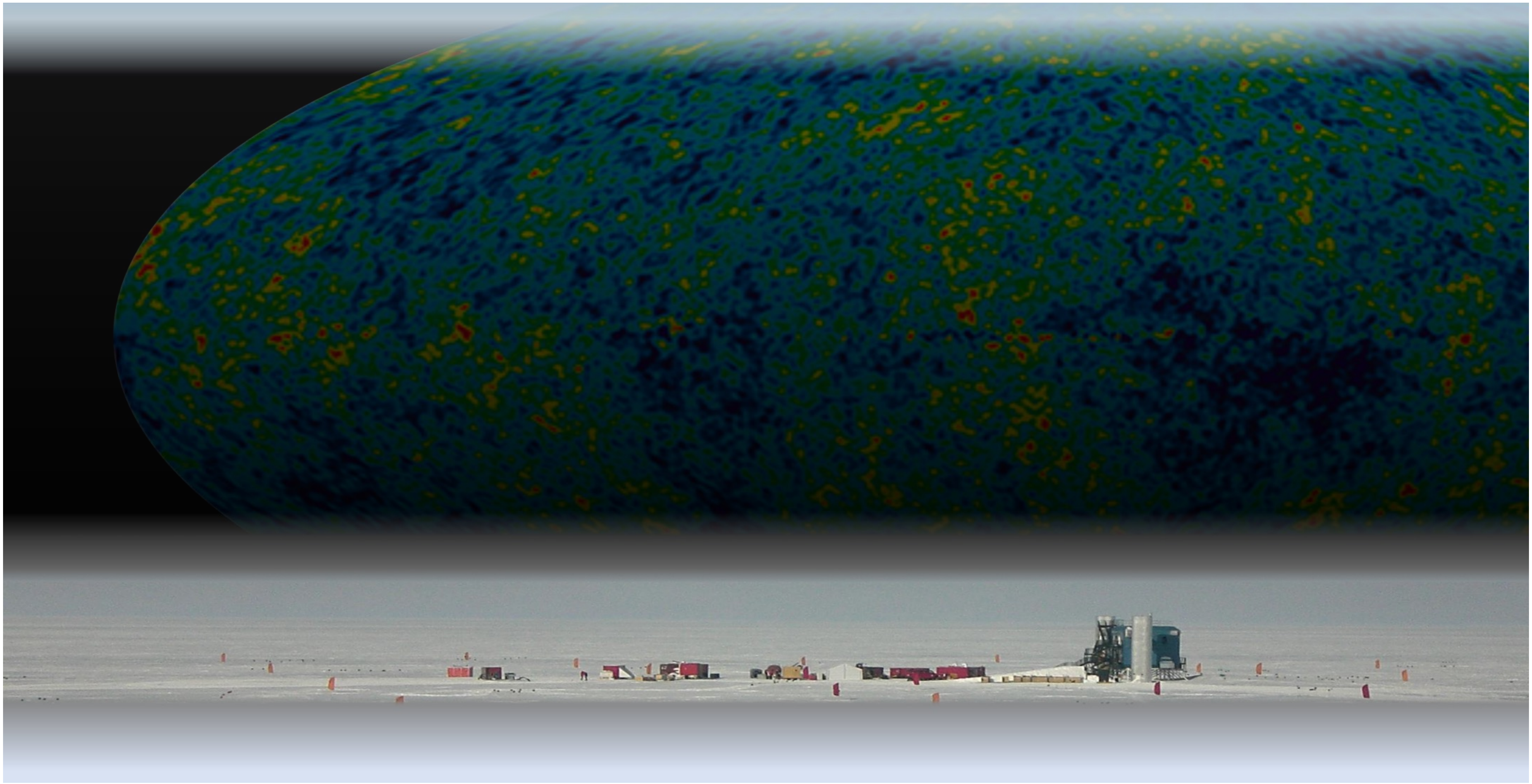
Radio Detection of Neutrinos

Mike DuVernois

IceCube Upgrade & Gen2 Technical Coordinator

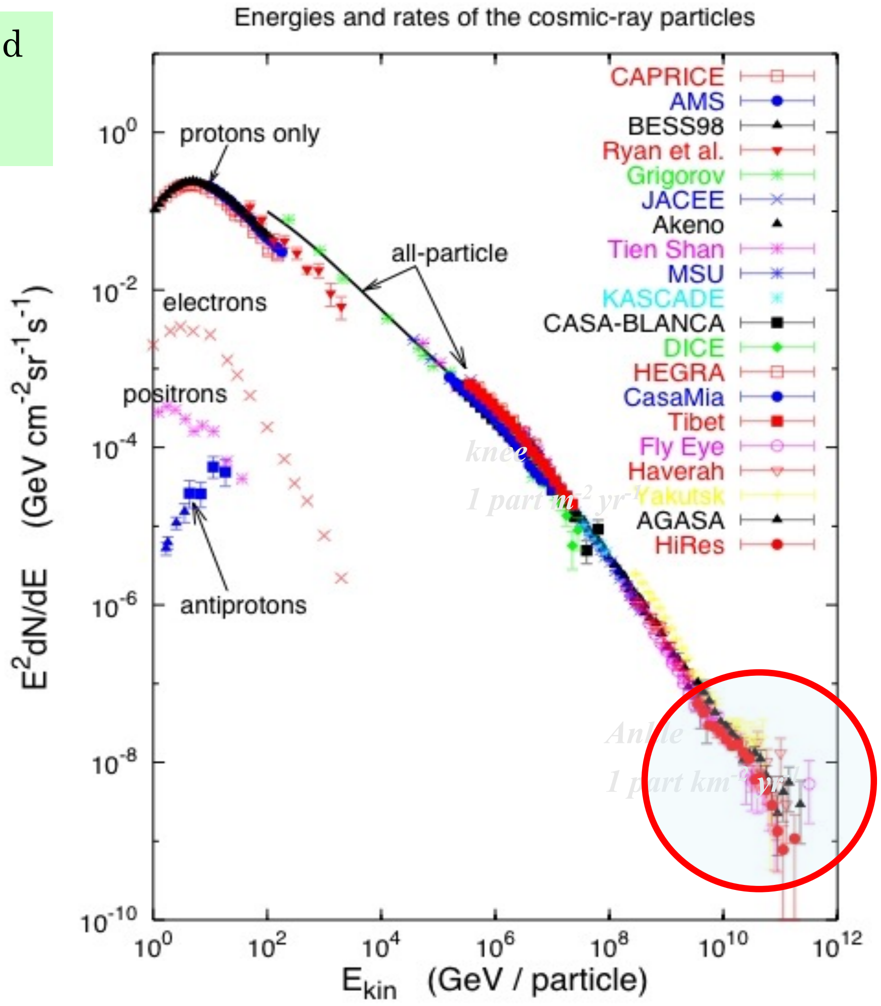


This field has had many starts and stops over the years, and you can probably see that in several generations of slides I have stolen (mostly from myself).

COSMIC RAYS & NEUTRINOS

High energy Cosmic Rays

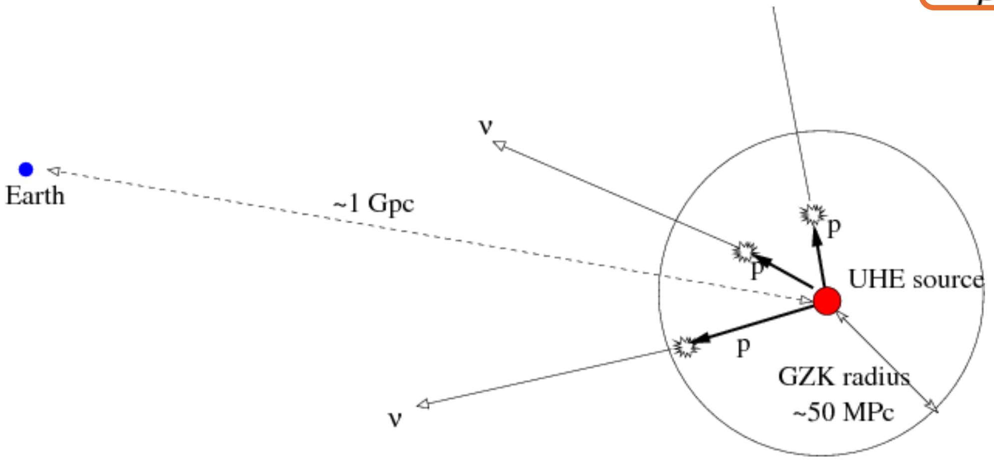
Cosmic rays have been observed to energies beyond 10^{20} eV. Their origin is unknown.



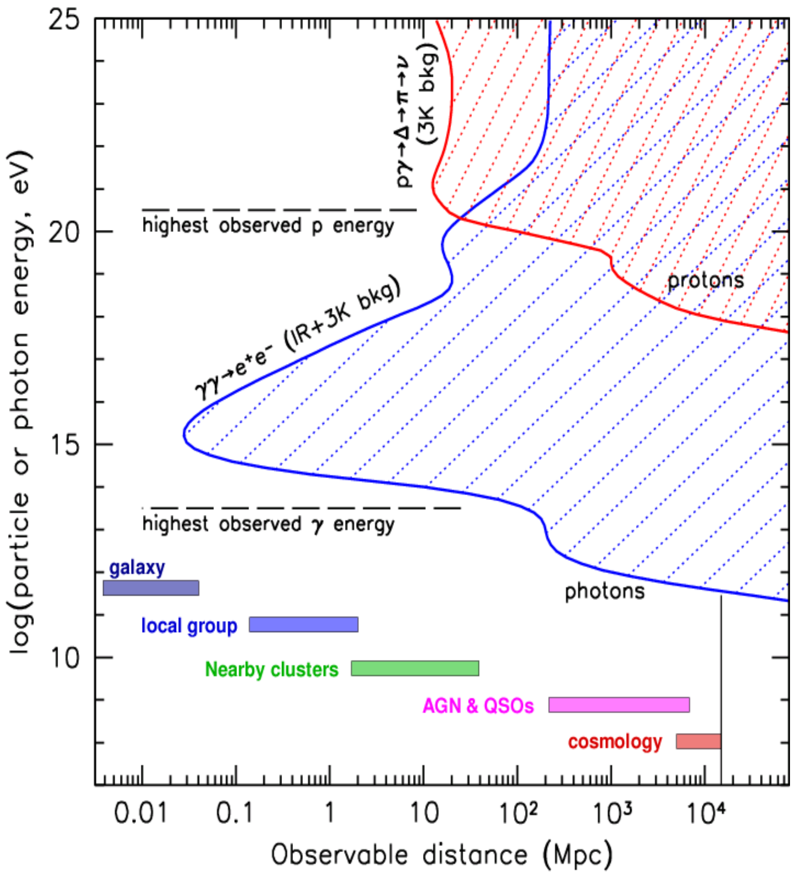
GZK neutrino production

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

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



Neutrinos as messengers



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

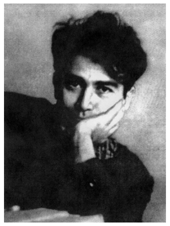
Neutrino detection associated with EM sources will ID the UHECR sources

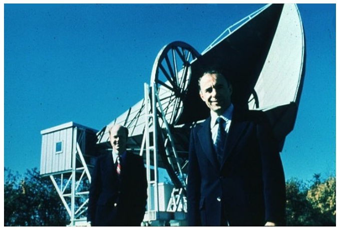
“EM Hidden” sources may exist, visible only in neutrinos.

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

ASKARYAN

UHE Neutrino historical roots: the 60’s





Four crucial events from the 1960’s

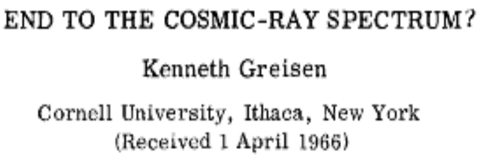
1. **1961: First 10^{20} eV cosmic ray air shower observed**
   - John Linsley, Volcano Ranch, Utah
2. **1962: G. Askaryan predicts coherent radio Cherenkov from showers**
   - His applications? Ultra-high energy cosmic rays & neutrinos
3. **1965: Penzias & Wilson discover the 3K echo of the Big Bang**
   - 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

$p, \gamma + \gamma(3K) \longrightarrow$ pions, e+e-

$\downarrow$

“GZK cutoff” process

GZK neutrinos



END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

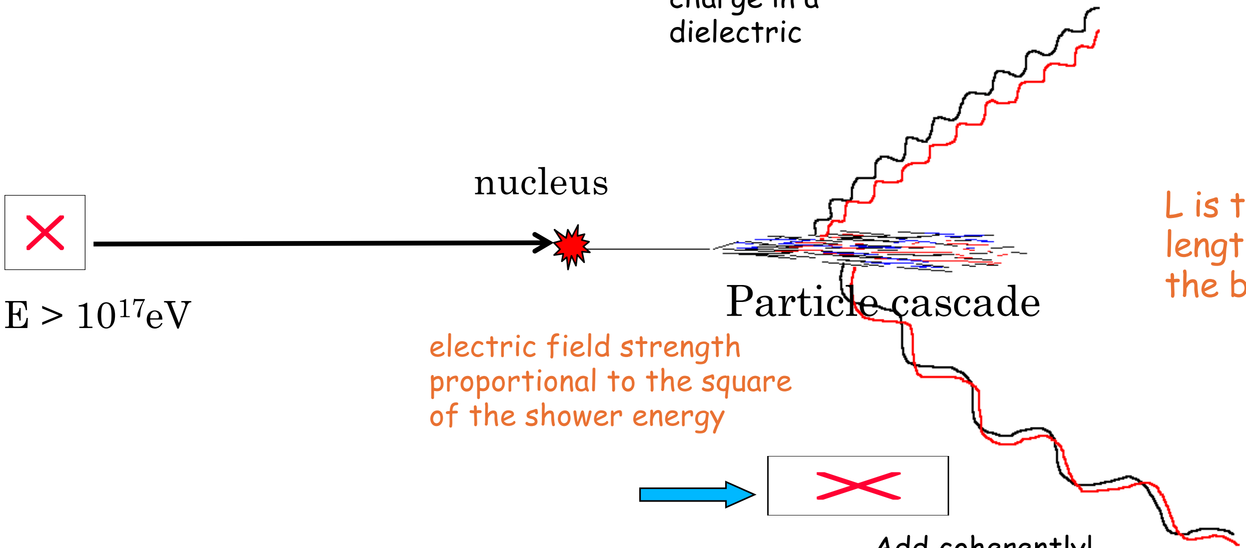
Cornell University, Ithaca, New York
(Received 1 April 1966)

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



L is the length of the bunch

electric field strength proportional to the square of the shower energy

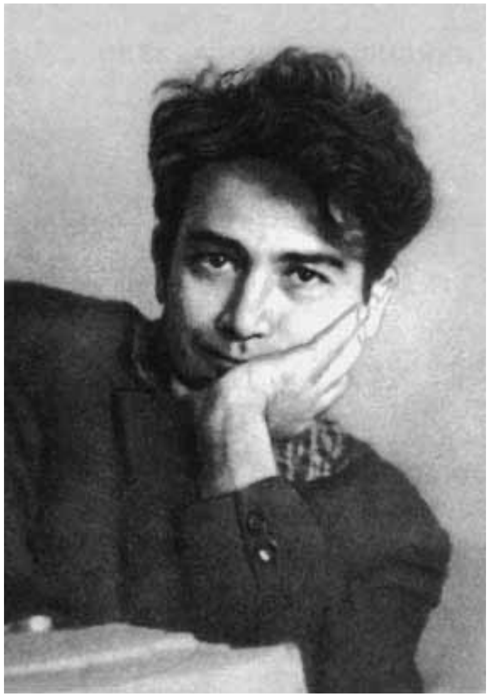
Add coherently!

Askaryan Effect

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

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

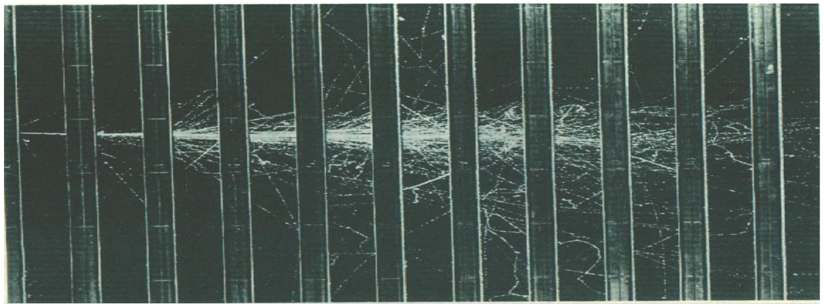
Positron annihilation: $e^+ + e^-_{\text{(at rest)}} \rightarrow \gamma + \gamma$

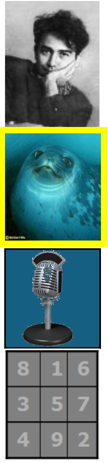


In dense material, $R_{\text{Moliere}} \sim 10\text{cm}$:

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

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





Measurements of the Askaryan effect

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

Results:

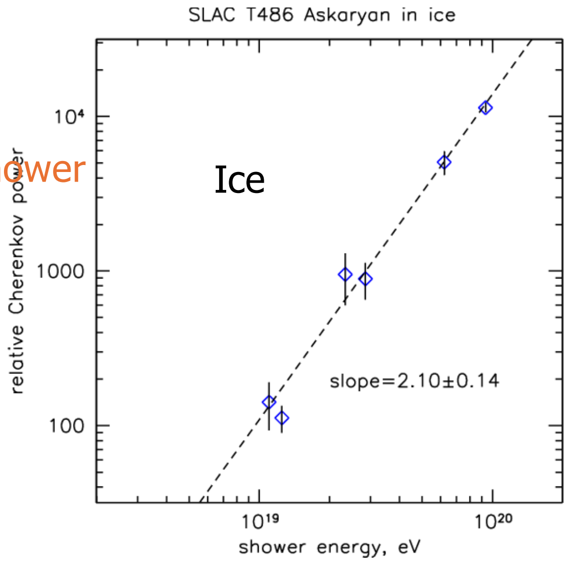
✓ RF pulses were correlated with presence of shower

✓ Expected shower profiled verified

✓ Expected polarization verified (100% linear)

✓ Coherence verified.

✓ SLAC, for ANITA calibration – in Ice

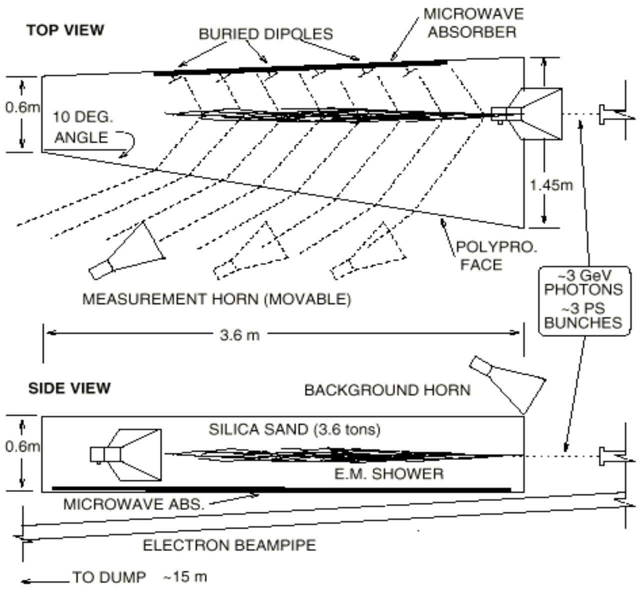


D.Salzberg, P. Gorham et al.

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

experimental results

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!

Validation at SLAC

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

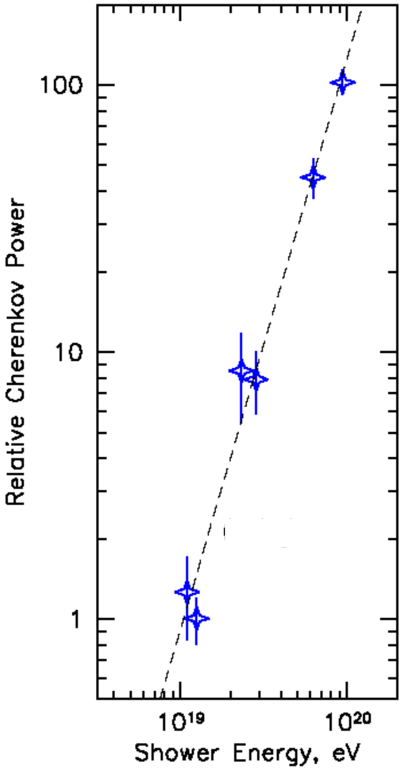
- Coherent (Power ~ E^2)
- Linearly Polarized

“Little Antarctica”

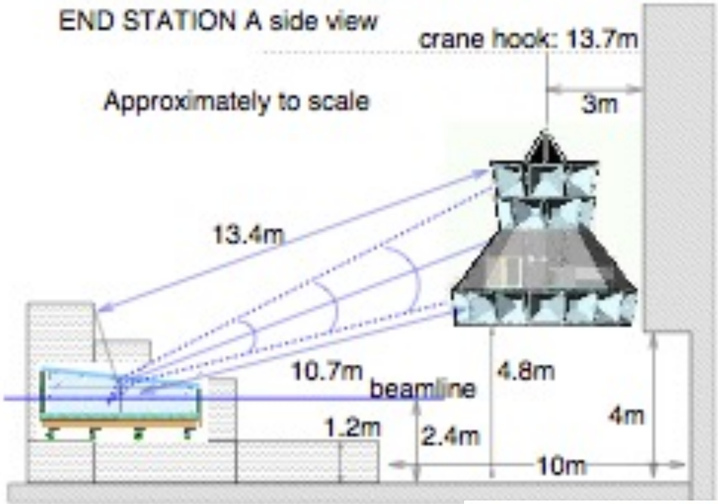
PHYSICAL
REVIEW
LETTERS

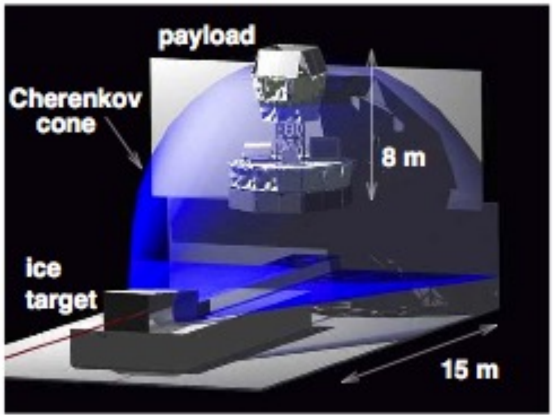
Articles published week ending
26 OCTOBER 2007
Volume 99, Number 17

Published by The American Physical Society

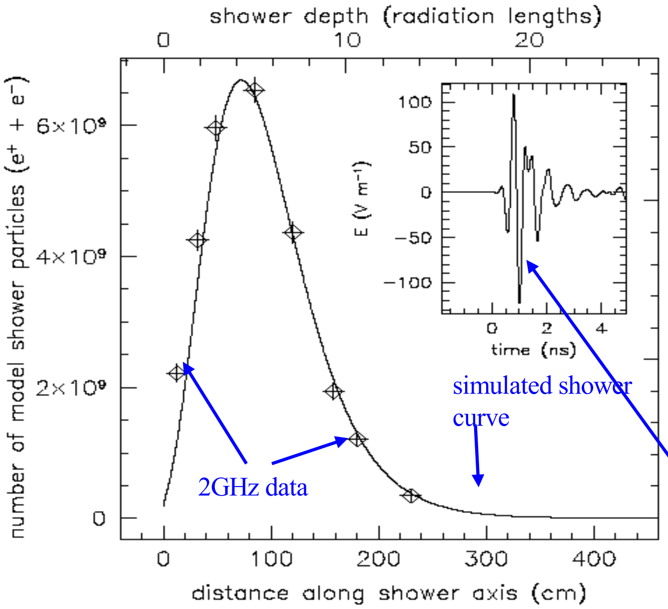


IN-ICE MEASUREMENT OF ASKARYAN EFFECT (SLAC, “LITTLE ANTARCTICA”)





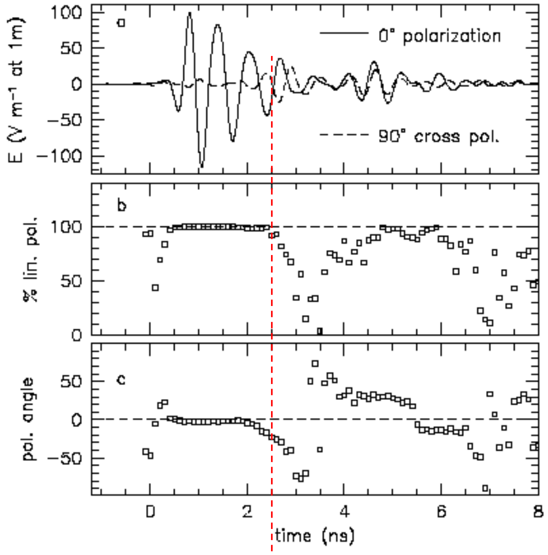
Shower profile observed by radio@2GHz



2GHz data

simulated shower curve

Sub-ns pulse,
Ep-p~ 200 V/m!



