Challenges in Radio Detection Techniques

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Detector R&D WS, Fermilab

Oct. 2010

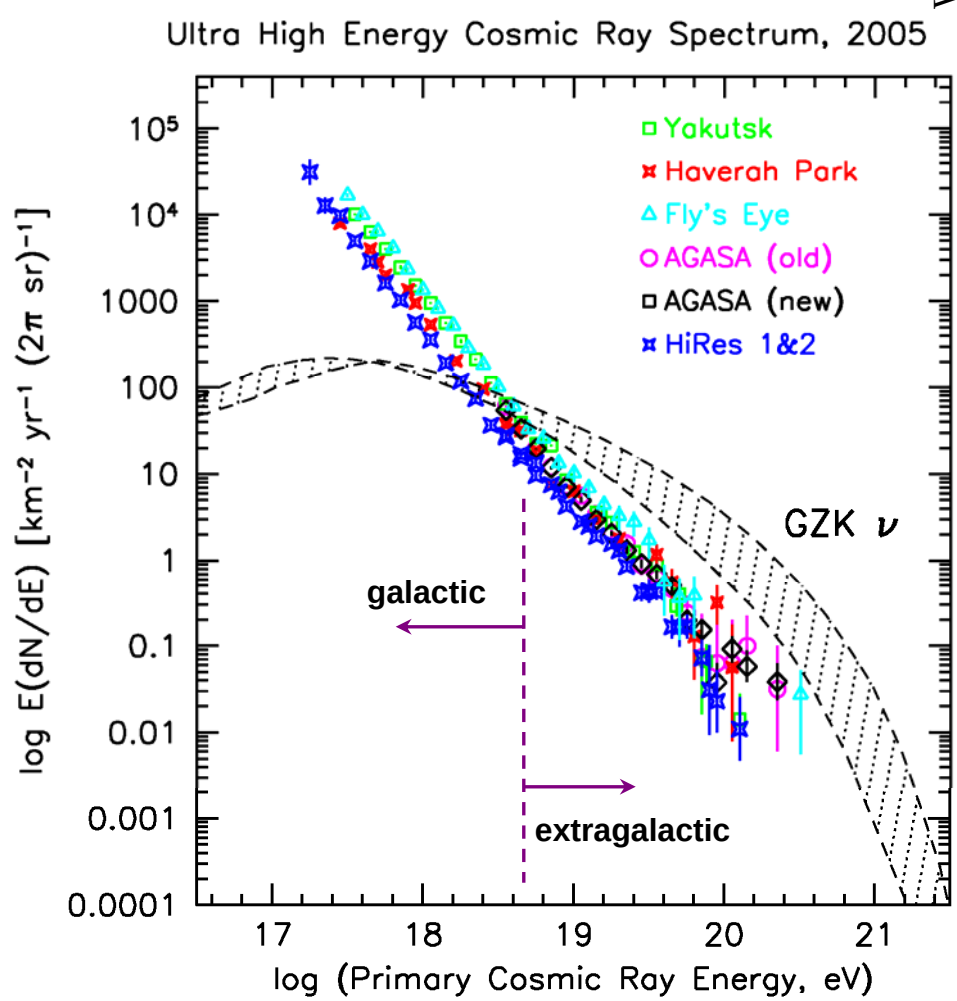
Why Radio??
(Ultra-)High Energy Physics of Cosmic rays & Neutrinos

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

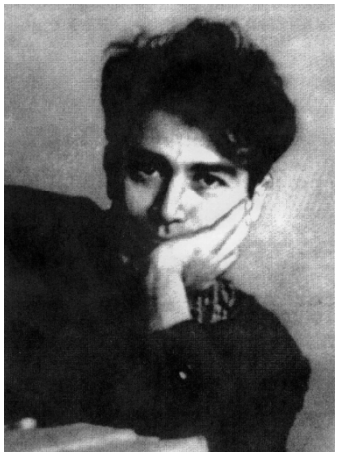
- A paradox:
  - No *nearby* sources observed
  - distant sources *excluded* due to process below

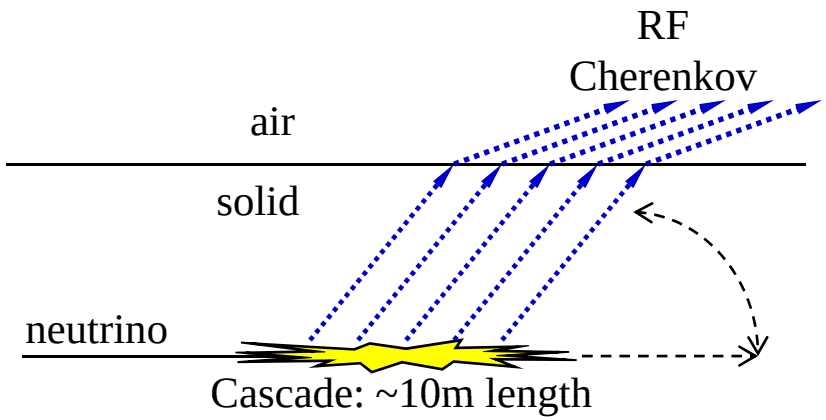
- **Neutrinos** at $10^{17\text{-}19}$ eV **required** by standard-model physics

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



Radio Observation in dense media



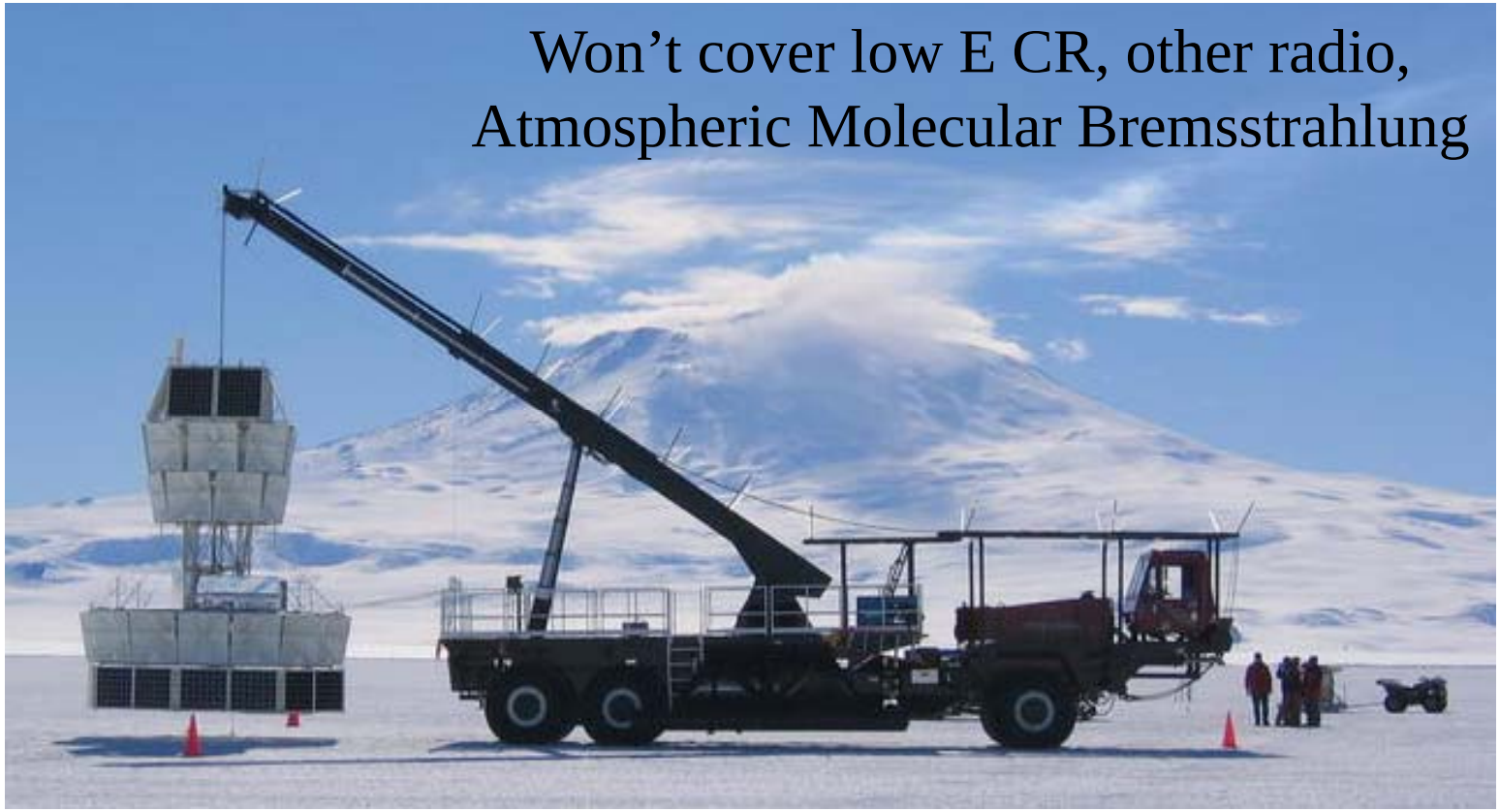


1960's: Askaryan predicted that the resultant compact cascade shower (1962 JETP **14**, 144; 1965 JETP **21**, 658):

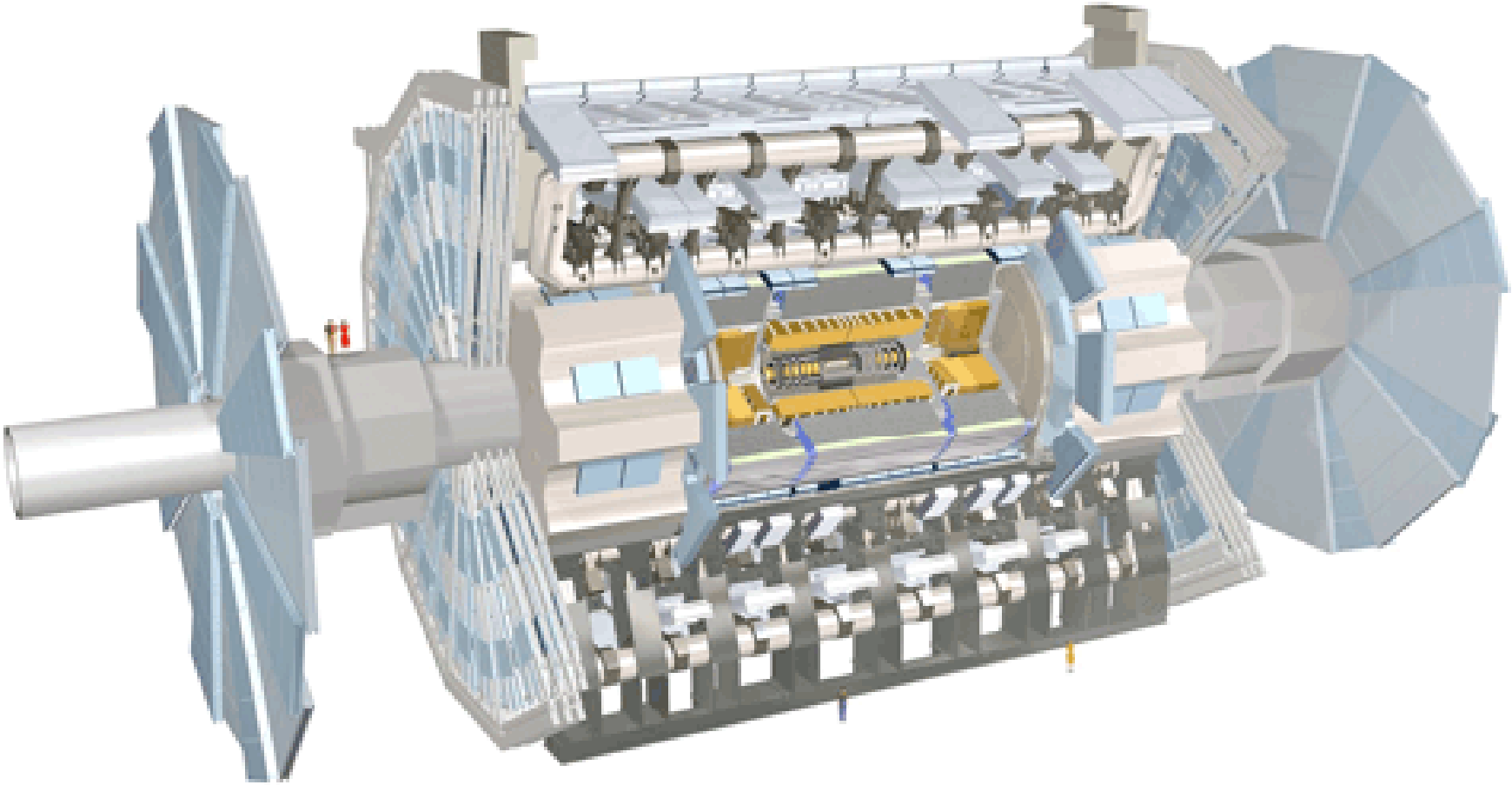
- would develop a local, relativistic net negative charge excess
- would be coherent ($P_{rf} \sim E^2$) for radio frequencies
- for high energy interactions, well above thermal noise:
  - detectable at a distance (via antennas)
  - polarized – can tell where on the Cherenkov cone

In the last decade or so... radio detection techniques finally flourishing

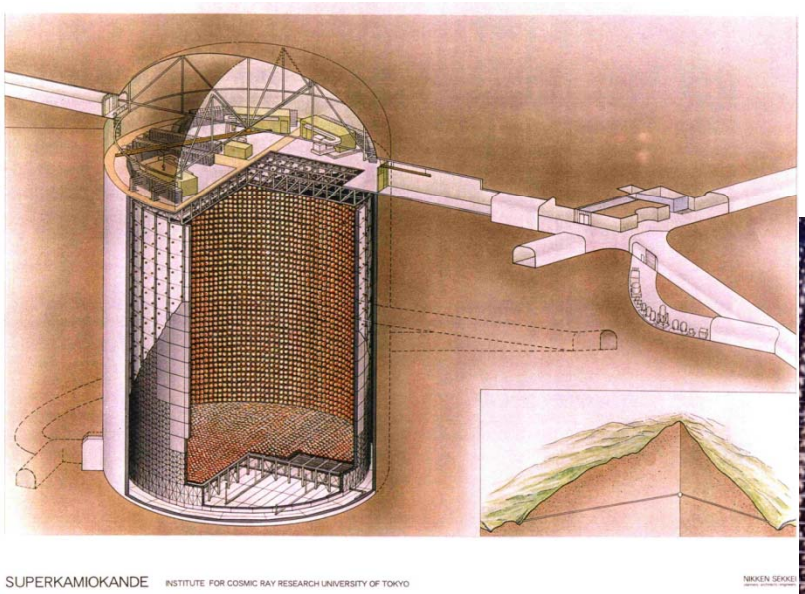
1. Radio Detection of UHE neutrinos
2. ANtarctic Impulsive Transient Antenna (ANITA)
3. Serendipitous observation of UHE CR
4. Tera-ton Initiatives (the last shall be first)

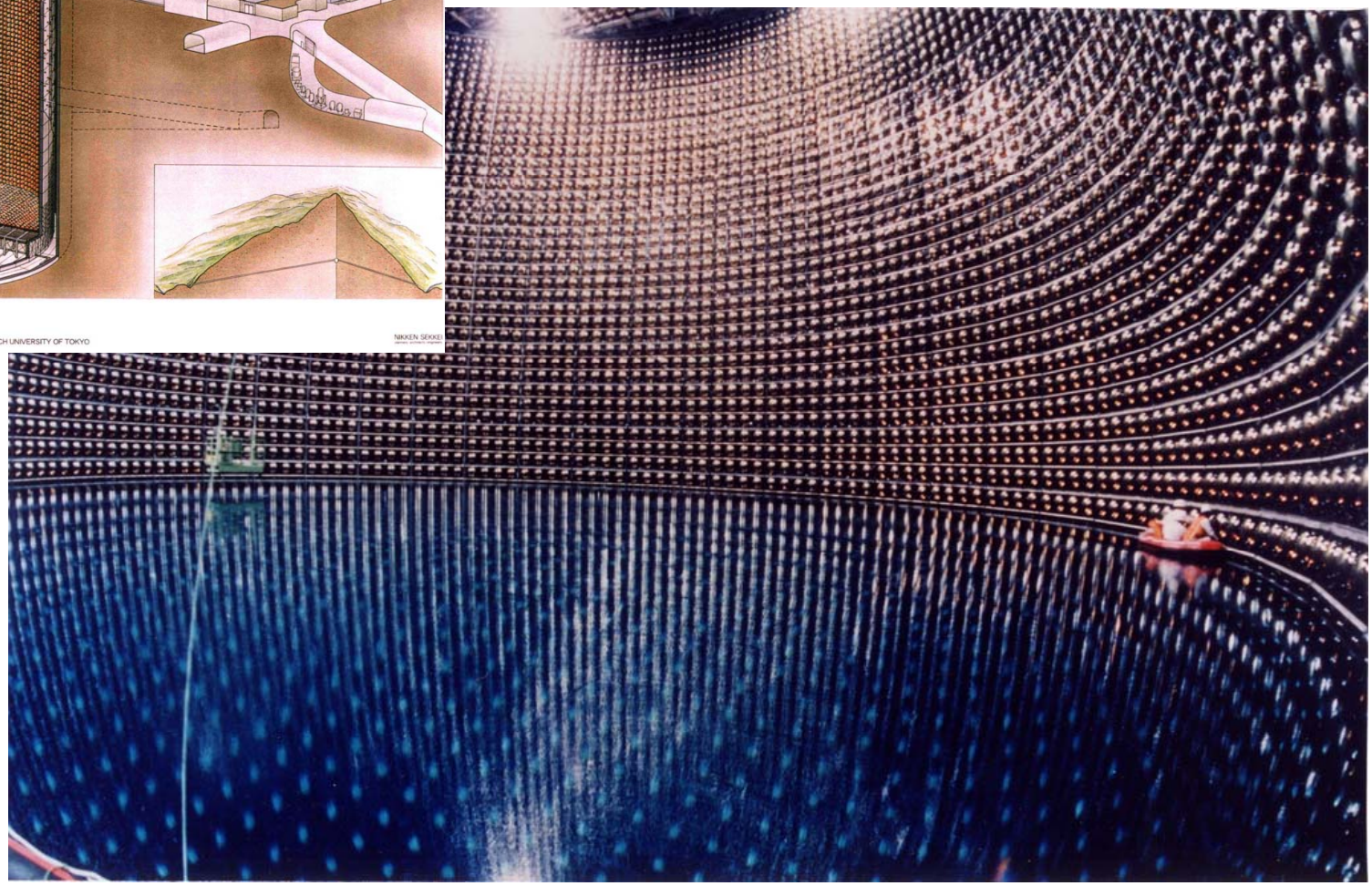


Detector Energy Scales – the tonne



Detector Energy Scales – the kT



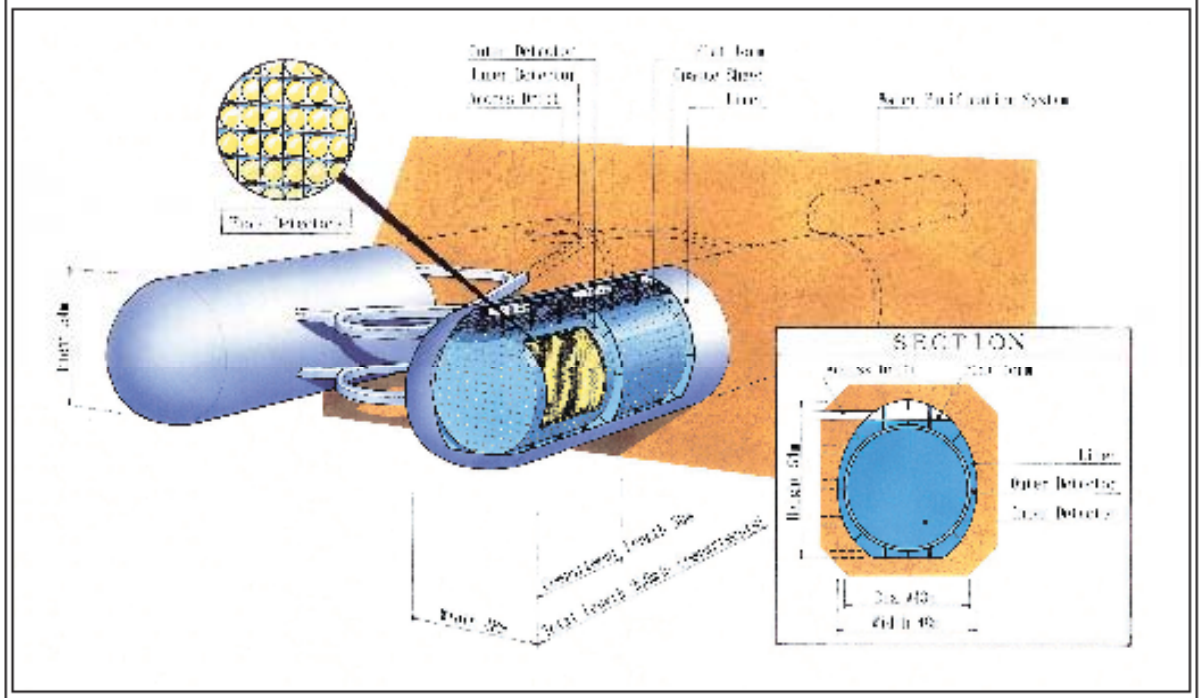


Detector Energy Scales – the MT

MEGA-DETECTORS

Thinking big: the next generation of detectors

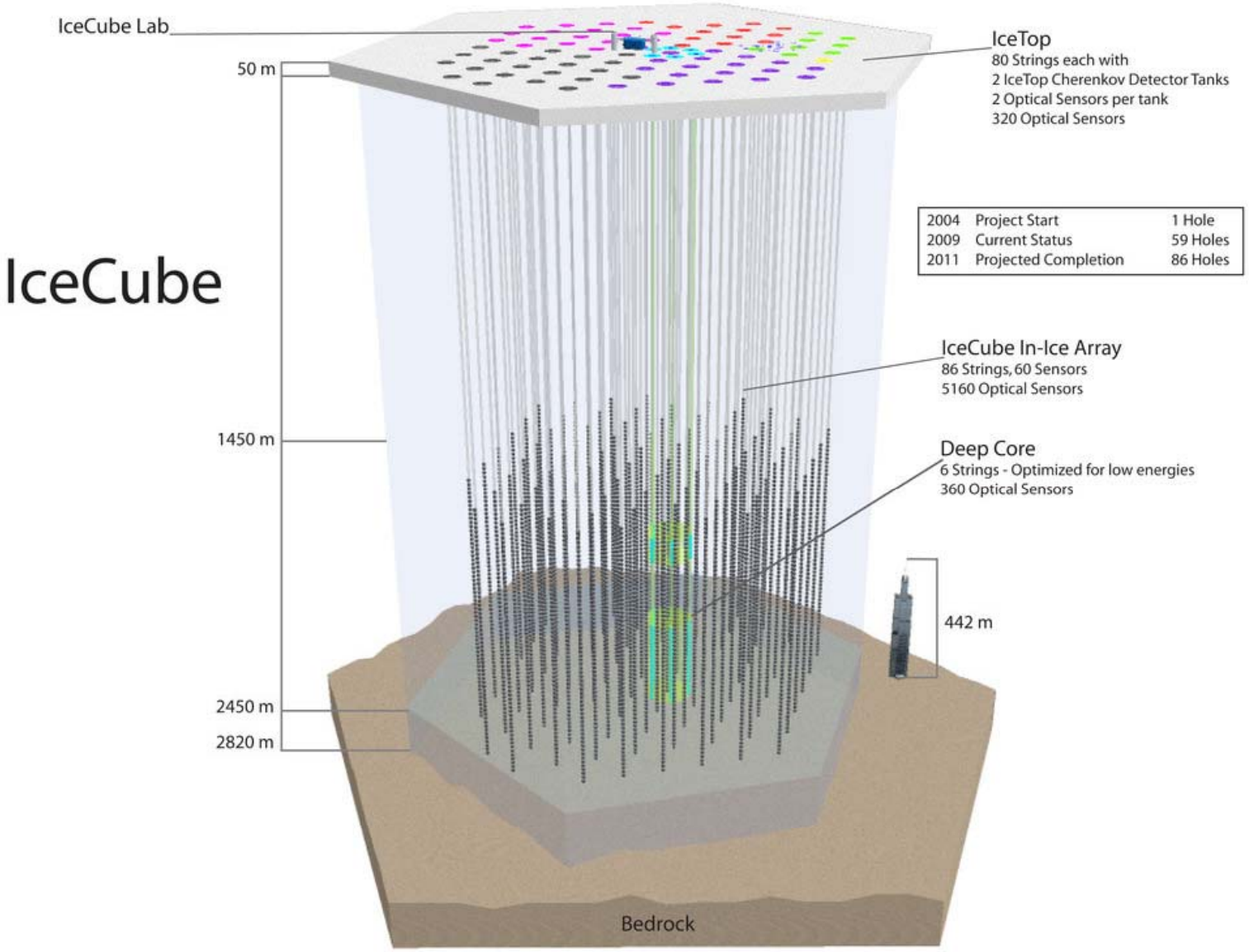
The conference on the Next Generation of Nucleon Decay and Neutrino Detectors looked at the development of new, large-scale detectors. **Alain de Bellefon** reports.



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

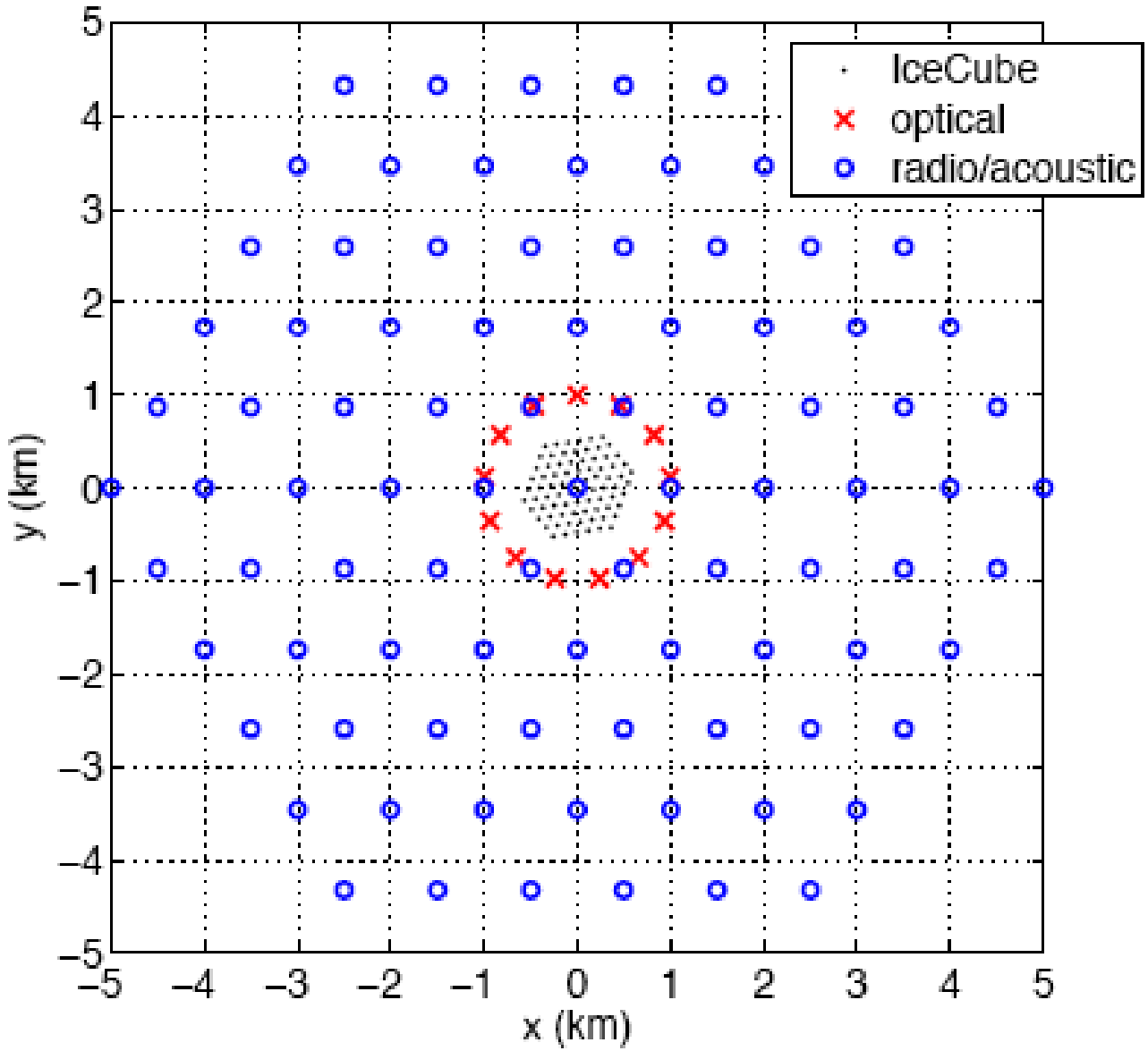
Detector Energy Scales – the GT



Detector Energy Scales – the TeraT

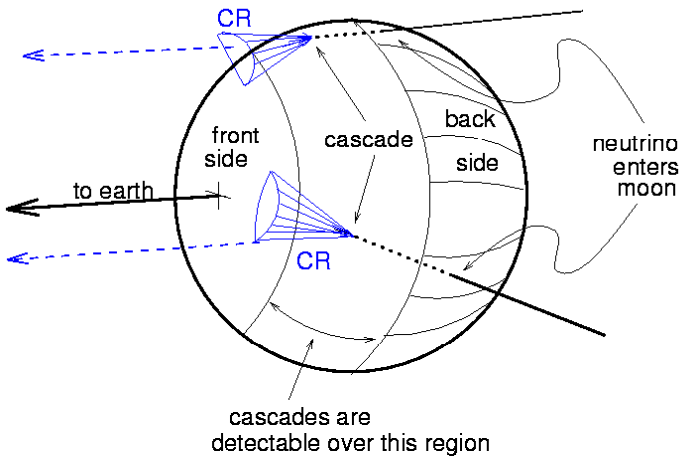
IceCube
~200M$

Simply
scaling
up??

