Askaryan Radio Array: Instrumentation For Radio Pulse Measurements of Ultra-High Energy Neutrinos

M. A. DuVernois, University of Wisconsin, Madison

for the ARA Collaboration

Outline

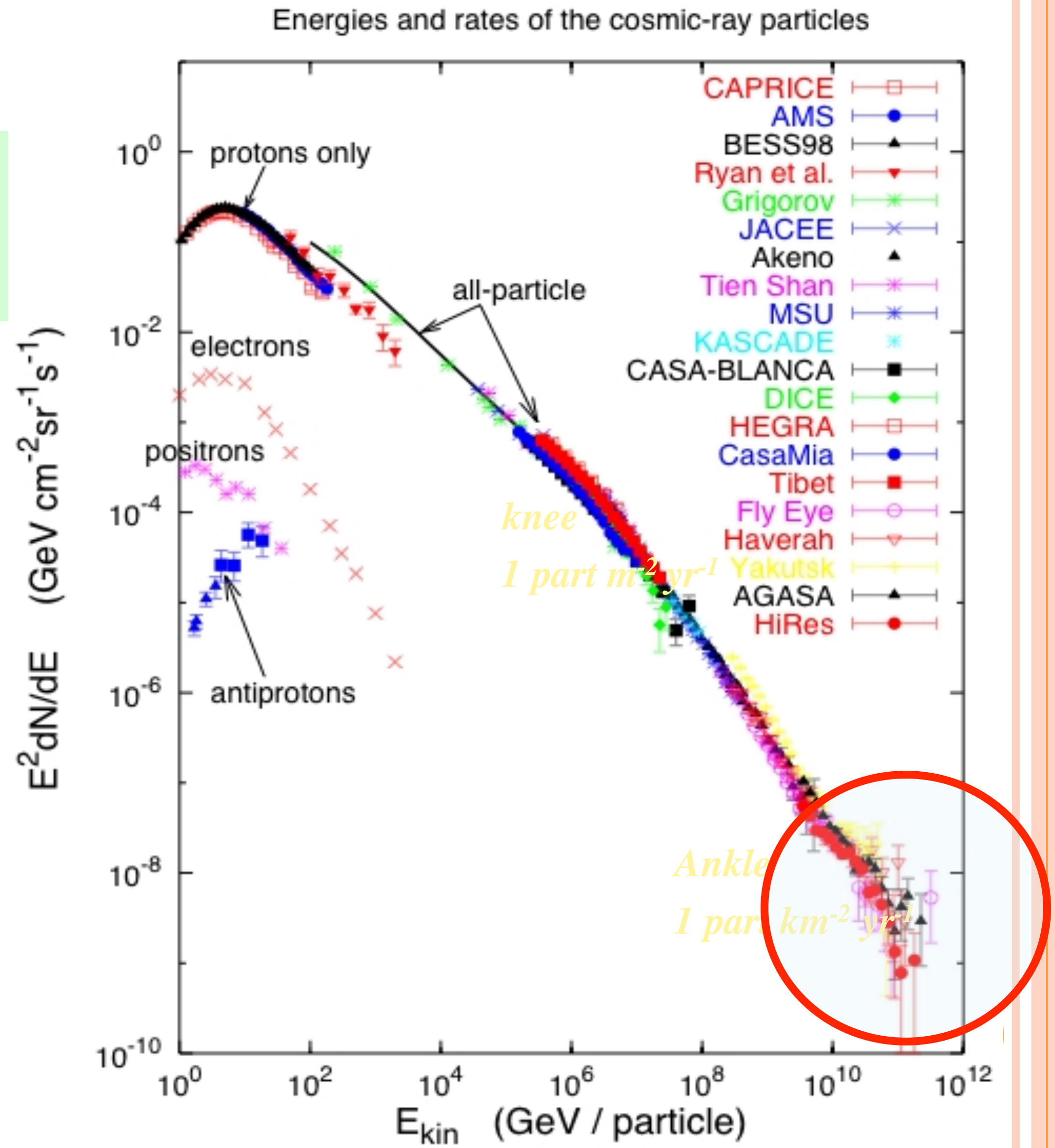
- Want to talk hardware, but first…
- Cosmic rays + neutrinos @ high energies
- Askaryan Effect in matter
- Preceding experiments

- ARA concept, design, & execution
  - Layout
  - Stations with antennas on strings
  - DAQ
- Plans

High energy Cosmic Rays

Cosmic rays have been observed to energies beyond 10^{20} eV. Their origin is unknown.

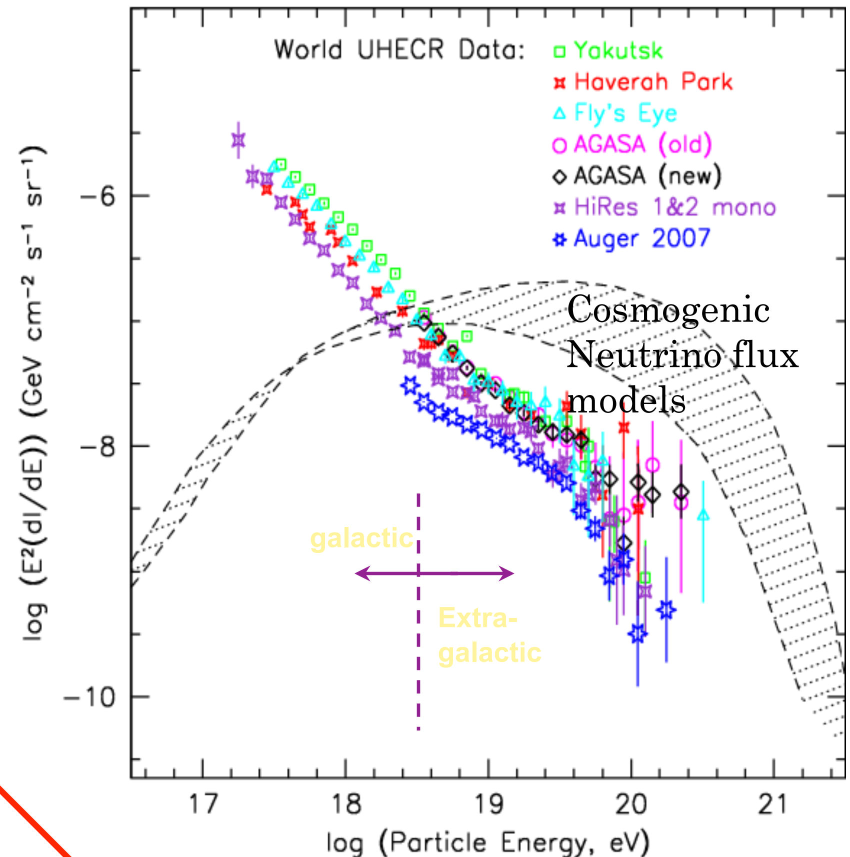
T. Gaisser 2005



ULTRA-HIGH ENERGY COSMIC RAYS REQUIRE NEUTRINOS

- Neither origin nor acceleration mechanism is known for cosmic rays above 10^{19} eV, **after 40 years!**
- **A paradox**:
  - No nearby (<50Mpc) sources observed.
    - Auger: maybe?, HiRes: No!
  - More distant sources are not observable in cosmic rays due to collisions with microwave background.
- Neutrinos at $10^{17\text{-}19}$ eV <u>required</u>* by standard-model physics
  - Lack of neutrinos:
    - **UHECRs all heavy nuclei?**
    - **"Just so" source spectra?**
    - **New physics?**

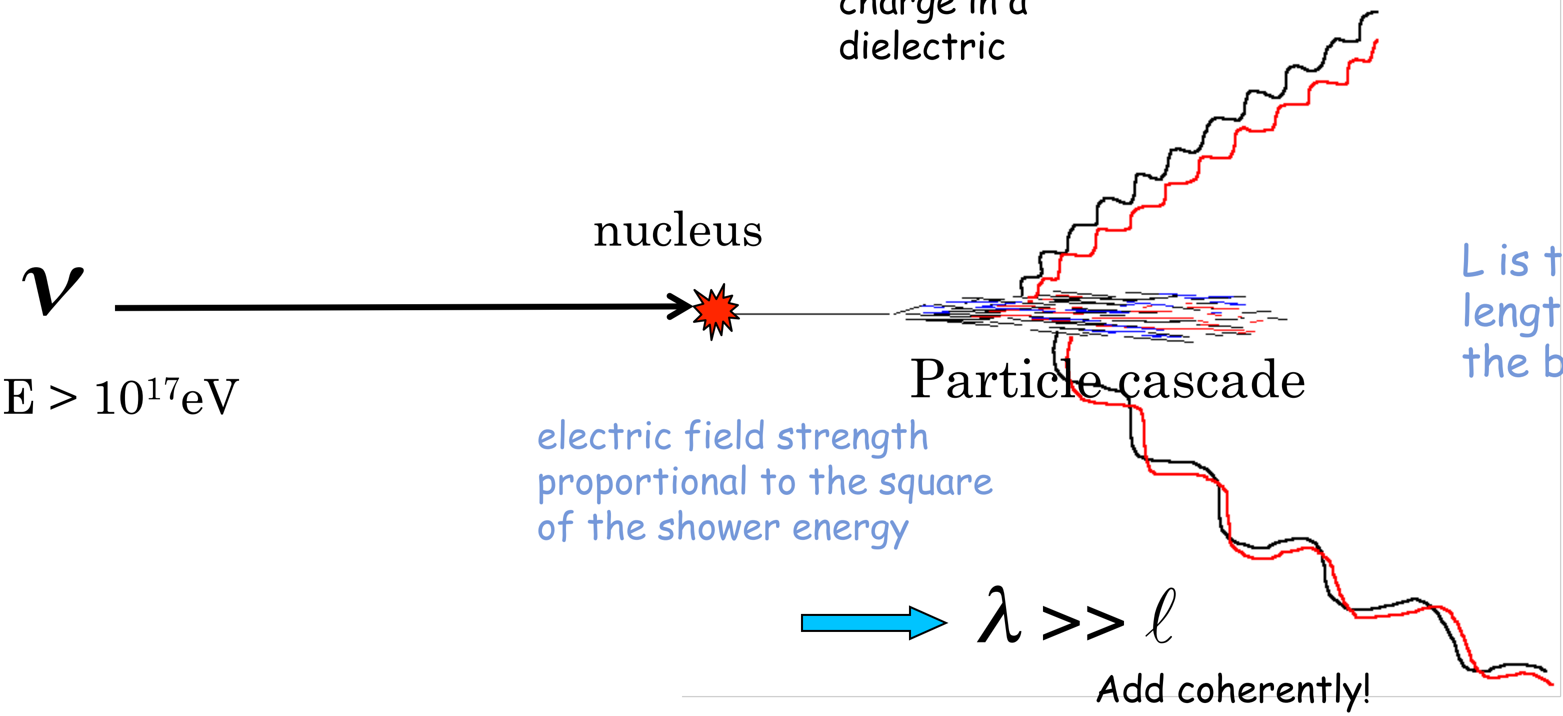
* Berezinsky & Zatsepin 1970, many others since



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

Detection mechanism proposed by G. Askaryan (1962): Measure the coherent RF signal generated by neutrino interaction in dielectric media (such as ice)

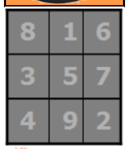
charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower → moves as a compact bunch, a few cm wide and ~1cm thick → Moving net charge in a dielectric → wavelengths shorter than the bunch length suffer from destructive interference



electric field strength proportional to the square of the shower energy

→ $\lambda >> \ell$

Add coherently!



Measurements of the Askaryan effect

- Were preformed at SLAC (Saltzberg, Gorham et al. 2000-2006) on variety of mediums (sand, salt, ice)
- 3 Gev electrons are dumped into target and produce EM showers.
- Array of antennas surrounding the target Measures the RF output

Results:

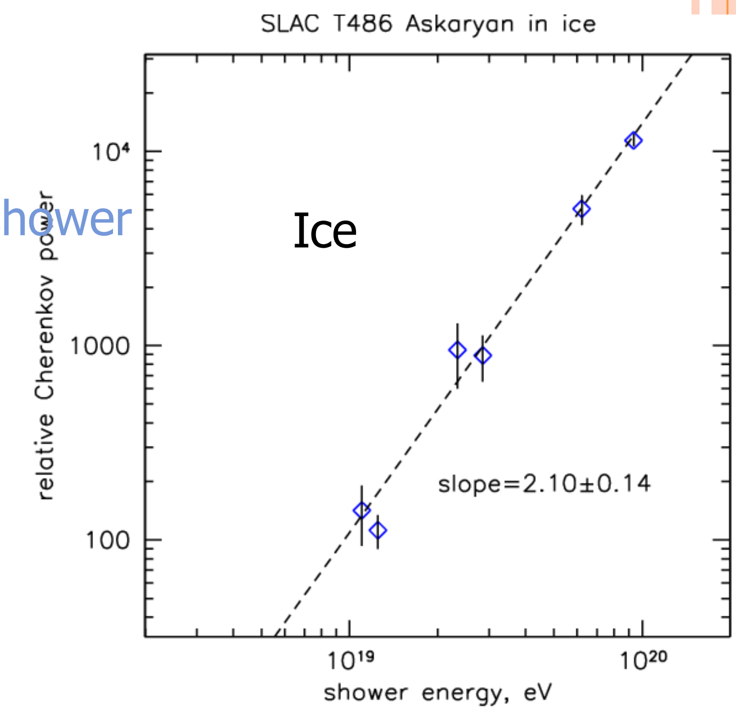
✓ RF pulses were correlated with presence of shower

✓ Expected shower profiled verified

✓ Expected polarization verified (100% linear)

✓ Coherence verified.

✓New Results, for ANITA calibration – in Ice

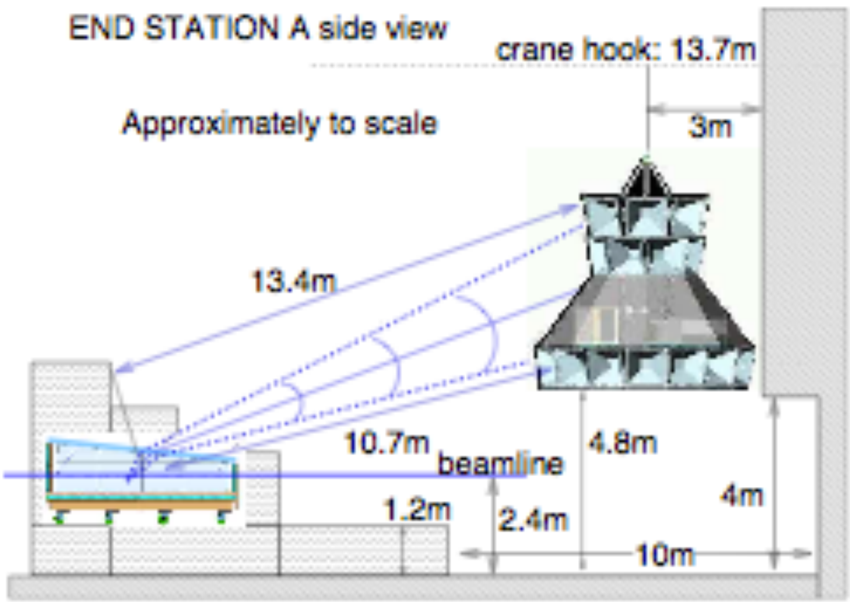


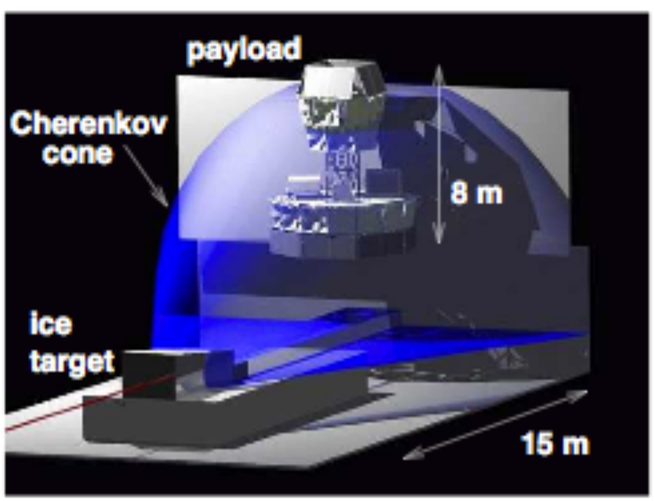
D.Salzberg, P. Gorham et al.

PHYSICAL REVIEW D **74**, 043002 (2006)

experimental results

In-Ice Measurement of Askaryan Effect (SLAC, "Little Antarctica")





PAST ANTARCTIC ASKARYAN DETECTORS…

RICE

array of single dipole antennas deployed between 100 and 300m near the Pole. covered an area of 200m x 200m. (mostly in AMANDA holes) Used digital oscilloscope on surface for data acquisition

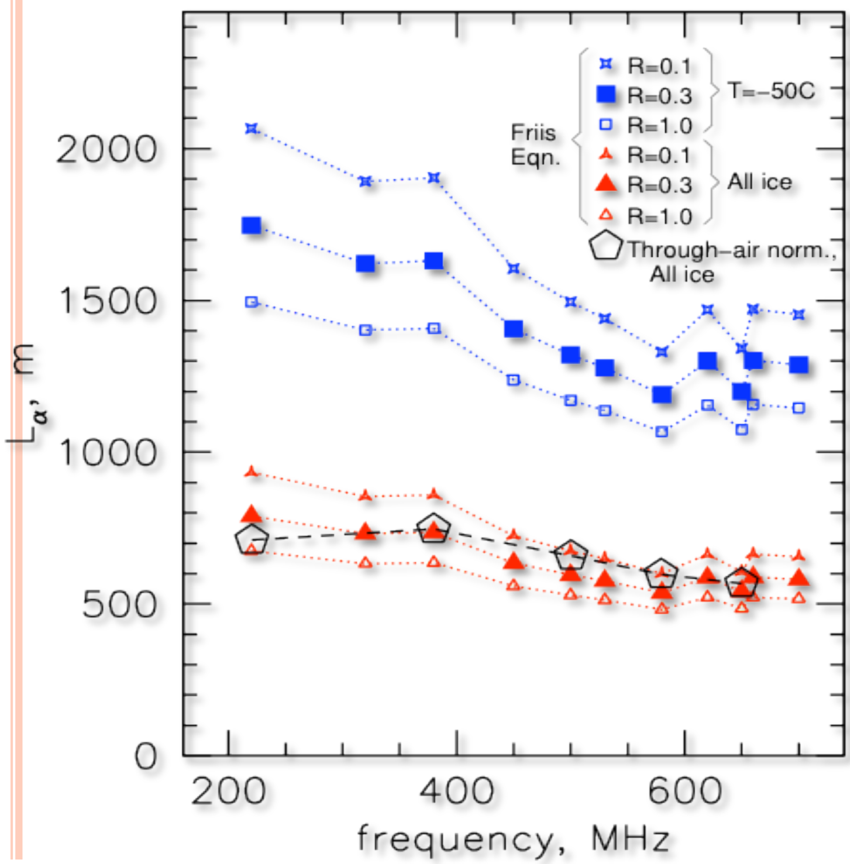
ANITA ANtarctic Impulsive Transient Antenna : surveys the ice cap from high altitude for RF refracted out of the ice (~40 km height of fly, ~1.1M km2 field of view)

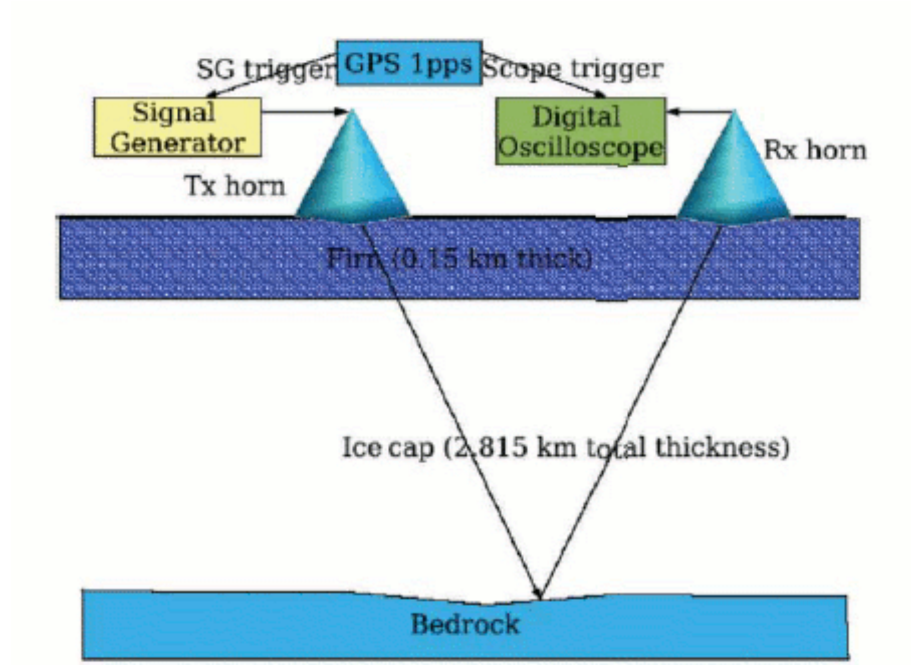
IceCube Radio (NARC)

Co deployed with IceCube at 30m, 350m and 1400 m. Full in ice digitization.

