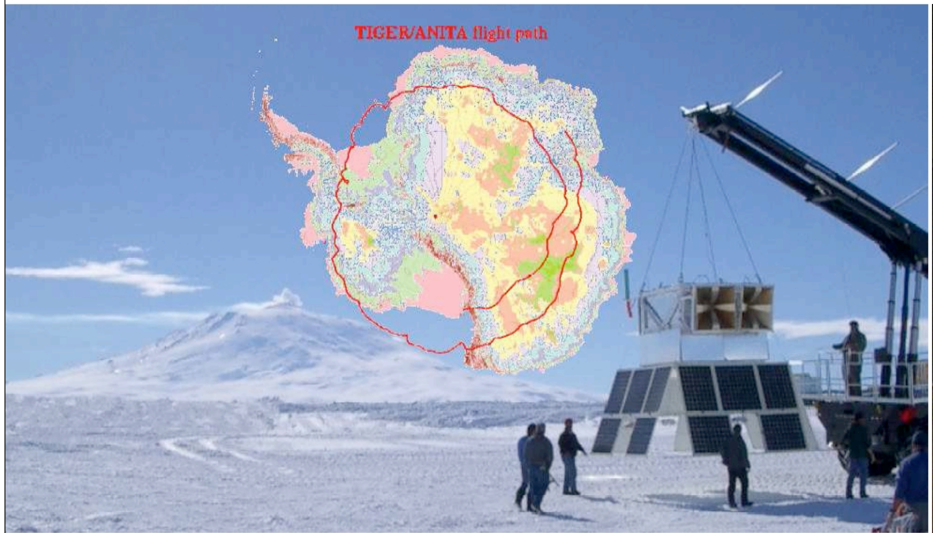
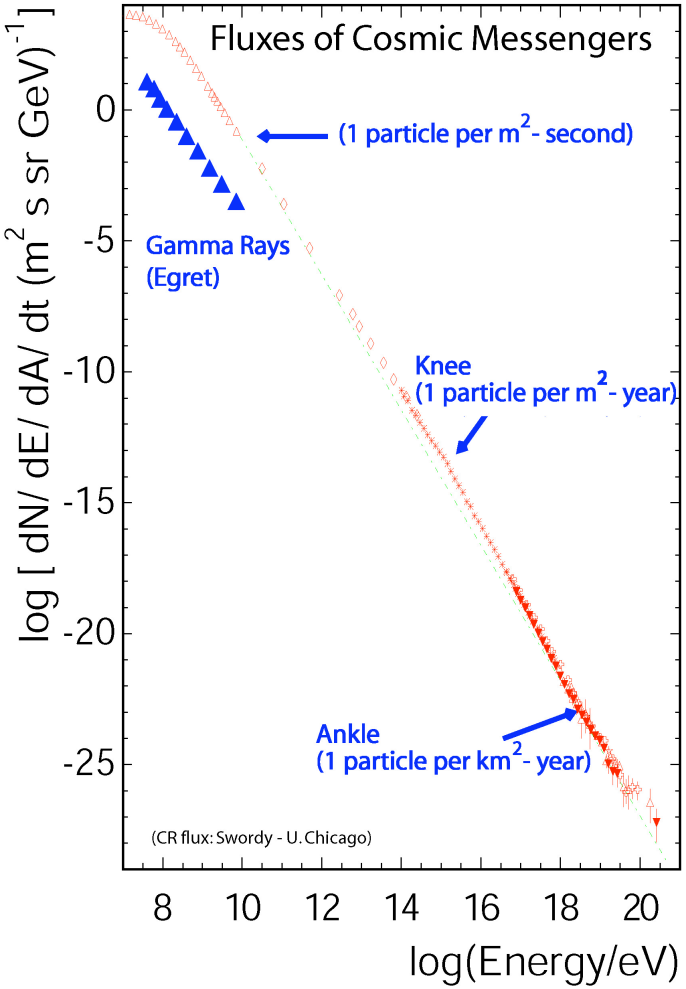
Closing in on Ultra-High Energy Cosmogenic Neutrinos with the Radio Detection Technique



Amy Connolly
University College London

Lancaster University
November 9th, 2007

A Multi-Messenger View of the Observed High Energy Universe



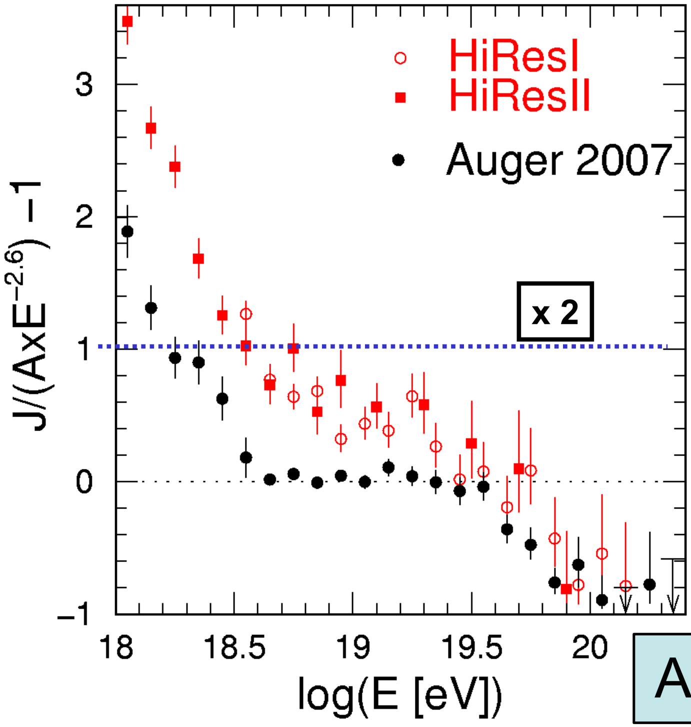
- (Charged) cosmic rays
  - Measured over 14 orders of magnitude
  - Redirected by magnetic fields -do not point back to their source
  - (Except at the highest energies)
- Cutoff expected above ~$10^{19.5}$ eV
- Gamma rays
  - Point back to their source
  - Attenuated by pair production with CMB above ~30 TeV $\gamma\gamma \rightarrow e+\ e-$

No diffuse cosmic neutrino spectrum observed

The Highest Energy Cosmic Rays

Highest energy CR's carry one Joule of energy

That's the kinetic energy of a fast pitch baseball



- Acceleration mechanisms are difficult to construct
- Most models assume they are accelerated while contained in a B field
- Some candidates:
  - Active Galactic Nucleii (AGN)
    - Black holes accreting mass
  - Blazars (Jets emitted in our direction by an AGN)
  - Gamma Ray Bursts
    - Most luminous events in the universe

Auger has correlated CR's with AGN's!

"Guaranteed" Source of Neutrinos

- Greisen-Zatsepin-Kuzmin (GZK): Cosmic rays $>10^{19.5}$ eV slowed by cosmic microwave background (CMB) photons within ~50 Mpc:

Earth to Virgo cluster = 18 Mpc
Observable universe = 14 Gpc

$$p + \gamma_{CMB} \rightarrow \Delta^* \rightarrow n + \pi^+$$

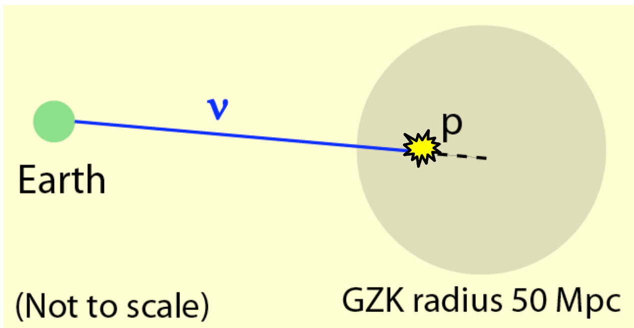
$$\hookrightarrow \mu^+ \nu_\mu$$

$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

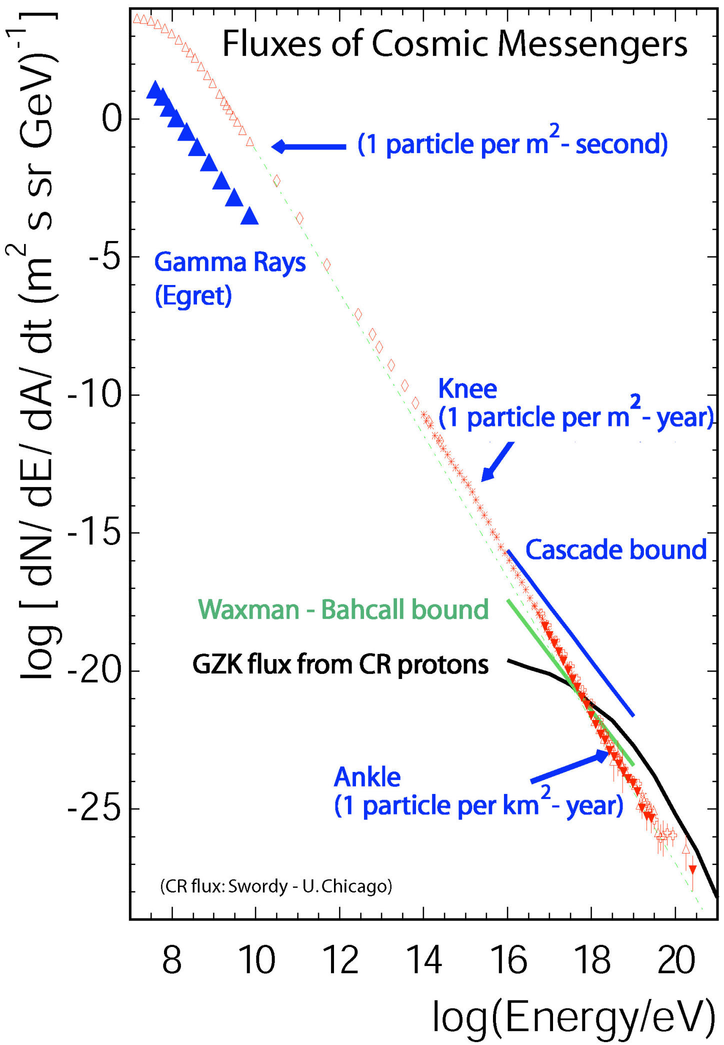
Neutrinos produced in the GZK process

$\delta\theta$ ~ 10 Mpc / 1000 Mpc ~ 30 arcminutes → Point back to the source!

Photohadronic interactions at the source would also produce neutrinos through π decay



How Neutrinos Will Fit in the Picture

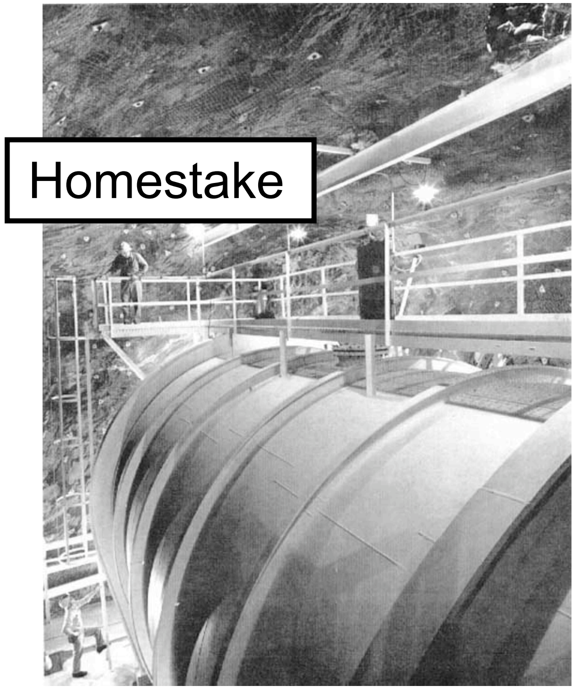


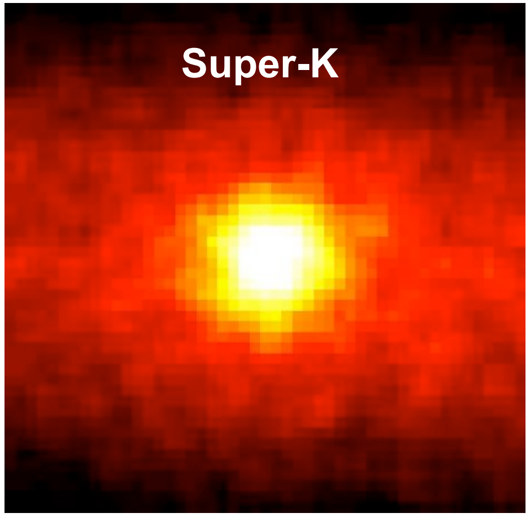
- Neutrinos should
  - Point back to their source
  - Travel cosmological distances unattenuated
  - Extend beyond CR cutoff
- Neutrino flux from astro sources bound from above
  - Cascade bound: "optically thick" sources
  - Waxman-Bahcall: "optically thin"
- Neutrino flux from the GZK process exceeds CR flux above ~10^{18} eV (UHE region)
  - Small interaction cross section →larger detector volume needed

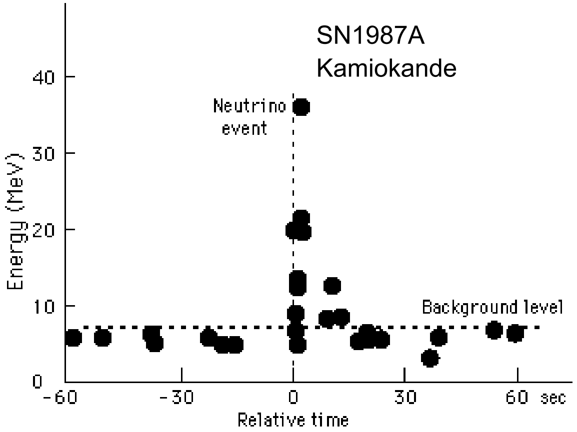
The only extraterrestrial neutrinos observed: The Sun and SN1987a

Each source has: 1. Had a important impact on particle physics

2. Looked deeper into the source than otherwise possible







Weak eigenstates ≠ mass eigenstates

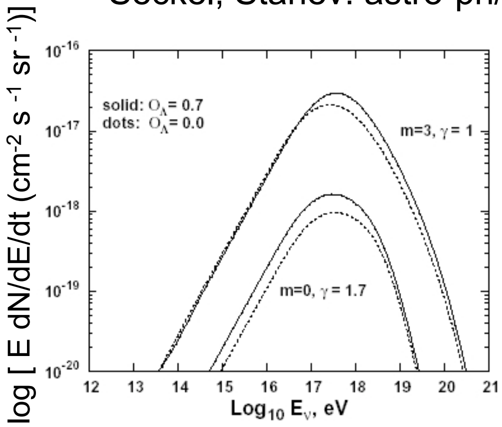
→ neutrinos have mass

Lack of dispersion

→ mass limits

What Messages Will UHE Neutrinos Carry

Seckel, Stanev: astro-ph/0502244



Source distribution, spectrum

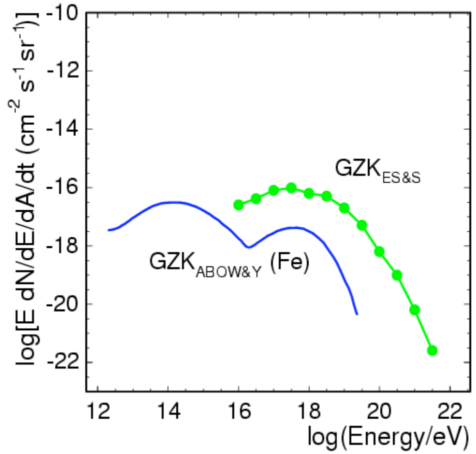
γ (CMB)

GZK process

p, Fe

Universe expansion
Λ (subtle)

Cosmic ray composition



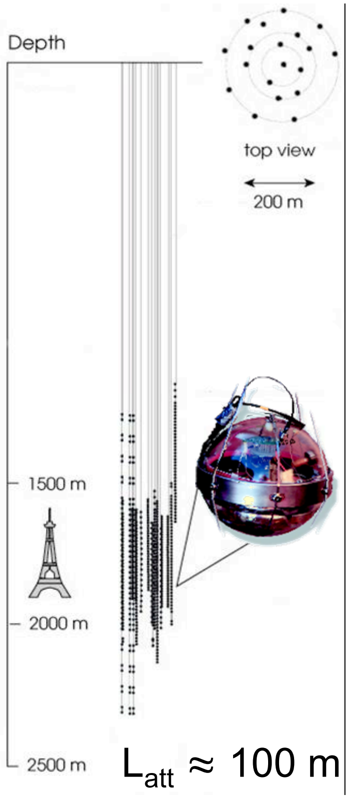
ν

Point back to the source

Center of mass energies > LHC !

