The Antarctic Impulsive Transient Antenna (ANITA)

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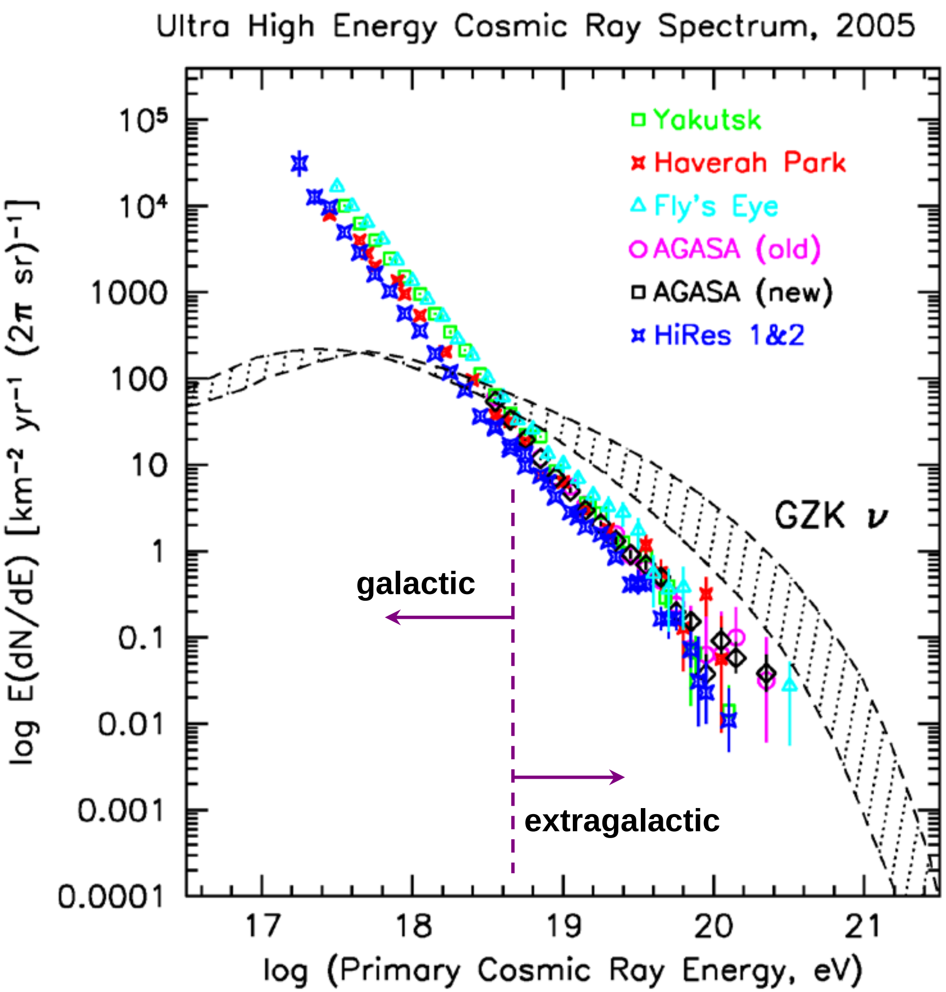
LGS Seminar, 名古屋大学 March, 2016

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

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

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

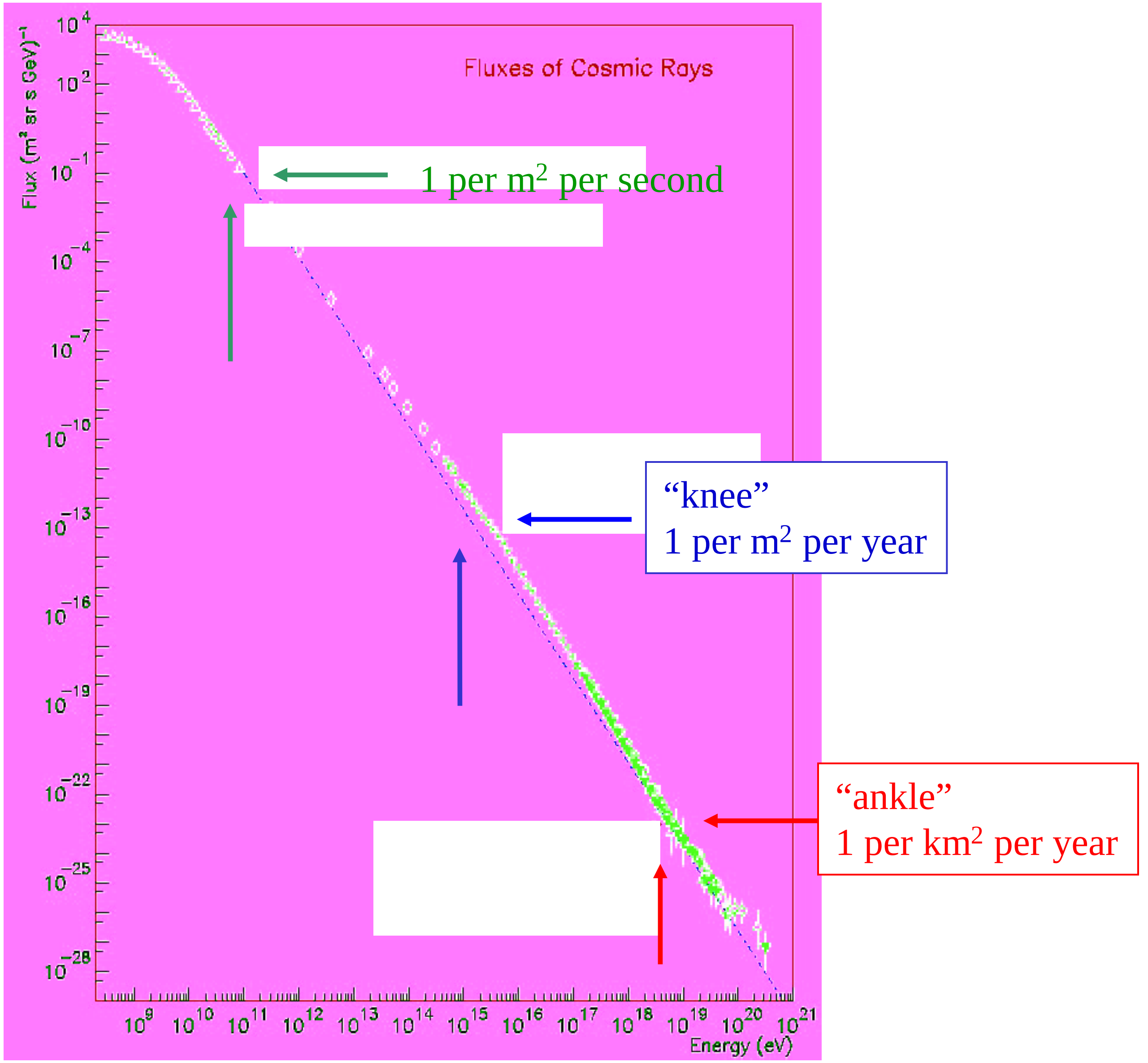


None have yet been observed

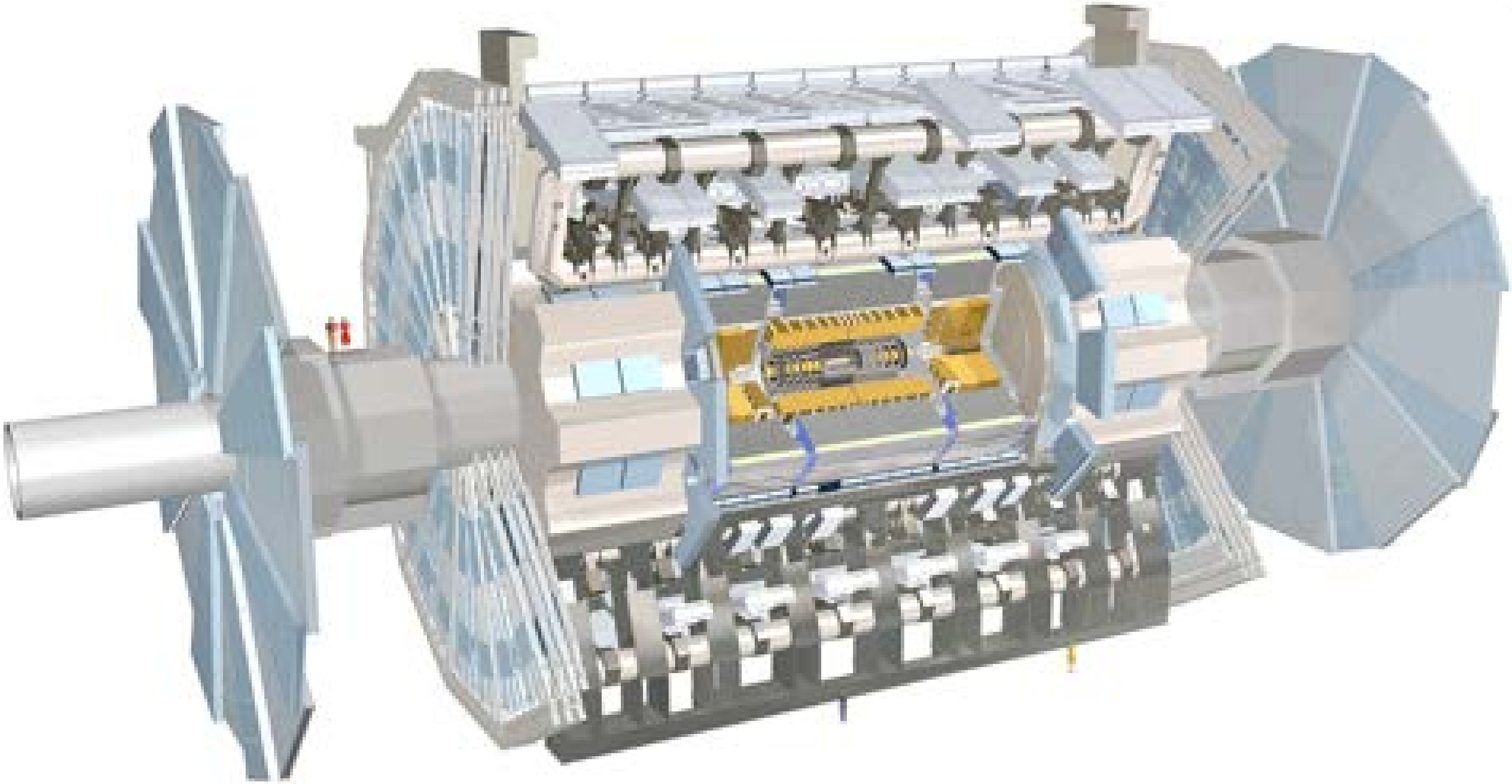
Why so Hard?? The Flux Problem

- At E>10^20...

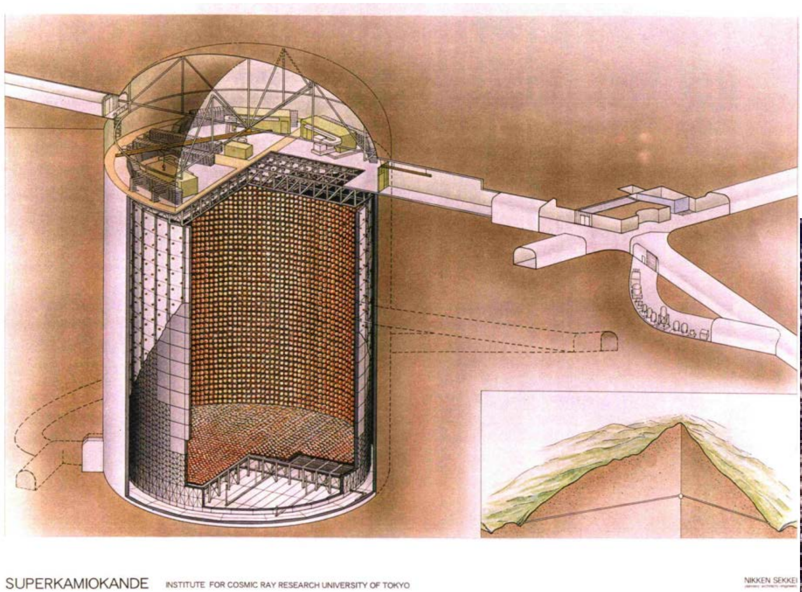
$$\iiint_{r,\phi,\theta} dr\,d\phi\,d\theta$$

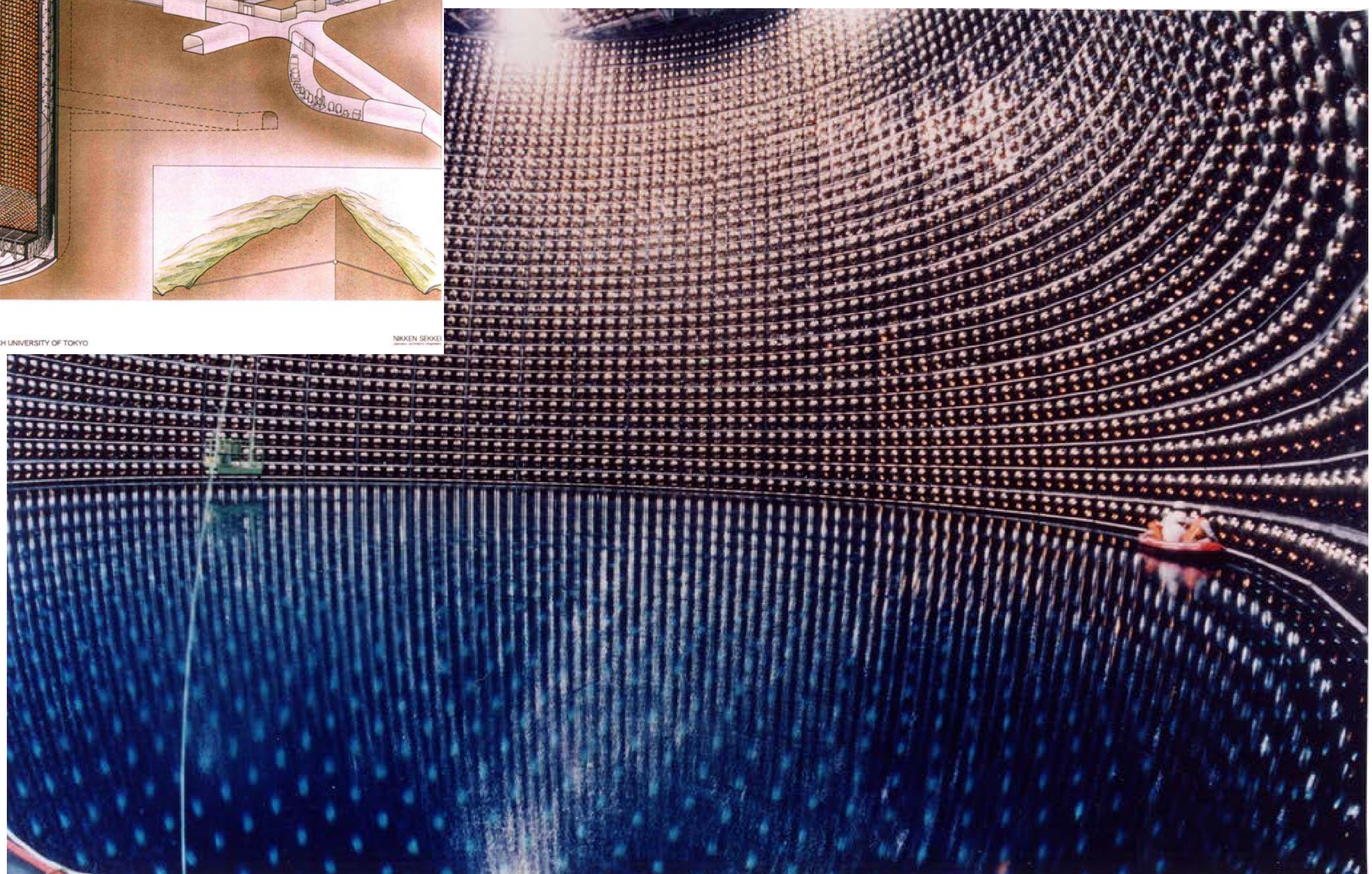


Detector Energy Scales – the tonne



Detector Energy Scales – the kT



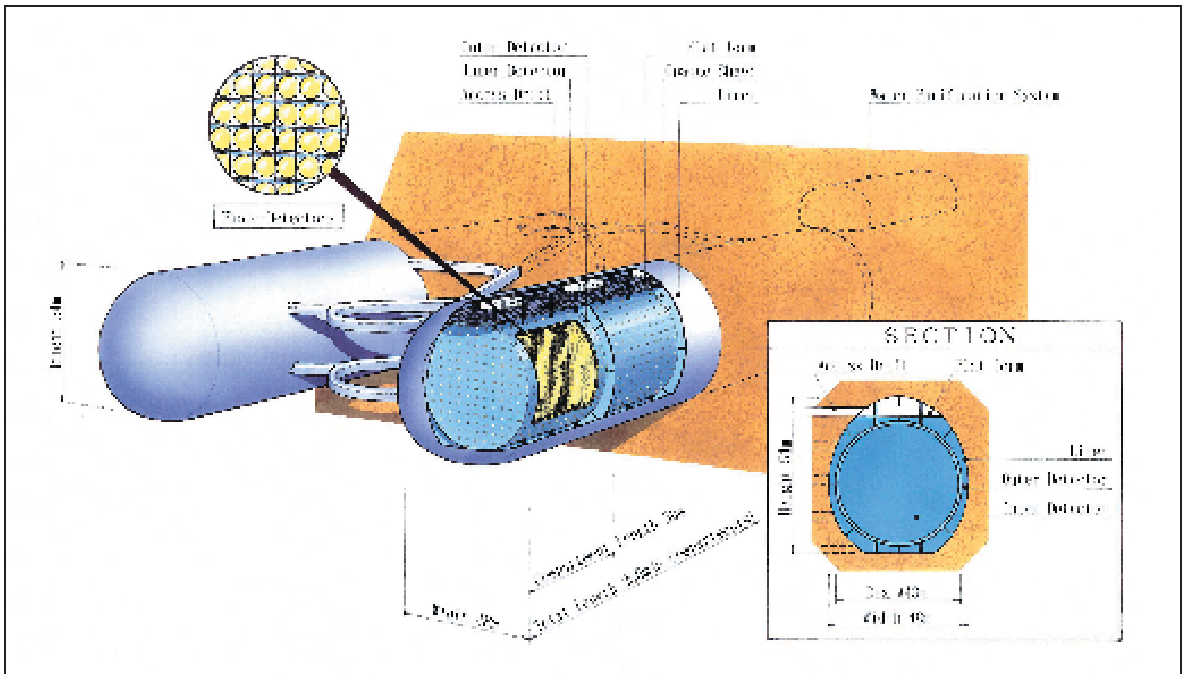


Detector Energy Scales – the MT

MEGA-DETECTORS

Thinking big: the next generation of detectors

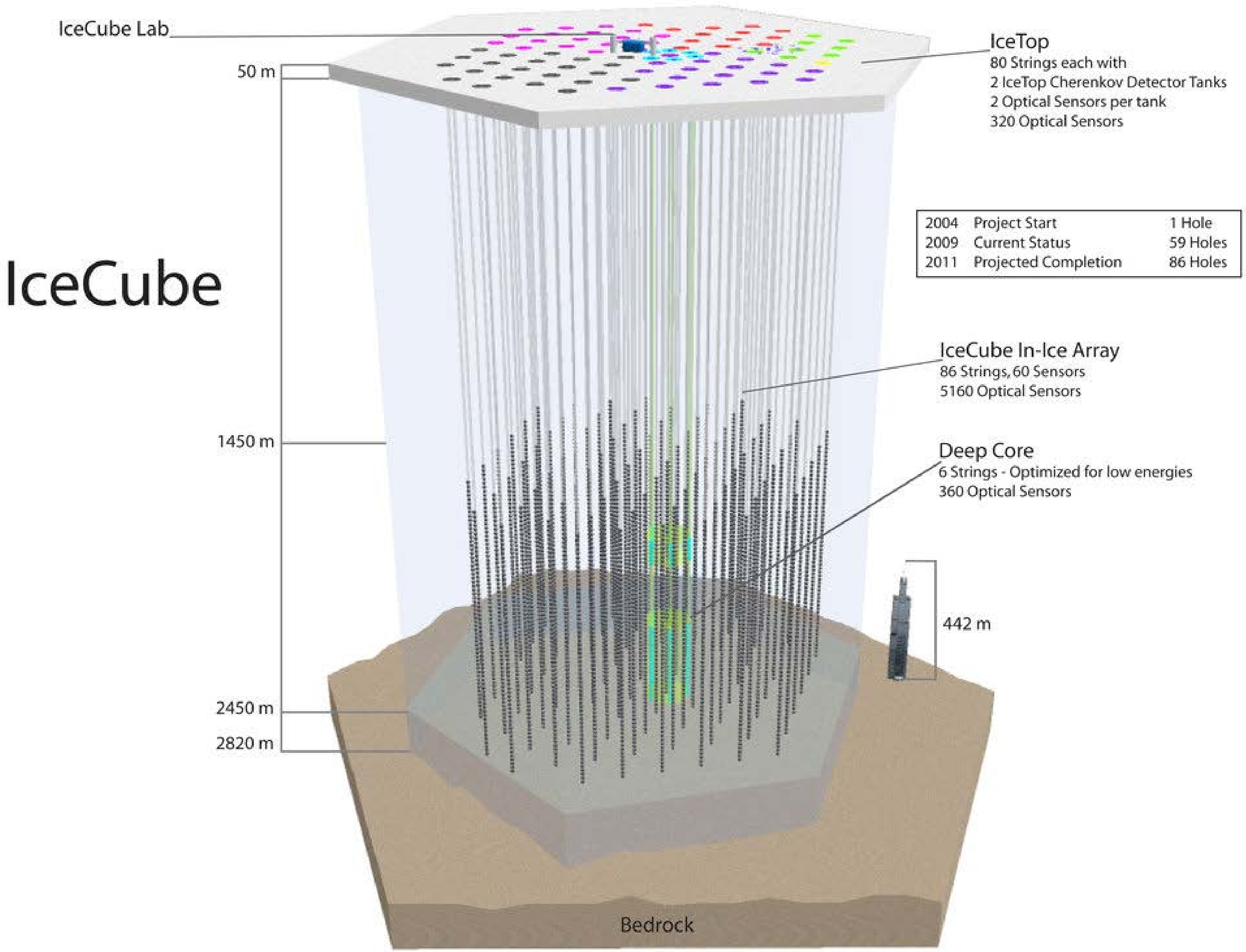
The conference on the Next Generation of Nucleon Decay and Neutrino Detectors looked at the development of new, large-scale detectors. **Alain de Bellefon** reports.



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

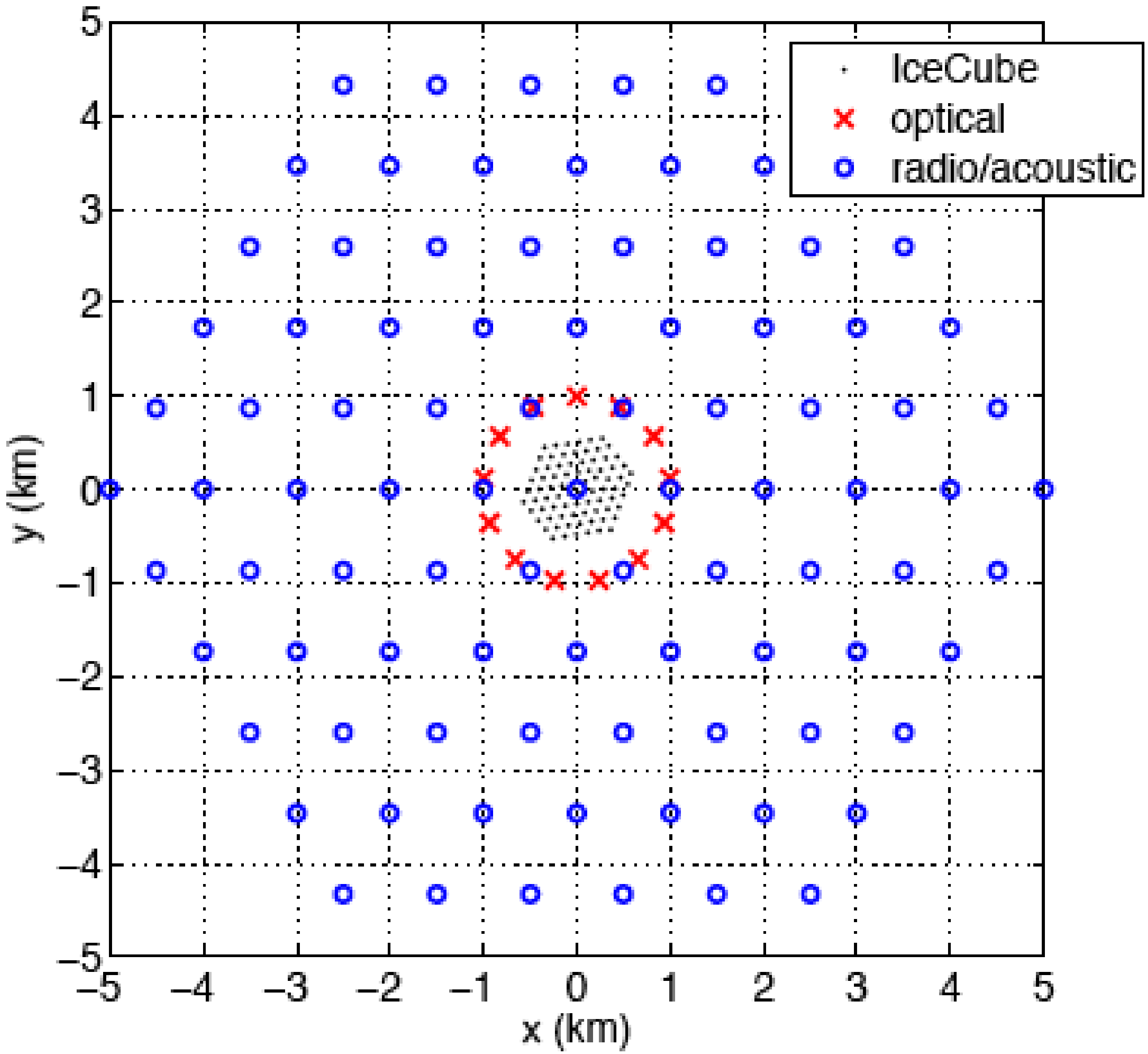
Detector Energy Scales – the GT



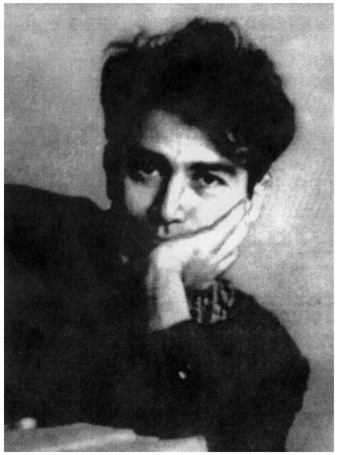
Detector Energy Scales – the TeraT

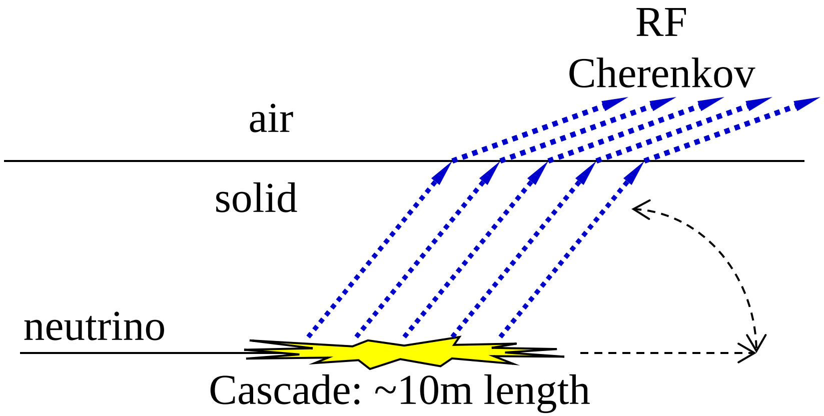
IceCube
~200M$

Simply scaling up??