Ice Attenuation Length

- Most radio transparent material on Earth!
- Depends on ice temperature. Colder ice at the top.
- Reflection Studies (2004) (Down to bedrock, 200-700MHz): "normalize" average attenuation according to temperature profile.

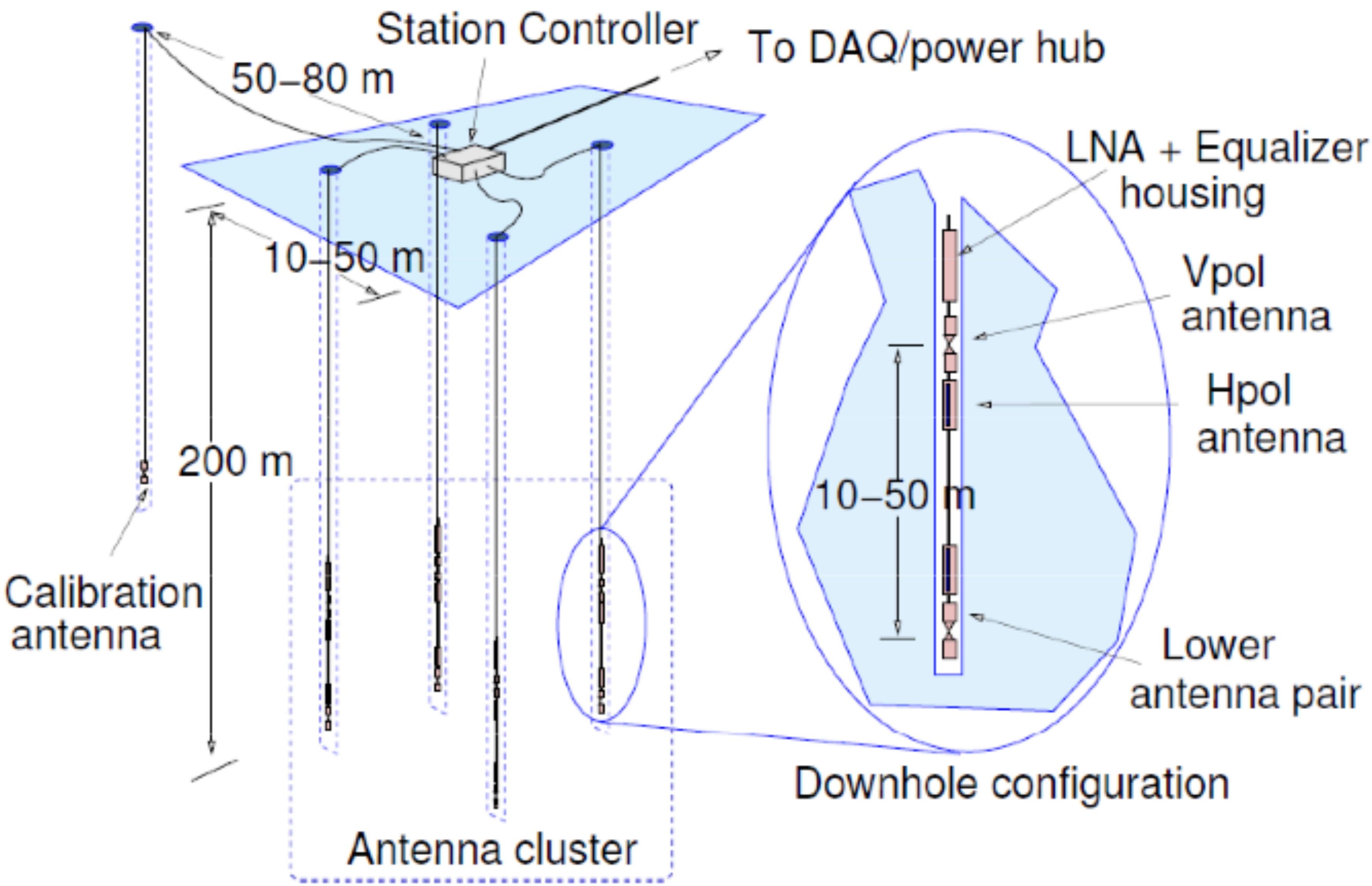




Besson et al. J.Glaciology, 51,173,231,2005

ARA-37 Layout

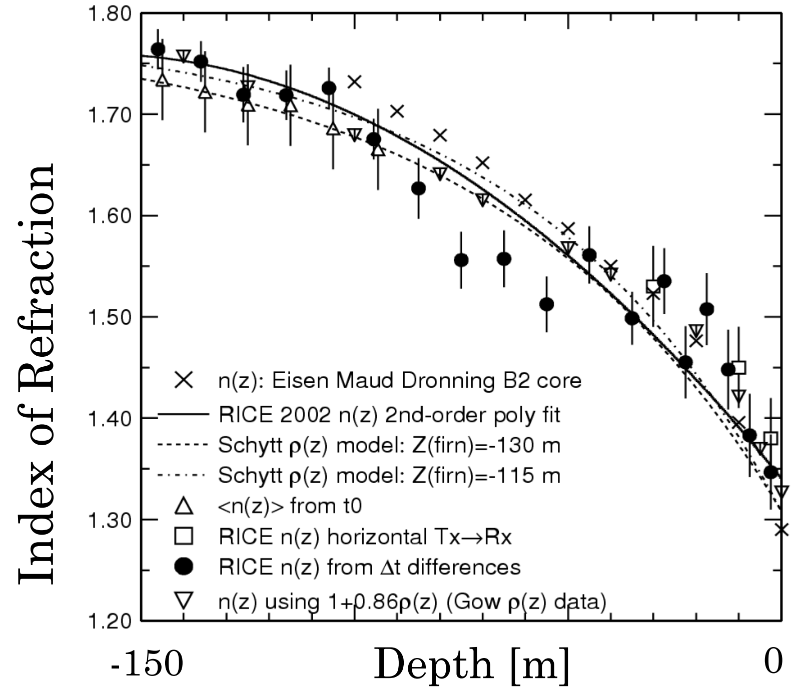
ARA Station & Antenna Cluster



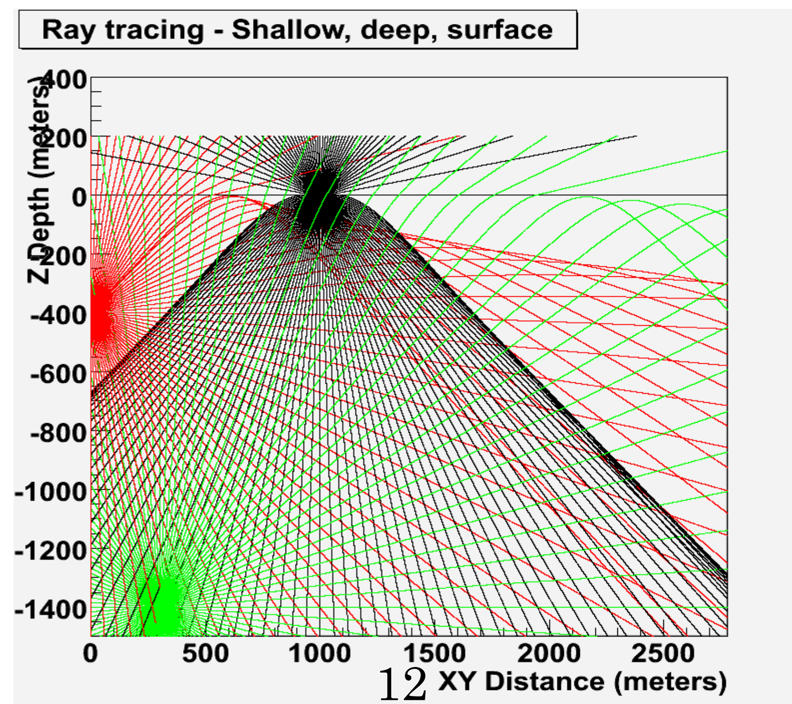
Why strings?

(rather than surface antennas)

- Acceptance: x2
  - Embedded detectors have larger acceptance due to shadowing caused by gradual change of index of refraction in the upper 200m of ice.
  - Gain at 200m depth compared to surface: > x2 event rate
- Background rejection:
  - Transient backgrounds, man made and natural come from surface!
  - Neutrino events generate vertex in the ice and the signal can be uniquely separated by basic event reconstruction.



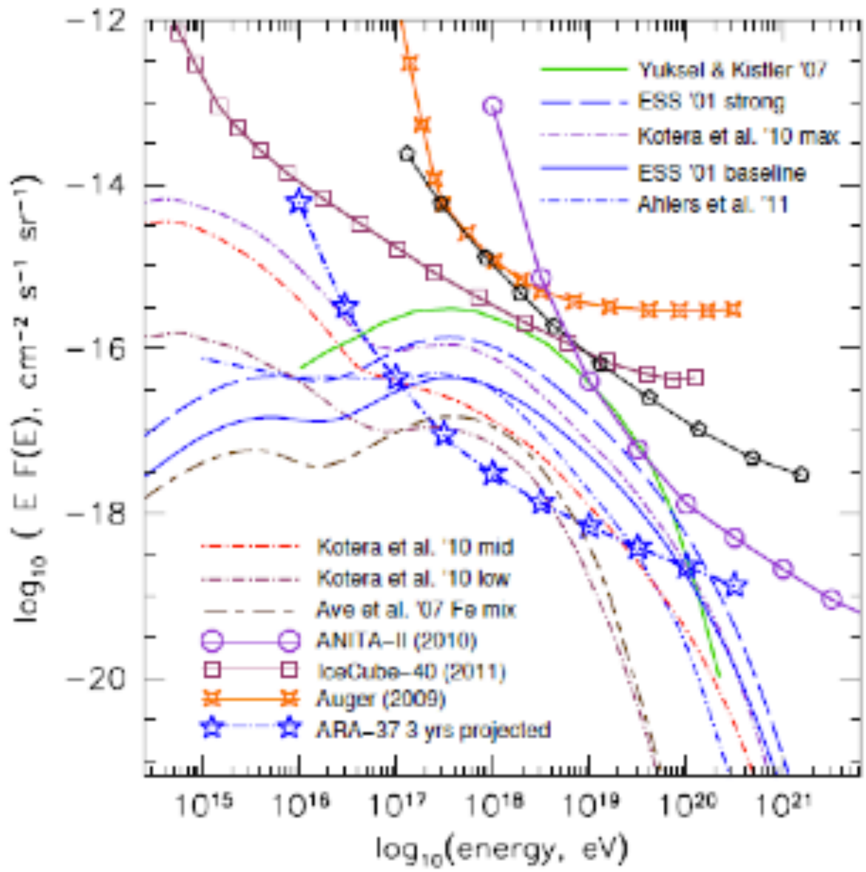
Kravchenko et al. J.Glaciology, 50,171,2004



Model & references N_ν:	ANITA (2008)	IC86 3 yrs	ARA 3 yrs
Baseline cosmogenic models:			
Protheroe & Johnson 1996[45]	0.6		59
Engel, Seckel, Stanev 2001[46]	0.33	2.4	47
Kotera *et al.* 2010[47]	0.5		59
Strong source evolution models:			
Engel, Seckel, Stanev 2001[46]	1.0		148
Kalashev *et al.* 2002[48]	5.8	4.8	146
Barger *et al.* 2006[50]	3.5		154
Yuksel & Kistler 2007[51]	1.7		221
Mixed-Iron-Composition:			
Ave *et al.* 2005[52]	0.01		6.6
Stanev 2008[53]	0.0002		1.5
Kotera *et al* 2010[47] upper	0.08		11.3
Kotera *et al.* 2010[47] lower	0.005		4.1
Fermi cascade-bounded models:			
Ahlers *et al.* 2010[55]	0.09	4.6	20.7
Waxman-Bahcall (WB) fluxes:			
WB 1999, evolved[16]	1.5	75	76
WB 1999, standard[16]	0.5	16.5	27

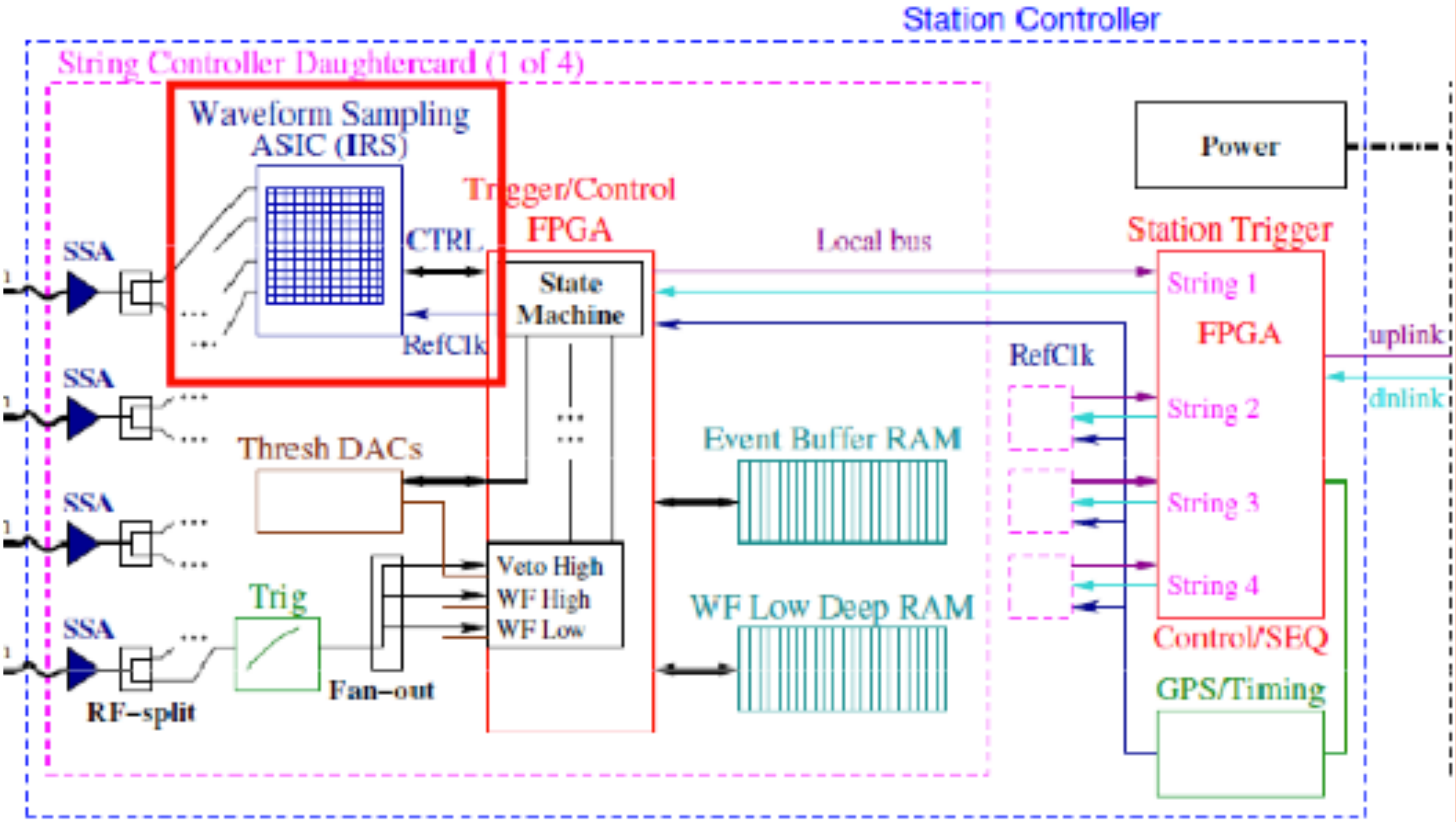
GZK Sensitivity Limits

- ARA-37 will extend the search for GZK neutrinos into and past the "mainline" models
  - Factor of 100 improvement or better depending on model
- Modular (station-based) design of ARA lends itself easily to extension to Tton scale detector



