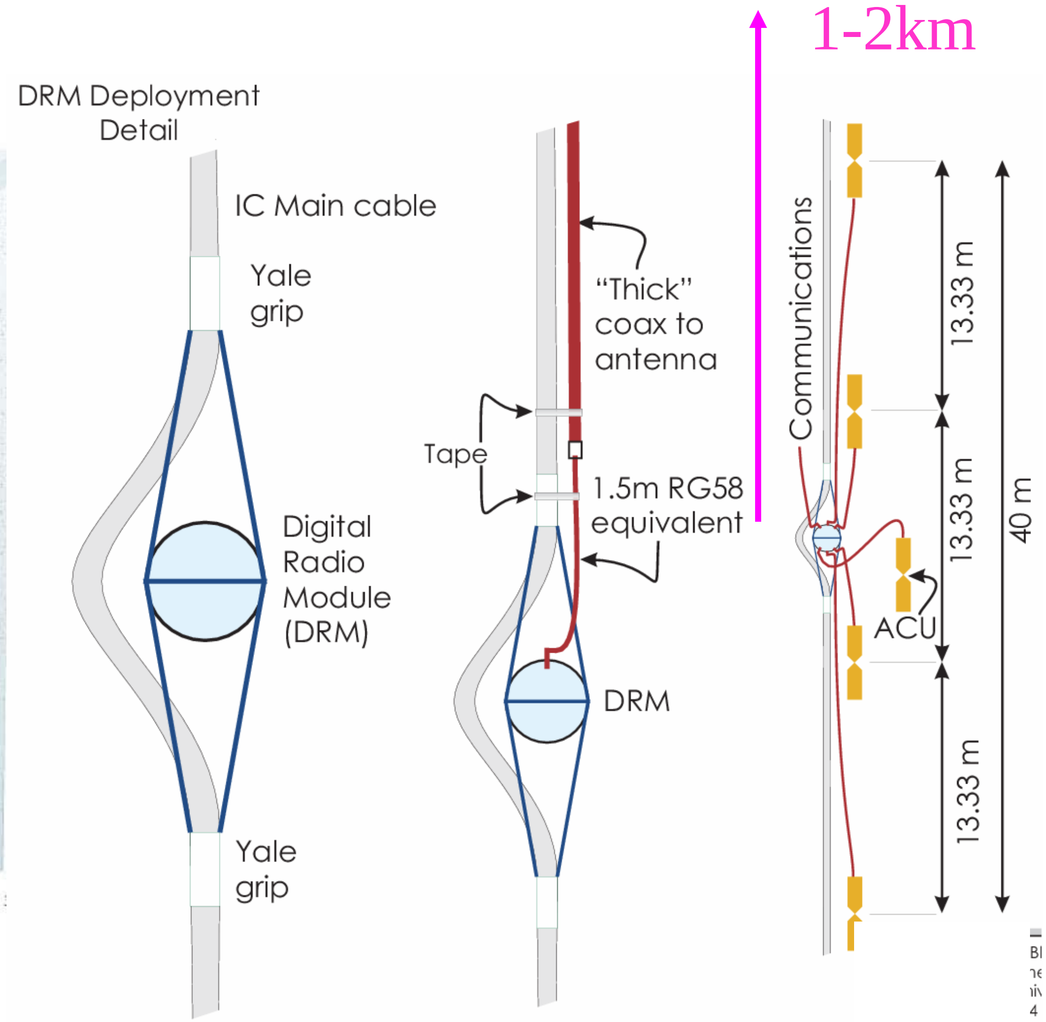
RICE readout



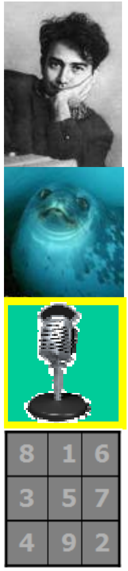


IceCube Opportunity

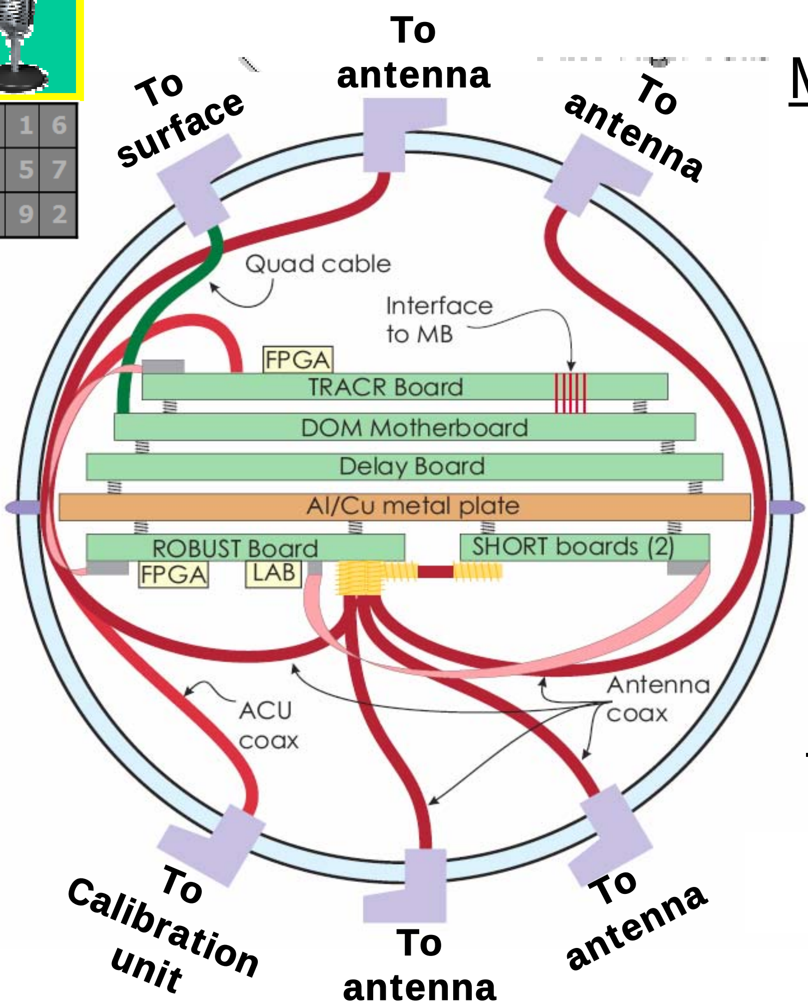




Utilize IC DAQ/Control Infrastructure



Digital Radio Module (DRM)



Modified glass sphere 6 Penetrators:

- 4 Antennas
- 1 Surface cable
- 1 Calibration unit

MB (Main board)

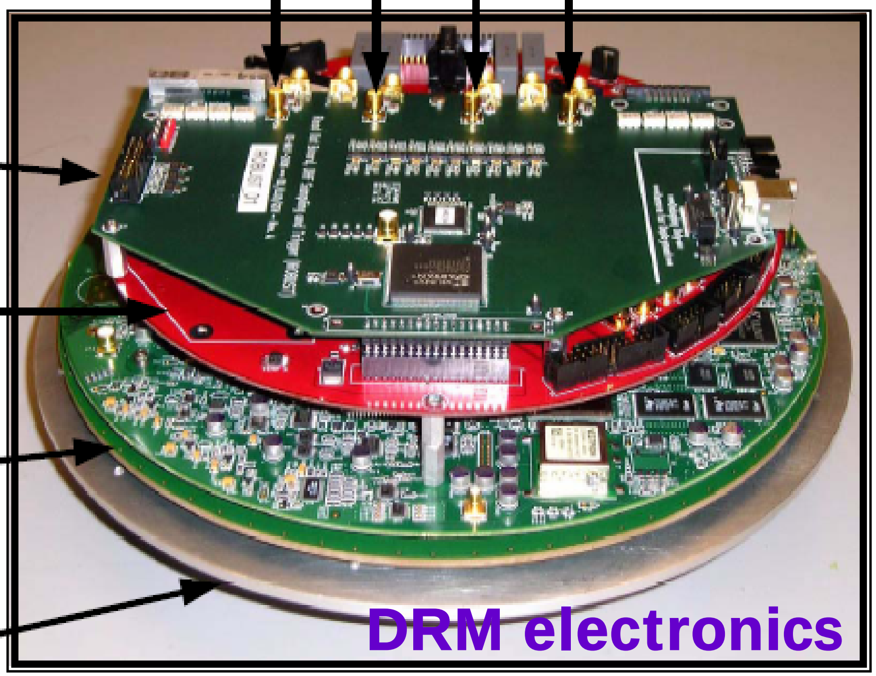
Communication, timing, connection to IC DAQ infrastructure,

Radio Boards

UHF Sampling, Triggering, Digitizing, data processing, trigger banding, interface to the mb


