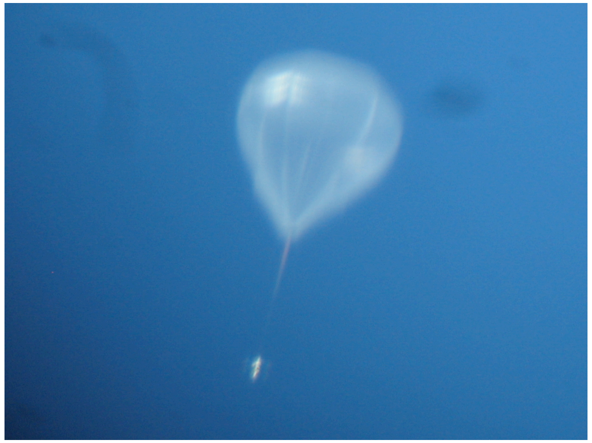
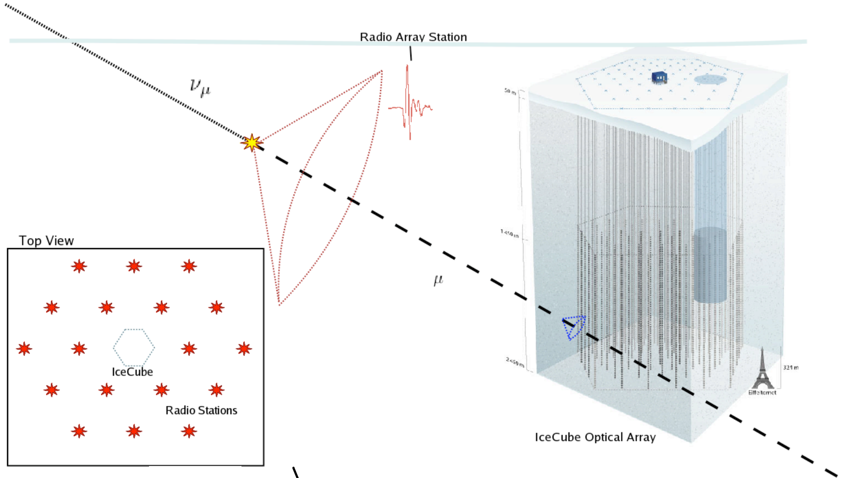
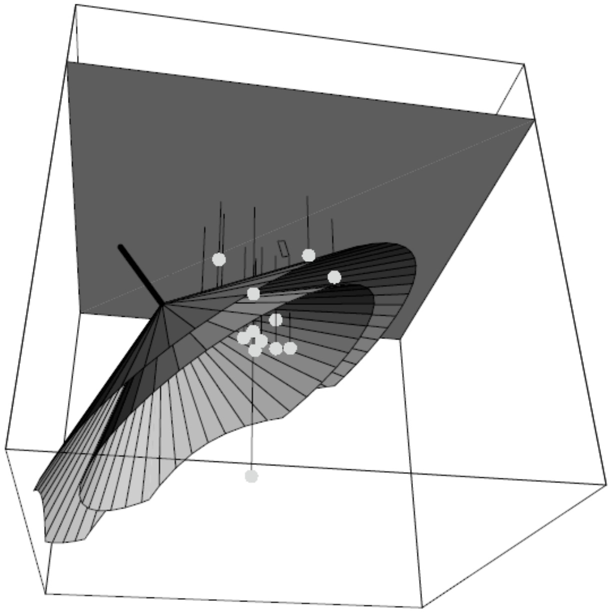
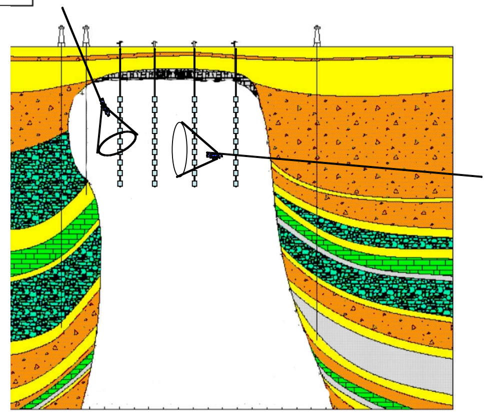
Detection of Cherenkov radiation of very long wavelength (radio region)



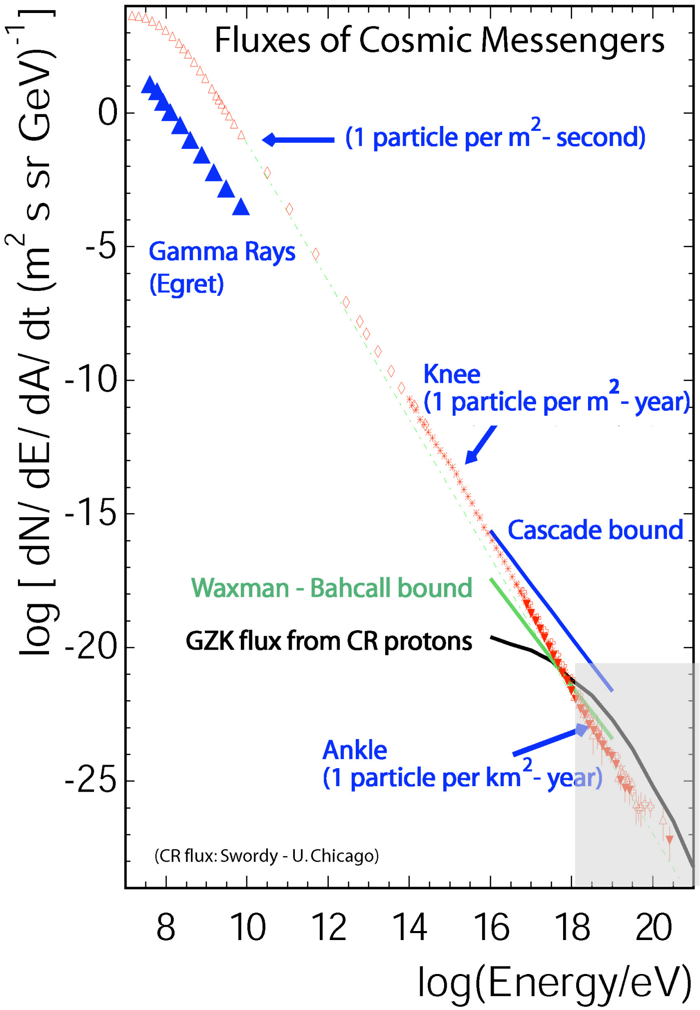






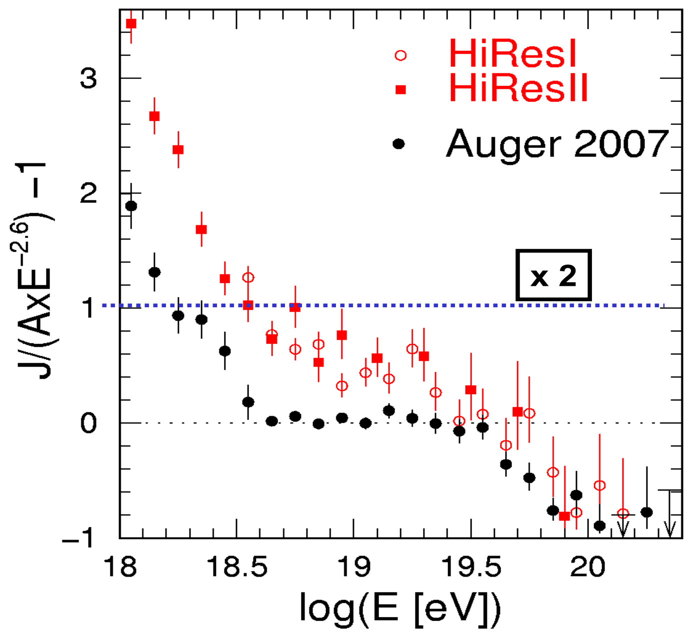
Dr. Amy Connolly
University College London

The Highest Energy Cosmic Messengers



- Greisen-Zatsepin-Kuzmin (GZK): Above $10^{19.5}$ eV:

$$\mathbf{p}\ \gamma_{\mathbf{CMB}} \rightarrow \mathbf{\Delta}^* \rightarrow \mathbf{n}\ \pi^+$$
$$\rightarrow \mathbf{n}\ \mathbf{e}^+\ \nu_\mu\ \nu_\mathbf{e}\ \bar{\nu}_\mu$$

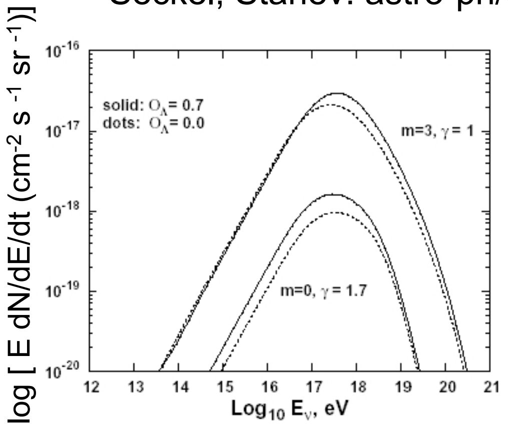


Expect ultra-high energy (UHE) neutrinos from GZK process

And from any photo-hadronic interactions producing CR's

What Messages Will UHE Neutrinos Carry

Seckel, Stanev: astro-ph/0502244



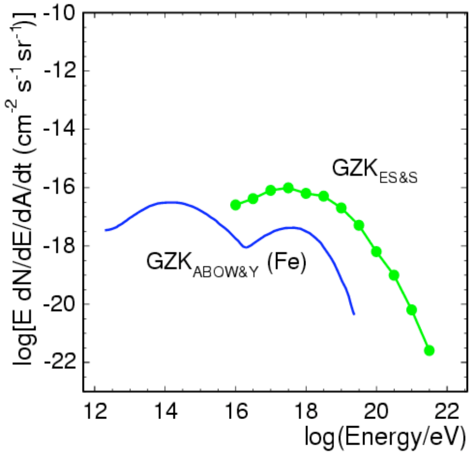
Source distribution, spectrum

γ (CMB)

GZK process

p, Fe

Cosmic ray composition



Universe expansion

Λ (subtle)

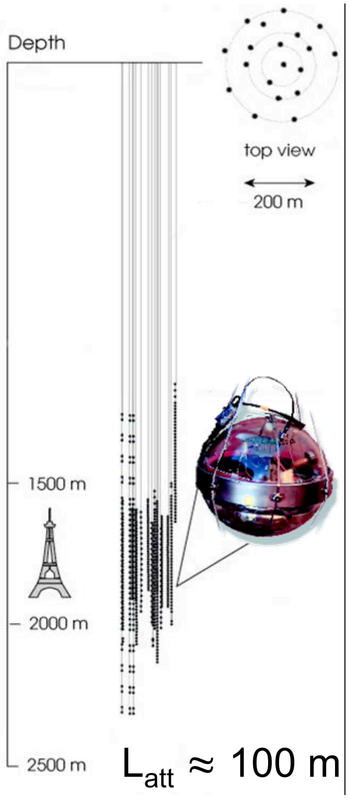
ν

Point back to the source

Center of mass energies > LHC !