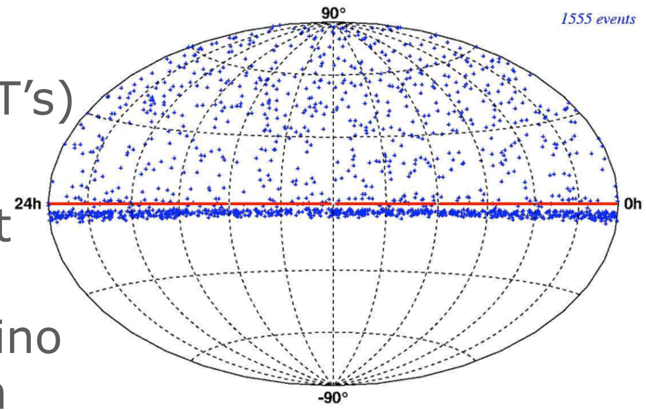
Physics potential of UHE neutrinos spans particle physics and astrophysics

Amanda II / IceCube



ν telescope at the South Pole

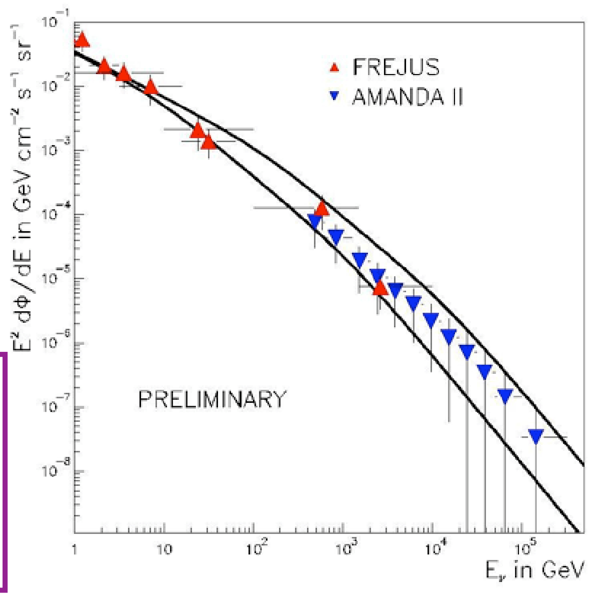
- Photomultiplier tubes (PMT's) deployed along strings
- Detect blue Cerenkov light from particle tracks in showers induced by neutrino interactions in ice medium



AMANDA II: 19 strings 1500-2000 m (1997 – present)
IceCube: 80 strings 1500-2500 m (first strings are operational)

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

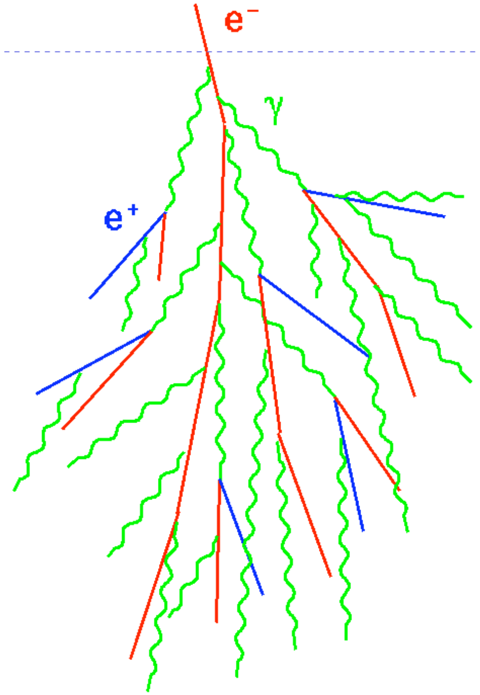
At most, we see 1/2 the sky

→ 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)

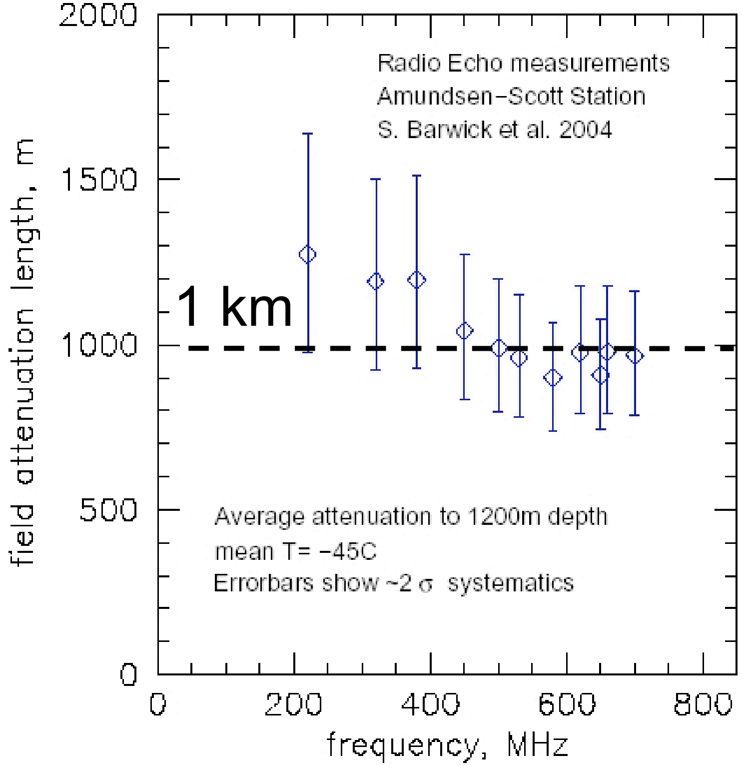
- Coherent Cerenkov signal from net "current," instead of from individual tracks
- A ~20% charge asymmetry develops:
  - Compton scattering: γ + e-(at rest) → γ + e-
  - Positron annihilation: e+ + e-(at rest) → γ + γ
- Excess moving with v > c/n in matter
- → Cherenkov Radiation $dP \propto \nu\, d\nu$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



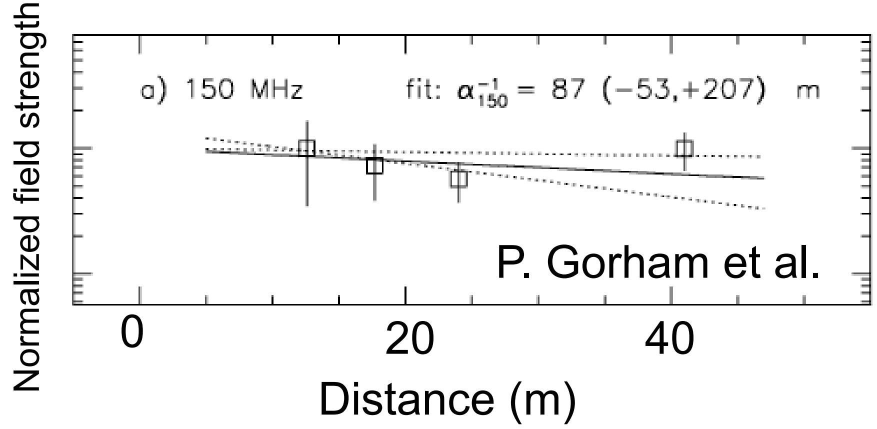
This effect was confirmed experimentally at SLAC in 2002

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

Long Attenuation Lengths in Radio / Microwave in Ice, Salt, Sand



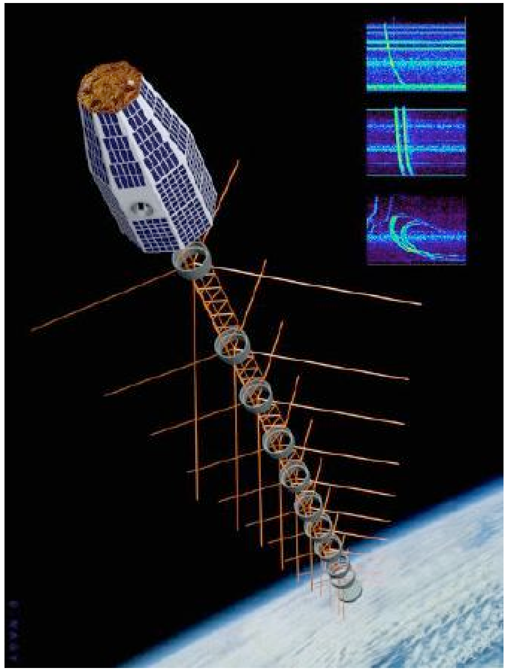
South Pole Ice



Hockley Salt Mine
near Houston, TX

Pioneering Radio Cerenkov Experiments

FORTE



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

GLUE

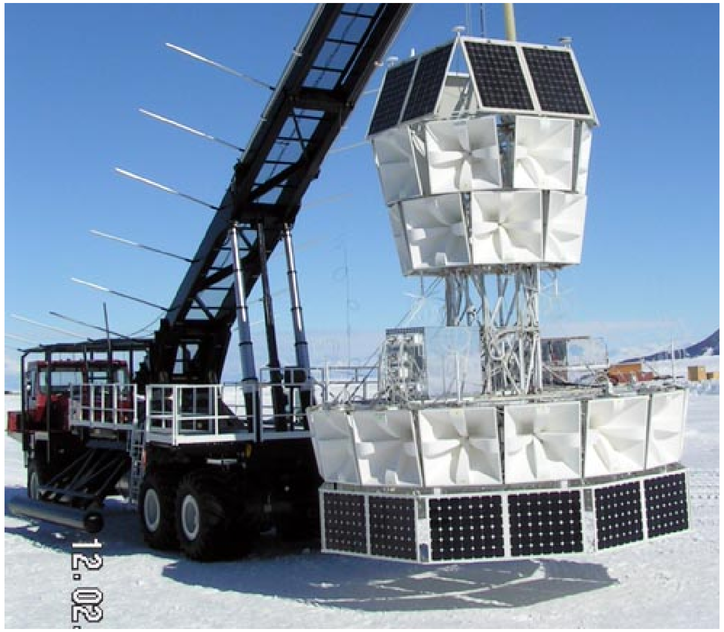
GLUE/Goldstone 99:
In Lunar regolith
~2 GHz
$A=6.10^5\ km^2.sr$

RICE

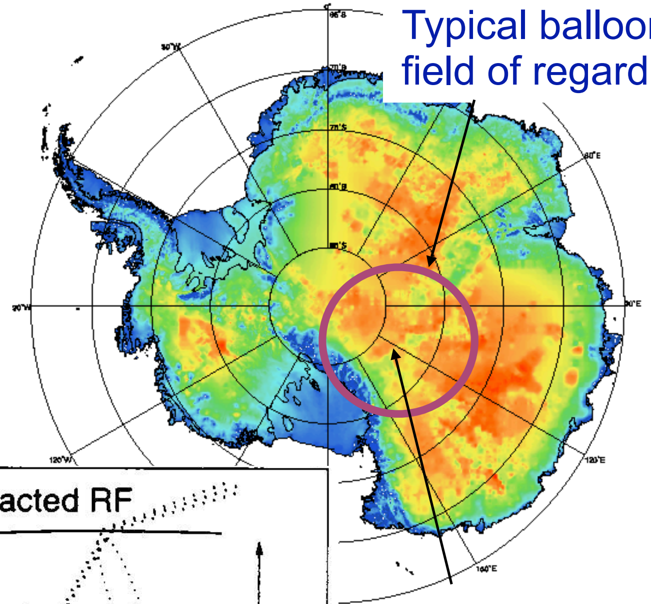
RICE 1999-present
Antennas on
AMANDA strings
100-1000 MHz dipoles
$V\sim10\ km^3.\ sr$
Data up to 2005
published

ANITA

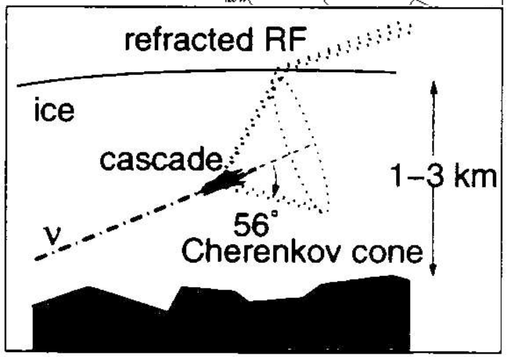
(ANtarctic Impulsive Transient Antenna)



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



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



~4km deep ice!

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

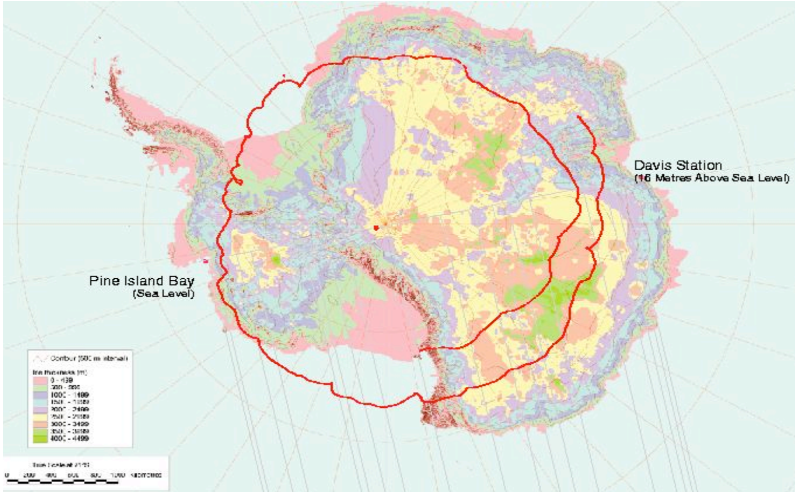
Ohio State University
Columbus, Ohio

Stanford Linear Accelerator Center
Pasadena, California

Washington University in St. Louis
St. Louis, Kansas

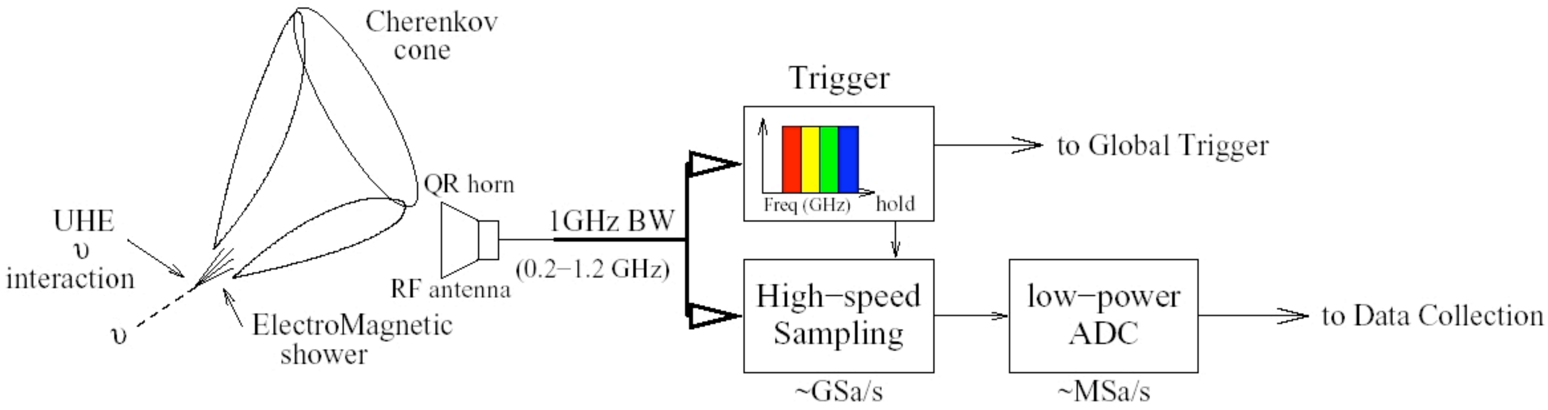
ANITA-lite 2003-2004

- Practice run with 2 antennas – piggybacked on TIGER
- 18 day flight
- Virtually every subsystem planned for ANITA tested
- Calibration pulses sent to payload from ~200 km away



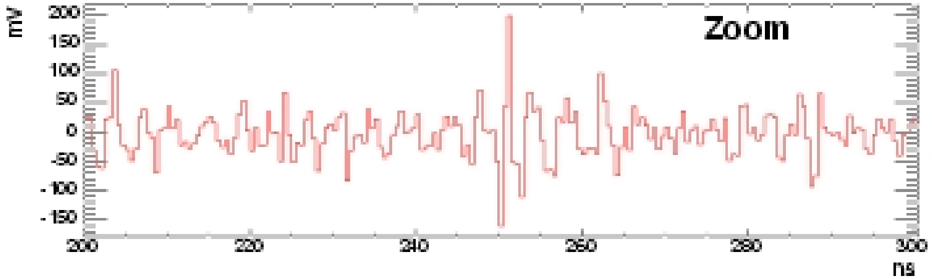
- Payload landed near Mawson Station
- Australians helped us retrieve the payload

