Studies of the Energy Resolution of the ANITA Experiment

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Motivation

- Greisen-Zatsepin-Kuzmin (GZK): Cosmic ray protons >$10^{19.5}$ eV will be slowed by CMB photons:

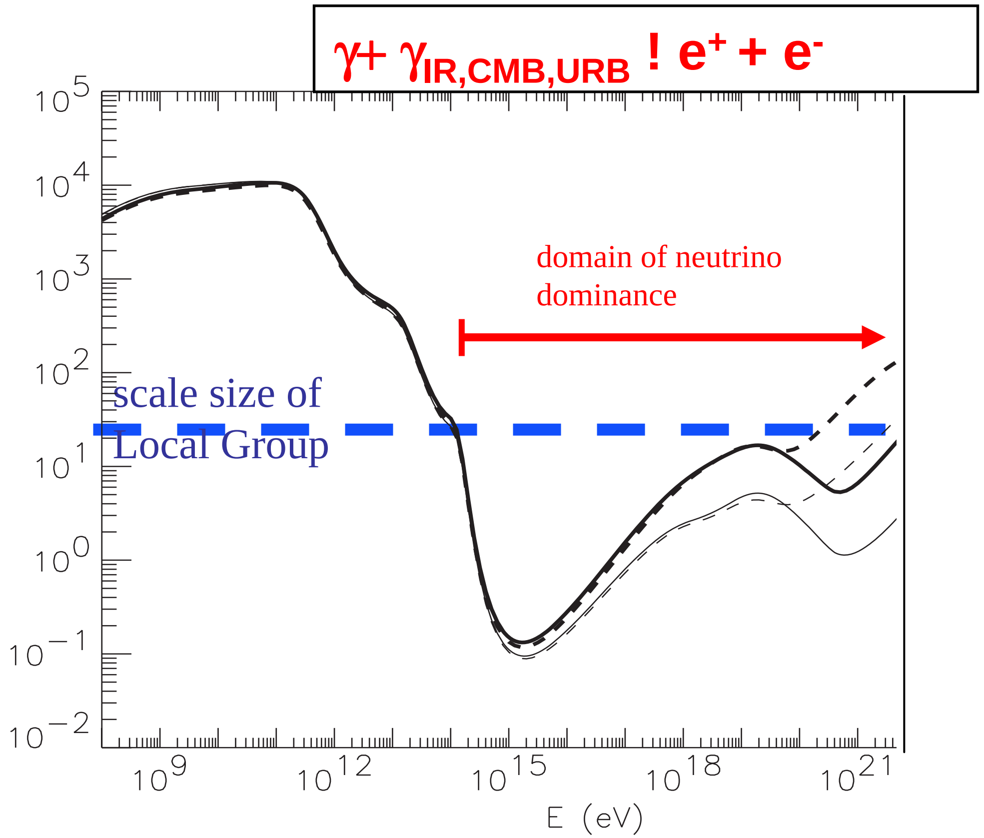
$$p + \gamma_{cmb} \rightarrow \Delta^* \rightarrow p + \pi$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$

- Protons should lose their energy within ~50 Mpc
- Nuclei, gamma rays travel even shorter distances
- Since
  - No known "local" sources
  - Galactic magnetic fields not sufficient to contain (accelerate) them
- We should see a cutoff in cosmic ray protons at ~$10^{19.5}$ eV
- But we should see neutrinos from the GZK process

Neutrinos are expected with or without a cutoff

They are an important part of the UHECR puzzle

Motivation (cont): Only useful messengers >100 TeV: ν's

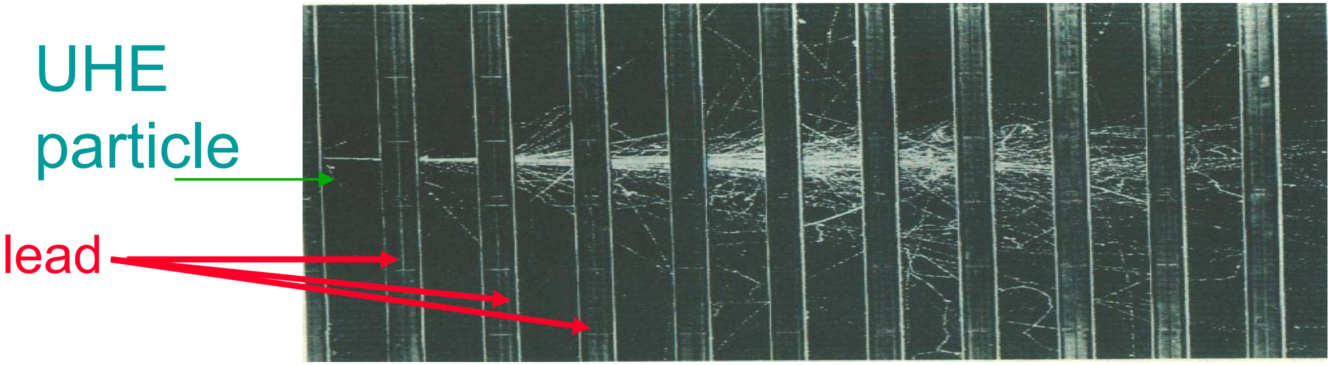


- **Photons lost above 30 TeV:** pair production on IR & μwave background
- **Protons & Nuclei:** scattered by B-fields or GZK process at all energies
- **But** the sources extend to $10^{20\text{-}21}$ eV

Neutrinos travel cosmological distances and they point back!