Hardware

ARA Station Level Setup

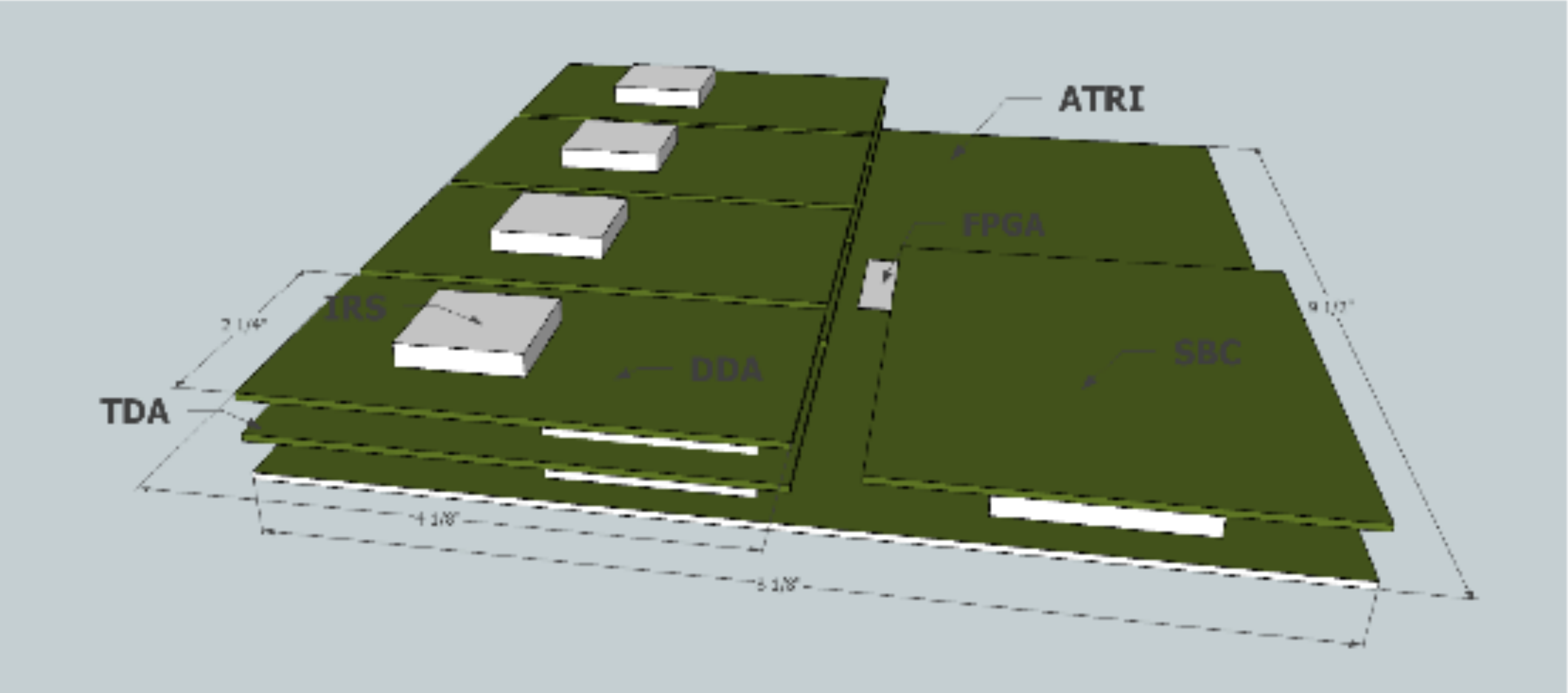


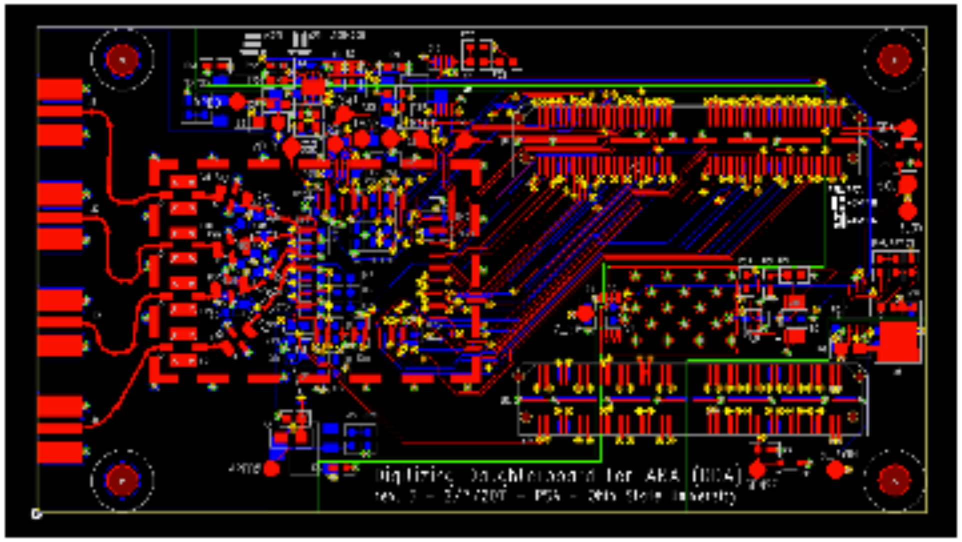
Ice Radio Sampler (IRS) Specifications

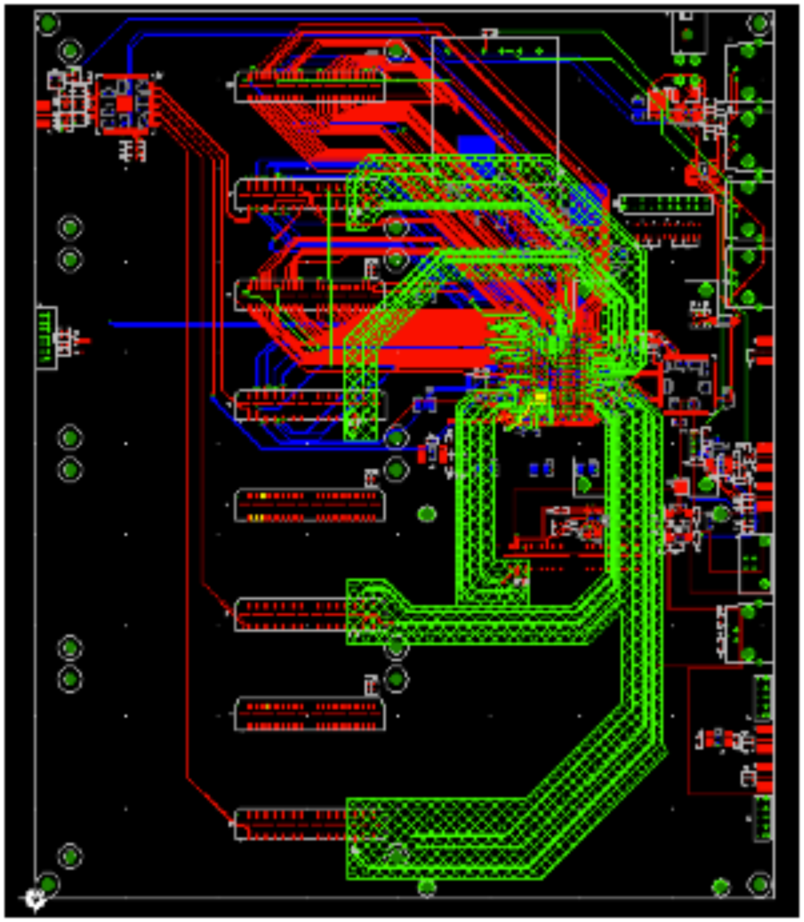
32768	samples/chan (16-32us trig latency)
8	channels/IRS ASIC
8	Trigger channels
~9	bits resolution (12-bits logging)
64	samples convert window (~32-64ns)
1-2	GSa/s
1	word (RAM) chan, sample readout
16	us to read all samples
100's	Hz sustained readout (multibuffer)

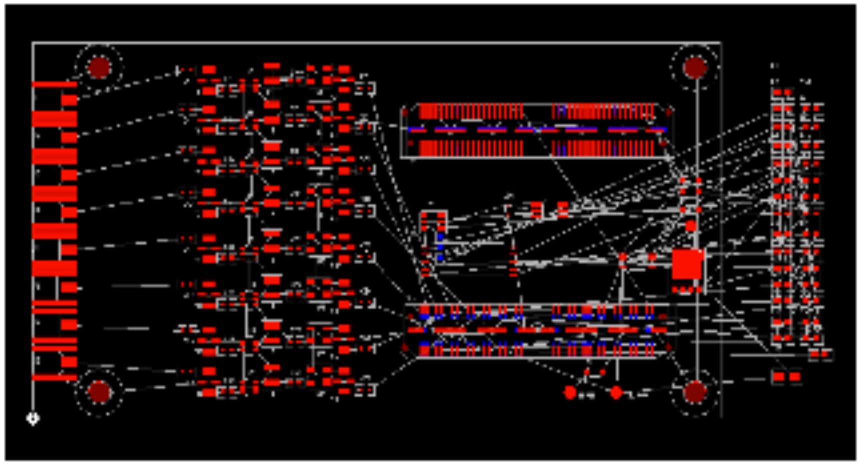
- Strictly only 5 channels necessary
  - 4x antenna, 1x reference channels
  - Note: because can sample and digitize/readout concurrently, could generate ~40MB/s/IRS2

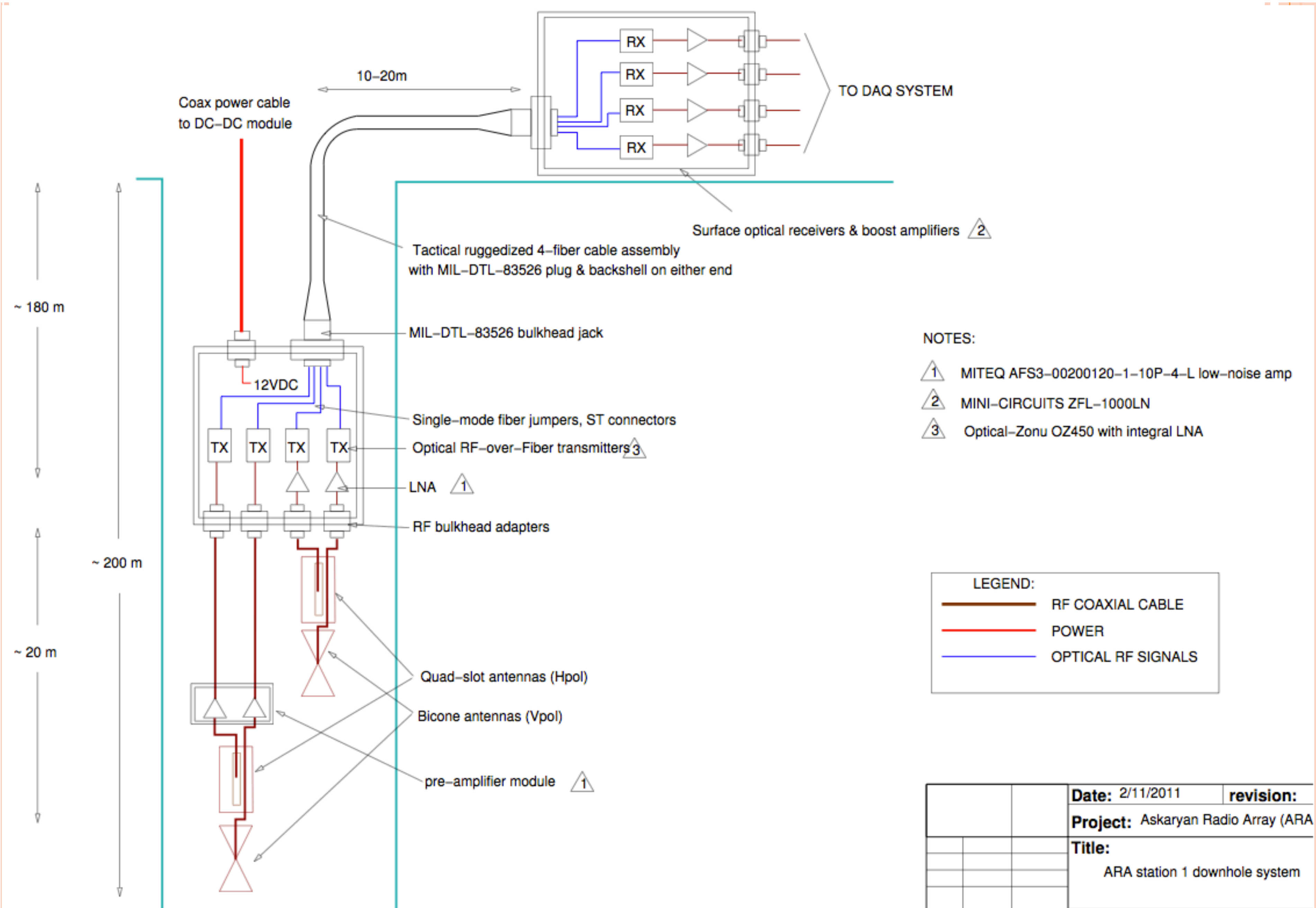
DAQ



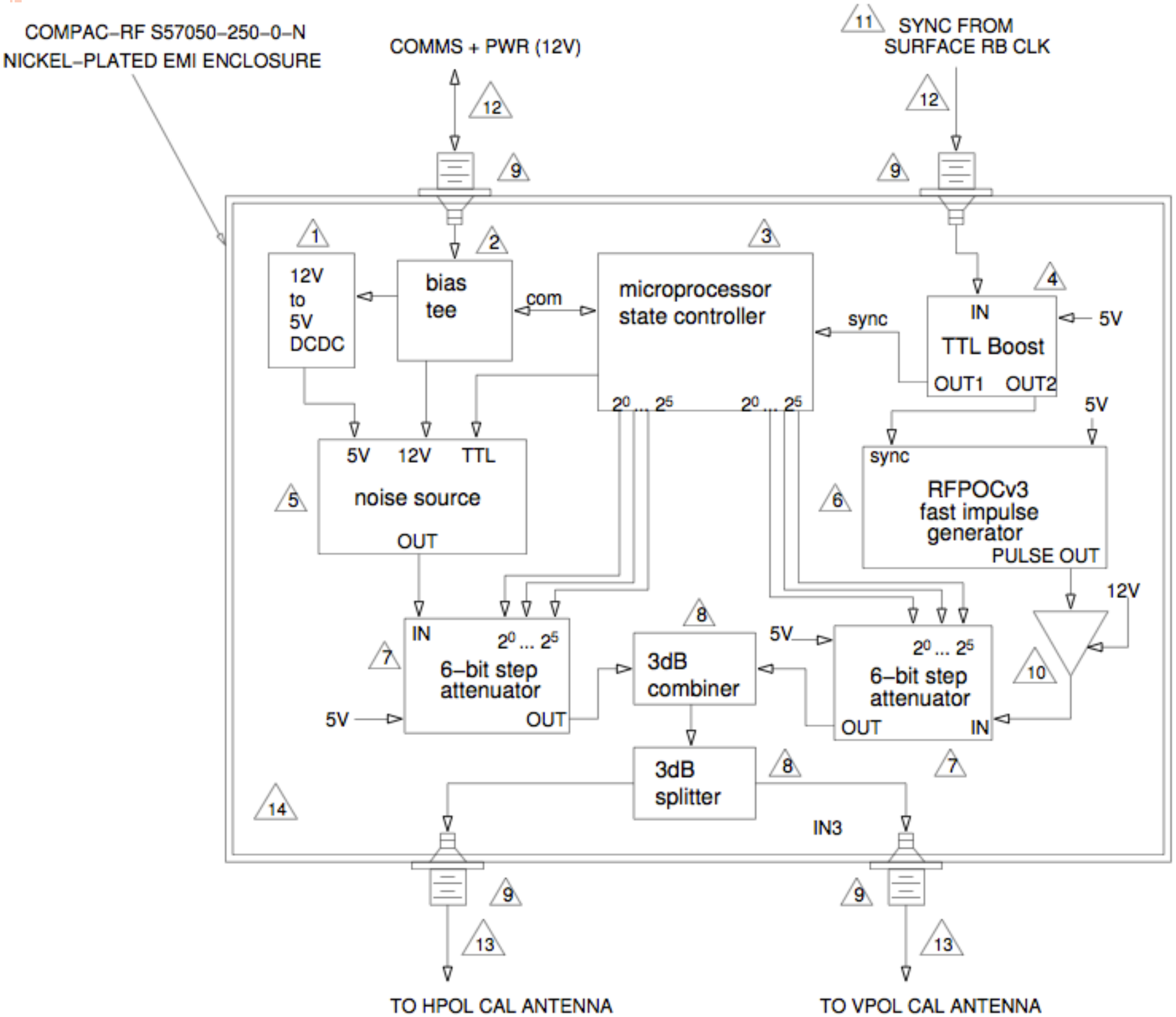

Digitizing Daughterboard for ARA (DDA)






RX
RX
RX
RX
TO DAQ SYSTEM
10–20m
Coax power cable
to DC–DC module
Surface optical receivers & boost amplifiers 2
Tactical ruggedized 4–fiber cable assembly
with MIL–DTL–83526 plug & backshell on either end
~ 180 m
~ 200 m
~ 20 m
MIL–DTL–83526 bulkhead jack
12VDC
Single–mode fiber jumpers, ST connectors
TX
TX
TX
TX
Optical RF–over–Fiber transmitters 3
LNA 1
RF bulkhead adapters
Quad–slot antennas (Hpol)
Bicone antennas (Vpol)
pre–amplifier module 1
NOTES:
1 MITEQ AFS3–00200120–1–10P–4–L low–noise amp
2 MINI–CIRCUITS ZFL–1000LN
3 Optical–Zonu OZ450 with integral LNA
LEGEND:
RF COAXIAL CABLE
POWER
OPTICAL RF SIGNALS
Date: 2/11/2011
revision:
Project: Askaryan Radio Array (ARA
Title:
ARA station 1 downhole system

CALIBRATION PULSER & NOISE SOURCE



NOTES:

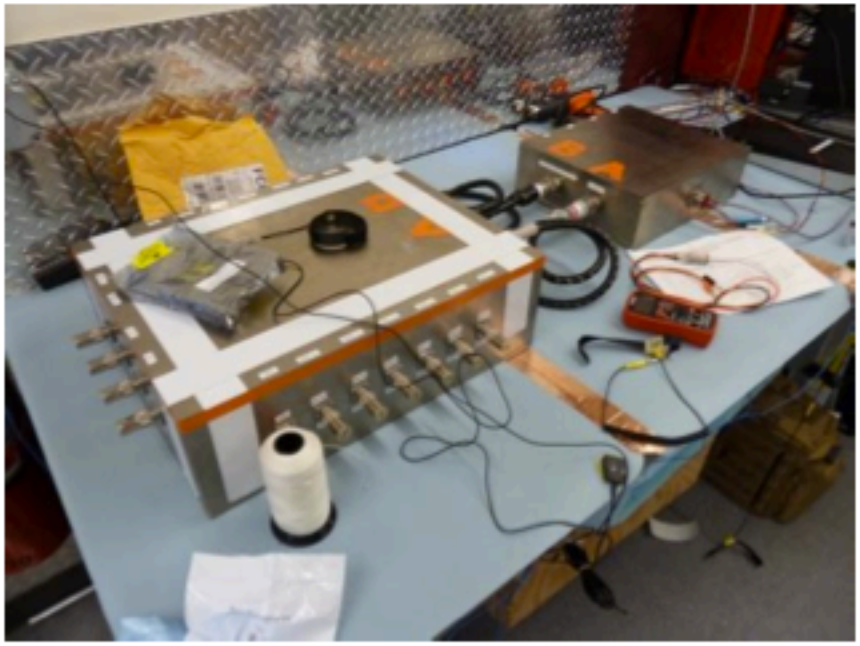
1. National LMZ1200–series switcher
2. MINI–CIRCUITS ZX85–12G+ BIAS TEE
3. TBD microcontroller
4. UH ID LAB TTL–BOOST 5V TTL DUAL DISCRIMINATOR
5. MICRONETICS NMA2510–2T BROADBAND NOISE SOURCE
6. UH IDLAB, L. RUCKMAN DESIGN RFPOCV3 PULSER
7. MINI–CIRCUITS ZSAT–31R5 STEP ATTENUATOR
8. MINI–CIRCUITS ZX10–2–12+ 2–1200MHZ SPLITTER
9. FAIRVIEW MICROWAVE SM4233 N–SMA ADAPTER
10. MINI–CIRCUITS ZKL–1R5 AMPLIFIER
11. DISABLE SURFACE SYNC PULSE TO DISABLE PULSER
12. CABLES FROM SURFACE: HELIAX LDF2–50 3/8" DIAMETER
13. CABLES TO XMIT ANTENNAS: TIMES M–WAVE LMR600
14. INTERNAL RF–CABLES: MINI–CIRCUITS 086– OR 141– SERIES FLEX–INTERCONNECTS, OR ASTROLAB MINI–BEND, OR EQUIVALENT