ANITA Signal Acquisition



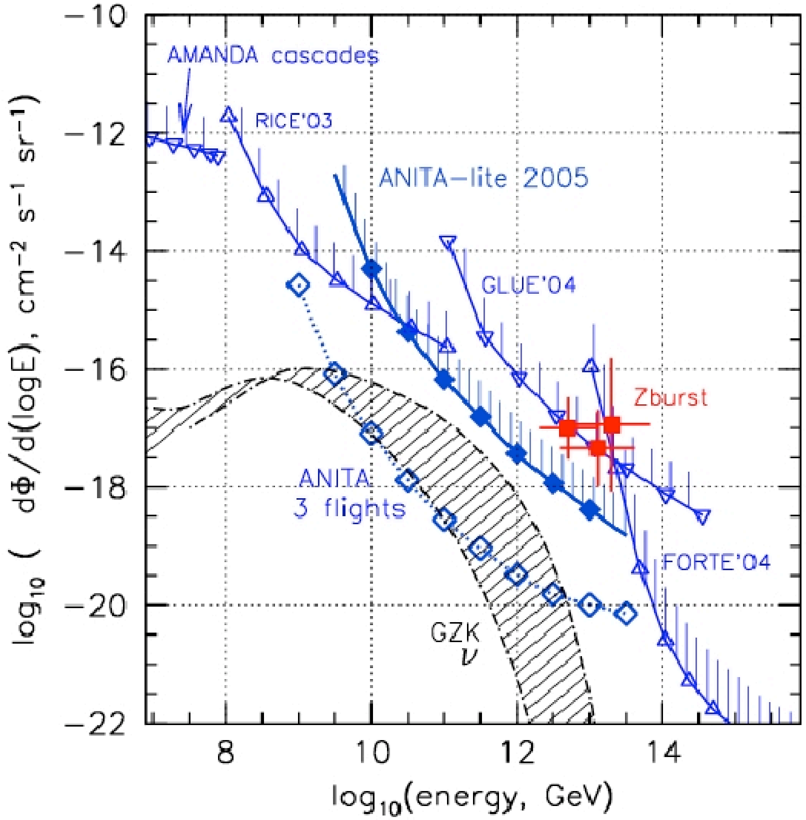
- Trigger: Signal divided into frequency sub bands (channels)
  - Powerful rejection against narrow bandwidth backgrounds
  - Multi-band coincidence allows better noise rejection
- 8 channels/ antenna
- Require 3/8 channels fire for antenna to pass L1 trigger
- Global trigger analyzes information across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

Anita-lite



- 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



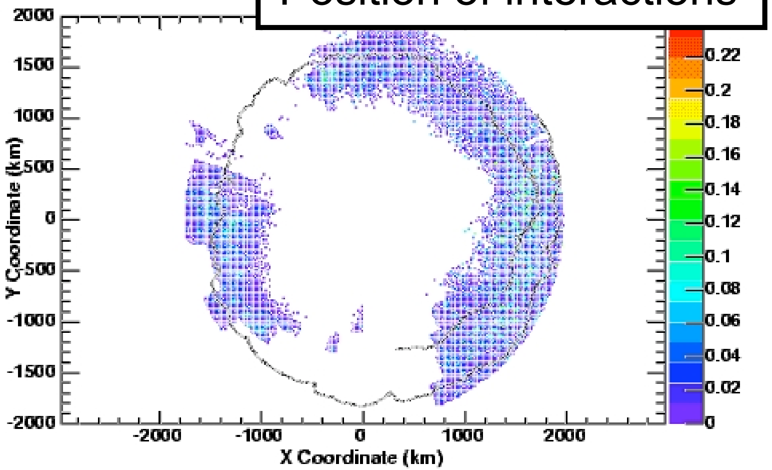
ES&S baseline (min)
Kalashev, *et al.*, saturate all bounds (max)

ANITA Simulation

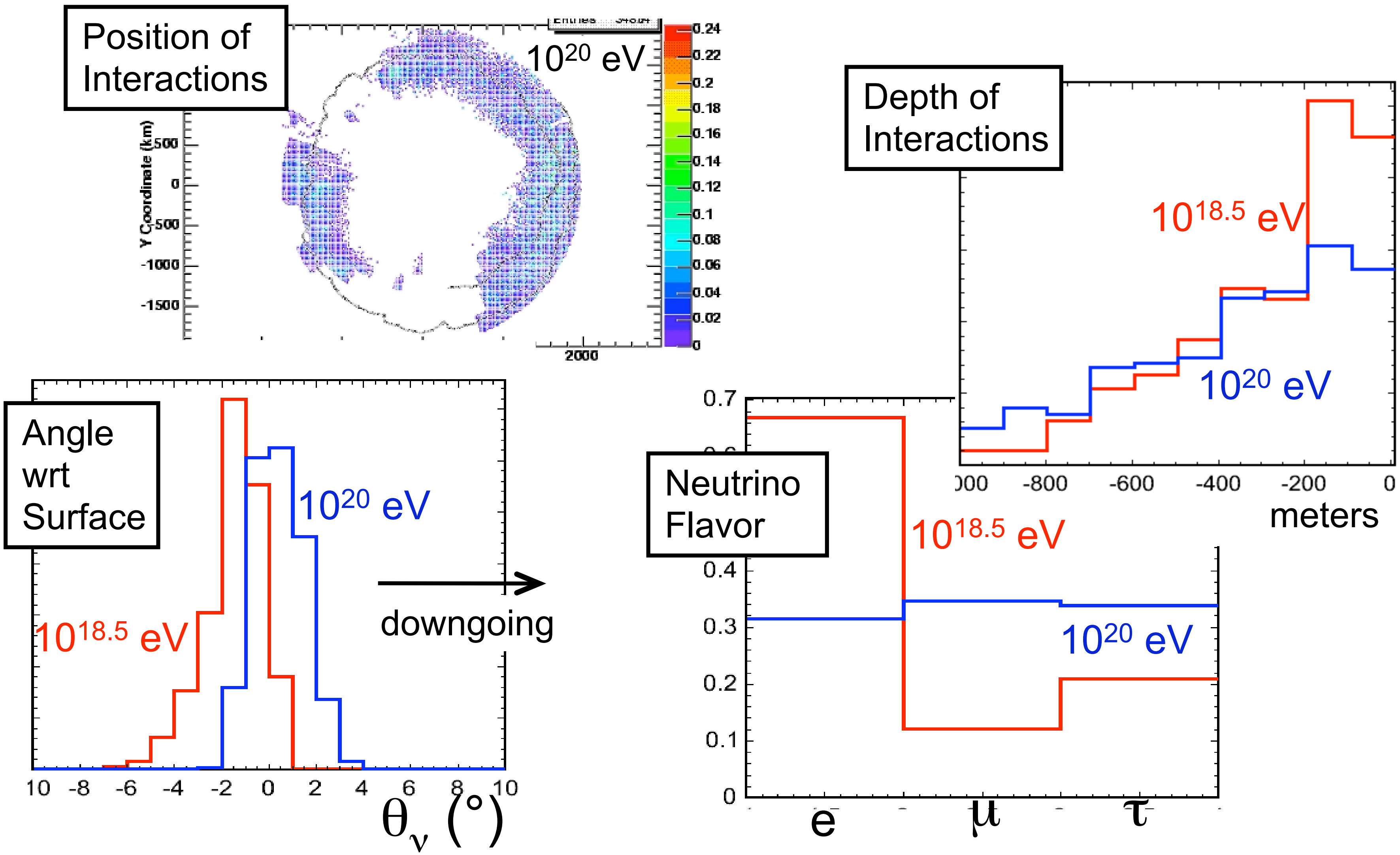
- Two complementary simulations: Hawaii (Gorham) and UCL (Connolly)
- Mainland program used by many institutions
- Flexible enough to
  - Guide design, operation decisions
  - Test new ideas
  - Spawn simulations of other experiments
- Ray tracing through ice, firn (packed snow near surface)
- Include surface slope and adding surface roughness
- All 32 quad ridged horn antennas arranged in 3 layers as they are on the payload
- Signal in frequency domain, but moving to time domain
- Models 3-level trigger system

- Choice of neutrino spectra
- Weighting accounts for neutrino attenuation through Earth
- Map of ice depths/crust densities from geological data
- Secondary interactions included
- Fresnel coefficients
- Measured antenna response
- Actual payload flight path

Position of interactions

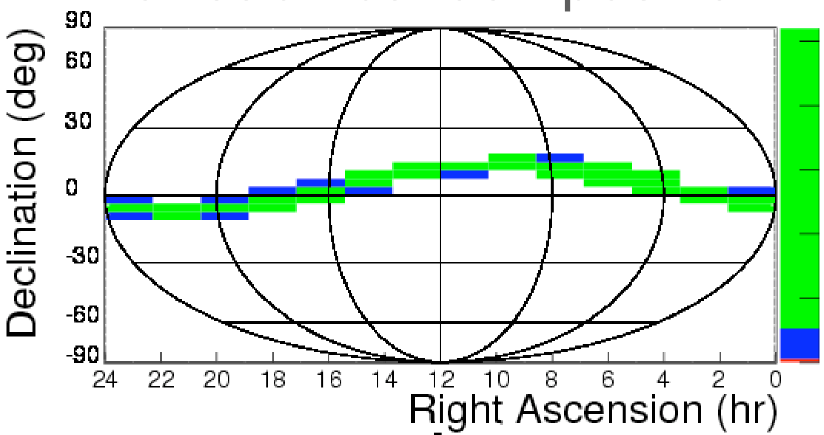


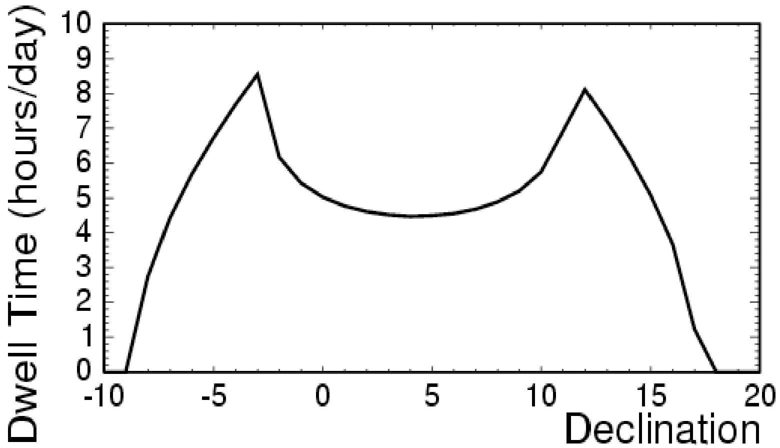
Characterizing ANITA's Sensitivity



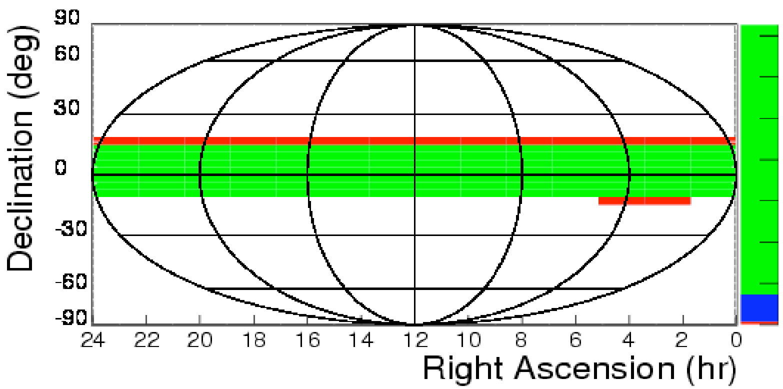
Skymaps

For each balloon position:





After a complete trip around the continent, cover all Right Ascensions

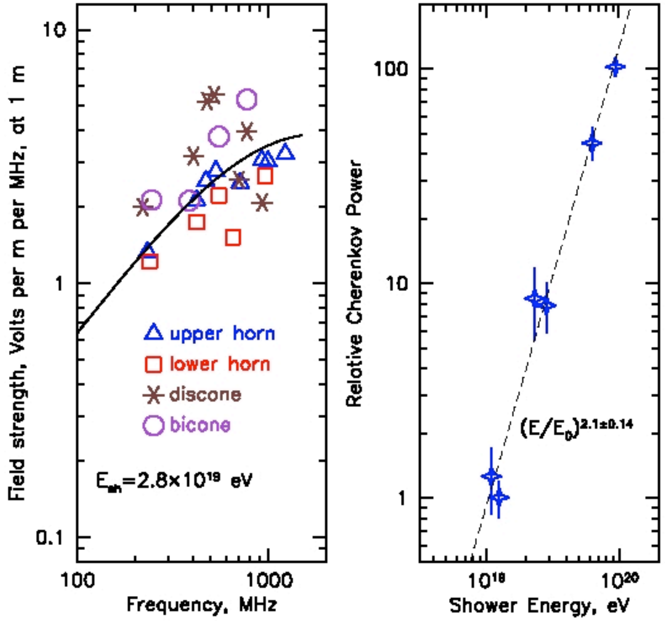


ANITA Calibration at SLAC: June 2006

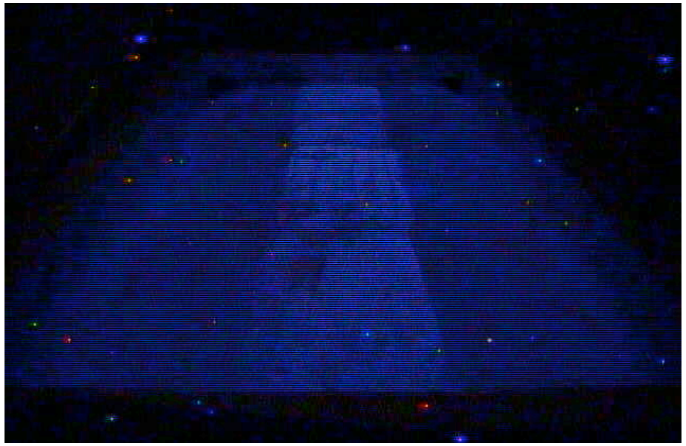
Produced Askaryan pulses in ice from a 28.5 GeV electron beam at SLAC

~10^9 particles per bunch

→ 10^{19}- 10^{20} eV showers

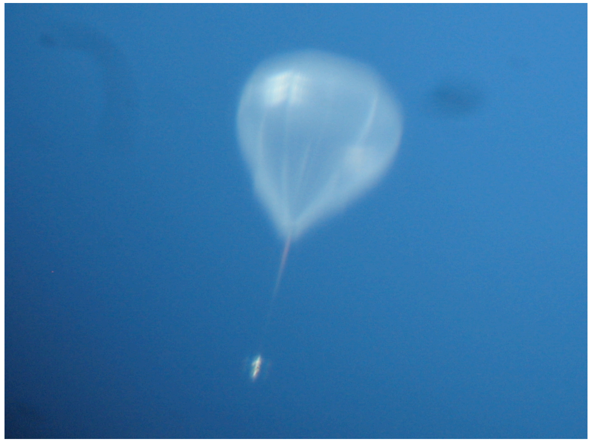


From there, off to Antarctica …



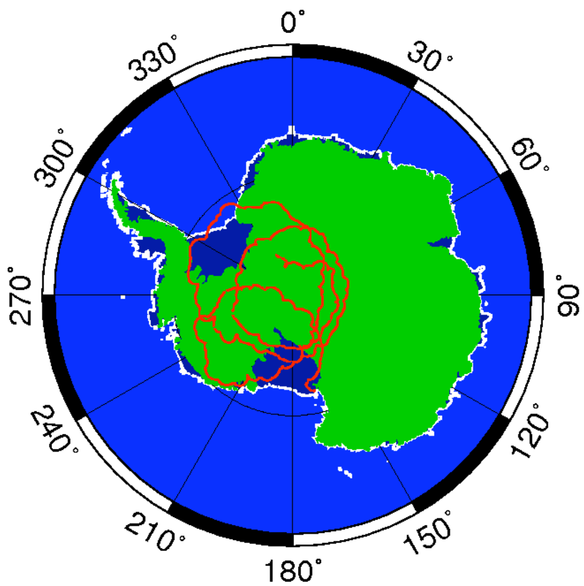
ANITA Flight

- ANITA launched on Dec. 15th
- Took 3 ½ 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