Every new energy band yields major discoveries

Idea by Gurgen Askaryan (1962)



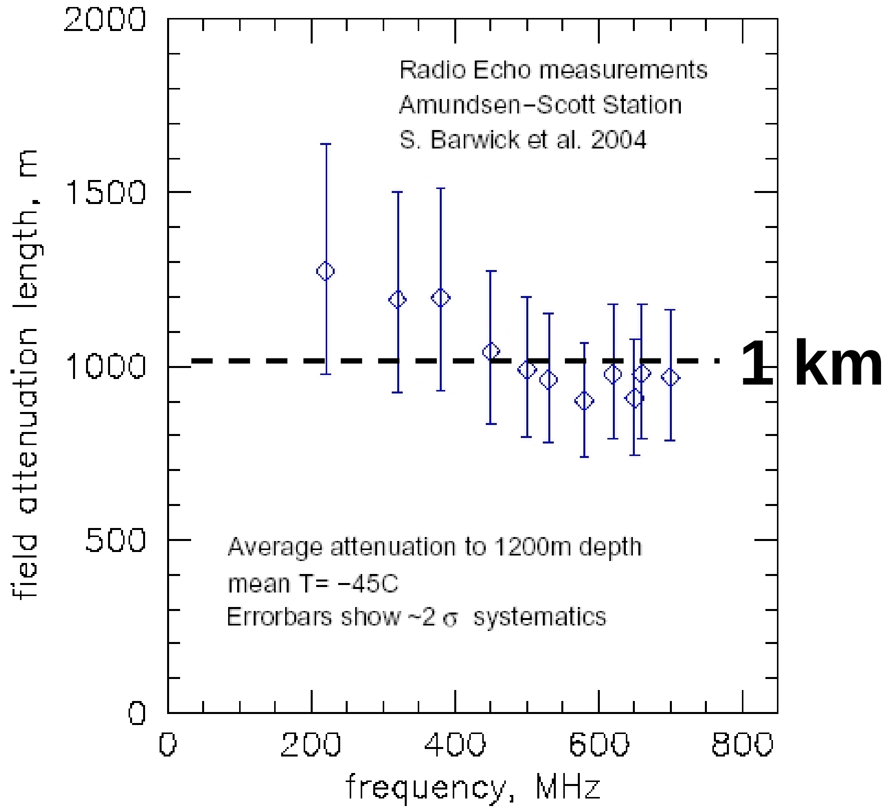
Bremsstrahlung:
$e^- \rightarrow e^- \gamma$
Pair Production:
$\gamma \rightarrow e^+ e^-$
$\rightarrow$ EM Shower

- A 20% charge asymmetry develops:
  - Compton scattering: $\gamma + e^-$(at rest) $\rightarrow \gamma + e^-$
  - Positron annihilation: $e^+ + e^-$(at rest) $\rightarrow \gamma + \gamma$
- Excess moving with v > c/*n* in matter
  $\rightarrow$ Cherenkov Radiation $dP \propto \nu\, d\nu$
- If $\lambda >> L \rightarrow$ **COHERENT EMISSION** $P \sim N^2$
- $\lambda \gtrsim L \rightarrow$ **RADIO/MICROWAVE EMISSION**

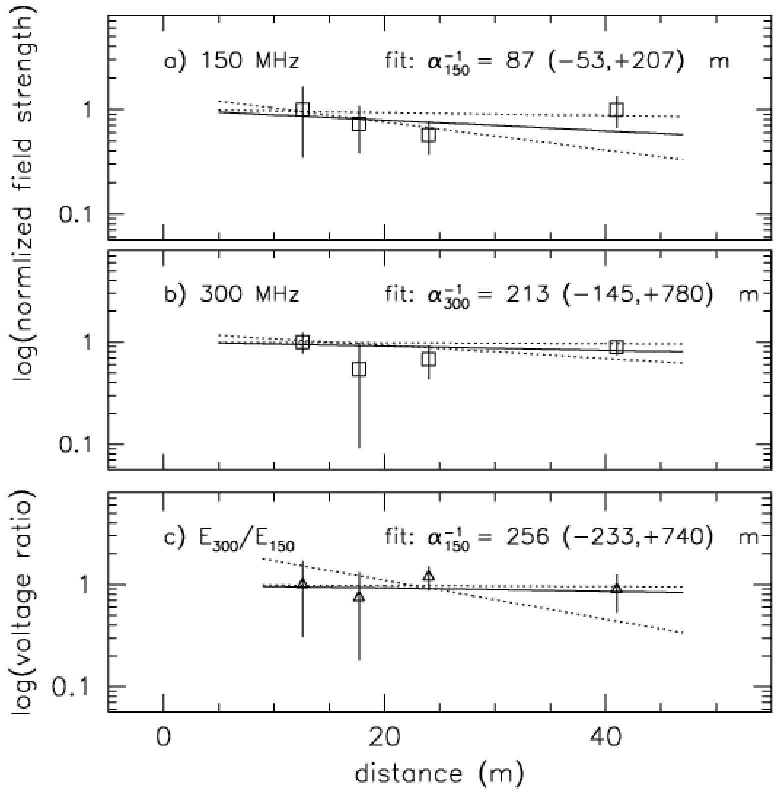
This effect was confirmed experimentally at SLAC in 2002