Sealing the DRM

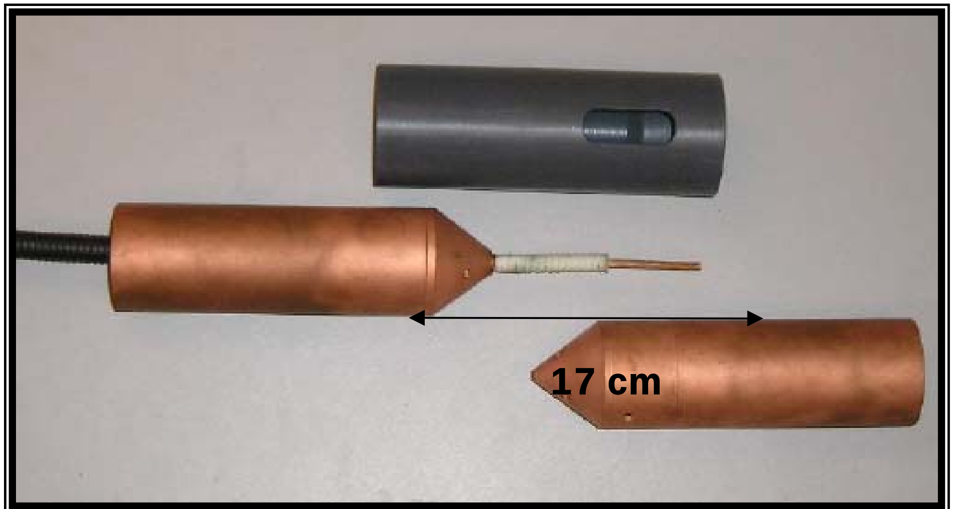

Surface Test

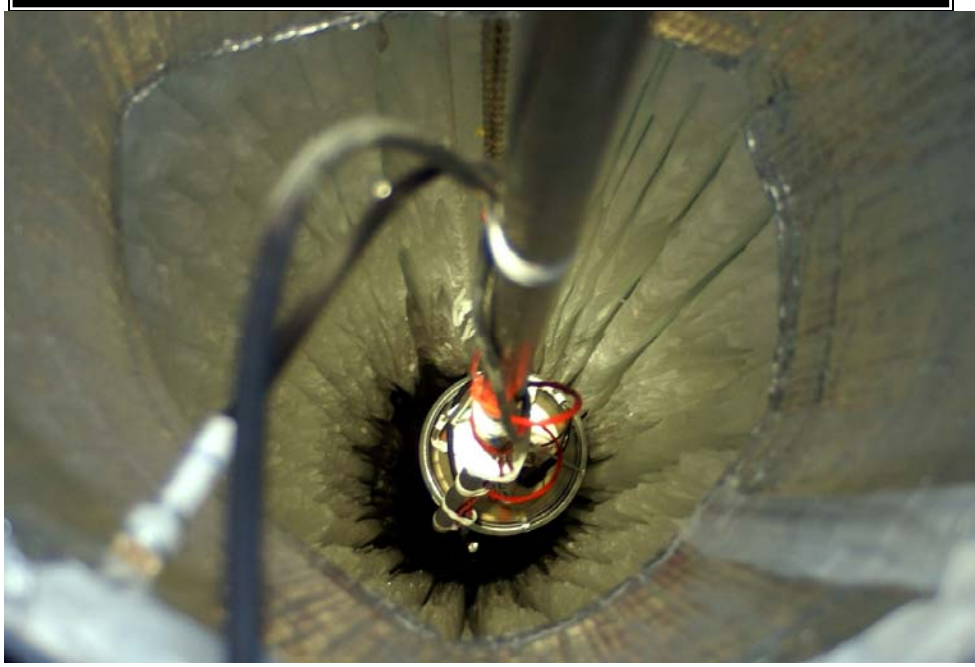


DRM electronics


Metal can /w electronics

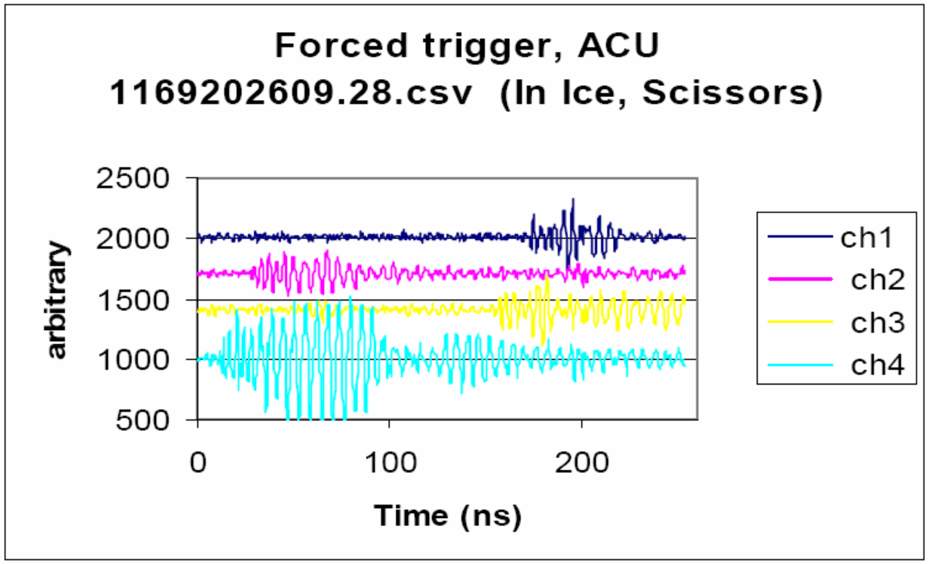
Antenna/DRM Deployment



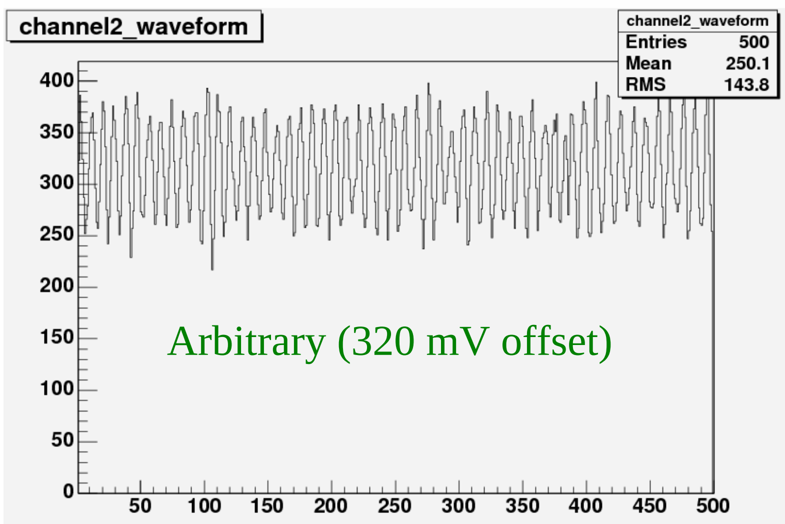


Data Streaming North

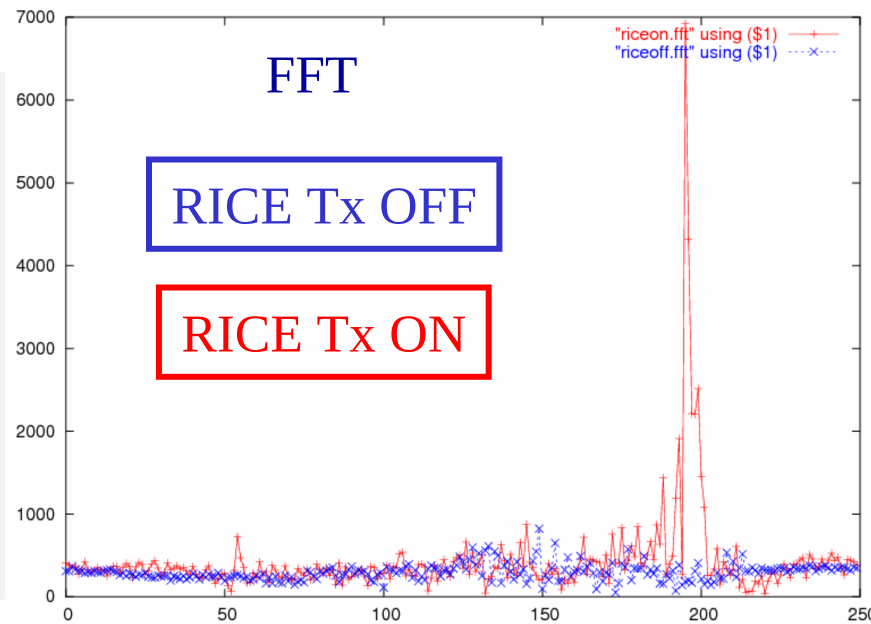
Local Pulser



RICE Pulser (sine Wave)

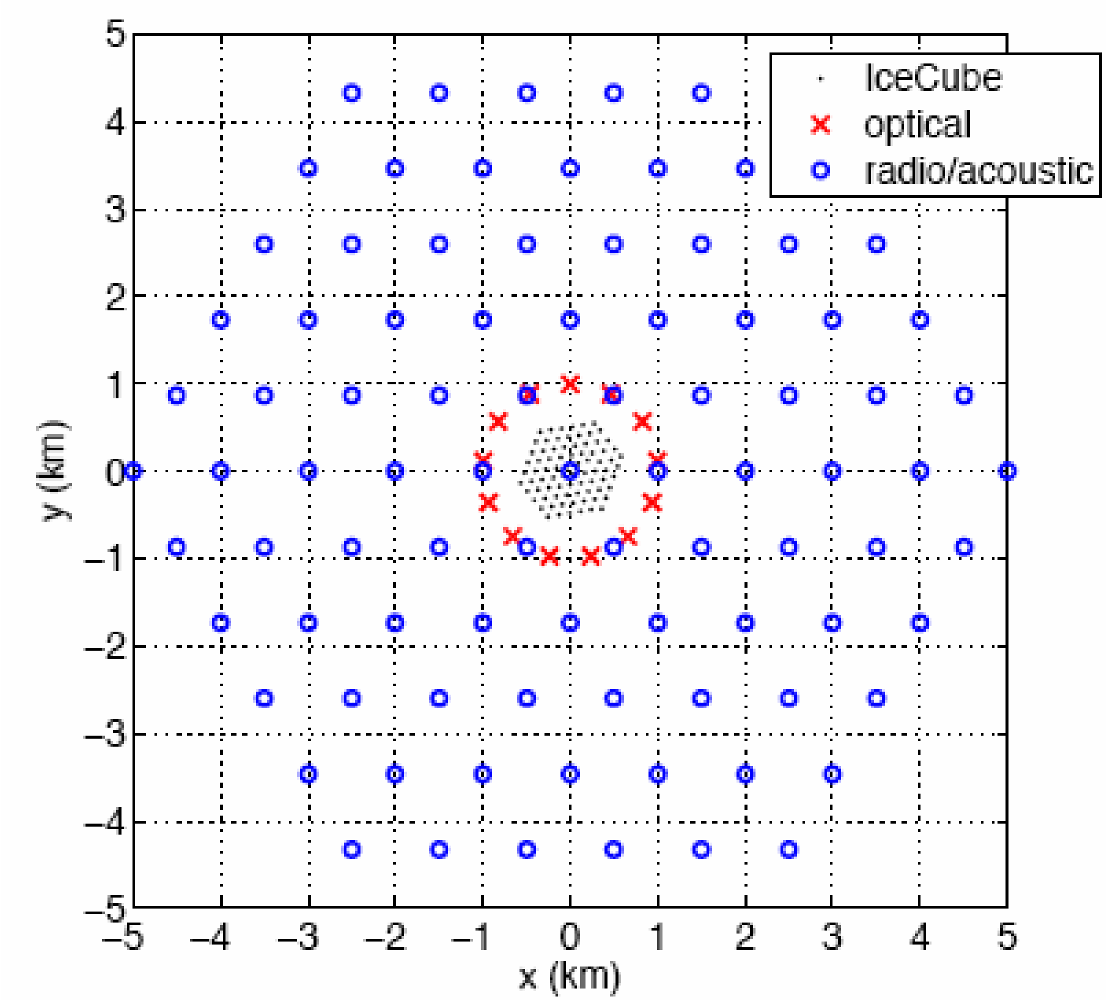


Time [ns]



Freq [MHz]

10-km Scale array



>= Tera-ton Array

Radio, acoustic have long reach, can be much sparser, shallower, and smaller diameter holes

R&D Emphasis

1. Lower amplifier costs
2. Lower trigger costs
3. Extend sensitivity

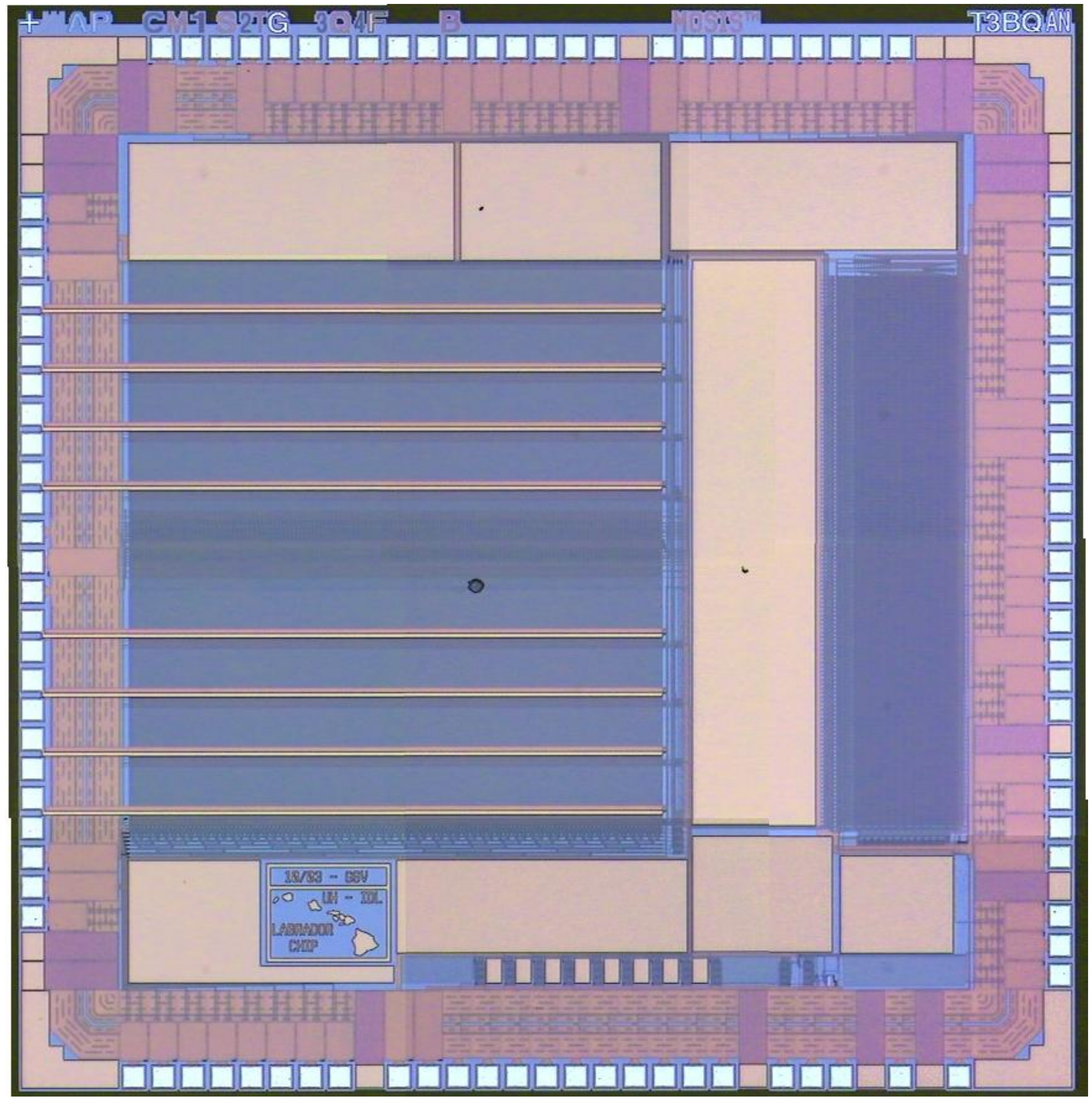
IceCube construction complete: 2011
Askaryan Observatory thereafter

An exciting year:

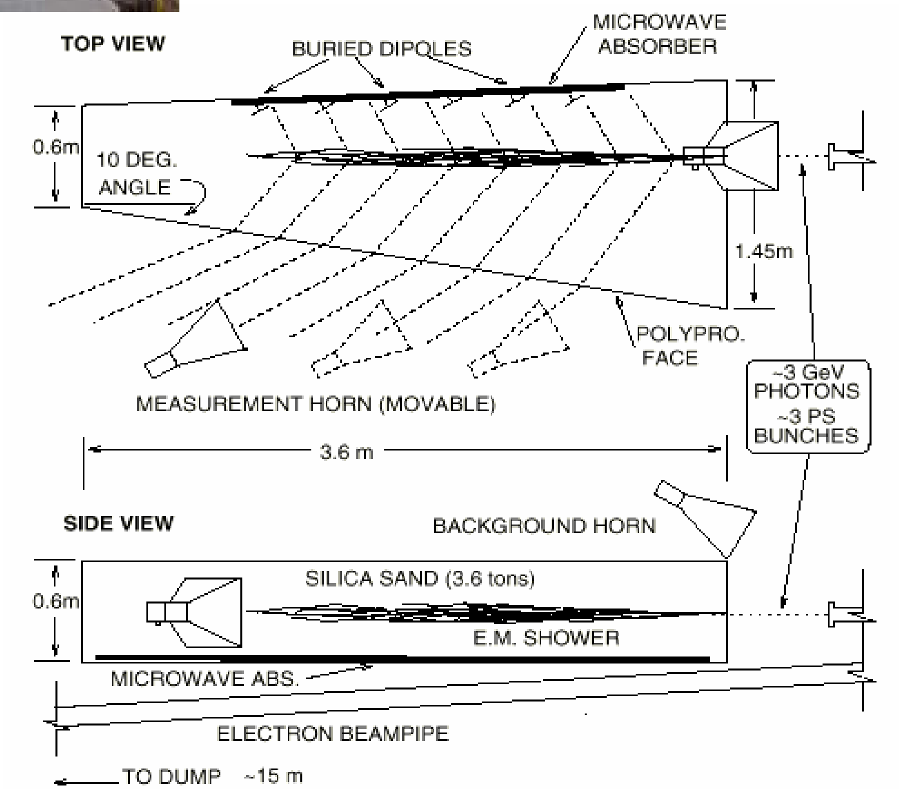
- ANITA will open the box hopefully by summer
  - Successful ice-target calibration run in June
  - First flight in Dec/Jan, another possible in 2008

- Tera-ton Detector prototype developments:
  - SalSA
    - Salt mine attenuation measurements
  - AURA
    - Deployed 3 antenna clusters this year, data flowing
  - ARIANNA
    - Deployed prototype station this year, MRI proposal being seriously considered

Back-up slides



Askaryan Confirmation: SLAC T444 (2000)

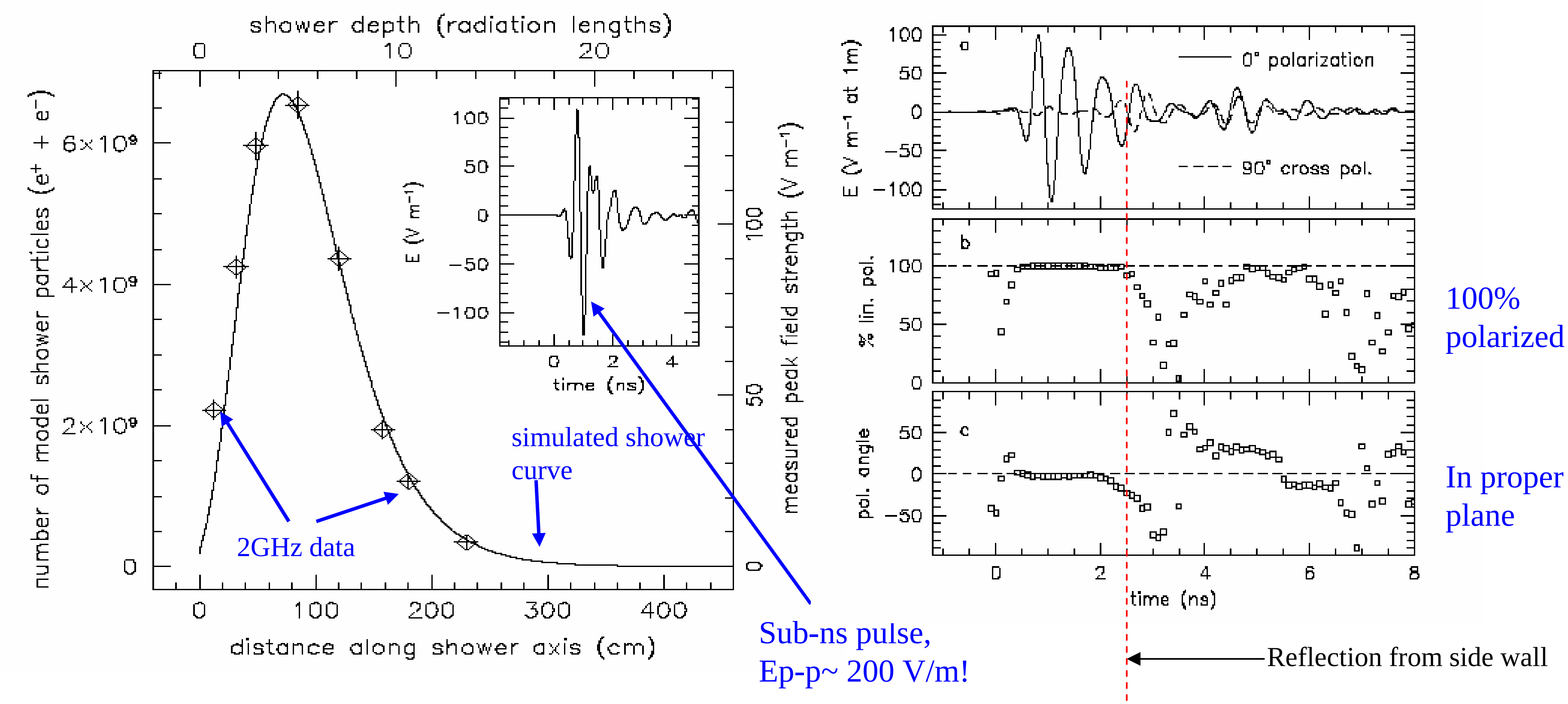


Saltzberg, Gorham, Walz *et al* PRL **86** 2802 (2001)

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

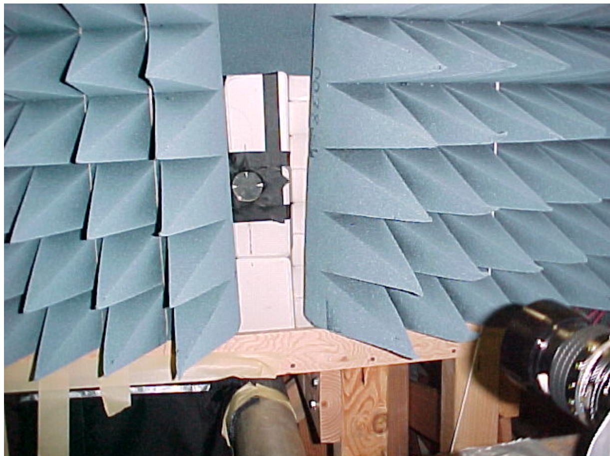
  ==> no transition radiation
- Monitor all backgrounds carefully
  - but signals were much stronger!

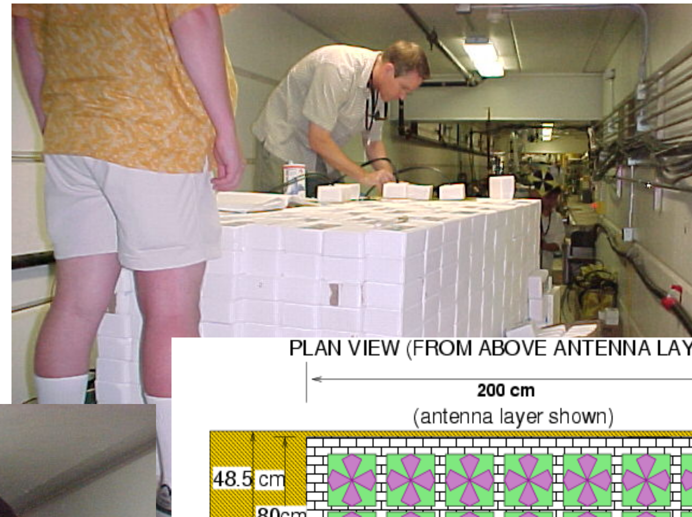
Shower profile observed by radio (~2GHz)

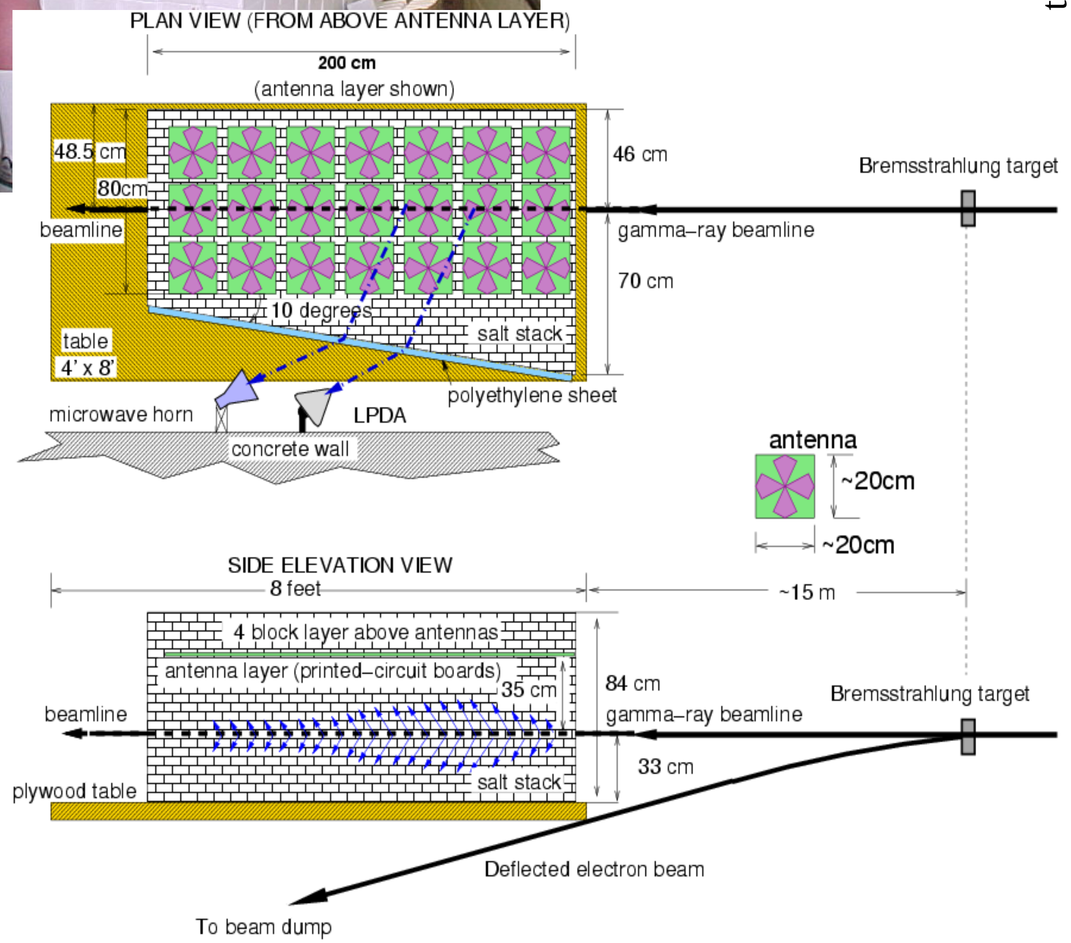


- Measured pulse field strengths follow shower profile very closely
- Charge excess also closely correlated to shower profile (EGS simulation)
- Polarization completely consistent with Cherenkov—can track particle source