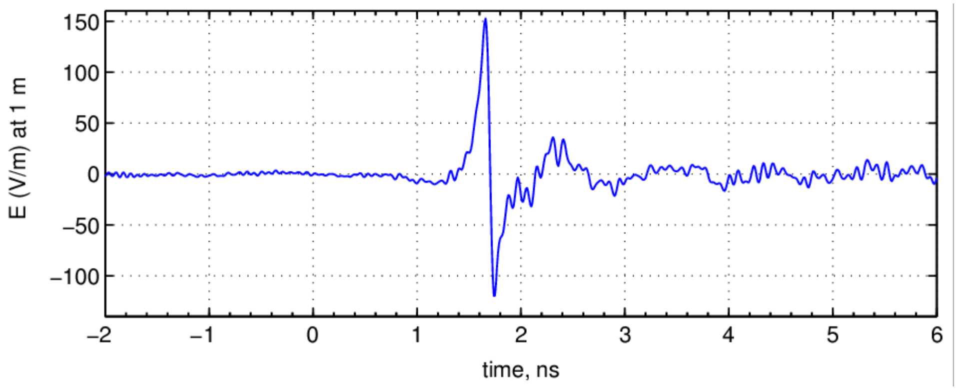
100%
polarized

In proper
plane

Reflection from side wall

- 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

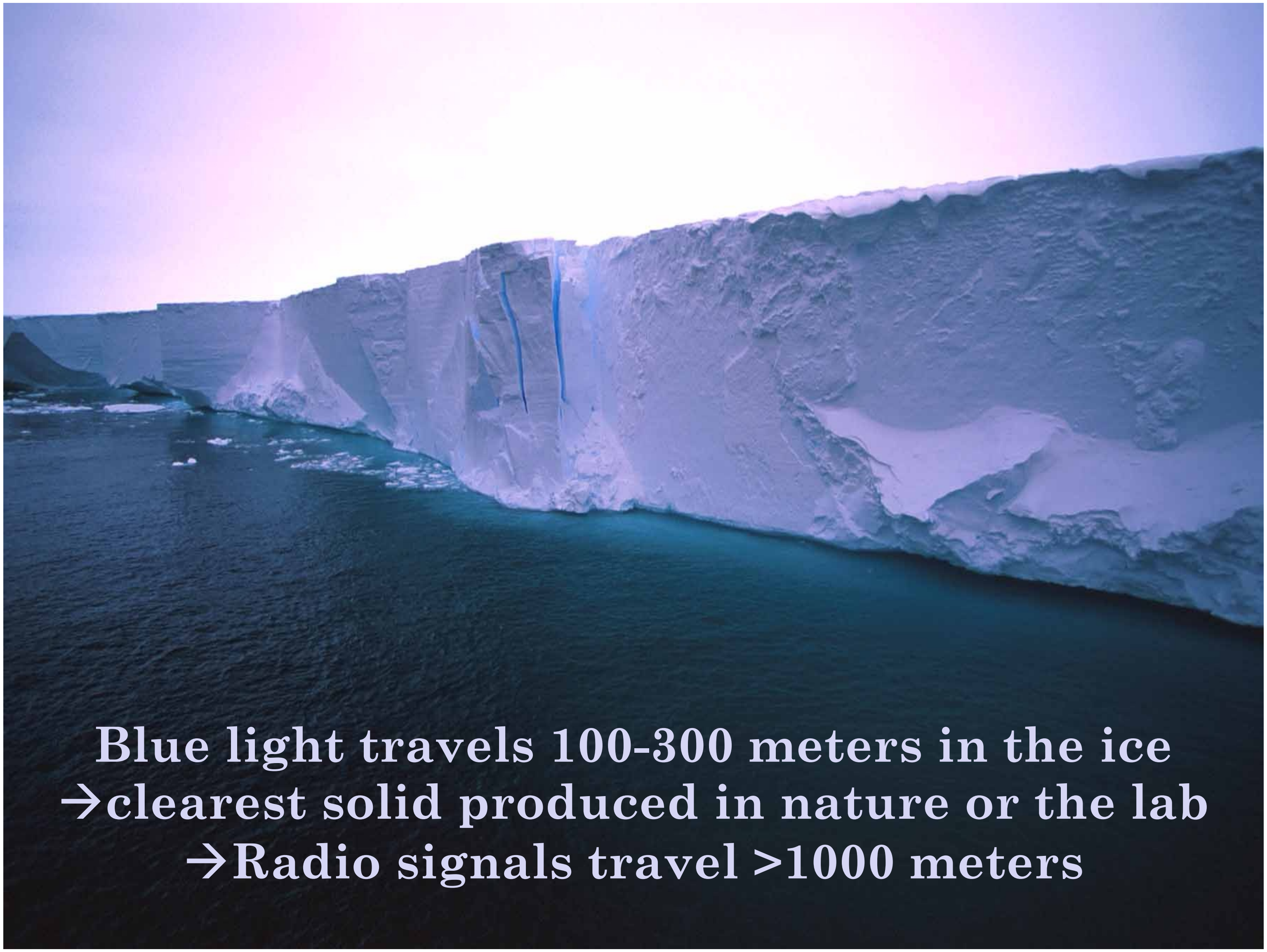


- Strong signal, bandwidth limited
- Characteristics very different than other, anthropogenic, impulsive signals (e.g., linear pol, very broadband, scale-free)
- Difficult to make an Askaryan signal generator

NATURAL TARGET MATERIAL? ON EARTH OR BEYOND…

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

ANTARCTICA…

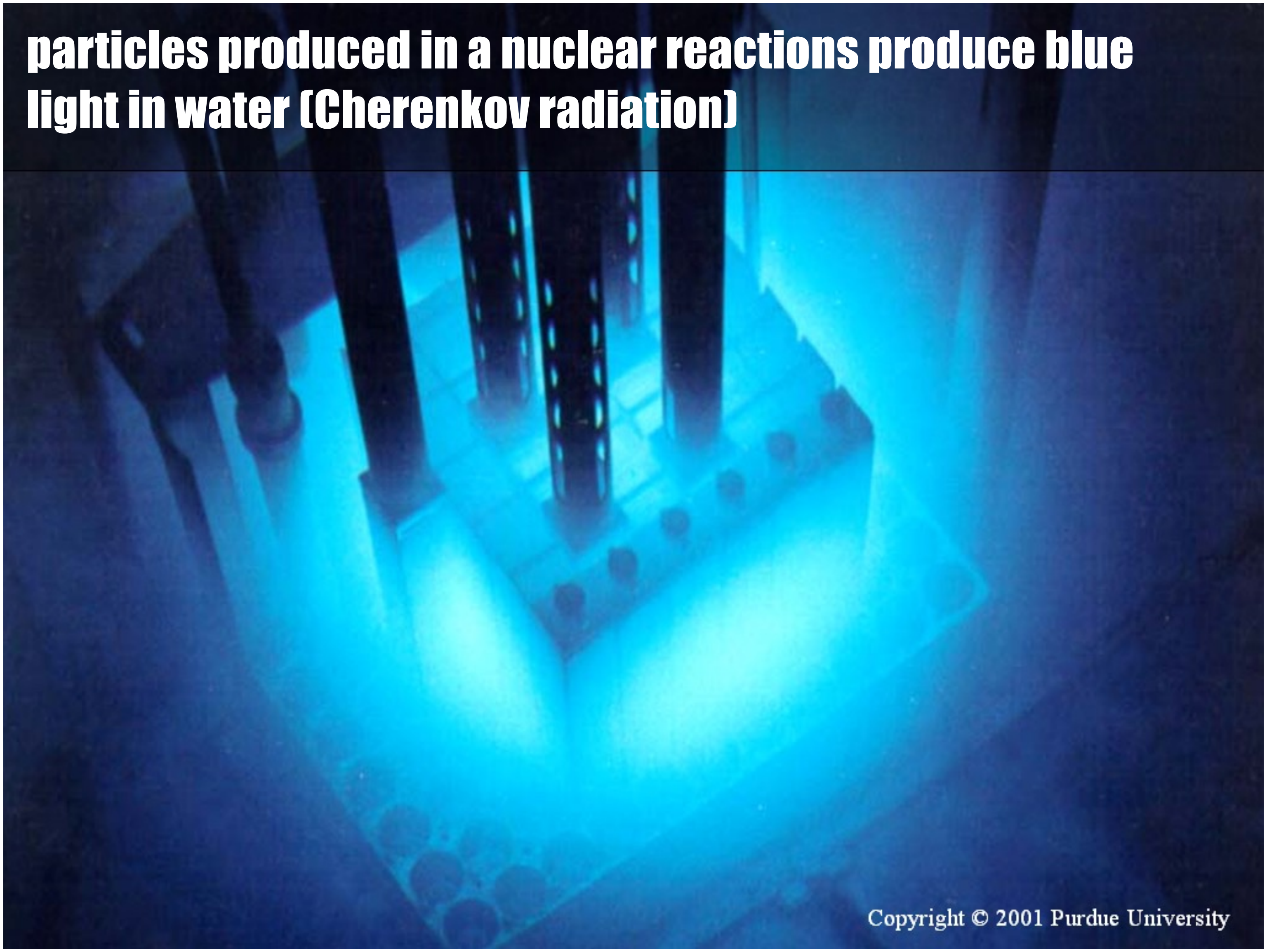


Blue light travels 100-300 meters in the ice

→clearest solid produced in nature or the lab

→Radio signals travel >1000 meters

particles produced in a nuclear reactions produce blue light in water (Cherenkov radiation)



PREVIOUS EXPERIMENTS

Using Antarctica

PAST ANTARCTIC ASKARYAN DETECTORS…

RICE

An 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 oscilloscopes on the surface for data acquisition

ANITA ANtarctic Impulsive Transient Antenna :

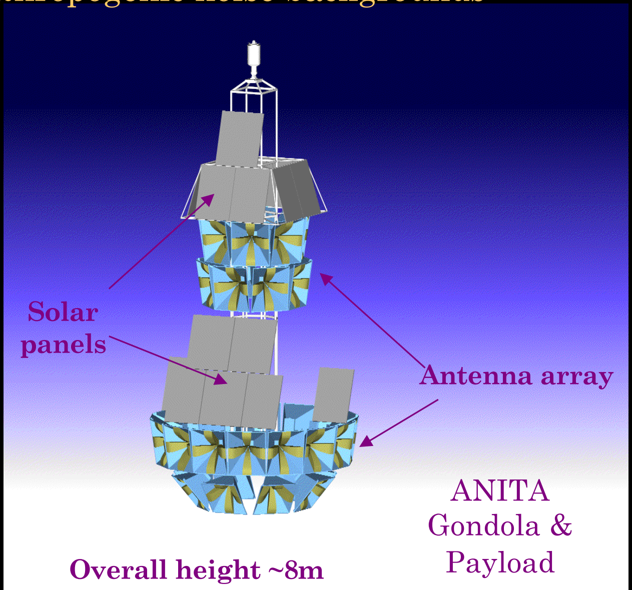
Surveys the ice cap from high altitude for RF refracted out of the ice (~40 km height, ~1.1M km^2 field of view)

IceCube Radio (NARC)

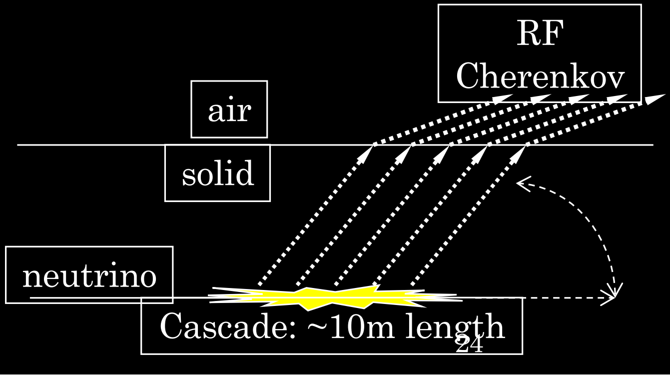
Co deployed with IceCube at 30m, 350m, and 1400 m. Full in ice digitization. High noise rates.

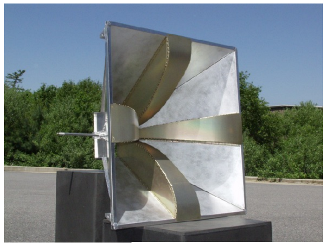
ANITA - Antarctic Impulsive Transient Antenna Experiment

Very large detection volume,
Small solid angle,
Completed another successful missions
Anthropogenic noise backgrounds



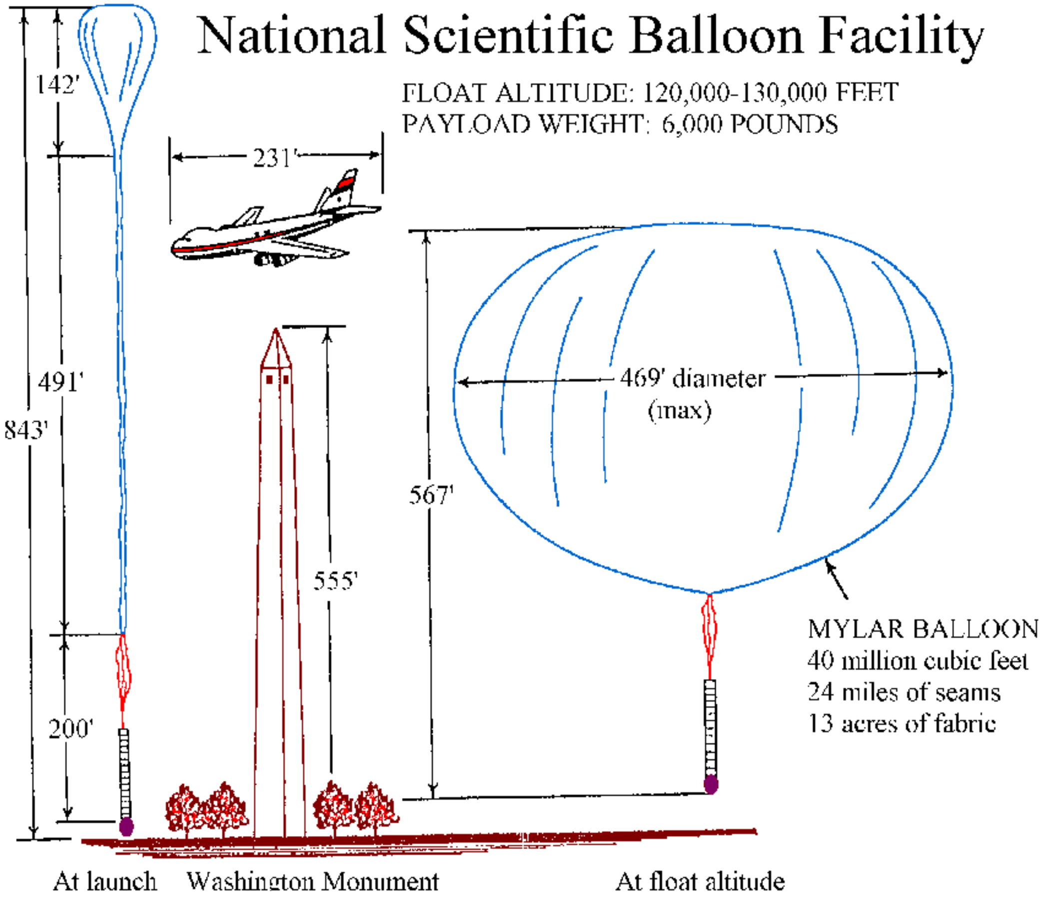
searching for GZK neutrinos with radio detection in Antarctic ice





National Scientific Balloon Facility

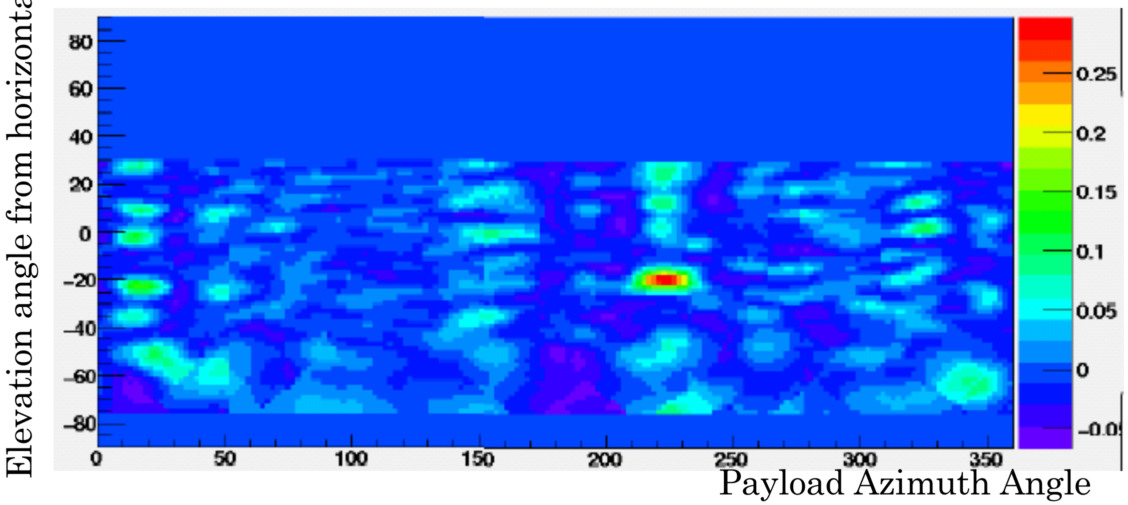
FLOAT ALTITUDE: 120,000-130,000 FEET
PAYLOAD WEIGHT: 6,000 POUNDS



MYLAR BALLOON
40 million cubic feet
24 miles of seams
13 acres of fabric


¡ANITA!

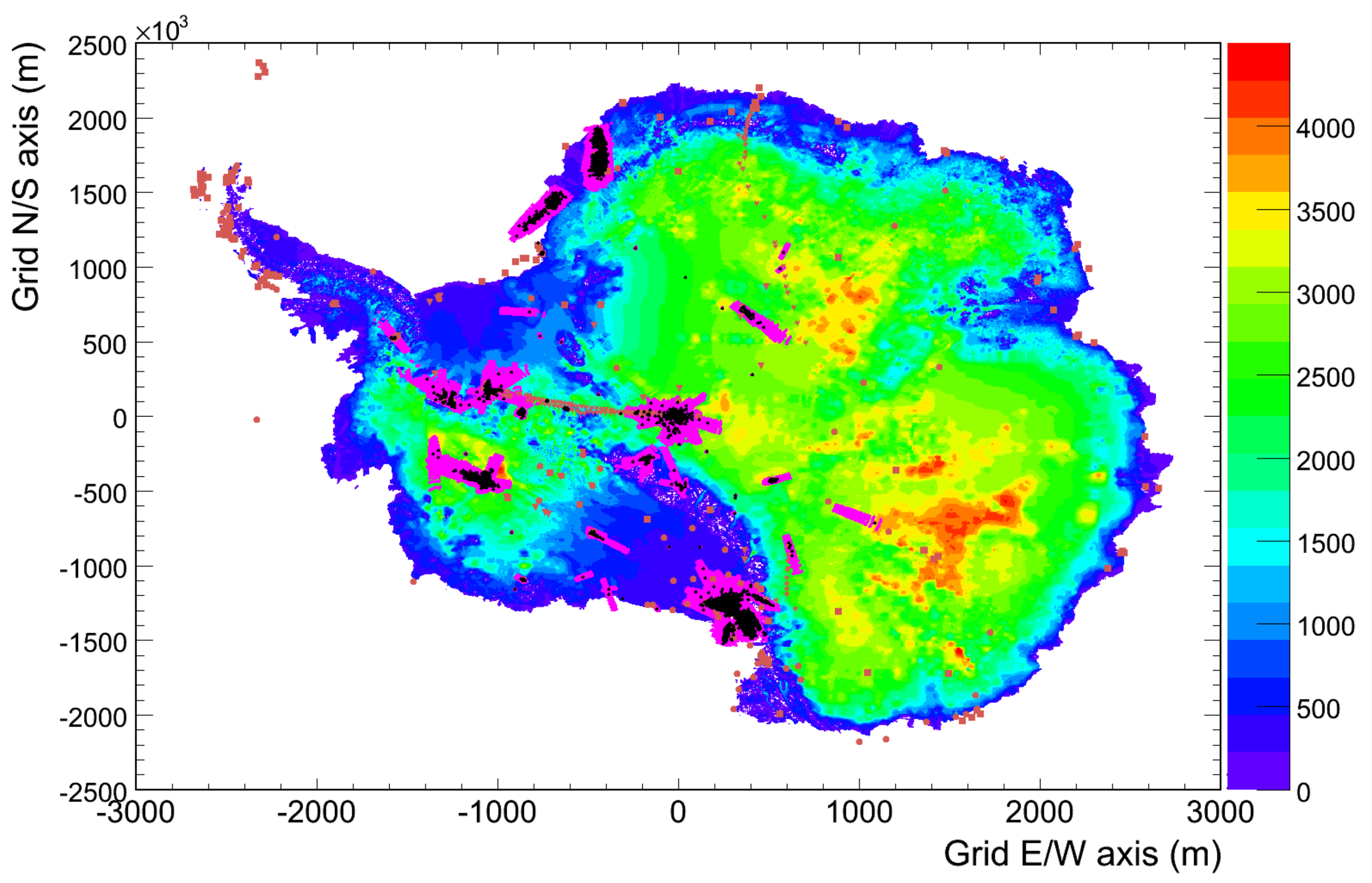
Pointing Events (ANITA)



(Taylor Dome Calibration Pulser Event)

Making an Interferometric Image:

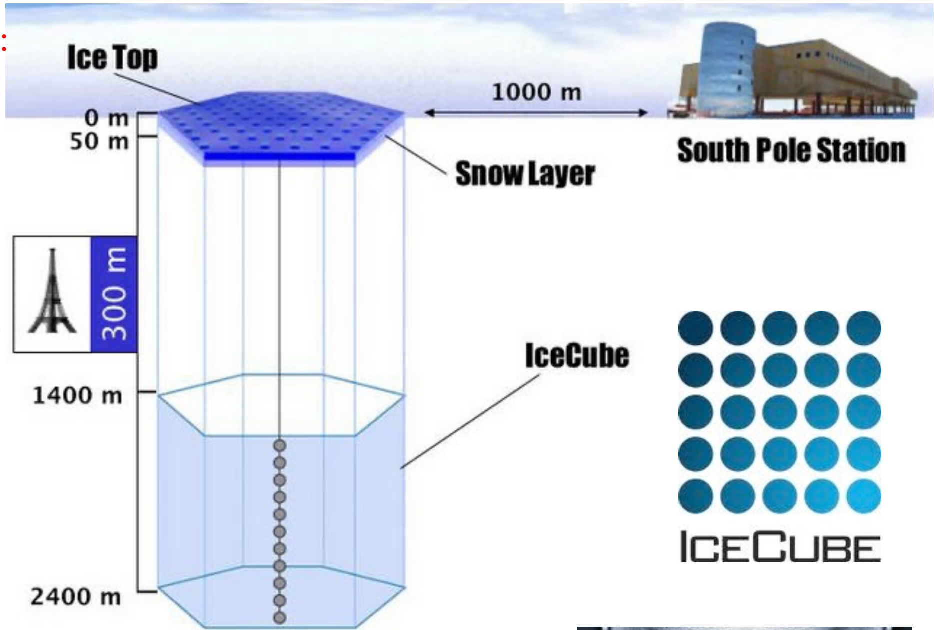
- calculate cross-correlation of antenna waveforms
- use timing delay given by direction
- sum over the whole payload


×10^3
Grid N/S axis (m)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-2000
-1000
0
1000
2000
3000
Grid E/W axis (m)
4000
3500
3000
2500
2000
1500
1000
500
0

NARC – NEUTRINO ARRAY RADIO CALIBRATION
CALIBRATION INSTRUMENTS EMBEDDED WITH ICECUBE

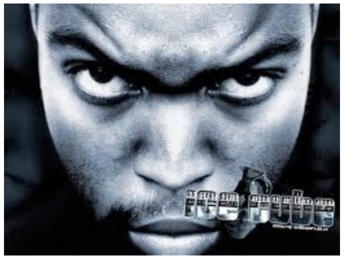
➔ In ice digitization . Combination of
ANITA/IceCube/RICE technology:
2 clusters in 2006-2007
3 clusters in 2008-2009
Depth of 1450 m or 300 m
aka "AURA"

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



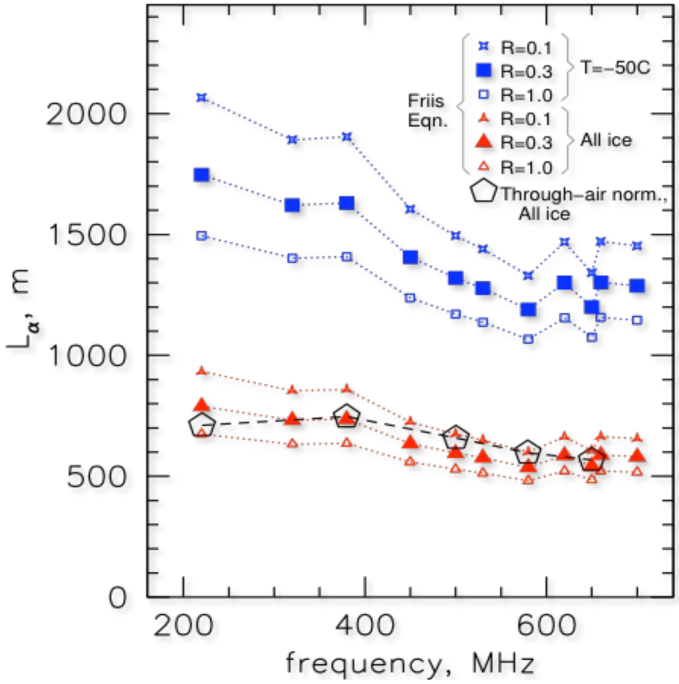
➔Calibration

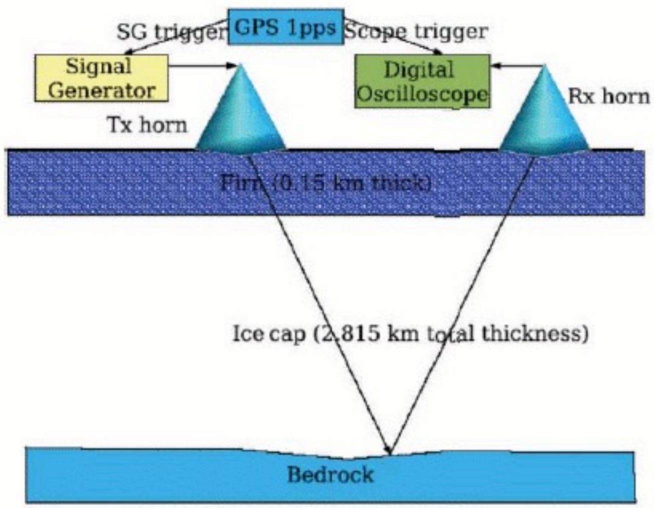
Set of transmitters and passive antennas for calibration
(including cable symmetrical antennas)



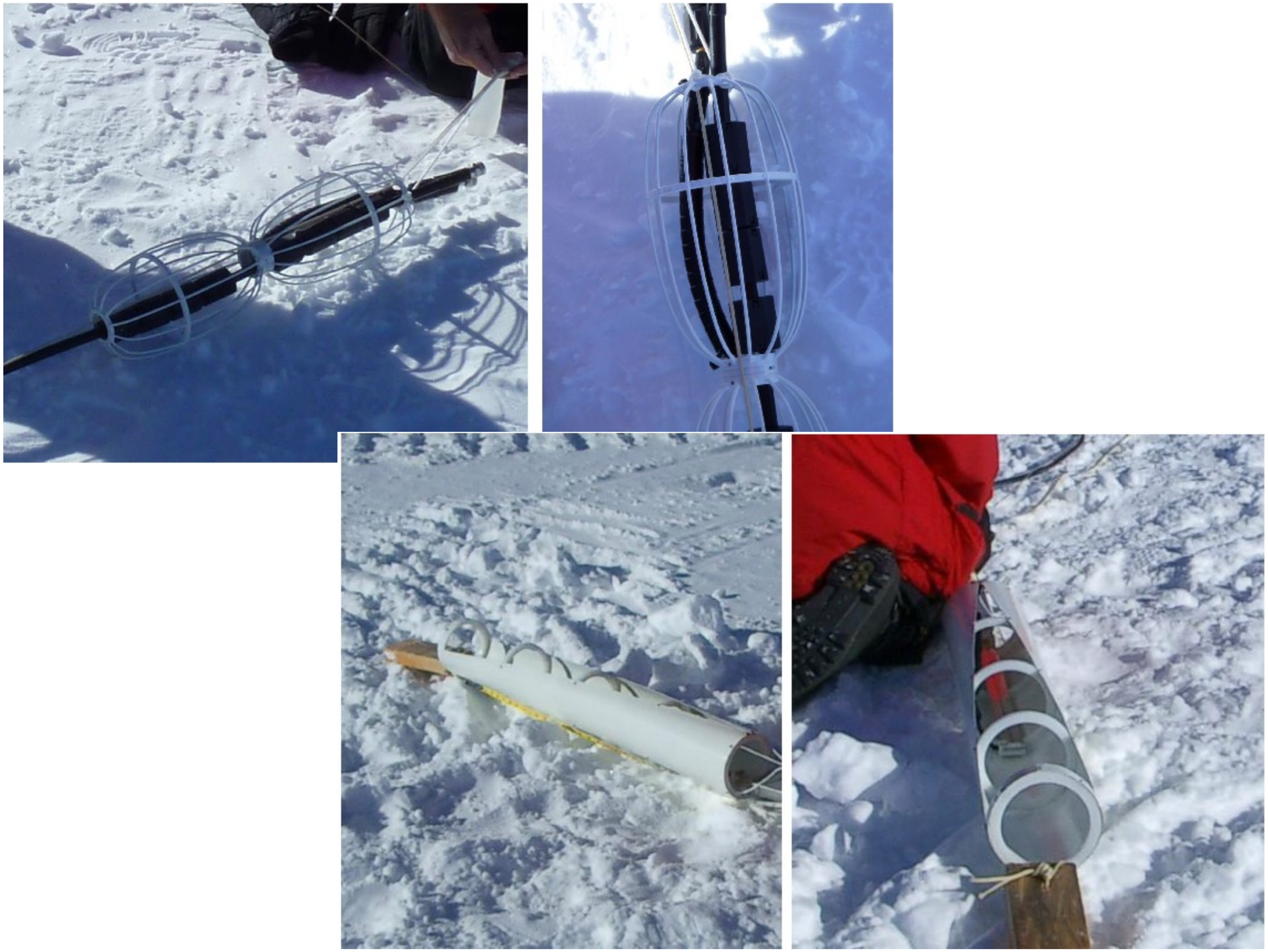
ICE ATTENUATION LENGTH

- 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.