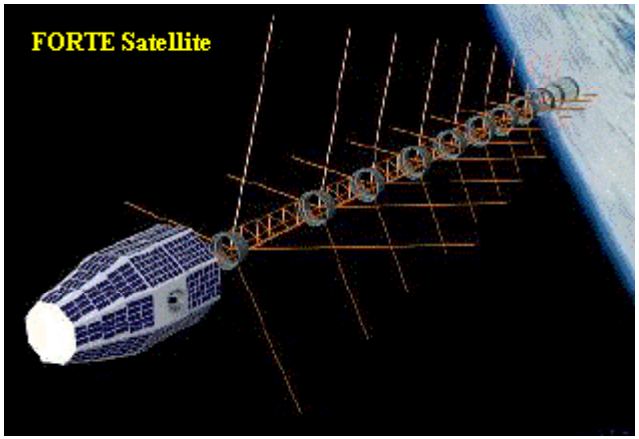


Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

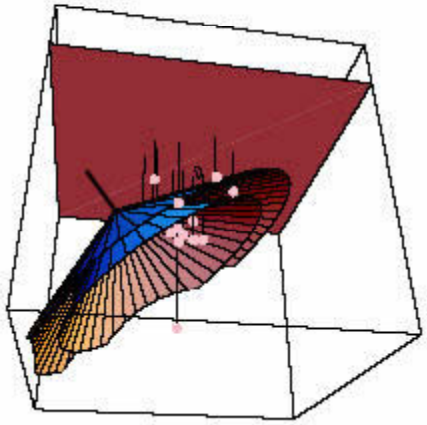
• PRL 93:041101 (2004) limits published

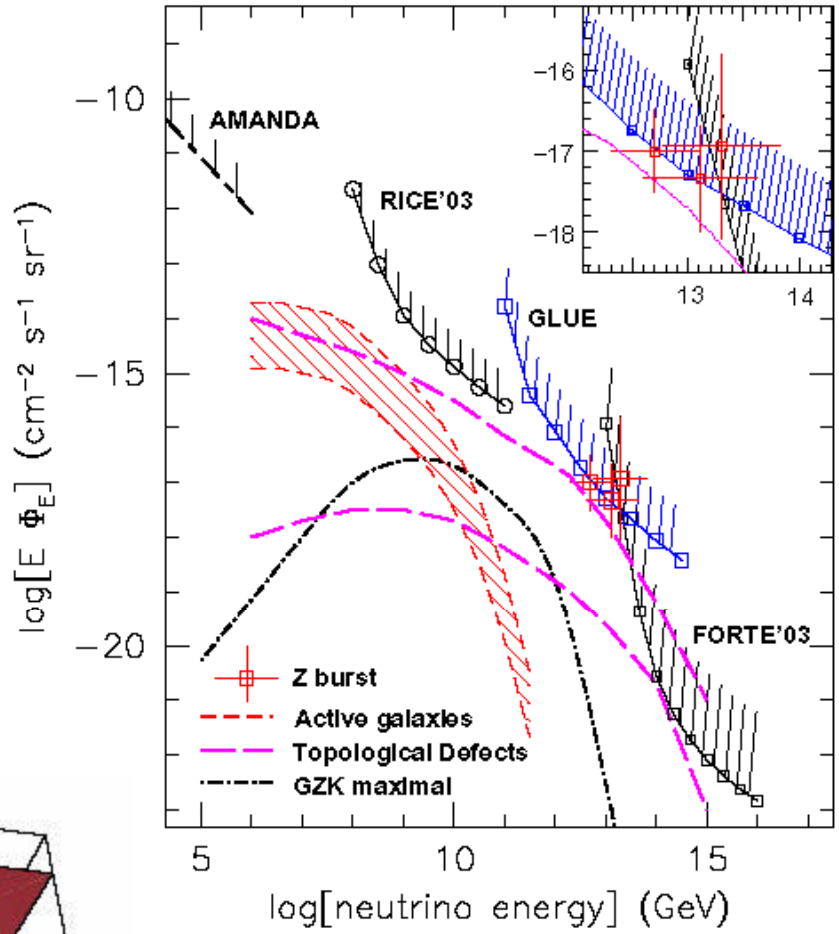


Greenland Ice



• PRD 69:0133008 (2004)





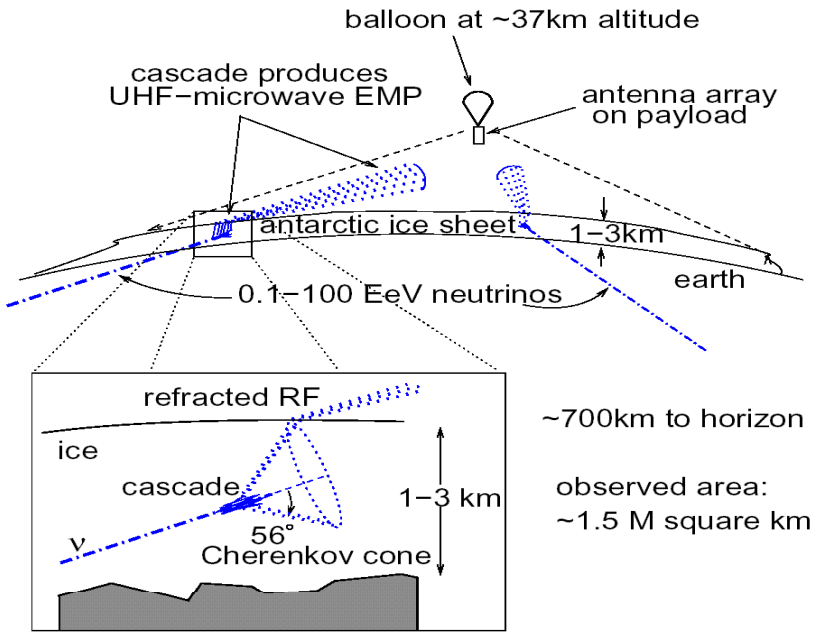
Radio Ice Experiment (RICE) @ South Pole

• Astropart.Phys.20:195 (2003)

Design for discovery of GZK ν flux

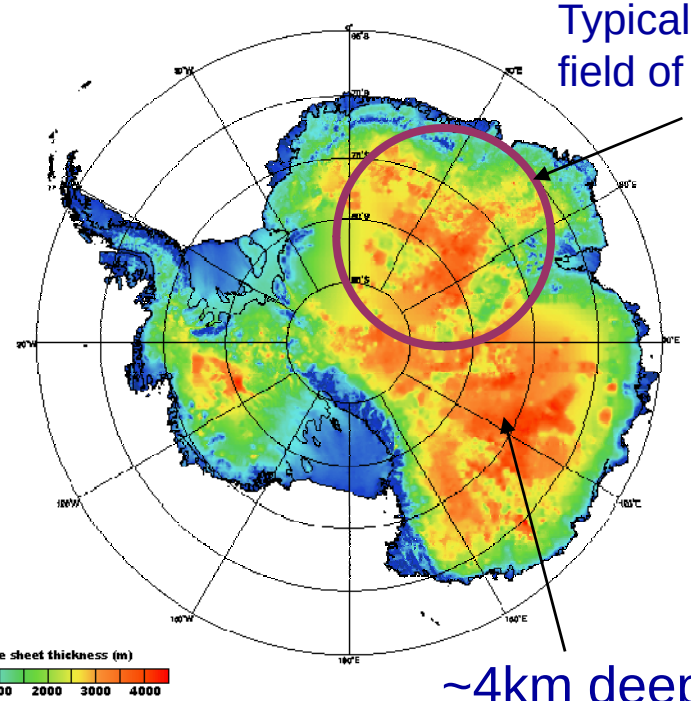
- Huge Volume of solid, RF-transparent medium: Antarctic Ice Sheet
- Broadband antennas, low noise amplifiers and high-speed digitizers to observe them
- A very high vantage point, but not too high nor too far away
- The end result: ANITA (balloon altitude)

ANITA concept



~700km to horizon

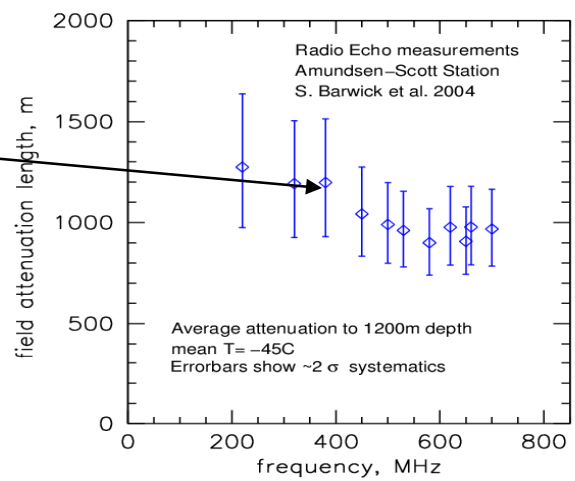
observed area:
~1.5 M square km



Typical balloon field of regard

~4km deep ice

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



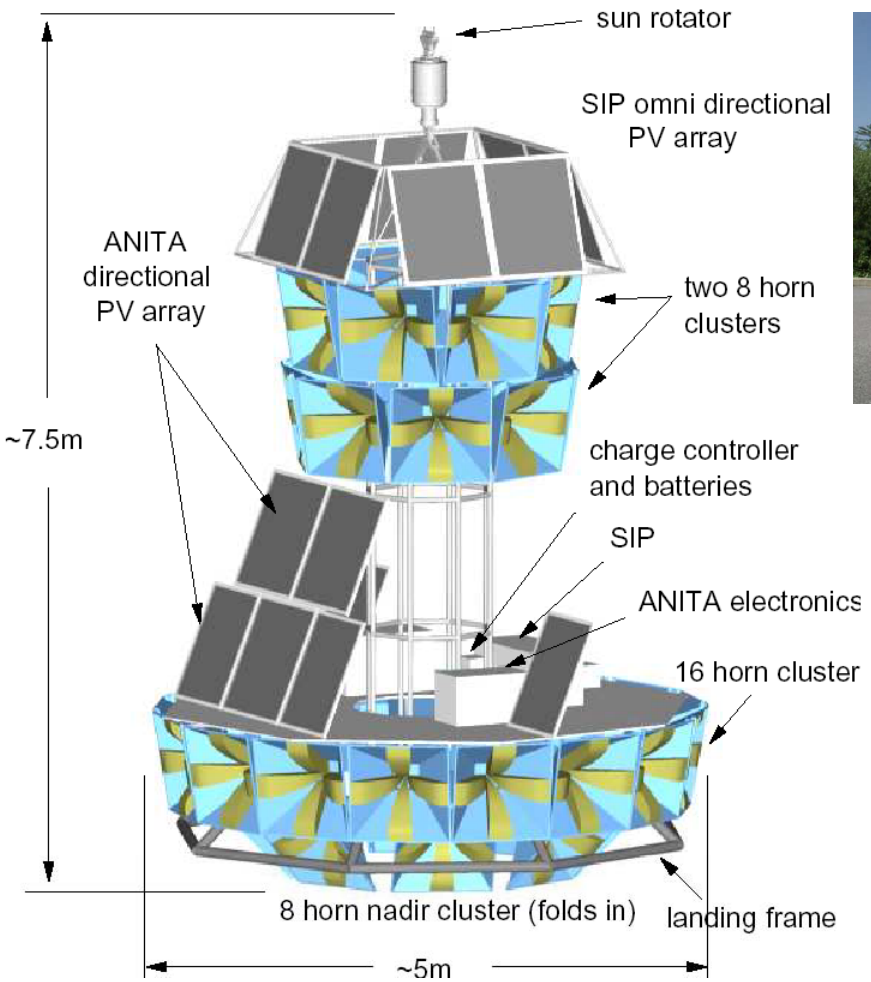
Effective "telescope" aperture:

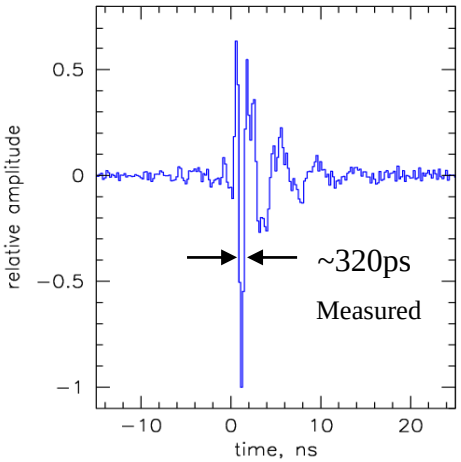
- ~250 km^3 sr @ 10^{18} eV
- ~10^4 @ km^3 sr 10^{19} eV

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

Flight Payload Design

A radio "feedhorn array" for the Antarctica Continent





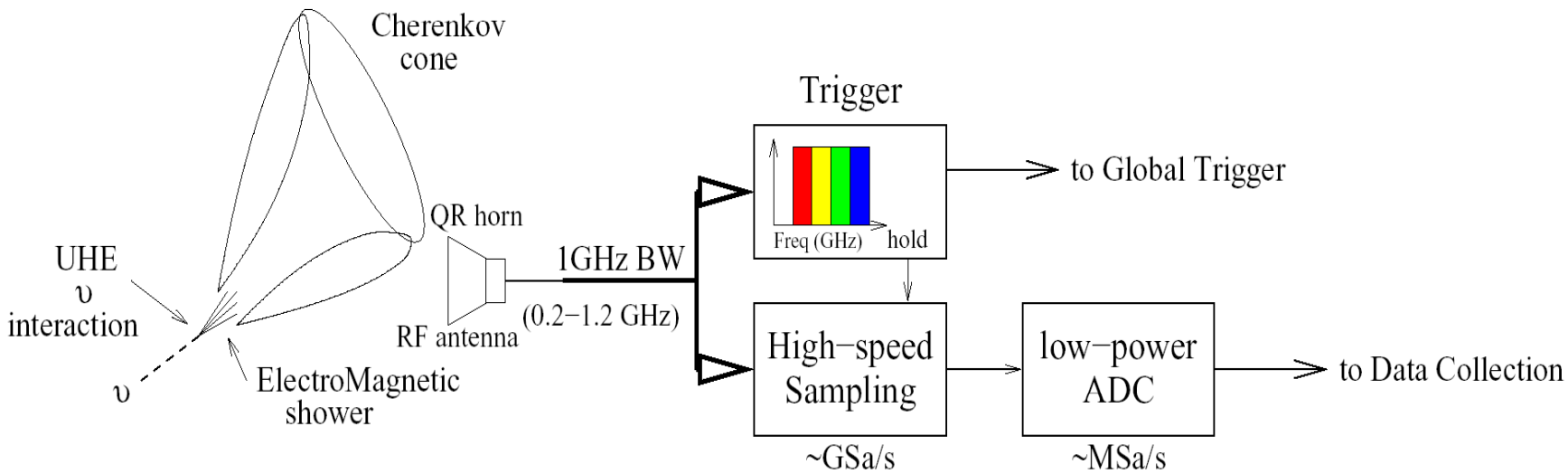
- Quad-ridged horn antennas provide superb impulse response & bandwidth (200-1200 MHz)
- Interferometry & beam gradiometry from multiple overlapped antenna measurements

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

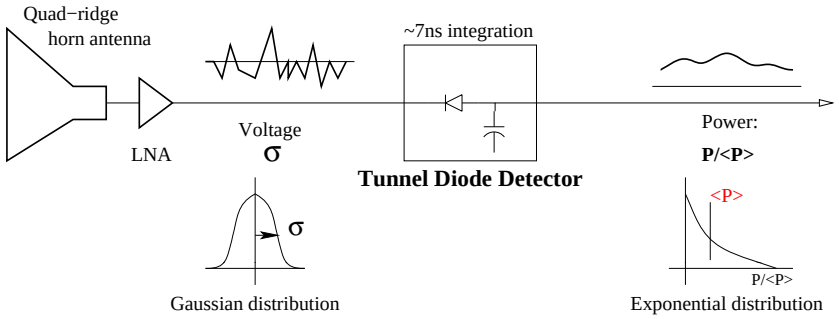


- Split signal: 1 path to trigger, 1 for digitizer
- Digitizer runs ONLY when triggered to save power

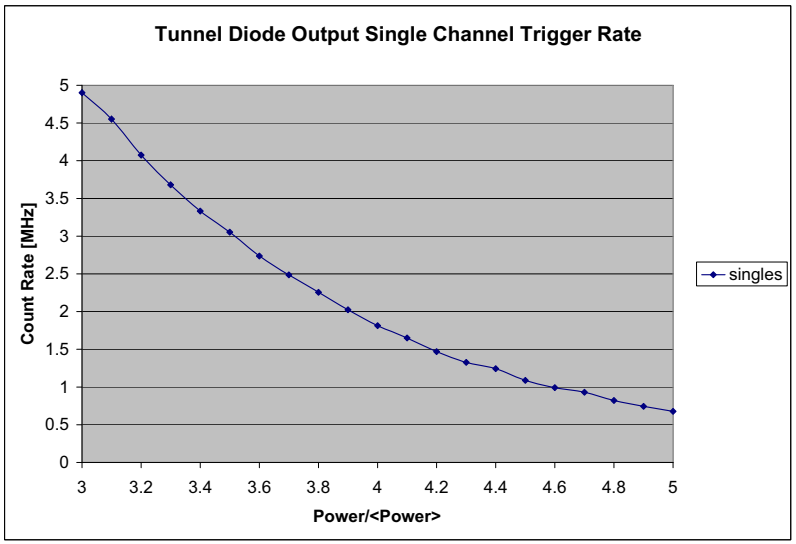
Three key technologies:

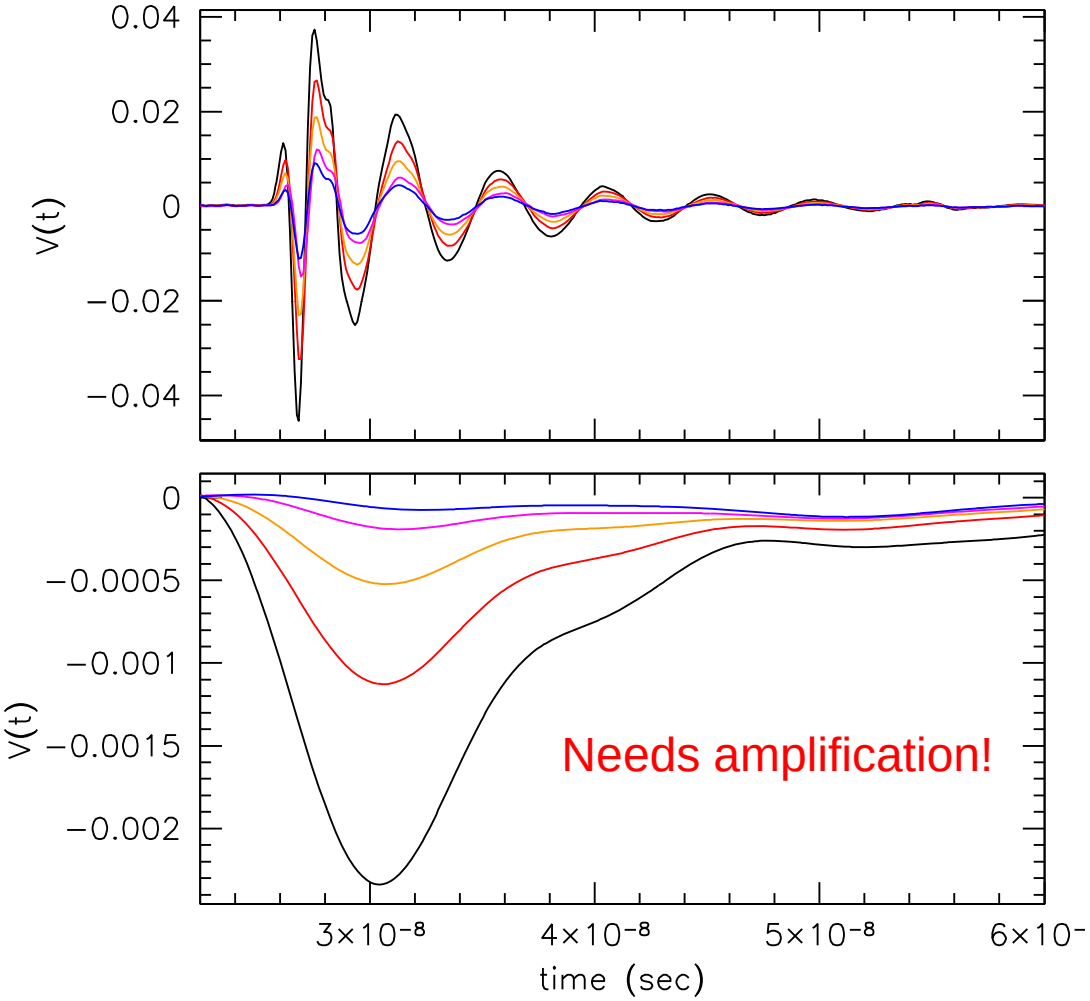
1. Very low-noise (low power) amplifiers
2. Efficient, thermal-noise limited triggering
3. Low power, Gsa/s waveform sampling

Diode detector Response



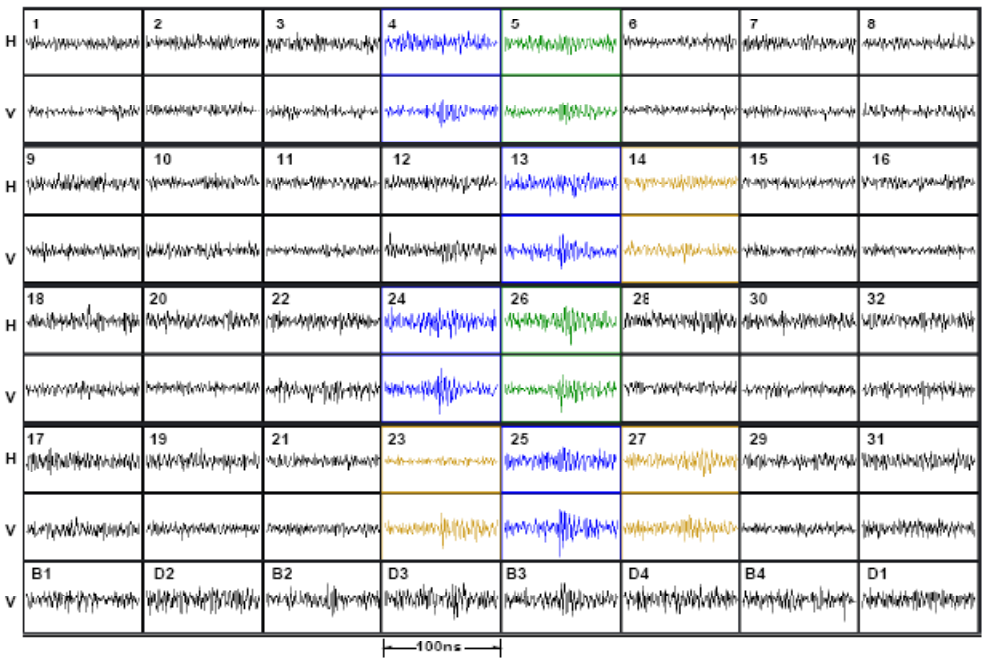
2.3σ ~= 3.9 P/<P>

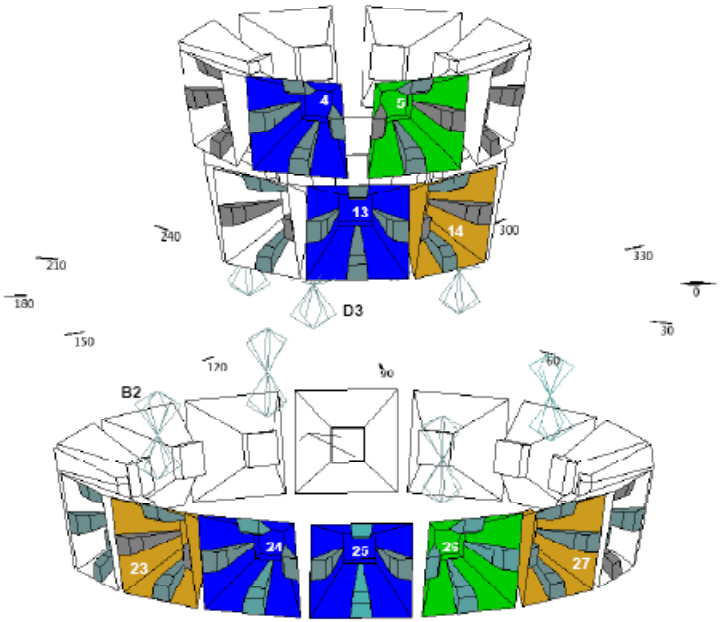




Hierarchical triggering

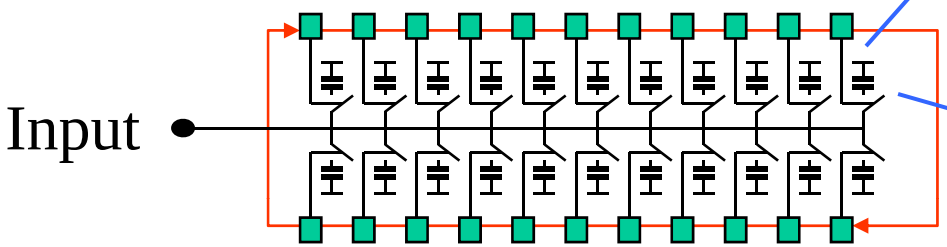
- Event most likely West Antarctica camp noise
- Triggers:
  - Yellow, L1: impulse above thermal noise for an individual antenna; ~150 kHz
  - Green, L2: coincidence between adjacent L1 in the same ring; ~40kHz
  - Blue, L3: coincidence between L2 triggers in same phi sector; ~5Hz

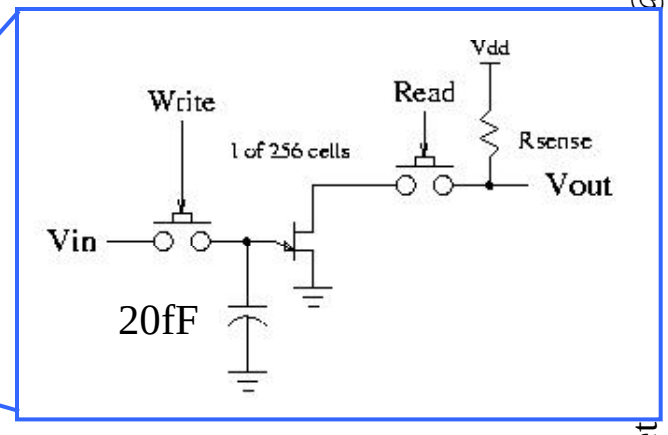




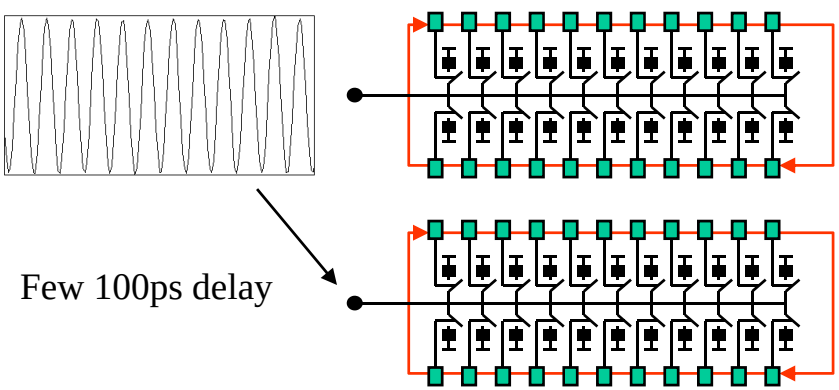
Switched Capacitor Array Sampling

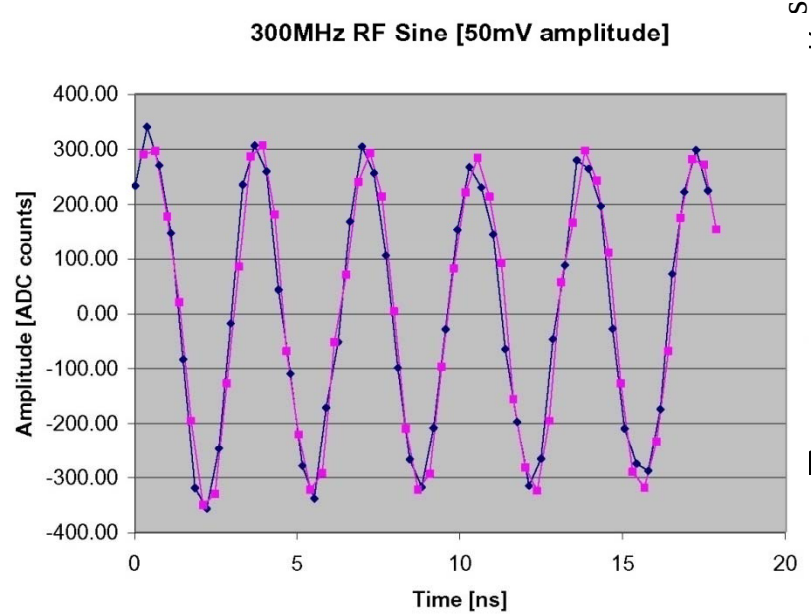
- Write pointer is ~4-6 switches closed @ once