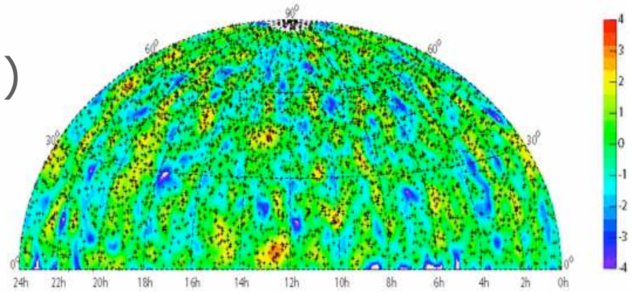
Physics potential of UHE neutrinos spans particle physics and astrophysics

Amanda II / IceCube



ν telescope at the South Pole

- Photomultiplier tubes (PMT's) deployed along strings
- Detect blue Cerenkov light from particle tracks in showers induced by neutrino interactions in ice medium

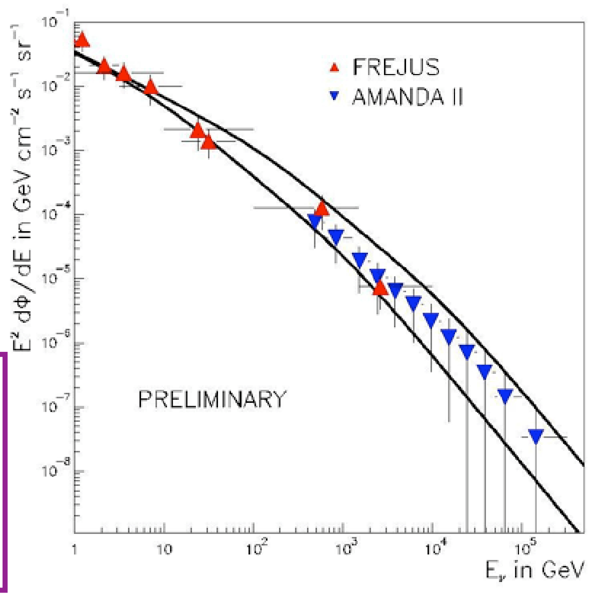


IceCube Collaboration, astro-ph/0607003

AMANDA II: 19 strings 1500-2000 m (1997 – present)
IceCube: 70 strings 1500-2500 m (22 strings are deployed)

Using earth as a filter, search for ***upgoing neutrinos***

Largest background from CR interactions in atmosphere: ***atmospheric neutrinos***



- No excess observed over atmospheric neutrino expectation
  - No cosmic diffuse ν flux observed
- Observed neutrinos show no significant deviation from isotropic
  - No point sources observed

Need for Detection Volume Beyond km^3-Scale

~ 10 GZK neutrinos / km^2 / year

10^{18} eV: ν N interaction length ≈ 300 km

→ 0.03 neutrinos / km^3 / year

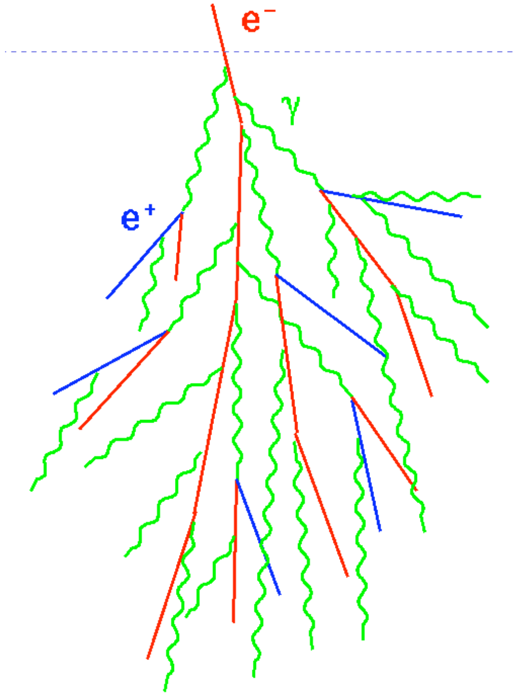
At most, we see 1/2 the sky

→ 10^{-2} neutrinos / km^3 / year

To be assured sensitivity to "guaranteed" GZK neutrino flux, we need >>10^2 km^3 detection volume

Idea by Gurgen Askaryan (1962)

- Coherent Cerenkov signal from net "current," instead of from individual tracks
- A ~20% charge asymmetry develops:
  - Compton scattering:
    γ + e-(at rest) → γ + e-
  - Positron annihilation:
    e+ + e-(at rest) → γ + γ
- Excess moving with v > c/n in matter
- → Cherenkov Radiation $dP \propto \nu \, d\nu$
- If $\lambda >> R_{Moliere}$ → Coherent Emission
  $P \sim N^2 \sim E^2$



Long radio attenuation lengths in ice, salt, sand

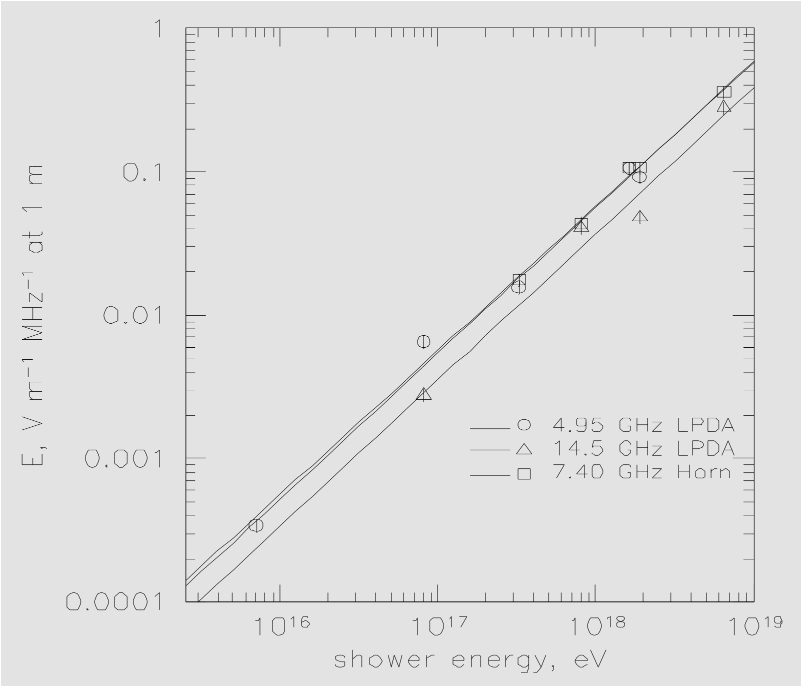
Macroscopic size: $R_{Moliere} \approx 10$ cm, L ~ meters

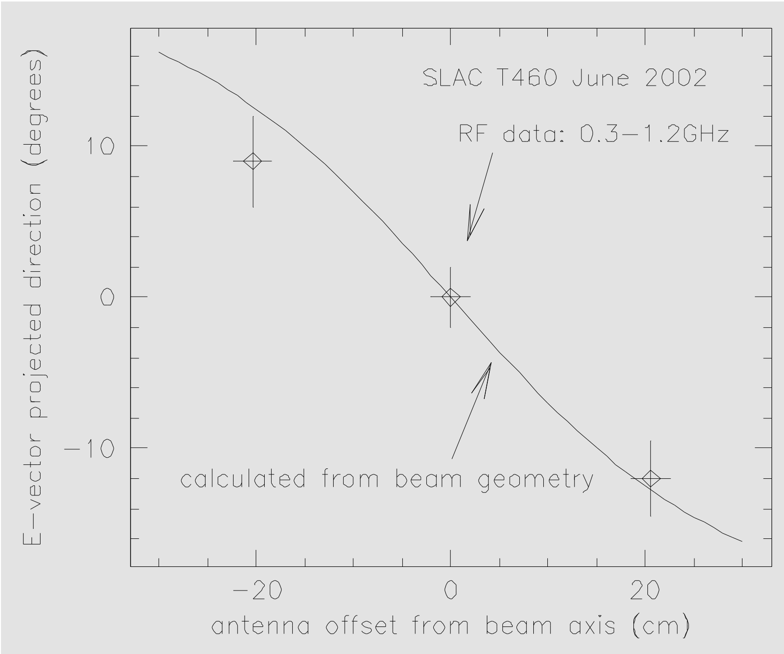
Accelerator Measurements of Askaryan Signal

Argonne: P. Schoessow, JPL: G. Resch
SLAC: C. Field, R. Iverson, A. Odian, D. Walz
UCLA: D. Saltzberg, D. Williams
UH Manoa: P. Gorham, E. Guillian, R. Milincic

Beam measurements at SLAC using photon beam incident on

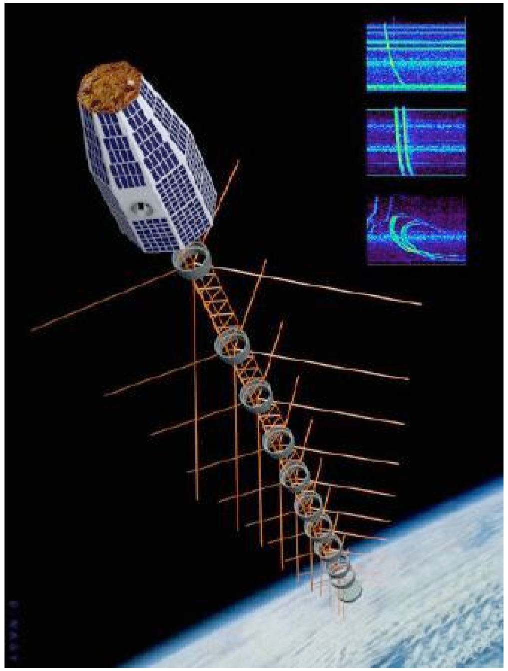
- Sand (2000)
- Salt (2002)





Pioneering Radio Cerenkov Experiments

FORTE



FORTE 97-99
Greenland Ice
Log periodic antenna,
20-300 MHz
A=10^5 km^2.sr

GLUE

GLUE/Goldstone 99:
In Lunar regolith
~2 GHz
A=6.10^5 km^2.sr

RICE

RICE 1999-present
Antennas on
AMANDA strings
100-1000 MHz dipoles
V~10 km^3. sr
Data up to 2005
published

Radio Ice Cerenkov Experiment

MIT, Whitman College, U. of Delaware, U. of Canterbury,
University of Kansas, University of Kansas Design Laboratory

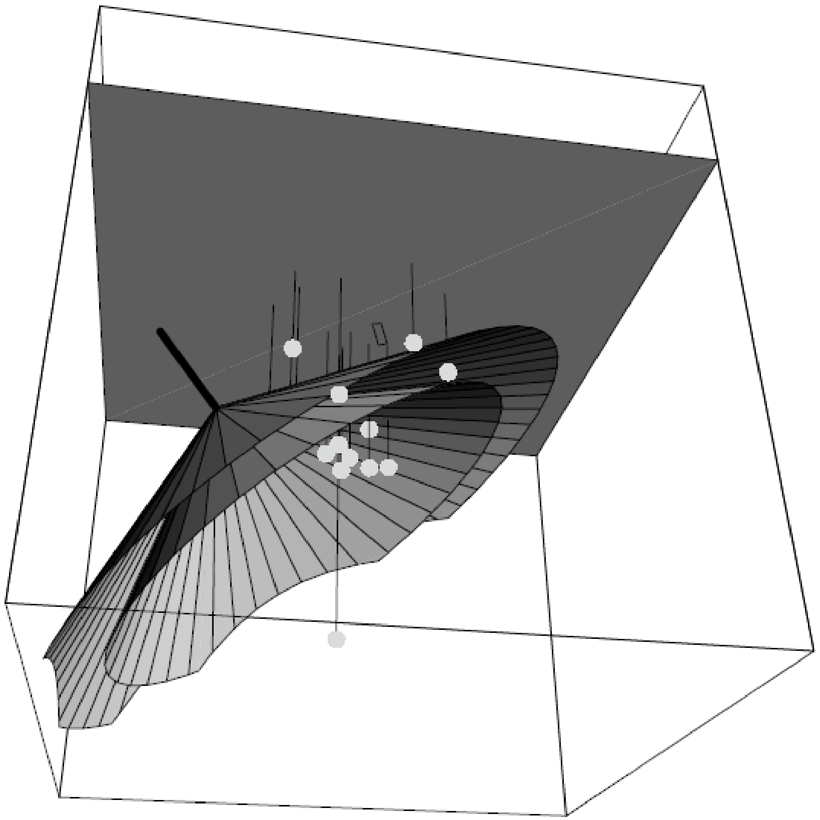
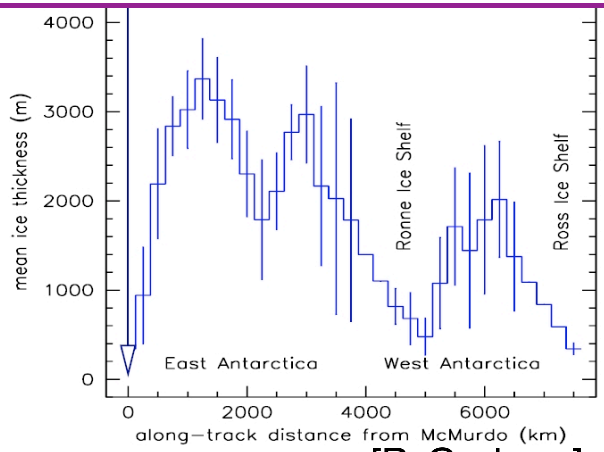