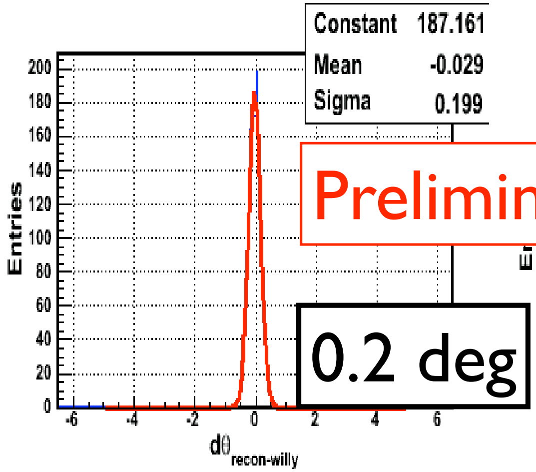
View of ANITA from the South Pole

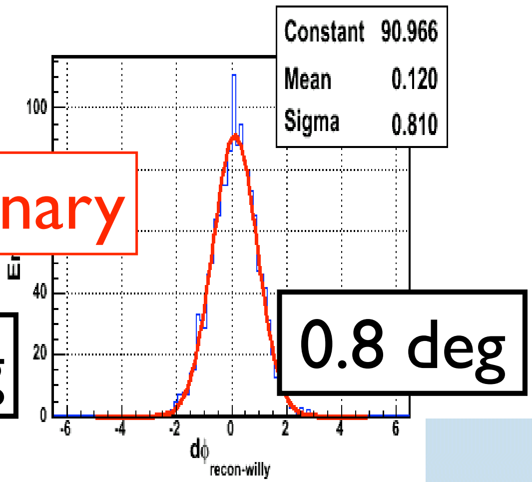
Picture taken by James Roth



ANITA Event Reconstruction

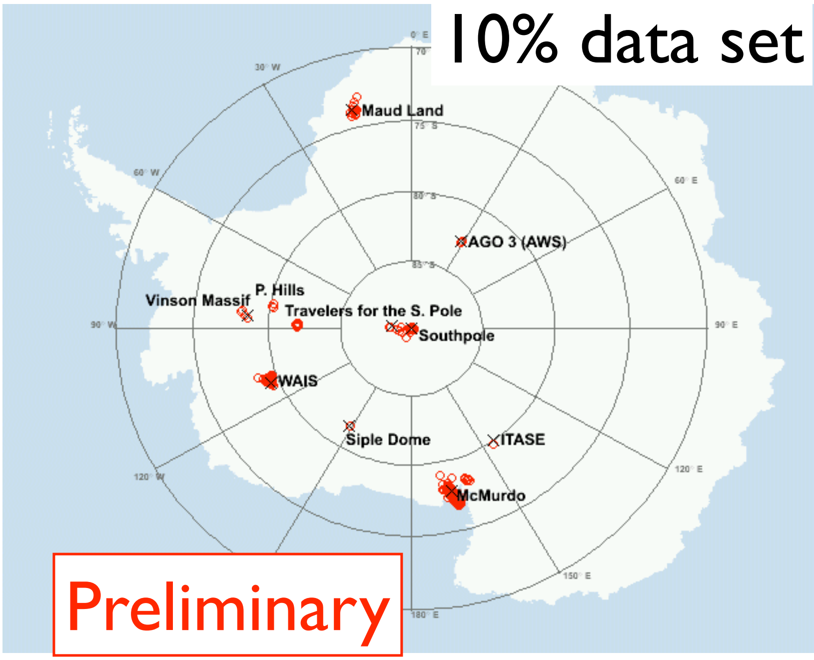
Data (Borehole)





up-down left-right

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



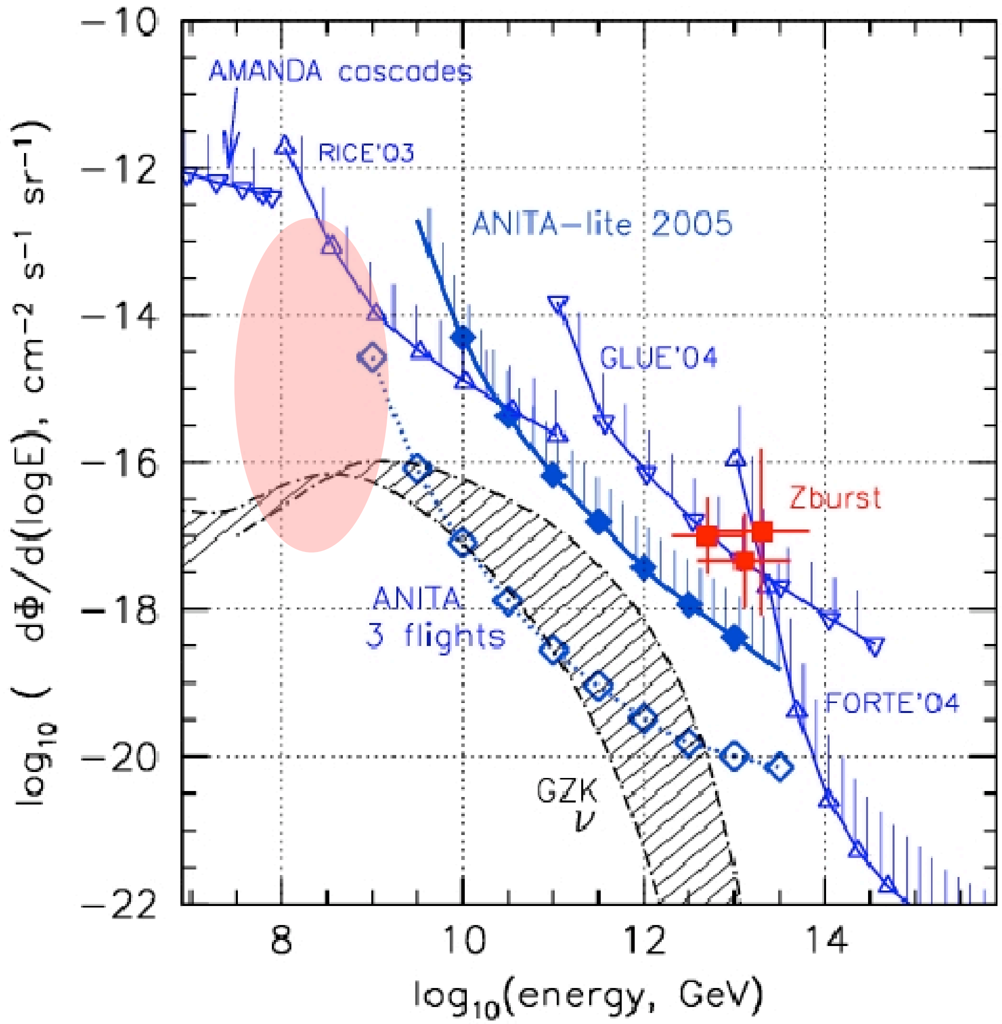
- Preliminary analysis with 10% data set
- V>3sigma
- Establish angular reconstruction, select good events
- Time profile, FFT consistent with expectation
- All associated with camps, travelers, automatic weather stations

Have not looked at remaining 90%

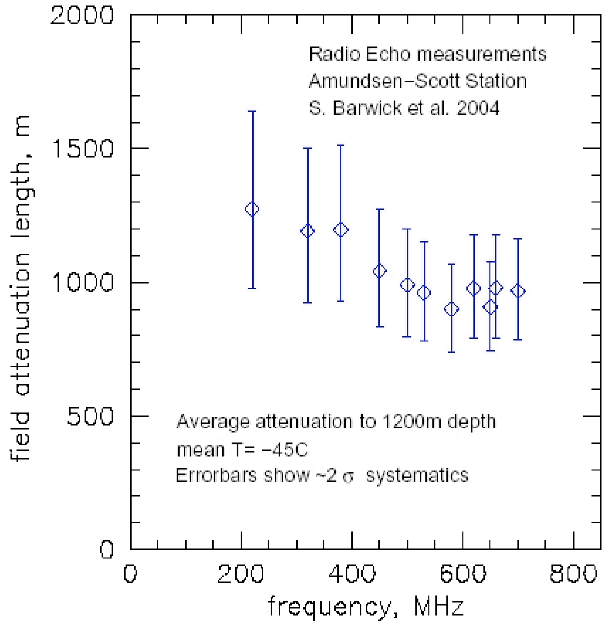
ANITA II approved - flight 2008-2009

Embedded Radio Detectors Designed to Target Energy Gap

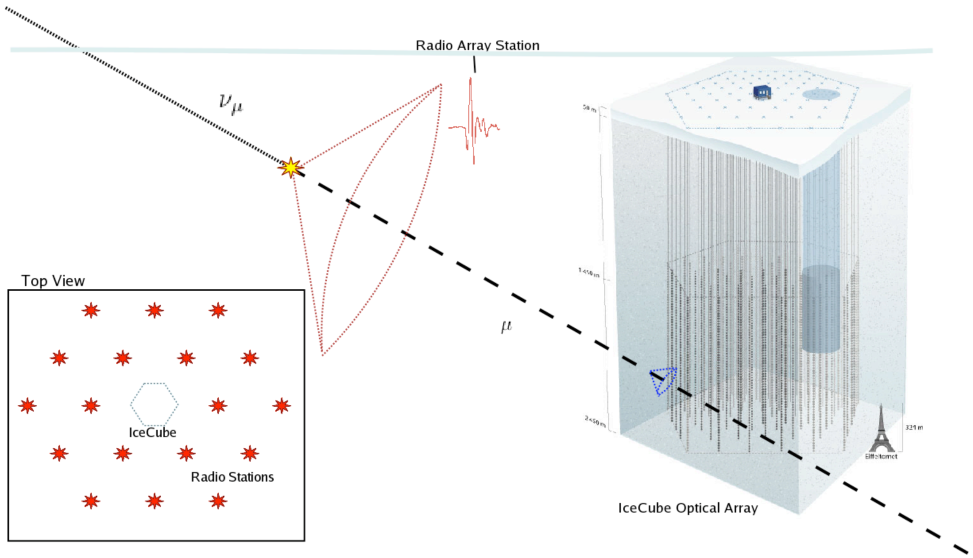
- Detectors embedded in the interaction medium have lower threshold
- Variety of embedded radio detector projects being studied or planned
- Antarctic ice and salt



South Pole Askaryan Array



- Attenuation lengths in South Pole ice measured at ~1 km
- A radio array at the South Pole could have a larger spacing than optical detector->Larger volume



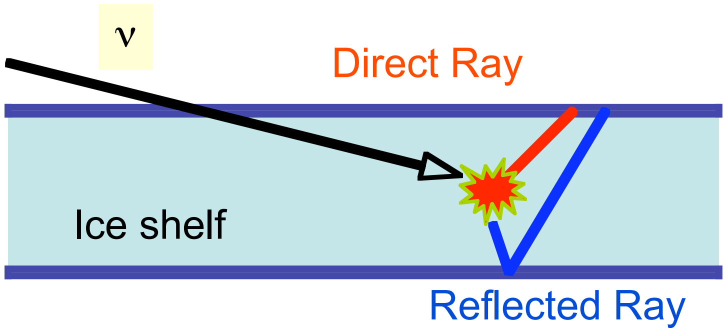
Antennas could be placed

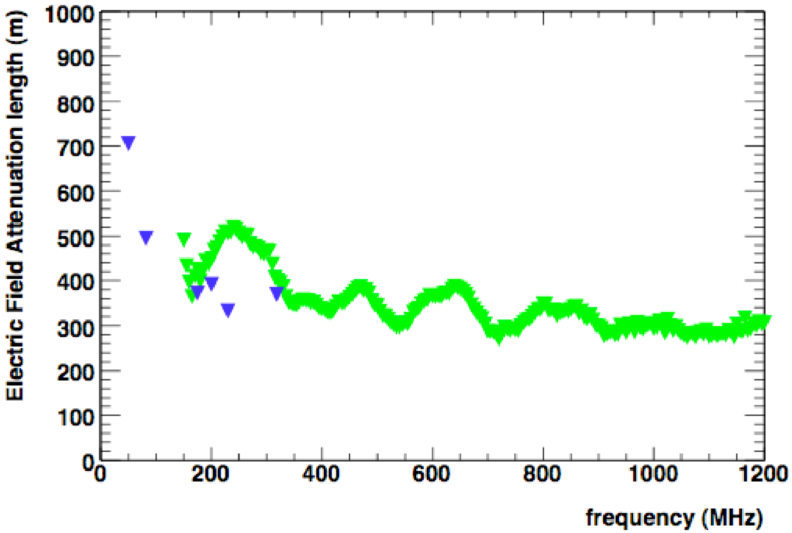
- On existing IceCube strings
- On surface
- On strings in dedicated radio boreholes

An event could be measured in both radio and optical

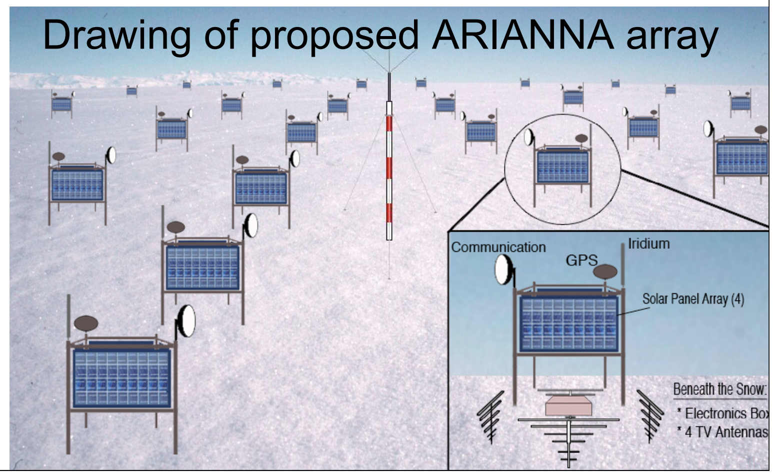
Ross Ice Shelf Array (ARIANNA)

An array could also be deployed on the Ross Ice Shelf



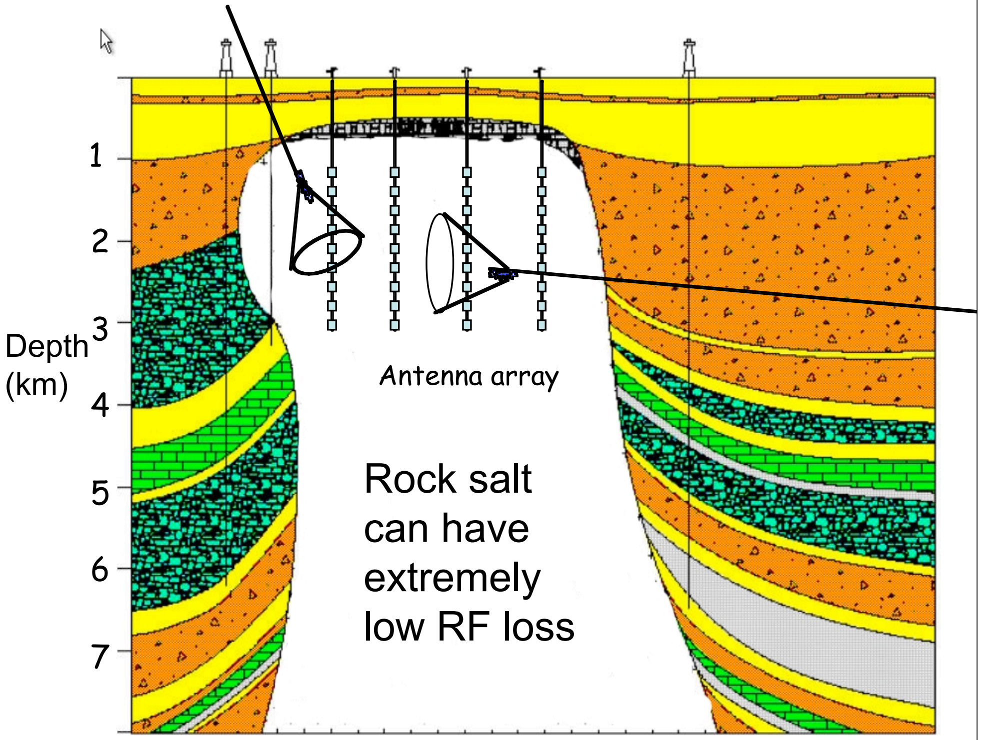


- Highly reflective surface at interface with seawater
- Could observe reflections -> more solid angle

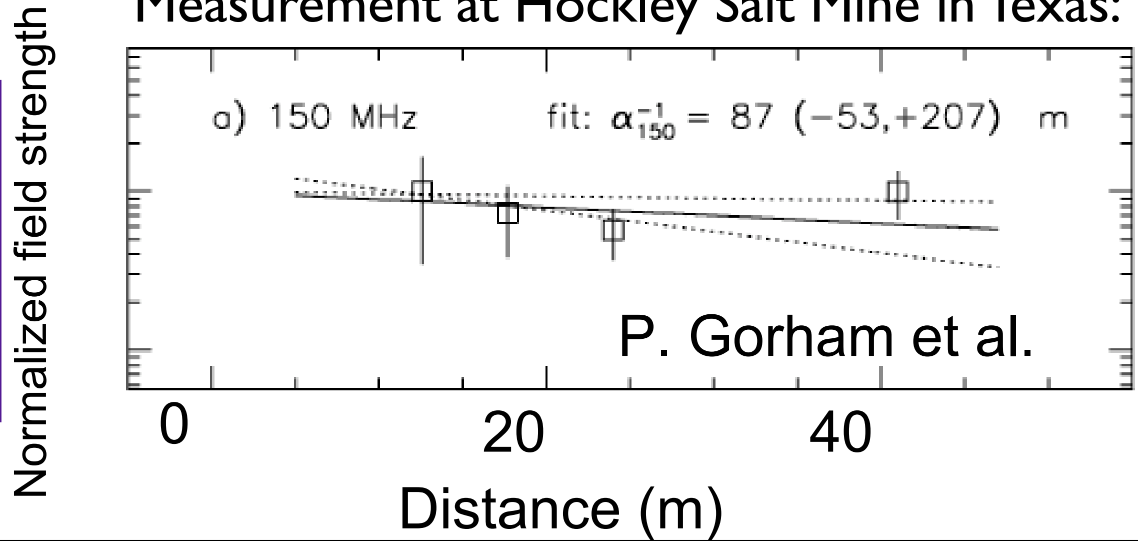


SalSA

- 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



Measurement at Hockley Salt Mine in Texas:



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

SALSA Collaboration

University of Delaware

University of Hawaii

University of Minnesota

U.C.L.A.

