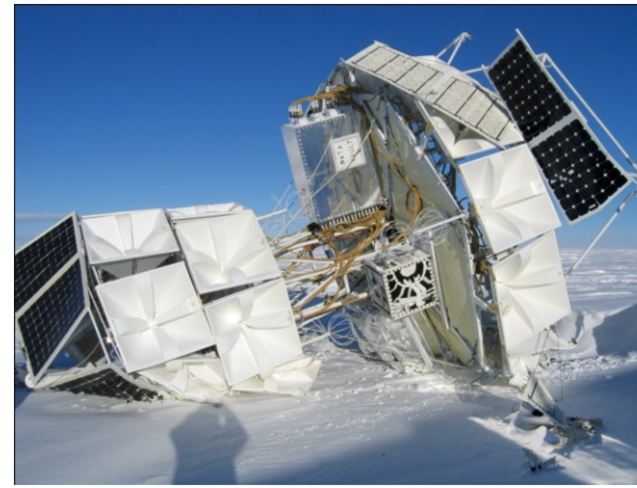
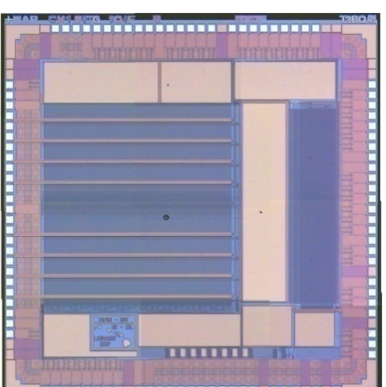
Radio Detection of UHE neutrinos

Photo courtesy Eric Sturm



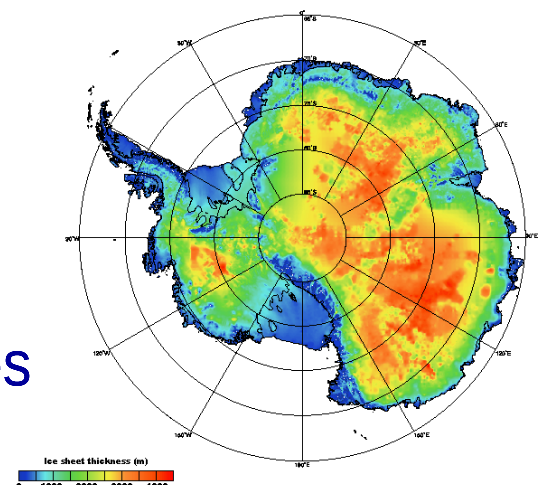


Gary S. Varner

University of Hawai’i

Service de Physique des Particules

Saclay, 2-DEC-2013

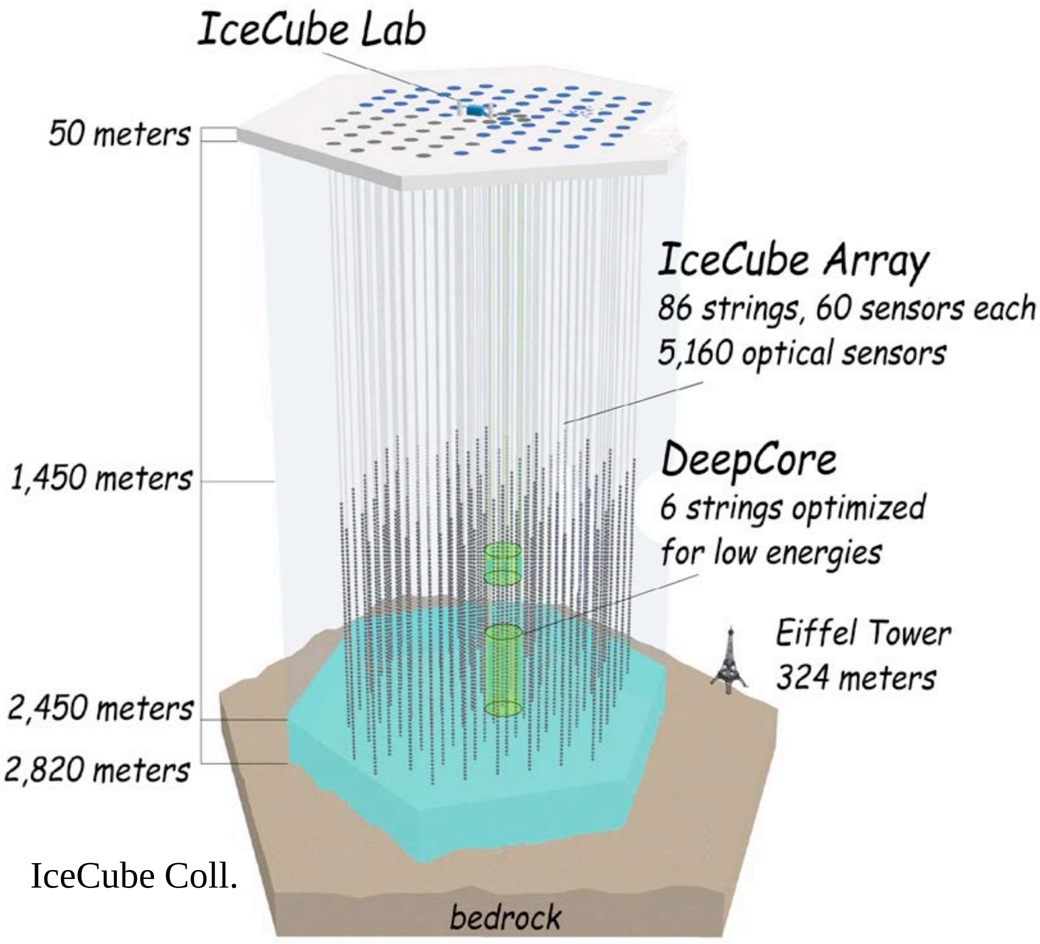


A Search for What Ought to Be

1. A brief introduction to UHE neutrinos
2. Radio Detection of UHE neutrinos
3. ANtarctic Impulsive Transient Antenna (ANITA)
4. Flight # 2 improvements, results
5. Flight # 3, large-scale prospects

Recent Hints from IceCube

First cosmic neutrino events?

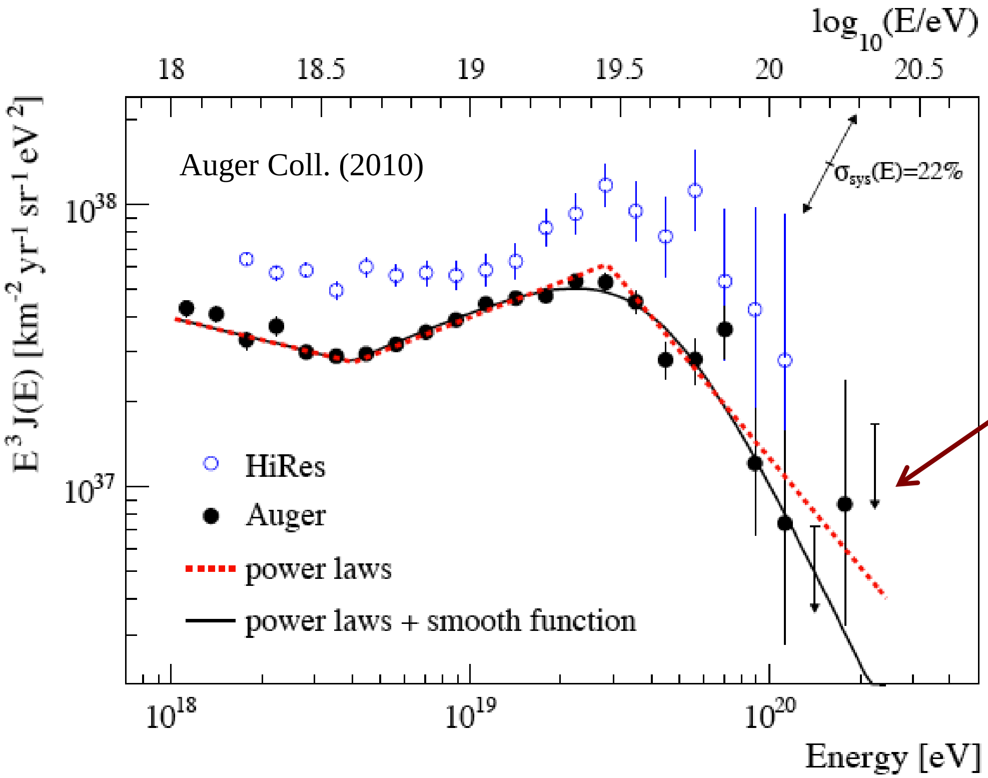


IceCube Coll.

- High energy neutrino analysis
- 672.7 live days (2010-2012)
- 79 string and 86 string configurations
- Two events observed on a background (atmospheric muons and neutrinos) of 0.14
- Energy: (1-2) x 10^{15} eV

Neutrinos: The Ideal UHE Messenger

UHE Cosmic Ray Flux



- Photons lost above 100 TeV (pair production on CMB & IR)
  - Protons and Nuclei suffer curvature induced by B fields
- But: we know there are sources up to 10^{20} eV!!

UHE Neutrino Detectors:

- Highest energy observation of extragalactic sources
  - Very distant sources
  - Deep into opaque sources

UHE Neutrinos: The GZK Process

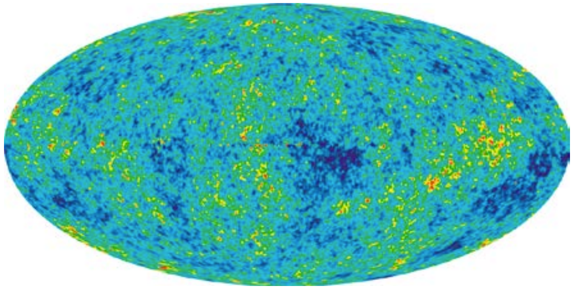
GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\rightarrow e^+ + \boxed{\bar{\nu_\mu} + \nu_e}$$

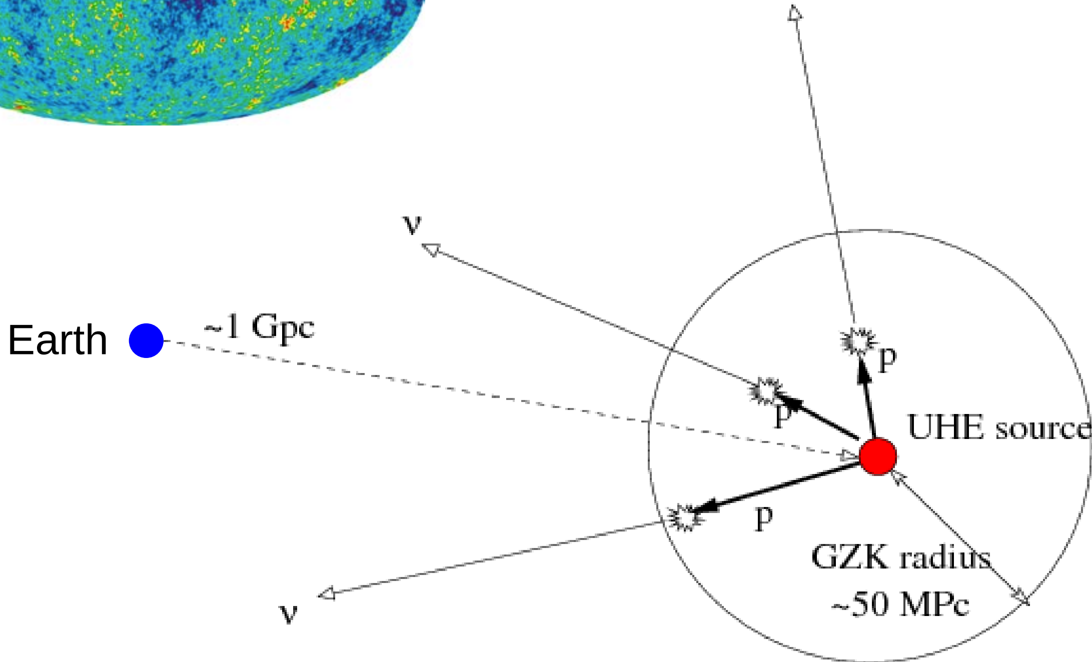
cosmic rays

+

CMB

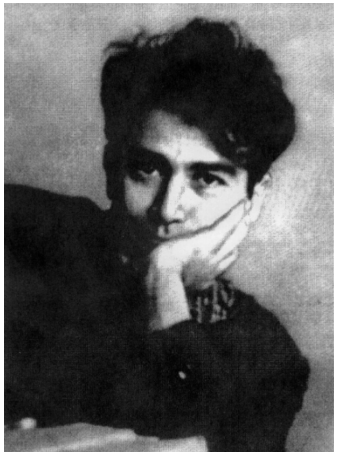


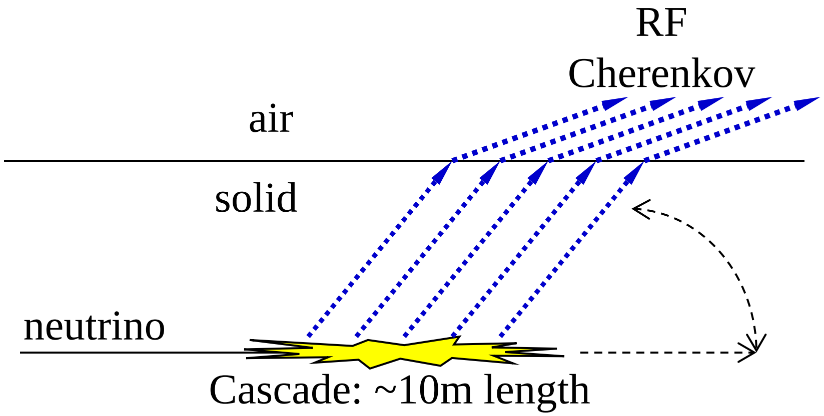
= Neutrino Beam!



Discover the origin of high energy cosmic rays through neutrinos?

Radio Observation in dense media





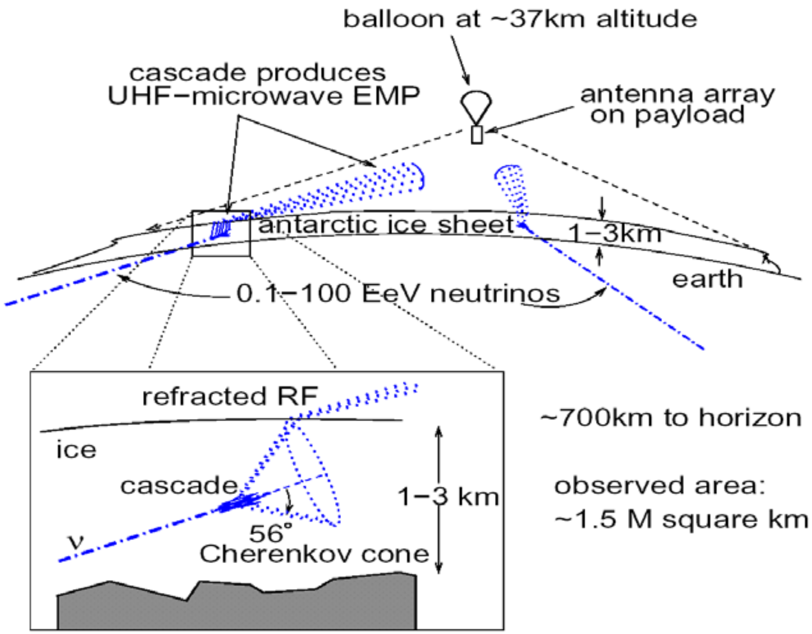
1960's: Askaryan predicted that the resultant compact cascade shower (1962 JETP **14**, 144; 1965 JETP **21**, 658):

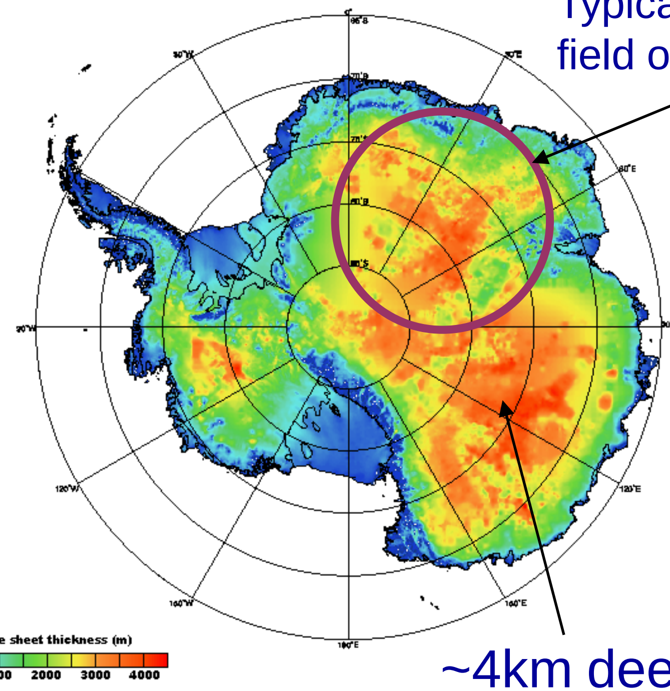
- would develop a local, relativistic net negative charge excess
- would be coherent ($P_{rf} \sim E^2$) for radio frequencies
- for high energy interactions, well above thermal noise:
  - detectable at a distance (via antennas)
  - polarized – can tell where on the Cherenkov cone

Design for discovery of GZK ν flux

- Huge Volume of solid, RF-transparent medium: Antarctic Ice Sheet
- 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 (balloon altitude)

ANITA concept

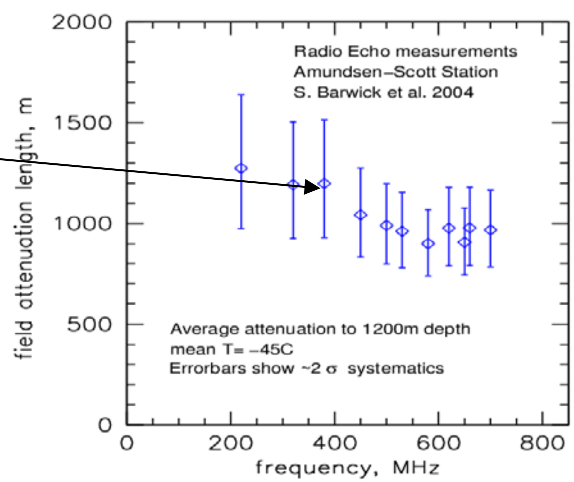




Typical balloon field of regard

~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)

However, there were skeptics

Askaryan Effect Observed at SLAC

Beamtest at SLAC: proof of Askaryan effect in ice

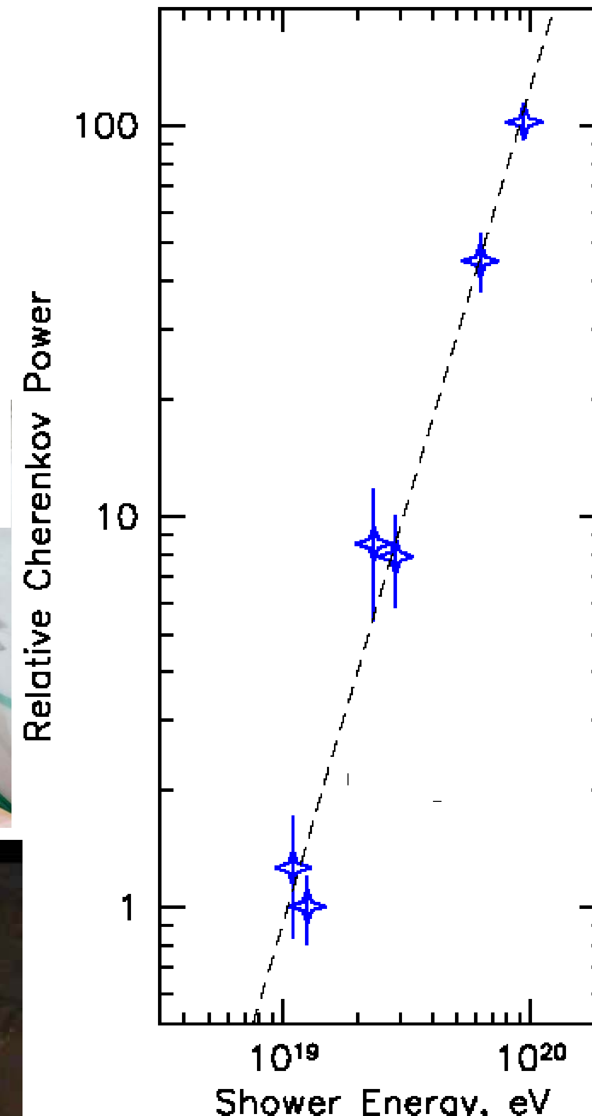
28.5 GeV shower x 10^9 particles/shower

- Coherent ($P \sim E^2$)
- Linearly Polarized

Askaryan Effect also seen in the lab in sand and salt

7.5 tons of ice

ANITA Coll., PRL (2007)



The Faces Behind ANITA

University of California, Irvine

Ohio State University

University of Kansas

Washington University in St. Louis

University of Delaware

University of California, Los Angeles

University of Hawaii at Manoa

National Taiwan University

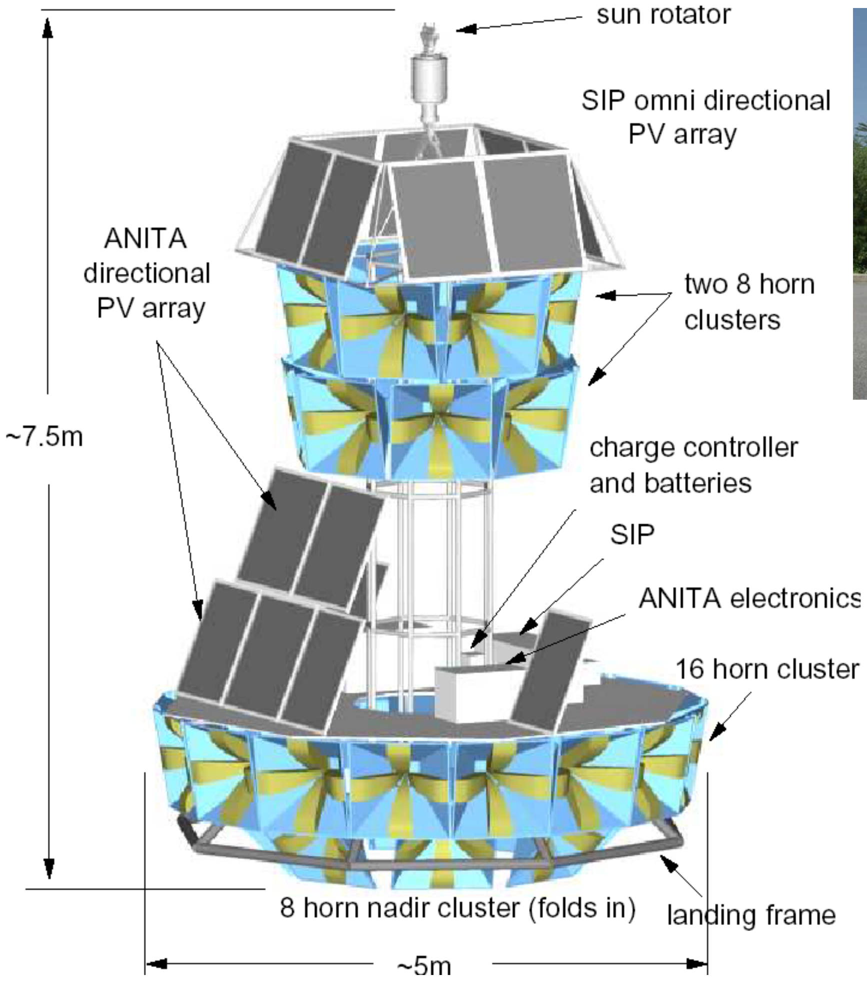
University College London

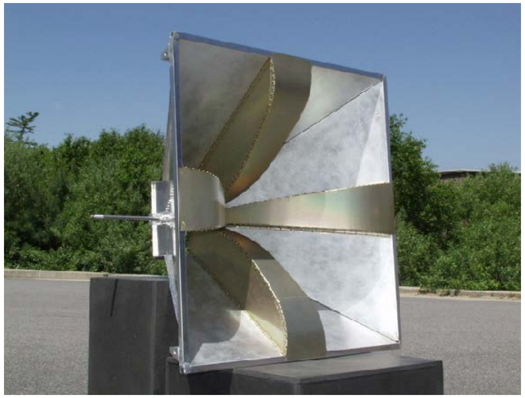
Jet Propulsion Laboratory

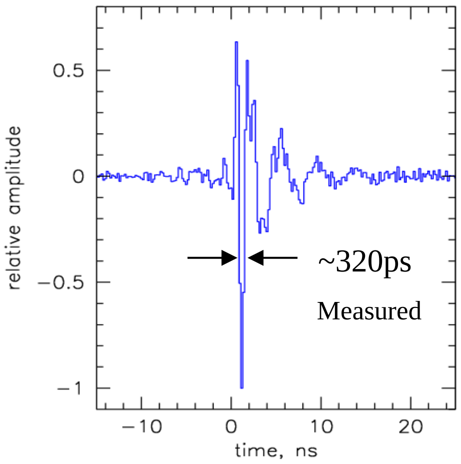
Stanford Linear Accelerator Center

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

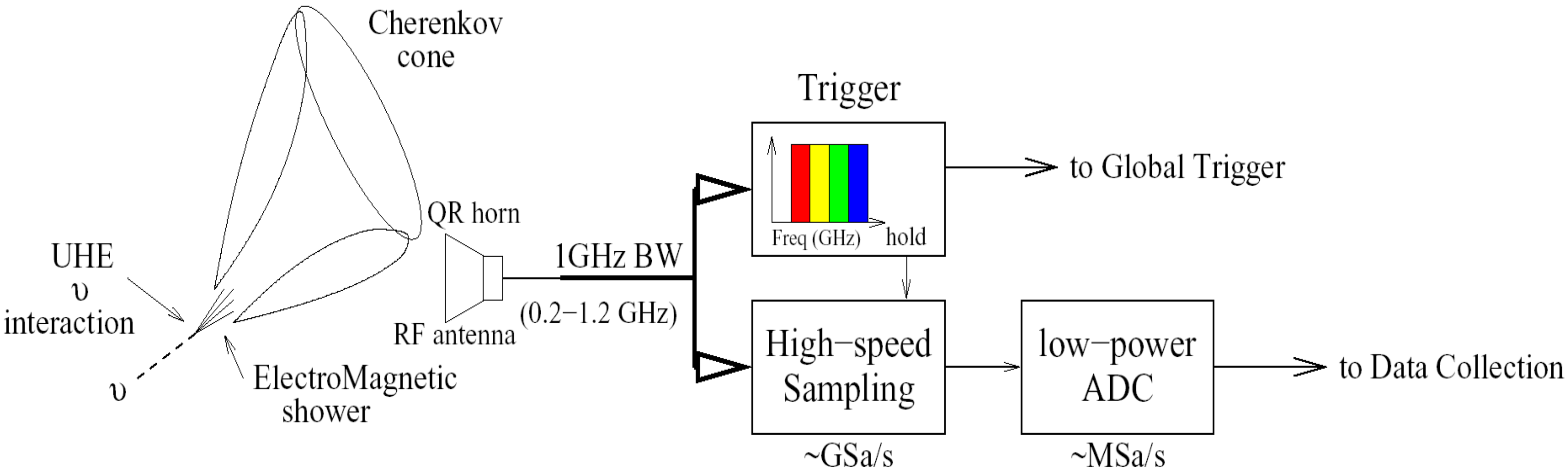
Major Hurdles

- No commercial waveform recorder solution (power/resolution)

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

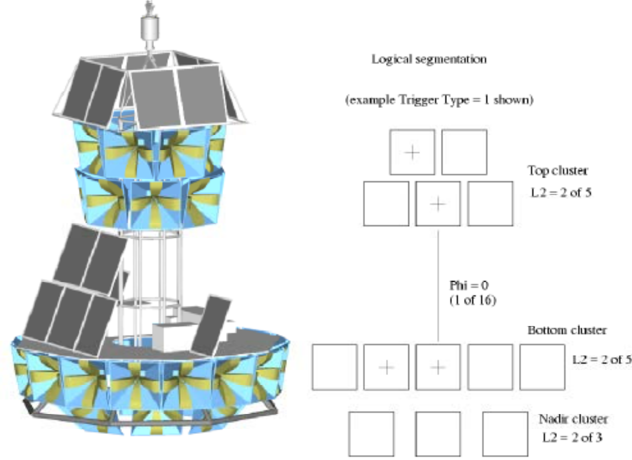
- Without being able to record or trigger efficiently, there is no experiment

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

Trigger Reduction



Raw Signals

Level-1

Antenna

3-of-8

Level-2

Cluster

2-of-5

Level-3

Phi

2-of-2

Prioritizer (+compress)

Few events/min TDRSS

80 RF channels
@ 1.5By * 2.6GSa/s
= 312 Gbytes/s

100-200kHz
@ 36kBy/evt
= 3.6-7.2Gby/s

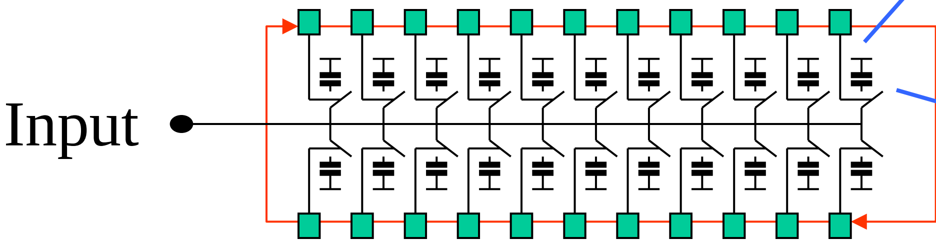
Few kHz
@ 36kBy/evt
= 36-72Mby/s

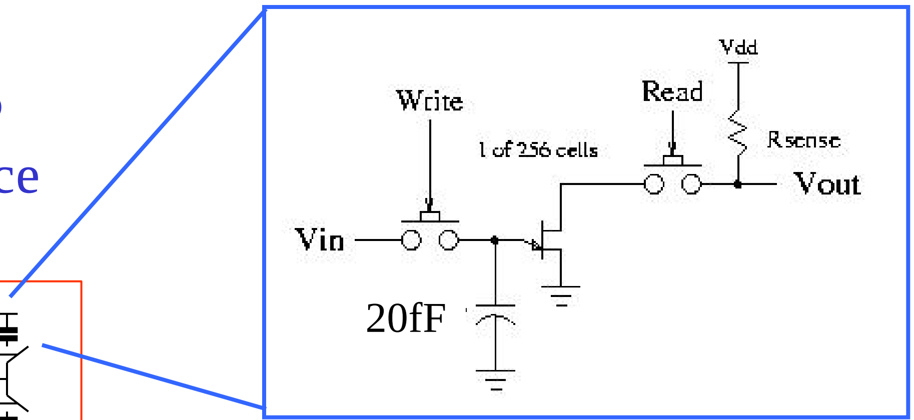
5-10Hz
@ 36kBy/evt
= 180-360kBy/s

To disk

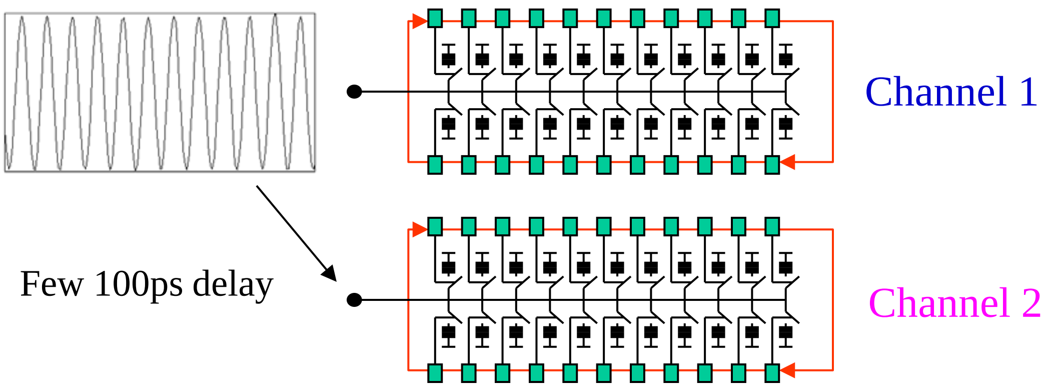
Switched Capacitor Array Sampling

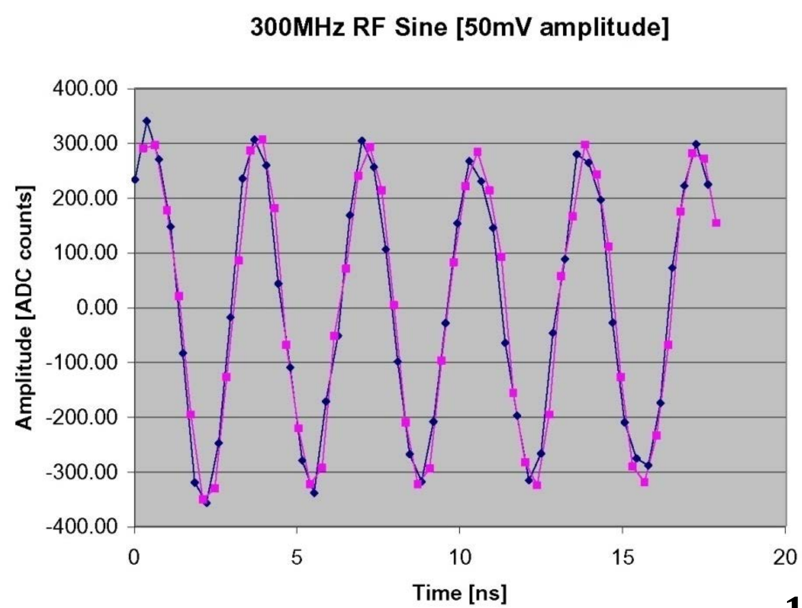
- Write pointer is ~4-6 switches closed @ once