Figure Credit: Kravchenko et al., 2003

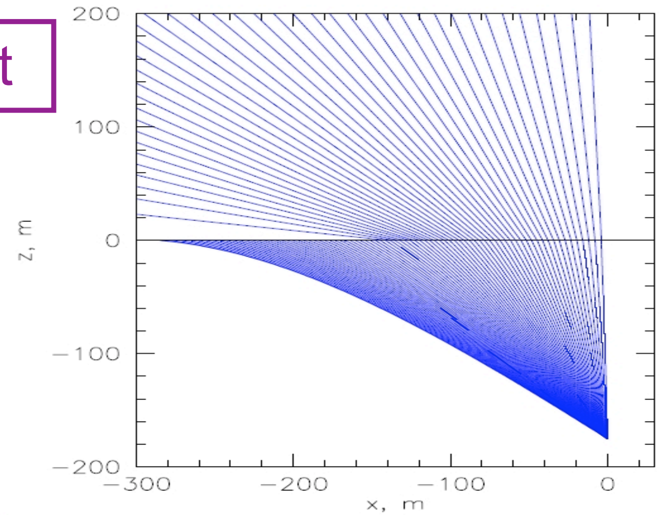
- Martin A. Pomerantz Observatory
  - 1 km from S. Pole
- 16 buried radio receivers in 200 m x 200 m x 200 m area
- Detects Cerenkov radiation in 0.2 GHz to 1 GHz frequency range

Antarctic Ice Properties

Ice thicknesses across continent



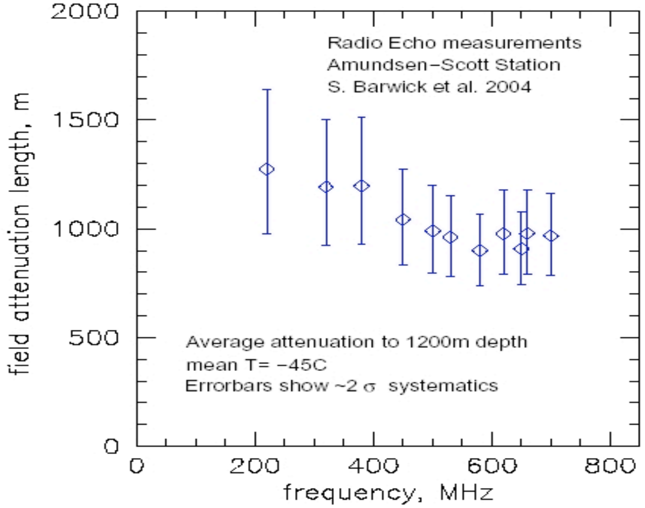
[P. Gorham]



[D. Besson]

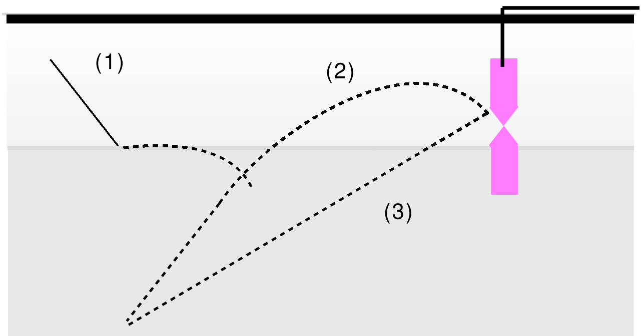
Rays paths near surface with depth-dependent index of refraction.

Depth of South Pole Ice: 2.5 km



Attenuation lengths measured at the South Pole

n(z): 1.78 in deep ice
1.33 at surface

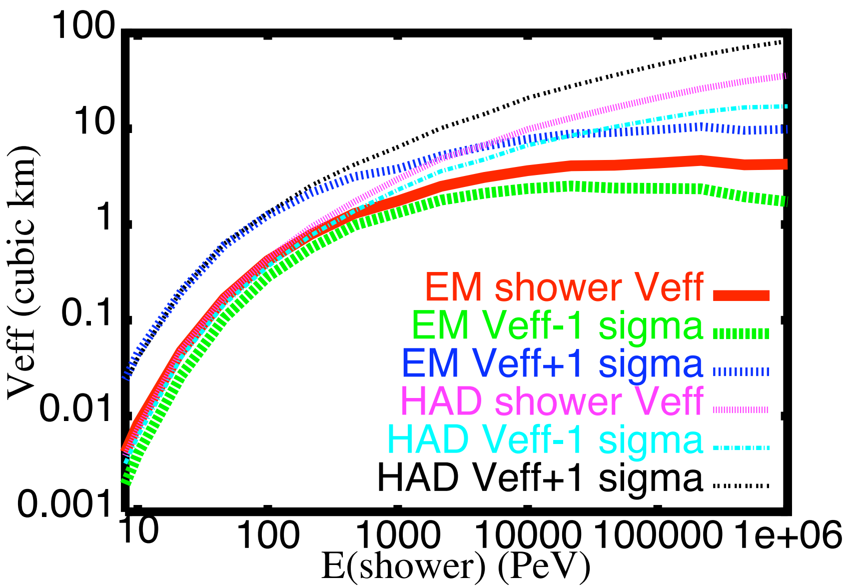


I. Kravchenko, et al., 2006

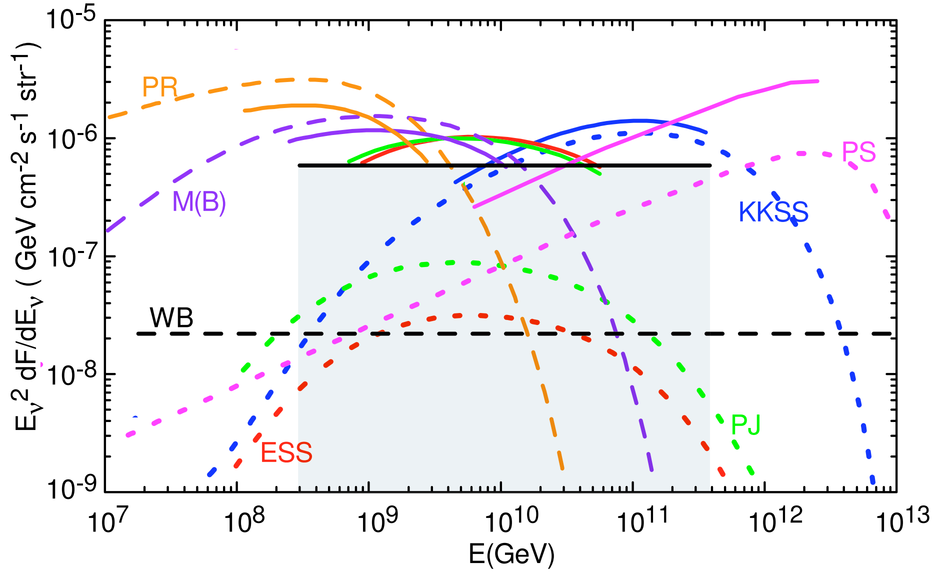
RICE Results

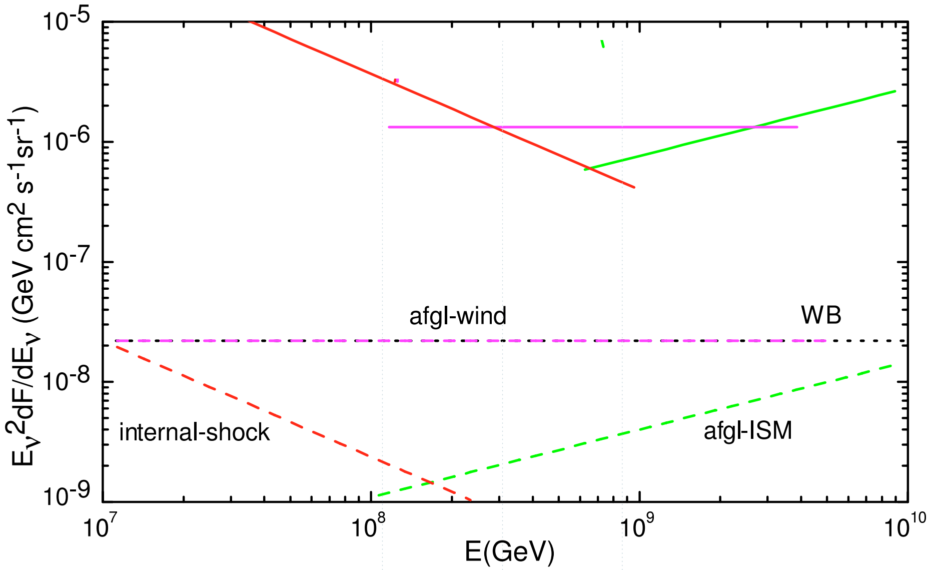
I. Kravchenko et al., 2006

- 2001-2005: No neutrinos detected in 1.85 years of livetime.



RICE rules out the most intense neutrino flux model predictions





RICE Limits on Magnetic Monopoles

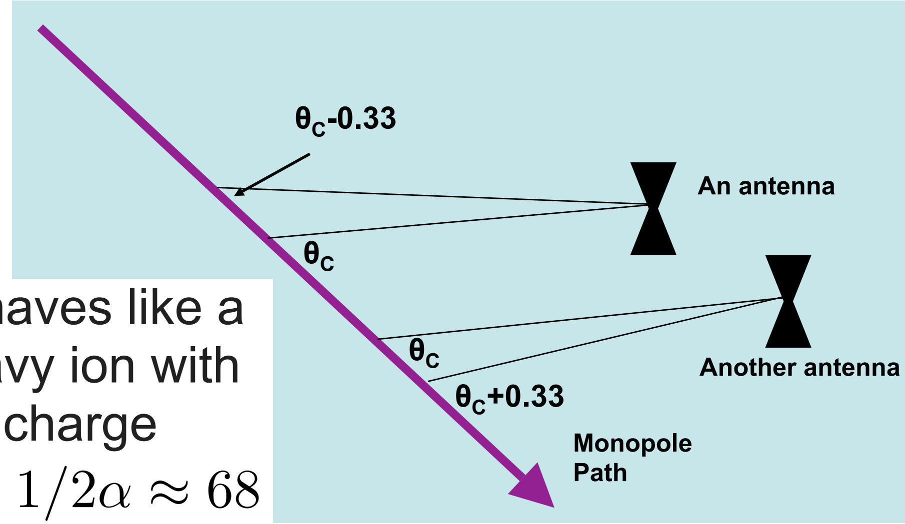
Daniel Hogan, Kansas University, RICE Collaboration