S.L.A.C. and Stanford University

Louisiana State University

Washington University

University of Kansas

UC Berkeley and LBNL

University of Utah

Endeavour Corporation

Deutsches Elektronen Synchrotron (Germany)

UT Austin

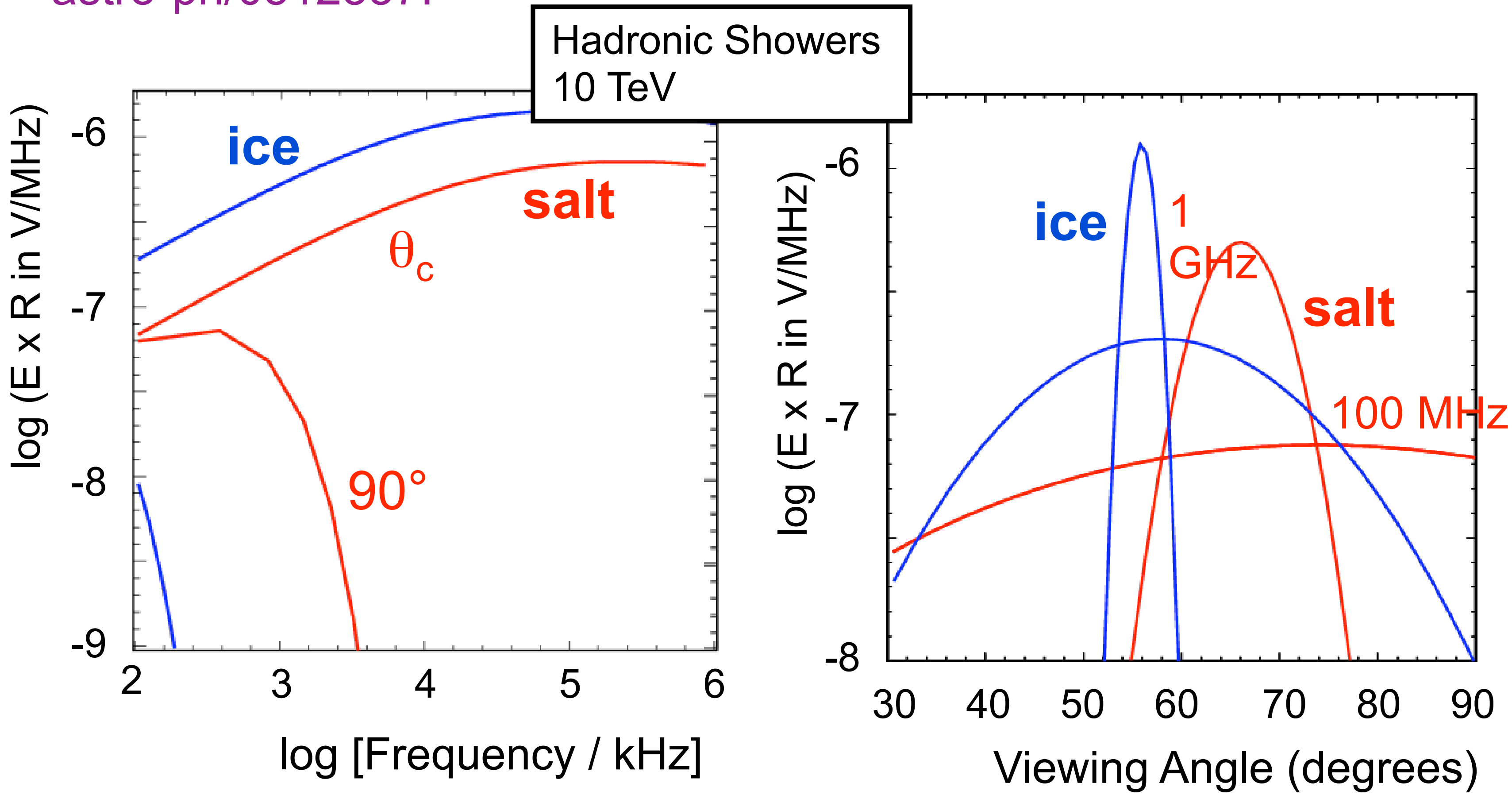
Kernfysisch Versneller Instituut (Netherlands)

Ohio State Univesity

UC Irvine

Comparing Askaryan Signal in Ice and Salt

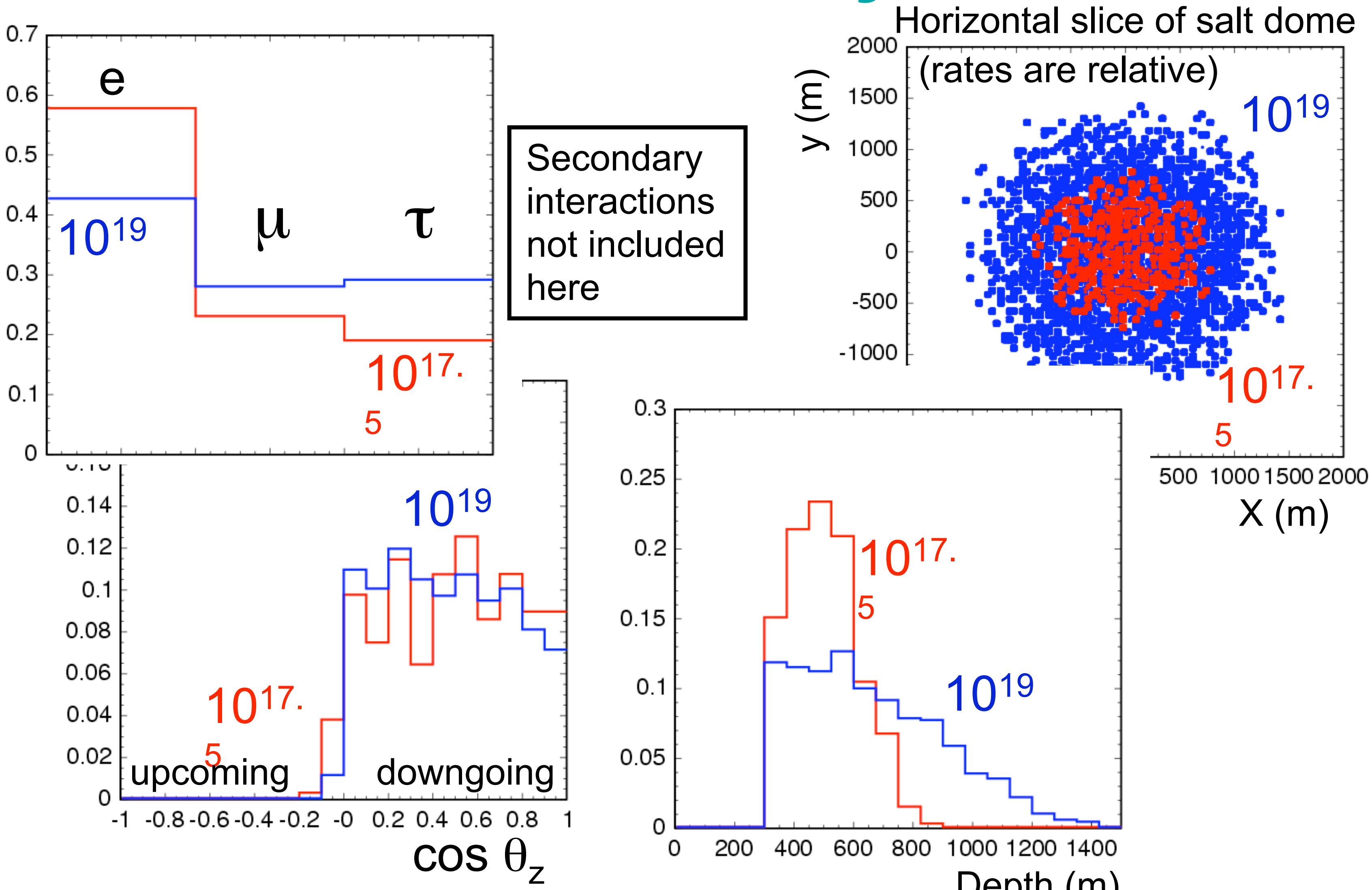
Parameterization in the simulation from J. Alvarez-Muniz astro-ph/0512337:



Electric field α shower energy

Electromagnetic showers narrow beyond ~ 10 PeV due to LPM effect

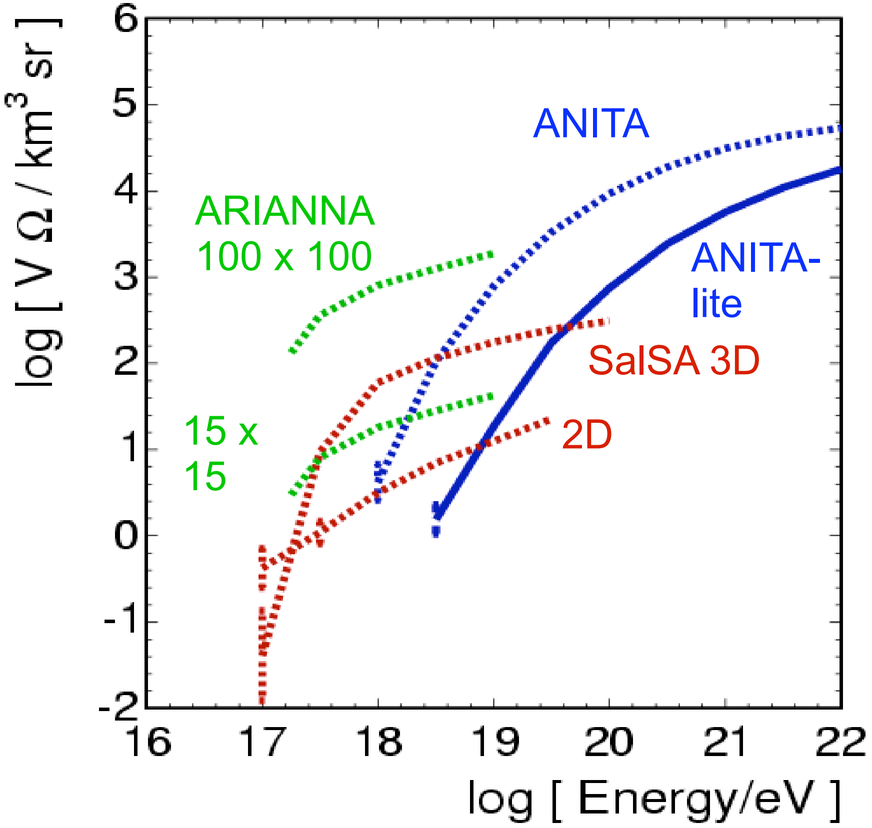
Characterizing Sensitivity of Planar Array



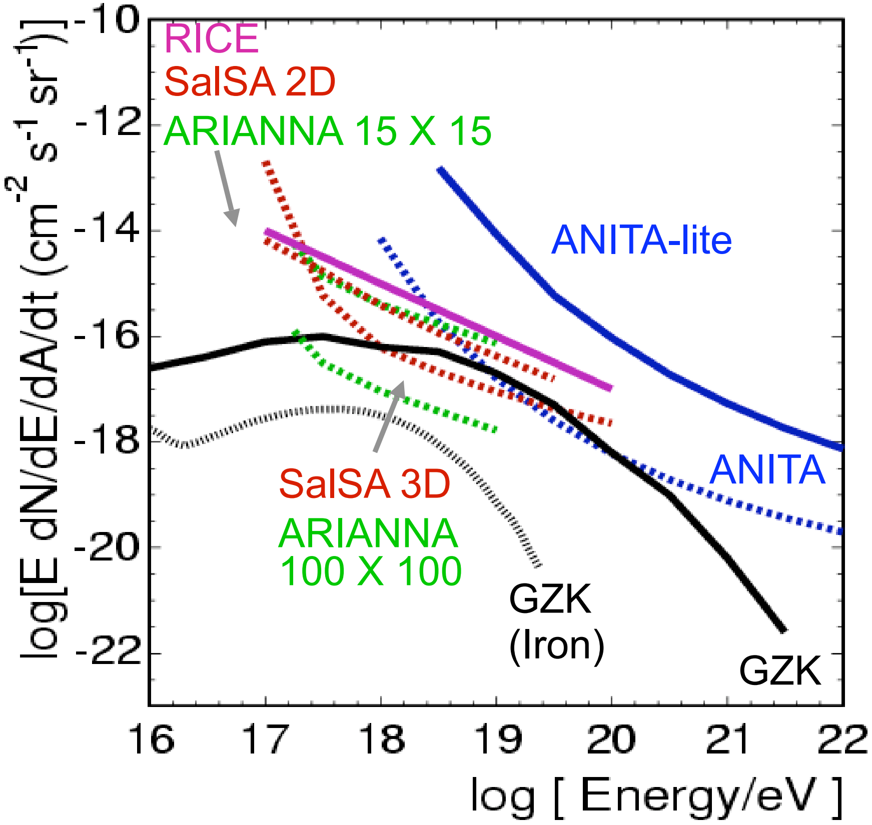
Secondary interactions not included here

Comparing Sensitivities

Effective Volume x Steradian



Flux Limits

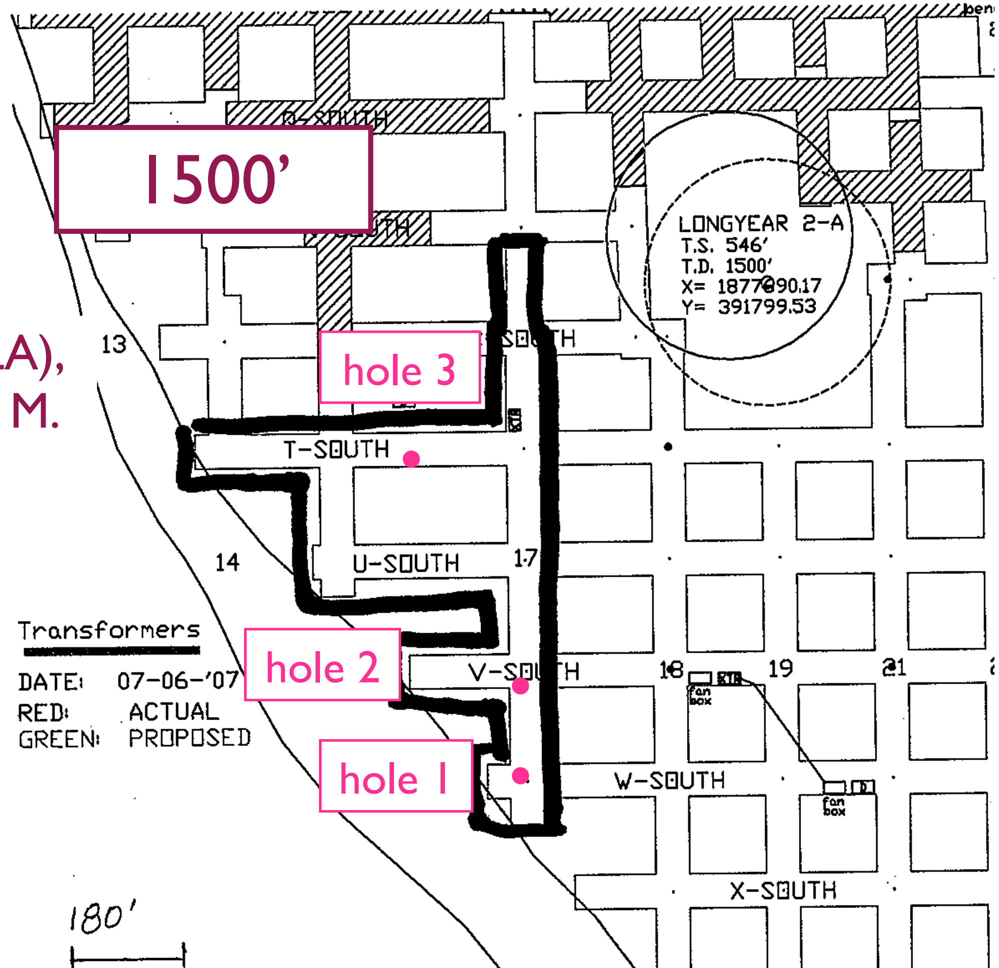


ANITA: 2 events expected (pre-flight) from reasonable proton GZK model
ARIANNA: 25 events / 6 months (100 x 100), 0.6 events / 6 months (15 x 15)
SalSA: 10-20 events / year (3D), 0.6 events / year (2D)

SalSA: Attn. Length Measurements

- We have been visiting the Cote Blanche salt mine in Louisiana to confirm the low transmission observed by GPR experts