Date: 3/18/2011 **revision:** 1
Project: Askaryan Radio Array (ARA)

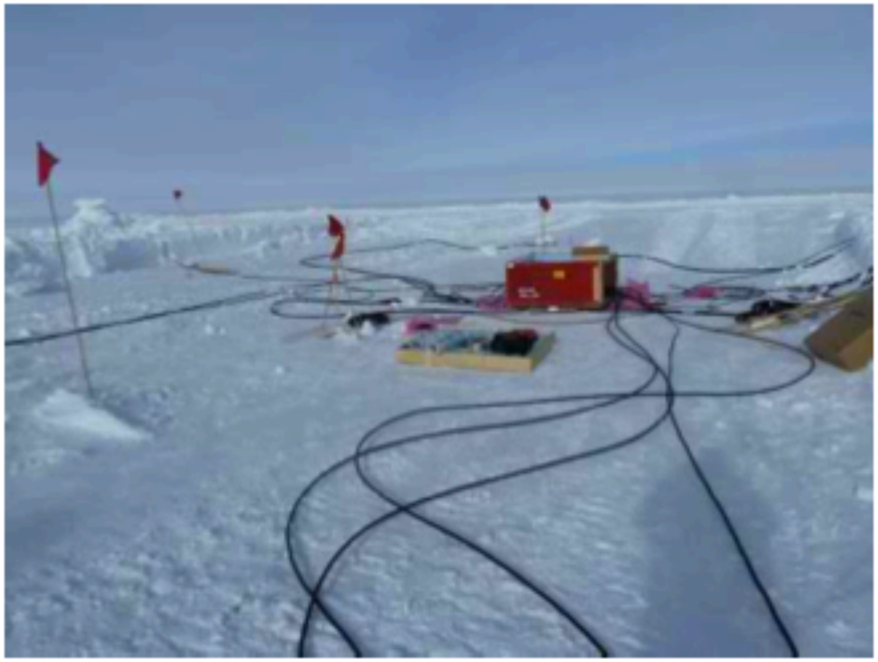
TestBed

- Installed a mix of five different types of antennas, shallow & deep, Vpol and Hpol, and tested transient detectors as well
- Site is quiet save for signals from Met balloons, aircraft, and NGO handhelds (should be quieter still in Winter)
- Preliminary (uncalibrated) look at the data, timing resolution of ~170ps, loud pulsers, and verified hardware for Antarctic deployment

2010-2011 Deployment: "TestBed"



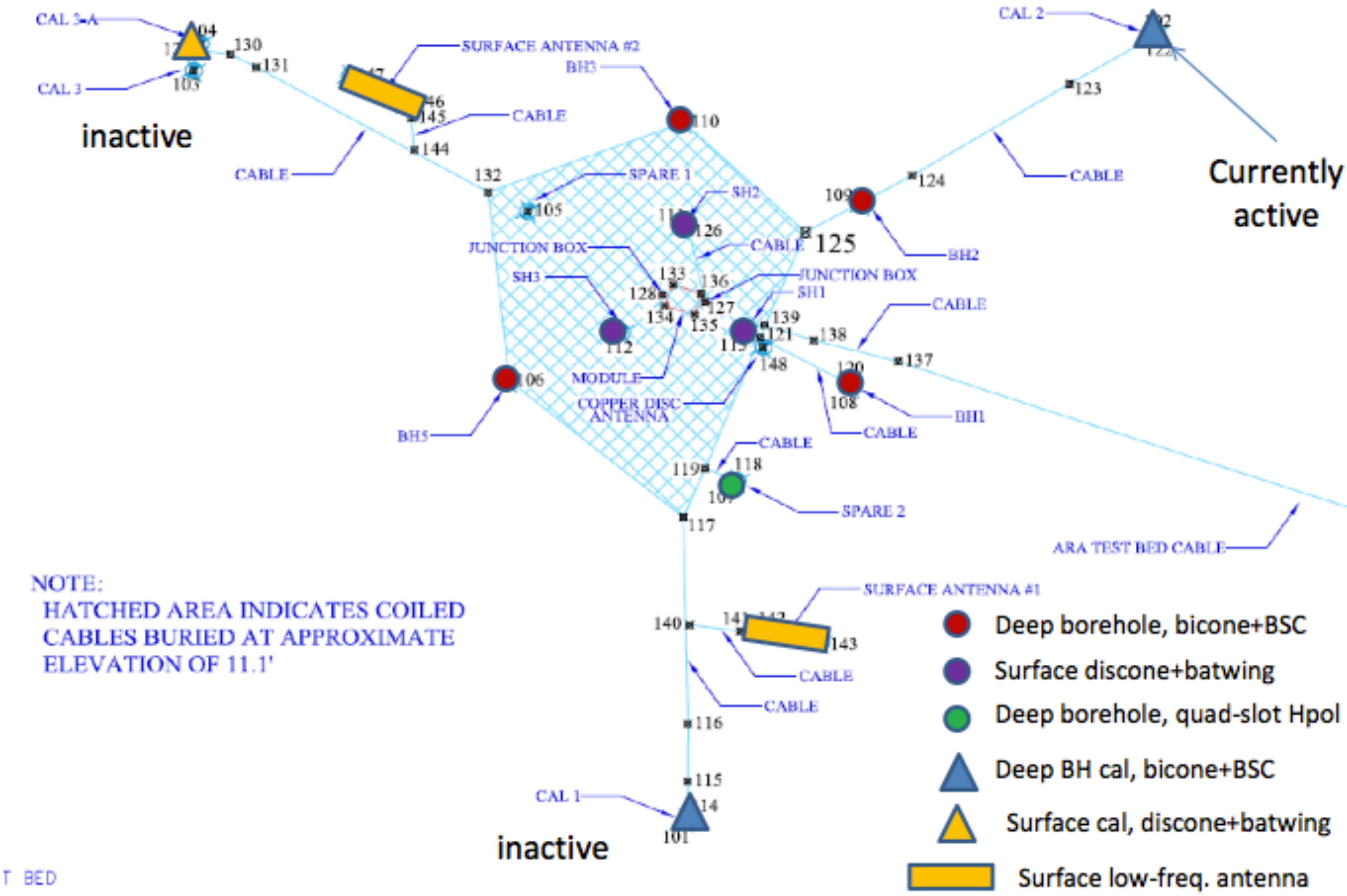
Testbed electronics plus DC-DC converter box



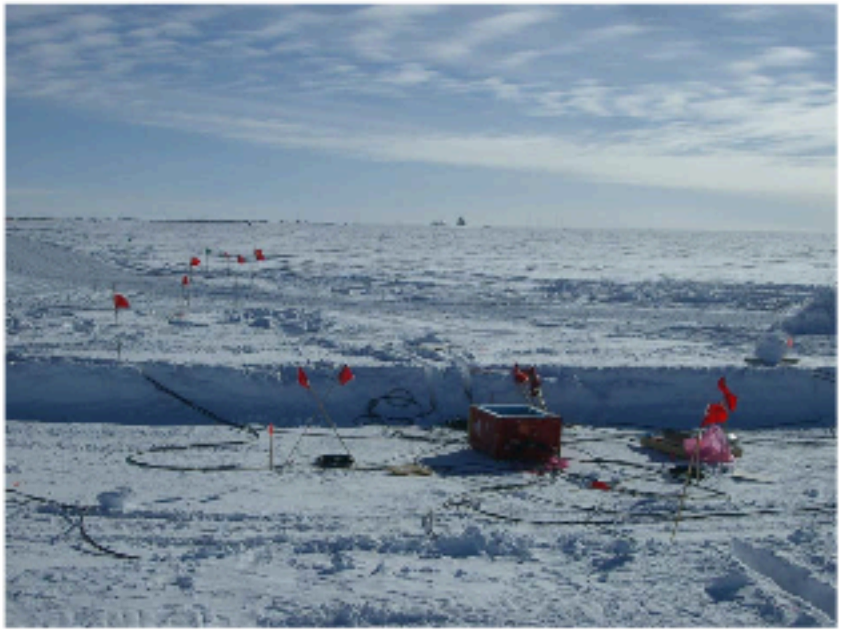
Electronics at deployment site

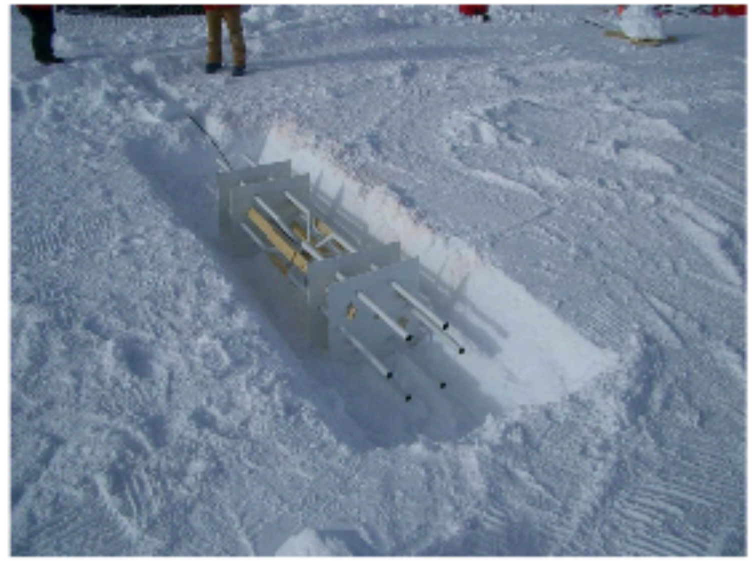
ARA TEST BED ASBUILT

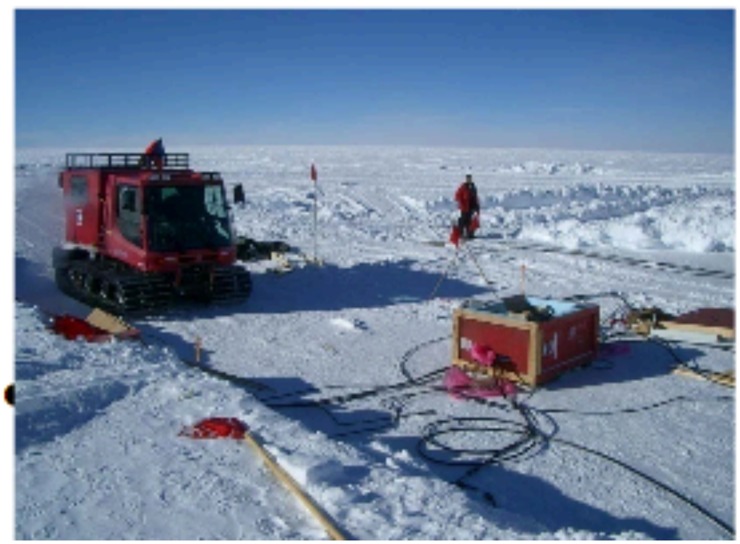
SURVEYED ON 12/31/10 & 01/05/11

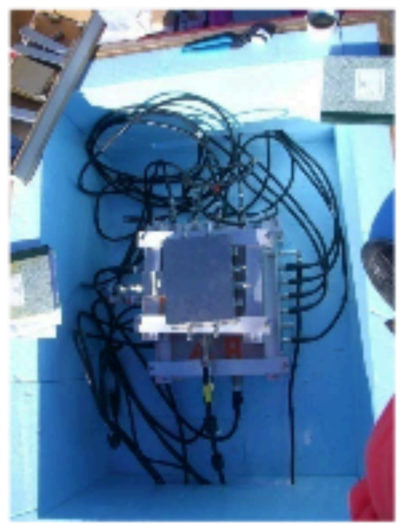


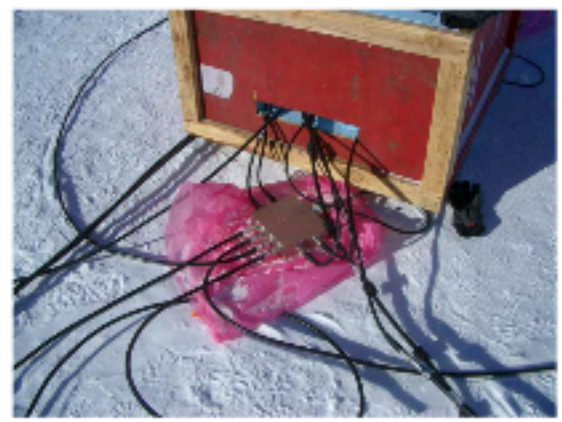
Testbed site & hardware



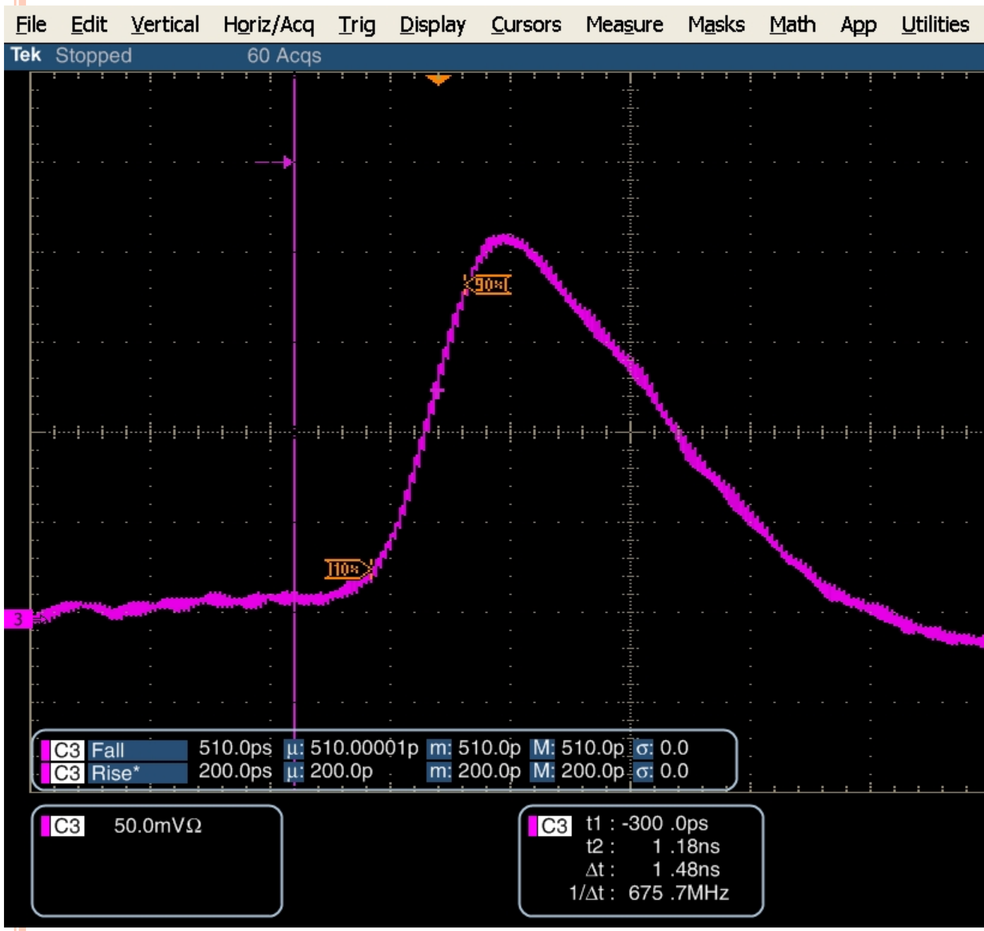








Deep pulser installation



ARA Schedule & Plans

- May 2011 arxiv paper on TestBed performance and ARA-37 acceptance
- June 2011 Full proposal to the NSF
- 2011-2012 Austral Summer deployment of first full ARA Station (power tethered to the station)
- 2012-2013 Additional station deployments, transition to autonomous power
- 2015 ARA-37 >200 km^3 fiducial volume

BACKUP SLIDES:

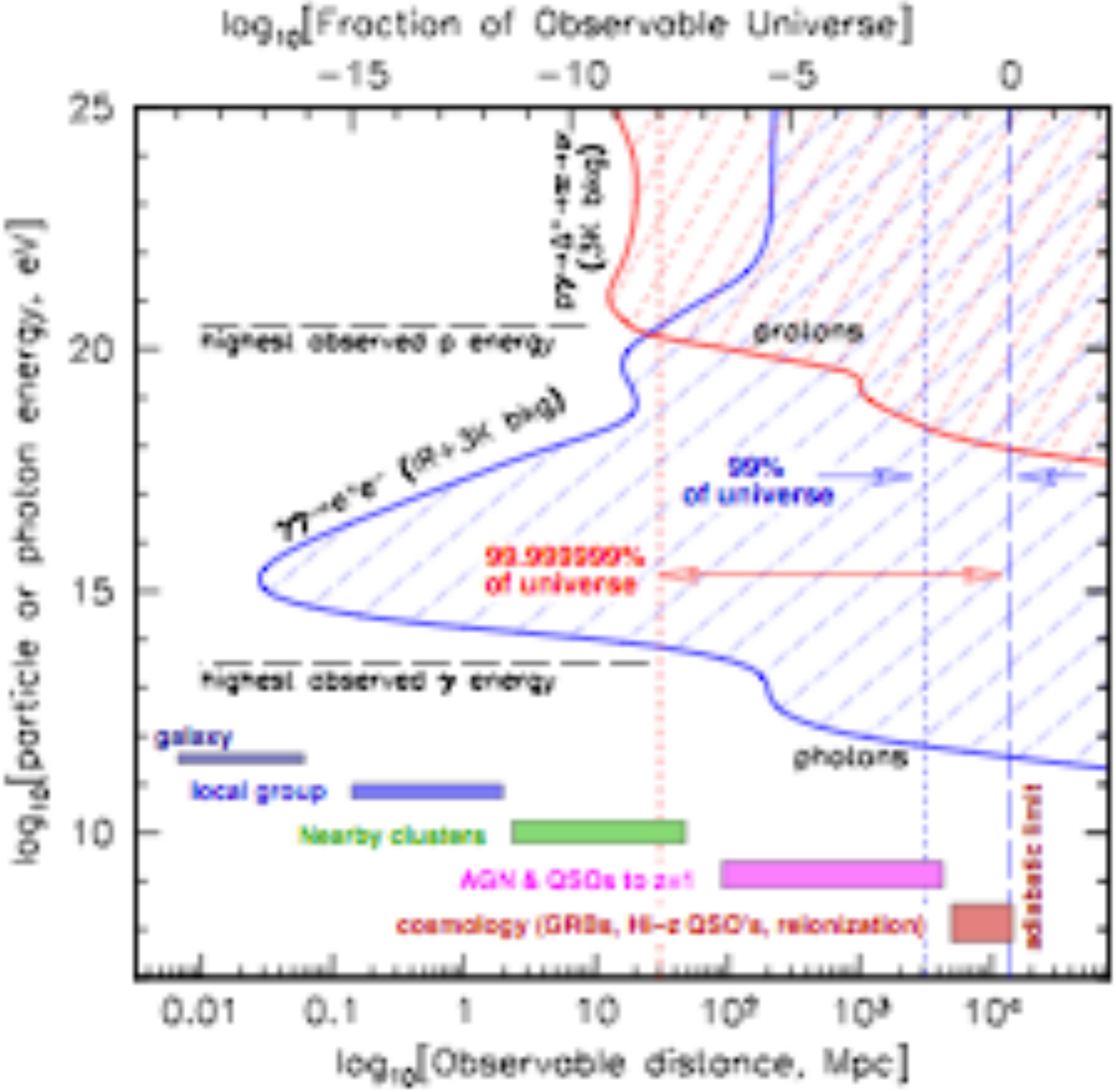
ARA 2010-2011

Test Bed + Pulsers

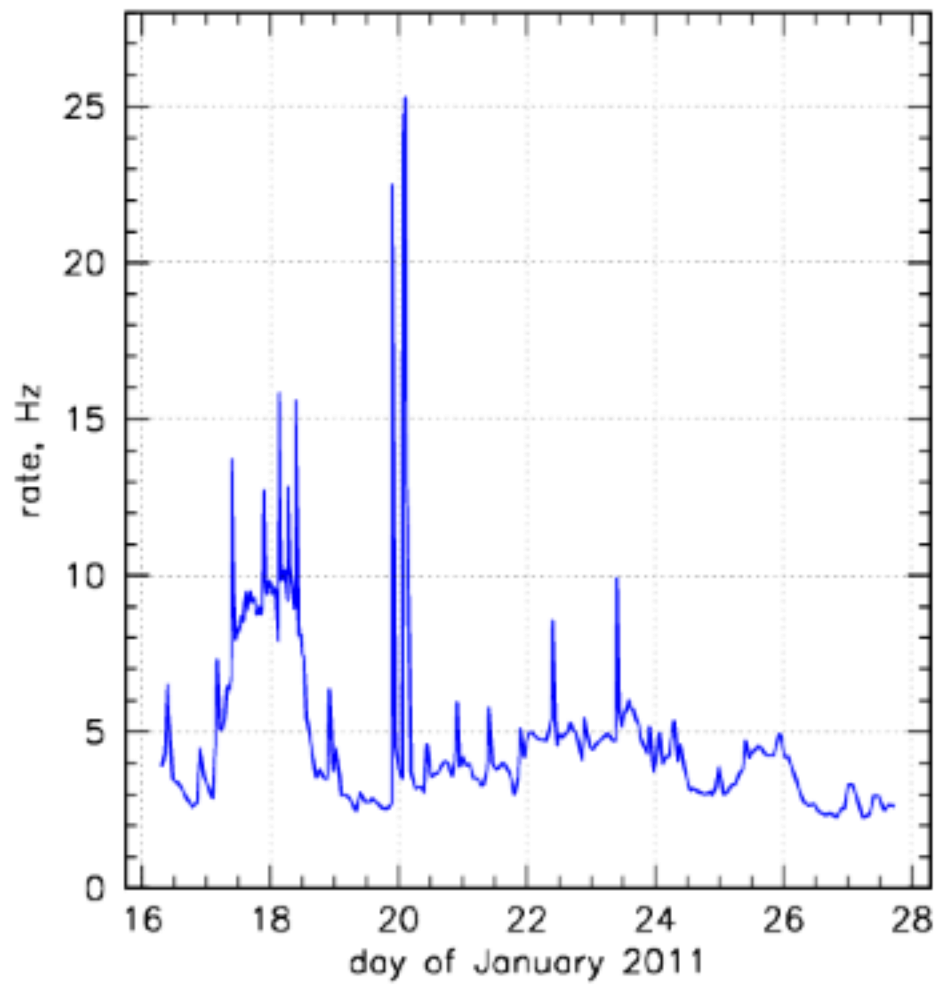
Drilling (hot water + RAM)

Wind Turbines

Neutrino Astronomy: Why?

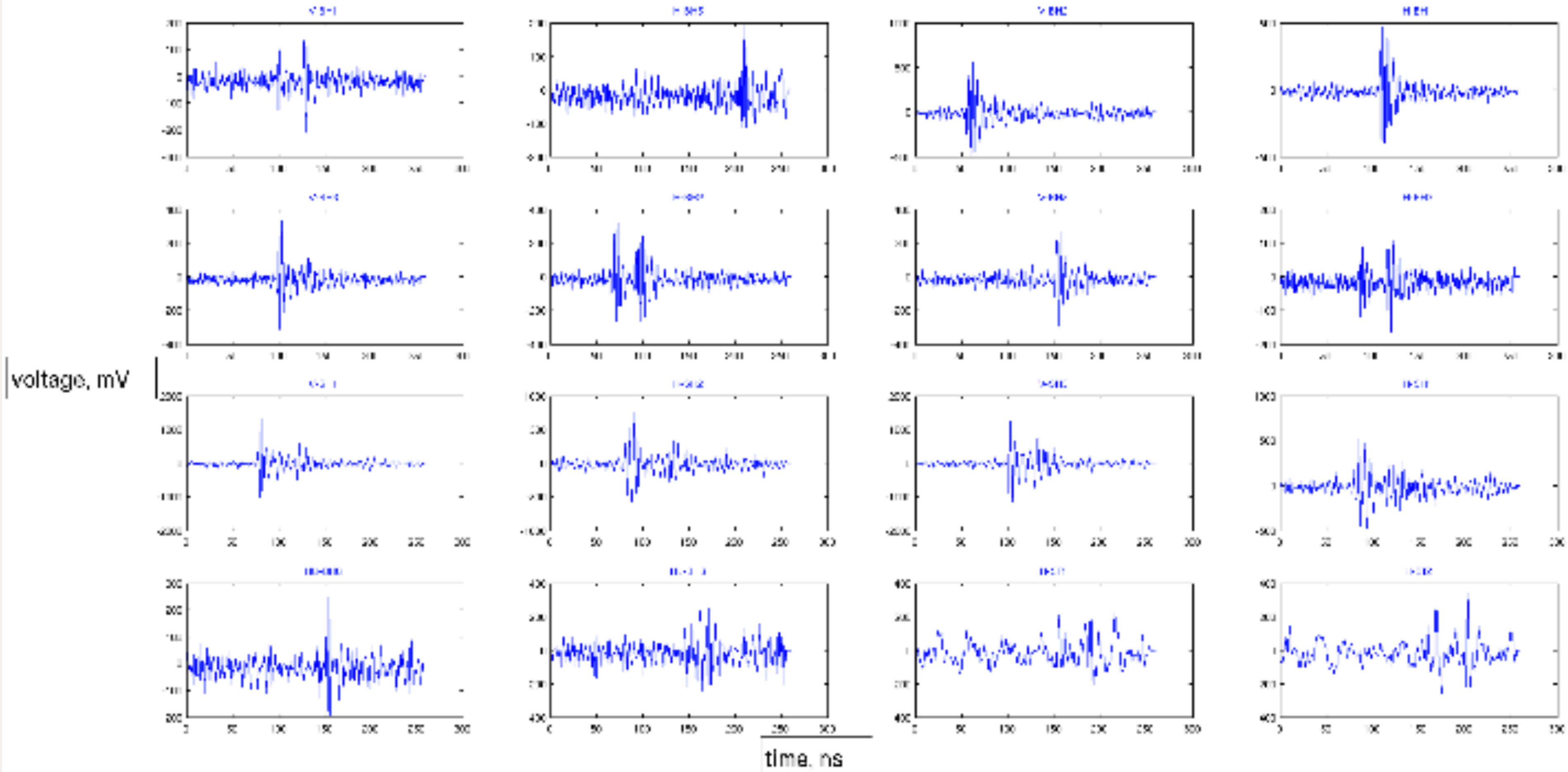


Rates for last ~11 days



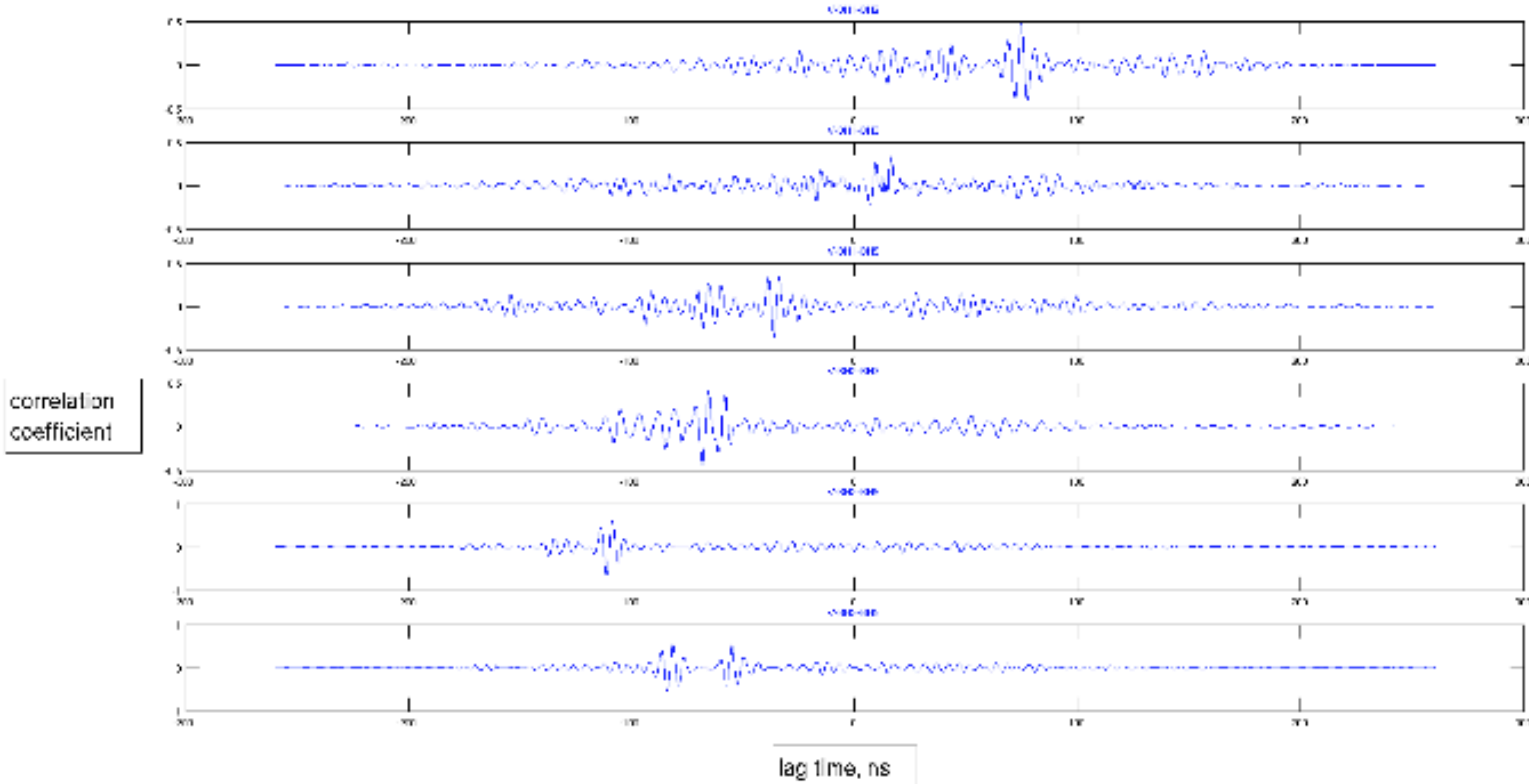
- Generally very quiet, RF events are almost all thermal-noise triggers
  - Data check this morning, cal pulser + thermal was all I could see!
- "Base" rate here is 1.5Hz, so currently ~1Hz of RF triggers
- Above 6-8Hz, livetime effect becomes noticeable (<90% or so)
- So far we are running at very high average livetime, probably >95%
- Good news for ARA!

Data: Cal pulser



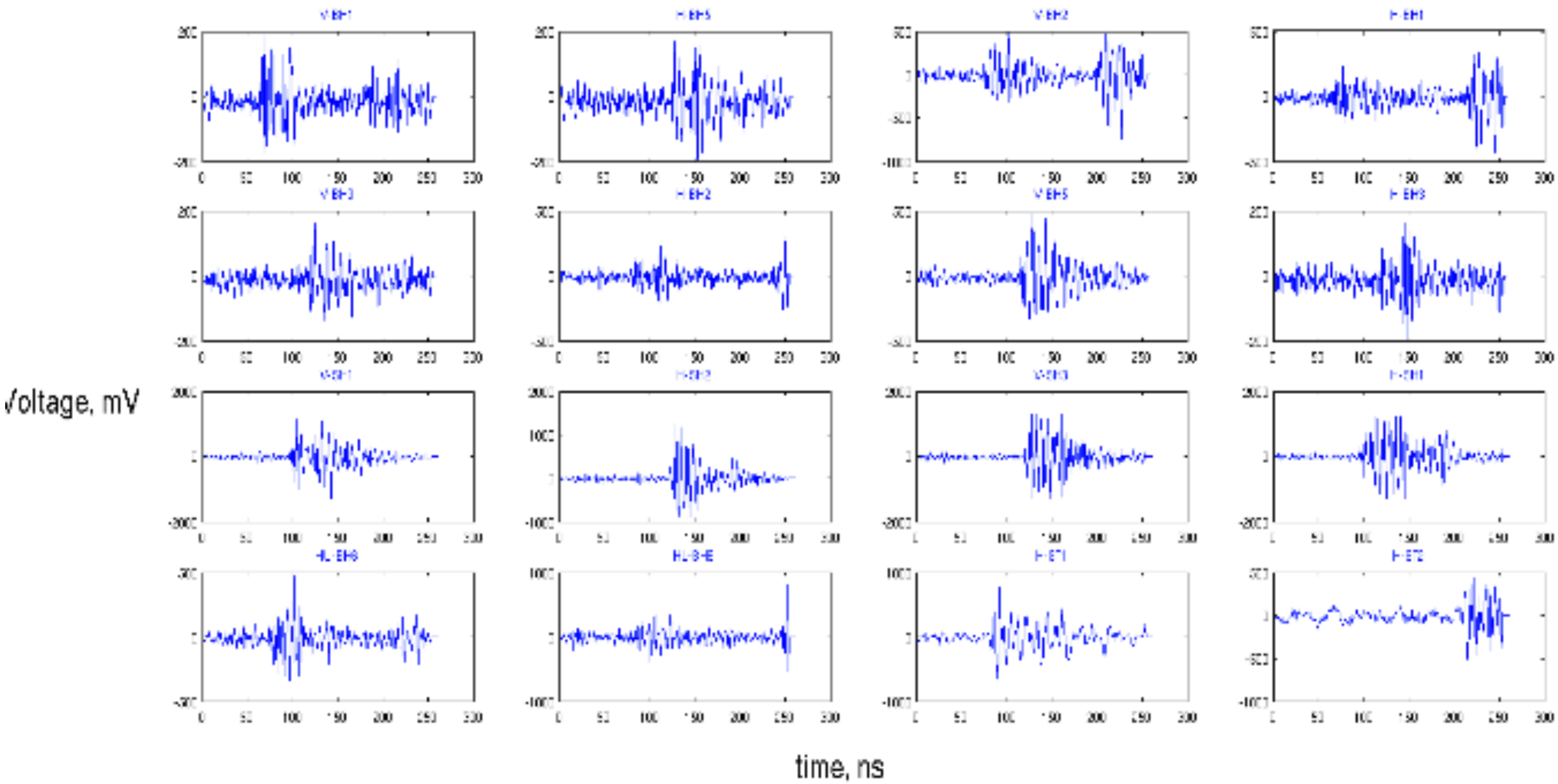
- Cal pulser #2 was used (not the cleanest, but had interesting reflections)
- Clean separation of polarizations (recall have both Vpol+Hpol xmit)

Cal pulser cross-correlations



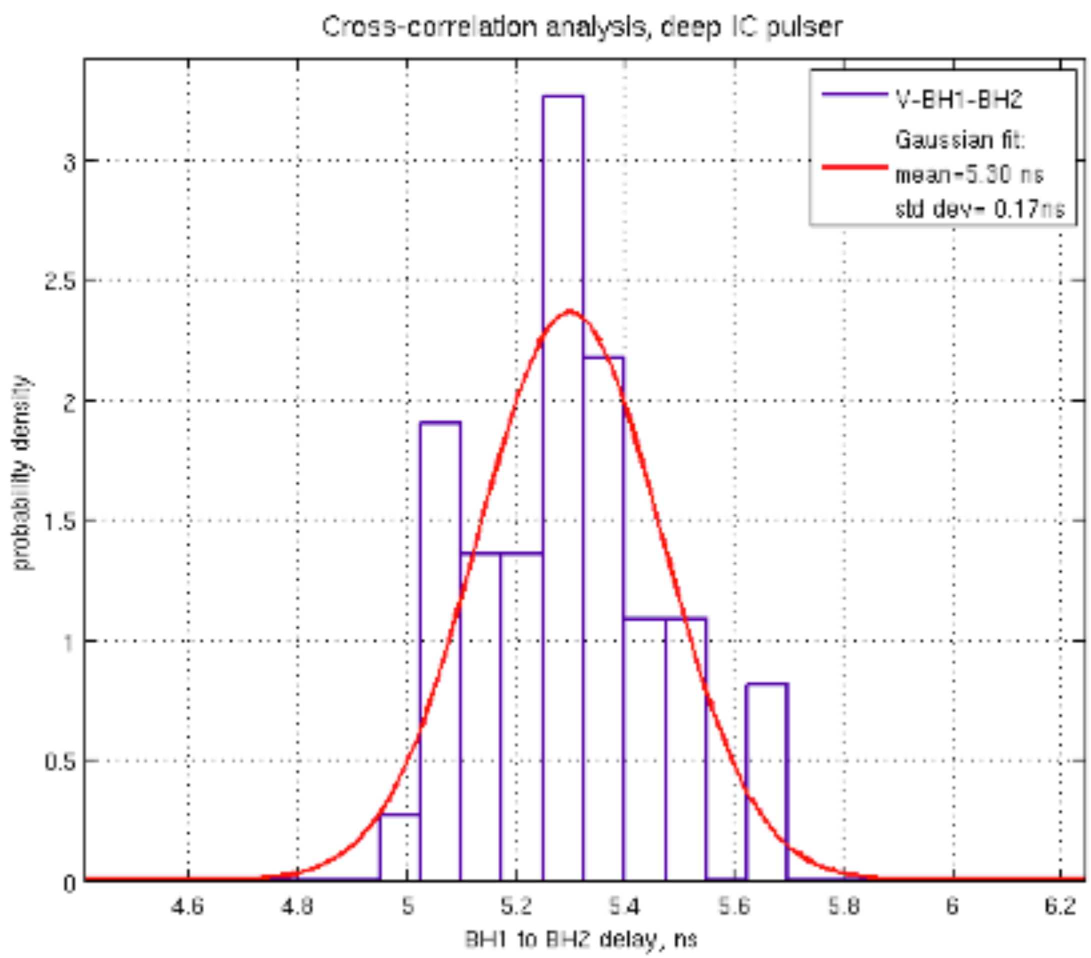
- Here only 6 baselines from 4 Vpol deep antennas shown
- Cross-correlation, both primary and reflections evident

Data: deep pulser



- Deep pulser structure a bit mushy, dominated by lower frequencies
- Lots of Hpol, and a complex reflection at ~120 ns seen in both