Tiny charge: 1mV ~ 100e^{-}

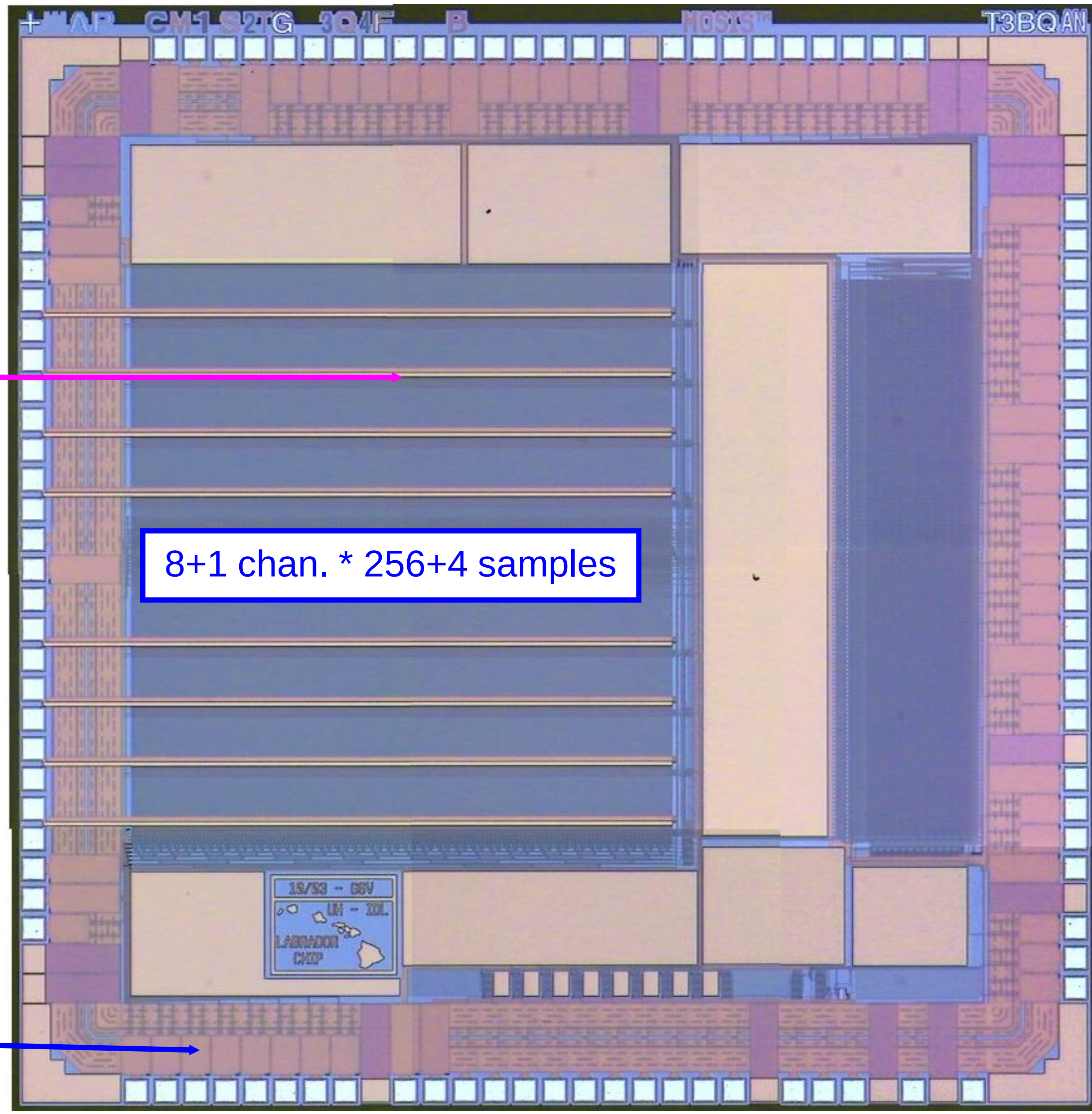




Large Analog Bandwidth Recorder and Digitizer with Ordered Readout [LABRADOR]

Straight
Shot
RF inputs

- Switched Capacitor Array (SCA)
- Massively parallel ADC array
- Similar to other WFS ASICs → <u>analog bandwidth</u>



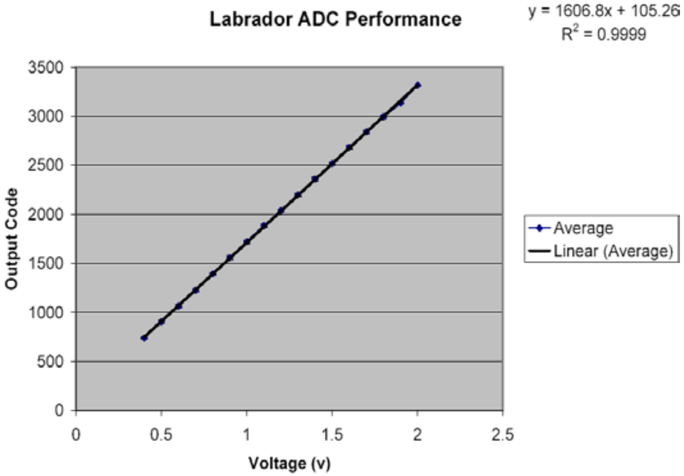
- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 31μs (all 2340 samples)
- Data transfer takes 80μs
- Ready for next event in <150μs

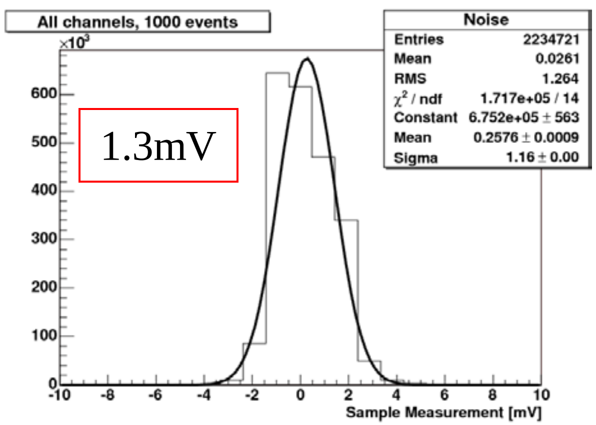
Random access:

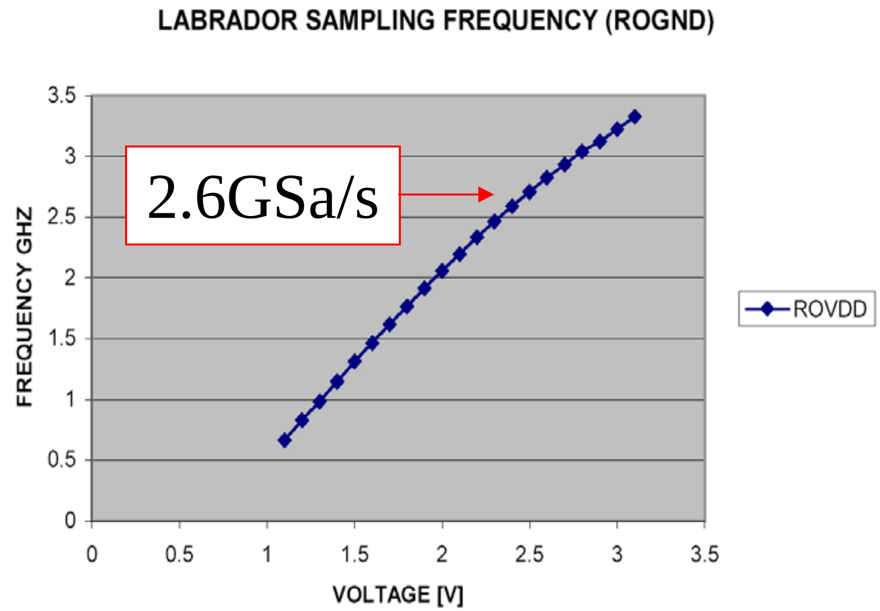
NIM A583:447-460, 2007

LABRADOR performance

12-bit ADC



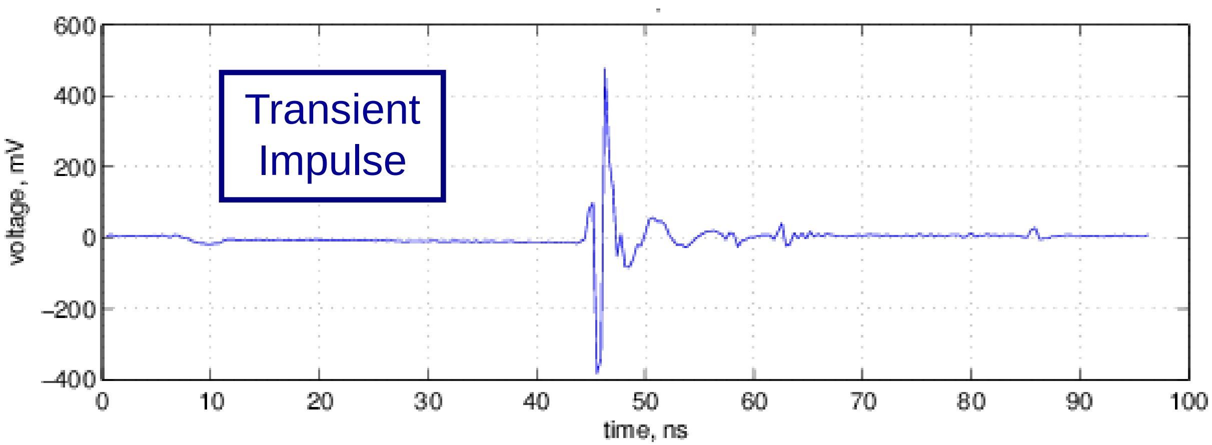


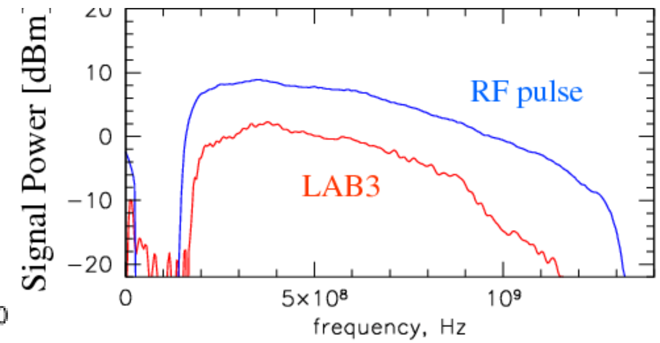


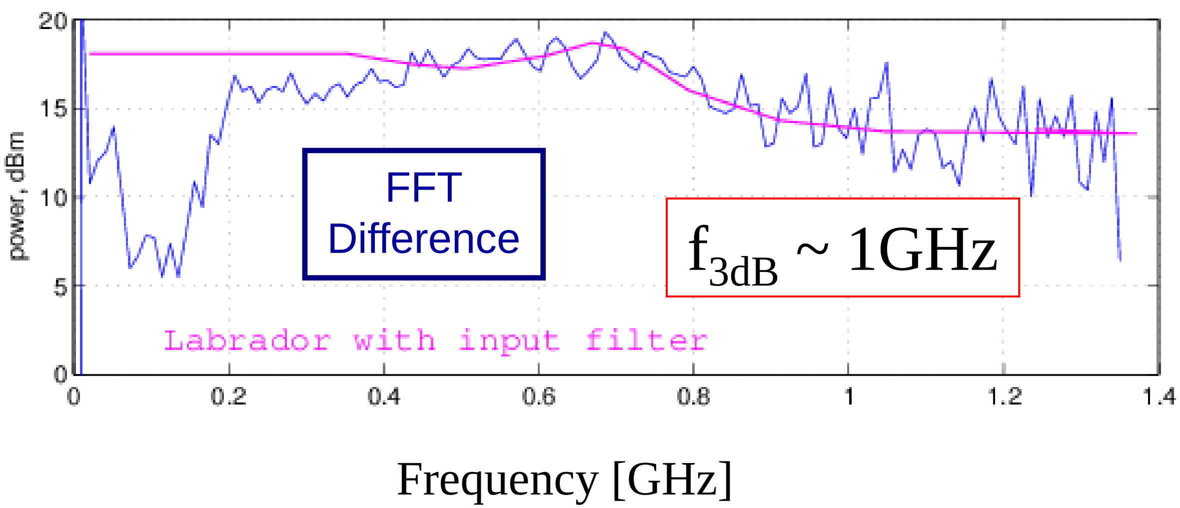
- 10 real bits (1.3V/1.3mV noise)

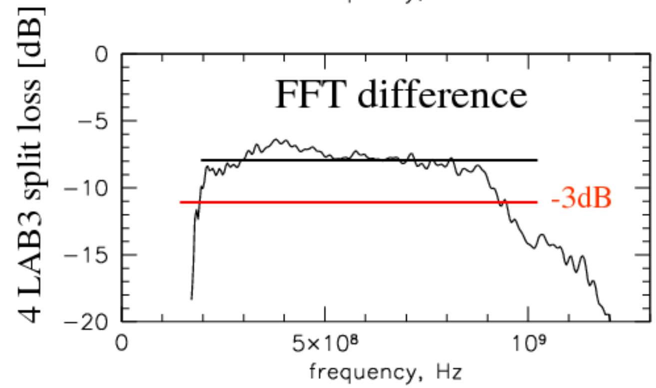
- Excellent linearity, noise
- Sampling rates up to 4 GSa/s with voltage overdrive

Bandwidth Evaluation



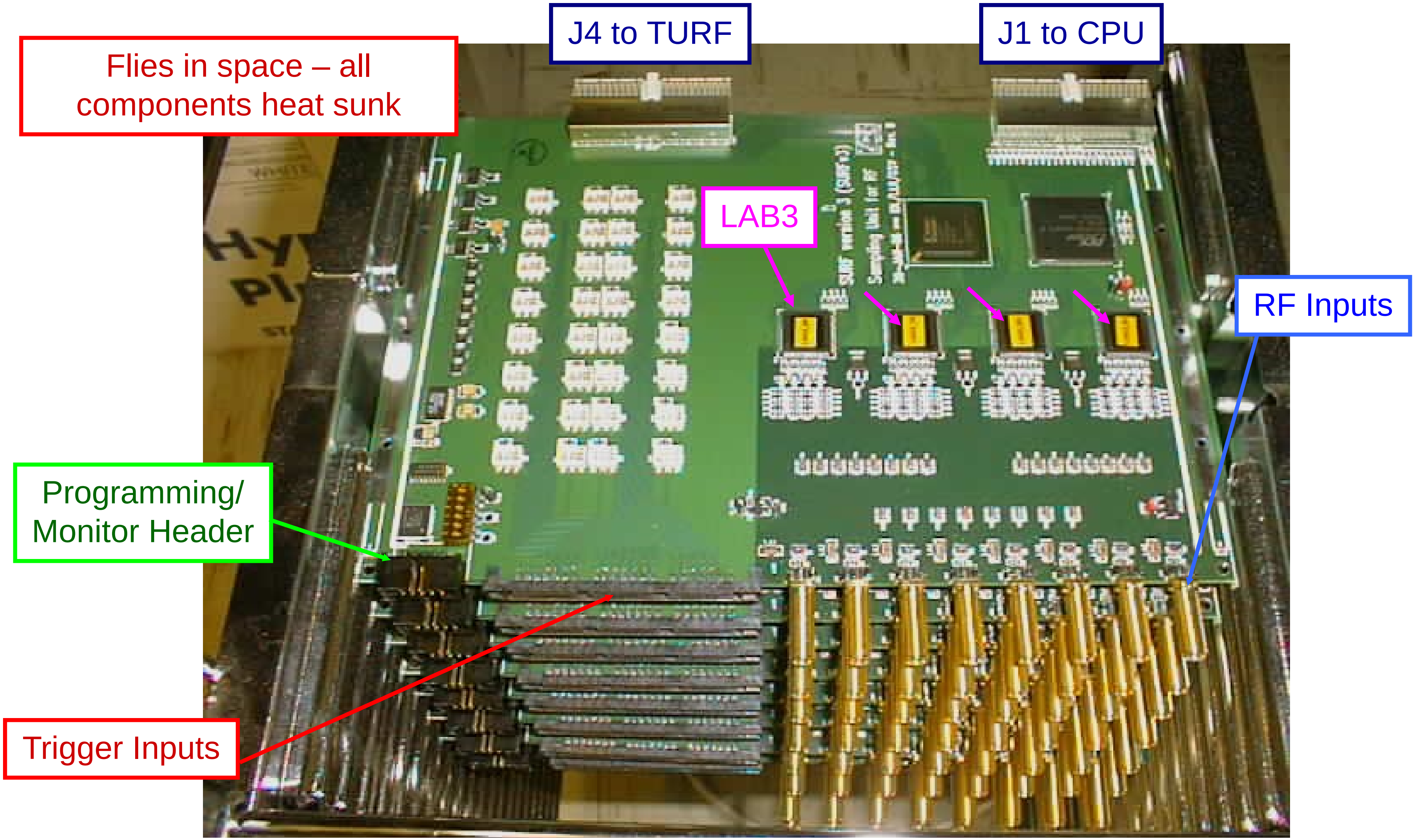




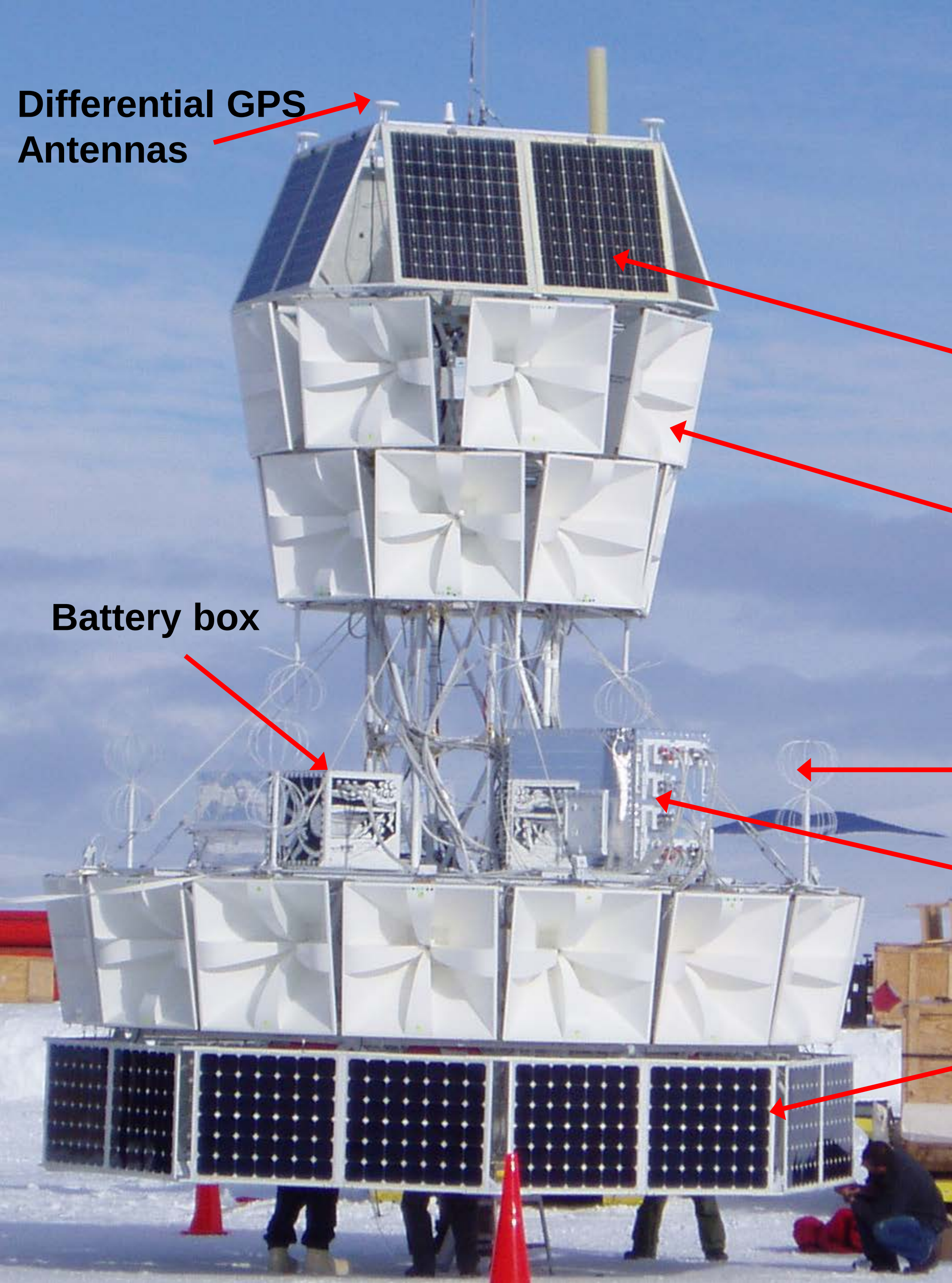


SURFv3 Board

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



ANITA-1 pieces



"instrument paper"
arXiv:0812.1920 [astro-ph]

Solar cells for NASA equipment

32 Quad-ridge horn antennas
- 200 MHz to 1200 MHz
- 10 degree downward angle

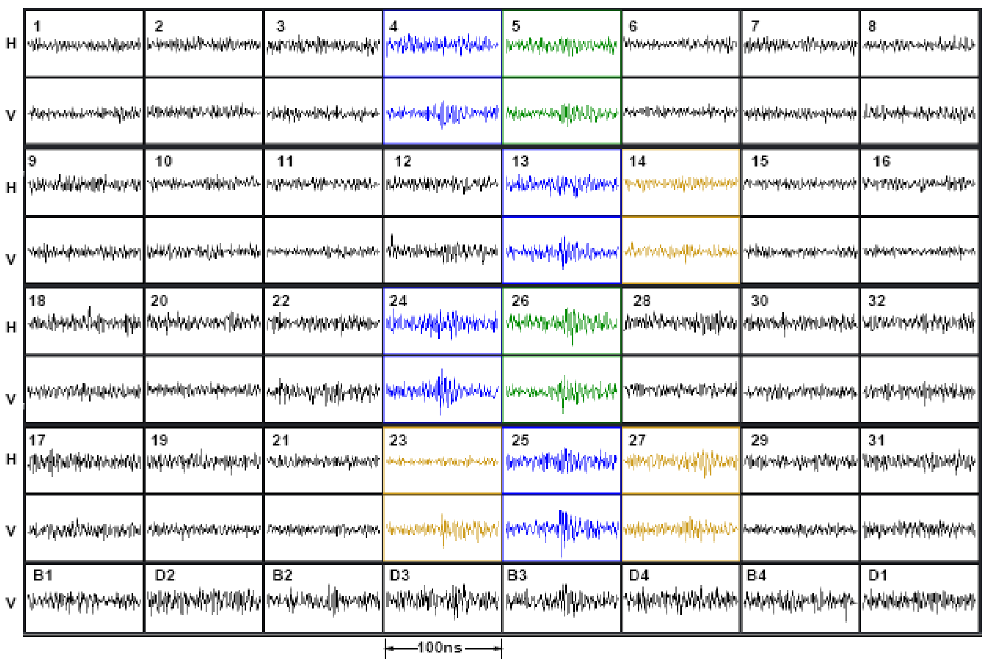
8 low gain antennas to monitor payload-generated noise

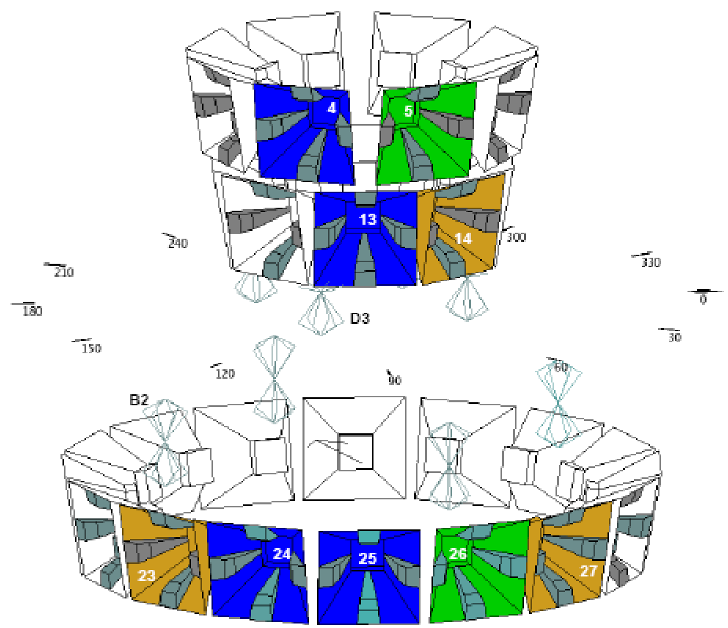
ANITA electronics box

Solar panels for science mission

Trigger/Readout information

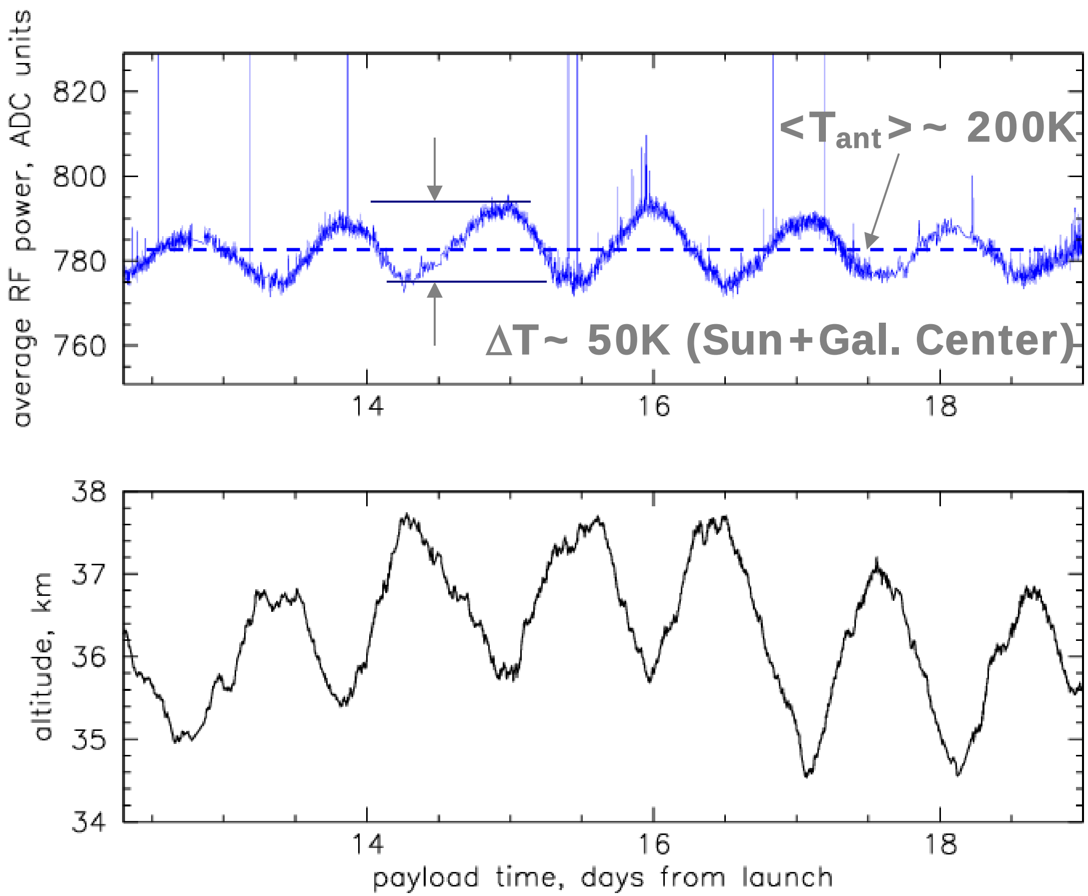
- This example Event most likely West Antarctica camp noise
- Triggers:
  - Yellow, L1: impulse above thermal noise for an individual antenna; ~150 kHz
  - Green, L2: coincidence between adjacent L1 in the same ring; ~40kHz
  - Blue, L3: coincidence between L2 triggers in same phi sector; ~5Hz





Gorham et al., arXiv:0812.1920v1 [astro-ph]

Flight sensitivity snapshot



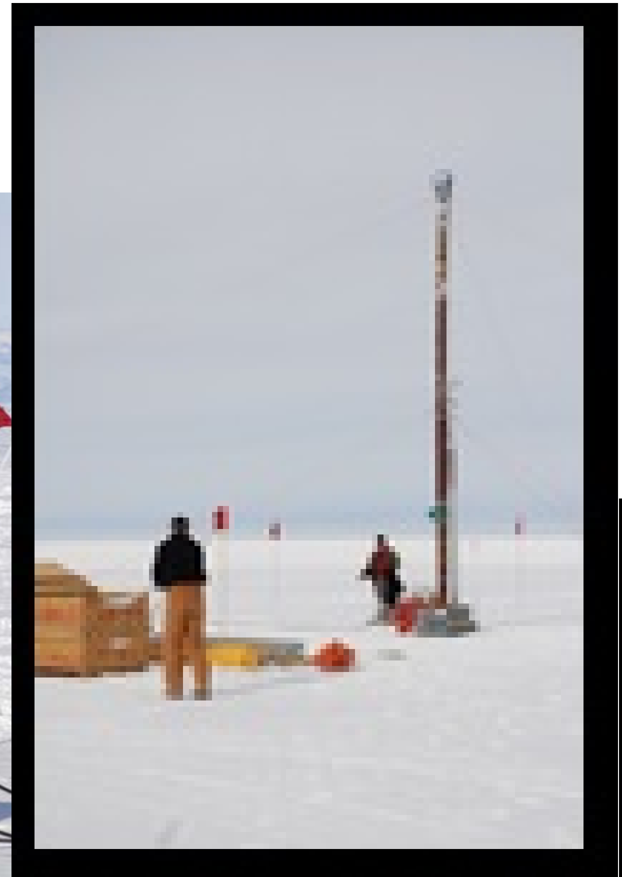
- ANITA sensitivity floor defined by thermal (kT) noise from ice + sky
- Thermal noise floor seen throughout most of flight—but punctuated by station & satellite noise
- Significant fraction (>40%) of time with pristine conditions

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

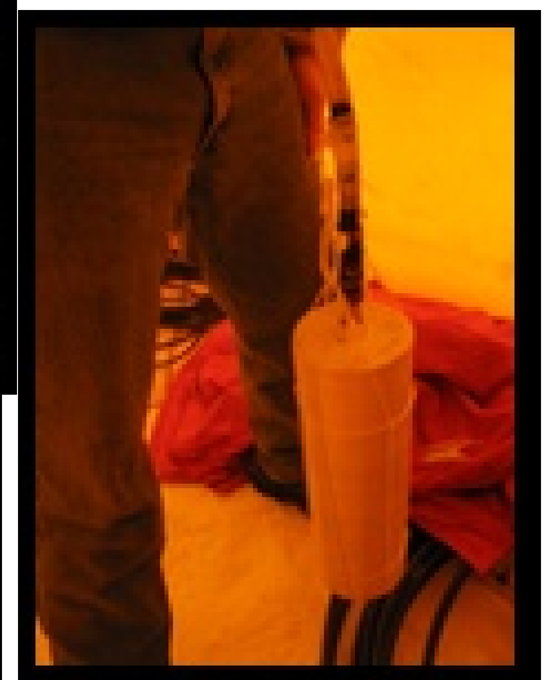
Quiet, but are we sensitive?