Askaryan in Salt: SLAC T460

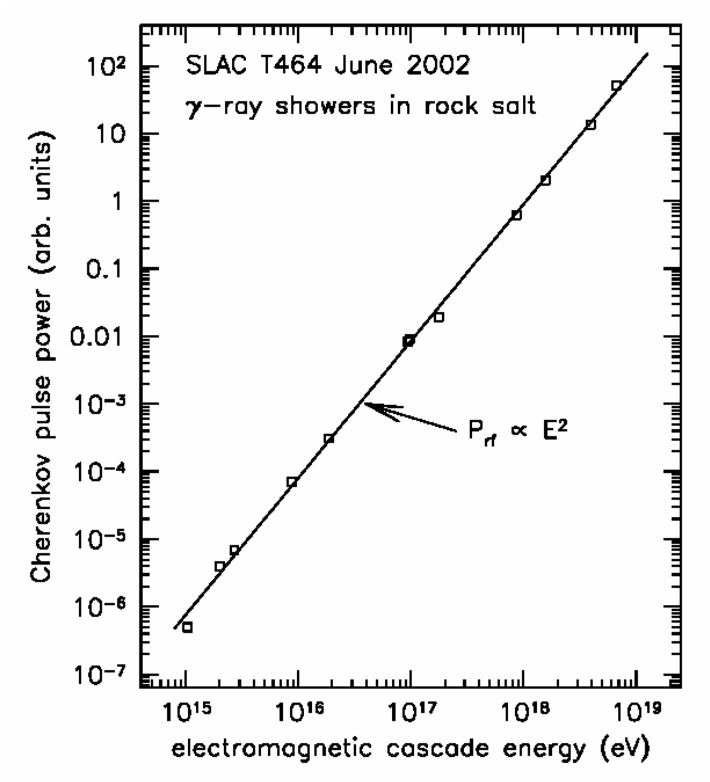


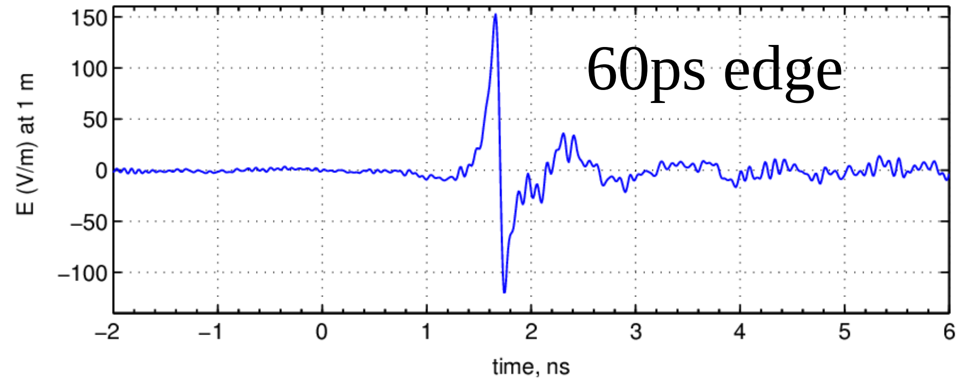


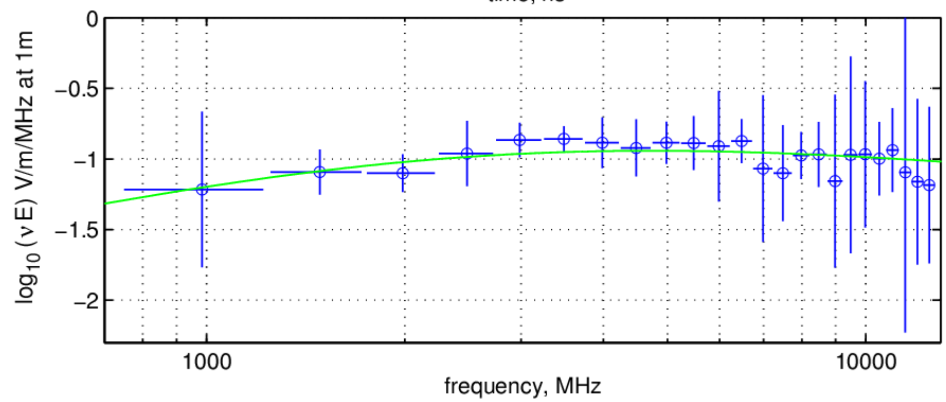


- Target: 6 tons of Morton brick salt
- Provide shower volume and embedded antenna matrix
- Antennas sample 21 grid-points along shower, dual polarization

RF Coherence vs. energy & frequency



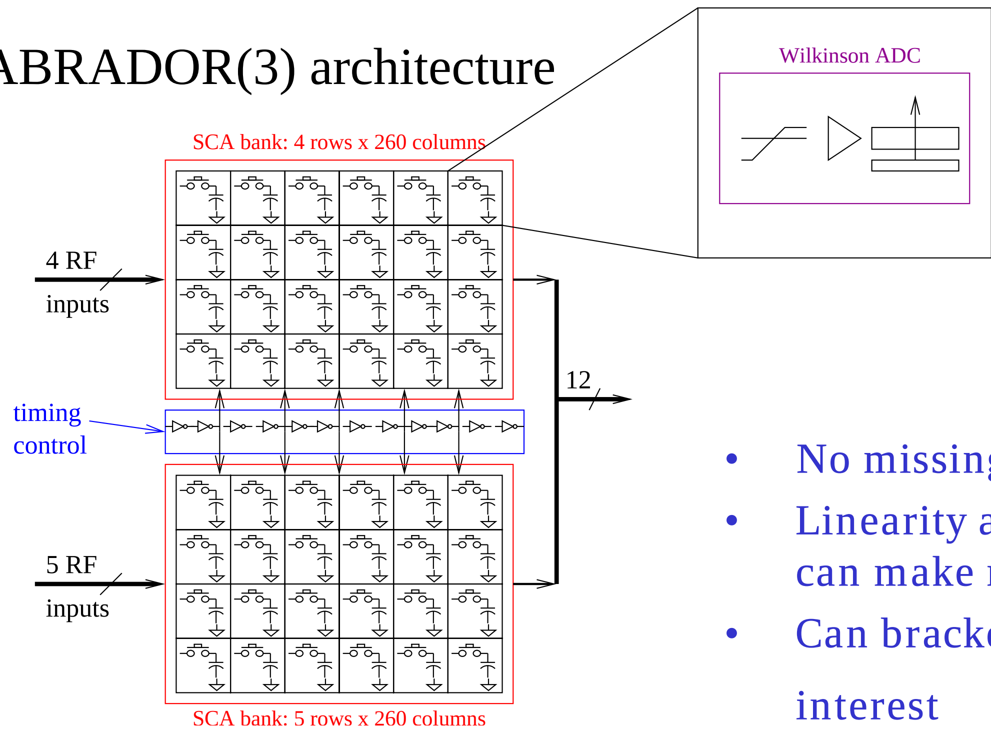


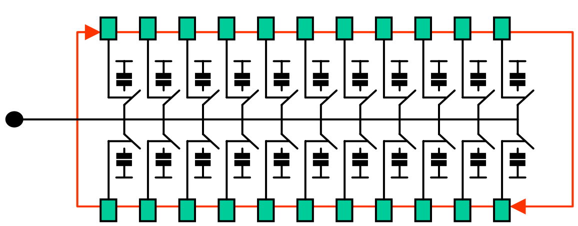


- **Much wider energy range covered than previously: 1PeV up to 10 EeV**
- **Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power**
- **Differs from actual EeV showers only in leading interactions==> radio emission almost unaffected**

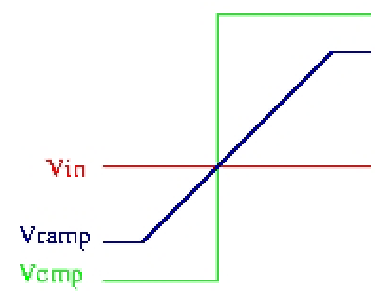
LAB3 Architecture Details

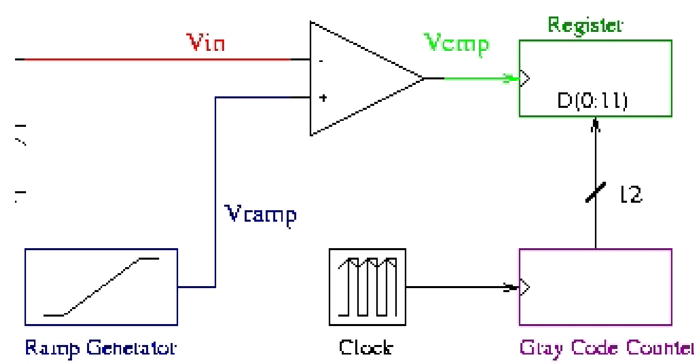
LABRADOR(3) architecture



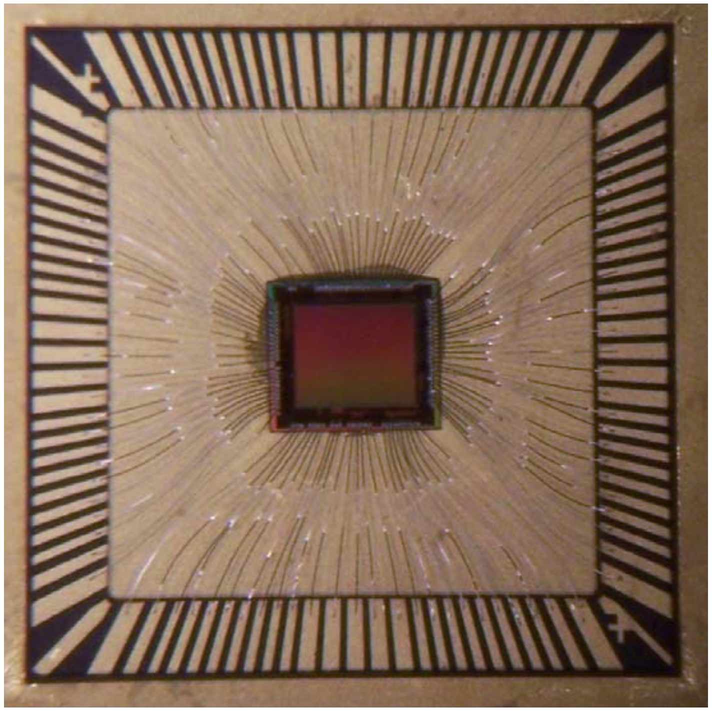


- No missing codes
- Linearity as good as can make ramp
- Can bracket range of interest

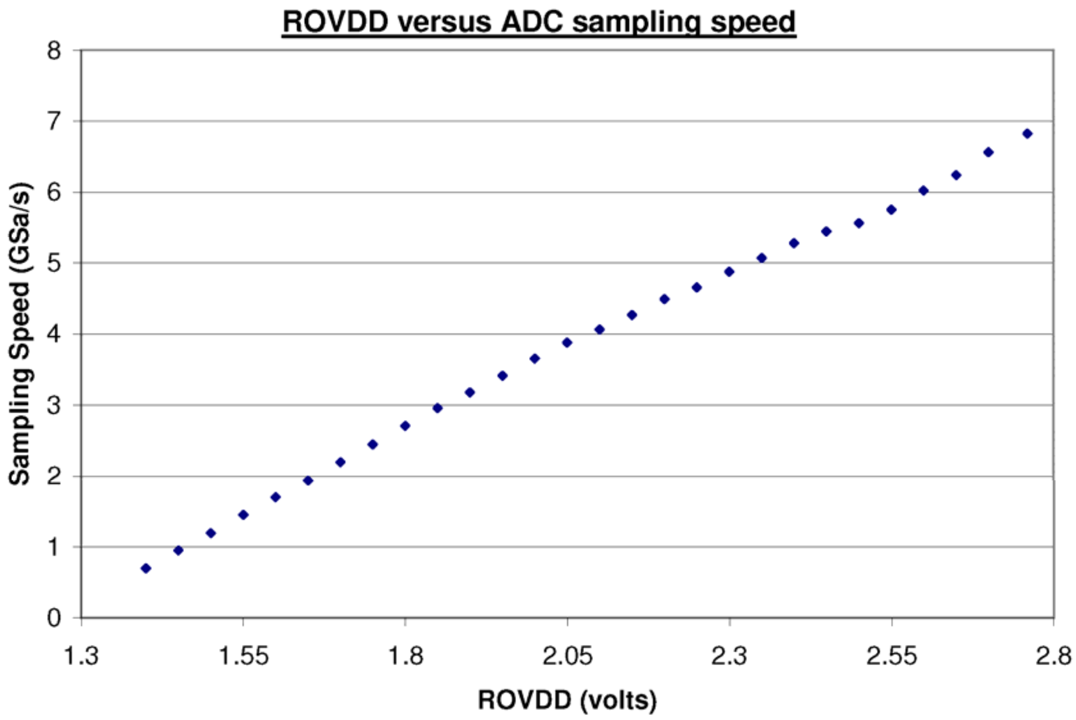




Buffered LABRADOR (BLAB1) ASIC



3mm x 2.8mm, TSMC 0.25um

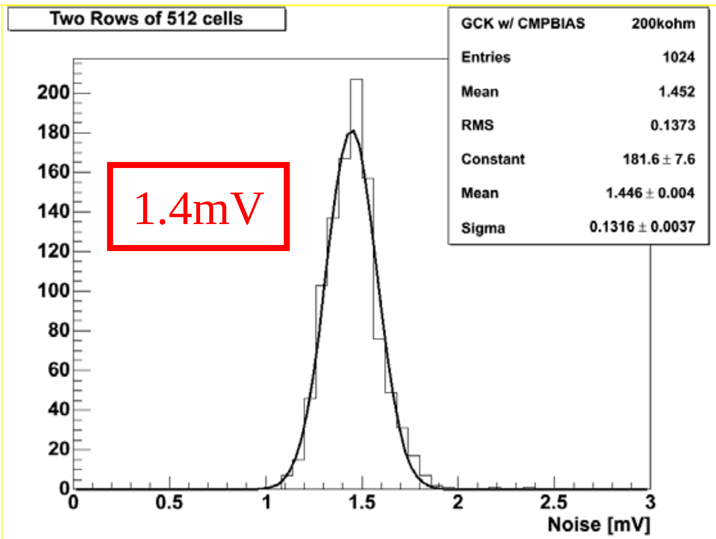


- 64k samples deep
- Multi-MSa/s to Multi-GSa/s
- Local/Global readout mode
- 32-64us to form Global trigger
- See WG7 for details