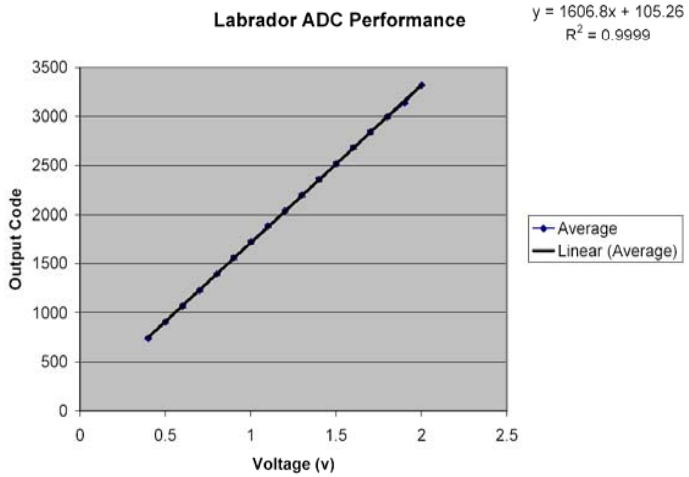
Tiny charge: 1mV ~ 100e-

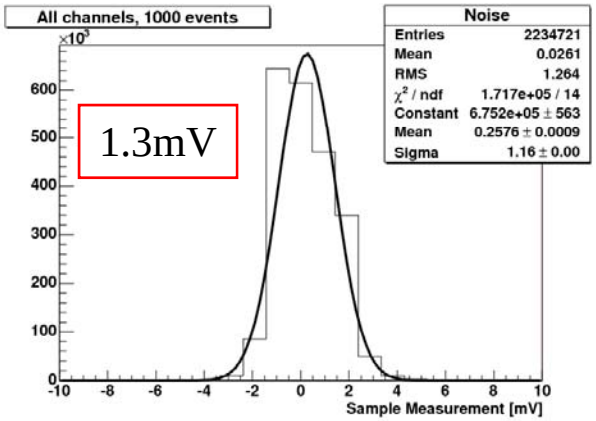


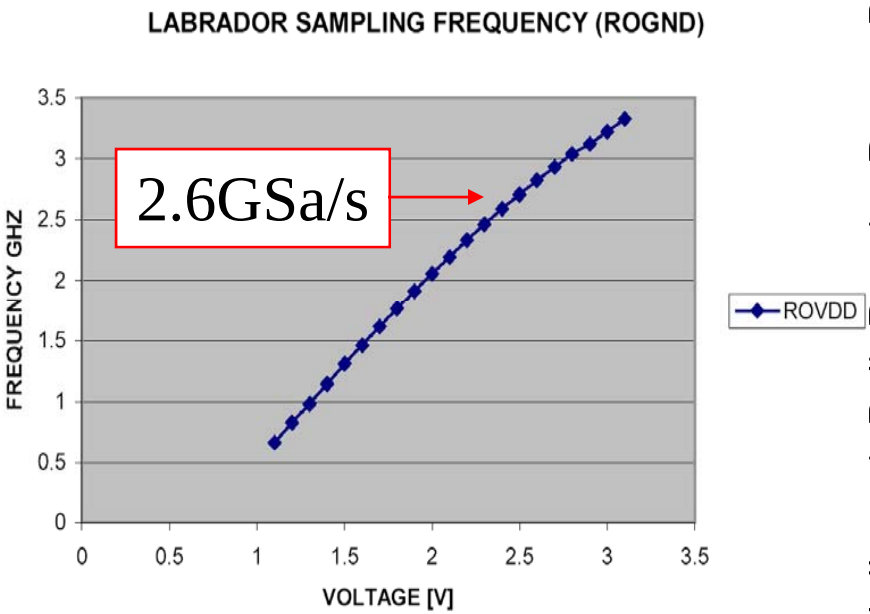


LABRADOR performance

12-bit ADC



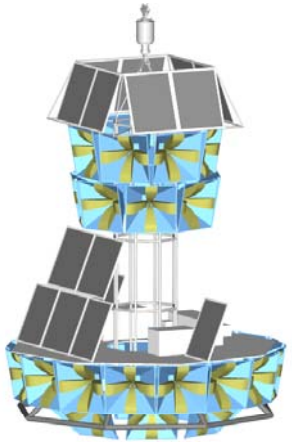


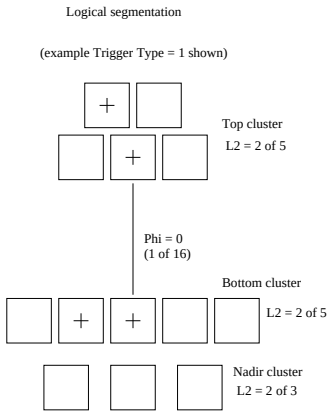


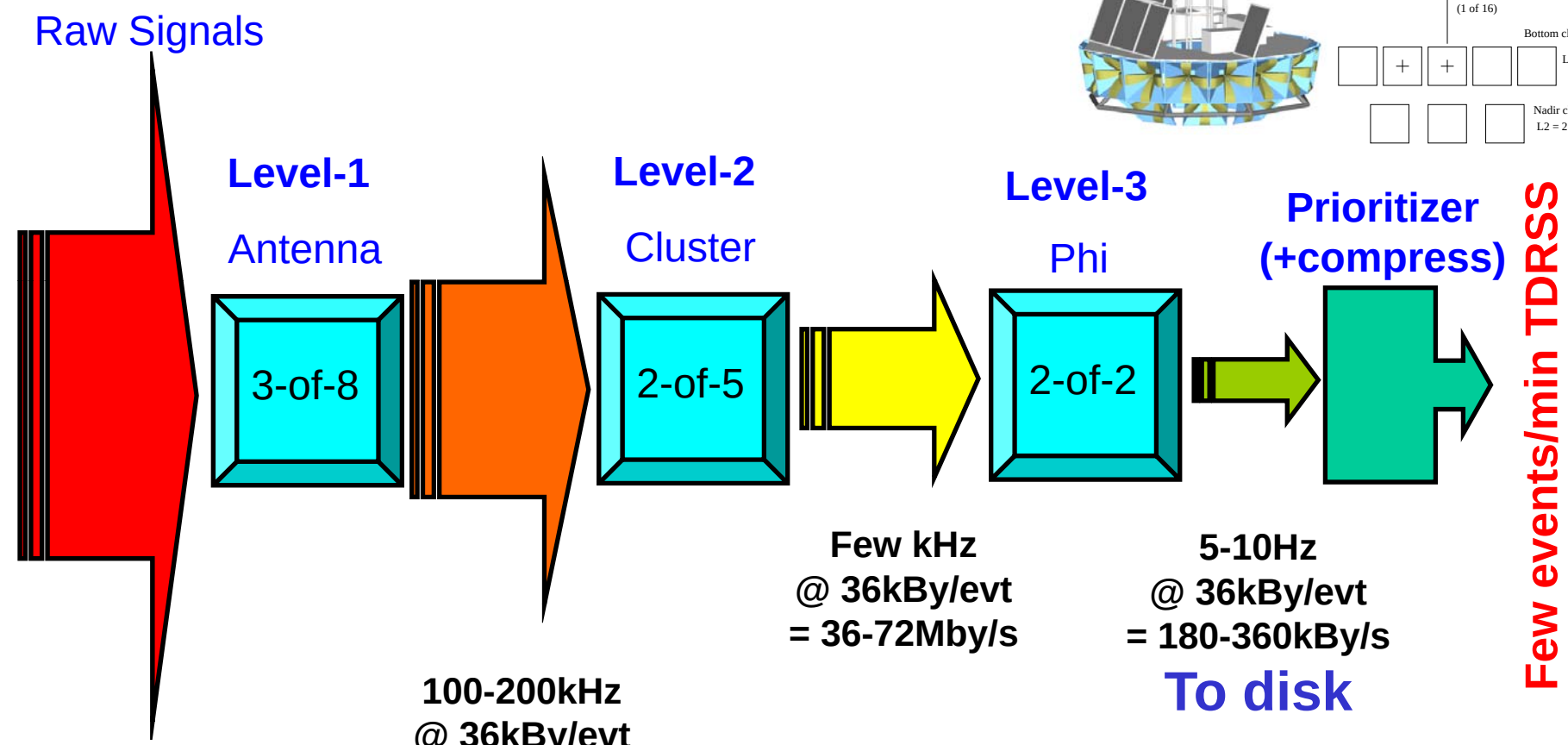
- 10 real bits (1.3V/1.3mV noise)

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

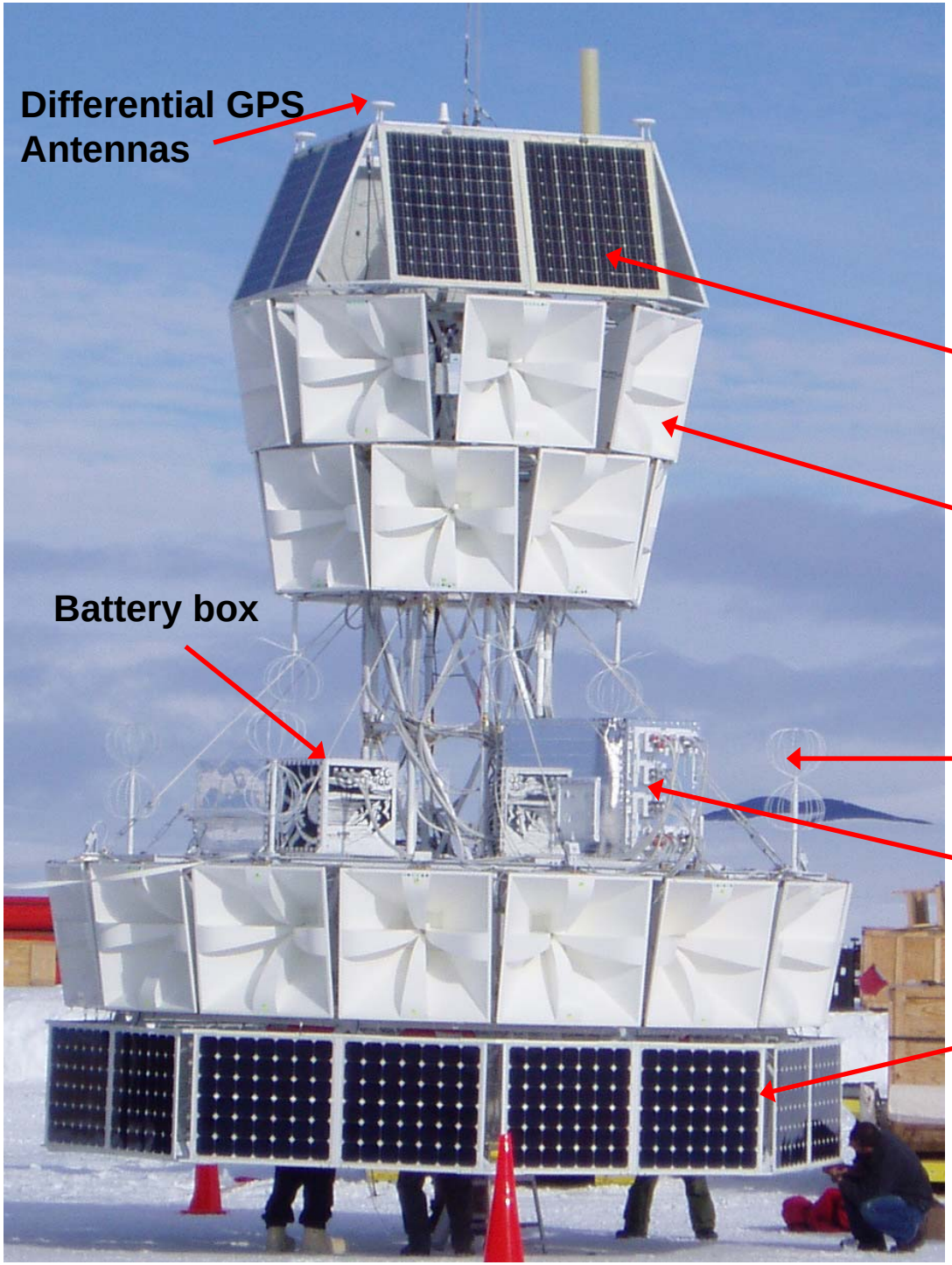
A solar powered, airborne HEP experiment







ANITA-1 pieces



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

Solar cells for NASA equipment

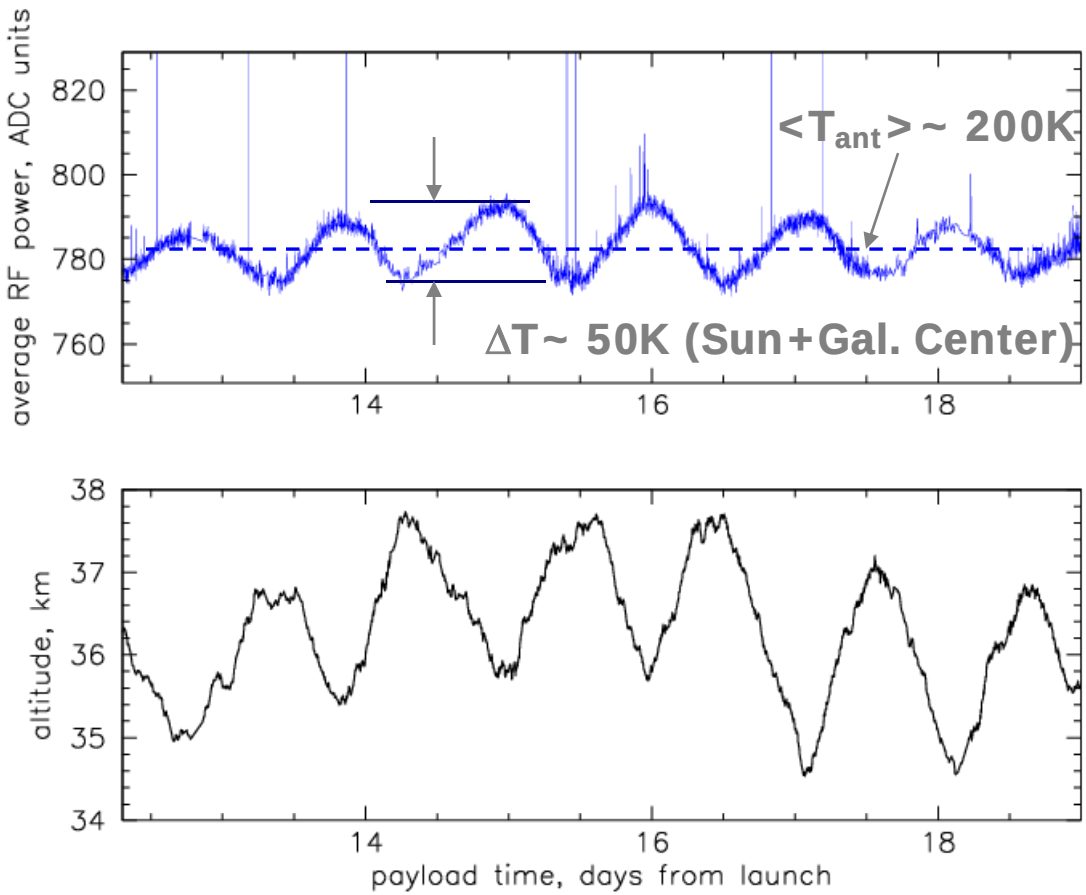
32 Quad-ridge horn antennas
- **200 MHz to 1200 MHz**
- **10 degree downward angle**

8 low gain antennas to monitor payload-generated noise

ANITA electronics box

Solar panels for science mission

Flight sensitivity snapshot (preliminary)

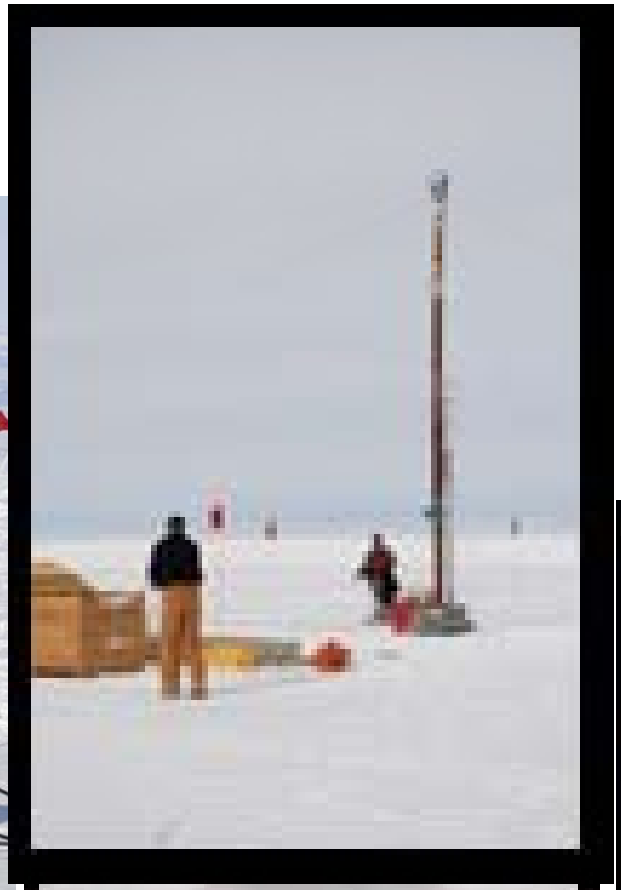


- ANITA sensitivity floor defined by thermal (kT) noise from ice + sky
- Thermal noise floor seen throughout most of flight—but punctuated by station & satellite noise
- Significant fraction (>40%) of time with pristine conditions

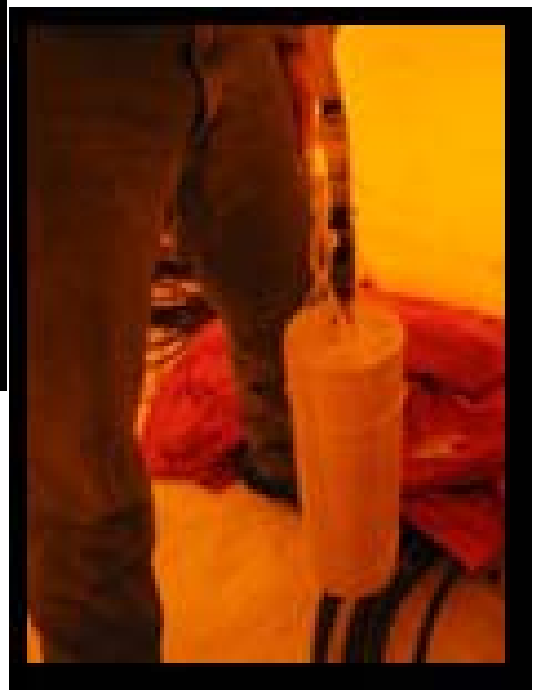
- T anti-correlated to altitude:
  - higher altitude at higher sun angle
  - sun+GC higher ➔ farther off main antenna beam

Quiet, but are we sensitive?

Ground pulser



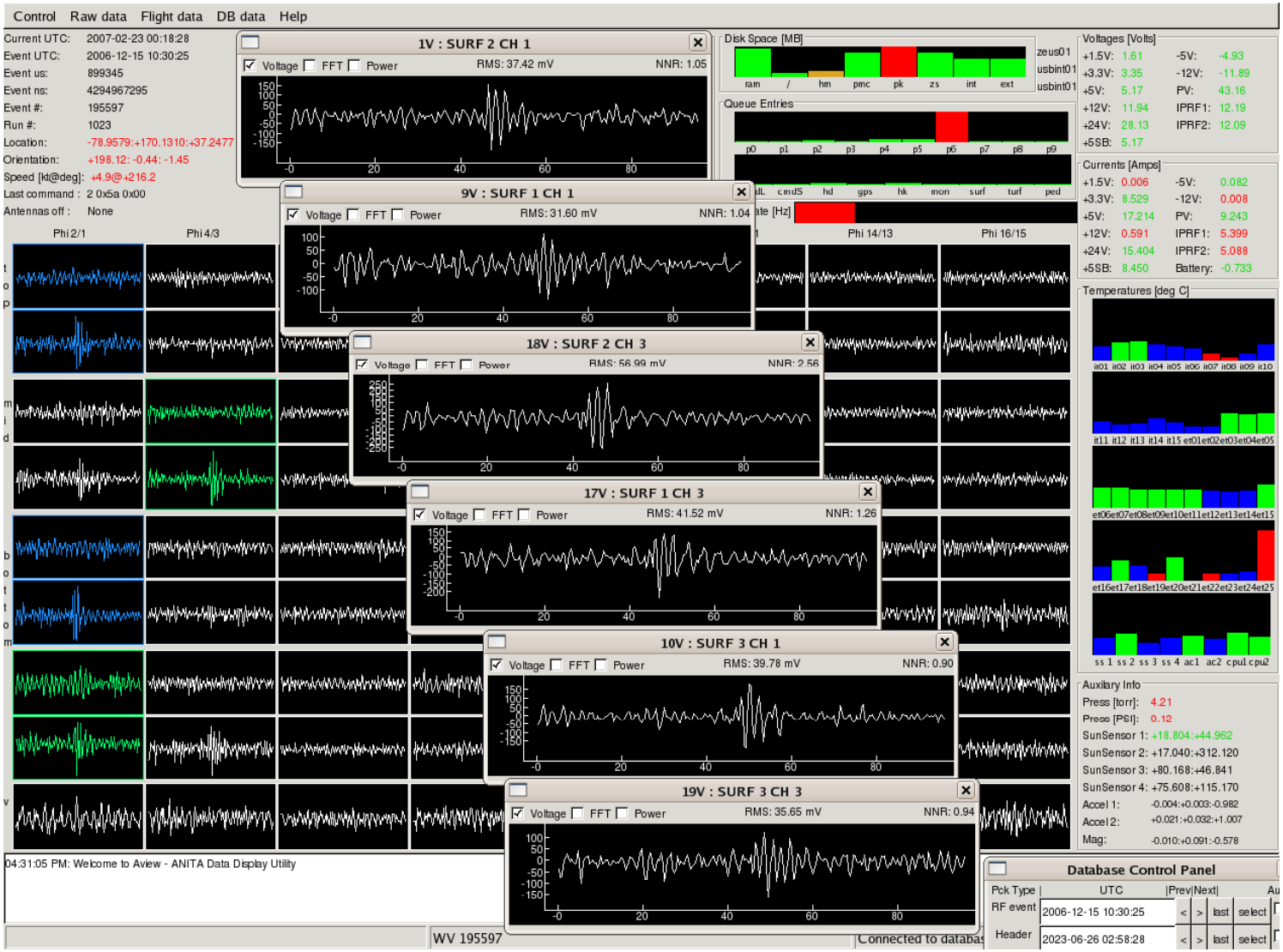
Bore hole pulser



Dipole

- Ice 80m thick and messy

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)

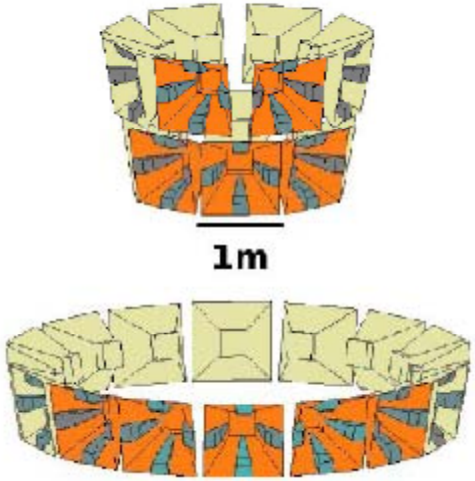
Ultrawide-band Interferometry

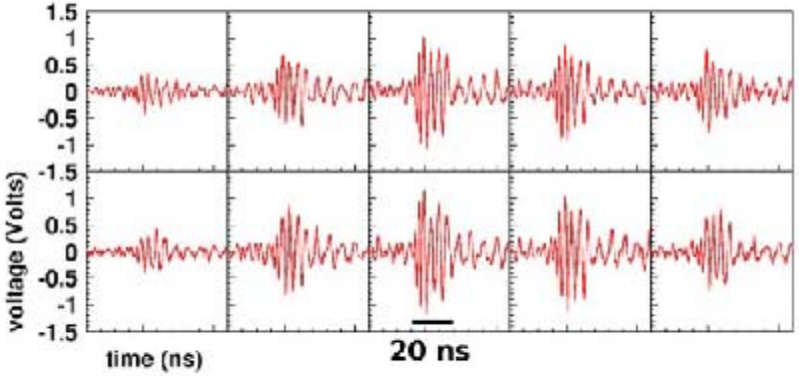
-Interferometric technique applied by radio astronomers.

-They use single narrow band frequency.

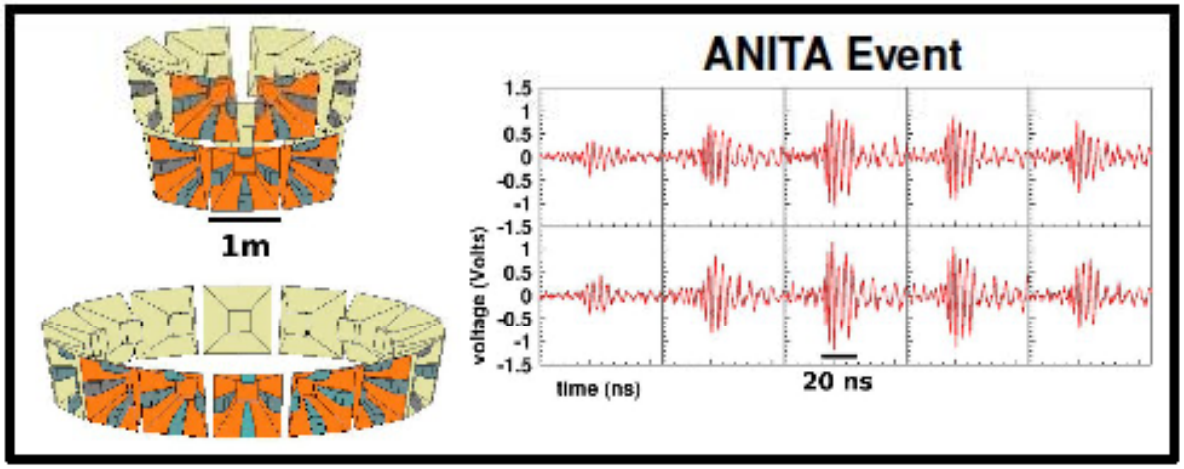
-More interested in source imaging rather than point source direction reconstruction.