Ground pulser

- Ice 80m thick and messy

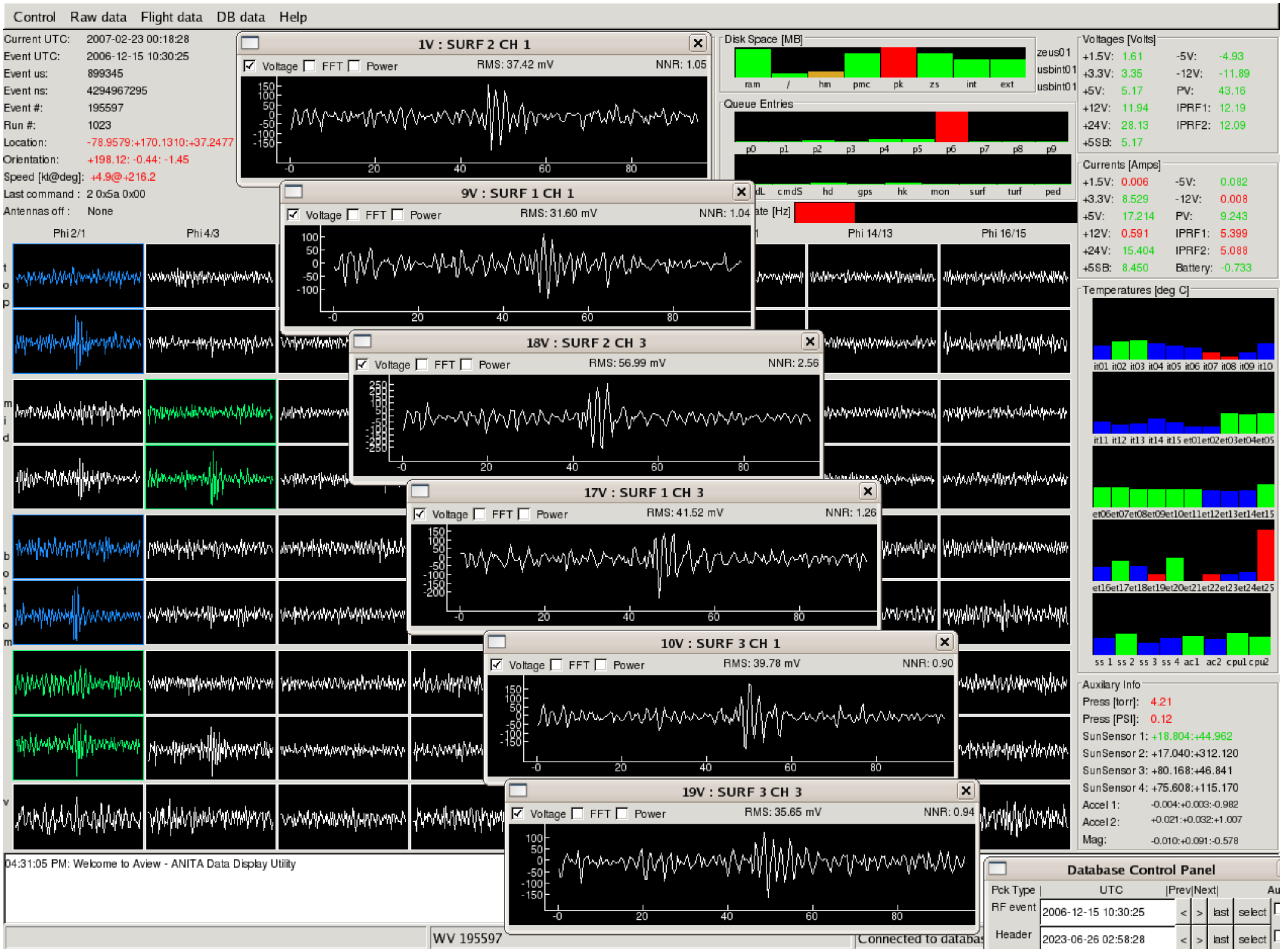


Bore hole pulser



Dipole

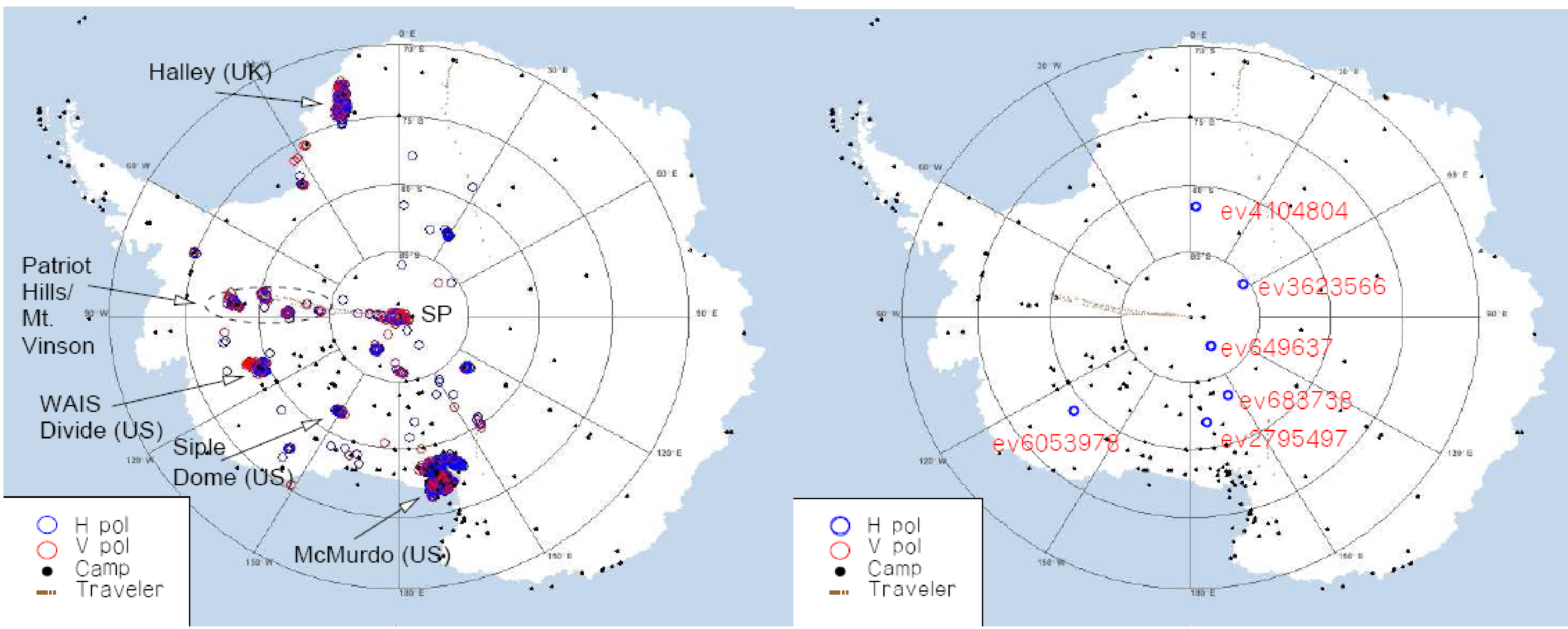
Validation data: borehole pulser



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

ANITA 1 Data

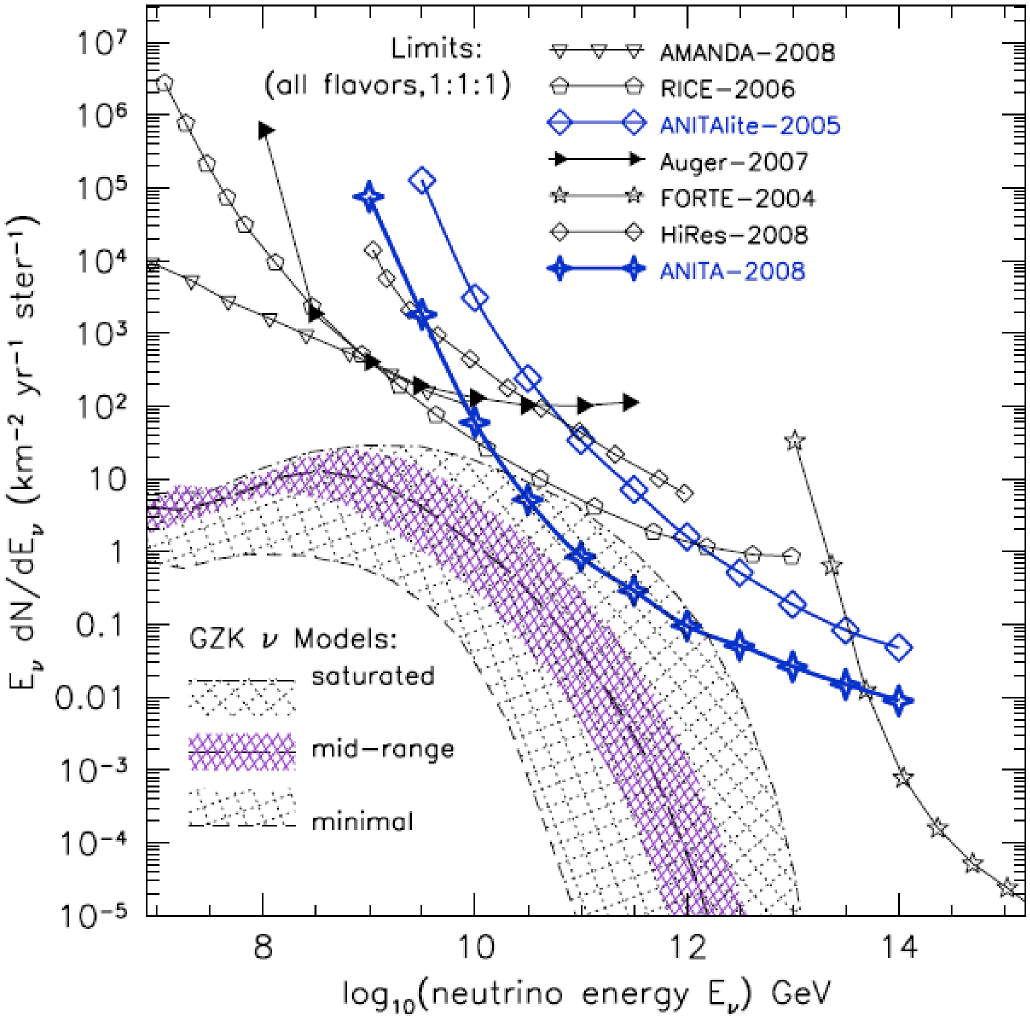
- 8.2 M hardware triggers
- Cuts optimized on 10% data set (blind analysis)
  - Require upcoming plane wave, impulsive broadband, isolated from camps and other events.



Gorham et al., arXiv:0812.2715v1 [astro-ph]

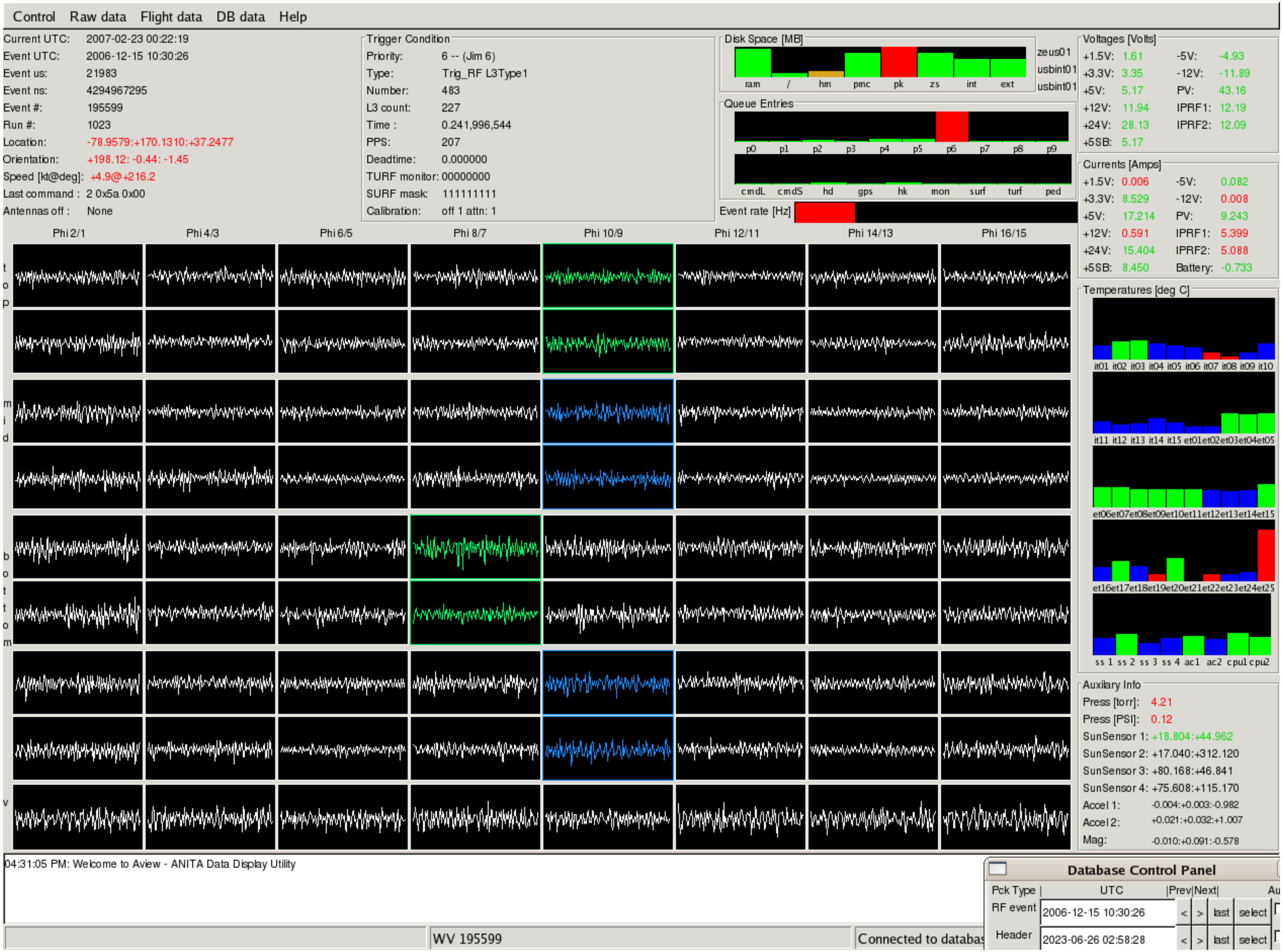
ANITA 1 Results

- 6 H-pol, 0 V-pol survive cuts
  - H-pol originate above ice sheet (not ν candidates)
    - Fresnel transmission
    - Askaryan impulse generation
- In absence of observed ν, a limit is set
- First result to constrain GZK ν production models



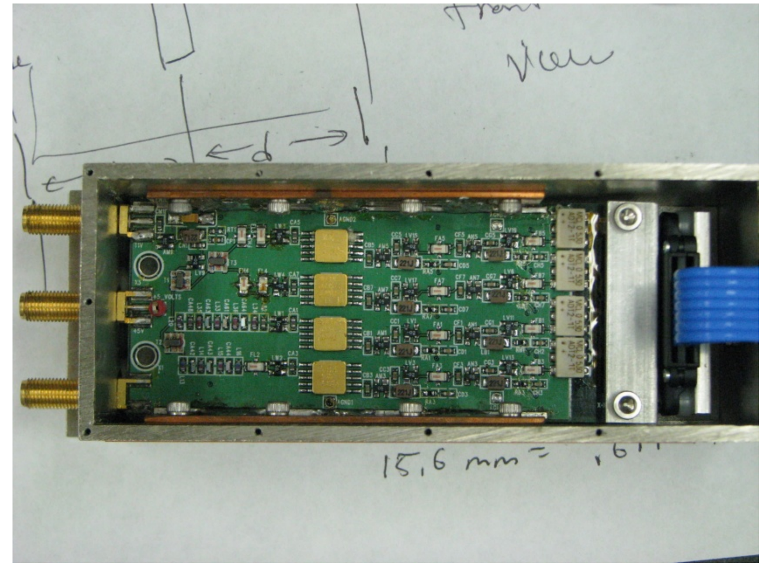
Gorham et al., arXiv:0812.2715v1 [astro-ph]

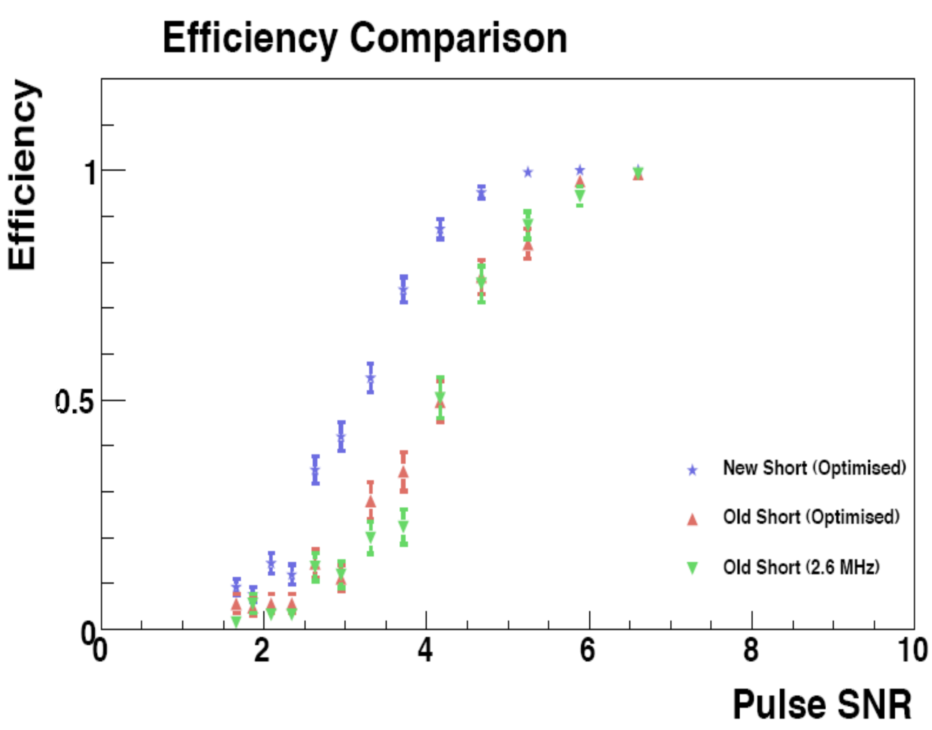
99.99+% of triggers: incoherent thermal noise



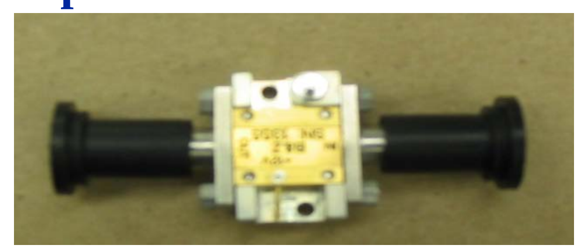
ANITA-2 Upgrades...

- More typical flight path
- Change L1 trigger
  - only trigger on V-pol signal,
  - 3 narrow-band channels + 1 full band
  - Move preamps to the antenna (-20K)
- New preamps (-20K)
- New front end filters (-20K)
- Faster CPU
- Redundant Differential GPS





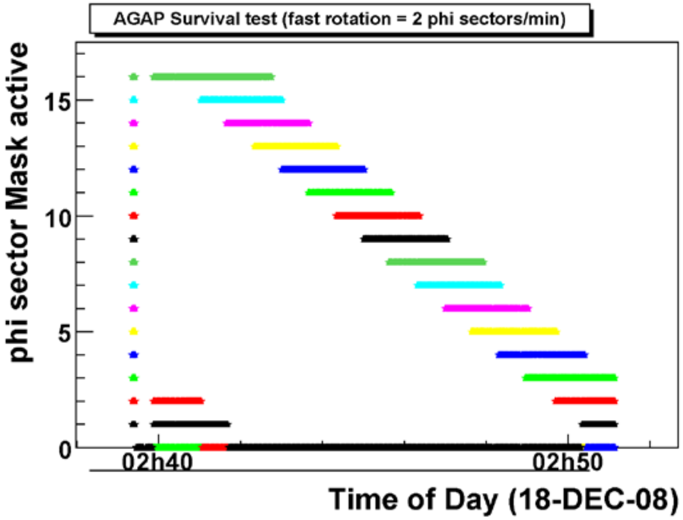
New preamp



New front end filter

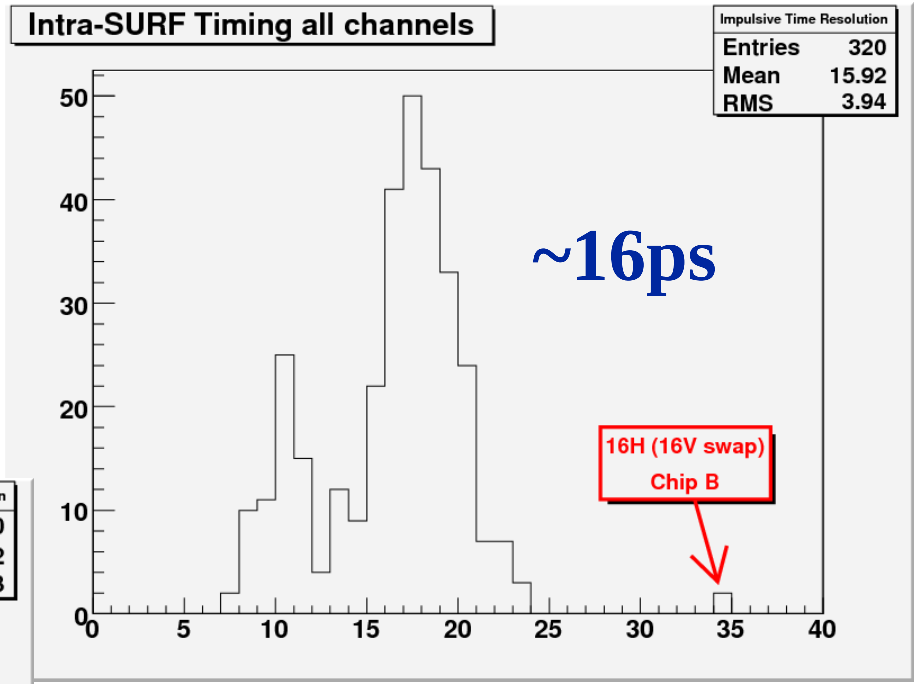
ANITA 2 Improvements

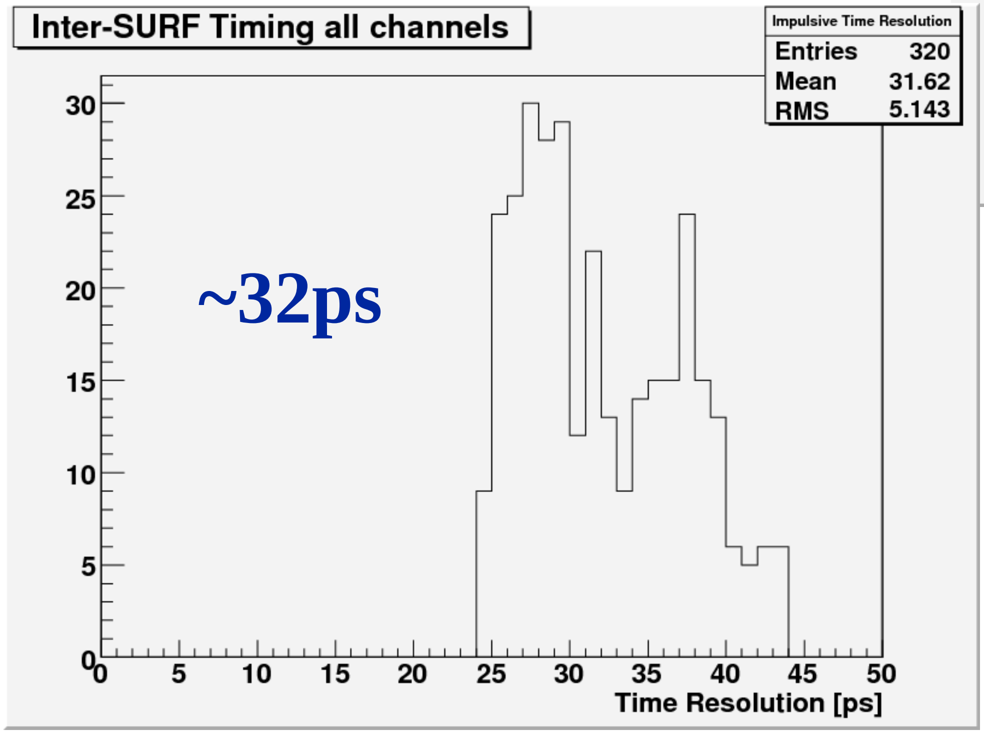
- "Dynamic Phi-Masking"
  - Active suppression of phi-sector readout during transit over noisy areas
    - McMurdo, South Pole, etc
  - Automatically activated
- 8 "nadir" antennas
  - One antenna shared w/ 2 phi sectors
- Only trigger on V-pol
- Improve T_{sys} by 40K
  - New Low-Noise Amplifier
- Overall energy threshold improvement:
  - Factor of ~1.7
  - ANITA gains as E_{th}^{-2}, so ~ factor of 3 event rate increase



Improved Timing Calibration

- Faster Reference Clock
- Better thermal, timebase calibration





To be compared with 40, 60 ps For ANITA-I

Pulse Phase interferometry

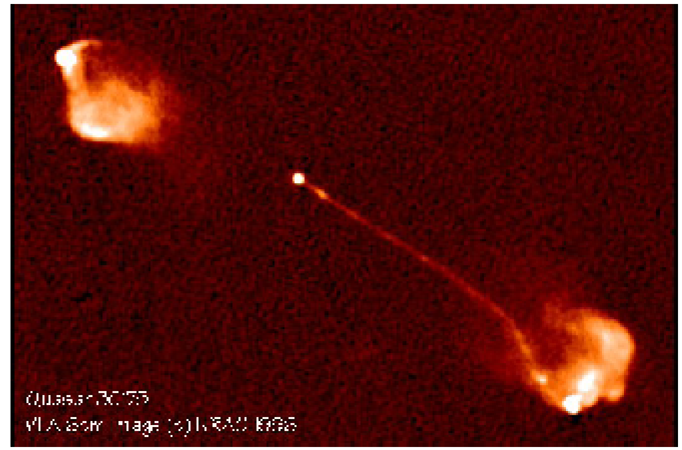
A. Romero-Wolf (Hawaii)

Ultrawide-band Interferometry

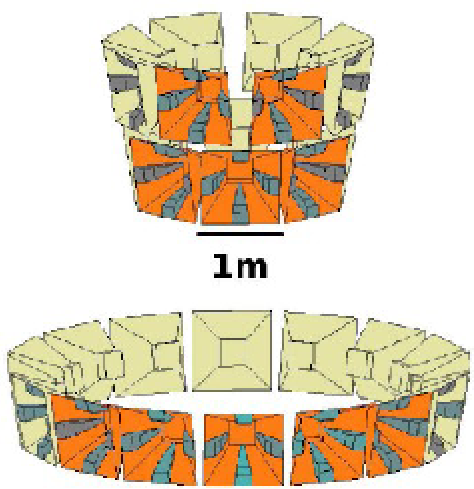
-Interferometric technique applied by radio astronomers.

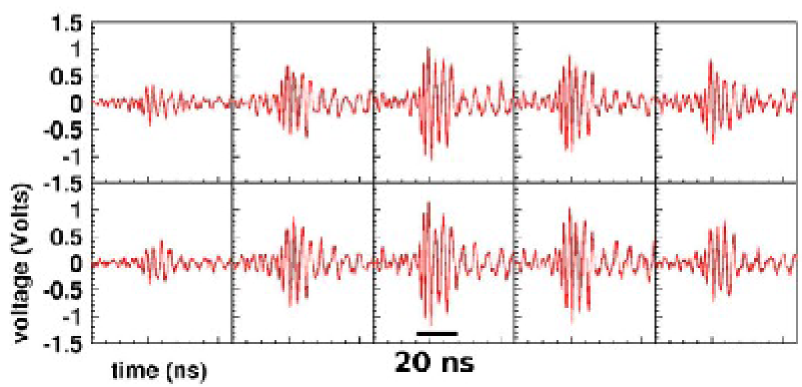
-They use single narrow band frequency.

-More interested in source imaging rather than point source direction reconstruction.

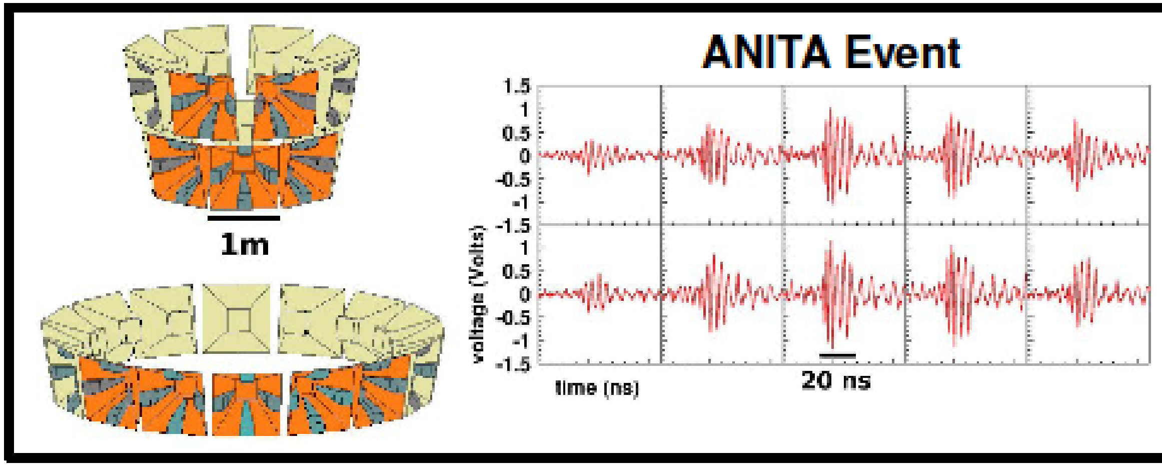


Produce Ultrawide-band Interferometric Images with ANITA

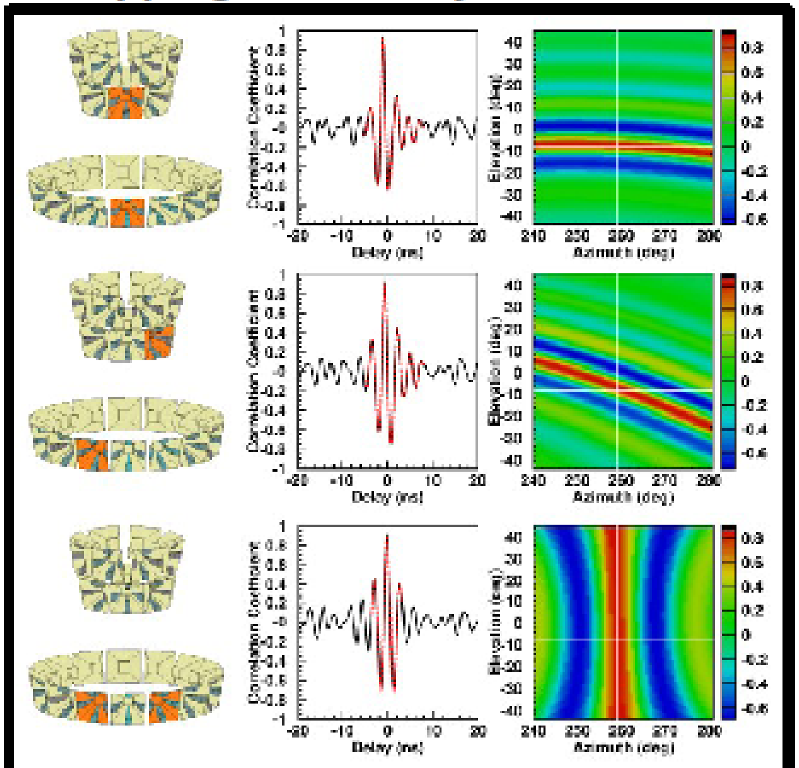




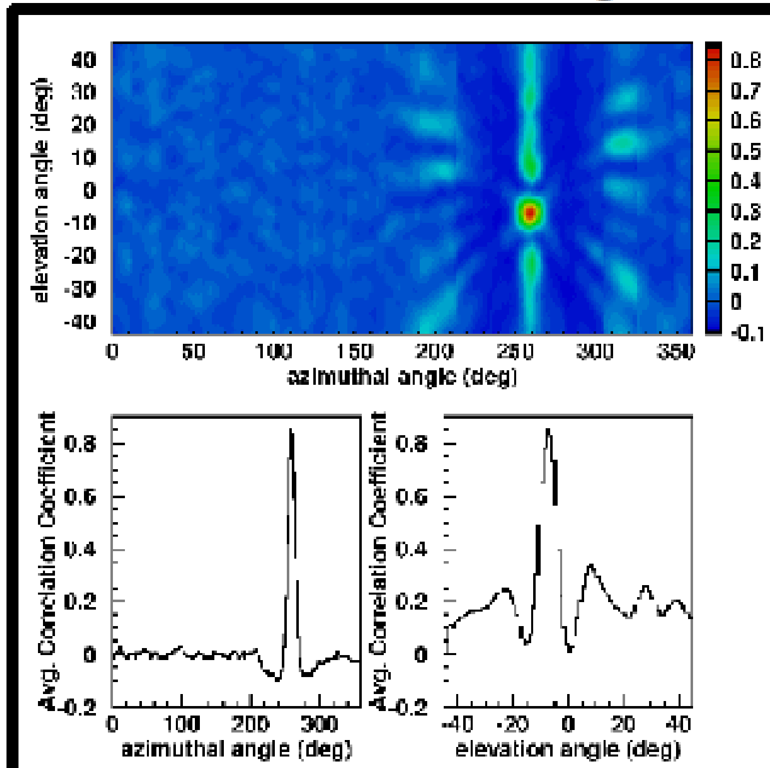
Mapping Waveforms to Interferometric Images