- (Wick et al. '03) Monopole mass < 10^{14} GeV

➡ relativistic

- Energy ~ 10^{16} GeV
- Relativistic monopoles cause EM showers in ice

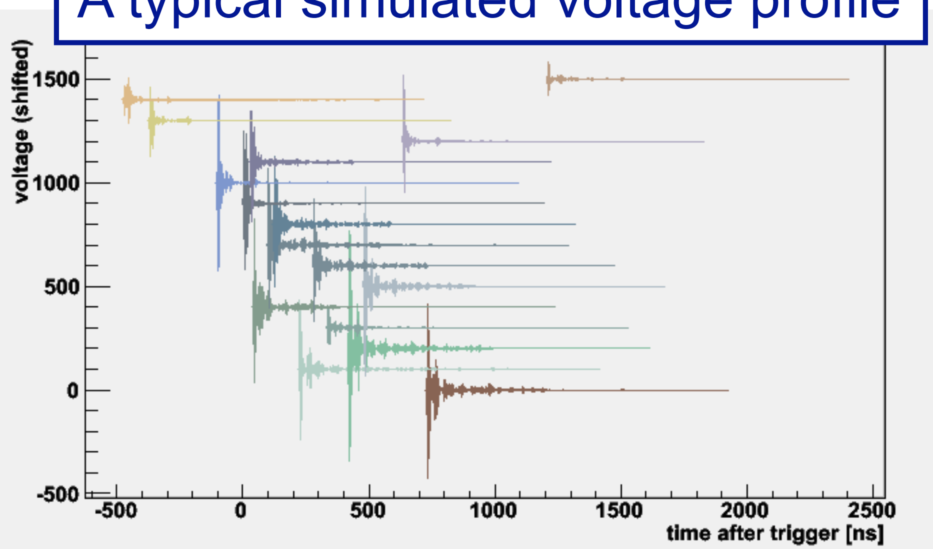
➡ Cerenkov signal

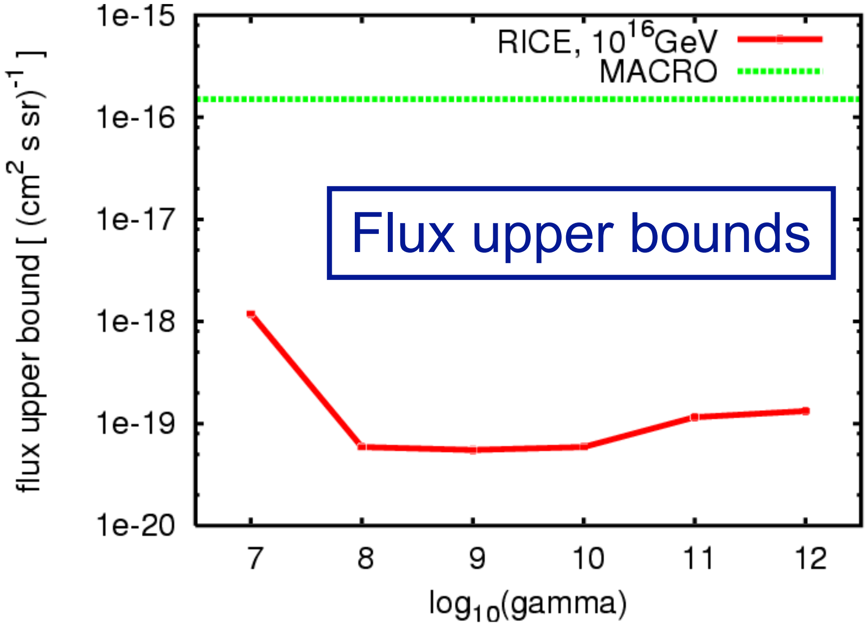


Behaves like a heavy ion with charge

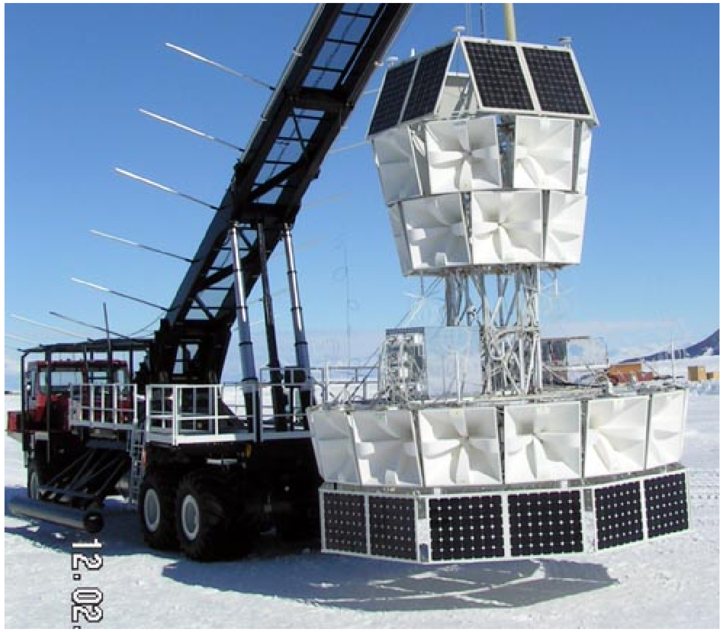
$$Z = 1/2\alpha \approx 68$$

A typical simulated voltage profile

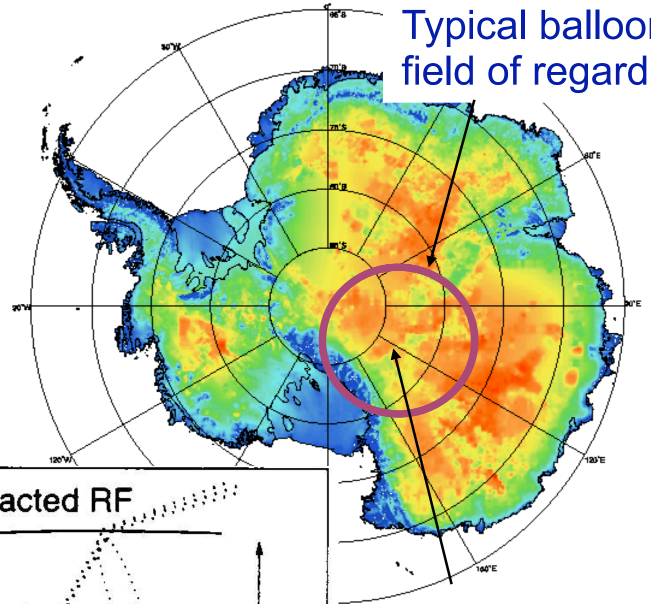




ANITA
(ANtarctic Impulsive Transient Antenna)

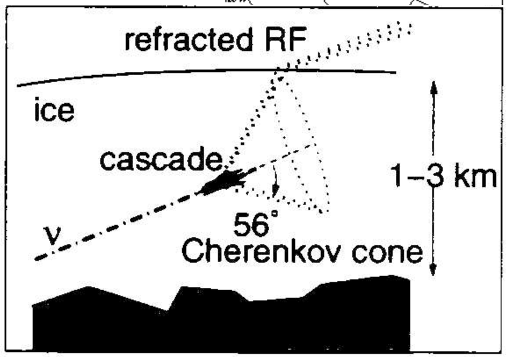


First full physics flight: Dec. 15th 2006 – Jan 18th 2007!



Typical balloon field of regard

~4km deep ice!



32 quad-ridged horn antennas, dual-polarization, 200-1200 MHz, 10° cant

Balloon flies 37 km above the ice

Balloon operations by the Columbia Scientific Balloon Program (NASA)

Downgoing - not seen by payload
Upcoming – absorbed in the earth
→ ANITA sees "skimmers".

Observes ~1.5 x 10^6 km^2 of ice at once!

The ANITA Collaboration

University of Hawaii at Manoa
Honolulu, Hawaii

University of California at Irvine
Irvine, California

University of California at Los Angeles
Los Angeles, California

University College London
London, England

University of Delaware
Newark, Delaware

Jet Propulsion Laboratory
Pasadena, California

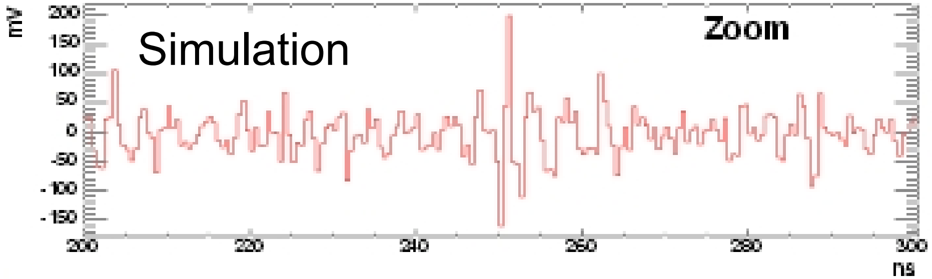
University of Kansas
Lawrence, Kansas

Ohio State University
Columbus, Ohio

Stanford Linear Accelerator Center
Pasadena, California

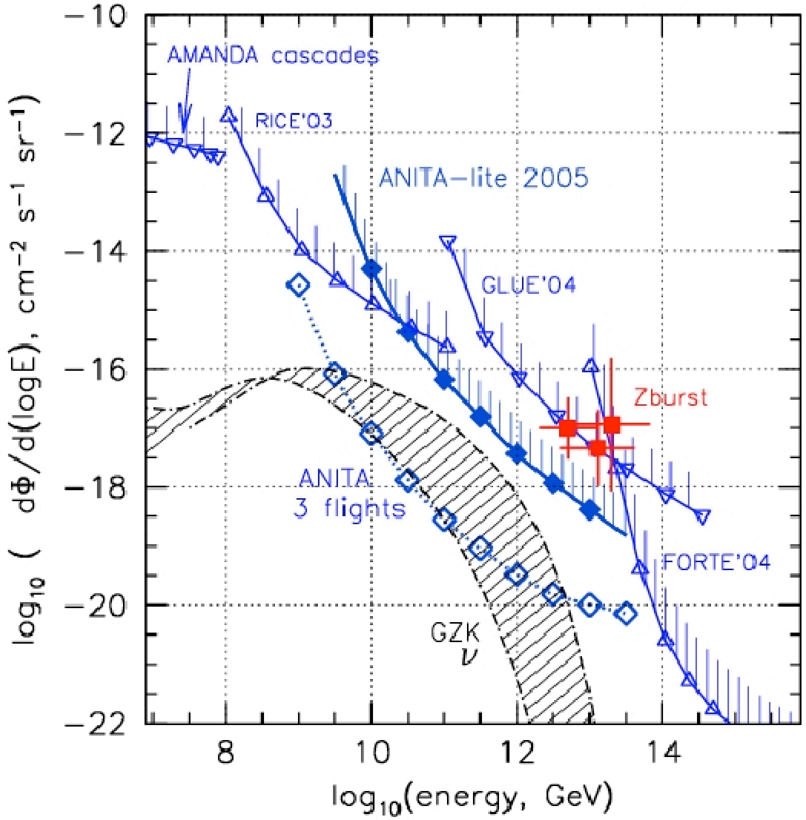
Washington University in St. Louis
St. Louis, Kansas

Anita-lite: 2 antennas, 2003-2004 Season



- Designed cuts to select Askaryan-like events
  - # cycles in a waveform
  - Integrated power
  - Time coincidence between channels
- Reduce noise with cross-correlation analysis
- Both analyses find analysis efficiency ~50%
- ANITA-lite ruled out Z-burst models

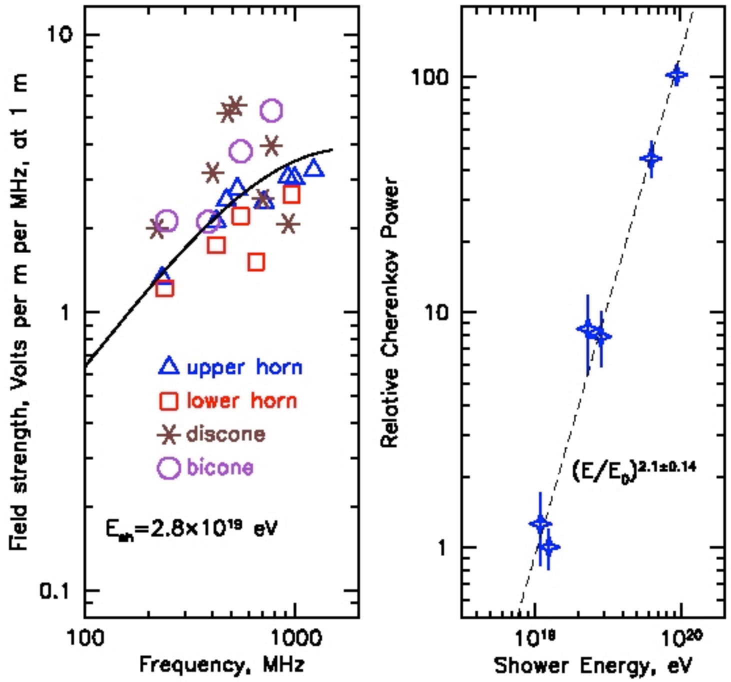
- Two independent analyses modeled time dependent pulse on measured noise