Just to show not
"pie in the sky"

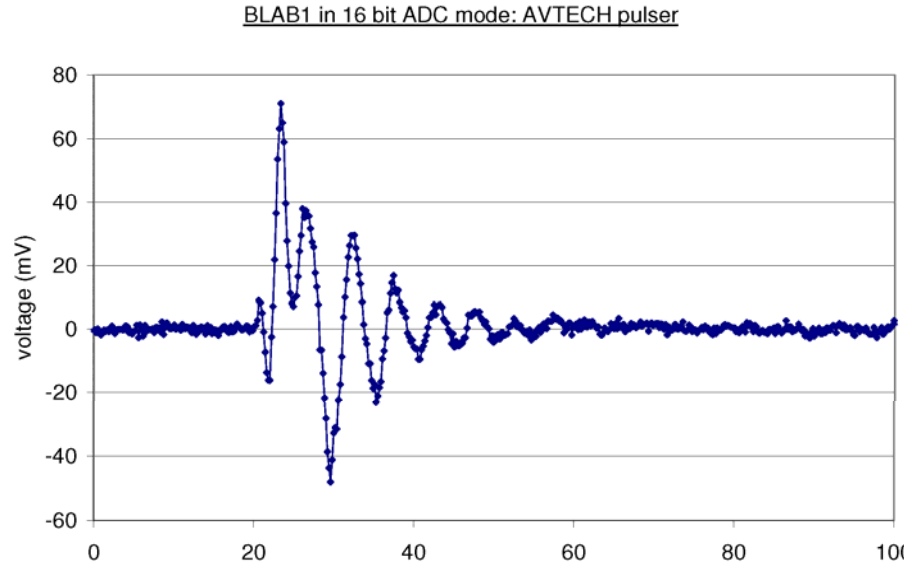
Buffered LABRADOR (BLAB1) ASIC

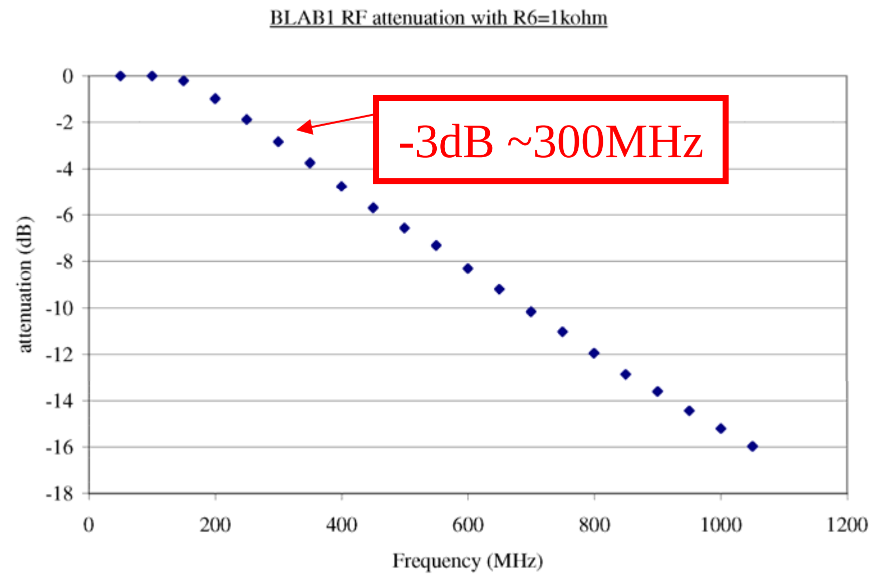
Measured Noise



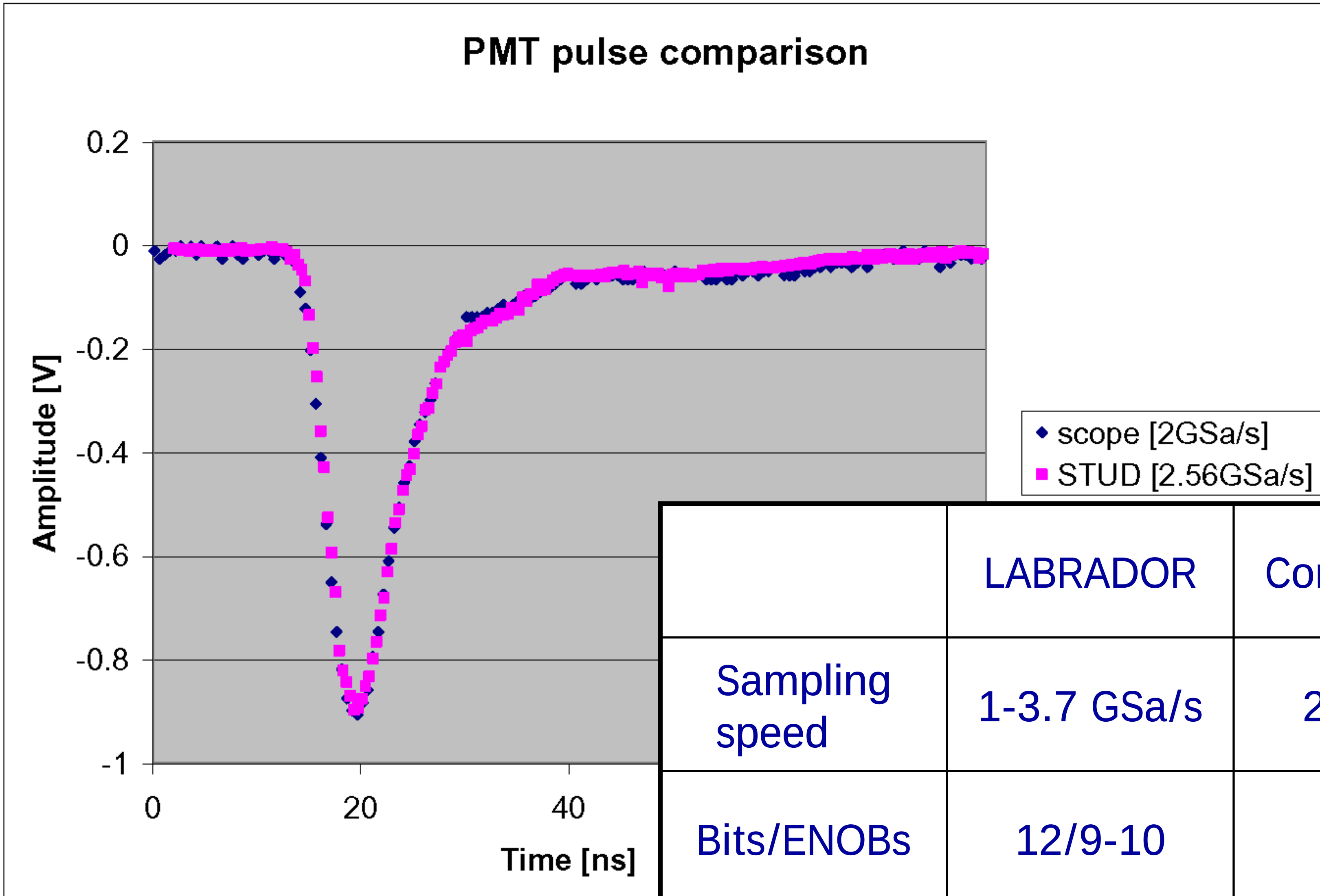
1.8V dynamic range

- 10 real bits of dynamic range
- A few fixes (lower power, higher BW)
- BLAB2 when have money