Produce Ultrawide-band Interferometric Images with ANITA

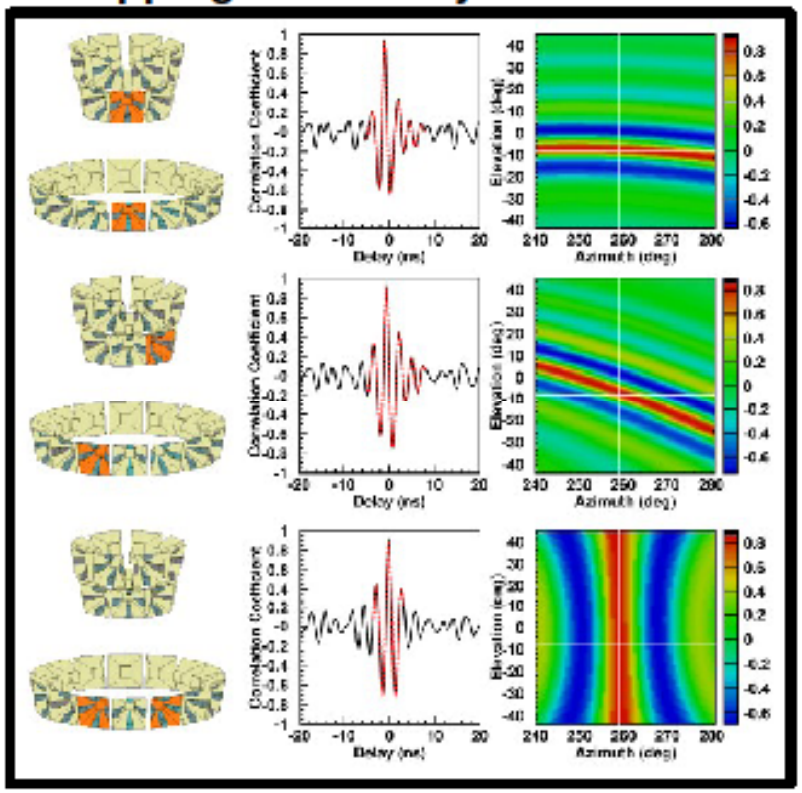




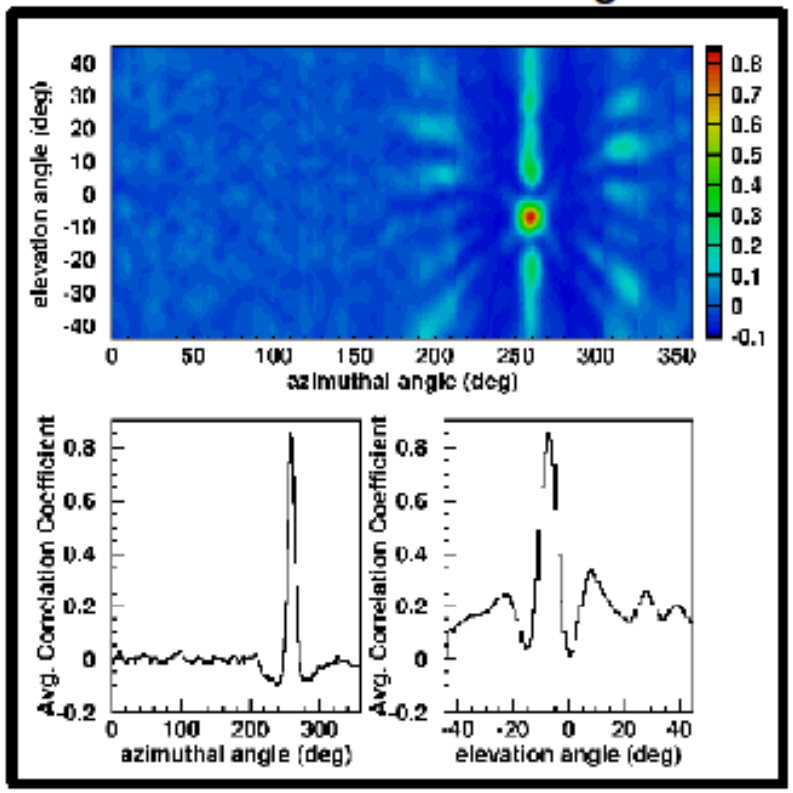
Mapping Waveforms to Interferometric Images



Mapping Time Delay Correlations

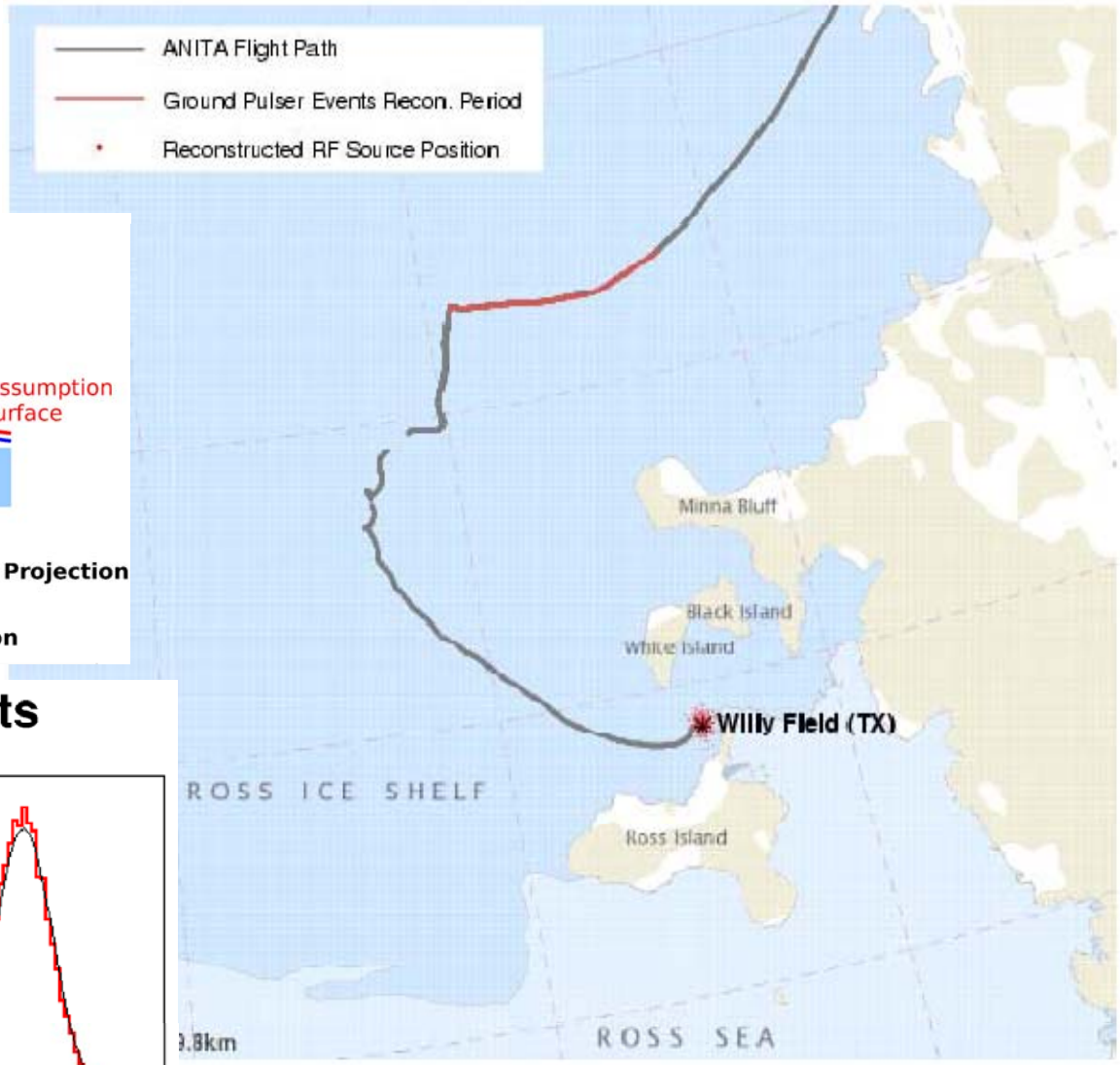


Interferometric Image

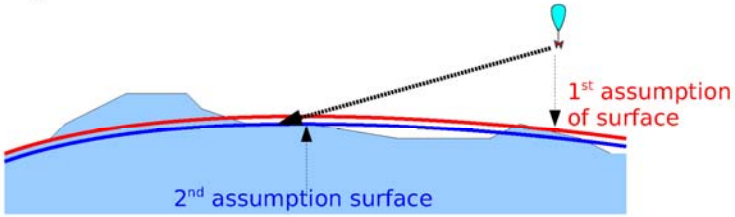


After full calibration – 100's km

<30ps timing



RF Projection onto the surface



Fast Algorithm: Line Sphere intersection

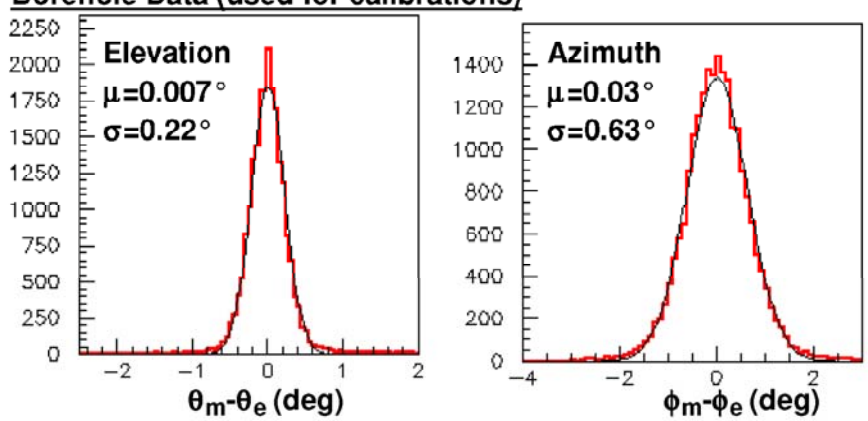
1st R_{earth}=Geoid + Surface @ Ballon position -> Rough Projection

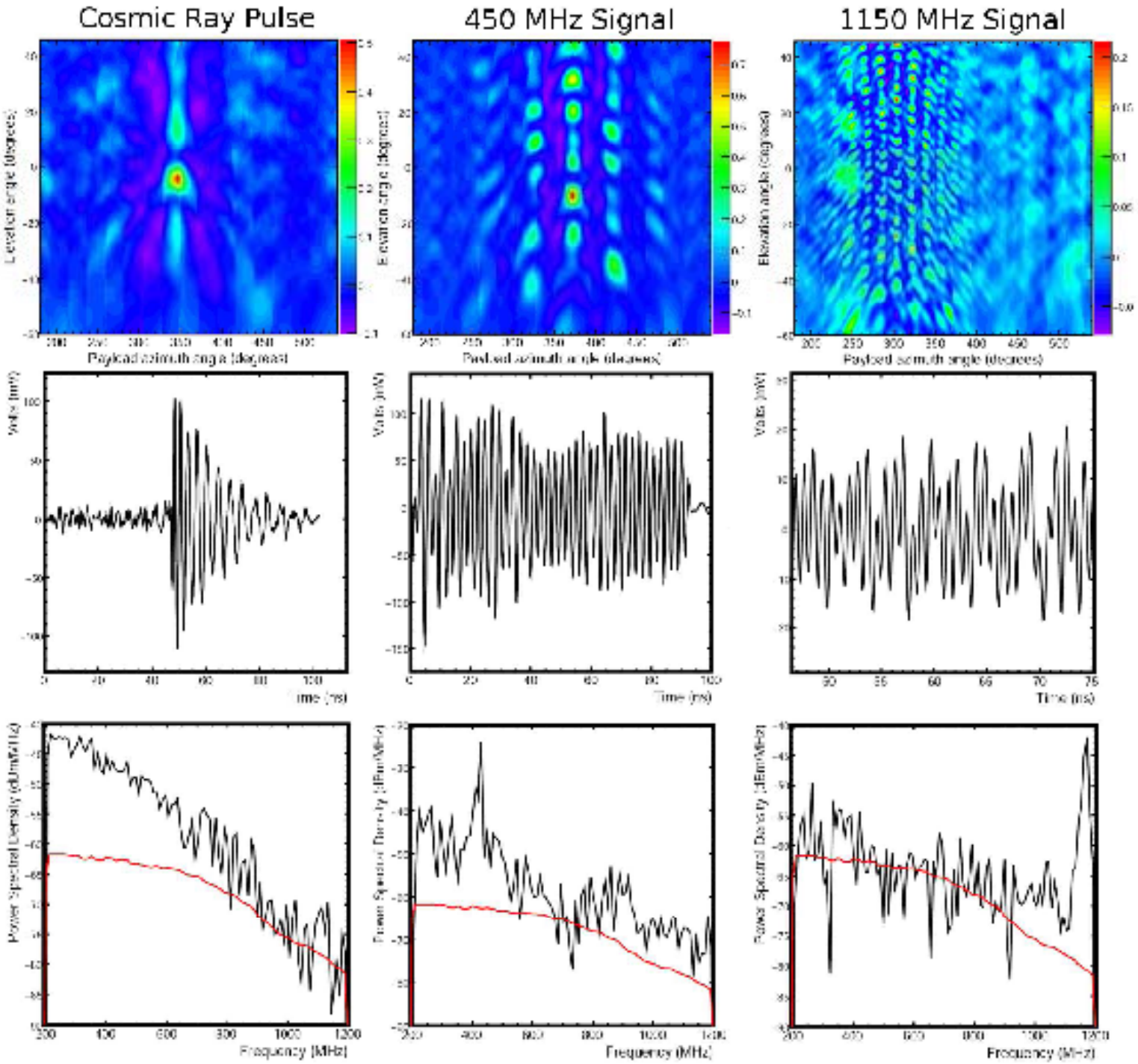
2nd R_{earth} = Geoid + Surface @ (position from 1st)

3rd: one more iteration -> converged after 2nd iteration

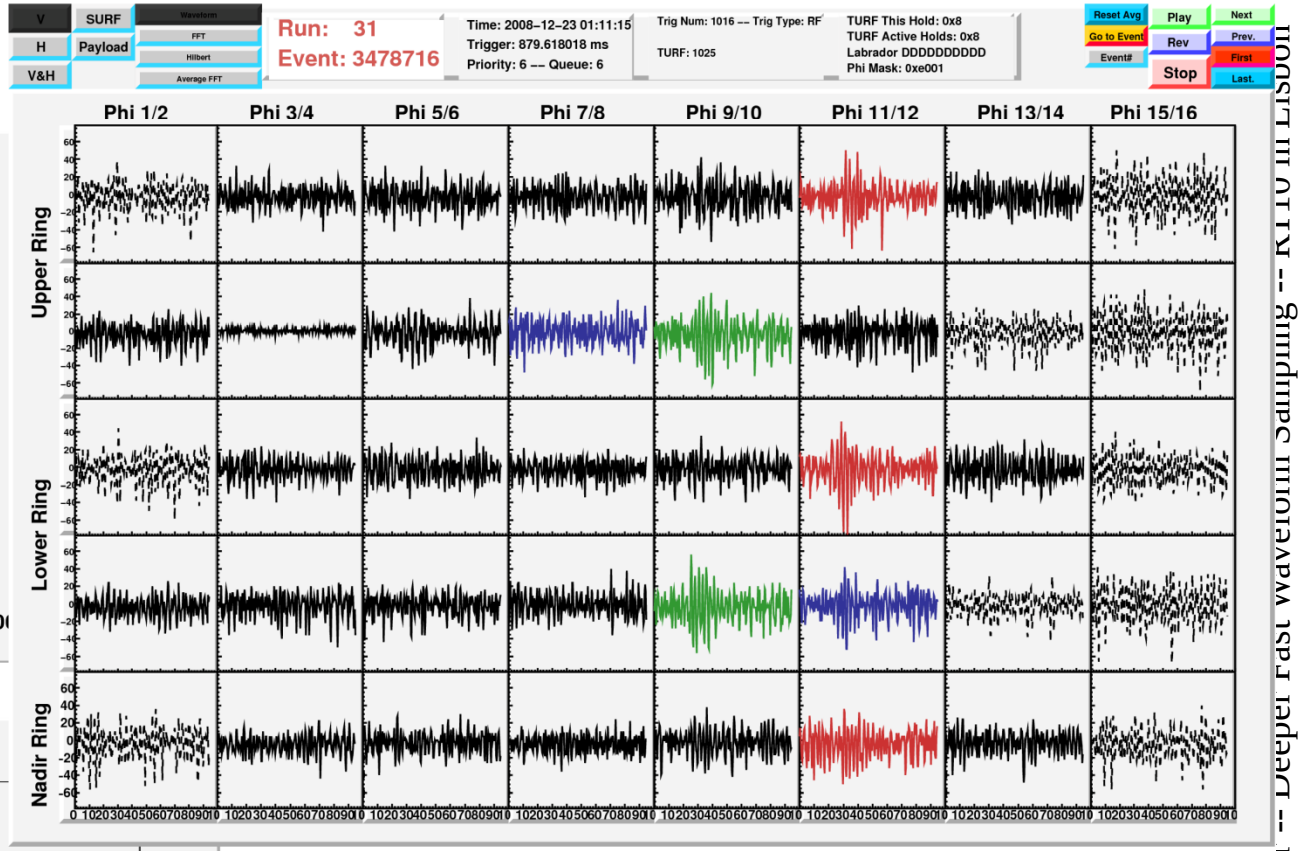
V-pol results

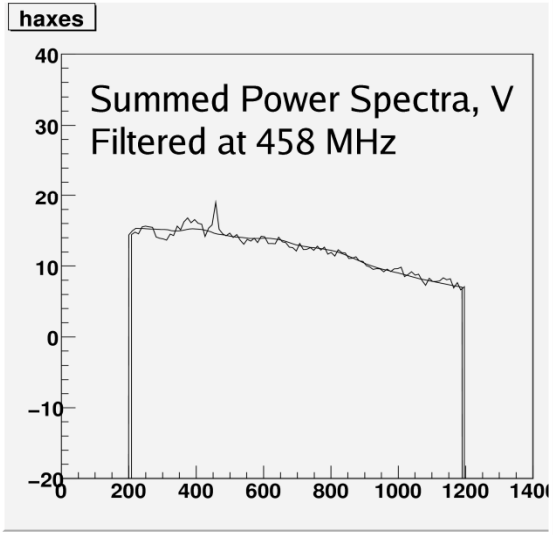
Borehole Data (used for calibrations)

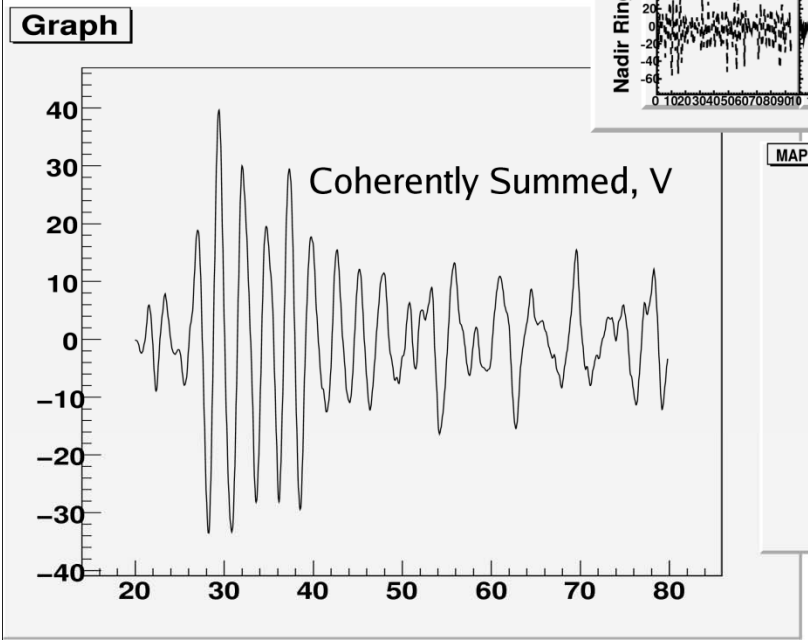


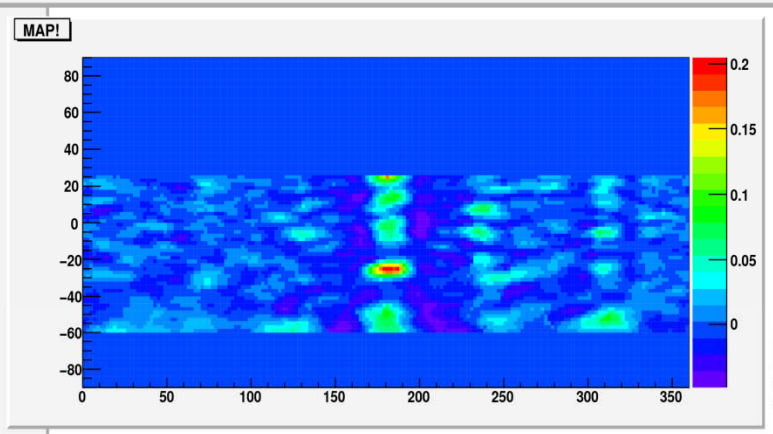

Cosmic Ray Pulse
450 MHz Signal
1150 MHz Signal

Event 3478716









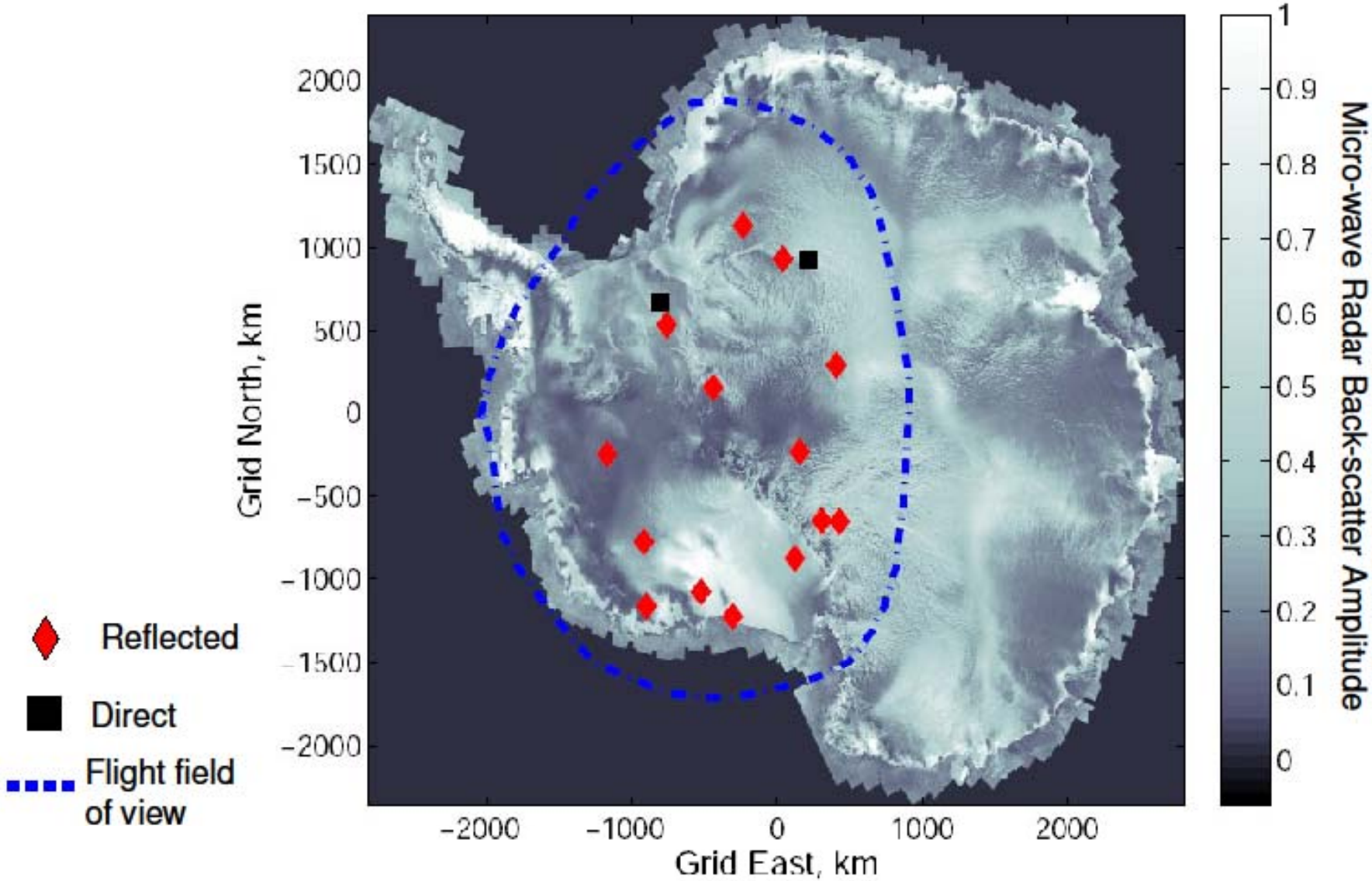
Near Transantarctic Mountains

Polarization Angle = 57.6 degrees

Elevation Angle = 25.2 degrees

Distance=107 km, LL=2804 from nearest event

Cosmic-Ray Candidate Event Locations

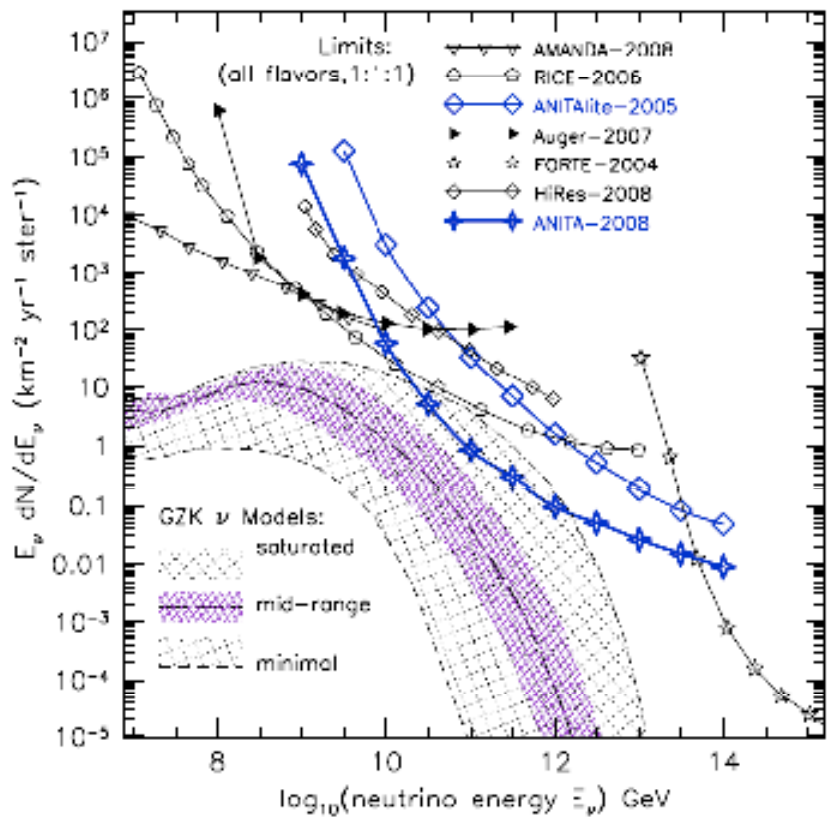


S. Hoover (UCLA)

ANITA-1 Neutrino Flux Model Expectations and Constraints

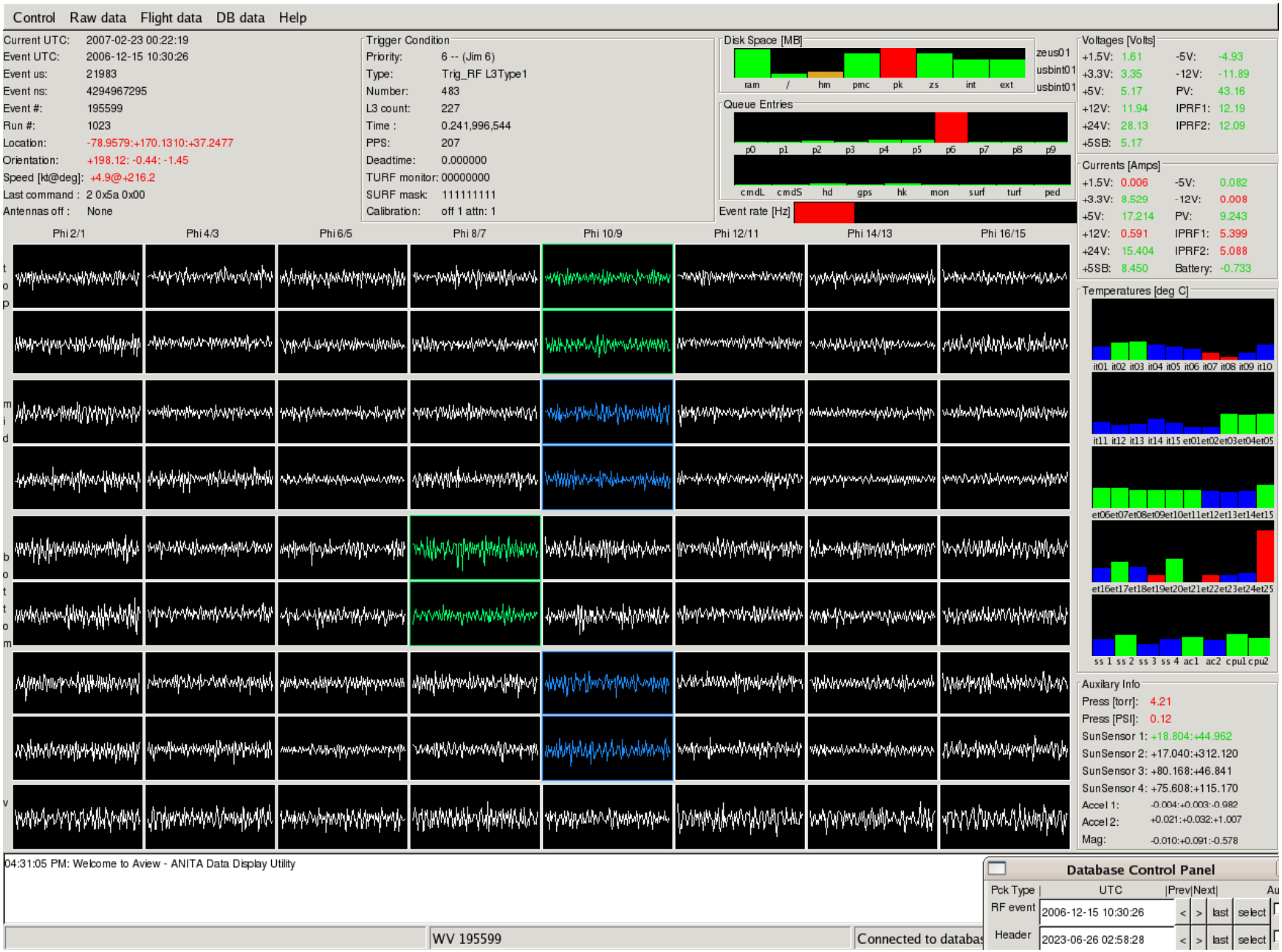
Phys.Rev.Lett.103:051103,2009

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!