ES&S baseline (min)
Kalashev, *et al.*, saturate all bounds (max)

ANITA Calibration at SLAC: June 2006

Produced Askaryan pulses in ice from a 28.5 GeV electron beam at SLAC
~10^9 particles per bunch
→ 10^{19}- 10^{20} eV showers

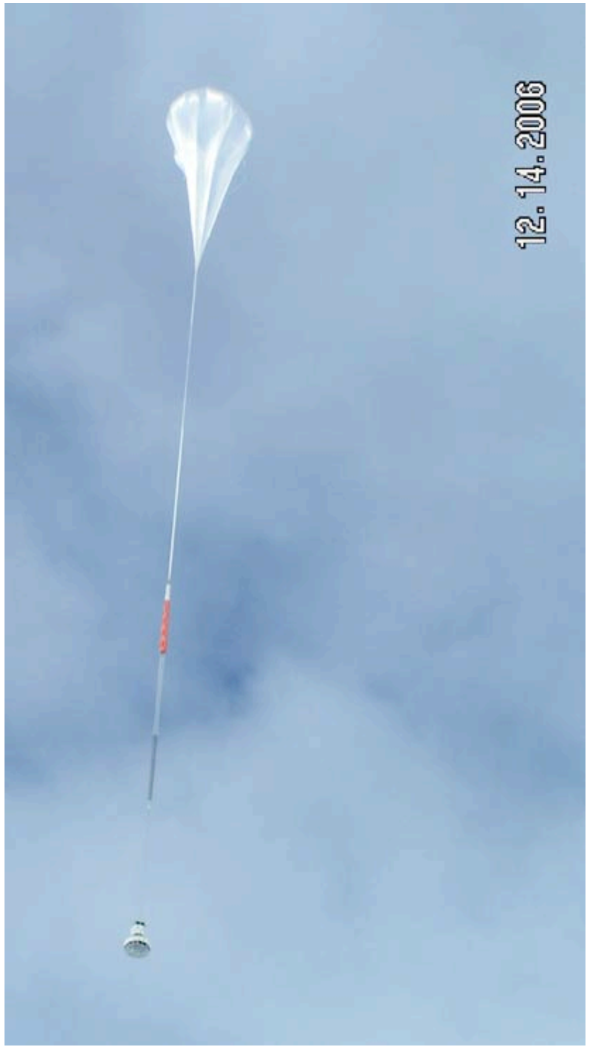


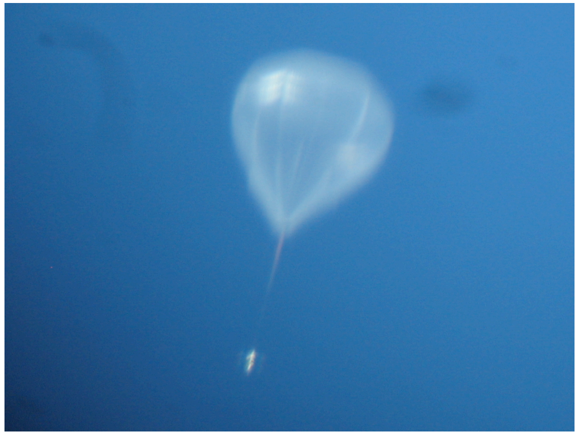
ANITA Collaboration (P.W. Gorham et al.)
hep-ex/0611008

From there, ANITA was off to Antarctica…

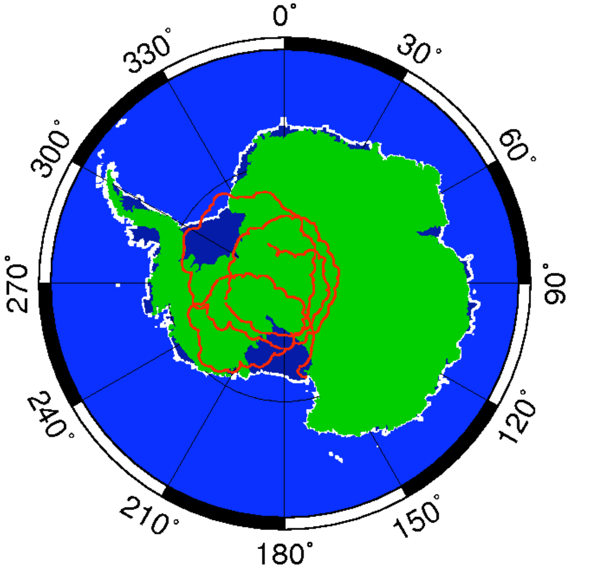
ANITA Flight

- ANITA launched on Dec. 15th
- Took 3.5 trips around Antarctica
- In flight for 35 days
- Terminated on Jan 18th
- Full recovery completed
- Analysis is underway
- Expect to either be the first to discover UHE neutrinos or set world's best limits

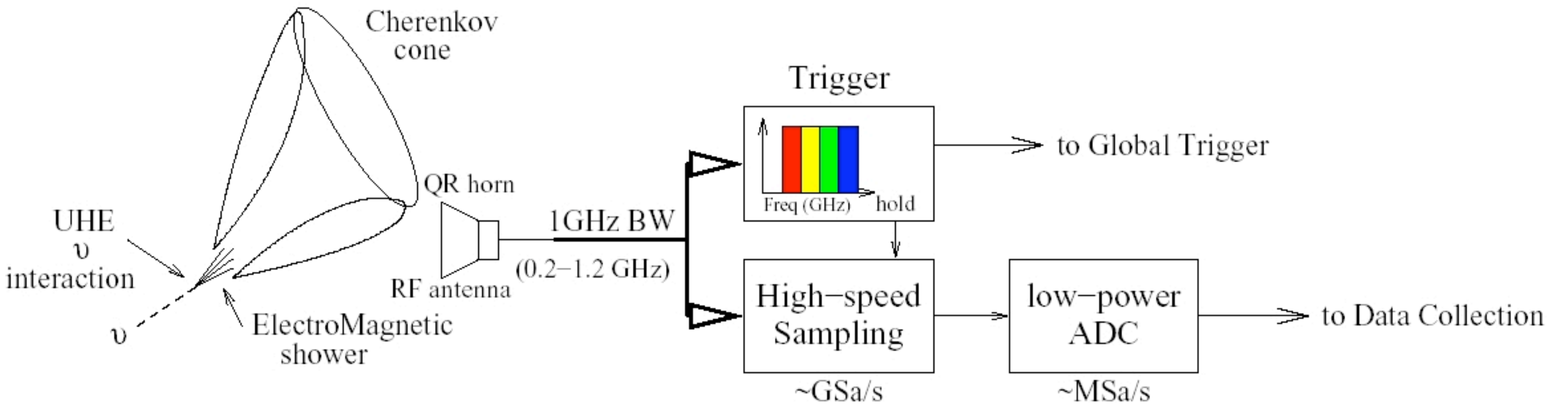




View of ANITA from the South Pole
Picture taken by James Roth



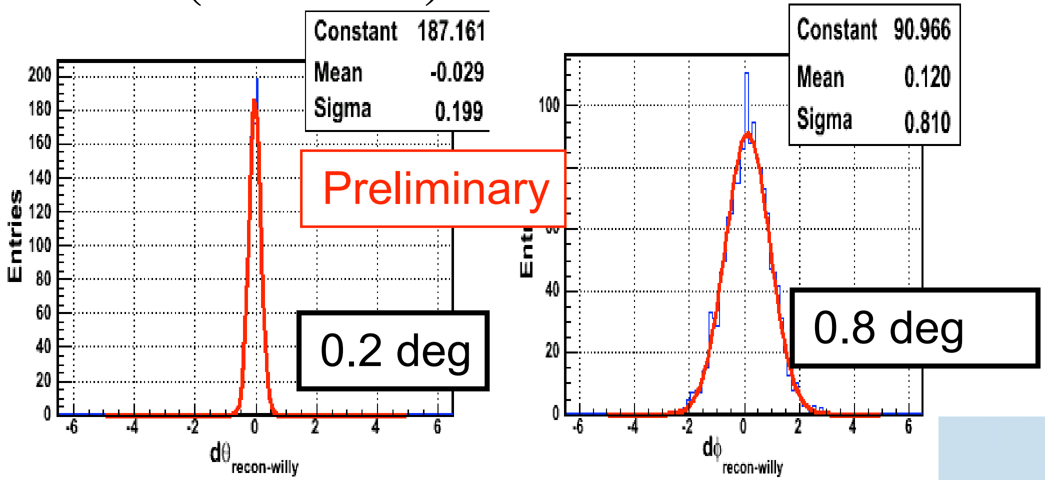
ANITA Signal Acquisition



- Trigger: Signal divided into frequency sub bands (channels)
  - Powerful rejection against narrow bandwidth backgrounds
  - Multi-band coincidence allows better noise rejection
- 8 channels/ antenna
- Require 3/8 channels fire for antenna to pass L1 trigger
- Global trigger analyzes information across antennas
- For Anita-lite, no banding: 4 channels, require 3-fold coincidence

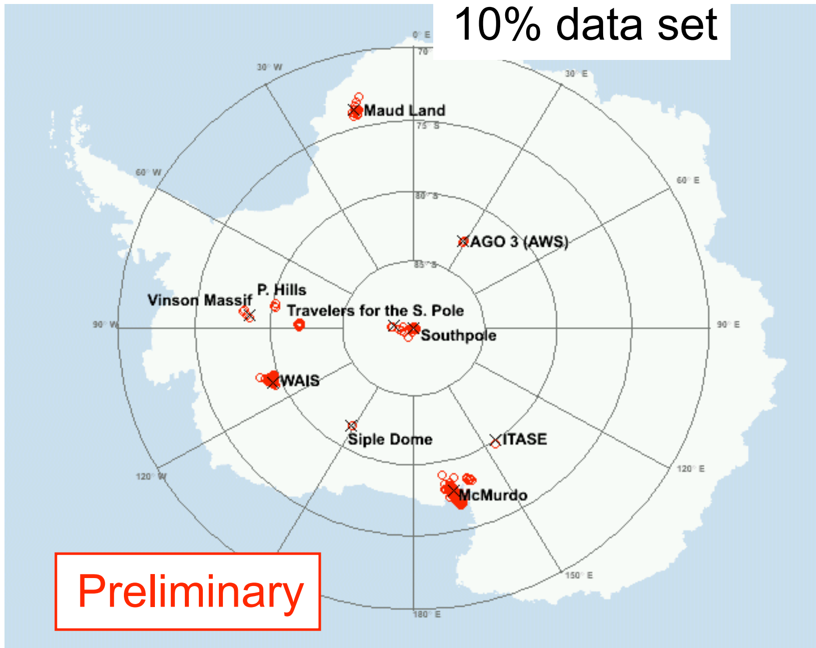
ANITA Event Reconstruction

Data (Borehole)



up-down left-right

- Calibration pulses sent to the payload while ANITA was in view of McMurdo
- From the surface and from borehole



