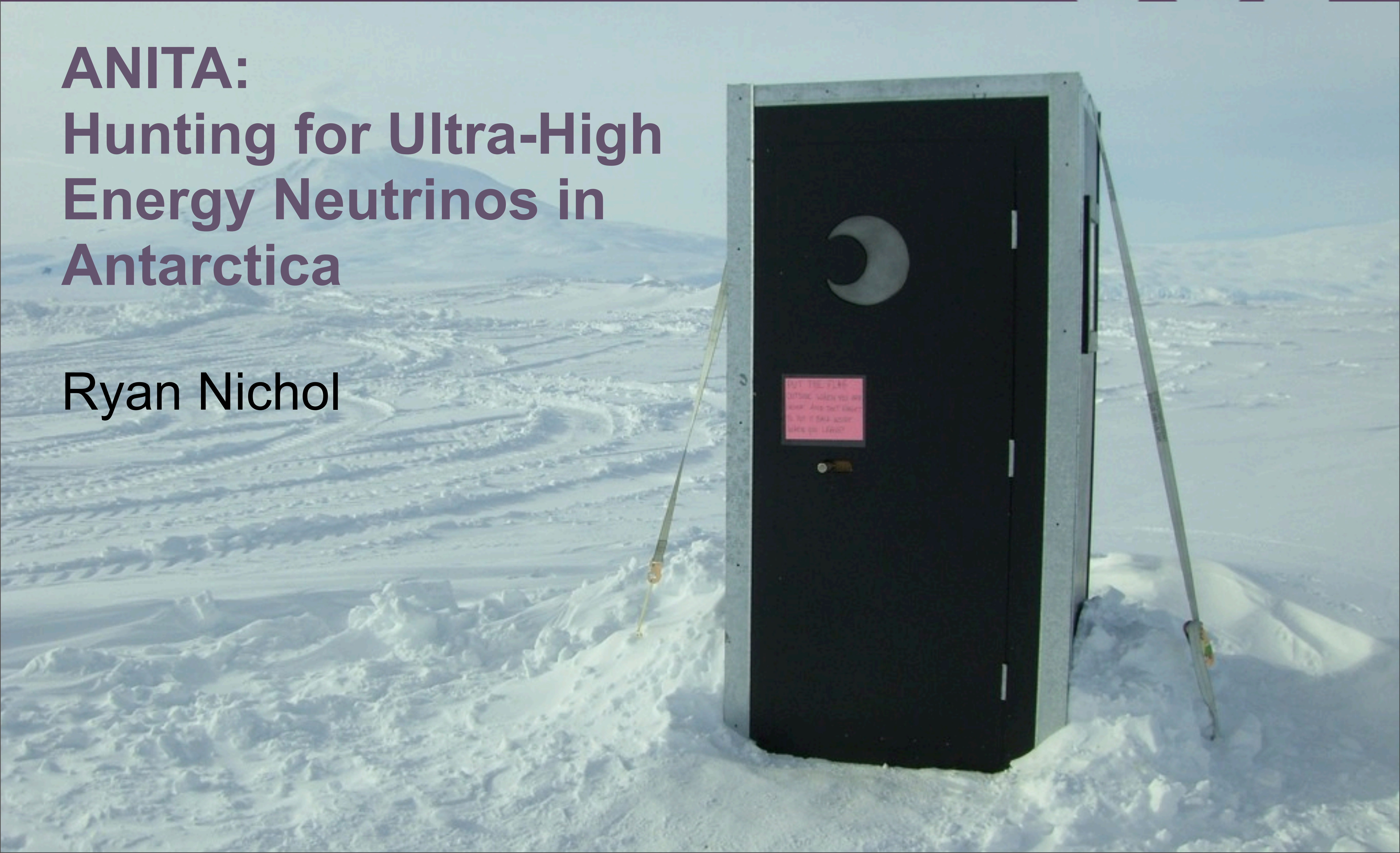
ANITA: Hunting for Ultra-High Energy Neutrinos in Antarctica

Ryan Nichol



Outline

- Timeline
  - From Austria in 1912 to Antarctica in 2006/8
- Motivation
  - For Astronomers, Astrophysicists and Particle Physicists
- Detection
  - Problem of size
  - Askaryan effect
- ANITA
  - Why Antarctica
  - Detector Concept
  - Results
- Future Prospects

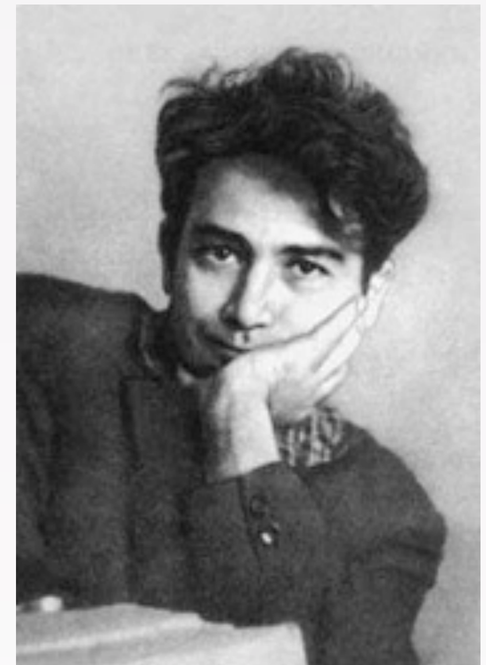
Brief scientific timeline leading to ANITA

1912

Victor Hess discovers cosmic rays, by flying balloons up to 3 miles above Austria

Wolfgang Pauli does "something very bad"... he postulates the neutrino

1930

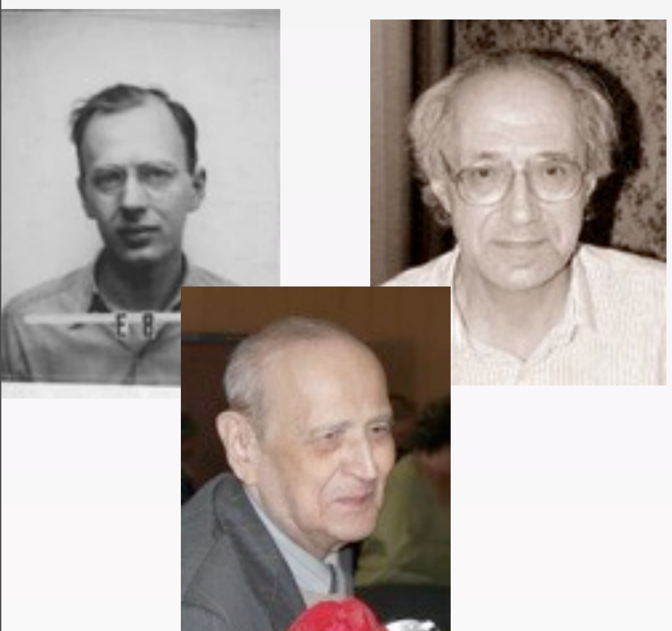


1962

Gurgen Askaryan hypothesises coherent radio emission from particle cascades in dielectric media

Wilson and Penzias discover the cosmic microwave background

1965

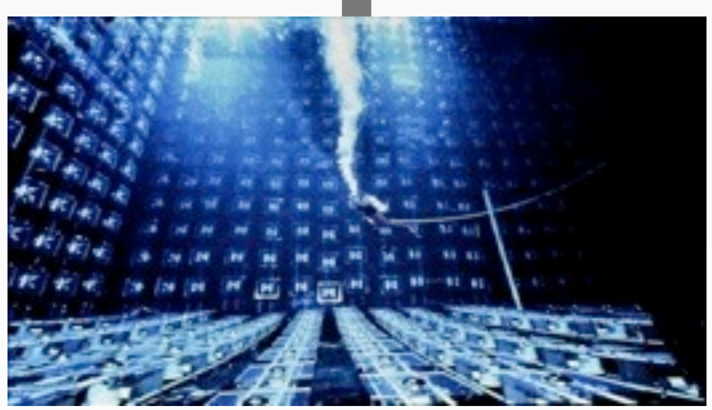


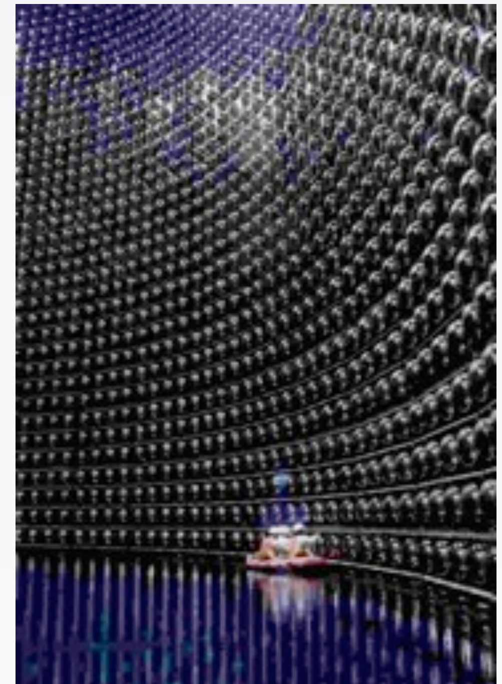
1966

Greisen, Zatsepin & Kuzmin predict the end of the cosmic ray spectrum

Kamiokande, IMB and Baksan detect neutrinos from a nearby supernova

1987





1998

Super-Kamiokande discover neutrinos have mass. Using neutrinos produced by cosmic rays in the atmosphere

ANITA-I launches from Williams Field in Antarctica

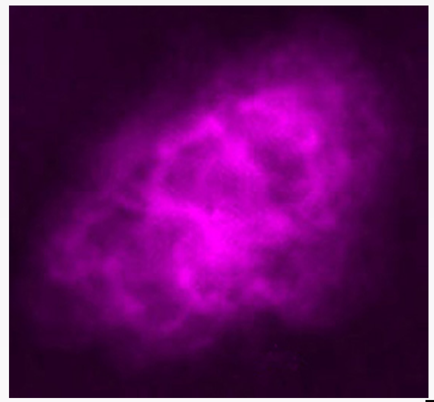
2006

Why?

Why Ultra-High Energy Neutrinos?

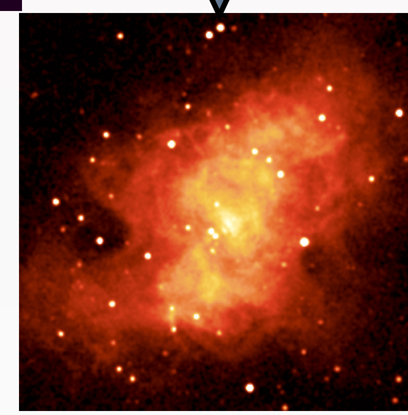
For Astronomers
For Astrophysicsts

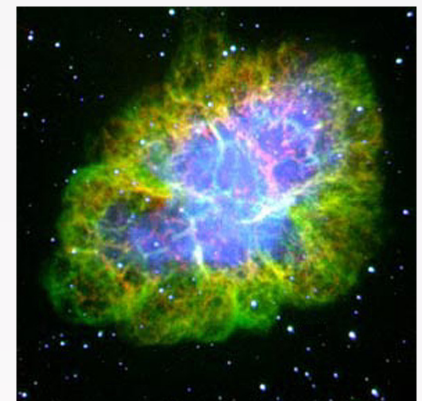
The Pretty Pictures Argument



Radio

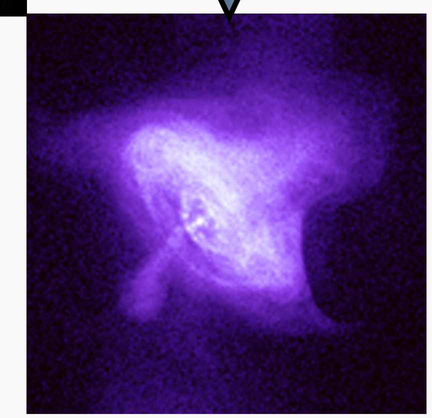
Infrared



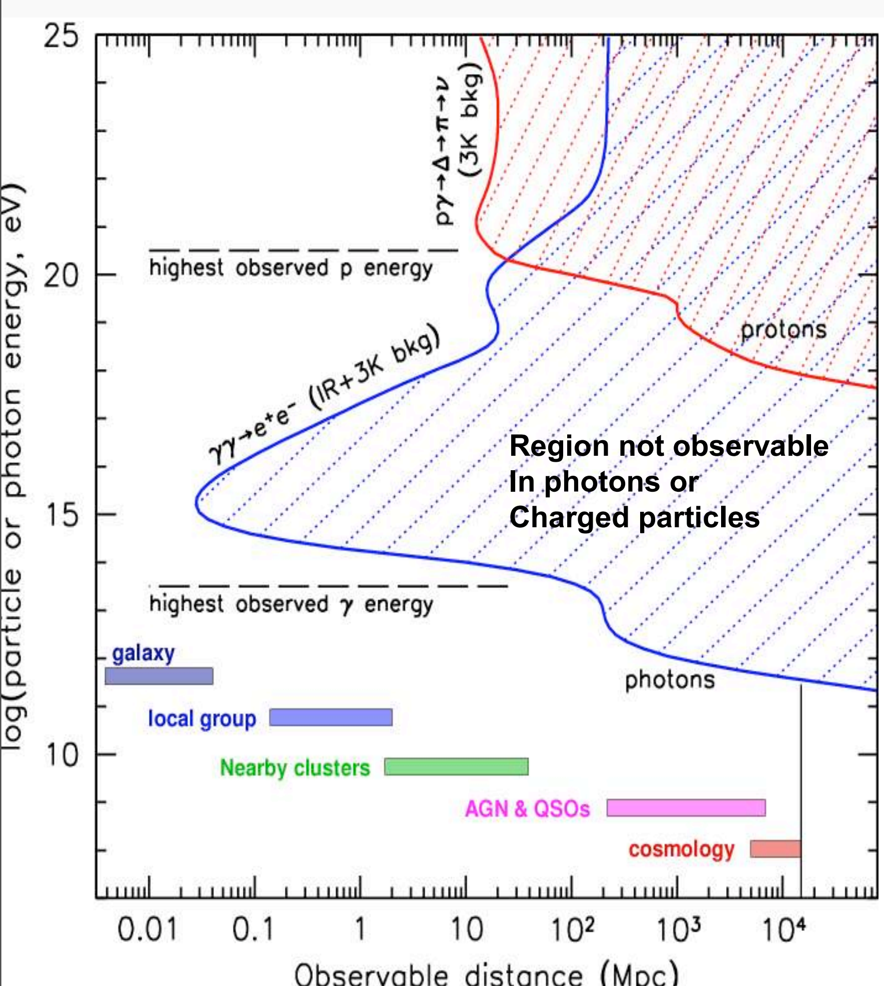


Optical

X-Ray



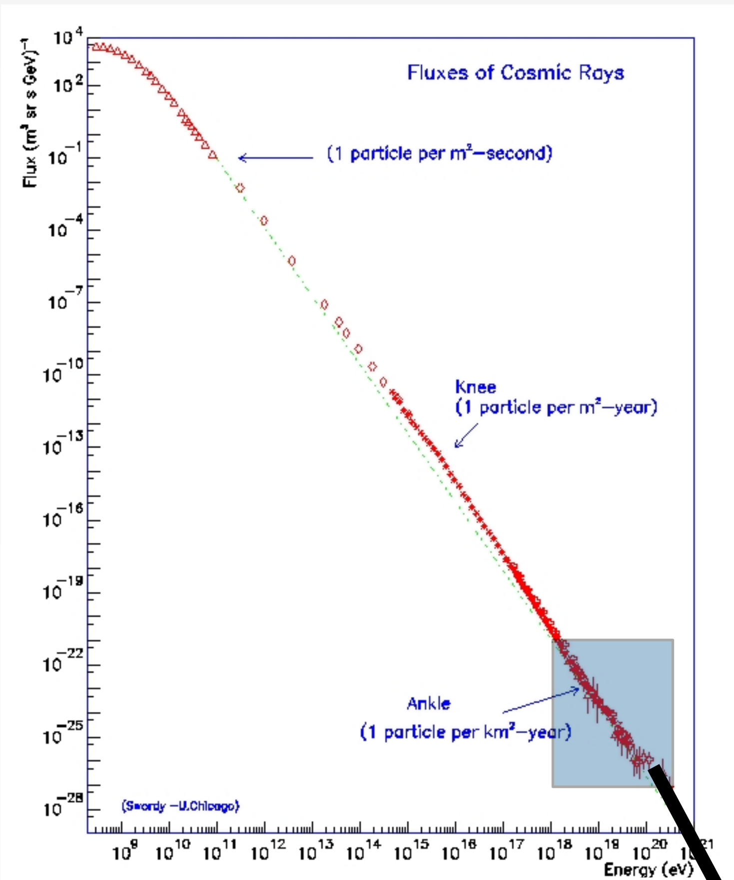
Neutrinos?

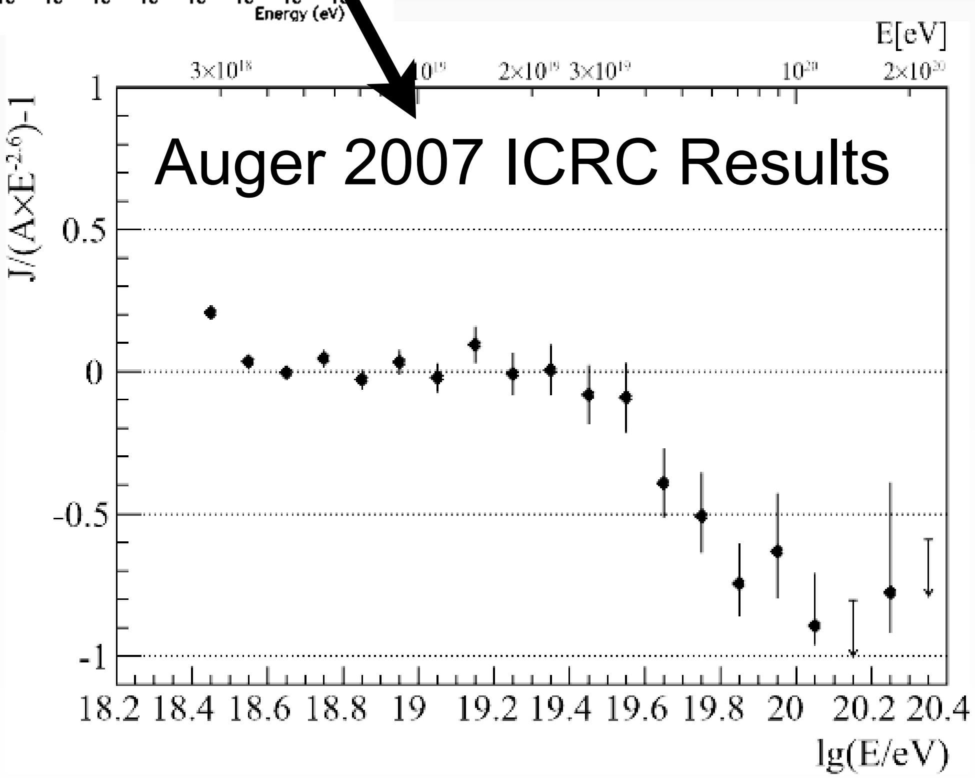


Neutrinos can probe the distances and energies that other particles can't reach.

The Heineken Particle

Aside -- The GZK Effect



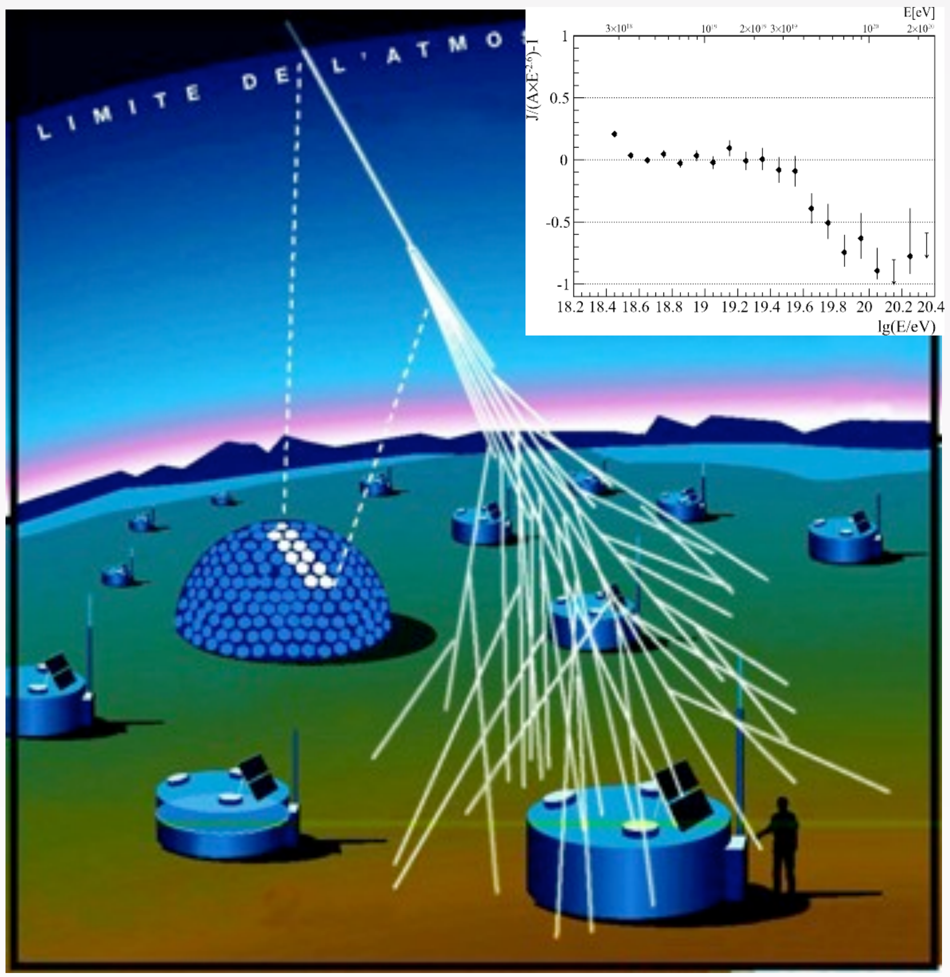


- Greisen-Zatsepin-Kuzmin (GZK) calculated cosmic rays above $10^{19.5}$eV should be slowed by CMB within 50MPc.

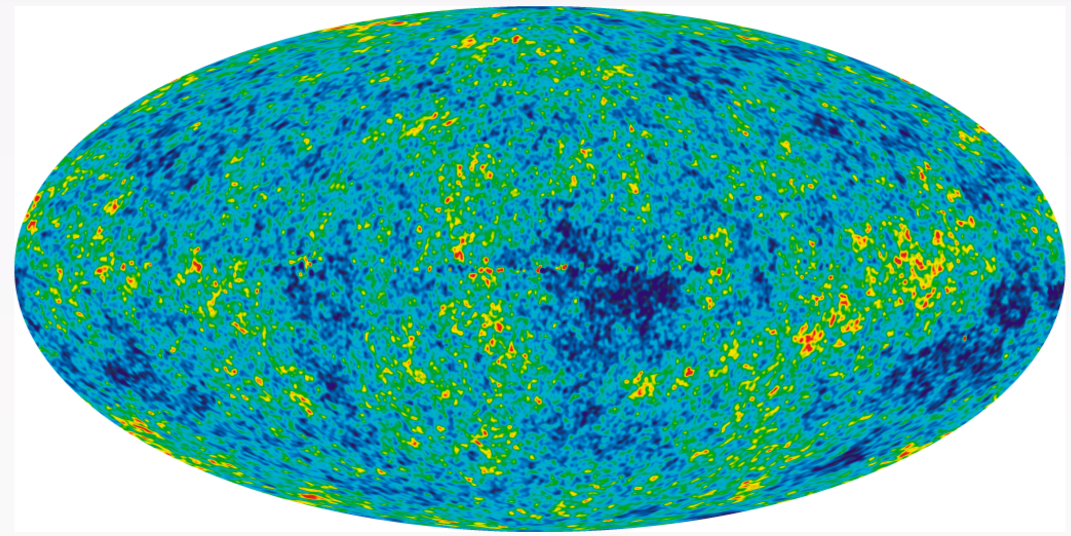
$$p + \gamma_{CMB} \rightarrow \Delta^* \rightarrow n + \pi^+$$
$$\searrow \mu^+ + \nu_\mu$$
$$\searrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Have Auger detected the GZK cut-off?

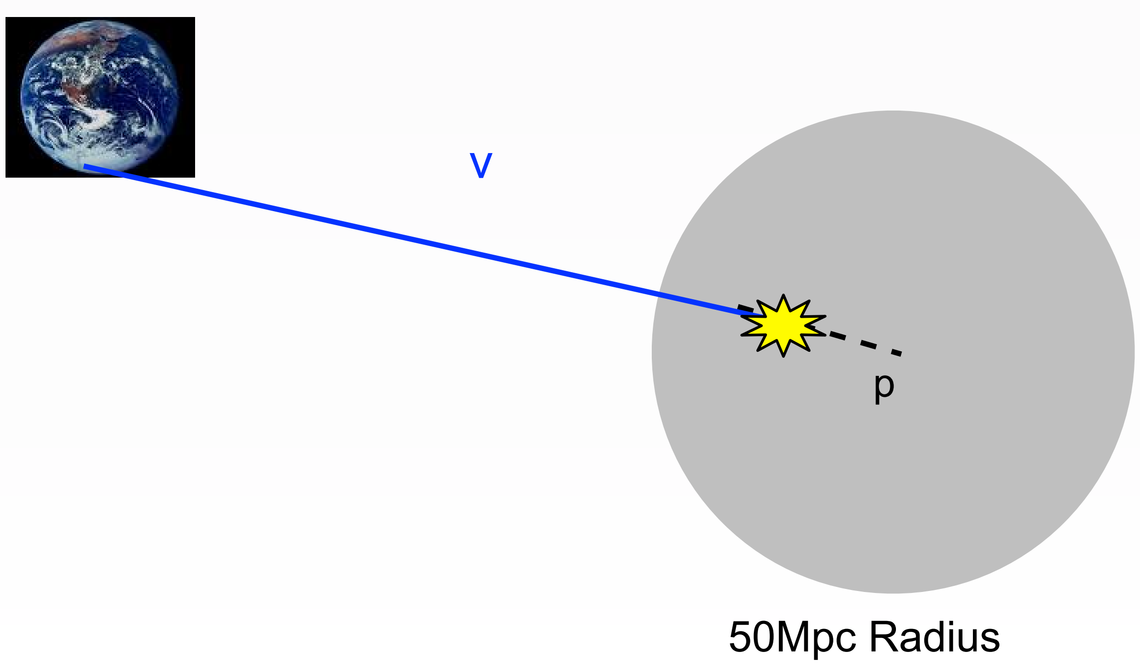
GZK Effect in Pictures



+



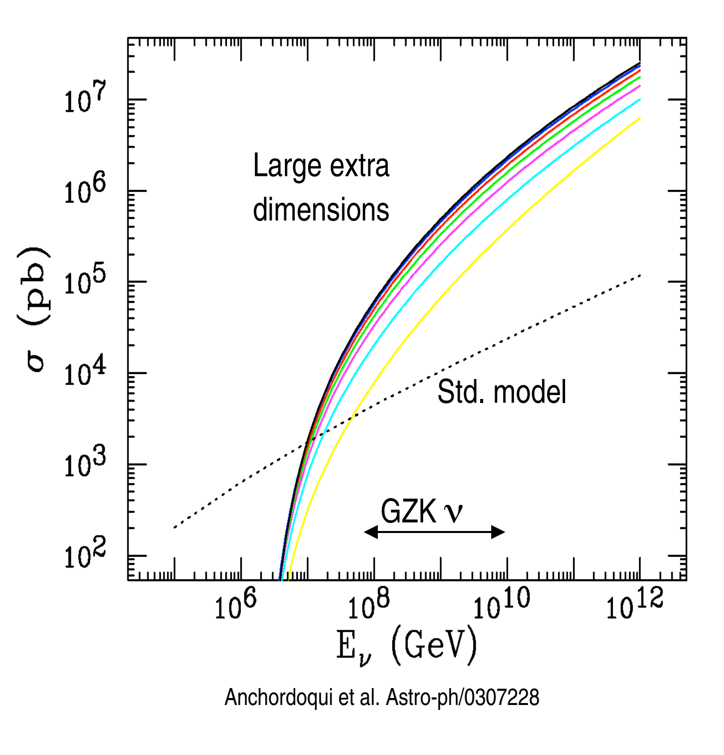
= “Guaranteed” Neutrino “Beam”!