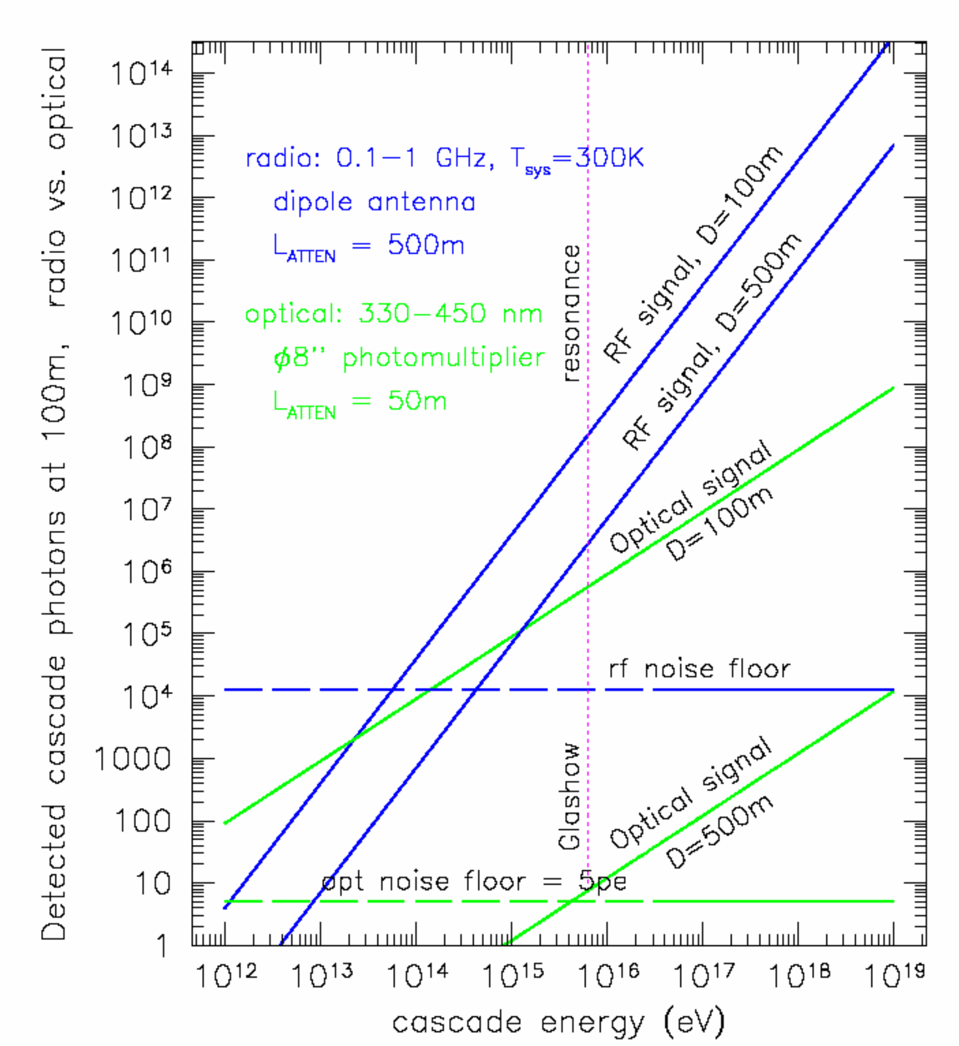


High Speed sampling

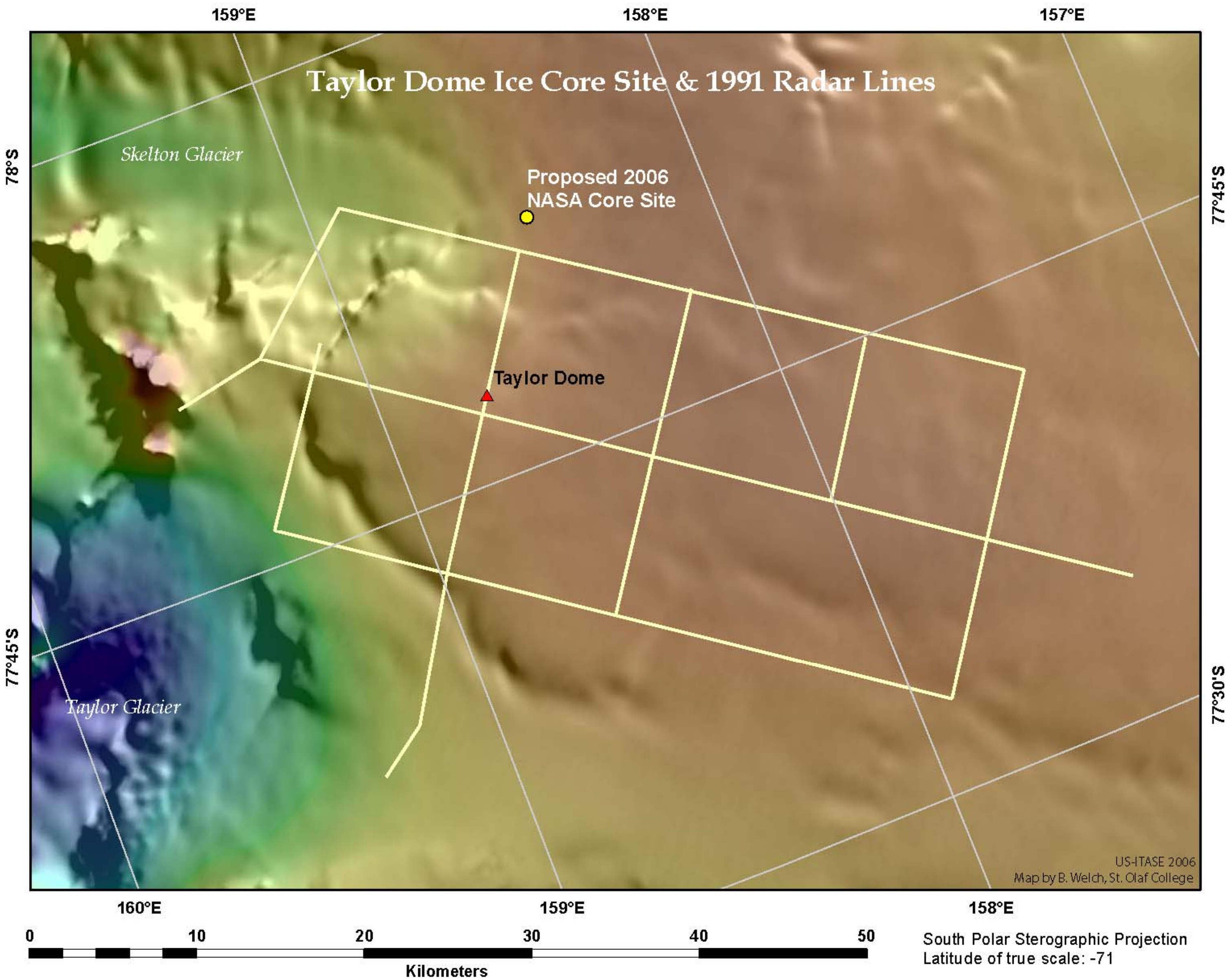


	LABRADOR	Commercial
Sampling speed	1-3.7 GSa/s	2 GSa/s
Bits/ENOBs	12/9-10	8/7.4
Power/Chan.	<= 0.05W	5-10W

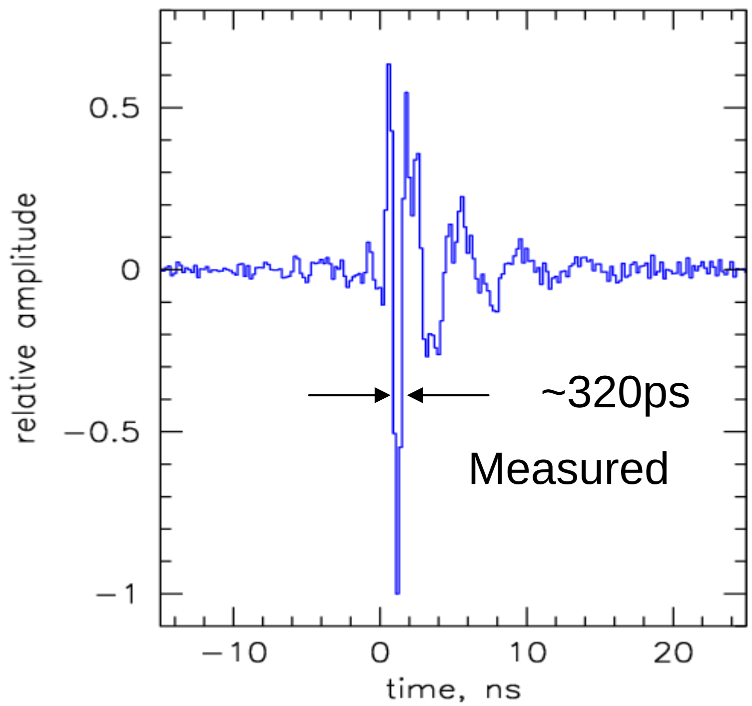
RF/Optical complementarity

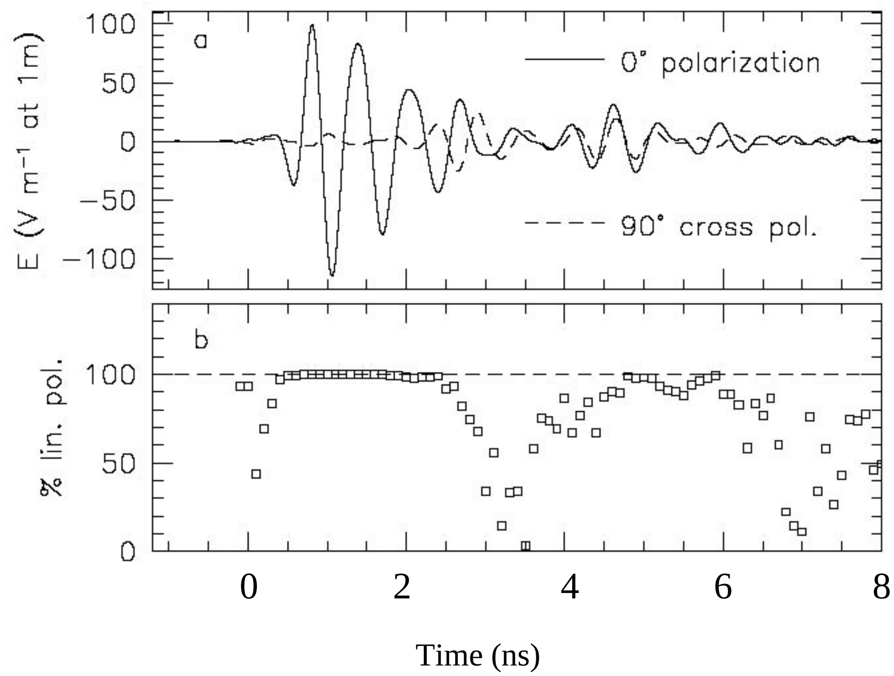


Bore hole pulser at Taylor Dome



Askaryan Signature



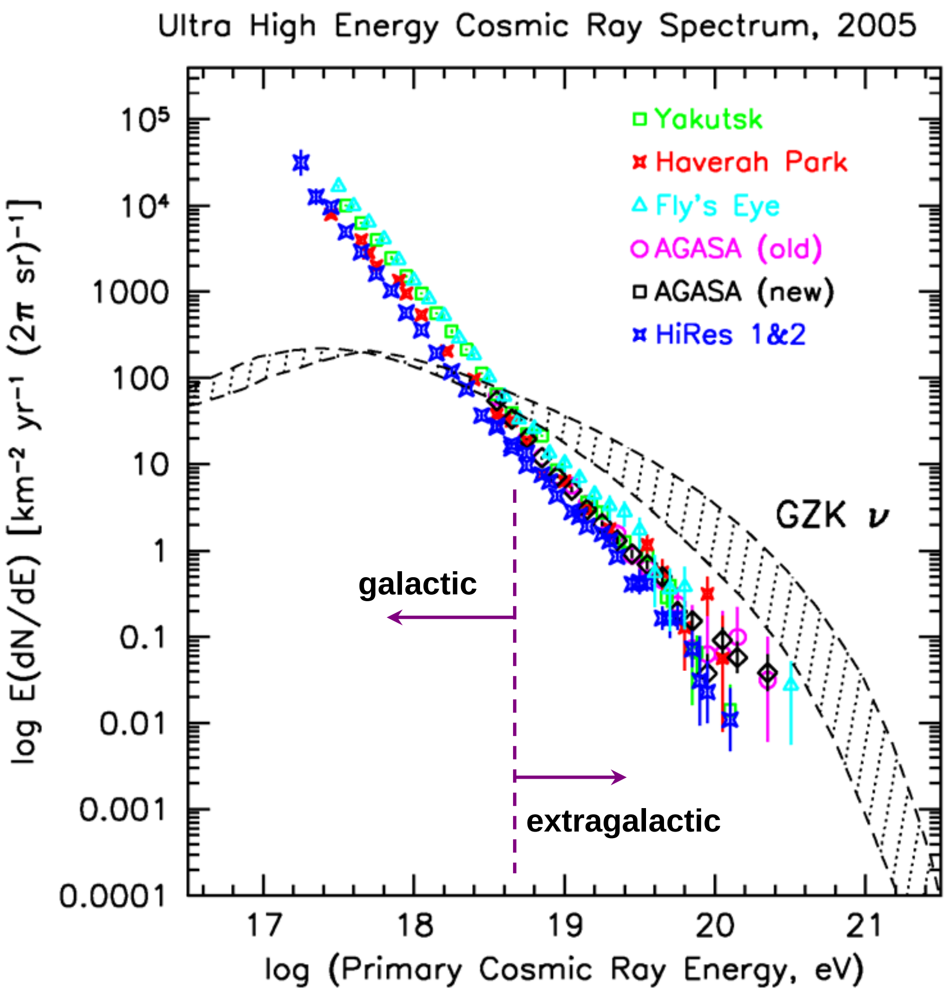


- Significant signal power at large frequencies
- Strong linear polarization (near 100%)

(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



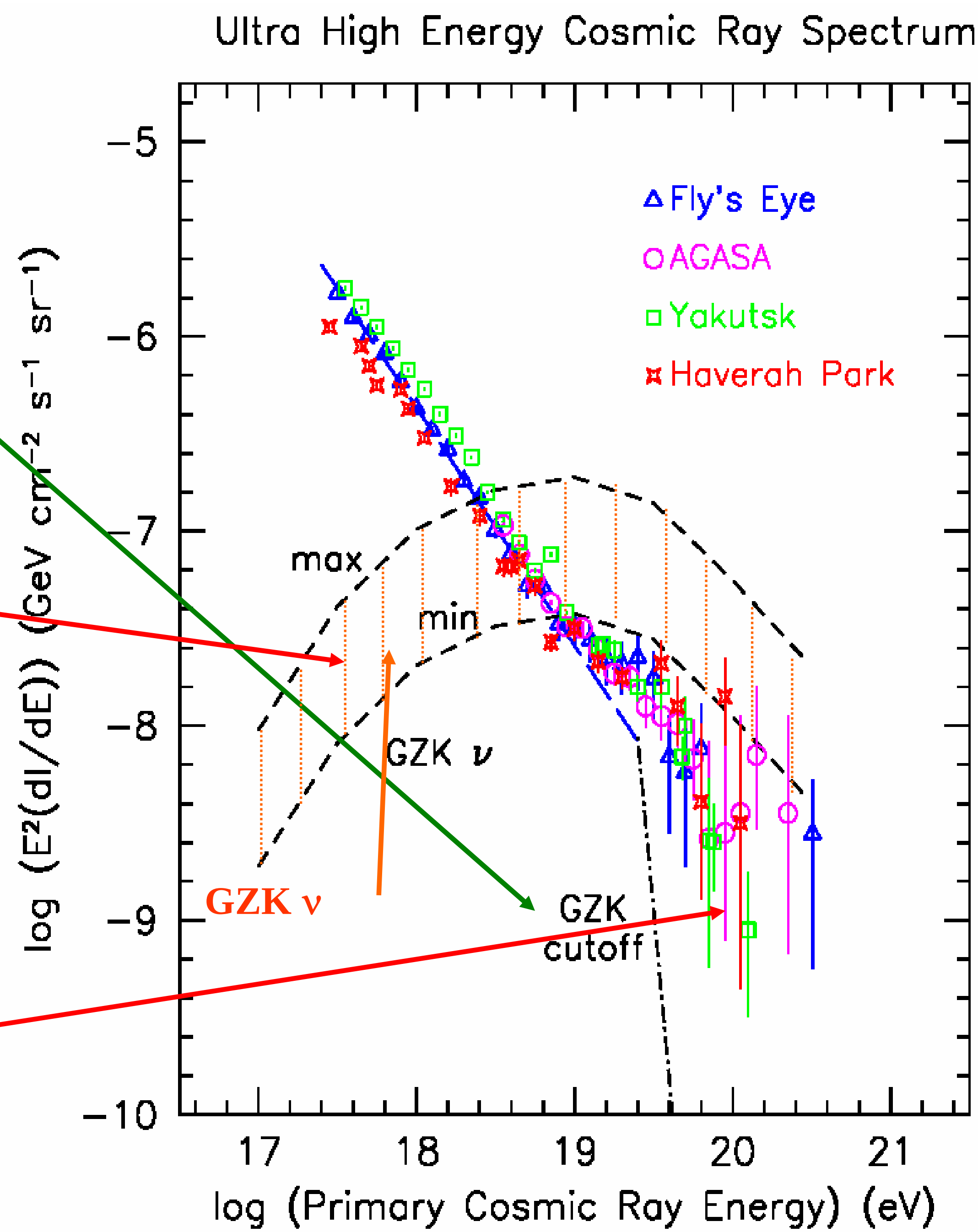
Expectations:

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

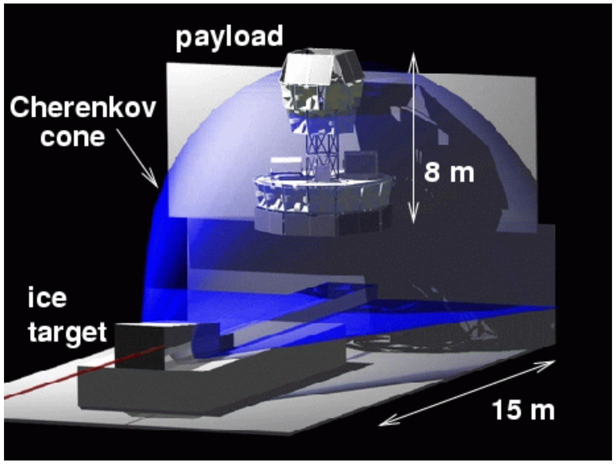
$p * \gamma \rightarrow \Delta \rightarrow n + \pi \rightarrow \nu$

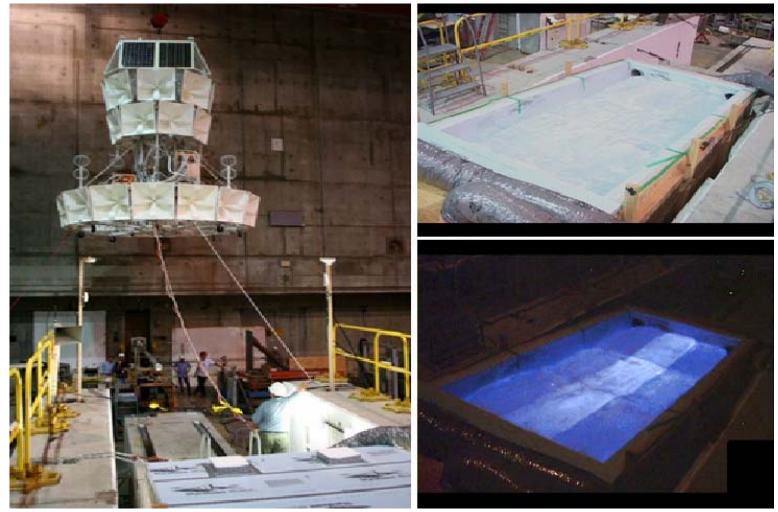
2. These interactions produce a corresponding neutrino flux

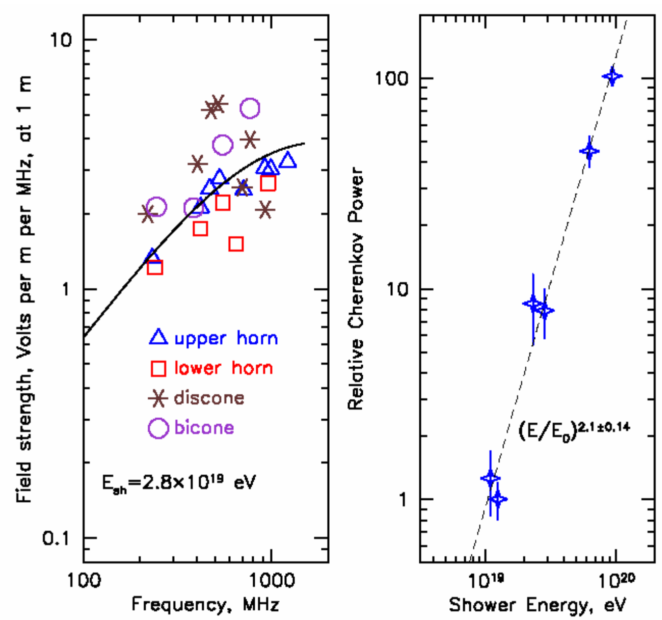
3. Provides a handle on what is going on for these "extra-GZK" events



June 2006, SLAC T486: “Little Antarctica”

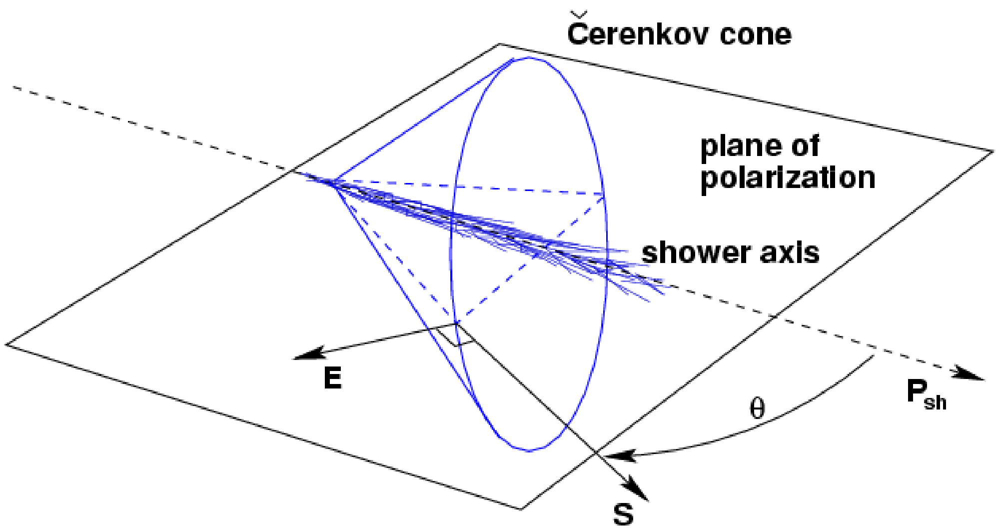






- Stanford Linear accelerator
- Particle (e^-) bunches with composite energy same as UHE neutrinos
- Best possible calibration for ANITA

Cherenkov polarization tracking

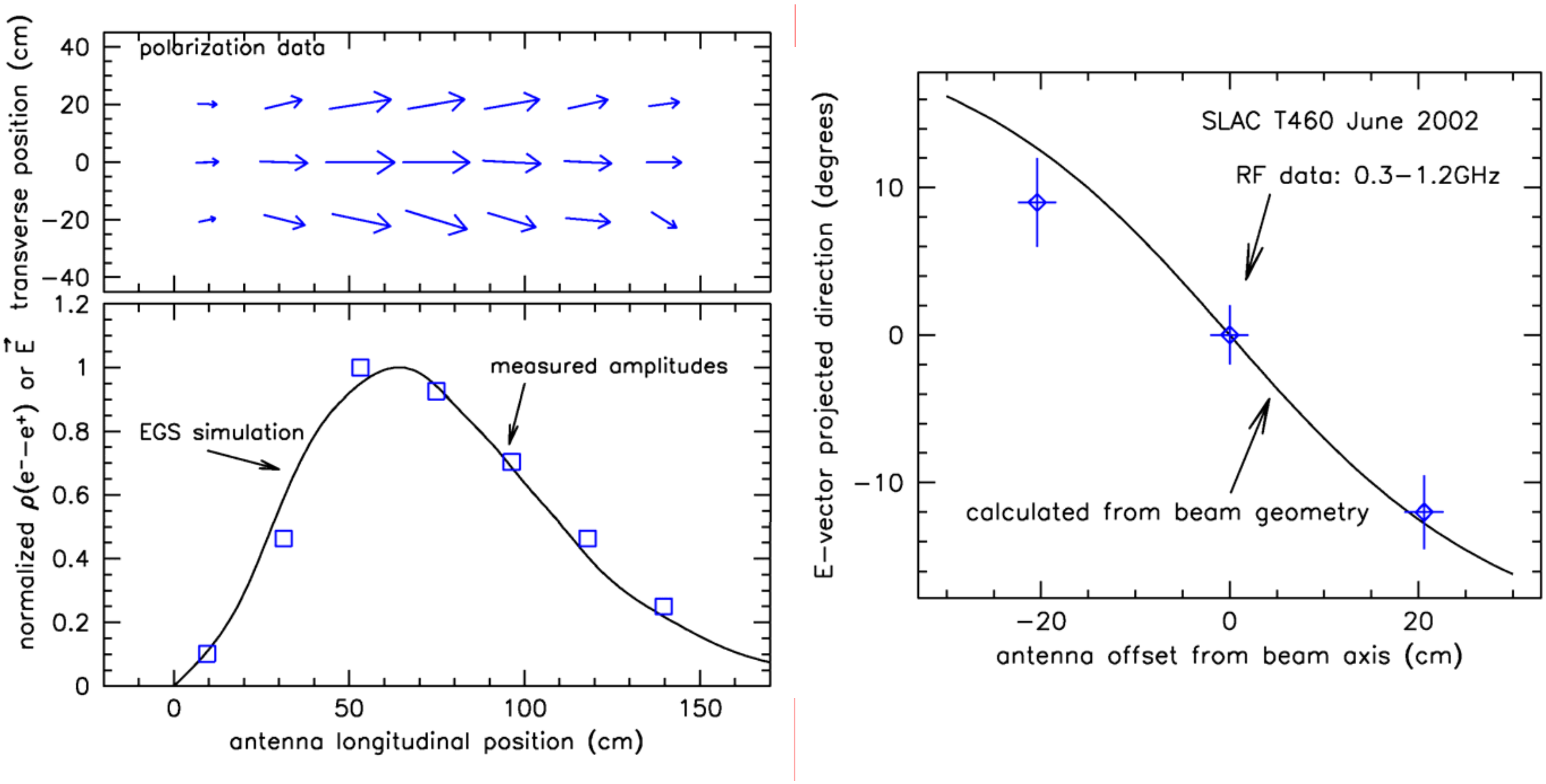


- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - **Intersection of these planes defines shower track**

Cherenkov radiation predictions:

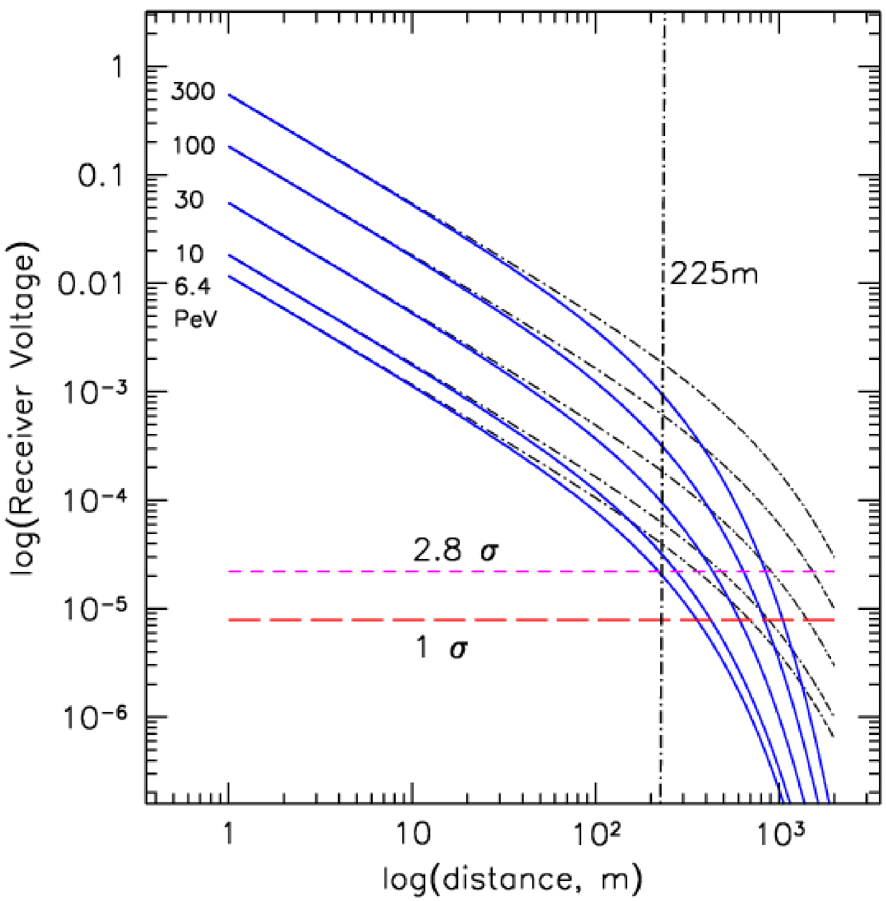
- 100% linearly polarized
- plane of polarization aligned with plane containing Poynting vector **S** and particle/cascade velocity **U**