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

Long Attenuation Lengths in Radio in Ice, Salt, Sand



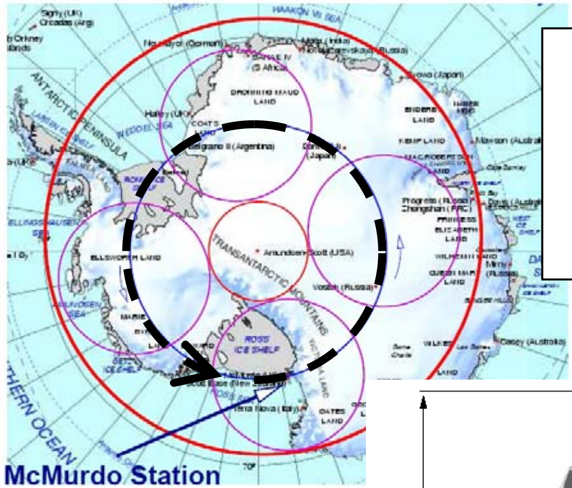
South Pole Ice



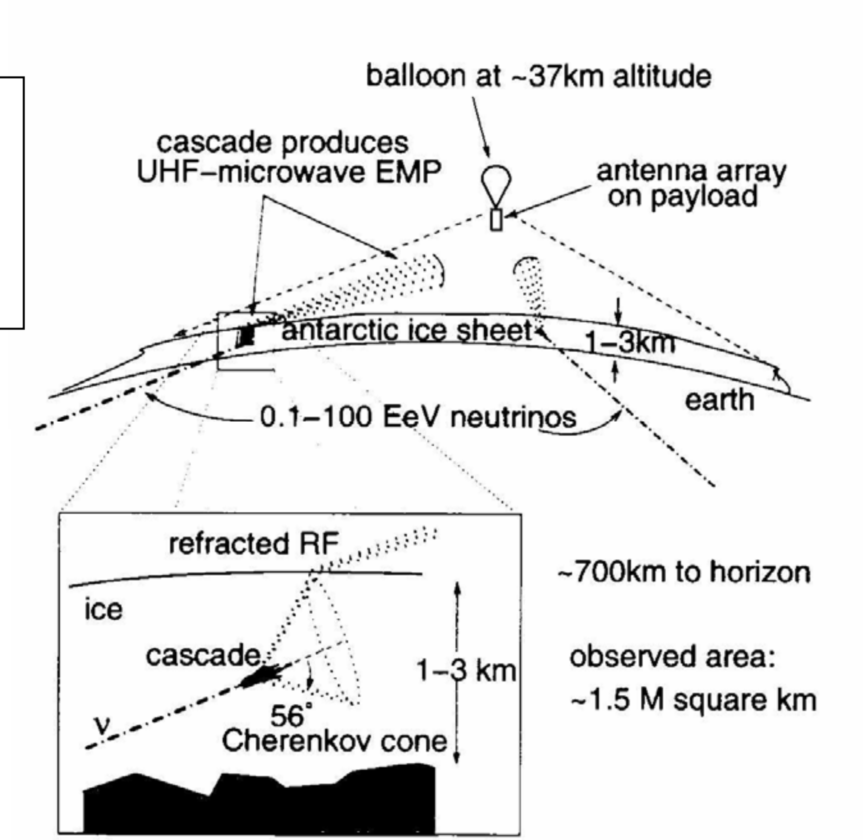
Hockley Mine near Houston, TX

The GLUE experiment sought UHE neutrinos by observing the moon’s regolith.

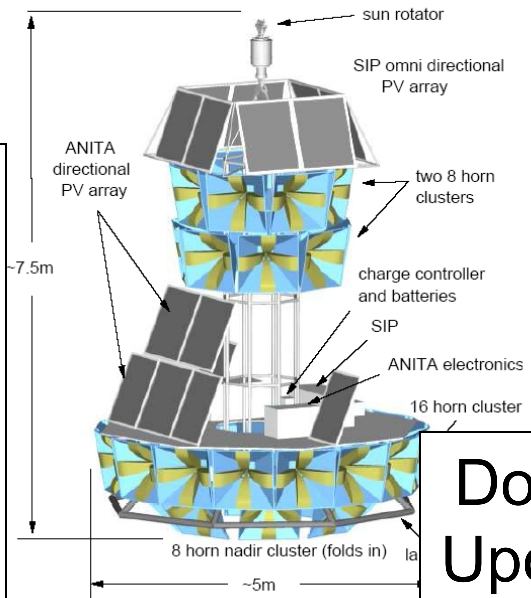
ANITA
(ANtarctic Impulsive Transient Antenna)