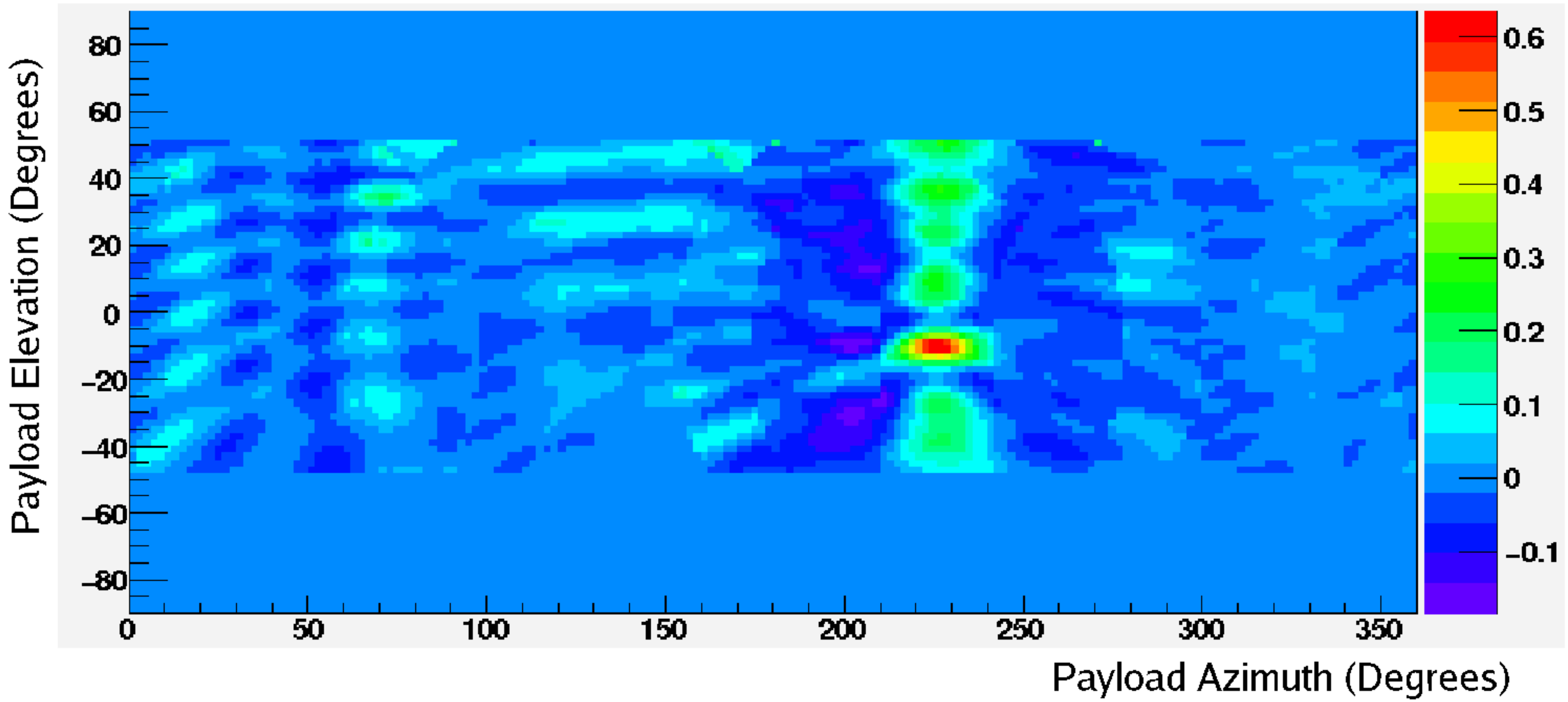
Mapping Time Delay Correlations



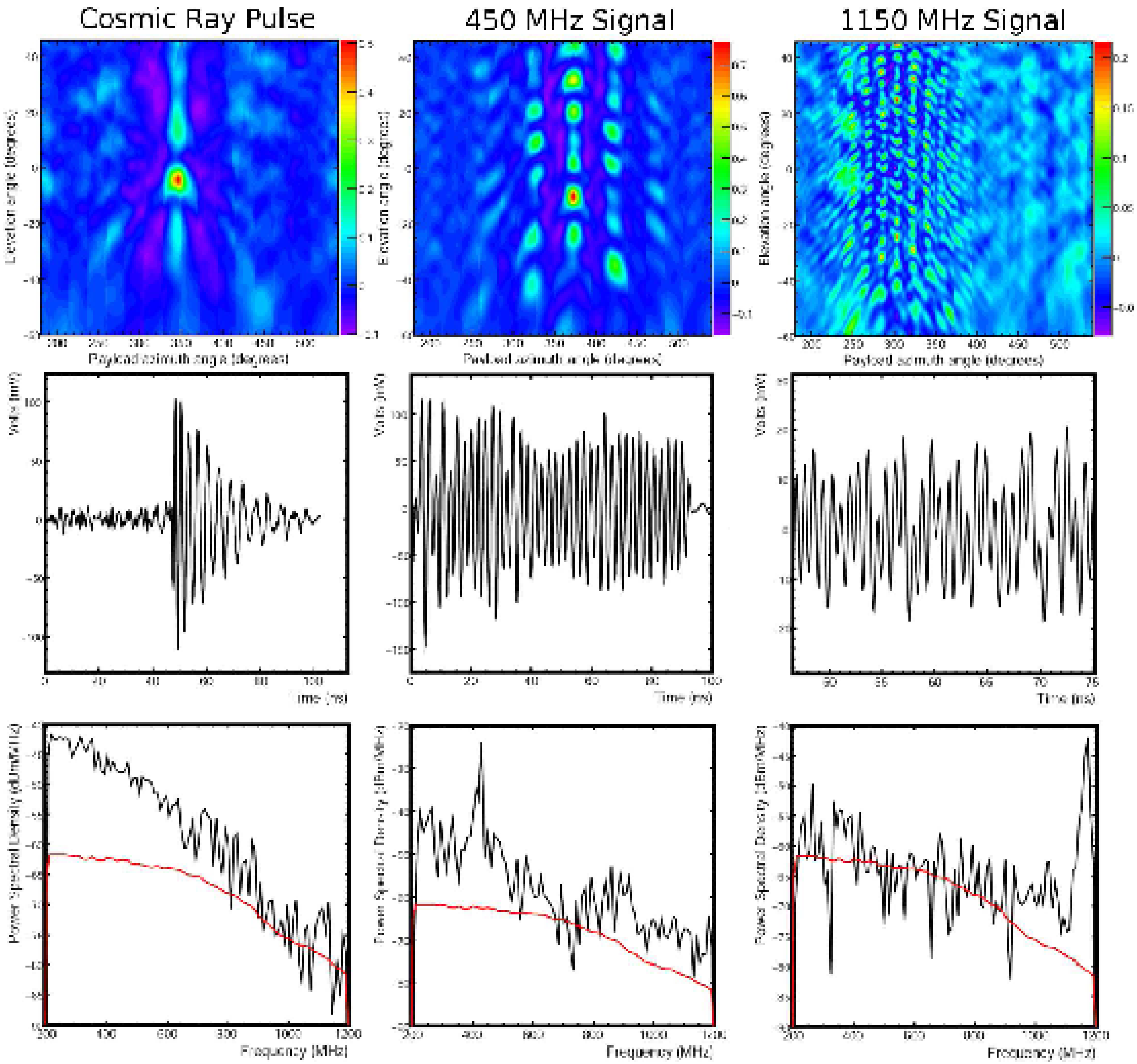
Interferometric Image



ANITA-2
Deep Field Pulser Event:



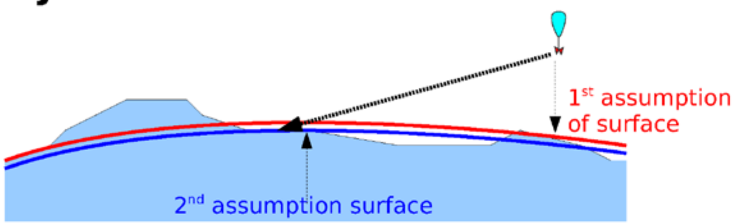
> 200,000 calibration pulser events from deep field for ANITA –II


Cosmic Ray Pulse
450 MHz Signal
1150 MHz Signal

After full calibration – 100's km

<30ps timing

RF Projection onto the surface

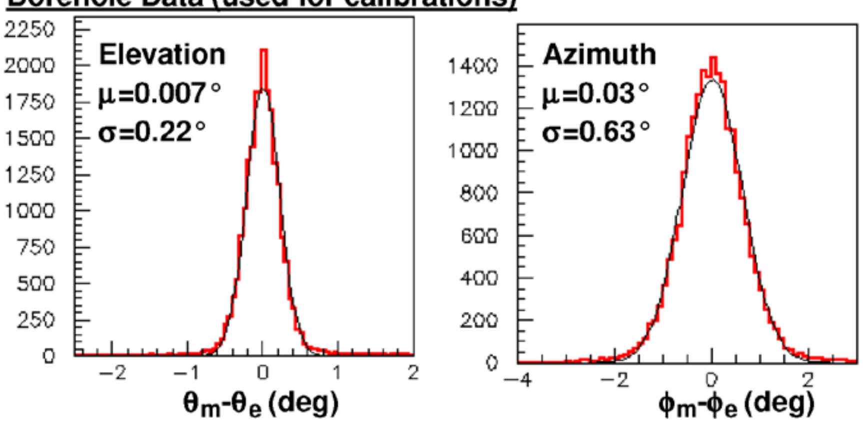


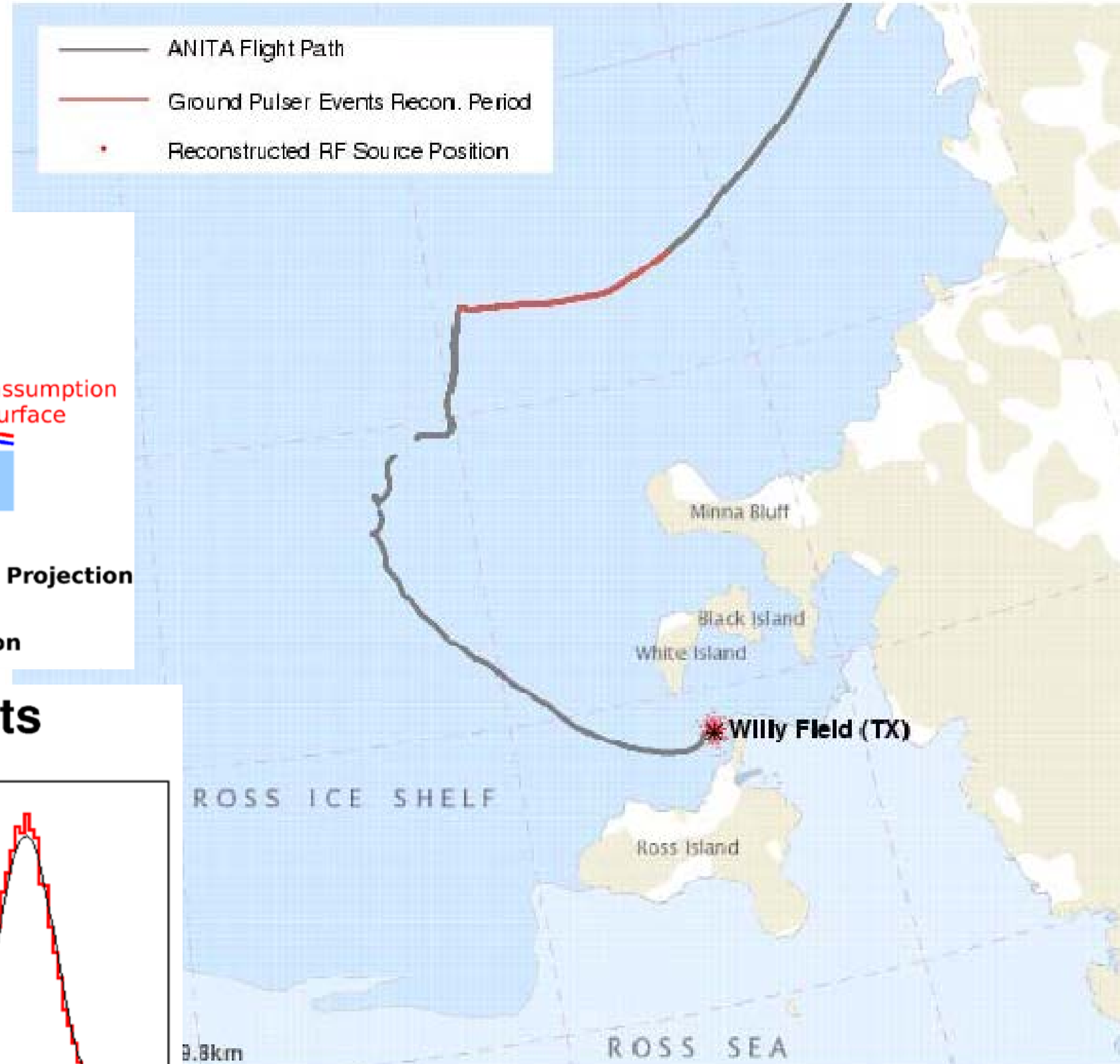
Fast Algorithm: Line Sphere intersection

- 1^{st} R_{earth}=Geoid + Surface @ Ballon position -> Rough Projection
- 2^{nd} R_{earth} = Geoid + Surface @ (position from 1^{st})
- 3^{rd}: one more iteration -> converged after 2^{nd} iteration

V-pol results

Borehole Data (used for calibrations)





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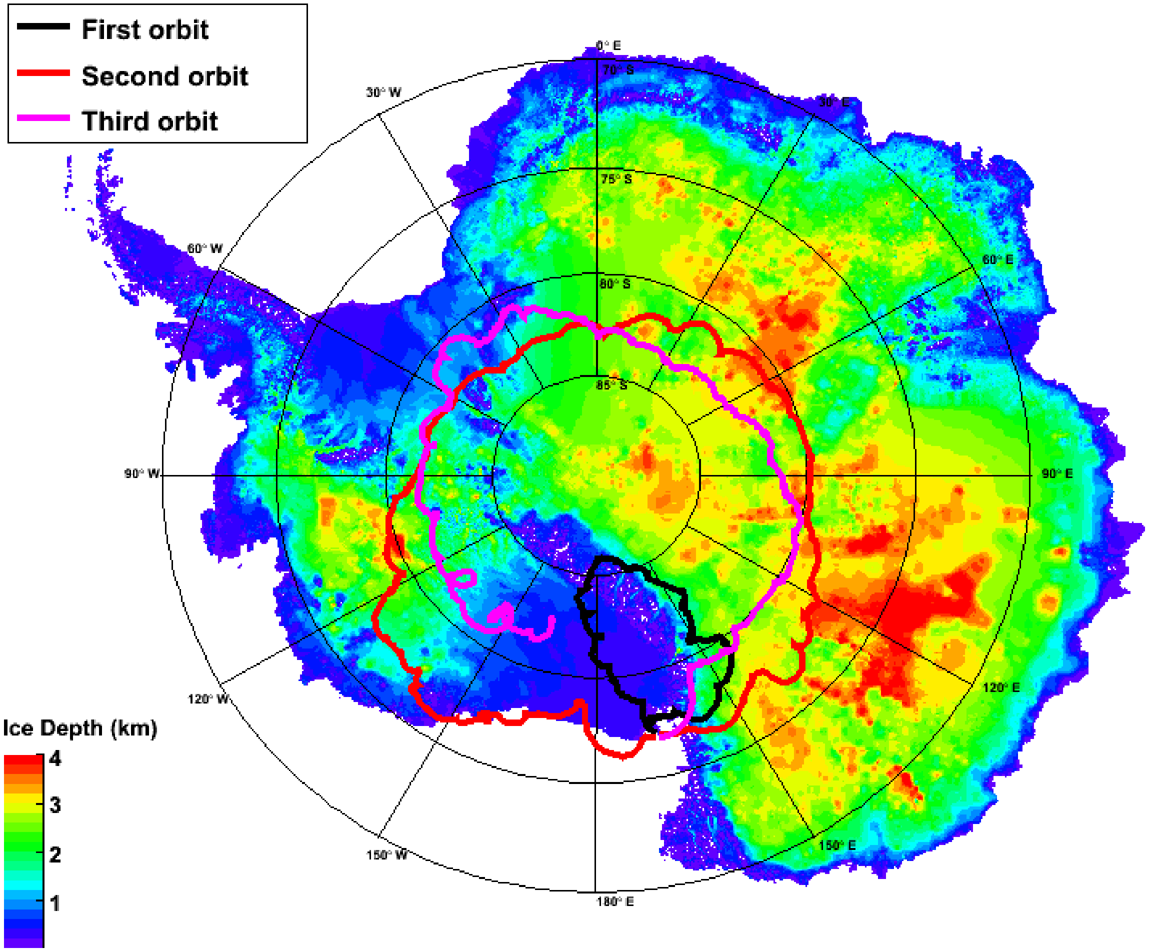
ANITA 2 Flight Path

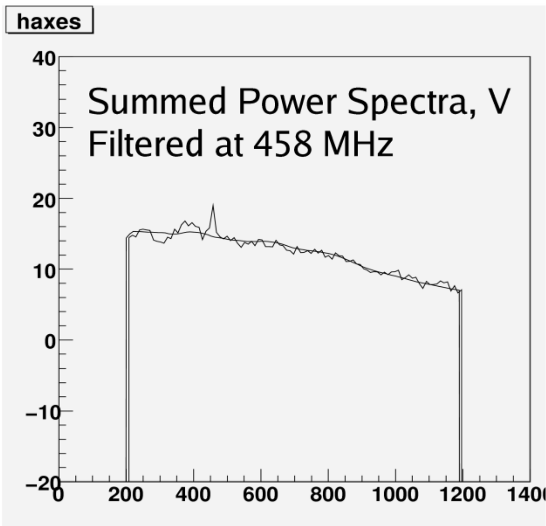
- 2+ Orbits
- Time aloft: 30d 14h 45m
- Compared with ANITA 1...
  - More time near E. Antarctica
  - Less time near SP
- Dynamic phi masking seemed to work as advertized...

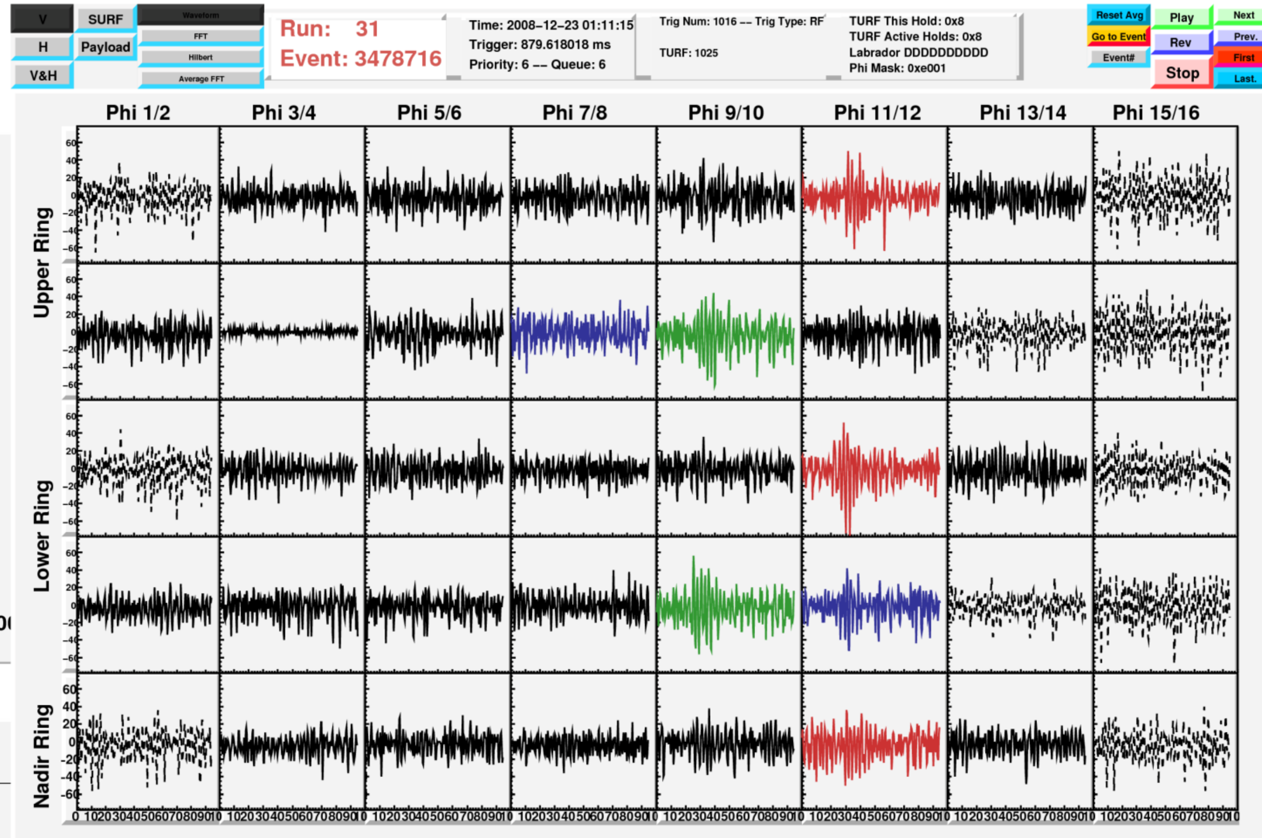


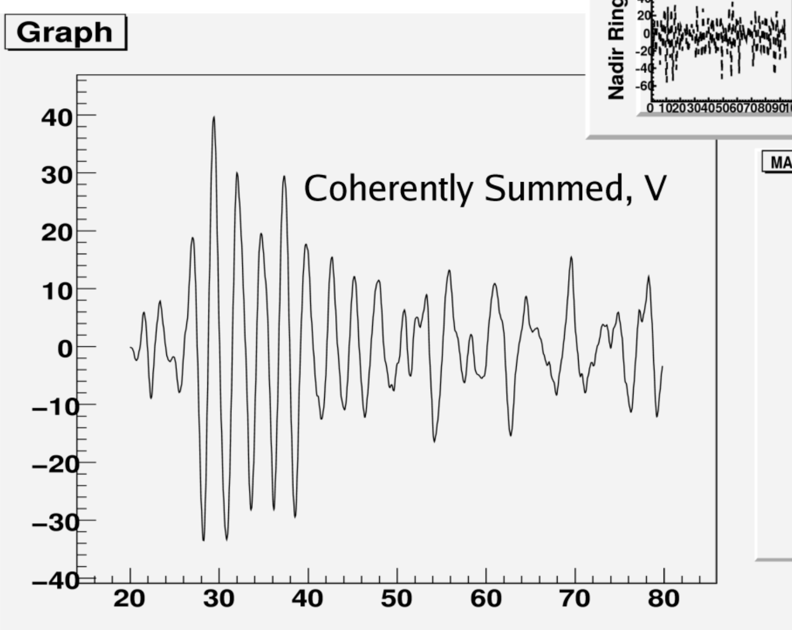
Courtesy Kim Palladino

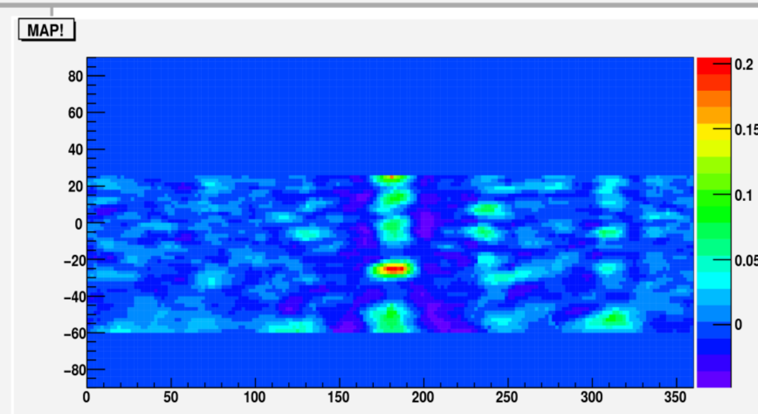
A. Vieregg (UCLA)

Event 3478716









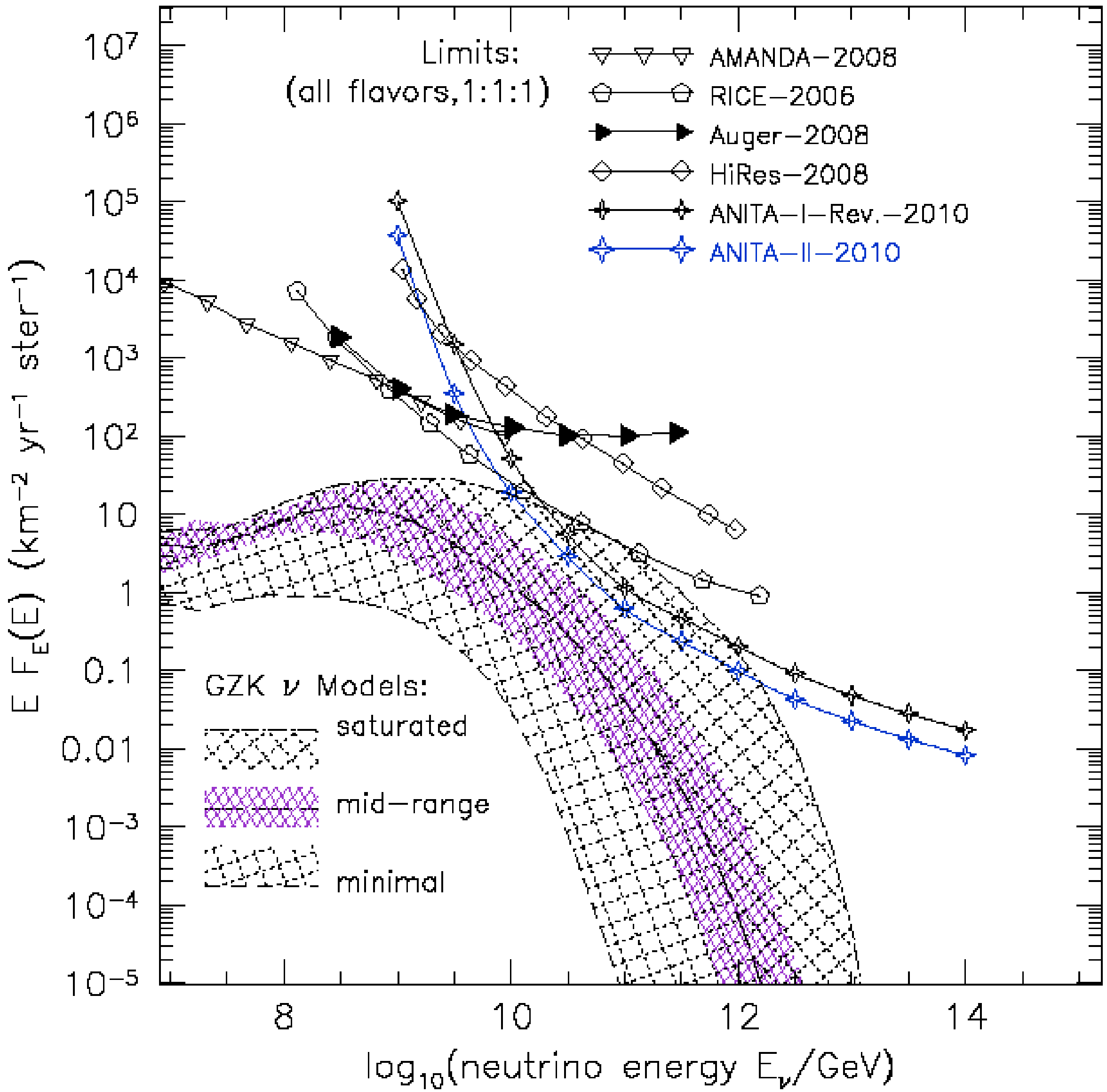
Near Transantarctic Mountains

Polarization Angle = 57.6 degrees

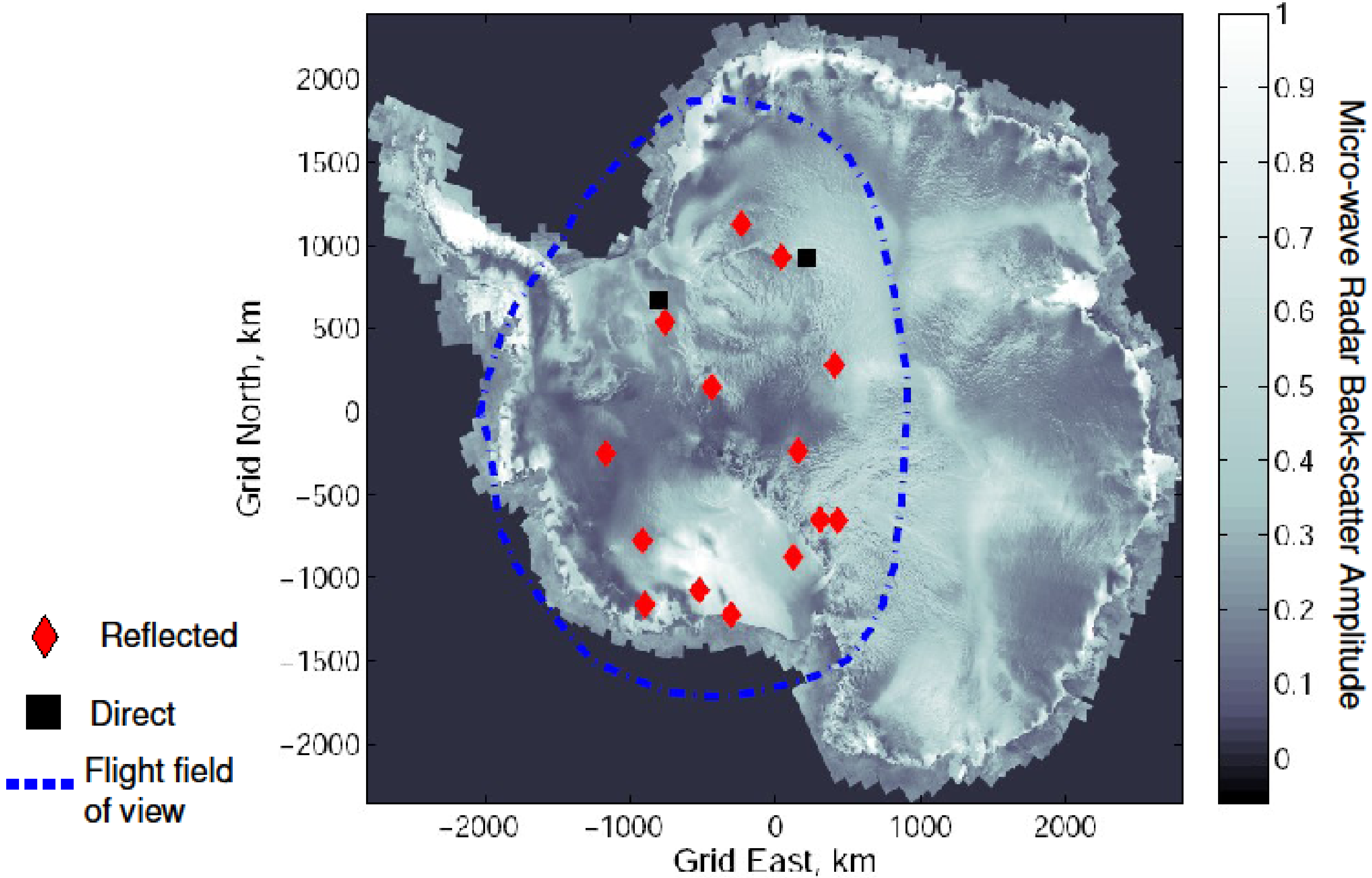
Elevation Angle = 25.2 degrees

Distance=107 km, LL=2804 from nearest event

ANITA2 Results



Cosmic-Ray Candidate Event Locations



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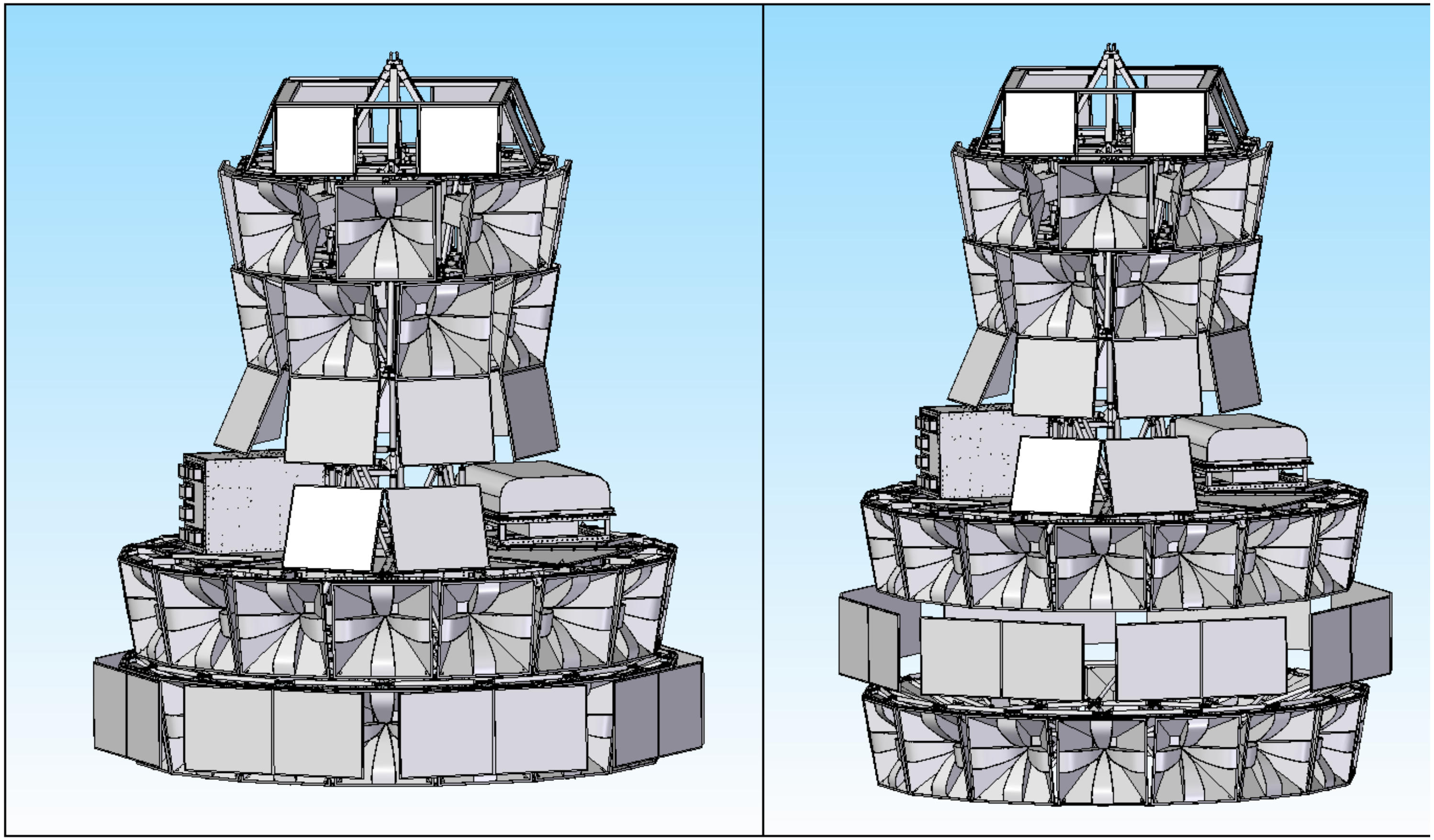
S. Hoover (UCLA)