Timing resolution, take 1



Here use uncalibrated data, look at deep pulser peak from antennas V1 and V2 (BH1 and BH2)

Resolution is about 170 picoseconds

Corresponds to about 0.2° for the ~10m separation of these antennas

- **About 3 cm resolution in the ice**

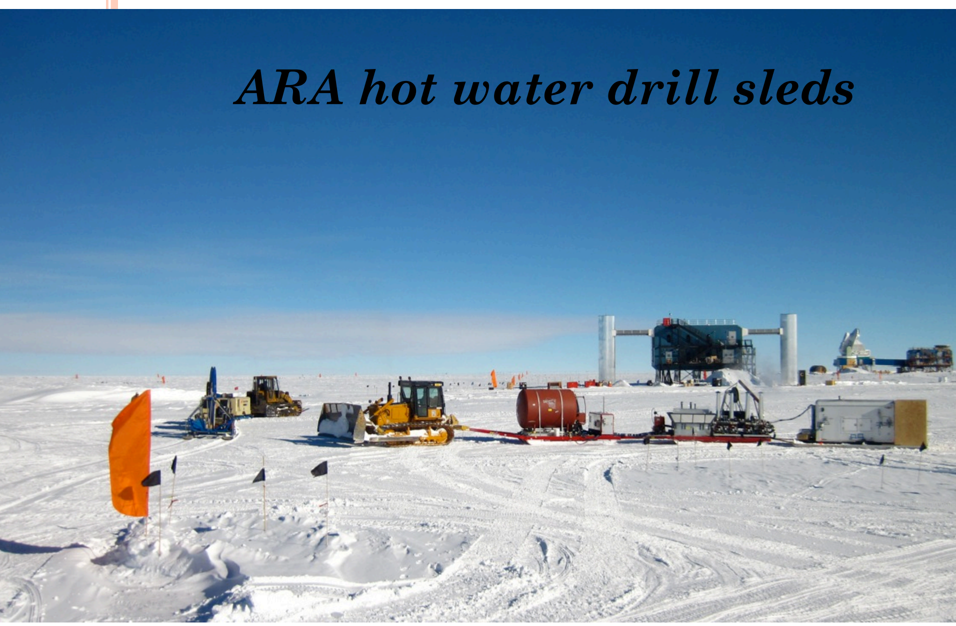
Good news: calibration will make it even better

Drilling

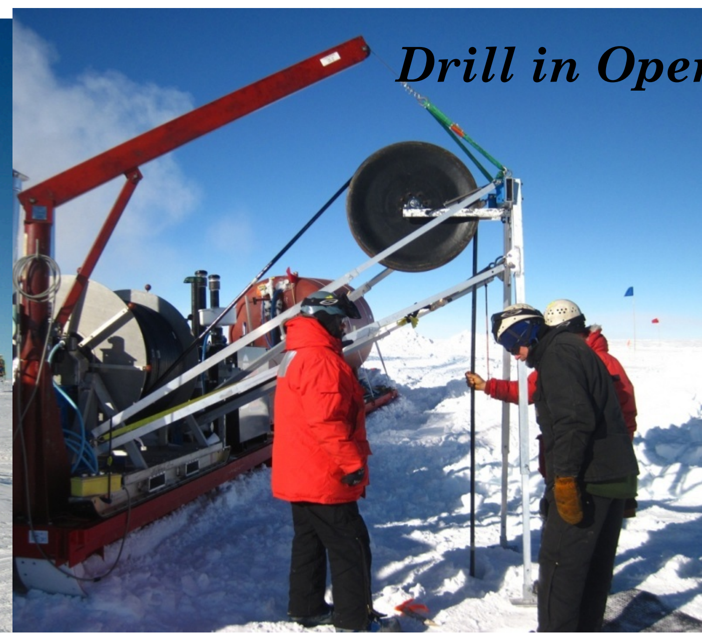
- Two drills: RAM drill (rapid air movement, 4" holes, never used at Pole before) & hot water drill (IceCube heritage, 6" holes)
- TestBed antenna deployments down the 6" holes, plan to use 4" holes for radio studies next season
- Near-term ARA stations will use the hot water drill with pumping to go down to 200m

Drill Test 1 : Hot water drill

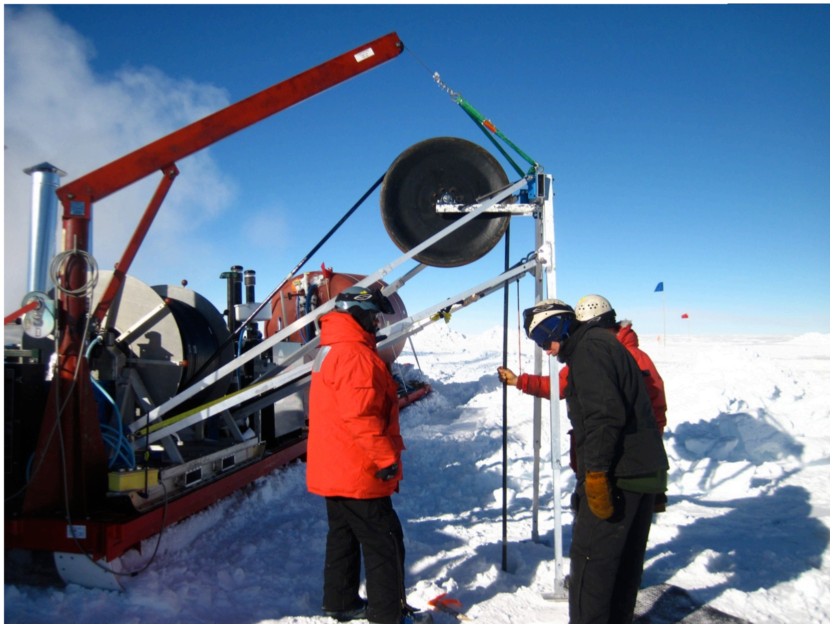
- Carried on three sleds pulled by tractor
- 0.5 – 1m per minute / 200m in ~1/2 day
- 6" hole
- Wet hole- must be pumped out or electronic made watertight
- Deepest holes drilled in 10/11: ~160 m



ARA hot water drill sleds




Drill in Operation




Drill Test 1 : Rapid Air Movement

<u>RAM drill</u>

•Cutter head drill hole-shavings extracted using compressed air

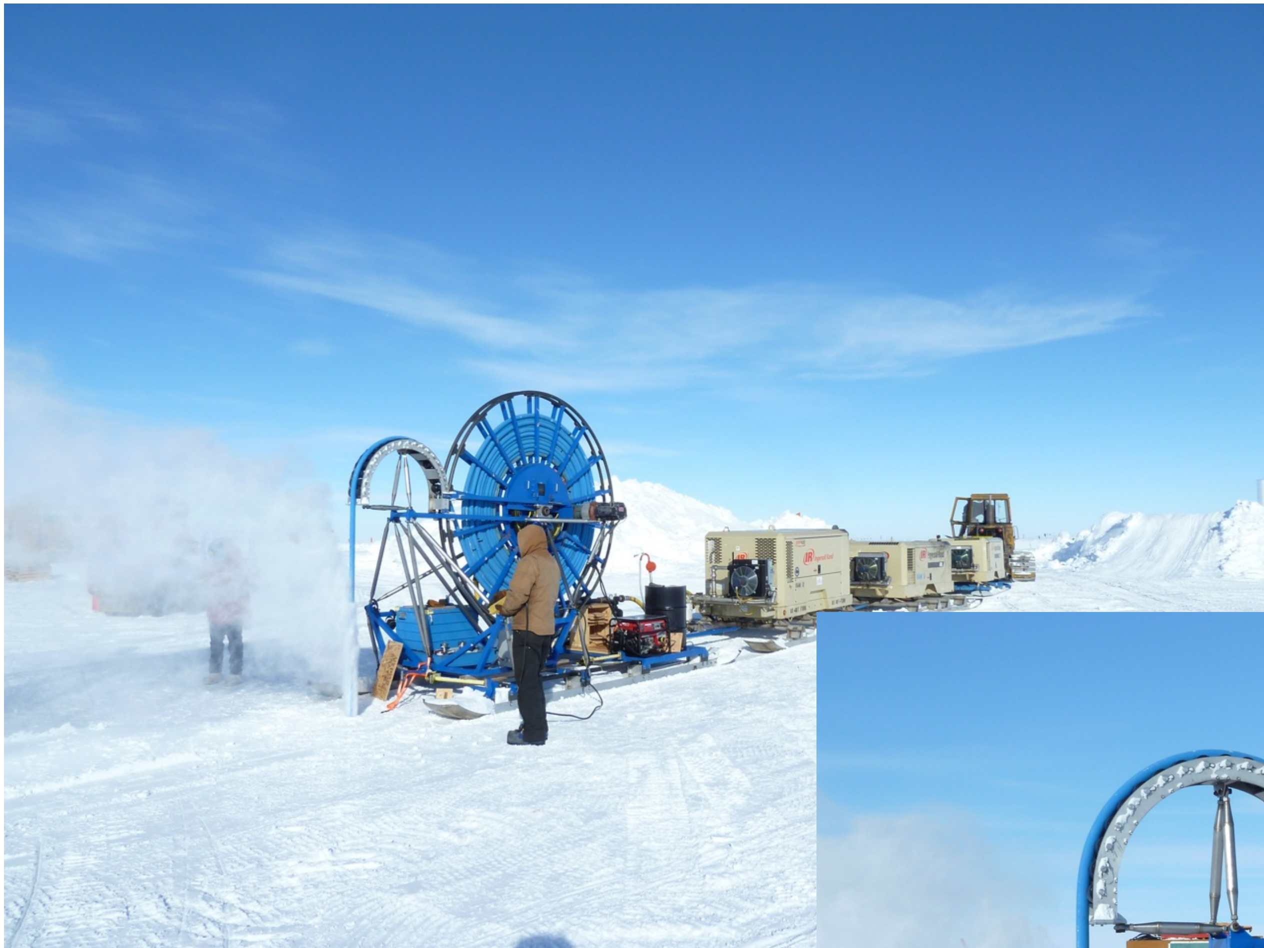
•Extra compressors required at SP altitude

•lots of cargo to get it to the Pole

•Dry, 4 inch hole

•Deepest holes achieved: ~60 m (only took 15 minutes!)

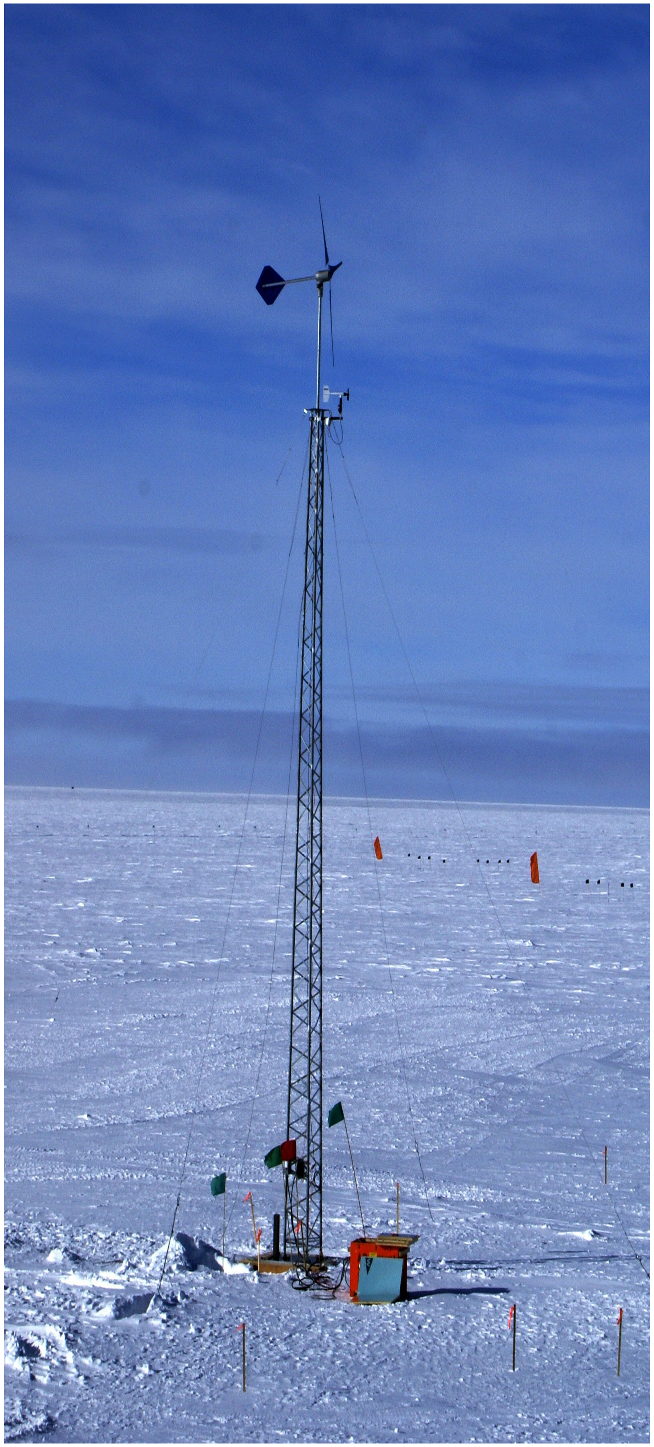
•Limited by air pressure leakage through the firn

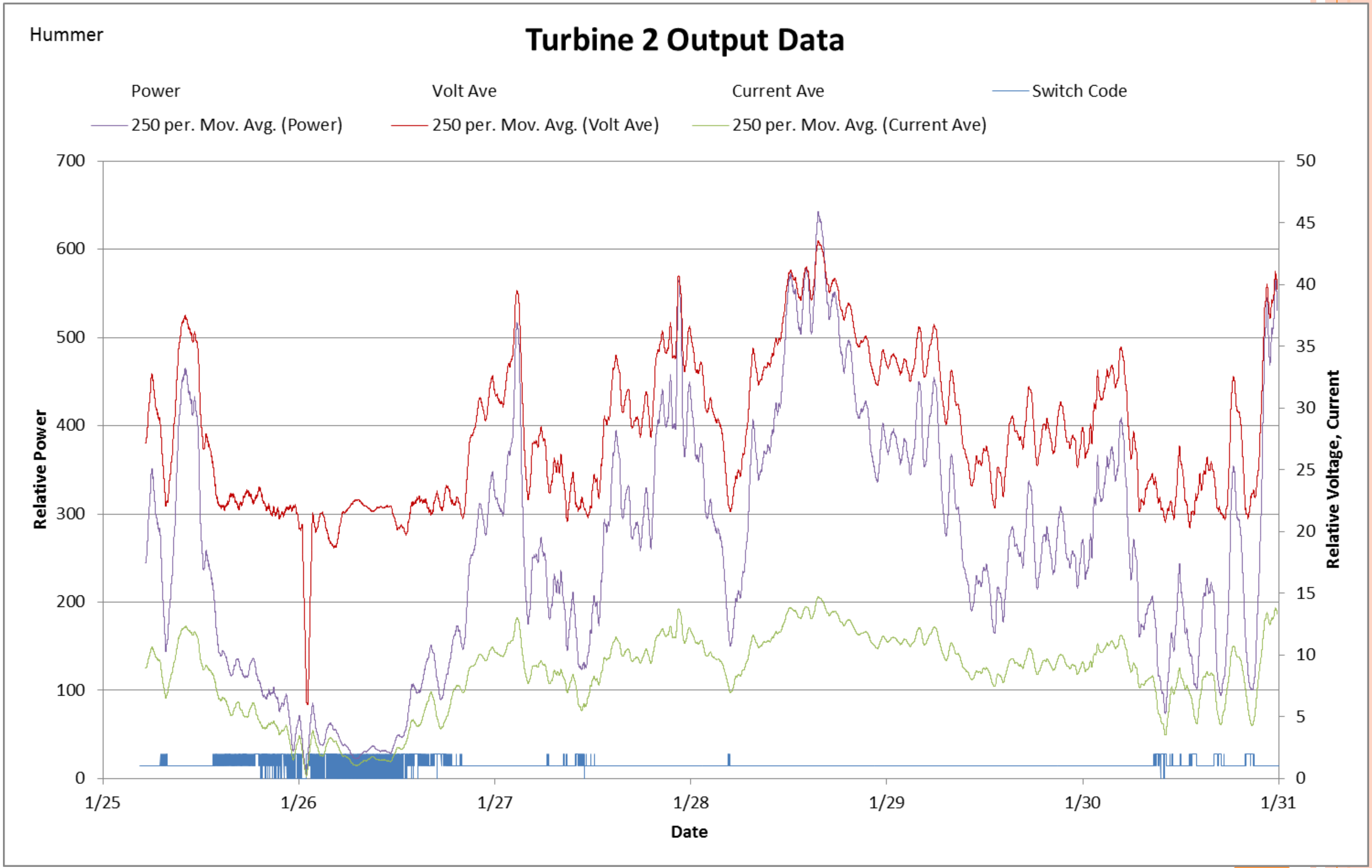



DANGER
HIGH VOLTAGE

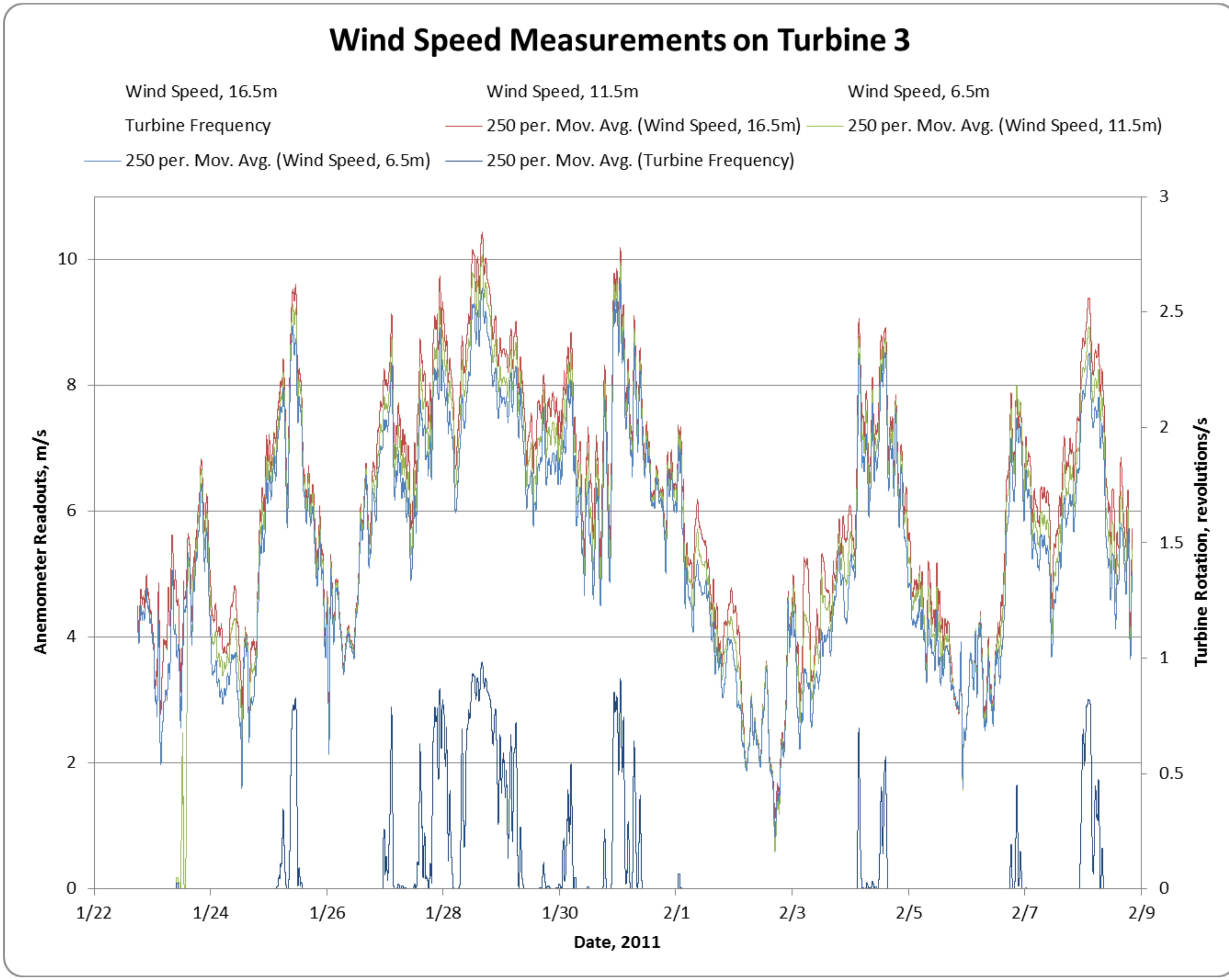
Wind Turbines

- Three different turbines, three different towers, tests of RFI-safe cabling, anemometers at different heights
- All of the systems are for initial South Pole testing to gain experience towards autonomous power for future ARA stations