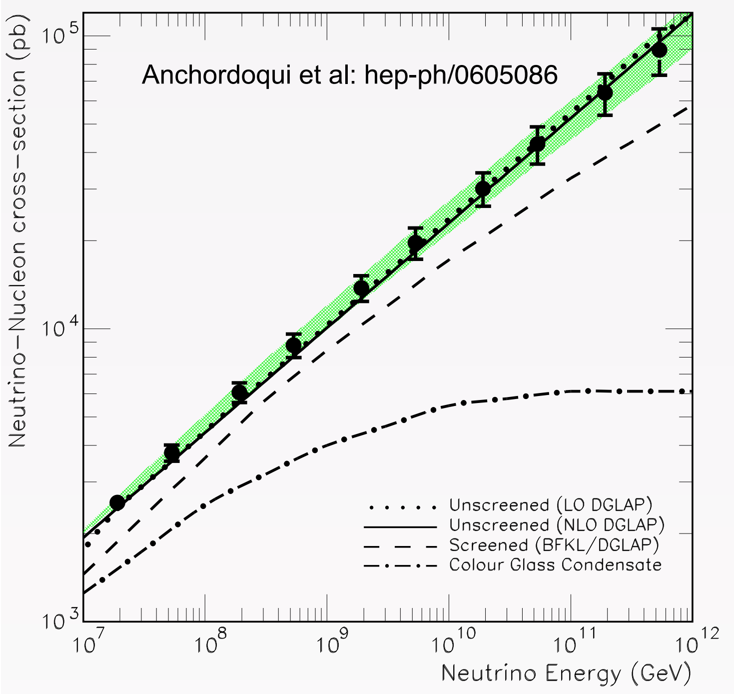


GZK Neutrinos Point Back to original proton source

Particle Physics with 300TeV (CoM) Neutrino Beam

- Neutrino-nucleon cross section in new regime
  - Large extra dimensions
  - Micro blackholes
- Neutrino mixing:
  - z=1 is v. long baseline





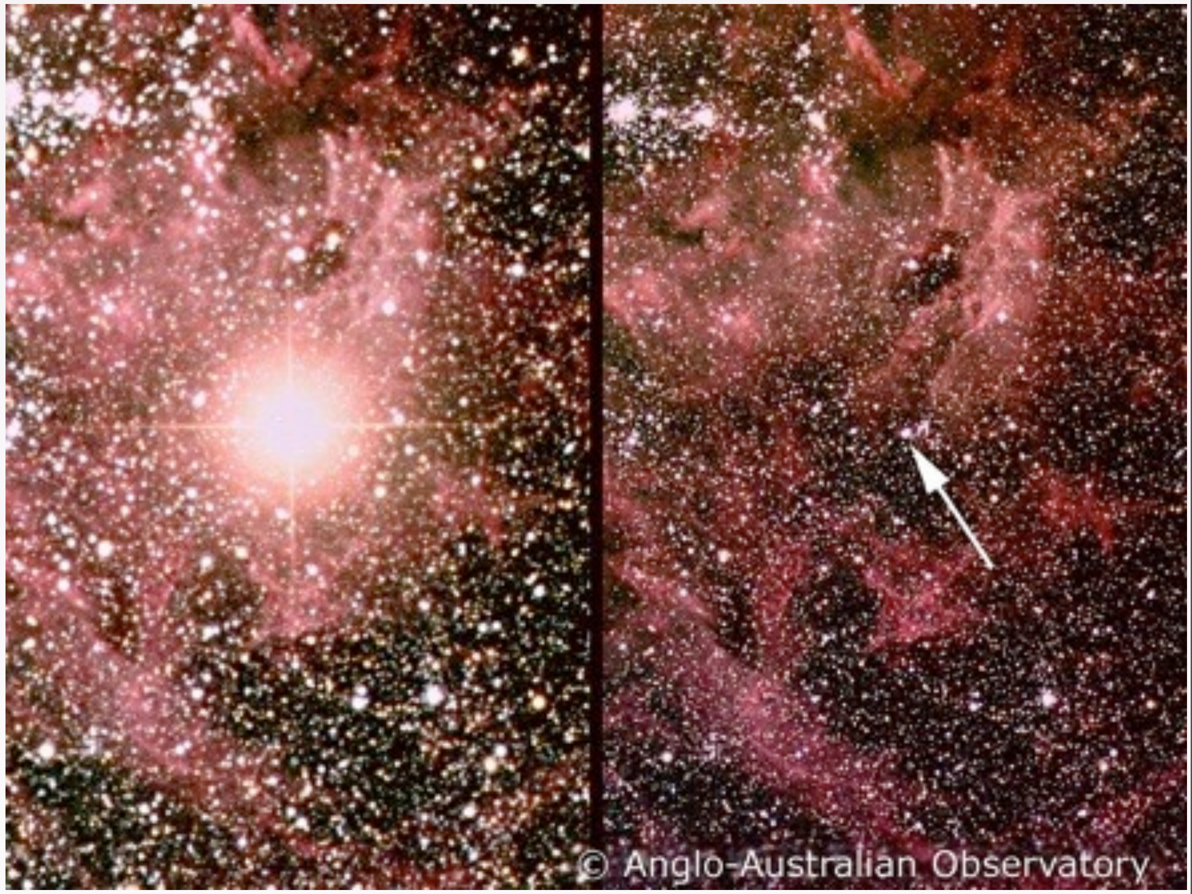
Order of magnitude:

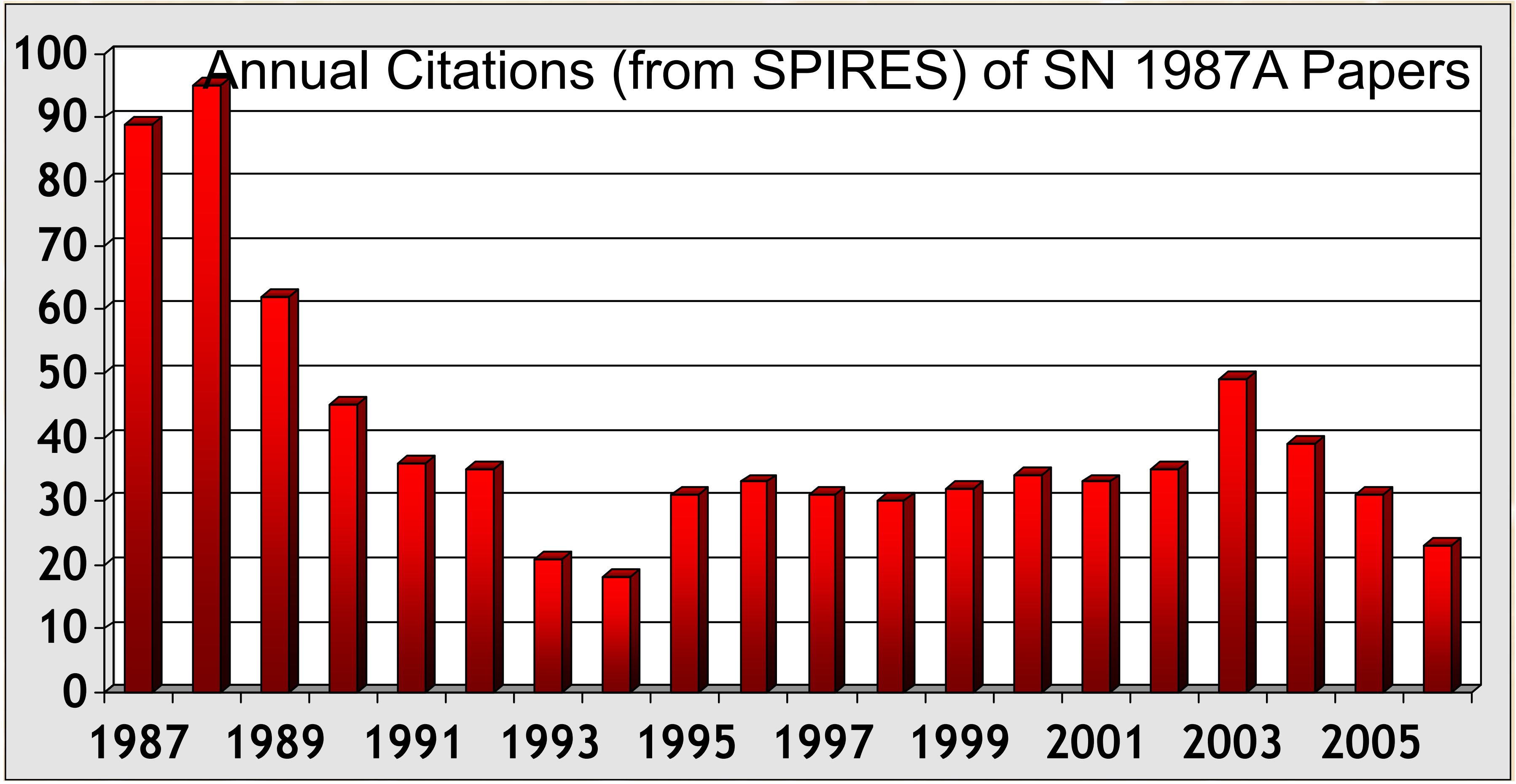
type	L/E	$t_{proper} \sim (L/c)(m_\nu/E)$
CERN SpS/WANF	500 m/25 GeV	3 attoseconds
Stopped μ (LAMPF)	30 m/ 40 MeV	130 attoseconds
NUMI	735 km/ 4 GeV	30 femtoseconds
Reactor (KamLAND)	150 km/5 MeV	800 femtoseconds
Atmospheric	10,000 km/1 GeV	2 picoseconds
Sun	150,000,000 km/5 MeV	800 nanoseconds
GZK	1 Gpc/100 PeV	50 milliseconds
SN-1987a	50 kpc/15 MeV	1 hour

Table from David Saltzberg

Case Study: SN1987A

- 20-some neutrinos
- Scientific output including
  - Neutrino mass limits
  - Supernova mechanics
  - + lots more





Plots stolen from
Georg Raflett

How can you do it?

A Problem of Size

- Some Numbers:

  ~1 GZK neutrinos/km^2/year

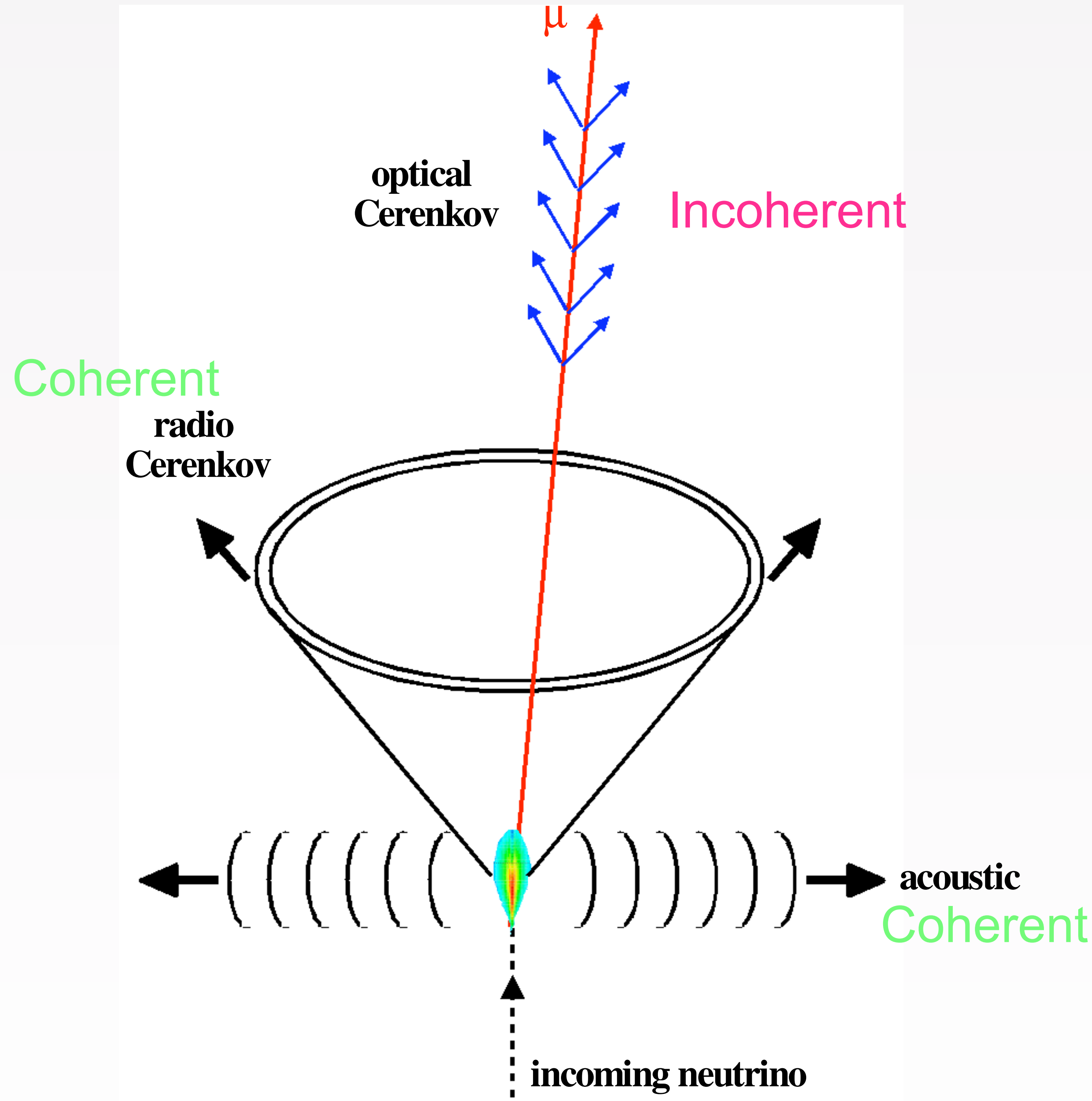
  @ 10^{18} eV the ν-N interaction length ~ 300km

  $\therefore$ 0.003 neutrino interactions/km^3/year

- Need a huge detector volume (>>100 km^3) to ensure detection
- Use naturally occurring medium
  - Transparent (to some signal)
  - Possibilities
    - Air, Ice, Salt, Water, The Moon

Possible Detection Methods

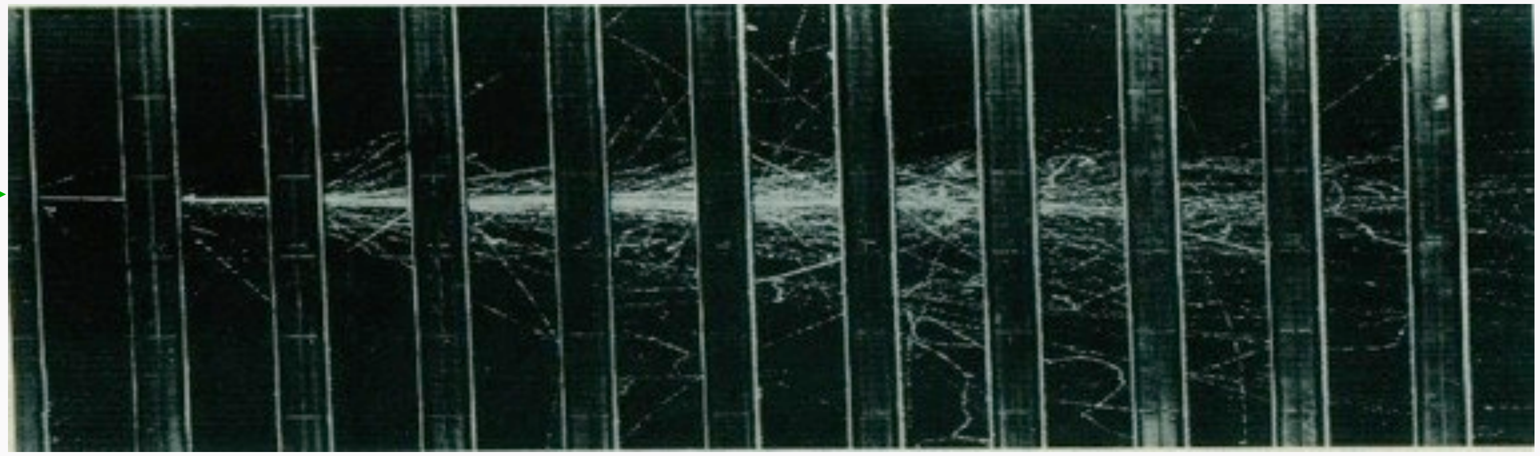
- Optical Cherenkov
  - Mature field but not scalable to huge volumes
- Radio Cherenkov
  - Active field best candidate for first detection
- Acoustic
  - Emerging field, with much R&D
- Other
  - Air showers



Radio Cherenkov -- The Askaryan Effect

- In 1962 Gurgen Askaryan hypothesised coherent radio transmission from EM cascades in a dielectric:

$e^{\pm}$ or Υ

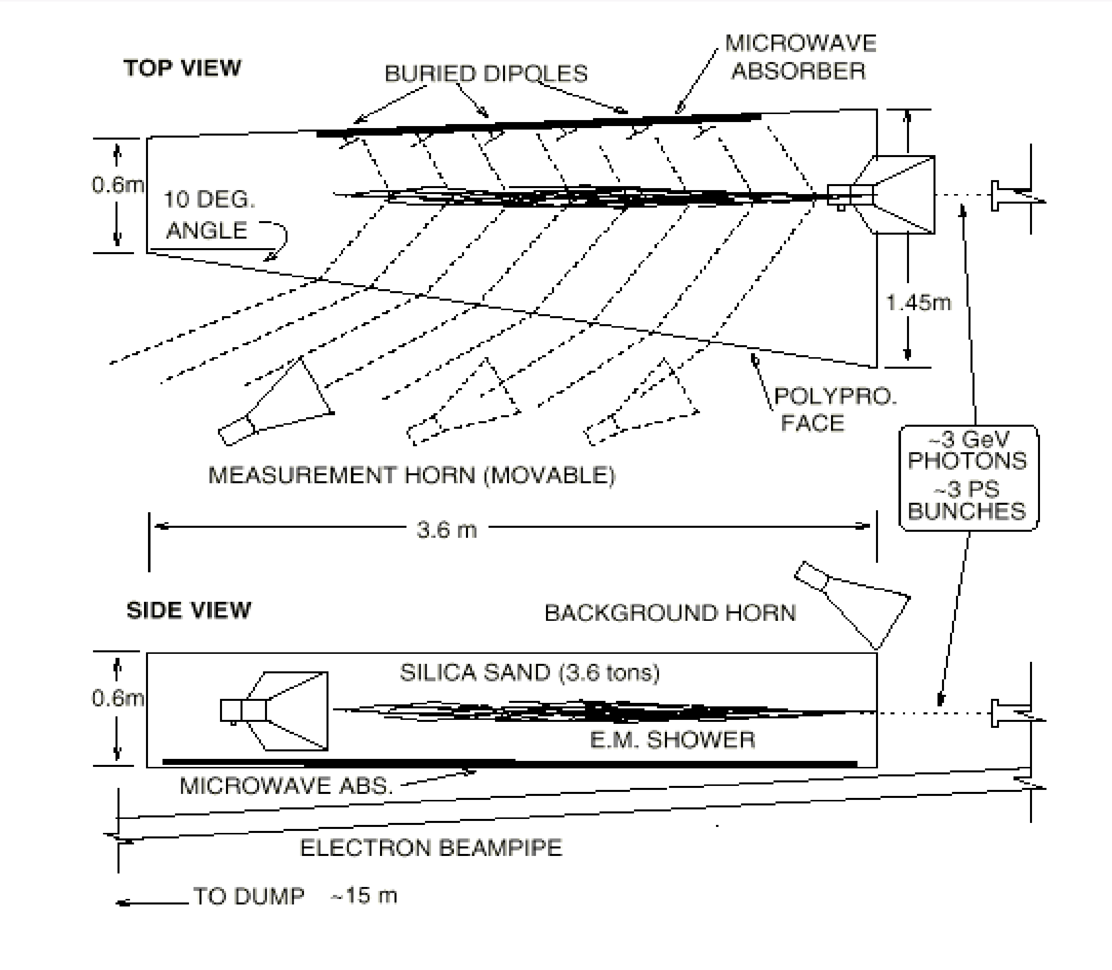


Typical Dimensions:
$L \approx 10$ m
$R_{Moliere} \approx 10$ cm

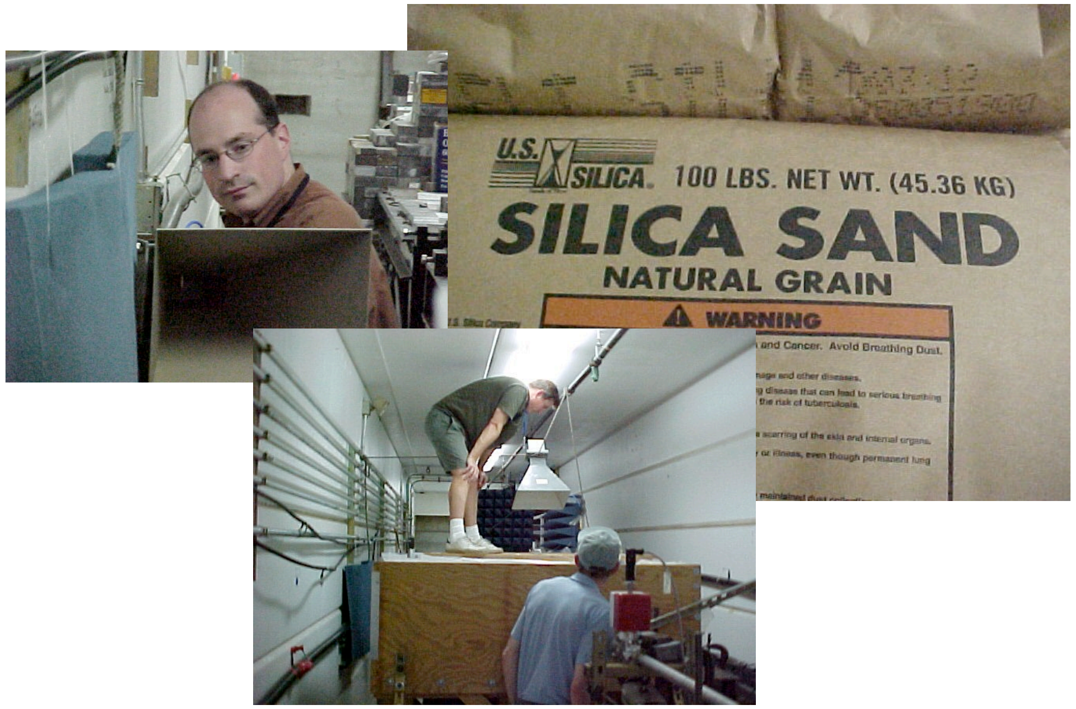
- 20% Negative charge excess:
  - Compton Scattering: $\Upsilon + e^-_{(rest)} \Rightarrow \Upsilon + e^-$
  - Positron Annihilation: $e^+ + e^-_{(rest)} \Rightarrow \Upsilon$
- Excess travelling with, $v > c/n$
  - Cherenkov Radiation: $dP \propto \nu \, d\nu$
- For $\lambda > R$ emission is coherent, so $P \propto E^2_{shower}$

Experimental Verification

- Askaryan effect experimentally confirmed in 2000



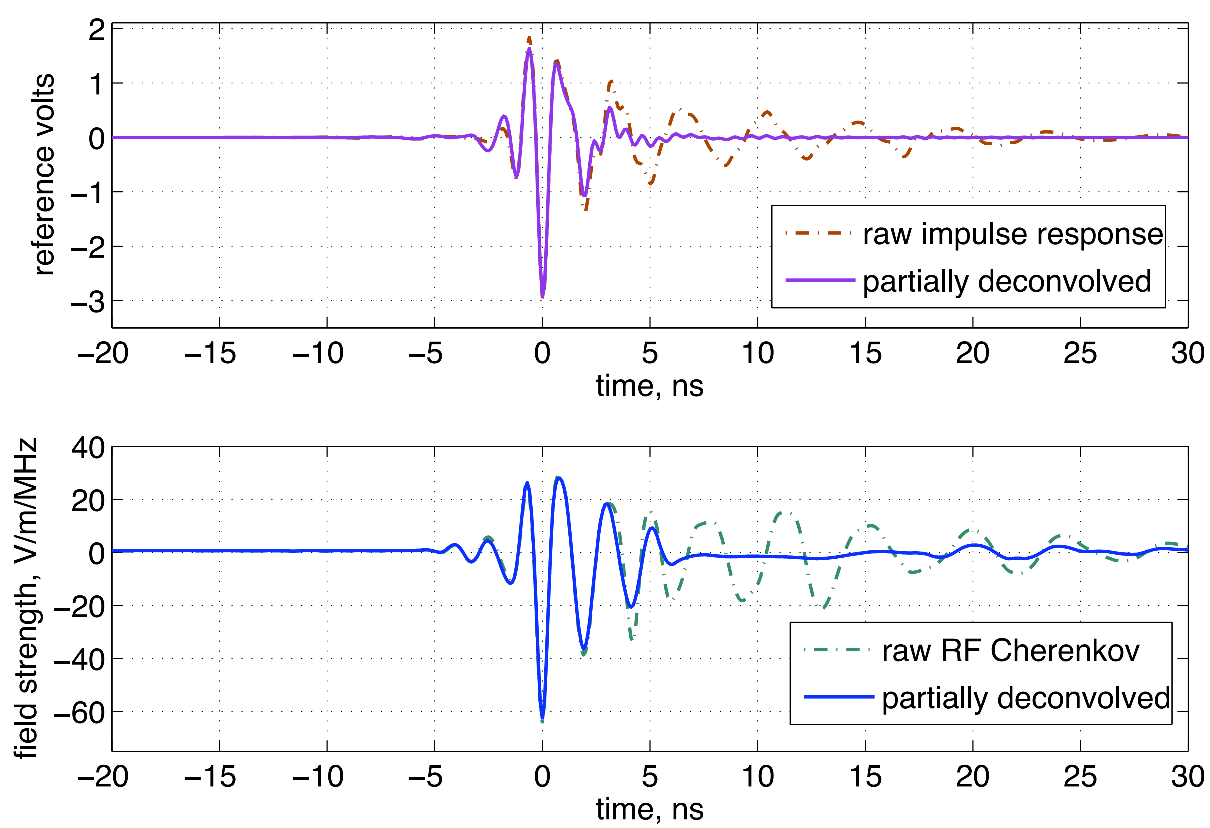
From Saltzberg, Gorham, Walz et al PRL 2001

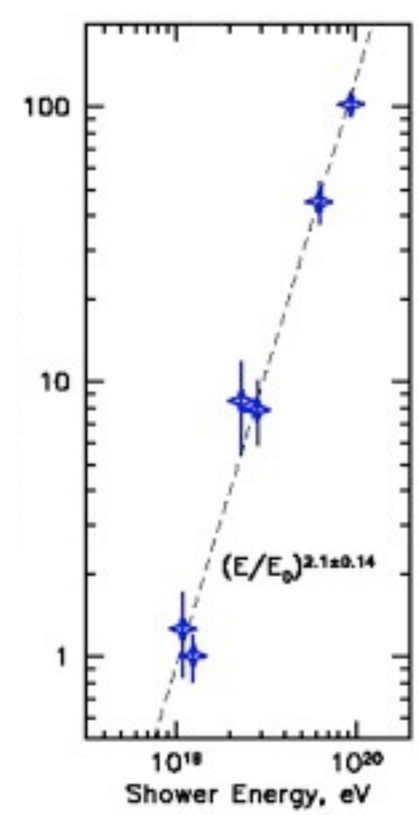


- Using 3.6 Tonnes of sand
  - (like a big cat's litter box)

Also in Ice

- ...so we took it to SLAC in summer 2006.
- and built a 7.5 tonne block of ice





From PRL 99, 171101 (2007)

Flashy Ice

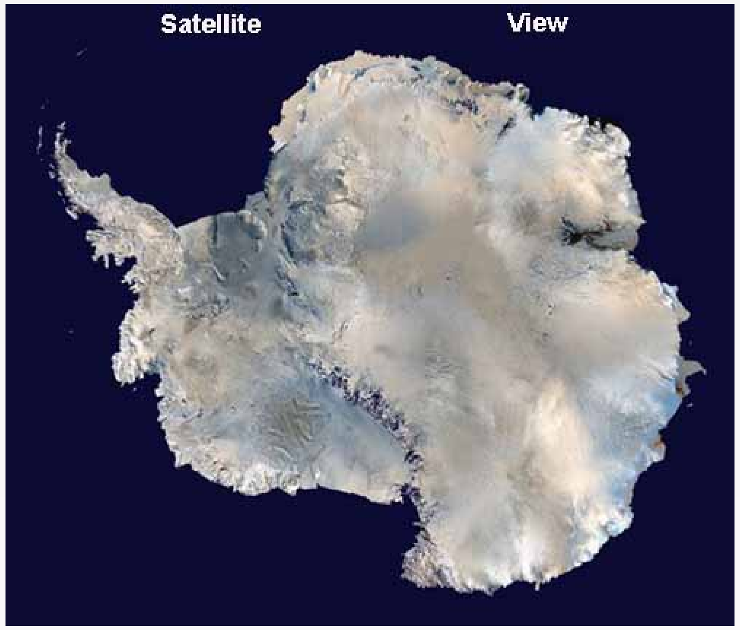
ANITA

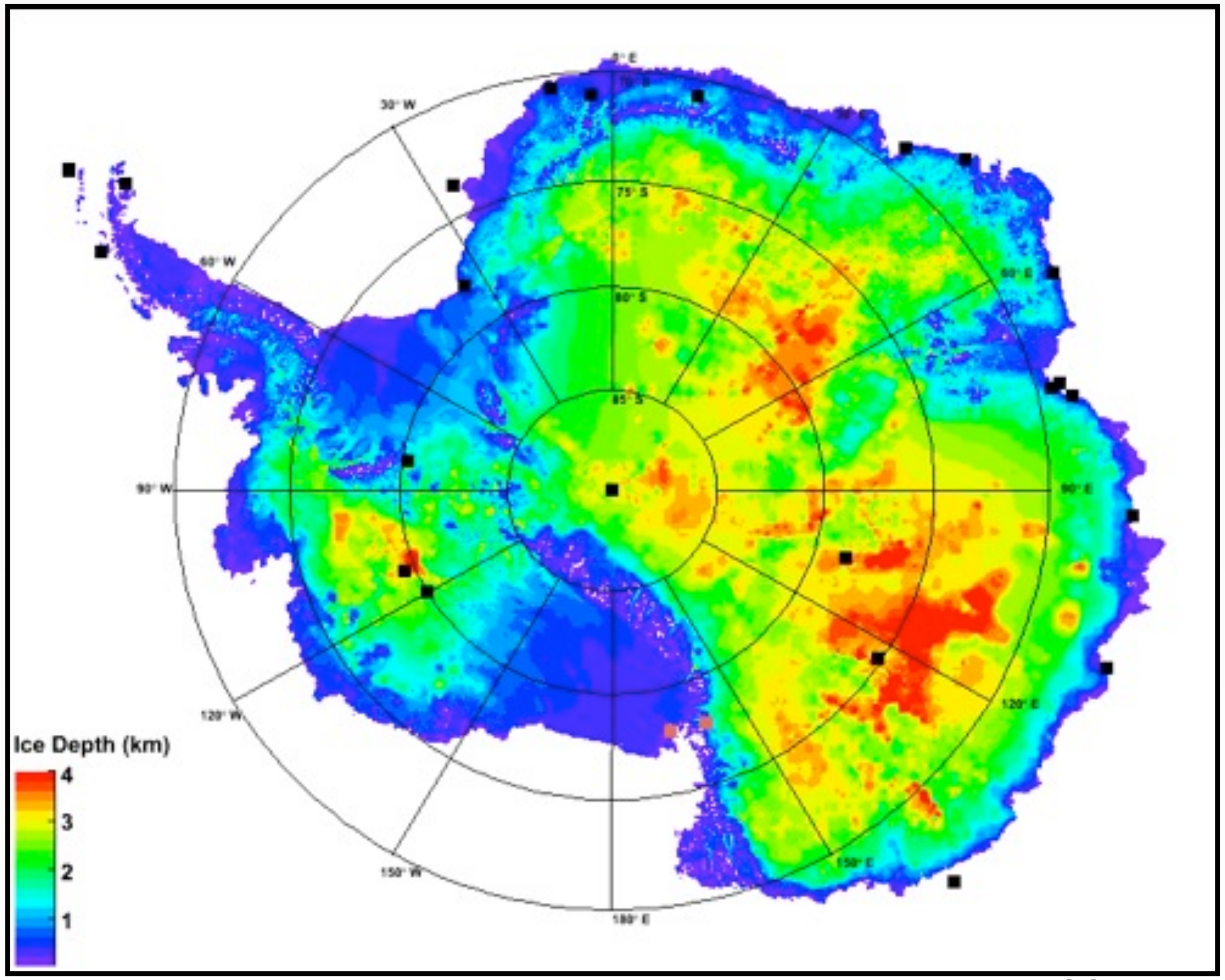
The ANITA Collaboration

- University of Hawaii at Manoa
  Honolulu, Hawaii, USA
- University of California at Irvine
  Irvine, California, USA
- University of California at Los Angeles
  Los Angeles, California, USA
- University College London
  London, UK
- University of Delaware
  Newark, Delaware
- Jet Propulsion Laboratory
  Pasadena, California, USA
- University of Kansas
  Lawrence, Kansas, USA
- University of Minnesota
  Minneapolis, Minnesota, USA
- The Ohio State University
  Columbus, Ohio, USA
- Stanford Linear Accelerator Center
  Menlo Park, California, USA
- National Taiwan University
  Taipei, Taiwan
- Washington University in St. Louis
  St. Louis, Missouri, USA

Why Antarctica?