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

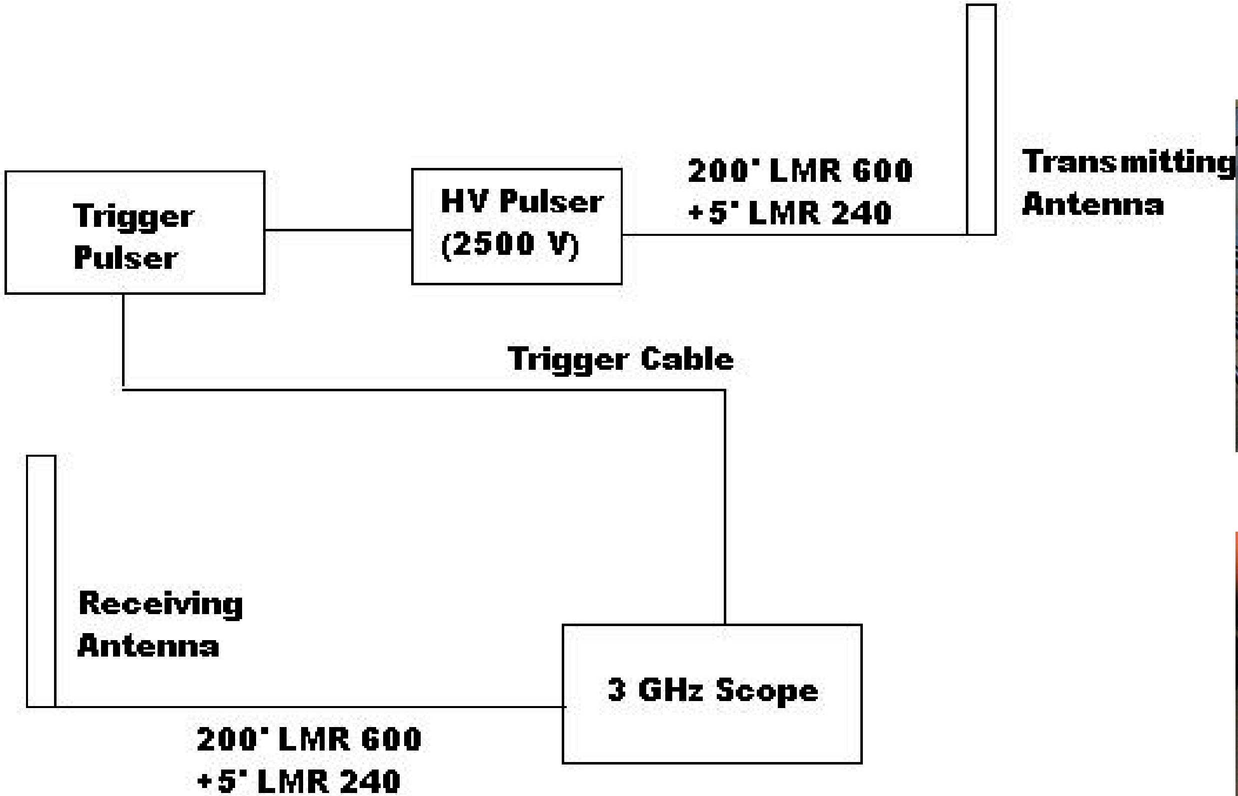


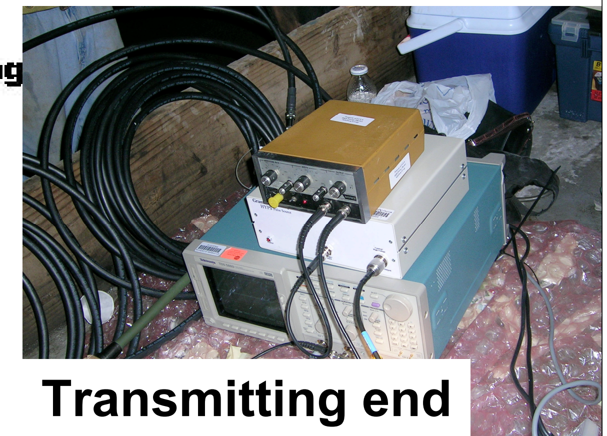
3 holes - maximum distance 553 ft.
depths 100-200 ft.

System Diagram for Transmission

High voltage (2500V), fast (100 ps) pulser

Long transmission and broad bandwidth



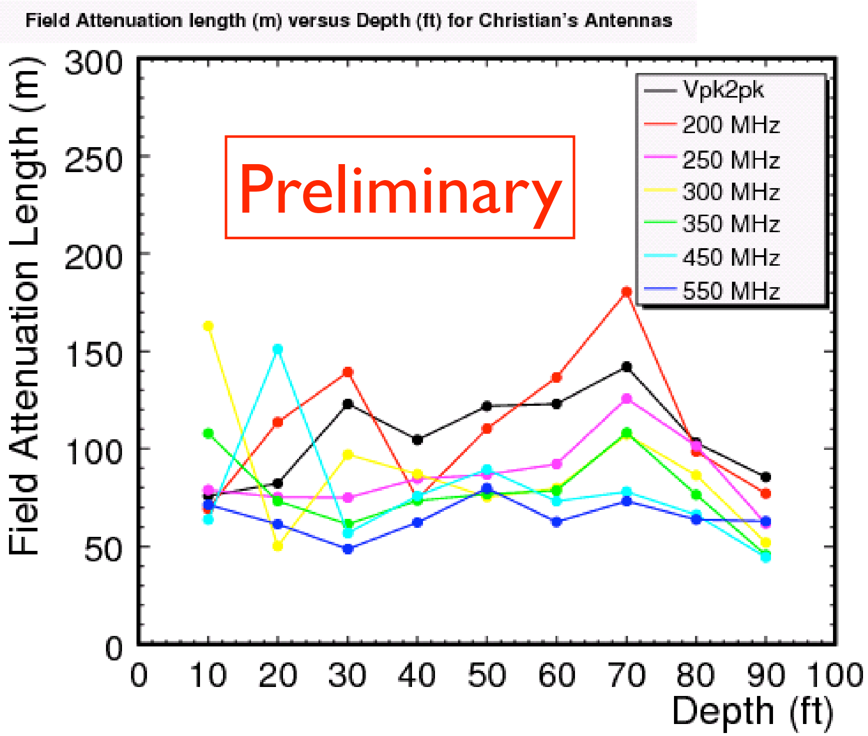


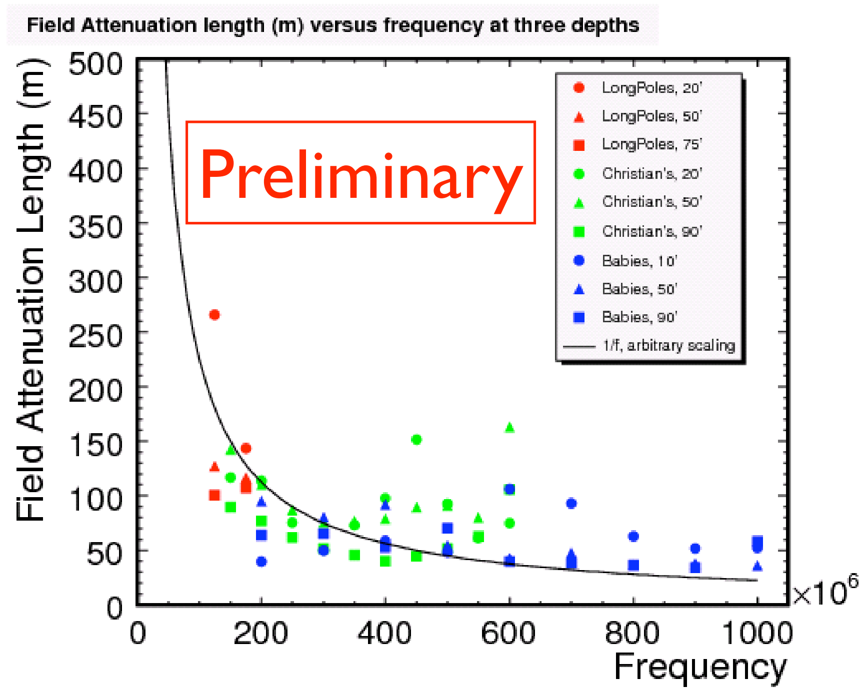
Transmitting end

Receiving end

Variety of dipole antennas 100-850

Attenuation Length vs. Depth and Frequency





- Frequency Bins are 50 MHz wide
- Cut all waveforms to the same time window to isolate the directly transmitted pulse (37 ns wide for Christian's Antennas, 12 ns for the baby antennas, and 38 ns wide for the longpoles)

- 1/f frequency dependence for attenuation length is expected if there is a constant loss tangent.

Work in progress - Observed reflections with paths up to 750 ft.

Is this troubling news for SalSA?

- These results are difficult to reconcile with GPR measurements
- If long attenuation lengths are confirmed in deep salt, SalSA:
  - Can operate all year round
  - Mines more accessible than Antarctic Ice Shelf, no weather difficulties
  - View northern sky

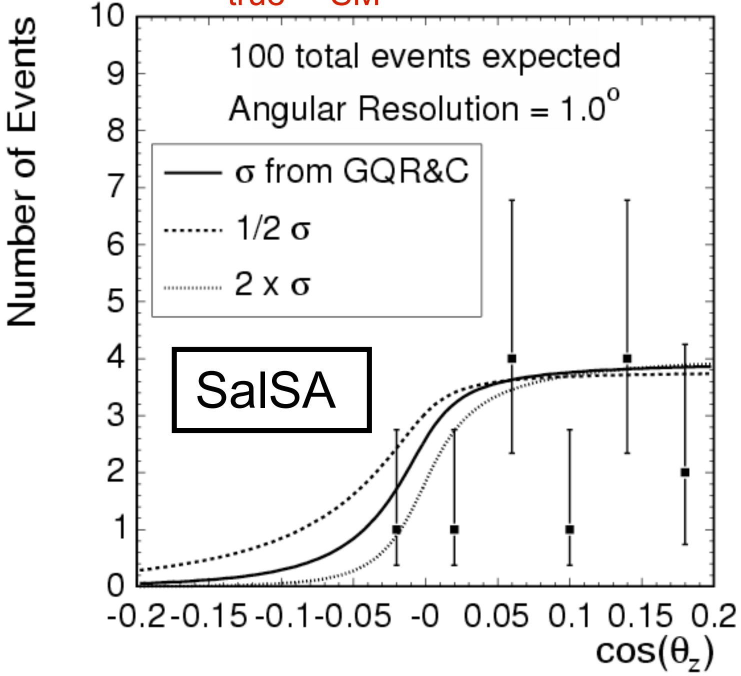
We are making steady progress in characterizing mine salt
Mine management and miners at Cote Blanche are very supportive of our efforts

Embedded Detectors Can Measure ν-N

- COM of UHE ν interactions exceed LHC energies
- SM predictions of ν-N cross section σ at high energies rely on measurements of quark, anti-quark number densities at low x
  - Beyond 10^{17} eV, calculations rely on $x<\sim10^{-5}$ (Ralston, McKay, Frichter, astro-ph/9606007)
  - HERA measures x down to 10-4-10-5
  - See growth in number density with decreasing x -> rise in predicted $\sigma \sim E_{\nu}^{0.35}$ (Ghandi et al.)
- Deviations from SM σ may indicate
- Low σ: leveling off of number densities at x below 10^{-5} (Ralston, McKay, Frichter)
- High σ: exotic physics (e.g., extra-dimensions, Muniz et al. hep-ph/0202081)

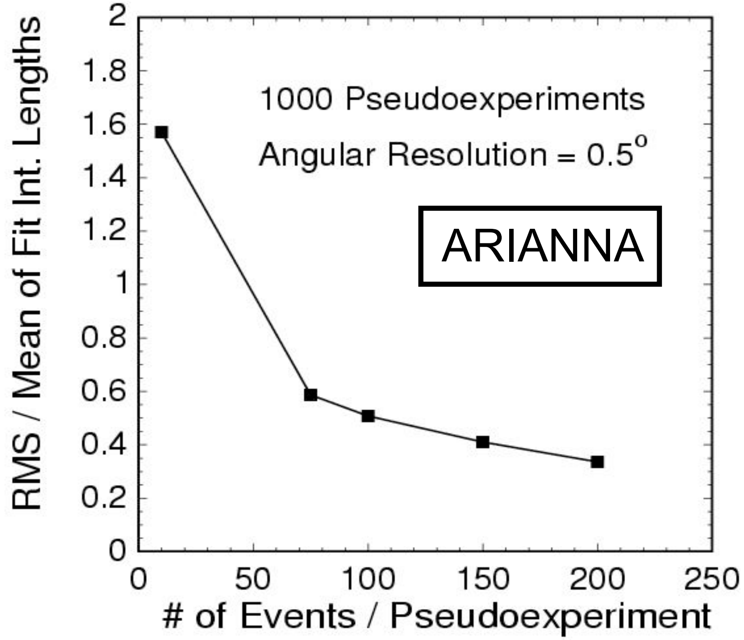
Cross Section Measurement

- ν N cross section can be measured from cos θ_z distribution
- Model cos(θ_z) dependence with analytical expression f(θ_z, A)
  - A = $\sigma_{true}/\sigma_{SM}$



At SM σ, only 10% of events in sensitive region

- f(θ_z,A) takes measured energy spectrum from simulation
- Consider many pseudo-experiments
- Fit to find A for each



Theoretical uncertainties at these energies ~factor of 10

Summary

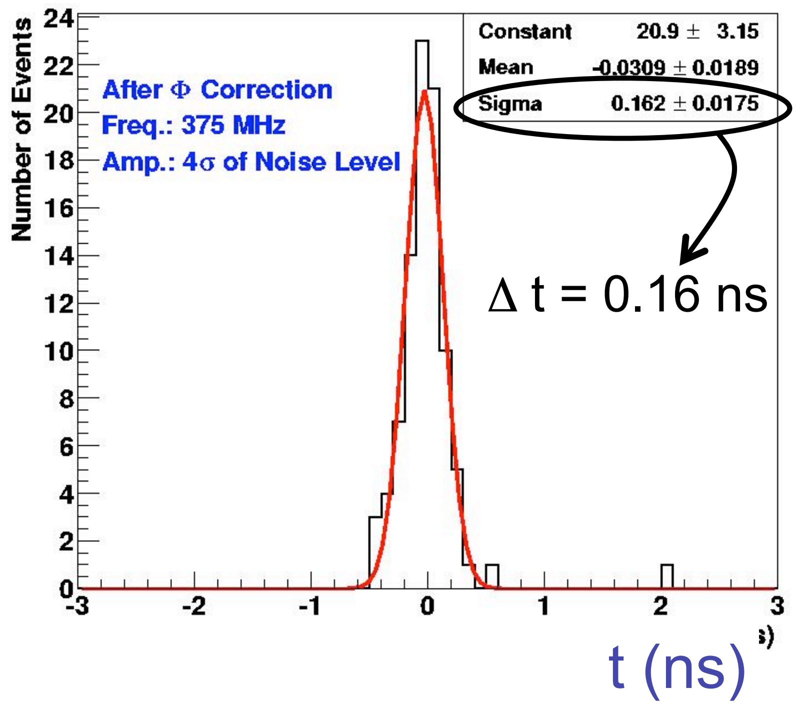
- Radio detection technique brings neutrino astronomy to >100's km^3 detection volumes
  - The field is already giving important results
- It is an exciting, dynamic field
- ANITA has completed its first full physics flight and analysis is underway
- Simulations are mature, constantly improving
  - Valuable tool for testing ideas, assessing sensitivity
- In tandem, we are working on developing next-generation projects, and finding the best path forward for the field based on
  - Experience with existing projects
  - Site selection studies
  - Simulations

The race is on for UHE neutrino detection!