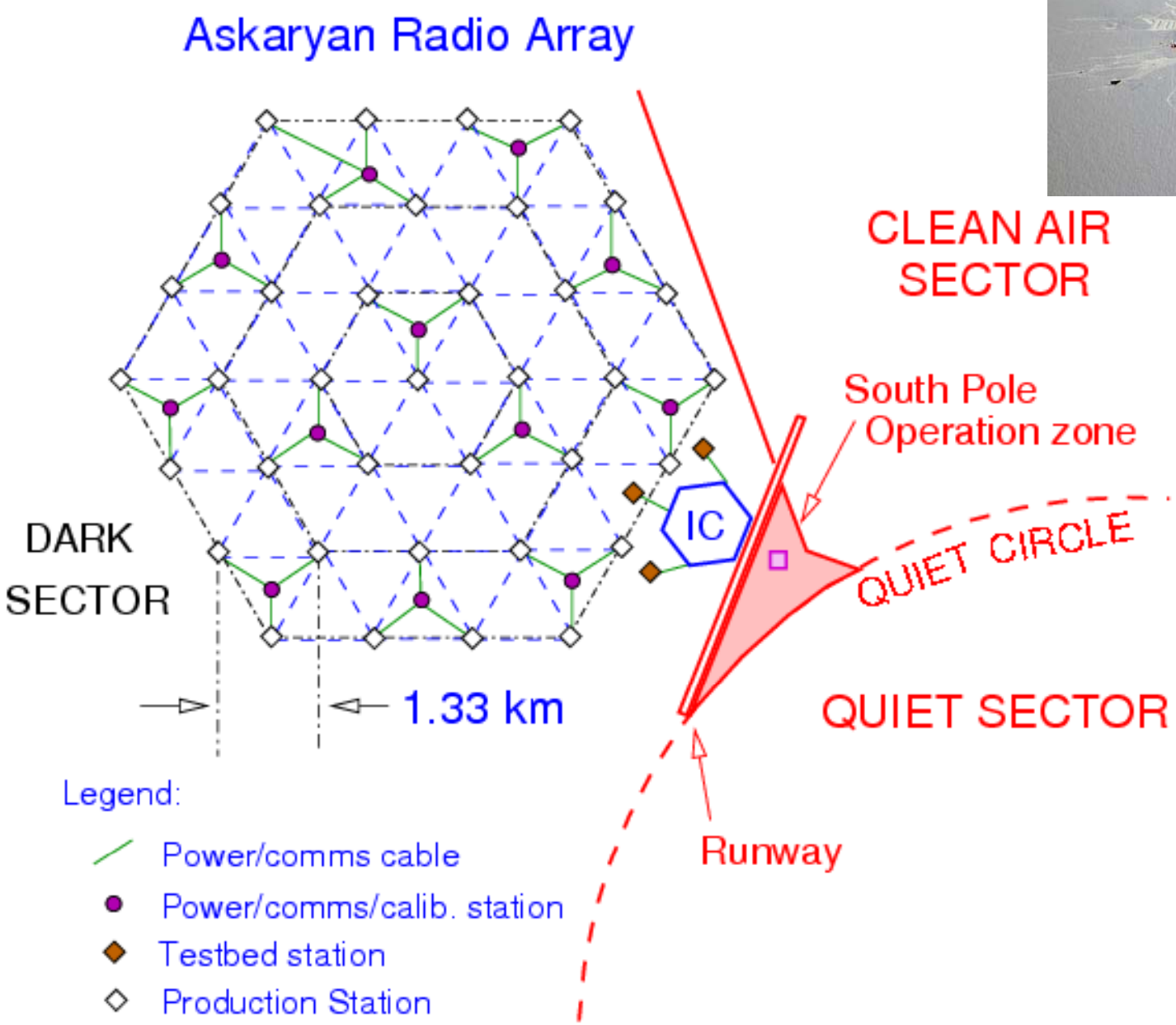
99.99+% of triggers: incoherent thermal noise



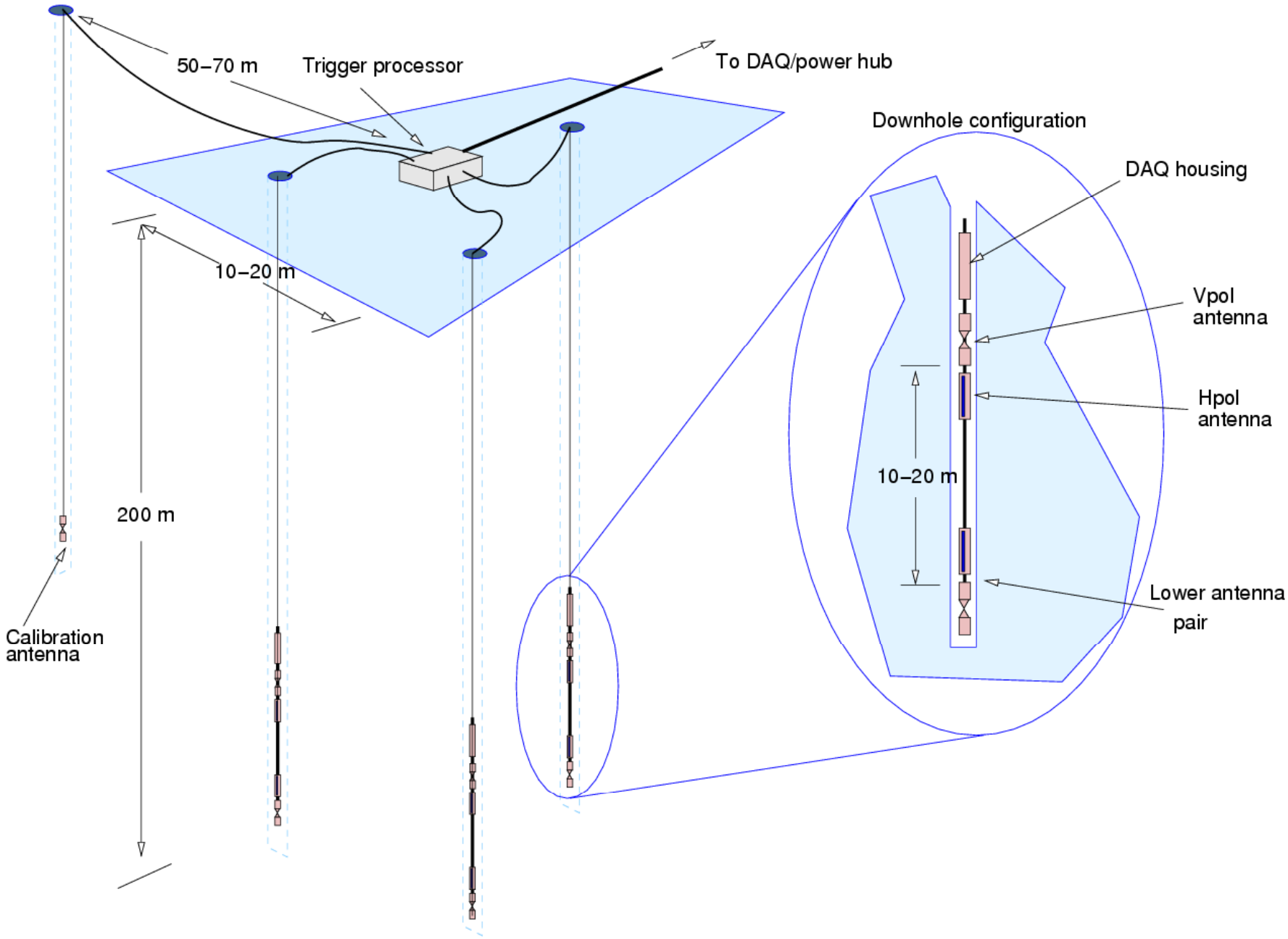
How to “go big” ?

- Salt
  - Salt domes
- Ice
  - In situ (RICE → AURA → IceRay→ARA)
  - Overflight (satellite) [high threshold]
- Silica sand
  - Lunar regolith (GLUE) [high threshold]

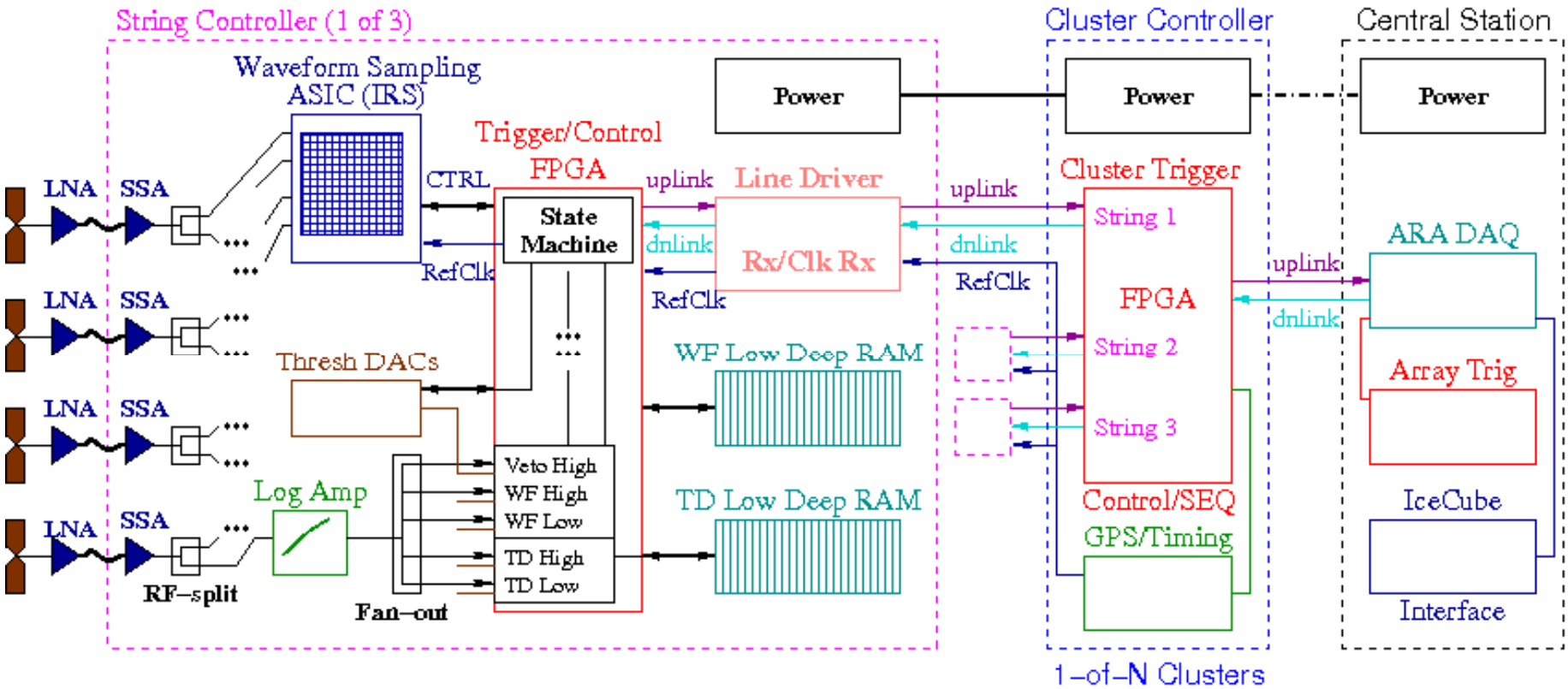
Askaryan Radio Array (ARA)



Cluster Station

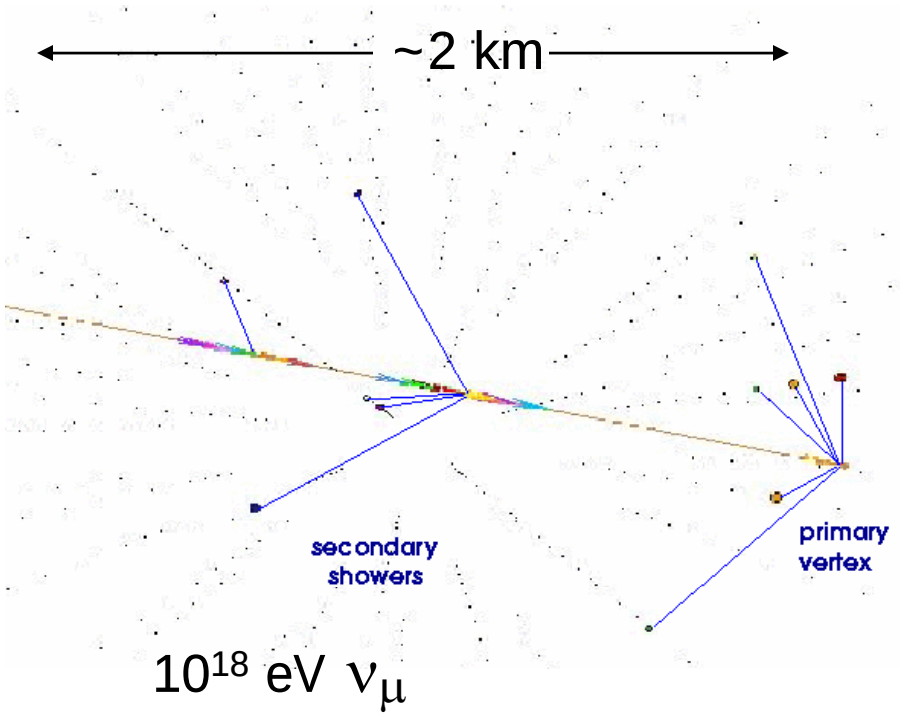


ARA Readout Electronics



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

Neutrino Flavor/Current ID

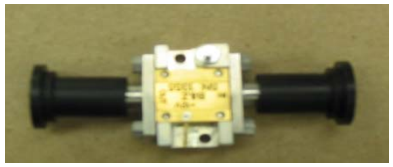


	Charged current (SM: 80%)	Neutral current (SM: 20%)
e	25% hadronic + 75% EM shower at primary vertex; LPM on EM shower	Single hadronic shower at vertex
μ	25% hadronic at primary, 2ndary lepton showers, mainly EM	Single hadronic shower at vertex
τ	25% hadronic at vertex, 2ndary lepton showers, mainly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

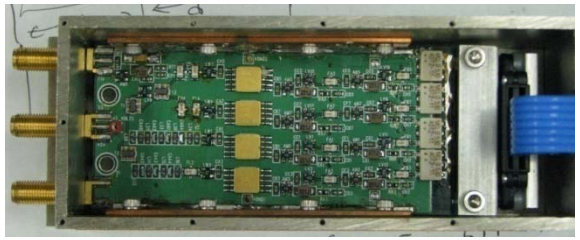
- Charged/neutral current & flavor ID possible on subset of SalSA events
- At least 20% of GZK CC events will get first order flavor ID
- Detailed initial studies – looks very promising [BLAB ASIC – 64us deep version of LABRADOR makes possible [**NIM A591** (2008) 534]

Directions for future Det R&D

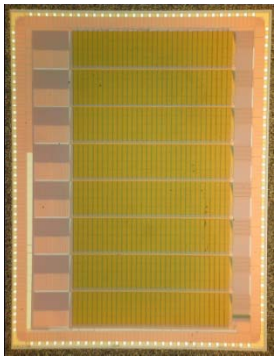
- Low noise amplifiers
  - Lower noise figure, lower power



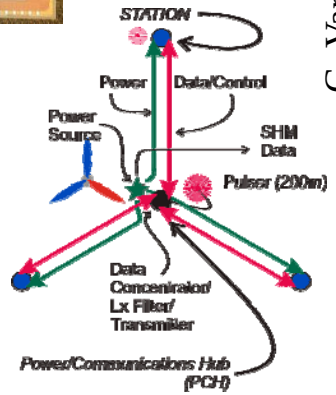
- Better triggering
  - Improve on tunnel diodes?
  - Real-time noise correlator



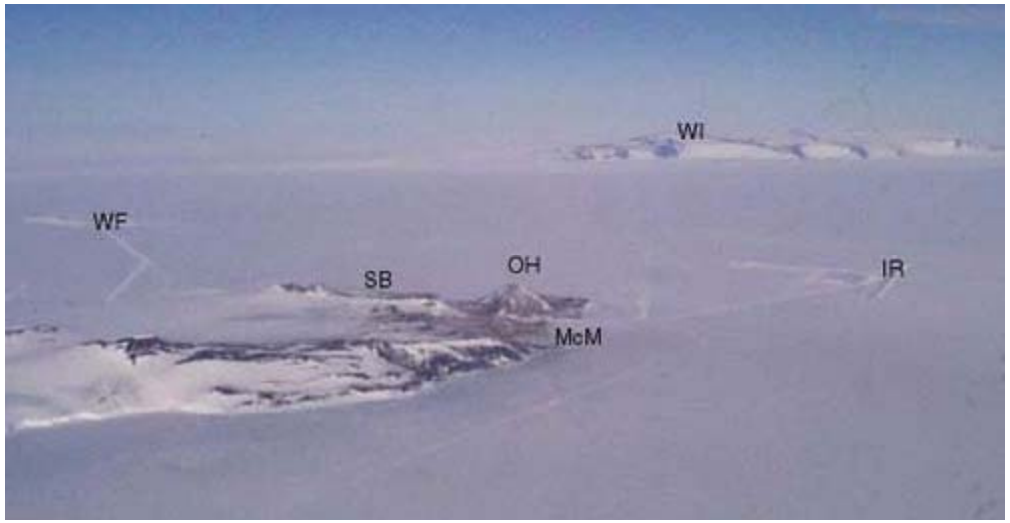
- Deeper waveform sampling
  - Already at ~100us analog storage
  - Higher frequency?



- Lower power!
  - Solar, wind, ???
  - Autonomous, robust comm links
  - Design for manufacture**



Why keep going on about power?!?



Summary

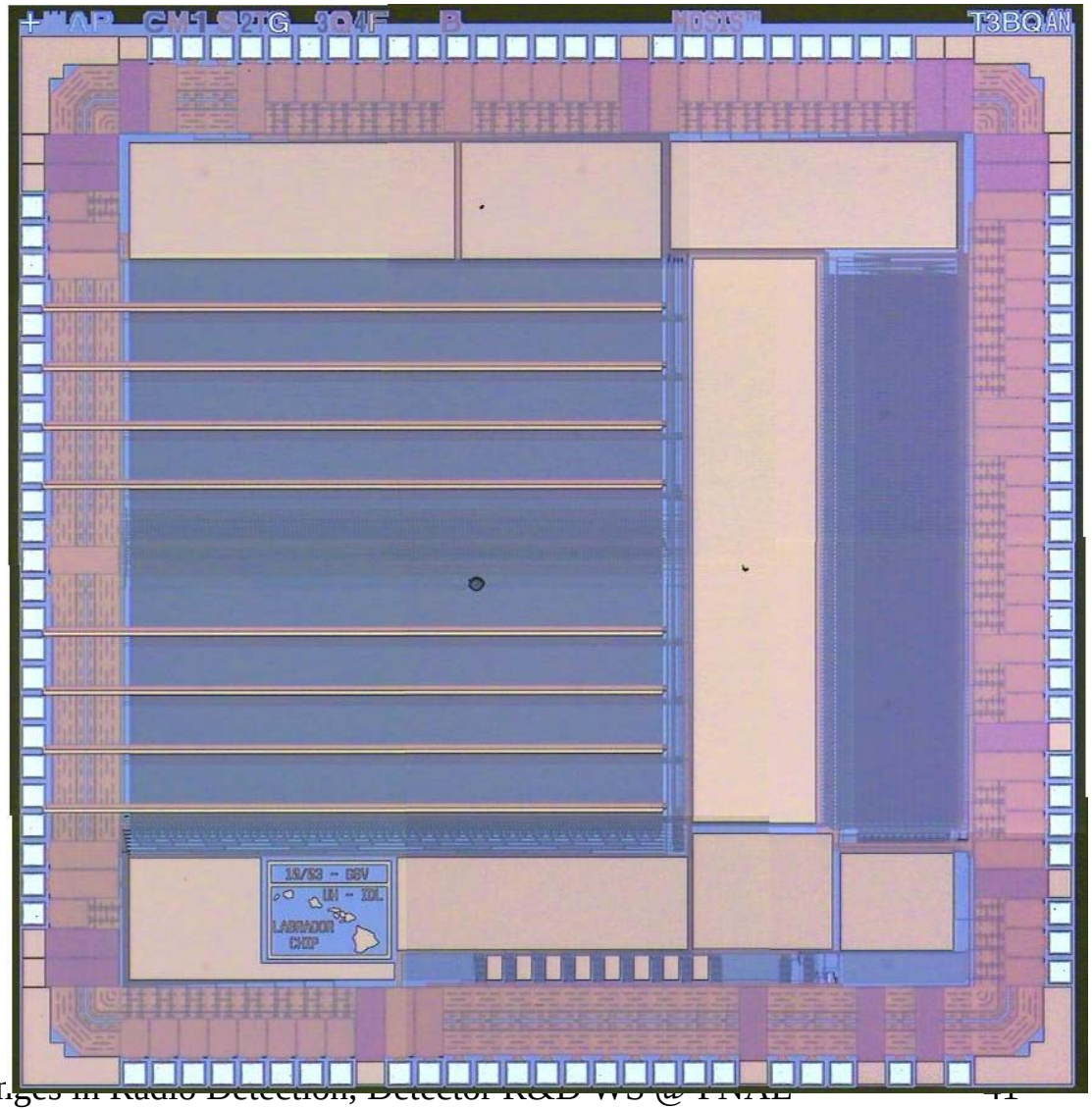
Radio Detection has a bright future:

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

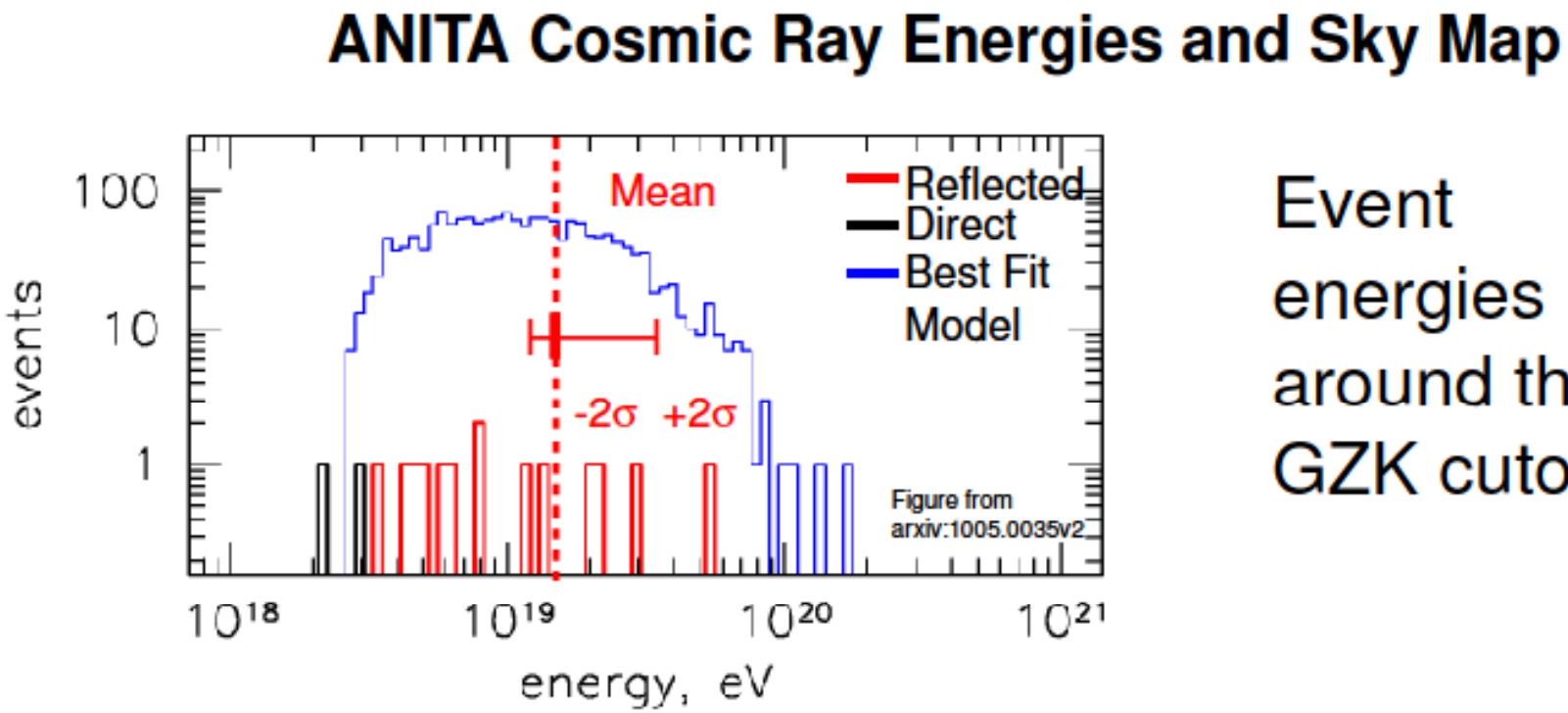
- Interesting problems with much overlap in other fields

- "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" Super-K a good idea?)

Back-up slides



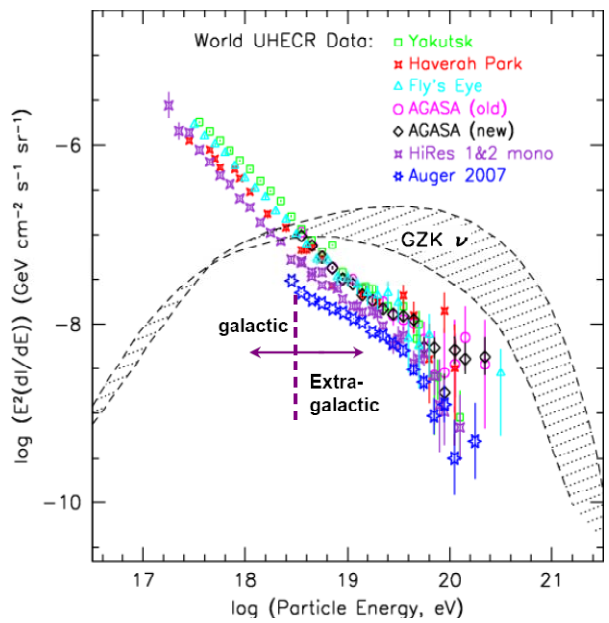
UHE CR Energy Estimate



Event energies lie around the GZK cutoff

Cosmogenic Neutrinos

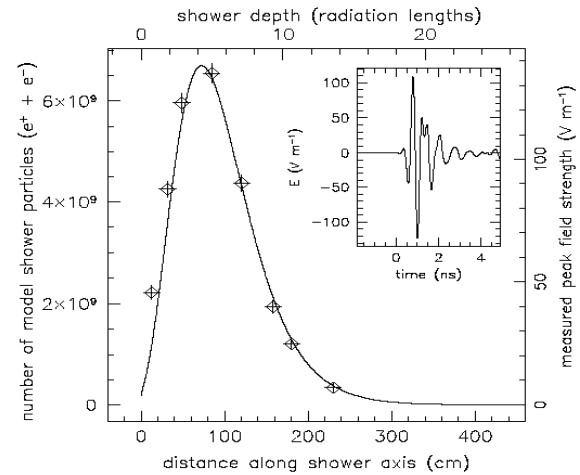
- 10^{18} eV neutrinos predicted by many acceleration and interaction processes at source locations
  - Observations, interaction physics suggest ultra-high energy cosmic rays will interact with the CMB to produce neutrinos
- Berezinsky & Zatsepin, 1970, REQUIRE 10^{18} eV neutrinos
  - Lack of neutrinos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



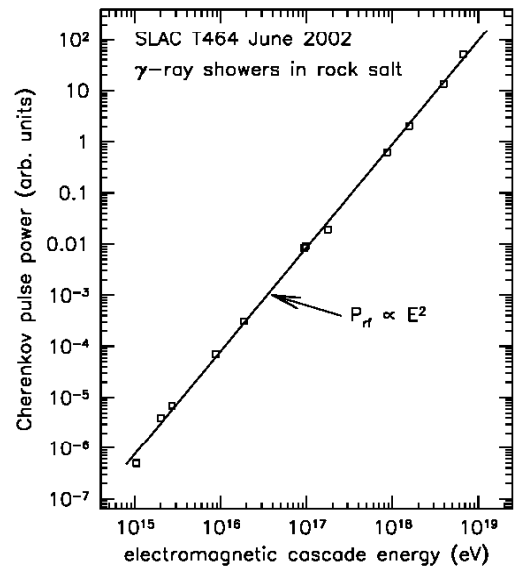
Courtesy Peter Gorham

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**



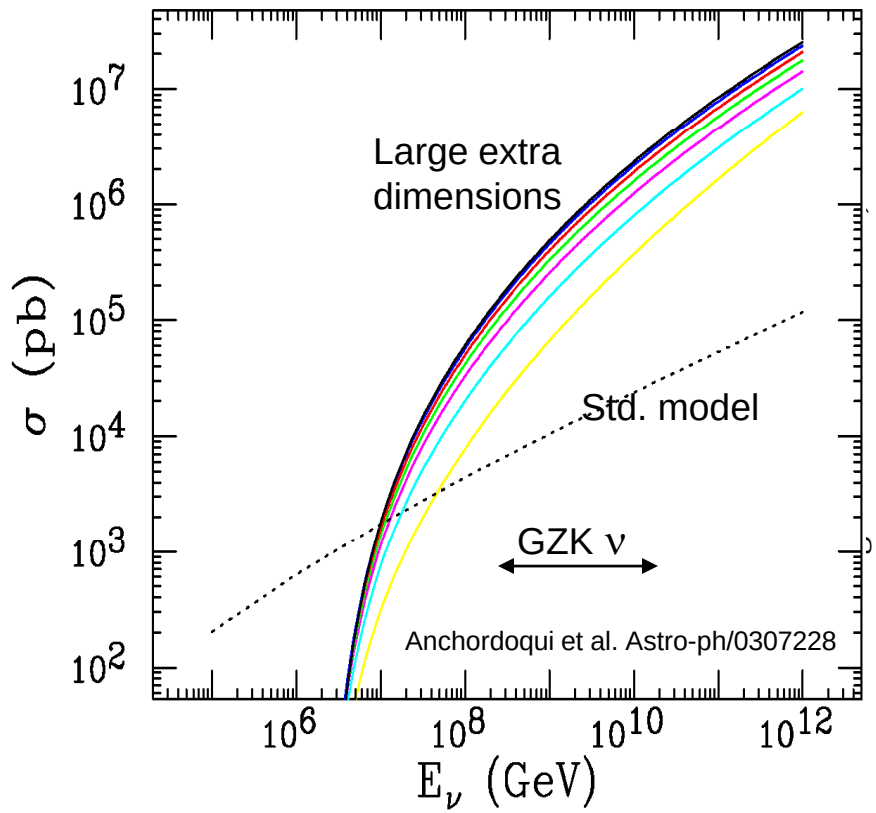
Saltzberg, et al PRL 2001



Gorham, et al PRD 2004

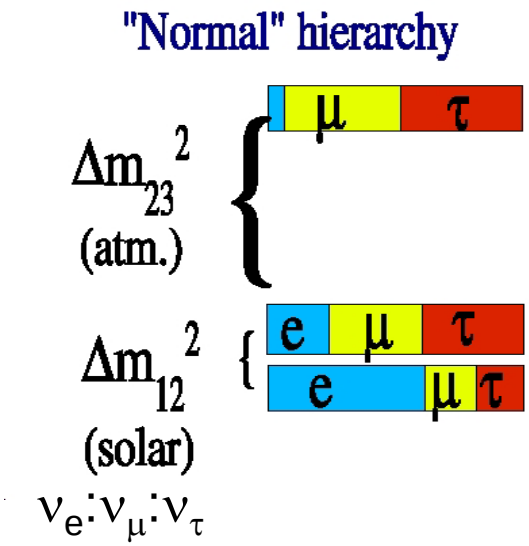
Particle Physics: Energy Frontier

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



Particle Physics: Neutrinos

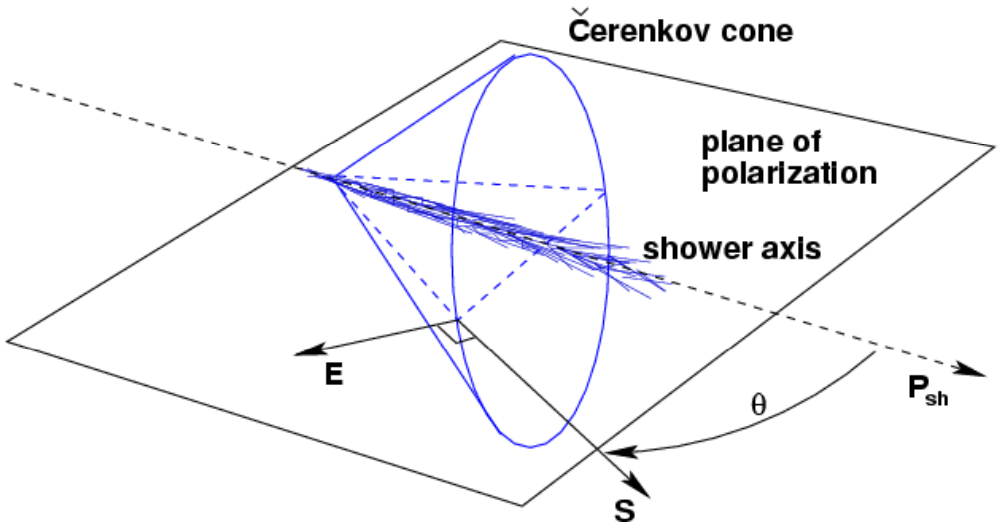
- GZK neutrinos are the "longest baseline" neutrino experiment:
  - Longest L/E (proper time) for: sterile ν admixtures & anomalous ν decays
    - SUN: L/E ~ 30 m/eV
    - GZK: L/E ~ 10^9 m/eV
- Measured flavor ratios of $\nu_e:\nu_\mu:\nu_\tau$ can identify non-standard physics at source