Radio Observation in dense media



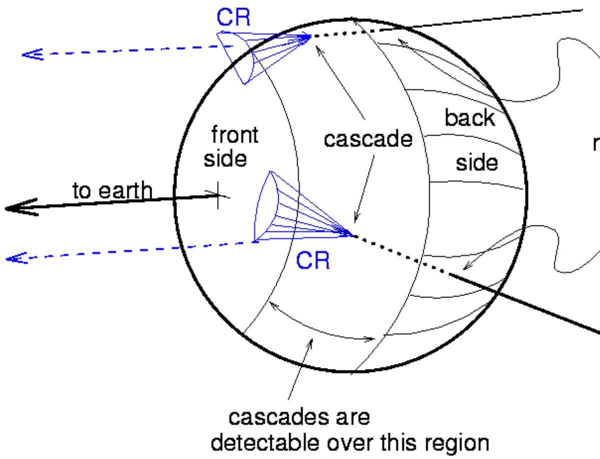


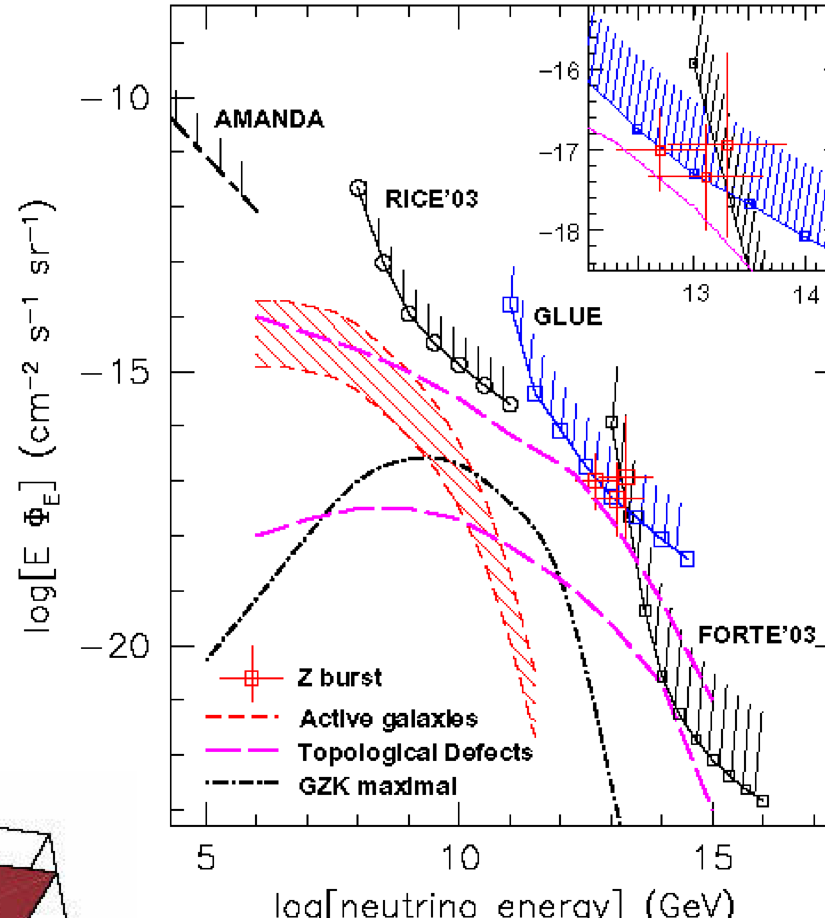
1960's: Askaryan predicted that the resultant compact cascade shower (1962 JETP **14**, 144; 1965 JETP **21**, 658):

- 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

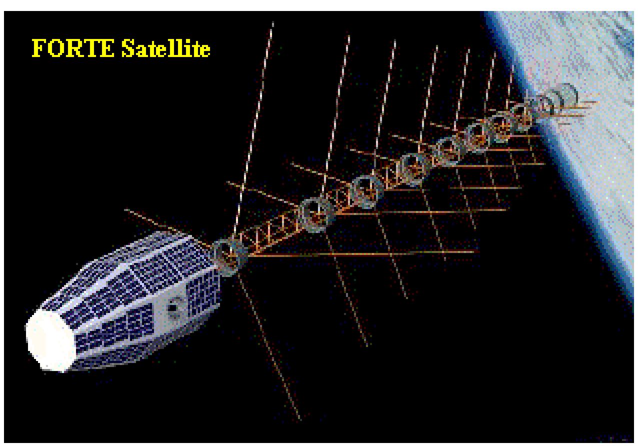
Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

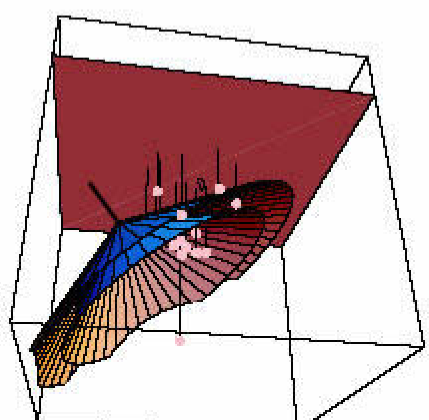
• PRL 93:041101 (2004) limits published





Greenland Ice





Radio Ice Experiment (RICE) @ South Pole

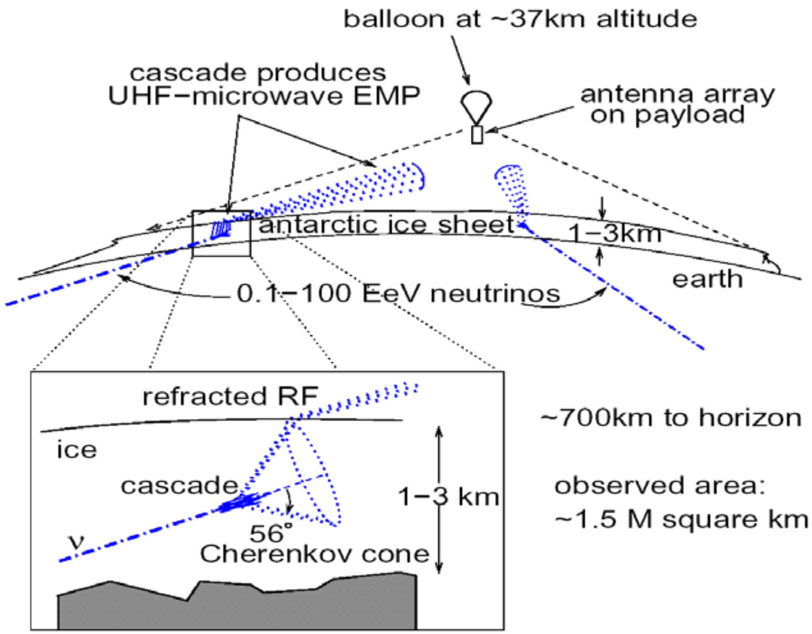
• PRD 69:0133008 (2004)

• Astropart.Phys.20:195 (2003)

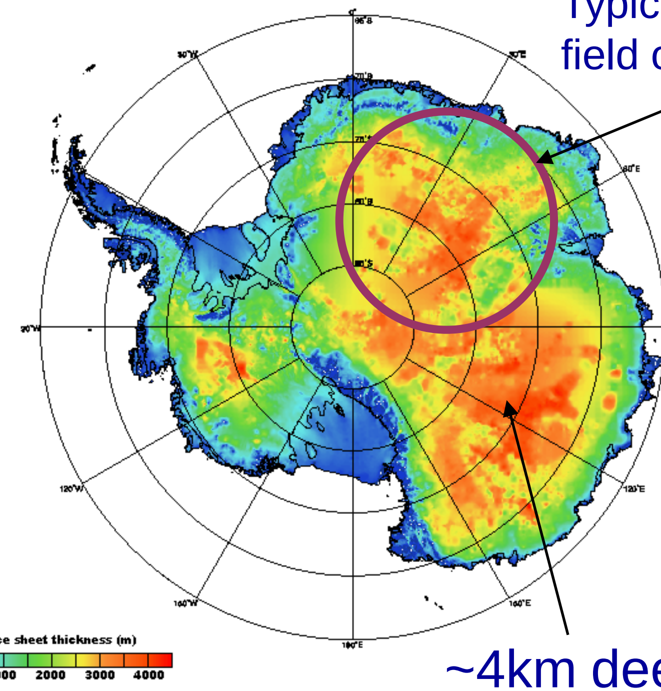
Design for discovery of GZK ν flux

- 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

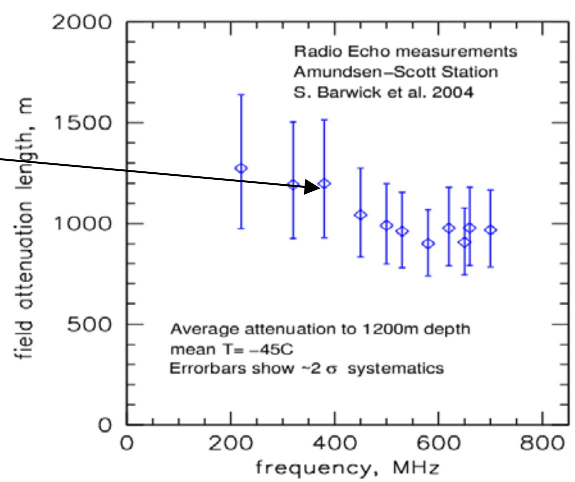


Typical balloon field of regard



~4km deep ice!

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



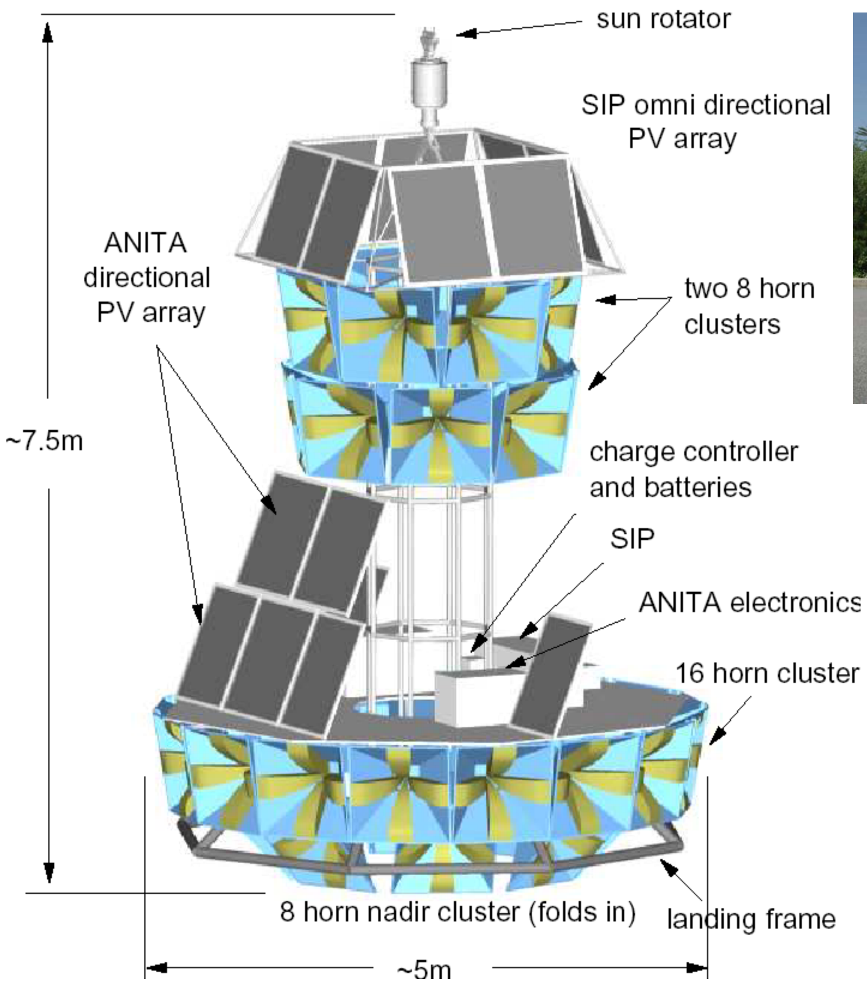
Effective "telescope" aperture:

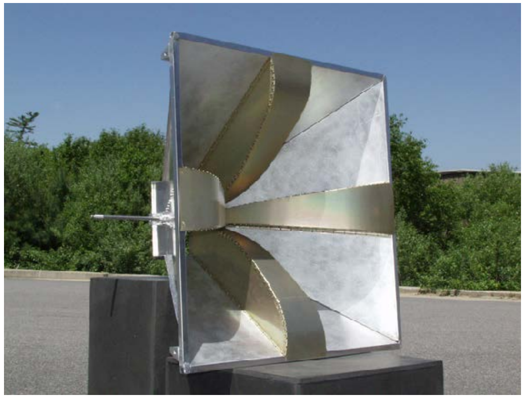
- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

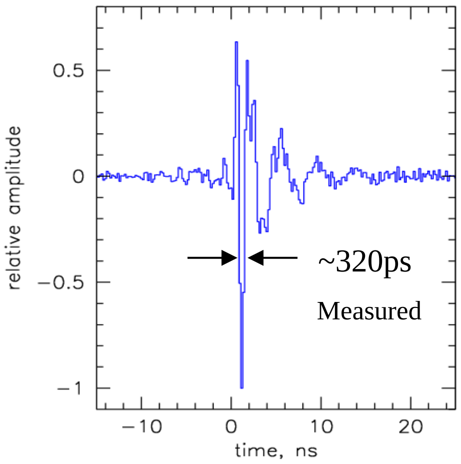
(compare to ~1 km^3 at lower E)

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

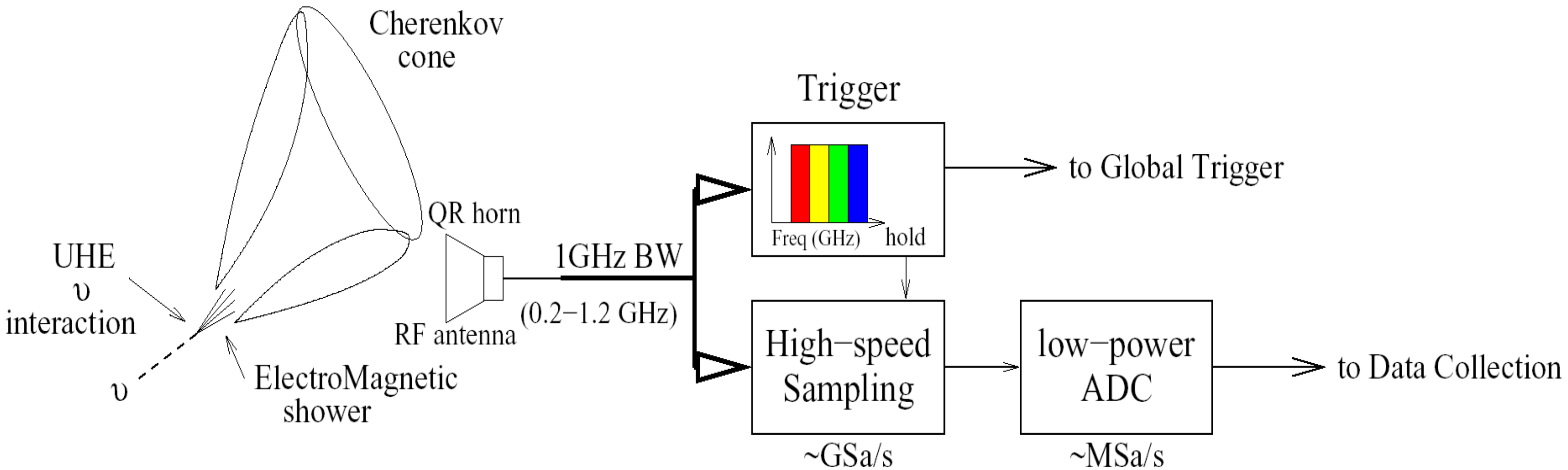
Major Hurdles

- 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

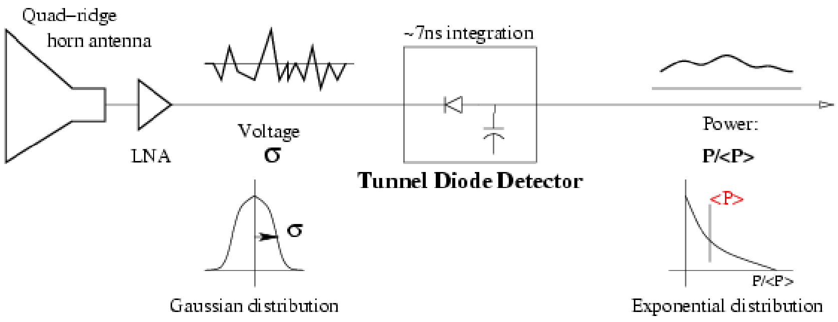


- Split signal: 1 path to trigger, 1 for digitizer
- Digitizer runs ONLY when triggered to save power (factor of 1,000!)

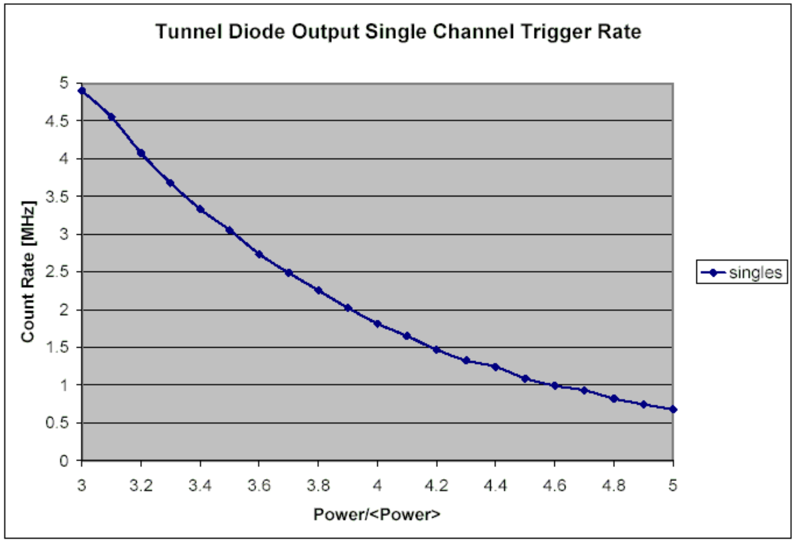
<u>Three key technologies:</u>

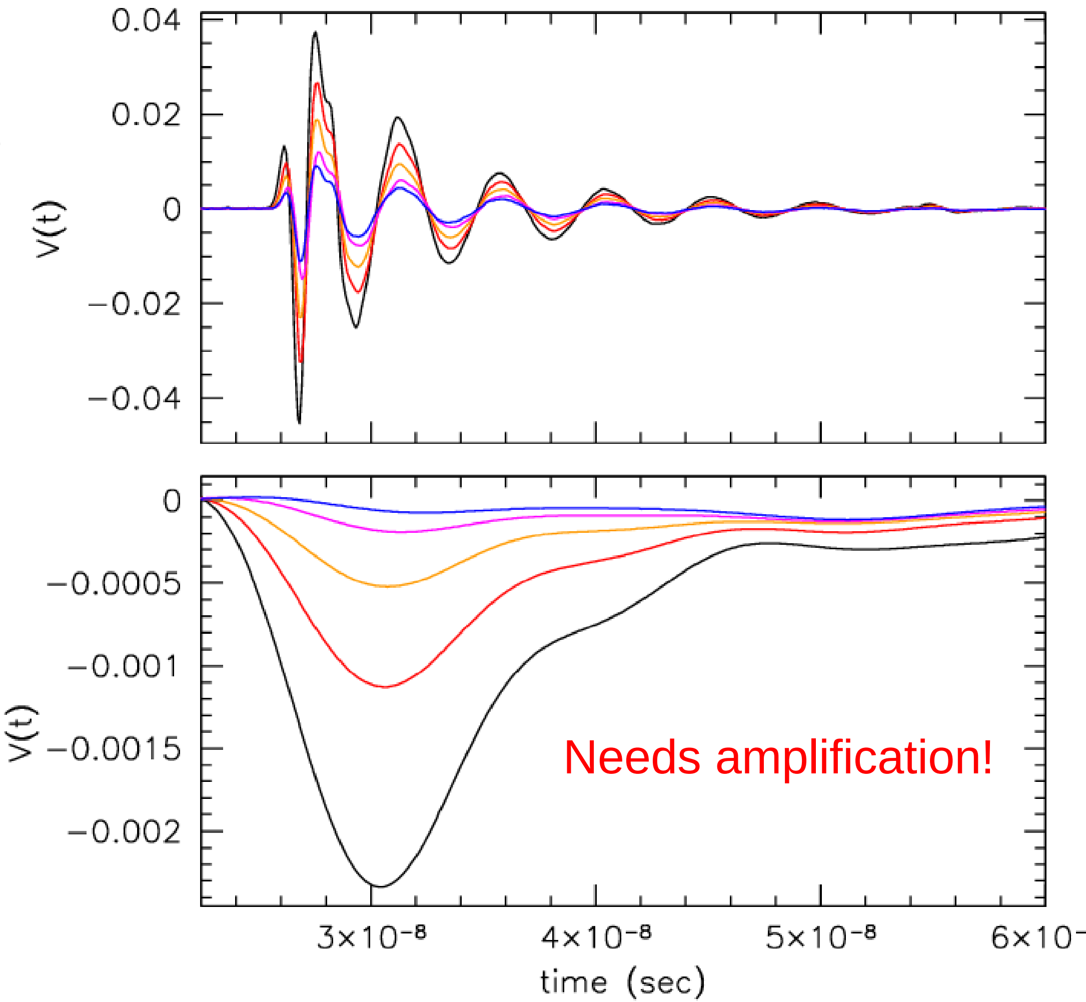
1. Very low-noise (low power) amplifiers
2. Efficient, thermal-noise limited triggering
3. Low power, Gsa/s waveform sampling

Diode detector Response



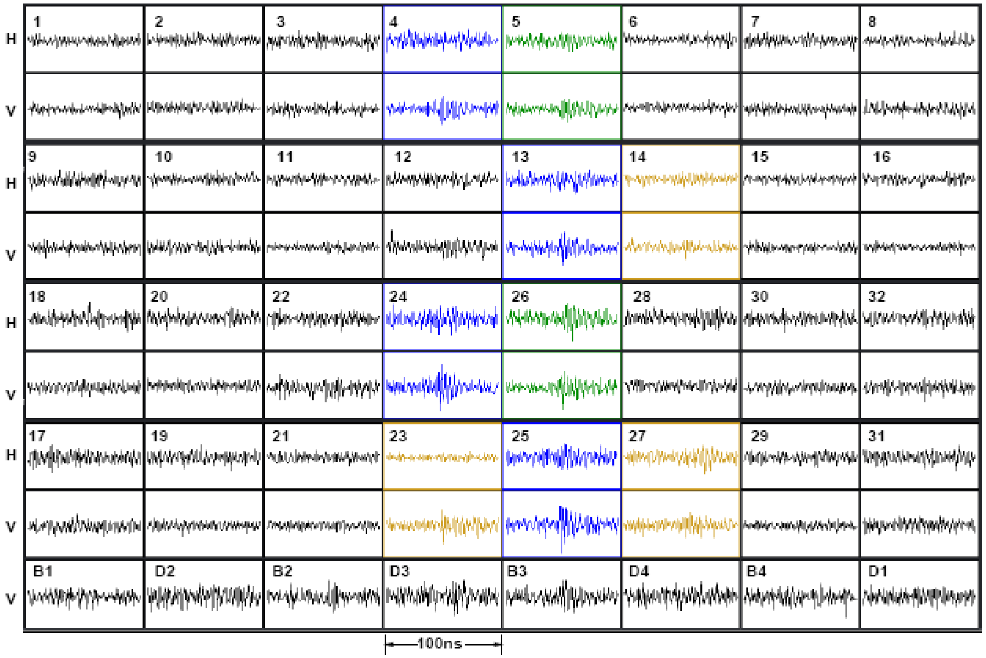
2.3σ ~= 3.9 P/<P>

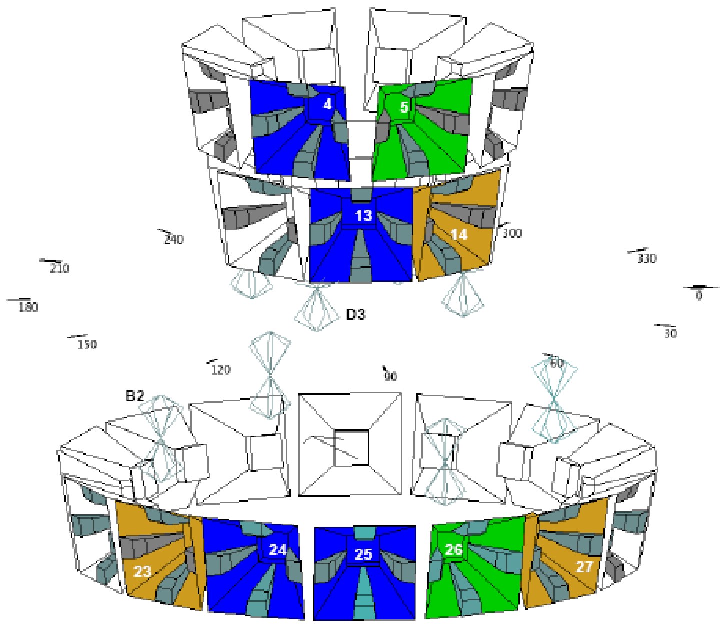




Hierarchical triggering

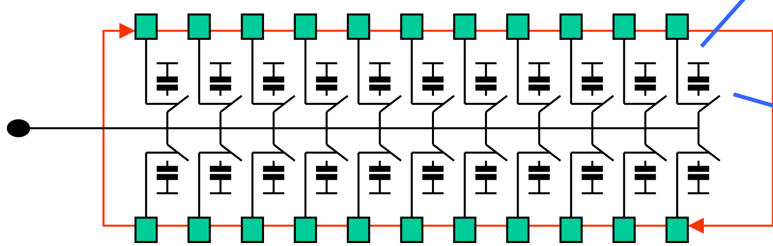
- Event most likely West Antarctica camp noise
- Triggers:
  - Yellow, L1: impulse above thermal noise for an individual antenna; ~150 kHz
  - Green, L2: coincidence between adjacent L1 in the same ring; ~40kHz
  - Blue, L3: coincidence between L2 triggers in same phi sector; ~5Hz