Each flight ~15 days – or more



32 quad-ridged horn antennas, dual-polarization, with 10± cant

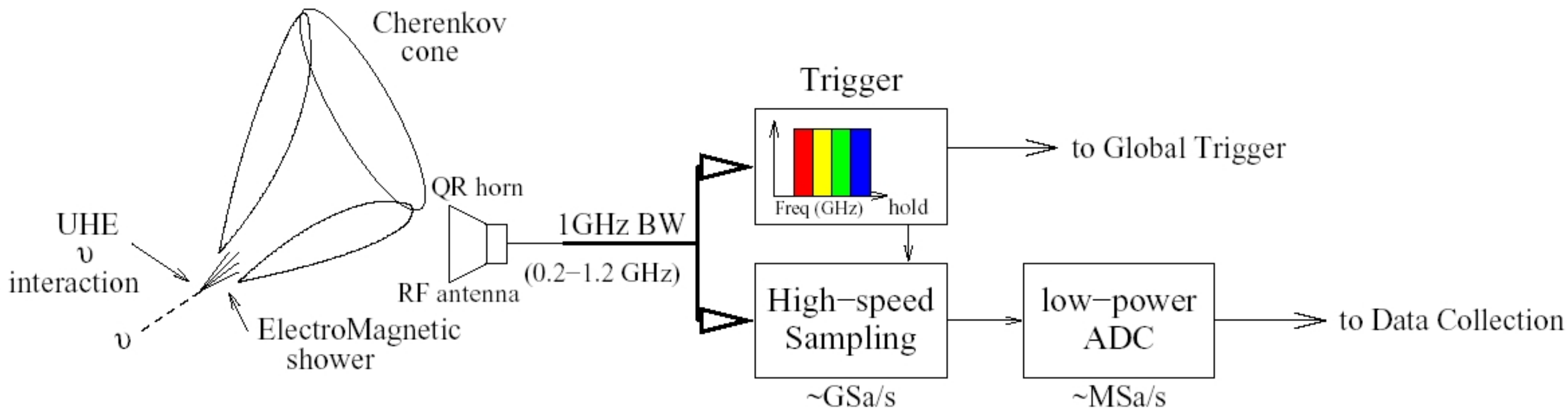


Downgoing - not seen by payload
Upcoming – absorbed in the earth
! ANITA sees “skimmers”.

The ANITA Collaboration

University of California at Irvine
Ohio State University
University of Kansas
Washington University in St. Louis
University of Minnesota
University of Delaware
University of California at Los Angeles
Pennsylvania State University
University of Hawaii at Manoa
Jet Propulsion Laboratory

ANITA Signal Acquisition



- Trigger: Signal divided into frequency sub bands
  - 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

Energy Measurements with ANITA

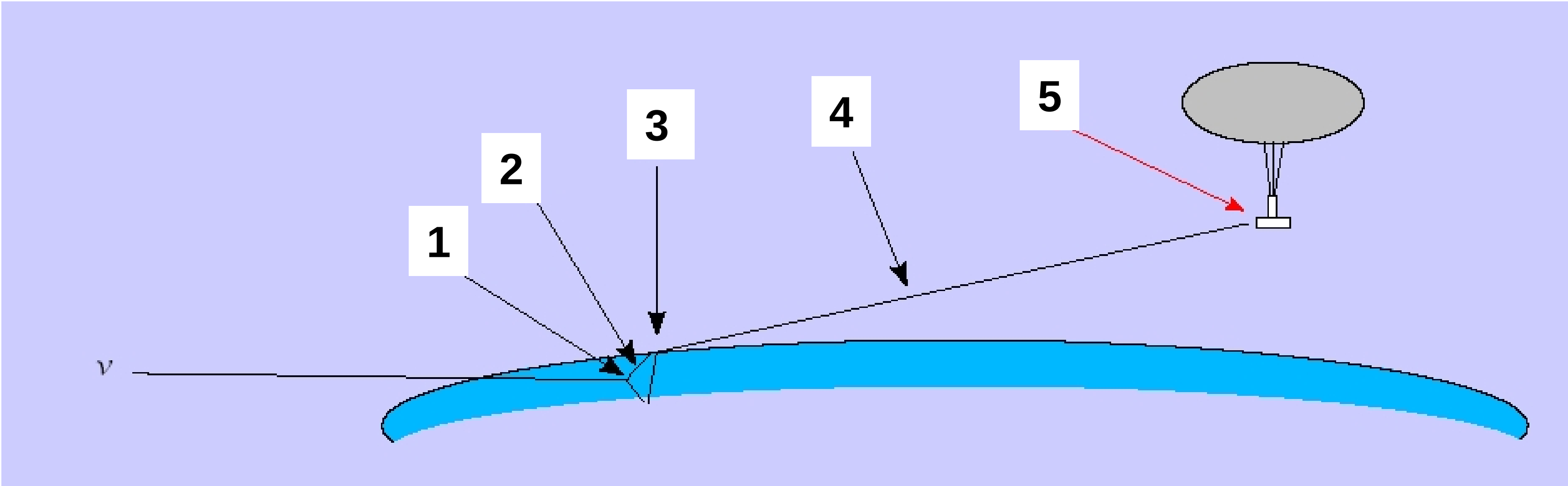
ANITA designed as a discovery experiment for ultra-high energy neutrinos, not a precision experiment

- Still, if ANITA sees a handful of events, what can we say about the neutrino energies?
- Two complementary methods to quantify neutrino spectrum
  - Direct Method: Estimate energy of the shower for each event
  - Likelihood Method: Use likelihood method to determine if events are consistent with E^{-1}, E^{-2}, E^{-3} ν spectra

Typical models for ν spectra from the GZK process similar to E^{-2}

- I will discuss the primary limitations of the Direct Method, then focus on the Likelihood method