Polarization tracking



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

Estimated SalSA Energy threshold

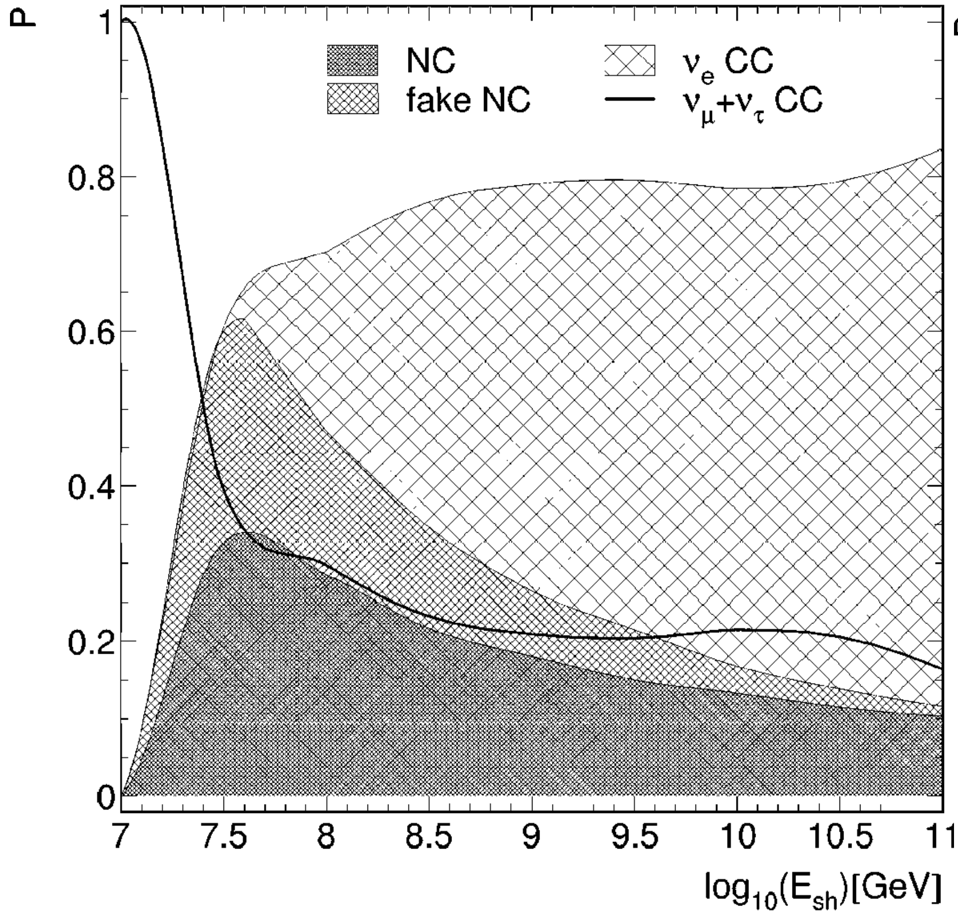


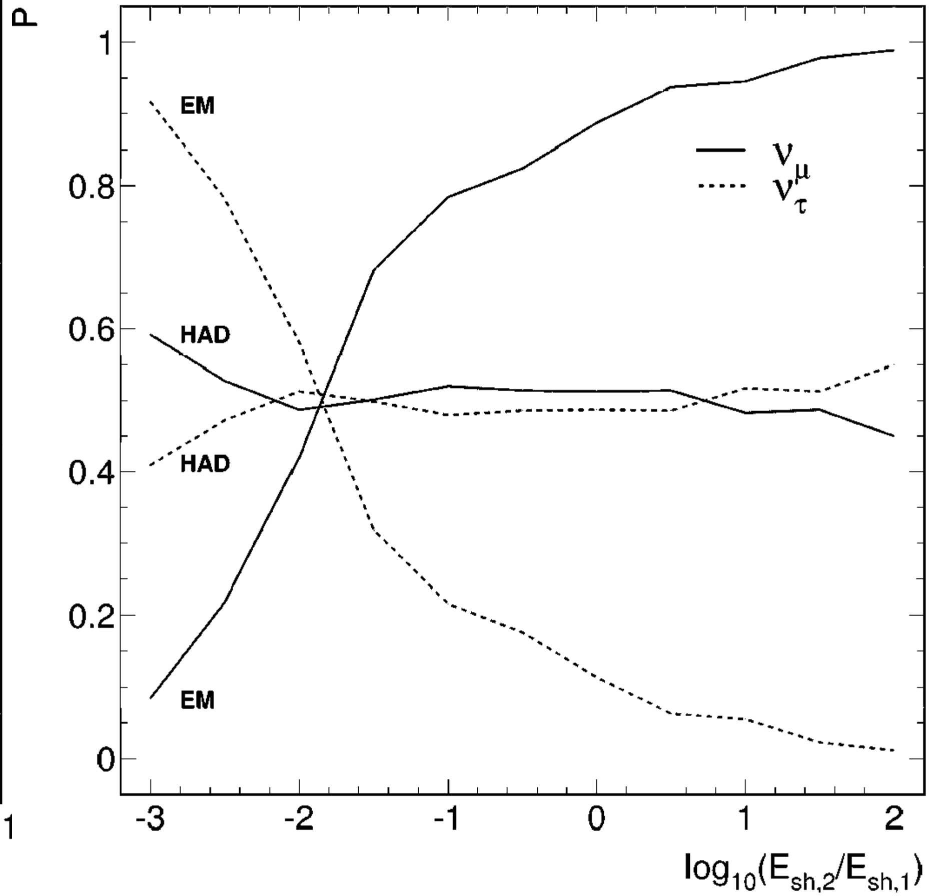
- Ethr < 300 PeV (3 x 10^{18} eV) best for full GZK spectral measurement

- 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

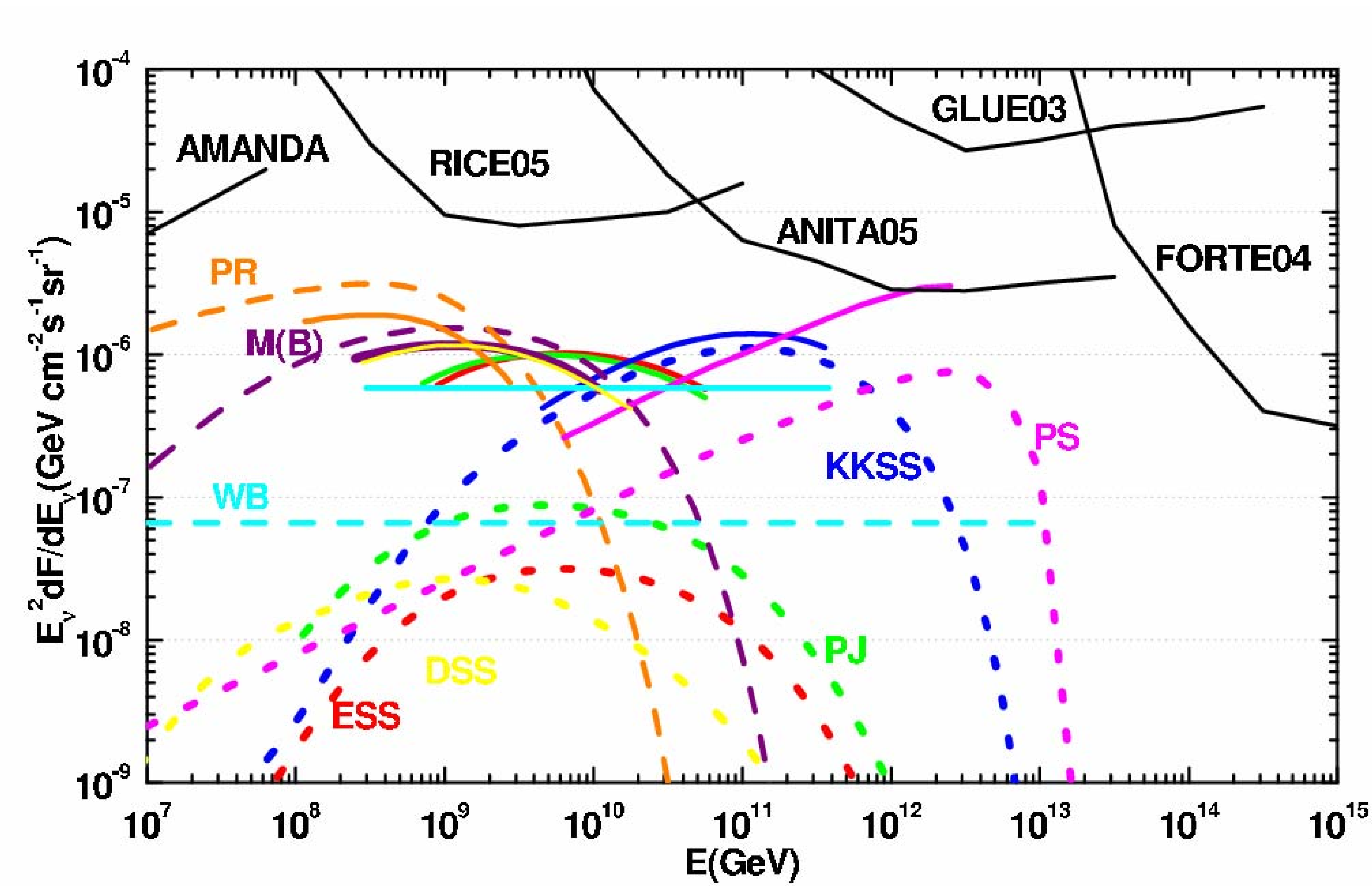
Interaction/PID

Ped Miocinovic (UH)





Upper limits (Hussain)



Cautions: 1) presented upper limits can `float' horizontally (no energy resolution), 2) different model parameters used for different modes, 3) 90% vs. 95% C.L. limits, 4) results depend on binning

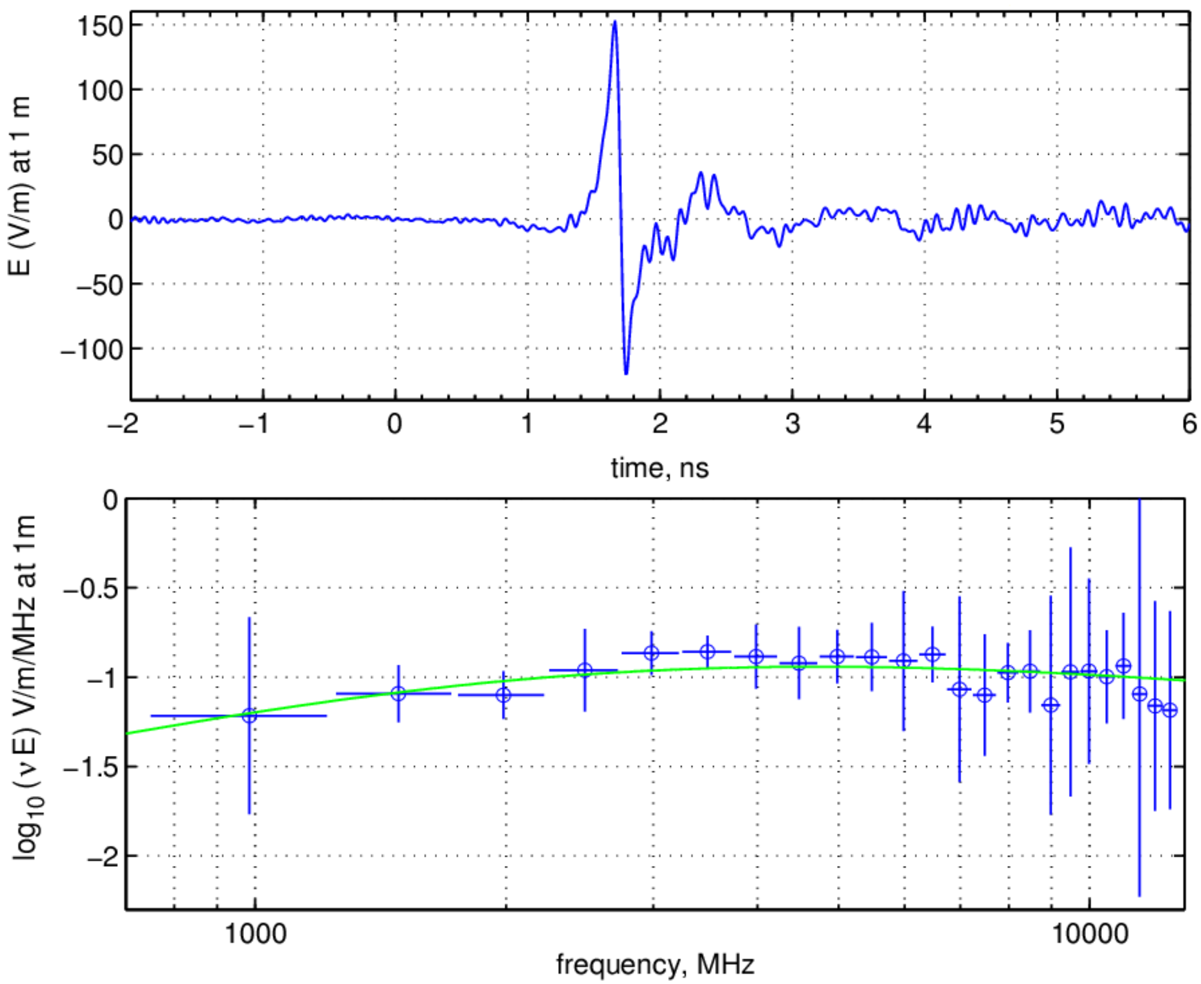
T460 rock-salt target

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