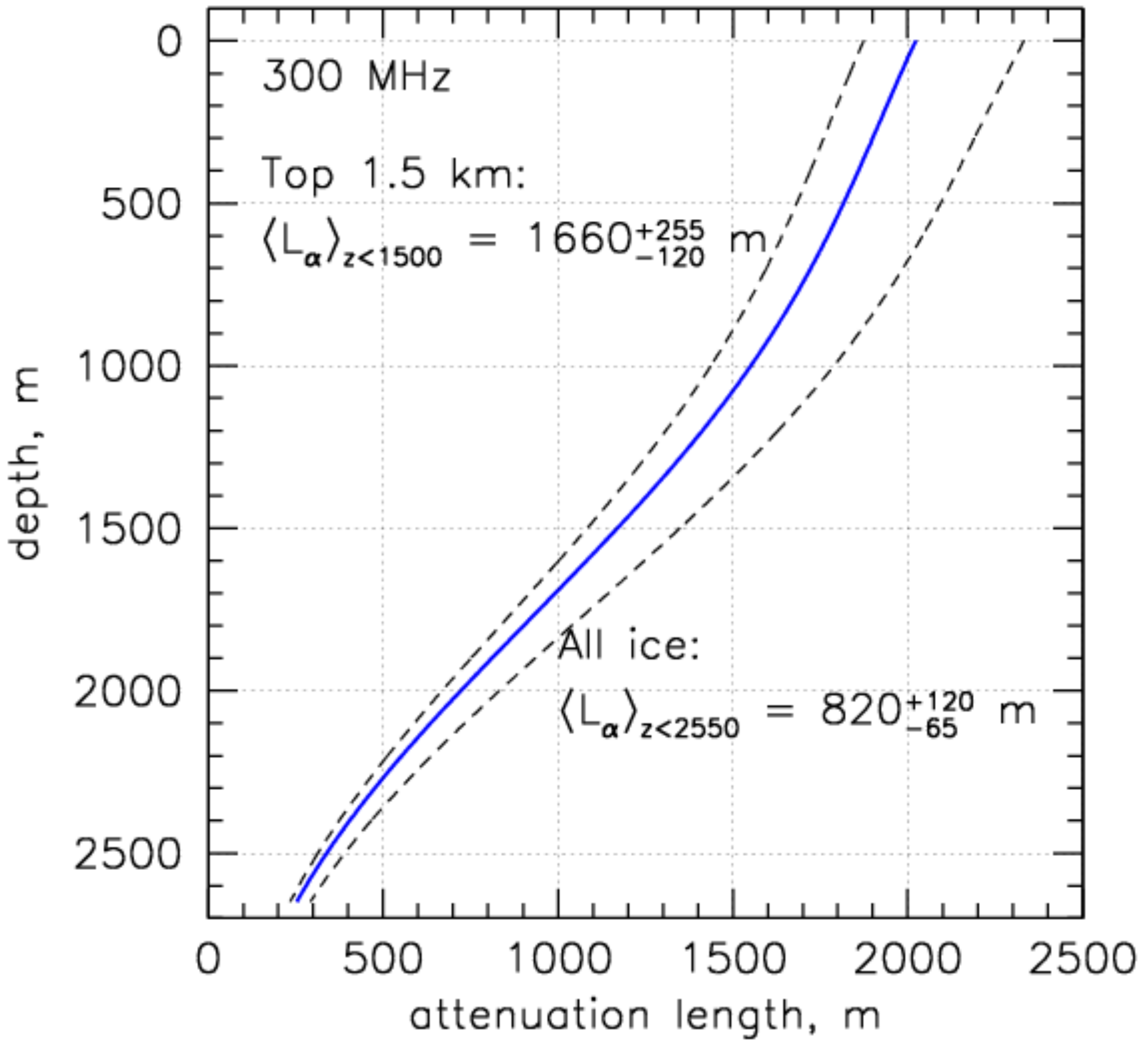
Besson et al. *J.Glaciology*, 51,173,231,2005



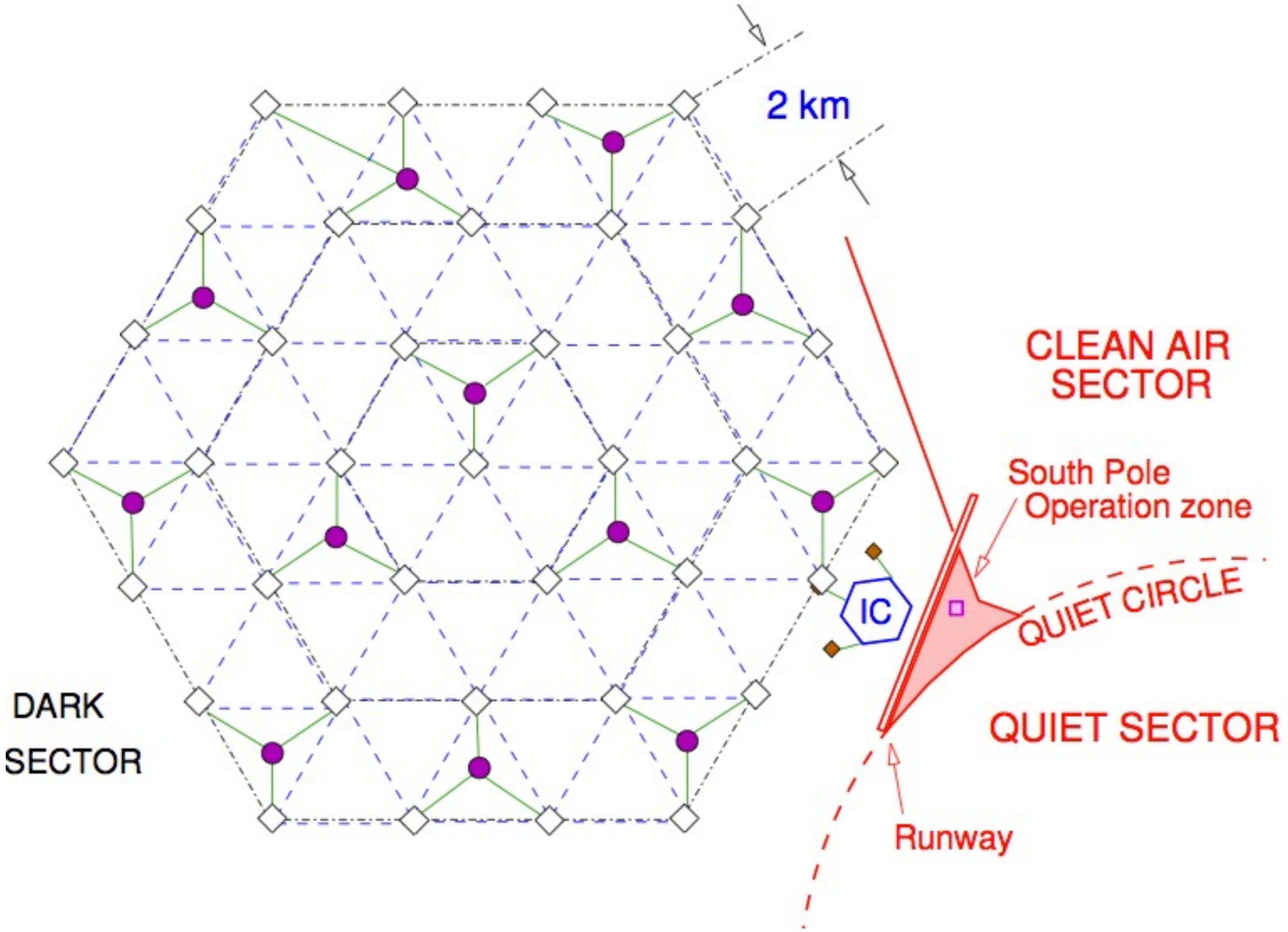
DESIGN A NEW PROJECT

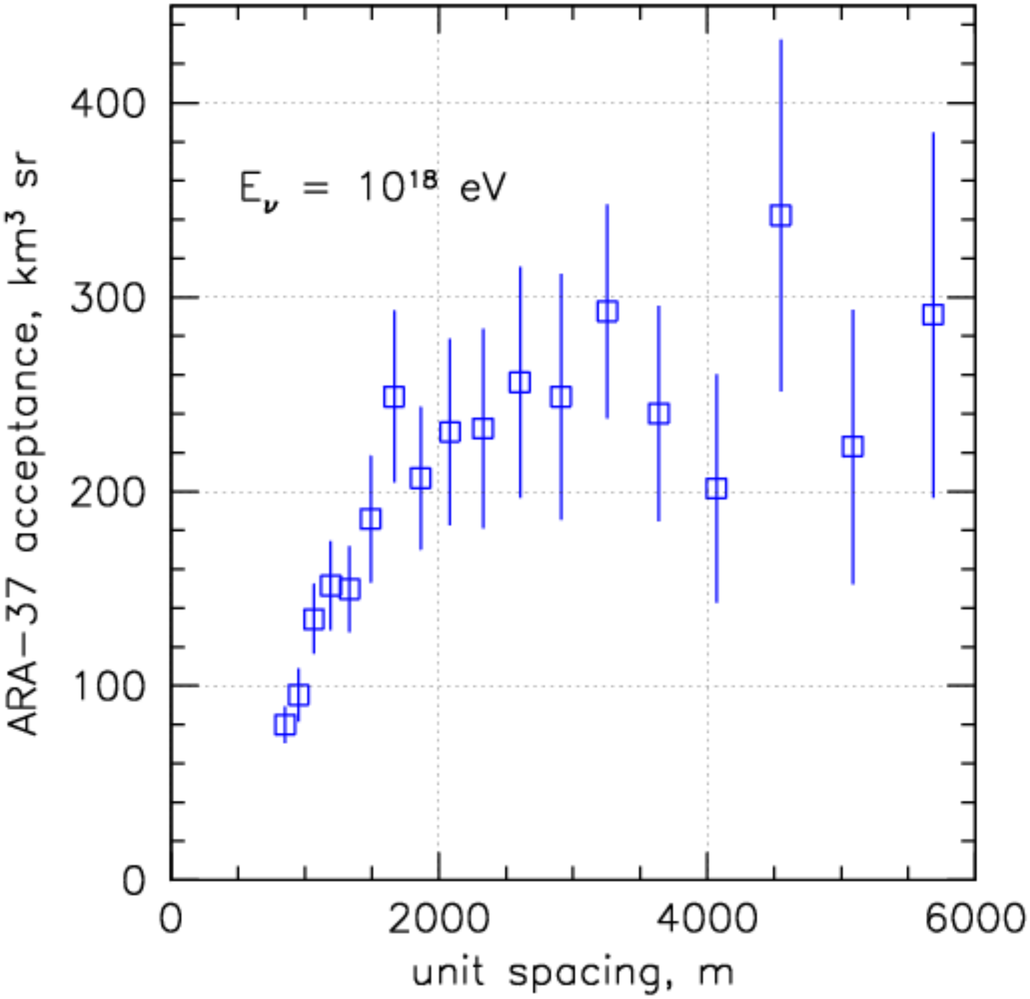
Guided by the past projects

“ARA” Askaryan Radio Array

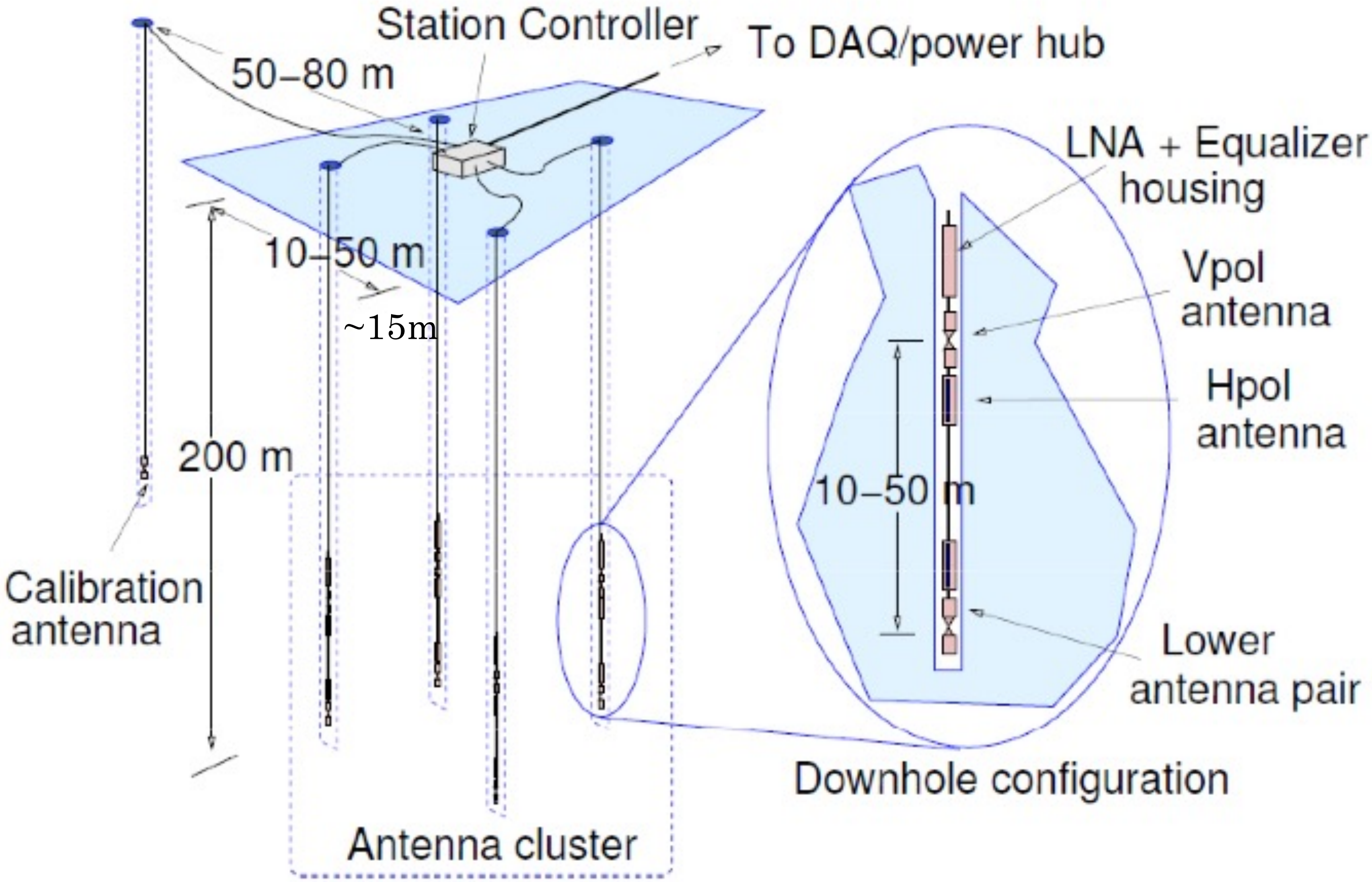

300 MHz
Top 1.5 km:
$\langle L_\alpha \rangle_{z<1500} = 1660^{+255}_{-120}$ m
All ice:
$\langle L_\alpha \rangle_{z<2550} = 820^{+120}_{-65}$ m
depth, m
0
500
1000
1500
2000
2500
0
500
1000
1500
2000
2500
attenuation length, m

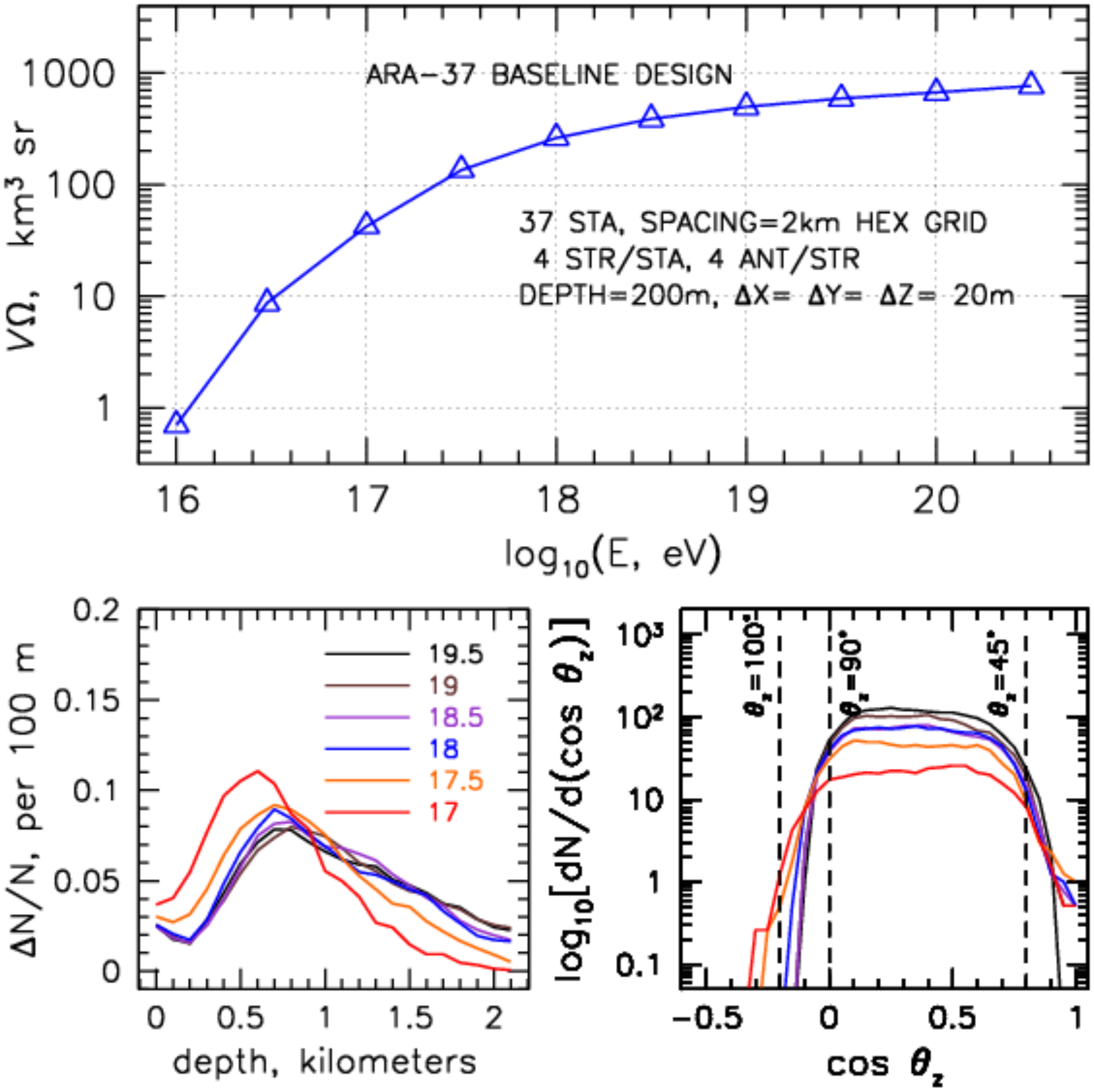
ARA-37 LAYOUT




E_ν = 10^{18} eV
ARA−37 acceptance, km³ sr
unit spacing, m
0
100
200
300
400
0
2000
4000
6000

ARA Station & Antenna Cluster



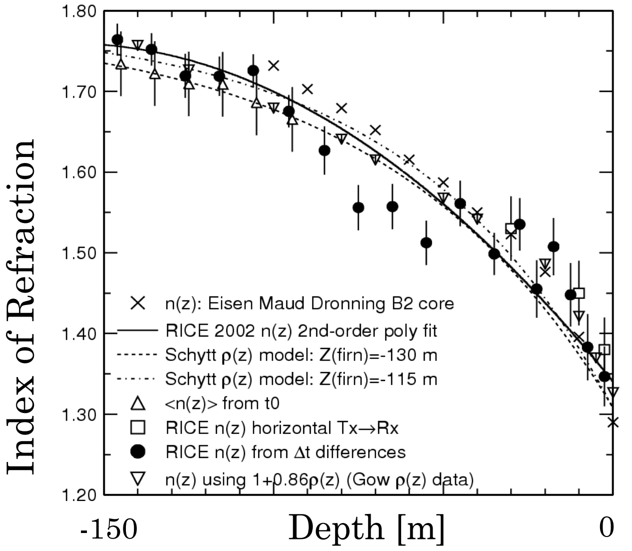

ARA−37 BASELINE DESIGN
37 STA, SPACING=2km HEX GRID
4 STR/STA, 4 ANT/STR
DEPTH=200m, ΔX= ΔY= ΔZ= 20m
VΩ, km³ sr
1
10
100
1000
16
17
18
19
20
log₁₀(E, eV)
19.5
19
18.5
18
17.5
17
ΔN/N, per 100 m
0
0.05
0.1
0.15
0.2
0
0.5
1
1.5
2
depth, kilometers
log₁₀[dN/d(cos θz)]
0.1
1
10
10²
10³
θz=100°
θz=90°
θz=45°
−0.5
0
0.5
1
cos θz

Why strings?

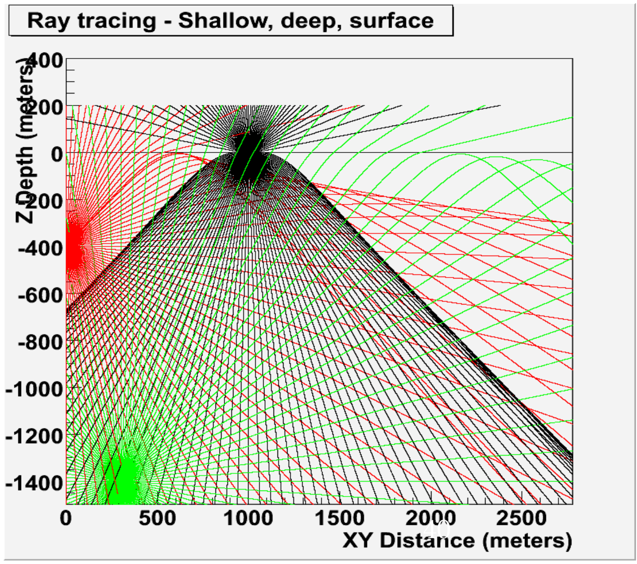
(rather than surface antennas)

- 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



ARA!

ARA Collaboration

California Polytechnic State University · 1901

Discere Faciendo

The Ohio State University

South Pole

Askaryan Radio Array

Crescat scientia vita excolatur

The University of Chicago

Wisconsin

University of Wisconsin–Madison

Wisconsin IceCube Particle Astrophysics Center

University of Delaware

University of Maryland 1856

KU

The University of Kansas

國立臺灣大學

National Taiwan University

University of Nebraska Lincoln

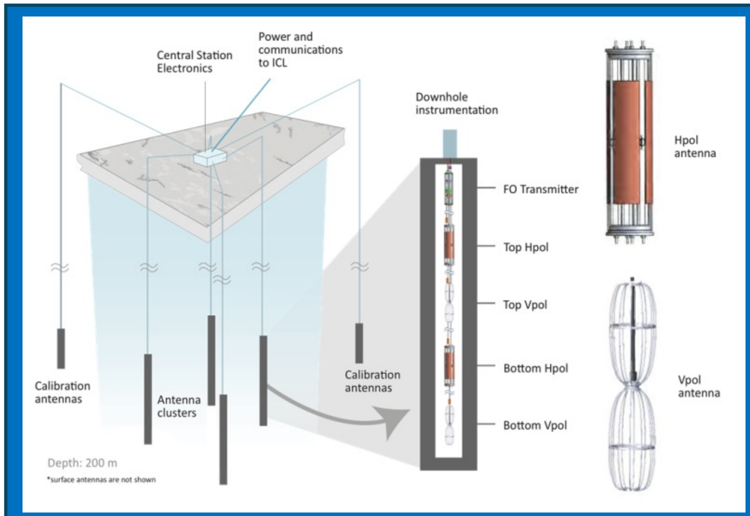
Weizmann Institute of Science

UCL

ULB

Université Libre de Bruxelles

The Askaryan Radio Array

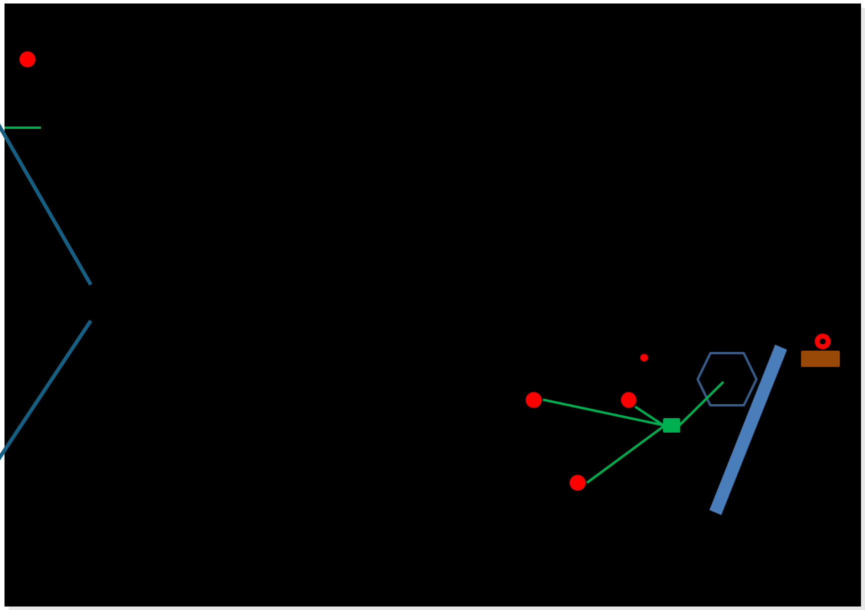


One station:

- **Measurement system:**
  - 4 holes, 20 m spacing
  - Deployed at depth of 180 m
  - 16 antennas, 150 MHz – 850 MHz
    (8 horizontally polarized., 8 vertically pol.)
- **Calibration system:** 4 pulsing antennas

Each station is an autonomous detector!

3 of 37 planned currently deployed plus ARA TestBed used to evaluate the EMI env at Pole and ended up producing good scientific results (CGP talk today).