Factors that Impact the Signal Strength

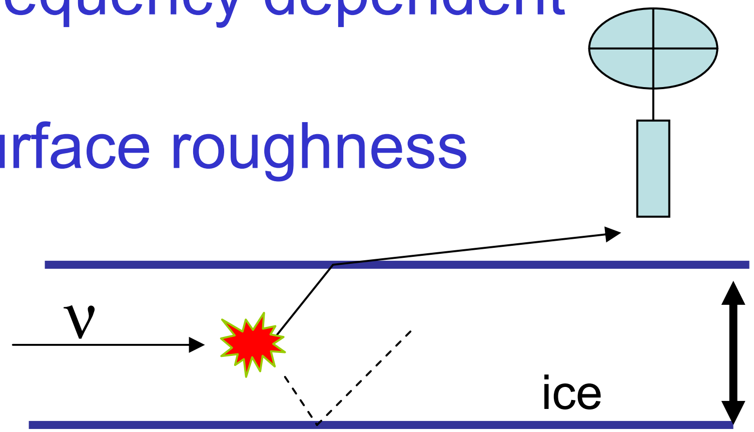


1 - Electric Field of Askaryan pulse at interaction
2 – Angle with respect to Cherenkov angle viewed by balloon
3 – Fresnel coefficients at ice-air interface
4 – Distance from interaction to surface, to balloon
5 – Voltage read by antennas for the incident electric field

ANITA Simulation

- Two major simulation efforts: Hawaii (Gorham) and UCLA (Connolly)
- Signal in frequency domain, but moving to time domain
- Secondary interactions included
- Ray tracing through ice, firn (packed snow near surface)
- Attenuation lengths are depth and frequency dependent
- Fresnel coefficients
- Include surface slope and adding surface roughness
- All 32 quad ridged horn antennas arranged in 3 layers as they are on the payload
- Measured antenna response
- Models 3-level trigger system
- Weighting accounts for neutrino attenuation through Earth

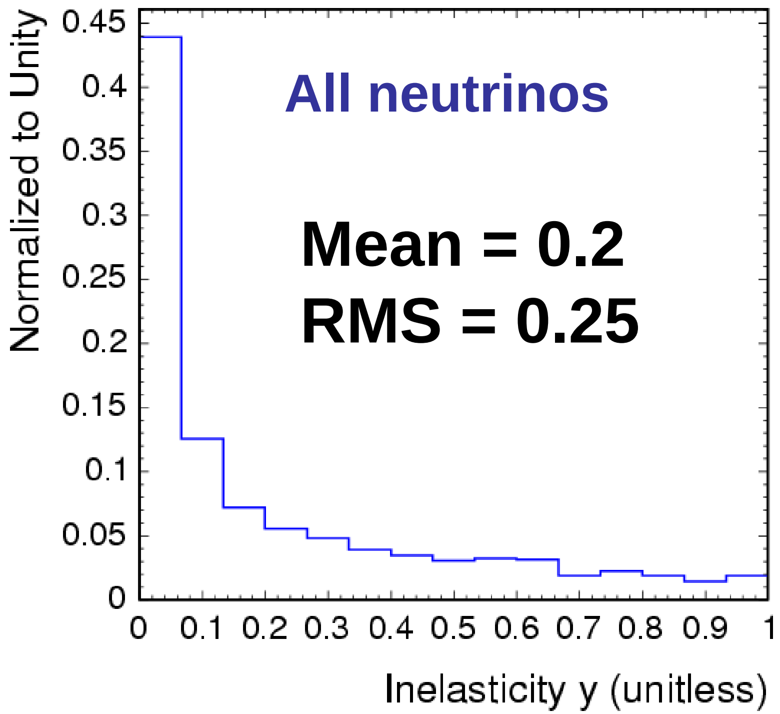
Complementary simulations being developed – essential!

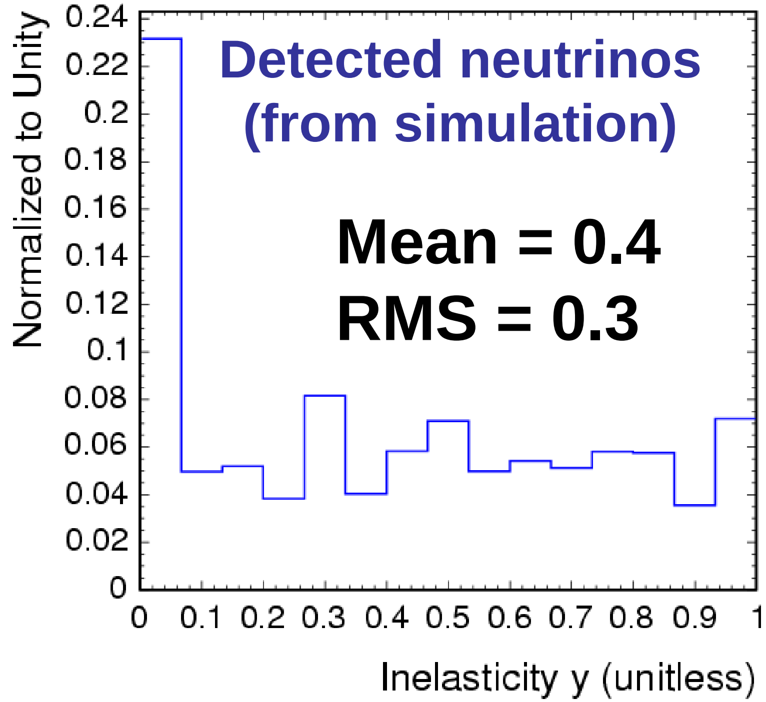


[S. Barwick]

Primary Limitation on Direct Energy Measurement: Inelasticity

- Only possible to observe shower energy
- Energy resolution ΔE strongly limited by width of inelasticity distribution: $y=E_{had}/E_{\nu}$