Hummer
Turbine 2 Output Data
Power
Volt Ave
Current Ave
Switch Code
250 per. Mov. Avg. (Power)
250 per. Mov. Avg. (Volt Ave)
250 per. Mov. Avg. (Current Ave)
700
600
500
400
300
200
100
0
Relative Power
50
45
40
35
30
25
20
15
10
5
0
Relative Voltage, Current
1/25
1/26
1/27
1/28
1/29
1/30
1/31
Date

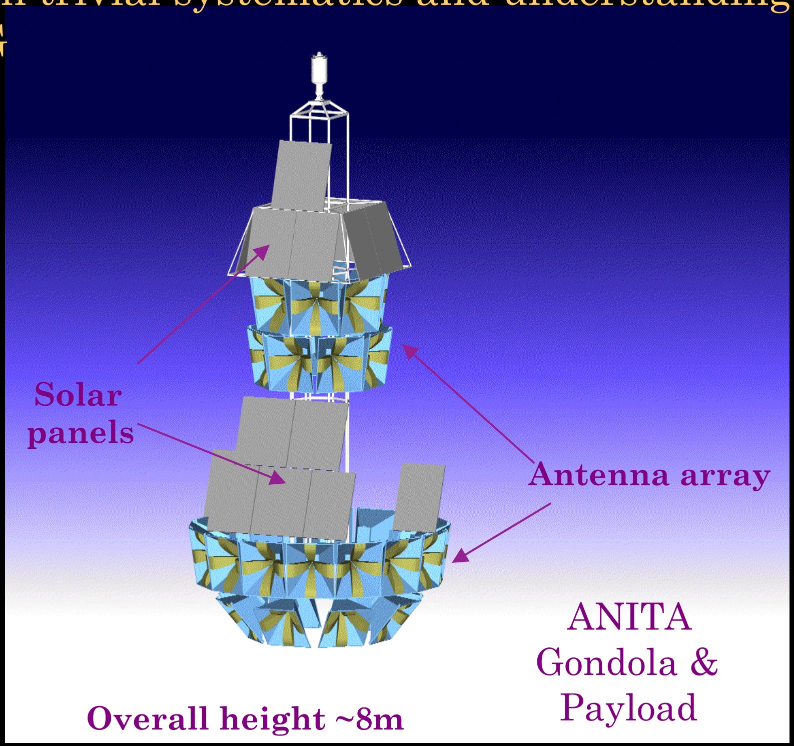

Wind Speed Measurements on Turbine 3
Wind Speed, 16.5m
Wind Speed, 11.5m
Wind Speed, 6.5m
Turbine Frequency
250 per. Mov. Avg. (Wind Speed, 16.5m)
250 per. Mov. Avg. (Wind Speed, 11.5m)
250 per. Mov. Avg. (Wind Speed, 6.5m)
250 per. Mov. Avg. (Turbine Frequency)
Anemometer Readouts, m/s
0
2
4
6
8
10
Turbine Rotation, revolutions/s
0
0.5
1
1.5
2
2.5
3
1/22
1/24
1/26
1/28
1/30
2/1
2/3
2/5
2/7
2/9
Date, 2011

ARA RADIO GLACIOLOGY

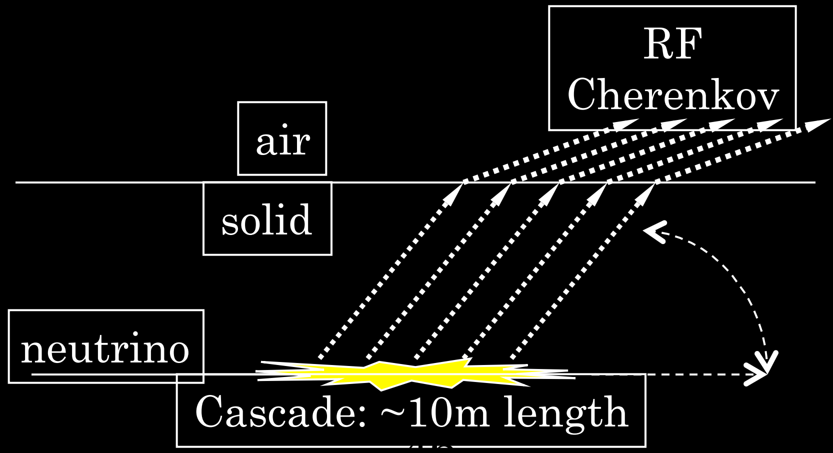
- A: embed precision Rubidium oscillators at both receive and transmit end to ensure <250 ps signal synchronization!
- Allows essentially unlimited signal averaging.
- E.g., expect single-shot S:N~3:1 at r~5 km =>S:N~3.3x10-3at 10 km, including 1/R, assume L~1km for bottom Tx (better for Tx @ 1.5 km)
- 100K shots, synchronized, and averaged (<1 hour of running) achieves 3:1 S:N
- Goal: Complete and first-ever 3-d mapping of radio ice properties over multi-km scales!
- (radio complement of IceCube ice studies in optical : see Delia Tosi talk)

ANITA - Antarctic Impulsive Transient Antenna Experiment

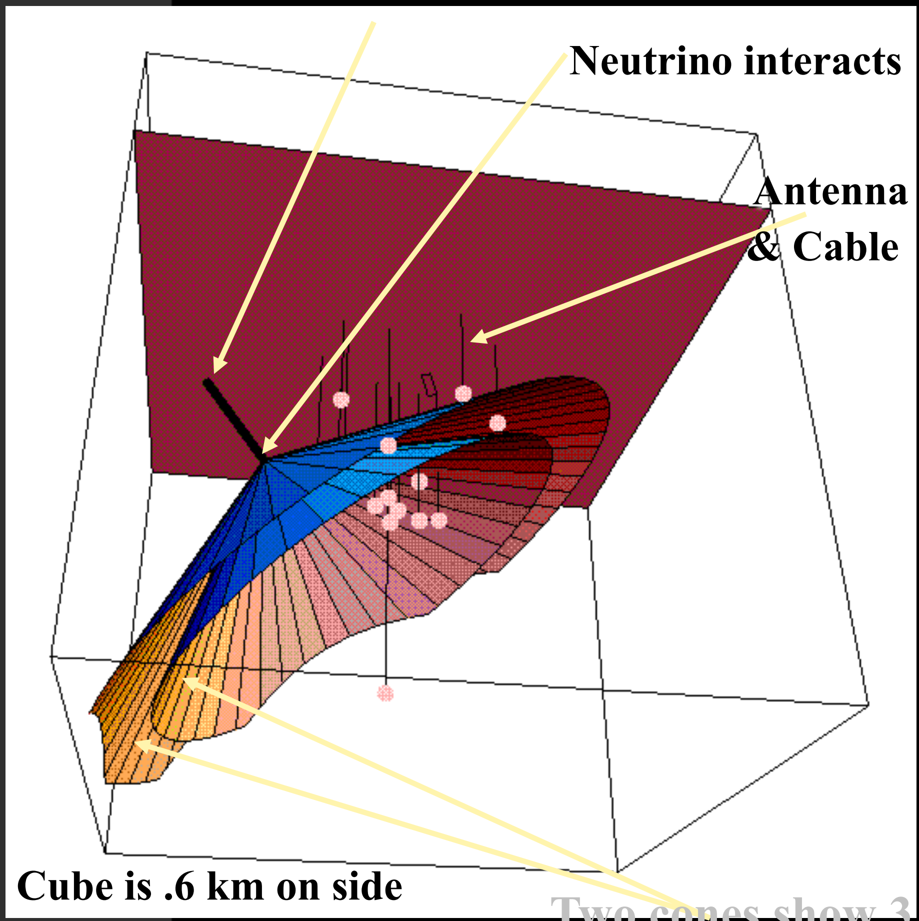
Very large detection volume,
Small solid angle,
Completed another successful mission
Non trivial systematics and understanding BG



searching for GZK neutrinos with radio detection in Antarctic ice



RICE
Radio Detection in South Pole Ice



- Installed ~15 antennas few hundred m depth with AMANDA strings.
- Tests and data since 1996.
- Most events due to local radio noise, few candidates.
- Continuing to take data, and first limits prepared.
- Proposal to Piggyback with ICECUBE

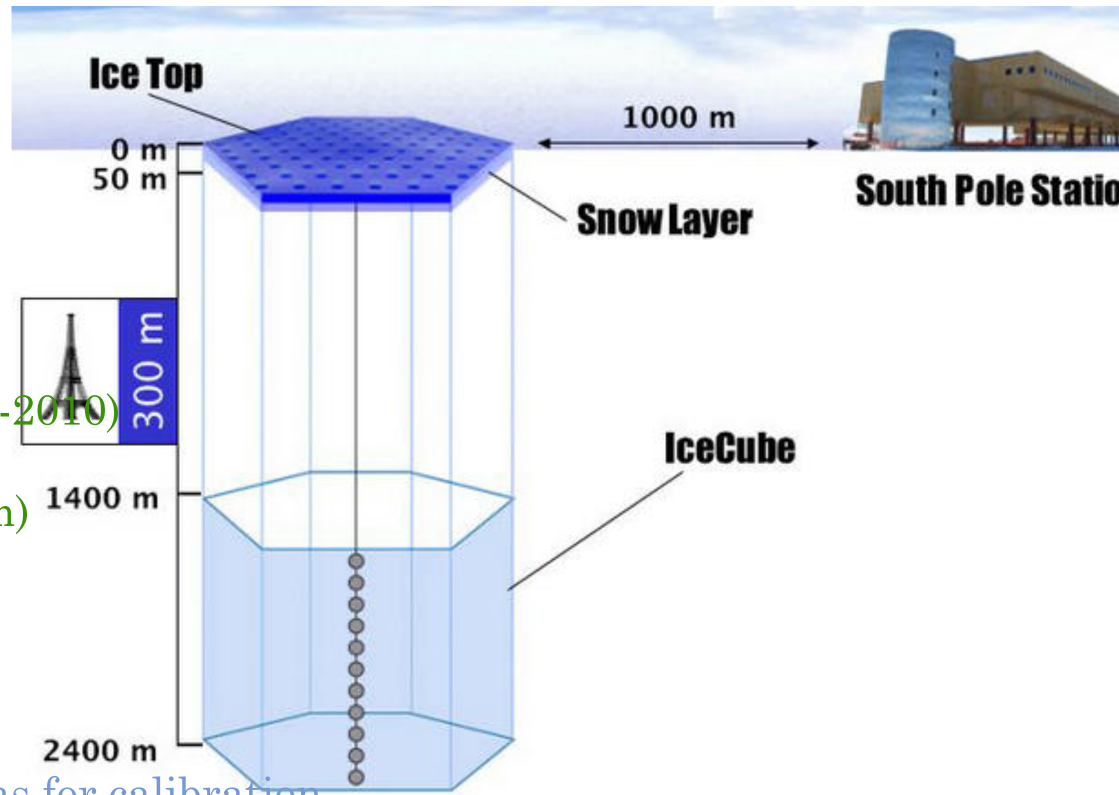
NARC – Neutrino Array Radio Calibration
Calibration instruments embedded with IceCube

- ➔ In ice digitization . Combination of ANITA/IceCube/RICE technologies:
  2 clusters in 2006-2007
  3 clusters in 2008-2009
  Depth of 1450 m or 300 m
  AKA "AURA"

- ➔ Envelope detection.
  6 units deployed at -35, -5 meters (2009-2010)
  6 units in other depth/location
  (On top of a building, terminated, -250m)
  AKA "SATRA"

- ➔ Calibration

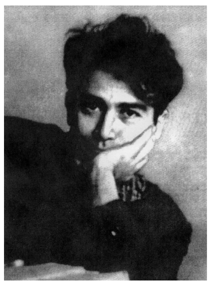
  Set of transmitters and passive antennas for calibration
  (including cable symmetrical antennas)



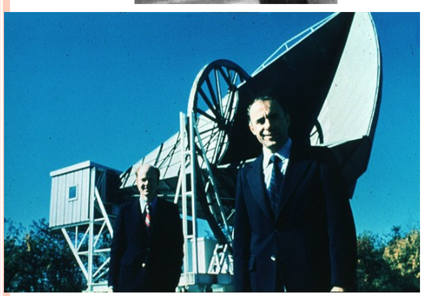
UHE Neutrino science roots: the 60's

Four crucial events from the 1960's

1. **1961: First 10^{20} eV cosmic ray air shower observed**
   – John Linsley, Volcano Ranch, Utah



2. **1962: G. Askaryan predicts coherent radio Cherenkov from showers**
   – His applications? Ultra-high energy cosmic rays & neutrinos
3. **1965: Penzias & Wilson discover the 3K echo of the Big Bang**
   – while looking for bird droppings in their radio antenna



4. **1966: Cosmic ray spectral cutoff at $10^{19.5}$ eV predicted**
   – K. Greisen (US) & Zatsepin & Kuzmin (Russia), independently
   – Cosmic ray spectrum *must end* close to ~10^{20} eV

p, γ + γ(3K) ⟶ pions, e+e- ⟶ GZK neutrinos

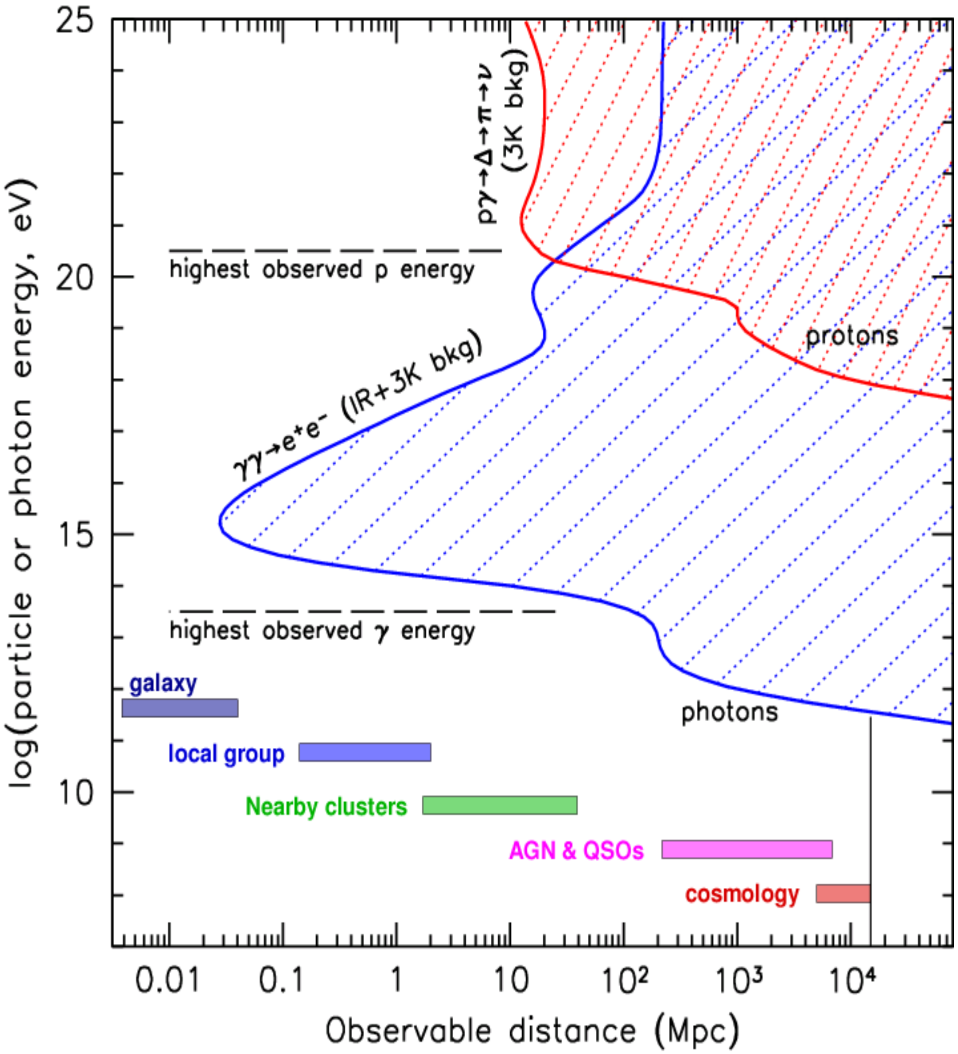
"GZK cutoff" process

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

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

NEUTRINOS AS MESSENGERS



April 2010

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**

Existence of extragalactic neutrinos inferred from CR spectrum, up to 10^{20} eV, and similarly, Galactic up to 10^{18} eV

Need gigaton (km^3) mass (volume) for TeV to PeV detection, and teraton at 10^{19} eV

Neutrino detection associated with EM sources will ID the UHECR sources

"EM Hidden" sources may exist, visible only in neutrinos.