ANITA3 Upgrades



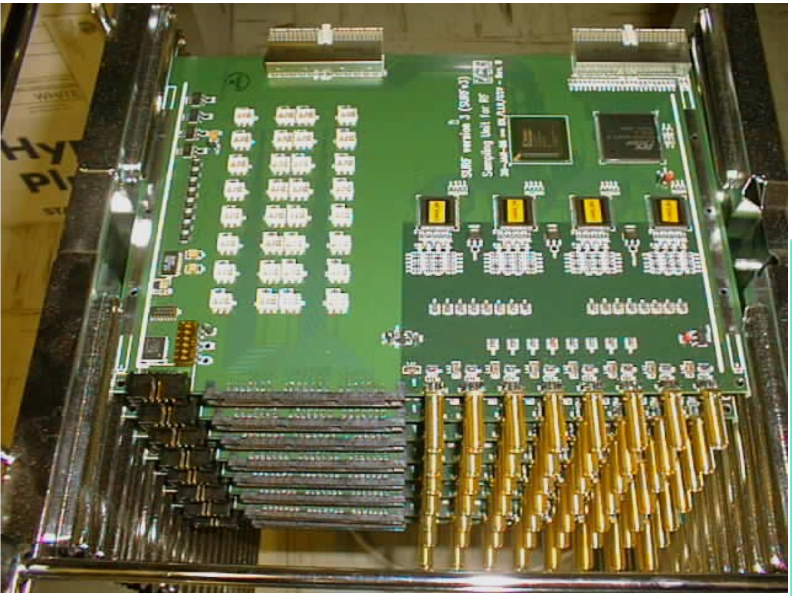
Not deployed Deployed

→New trigger
→Digitzer
→Reduce threshold!
→To fly Austral summer 2014

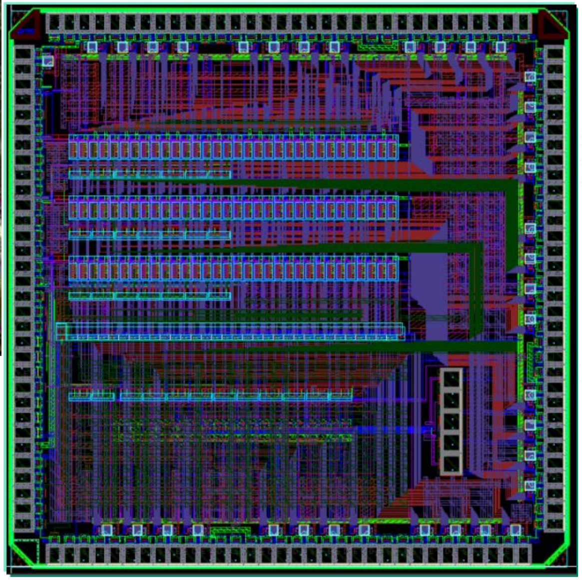
2x new ASICs

The last hurrah

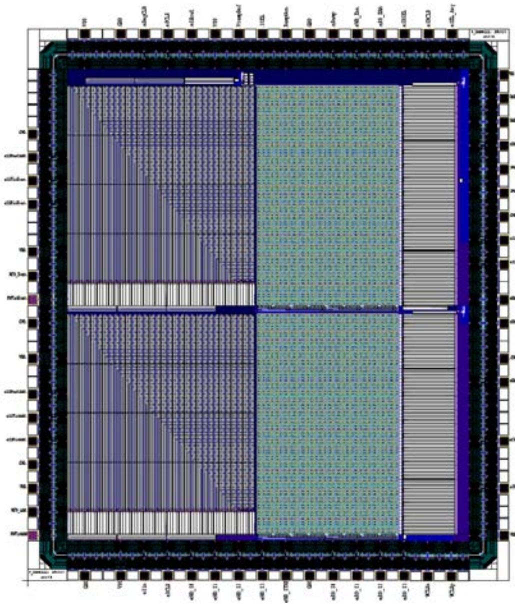
New SURF & TURF



- Rebuild "space flight" readout instrumentation (half a decade old technology)
- Threshold limited – new trigger ASIC (RITC)
- New digitizer (LAB4) to go to longer waveforms
- "go for broke" – ARA/ARIANNA/GNO is successor



RITC



LAB4

Where we might be in a few years...

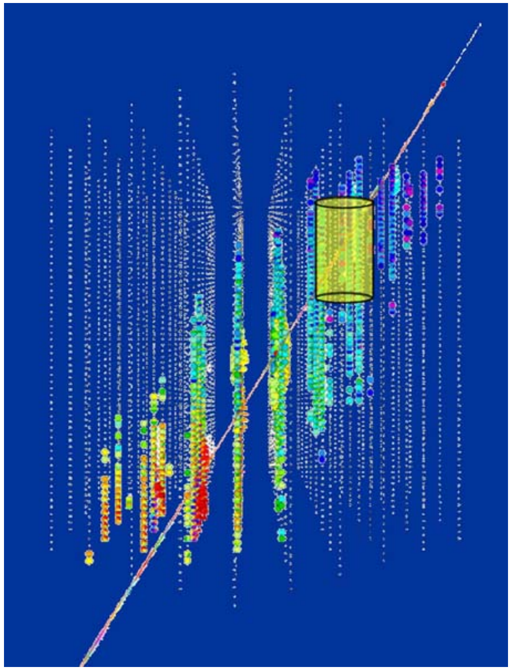
- <u>IceCube</u>
  - Discovery of bottom-up sources
  - Discovery of ~ few GZK neutrinos

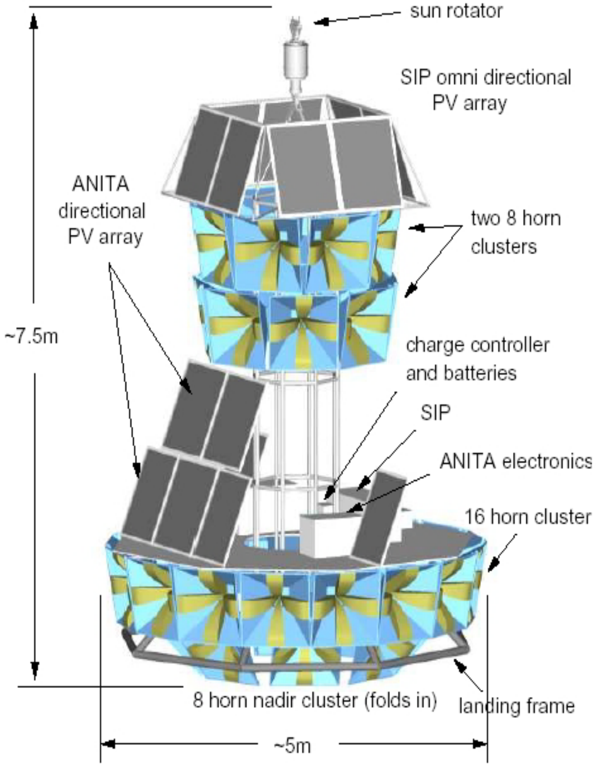
- <u>ANITA-III:</u>

  Discovery of ~few GZK neutrinos?

  (or limit !!)

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

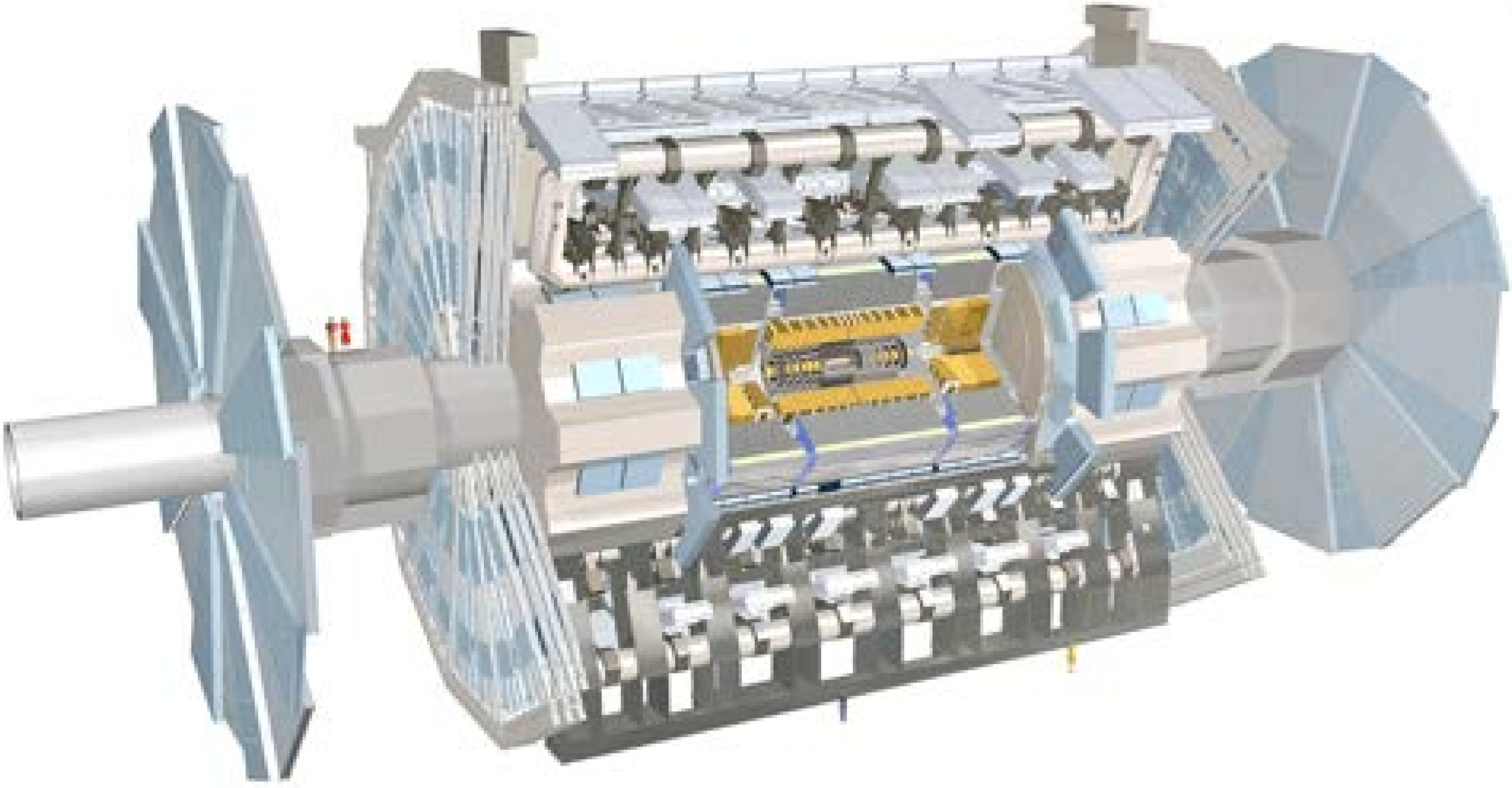




How to "go big" ?

- Salt
  - Salt domes
- Ice
  - In situ (RICE → AURA → IceRay)
  - Ultra-Longer duration Balloon (EVA)
  - Overflight (satellite)
- Silica sand
  - Lunar regolith (GLUE)

Detector Energy Scales – the tonne



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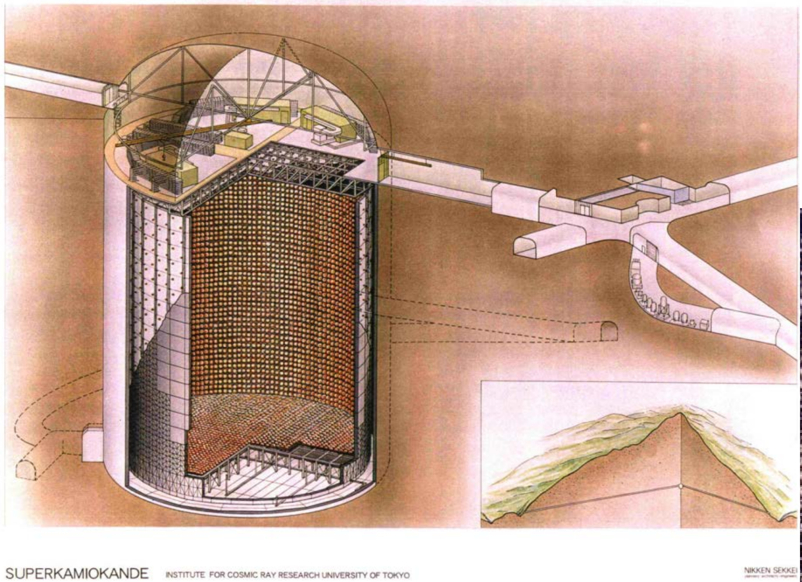
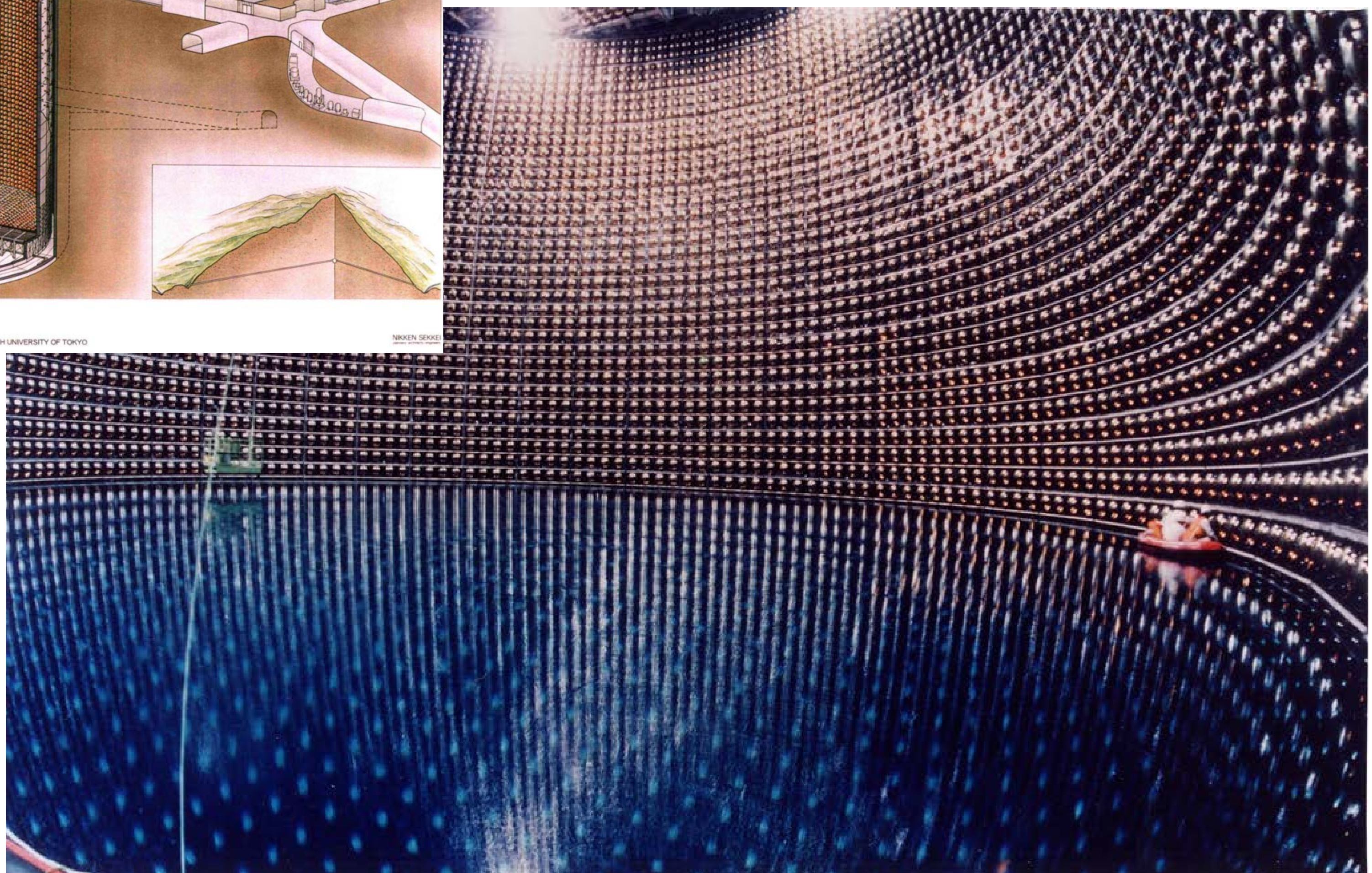
Detector Energy Scales – the kT





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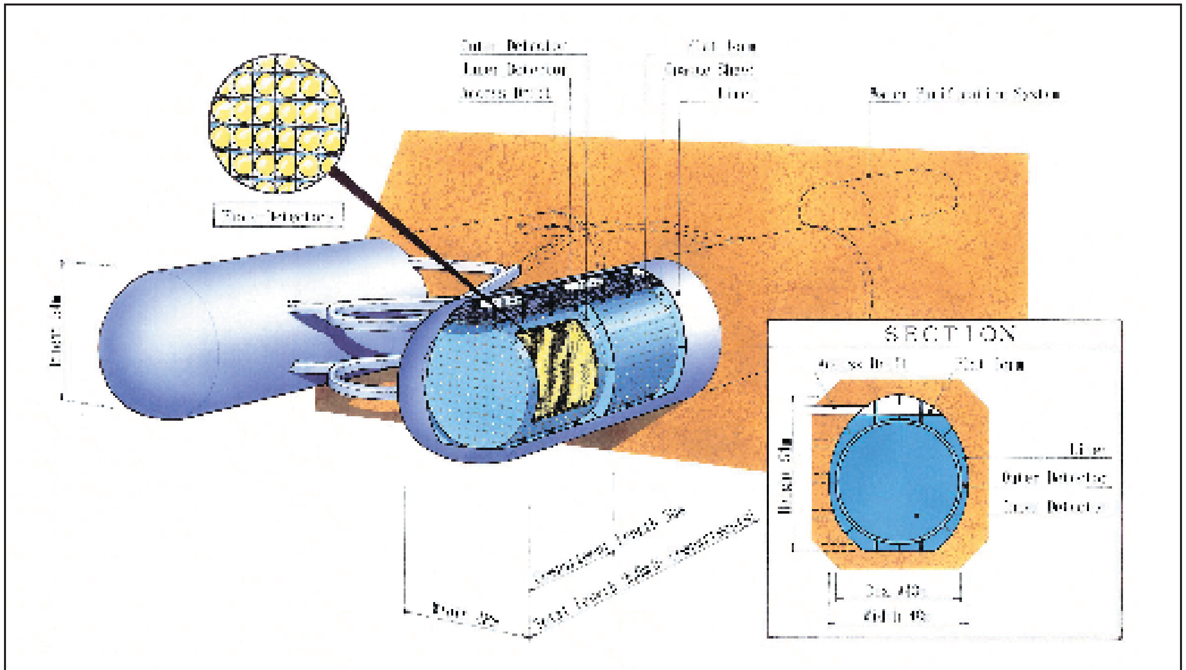
Detector Energy Scales – the MT

MEGA-DETECTORS

Thinking big: the next generation of detectors

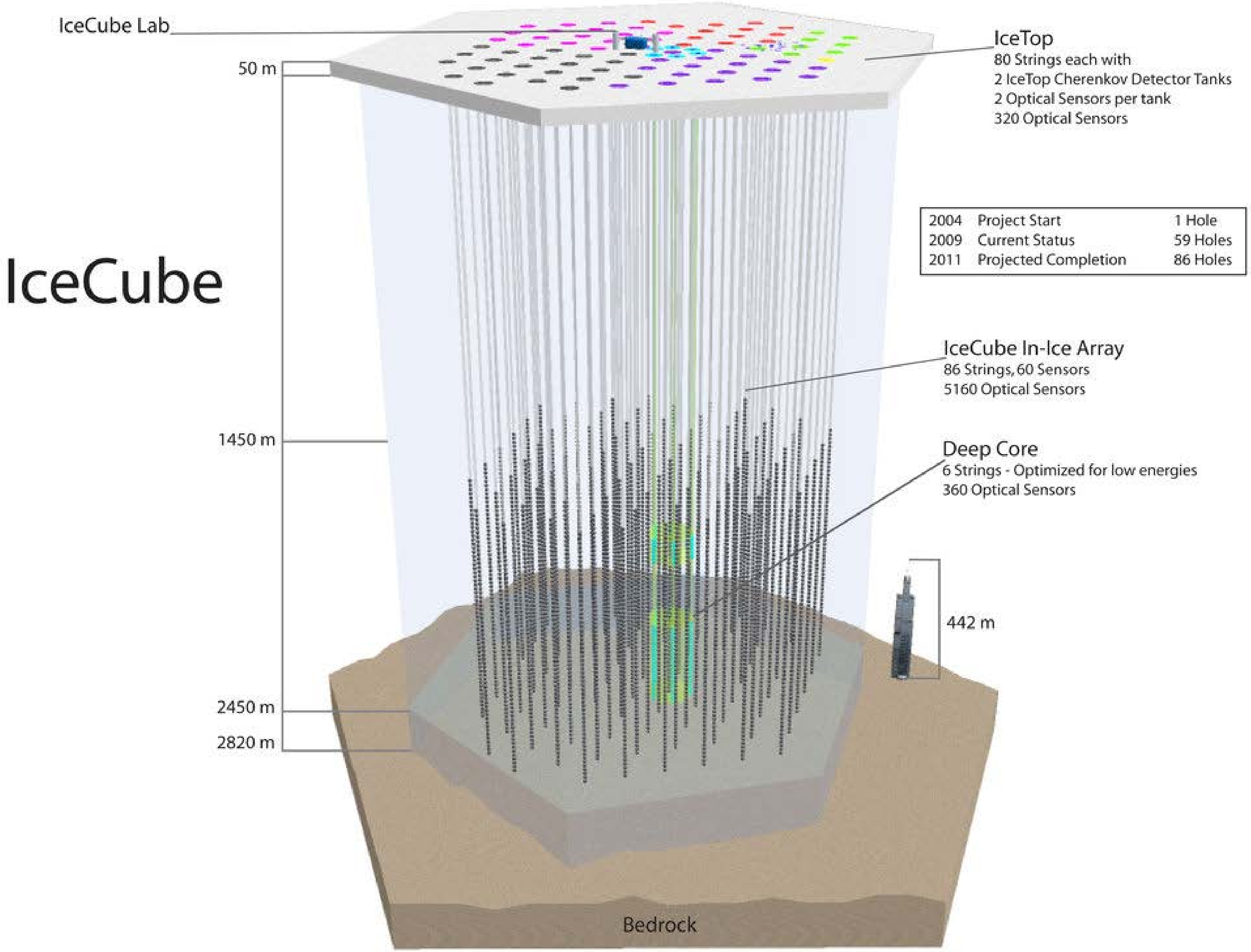
The conference on the Next Generation of Nucleon Decay and Neutrino Detectors looked at the development of new, large-scale detectors. **Alain de Bellefon** reports.



Detailed schematic of a second-generation detector. Hyper-Kamiokande, a megatonne water Cherenkov detector, is proposed as a successor to Super-Kamiokande. It is located at Tochibora, a few kilometres from the Kamioka site.

Pushing bounds of civil construction

Detector Energy Scales – the GT



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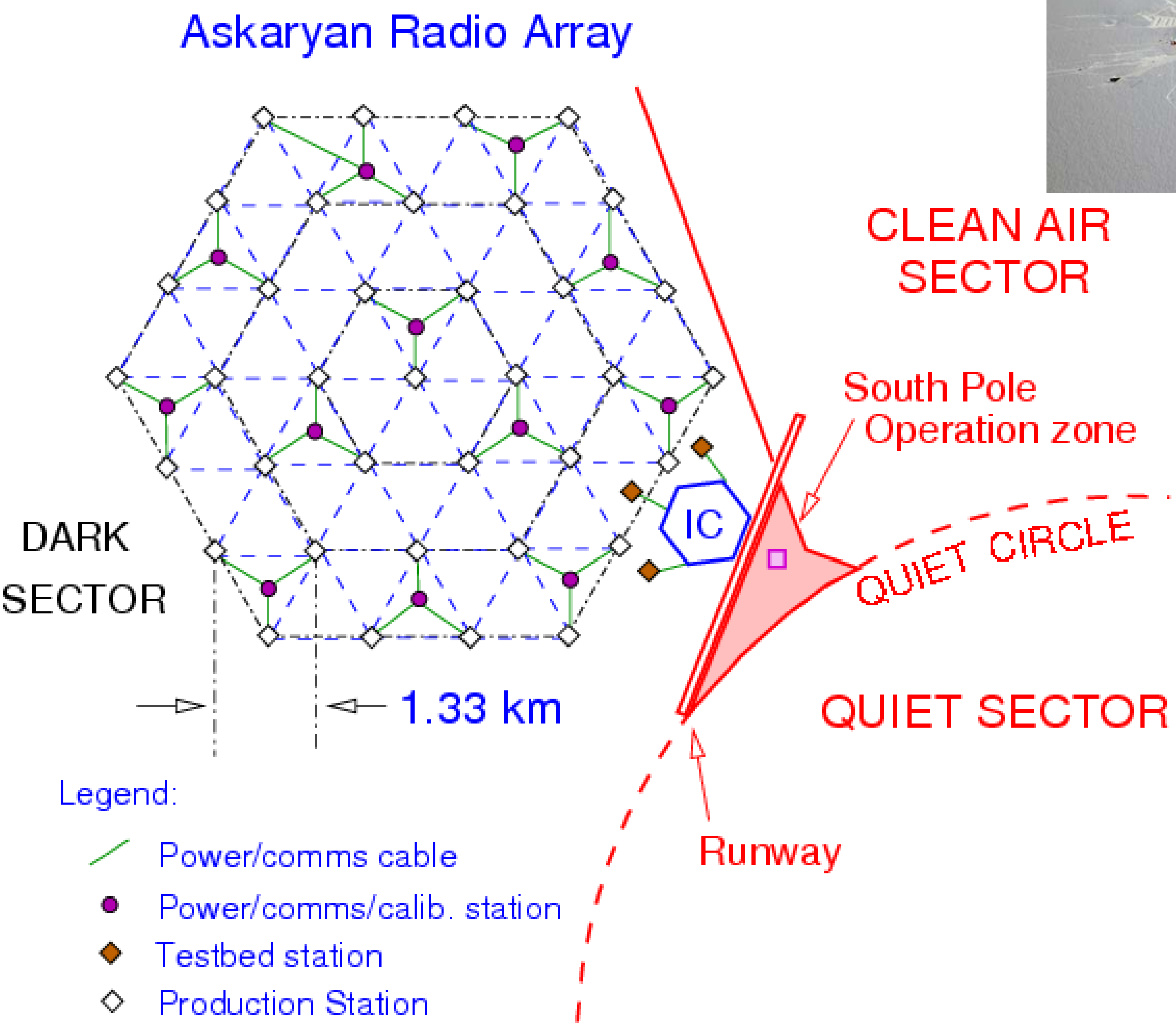
How to "go big" ?