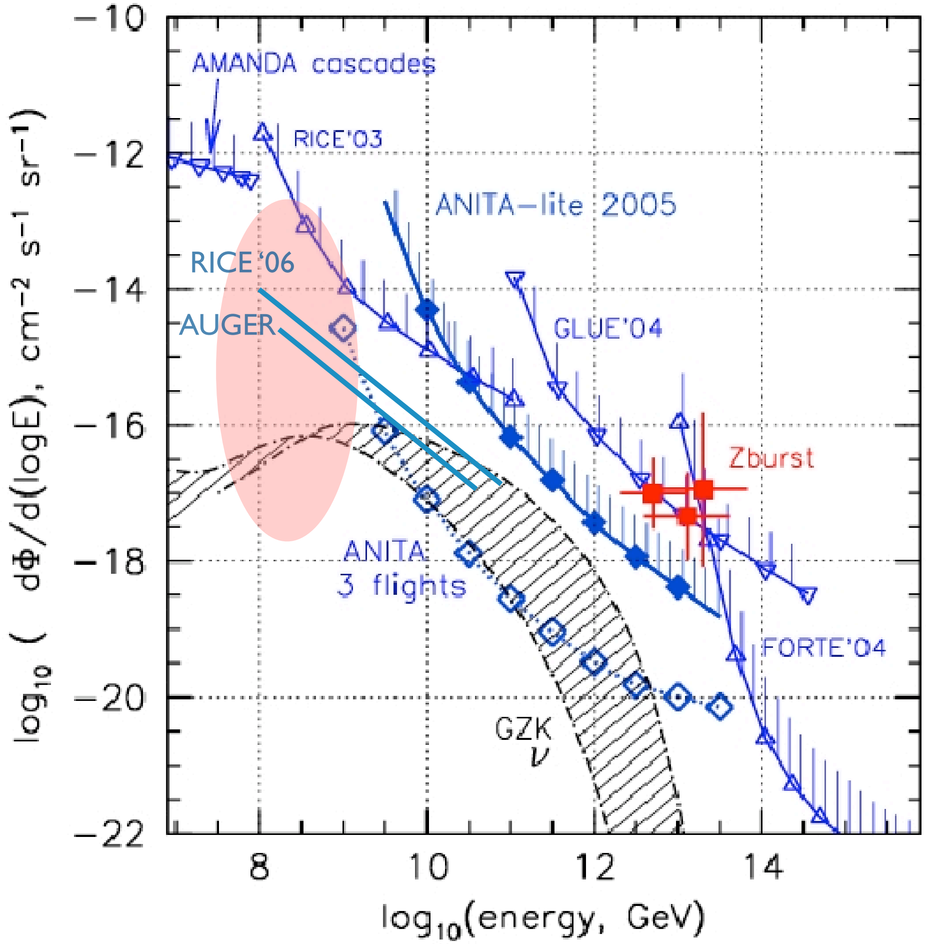
- Preliminary analysis with 10% data set
- V>3sigma
- Establish angular reconstruction, select good events
- Time profile, FFT consistent with expectation
- All associated with camps, travelers, automatic weather stations

Haven't looked at remaining 90%

ANITA II approved - flight 2008-2009

Embedded Radio Detectors Designed to Target Energy Gap

- Detectors embedded in the interaction medium have lower threshold
- Variety of embedded radio detector projects being studied or planned
- Antarctic ice and salt
- Goal of any next-generation experiment: 100 GZK neutrinos/year



Limit curves from Barwick et al., Phys.Rev.Lett 96:171101,2006 and references therein, (RICE '06) I. Kravchenko et al., 2006, Phys.Rev.D73:082002,2006, and (AUGER) L.Anchordoqui et al., ICRC Proceedings 2007

AURA
Askaryan Under ice Radio Array

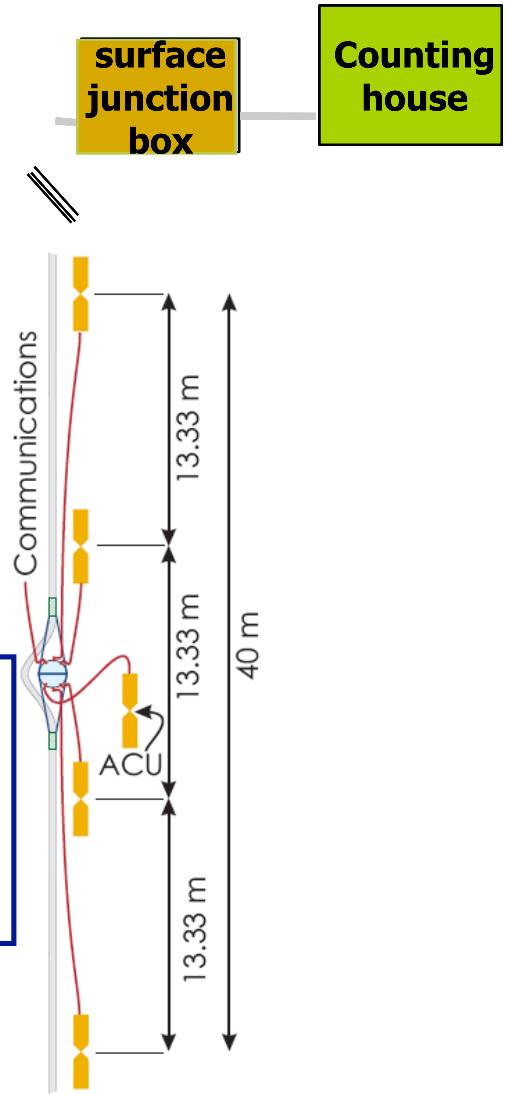
Information on AURA slides from Hagar Landman (Wisconsin) for the IceCube Collaboration

- Utilize existing infrastructure and technology for Radio Frequency neutrino detector at the South Pole
  - RICE - Antennas, electronics and control
  - ANITA – Digitizer and triggering
  - IceCube- Main board, DAQ, holes, cables

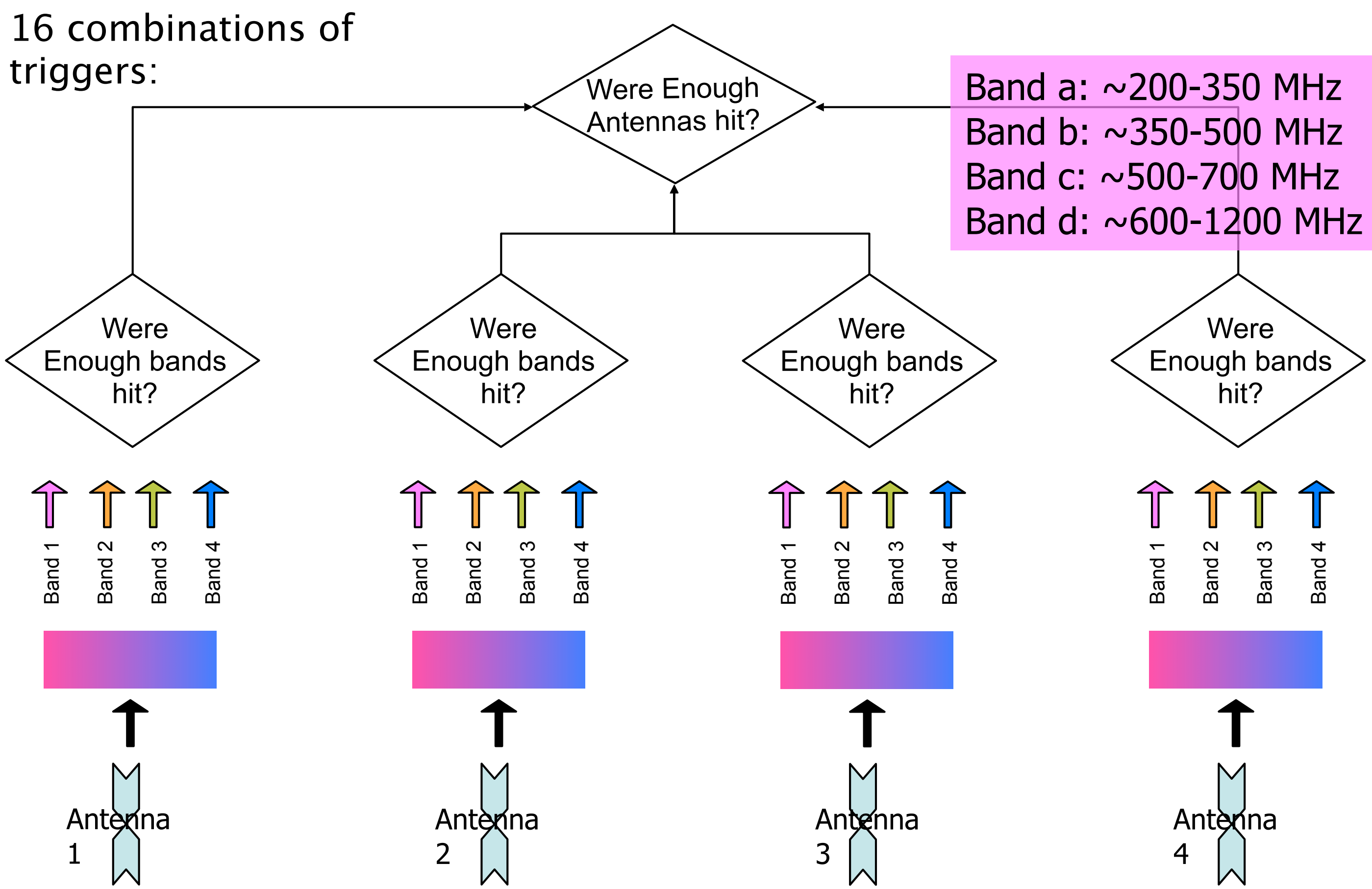
AURA Cluster

- Digital Radio Module (DRM) – Electronics
- 4 Antennas
- 1 Antenna Calibration Unit (ACU)

3 Radio clusters were deployed in the 06-07 polar season at the South Pole



AURA Triggering

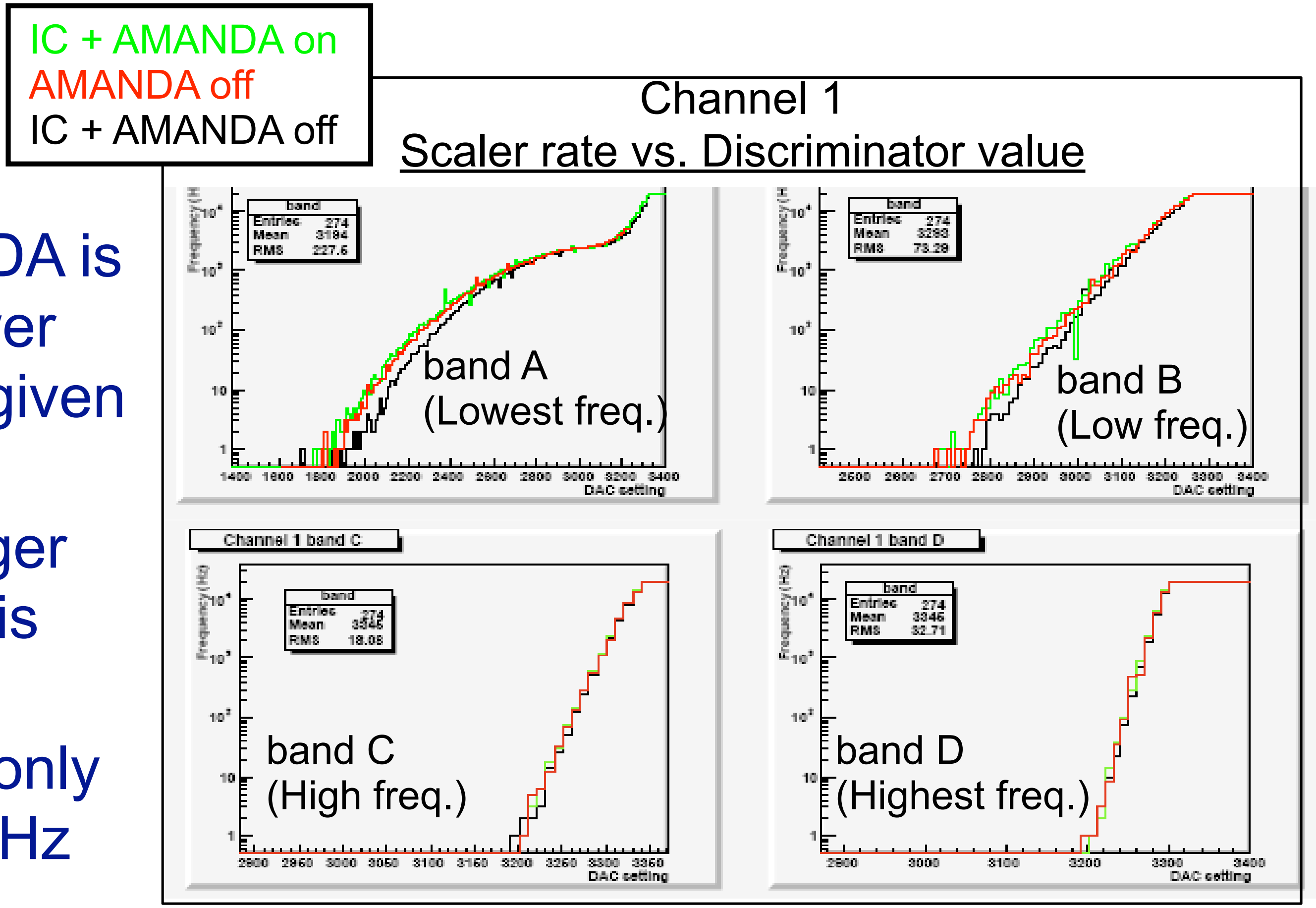


- Antennas: Broad band dipole, centered at 400 MHz
- Front end electronics: 450 MHz Notch filter, 200 MHz High pass filter ~50dB amplifiers (+20 dB in DRM)
- Each antenna sampled using two 1 GHz channels to total of 512 samples / 256 ns (2 GSPS)