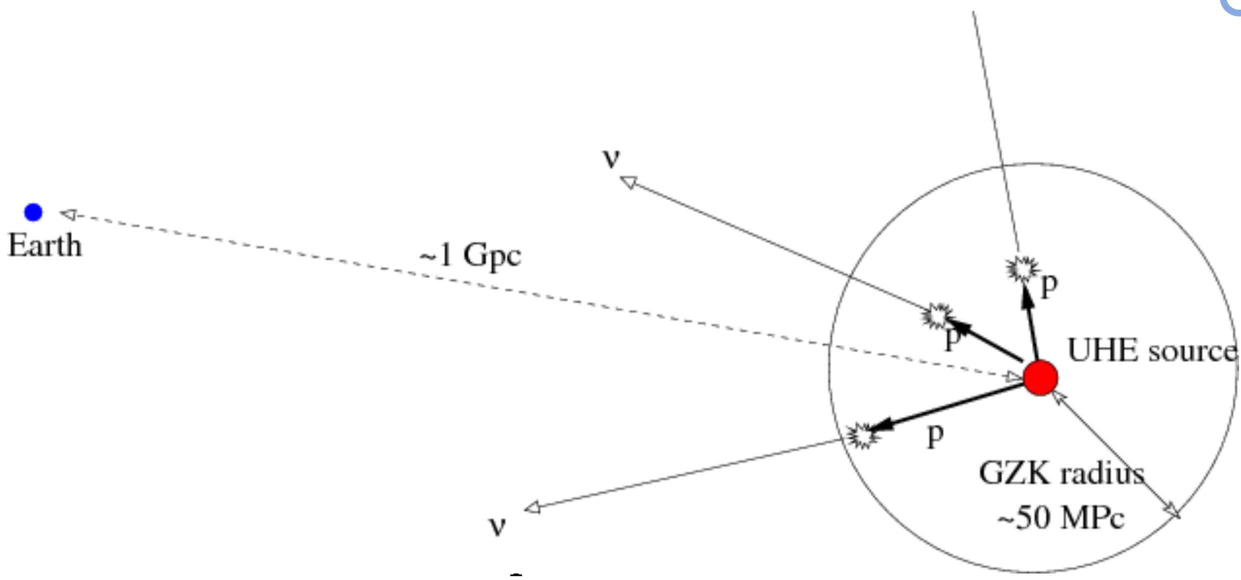
Neutrino eyes see farther (z>1), and deeper (into compact objects), than gamma-photons, and straighter than UHECRs,with no absorption at (almost) any energy

GZK NEUTRINO PRODUCTION

- GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB
  - $p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$

$$\rightarrow \mu^{+} + \boxed{\nu_{\mu}}$$

$$\rightarrow e^{+} + \boxed{\bar{\nu_{\mu}} + \nu_{e}}$$



Askaryan Effect

In electron-gamma shower in matter, there will be ~20% more electrons than positrons.

Compton scattering: $\gamma + e^-_{(at\ rest)} \rightarrow \gamma + e^-$

Positron annihilation: $e^+ + e^-_{(at\ rest)} \rightarrow \gamma + \gamma$

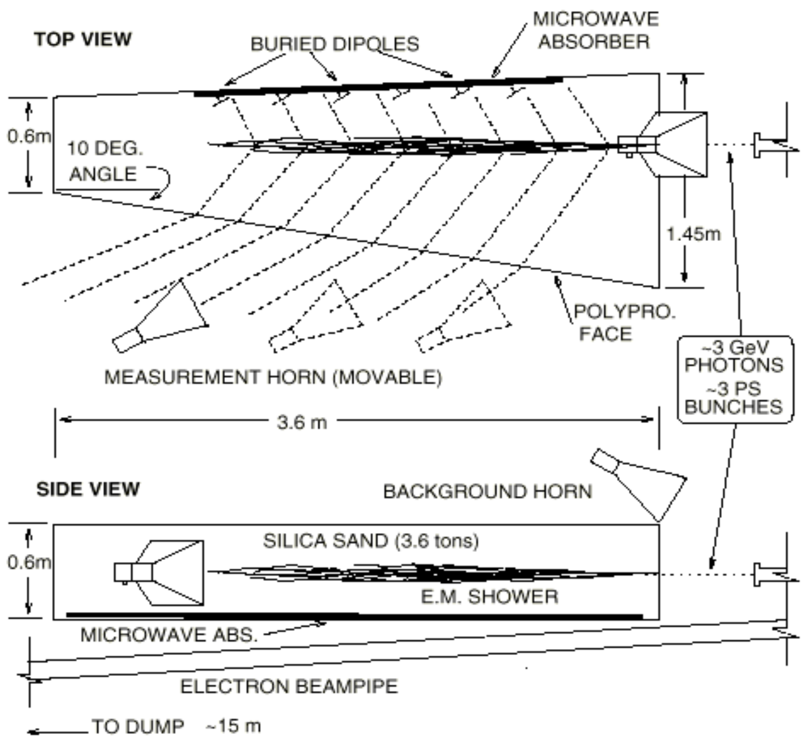
In dense material, $R_{Moliere} \sim 10$cm:

$\lambda \ll R_{Moliere}$ (optical case), random phases $\Rightarrow$ **$P \propto N$**

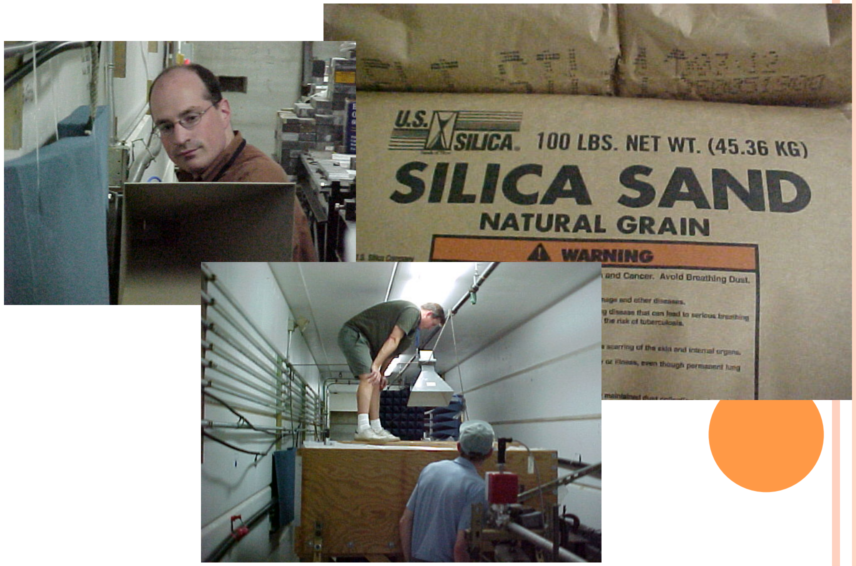
$\lambda \gg R_{Moliere}$ (microwaves), coherent $\Rightarrow$ **$P \propto N^2$**

$$\frac{dP_{CR}}{d\nu} \propto \nu d\nu$$

Askaryan Effect: SLAC T444 (2000)



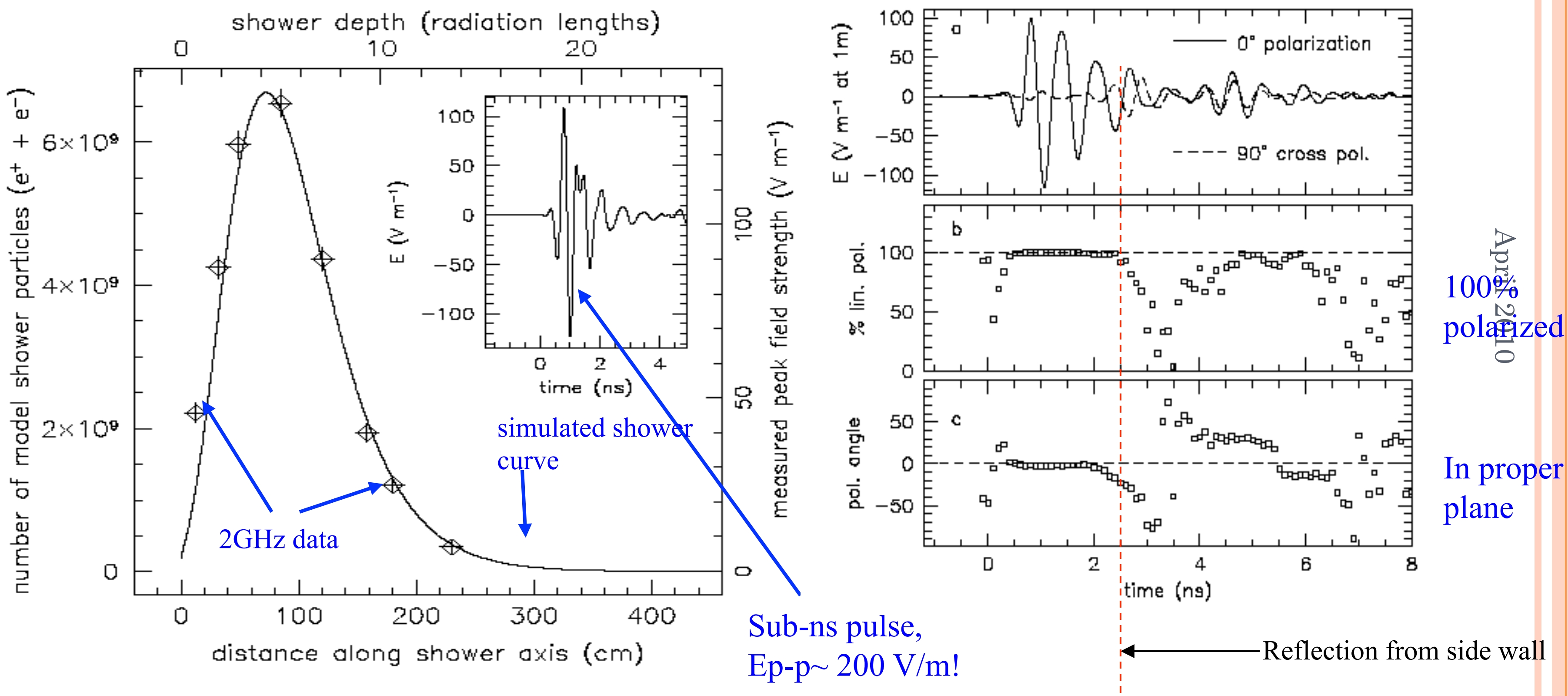
From Saltzberg, Gorham, Walz et al PRL 2001



- Use 3.6 tons of silica sand, brem photons to avoid any charge entering target
  ==> avoid RF transition radiation
- RF backgrounds carefully monitored
  - but signals were much stronger!

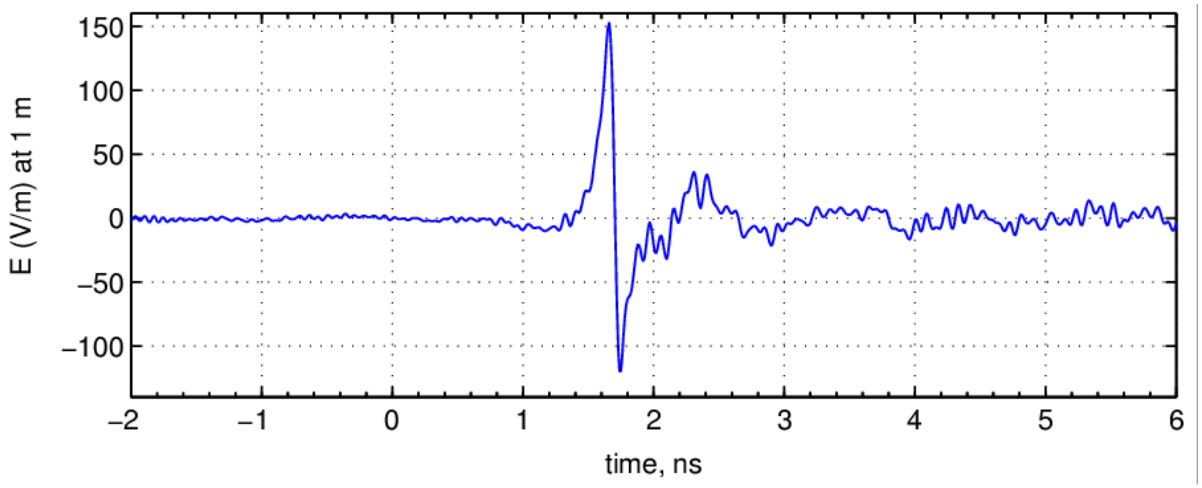
April 2010

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**

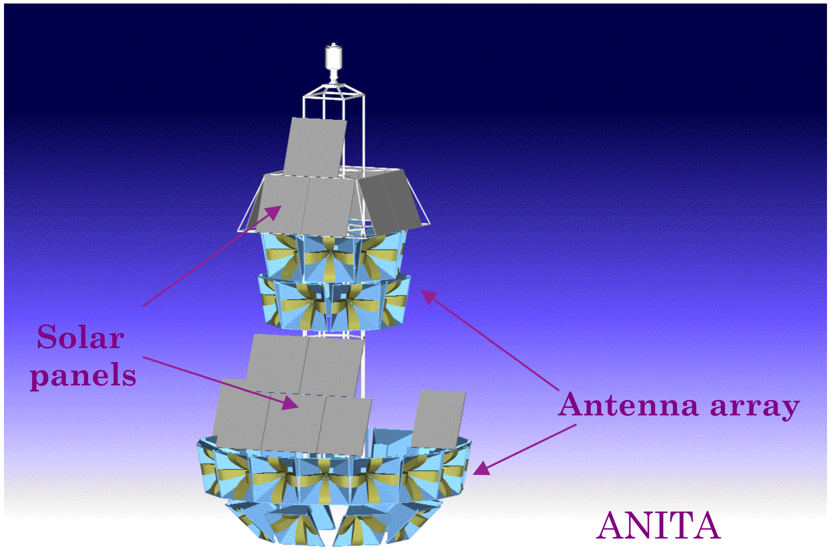
Signal particulars



- Strong signal, bandwidth limited
- Characteristics very different than other, anthropogenic, impulsive signals (e.g., linear pol, very broadband, scale-free)
- Difficult to make an Askaryan signal generator

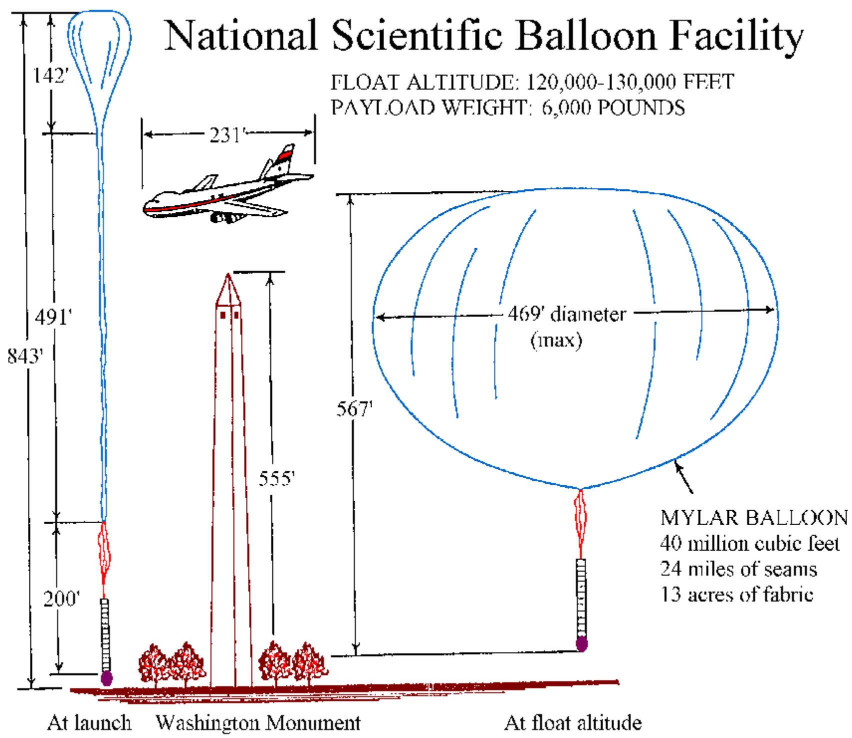
NATURAL TARGET MATERIAL?

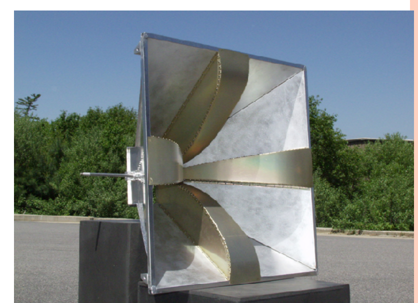
- Lunar regolith (20m attenuation length)
  Parkes Telescope; GLUE; WSRT
- Ice (100-1500m attenuation lengths) Forte (satellite); ANITA (balloon)
- Salt (100-500m attenuation lengths?)
  SalSA (proposed)
- Air is too thin
- Water is RF lossy. Desert sand (as opposed to pure silica) is also lossy.



ANITA Gondola & Payload

Overall height ~8m



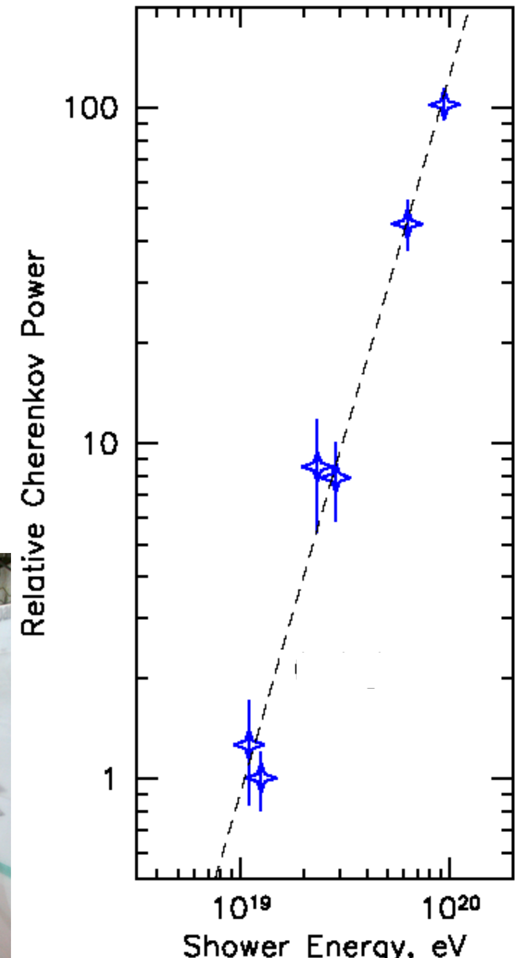


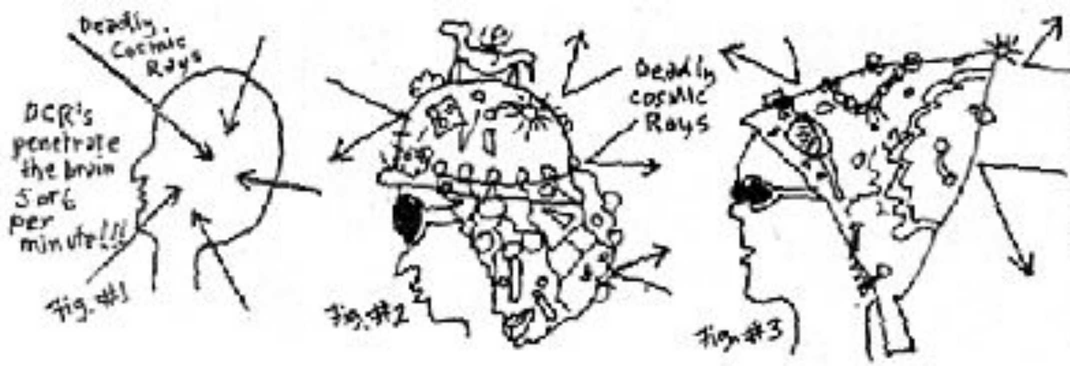
Validation at SLAC

ANITA I beamtest at SLAC (June06): proof of Askaryan effect in ice

- Coherent (Power ~ E^2)
- Linearly Polarized

"Little Antarctica"





The Cosmic-ray Deflection Society of North America.