- It is the coldest, driest, windiest place on Earth
- But...
  - Lots of Ice
    - Despite our best efforts
    - Over 4km thick in places
  - Also:
    - The only continent exclusively dedicated to scientific research
    - No indigenous (human) population
      - So relatively free of manmade noise

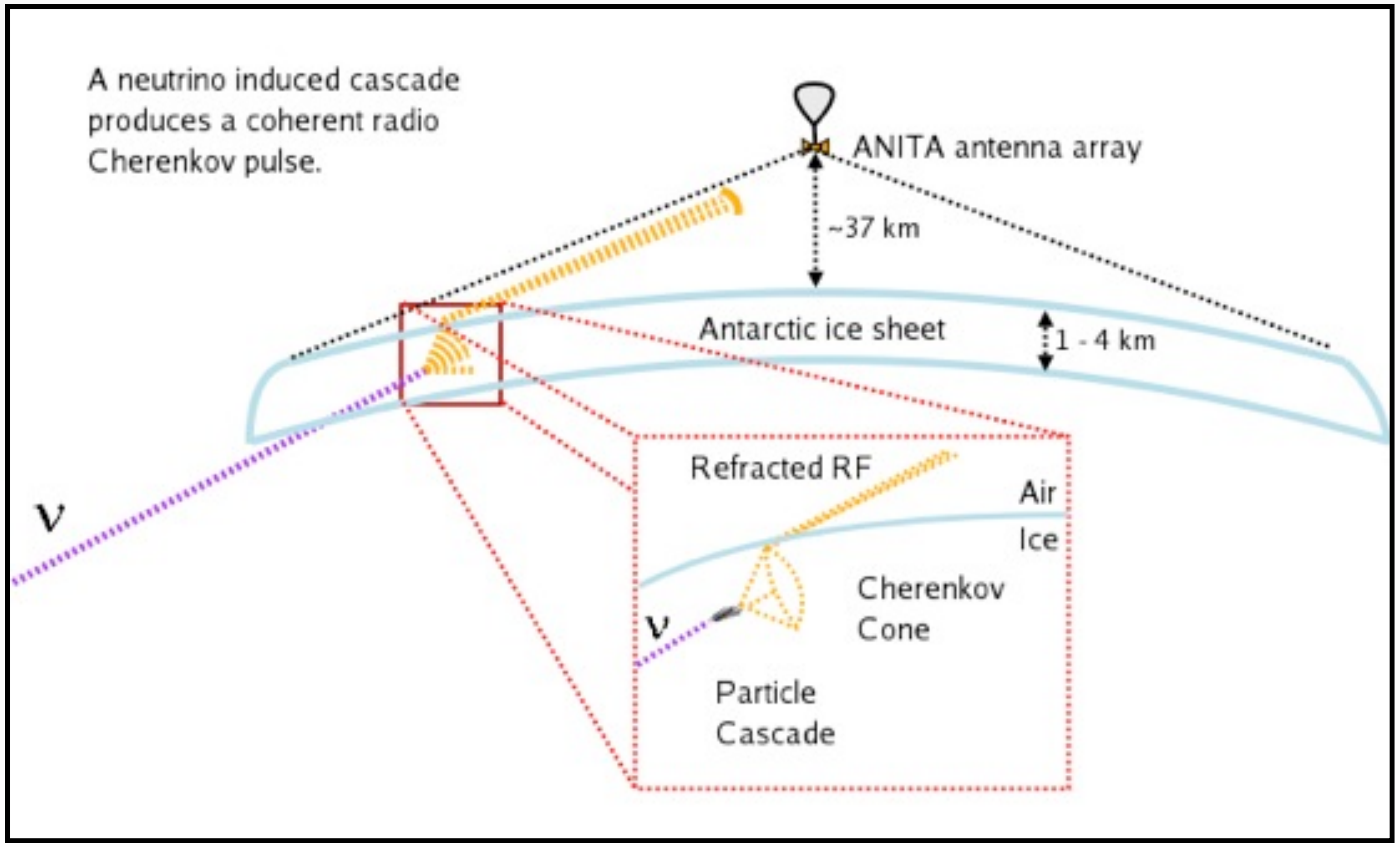


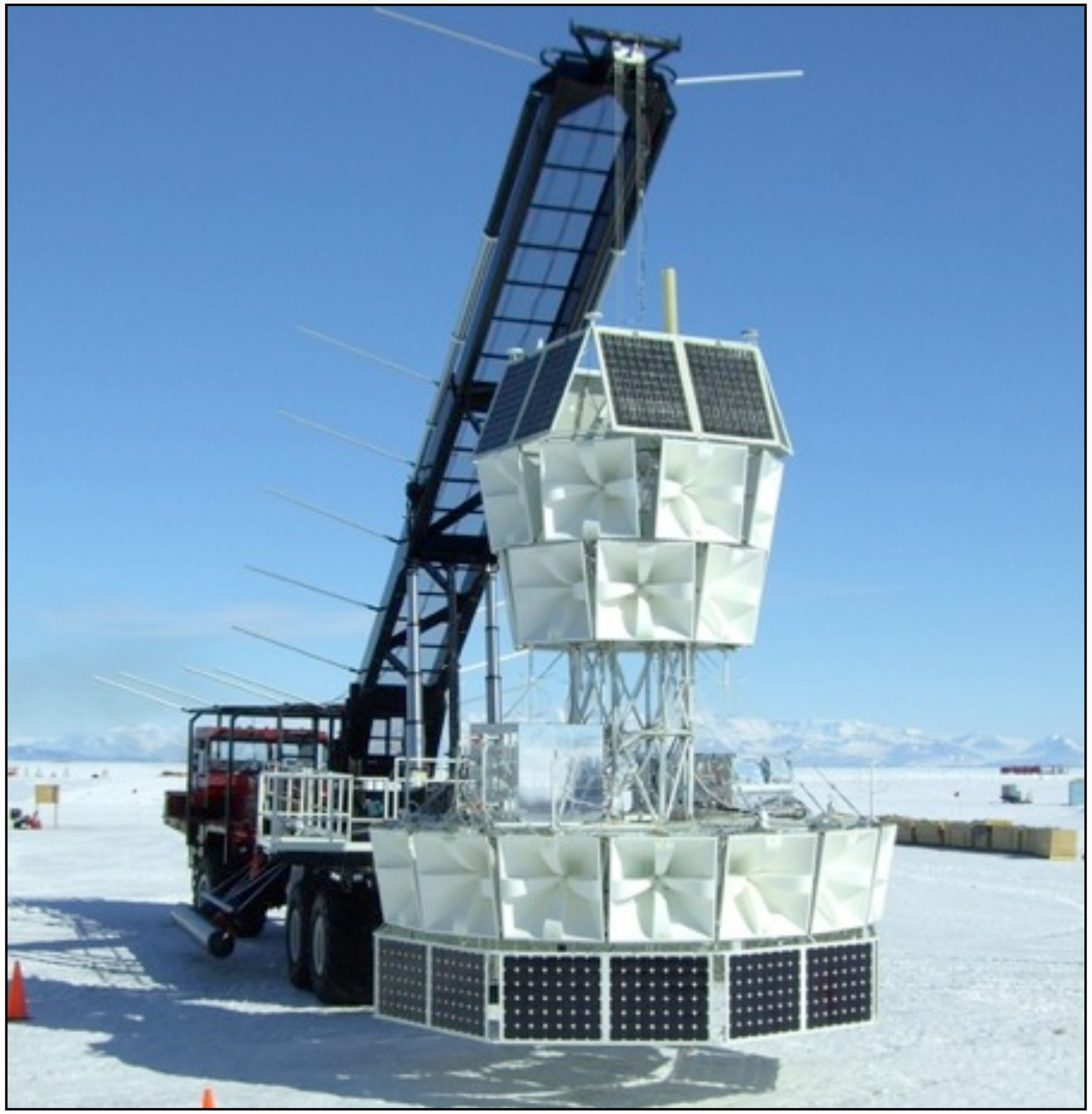


Ice depth data from BEDMAP consortium

ANITA

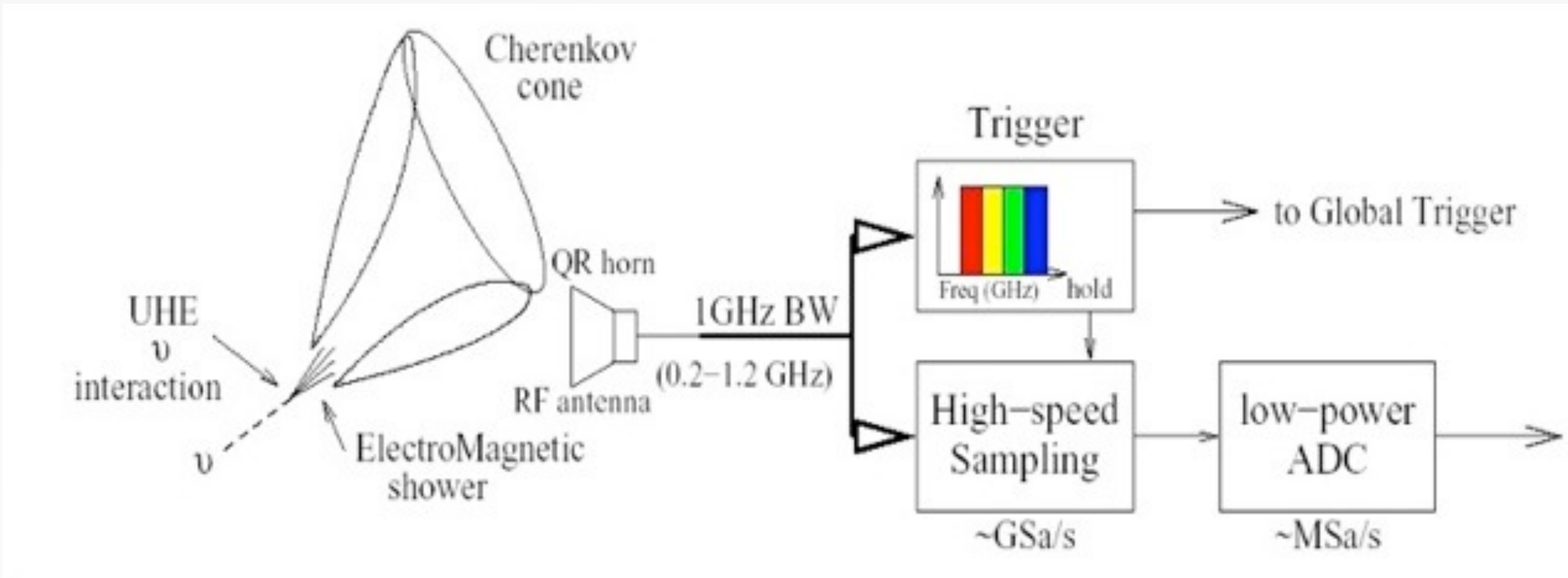
- The ANtarctic Impulsive Transient Antenna
  - A balloon borne experiment
    - 32 dual polarization antennas
    - Altitude of 37km (120,000 ft)
    - Horizon at 700km
    - Over 1 million km^3 of ice visible

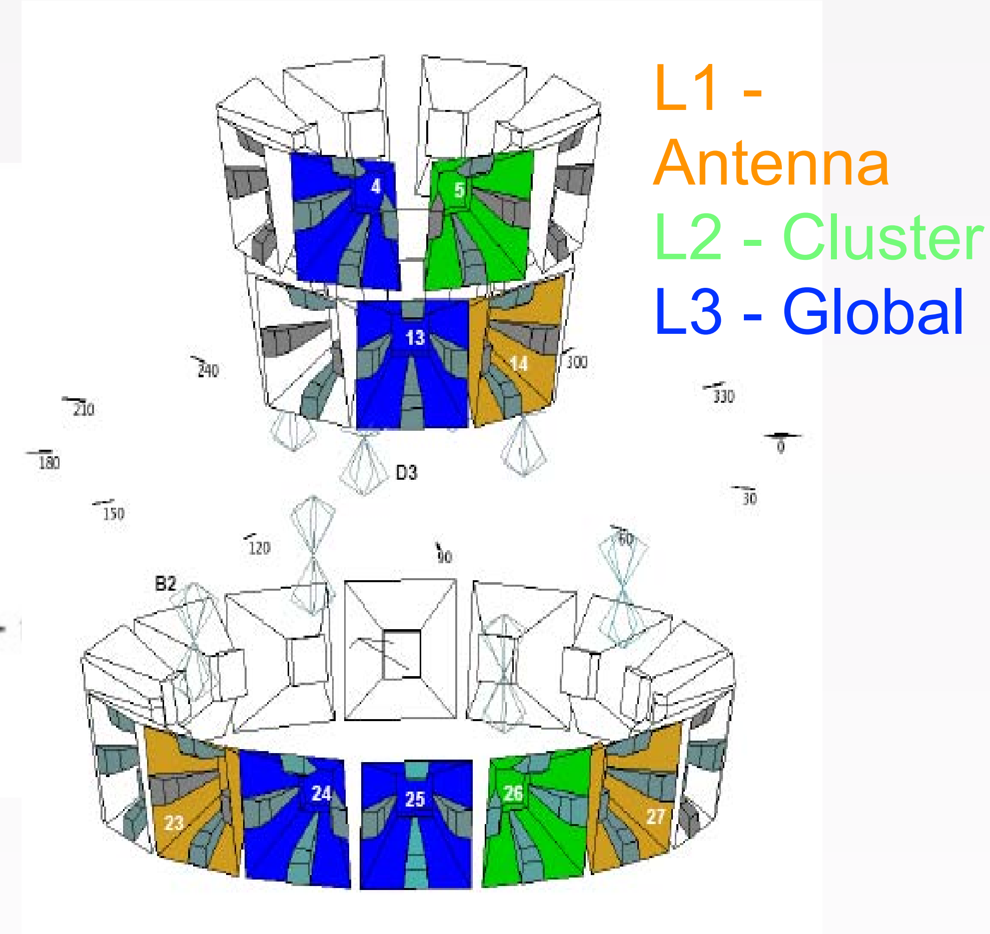




ANITA Electronics and Trigger

- Need a low power (only solar energy), 90 channel, GHz bandwidth oscilloscope.

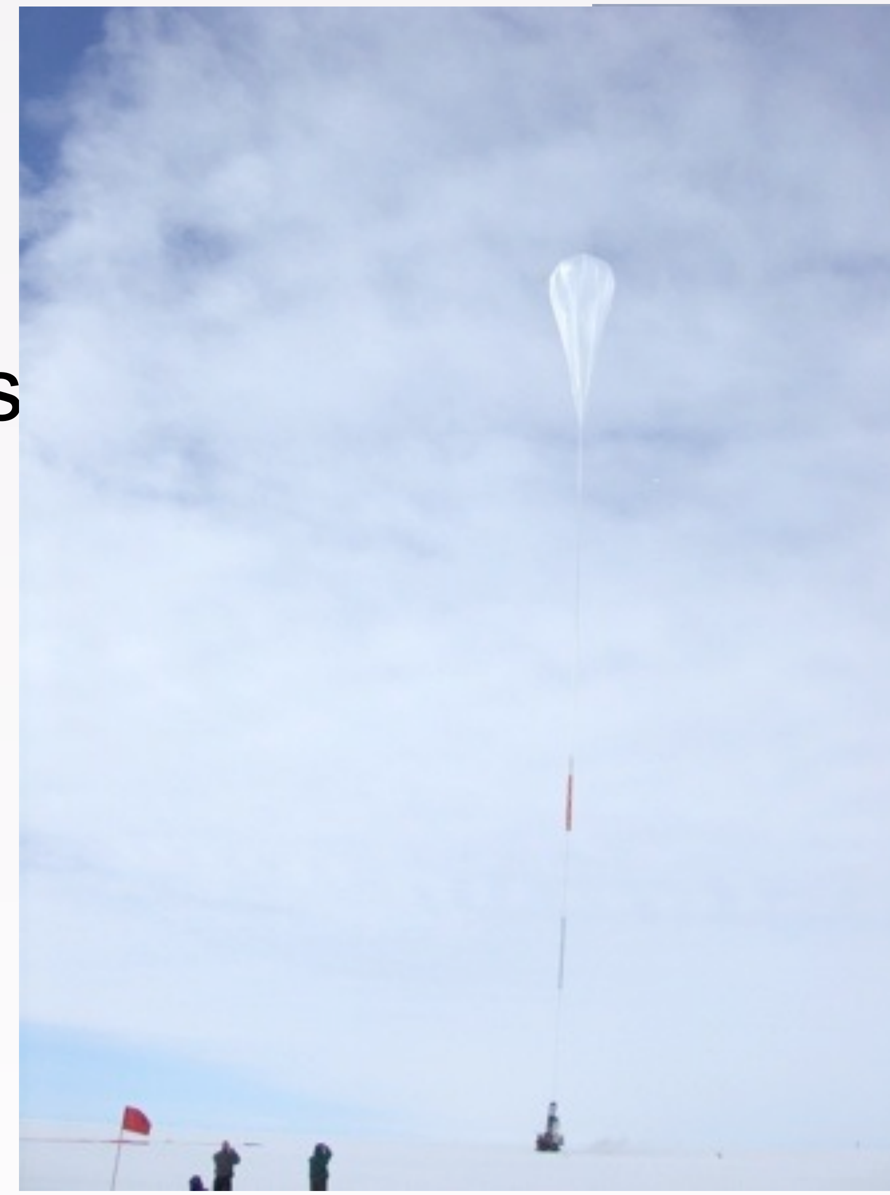


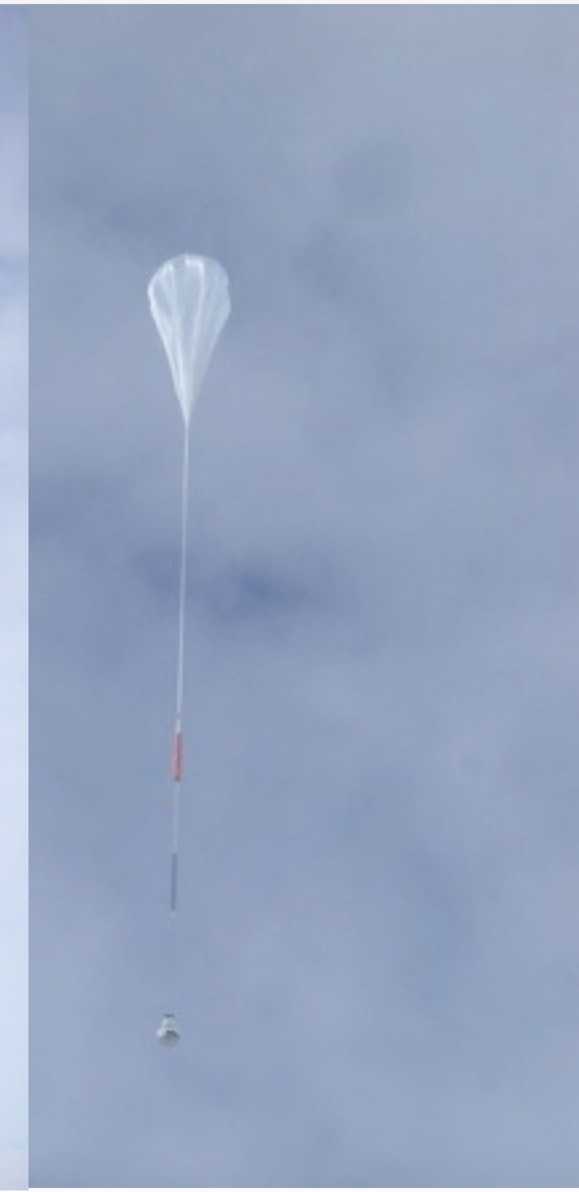


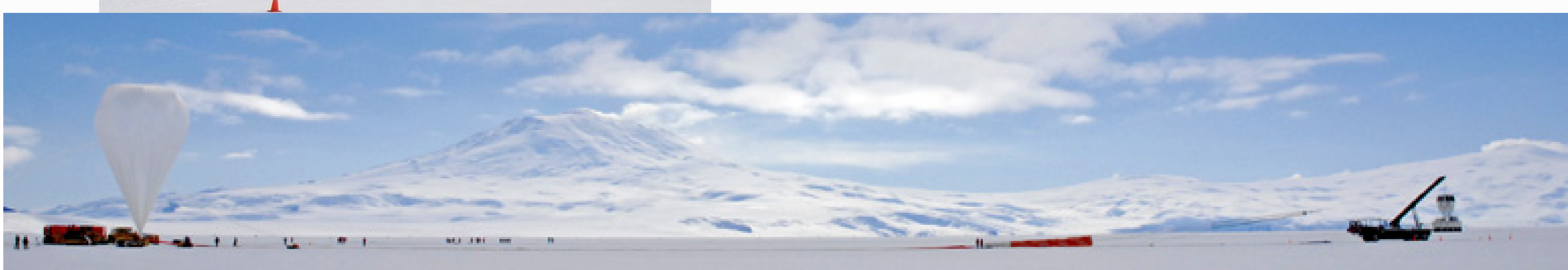
- Split trigger and waveform paths
- Use multiple frequency bands for trigger
- ‘Buffer’ waveform data in switched capacitor array
- Only digitise when we have a trigger

Up, up and away

- The Balloon
  - Just 0.02mm thick
  - Takes 100 million litres of helium (and several hours) to fill

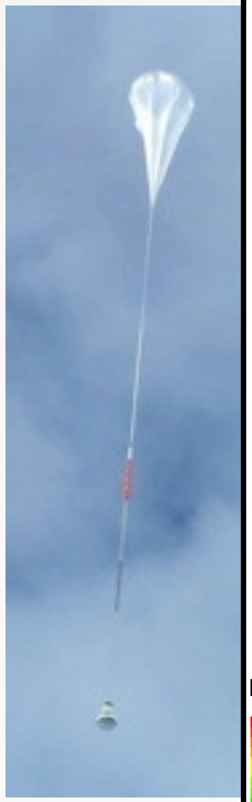


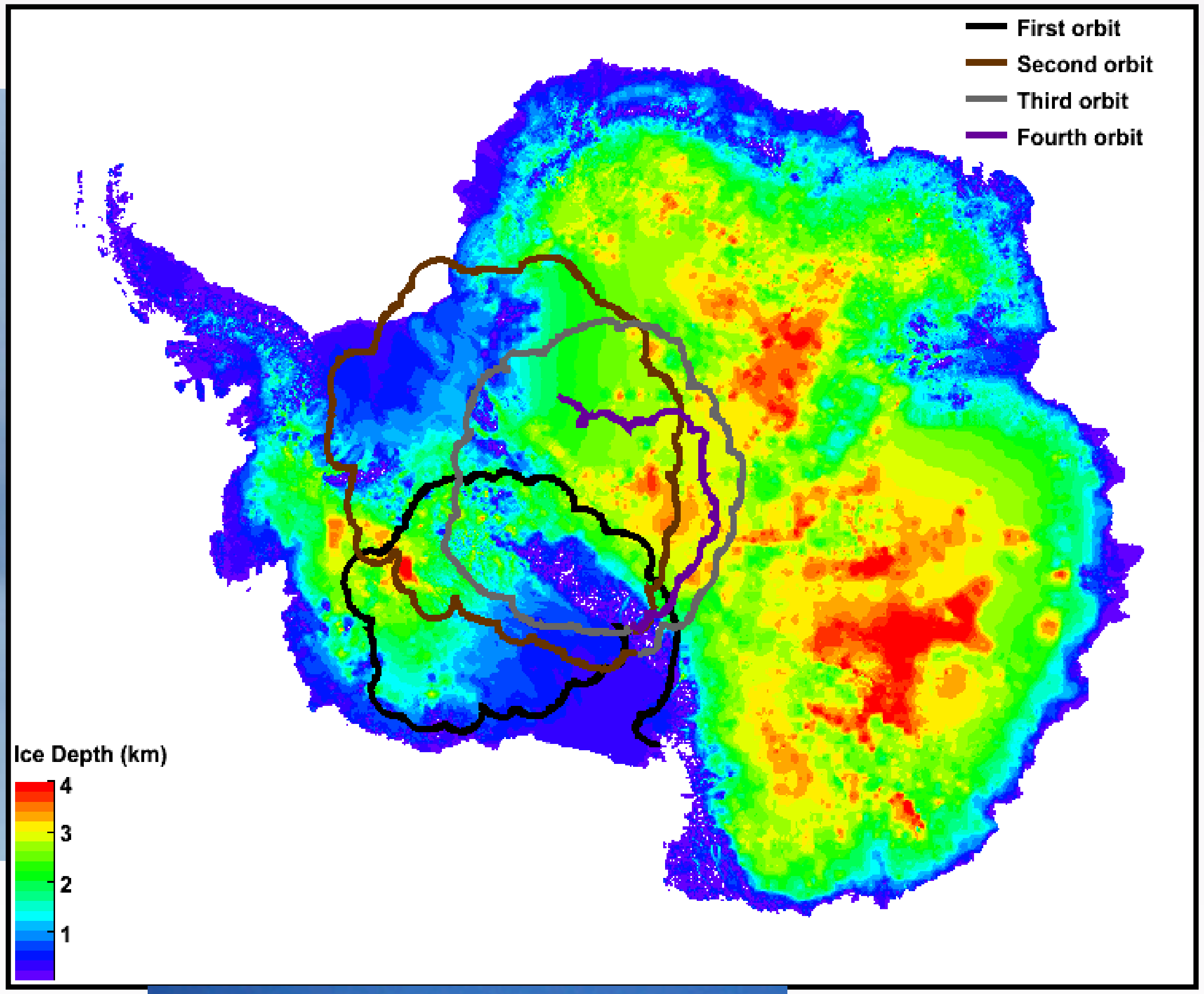


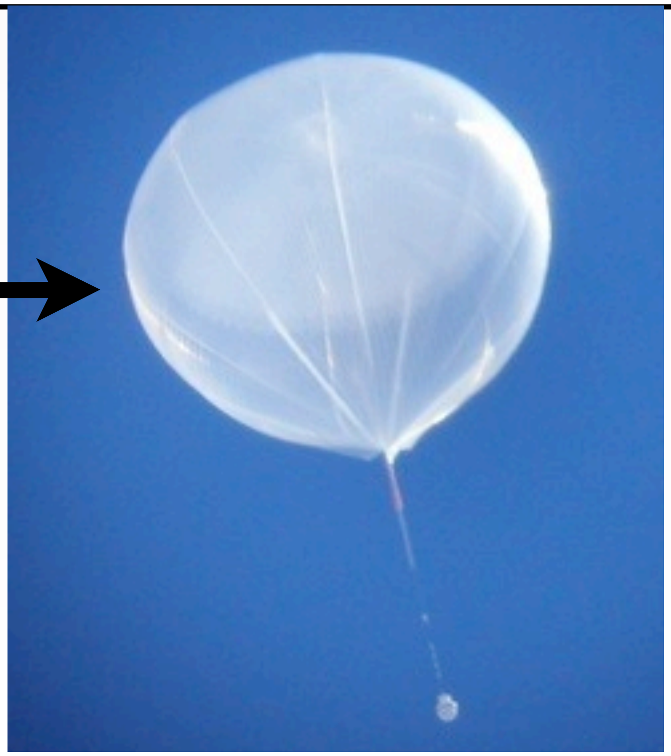


The First Flight

- Lasted 35 days (the record is 42)
  - Three and a half sort of polar orbits
  - Recorded over 8 million triggers
    - Maybe 1 or 2 neutrinos



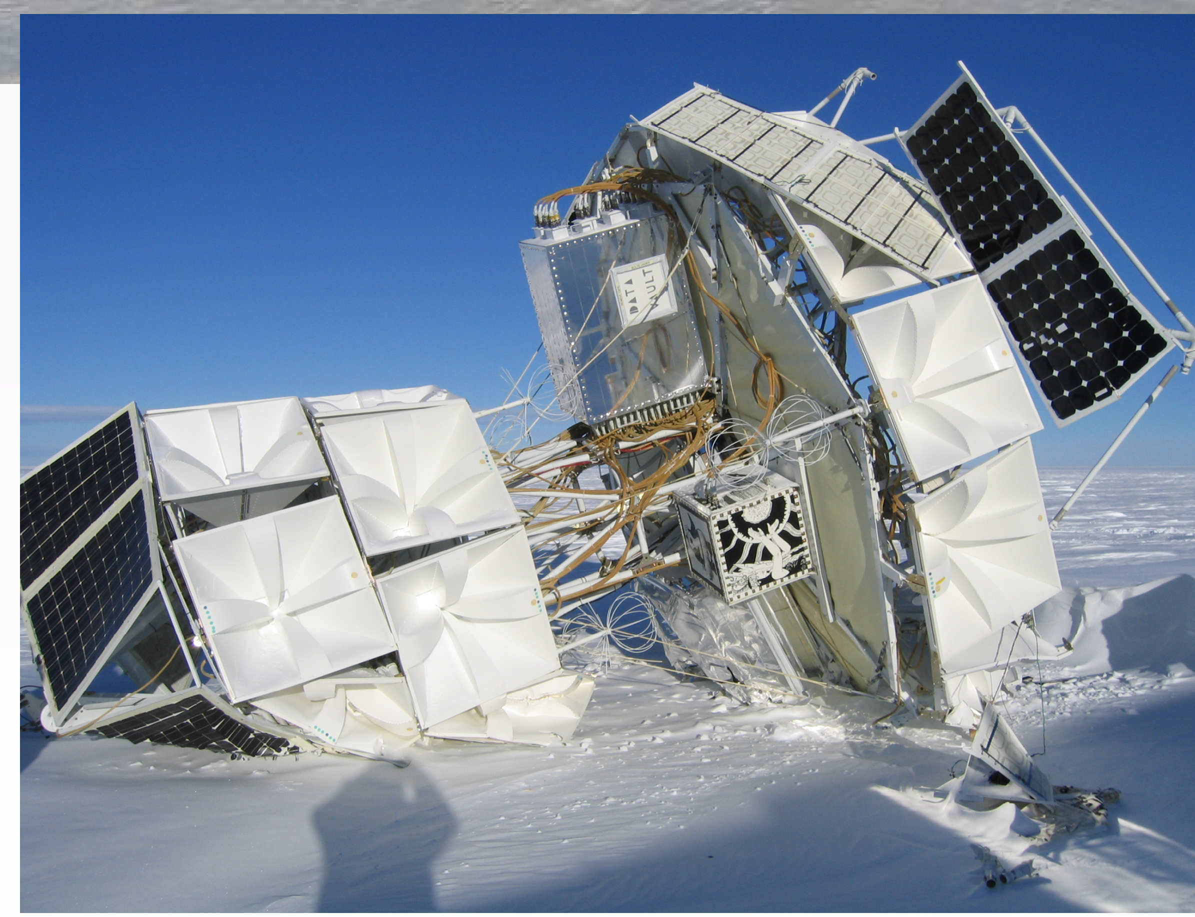




Fits inside the balloon at altitude

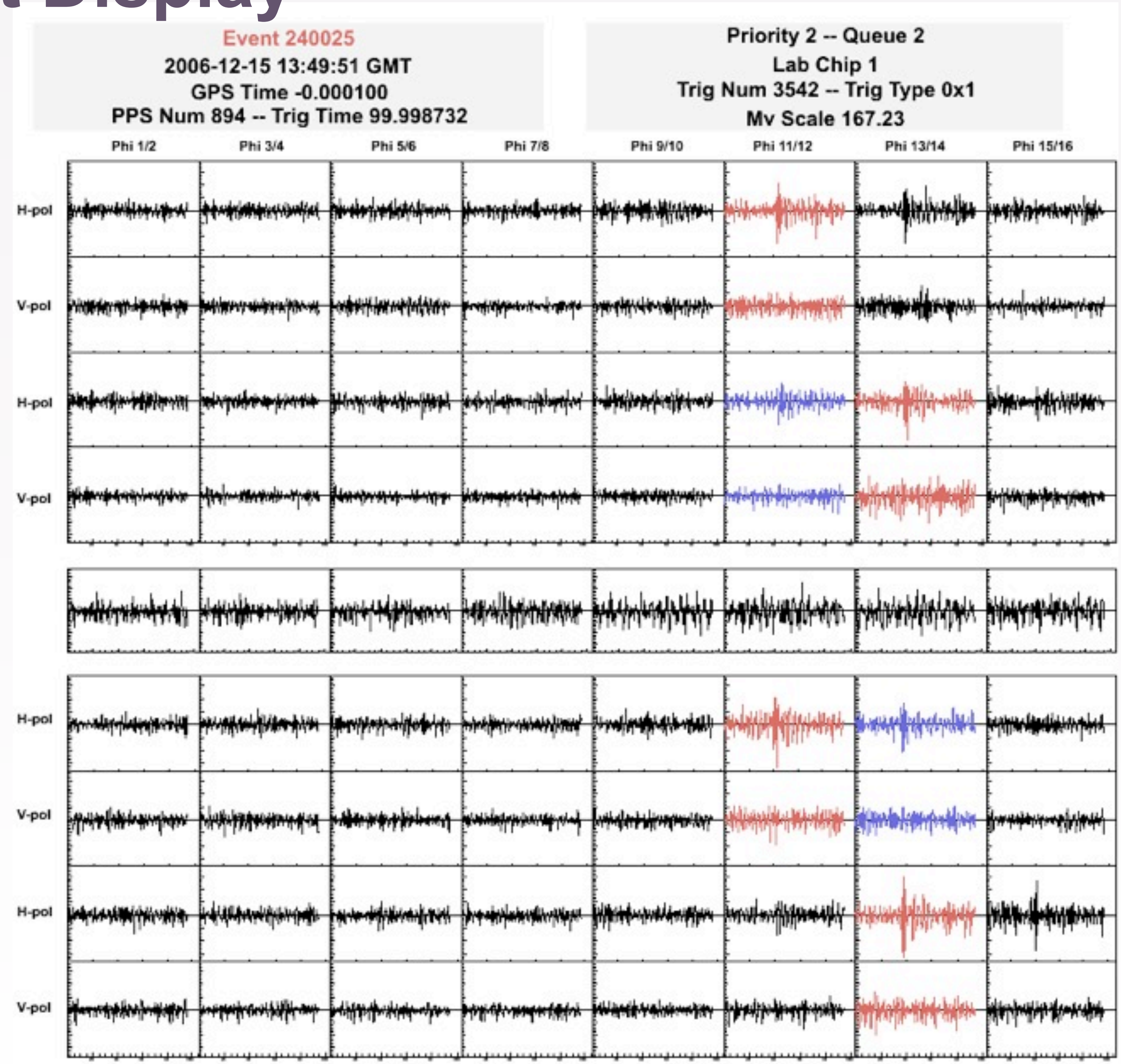
What Goes Up...