Suitability of IceCube environment for AURA

- Channel and cluster trigger rates were compared when IceCube/AMANDA were idle and taking data.

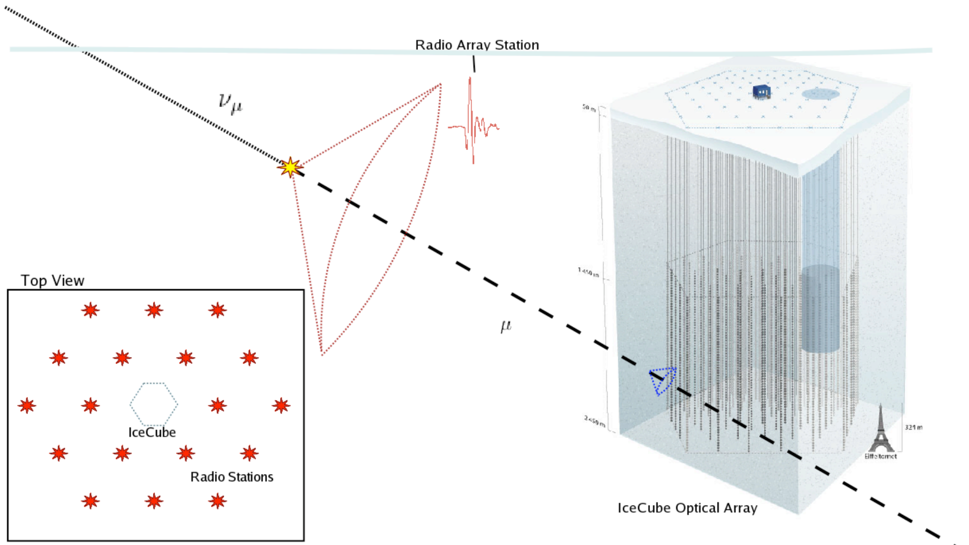
- Noise from IceCube/AMANDA is enhanced in lower frequency on a given channel/band
- Combined trigger reject most of this noise
- Measurement only down to ~200 MHz



IceRay / AURA

A next-generation array could deploy antennas:

- On surface (IceRay)
- Deep (AURA):
  - On existing IceCube strings
  - On strings in dedicated radio boreholes



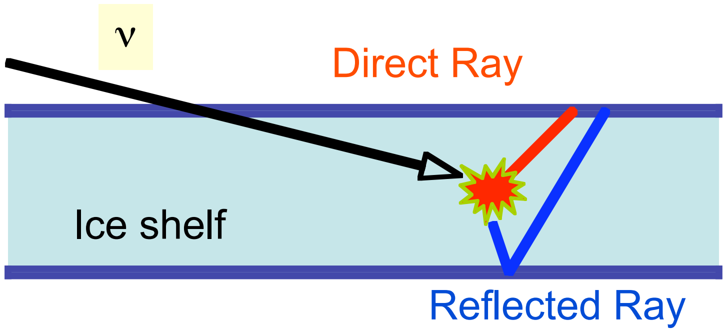
Preliminary simulations:

- An array of 18-36 stations that could be built by ~2012 could detect 4-8 GZK neutrinos/year
- Pre-curser to larger array that would detect 100 GZK neutrinos/year

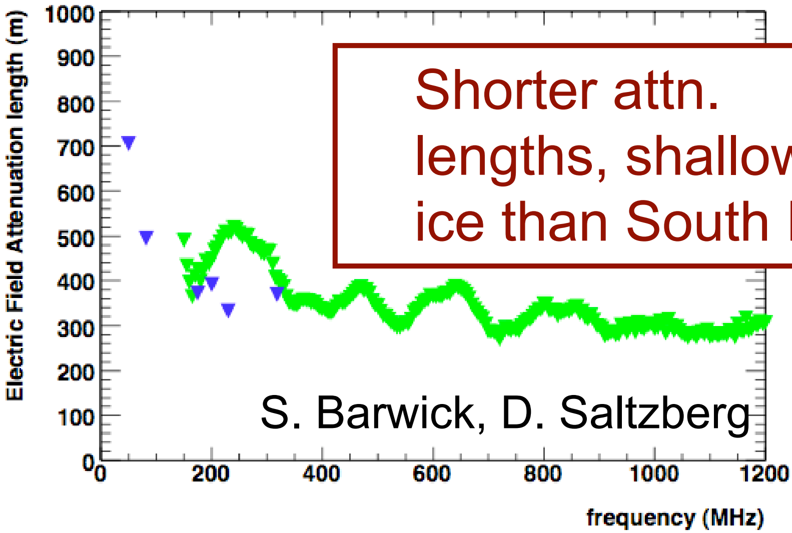
A fraction of events could be measured in both radio and optical instruments

Ross Ice Shelf Array (ARIANNA)

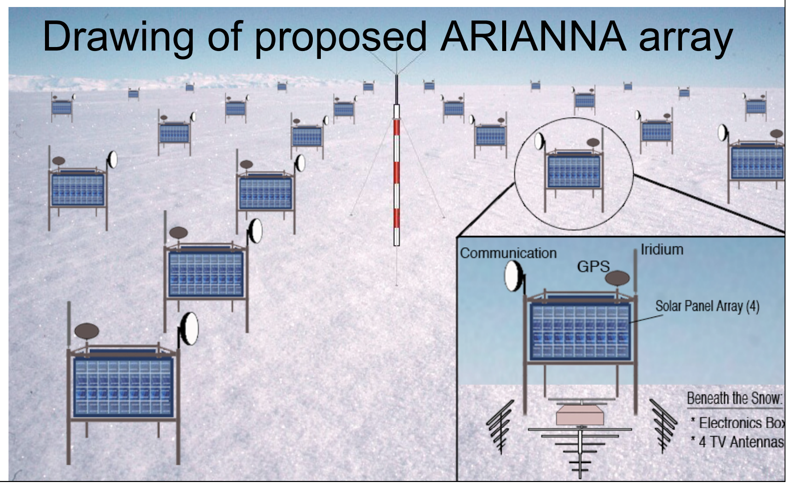
An array could also be deployed on the surface of the Ross Ice Shelf



- Highly reflective surface at interface with seawater
- Could observe reflections -> more solid angle

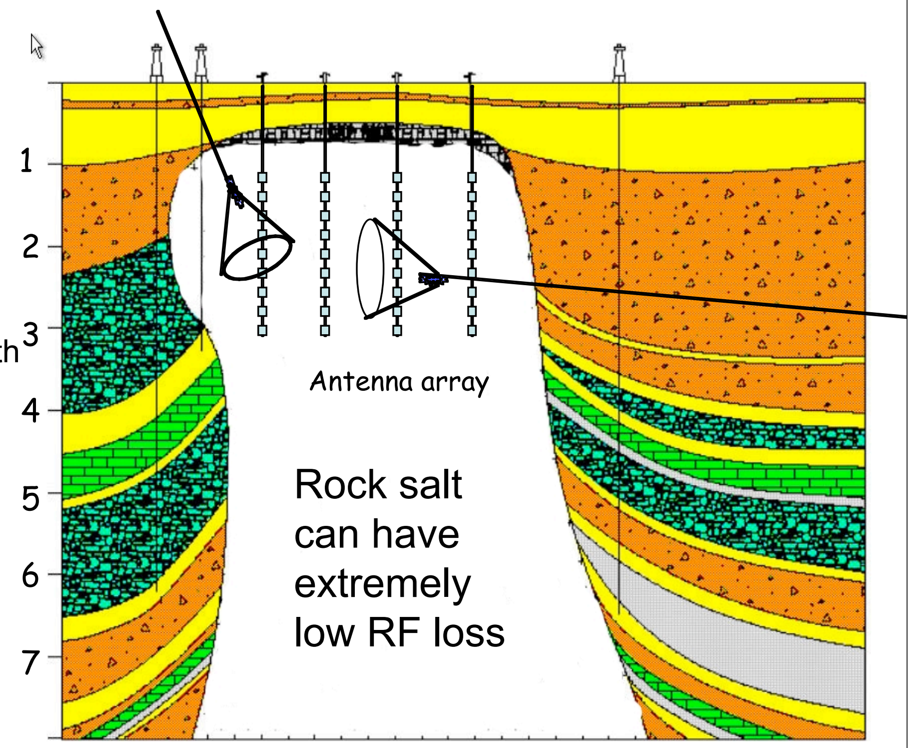


Shorter attn. lengths, shallower ice than South Pole



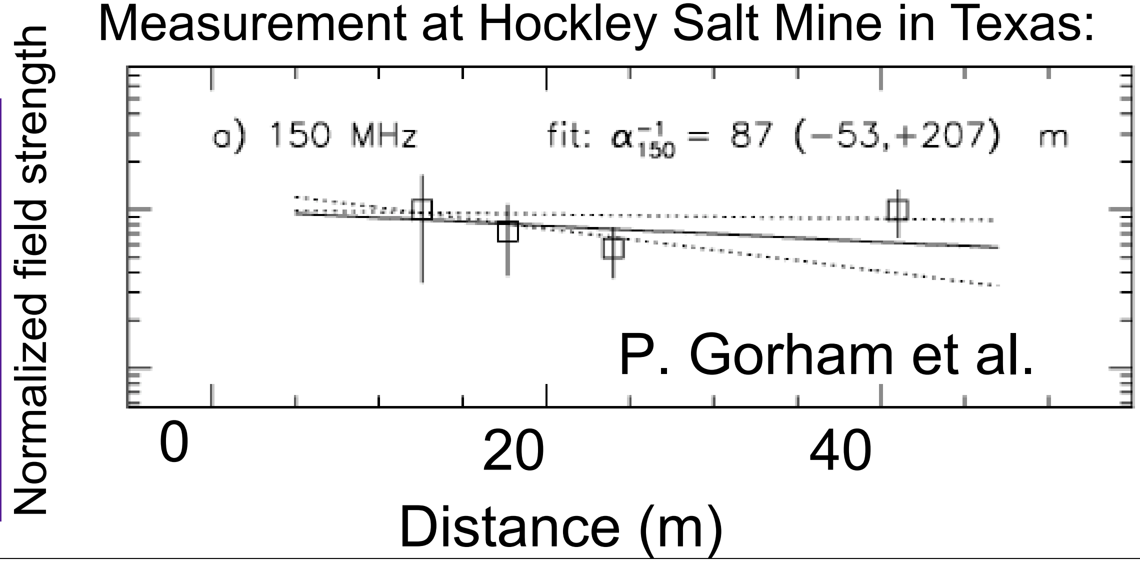
SalSA

- Salt formations can extend several km's wide x 10 km deep
- Salt domes can be very pure
- Ground penetrating radar (GPR) has shown very low loss
- Askaryan array in salt could be drilled from surface (expensive) or laid along floors of a salt mine