Contribution to Δ E due to inelasticity ¼ 100% E

Including other uncertainties, Δ E ~ 2-3 E

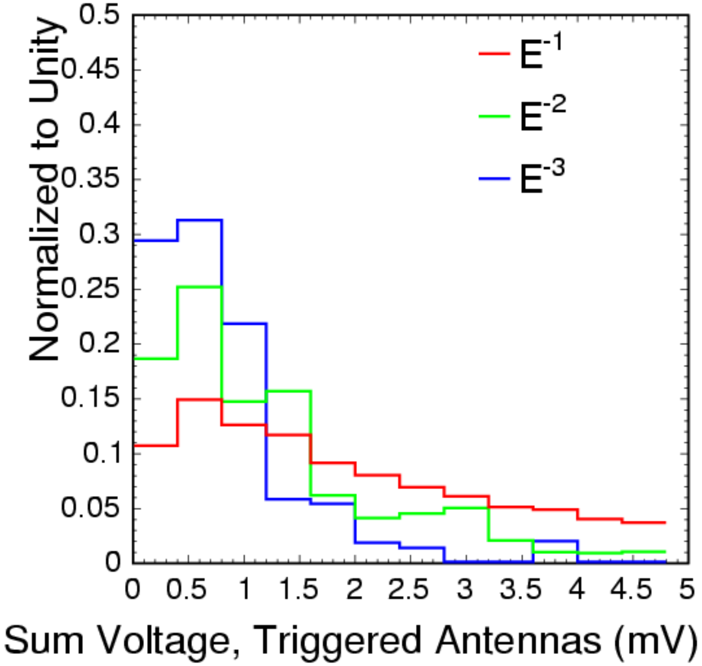
Likelihood Method

- Studying the feasibility of using likelihood method to distinguish between ν spectra
- Consider observables that correlate with the neutrino (really shower) energy
- Construct likelihoods $L(\alpha_i)$ for each distribution $E^{-\alpha}$
  - For each event, maximize $L(\alpha_i)$ to find most likely α_i
  - For an ANITA experiment with, say, 5 events observed, can we distinguish between E^{-1}, E^{-2}, E^{-3} etc.?

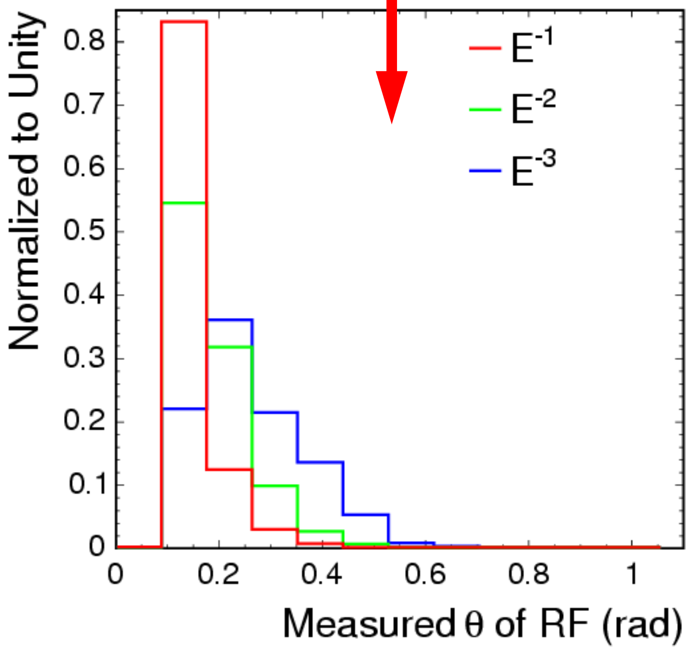
Requires independently measured variables

Three Independent Quantities

- Magnitude of measured signal
  - Measured voltage α shower energy



- Zenith angle of measured signal



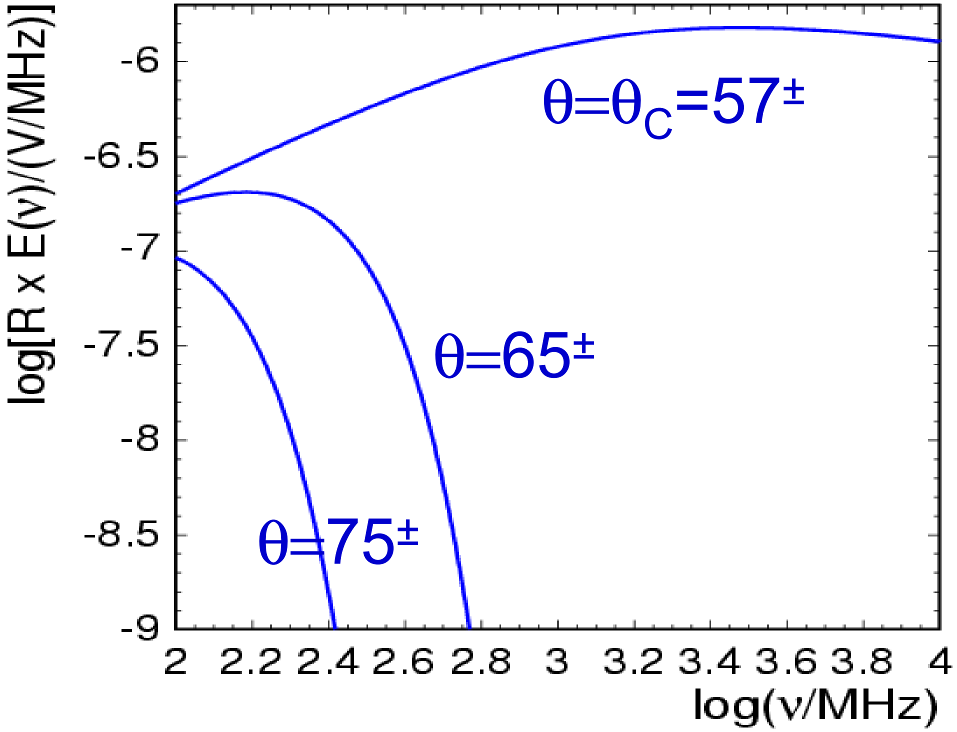
– Signals from higher energy showers can survive a longer trip through air