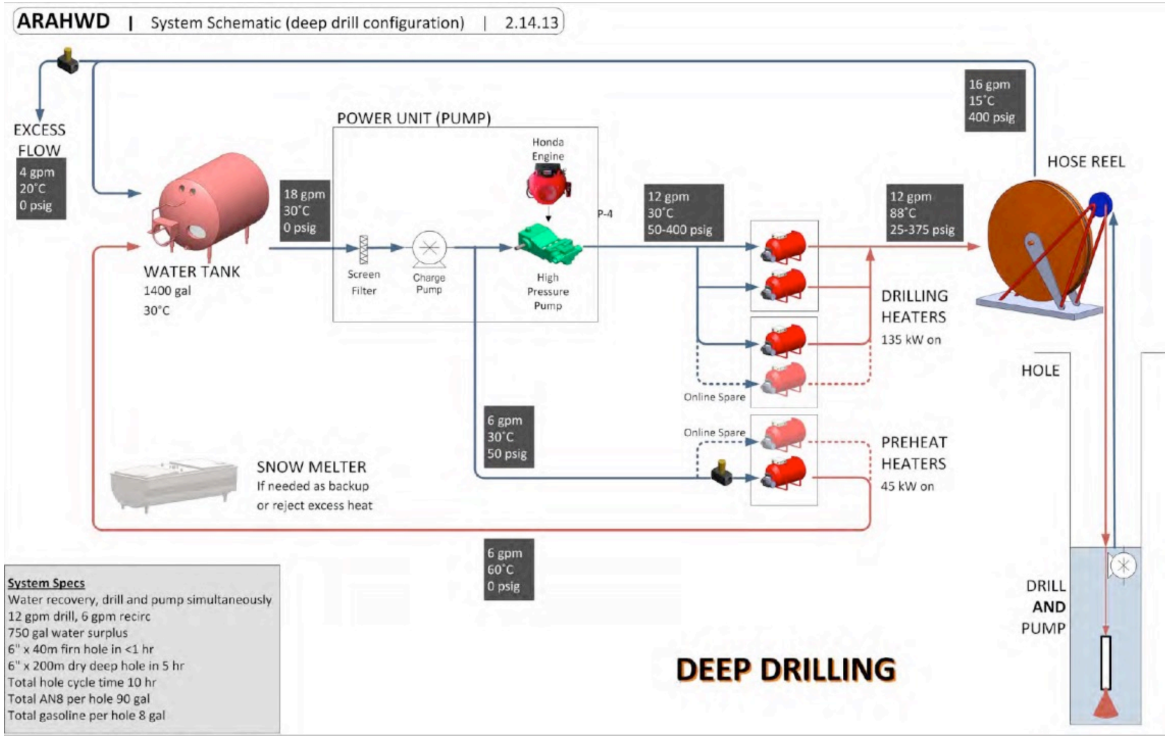


During 2013 season ARA-1 was not operational – hence this analysis only covers ARA-2 and 3 data.

Shallow Ice Drilling

ARA 2012-13 Hot Water Drill delivered 200 m, 15 cm dry holes for deployment of ARA2, ARA3 instrumentation:

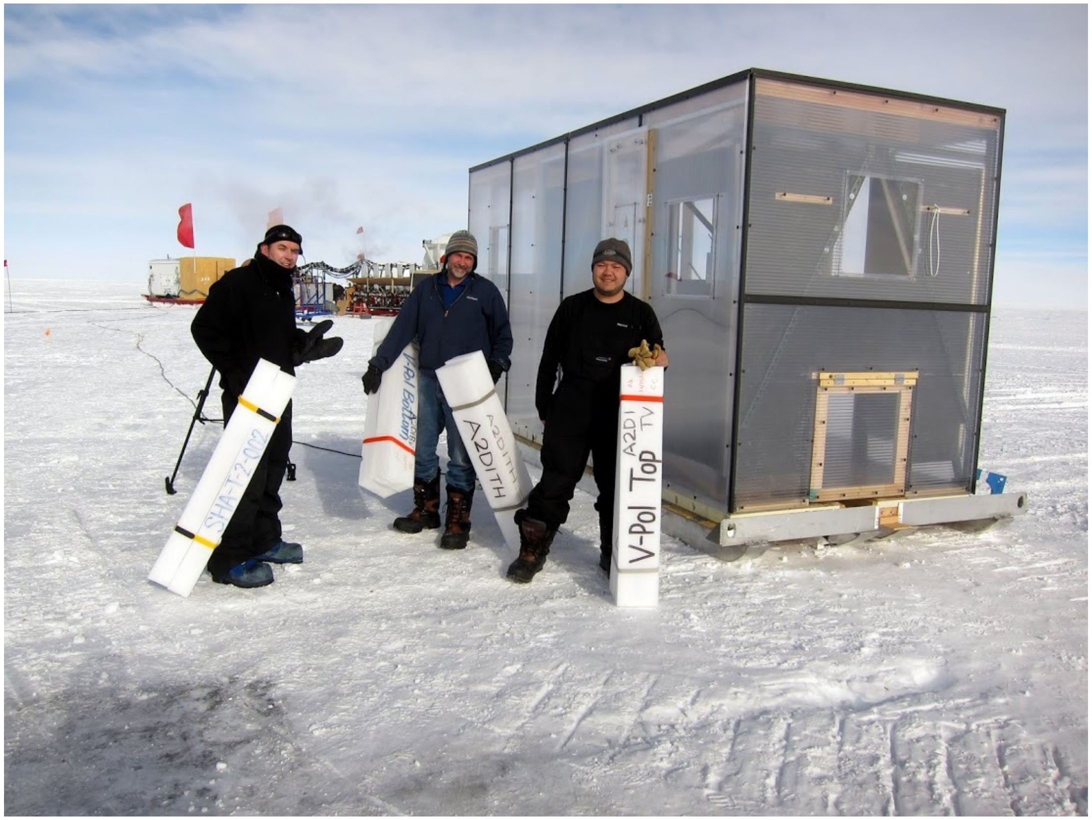
- 0.6 – 1.0 m/min drill speed → 5h drill time to 200 meters;
- Improvement over previous (tough) season include closed loop water system → 100% of heat generation went down hole instead of melting snow to make hot water.

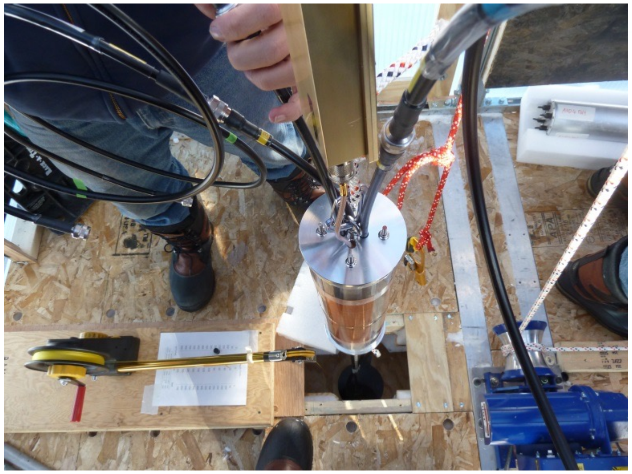


System Specs
Water recovery, drill and pump simultaneously
12 gpm drill, 6 gpm recirc
750 gal water surplus
6" x 40m firn hole in <1 hr
6" x 200m dry deep hole in 5 hr
Total hole cycle time 10 hr
Total AN8 per hole 90 gal
Total gasoline per hole 8 gal

Shallow Ice Drilling

Instrument Deployment





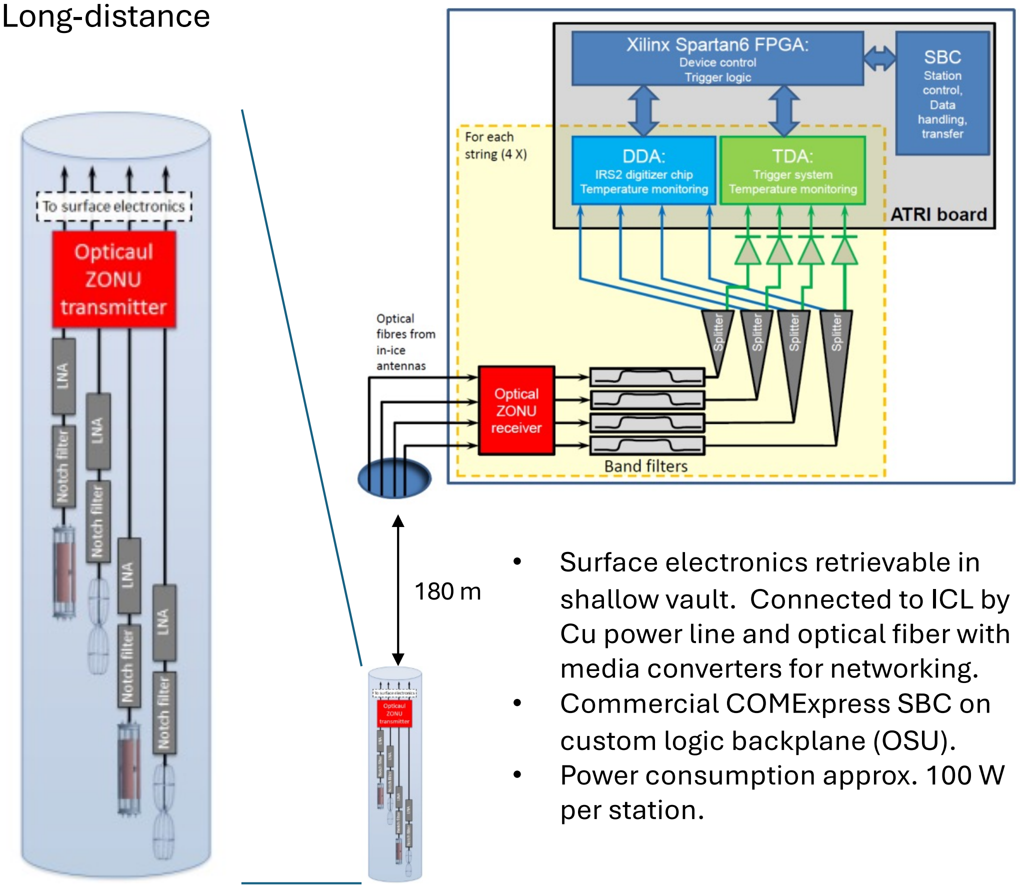
The ARA Signal Chain and DAQ

Each string has 2 Vpol and 2 Hpol antennas with local LNA. Long-distance (200 m) RF signal transport via fiber-optic translator.

Triggering via tunnel diode power estimators + fast pulse discriminators with tunable threshold.

Digitization performed by IRS2 (G. Varner, U. Hawaii). 8-ch SCA with 32k/ch analog buffer depth, divided into 512 64-sample blocks each randomly accessible. Analog sampling rates up to 4 GSPS possible – ARA configured to 3.2 GSPS (20 ns per 64 sample block). In principle ZeroDT capture for trigger rates ~ kHz. Early version of ASIC has some noise problems which prevented operation in this mode. Low power consumption ~ 20 mW/ch.

Sample jitter of 100’s ps and and severe non-linear amplitude response requires careful calibration. Time resolution of ~95 ps achieved on pulses from nearby calibration pulsers.

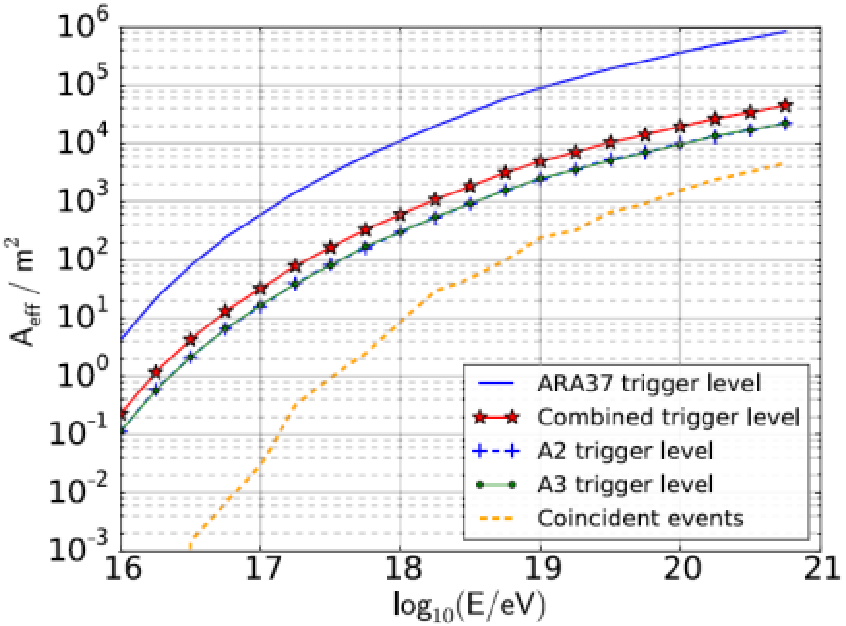


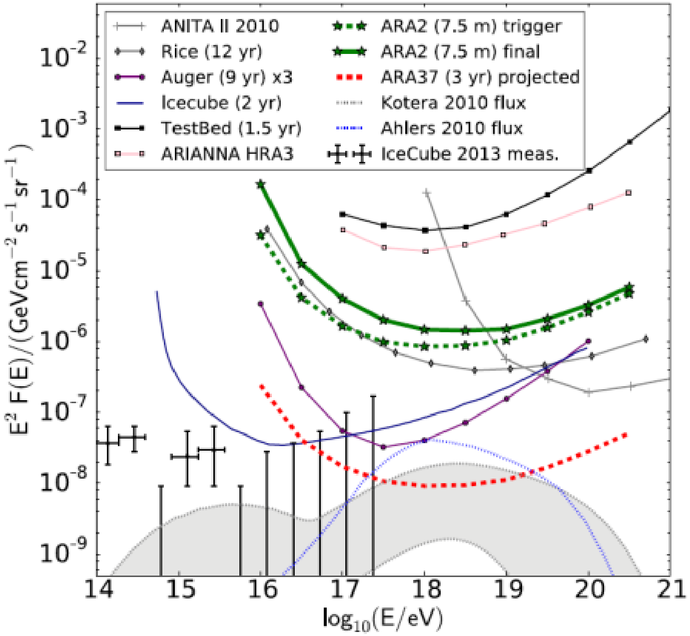
- Surface electronics retrievable in shallow vault. Connected to ICL by Cu power line and optical fiber with media converters for networking.
- Commercial COMExpress SBC on custom logic backplane (OSU).
- Power consumption approx. 100 W per station.

Data Analysis Steps

- Begin with 150 million triggers in 10 months data
- Wait until next year because ARA only gets 1 GB/day of satellite transfer (1% of IceCube) so tapes, now disks, have to be physically transported to Madison and placed online.
- Expectation:
  - 0.2 GZK/BZ neutrinos
  - 1000 impulsive RF events – non-thermal
  - Rest are thermal noise triggers
- Step #1 – eliminate thermal noise
- Step #2 – reconstruct emission vertex

Analysis Effective Area & UHE Neutrino Limit





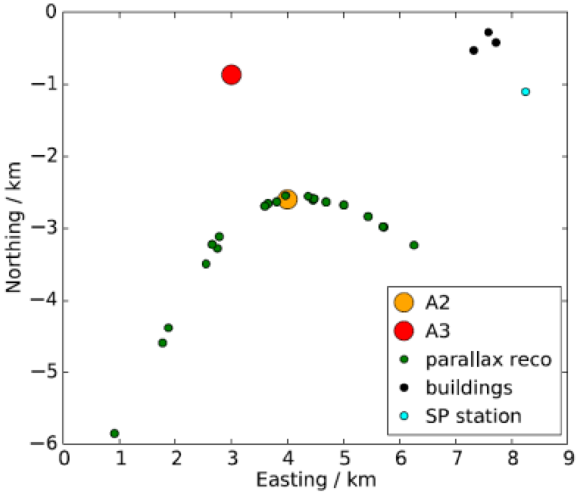
LC-130 Cross-Check

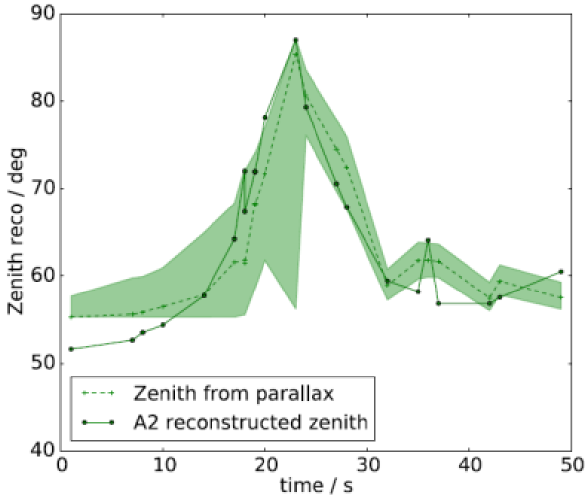
Instead of using drones ARA profited from opportunity to record transmissions of LC-130 departing from NPX.

Compare angular reconstruction of ARA-2 alone with parallax reconstruction using combined signals in ARA-2 and ARA-3 stations.

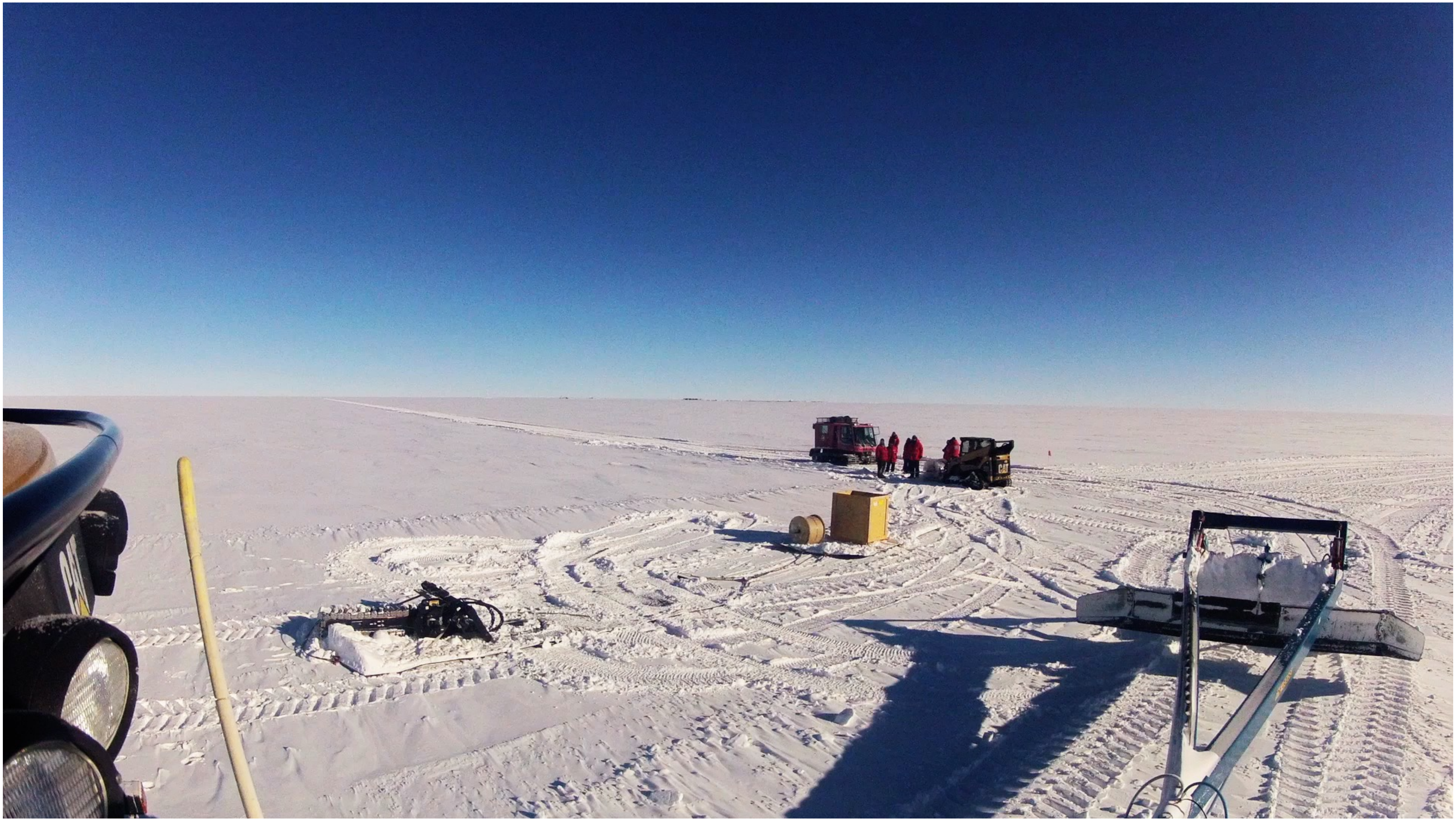
This required first aligning clocks which are normally not synchronized.

Ground track of LC-130





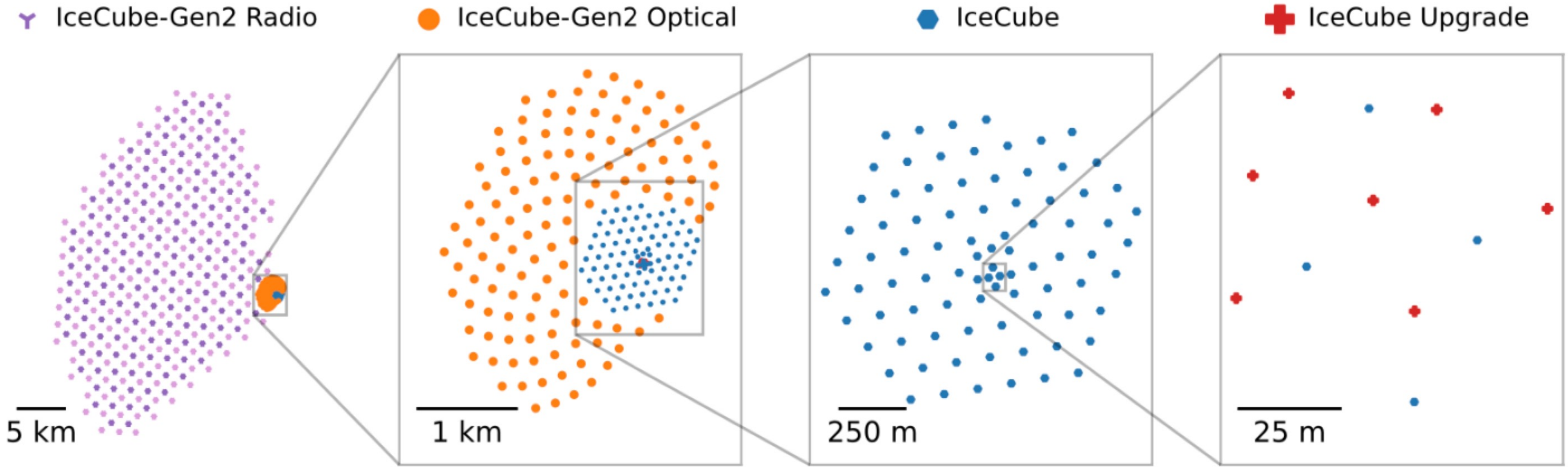
Comparison of single station vs. multiple station reconstruction. The green band is error in parallax reconstruction.


CAT
CAT

IceCube-Gen2

Arrays of IceCube-Gen2

Radio Array targets the Ultrahigh-Energy Regime



- 169 hybrid stations, 1.75 km spacing on square
- 192 shallow stations, interspersed 1.24 km spacing

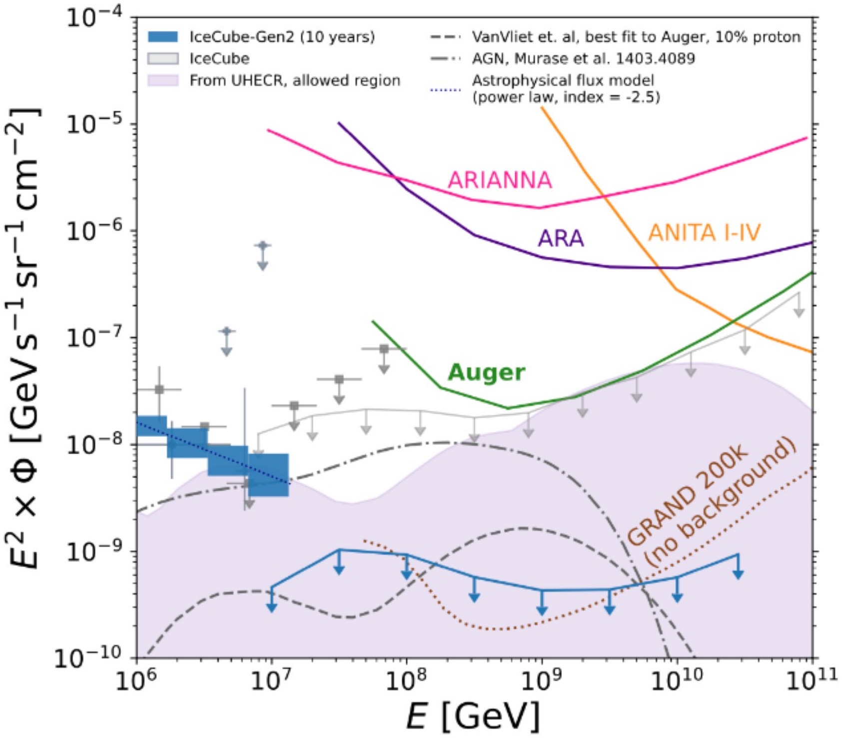
IceCube-Gen2 Collaboration TDR

Science Case

Discovery-level array at Ultrahigh Energies

- **Astrophysical neutrinos:**
  - Resolve the high-energy neutrino sky from TeV to EeV energies
  - Mutlimessenger observations
  - Energy, spectrum, and flavor
- **Cosmogneic neutrinos:** origin of cosmic ray accelerators
  - Targeting discovery at flux level where 10% of the UHECR are protons, with five years of data
- **Fundamental physics** at UHE energies
- Expect 3 deg. angular resolution and 65% energy resolution (68% containment)

➡ Requires scaling up from existing in-ice radio arrays by several orders of magnitude

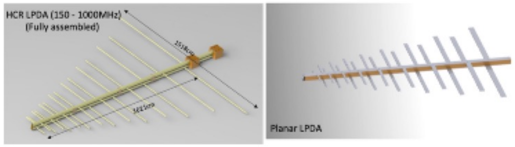


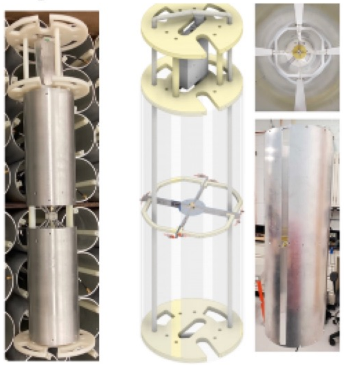
IceCube-Gen2 Collaboration TDR

Station Designs

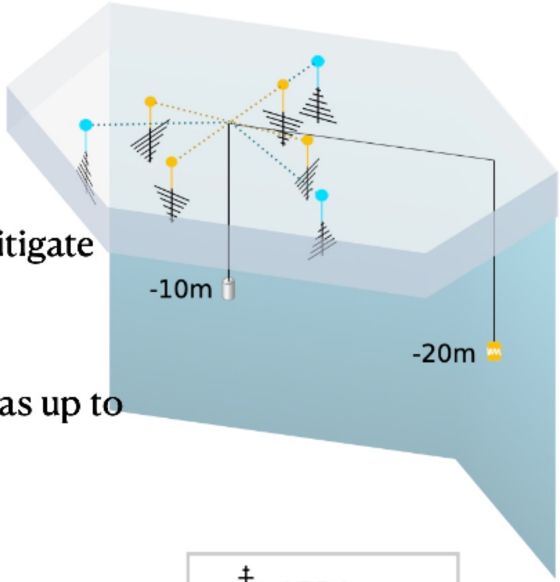
A Hybrid Approach

- Robust discovery-level instrument that combines shallow and deep antennas to mitigate against systematics with two approaches
- **Hybrid:** 24 channels (17 deep cylindrical antennas up to 150 m maximum depth, 7 LPDAs surface)
- **Shallow:** 7 LPDAs, one 10-m deep dipole