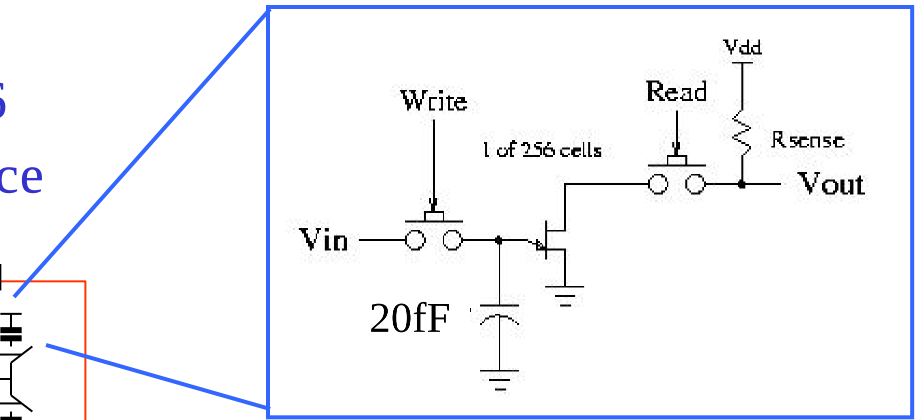




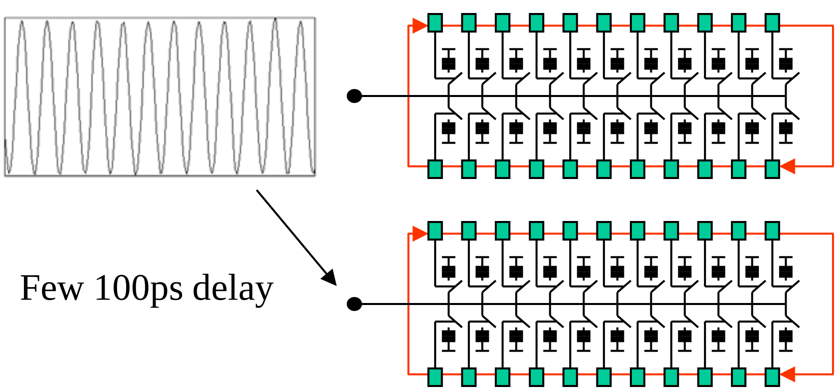
Switched Capacitor Array Sampling

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

Input 

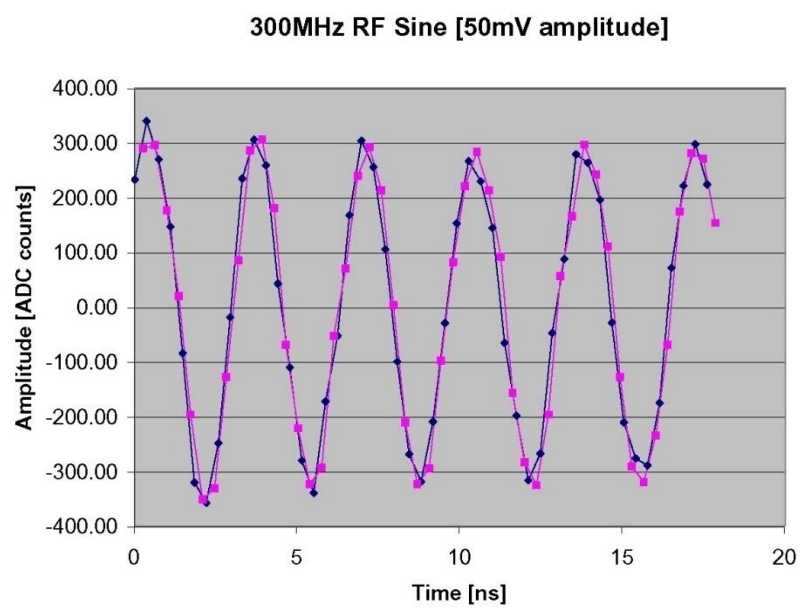


Tiny charge: 1mV ~ 100e⁻

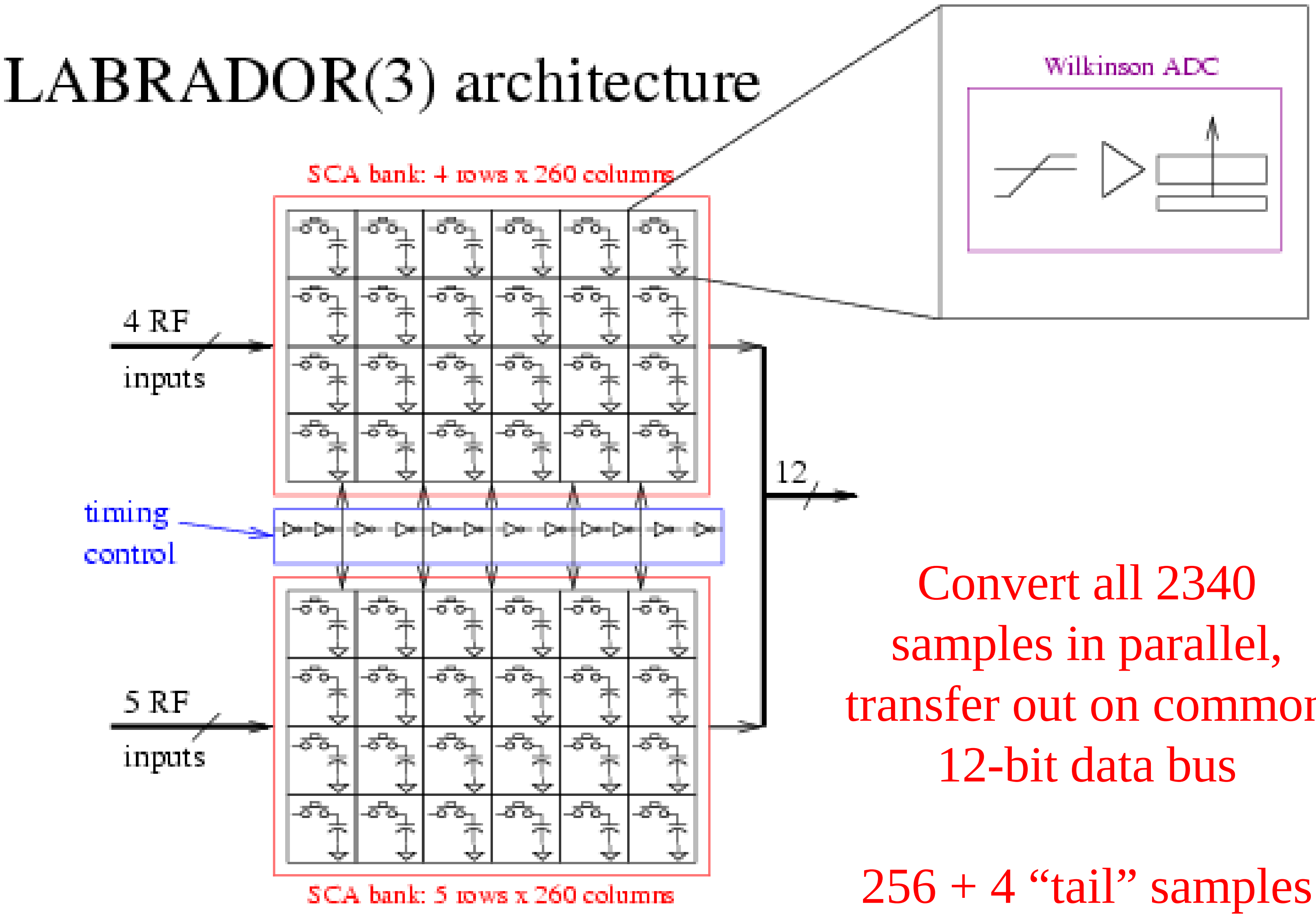


Channel 1

Channel 2



9 x 260 samples = 2340 storage cells



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

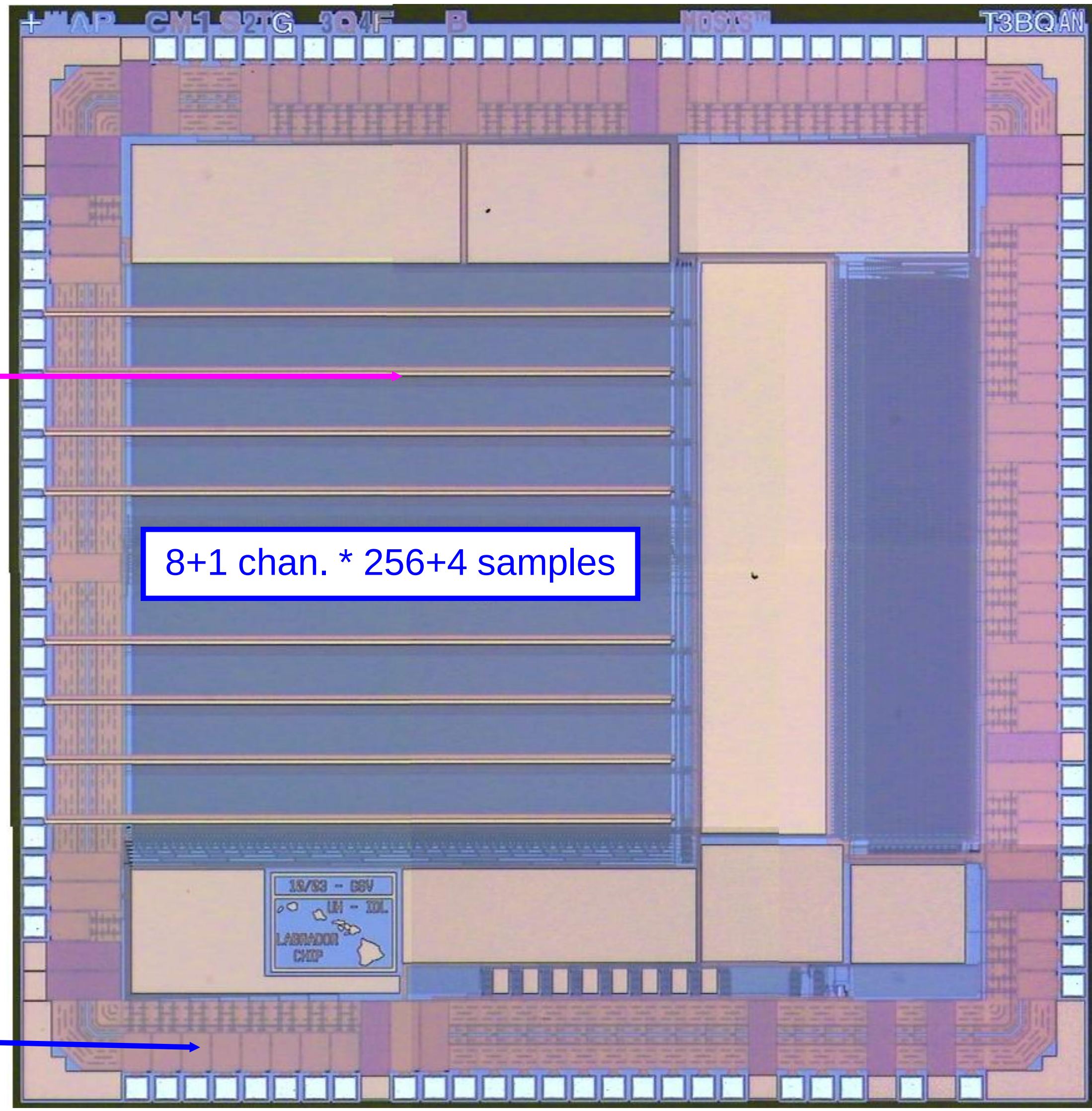
256 + 4 “tail” samples

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>

Random access:

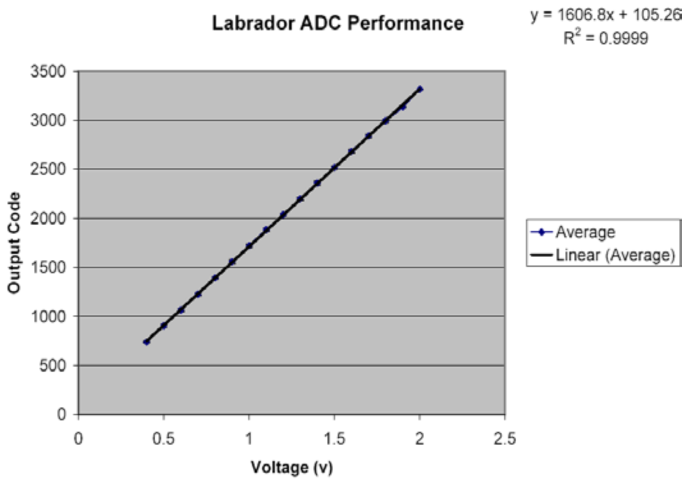


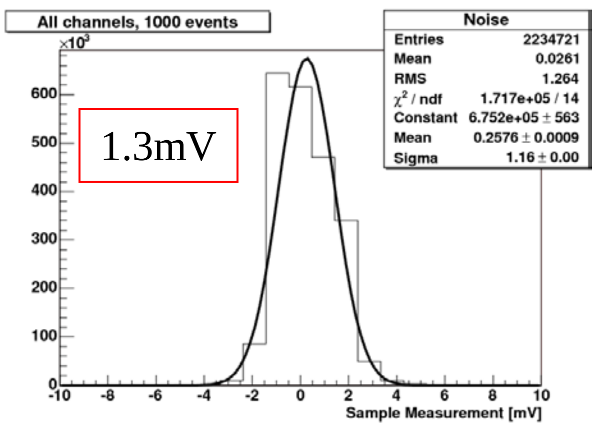
- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 31μs (all 2340 samples)
- Data transfer takes 80μs
- Ready for next event in <150μs

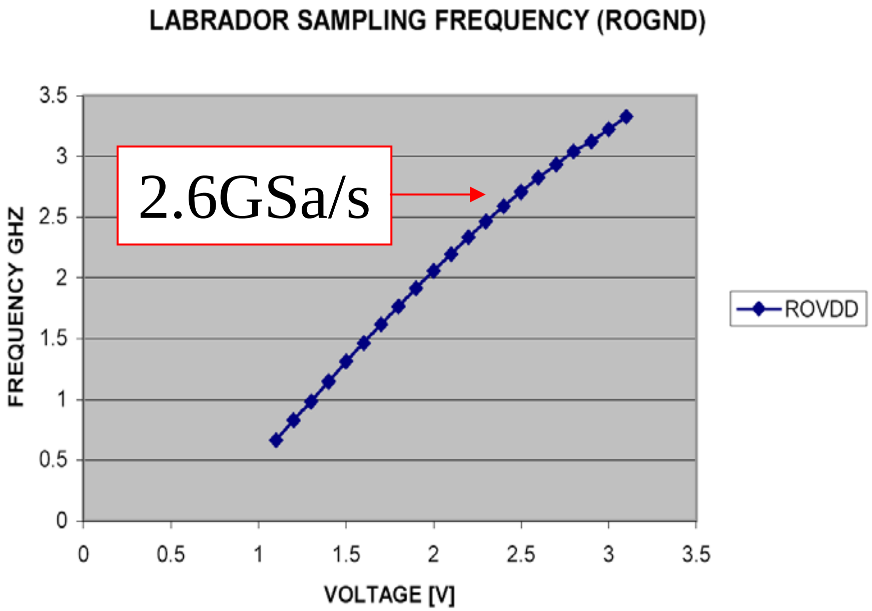
NIM A583:447-460, 2007

LABRADOR performance

12-bit ADC



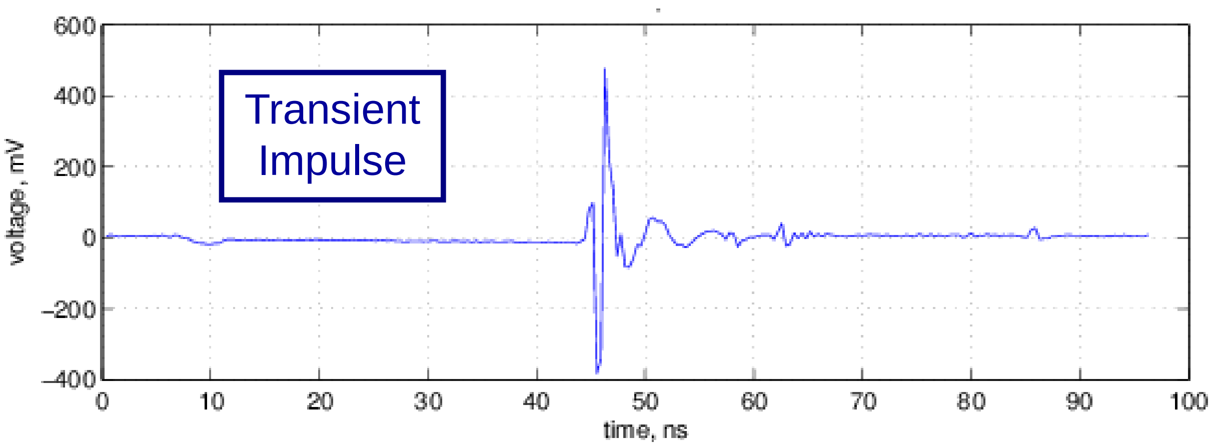


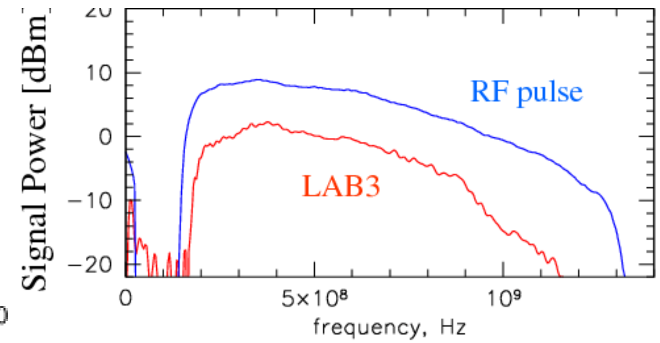


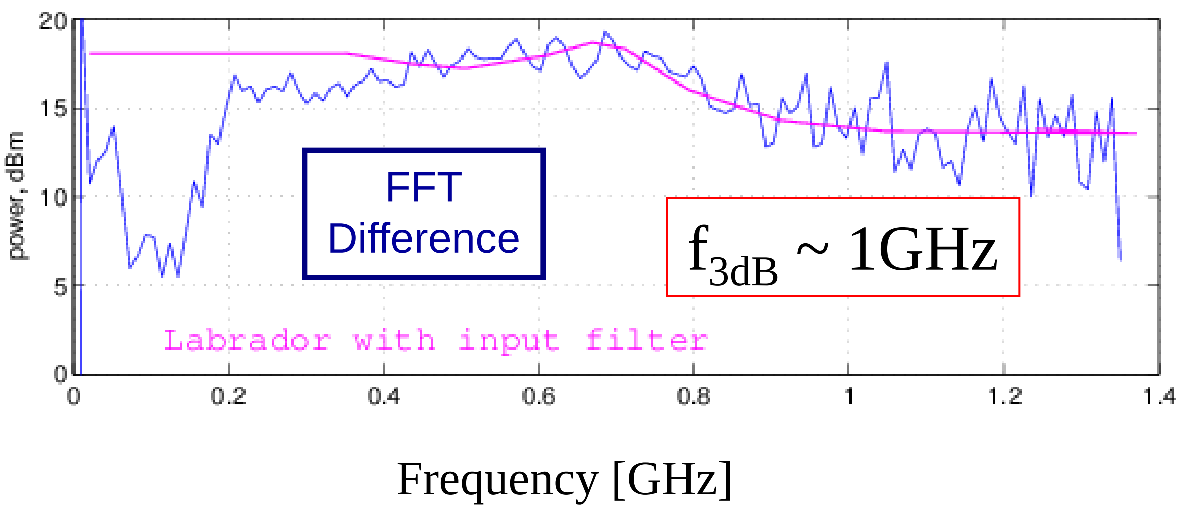
- 10 real bits (1.3V/1.3mV noise)

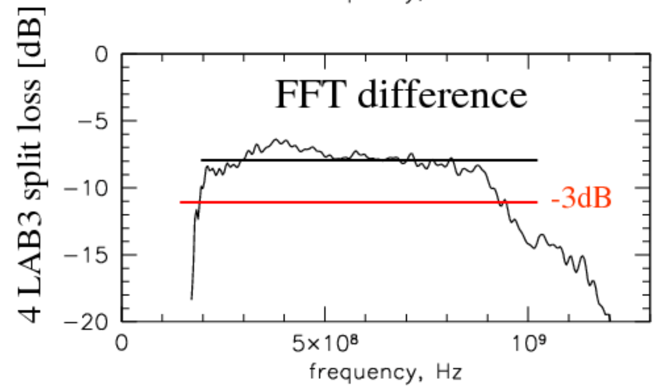
- Excellent linearity, noise
- Sampling rates up to 4 GSa/s with voltage overdrive