- Salt
  - Salt domes
- Ice
  - In situ (RICE → AURA → IceRay)
  - Ultra-Longer duration Balloon (EVA)
  - Overflight (satellite)
- Silica sand
  - Lunar regolith (GLUE)

Volume saturates

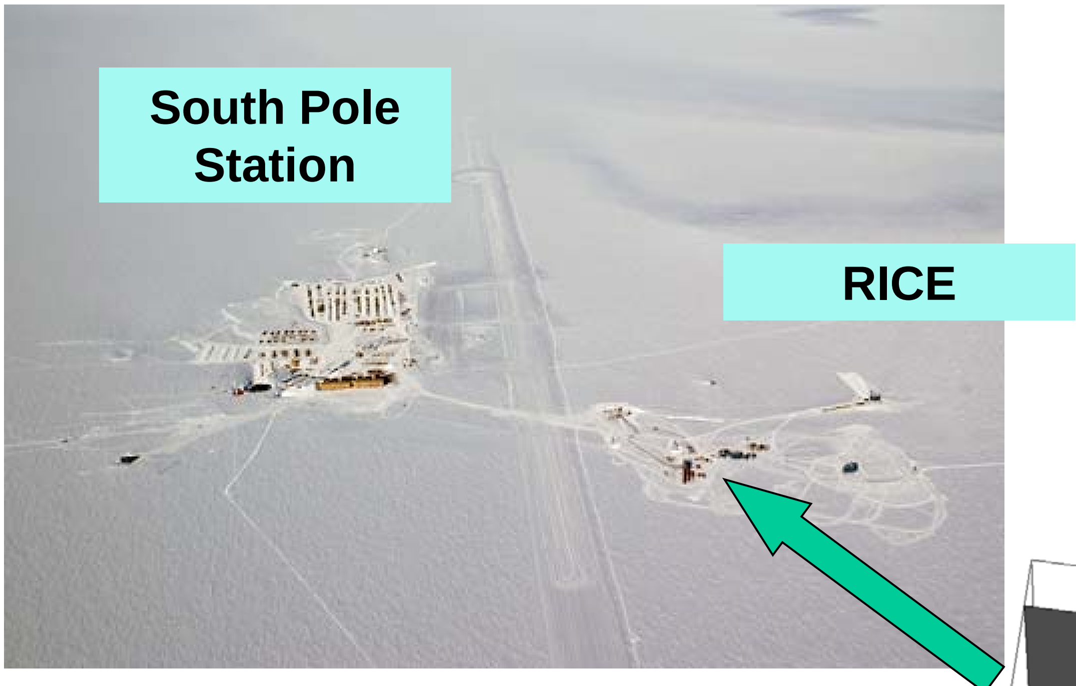
High Threshold

Askaryan Radio Array (ARA)

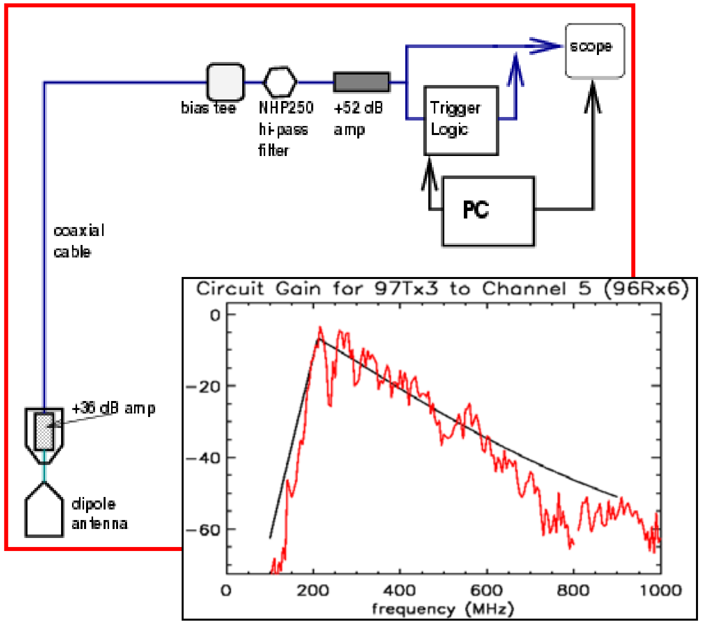


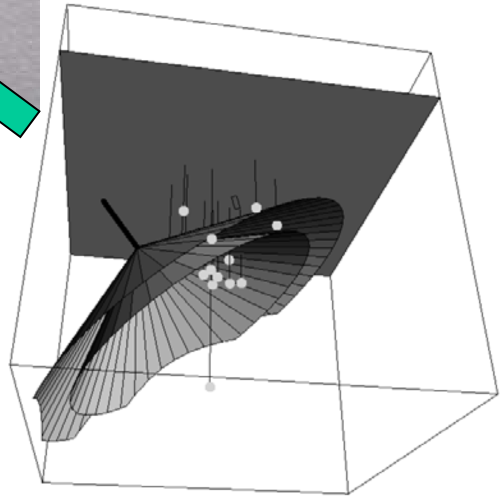
South Pole? RICE started late ’90’s

- Deployed with AMANDA
- Challenging EMI backgrounds

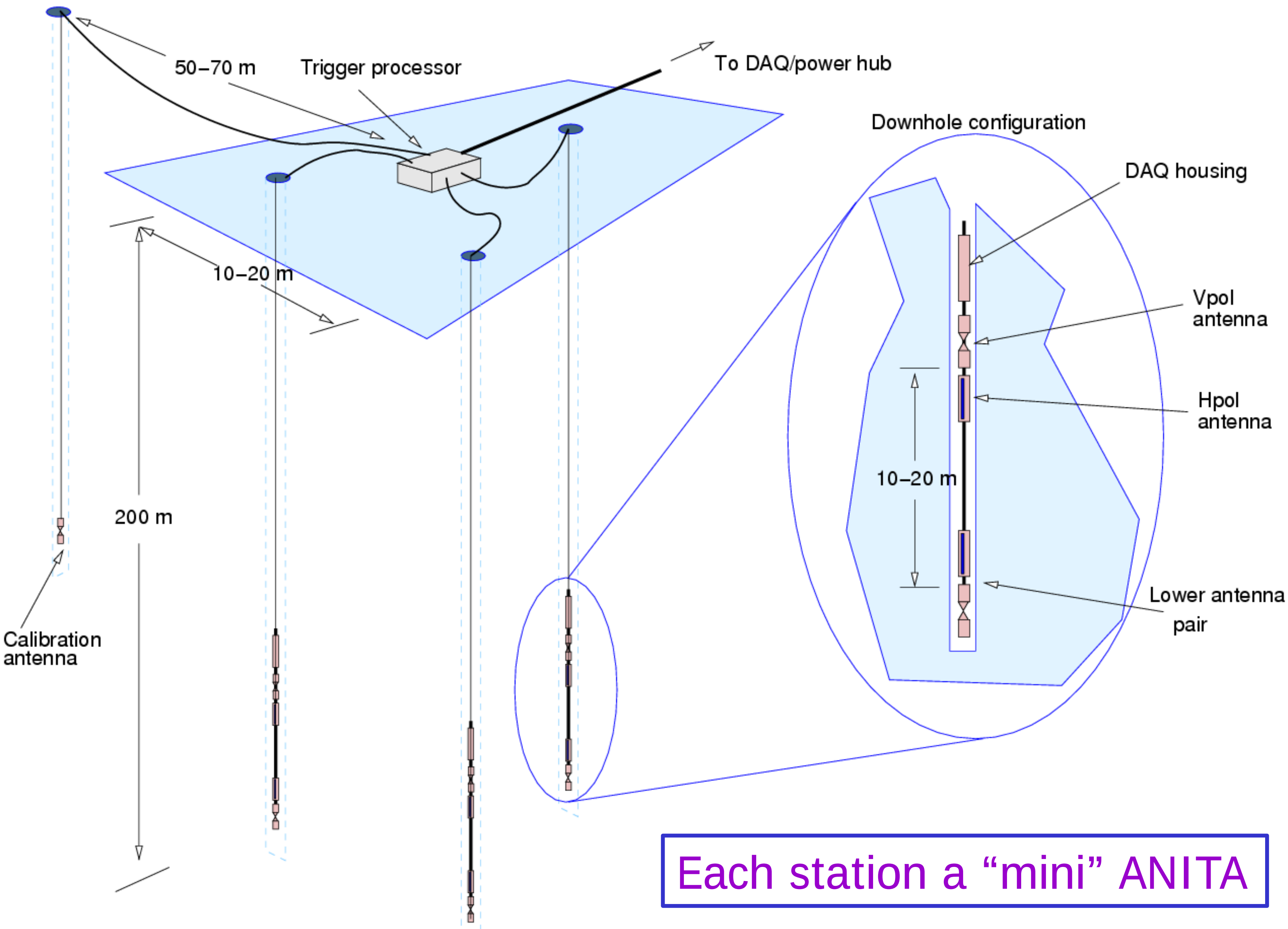


RICE readout





Cluster Station



Each station a “mini” ANITA

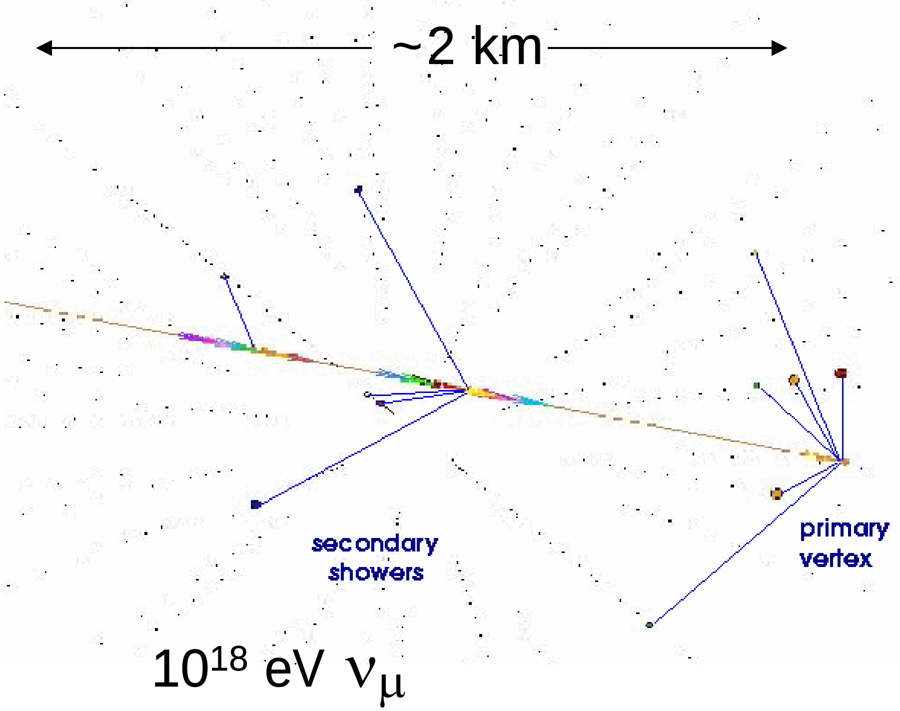
Askaryan Radio Array (ARA)

1st station 2011-2012

2nd station 2012-2013

Power a HUGE issue

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

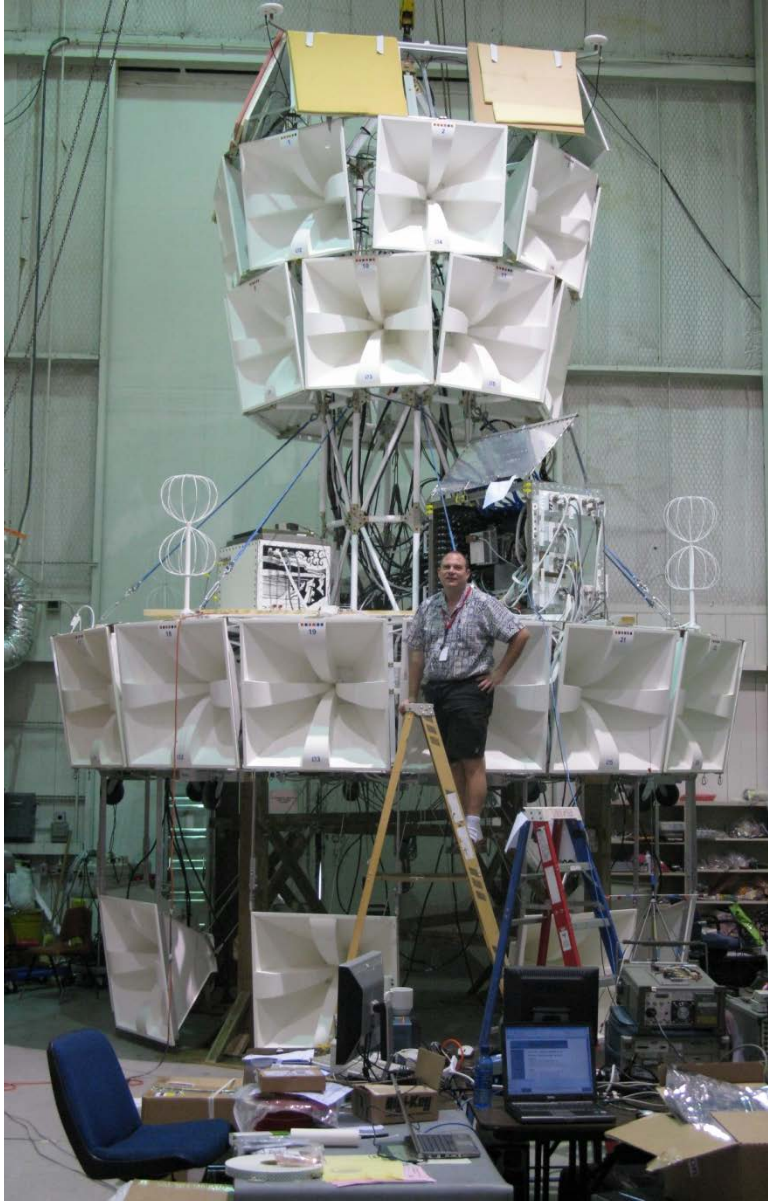
- Charged/neutral current & flavor ID possible on subset of SalSA events
- At least 20% of GZK CC events will get first order flavor ID
- Detailed initial studies – looks very promising [BLAB ASIC – 64us deep version of LABRADOR makes possible [**NIM A591** (2008) 534]

Summary

Radio Detection good bet to "discover" GZK neutrinos:

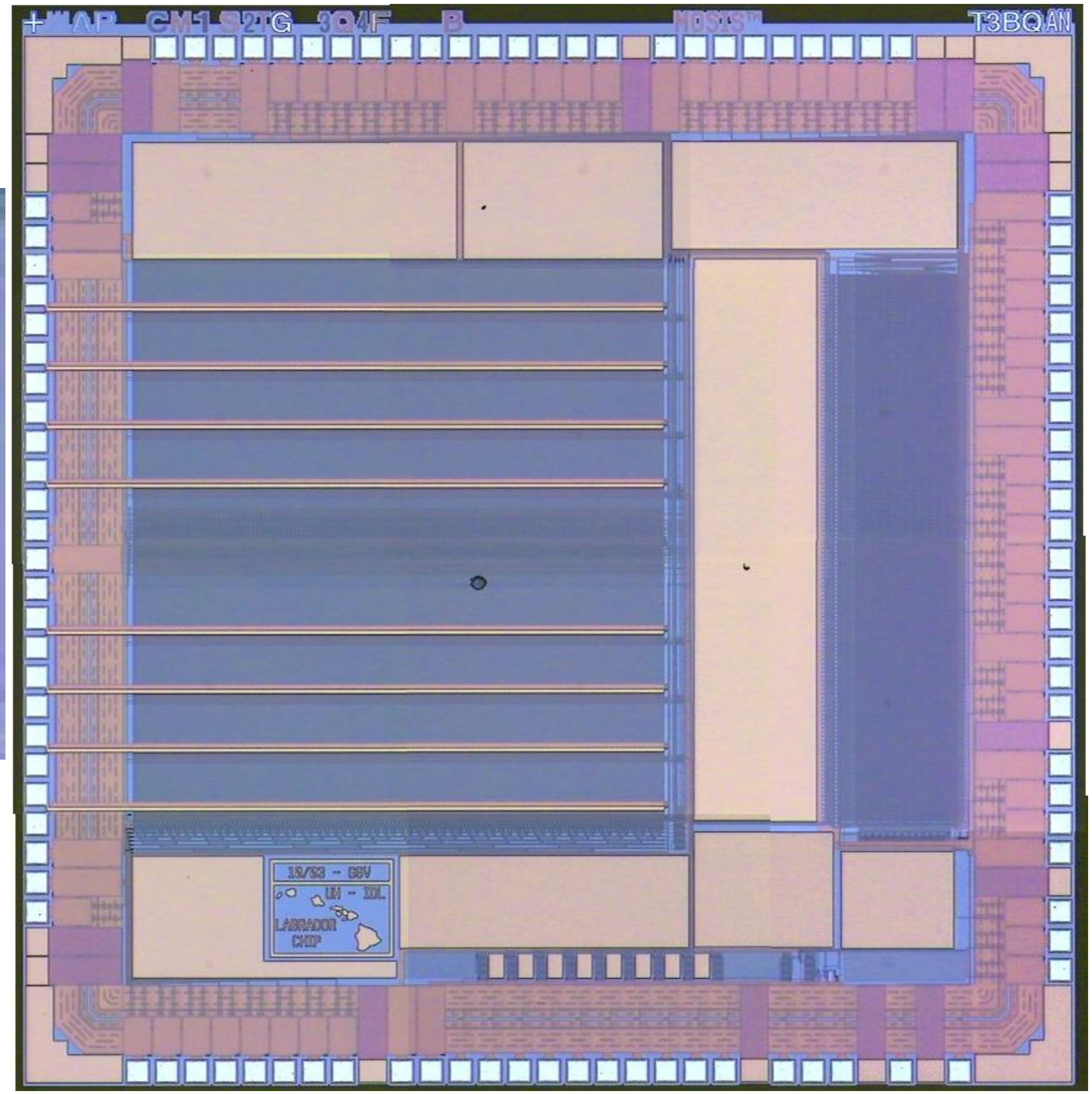
- ANITA first experiment to probe the "guaranteed" GZK flux
  - Many lessons from first flight
  - Very successful flight 2008/2009 Antarctic campaign
  - How to go larger?

- ANITA technology evolution → enables low-cost, extensive terrestrial arrays:
  - ARA first stations in operation
  - ARIANNA (Ross Ice Shelf)
  - GNO (Greenland Ice Shelf)

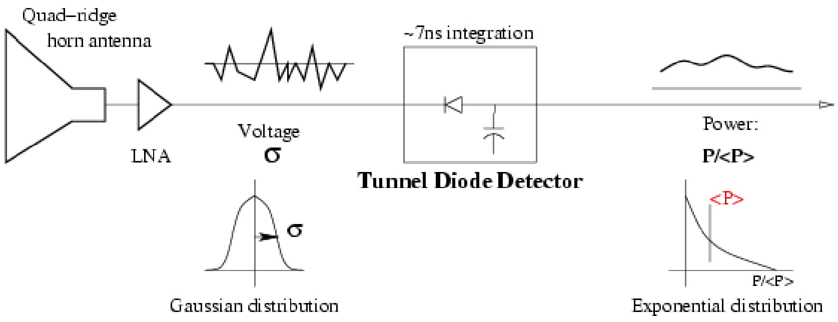


GZK nu's → the hunt continues

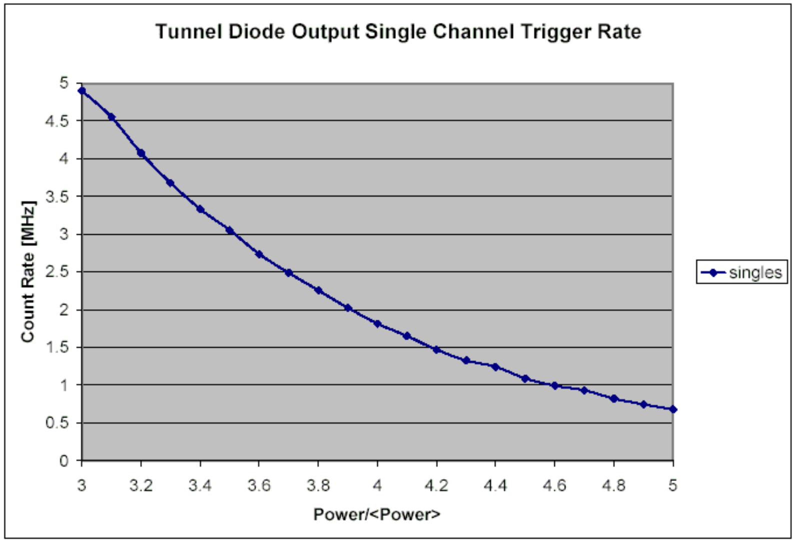
Back-up slides

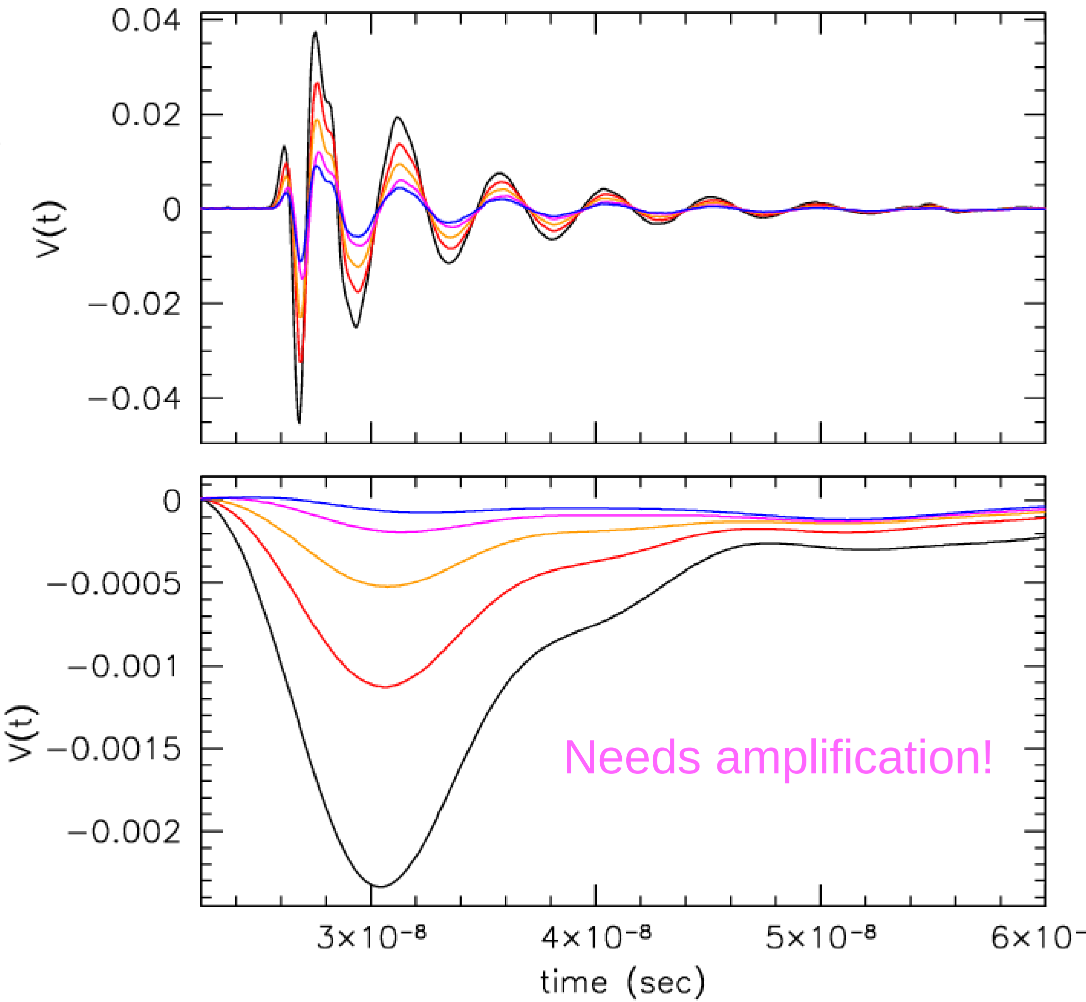


Diode detector Response



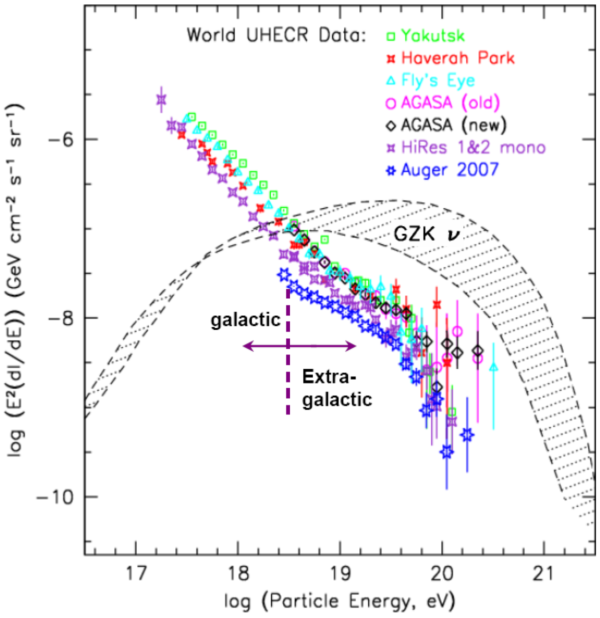
2.3σ ~= 3.9 P/<P>





Cosmogenic Neutrinos

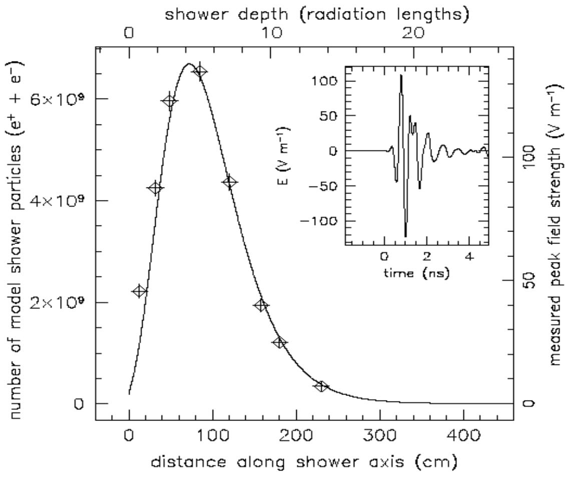
- 10^{18} eV neutrinos predicted by many acceleration and interaction processes at source locations
  - Observations, interaction physics suggest ultra-high energy cosmic rays will interact with the CMB to produce neutrinos
- Berezinsky & Zatsepin, 1970, REQUIRE 10^{18} eV neutrinos
  - Lack of neutrinos could mean
    - UHECRs are not hadrons (?!)
    - Lorentz invariance wrong (!!)
    - New physics…
- Expected fluxes are small
  - 1 neutrino per km^2 per week!



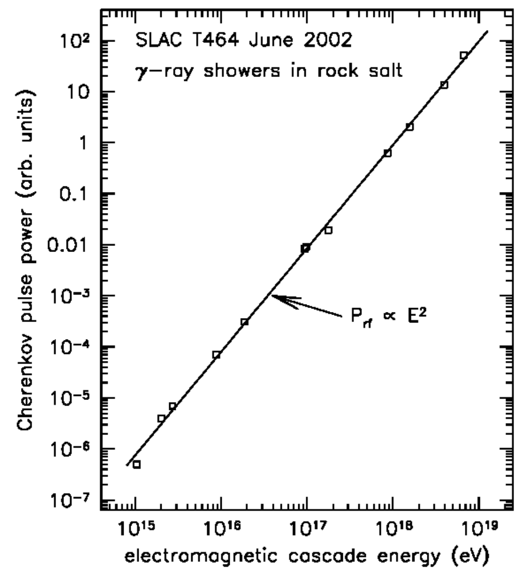
Courtesy Peter Gorham

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
  - Renewed interest: LOPES/Codelema
- **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**



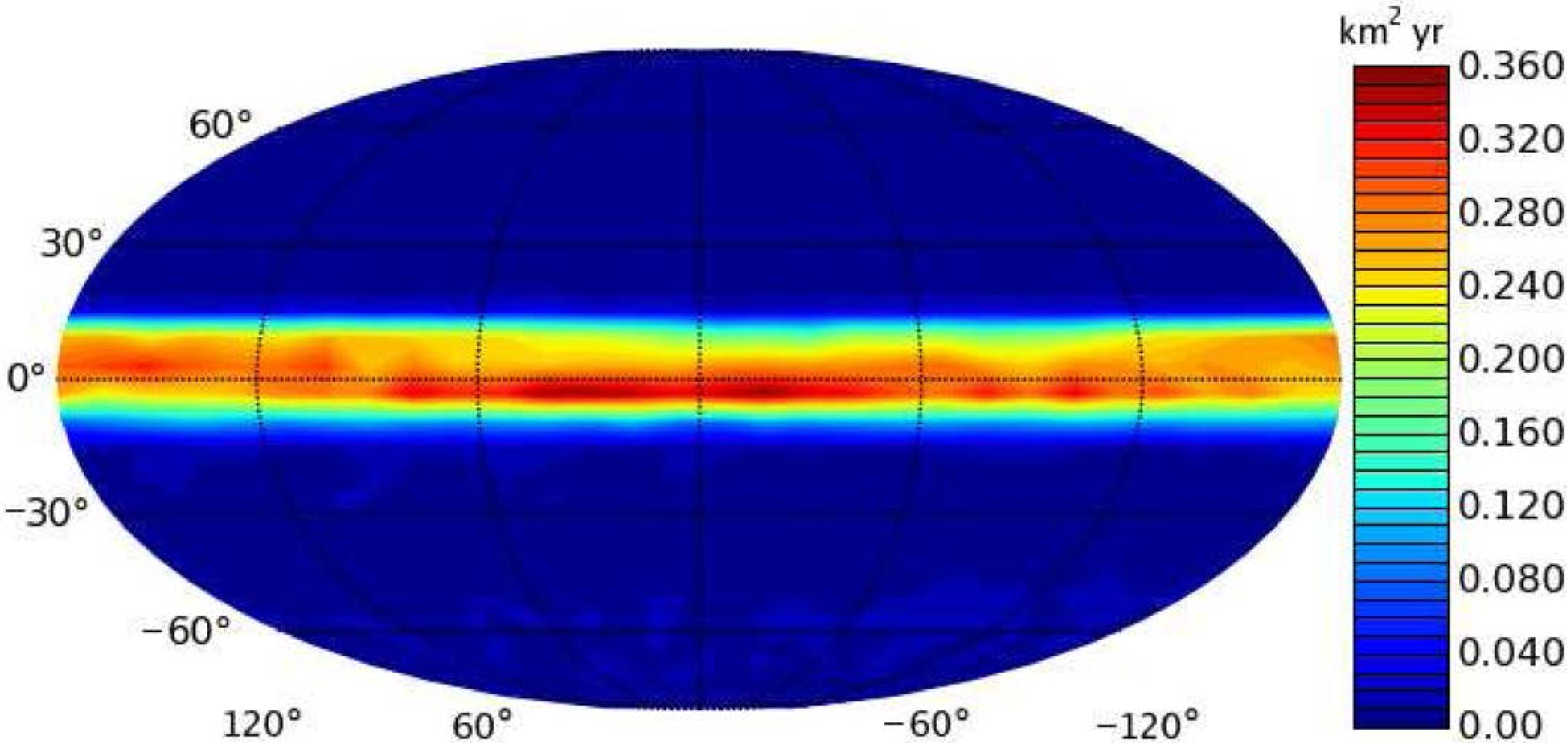
Saltzberg, et al PRL 2001



Gorham, et al PRD 2004

ANITA 1 Sensitivity

- Effective livetime: 17.3 days
- False color map in celestial coordinates (RA, Dec)
  - For 10^{20} eV neutrinos



Gorham et al., arXiv:0812.1920v1 [astro-ph]

Validation at SLAC

~7.5 metric tons ice

Gorham et al., PRL 99, 171101 (2007)

see also:

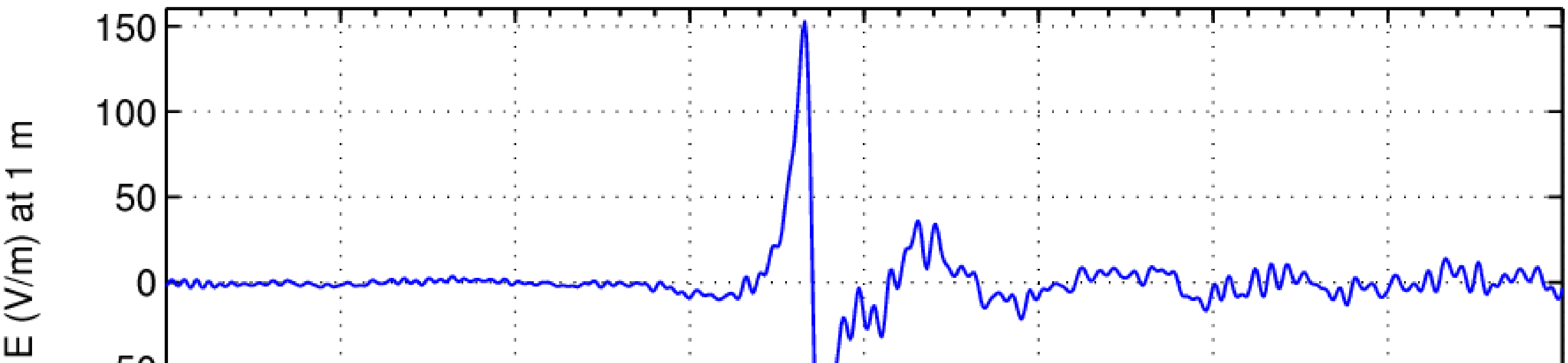
PRE 62, 8590 (2000),

PRL 86, 2802 (2001),

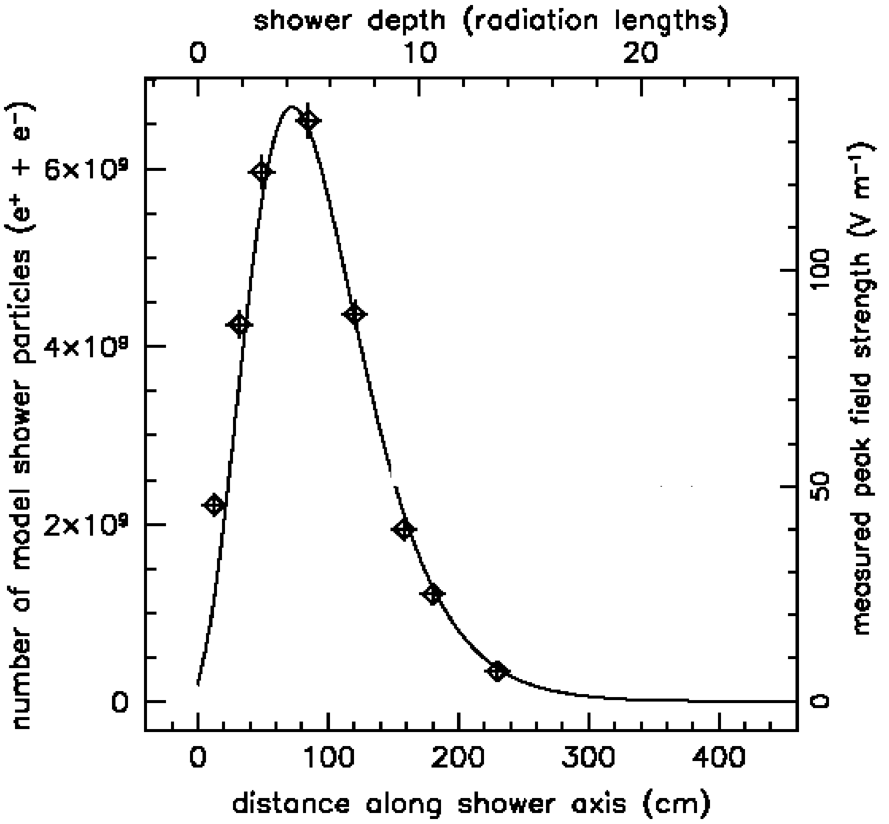
PRD 72, 023002 (2005)

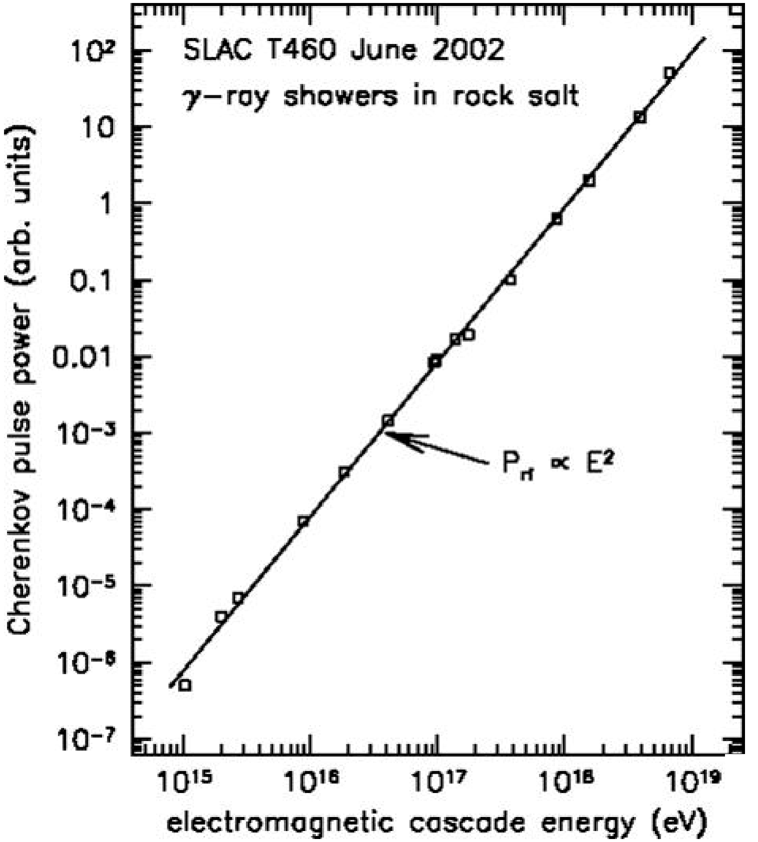
PRD 74, 043002 (2006)