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

Neutrino decay leaves a strong imprint on flavor ratios at Earth

Cherenkov polarization tracking

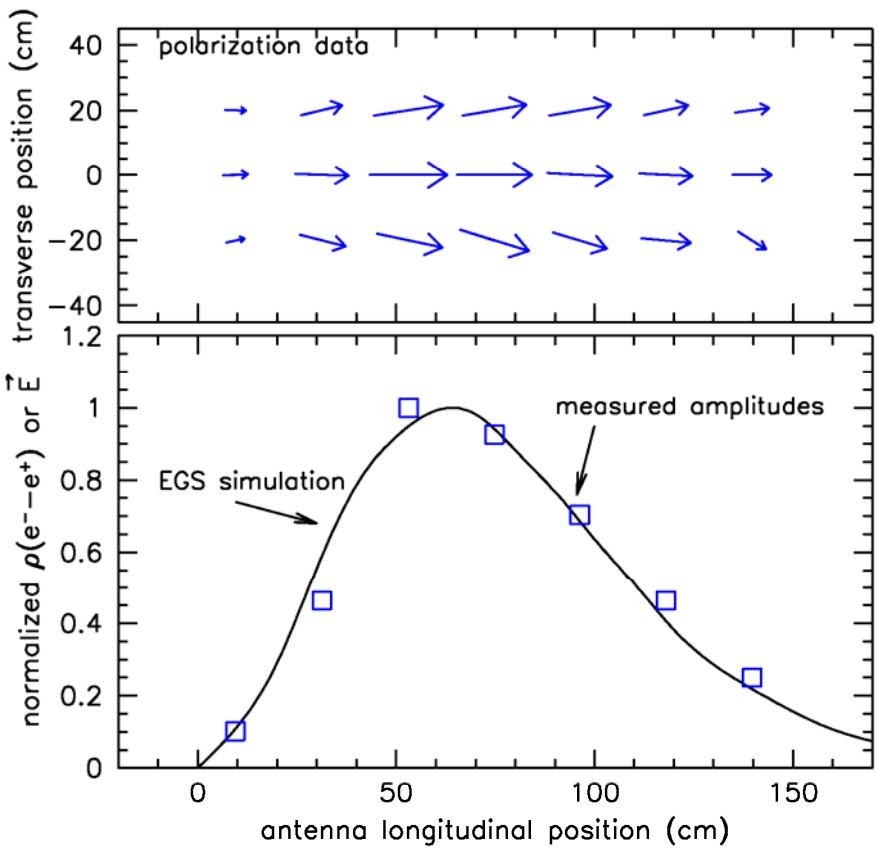


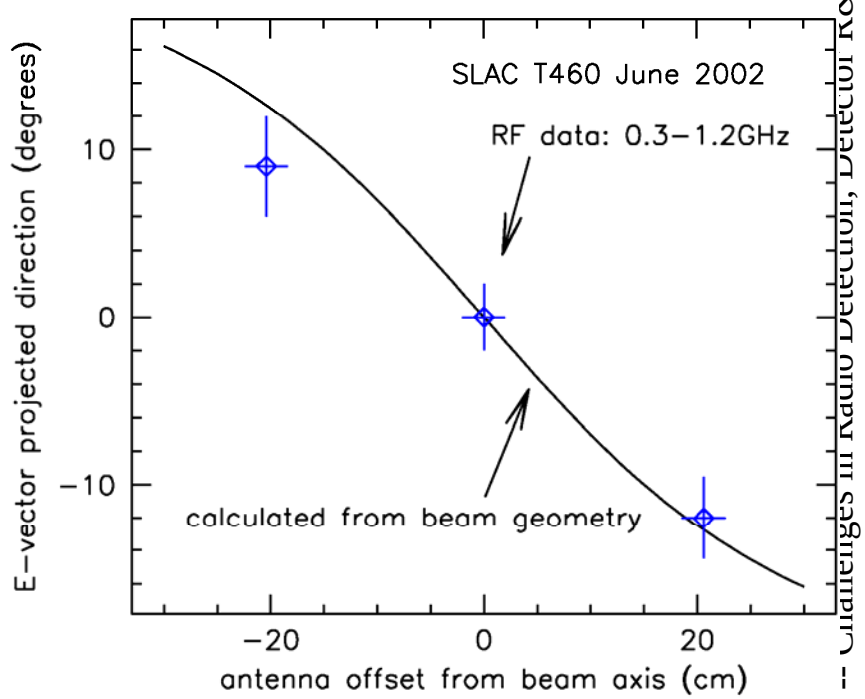
- Radio Cherenkov: polarization measurements are straightforward
- Two antennas at different parts of cone:
  - Will measure different projected plane of E, S
  - **Intersection of these planes defines shower track**

Cherenkov radiation predictions:

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

Polarization tracking

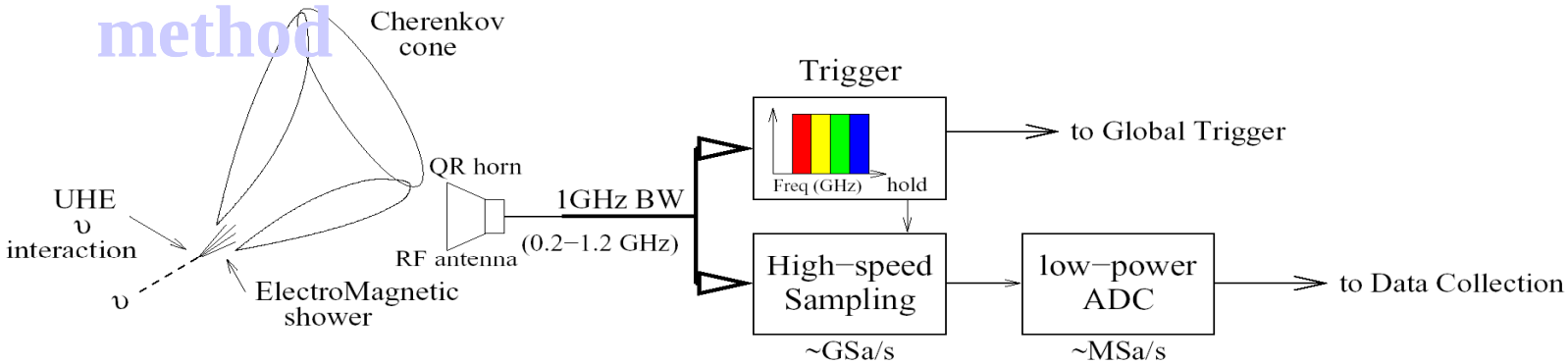




- Measured with dual-polarization embedded bowtie antenna array in salt

Trigger/Digitizer Specifications

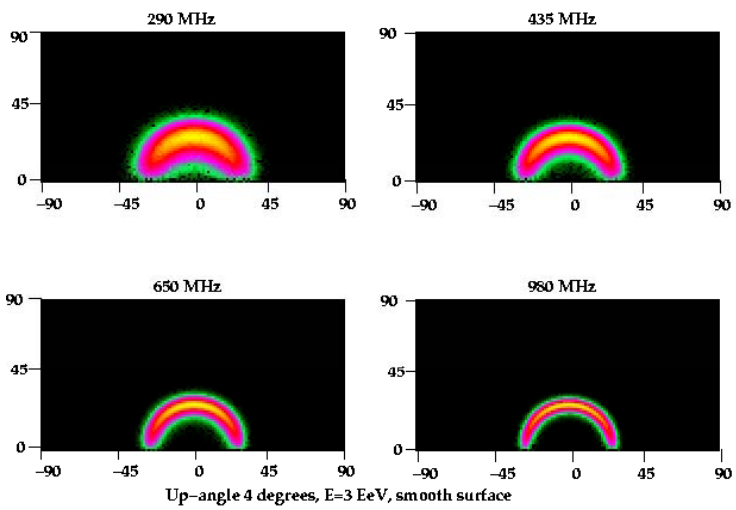
ANITA trigger & digitizer uses a proven dual-track method

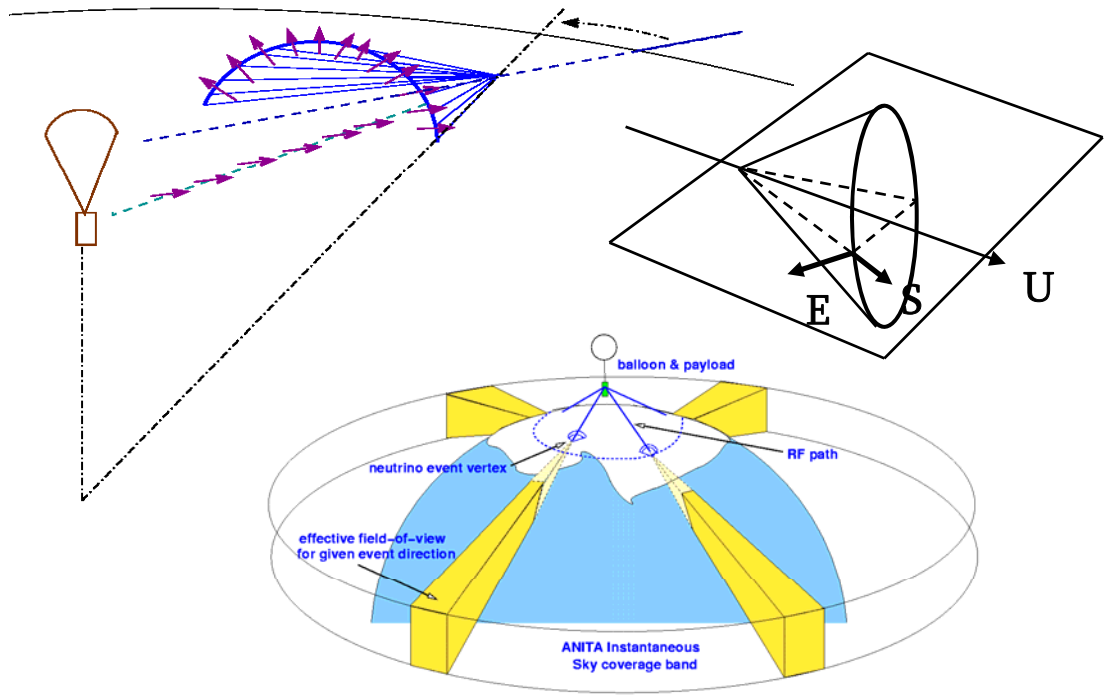


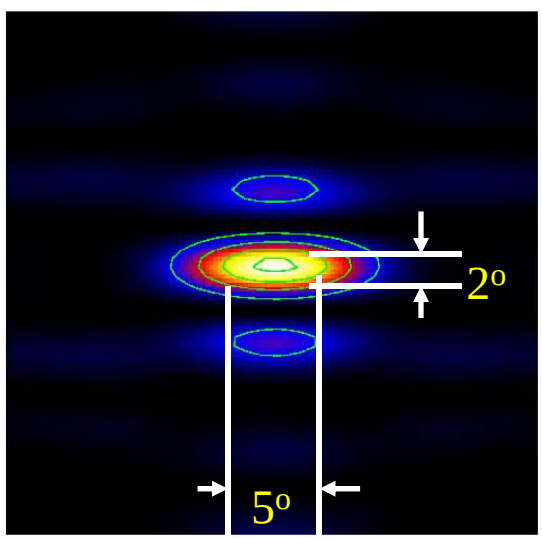
- Split signal: 1 path to trigger, 1 for digitizer
- Use multiple frequency bands for trigger
- Digitizer runs ONLY when triggered to save power

	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

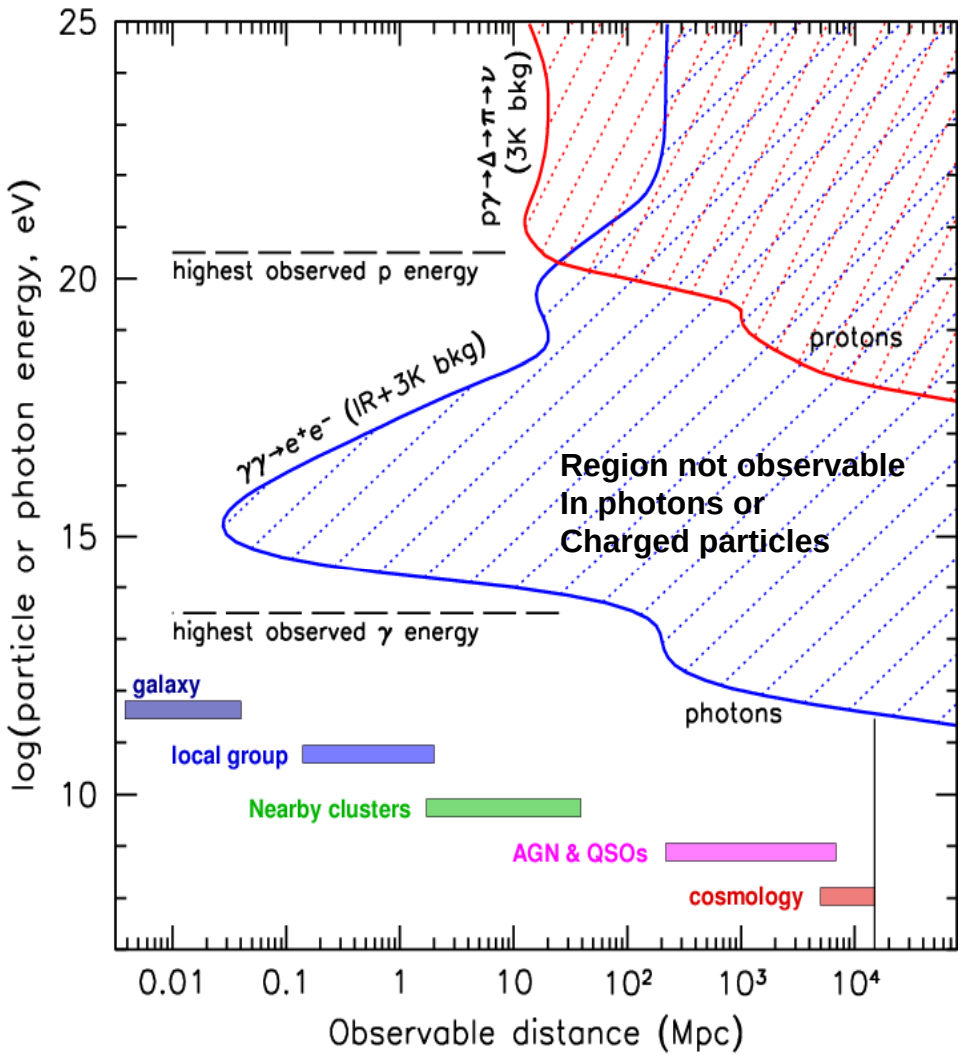






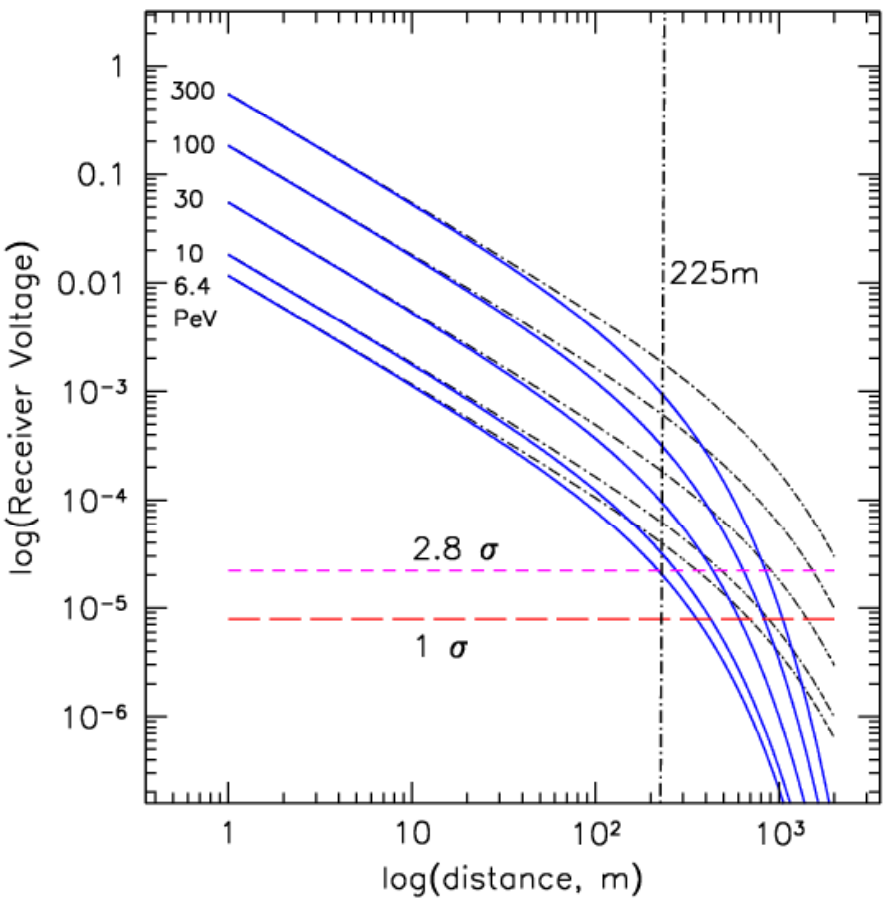
- Pulse-phase interferometer (150ps timing) gives intrinsic resolution of <1° elevation by ~1° azimuth for **arrival direction** of radio pulse
- **Neutrino direction** constrained to ~<2° in elevation by earth absorption, and by ~3-5° in azimuth by polarization angle

Neutrinos: The only known messengers at PeV energies and above



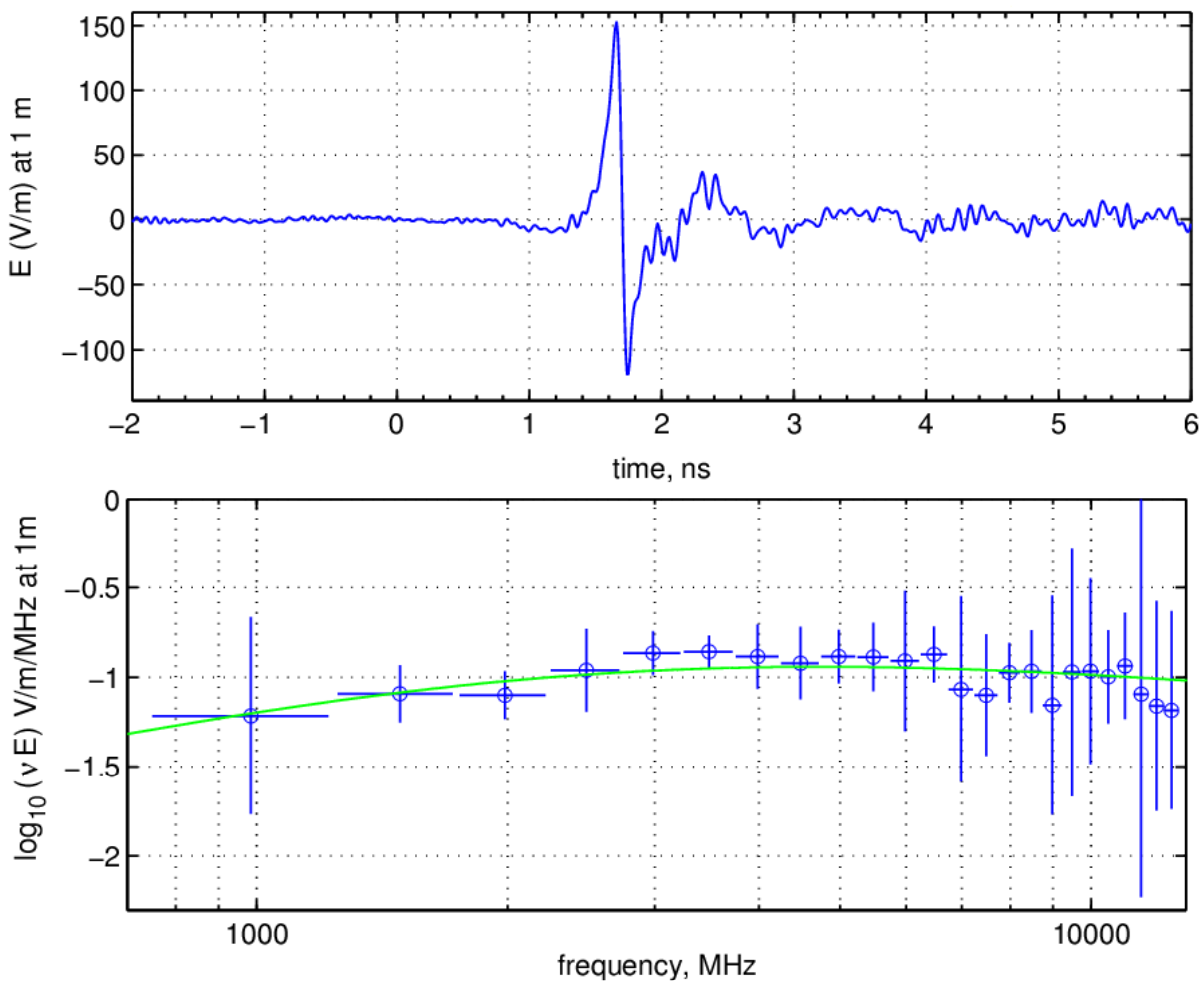
- **Photons lost above 30 TeV** pair production on IR & μwave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- Sources extend to 10^9 TeV !
- => Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors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

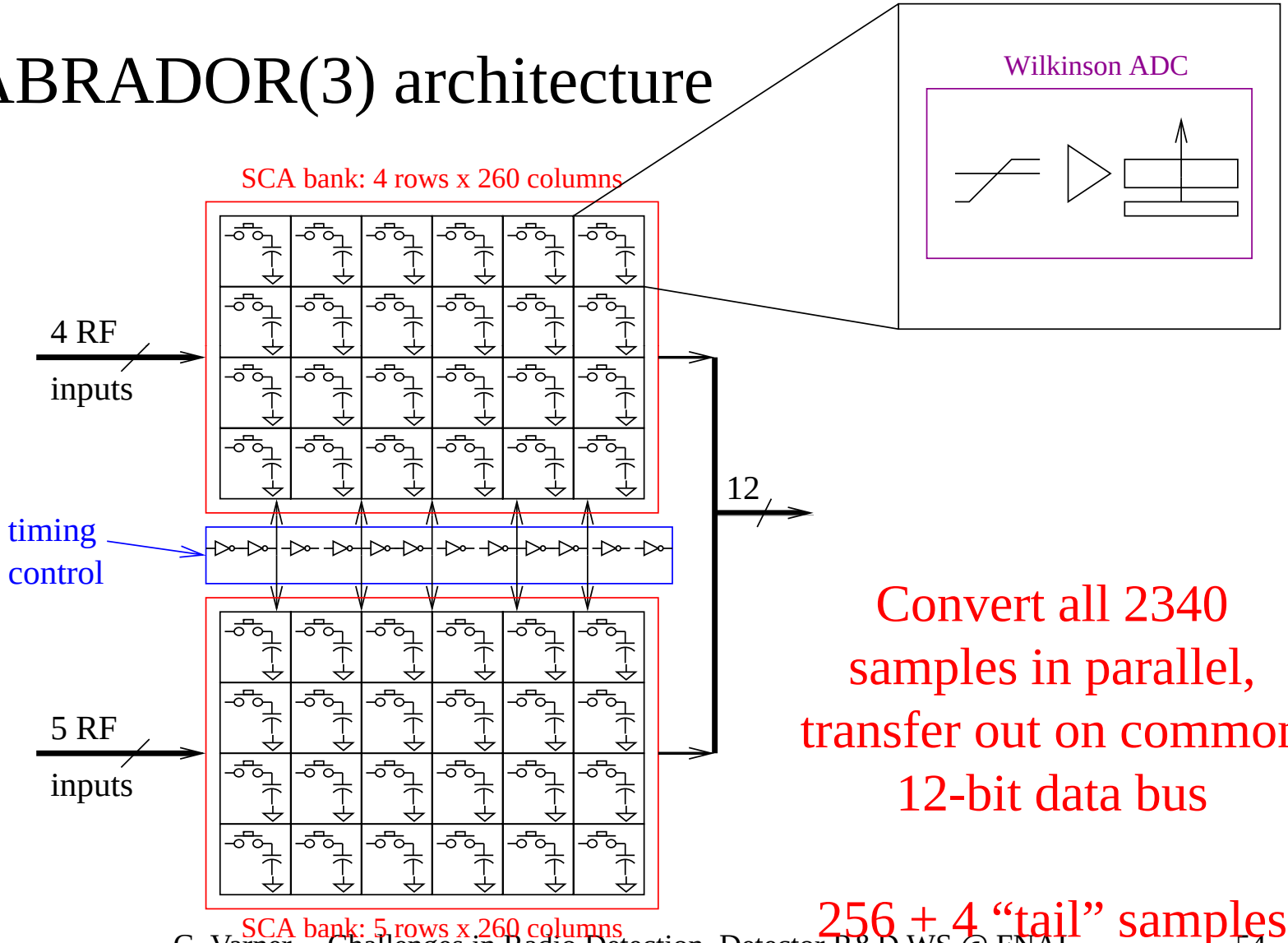
Ultra-wideband data on Askaryan pulse



- 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

9 x 260 samples = 2340 storage cells

LABRADOR(3) architecture



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

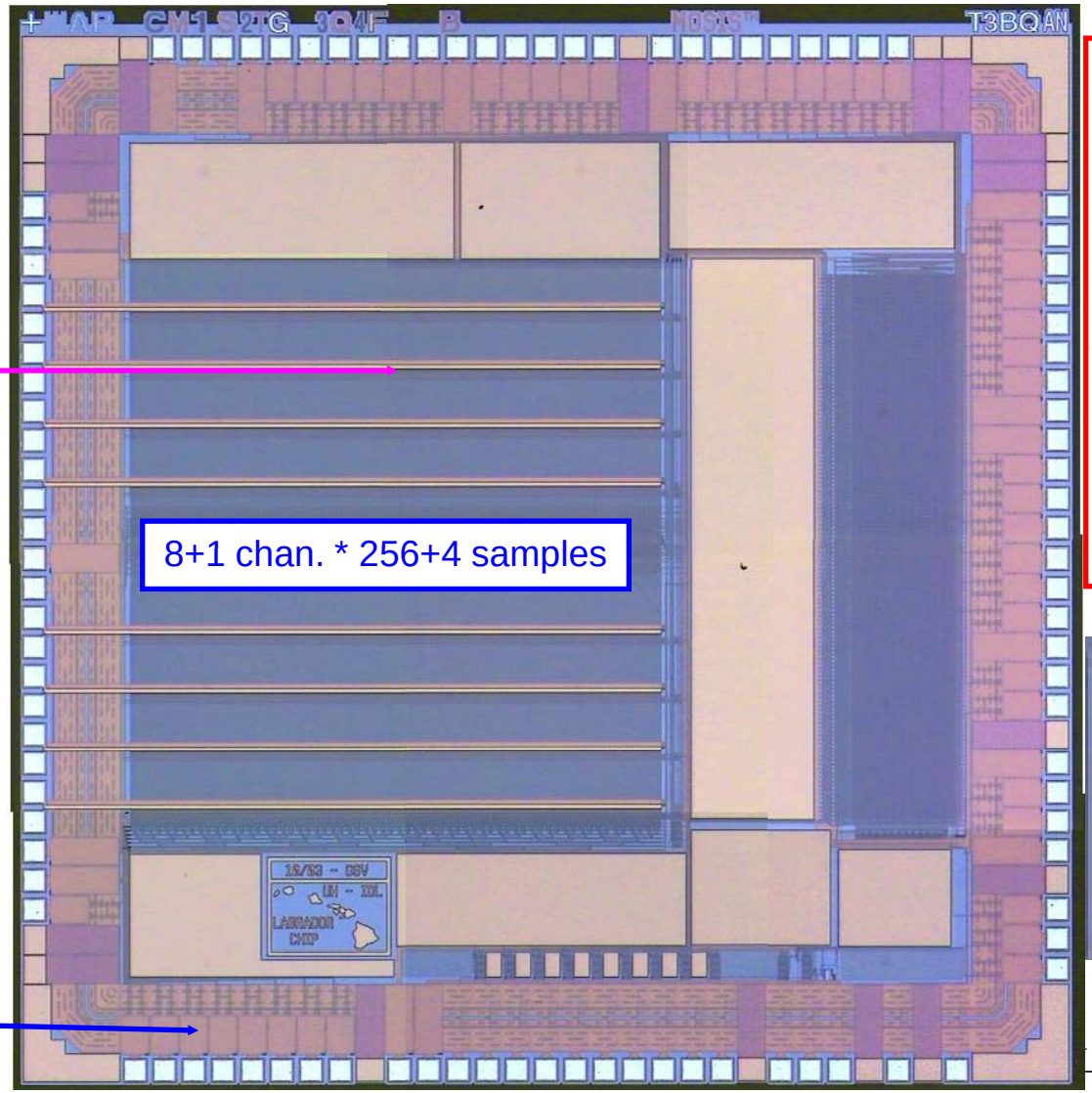
256 + 4 “tail” samples

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>

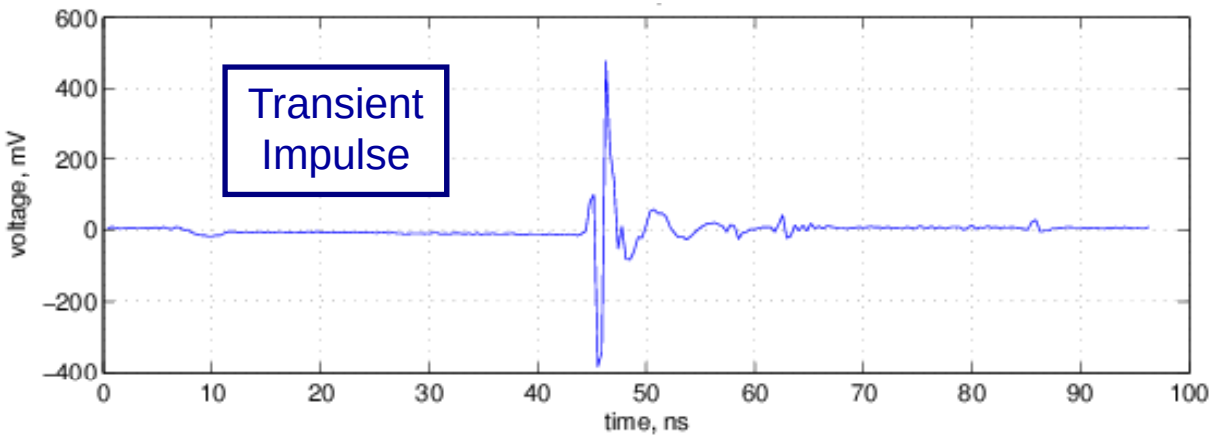
Random access:

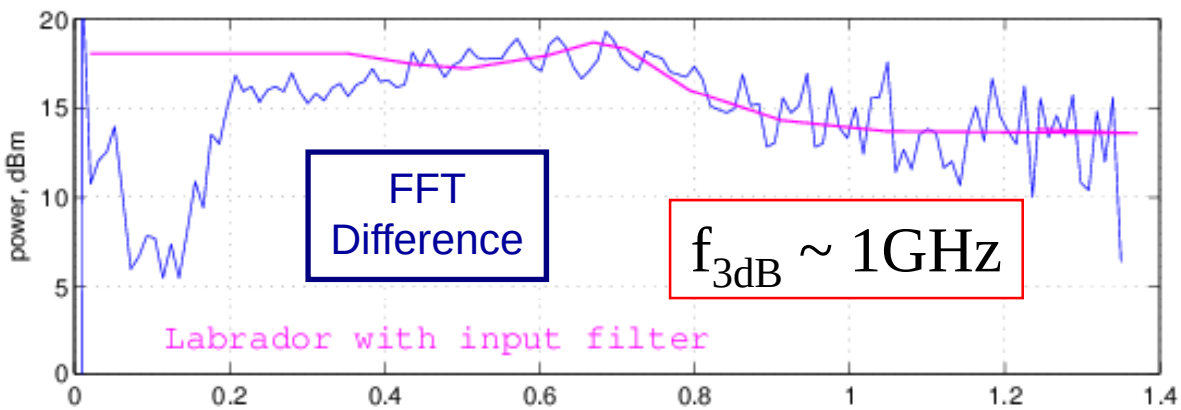


- Common STOP acquisition
- 3.2 x 2.9 mm
- Conversion in 31μs (all 2340 samples)
- Data transfer takes 80μs
- Ready for next event in <150μs

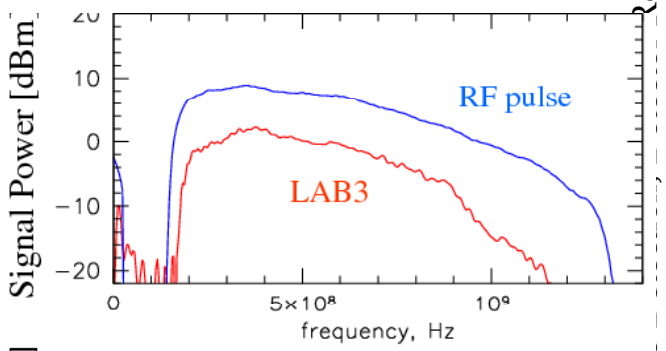
NIM A583:447-460, 2007

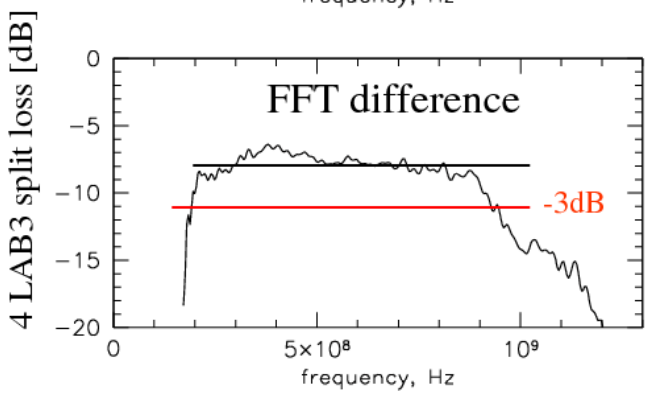
Bandwidth Evaluation



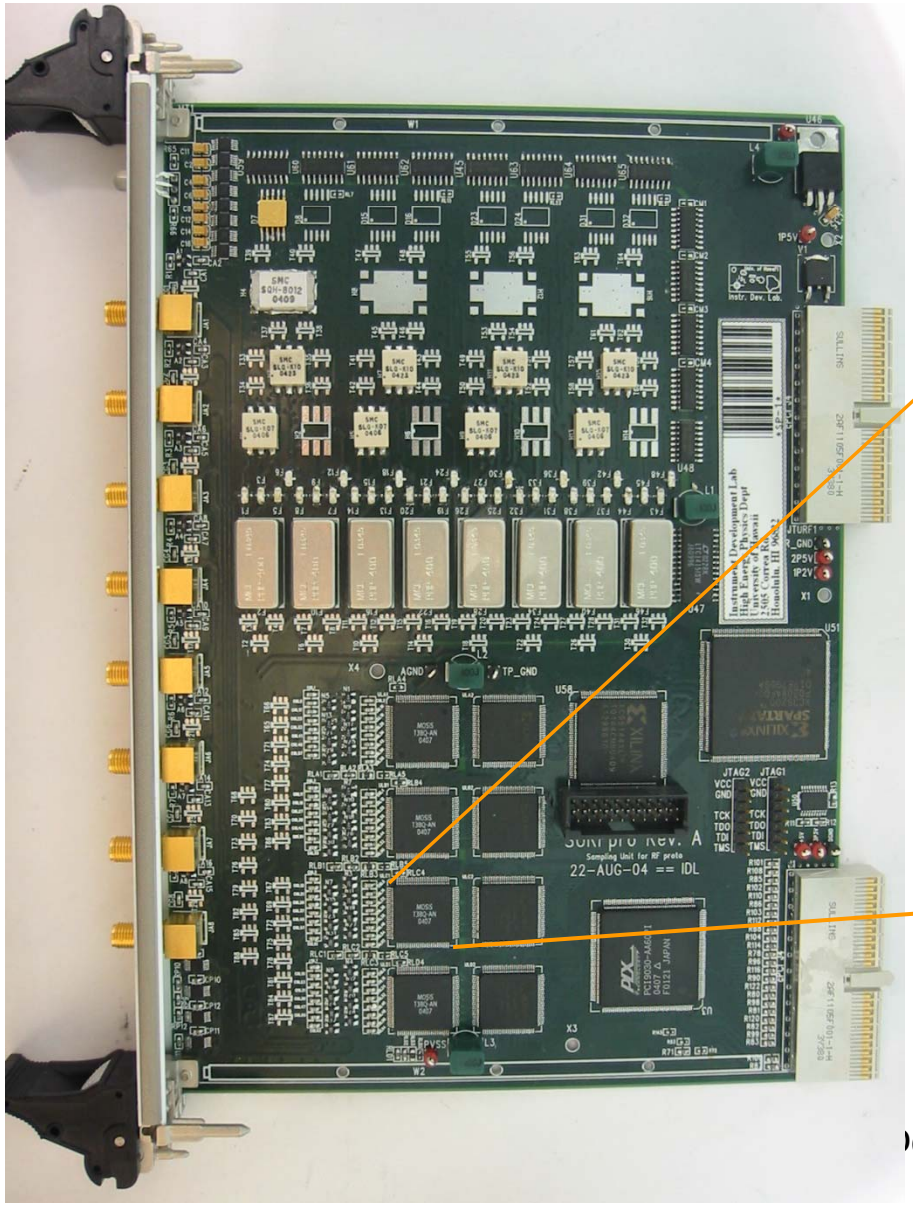


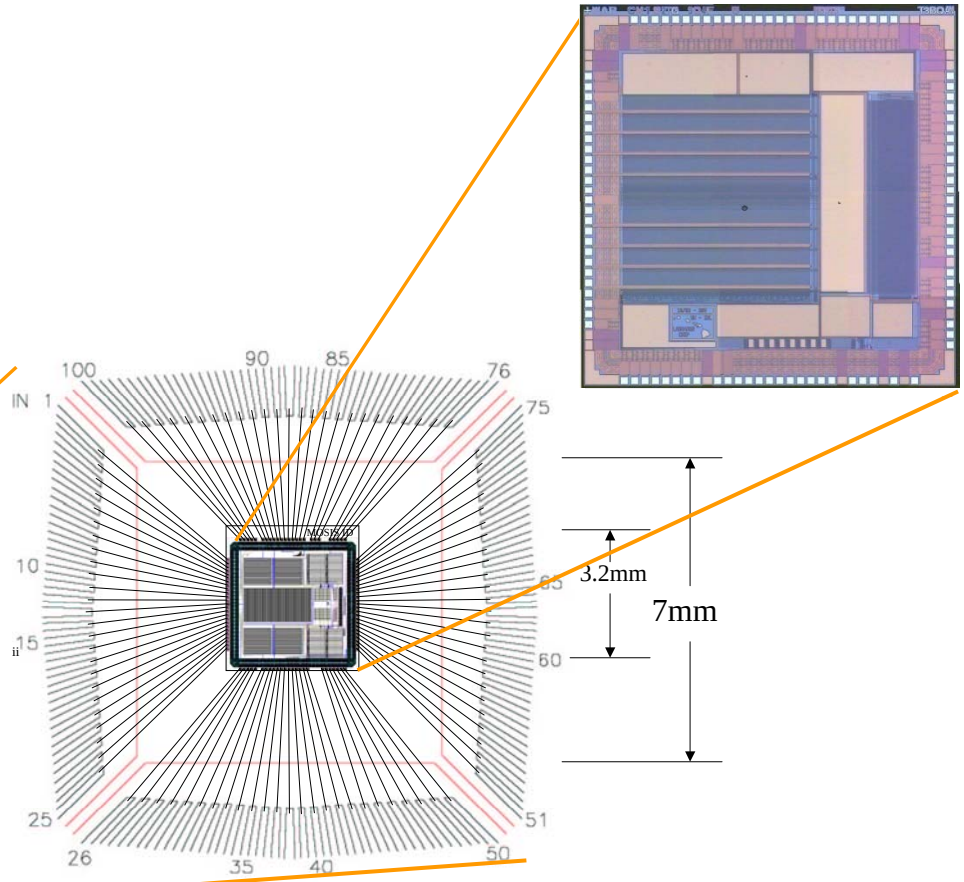
Frequency [GHz]





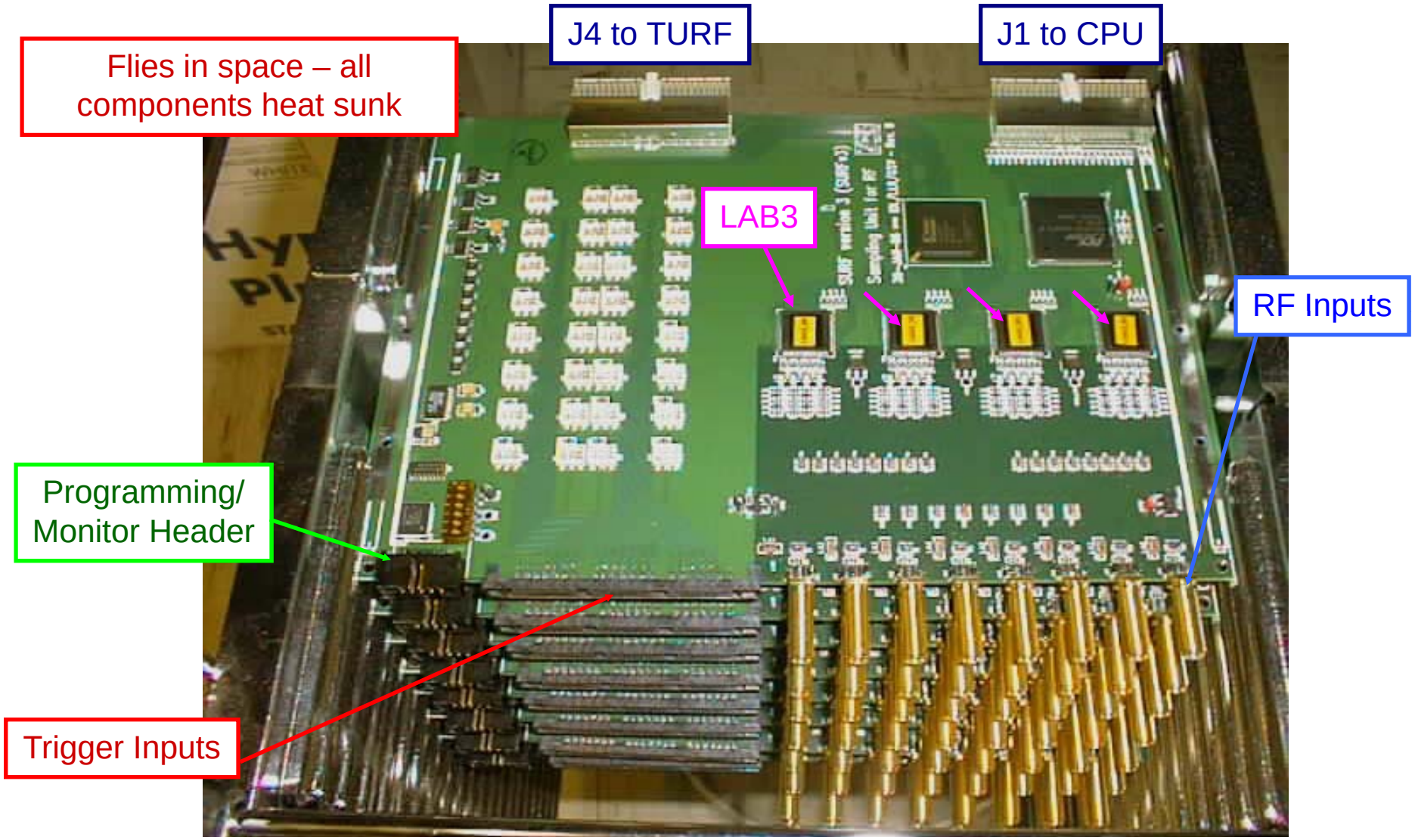
Sampling Unit for RF (SURF) board

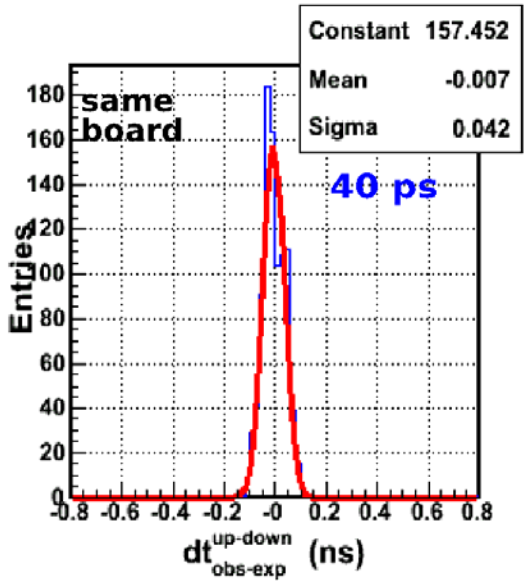


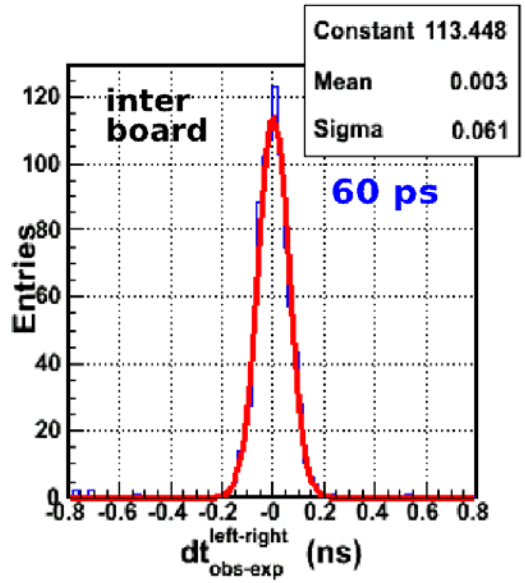


SURFv3 Board

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

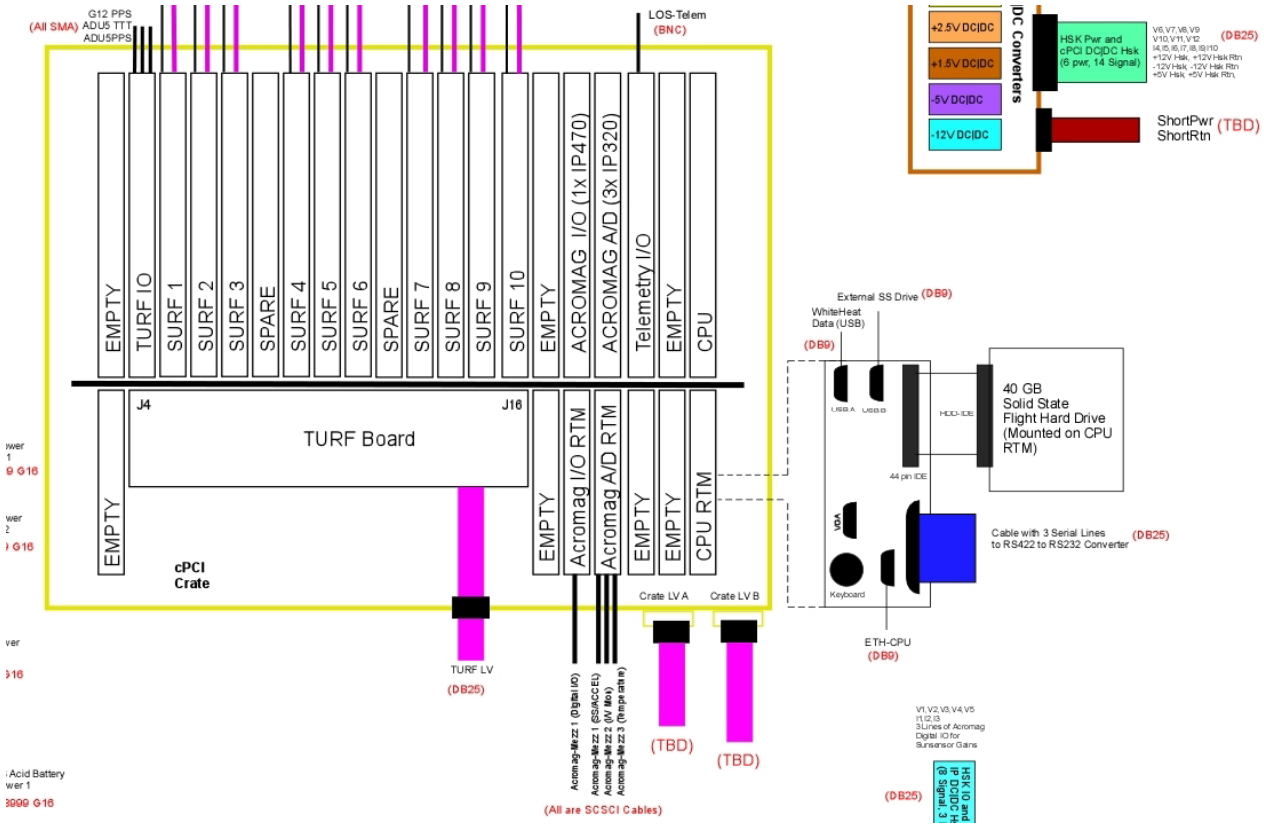






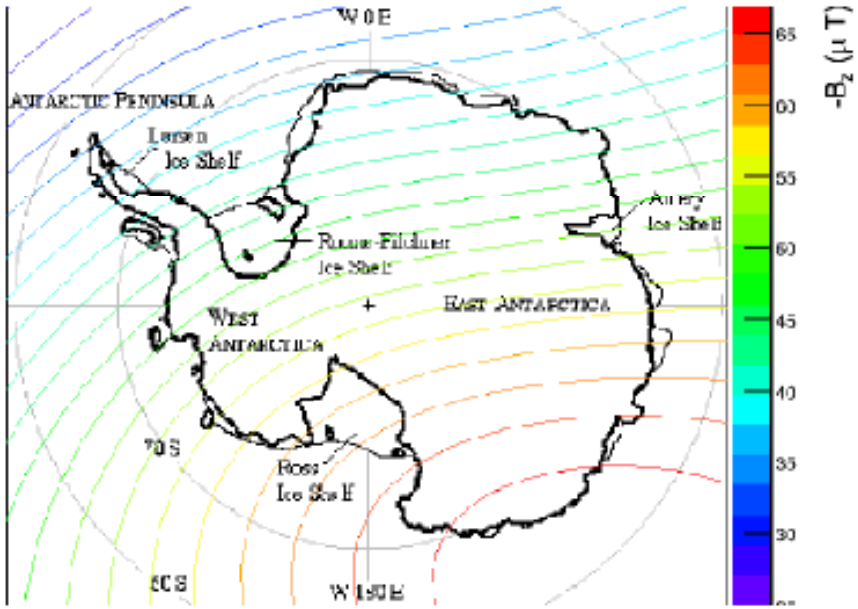
~47ps due to Time Ref. Passing

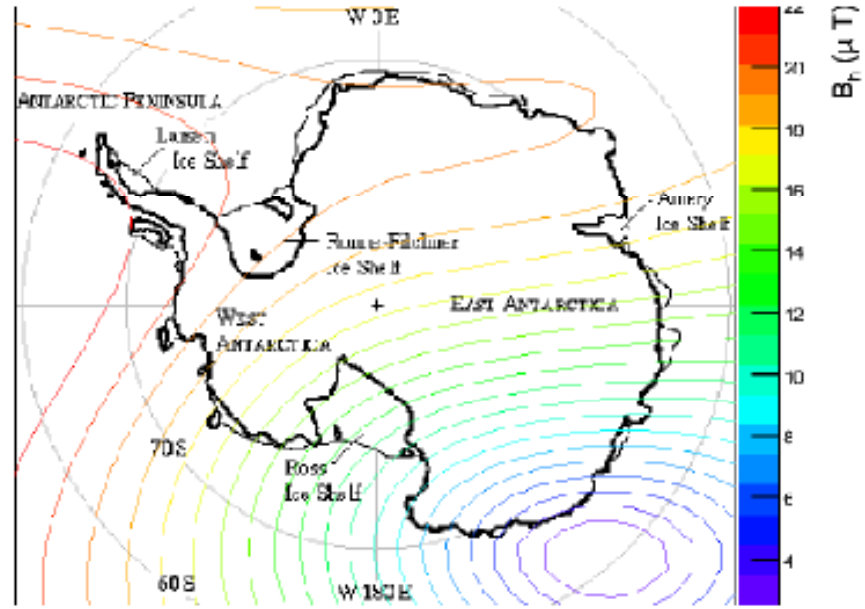
(33MHz clock)



Cosmic Ray Identification

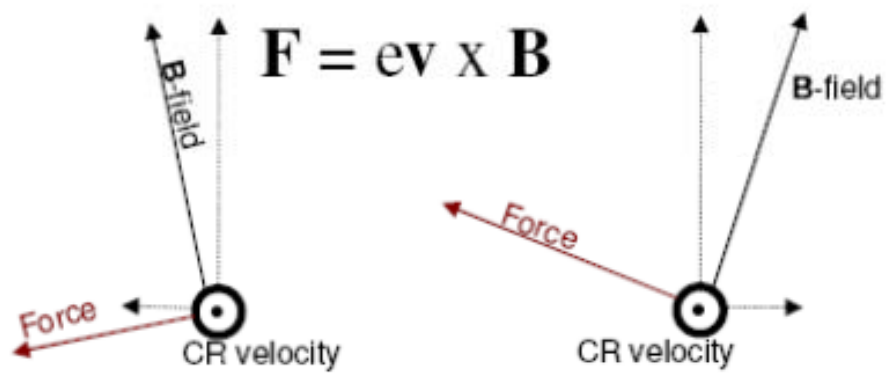
Polarization Correlation to Geomagnetic Field





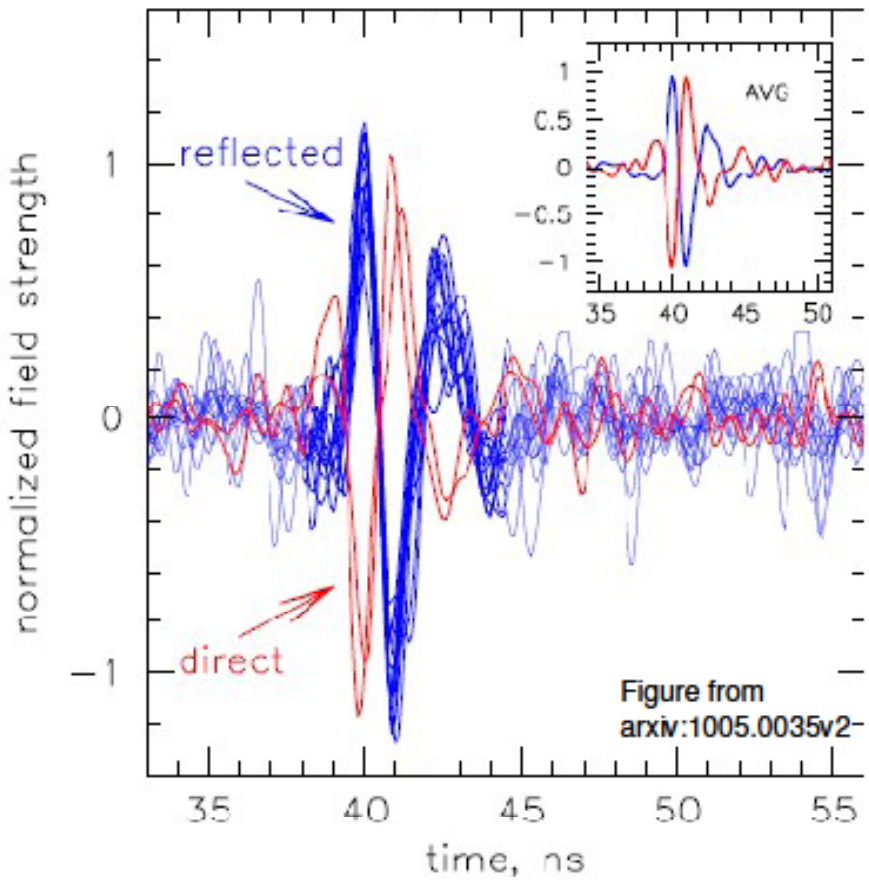
- CR moves towards payload.
- e+ and e- always curve away from each other due to dominant vertical B-field.
- H-pol emission always has the same polarization.
- V-pol magnitude and sign determined by the horizontal magnitude of the B-field.