- The Landing:
  - Initiated by detonating small explosive to separate from balloon
  - Descend gently on a parachute to the ground
  - Release parachute to prevent dragging
    - In 2006, BLAST was dragged for 100 miles (ending up in a crevice)
    - A few years ago one was dropped from 5000 feet

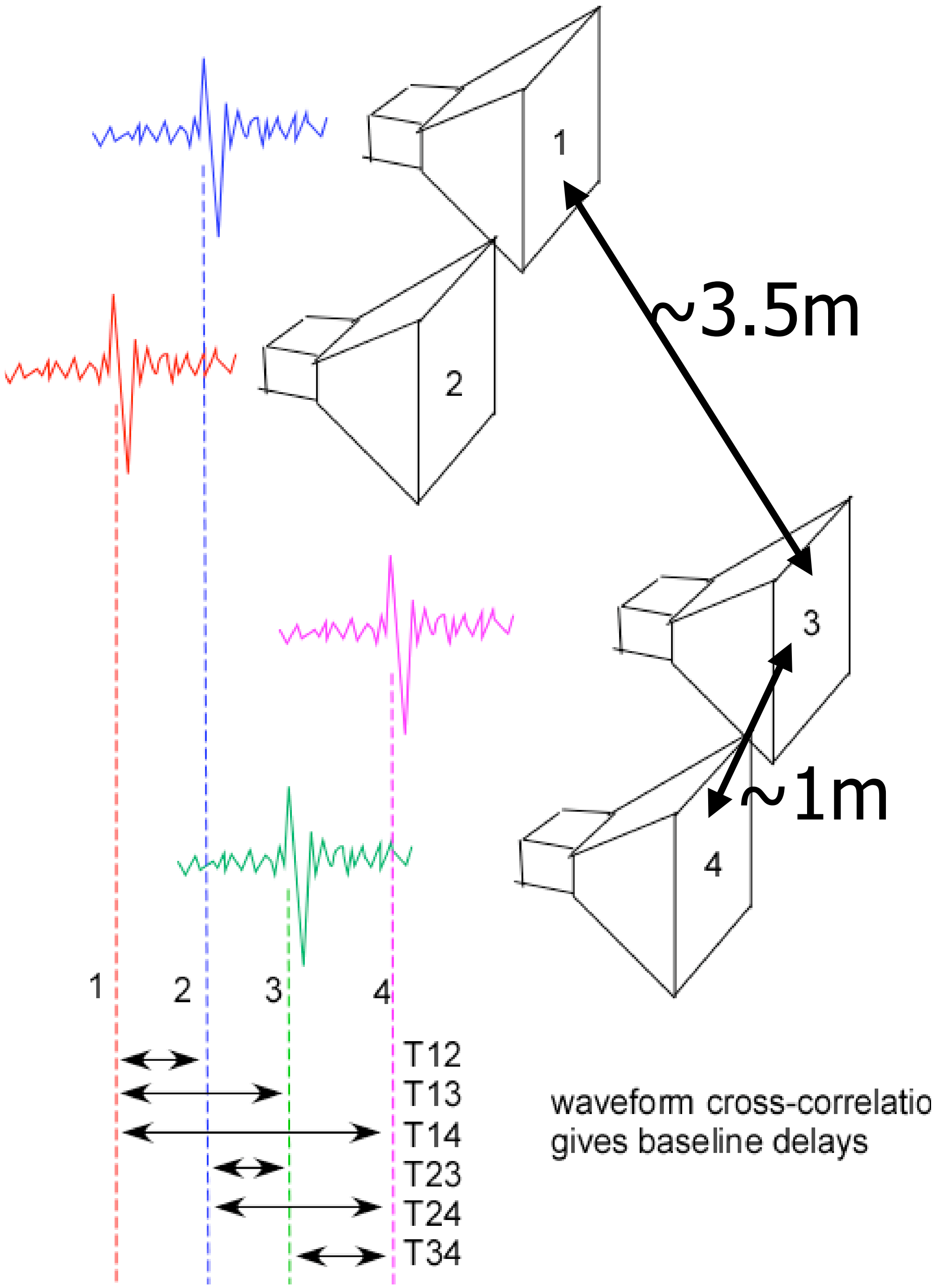


Photos from Dana Braun

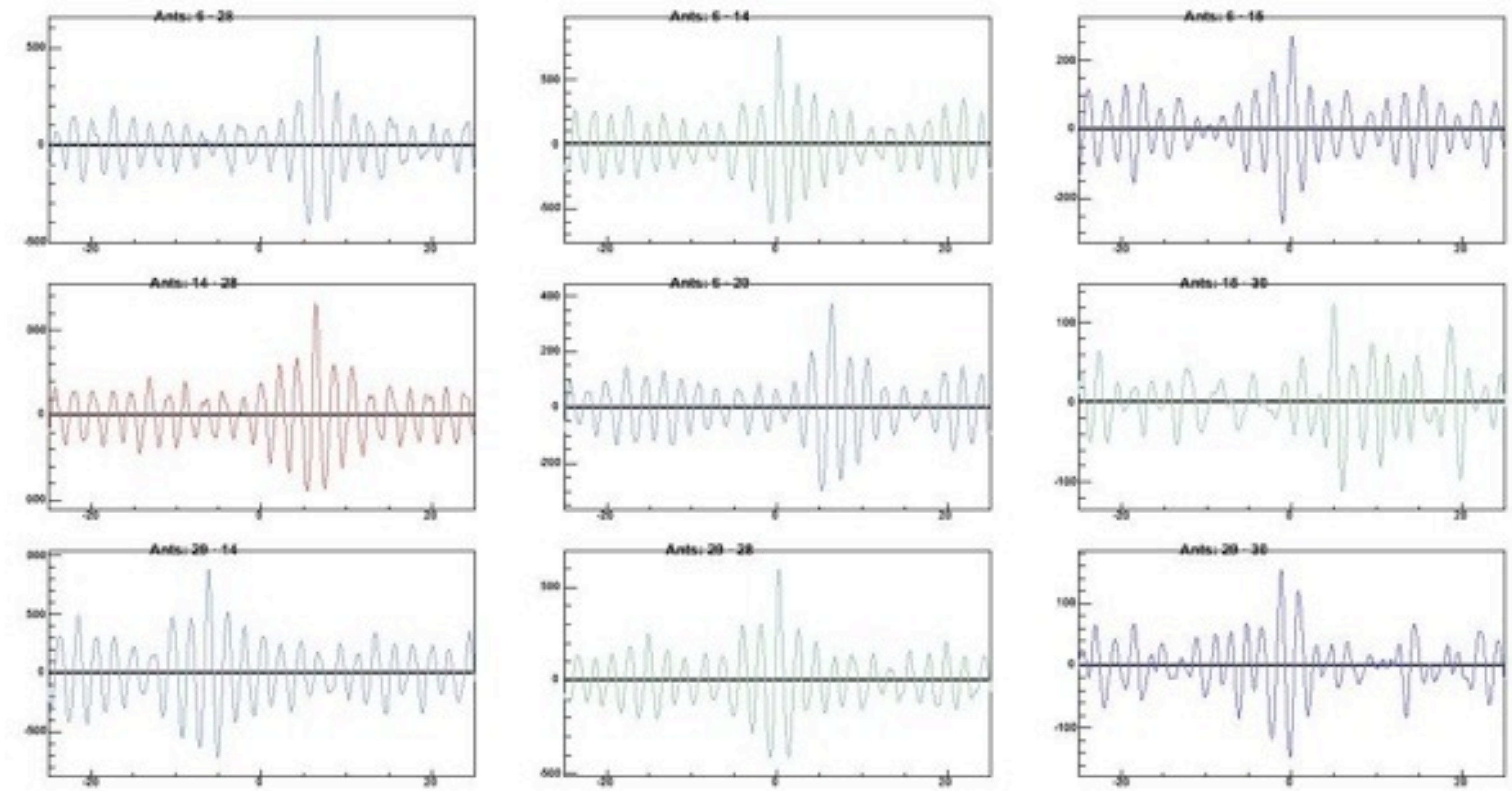
Event Display

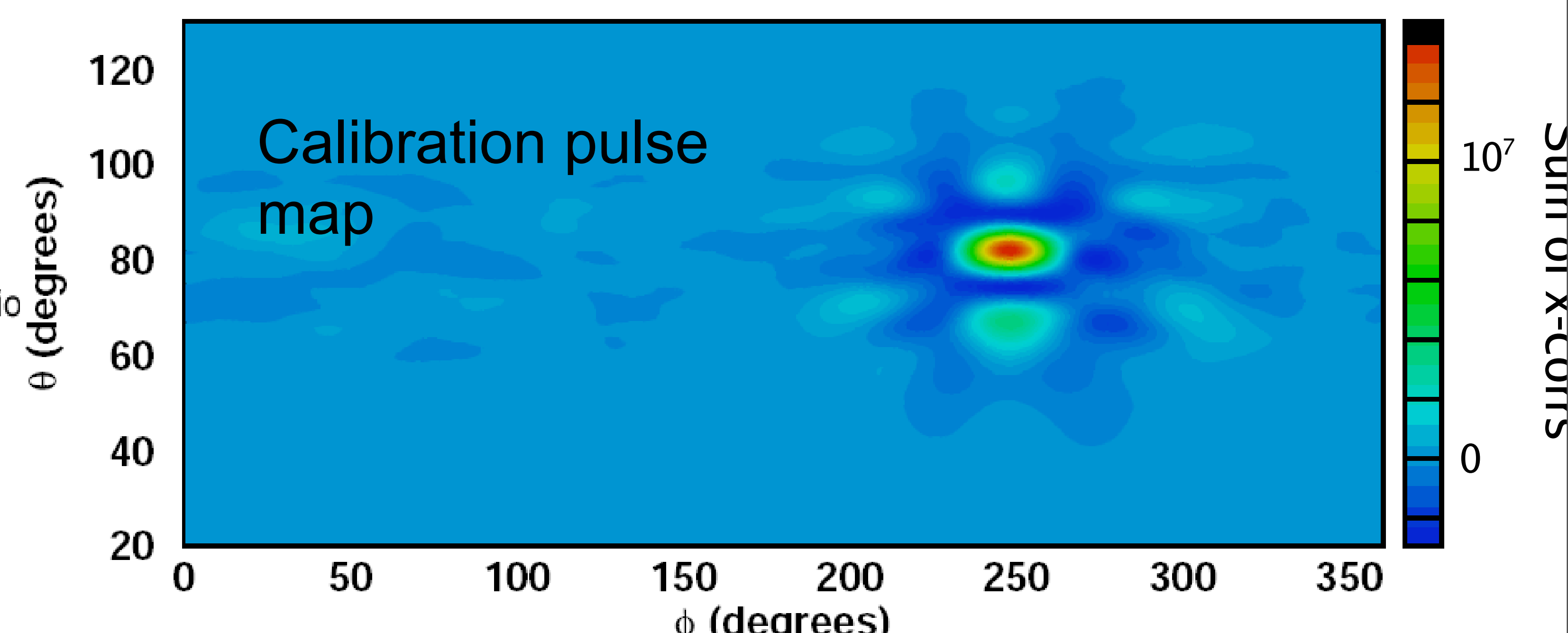


Event Reconstruction



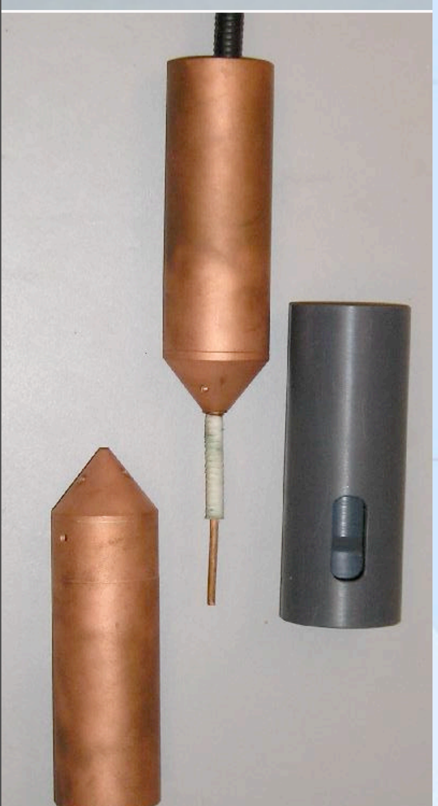
Cross-Correlated Waveforms

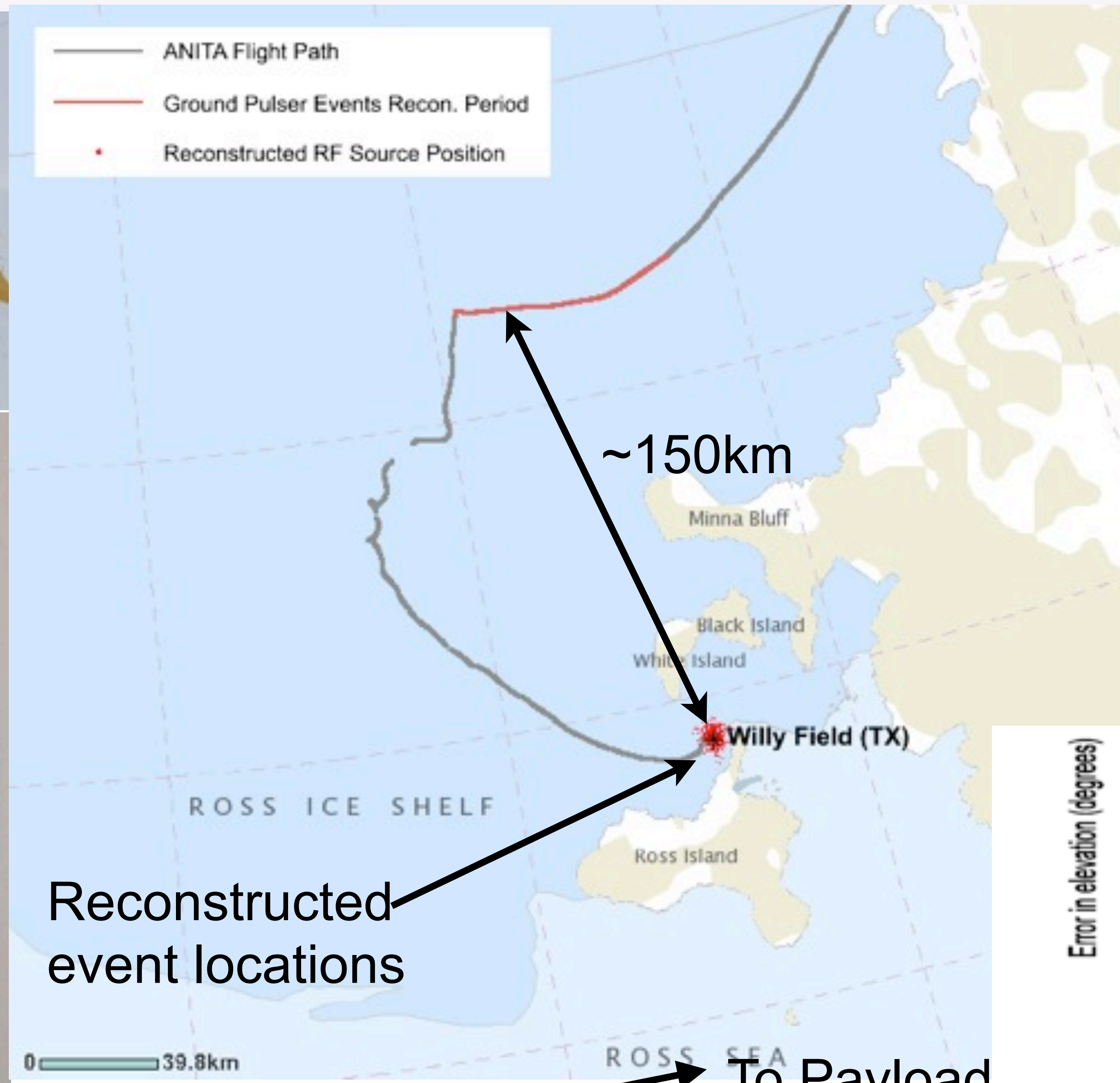


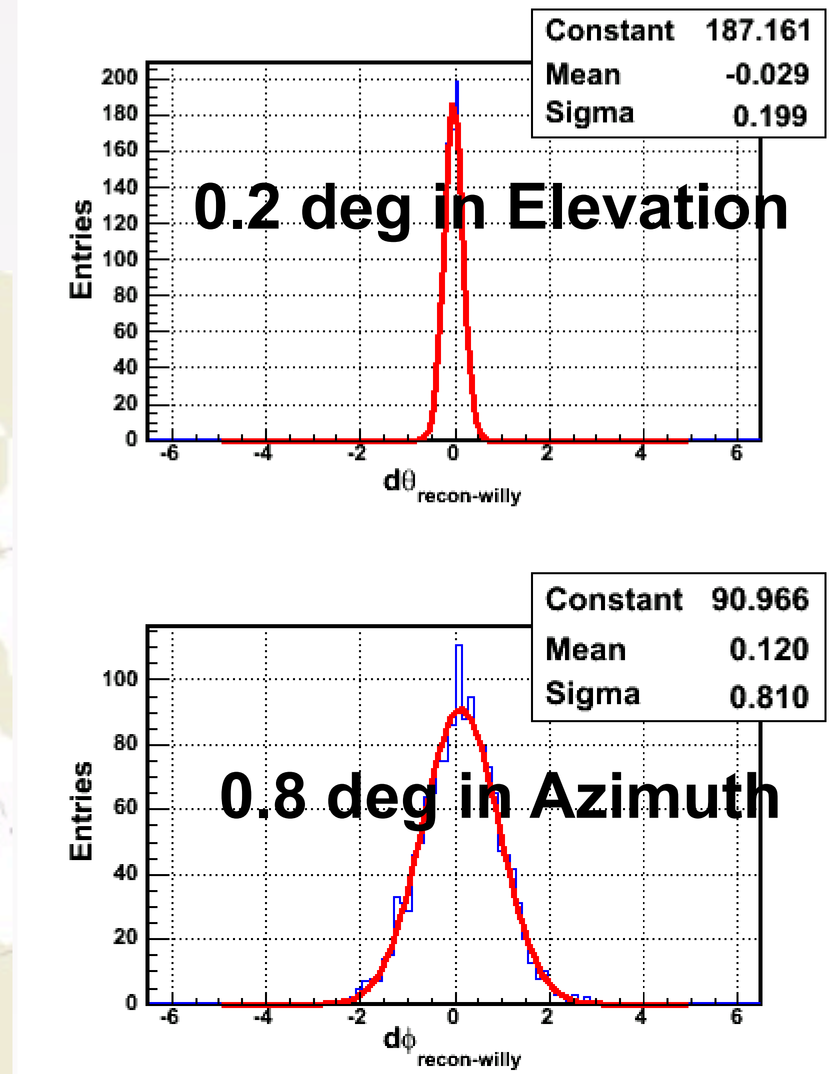


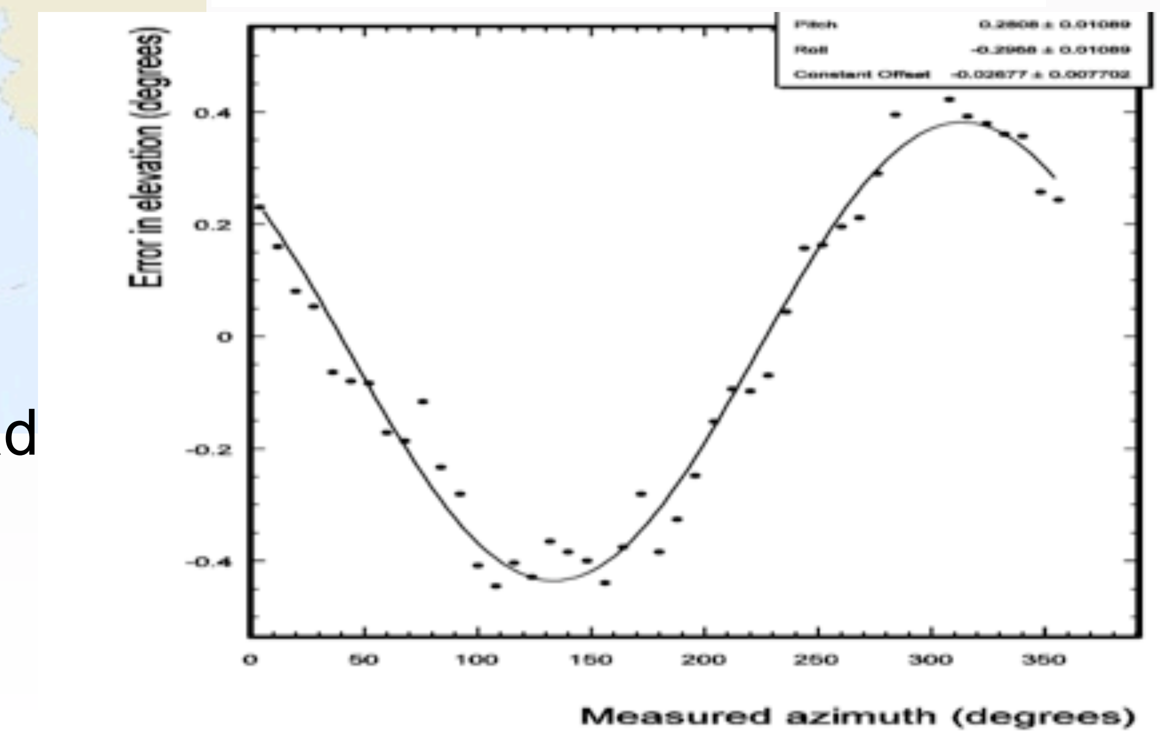
from A. Romero Wolf, Neutrino 2008

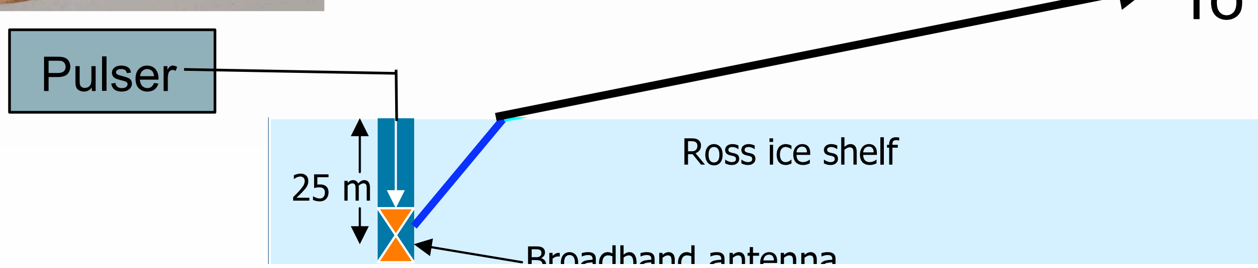
Borehole Calibration



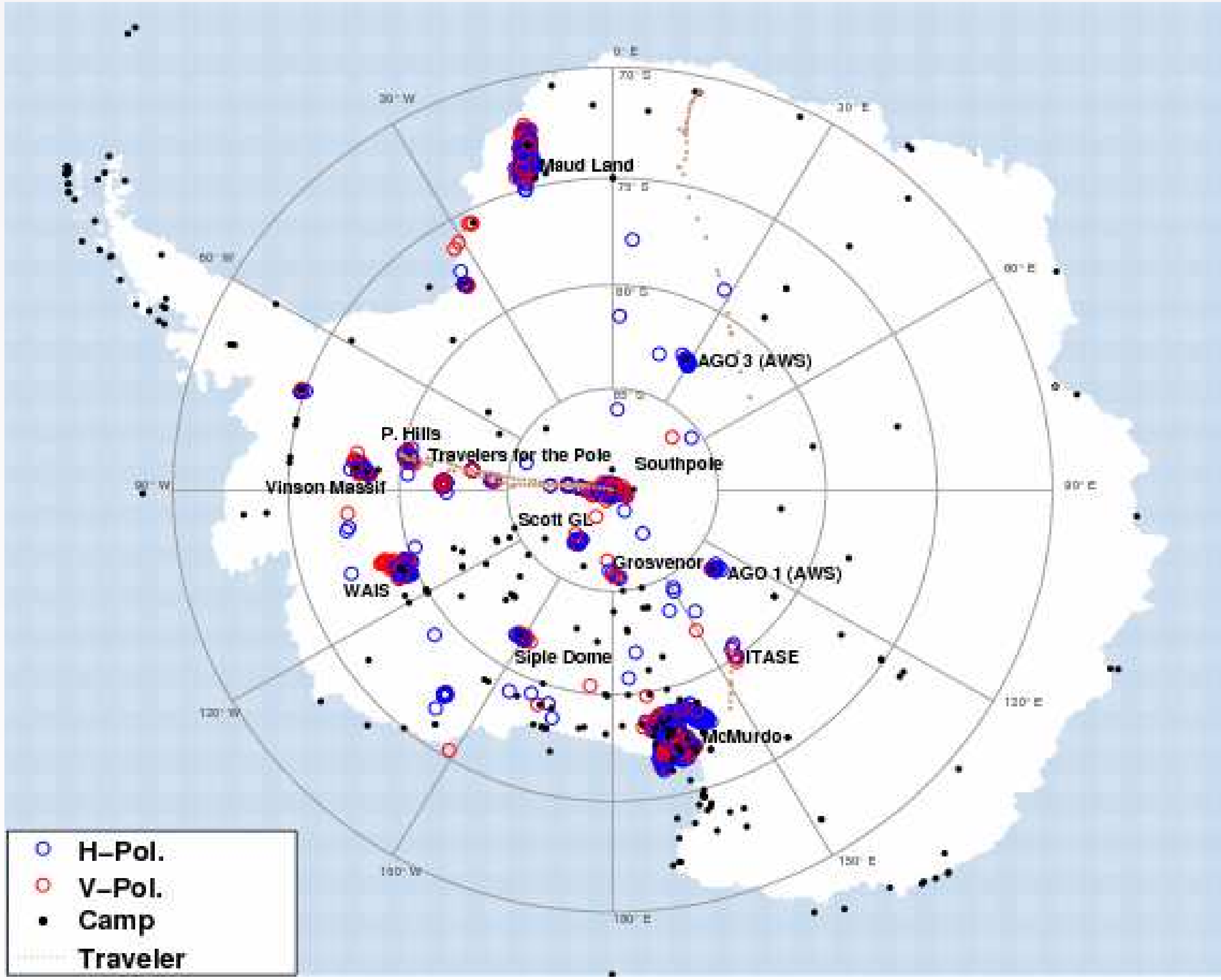








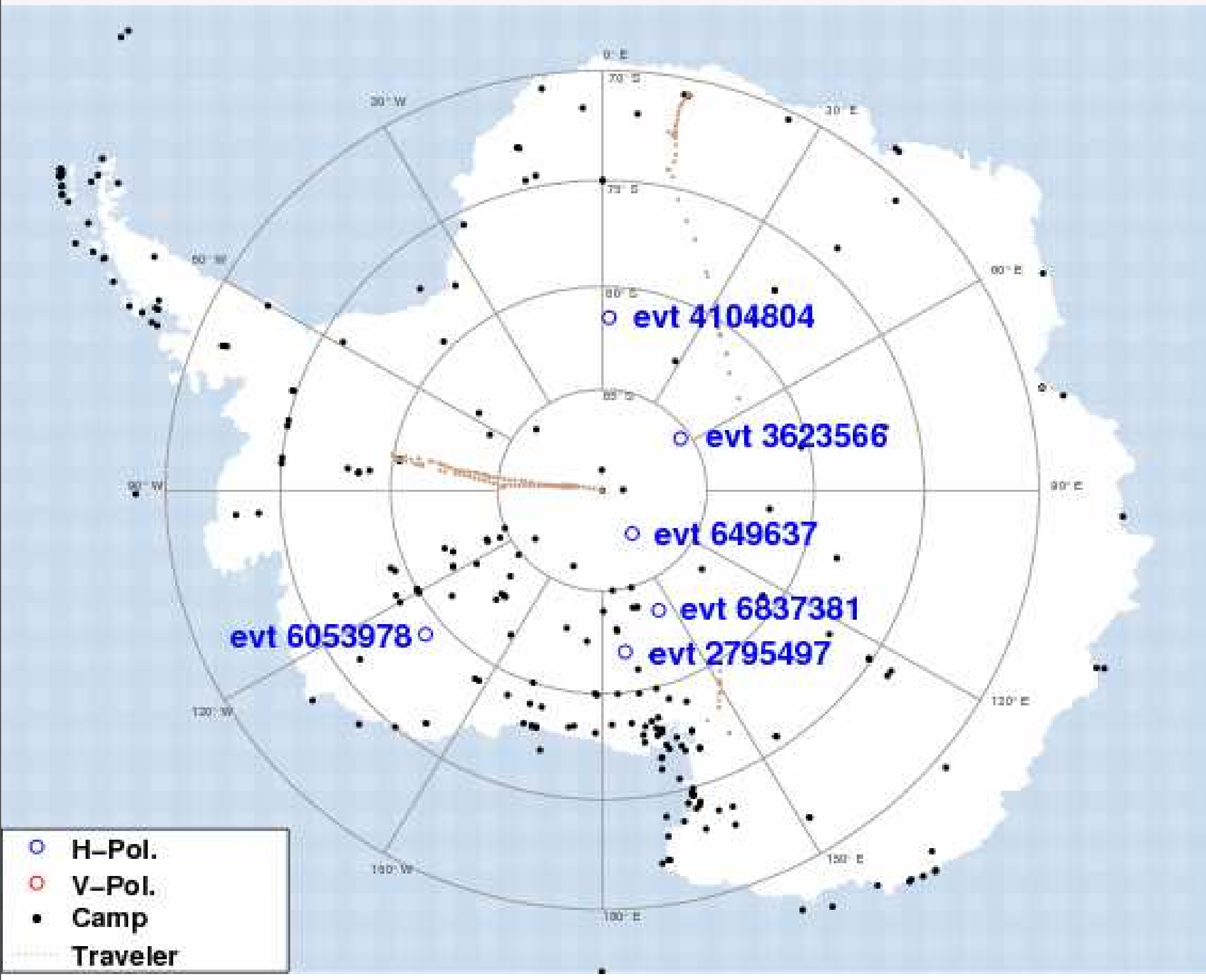
ANITA-I -- Initial High Threshold Analysis



- ~19K events (9.6K V-Pol & 10K H-Pol) are impulsive and reconstruct to Ant. ice
- Exclude all repeating locations (H, V, H+V)
- Exclude single events within 50km of known sites

“Camp” = any human-made installation, active or not

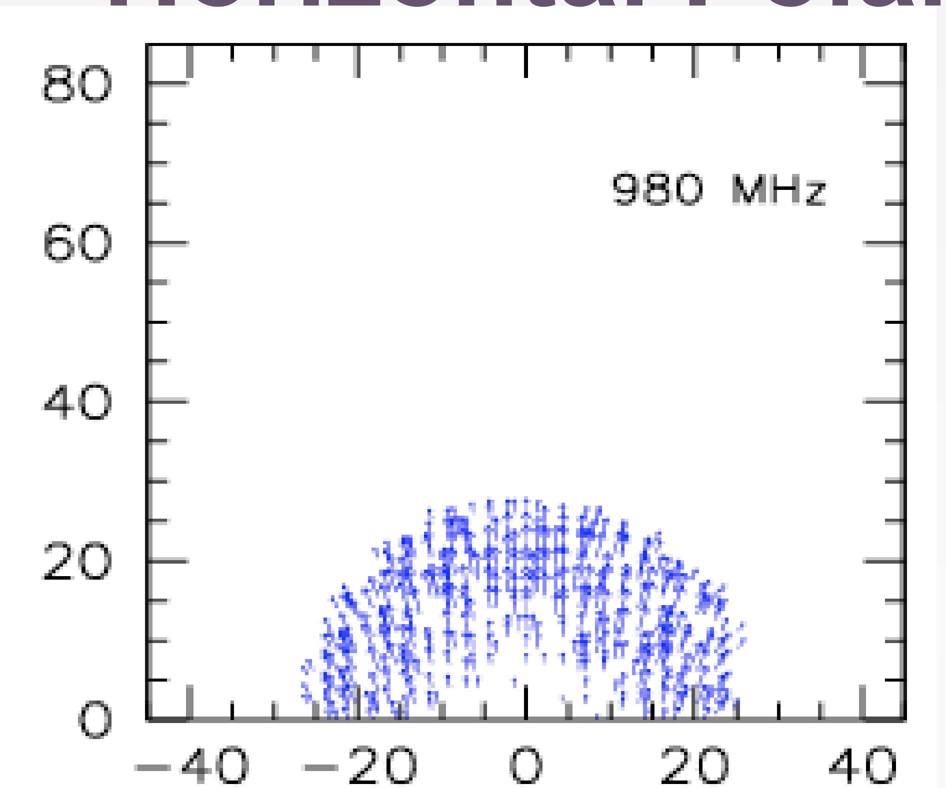
ANITA-I -- Initial High Threshold Analysis

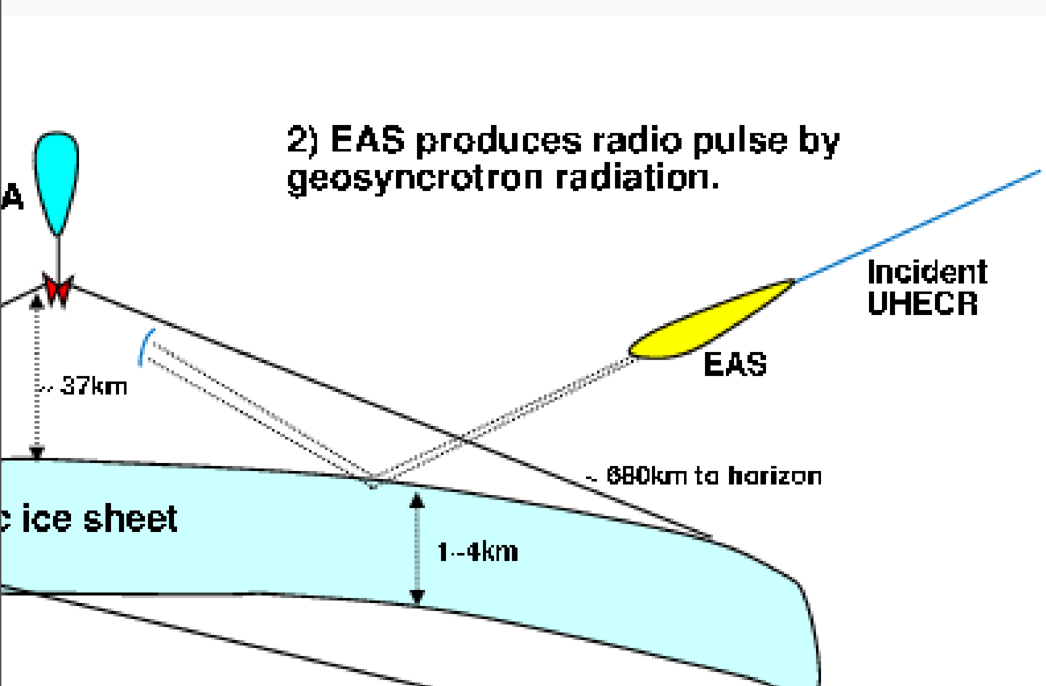


"Camp" = any human-made installation, active or not

- ~19K events (9.6K V-Pol & 10K H-Pol) are impulsive and reconstruct to Ant. ice
- Exclude all repeating locations (H, V, H+V)
- Exclude single events within 50km of known sites
- After these cuts:
  - 0 V-Pol (no Askaryan like neutrino signals)
  - 6 H-Pol

Horizontal Polarisation??