Bandwidth Evaluation

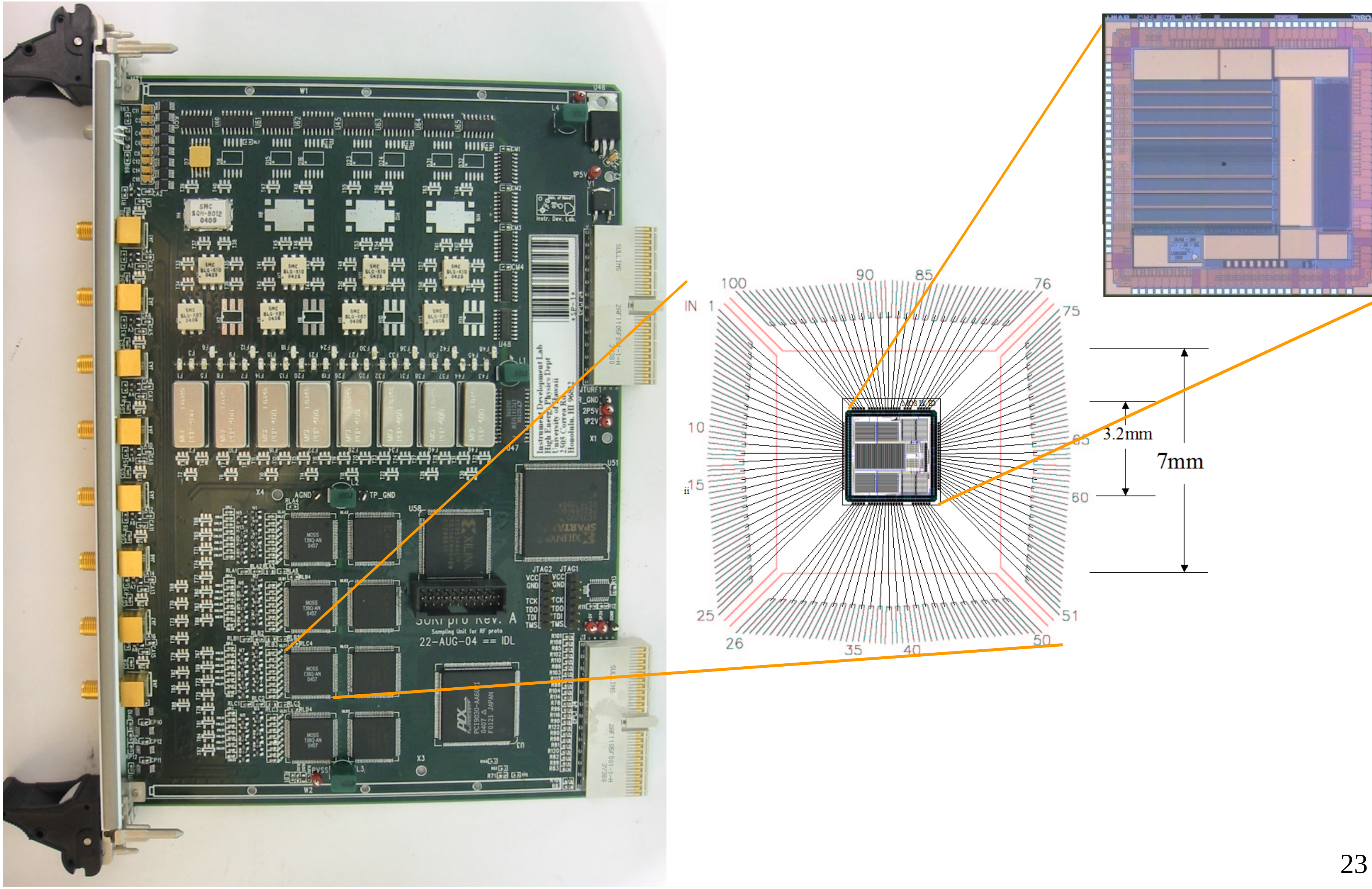






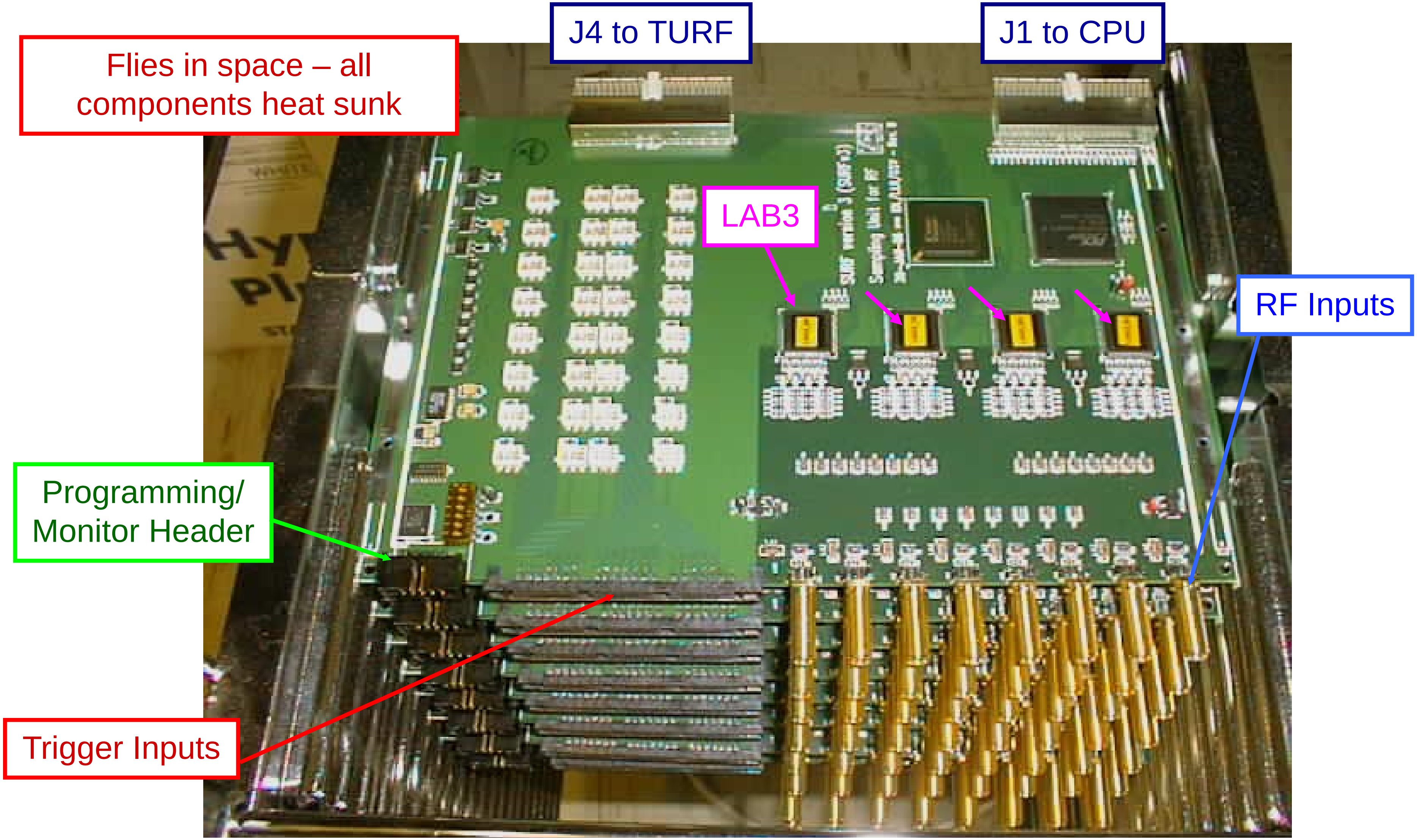


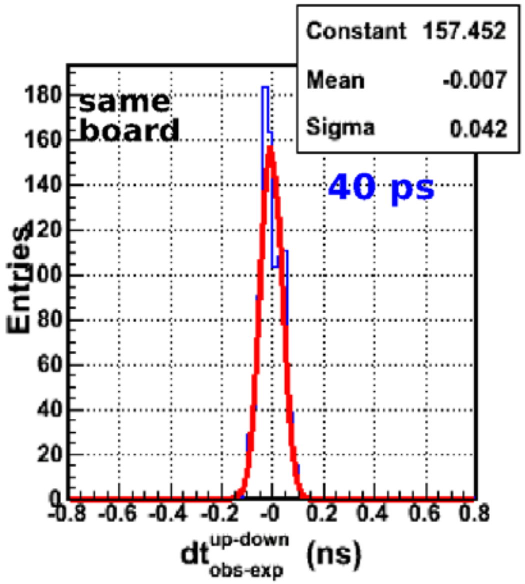
Sampling Unit for RF (SURF) board

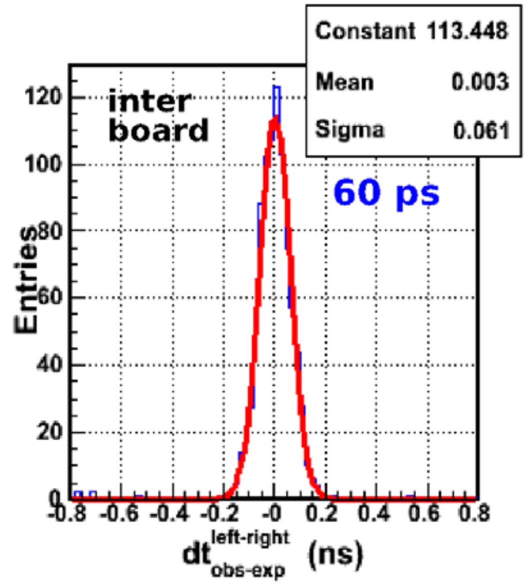


SURFv3 Board

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



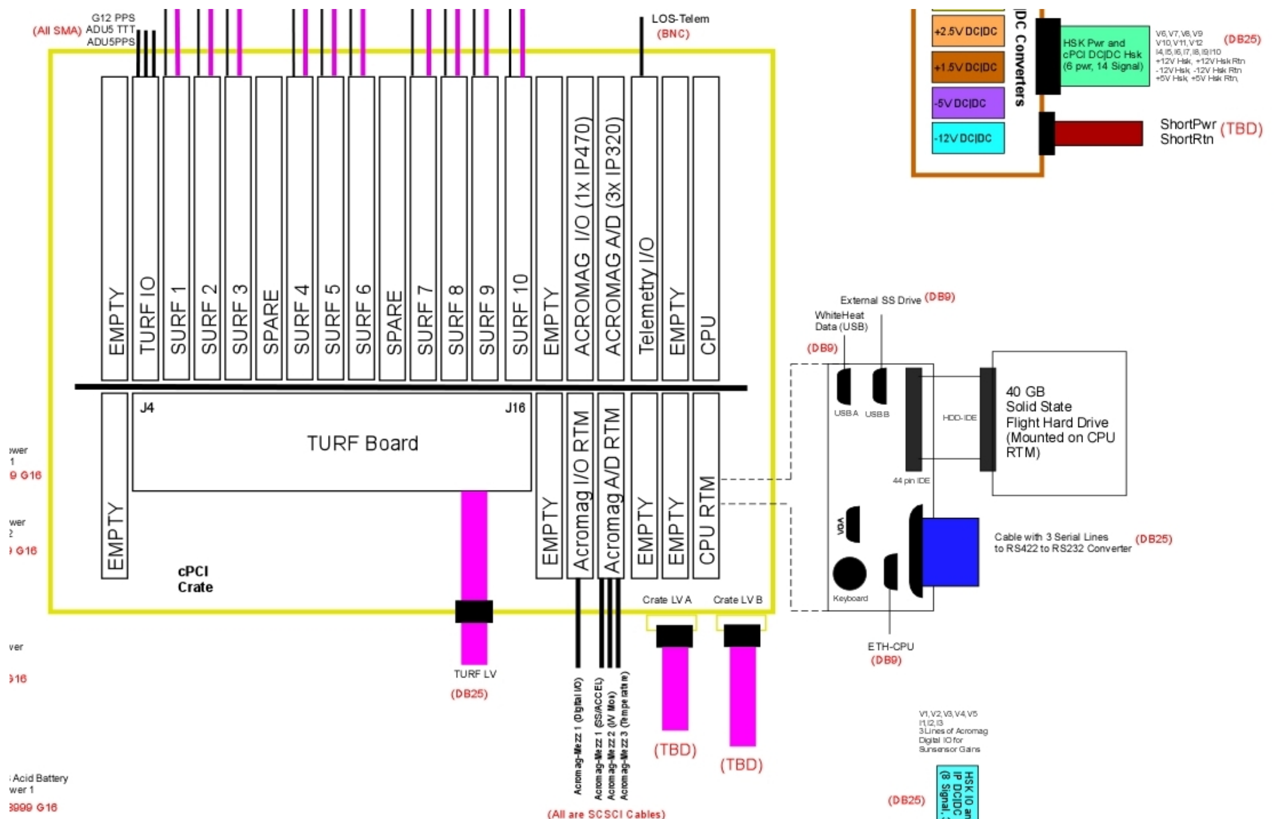




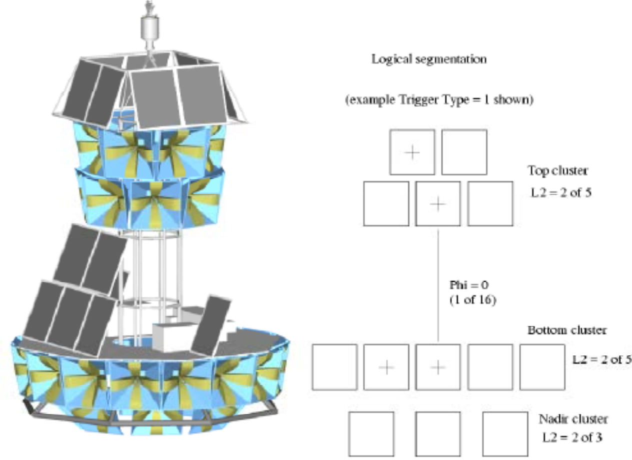
Eventually improved to 16ps, 30ps, respectively

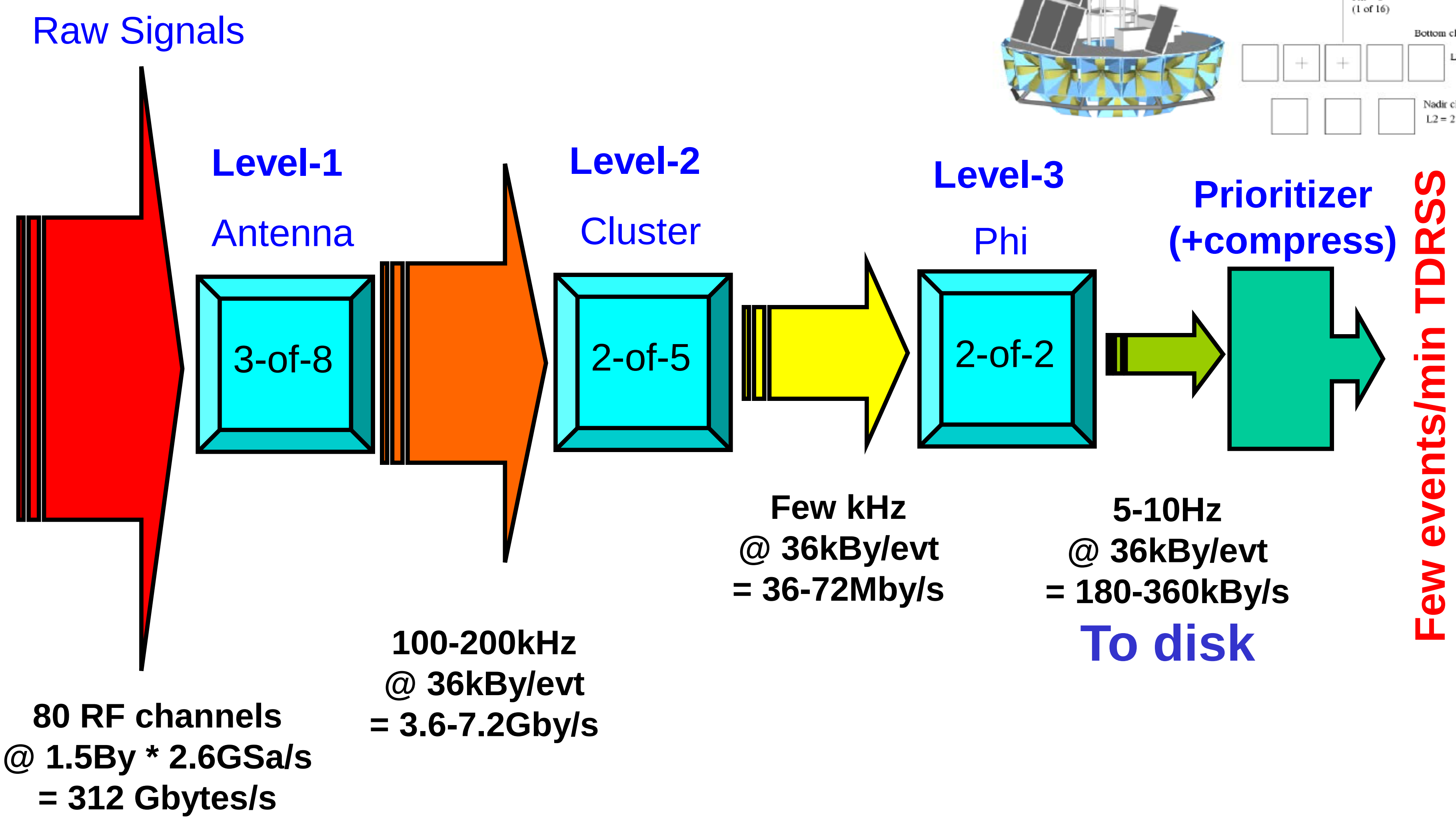
~47ps due to Time Ref. Passing

(33MHz clock)



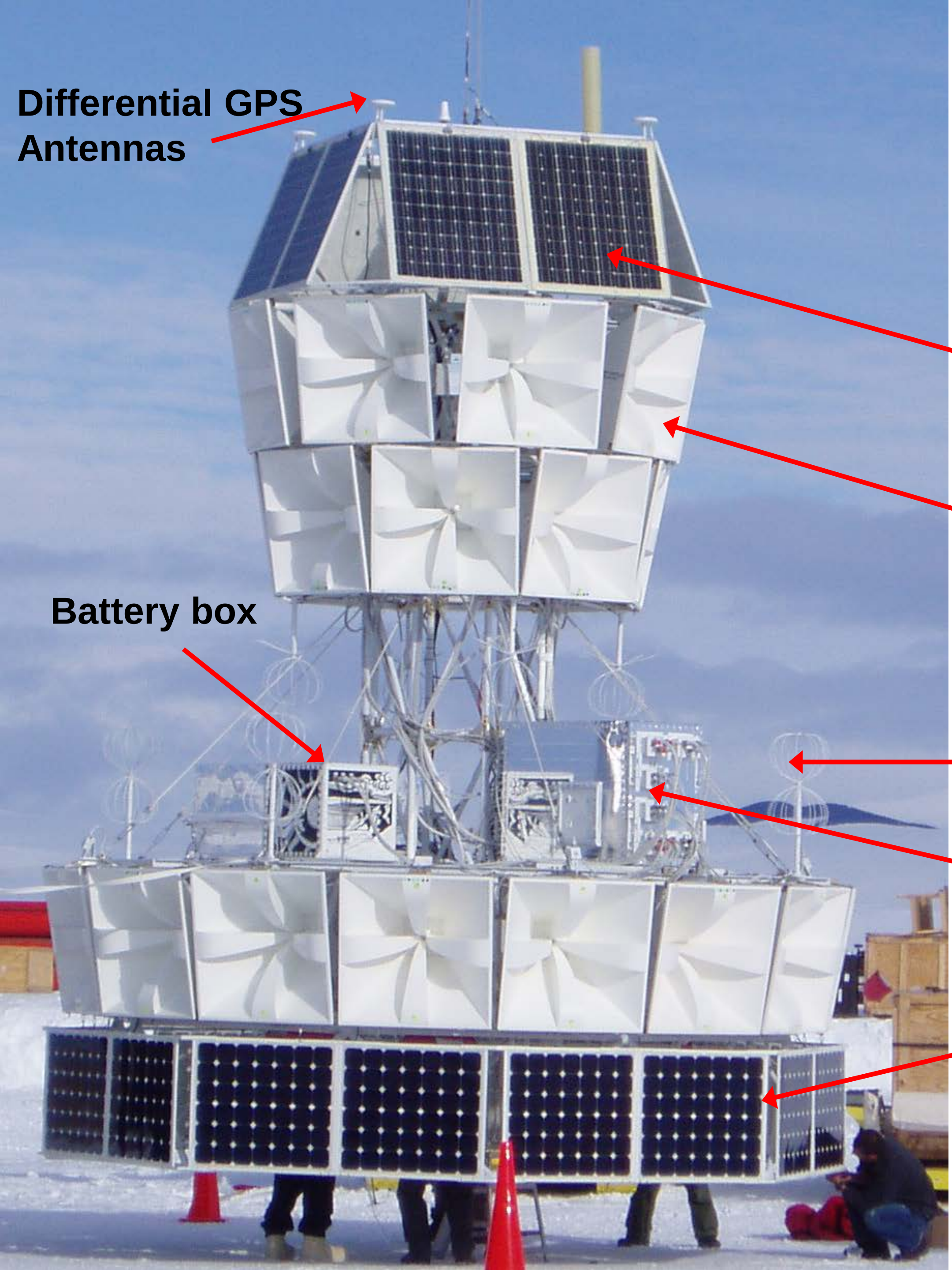
A solar powered, airborne HEP experiment





ANITA-1 pieces

“instrument paper”
arXiv:0812.1920 [astro-ph]



Solar cells for NASA equipment

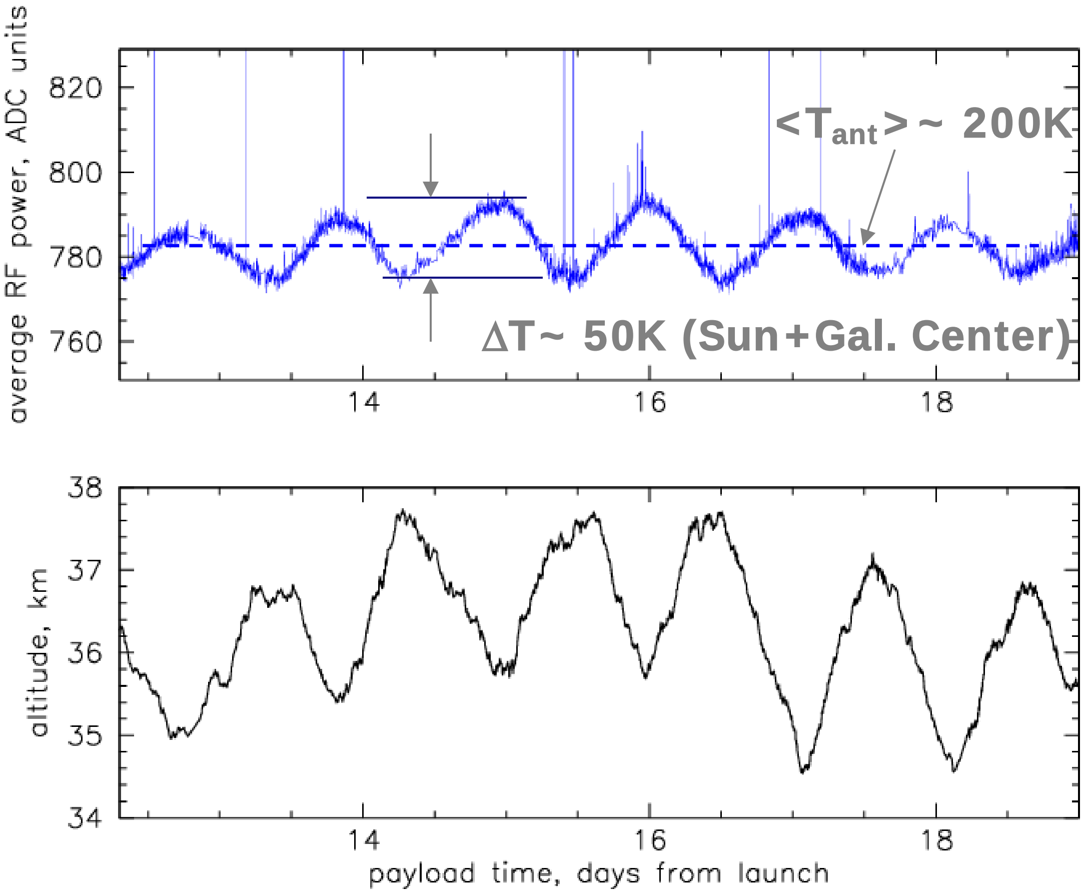
32 Quad-ridge horn antennas
- **200 MHz to 1200 MHz**
- **10 degree downward angle**

8 low gain antennas to monitor payload-generated noise

ANITA electronics box

Solar panels for science mission

Flight sensitivity snapshot

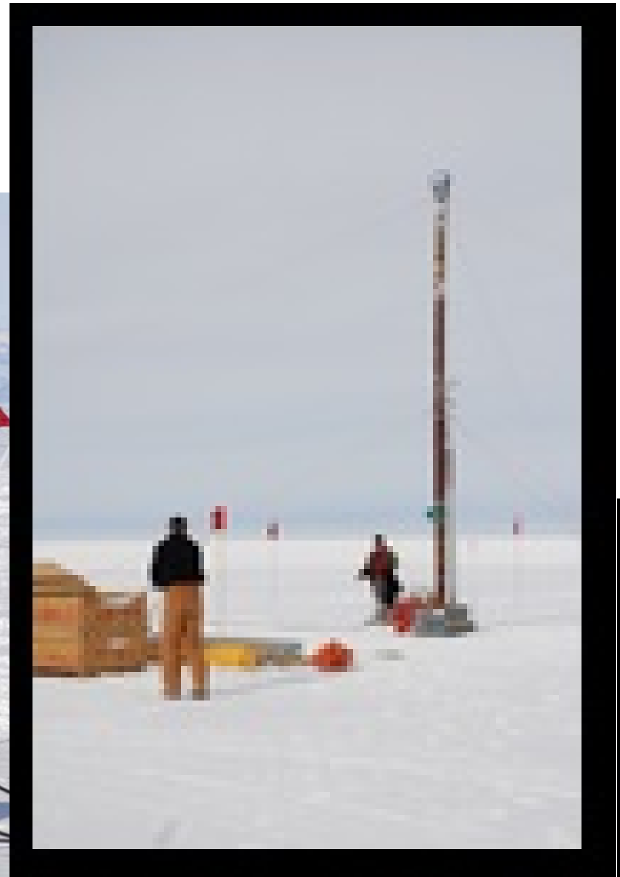


- ANITA sensitivity floor defined by thermal (kT) noise from ice + sky
- Thermal noise floor seen throughout most of flight—but punctuated by station & satellite noise
- Significant fraction (>40%) of time with pristine conditions

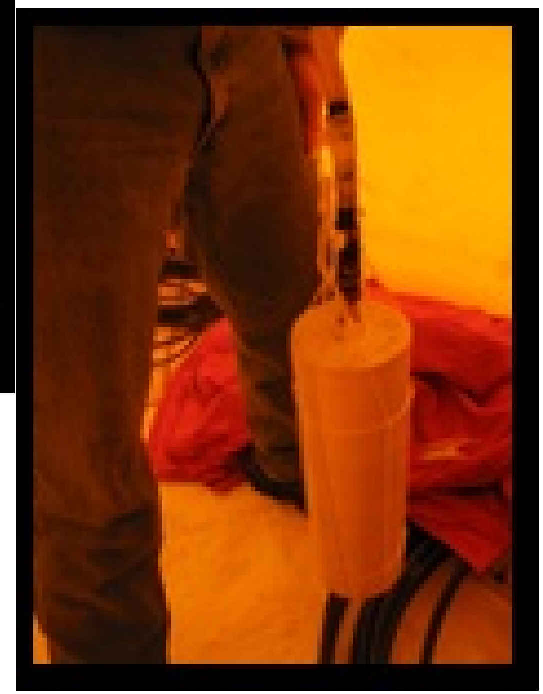
- T anti-correlated to altitude:
  - higher altitude at higher sun angle
  - sun+GC higher ➔ farther off main antenna beam

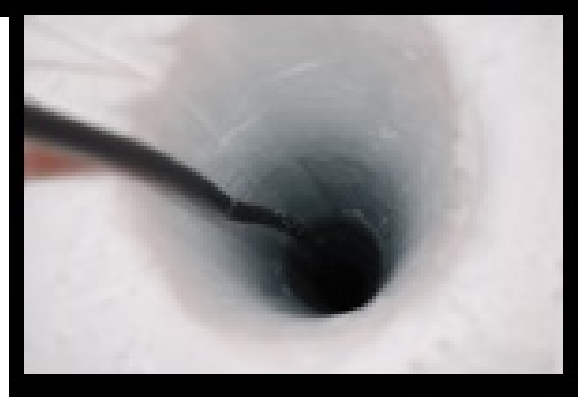
Quiet, but are we sensitive?

Ground pulser



Bore hole pulser

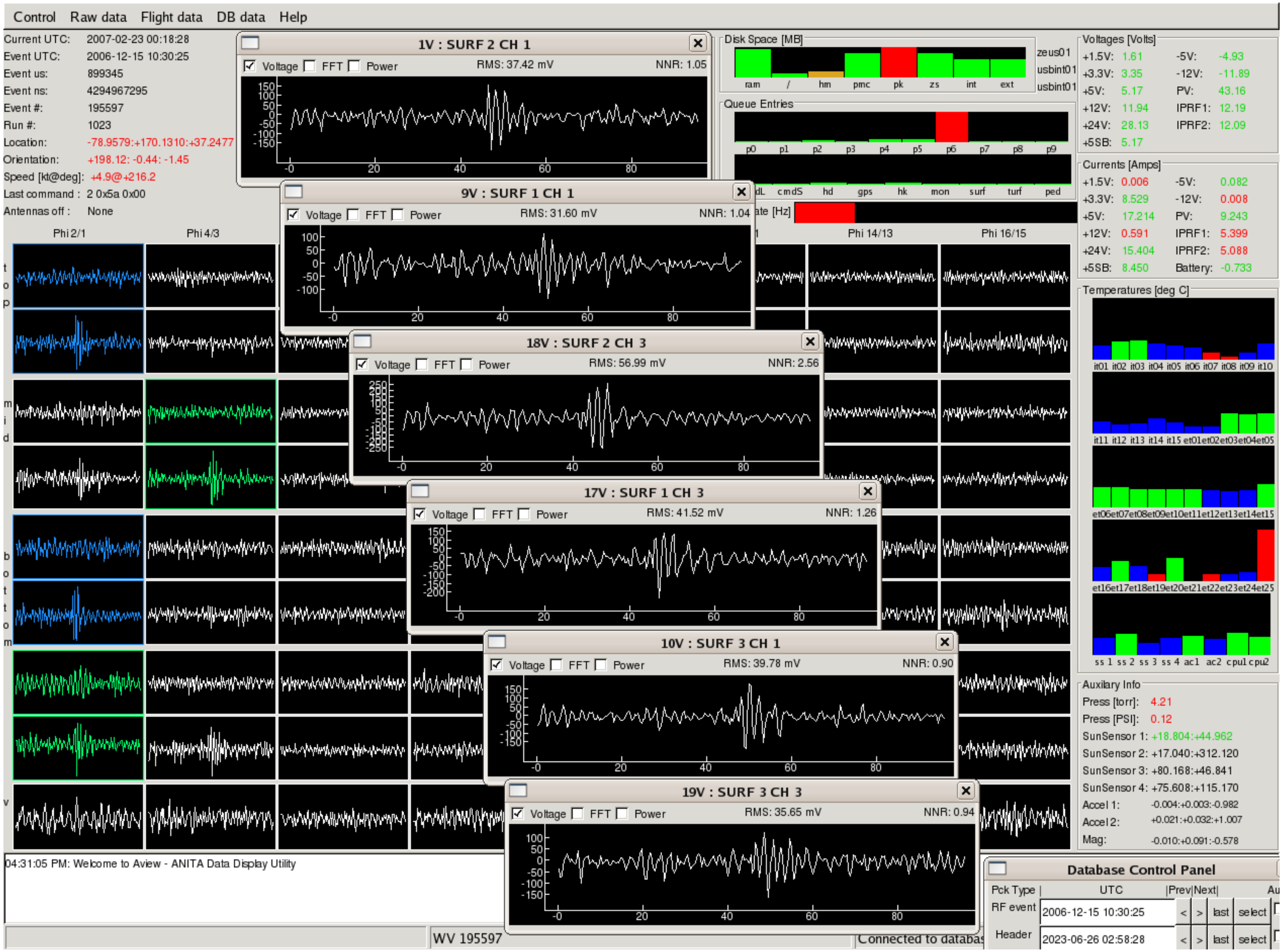




- Ice 80m thick and messy

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

Pulse Phase interferometry

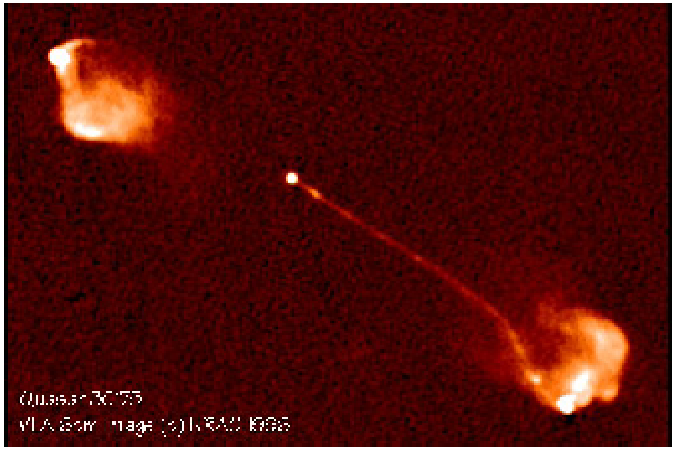
A. Romero-Wolf (Hawaii)

Ultrawide-band Interferometry

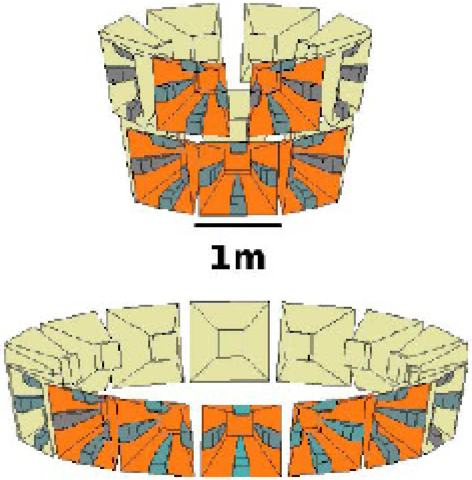
-Interferometric technique applied by radio astronomers.