Backup Slides

Anita-lite (cont)

- Flying two antennas with angular separation 22° allowed us to measure ANITA's angular resolution
- Compare time of arrival of calibration pulses



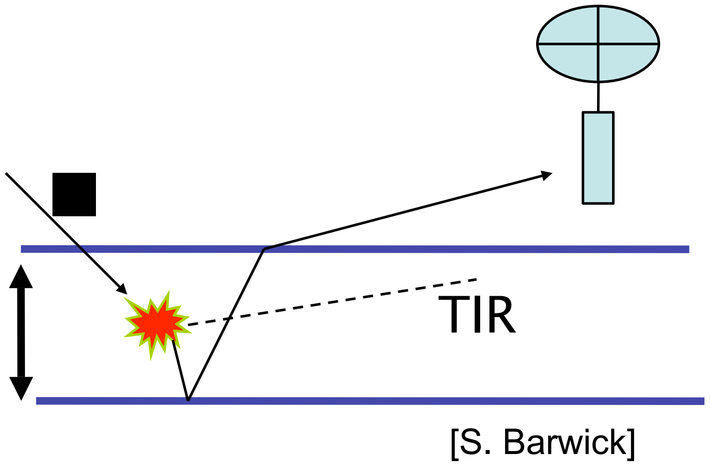
Angular resolution measured:
ANITA-lite: $\sigma(\Delta t)$=0.16 ns → $\sigma(\Delta\phi)$=2.3±
Full ANITA: expect $\sigma(\Delta t)$=0.1 ns → $\sigma(\Delta\phi)$=1.5°, $\sigma(\Delta\theta)$=0.5°

Remember that this is resolution on *RF direction*

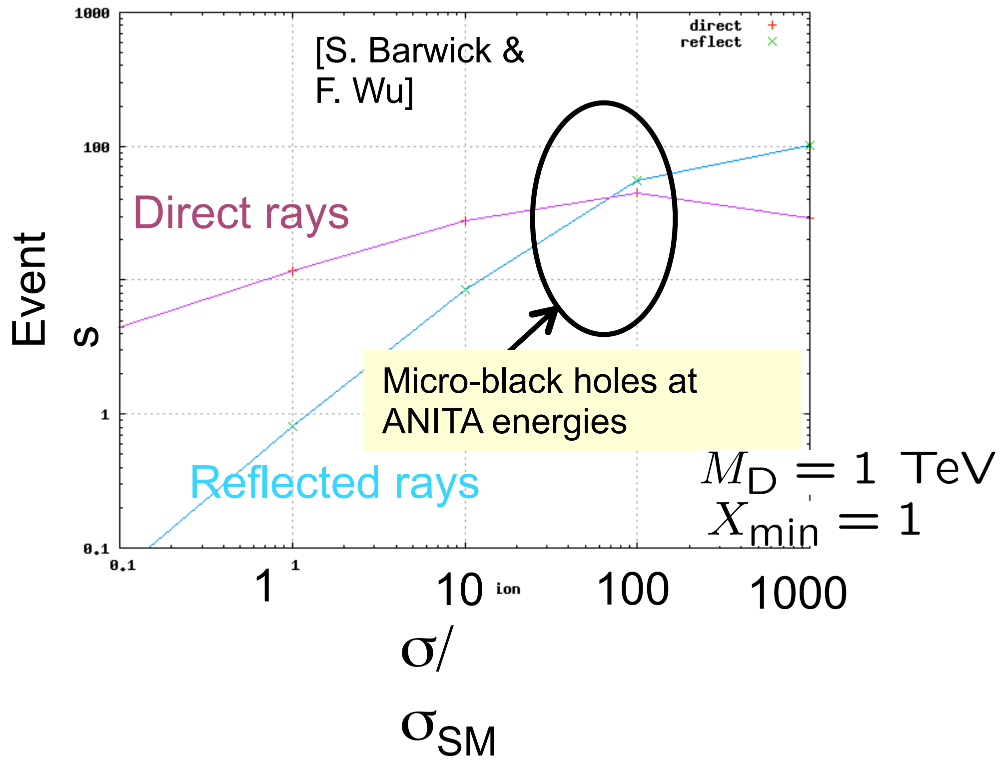
- Could verify that a signal comes from the ice
- Help discern near, far events → for energy measurement, for example

Reflected Rays

- ANITA could (possibly) detect events where a signal is reflected from ice-bedrock interface
- At SM σ's, reflected rays not significant
- At large cross-sections, short pathlengths → down-going neutrinos dominate ! reflected rays important



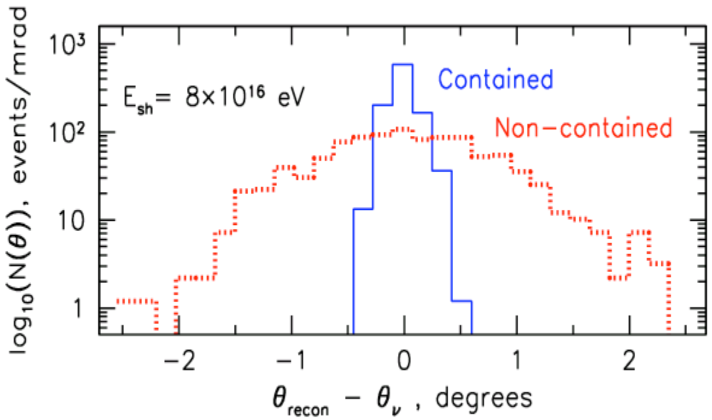
Signals suffer from extra attenuation through ice and losses at reflection



Angular Resolution of SalSA / ARIANNA

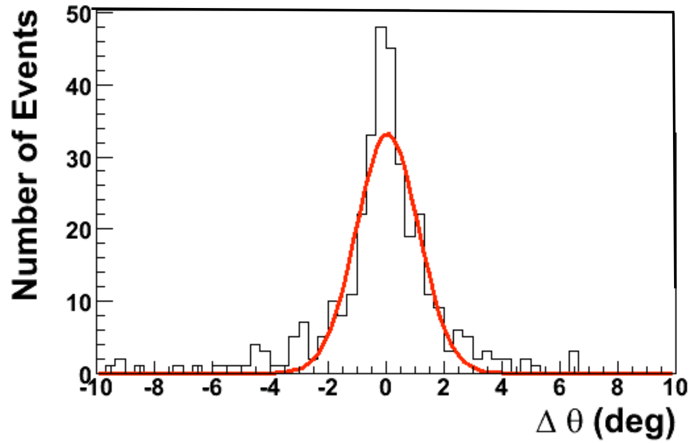
- Two complementary SalSA simulations also developed, UCLA (Connolly) and Hawaii (Gorham)
- Mainland simulation is a general “embedded detector” sim.
  - –Also models ARIANNA with different choice of inputs
- Antennas arranged in nodes of antennas
- Multilevel trigger requires coincidences between antennas within nodes, coincidence between hit nodes

SalSA 3D array



P. Gorham, University of Hawaii and Kevin Reil, SLAC

ARIANNA 2D array



F. Wu and S. Barwick, UCI

$\Delta\,\theta$ ~ fraction of a degree (contained)

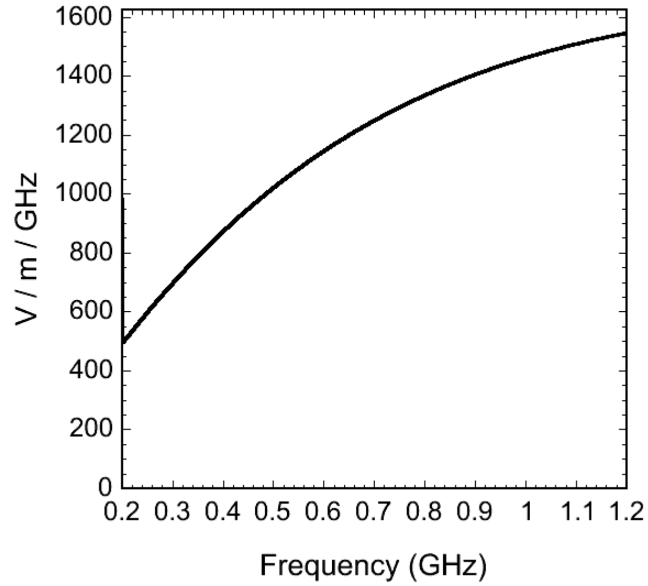
$\Delta\,\theta$ ~ 1 deg

This is the angular resolution on the *neutrino* direction!

Moving Trigger Simulation from Frequency Domain to Time Domain

- Currently, simulations model the signal strength by integrating the frequency profile
- Noise contribution is selected from a Gaussian
- Compare that signal + noise to threshold
- True system integrates power in time domain
- Thermal noise is our largest background ! essential that our system's response to noise is well understood

(J. Alvarez-Muniz, *et al.*, Phys.Rev.**D62**:063001,2000;
J. Alvarez-Muniz, *et al.*, Phys.Lett.**B411**:218-224,1997)



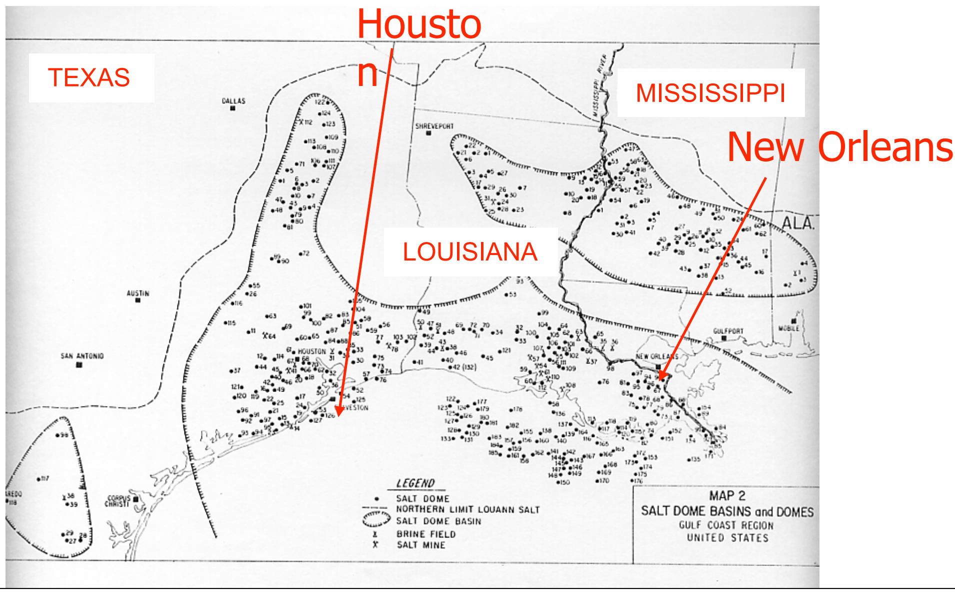
- Need to model channel dependent thresholds from ANITA flight

We have built the tools for a time domain simulation

Salt Dome Selection: U.S. Gulf Coast Most Promising

• Salt origin: Shallow Jurassic period sea, 150-200 M yrs old, inshore Gulf coast area dried ~150 Myrs ago
• Plasticity at 10-15 km depth leads to 'diapirism' : formation of buoyant extrusions toward surface

Stable salt diapirs all over Gulf coast



- Studying surveys from 70's, 80's by DOE for Nuclear Waste Repository sites
  - Requirements have large overlap with SalSA, large, stable dome, near surface, with dry salt, no economic usage
  - Strong candidates:
    - Richdon (MS), Vacherie (LA), Keechie (TX)
  - Visited dome sites to explore feasibility of

Visit to Vacherie Dome

near Shreveport, Louisiana

Visit to Vacherie Dome

ANITA Calibration at SLAC: June 2006

- Went 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

GOALS

- Produce Askaryan pulses in ice from a 28.5 GeV electron beam
- Self-trigger on pulses from full ANITA payload
- Record data at many positions to map out Cherenkov cone

10 ton Ice Target

- ~10 ton ice target
- Ironed sides of ice blocks to minimize gaps between blocks
- Ice blocks were assembled into a target 2.0 m x

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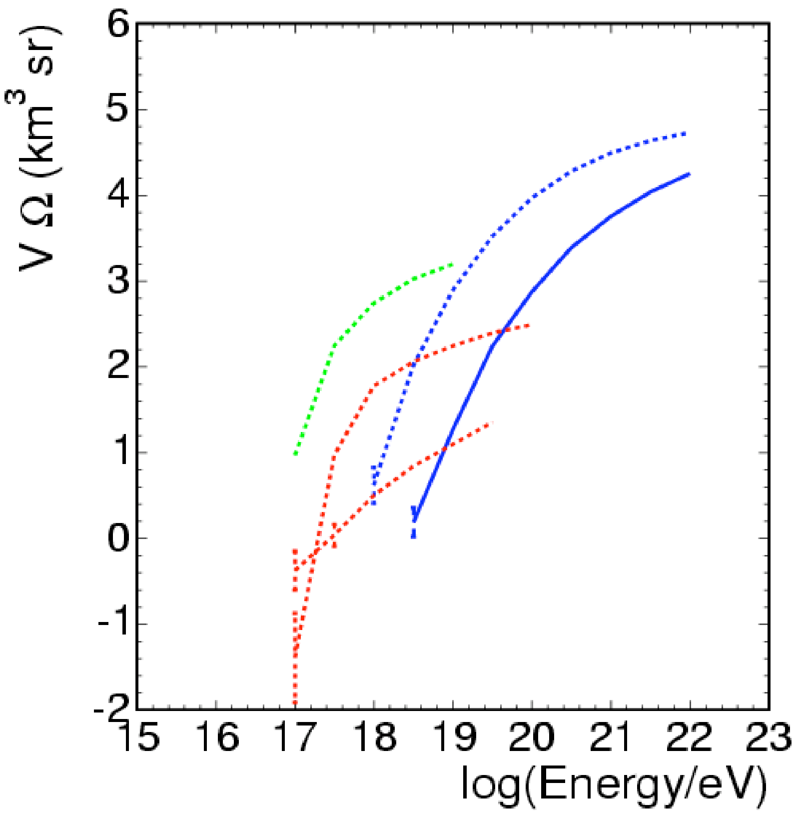
Volume * str



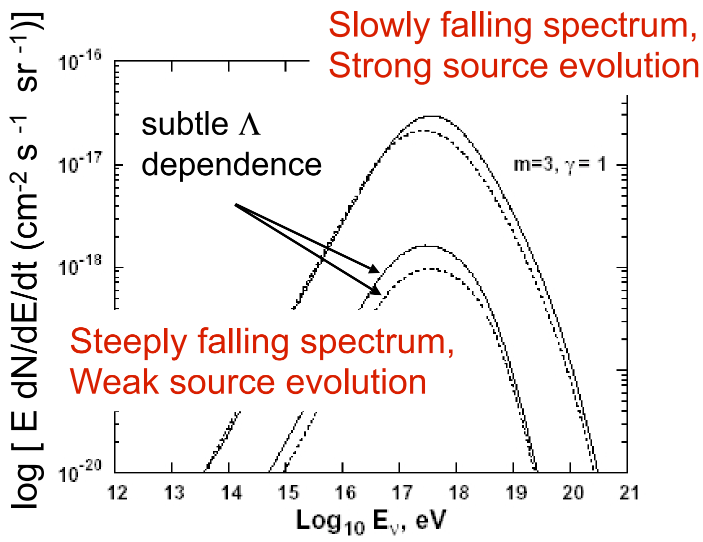
What Messages Will Neutrinos Carry

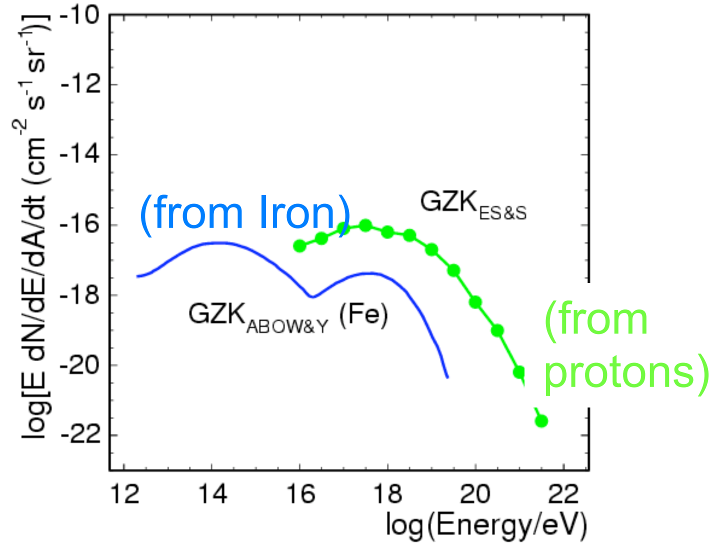
- Could point to new sources
- Neutrinos carry information about cosmic rays and their sources
  - Flux could reveal clues about the nature of CR sources
    - Spatial distribution
    - Injection spectra
  - Cosmological constant (subtle)
  - Composition of the CR's
- Center of mass of a 10^{17} eV neutrino incident on a nucleon is 14 TeV

→Beyond typical LHC energies

Potential for new physics

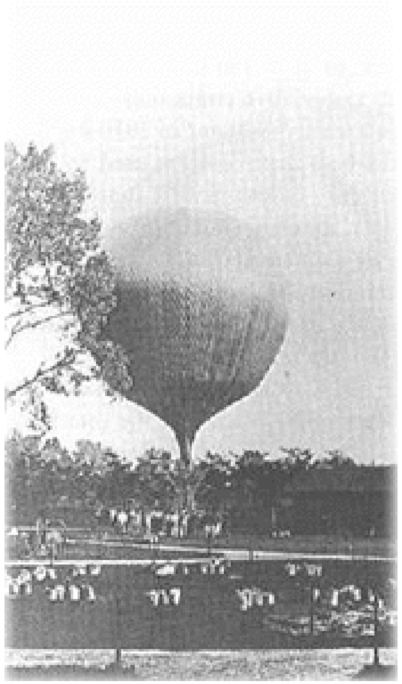
Seckel, Stanev: astro-ph/0502244





Cosmic Origin of Radiation

1912 Austrian Victor Hess boarded a balloon with a radiation counter
Went to 17,500 ft. altitude
Radiation increased with altitude
Established “cosmic” origin of natural radiation



Observations of cosmic particles have led to many groundbreaking discoveries:

- Particle physics: discovery of many subatomic particles (e^+, π^+, μ^+, K , …)
- Astrophysics: Discovery of new objects, insights into engines inside them

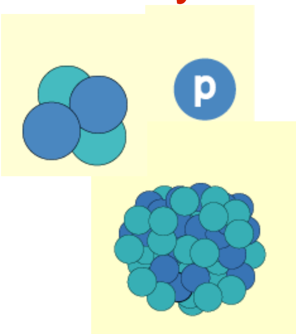
Ballooning remains an important means for probing the cosmos

I will describe how we are looking for a new class of cosmic radiation from a balloon at 120,000 ft. by looking “down” instead of “up”

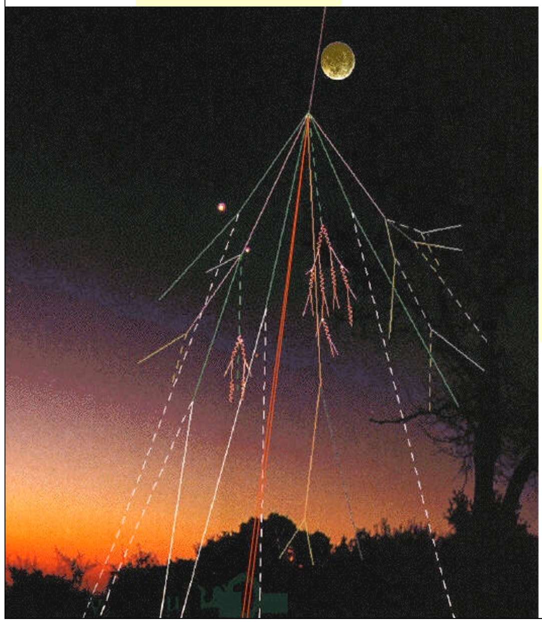
Types of Cosmic Radiation

Ordinary Matter

Protons and Heavy Nucleii



- Over 99% of cosmic radiation
- Positively charged
- Detected through ionization (high altitude) or showers of π, μ, γ in atmosphere