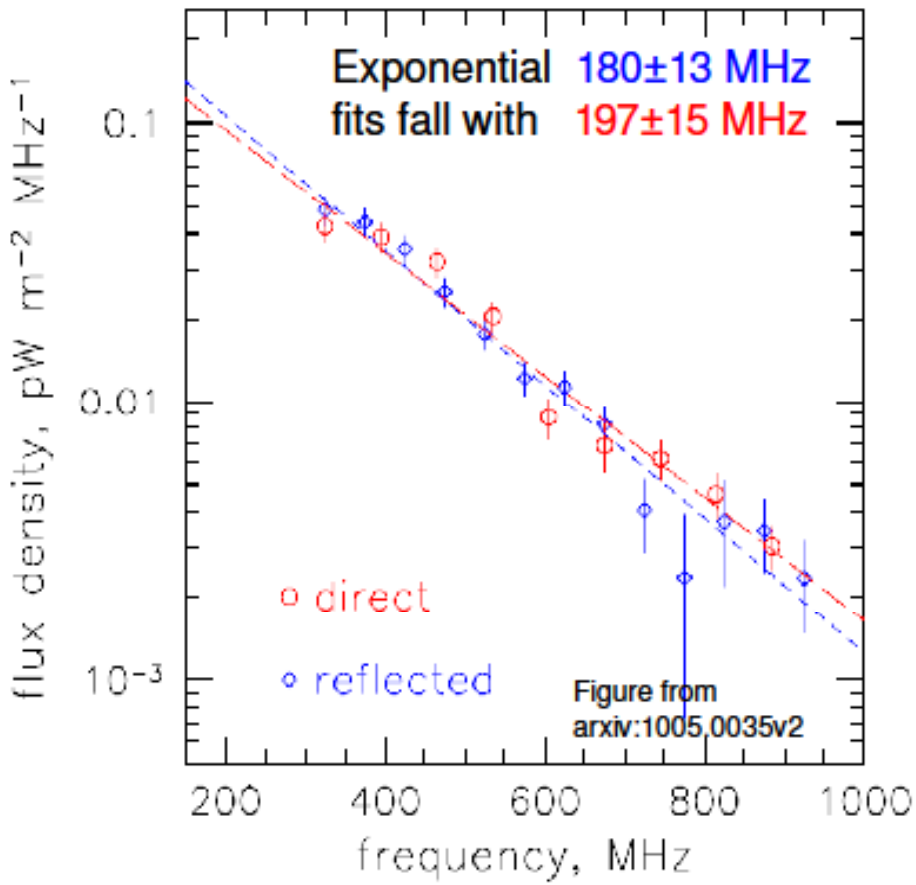
$$\mathbf{F} = e\mathbf{v} \times \mathbf{B}$$



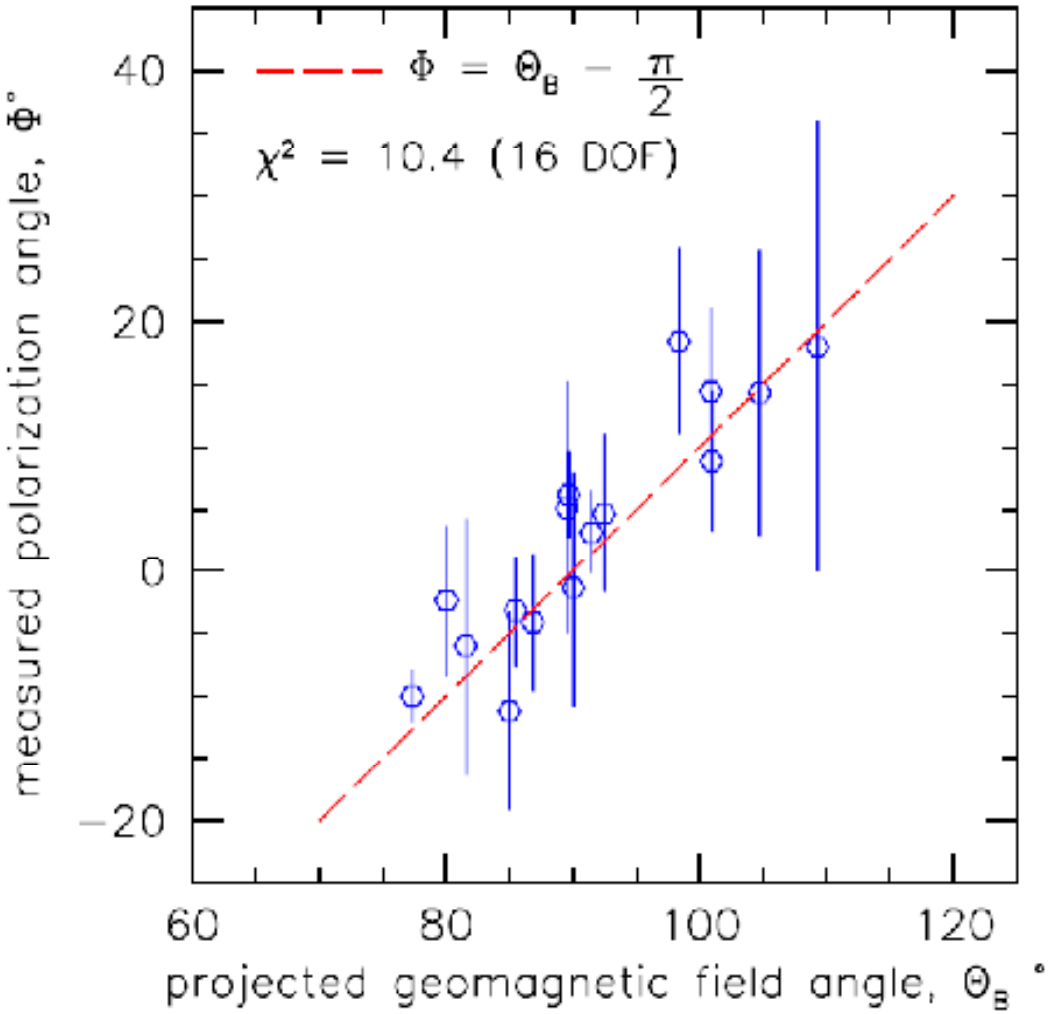
Cosmic-Ray Candidate Event Pulses

(Instrument response deconvolved)

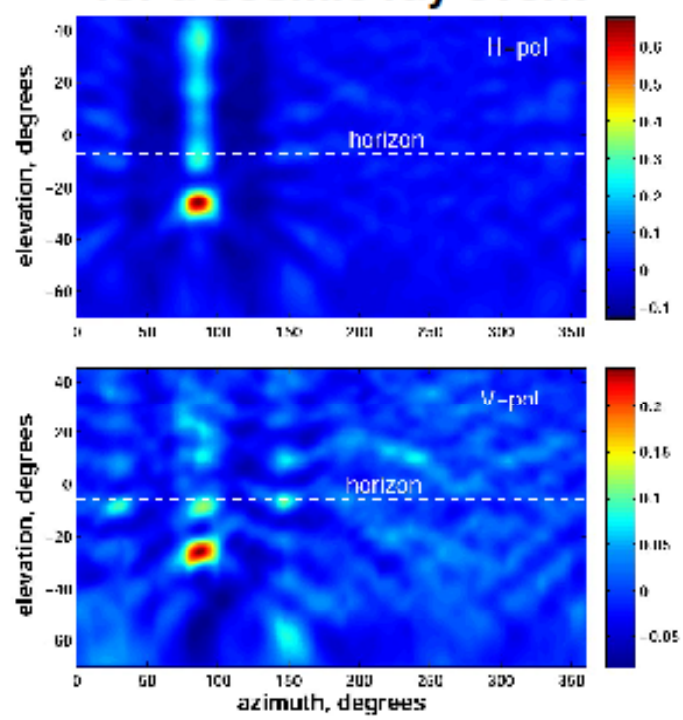




Correlation of Polarization Angle to Geo-Magnetic Field Angle

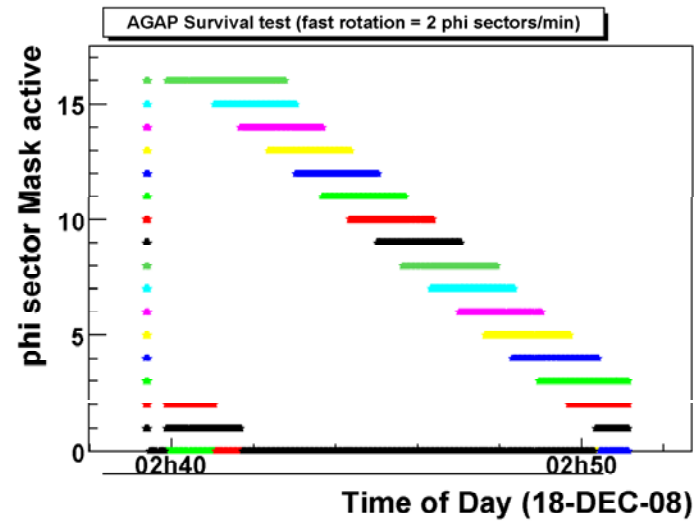


Interferometric image for a cosmic ray event



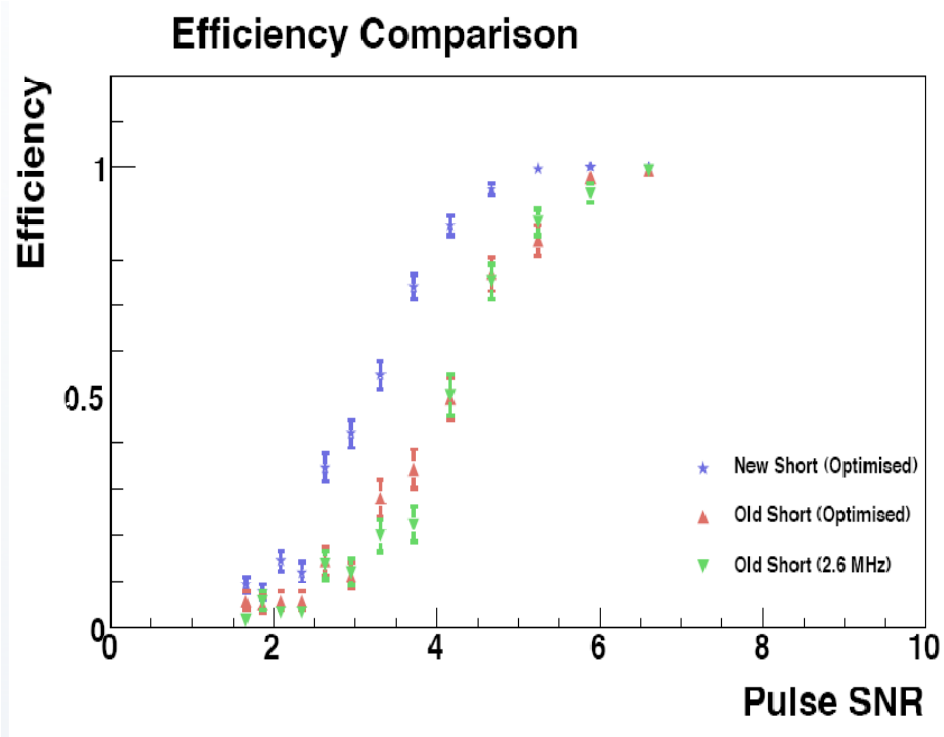
ANITA 2 Improvements

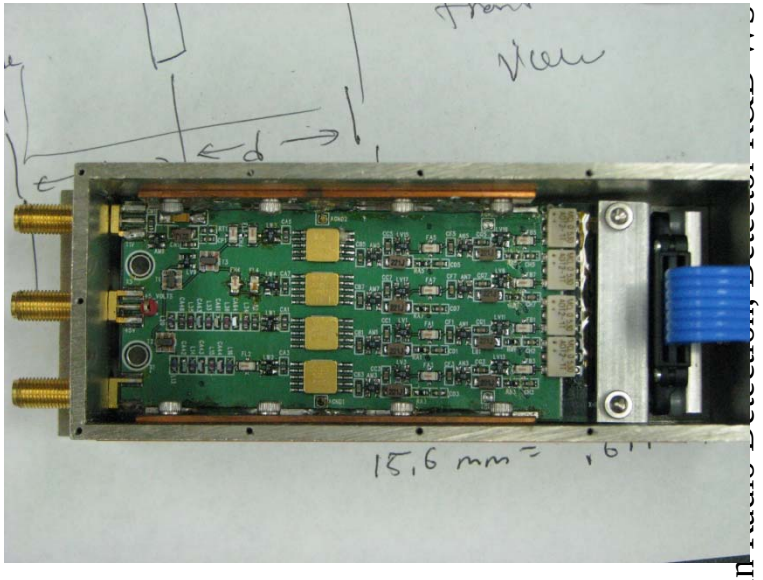
- "Dynamic Phi-Masking"
  - Active suppression of phi-sector readout during transit over noisy areas
    - McMurdo, South Pole, etc
  - Automatically activated
- 8 "nadir" antennas
  - One antenna shared w/ 2 phi sectors
- Only trigger on V-pol
- Improve T_{sys} by 40K
  - New Low-Noise Amplifier
- Overall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



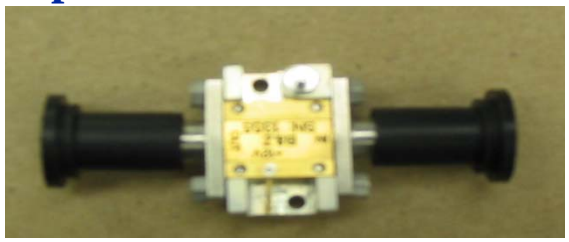
ANITA-2 Upgrades...

- 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

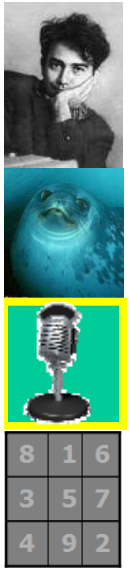




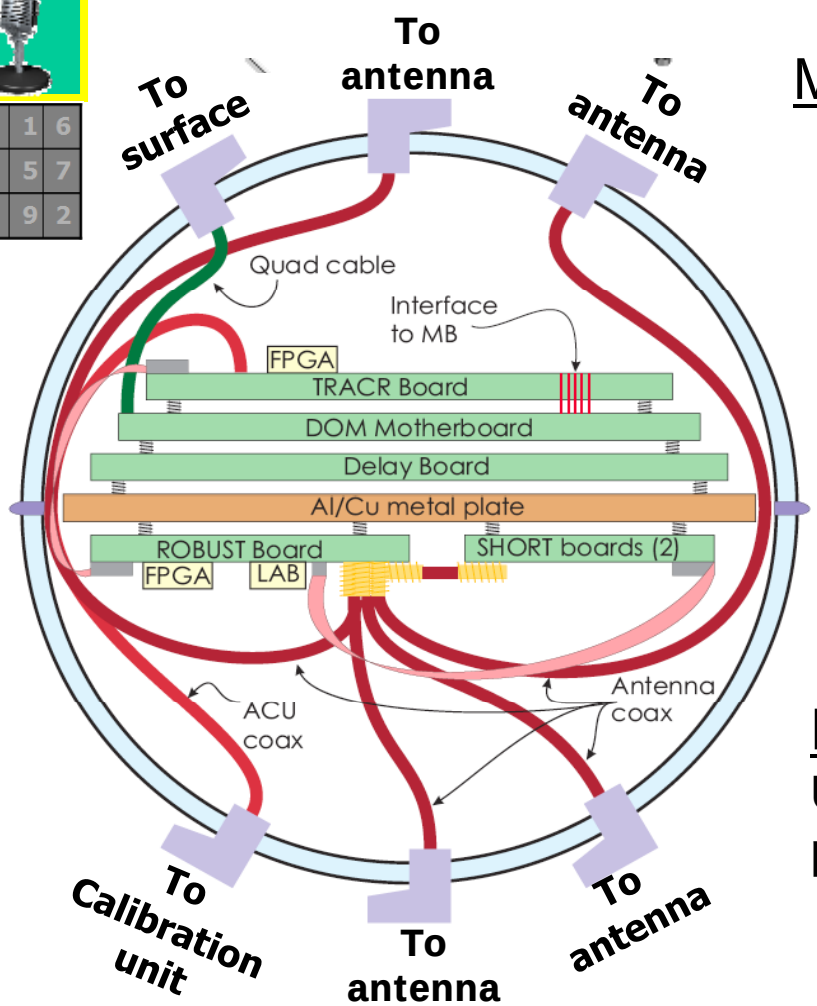
New preamp



New front end filter



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

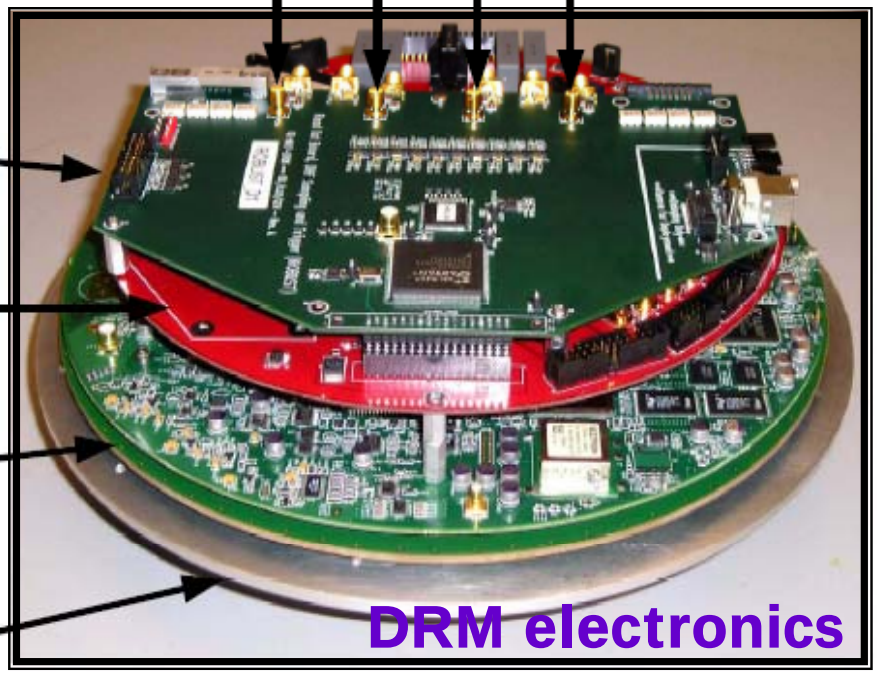
Antennas

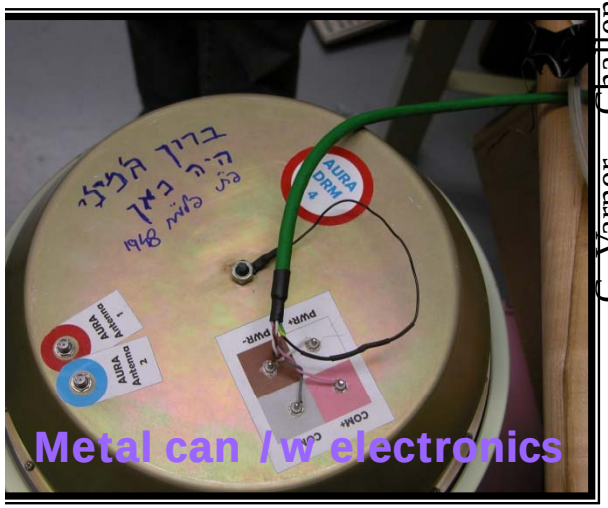
ROBUST

TRACR

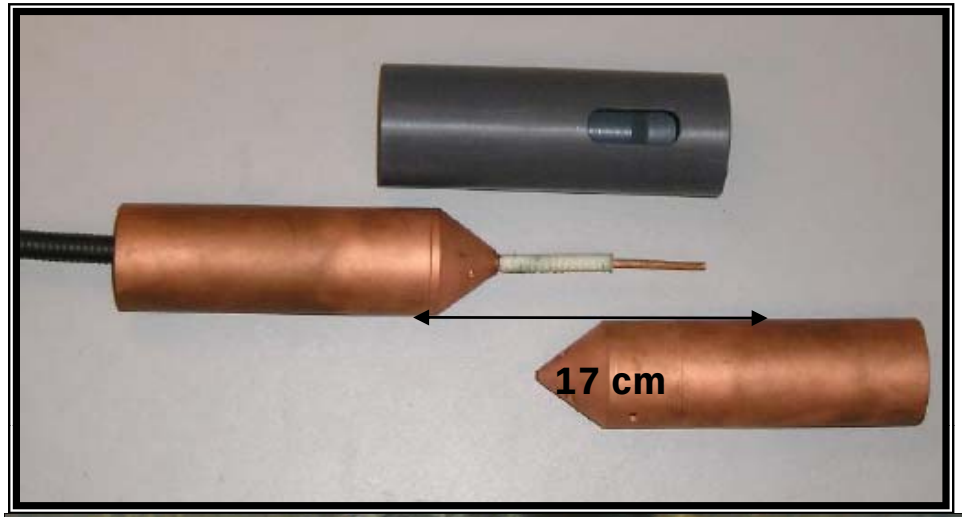
DOM-MB

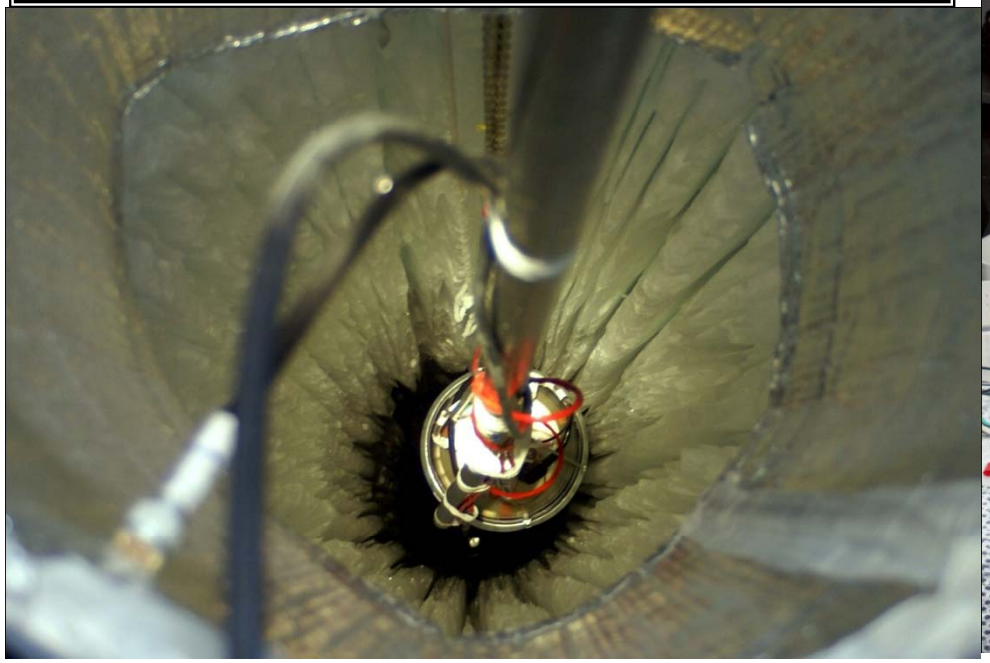
Metal Plate



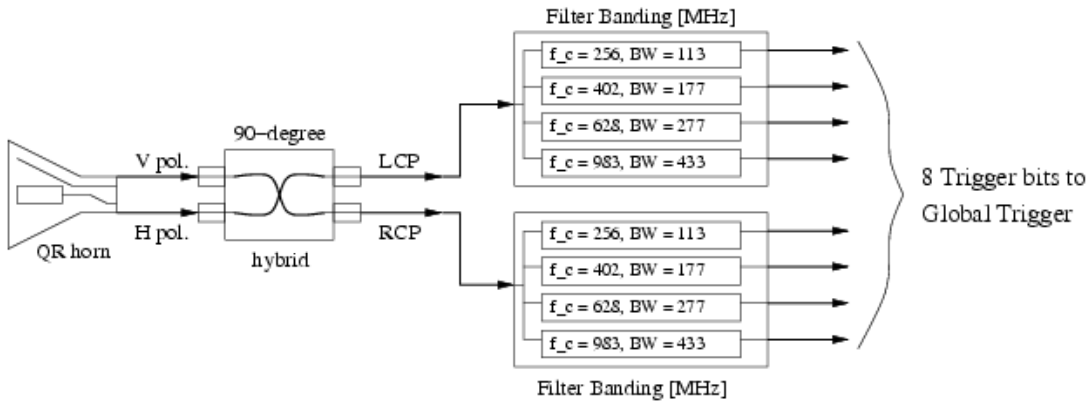


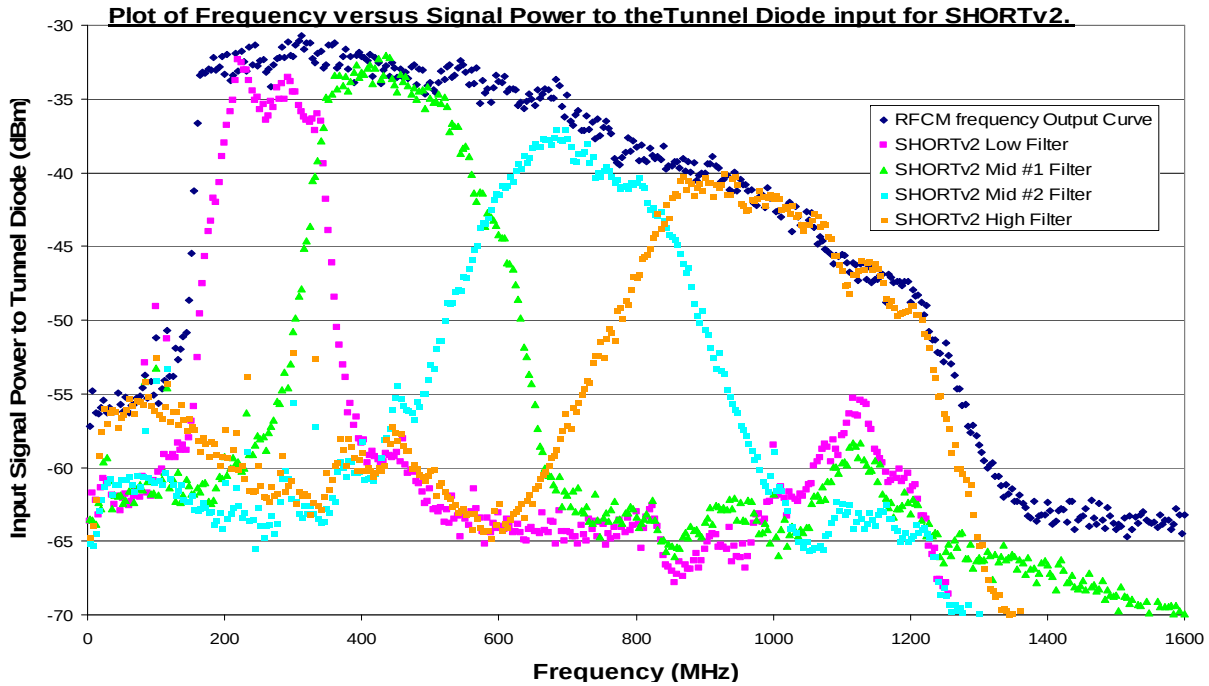
Antenna/DRM Deployment



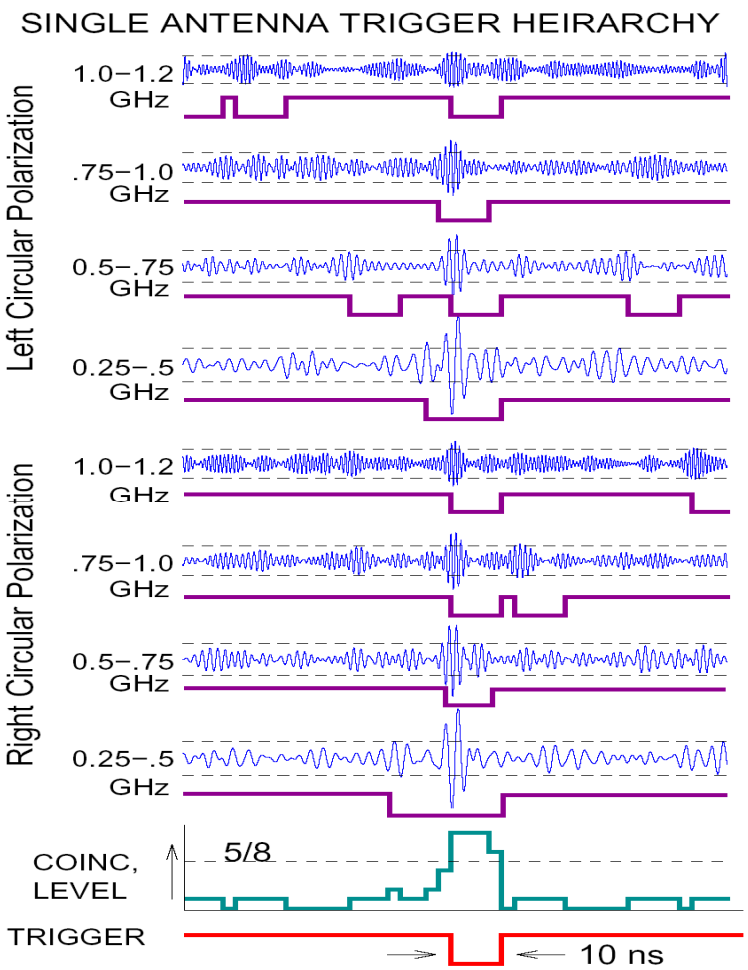


ANITA Level 1 – 3 of 8 Antenna





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