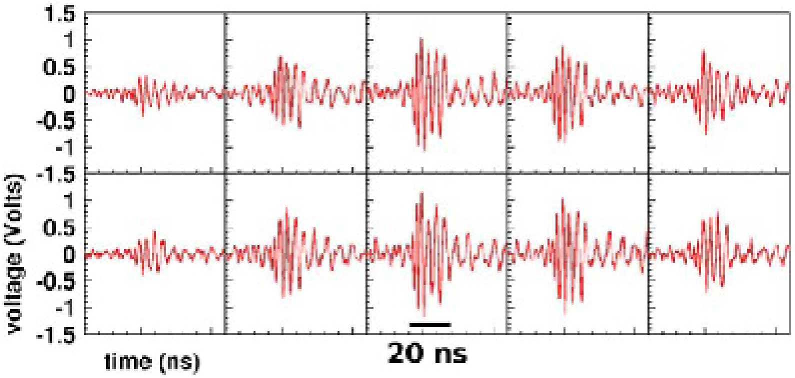
-They use single narrow band frequency.

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

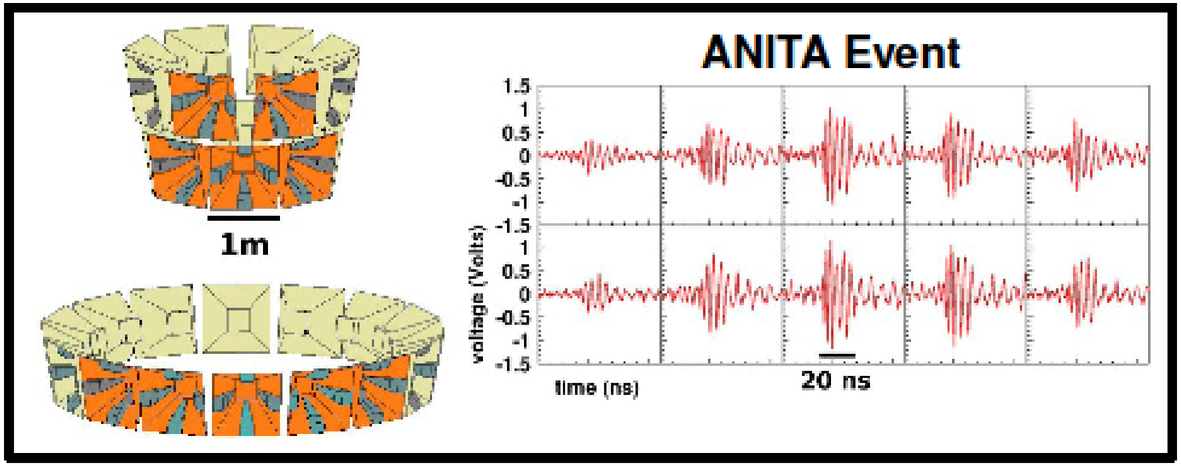


Produce Ultrawide-band Interferometric Images with ANITA

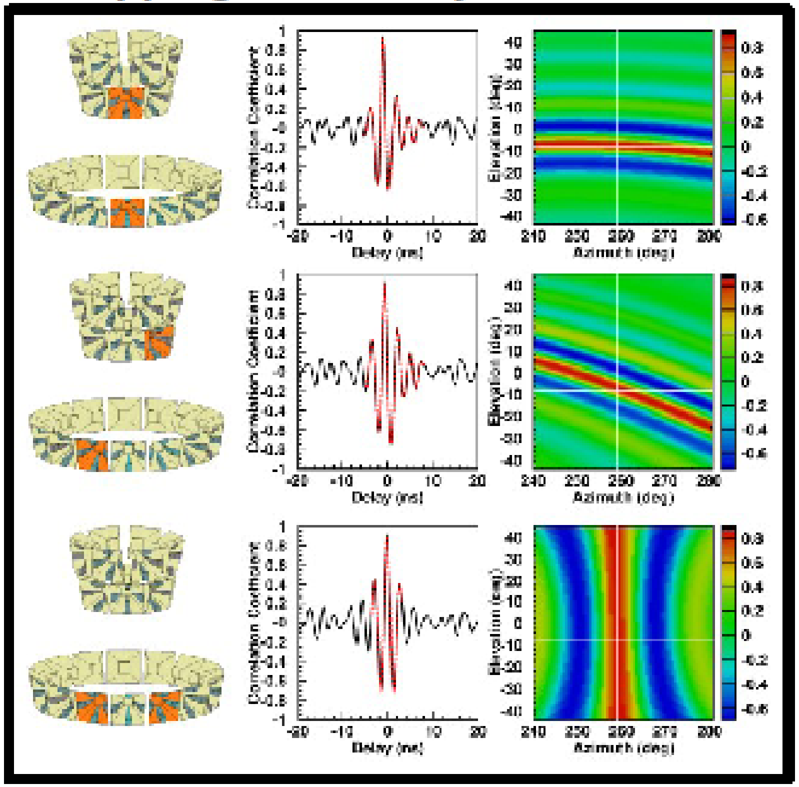




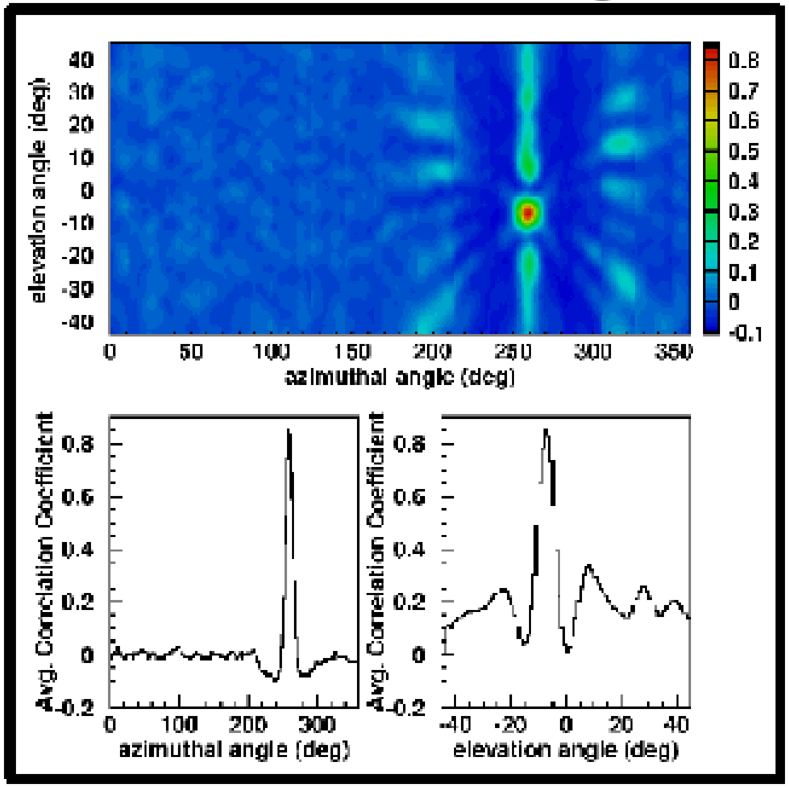
Mapping Waveforms to Interferometric Images



Mapping Time Delay Correlations

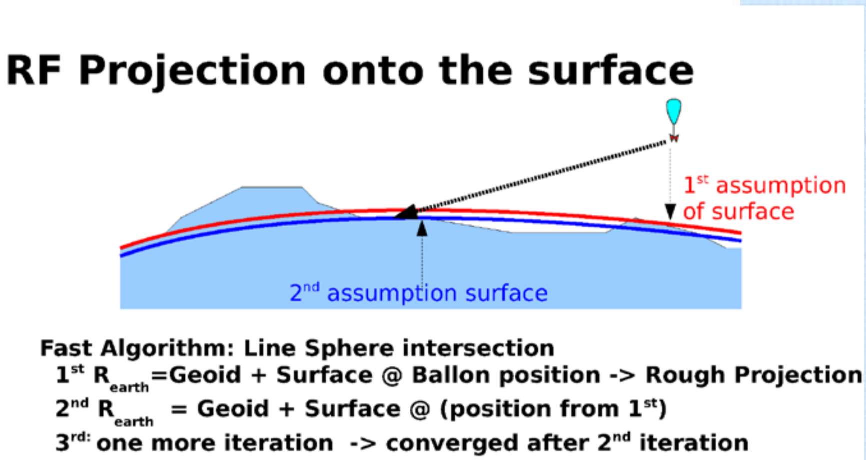


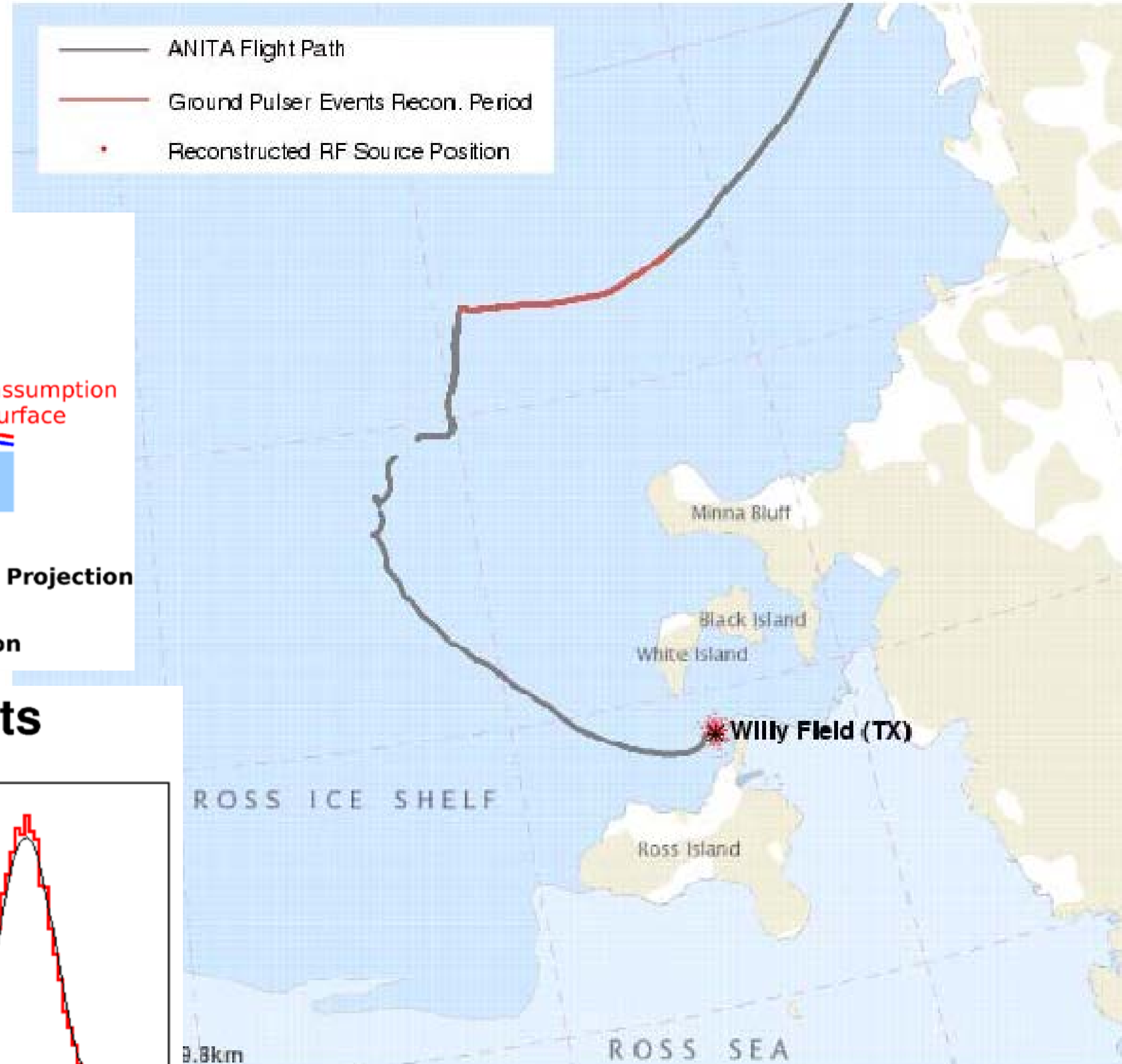
Interferometric Image

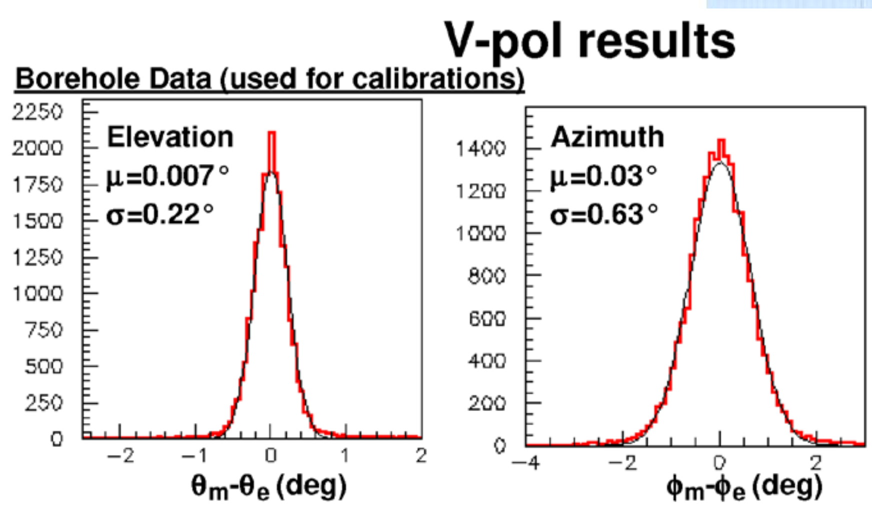


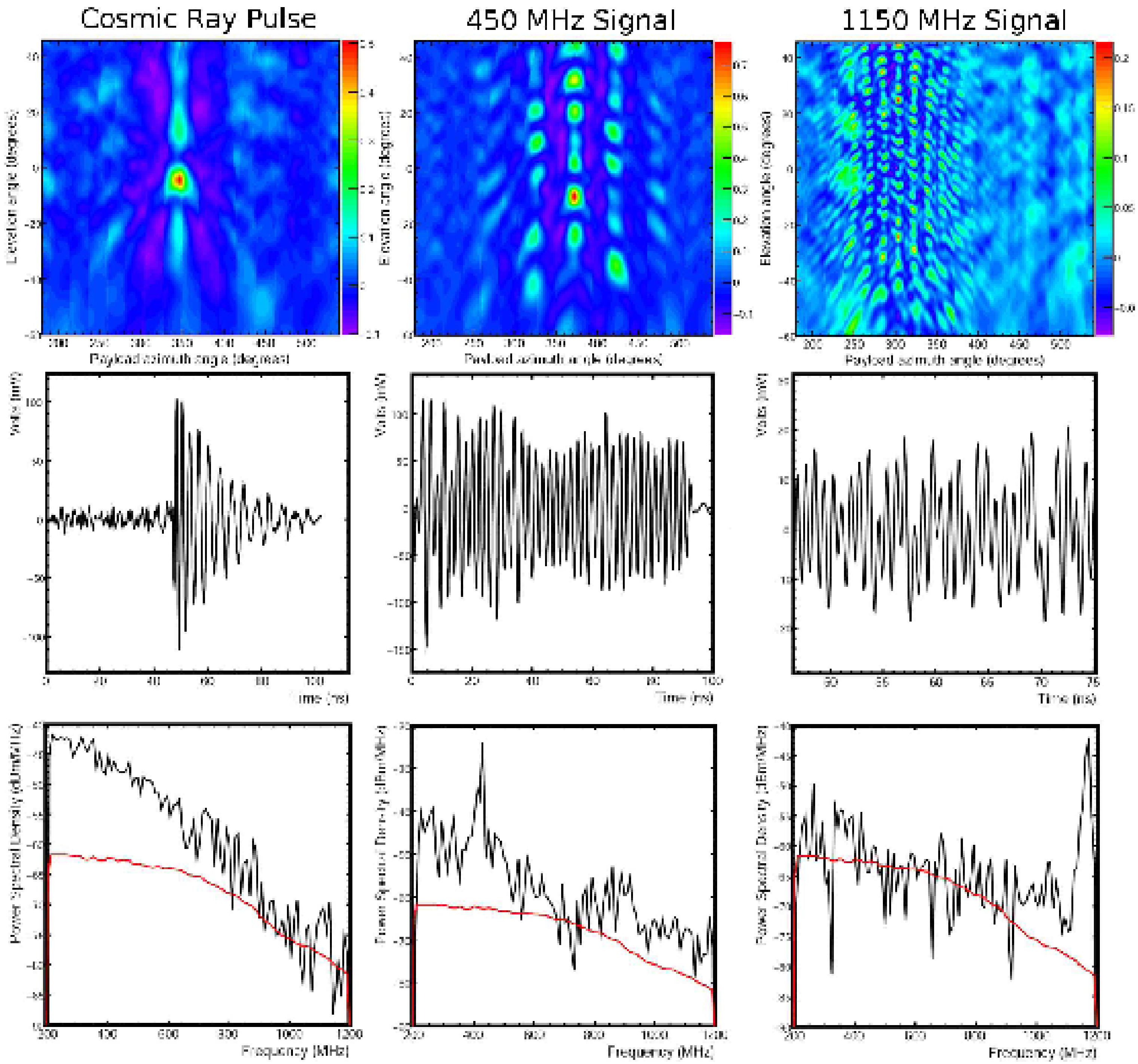
After full calibration – 100's km

<30ps timing

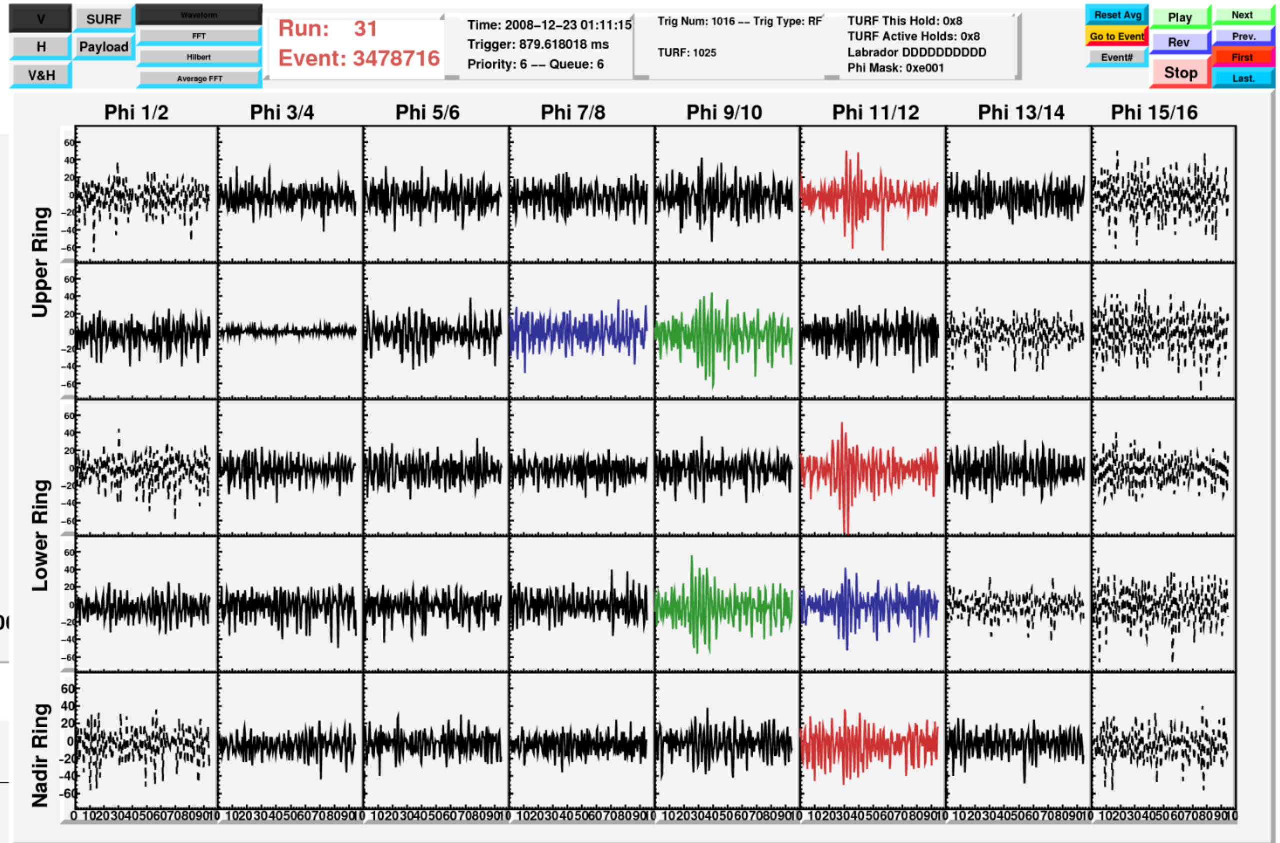


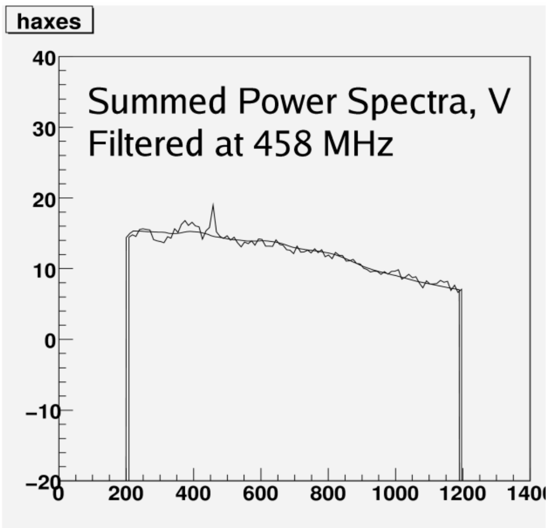


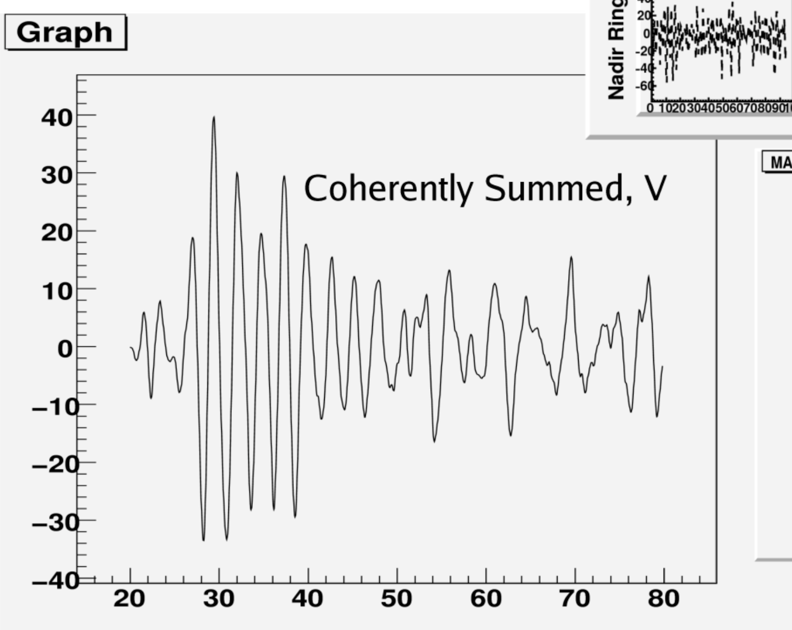


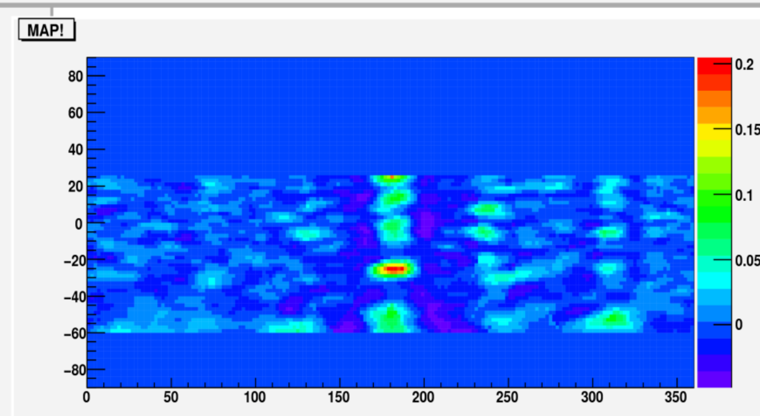

Cosmic Ray Pulse
450 MHz Signal
1150 MHz Signal
Payload azimuth angle (degrees)
Time (ns)
Frequency (MHz)

Event 3478716









Near Transantarctic Mountains

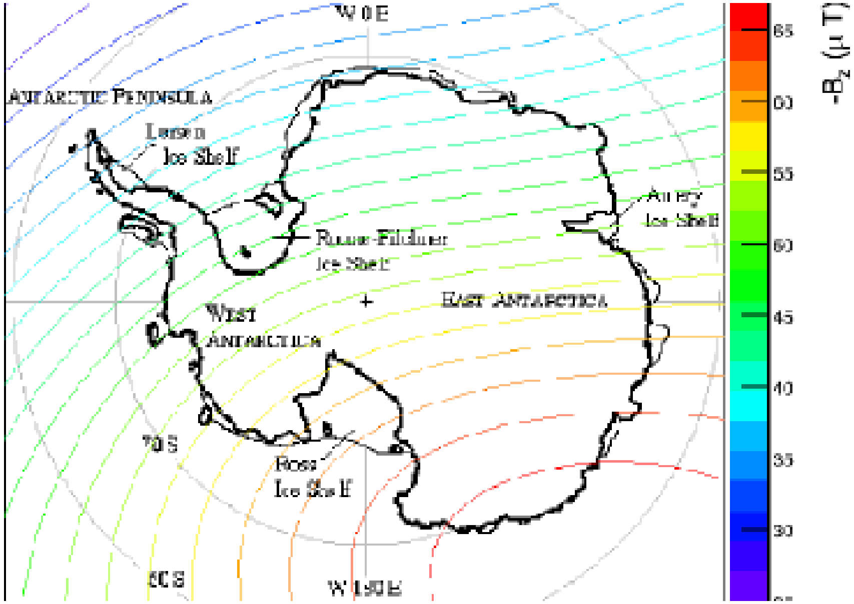
Polarization Angle = 57.6 degrees

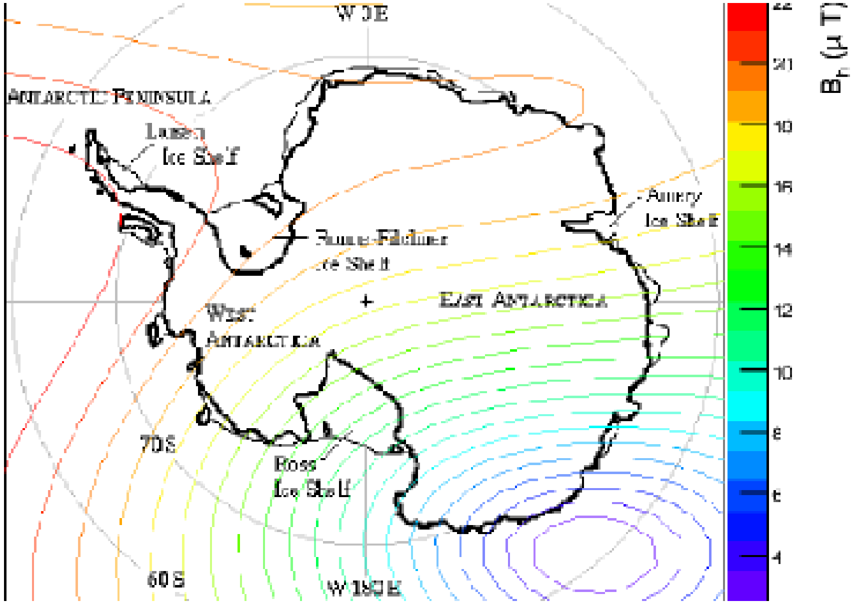
Elevation Angle = 25.2 degrees

Distance=107 km, LL=2804 from nearest event

Cosmic Ray Identification

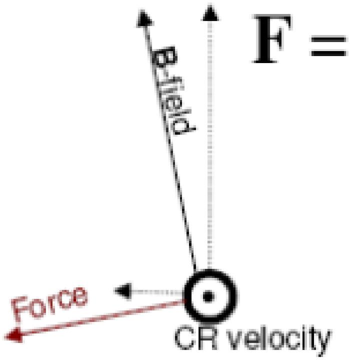
Polarization Correlation to Geomagnetic Field