Askaryan Effect in the Lab



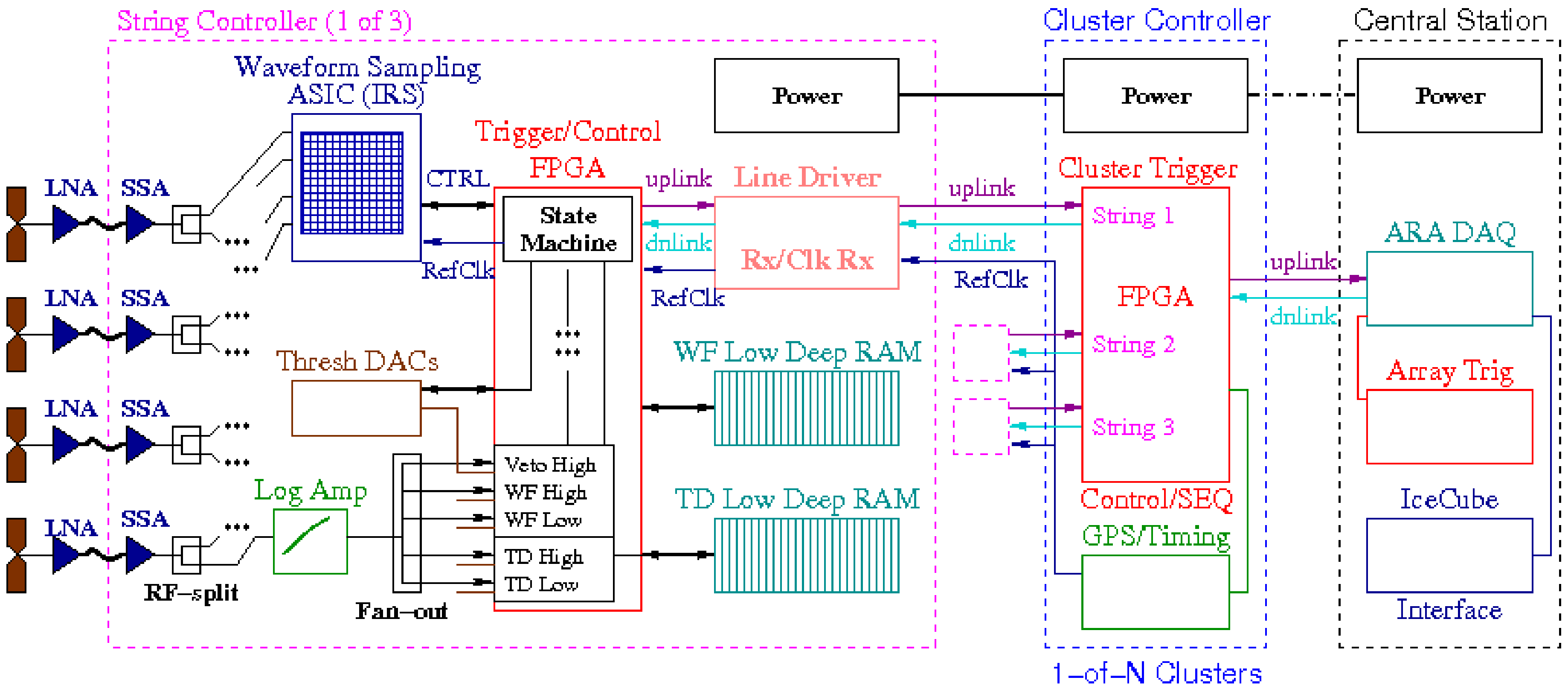
Askaryan Effect at SLAC





- Amplitude expected
- 100% linearly polarized
- Cherenkov angle

ARA Readout Electronics



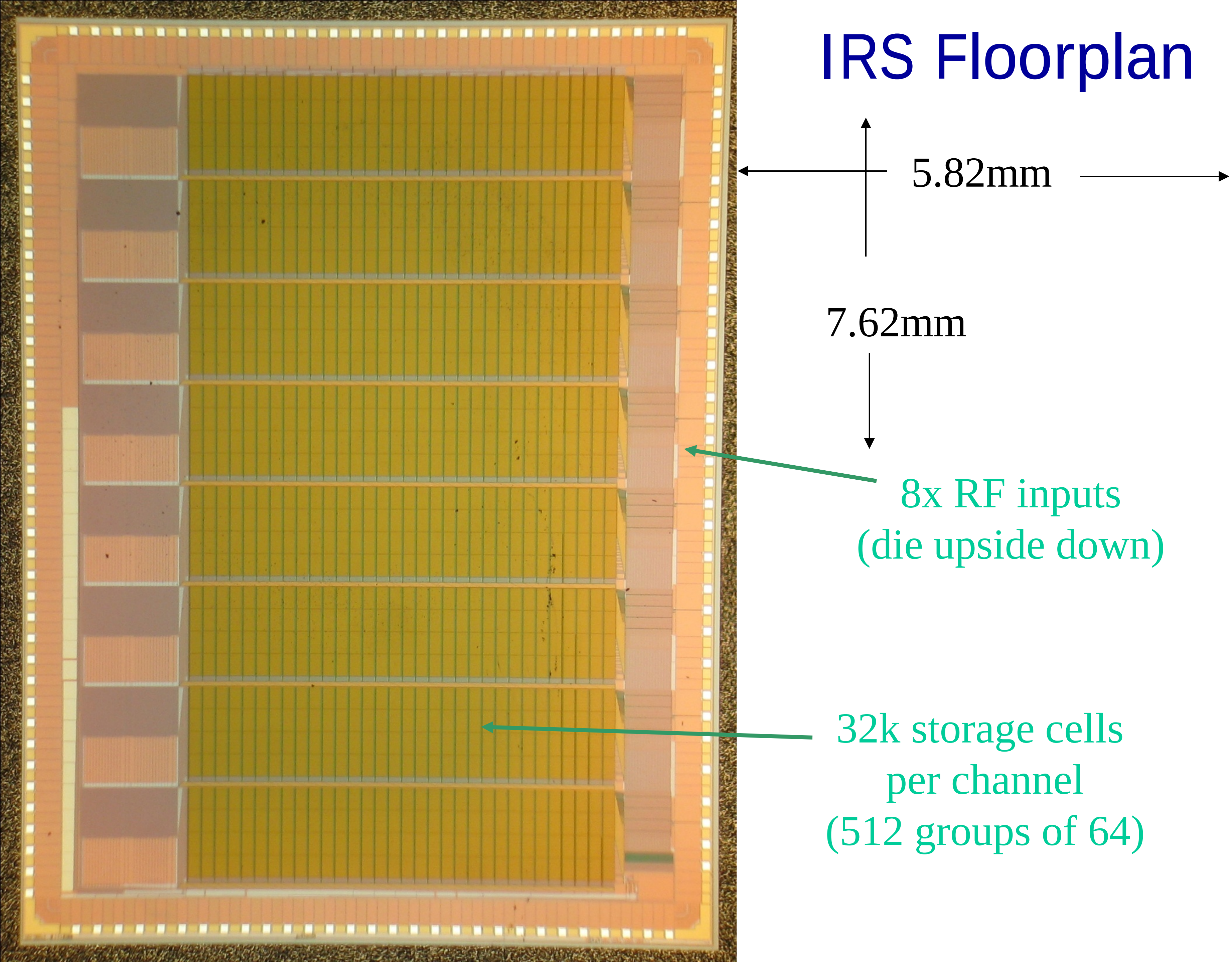
- Uplink bandwidth (~1Mbit/s [wireless])
  - First (test station) this season
  - 1 detector station each of next 2 seasons after (building more)

Ice Radio Sampler (IRS) Specifications

32768	samples/chan (16-32us trig latency)
8	channels/IRS ASIC
8	Trigger channels
~9	bits resolution (12-bits logging)
64	samples convert window (~32-64ns)
1-2	GSa/s
1	word (RAM) chan, sample readout
16	us to read all samples
100's	Hz sustained readout (multibuffer)

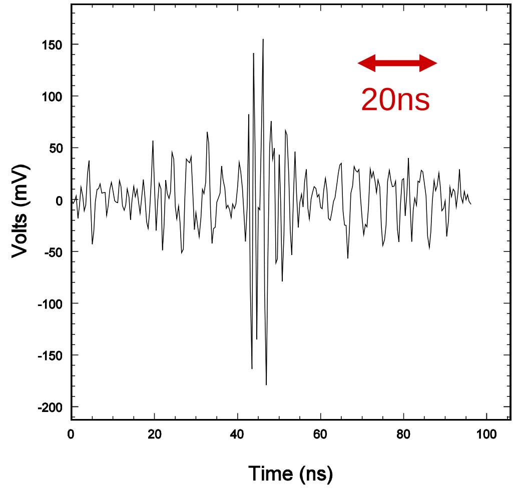
- Strictly only 5 channels necessary
  - 4x antenna, 1x reference channels
  - Could interleave for twice depth, or multiple reference channels

IRS Floorplan

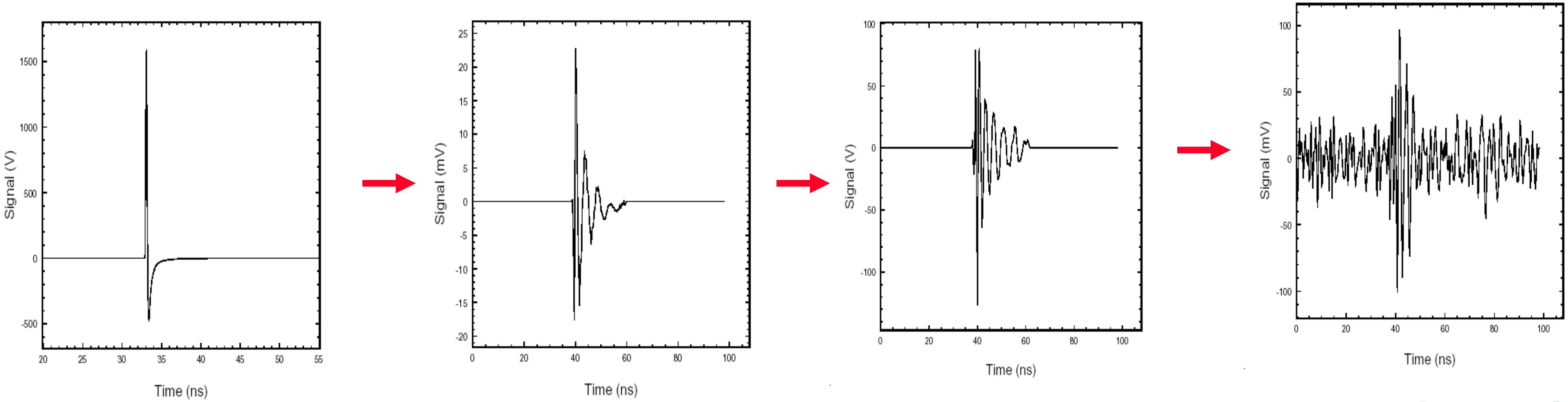


ANITA-1 Data

Data:



End-to-End Simulation:



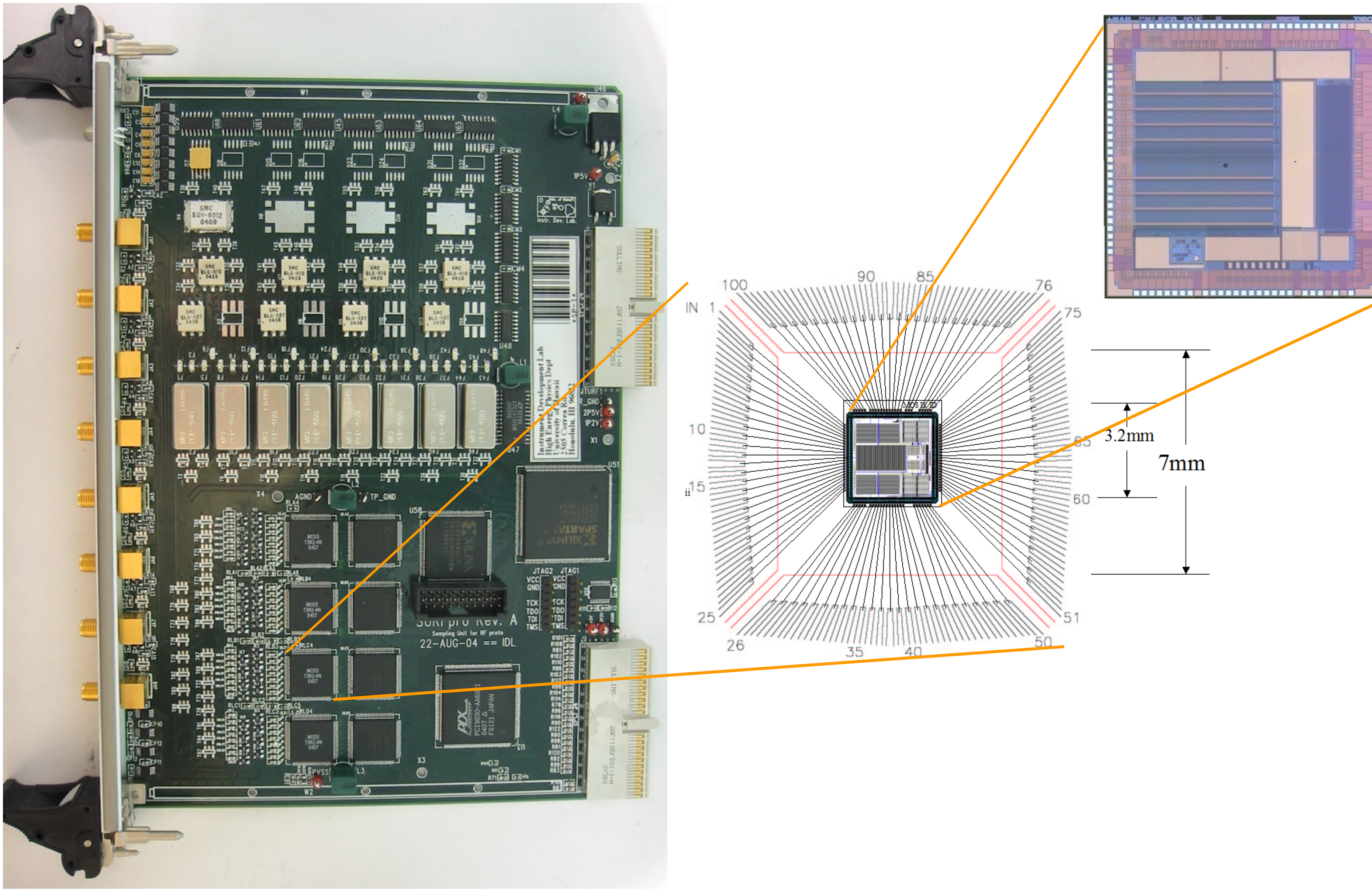
Askaryan

+antenna

+electronics

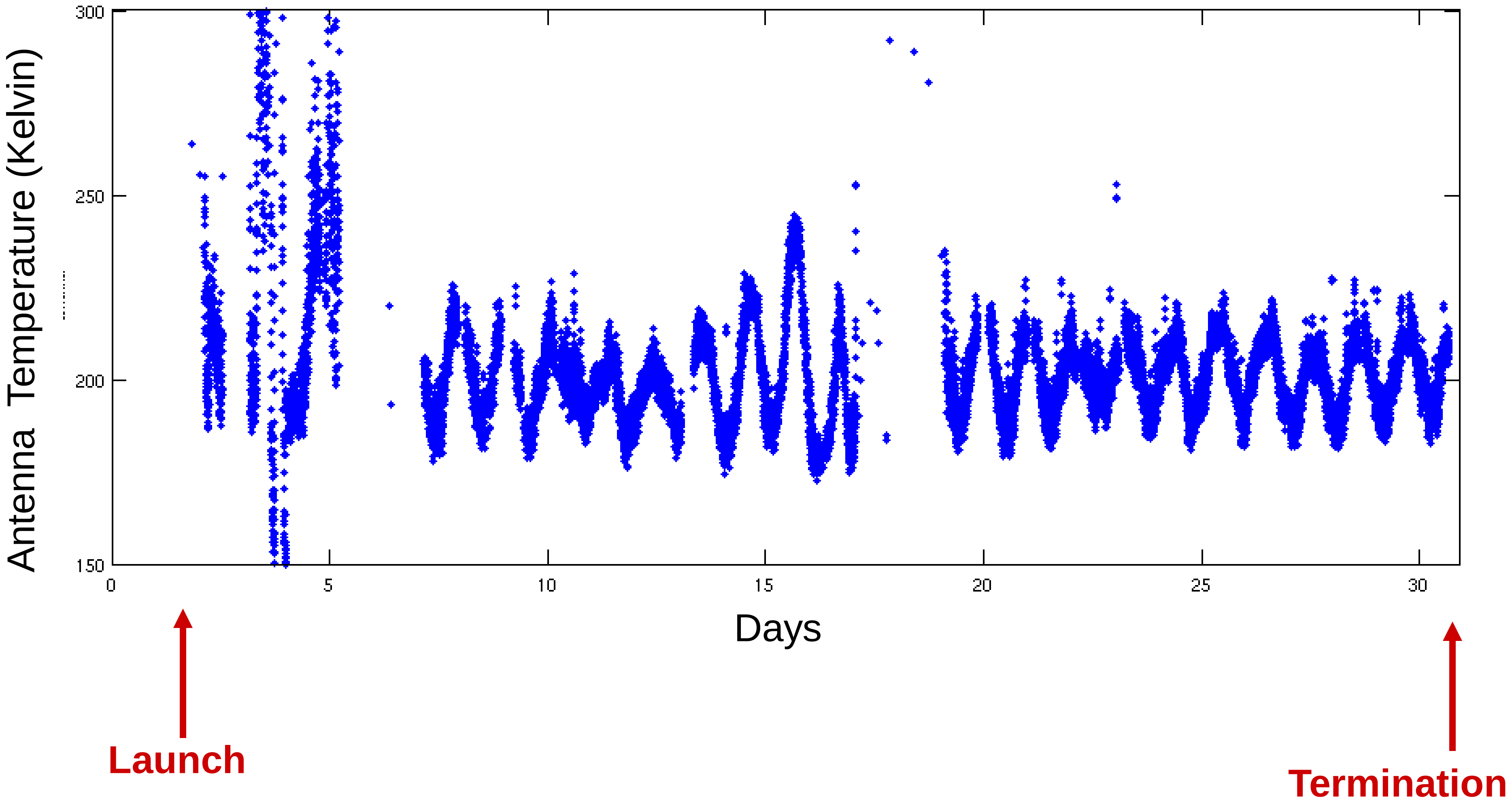
+ thermal noise

Sampling Unit for RF (SURF) board

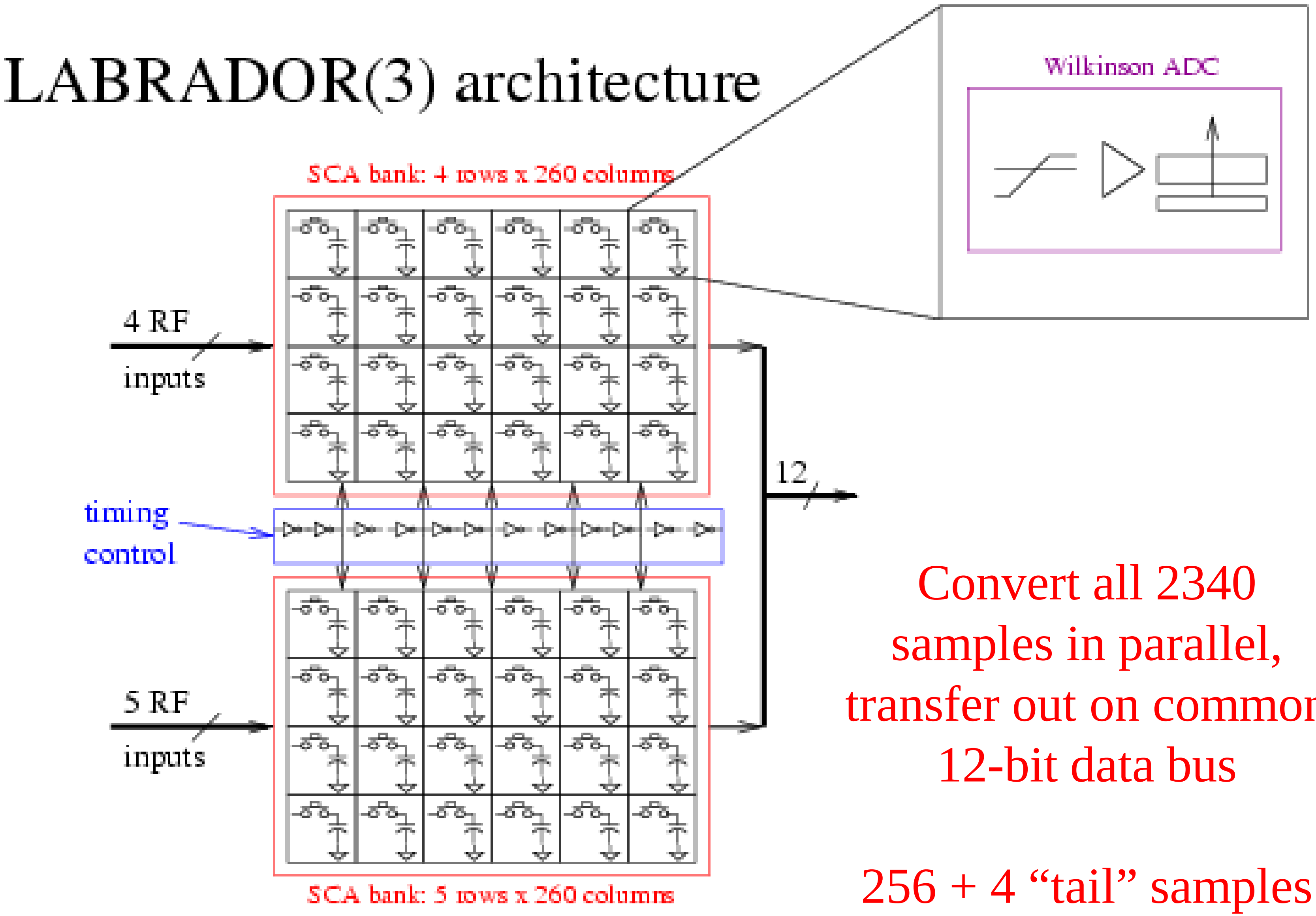


ANITA-2 Data

Antenna Noise Temperature (includes ice temp)



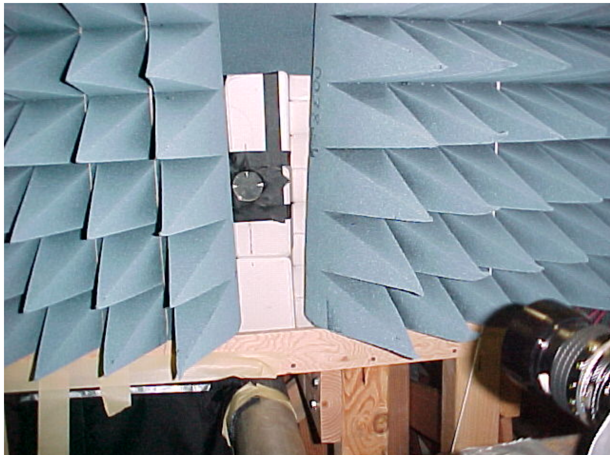
9 x 260 samples = 2340 storage cells

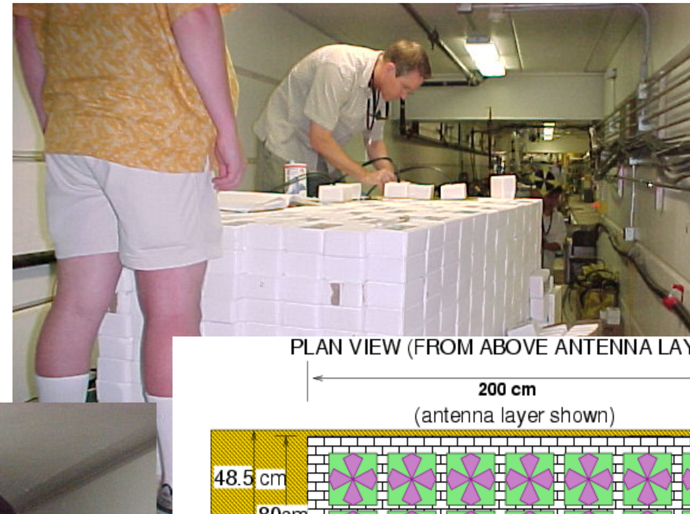


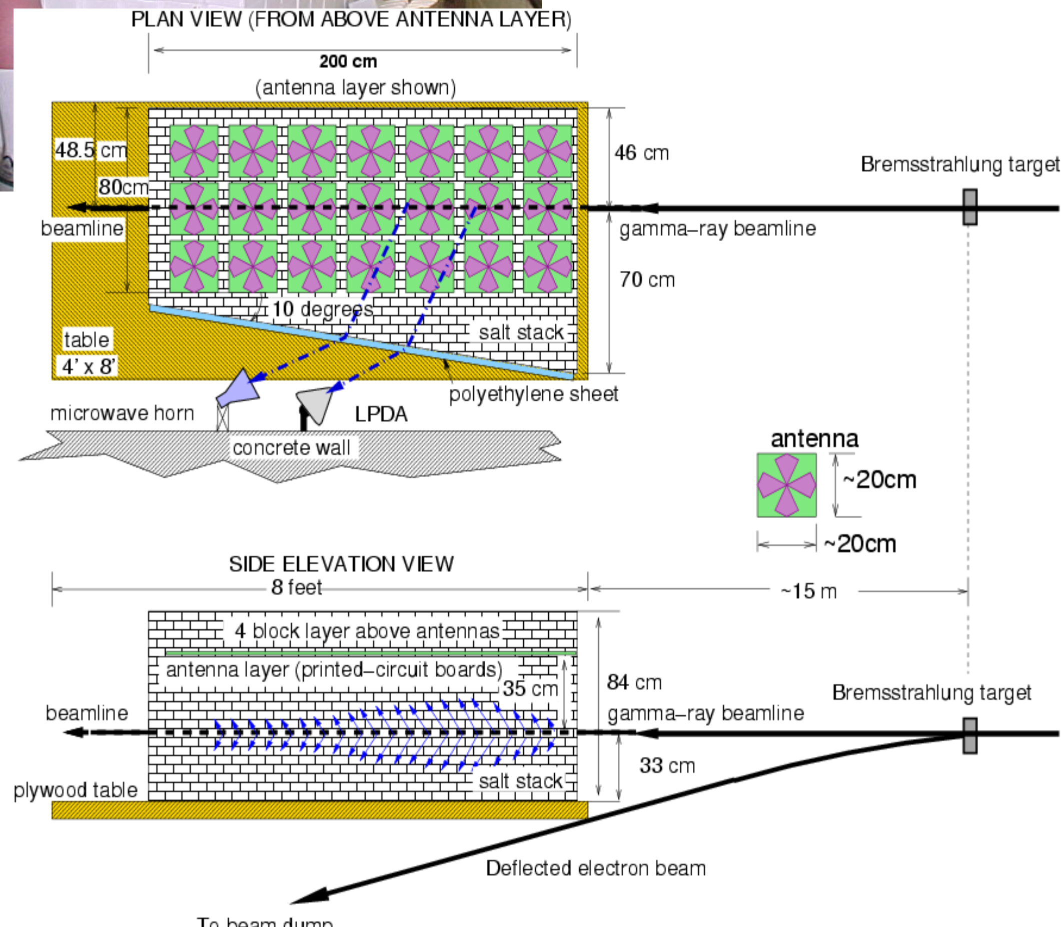
Convert all 2340 samples in parallel, transfer out on common 12-bit data bus

256 + 4 "tail" samples

Askaryan in Salt: SLAC T460

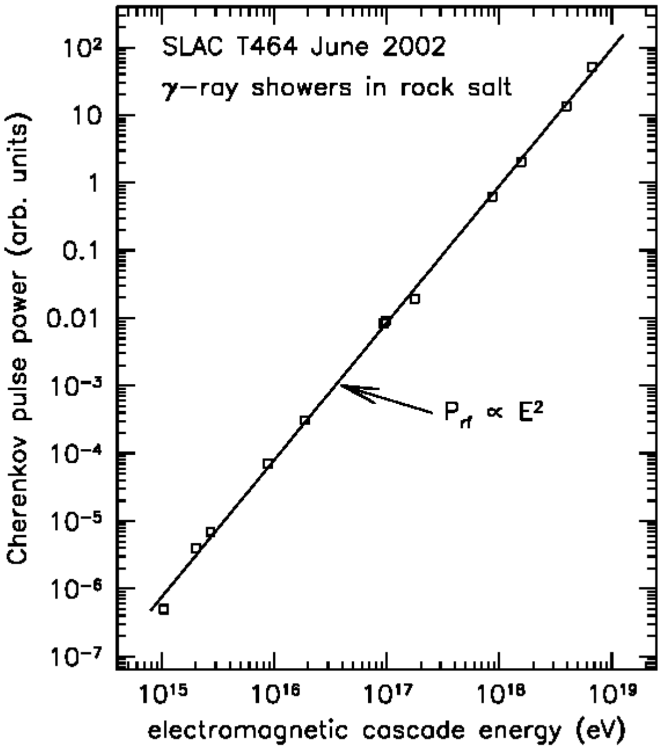


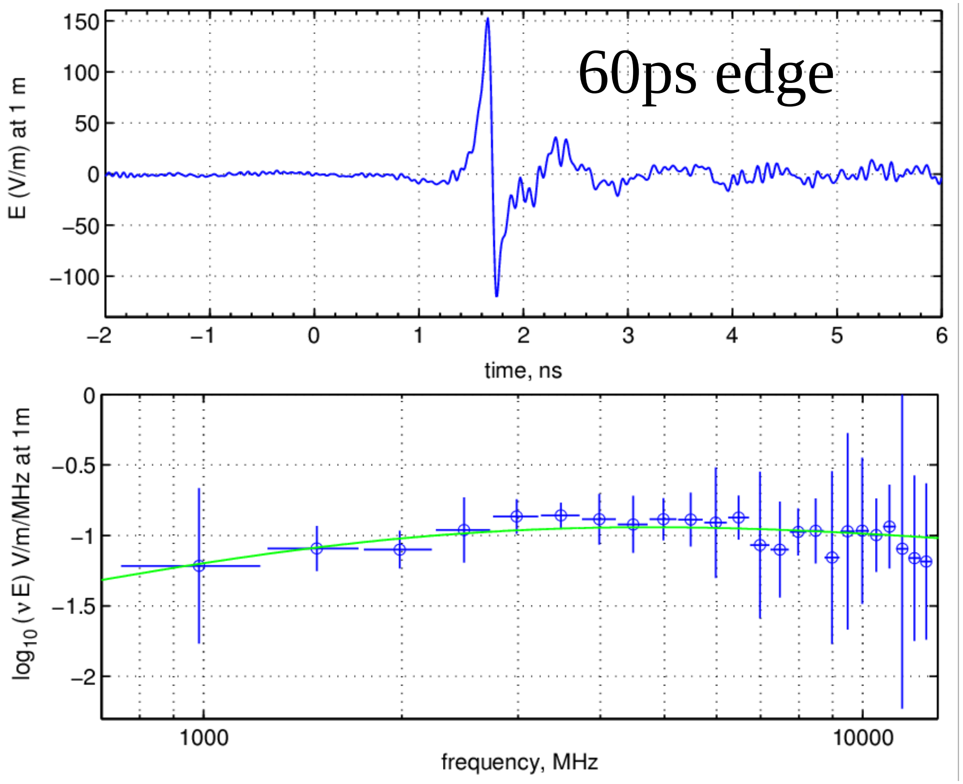




- Target: 6 tons of Morton brick salt
- Provide shower volume and embedded antenna matrix
- Antennas sample 21 grid-points along shower, dual polarization