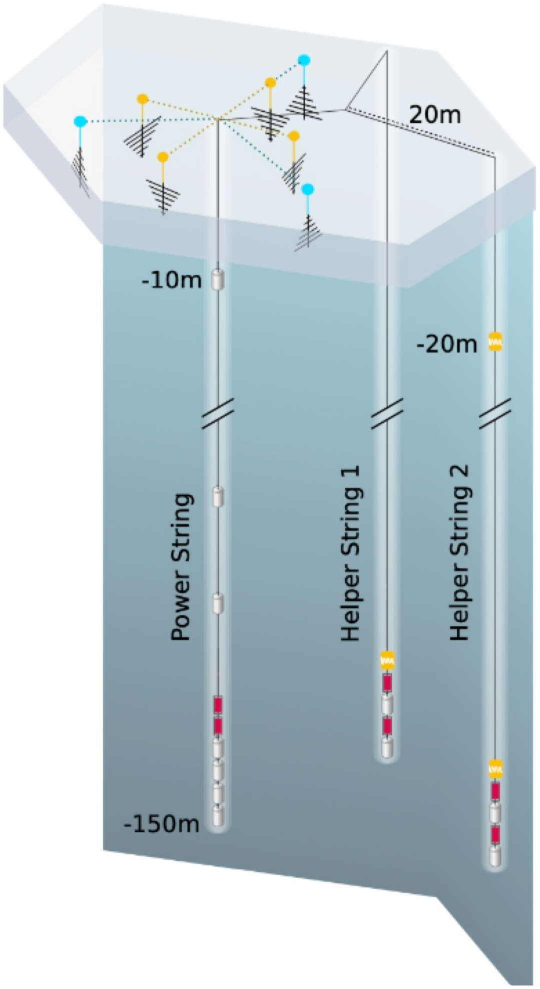




Shallow



Hybrid



LPDA

Calibration Pulser

Hpol

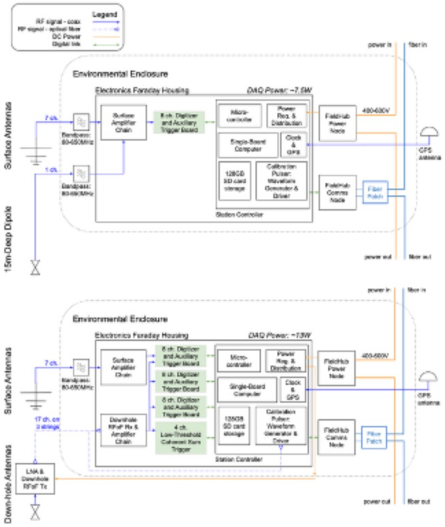
Vpol

Data Acquisition

Requirements

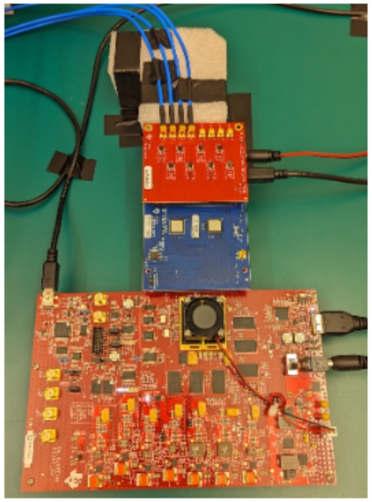
- Runs reliably 24/7, 80% uptime
- Records waveforms accurately without need for individual tuning
- Resources to support low-threshold triggers (phased arrays, neural networks)
- Modest power requirements

Reference: Modular Analog / Digital



- Modular system to accommodate both shallow and hybrid
- 8 ch ADC (1 W/ch for 24 W total)
- Custom ASIC
- **Advantage:** low power, simplified design
- Under design at Univ. Chicago (E. Oberla)

Fully Digital



- Digitization and triggers in the same location
- **Advantage:** COTS parts are robust & a simplified system
- Under design at Upsalla, UCI, Univ. Chicago, Penn State

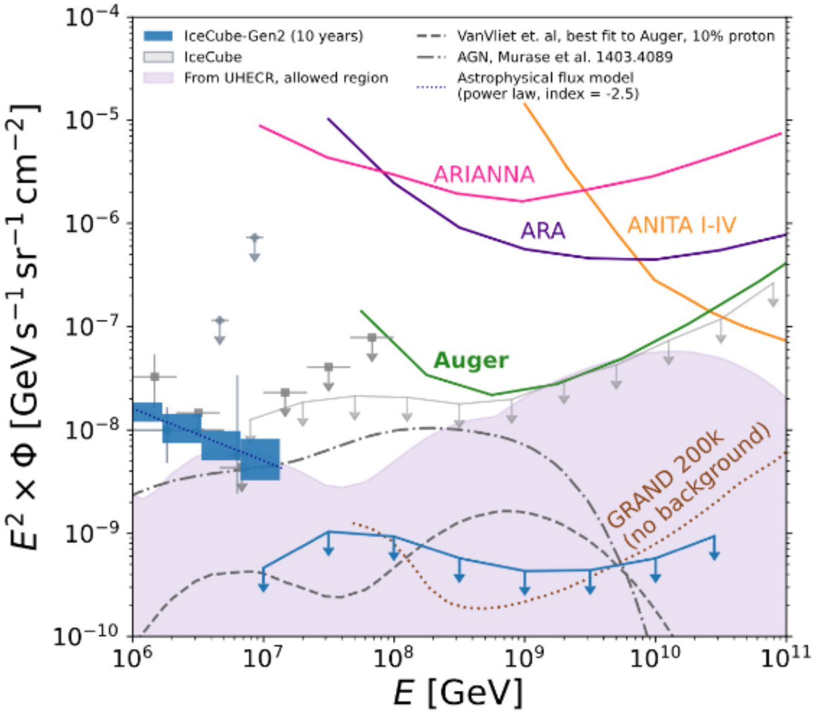
RFSoC

- RF System on chip
- **Advantage:** High dynamic range, powerful DSP and built-in FPGA logic
- Under design at Univ. Delaware, OSU (for PUEO / ARANext)

Conclusions

Radio Array of IceCube-Gen2

- Technical Design Report is published and details an achievable large volume UHE radio detector
- Reference design meets the science goals of sufficient effective volume for diffuse discovery at $E^2\phi = 2 \times 10^{-10}\,\mathrm{GeV\ cm^2\ sr\ s}$
  - Approach combines 8-channel shallow stations with 24-channel deep stations
  - Robust against present uncertainties in technical design and systematics by having multiple designs that meet the science requirements



backups

Goldstone Effort

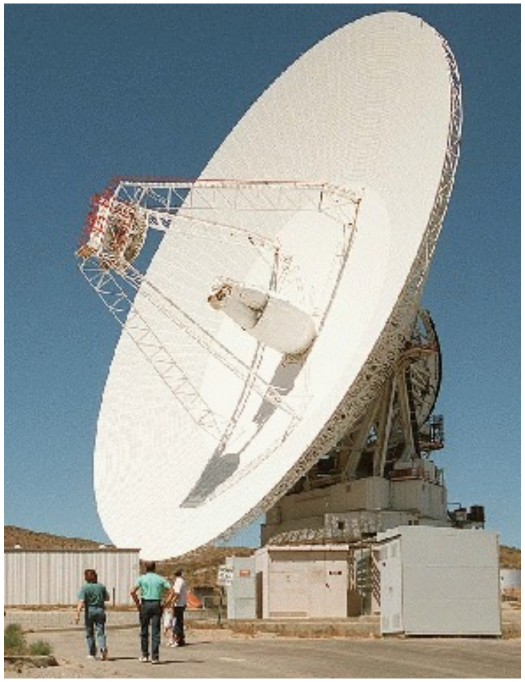
Background & motivation

- G. Askaryan, early 60's:
    - HE particle cascades produce ~20-30% more electrons than positrons
        - compton scattering, e+ annihilation, delta rays, etc.
        - => showers in dielectric produce coherent microwave Cherenkov radiation
    - One should look for low-loss microwave dielectrics abundant in nature
        - Ice, many rocks
        - Lunar regolith--a surface array on the moon!

- Immediate application was found in air showers (J. Jelley)
    - But the dominant process in EAS is not coherent Cherenkov
        - probably boosted dipole radiation from geomagnetic charge separation
    - No follow-up on Askaryan's suggestion of solid dielectrics till 80's

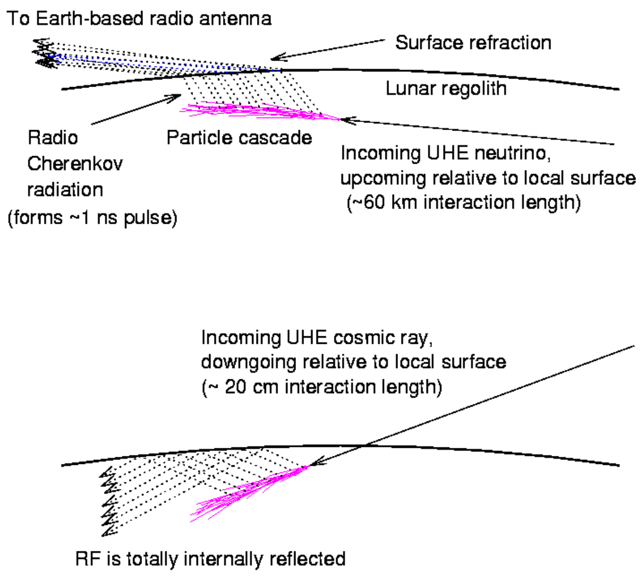
- 1988: I. Zheleznykh & R. Dagkesamansky:
    - propose that 1e20 eV neutrino events may be detectable from earth
    - First experiment (Hankins et al 96) done in 1994 w/ Parkes 64m
        - null result in 10 hours single-dish observation

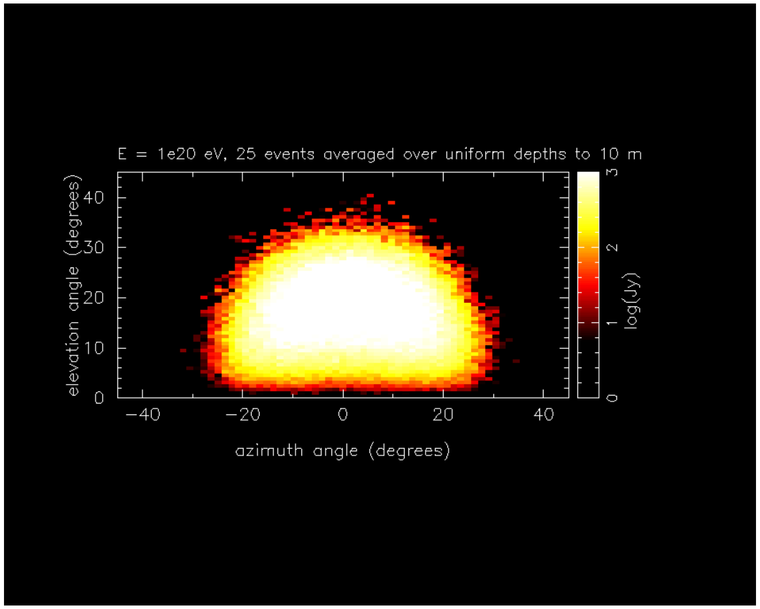
Goldstone experiment

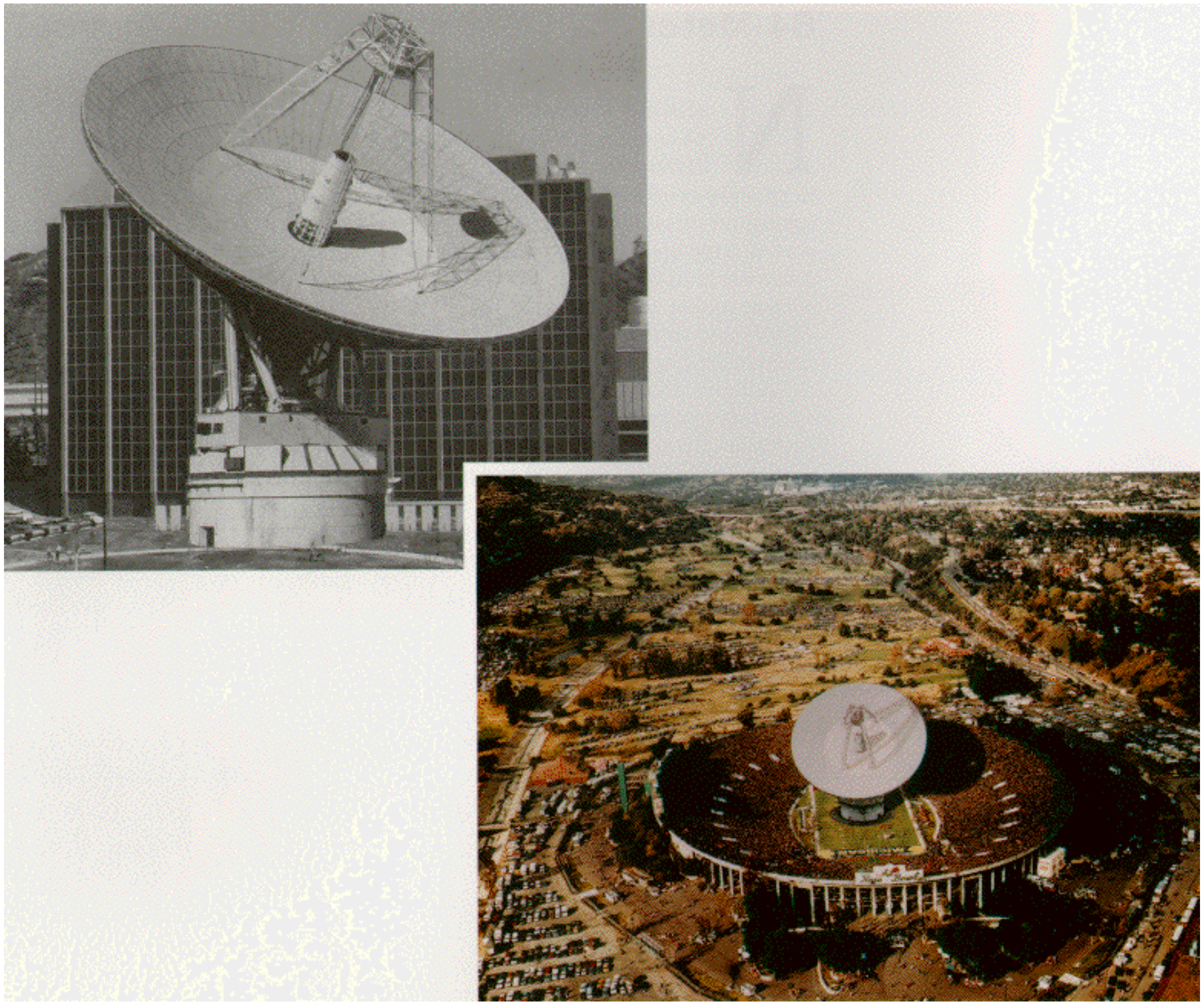


- Utilize Deep Space telecom 70m antenna DSS14 for lunar RF pulse search--fill gaps in SC sched.
- First observations late 1998:
  - approach based on Hankins et al. 1996 results from Parkes
  - utilize active RFI veto
- 1999: add 2nd 34 m fiber-linked antenna DSS13
  - initially used passive recording with local trigger at DSS14
- 2000: DSS14 down for first half, but ~20 hours livetime acquired since July
  - focussed on limb observations, lower threshold, better trigger system

Lunar Regolith Interactions & Cherenkov radiation

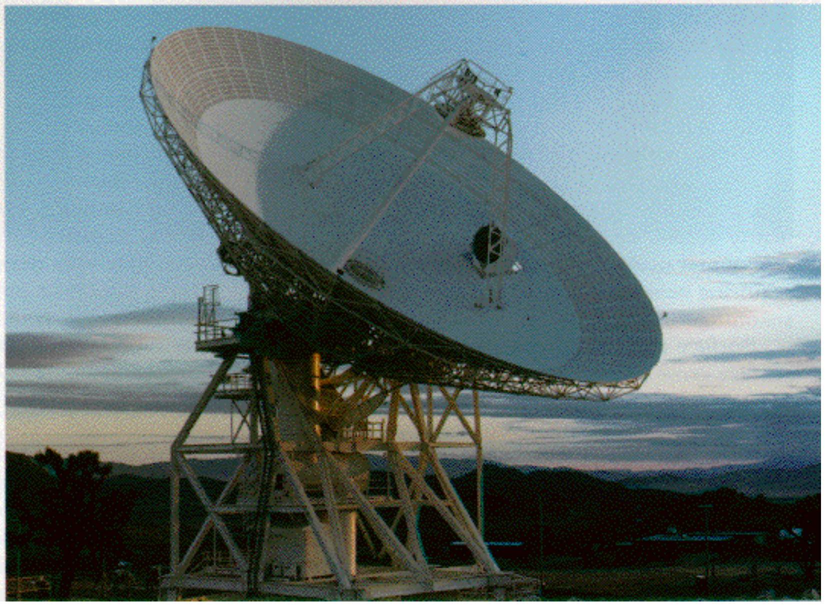






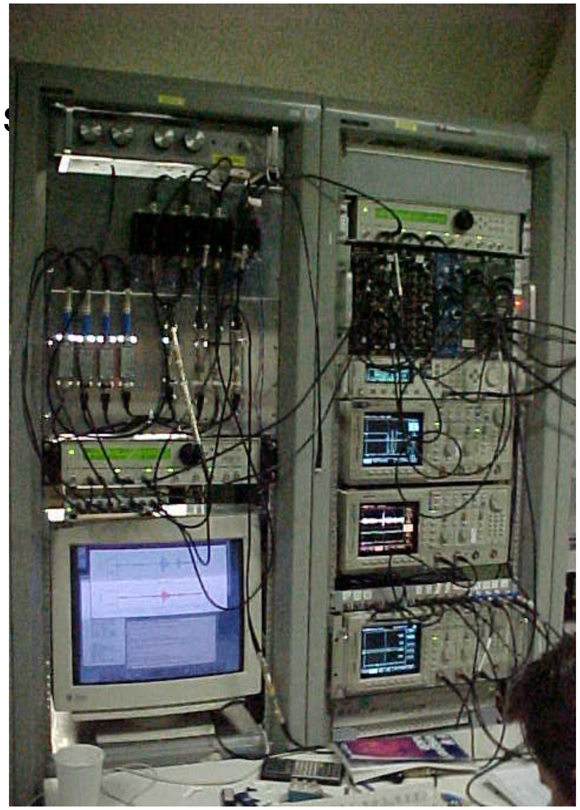
DSS13: 34 m Beam waveguide antenna

- DSS13: research antenna
- Uses “beam waveguide” optics
    - low-freq cutoff at ~1.8 GHz
- High efficiency, excellent surface
- At present: 140 MHz BW (S-band)
    - single pol, dual pol planned for ‘01

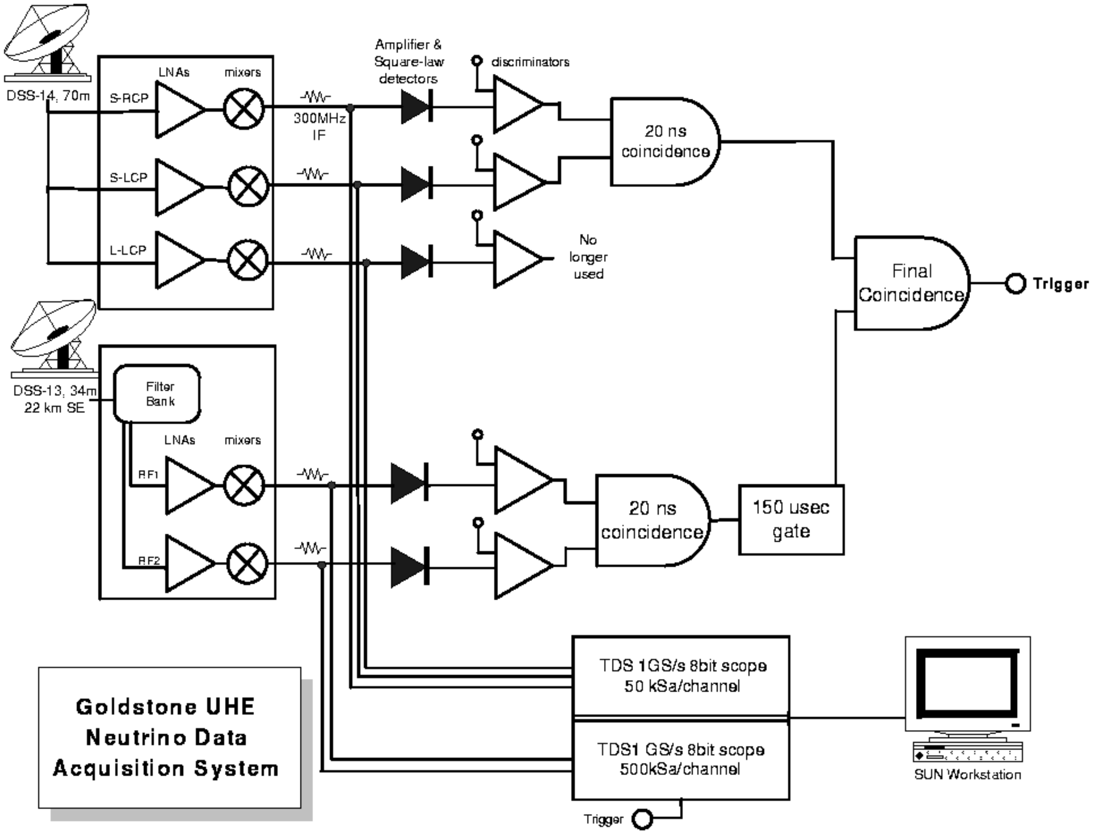


New RARG location

- Two relay racks of our own
- JPL tech support
- DSN committed to 120+ hours of expos
- New trigger
- ~8 visits, ~ 20-30 hours livetime



New Trigger

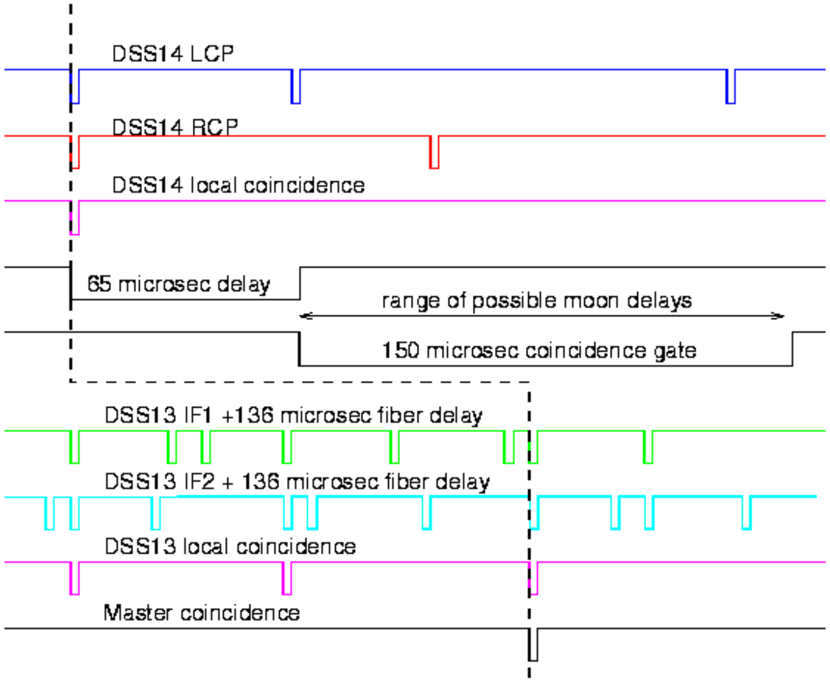


- RFI veto:
  - no longer in trigger
  - record off-axis L-band signal for post-analysis

- Pulses at both antennas now required for trigger
  - powerful interference rejection
  - disc. thresholds set according to relative aperture

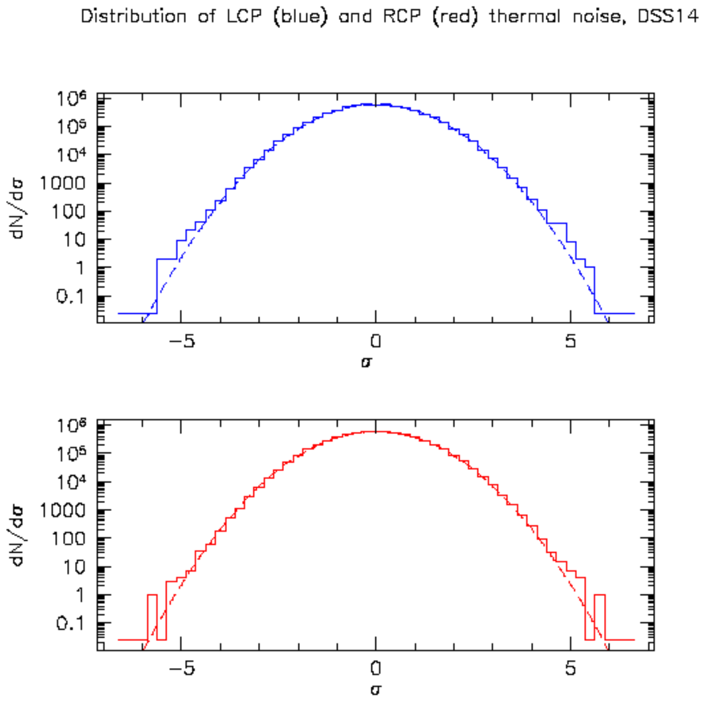
- Thermal noise coincidence rates ~0.2 per minute
  - but only ~1/day close to proper moon delay

Realtime dual antenna trigger



- Trigger must accommodate ~136 microsec fiber delay
- 4-fold coincidence formed in two-level trigger with delayed first gate
- 150 microsec window avoids need for realtime delay tracking

Thermal Noise Statistics


Distribution of LCP (blue) and RCP (red) thermal noise, DSS14

- Voltages proportional to pulse field strength: pure gaussian:
  - => dN/dV ~ exp(-V^2)

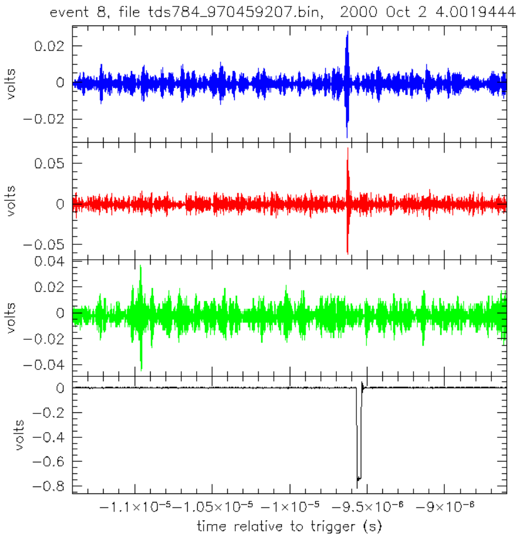
- Square-law detection used for discrimination
  - => Power ~ V^2/Z
  - => dN/dP ~ dN/dV
  - ~ exp(-I)

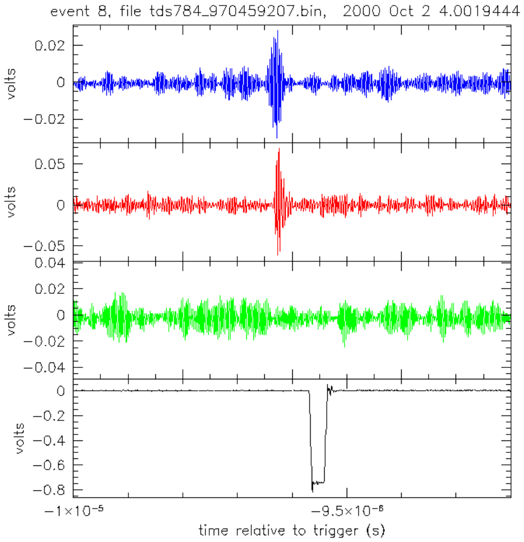
- Statistics of detected power are exponential