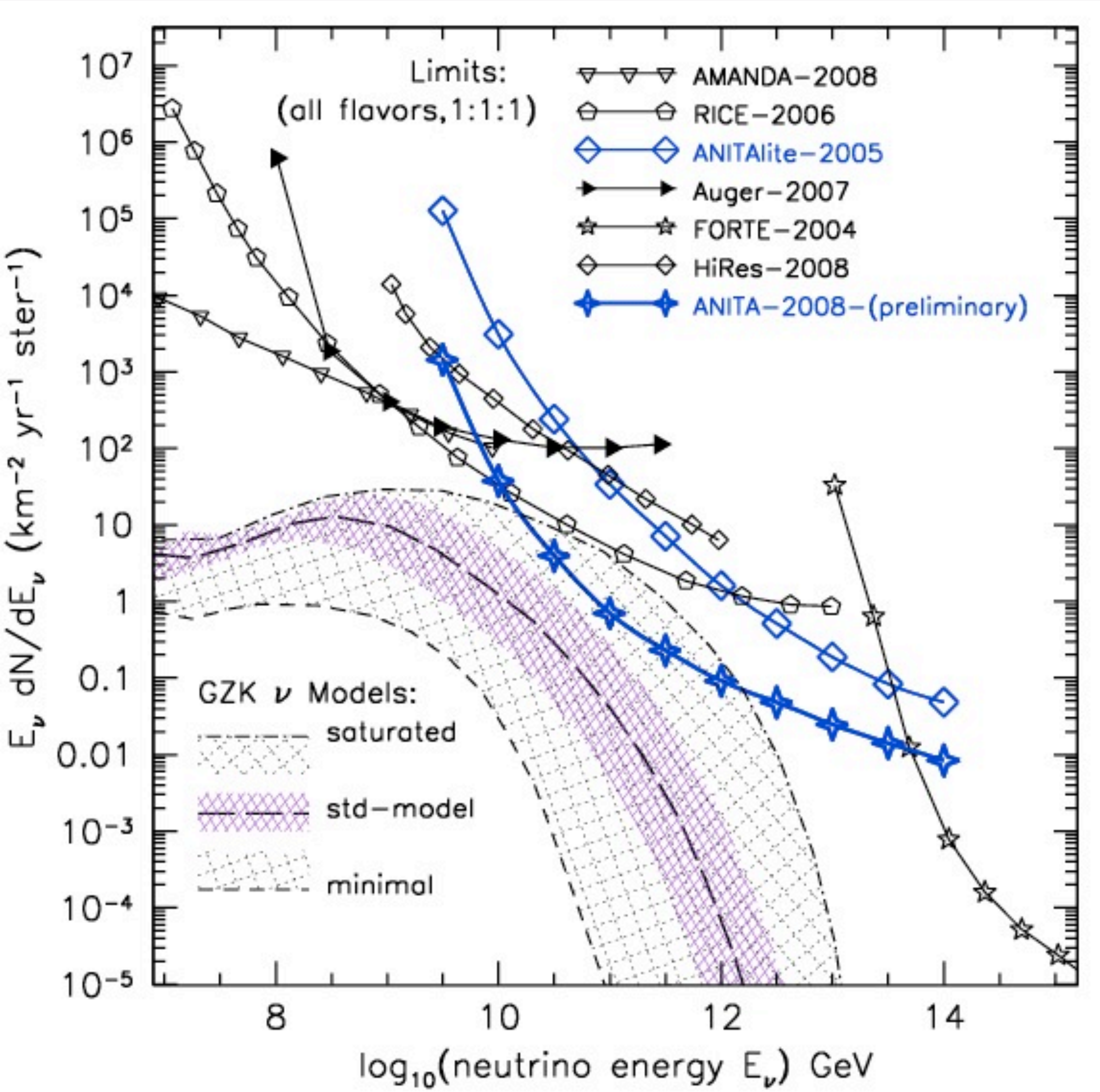


- Askaryan signals strongly favour vertical polarisation
  - Only top of Cherenkov cone escapes TIR at surface
  - Fresnel coefficients transmit more V-pol than H-pol
- Reflections from above the horizon sources would favour H-pol over V-pol at the balloon

H-pol events are not neutrinos but could be:

- Radio signals from cosmic ray air shower

ANITA-I Results

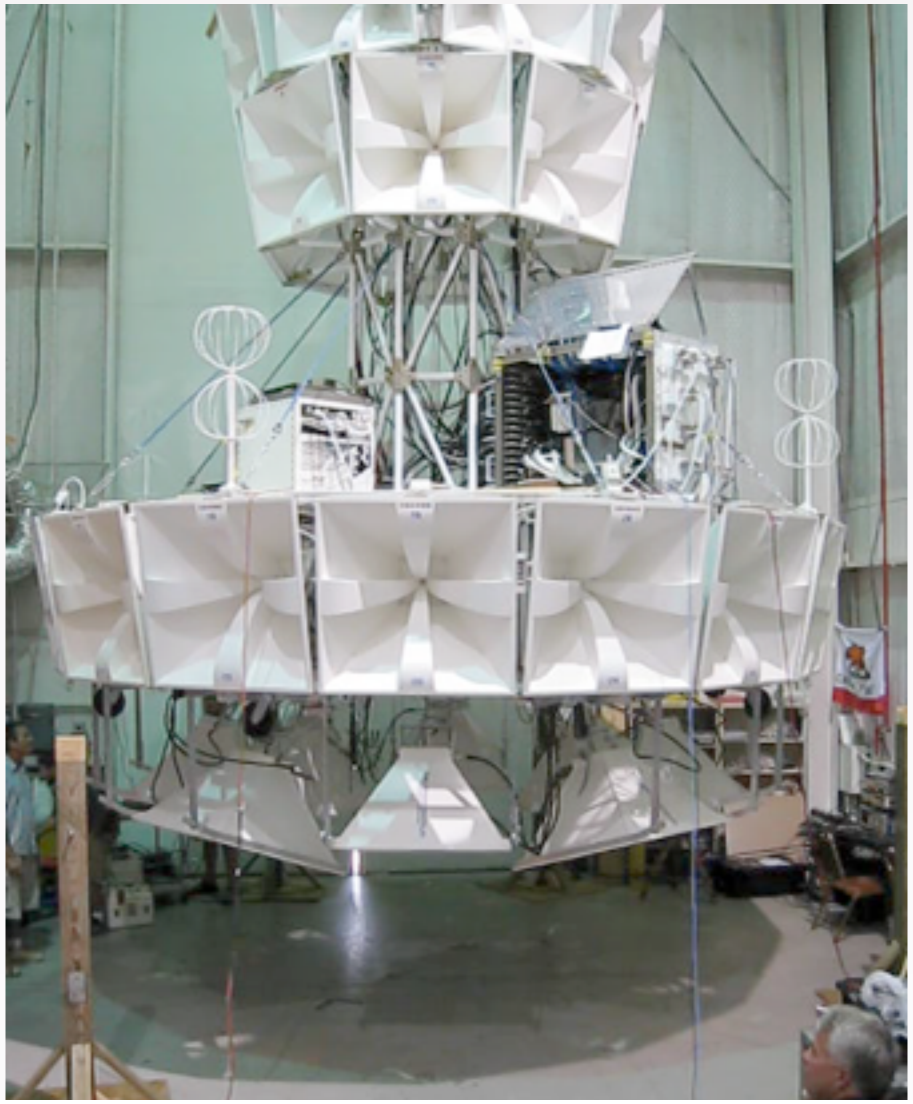


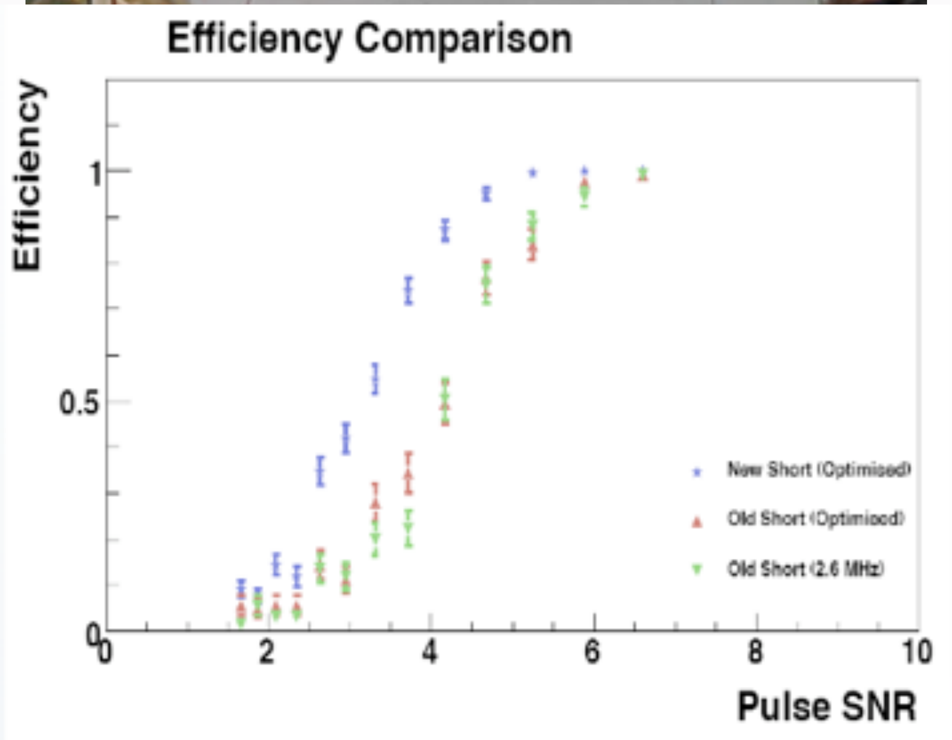
From PRL 103, 051103 (2009)

- ANITA-I limit has begun to constrain some of the highest (less likely) GZK models.
- ANITA-II (launched in Dec. 2008) with much improved sensitivity compared to ANITA-I

ANITA-II Improvements

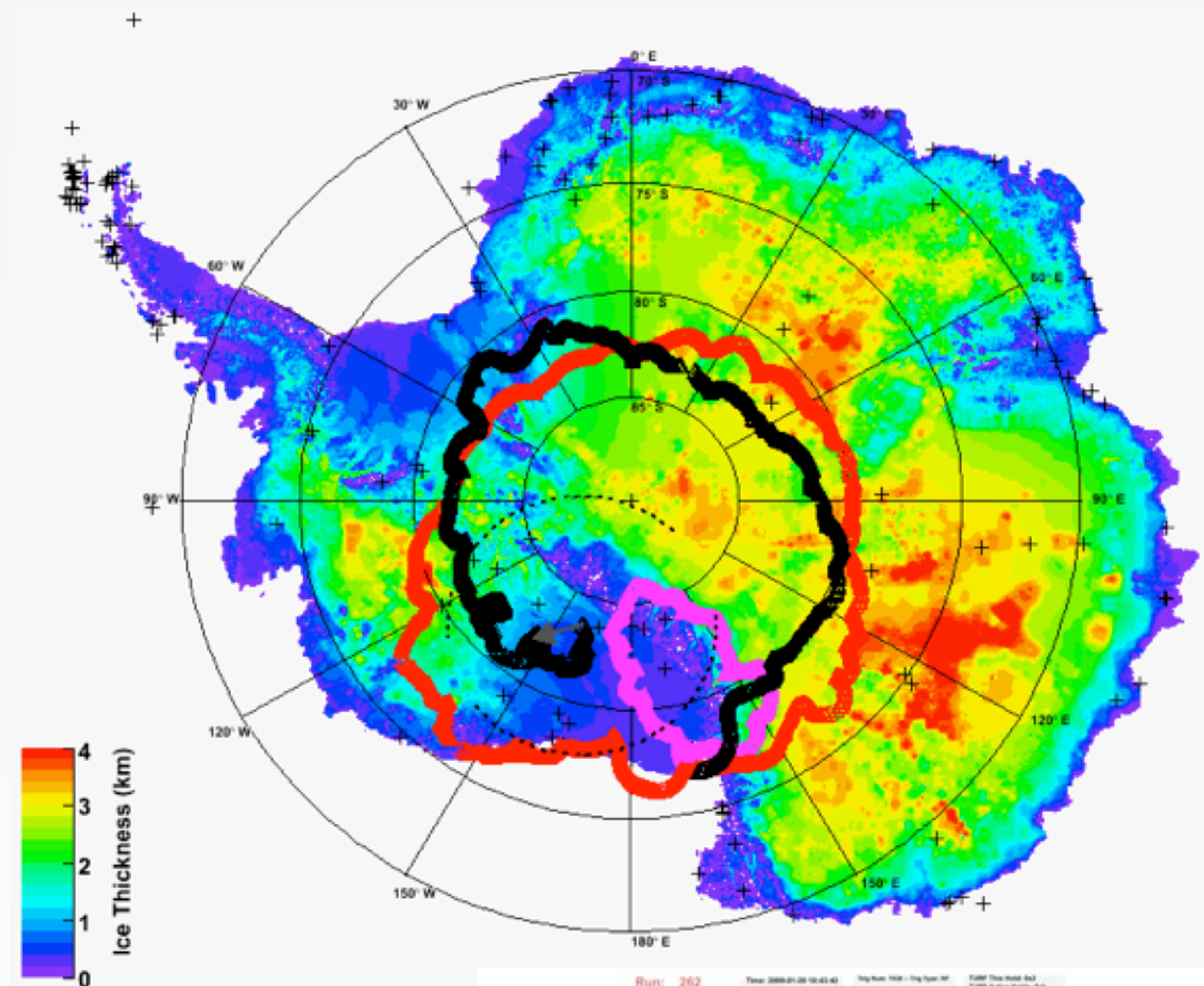
- New front end amplification system
  – Lower system temperature by ~40K
- Active direction trigger mask to blank out noise from camps and stations
  – Improve efficiency by ~20% (lower thresholds)
- Switch to vertical polarisation trigger
  – Improve sensitivity by ~30%
- Add third antenna (drop-down) ring
  – Improve sensitivity by ~30%
- Net improvement:
  – Factor of 1.7 in threshold --> x3 in event rate
  – Up to 30% in exposure (flight path dependent)
  – Up to 40% in livetime
  – Total factor > 5 in neutrino event rate

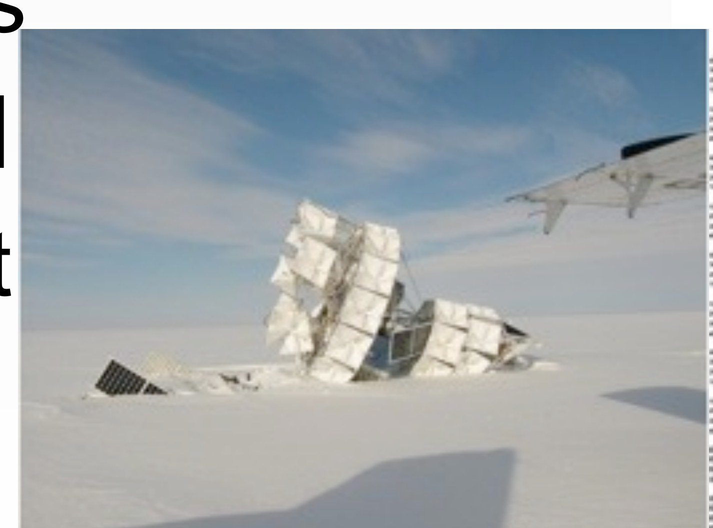


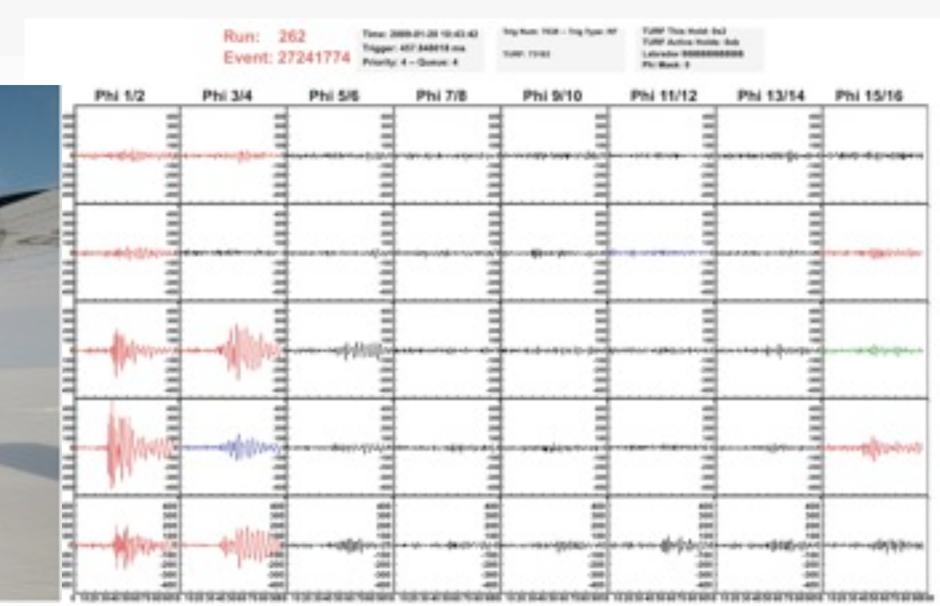


ANITA-II

- Launched Dec 2008
- Terminated after 30 days at float
- Little victories
  - Better flight path
  - Over 27 million events
  - Over 100,000 Taylor Dome pulses
- Data fully recovered
  - Two students spent a week camping out at crash site

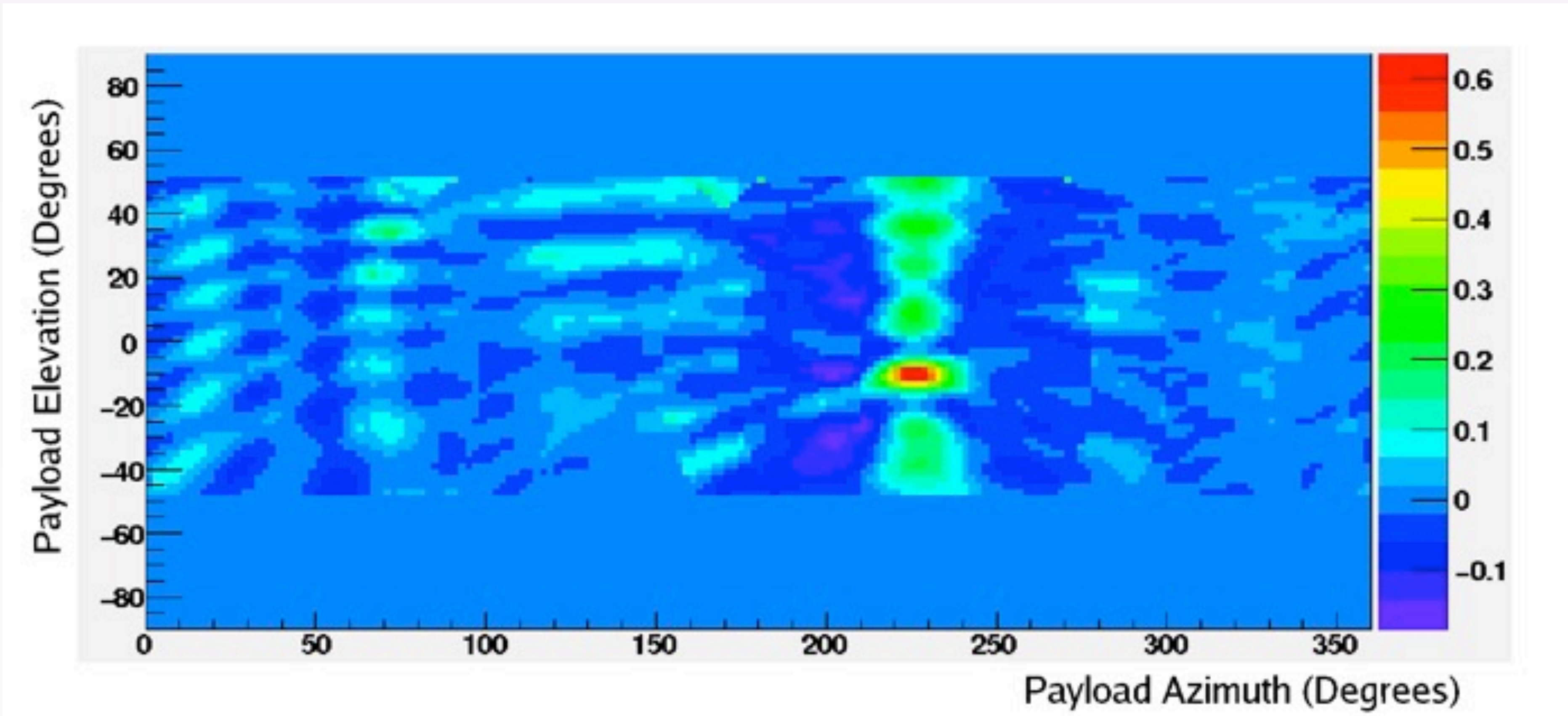


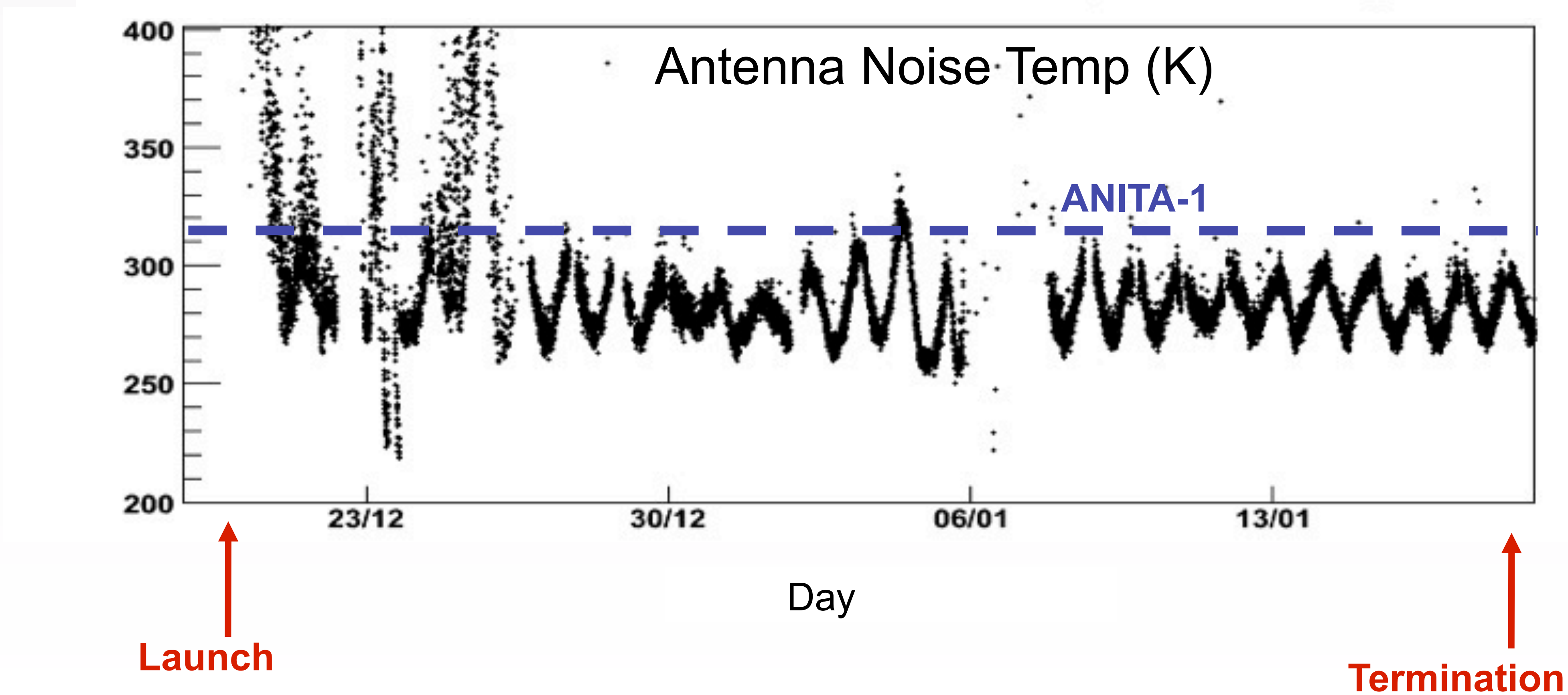




ANITA-II Recovery

ANITA-II Data





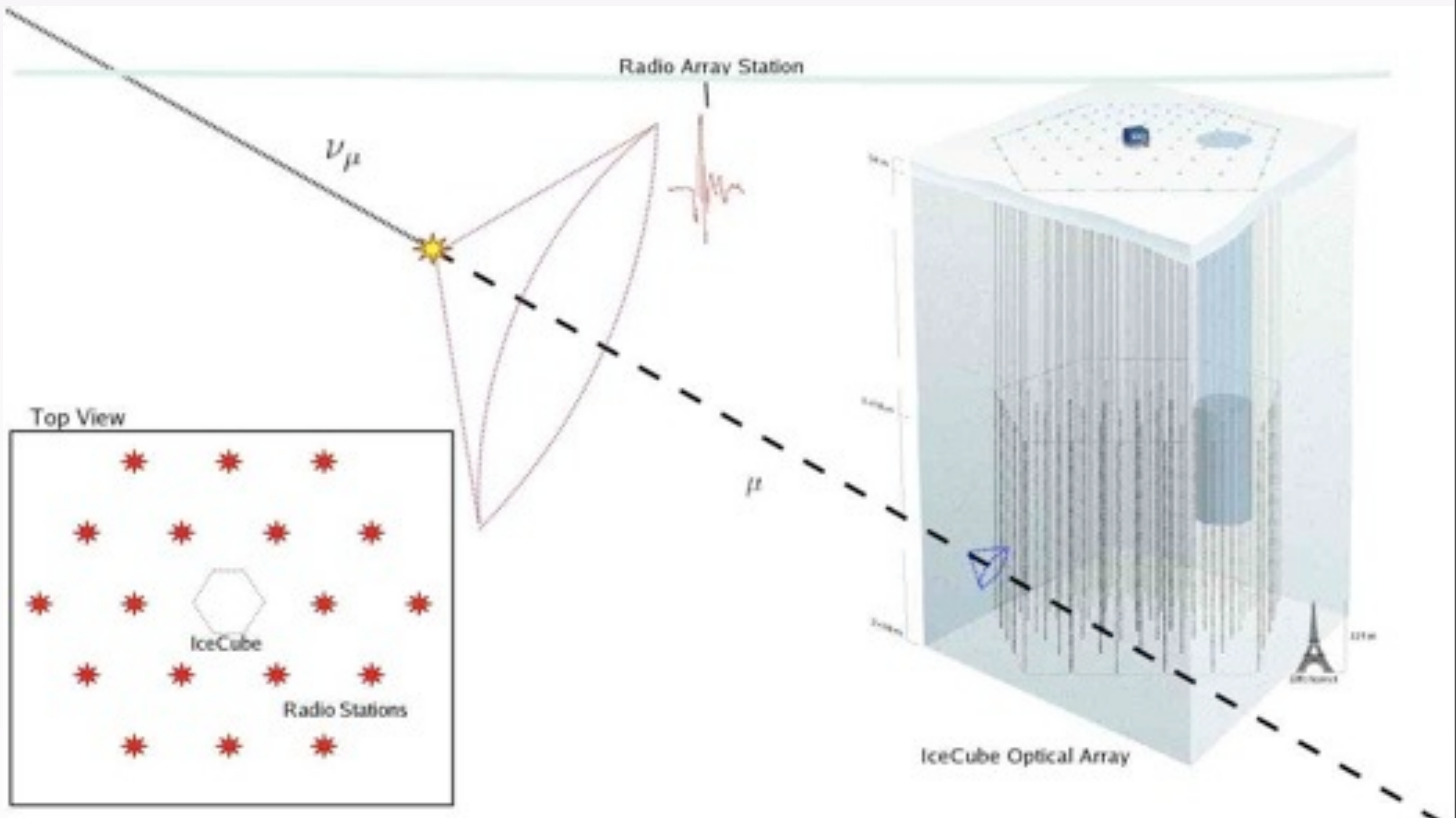
Future Prospects

ANITA-III and Super-ANITA

- ANITA-III will be an evolutionary upgrade to the ANITA-II payload.
  - ANITA-II payload is already as large as the launch vehicle can cope with
  - Possible augmentations include:
    - Re-instate H-pol trigger for UHECR
    - Another 8 drop down antennas (3 full rings)
    - Implementation of high level software trigger (data decimation)
    - Replace trigger hardware (power sensors)
- EeVA (Super-ANITA)
  - Turn the balloon in to the detector
  - Create a reflective radio mirror inside the balloon focussing the radio pulses to a central feed array