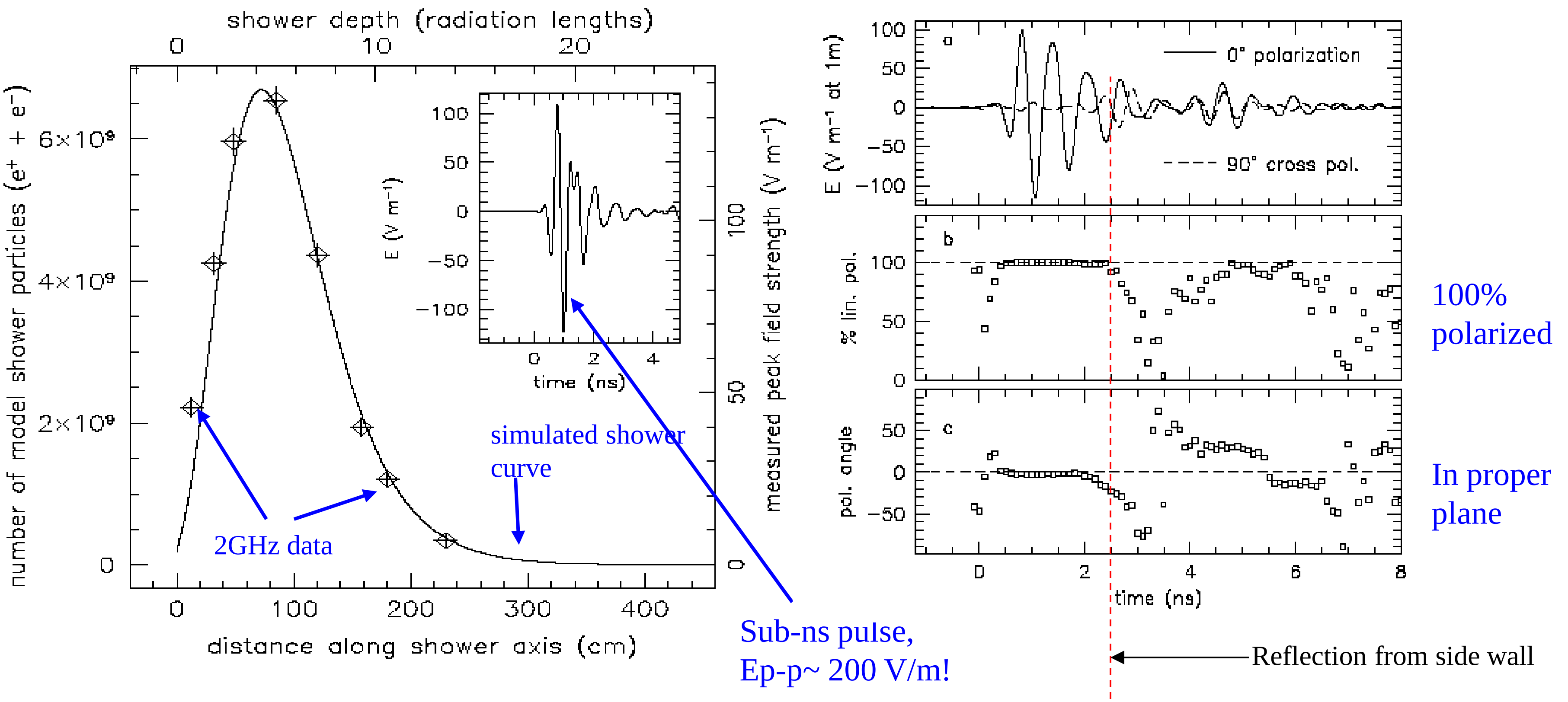
RF Coherence vs. energy & frequency





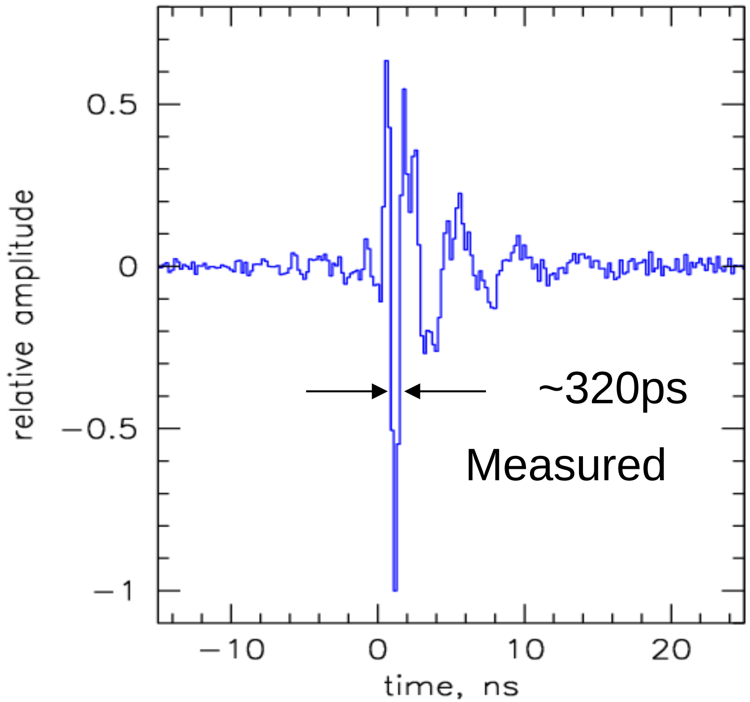
- Much wider energy range covered than previously: 1PeV up to 10 EeV
- Coherence (quadratic rise of pulse power with shower energy) observed over 8 orders of magnitude in radio pulse power
- Differs from actual EeV showers only in leading interactions==> radio emission almost unaffected

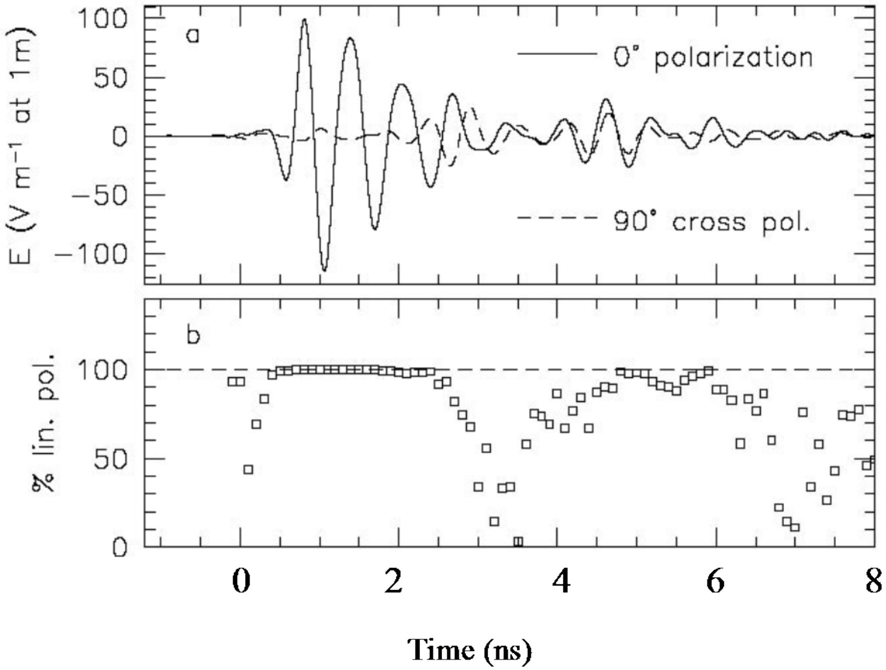
Shower profile observed by radio (~2GHz)



- 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

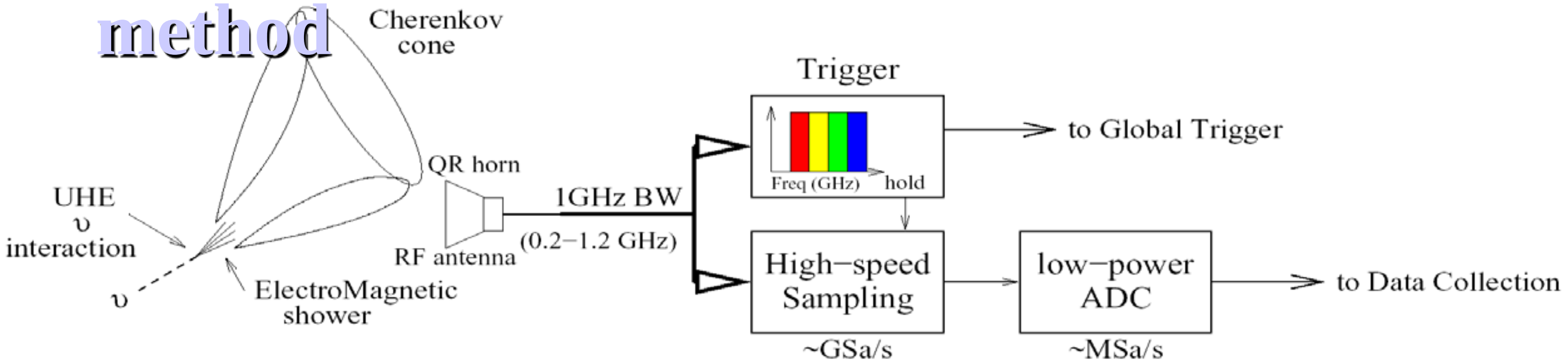




- Significant signal power at large frequencies
- Strong linear polarization (near 100%)

Trigger/Digitizer Specifications

ANITA trigger & digitizer uses a proven dual-track method

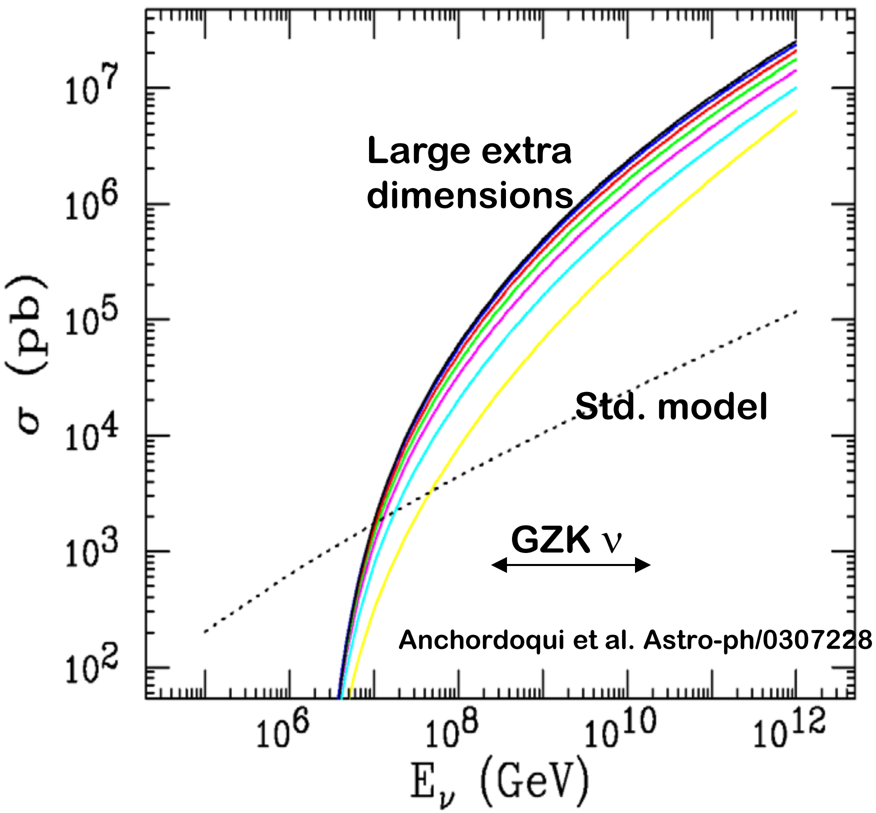


- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

	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

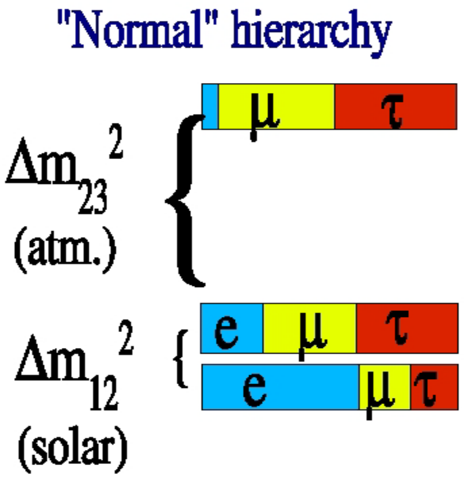
Particle Physics: Energy Frontier

- 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

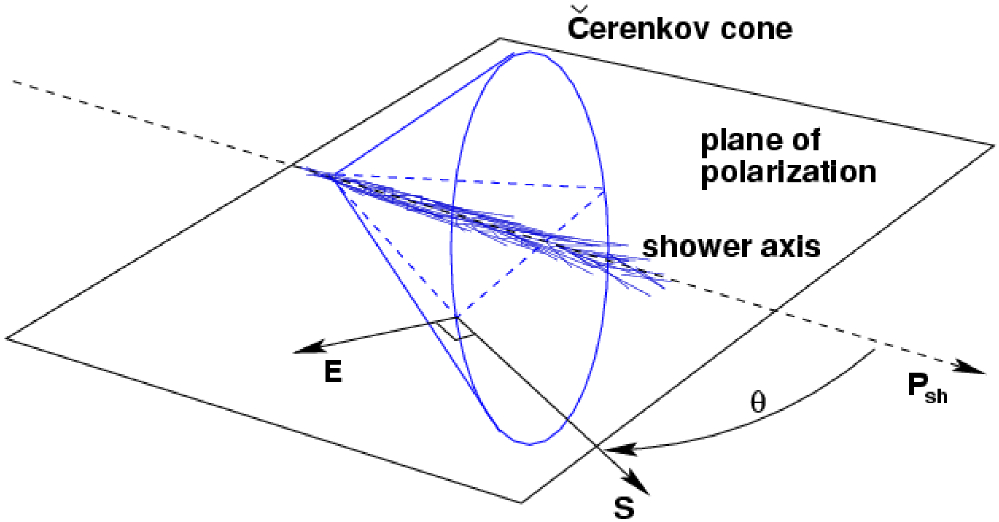


$\nu_e:\nu_\mu:\nu_\tau$

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

Neutrino decay leaves a strong imprint on flavor ratios at Earth

Cherenkov polarization tracking

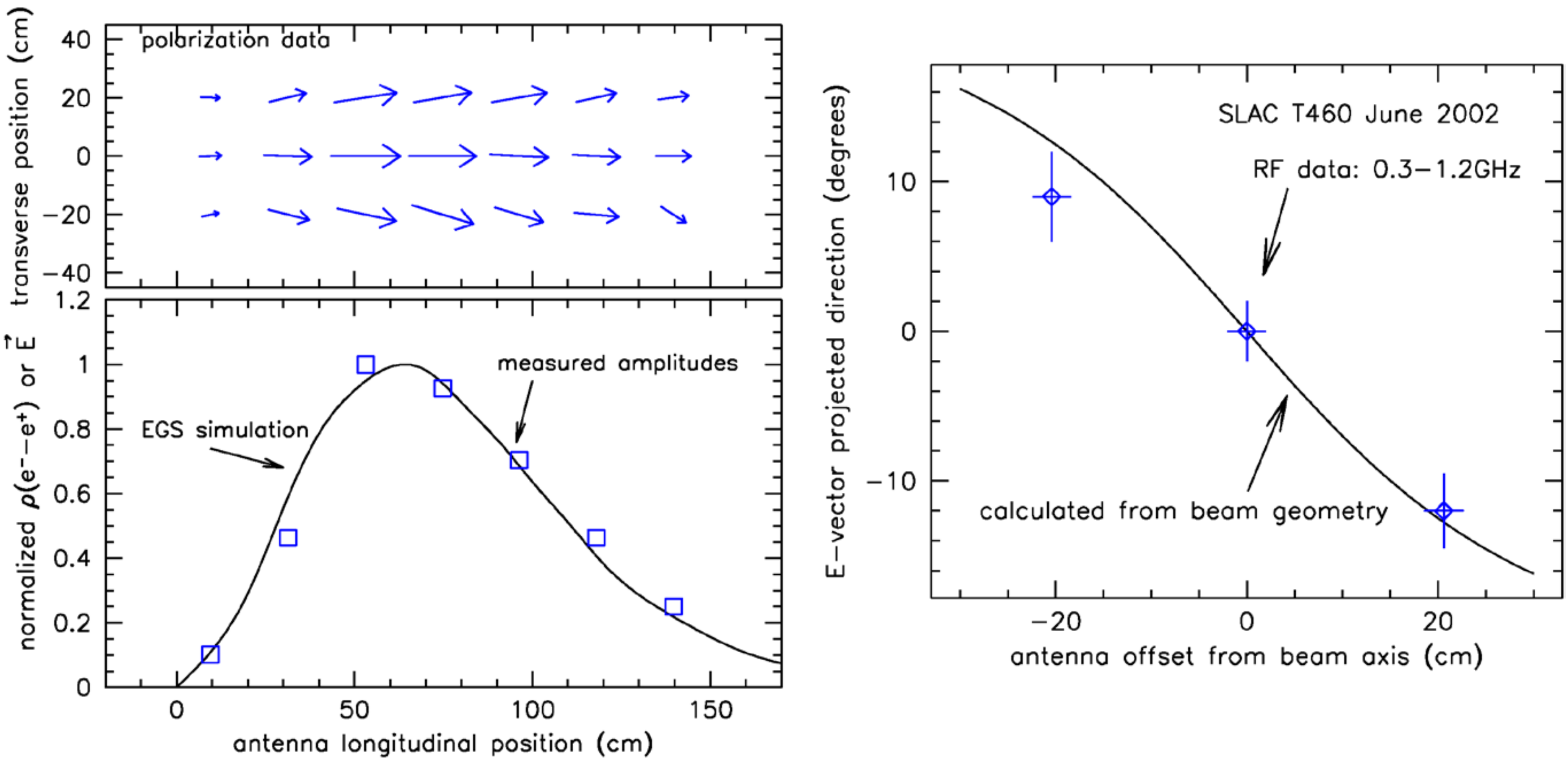


Cherenkov radiation predictions:

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

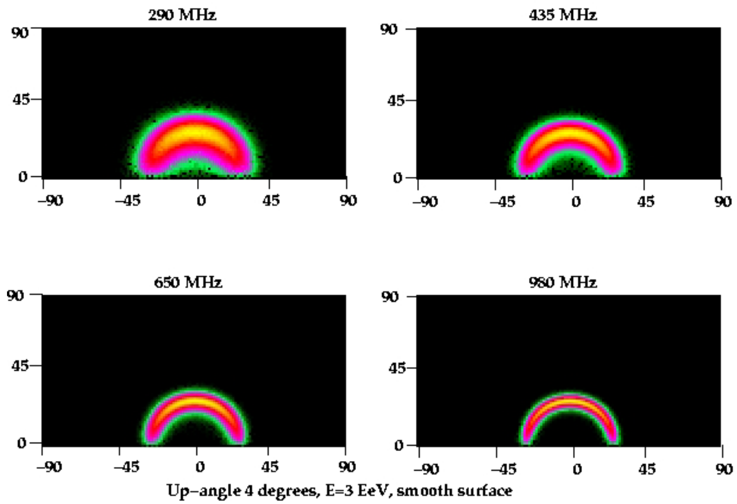
- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - **Intersection of these planes defines shower track**

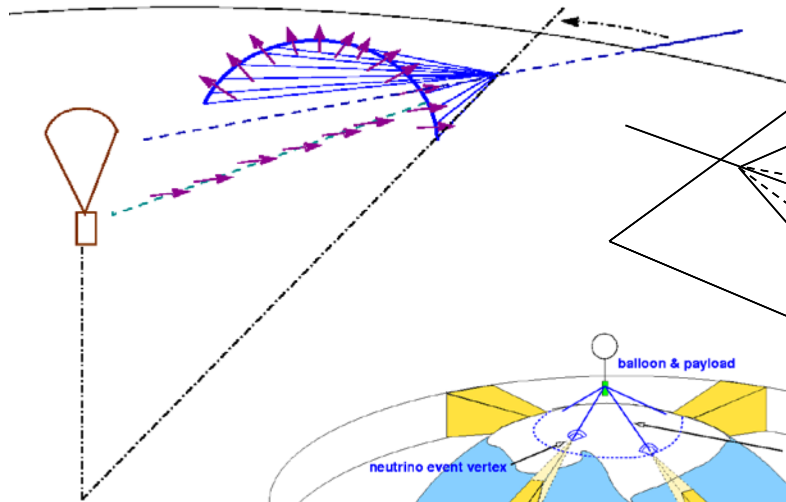
Polarization tracking

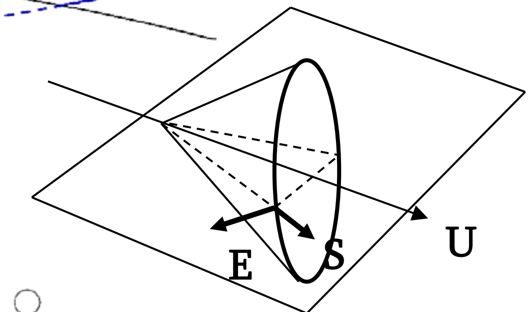


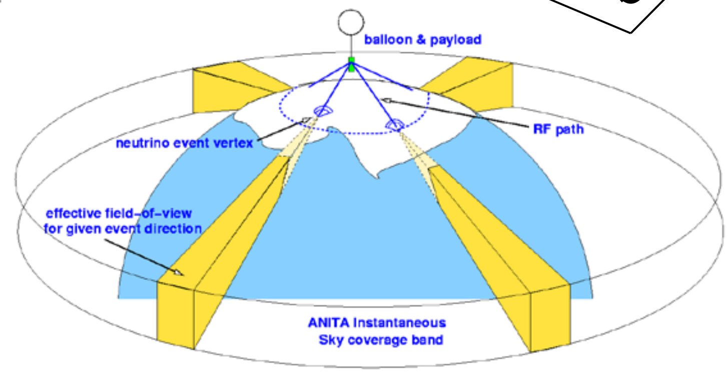
- Measured with dual-polarization embedded bowtie antenna array in salt

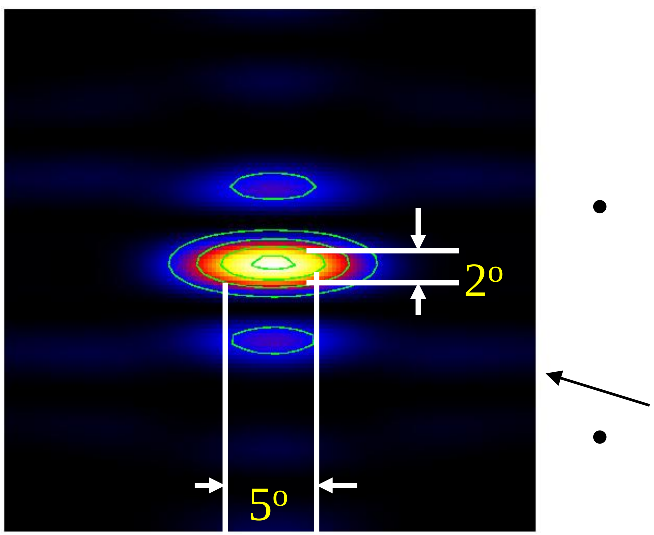
ANITA as a neutrino telescope







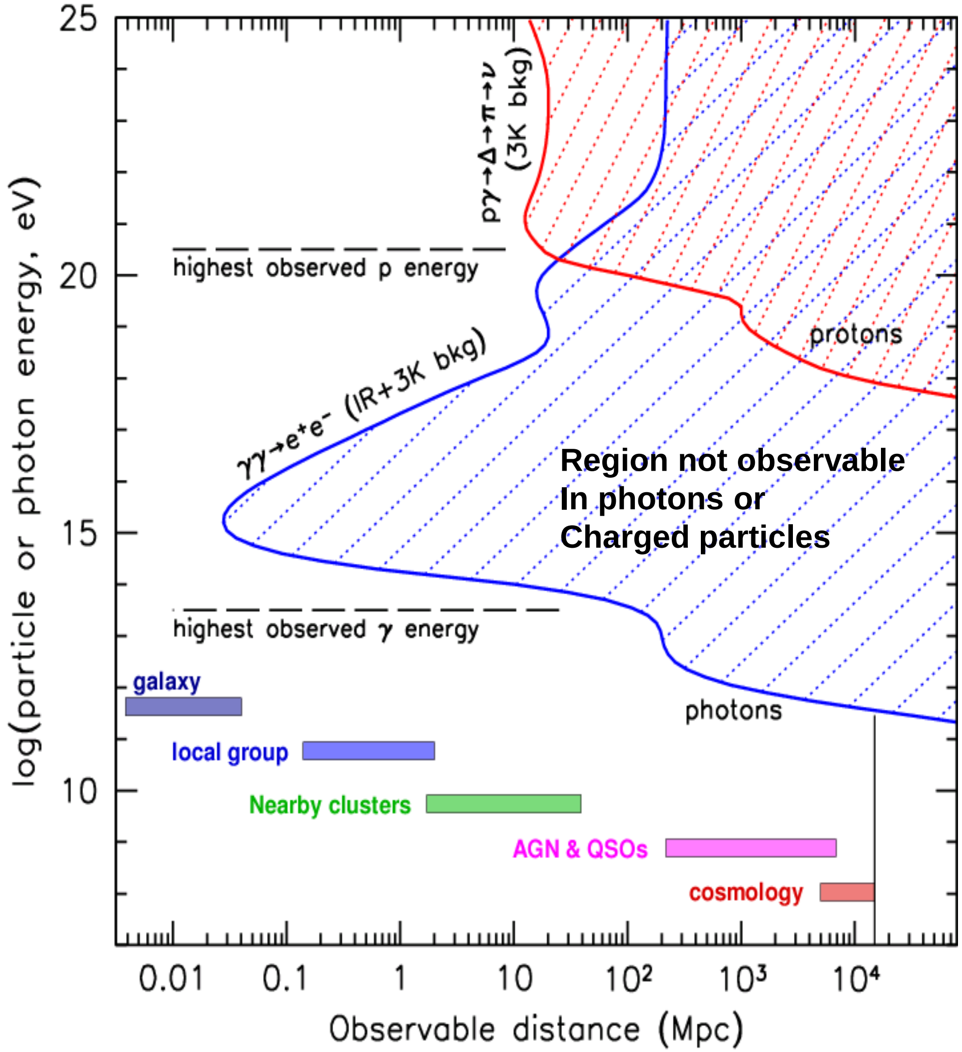




- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse

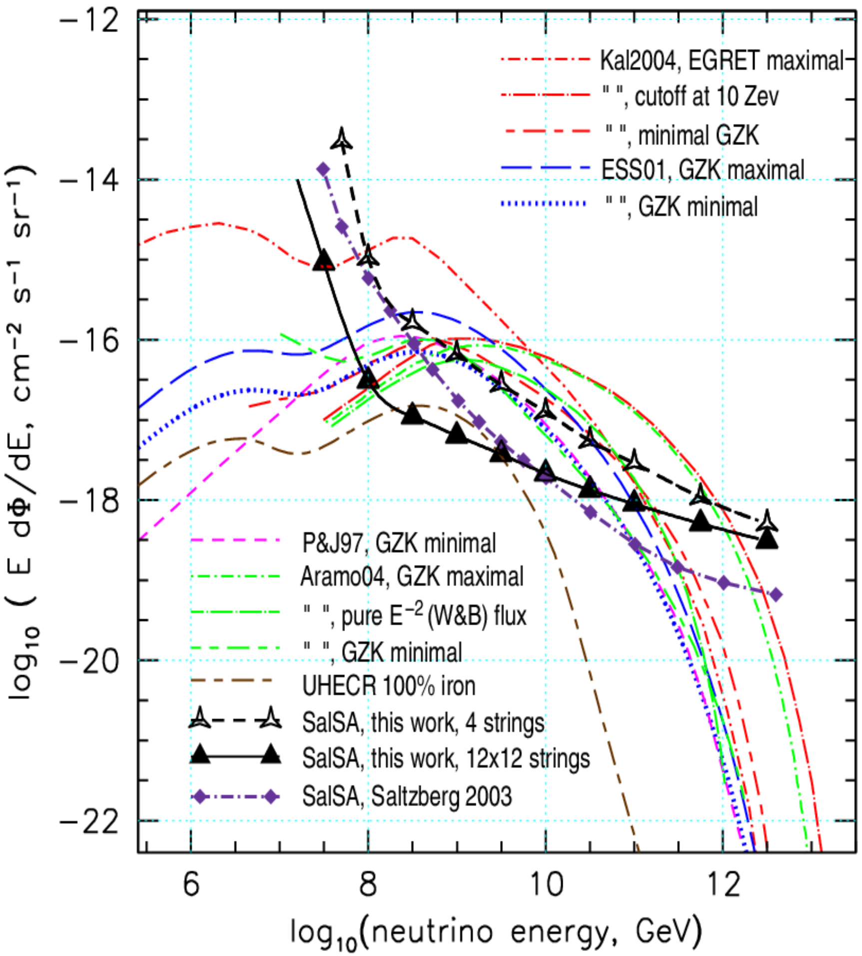
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

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**

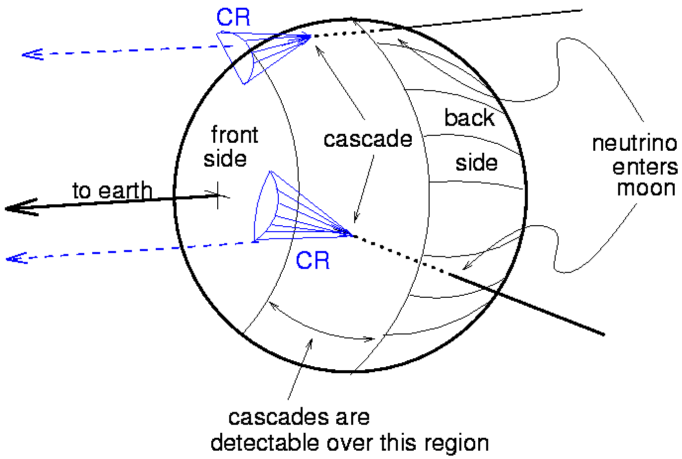
GZK neutrino sensitivity details, 1 yr

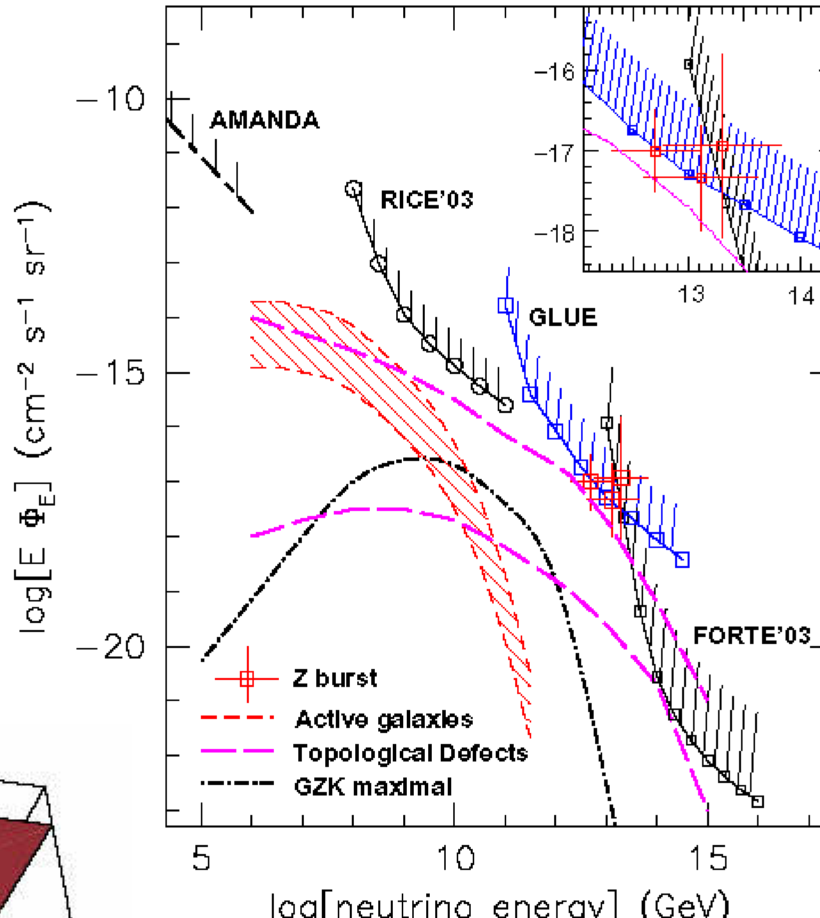


- 2 independent MC calculations: UCLA & UH
- UCLA: Saltzberg 2002 SPIE; also 2005 Nobel symposium
  - Simplified 10x10 strings, 10 antenna nodes per string
  - Did not truncate dome, so high energies extended
- UH: Gorham et al. PRD 2005
  - 12x12 strings, 12 nodes with realistic trigger sims
  - **Even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

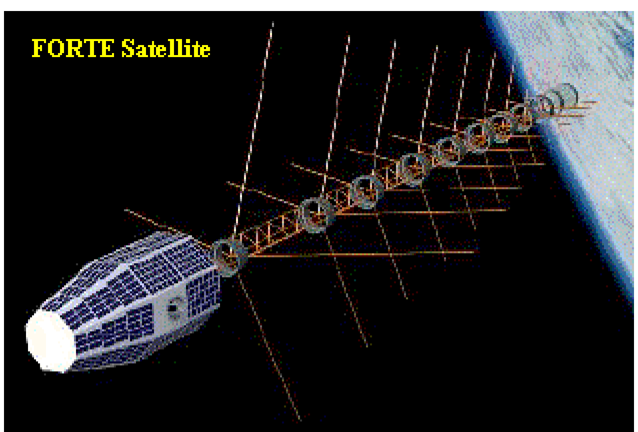
Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

• PRL 93:041101 (2004) limits published

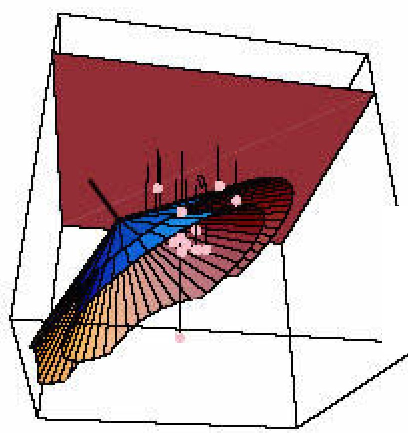




Greenland Ice



• PRD 69:0133008 (2004)



Radio Ice Experiment (RICE) @ South Pole

• Astropart.Phys.20:195 (2003)