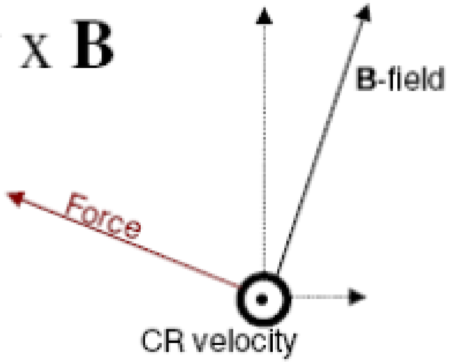




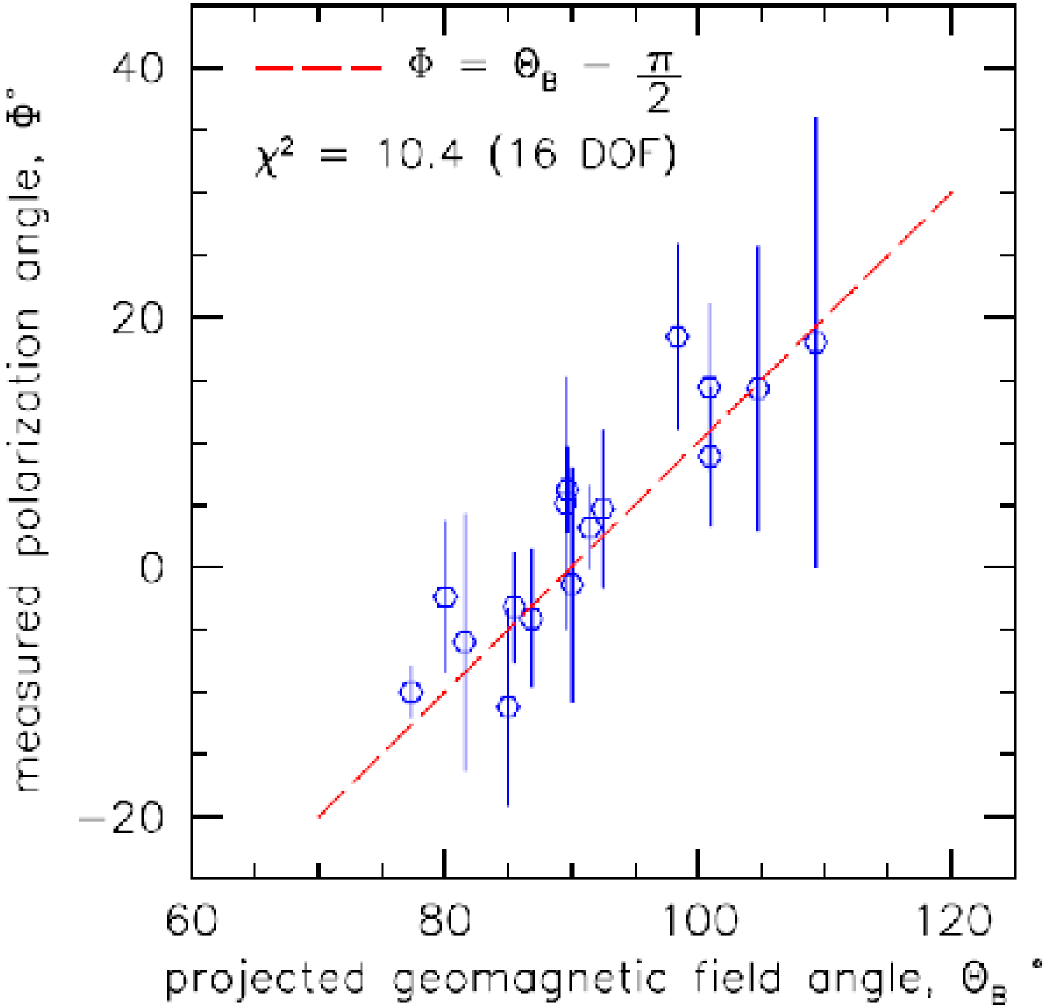
- CR moves towards payload.
- e+ and e- always curve away from each other due to dominant vertical B-field.
- H-pol emission always has the same polarization.
- V-pol magnitude and sign determined by the horizontal magnitude of the B-field.

$$F = ev \times B$$

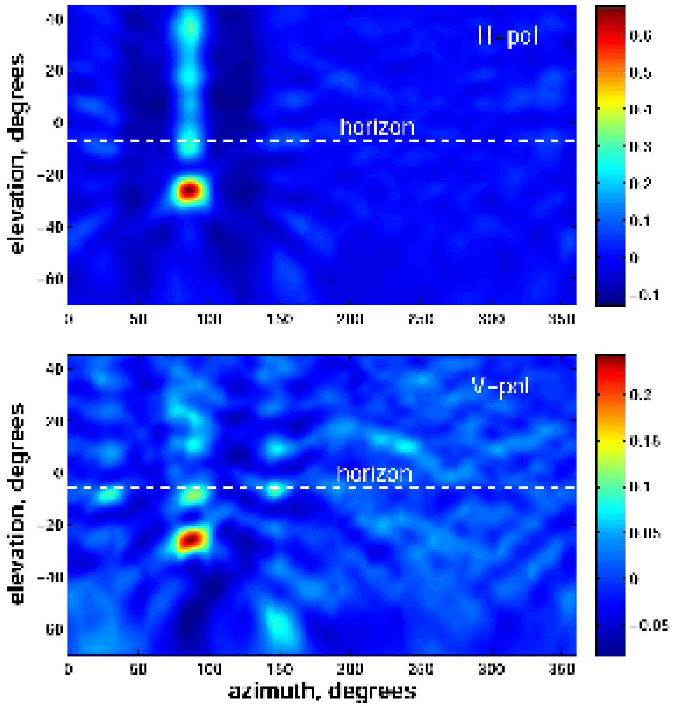




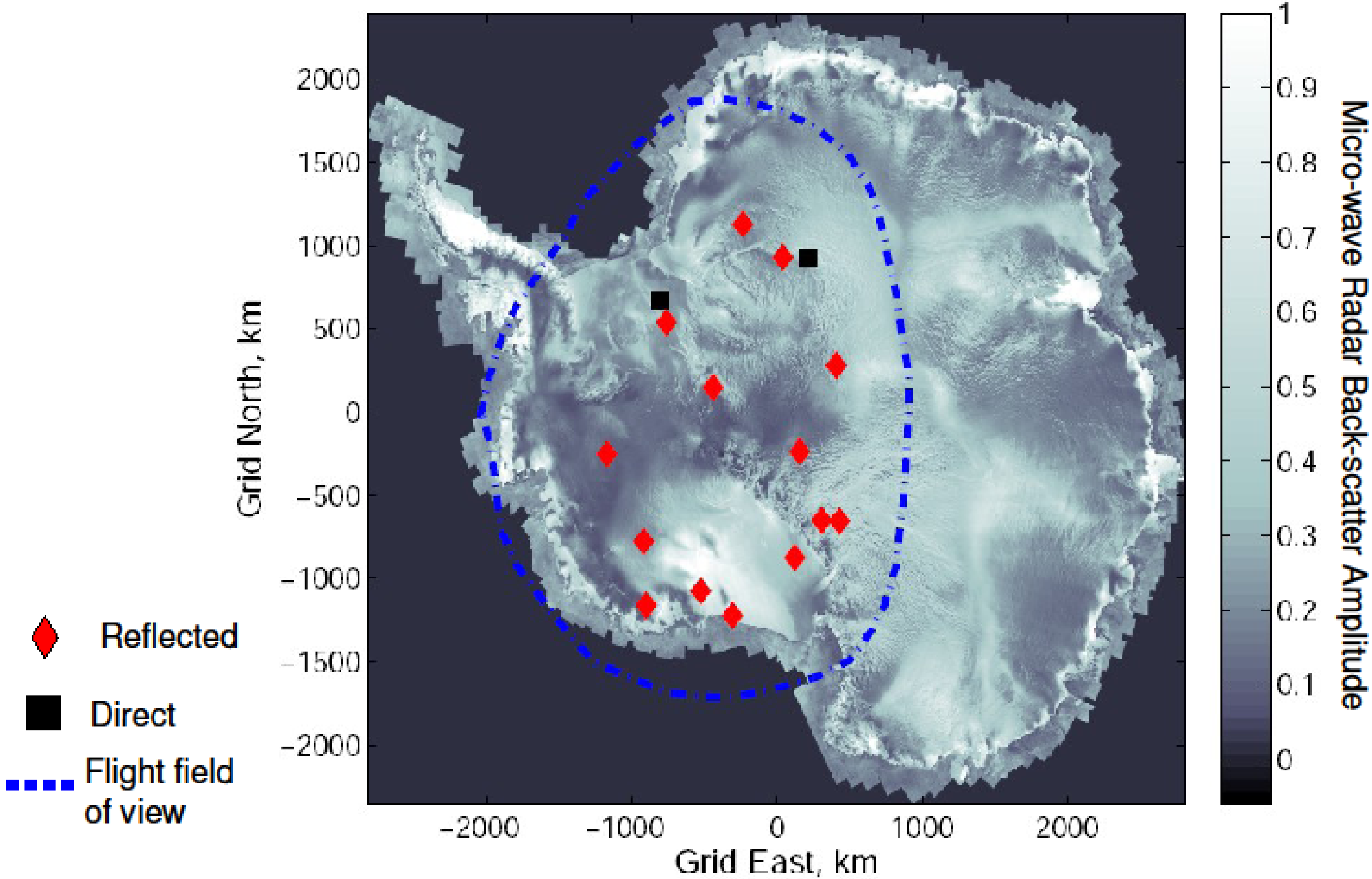
Correlation of Polarization Angle to Geo-Magnetic Field Angle



Interferometric image for a cosmic ray event



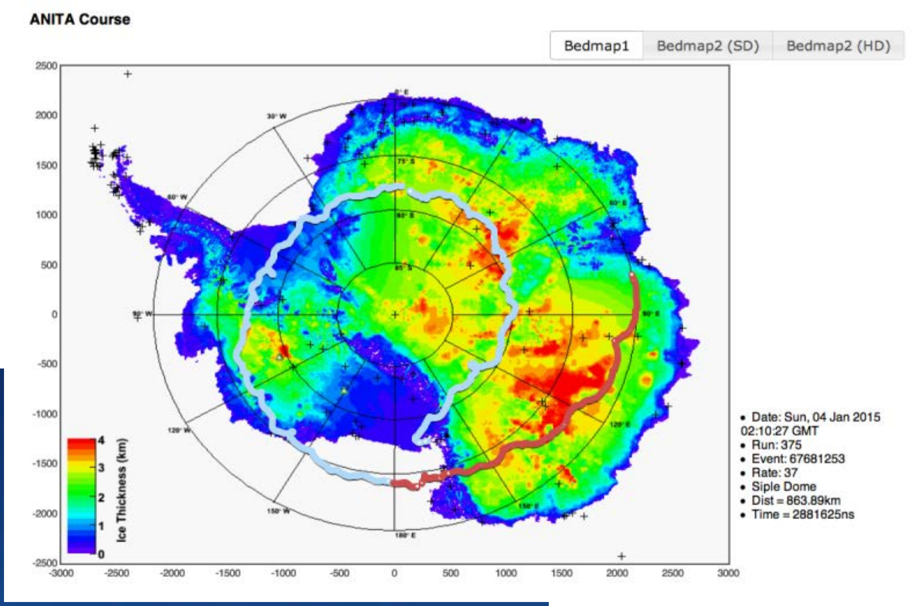
Cosmic-Ray Candidate Event Locations

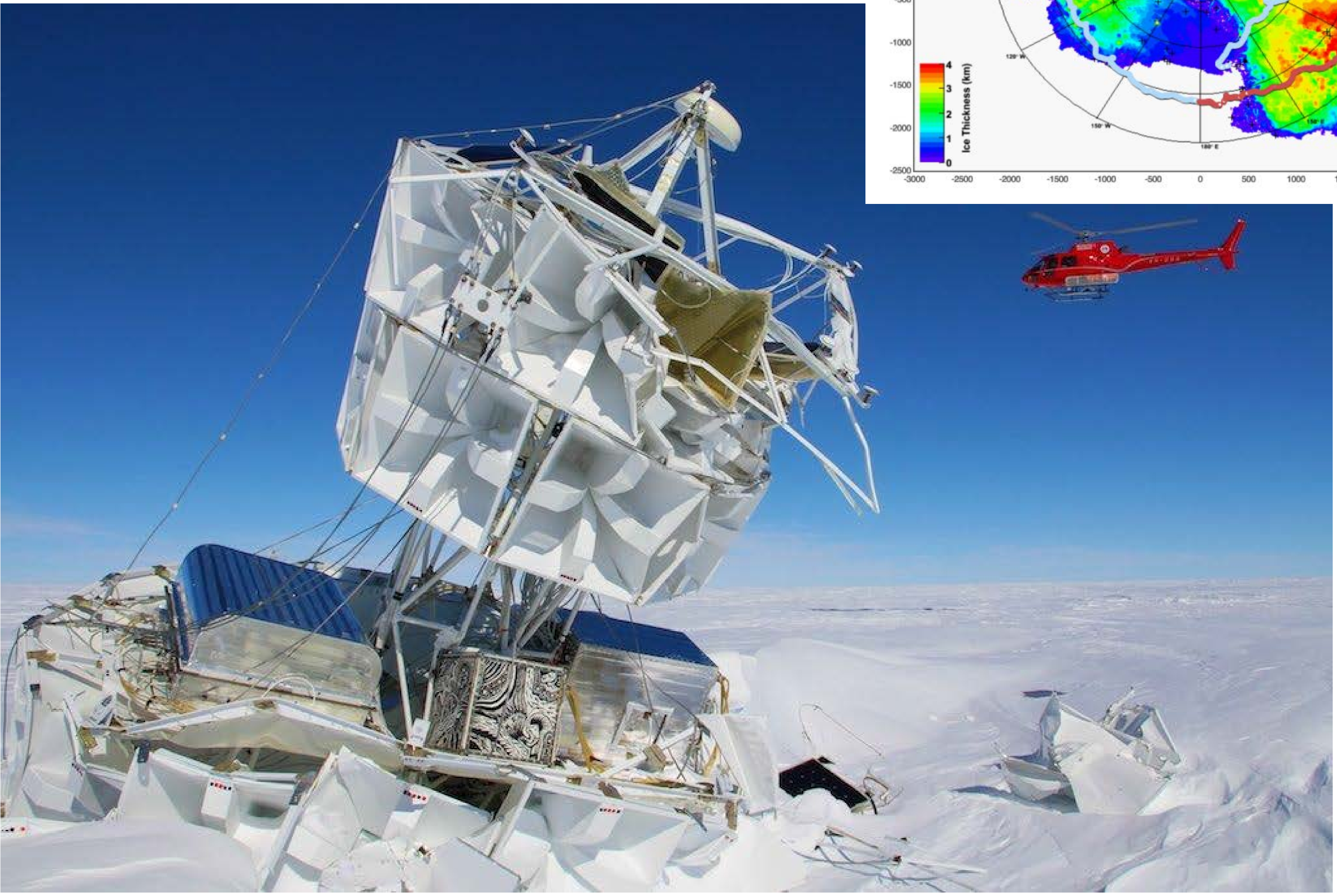


ANITA2 & 3

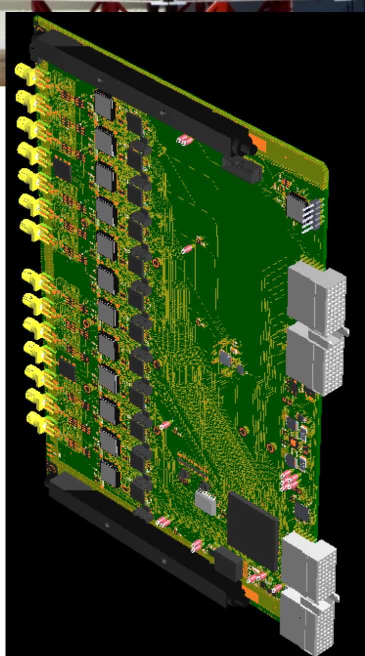
- Analysis of 1st and 2nd flights ➔ best limits at higher energies
- 2nd flight trigger tuned for neutrinos, lost cosmic rays
- 3rd Flight data analysis still ongoing
- Major Hardware Upgrade: ANITA4

ANITA4
(from the ashes)





ANITA4 Improvements



• Low-noise amplifiers & receivers with 30-40K noise figure decrease (20% in energy threshold)

• A real-time 3-bit signal correlator is expected to lower the trigger threshold by another 15-20%

• Programmable notch filters will allow much better response time and control of radio-frequency interference (~30% exposure improvement)

• Improvements in our GPU-based trigger processor will yield higher sustainable raw trigger rates and corresponding improvements of 10-15% in threshold.

Flight scheduled December, 2016

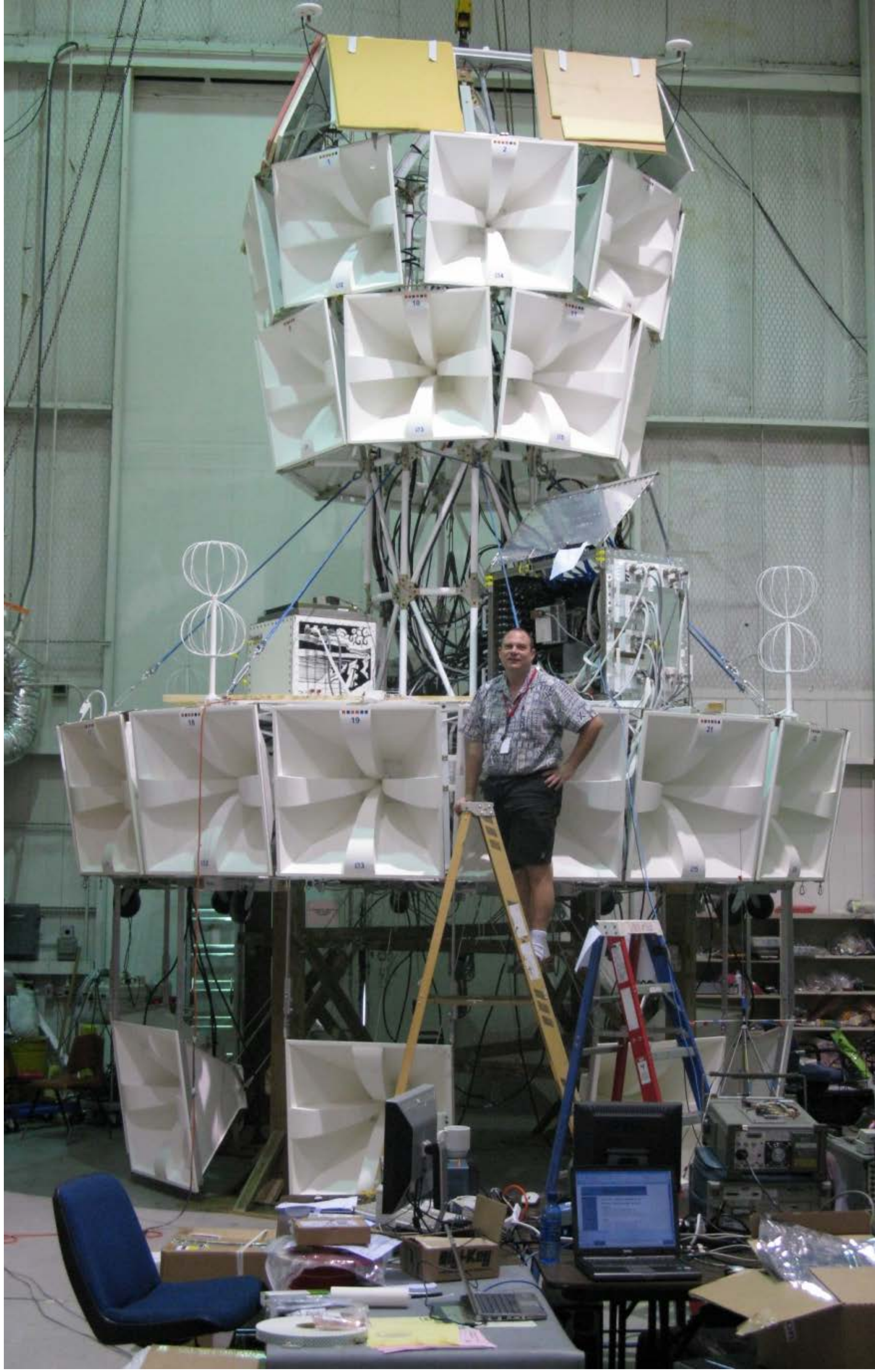
Summary

Radio Detection has a bright future:

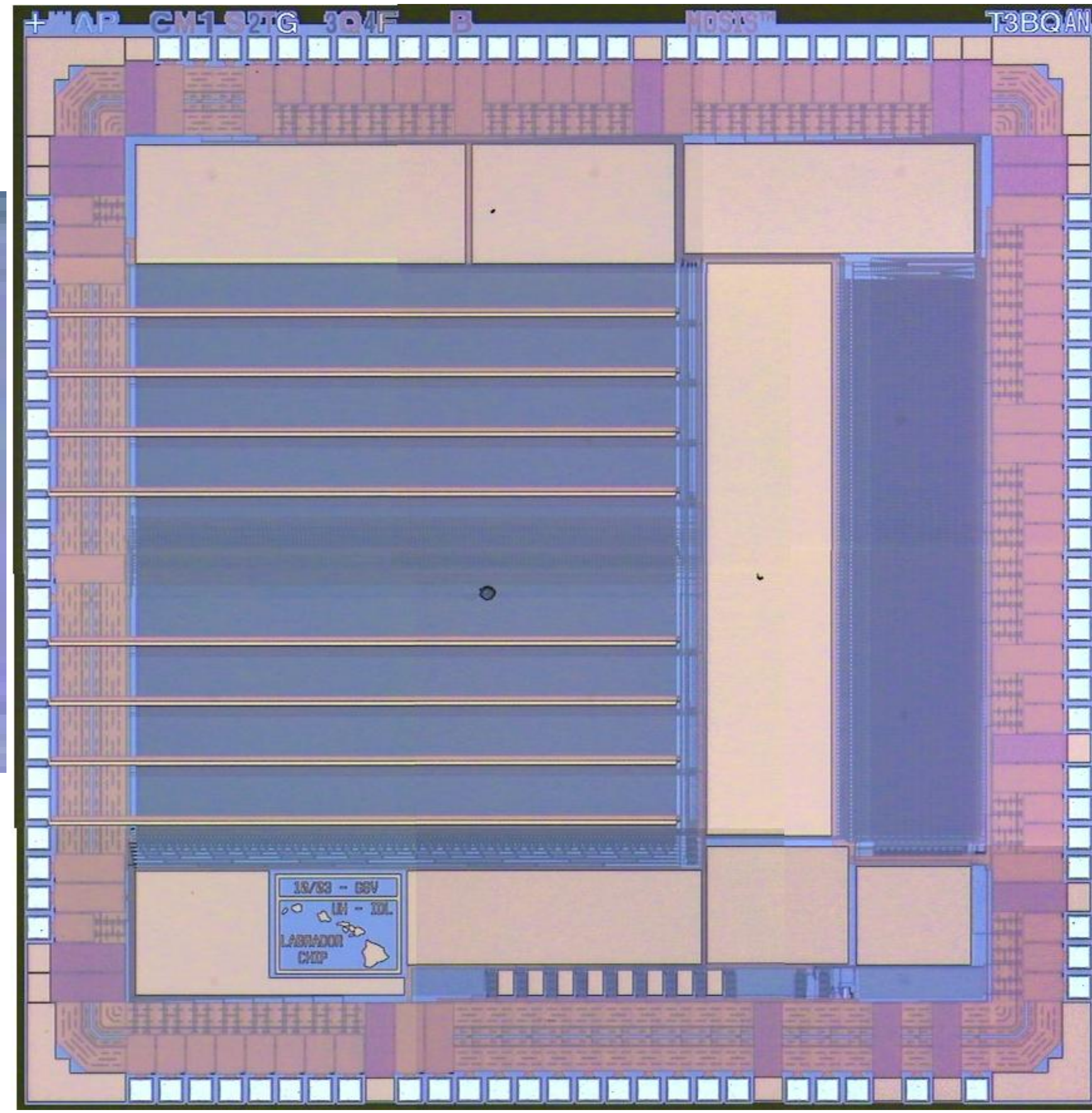
- Further discoveries will depend upon evolutionary improvements in the basic instrumentation

- Interesting problems with much overlap in other fields

- “Funding problems” are often mass manufacturing or operations cost issues – room for further ‘enabling technologies’ (it took 50 years for radio to get going… simply “scaling up” LHC a good idea?)