- => 5 sigma equivalent significance requires SNR~15

Timing & pulse shape calibration

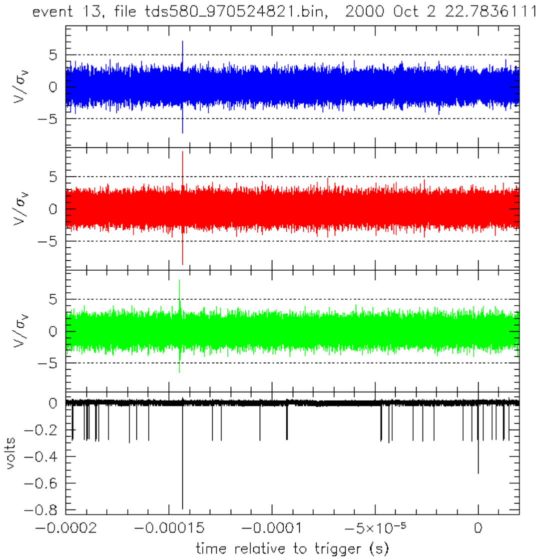
- S-band Monocycle pulser:
  - provides band-limited lin.pol. Pulses
  - checks amp. Linearity, net cable delays, band-limited pulse shape





- Zoomed version: LCP pulse is broader (40 MHz BW), RCP narrower (~100MHz BW); also slight timing offset

Typical RF interference trigger

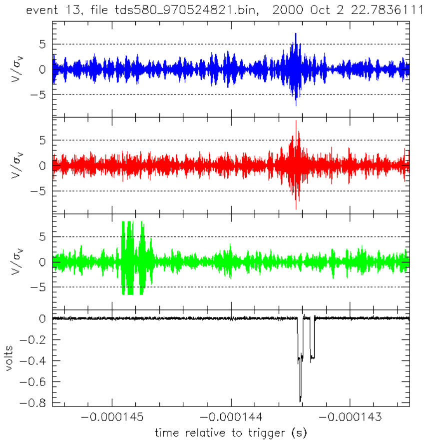


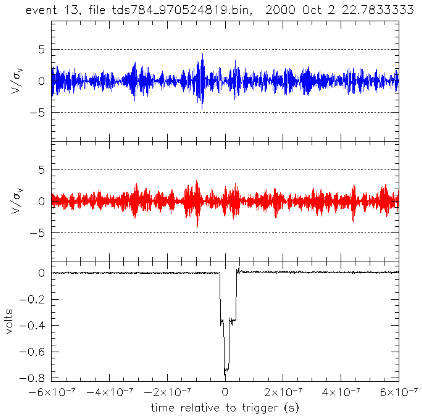
One of the 2 antennas may have high RFI singles rates

Will produce excess coincidence rate with 2nd antenna thermal noise

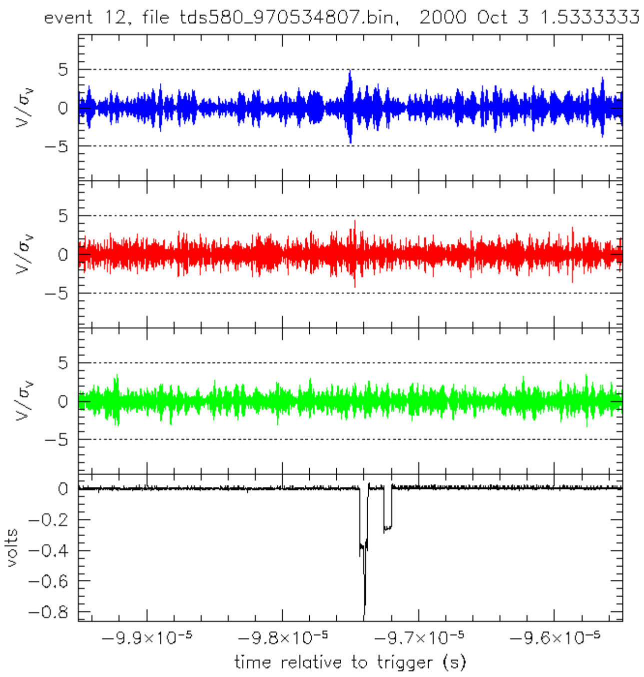
Events are clearly distinguishable: L-band channel pulse is present

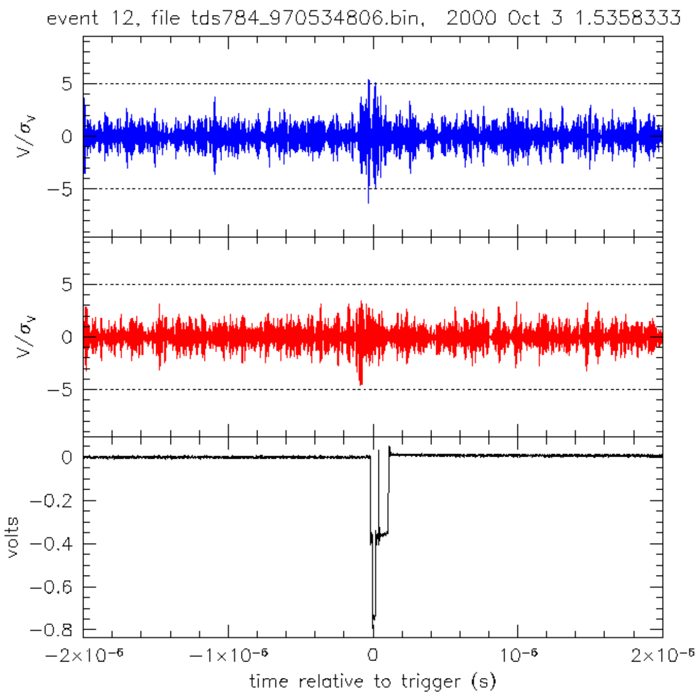
Overall increase in trigger rates ~10%



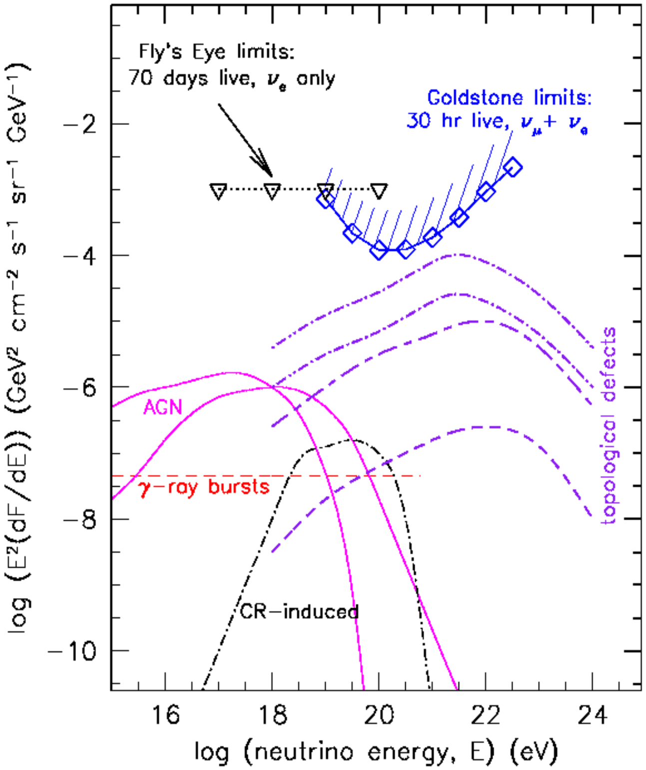


Typical Thermal Noise trigger



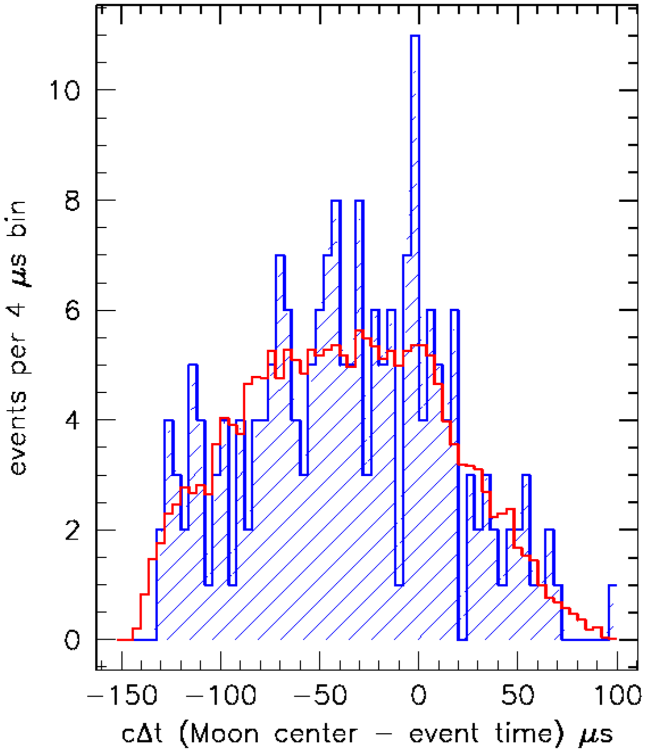


Goldstone diffuse neutrino flux limits



- ~30 hrs livetime (includes previous data)
  - No events above net 5 sigma
- New Monte Carlo estimates:
  - Xsection ‘down’ by 30-40%
    - moving target effect!
  - Full refraction raytrace, including surface roughness, regolith absorption
  - Y-distribution, LPM included
- Limb observations:
  - lower threshold, but much less effective volume
  - ‘Weaker’ limit but with more confidence
- Fly’s Eye limit: needs update!
  - Corrected here (PG) by using published CR aperture, new neutrino xsections

Statistics of non-RFI triggers near threshold



Cuts applied:

- tighter timing
- pulse width close to band-limited
- not obvious RFI

BKG weight determined by randomizing event UT within run period

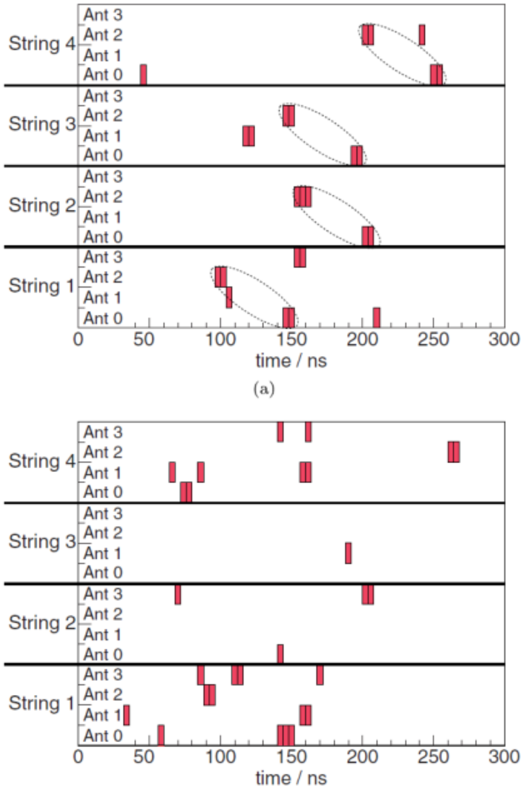
Some concentration of events near correct delay:

- not significant yet
- ~2 microsec offset hard to explain

ARA analysis

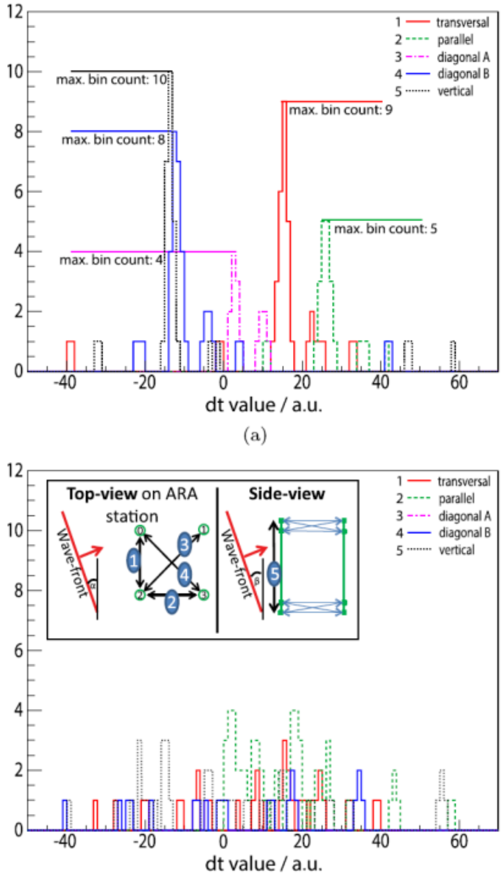
Thermal Noise Filter

- Fast and powerful noise rejection: from 1E18 – 1E19 92% signal retention and 99.9% background rejection.
- Algorithm initially conceived to run in firmware but was applied in software offline.
- Plane wave approximation – antennas with similar relative geometries will have similar speeds:
    - Histogram speeds in 5 different relative geom categories
    - Plane waves will exhibit peaks
    - Thermal noise evenly distributed



(a)

(b)

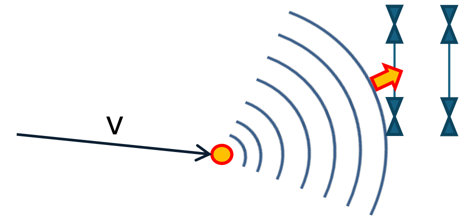


(a)

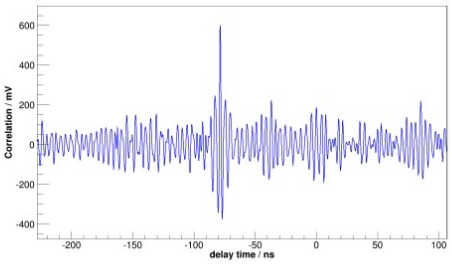
(b)

Vertex Reconstruction – Matrix Method

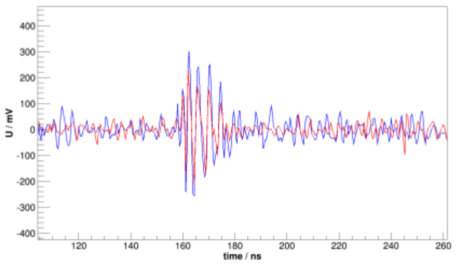
Point emitter in ice produces spherically expanding wave (ray bending optics ignored)



Determine time difference Δt by cross-correlation



Cross-correlation vs delay – make quality cut on max amplitude to reject weak pulses.



Cal pulser waveforms shifted by time delay determined by x-corr algo.

An expanding spherical front:

$$c^2(t_v - t_i)^2 = (x_v - x_i)^2 + (y_v - y_i)^2 + (z_v - z_i)^2$$

May be linearized by considering pairs of observations and subtracting:

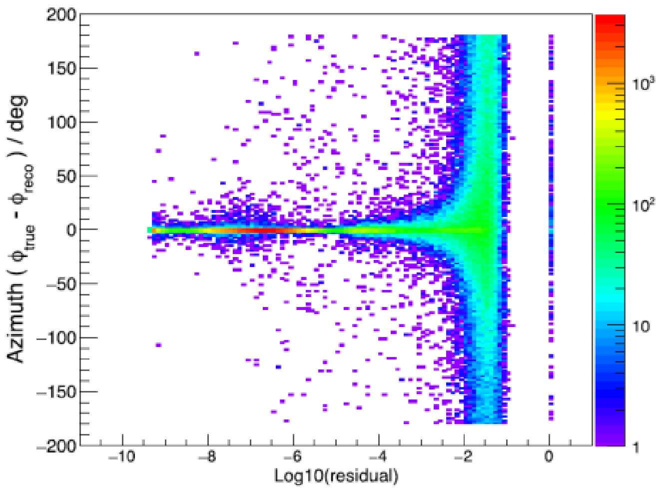
$$x_v \cdot 2x_{ij} + y_v \cdot 2y_{ij} + z_v \cdot 2z_{ij} - t_{v,\mathrm{ref}} \cdot 2t_{ij} = r_i^2 - r_j^2 - c^2(t_{i,\mathrm{ref}} - t_{j,\mathrm{ref}})$$

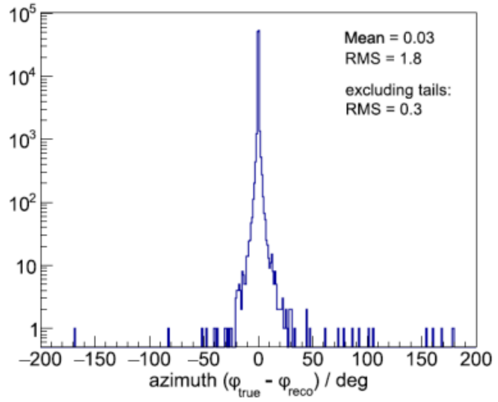
Linearization requires 5 observations to constrain solution (viz. 4 if you are willing to solve NL equations). Accommodates overconstrained system of linear equations → LLS or SVD fast matrix techniques exist for solution.

Residual turns out to be good quality parameter

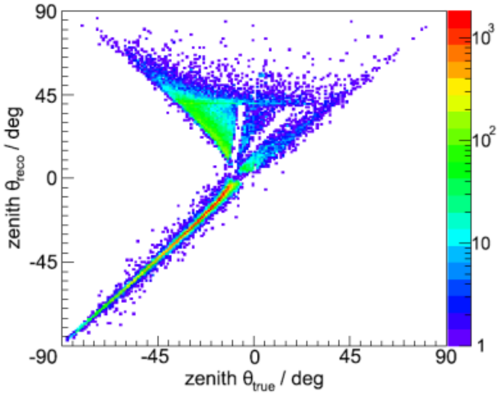
Vertex Reconstruction Performance

Simulated Signal



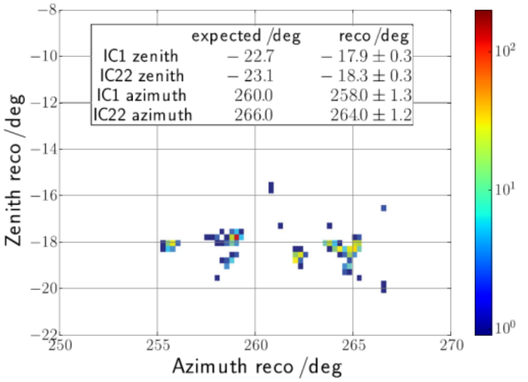


(a)



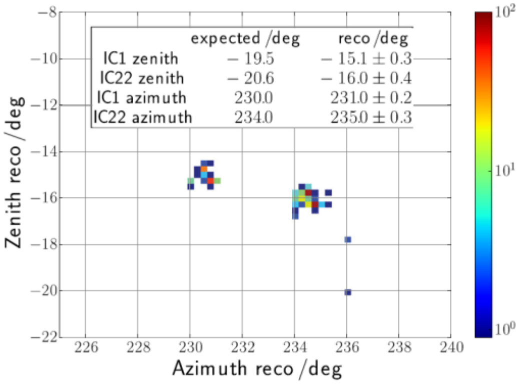
(b)

In-situ Calibration Pulsers



	expected /deg	reco /deg
IC1 zenith	− 22.7	− 17.9 ± 0.3
IC22 zenith	− 23.1	− 18.3 ± 0.3
IC1 azimuth	260.0	258.0 ± 1.3
IC22 azimuth	266.0	264.0 ± 1.2

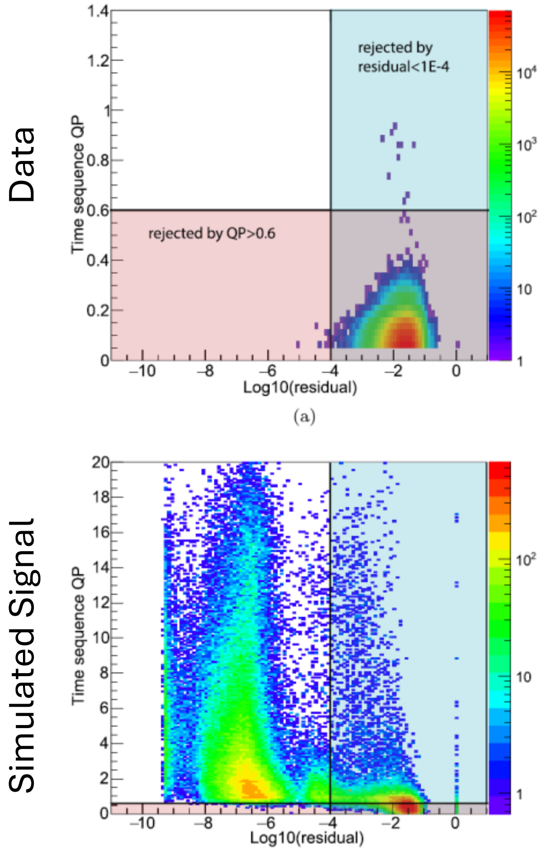
(a)



	expected /deg	reco /deg
IC1 zenith	− 19.5	− 15.1 ± 0.3
IC22 zenith	− 20.6	− 16.0 ± 0.4
IC1 azimuth	230.0	231.0 ± 0.2
IC22 azimuth	234.0	235.0 ± 0.3

(b)

Final Cuts



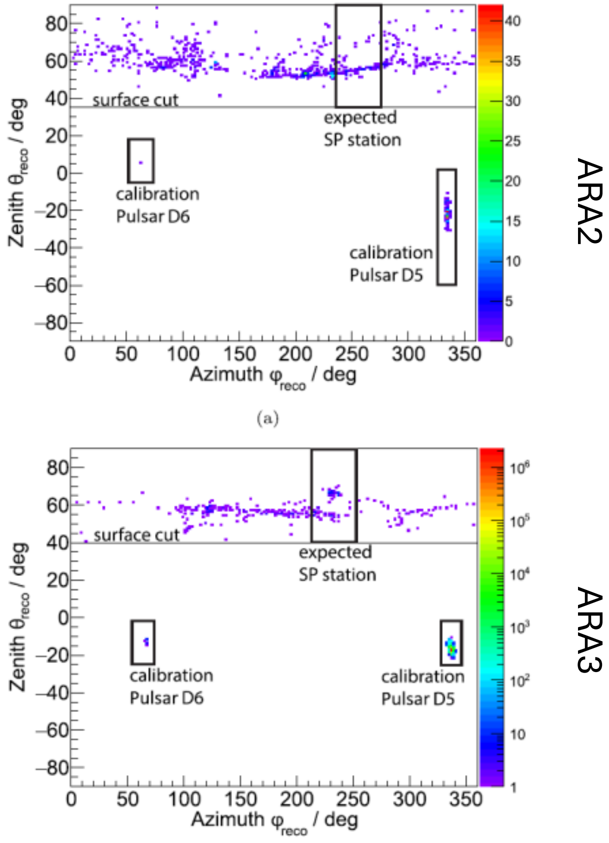
(a)

(b)

Only three cuts used to get to neutrino level:

1. Thermal noise QP > 0.6
2. Log_{10} (residual) < -4
3. Angular cuts to remove surface noise / pulsers

After evaluating cuts on 10% burn sample and obtaining OK to proceed with full 10 m evaluation, looked in the box and found no events which passed all cuts → neutrino limit

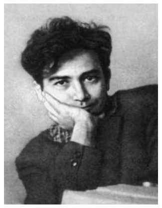


(a)

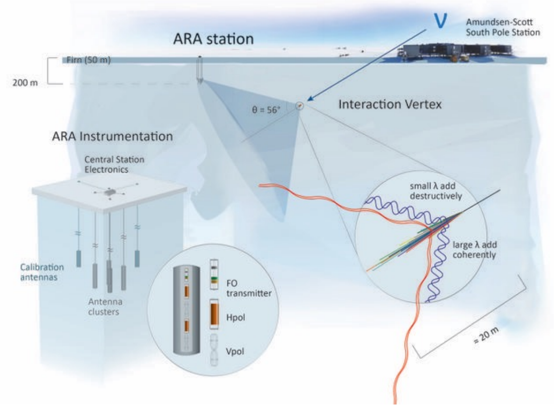
(b)

Another way of looking at the radio efforts…

Follow the signal chain



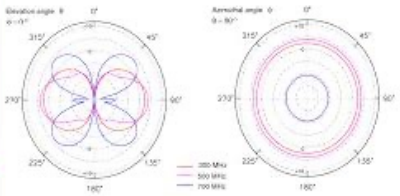
- Physics: location, environmental properties
- Antennas: location, frequency range, polarization, dispersion
- LNA: EMI effects, gain flatness, limiters, band definition filtration
- “Cables”: transmission distance, local digitizer, RFoF, equalizer circuit
- Triggering: power, envelope, interferometry, template, low bit ADC
- Digitization: readout window, oversampling, dead-time
- Data flow: thermal background, anthropogenic noise, monitoring
- Calibration: local, surface, distant
- Infrastructure: power, communications, deployme
- Data analysis/simulation: unified simulation tools, tracing, cross-correlation, map-making



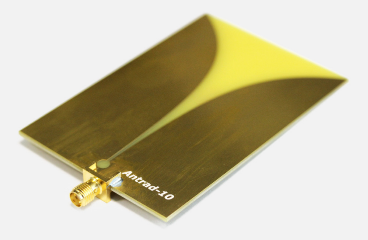
Location

- Talking here about Antarctic ice, but also have thought about Greenland ice, salt domes, lunar regolith, Europa/Enceladus…
- Then above surface, in surface layer, or sub-surface decisions
- Trade offs here could be discussed elsewhere, but the decisions show up throughout the following slides
- We've found South Pole to be a convenient place to work, with good infrastructure, but drilling has been viewed as logistically difficult to support in past years
- Station based: many antennas at a small number of locations, use geometry & curvature to range signal (ANITA, ARA, & ARIANNA)
- Antenna based: few antennas at a large number of locations, use time evolution of signals across array to range signal

Antennas



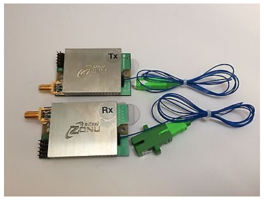
- Signals are broadband, but diminishing information at low frequencies (backgrounds dominate) and high frequencies (phase space/Cherenkov cone dominates), about 150-850MHz in ice
- Antenna designs
  - Dispersive: log-periodic, Yagi, ferrite-loaded wires, log-spiral, twisted
  - Non-dispersive: biconical, Vivaldi, discone, conical horn, surface spiral
- Dispersive (element-based, scaled) antennas are simple, cheap, & large antenna height, but reduce triggering ability by spreading signal in time across noise (tradeoff)
- In-ice borehole geometry reduces choices significantly
- Example: quad-slot ferrite-loaded design for ARA H-pol
- Circular polarization in-ice limited by birefringence



Low noise amplifiers

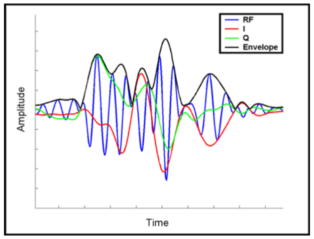
- Broadband LNA implies relatively high noise figure, but rapidly changing landscape
- 100-1000MHz example for 30dB gain, <1dB flat
  - In 2001, Miteq AFS3-00200120-09-1P-4-L $1100, NF=0.9dB (67K)
  - In 2017, SPF5189-based, two stages $20, NF=0.6dB (43K)
- EMI example: 450MHz LMR @ South Pole, deep notch to prevent saturation has led to an expensive band definition filter
- Limiter vs. insertion loss & gain flatness vs. NF tradeoffs
- Total system gain of about 80dB