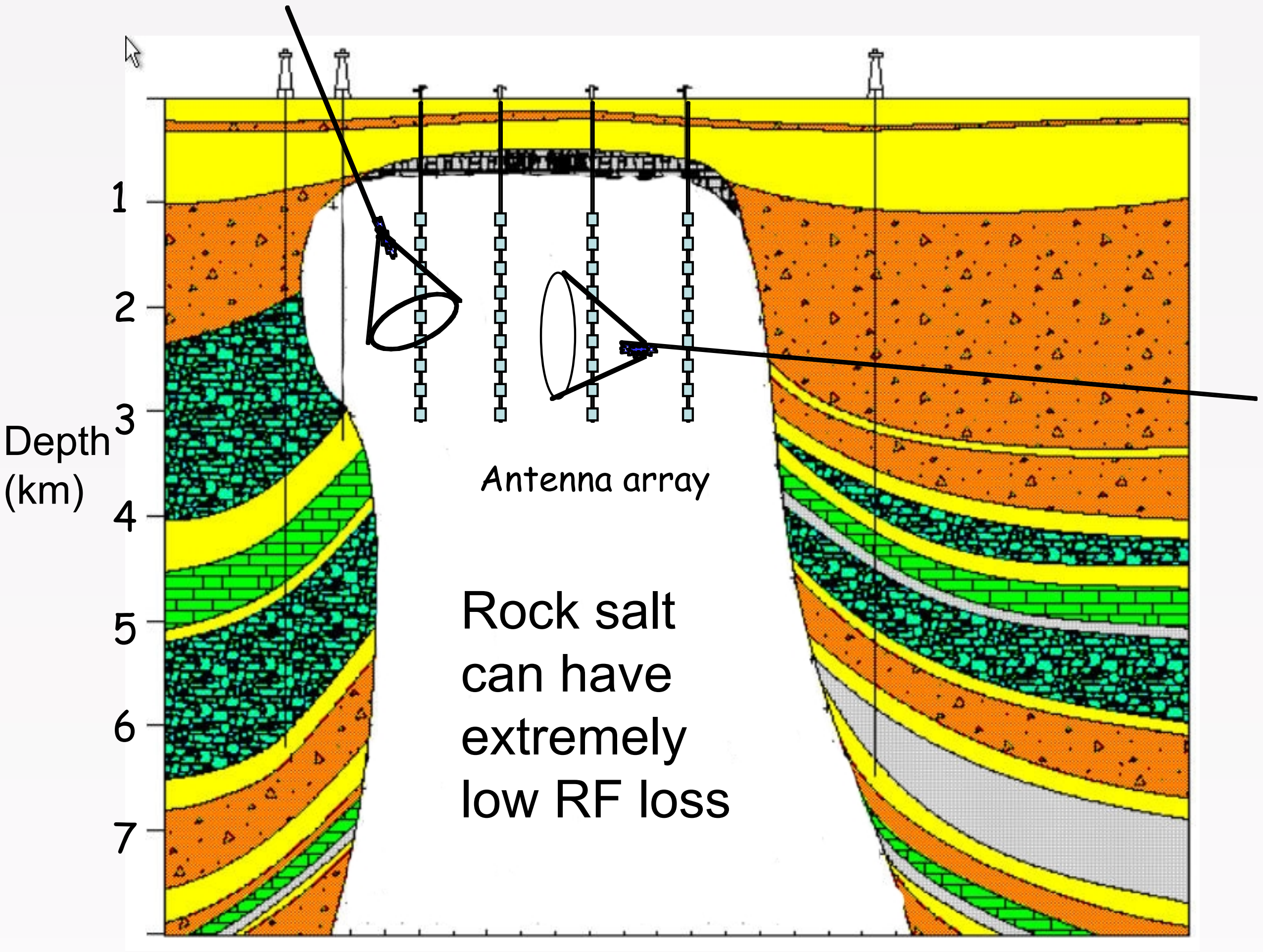
Extending IceCube to GZK Energies

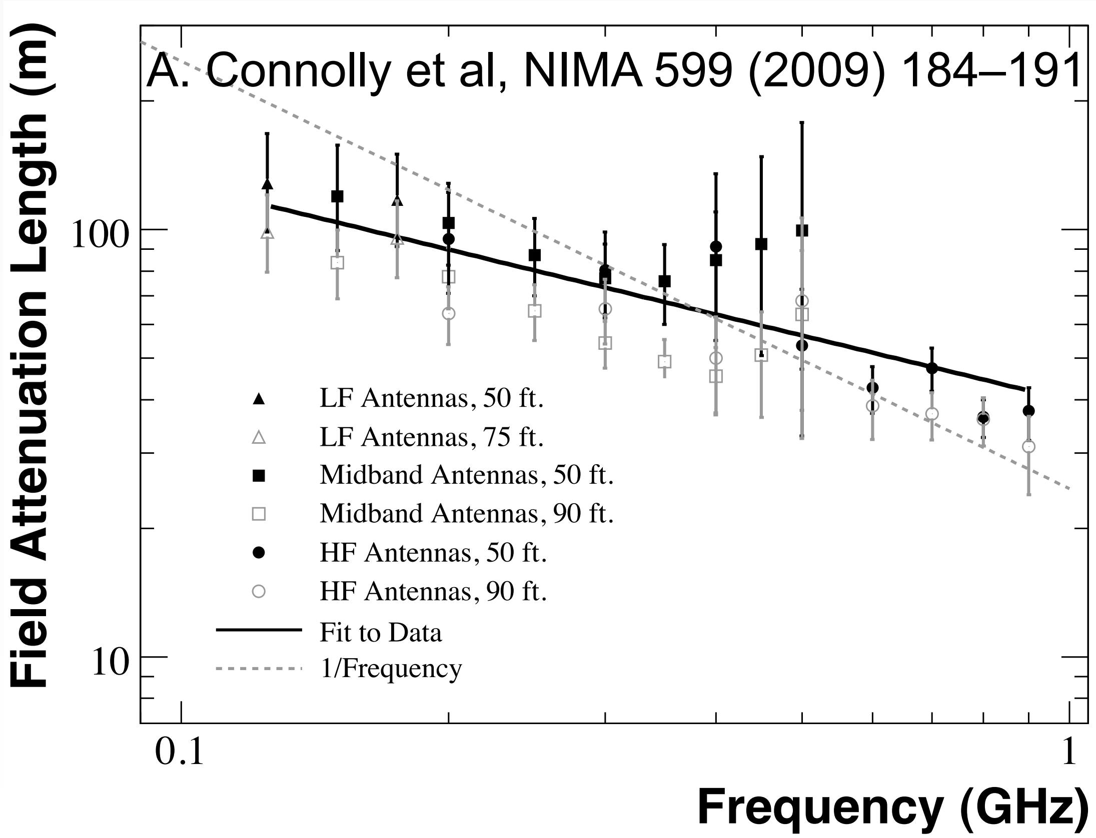
- ARA
  - Deploy radio detectors around the IceCube experiment
  - Possibility to measure neutrino with all three detection methods simultaneously
  - Need large footprint to detect GZK neutrinos



SalSA

- One of the proposed next generation arrays
  - SalSA (Salt Dome)
- Published in-situ attenuation length measurements





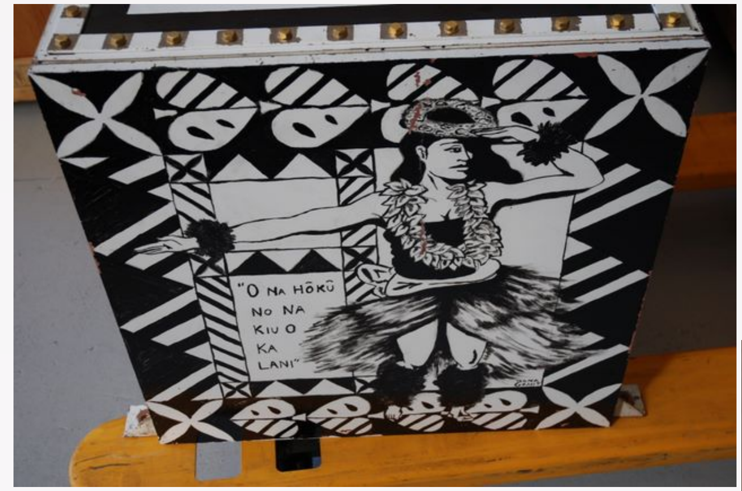
ANITA in Antarctica

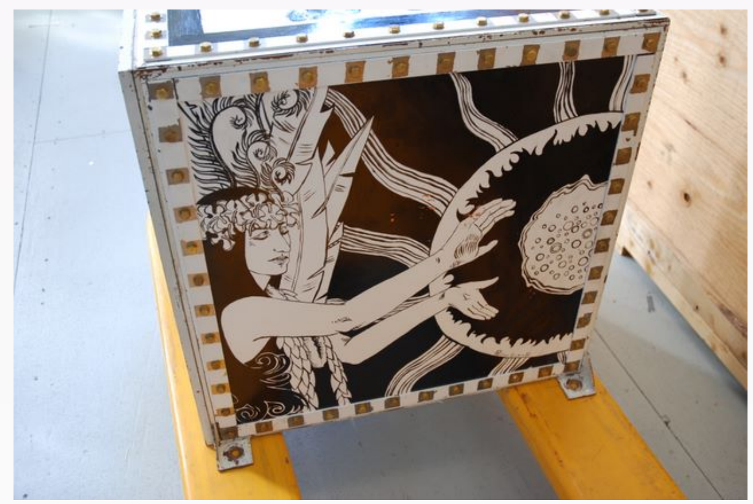
The Obligatory Collaboration Photo

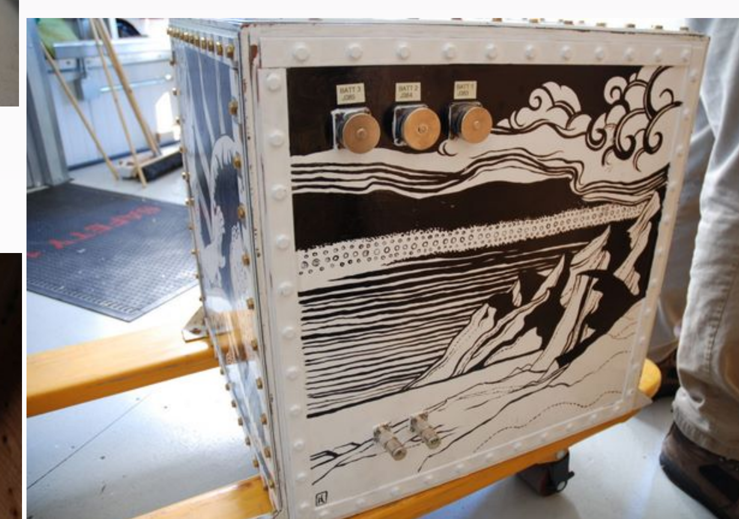
- And I was told it was blue skies research...

Battery Box

- Overheating is a major problem in Antarctica
  - At least at 37km
  - Paint everything white
- Battery box is like Goldilocks:
  - Not too hot
  - Not too cold
  - Need half black half white
- Antarctic Art Contest!

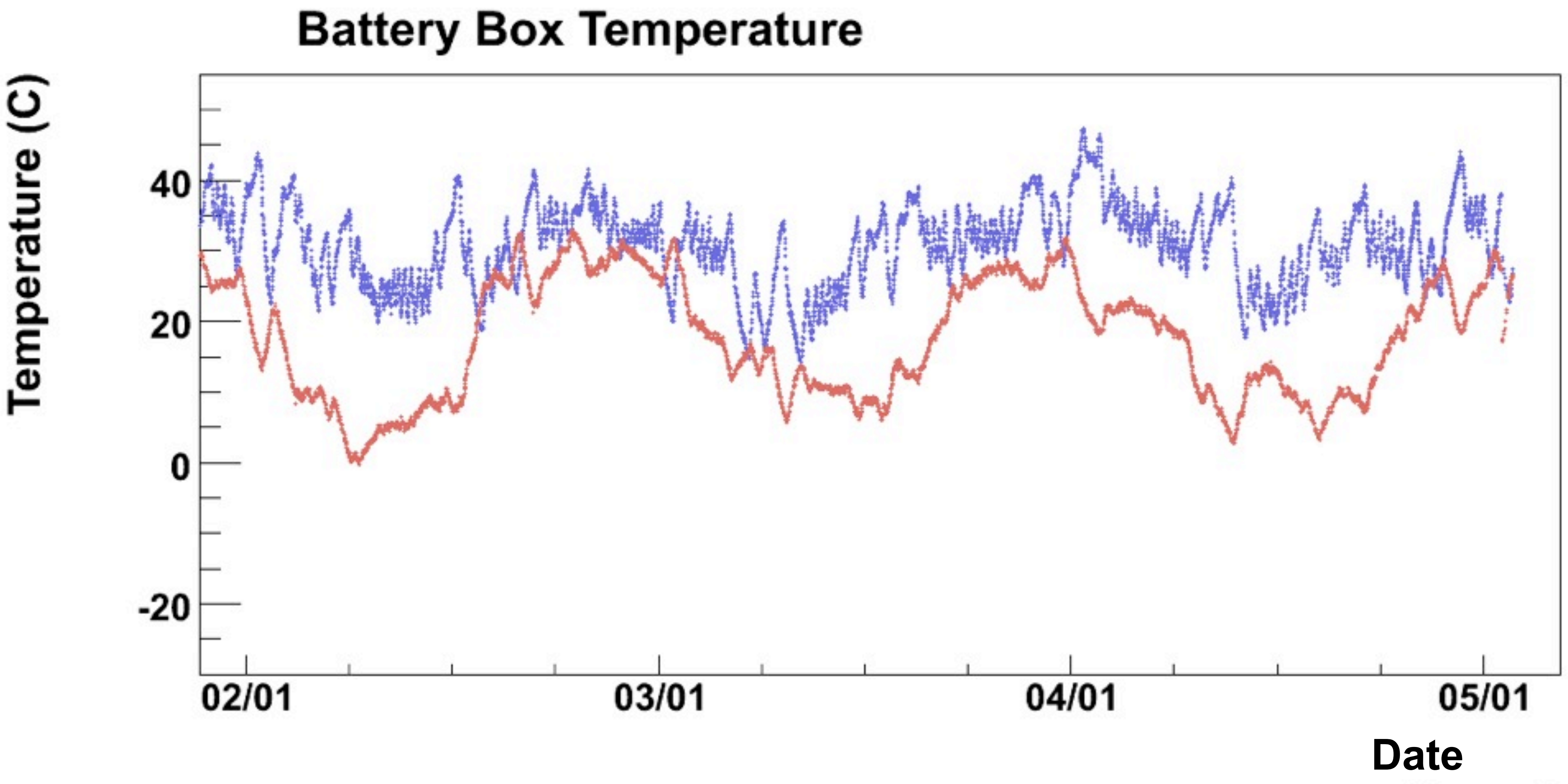






Thanks to the artists: Kai Smart, Dana Grant, Karen Joyce and ??? and Jeff Kowalski for the photographs

Paint Job Results



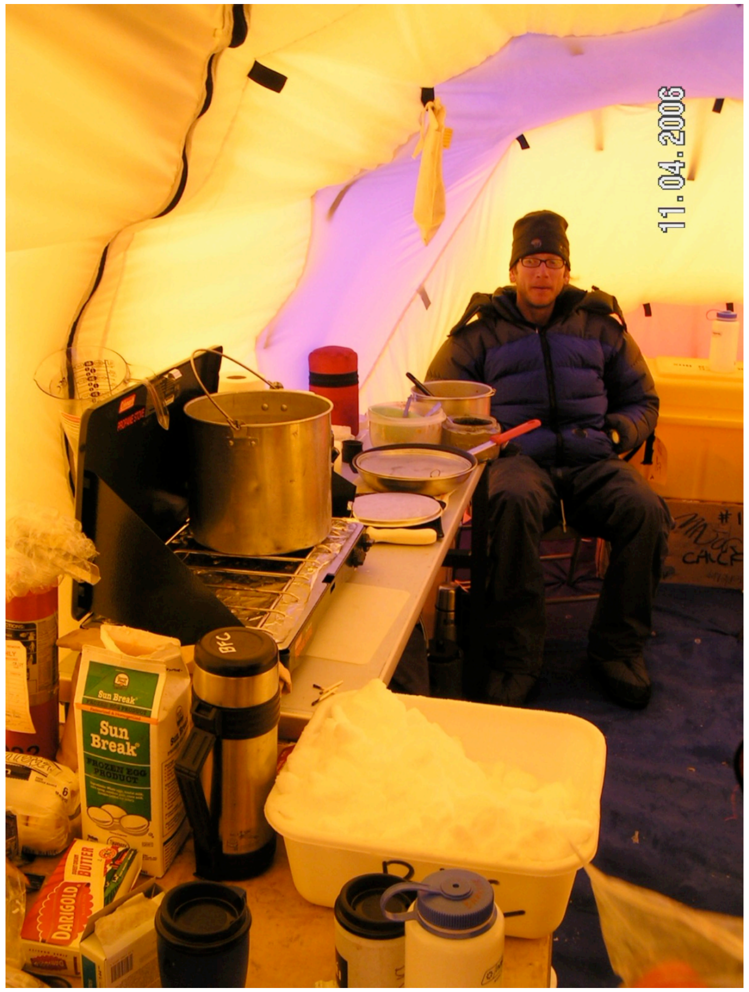
Summary

- These are exciting times in the ultra-high energy neutrino field.
- ANITA has completed its first full flight and initial analysis has set the current best limit on the flux of ultra-high energy neutrinos.
  - Second flight (December 2008) will start to constrain ‘standard’ GZK neutrino models.
- The next generation of neutrino astronomy facilities may finally realise the ambition of probing the universe with “new eyes”.
  - Probing fundamental physics at energies beyond the reach of terrestrial accelerators.
- Hopefully soon we will have the first detection of an UHE neutrino.

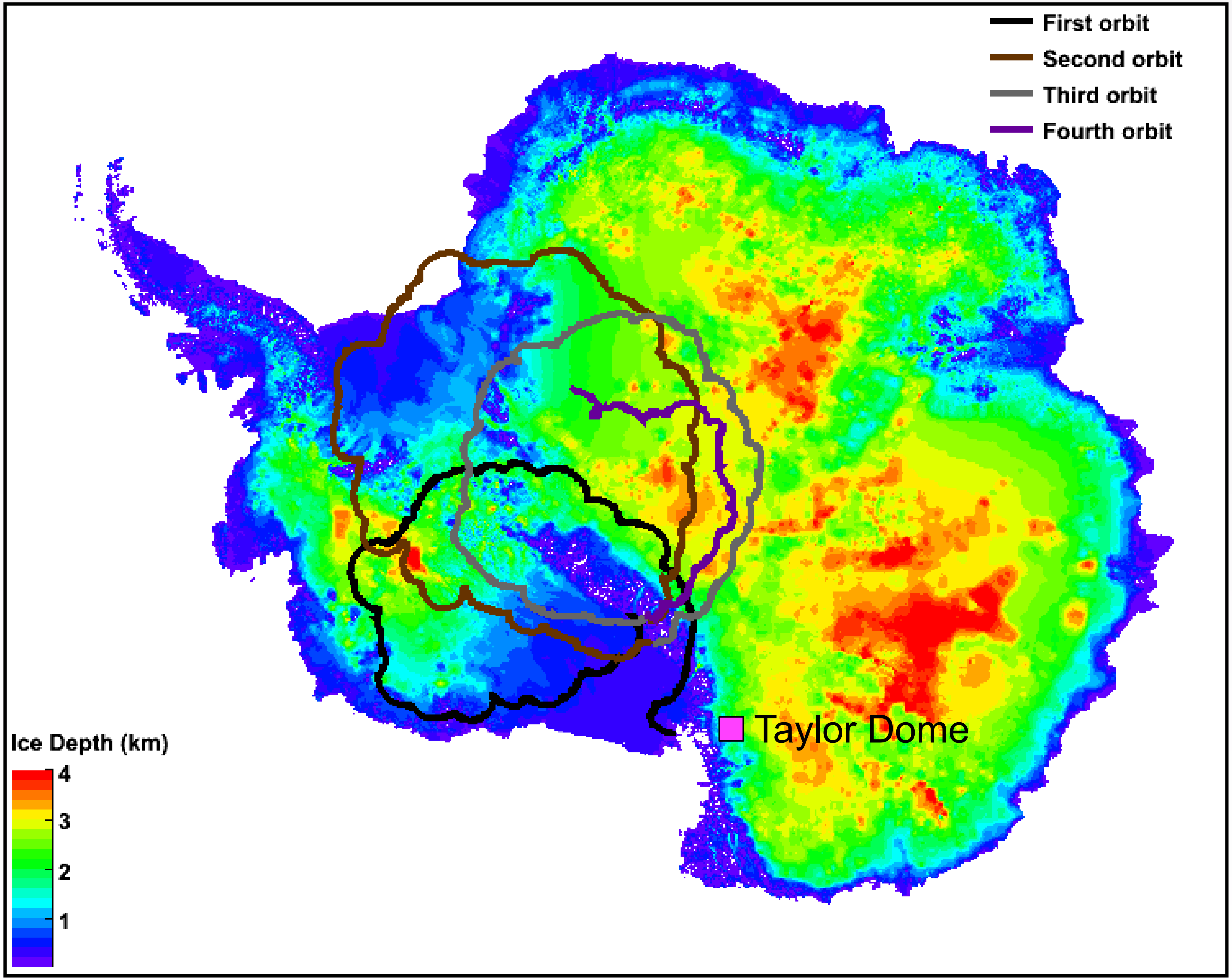
Me in front of the Royal Society Range

The Taylor Dome Tale

- Calibration Field Camp
  - 10 man weeks in a tent in the dry valleys
  - Waiting for the balloon to fly over



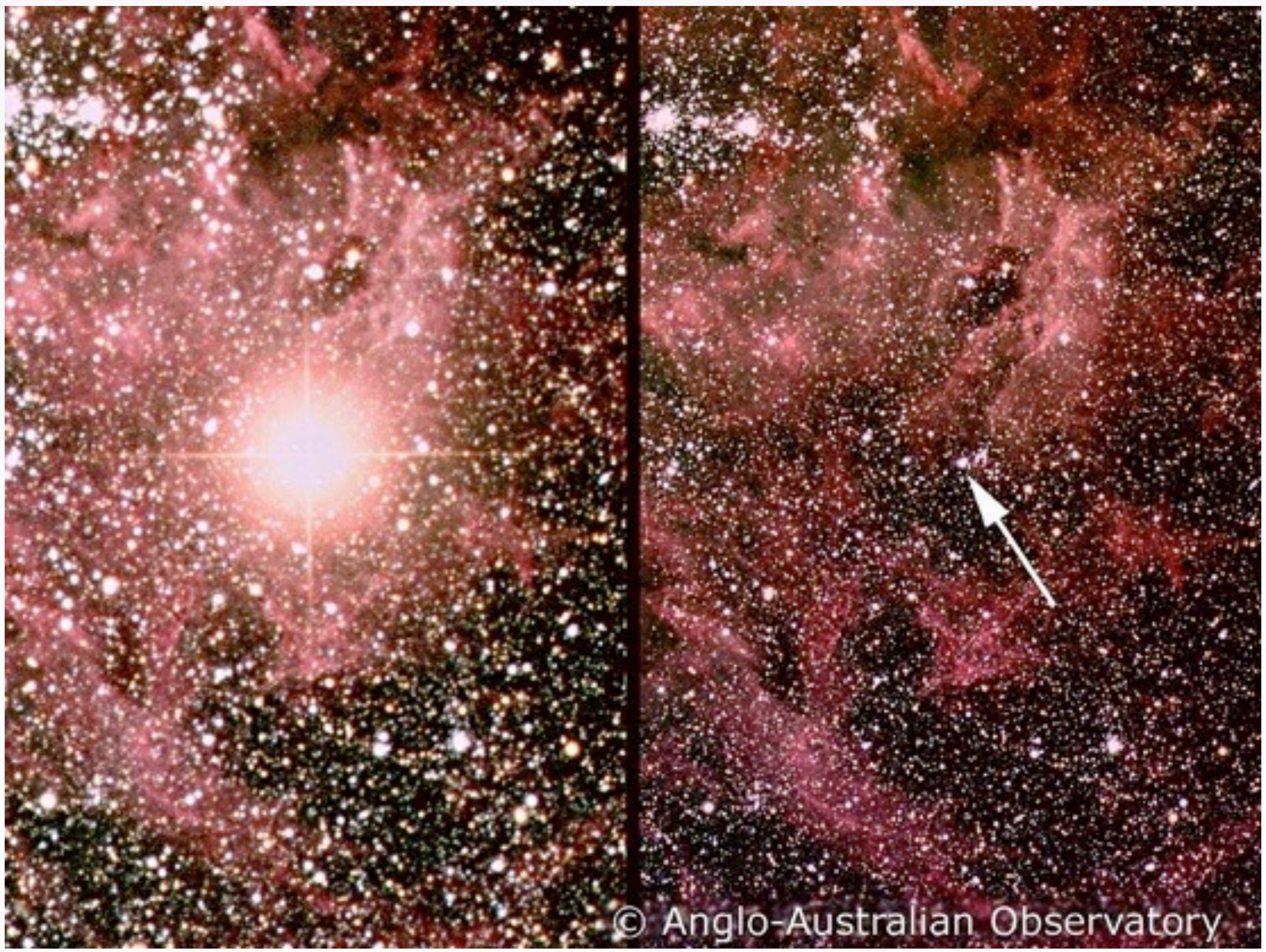
Better Luck Next Time?

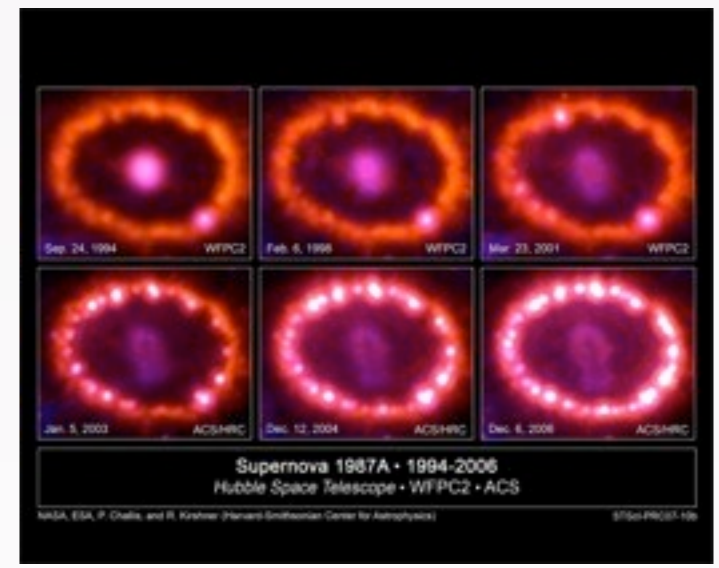


Backup Slides

Skewed History Lesson

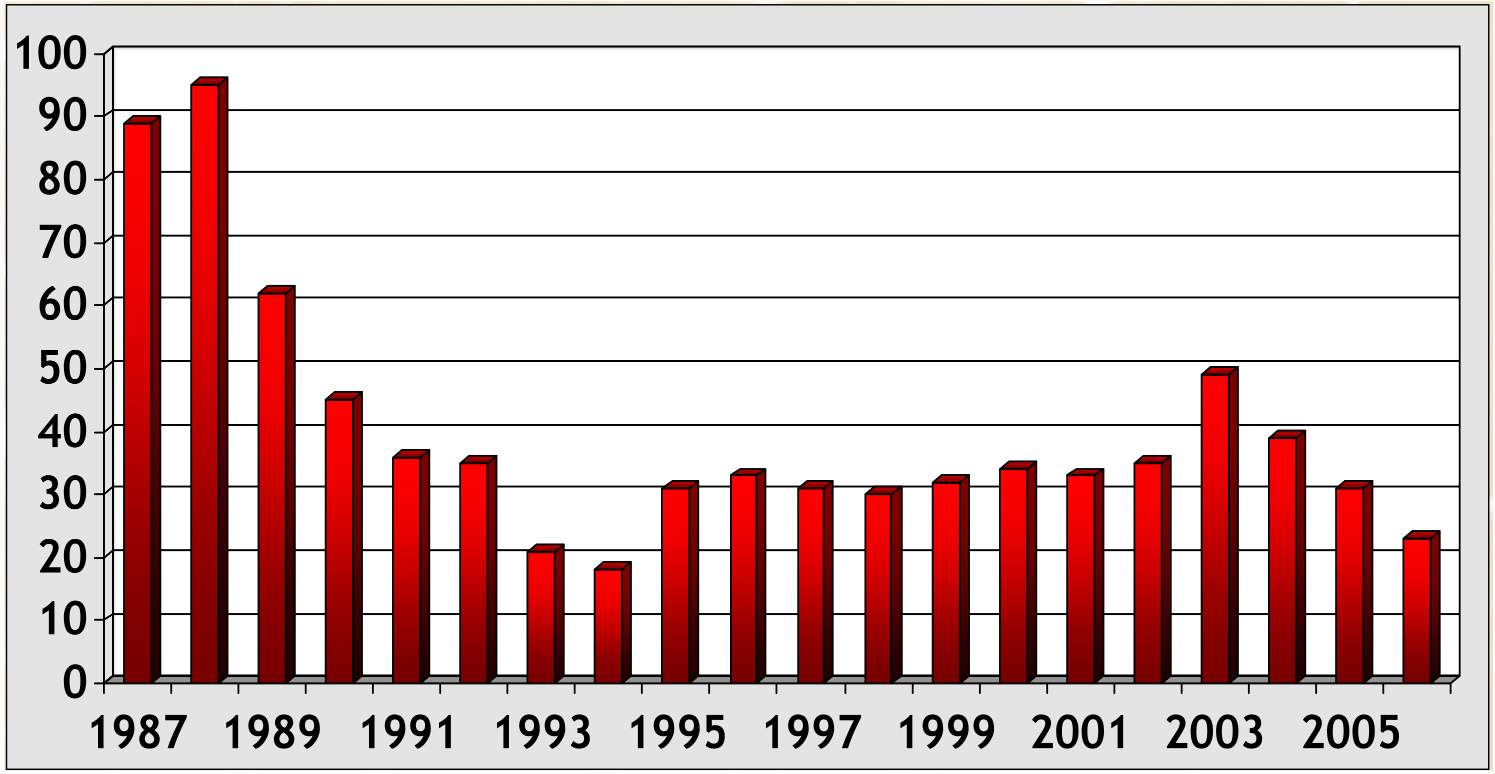
- Neutrino Astronomy started with a bang...