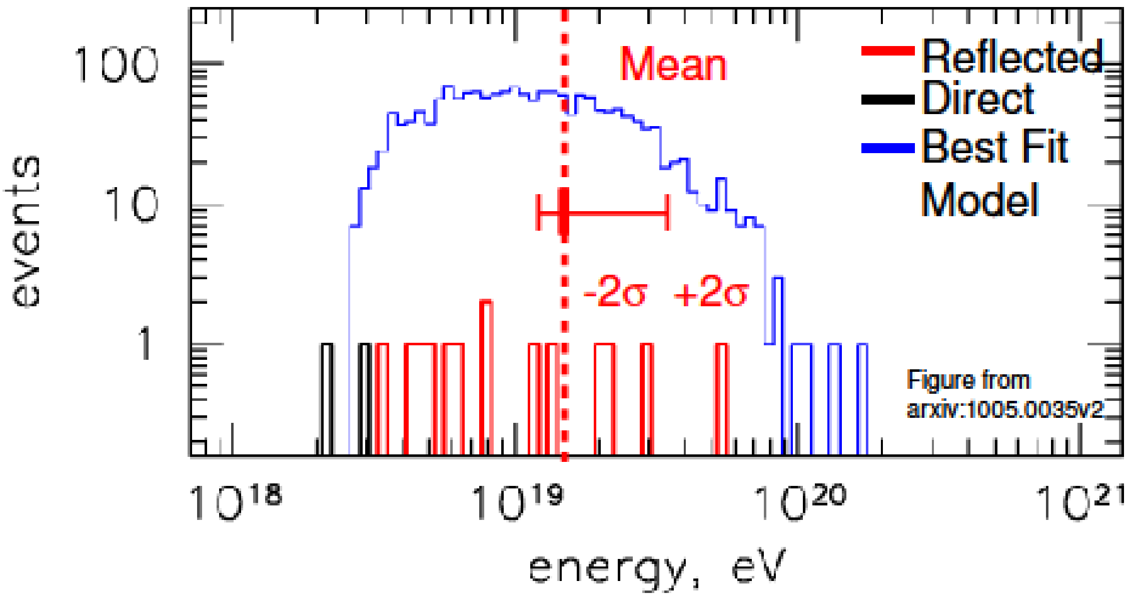


Back-up slides



UHE CR Energy Estimate

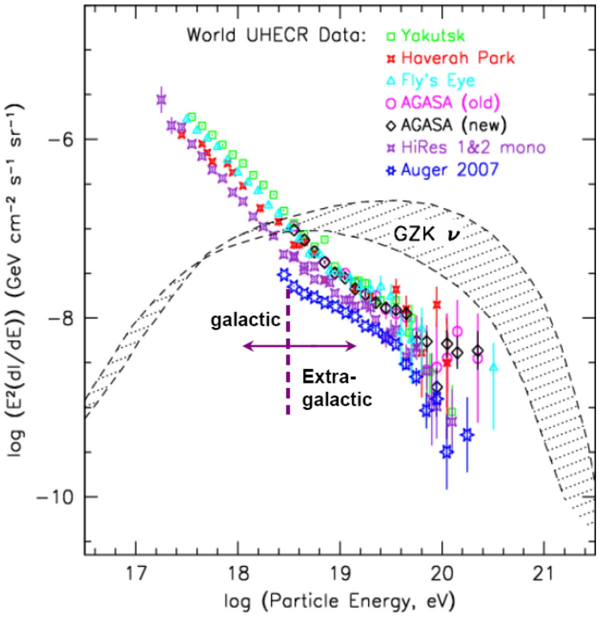
ANITA Cosmic Ray Energies and Sky Map



Event energies lie around the GZK cutoff

Cosmogenic Neutrinos

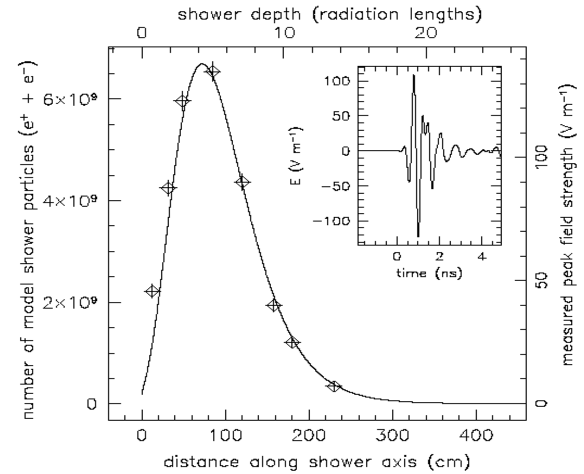
- 10^{18} eV neutrinos predicted by many acceleration and interaction processes at source locations
  – Observations, interaction physics suggest ultra-high energy cosmic rays will interact with the CMB to produce neutrinos
- Berezinsky & Zatsepin, 1970, REQUIRE 10^{18} eV neutrinos
  – Lack of neutrinos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



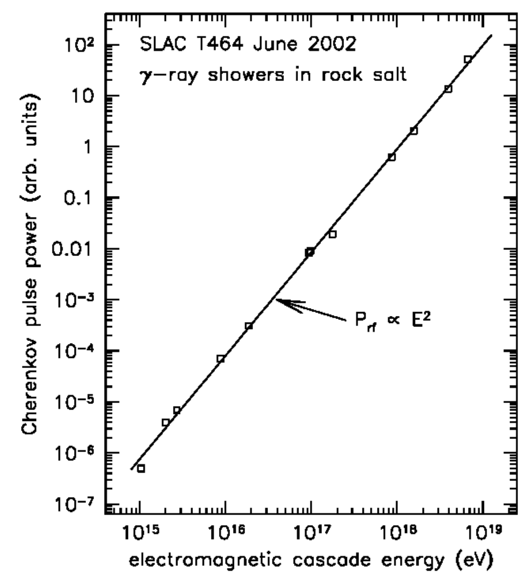
Courtesy Peter Gorham

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**



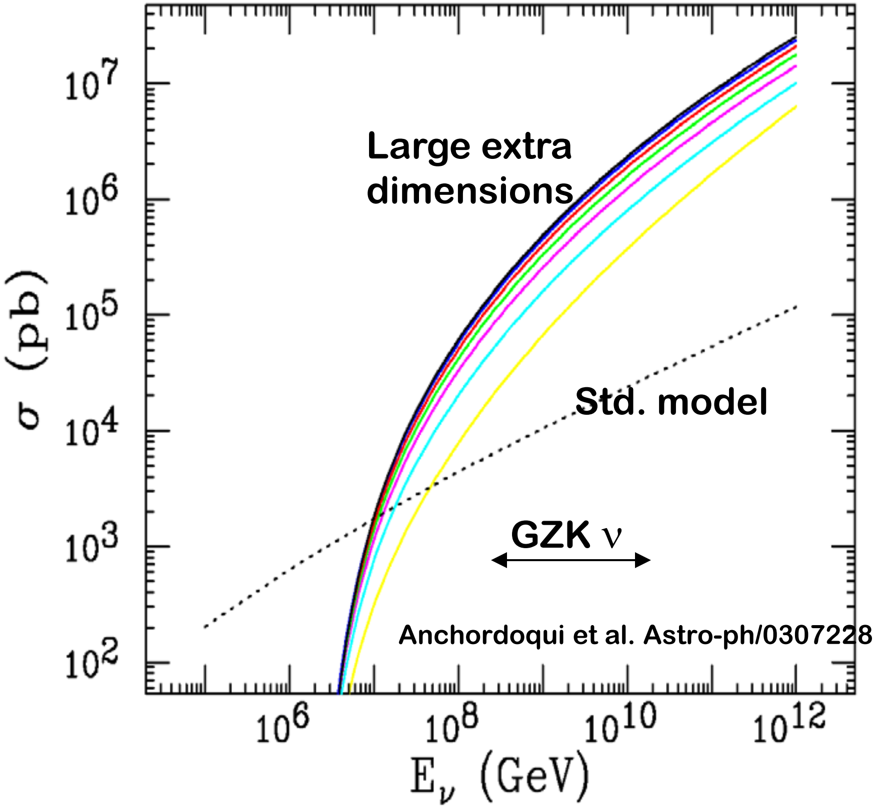
Saltzberg, et al PRL 2001



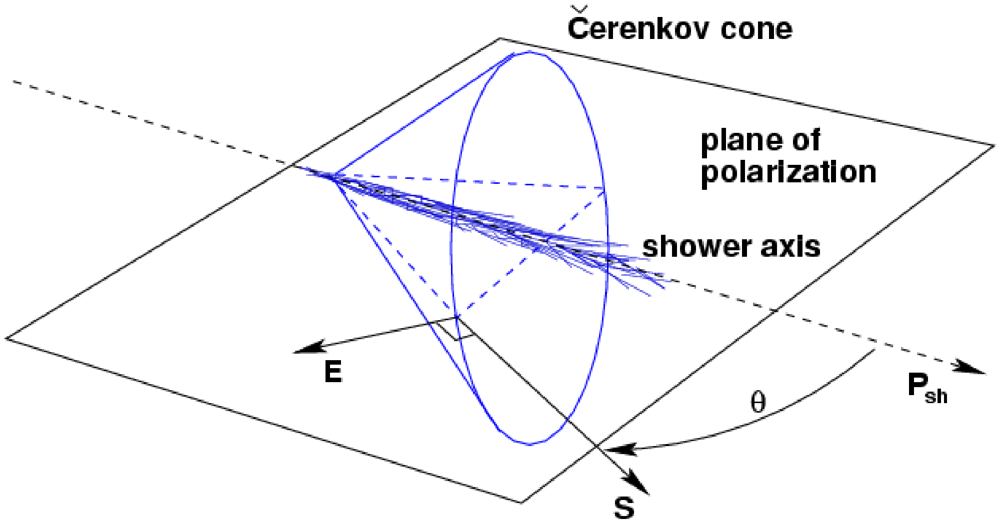
Gorham, et al PRD 2004

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



Cherenkov polarization tracking

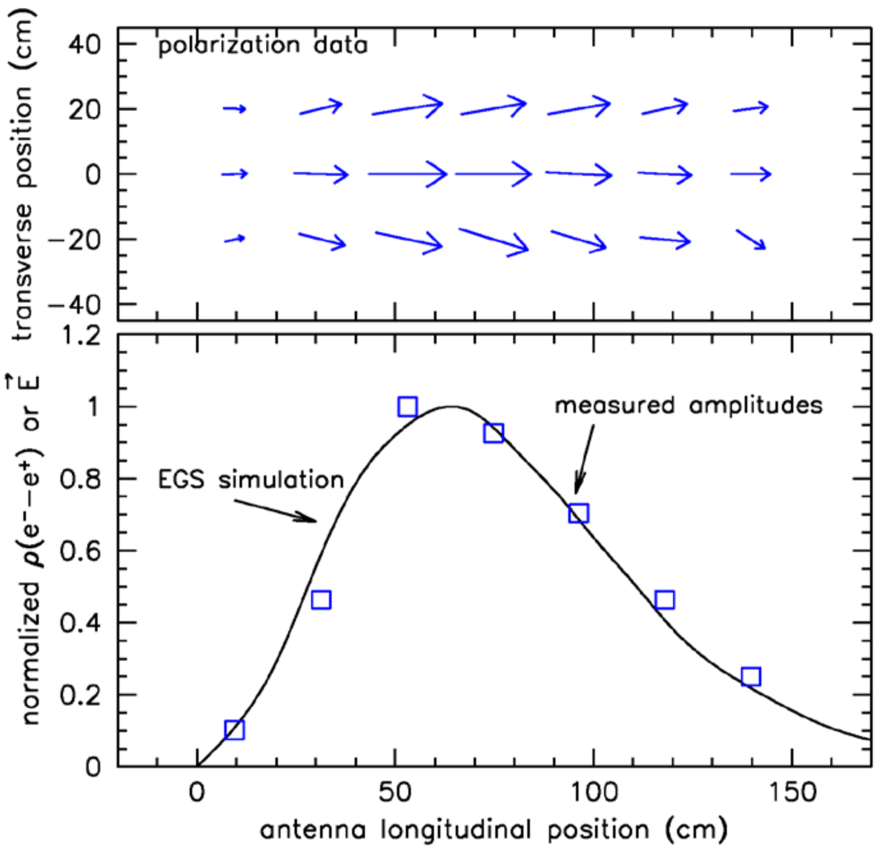


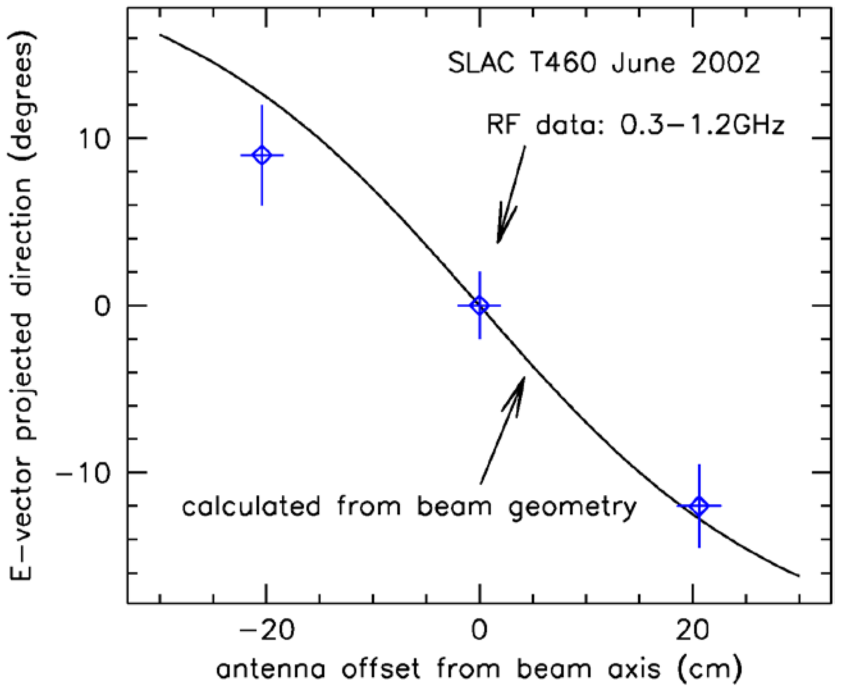
- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - **Intersection of these planes defines shower track**

Cherenkov radiation predictions:

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

Polarization tracking

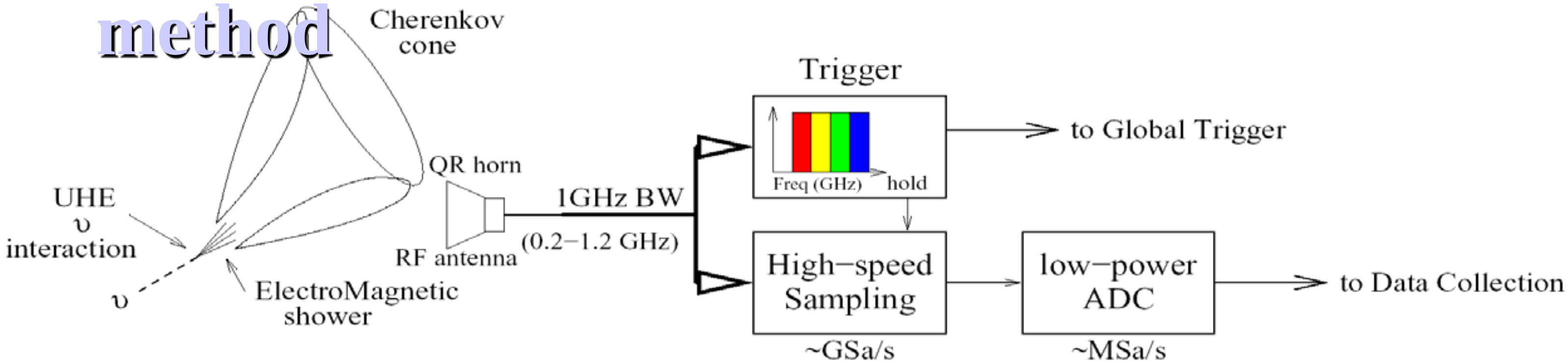




- Measured with dual-polarization embedded bowtie antenna array in salt

Trigger/Digitizer Specifications

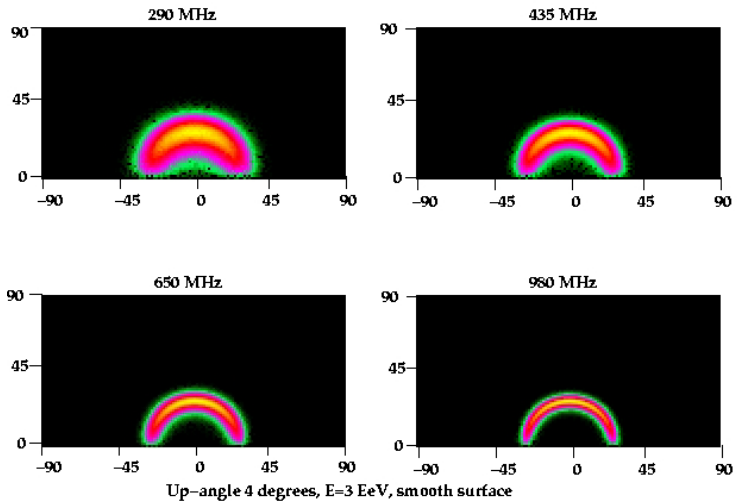
ANITA trigger & digitizer uses a proven dual-track method

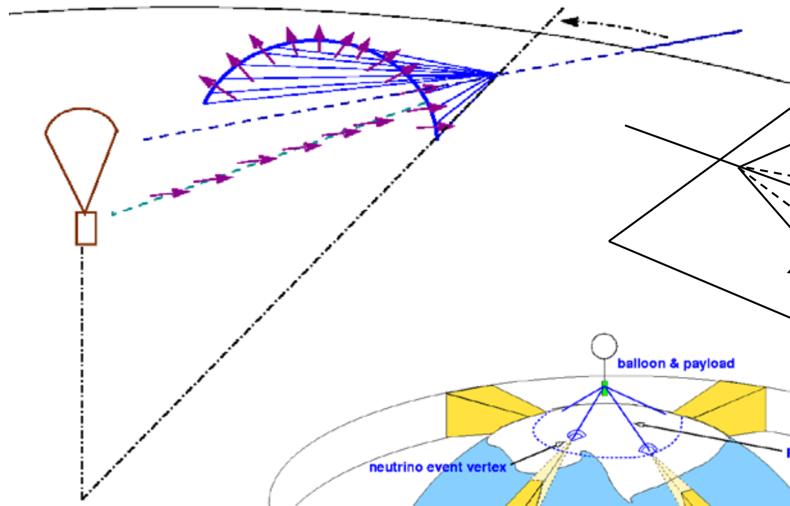


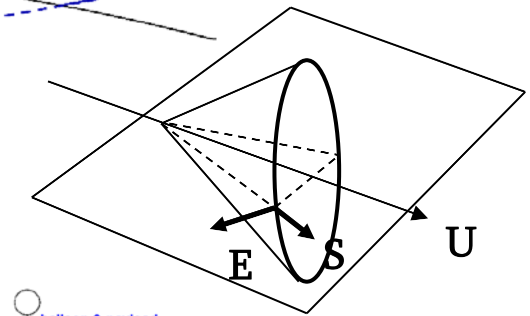
- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

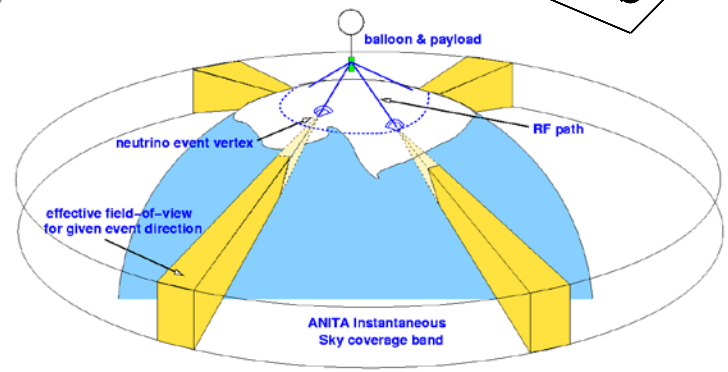
	parameter	**quantity**	**comments**
Sampling	# of RF channels	80	32 top; 32 bottom; 8 monitor; 8 veto
	Sampling rate	2.6 GSa/s	> Nyquist
	Sample resolution	> 9 bits	3 bits noise + dynamic range
	Samples per window	260	100ns time window
	# of Sample buffers	4	multi-hit + extended window
	Power/channel	< 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

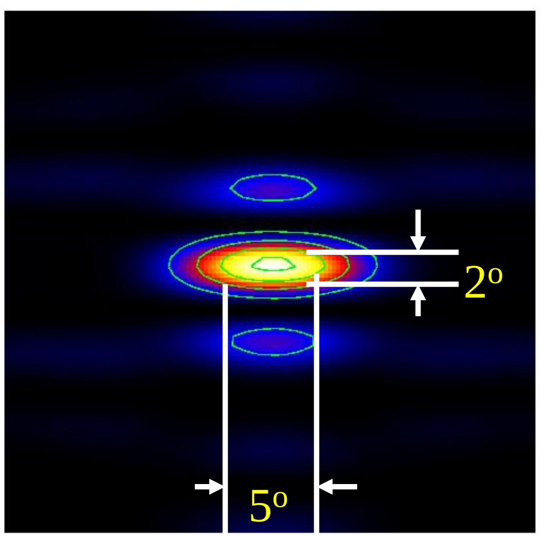
ANITA as a neutrino telescope







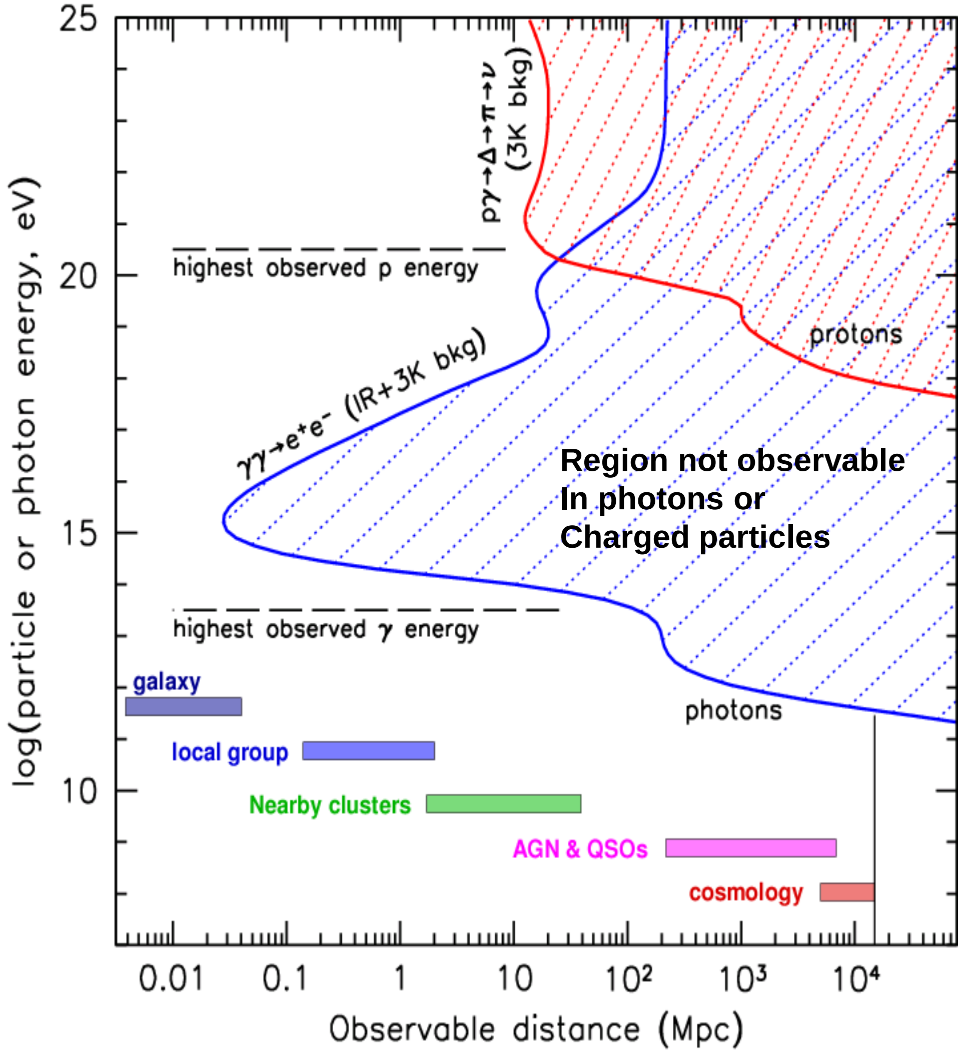




- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse

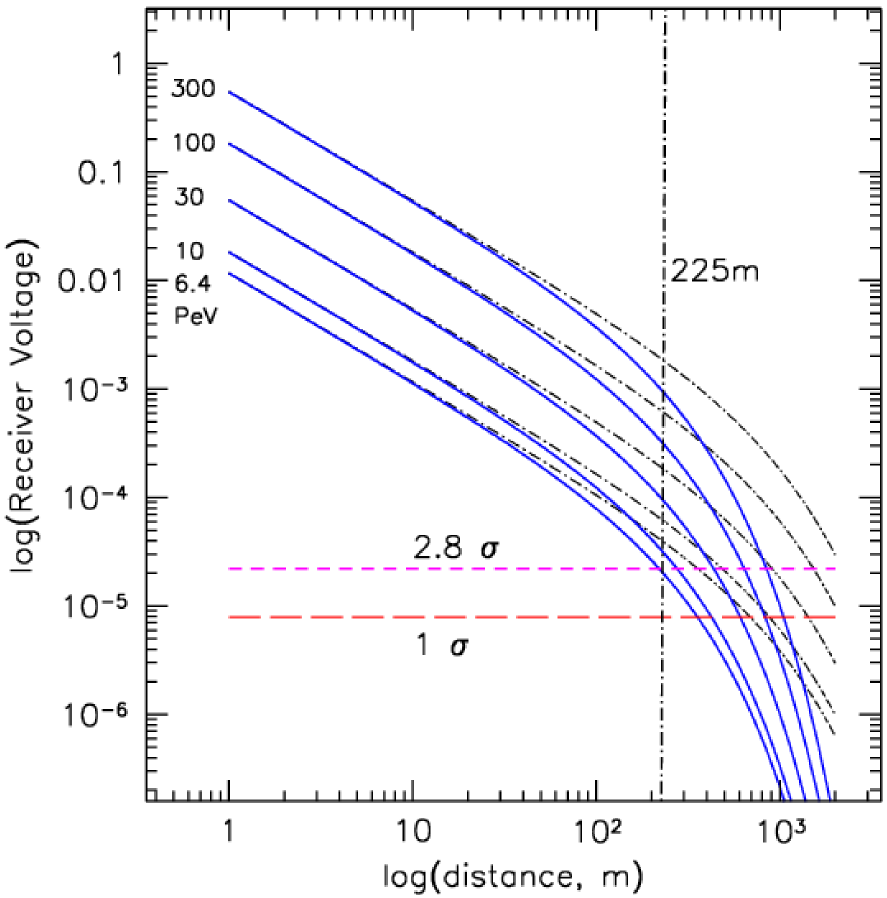
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