“Cables” a.k.a. moving the signal around



- More of an issue obviously in physically large detectors
- Cable loss is a strong function of frequency, if you want a trigger to use all of the frequency information, re-equalize the signal
- Digitize locally is also an option that has been studied
- For the 200m deep ARA stations latched onto RF over Fiber (“antenna remoting”), other designs might take an even more extreme view
  - Commercial product: Optical Zonu OZ450 (and successor products)
  - Dynamic range and low-reflection connections are the limiting issues with these systems
  - Looking at custom implementations for lower cost
- Still plenty of LMR-400 & LMR-500 UF down ARA holes & arou the DAQ box

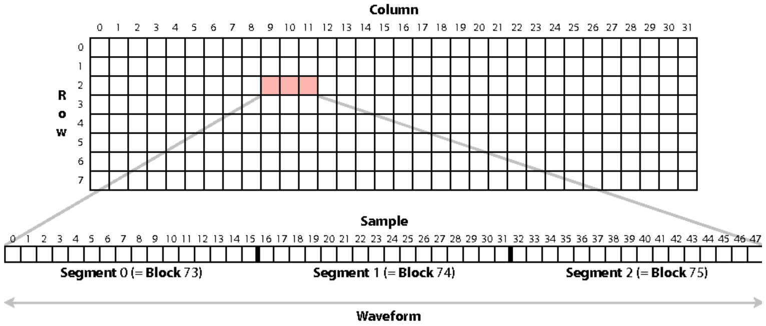
Triggering



- Lots of ideas, but triggering has been simple-minded in practice
- In deep ice, ½ of the signals are nearby, bright, & obvious, other ½ need sensitivity for the farther events
- Square-law diode detectors for a power trigger, comparators against RF voltage, either one feeding majority logic learned from NIM modules
- Could "weight" the multiplicity by signal strengths (multiple single antenna thresholds or few bit FADC), signal frequency content, or envelope "pointing"
- Could forgo triggering signal path and work digitally on the FADC trace (but power) and find antenna pattern or broad frequency input
- In principle can do the cross-correlations/interferometry in real-time in GPU or ASIC
- Could get a lot more antenna height or directional gain by phasing up

Digitization

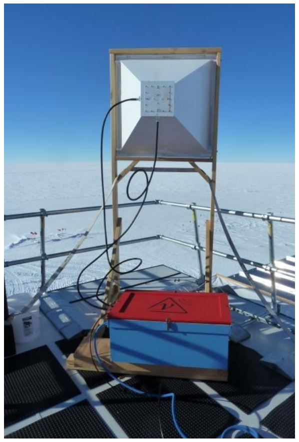
- Length of record for station size (up to 32k samples IRS2 down to 1k samples DRS4, 3-4GSaPS)
- Dynamic range, linear coverage of E field, compression has seemed risky,
- Switched capacitor array heritage in part at least for power savings
- FADCs with digital analysis might not be ridiculous in the near future (<1W/GSaPS for 10b)
- Deadtime especially important for complicated signal shapes (tau or propagation), LAB4c read and write simultaneously



Data flow

- Differing approaches based on how much thermal noise to take
- 100s Hz rate down to very low rates
- ARA stations about 20TB per year per station, including calibration & min-bias events
- ARIANNA data through Iridium in contrast

Calibration



- Taking advantage of all available calibration sources
- Local pulser & noise sources in the ice
- Pulser operations from the near surface & distance ICL roof
- Aircraft & balloon noise emissions, tracked
- Deep pulser co-deployed with IceCube at 1450m & 2450m deep
- Efforts in 2017-18 & 2018-19 & 2019-20 for RF (& optical/UV) measurements from the 1750m deep SPIceCore hole
- Similar interest in multiple calibration streams in ANITA: othe balloon, surface, and sub-surface transmitters
- Built in test equipment options for production

Infrastructure

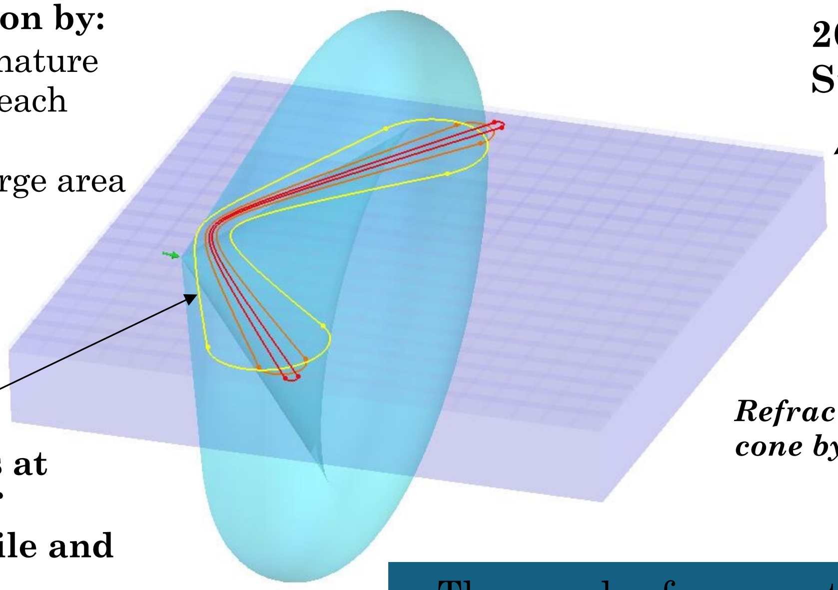
- With ARA, power/comms/cabling/vault/GPS/patch panels is about 6% of the station cost (10% in future HW cost-savings versions)
- South Pole is not very windy, sunny only in summer, batteries are heavy & expensive, and 2km runs are not that difficult
- Other situations/locations would vary
- Fiber communications allow high speed & possible White Rabbit timing
- Deploying downhole became well-rehearsed quite quickly

FURTHER IN THE FUTURE

Extremely large arrays of simpler detectors…

“KILOCUBE”

CONCEPTUAL 1000 KM^3 TIME-OF-ARRIVAL ARRAY



Event Confirmation by:
-spatiotemporal signature
-up-going waves at each string
-coincidence over large area

**20 km x 20 km
Sub-firn array**

Conic Sections at intersection of Askaryan profile and sensor plane.

Refraction of Askaryan cone by firn not shown

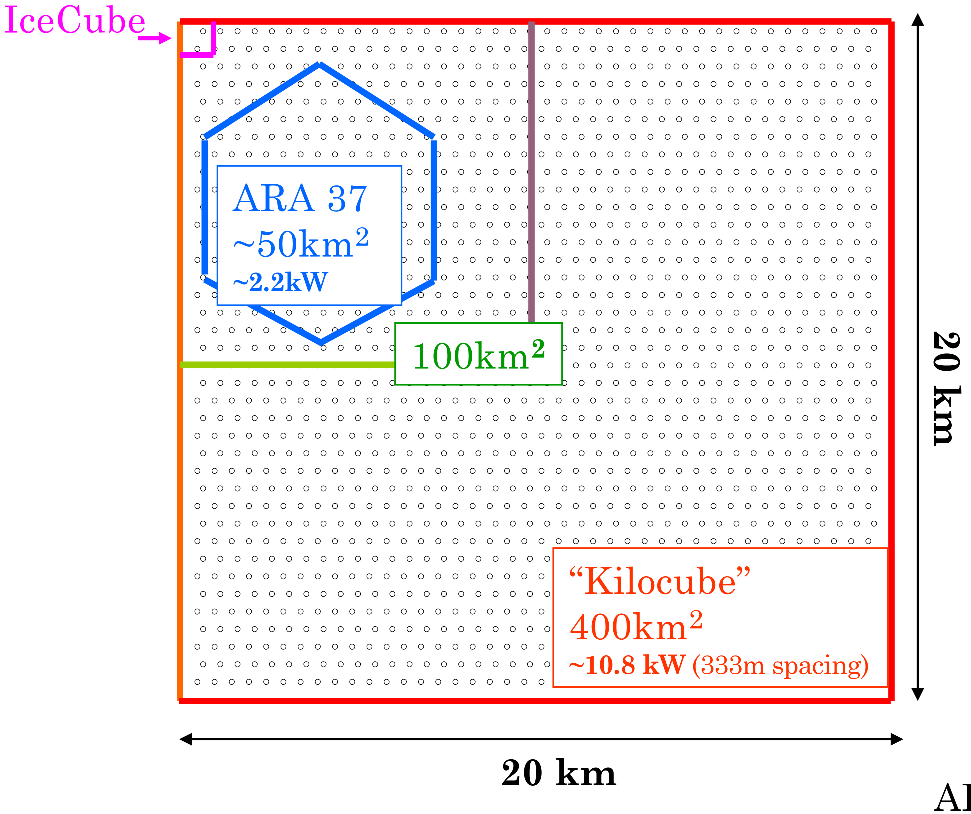
🟥 E max (r)

🟧 ~E max (r) /2

🟨 ~E max (r) /10

~ Thousands of sensor strings
~ $1K-$3K for each string
~ 200m hole depth
~ 200m hole spacing
~ a few watts / string

LARGE DETECTOR FOOTPRINTS

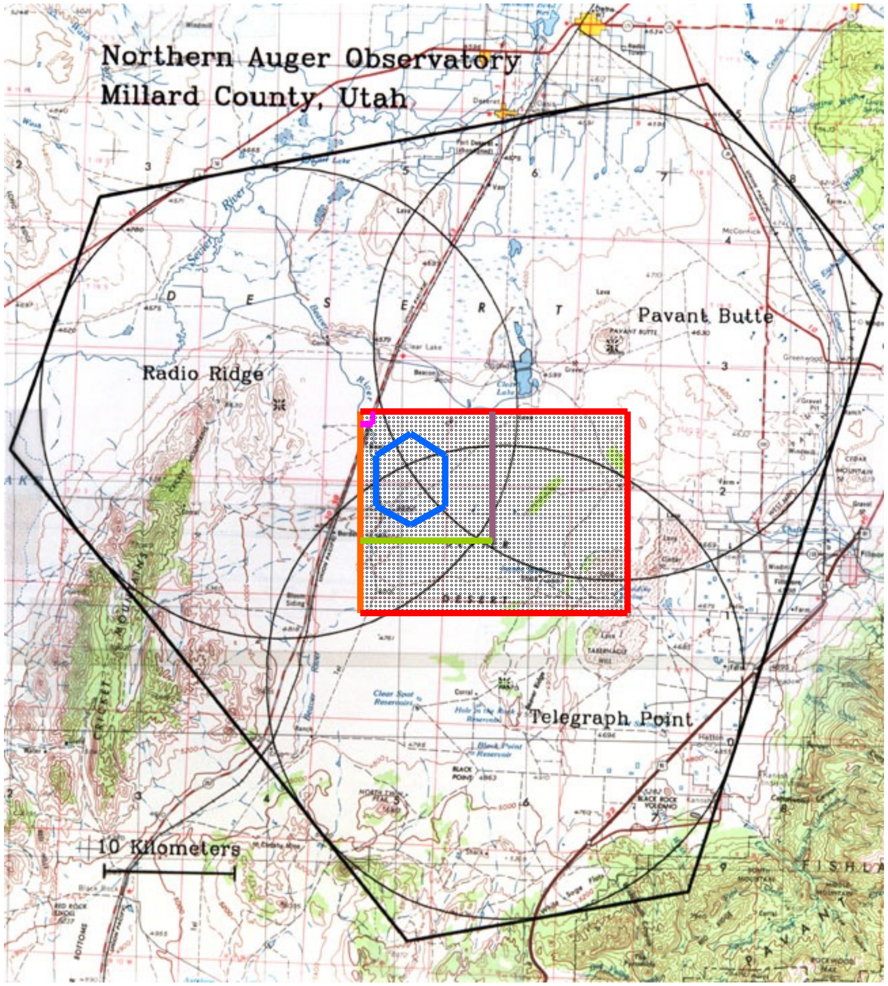


"Kilocube"
# of Sensor pairs vs.
Density and power:

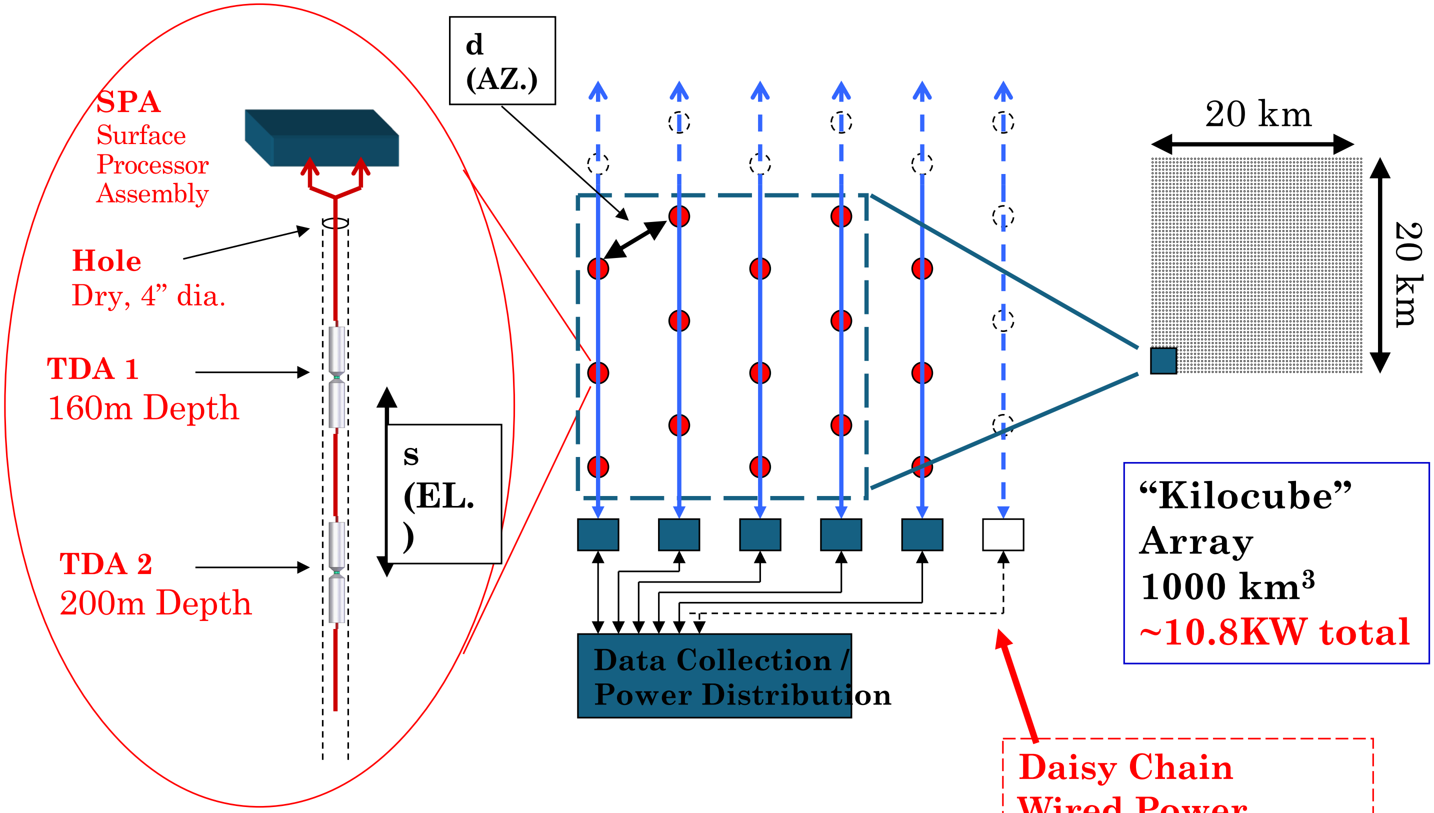
X Spacing (meters)	**Y** Spacing (meters)	**Total # of Holes Power**
1000	1000	**400** ***1.2kW***
500	500	**1600** ***4.8kW***
333	333	**3600** ***10.8kW***
333	1000	**1200** ***3.6kW***

ARA = 44 W / km^2
Kilocube = 27 W / km^2

Compared to Auger



Conceptual Transient Sensor Array Configuration & Power Requirements



“Kilocube”
Array
1000 km³
~10.8KW total

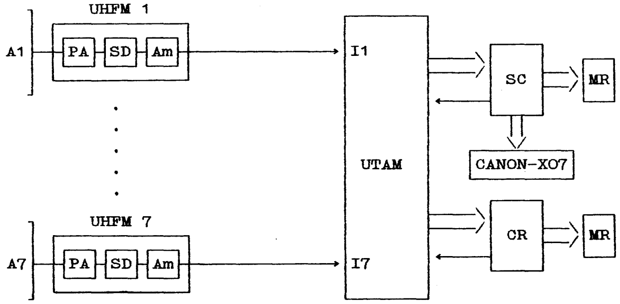
Daisy Chain
Wired Power
For *Entire Row*
***e.g.* #12, RG8, RG11**

Wavefront Angle Sensor Package (WASP)
~3Watts per hole

Hole (WASP) Spacing (d=333m shown)
180Watts/Row

RAMAND CA. EARLY 80S

Provorov's talk at "Neutrino Telescopes-1991", Proceedings, p.p.337-355



UTAM - unit of time and amplitude measurements; SC - system controller; CR - count rate controller; MR - magnetic recorder; UHFM - UHF module (PA - UHF amplifier, SD - square-law detector, Am - high-frequency amplifier); A - antenna

FIGURE 7

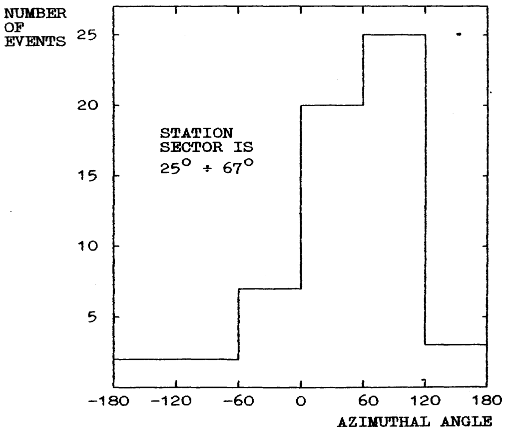
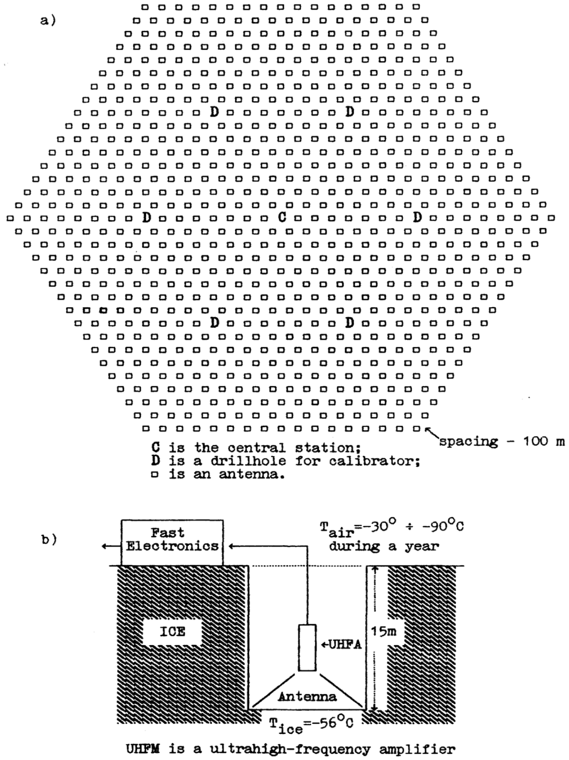


FIGURE 8



C is the central station;
D is a drillhole for calibrator;
□ is an antenna.

UHFM is a ultrahigh-frequency amplifier

FIGURE 9

FROM: Radio methods for detection of cosmic neutrinos and hadrons: RAMAND and RAMHAND experiments (past and prospects)

Igor Zheleznykh, Rustam Dagkesamanskii ARENA, 2008

IceCube Gen2 TDR

Gen2

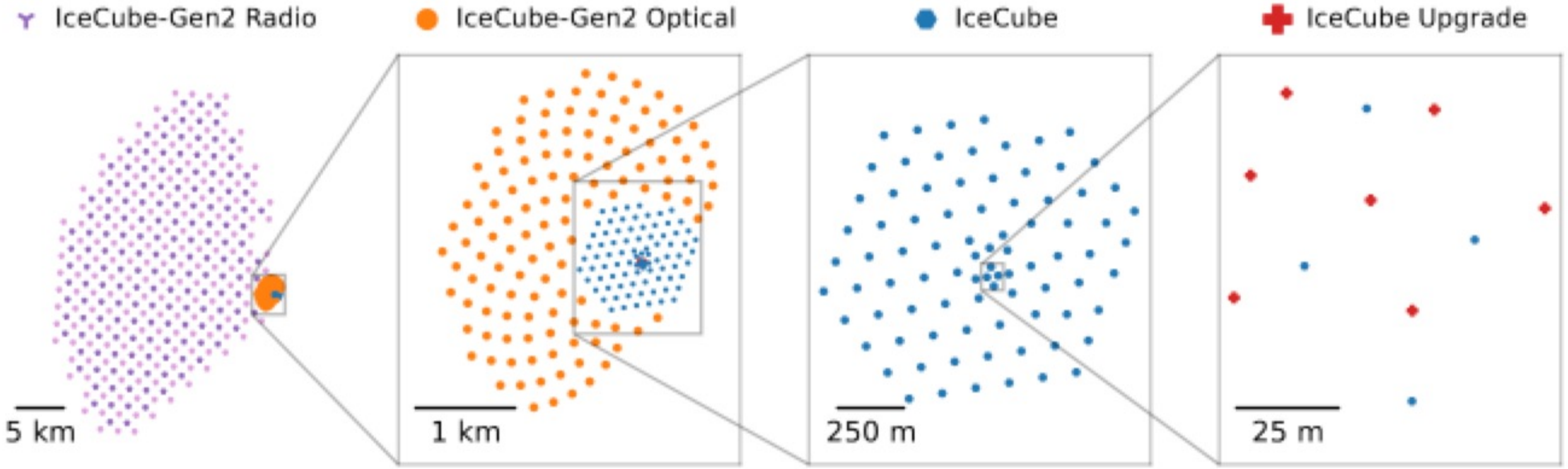
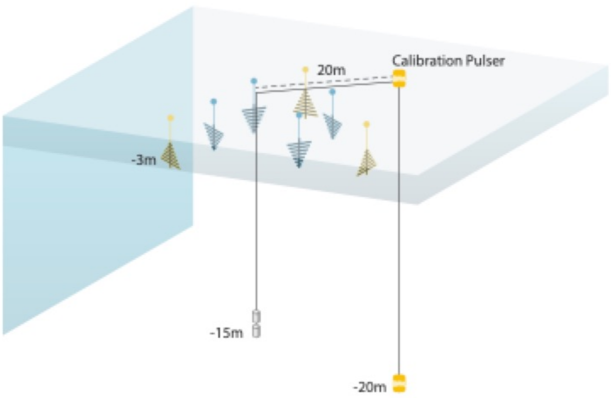


Figure 1: Top view of the detector illustrating the different length-scales. From left to right: Positions of the individual stations of the in-ice radio array of IceCube-Gen2, the positions of the strings of the optical array of IceCube-Gen2, IceCube, and IceCube Upgrade.

Gen2 stations



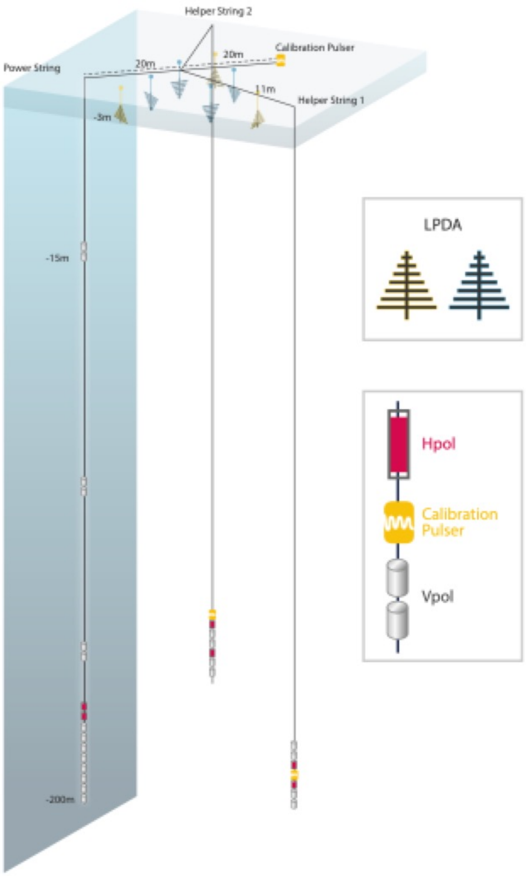


Figure 1: **(top)** Layout of a shallow detector station. It consists of 4 downward facing LPDAs and a vertically polarized dipole antenna at 15 m. These are complemented by 3 upward facing LPDAs to measure (and veto) cosmic rays as well as anthropogenic noise.

(right) Layout of a hybrid station featuring a shallow component (as in the shallow detector station) and a deep component. The latter consists of a 200 m deep phased array of vertically polarized dipole antennas for triggering and additional antennas for reconstruction with vertical and horizontal polarization response.

Gen2 Array

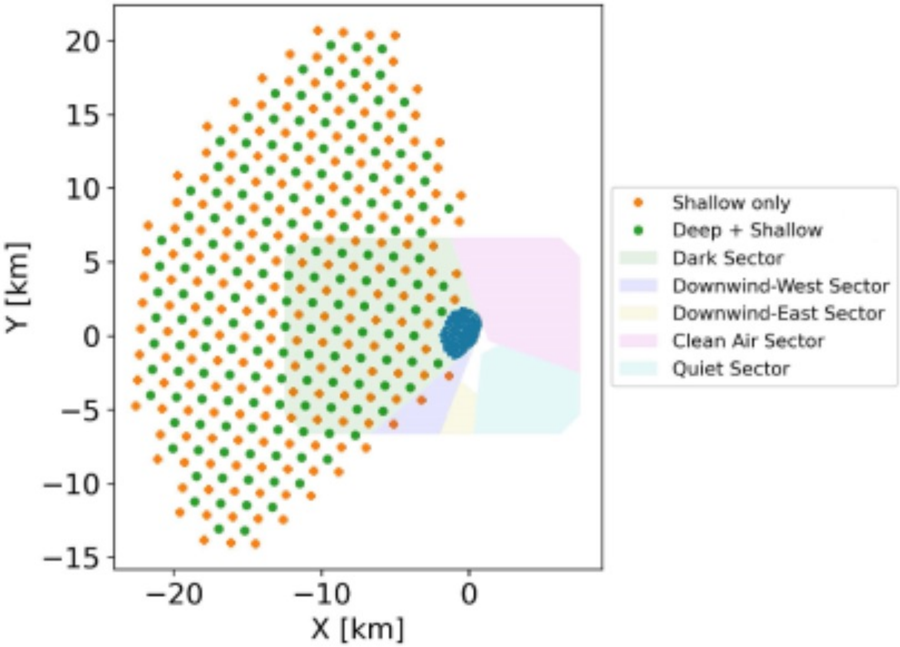


Figure 3: Reference array layout of the in-ice radio array of IceCube-Gen2. The shape of the array is determined by the desired spacing between different types of stations and the requirement to stay in the so called dark sector as defined by South Pole regulations.