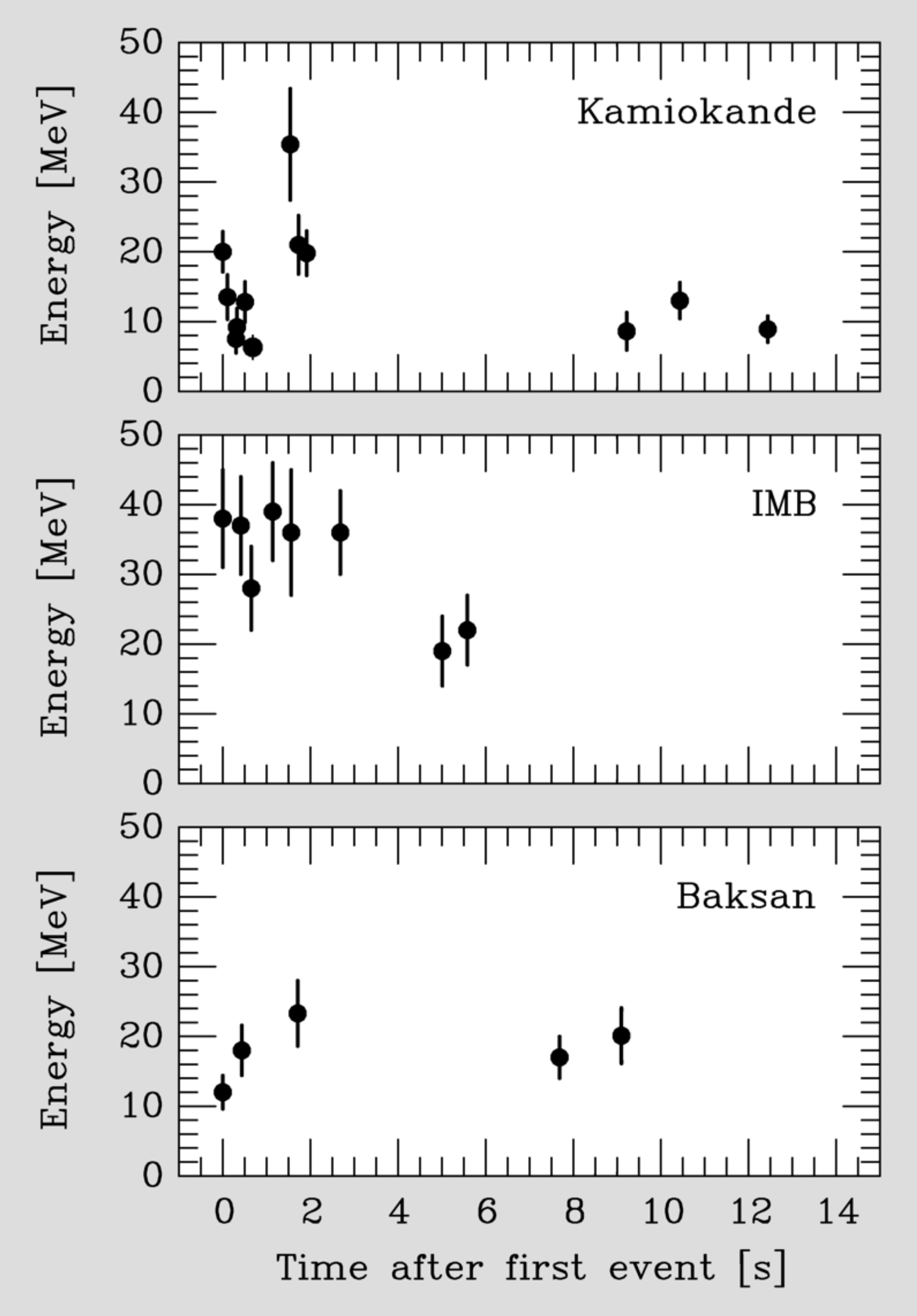


Pretty pictures from Hubble, Chandra (X-ray) and AAO

- ... and just a handful of neutrino events sparked a flurry of scientific interest



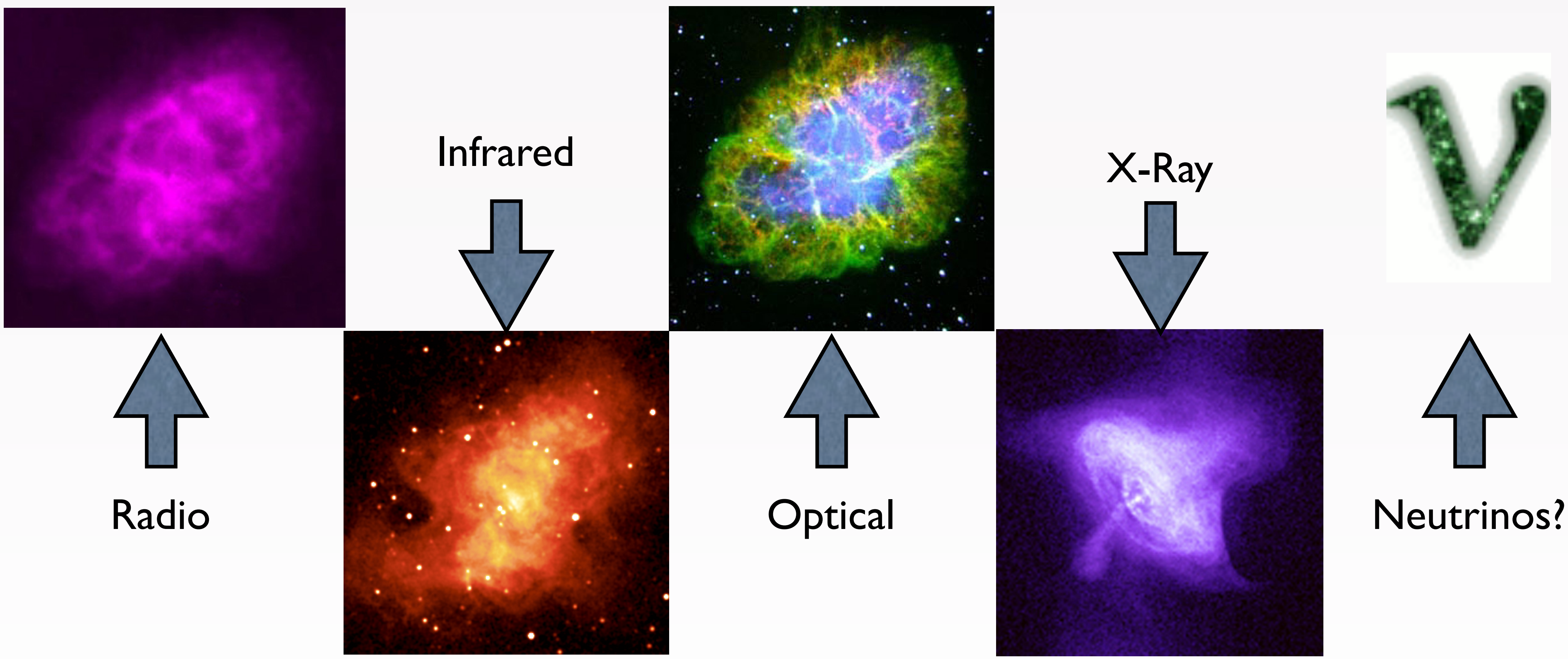
Annual Citations (from SPIRES) of SN 1987A Papers



Plots stolen from Georg Raflett

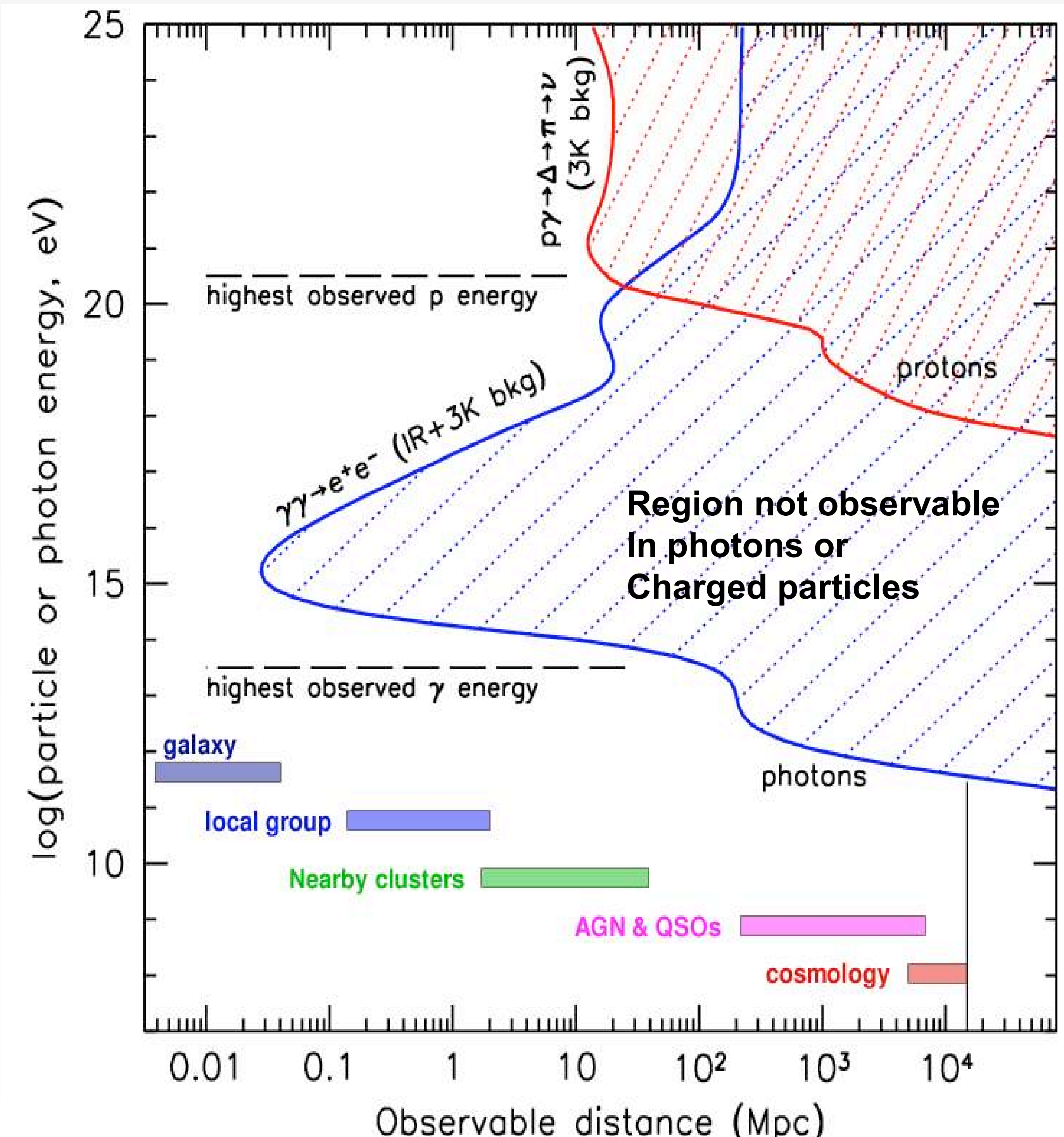
Why Ultra-High Energy Neutrinos?

– AstronThe pretty pictures answer.



"The real voyage of discovery consists not in seeking new landscapes, but in having new eyes." **Marcel Proust**

Neutrino Astronomy for Astrophysicists



- Photons attenuated by:
  - Infrared Background
  - CMB
- Protons:
  - Deflected by magnetic fields
  - Attenuated by CMB
- Neutrinos:
  - Can reach the energies and distances that other particles can't.

The Heineken Particle

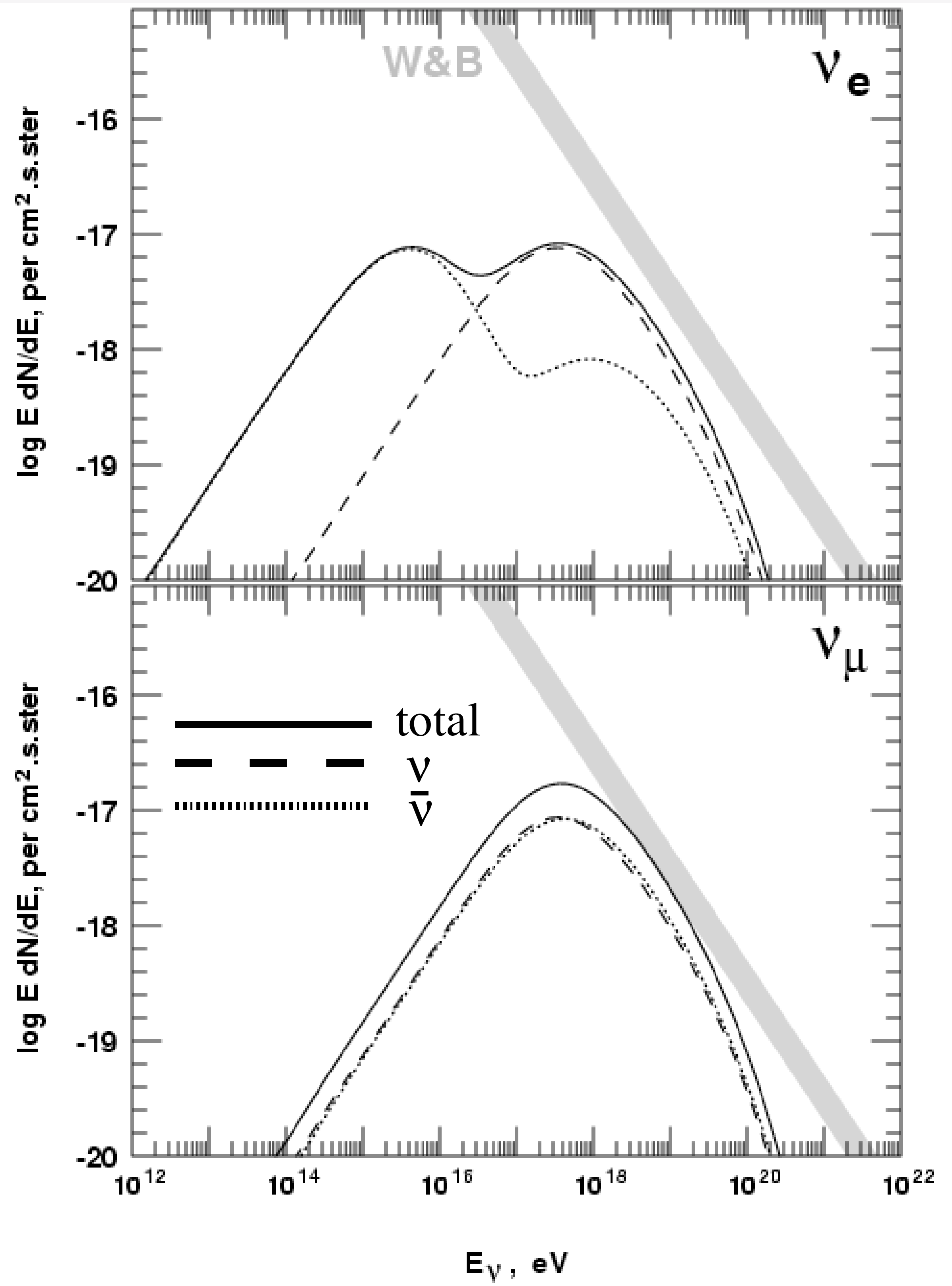
P. Gorham

GZK Flux

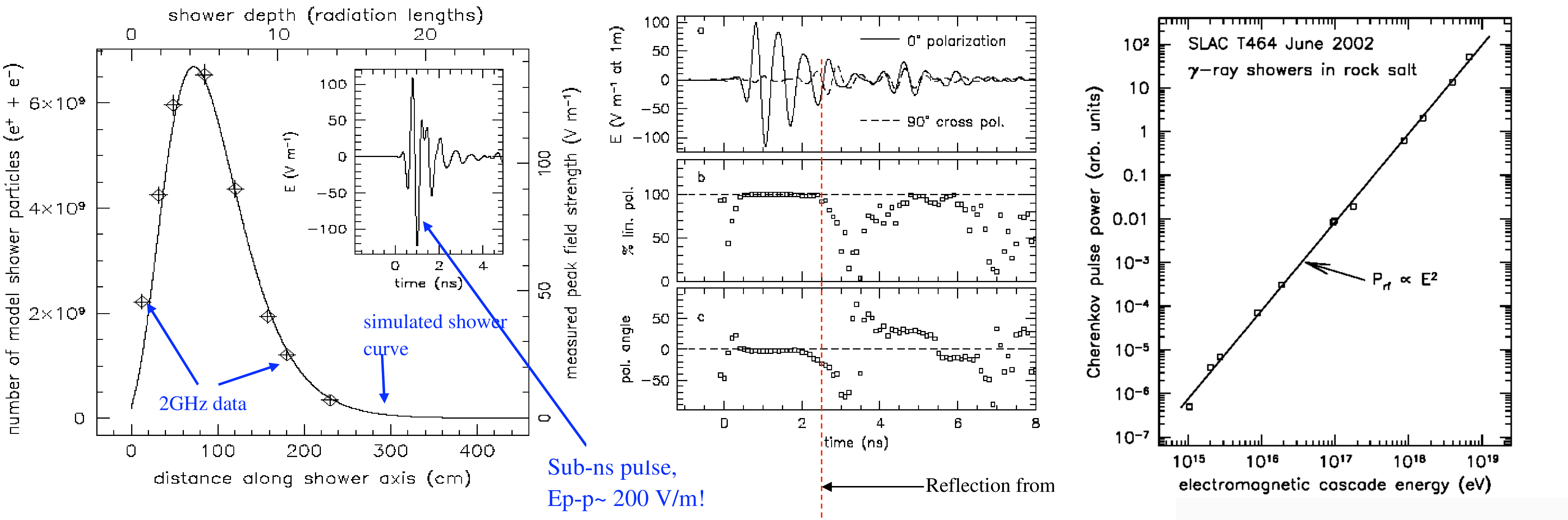
- Calculation contains many assumptions
  - Earth CR flux only
  - Injection Spectrum
  - Cosmological Evolution
  - Optical Density of Source

- Still ‘best known’ neutrino flux

Engel, Seckel & Stanev



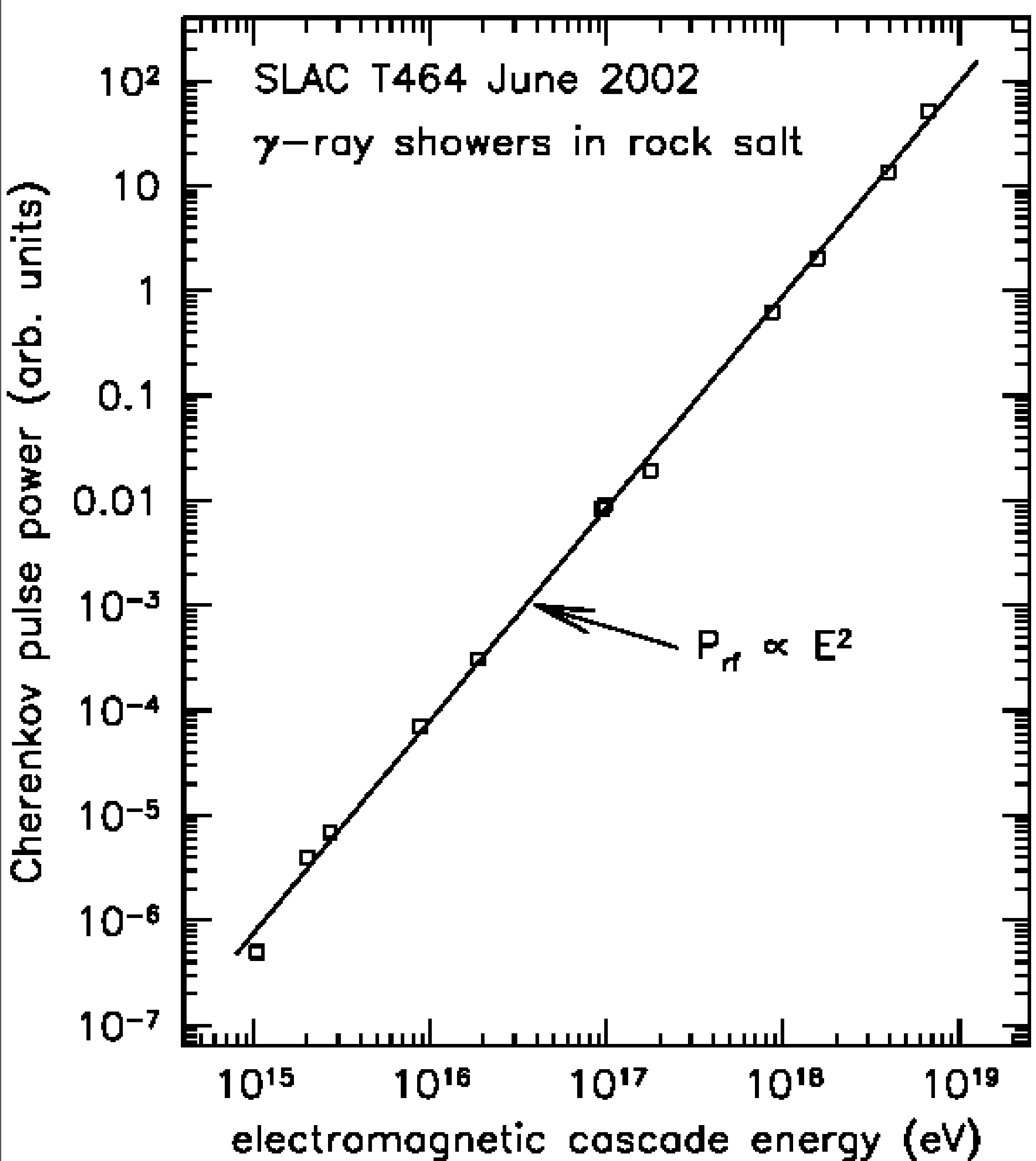
Results from Sand Box



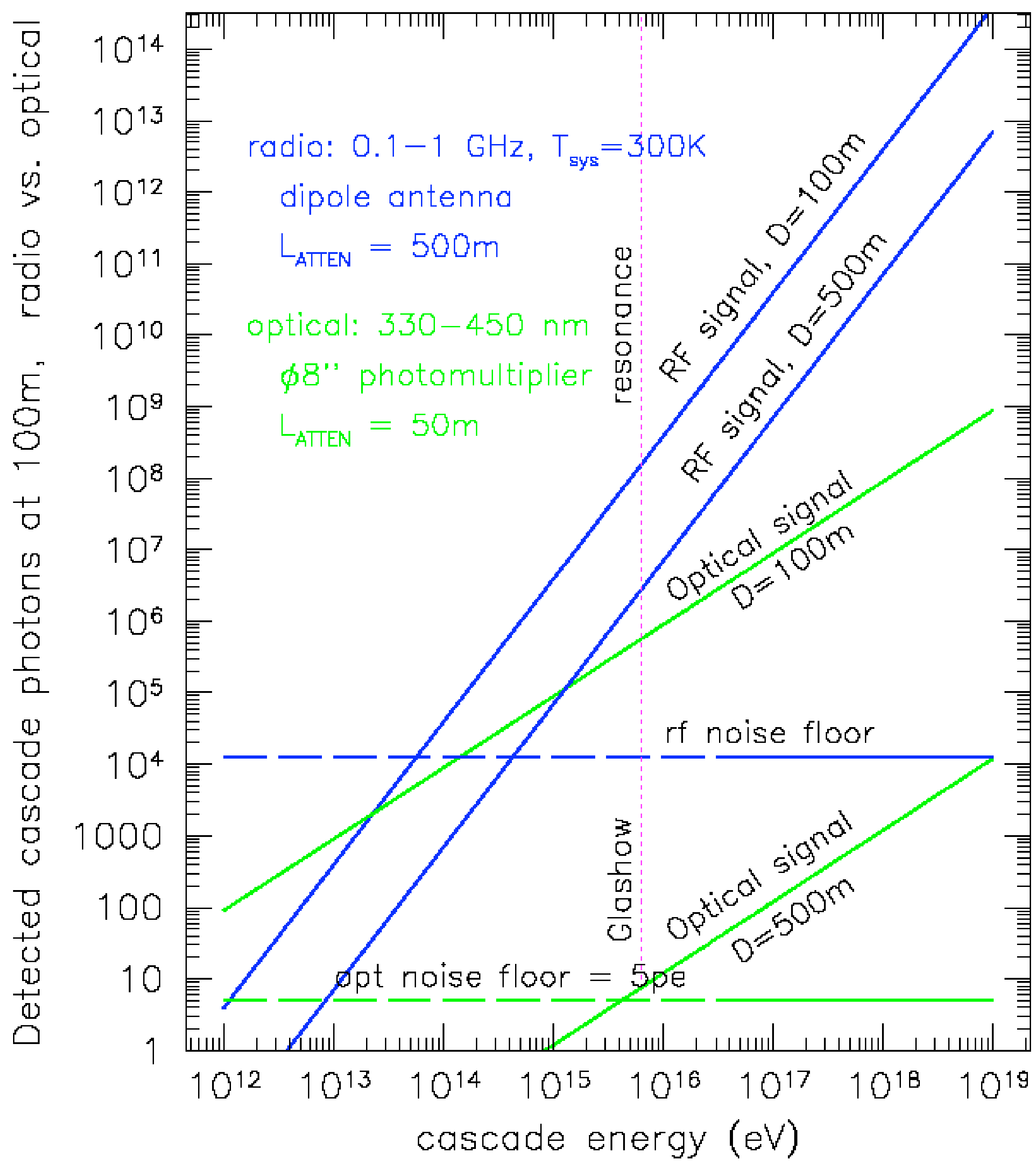
- Sub nanosecond pulse
- Excellent agreement between data and simulation of number of particles in shower
- Linearly polarised as expected
- Coherence confirmed

Coherent Signal

Coherent signal over 4 orders of magnitude

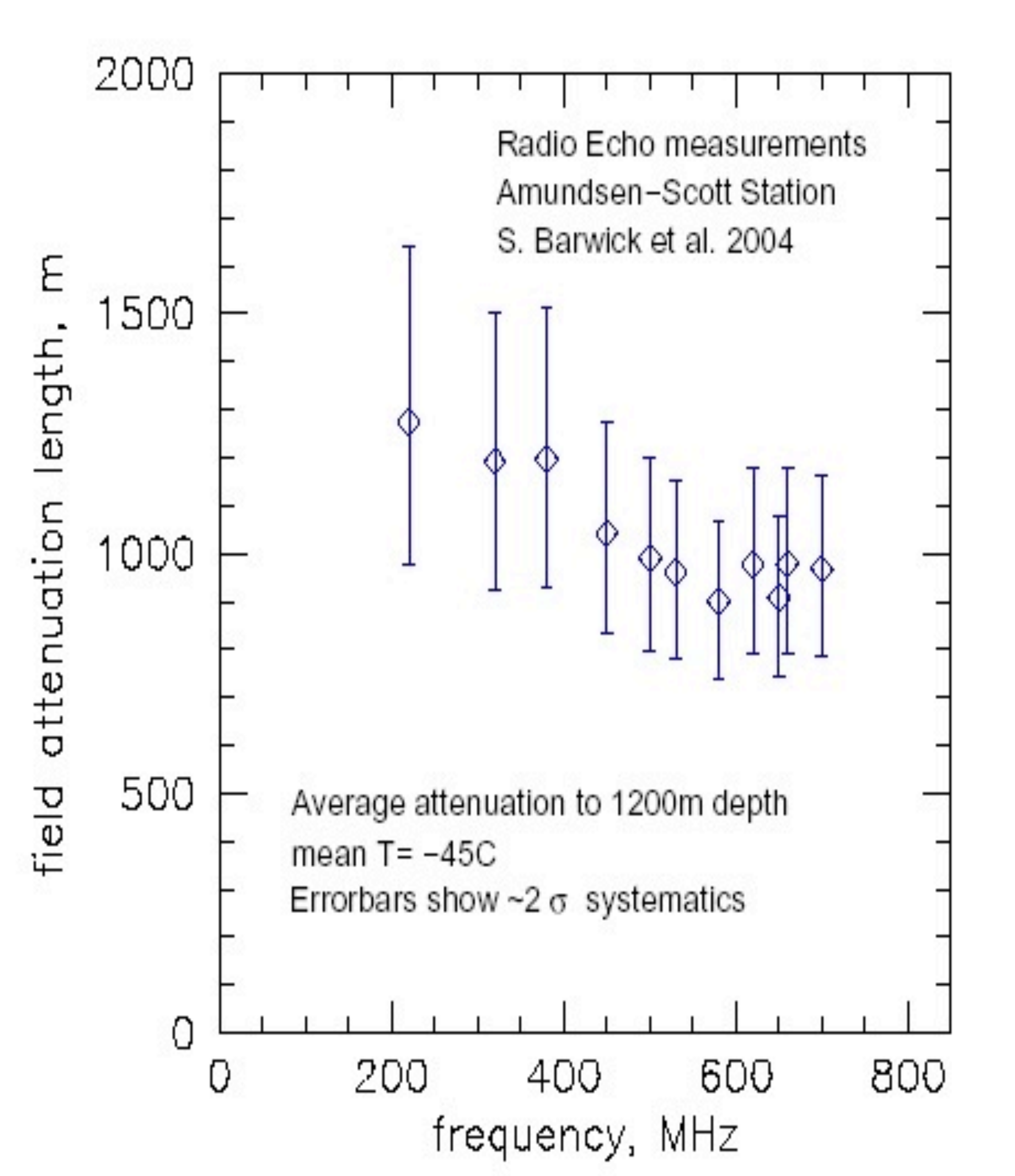


SNR dominant for E > 10 TeV



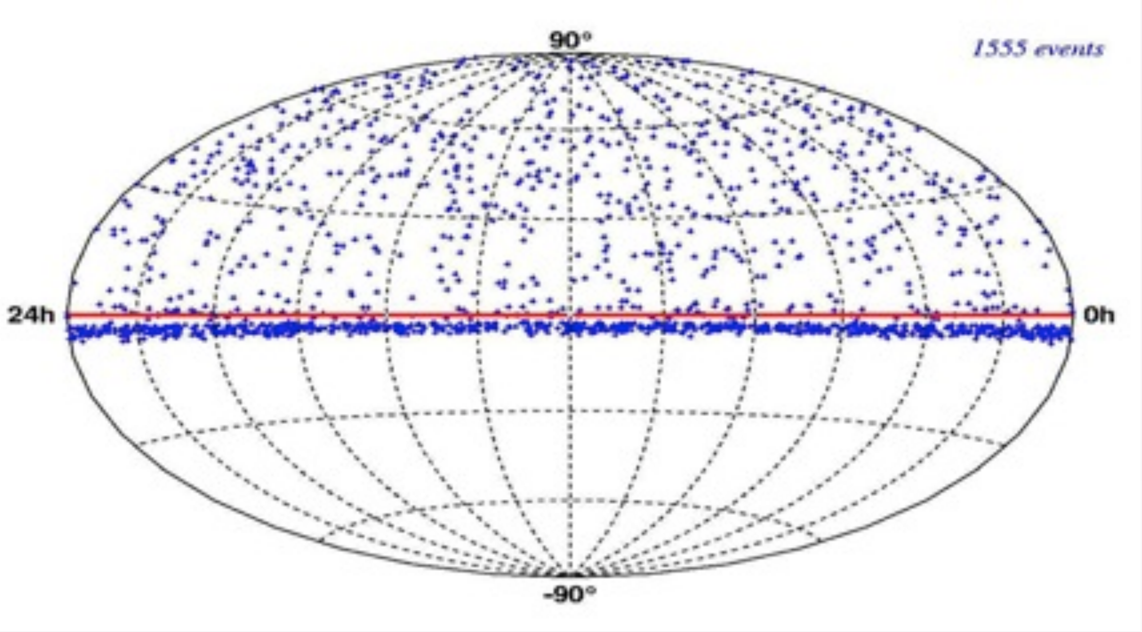
Long Radio Attenuation Lengths

- There are numerous *in situ* measurements of the attenuation length of Antarctic ice, they show:
  - Attenuation length is greater than 1km
  - Limits set on the birefringence
  - Many GPR measurements also