Electrons

- Only 1% of cosmic radiation

Photons

γ

- Less than 0.1% of cosmic radiation
- Detected directly with telescopes (high altitude) or showers of e,γ in atmosphere

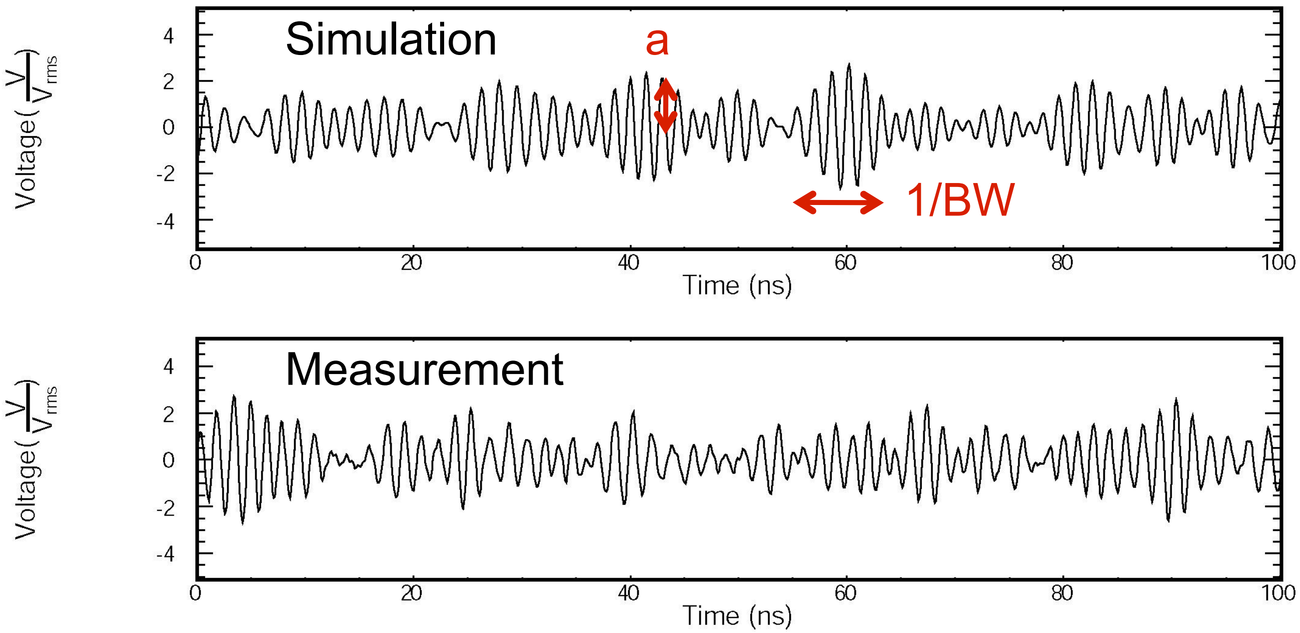
Neutrinos

ν

- Only extraterrestrial neutrinos observed from Sun, Supernova 1987a
- Only observed through weak interactions

Building Tools for Time Domain Trigger Simulation

Noise only (no signal) in the band from 550 to 750 MHz (Band 3):



Simulated by summing sin waves flat in frequency within the band, with random phases

Voltages distributed by a Gaussian:
$P(V)\,dV = 1/(\sqrt{2\pi}\,\sigma)\exp(-V^2/2\sigma^2)$

Raleigh:
$P(a)\,da = a/\sigma^2 \exp(-a^2/2\sigma^2)da$

- Essentially, the noise (at ~center frequency f_0) is acting as a carrier, to the “signal” (the bandwidth)
- Envelope magnitudes a following a Raleigh distribution

Consider a Power Integrator

Integration Time Δt: 1 oscillation

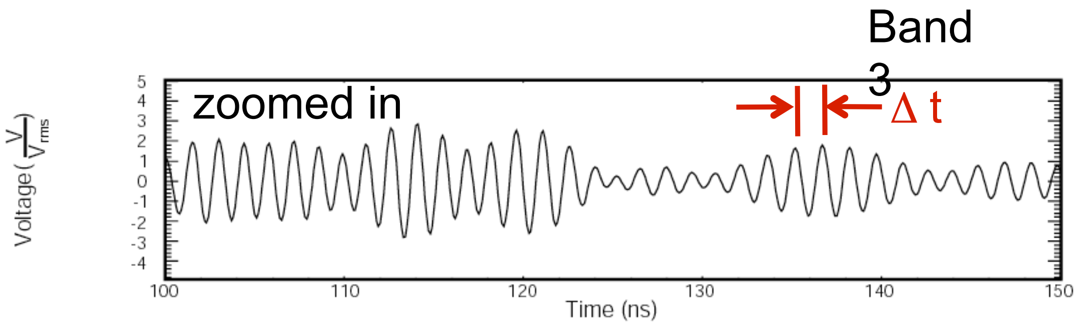
Within the window,

$V(t) \approx a \sin(2\pi f_0 t)$

$P(t) \approx a^2 \sin^2 (2\pi f_0 t)$

$\int P(t) \Delta t = a^2 / 2$

→ samples power envelopes $a^2=J$

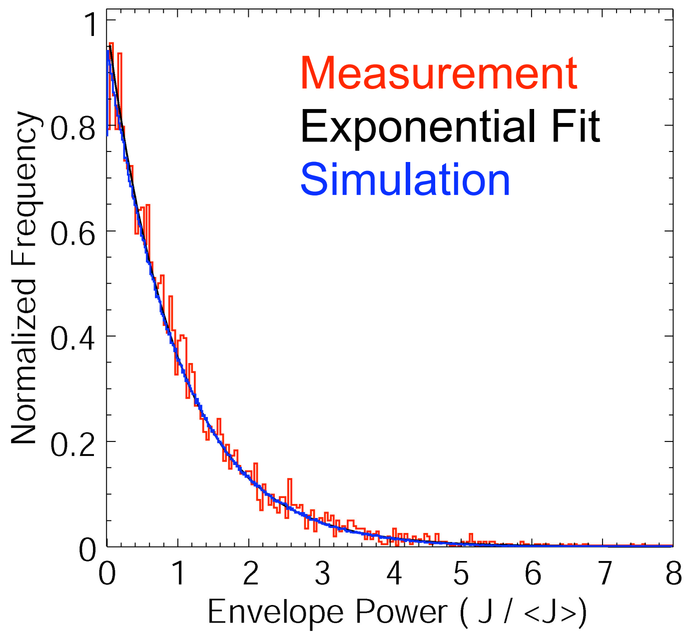


$$P(a)\, da = a/\sigma^2 \exp(-a^2/\sigma^2)\, da$$

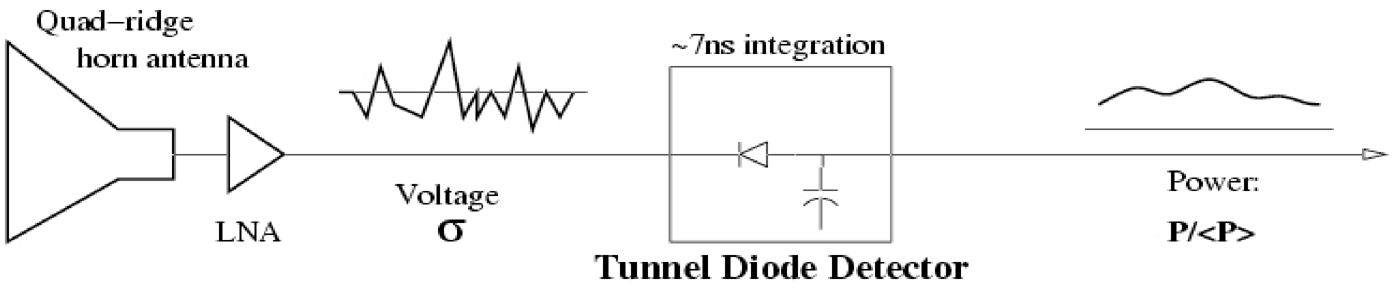
$$2\, a\, da = dJ$$

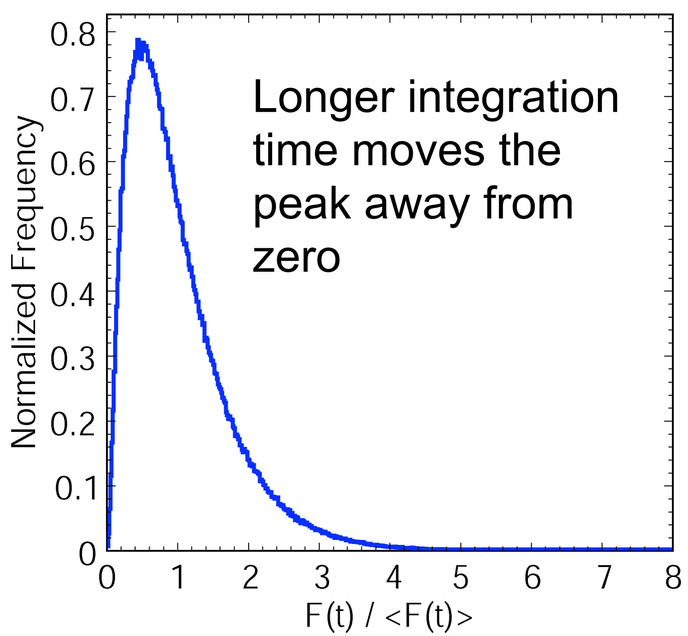
$$P(J) = 1/(2\sigma^2) \exp(-J/\sigma^2)\, dJ$$

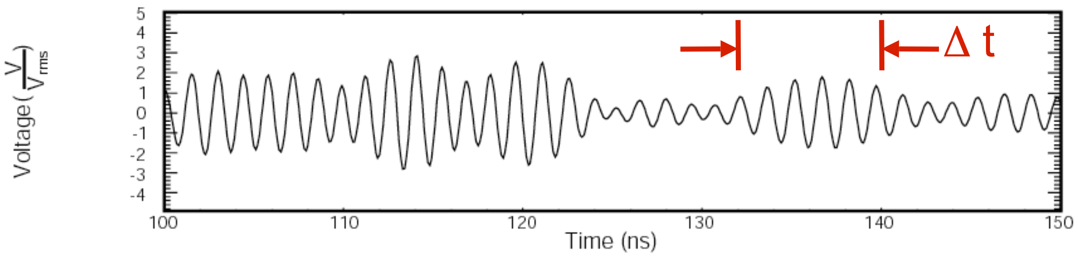
→ result is an exponential distribution



ANITA's Single-Channel (Level 1) Trigger Is





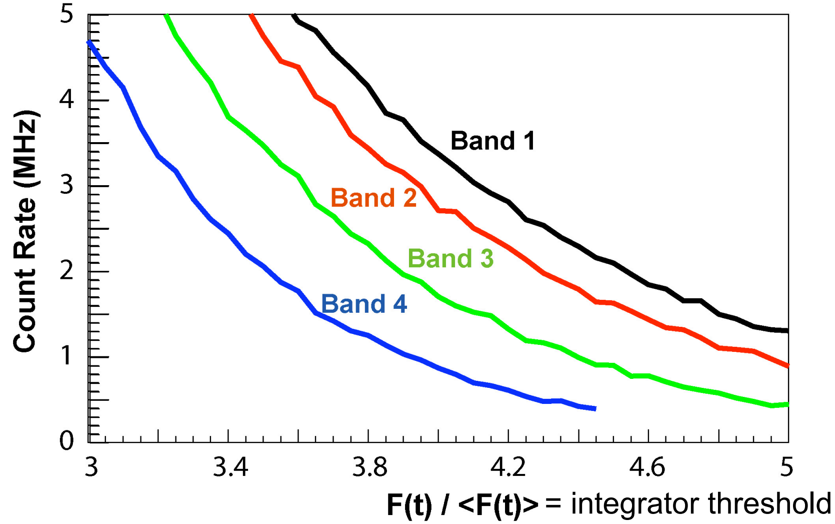


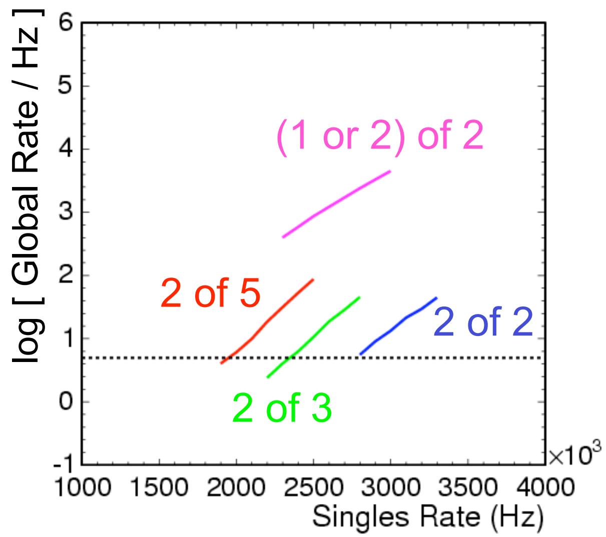
Band 3

- Model the tunnel diode as an integrator
  - Integration time Δ t = 7 ns
  - Exponential response τ = 5 ns
- Deadtime once a trigger is generated is 12 ns

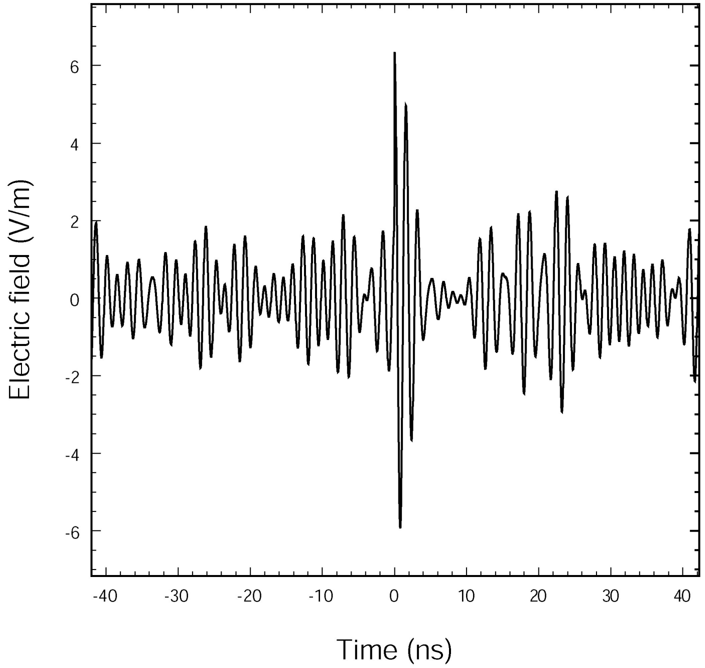
Trigger Rates

- Using our L1 trigger model, we calculate single-channel trigger rates
- Global trigger requires
  - L2: Coincidence between 2/3 neighboring antennas
  - L3: Coincidence in ϕ between L2 hits
- We calculate Global trigger rates with toy MC
- This analysis was used to guide
  - Choice of L2 trigger parameters
  - Trigger parameters during flight

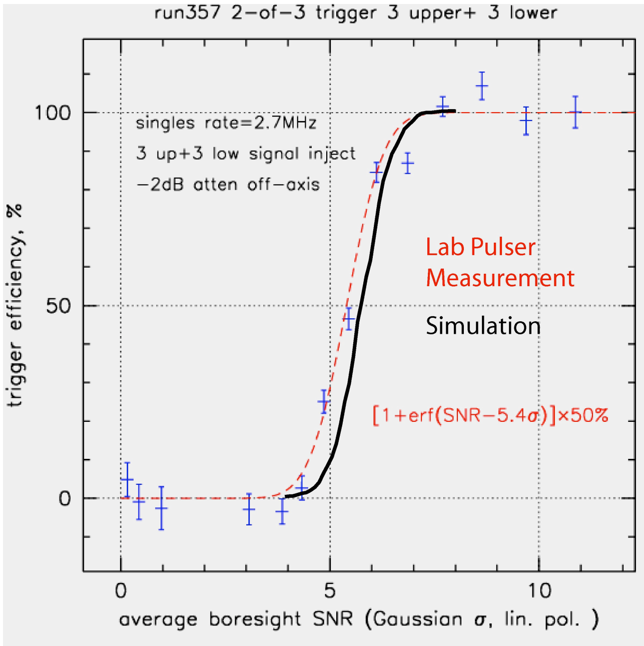




Adding in Signal



- Add FFT of signal parameterization onto simulated noise
- Calculate a global trigger efficiency vs. S/N



- Compare with lab measurement from a pulser with similar bandwidth
- Agreement looks very promising!
- Will be used to assess ANITA sensitivity with in-flight parameters