Gen2 Sensitivity

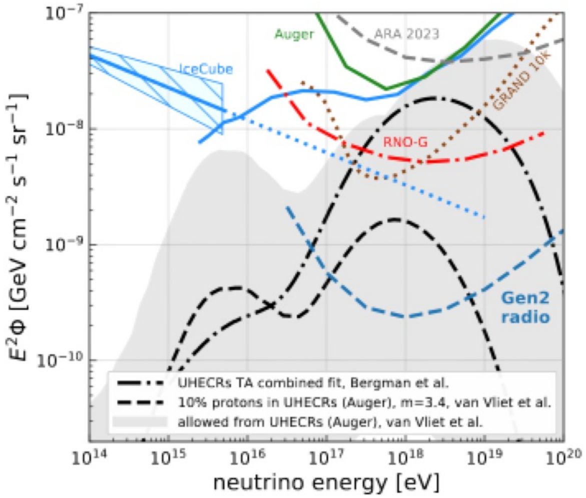


Figure 2: The ten year expected differential 90% CL sensitivity at trigger level for zero background of the simulated radio array to a diffuse neutrino flux is shown as dashed line. Solid lines show the astrophysical neutrino flux measured by IceCube [15] and experimental upper limits at higher energies. The expected sensitivities of ARA (for 2023), of RNO-G currently under construction and the proposed GRAND10k array (both for ten years) are also shown, as well as different predictions of the GZK neutrino flux based on UHECR data.

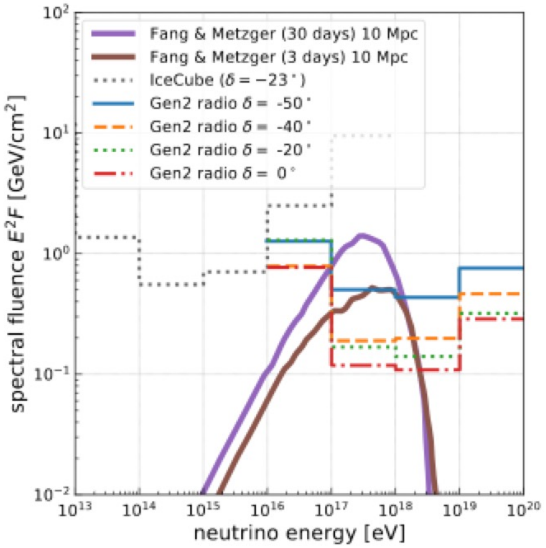


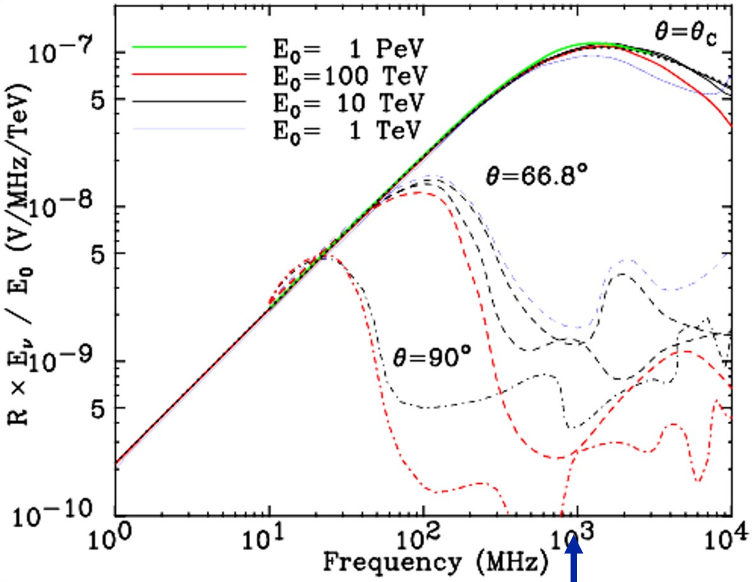
Figure 3: 90% CL fluence sensitivity for the IceCube-Gen2 Radio array for transient point sources located at different positions on the sky. Fluence predictions of neutron star – neutron star mergers as detected by gravitational wave observations [16] are added for comparison.

Two Good Ideas by Askaryan

#2. Excess charge moving faster than *c/n* in matter emit
Cherenkov Radiation

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

Halzen, Zas, Stanev, Alvarez



Modern simulations +
Maxwell's equations

Each charge emits field $|E| \propto e^{i\mathbf{k}\cdot\mathbf{r}}$

and Power $\propto |E_{tot}|^2$

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

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

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

Laboratory Observations of RF Askaryan Effect

- **Silica sand (SLAC 2000, photon initiated, PRL 86, 2802 (2001))**
- **Salt bricks (SLAC 2002, photon initiated, PRD 72, 023002 (2005))**
- **Ice (SLAC 2006, electron initiated, analysis in progress)**

NEW

ANITA views showers in Ice Target, July 2006 @ SLAC

Signal Coherence

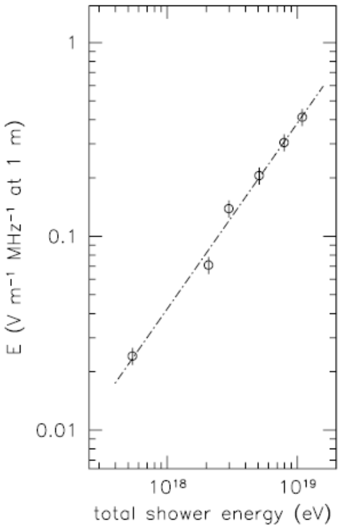
P_{rf} / N_{excess} (1 + f(λ) N_{excess}), where N_{excess} / E_{shower}

<u>coherence regime</u>:

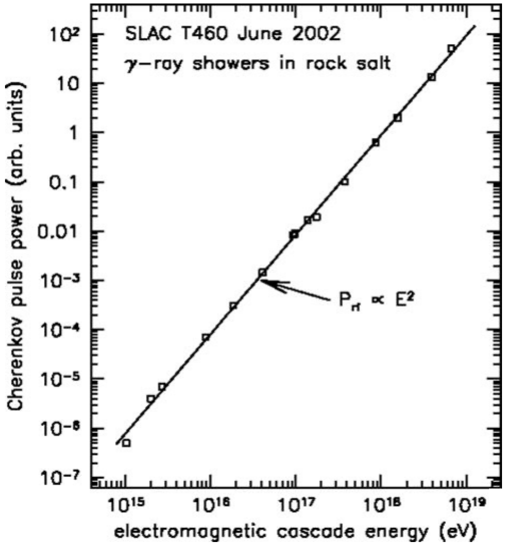
E-field proportional to E_{sh}

P_{rf} proportional to E_{sh}^2

SLAC T444 (2000) in sand



SLAC T460 (2002) Askaryan in salt

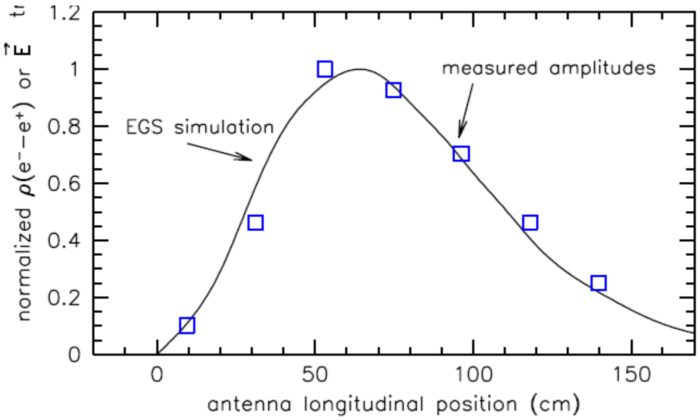


Studies of Askaryan Effect, 103 of 1

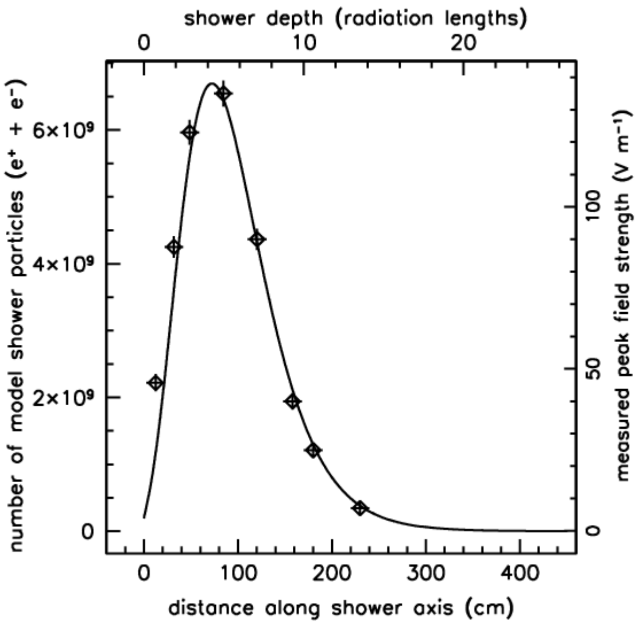
David Goldstein’s talk will show the 2006 result from ice.

Intensity matches Shower Profile

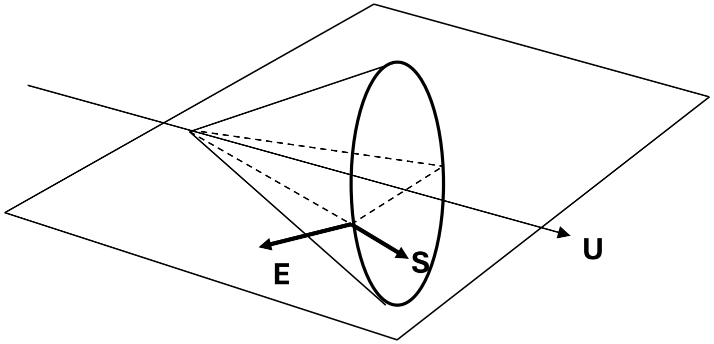
Salt

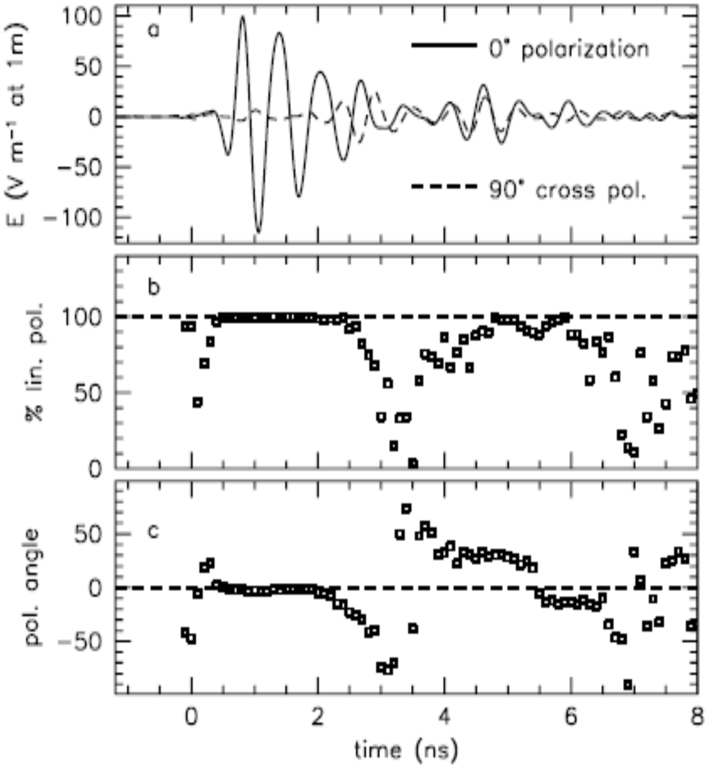


Sand

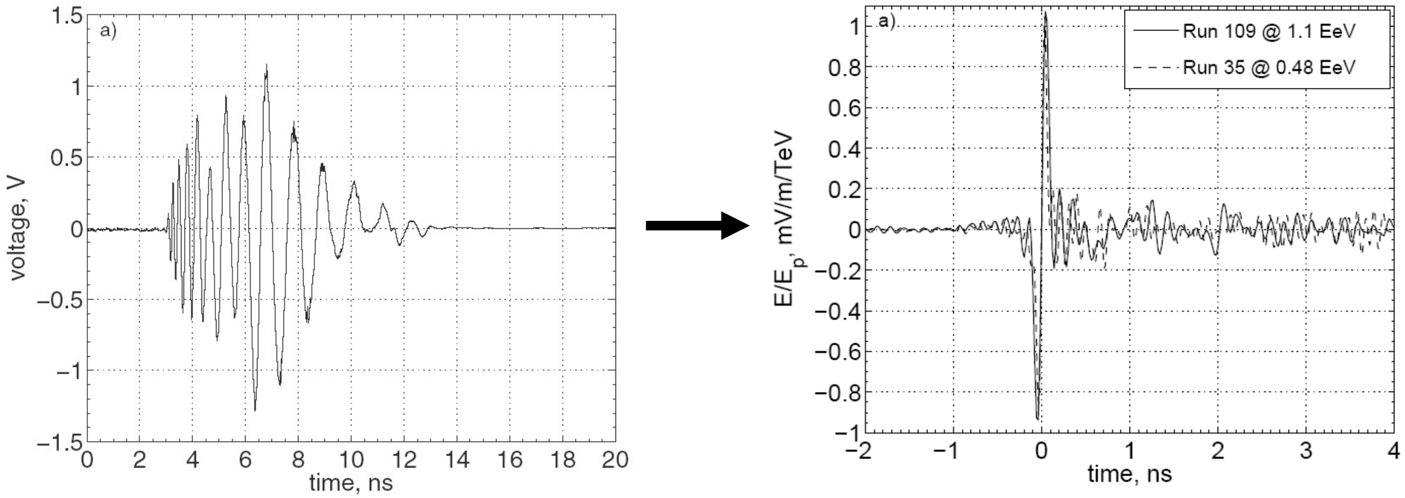


Cherenkov Radiation is 100% Polarized



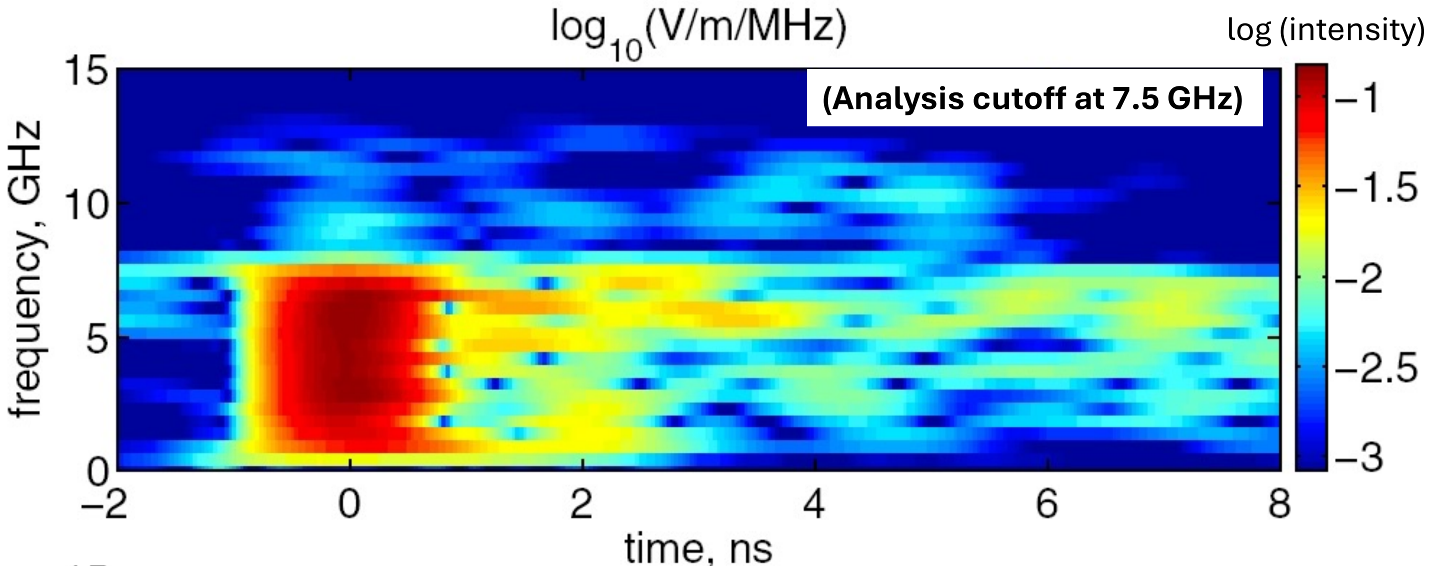


Frequency + Phase ➔ Reconstruct time domain pulse



- **Reconstructed signal is a brief, unresolved, bipolar pulse of radiation**
- **Details of analysis in PRD 74, 043002 (2006)**

Frequency Content



(Analysis cutoff at 7.5 GHz)

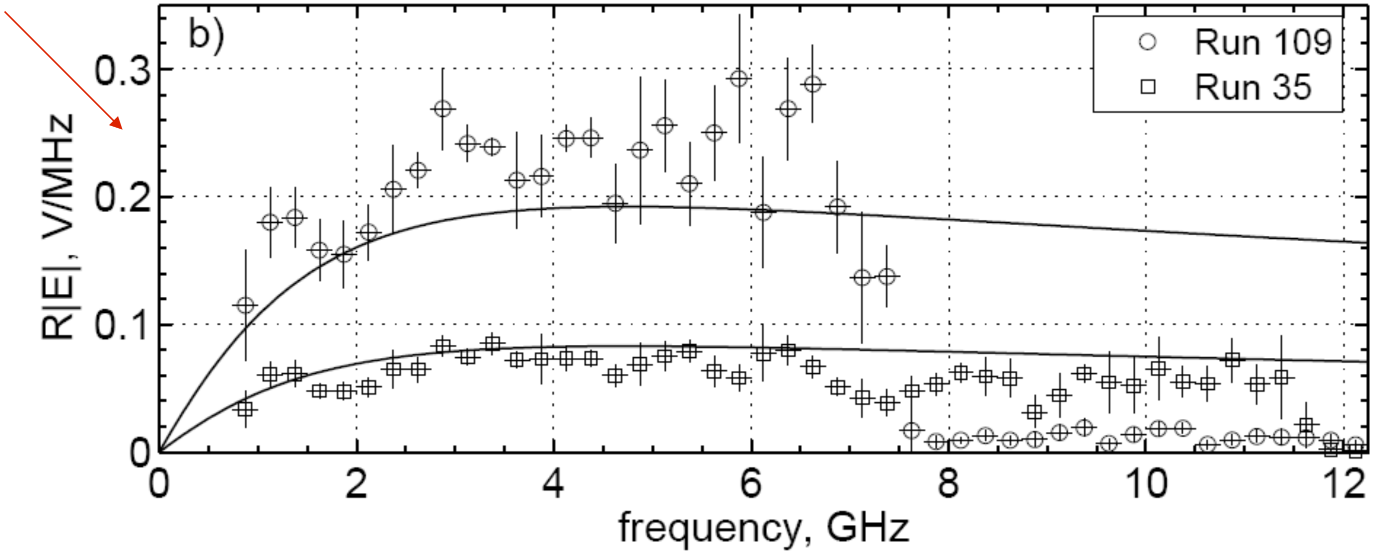
<u>Users</u> of Askaryan radiation do not go above ~1.2 GHz

Frequency Content

- **Radiation frequency profile from salt agrees with expectation**

  (with absolute normalization uncertain ~20%

- **Only a slow rolloff in salt ~10 GHz, will be clearer in ice**

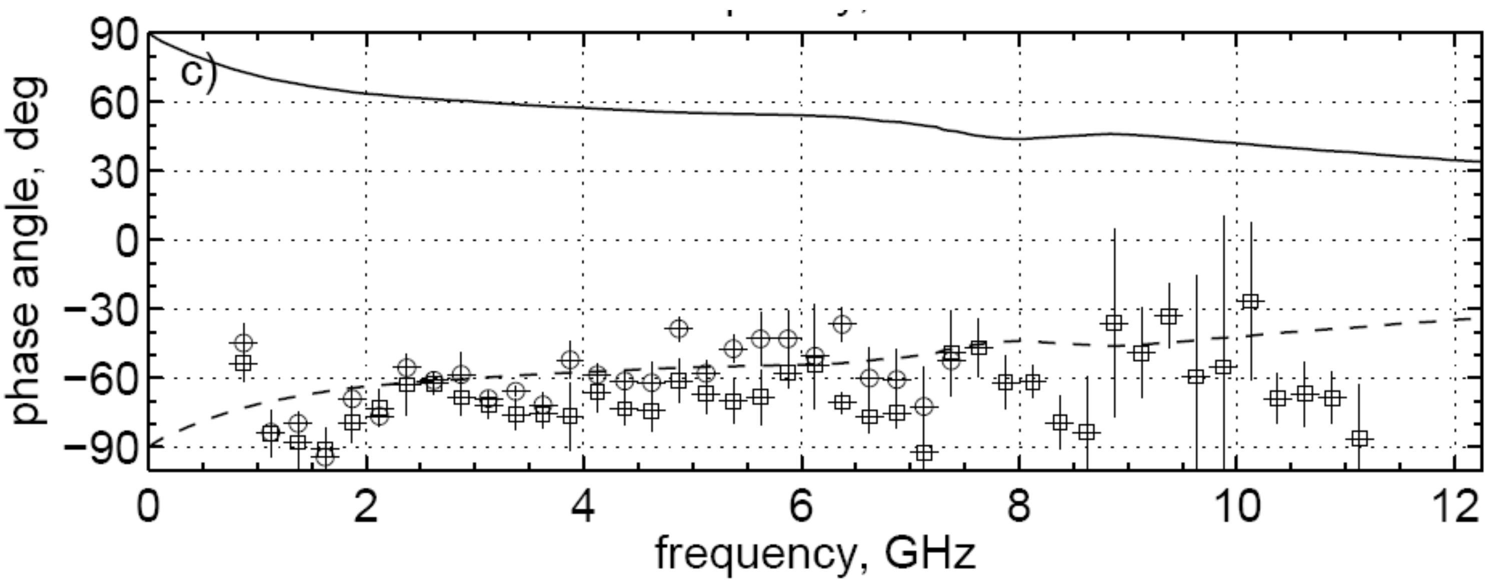


(Analysis cutoff at 7.5 GHz)

linear scale

Phase vs. Frequency

- **Radiation phase distribution seems to match expectation** **(theoretical work not documented well!)**
- **Phase calculated wrt signal midpoint in plot below**



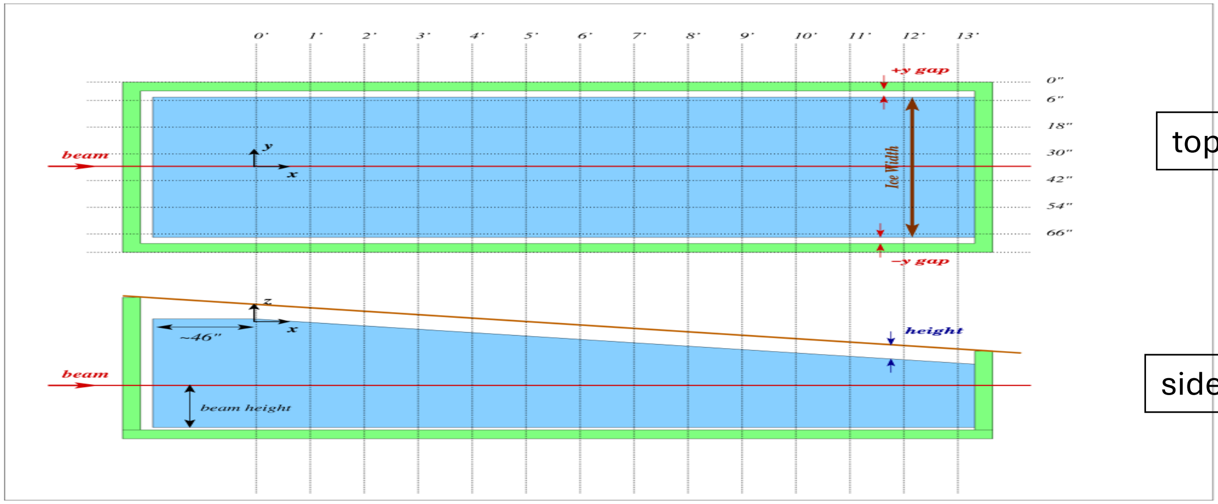
Work in progress

- **Very good, multi antenna data set recorded at SLAC in June 2006 with an ice target**

  0.2-18 GHz using various antennas

- **Expected results of the analysis**
  - **Spectral shape of signal in ice, with decoherence seen**
  - **Phase profile in ice**
  - **Confirmation of high polarization fraction**
  - **Signal transmission through imperfect surface**
  - **Mapping of Cherenkov cone width**
  - **Response validation of full ANITA antenna array**

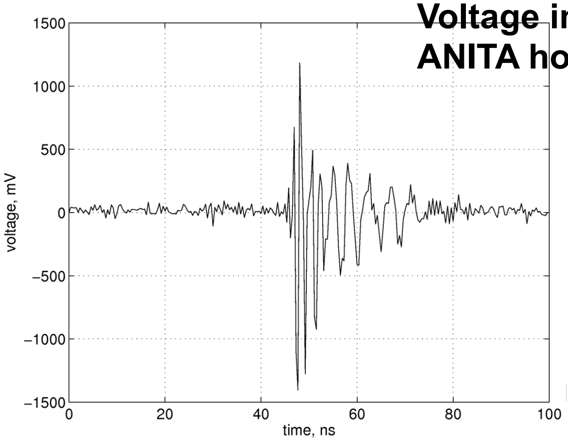
Data from SLAC 06 ice target



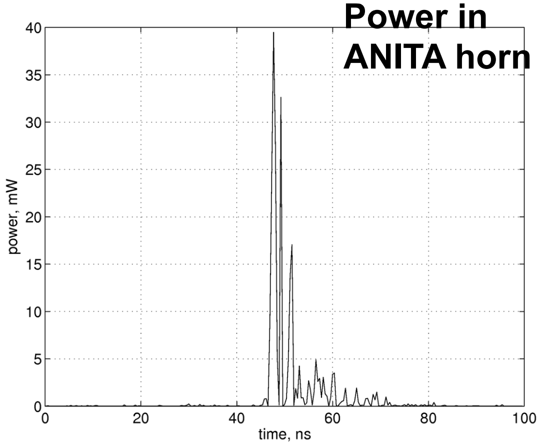
top view

side view

Voltage in ANITA horn



Power in ANITA horn



Further possible lab-based experimental work on Askaryan effect

- **Clear decoherence due to shower size can be observed in multiple media to test models**

- **Detailed measurement of signal phase is important; it encodes shower development**
    - **measure showers initiated by few particles (N_{part}~10^8 in past experiments) to study variation of phase**
    - **simulate LPM-extended showers (with muons maybe)**

- **Map out frequency dependent intensity of radiation away from Cherenkov angle**

Further experimental work needed to use Askaryan RF as research tool

- A ~5% verification useful here
- Study transmission of RF Cherenkov cone through rough surface
  - design accelerator targets with controllably rough surfaces
- Continue to study frequency-dependent attenuation lengths, birefringence, dispersion of possible radio detector sites
  - in salt domes, ice sheets, ice shelves, desert sands, regolith over next decade…

Further Room for Theoretical Investigations

- Behavior of radio emiting shower near surface of dielectic material (edge effects, formation zone quantification transmission efficiency, etc.)

- Radio signal from a shower near an infinite conductor plane, *e.g.* sea water

- Radio signal reflections and transmissions from/through sea surface, ice surface with realistic surface features

- Parameterization of shower emission via transition radiation