Neutrinos: The only known messengers at PeV energies and above



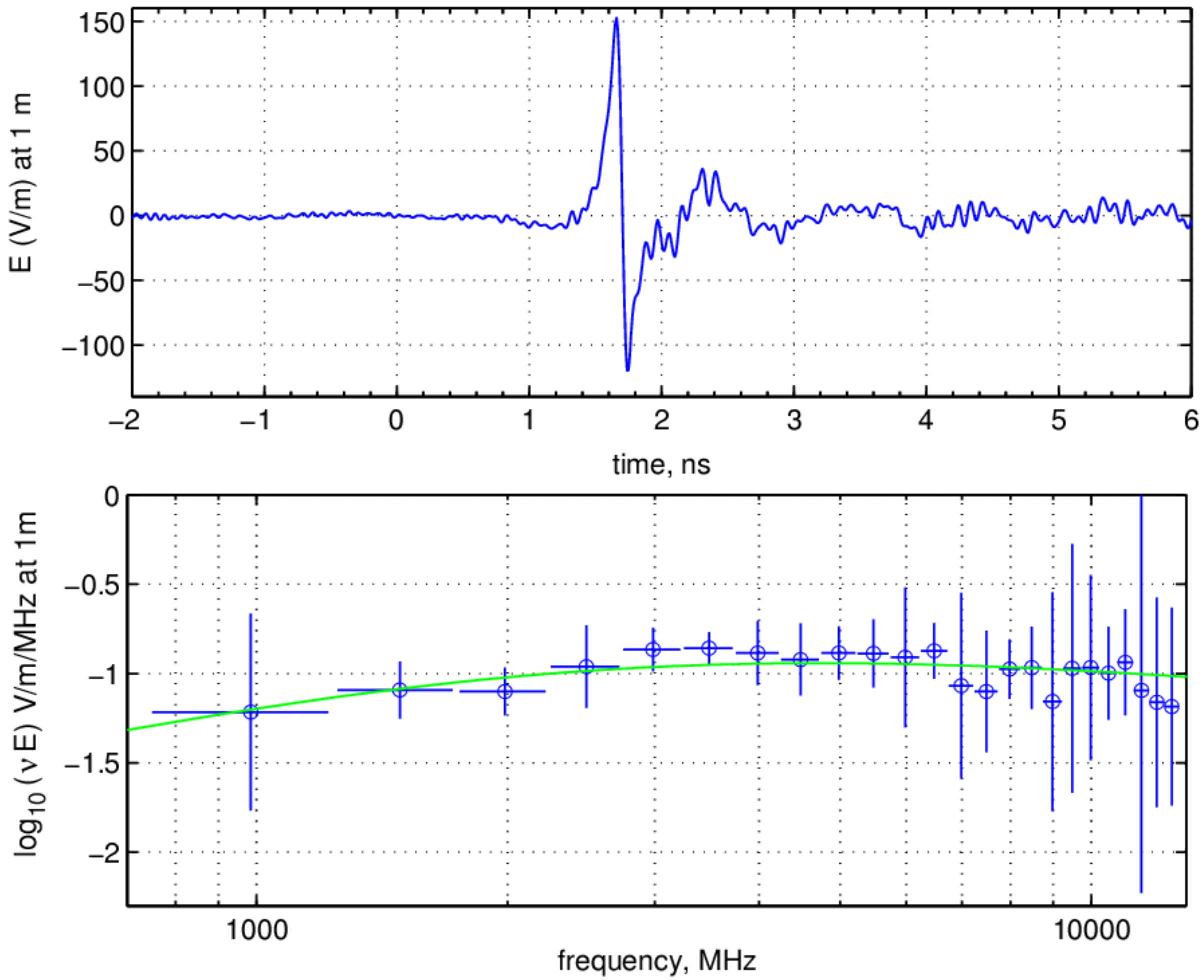
- **Photons lost above 30 TeV:** pair production on IR & μwave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- Sources extend to 10^9 TeV !
- => Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors
- To **guarantee** EeV neutrino detection, **design for the GZK neutrino flux**

Estimated SalSA Energy threshold



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

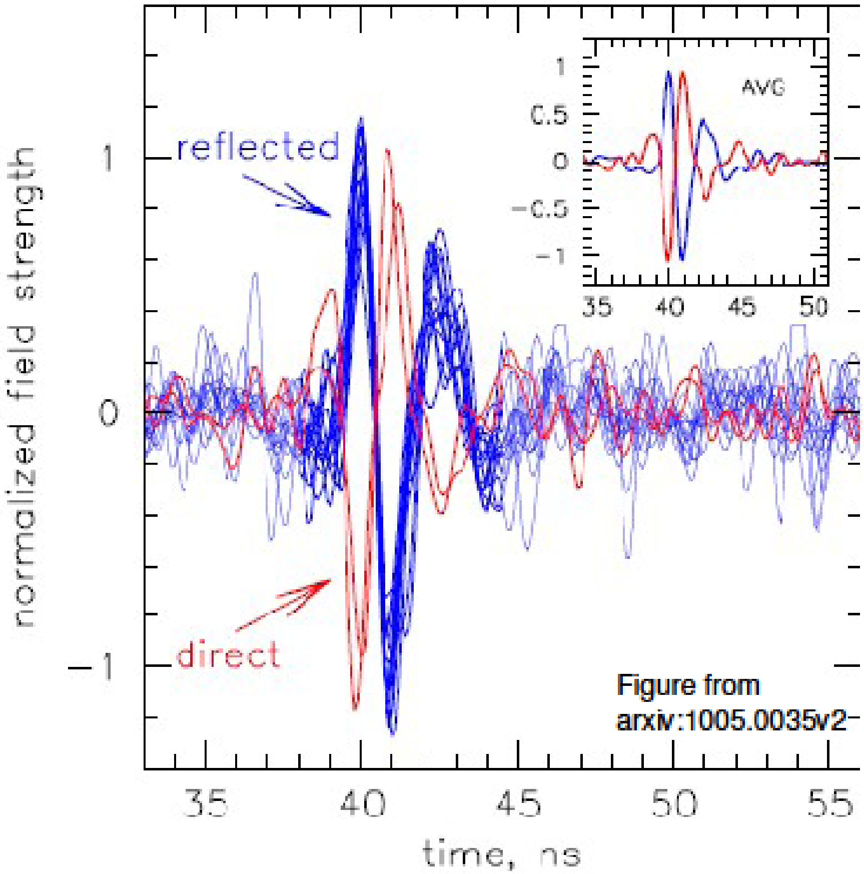
Ultra-wideband data on Askaryan pulse

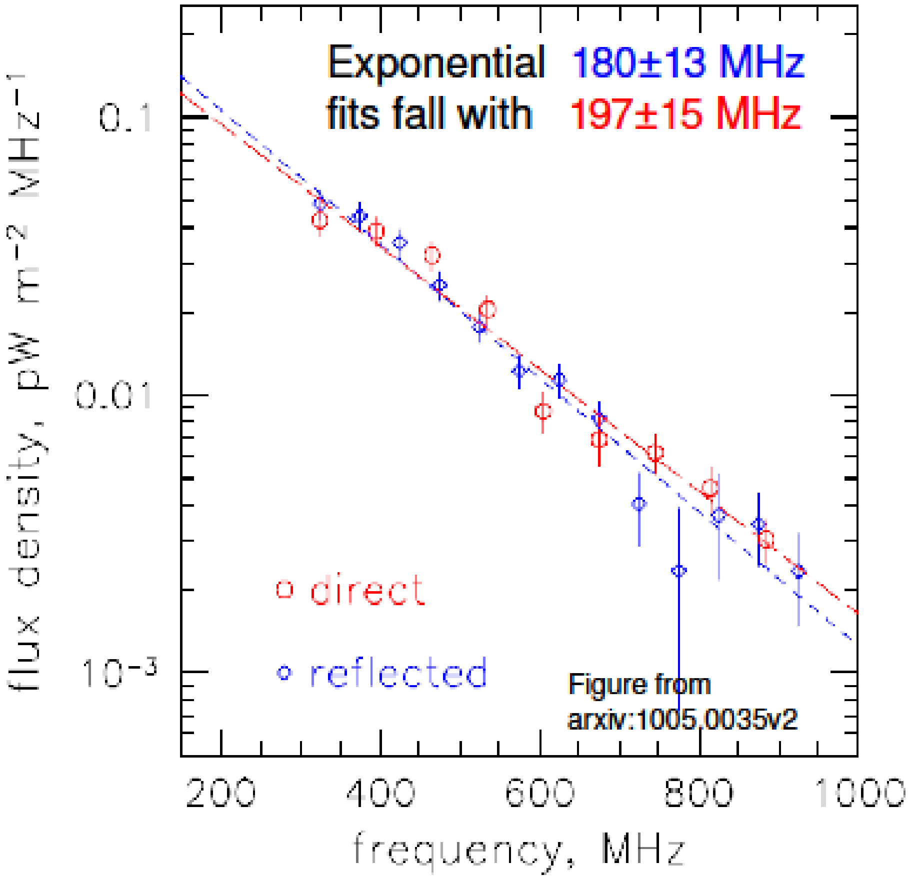


- 2000 & 2002 SLAC Experiments confirm extreme coherence of Askaryan radio pulse
- 60 picosecond pulse widths measured for salt showers
- Flat spectrum radio emission extends well into microwave regime

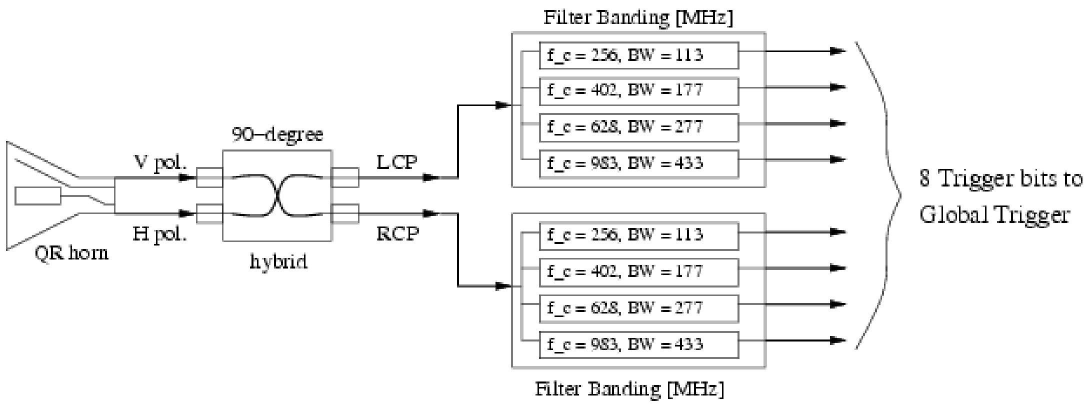
Cosmic-Ray Candidate Event Pulses

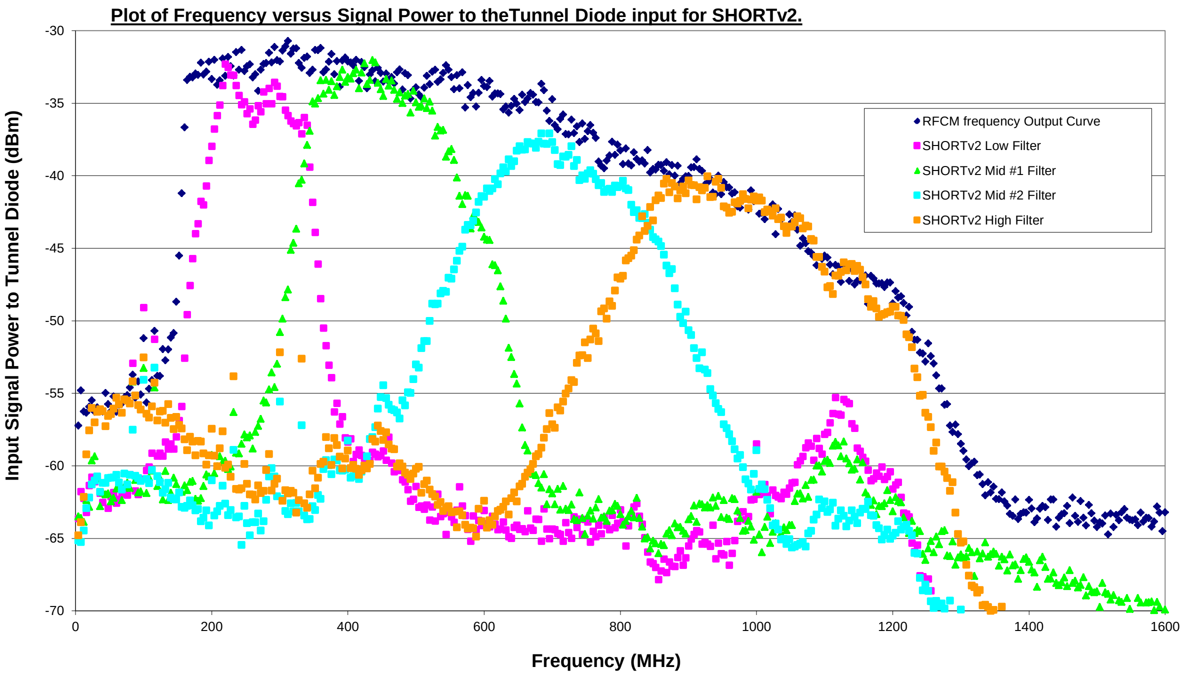
(Instrument response deconvolved)





ANITA Level 1 – 3 of 8 Antenna

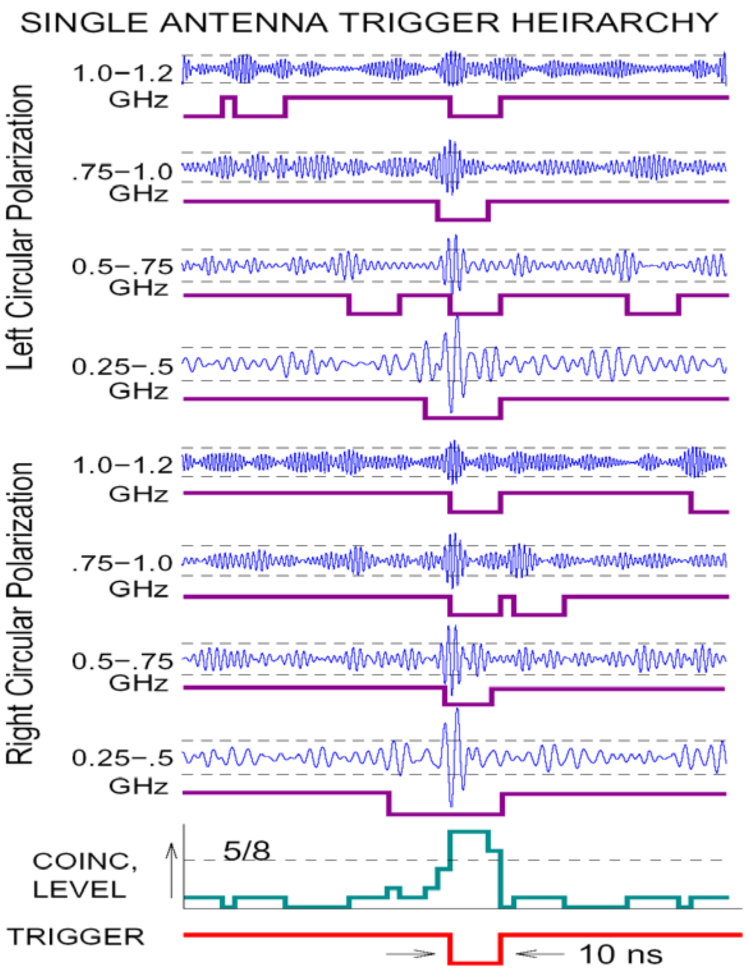




SHORTv2 ECOs: RT1=39 ohm, RT2=39 ohm,

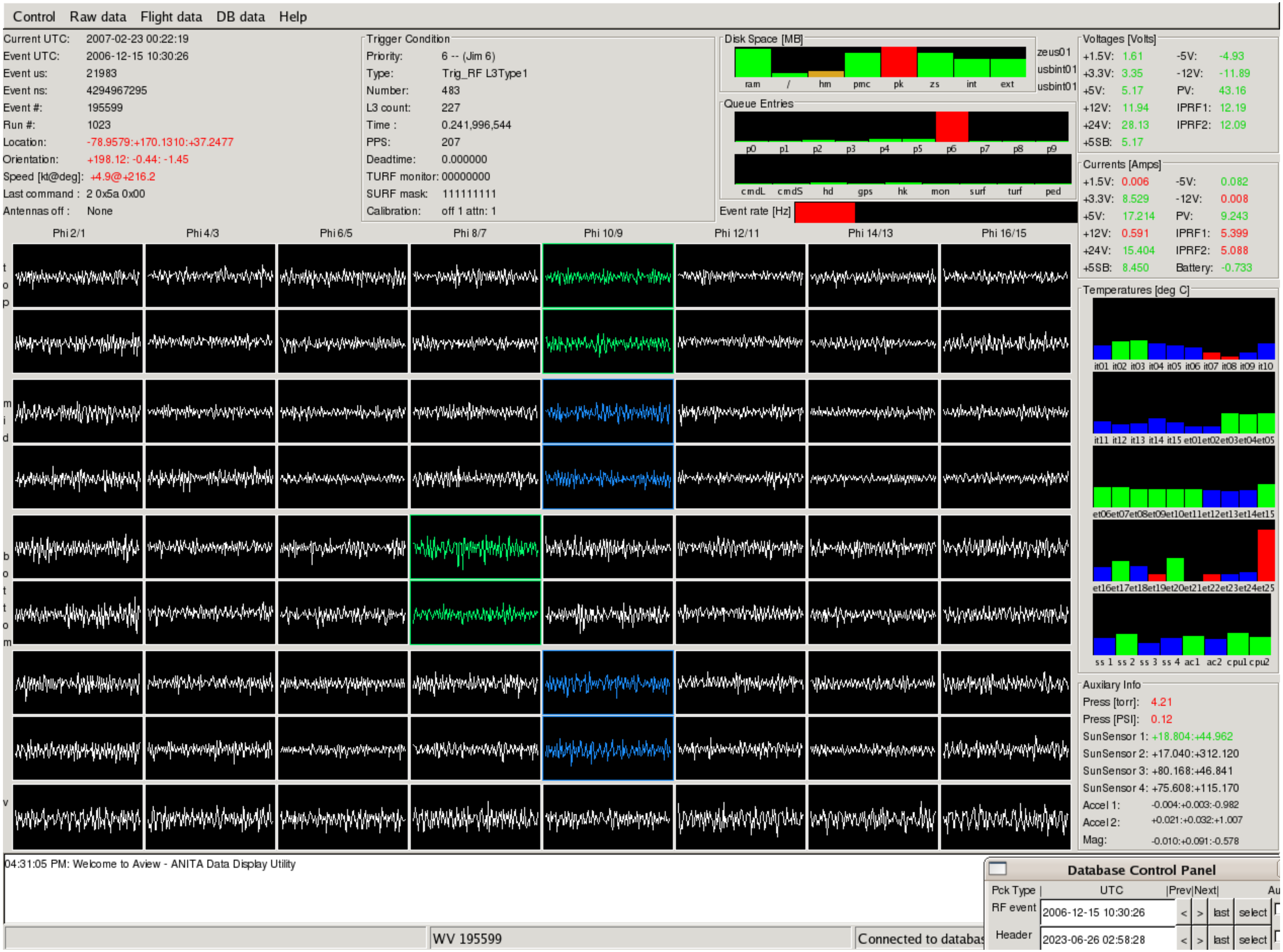
NOTE: RFCM data are not the input signal to the SHORTv2.

Single Antenna trigger



- Multi-band triggering essential to ANITA sensitivity
- 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

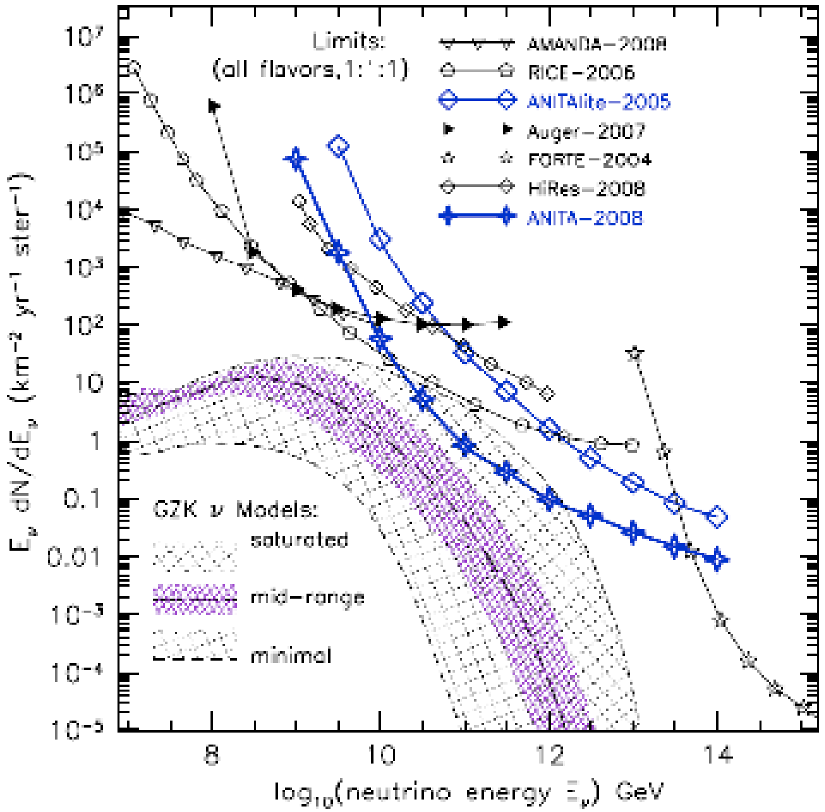
99.99+% of triggers: incoherent thermal noise



ANITA-1 Neutrino Flux Model Expectations and Constraints

Phys.Rev.Lett.103:051103,2009

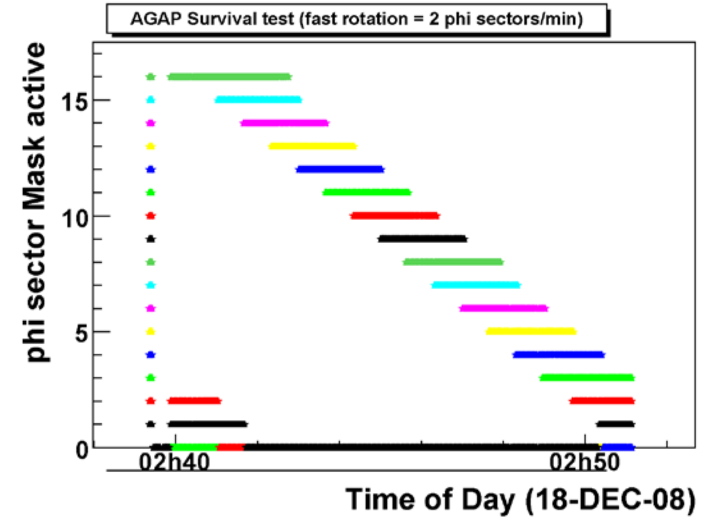
Model & references	predicted N_ν	CL,%
Baseline BZ models		
Protheroe & Johnson 1996 [21]	0.22	19.7
Engel, Seckel, Stanev 2001 [11]	0.12	11.3
Barger, Huber, & Marfatia 2006 [29]	0.38	31.6
Strong source evolution BZ models		
Engel, Seckel, Stanev 2001 [11]	0.39	32.3
Kalashev *et al.* 2002 [23]	1.03	64.3
Aramo *et al.* 2005 [26]	1.04	64.6
Barger, Huber, & Marfatia 2006 [29]	0.89	58.9
Yuksel & Kistler 2007 [28]	0.56	42.9
BZ Models that saturate all bounds:		
Kalashev *et al.* 2002 [23]	10.1	> 99.99
Aramo *et al.* 2005 [26]	8.50	> 99.98
Waxman-Bahcall fluxes:		
Waxman, Bahcall 1999, evolved sources [12]	0.76	53.2
Waxman, Bahcall 1999, standard [12]	0.27	23.7



Warning!!! Log Plot!

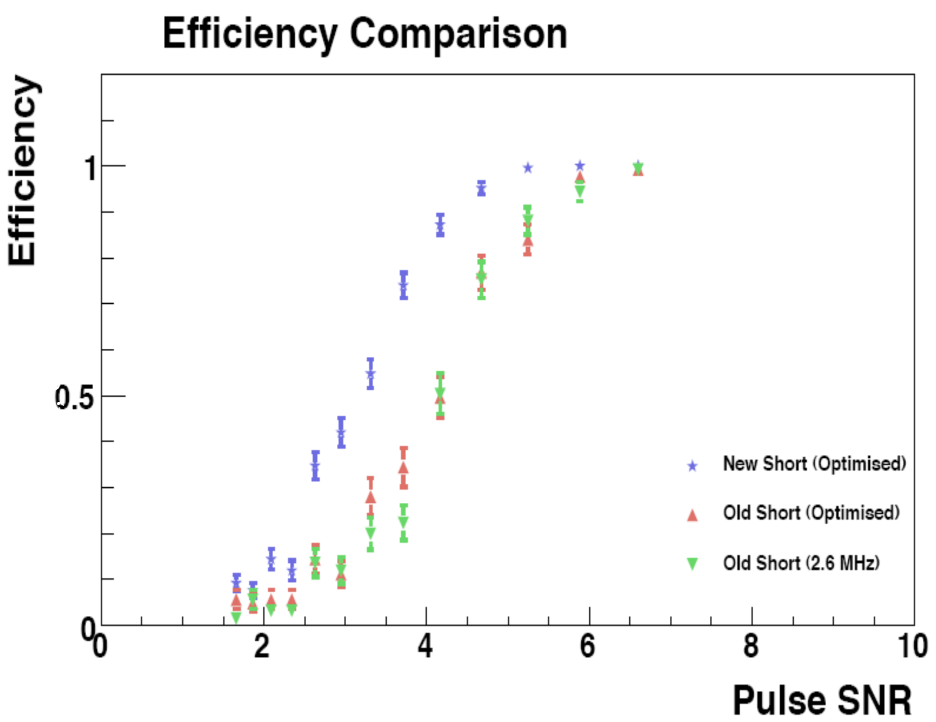
ANITA 2 Improvements

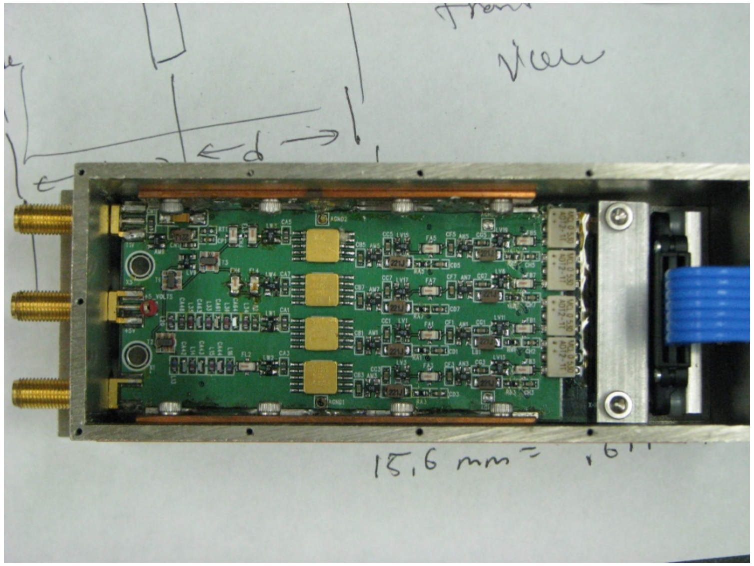
- "Dynamic Phi-Masking"
  - Active suppression of phi-sector readout during transit over noisy areas
    - McMurdo, South Pole, etc
  - Automatically activated
- 8 "nadir" antennas
  - One antenna shared w/ 2 phi sectors
- Only trigger on V-pol
- Improve T_{sys} by 40K
  - New Low-Noise Amplifier
- Overall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



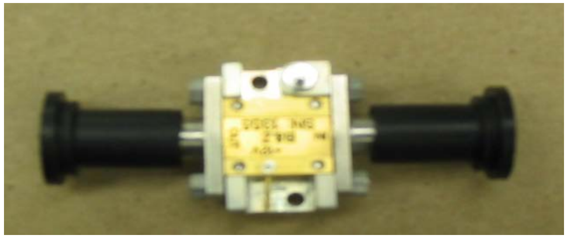
ANITA-2 Upgrades...

- 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

ANITA2 Flight instrument