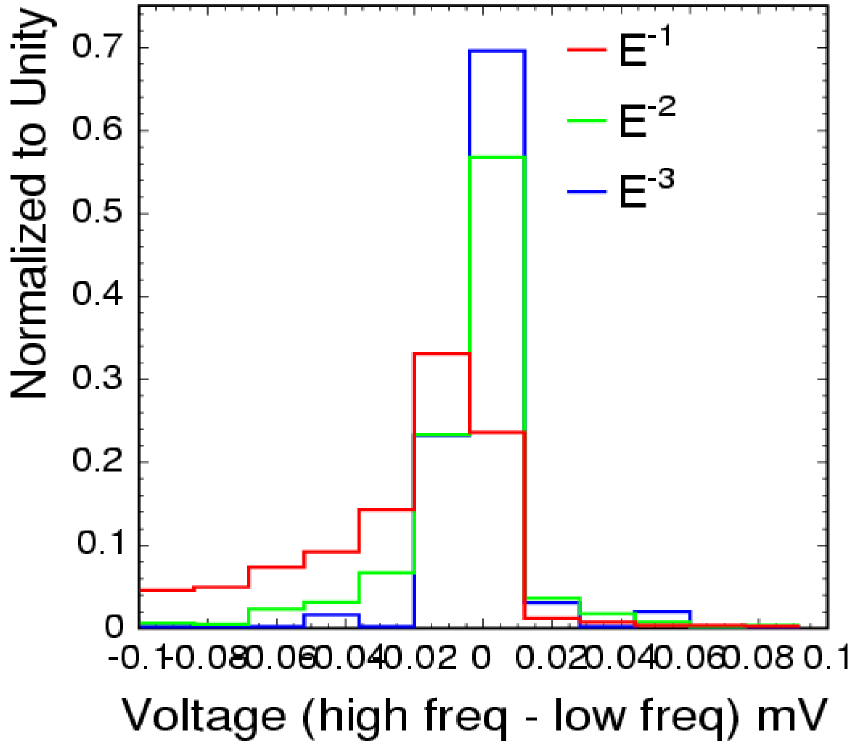
– Can originate from zenith angles closer to horizontal

– $\Delta\theta \sim 0.5^{\pm}$

Three Independent quantities (cont)

- Frequency dependence of measured signal
  - Higher frequencies ! narrower Cherenkov cone





–Signals from higher energy showers can be observed despite the dropoff at higher frequencies

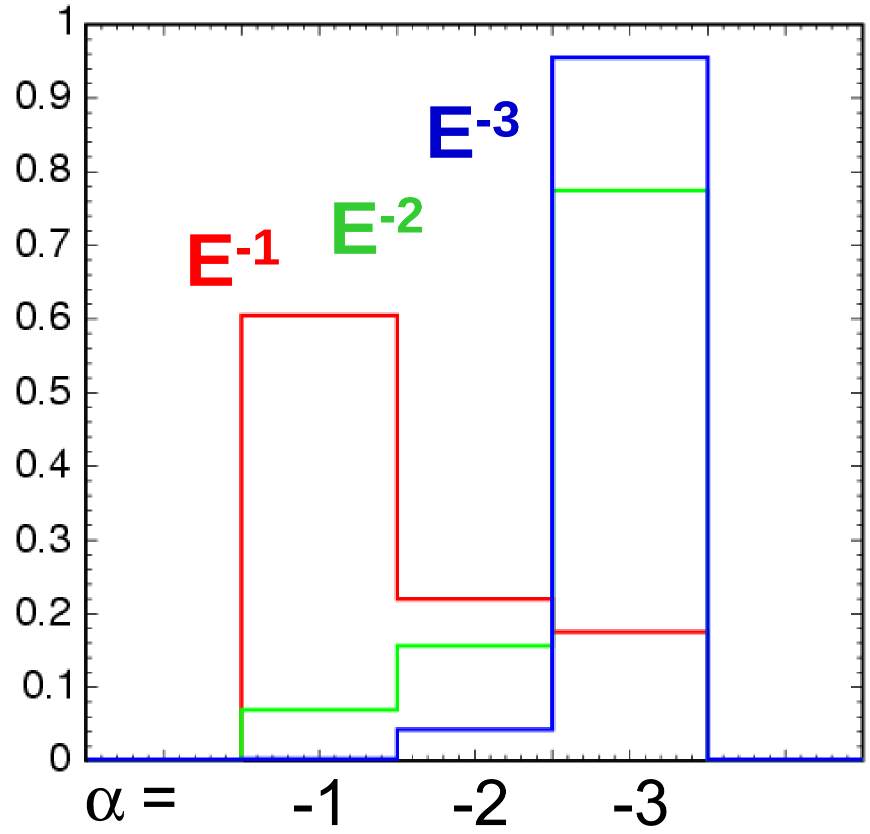
Likelihood

- For a given event, find most likely α by maximizing:

$$\prod_{j=1}^{3} \mathcal{L}_j(\alpha_i)$$

where j represents each independent variable

For a given input distribution:

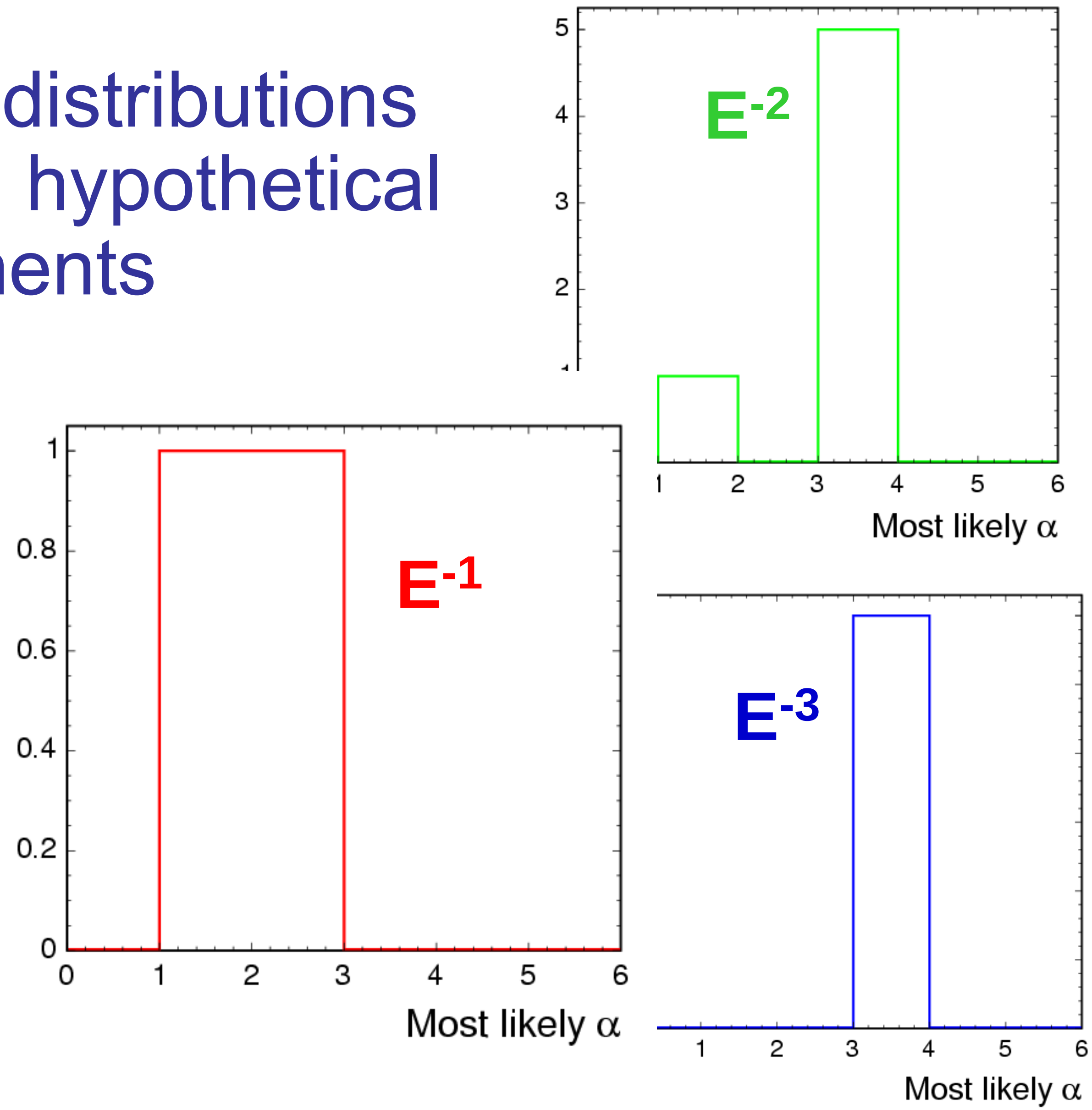


Distribution of most likely α's

E^{-1} input distribution clearly separated from E^{-2}, E^{-3}

Pseudoexperiments

- Examples of α distributions measured from hypothetical ANITA experiments
  - For 5 events expected
  - Showing one pseudoexperiment for each hypothetical true input distribution



ANITA Calibration at Stanford Linear Accelerator

- ANITA is going to SLAC for 2 weeks of beam time in End Station A during June 2006
  - **Full-up system calibration with actual Askaryan impulses from Ice**
  - **Uses one of SLAC's largest experiment halls (End Station A) 250'x200' w/ 50' crane**
  - **Build 1.6 x 1.6 x 5 m ice cube by stacking blocks, "zamboni" each surface before stacking, refrigerate**
- Will provide amplitude, phase, polarization, temporal, and spectral calibration of the antenna array, including all structure
- Excellent opportunity to calibrate the simulation, including aspects of energy resolution
- Payload will be shipped to Antarctica from CA after the SLAC test

Summary

- ANITA designed as a discovery experiment, not a precision experiment:
- ANITA's energy resolution by direct method $\sim\Delta E = 2\text{-}3\, E$
- From likelihood method, E^{-1} likely discernable from E^{-2}, E^{-3}
  - Could identify a diversion from a basic GZK neutrino spectrum
  - Related variables which may be more powerful are under investigation

Embedded detectors such as a proposed experiment in a salt formation (SalSA) will perform with improved energy resolution with the ability to reconstruct the cone.