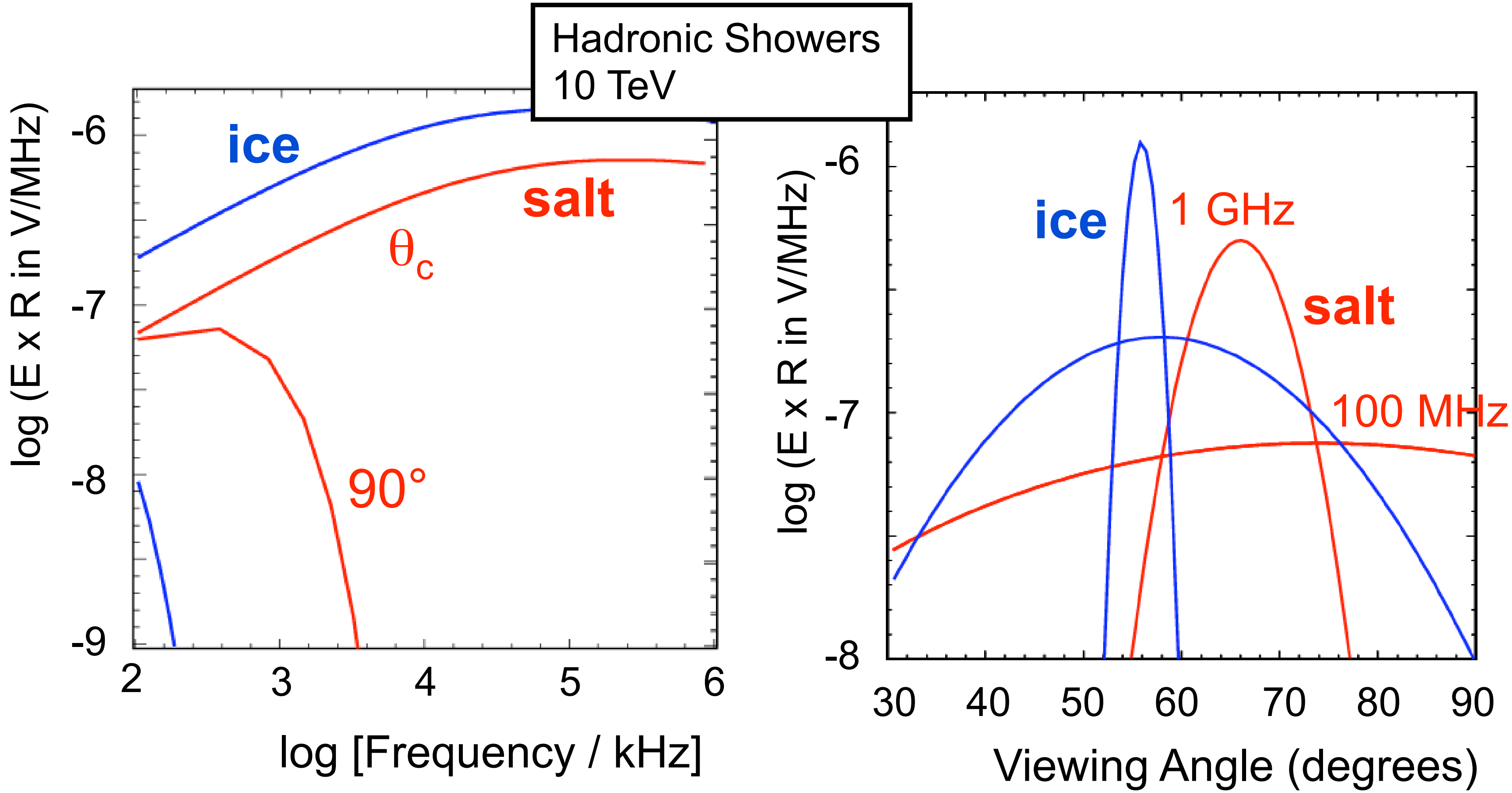
Before a SalSA experiment can proceed, long attenuation lengths for radio in salt need to be confirmed

Measurement at Hockley Salt Mine in Texas:



Comparing Askaryan Signal in Ice and Salt

Parameterization in the simulation from J. Alvarez-Muniz astro-ph/0512337:



Electric field α shower energy

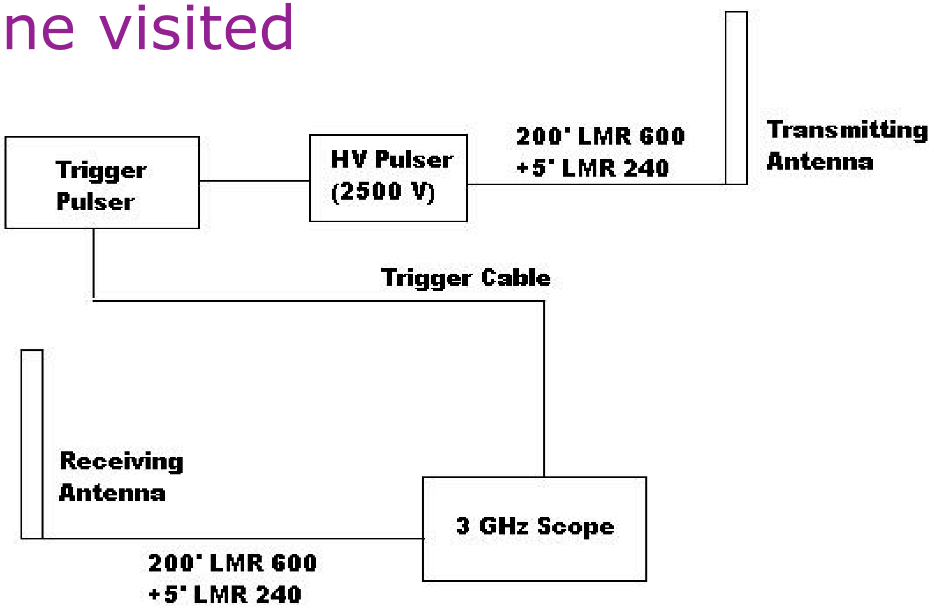
Electromagnetic showers narrow beyond ~ 10 PeV due to LPM effect

Attenuation Length Measurements in Salt

Cote Blanche Salt Mine, Louisiana, USA

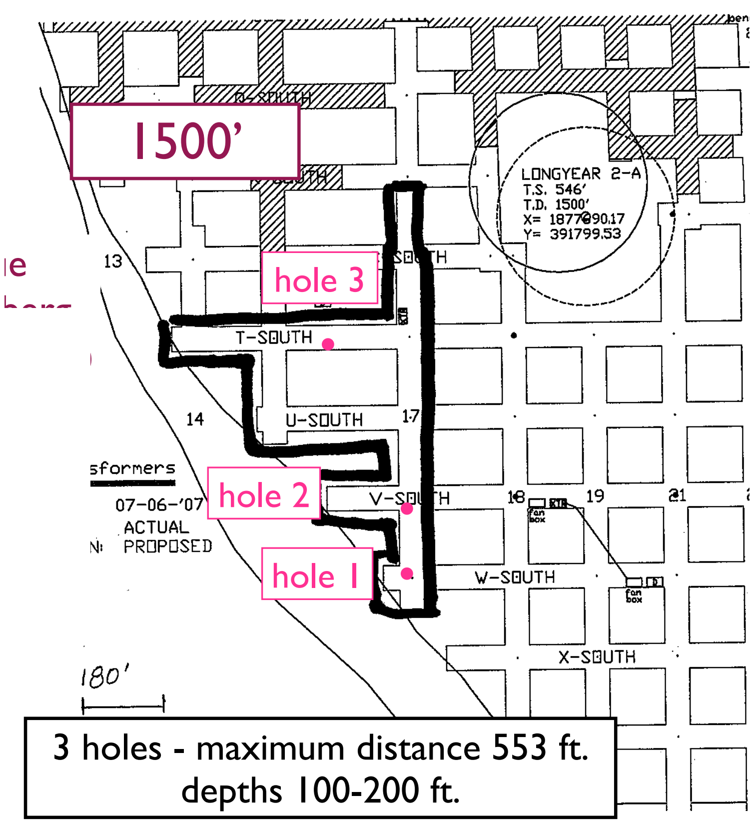
A. Connolly (UCL) ,A. Goodhue (UCLA),
R. Nichol (UCL), D. Saltzberg (UCLA),
M. Cherry (LSU), J. Marsh (LSU)

- Visited Cote Blanche salt mine to measure radio attn. lengths in salt
- Ground penetrating radar (GPR) experts saw lowest loss in any mine visited

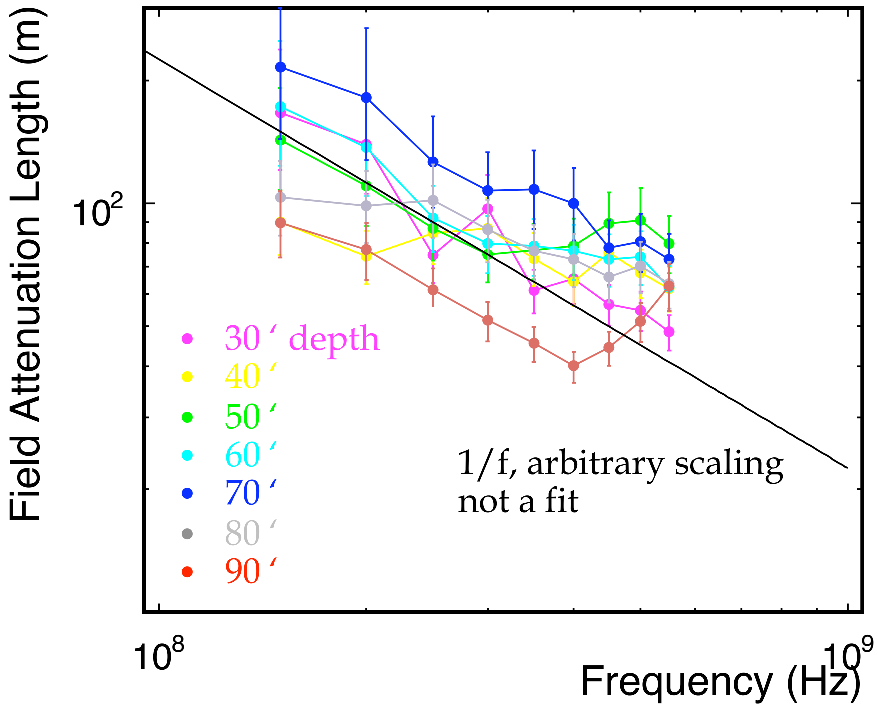


Attenuation Length Measurements in Salt

Cote Blanche Salt Mine, Louisiana, USA



3 holes - maximum distance 553 ft.
depths 100-200 ft.



Will be difficult for salt to compete with Antarctic ice in sensitivity, but SalSA could provide alternate view of northern sky

- ~100 meter attn. lengths observed
- Difficult to reconcile with GPR results
- Probably clearer salt yet to be seen

Summary

- Radio detection technique brings neutrino astronomy to >100’s km^3 detection volumes
  - The field is already giving important results
- It is an exciting, dynamic field
- Pioneering experiments FORTE, GLUE and RICE have set the stage for current and proposed projects to discover GZK neutrinos and measure a sample of them to extract their particle physics and astrophysics potential
- Development of next-generation projects is underway, and the field is finding the best path forward based on
  - Experience with existing projects
  - Site selection studies
  - Ever maturing simulations

The race is on for UHE neutrino detection!