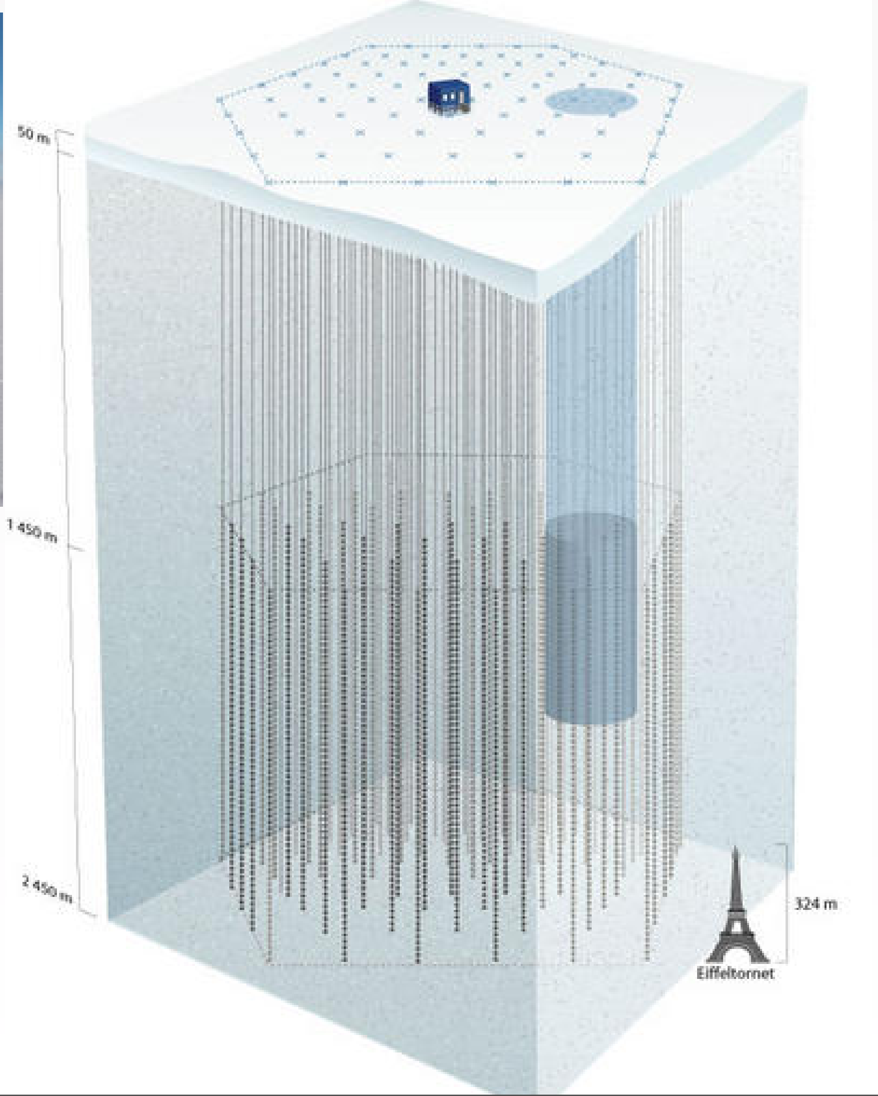


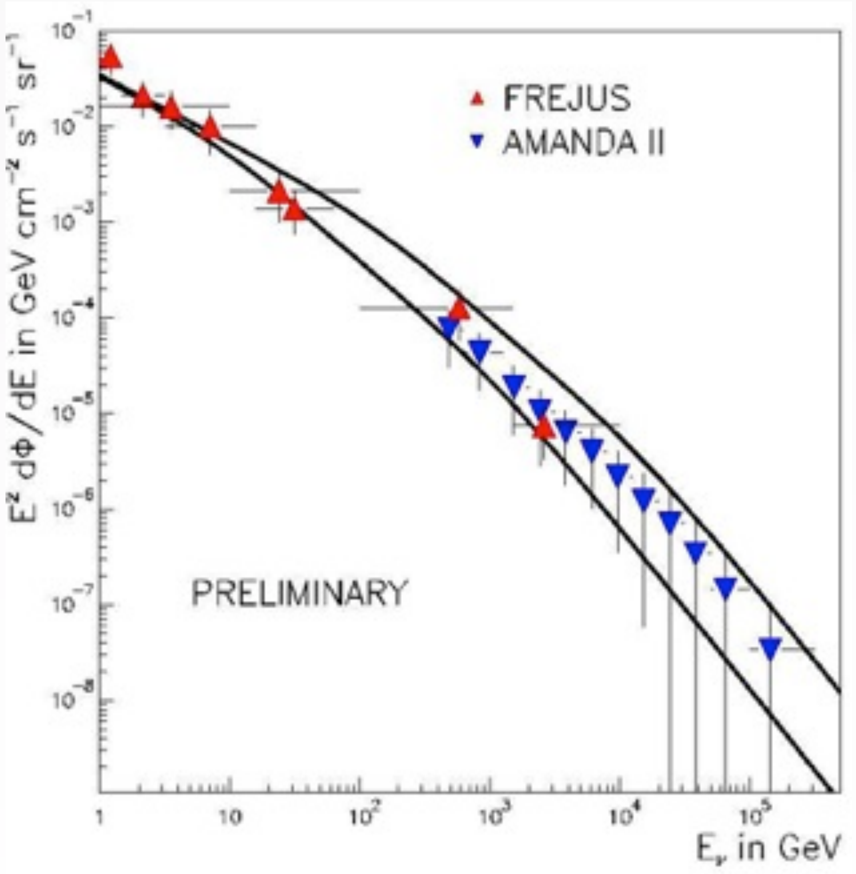
Amanda/IceCube

- Neutrino telescope at South Pole
  - Uses Optical Cherenkov method

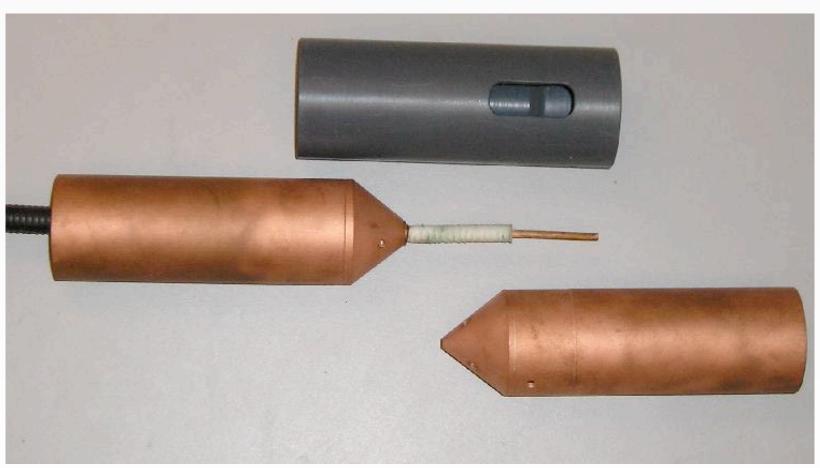


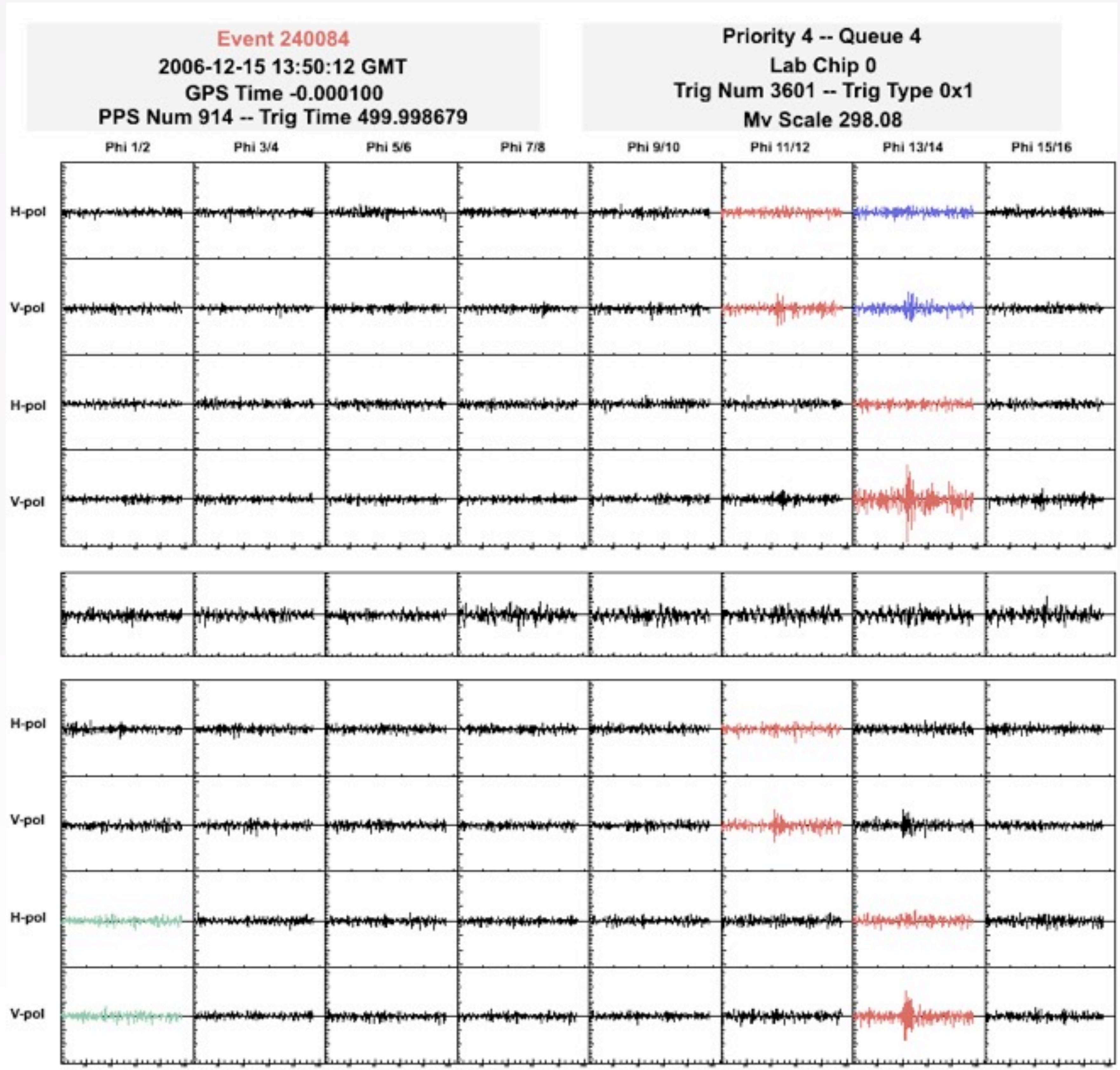
No excess above atmospheric neutrinos





Borehole Calibration

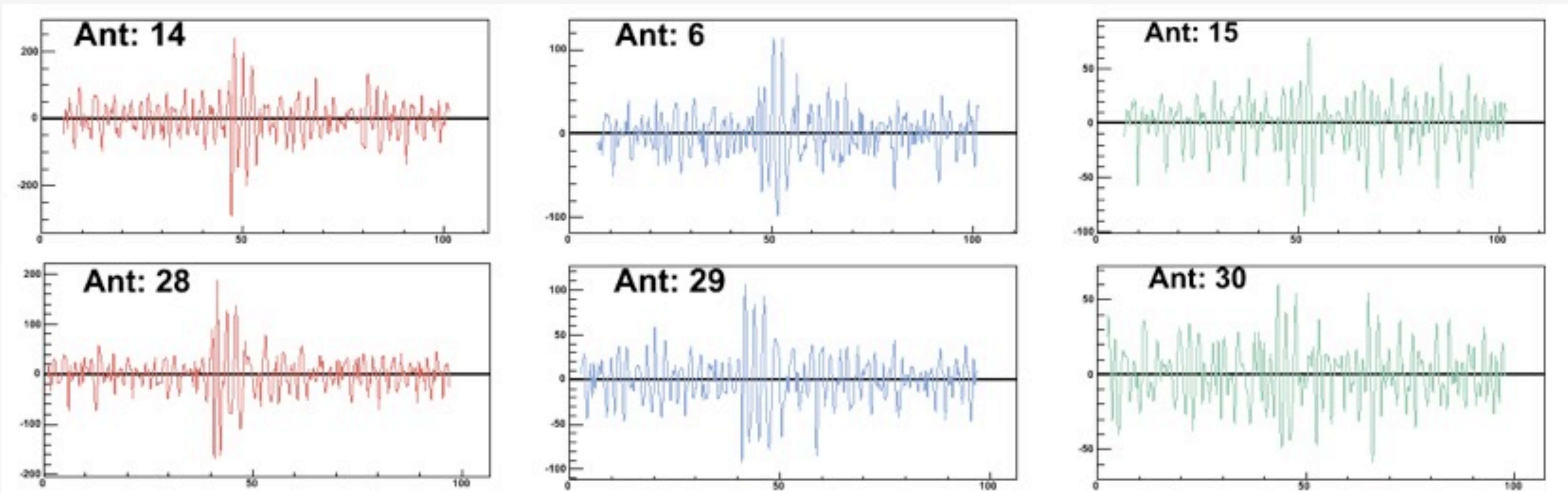




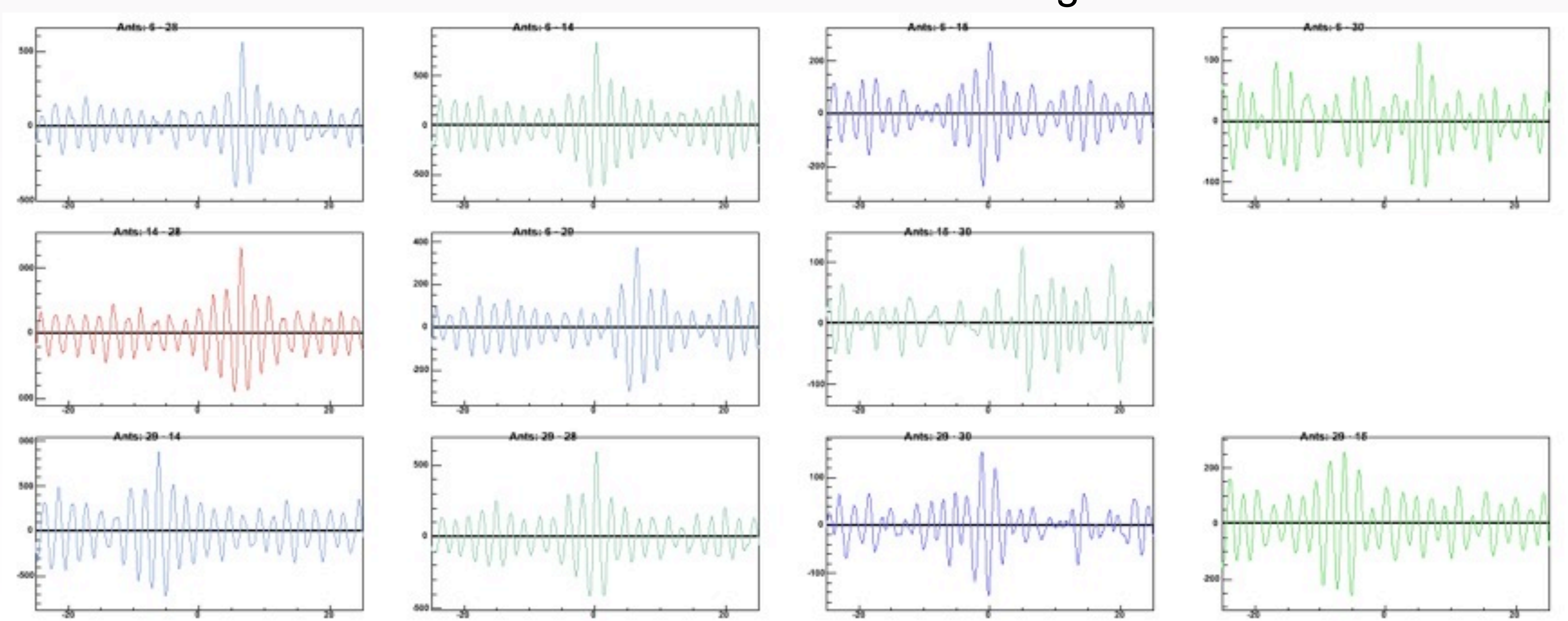
Event Reconstruction

Upper

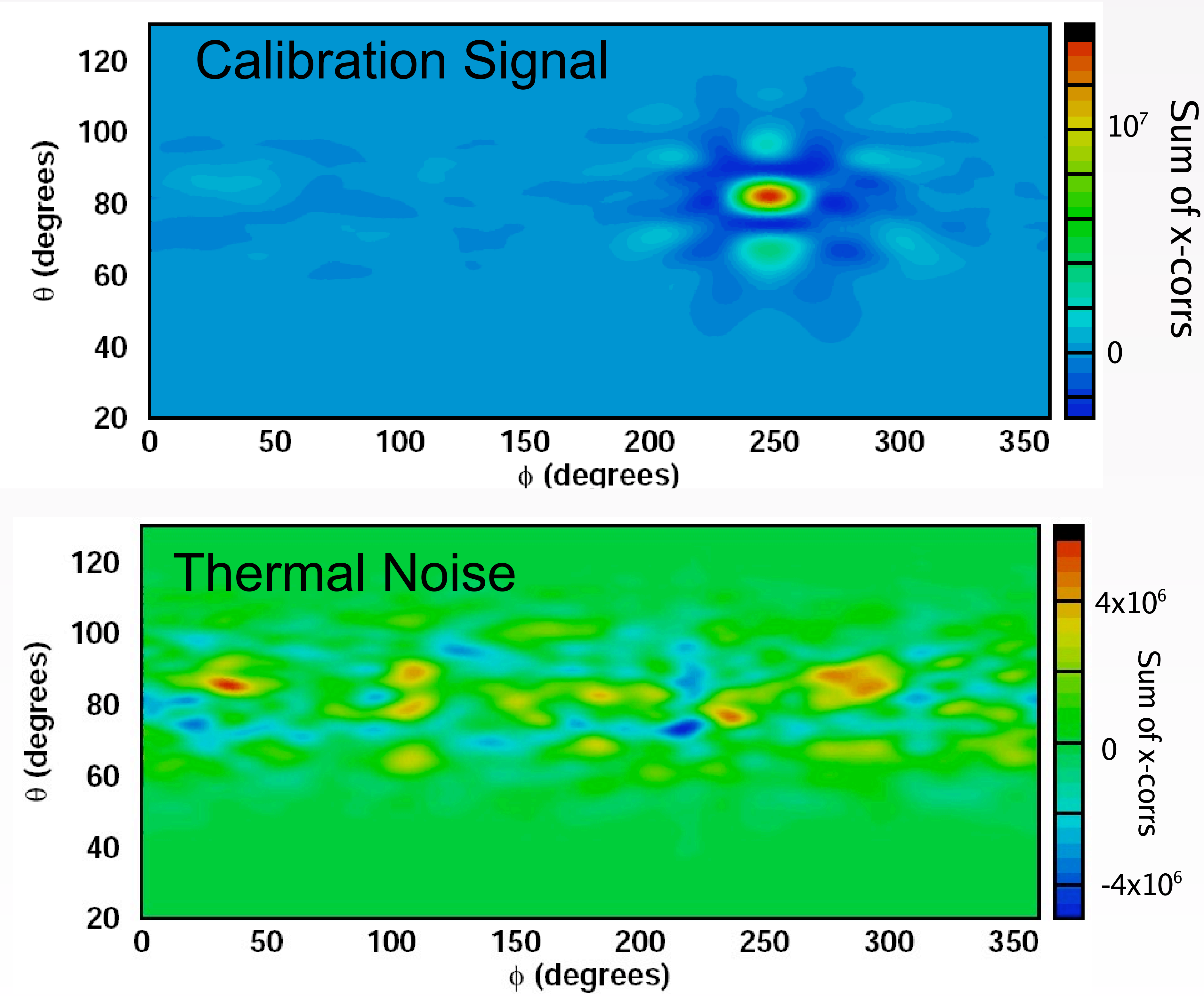
Lower



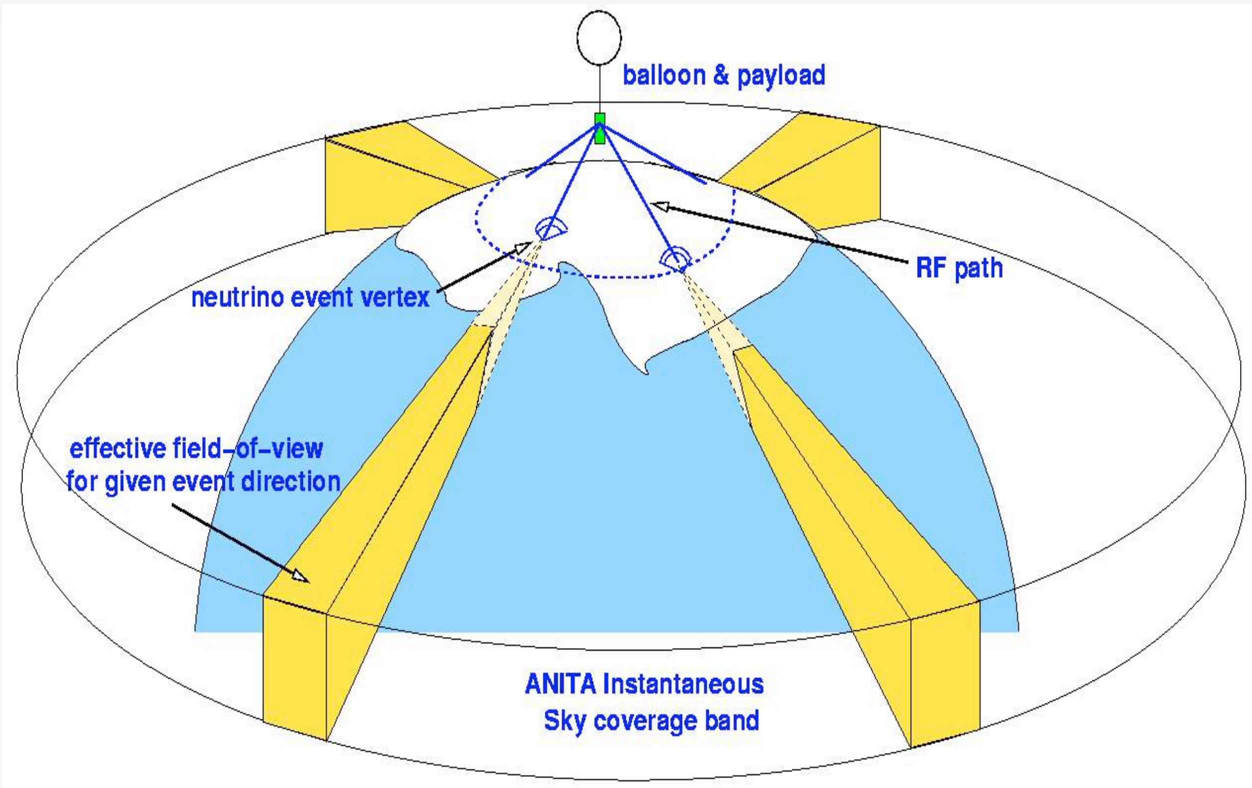
Measure Time Difference Between Antennas Using Cross-Correlations

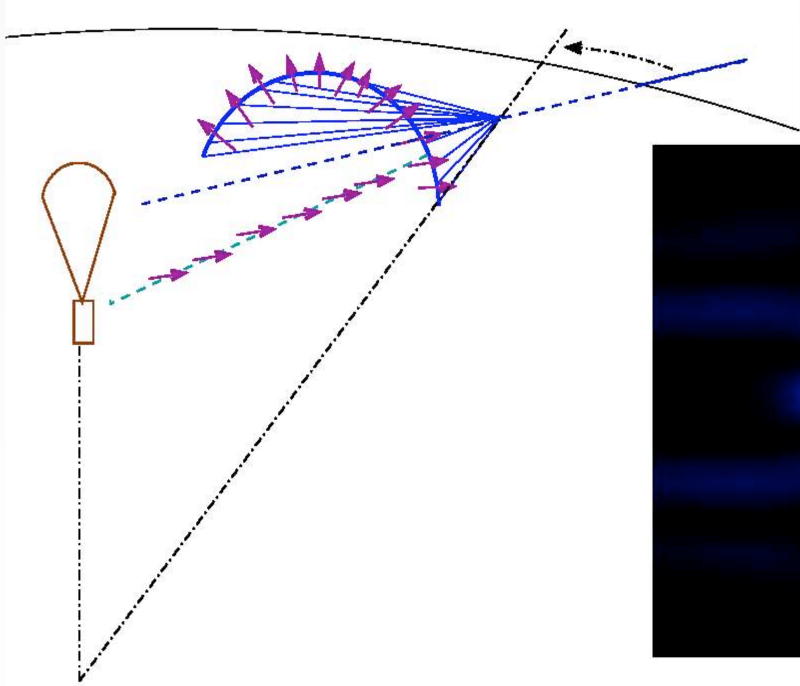


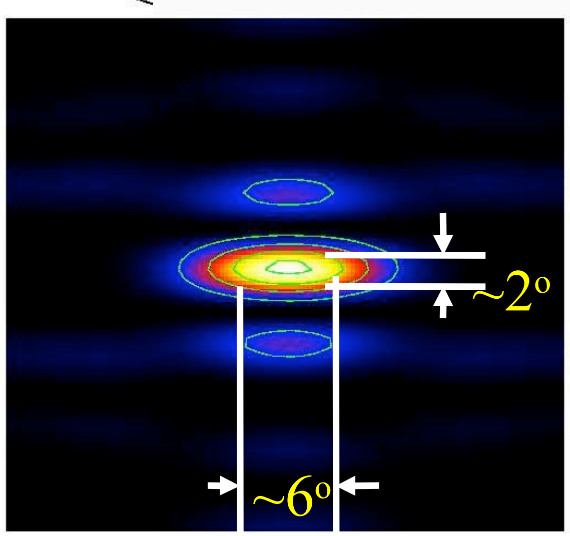
Imaging Interferometer -- (A. Romero-Wolf)



ANITA -- Angular Resolution



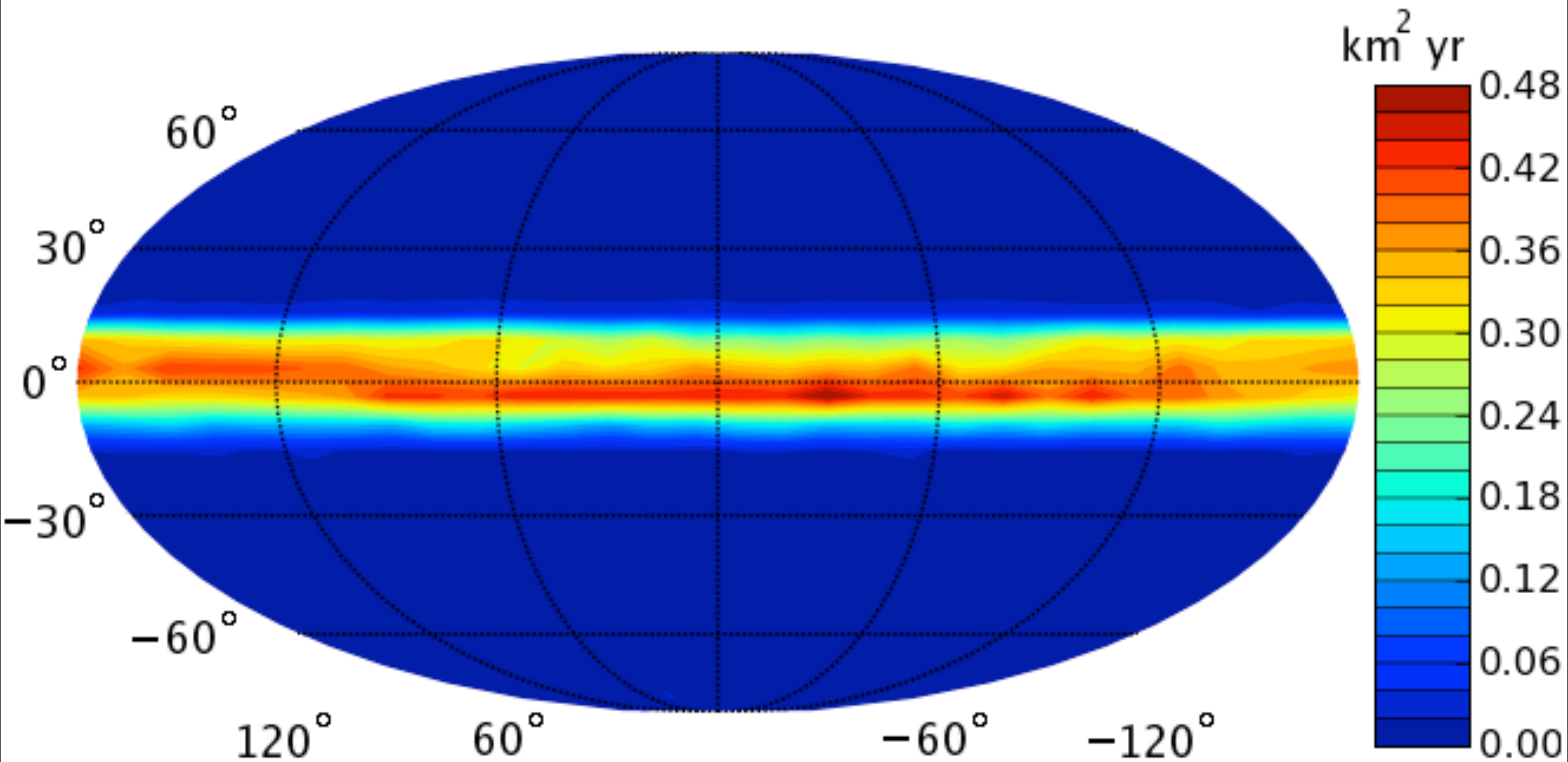




- Using signals from multiple antennas it is possible to measure the direction of arrival of radio pulse to ~0.5° in elevation and ~1.5° in azimuth (based on ANITA-lite calibration data)
- The neutrino direction can vary around radio pulse direction but is constrained to ~2° in elevation and by 3-5° in azimuth by polarization angle.

ANITA-1 Sky Map Sensitivity

- Expect GZK ν to be isotropic
- (RA, Dec) For 10^{20} eV neutrinos, 17.3 days



ANITA -- The Calorimeter

- The observed voltage V_{obs} is proportional to the neutrino energy E_ν:

$$V_{obs} \sim E_\nu \, y \, h_{eff} R^{-1} exp\left(-\frac{\beta^2}{2\sigma_\beta^2} - \alpha d \right)$$

y is the fraction of neutrino energy in the cascade

h_{eff} is the effective height of the antenna (gain)

R is the range to the cascade

Gaussian in β from observer position on Cerenkov cone

(estimated from RF spectrum)

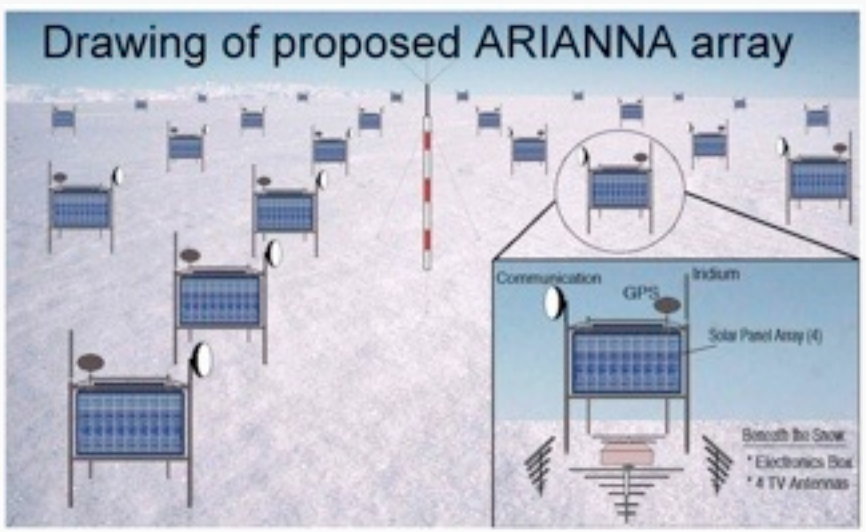
Exponential is attenuation in ice at depth *d*.

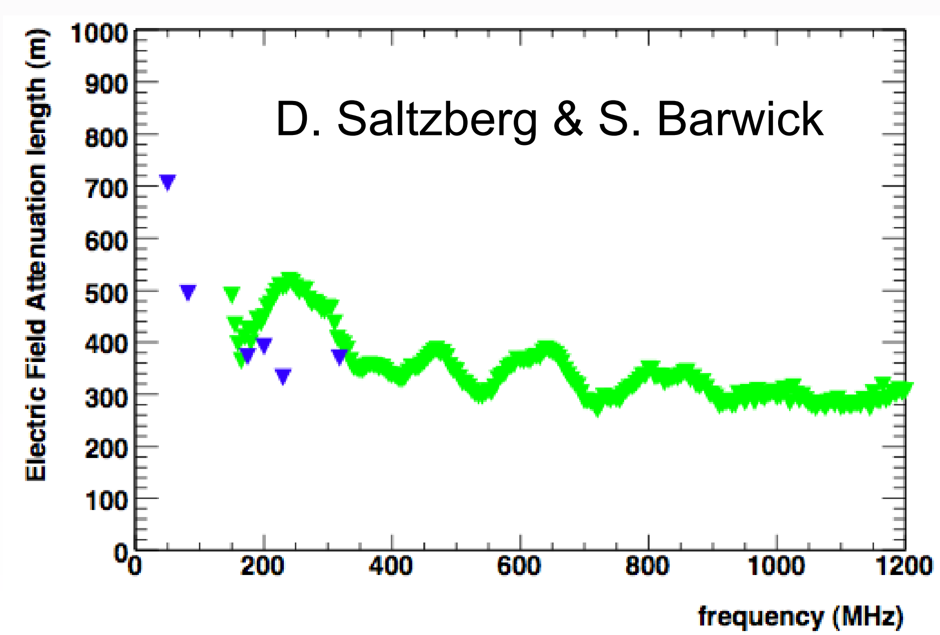
(estimated from RF spectrum and polarization effects)

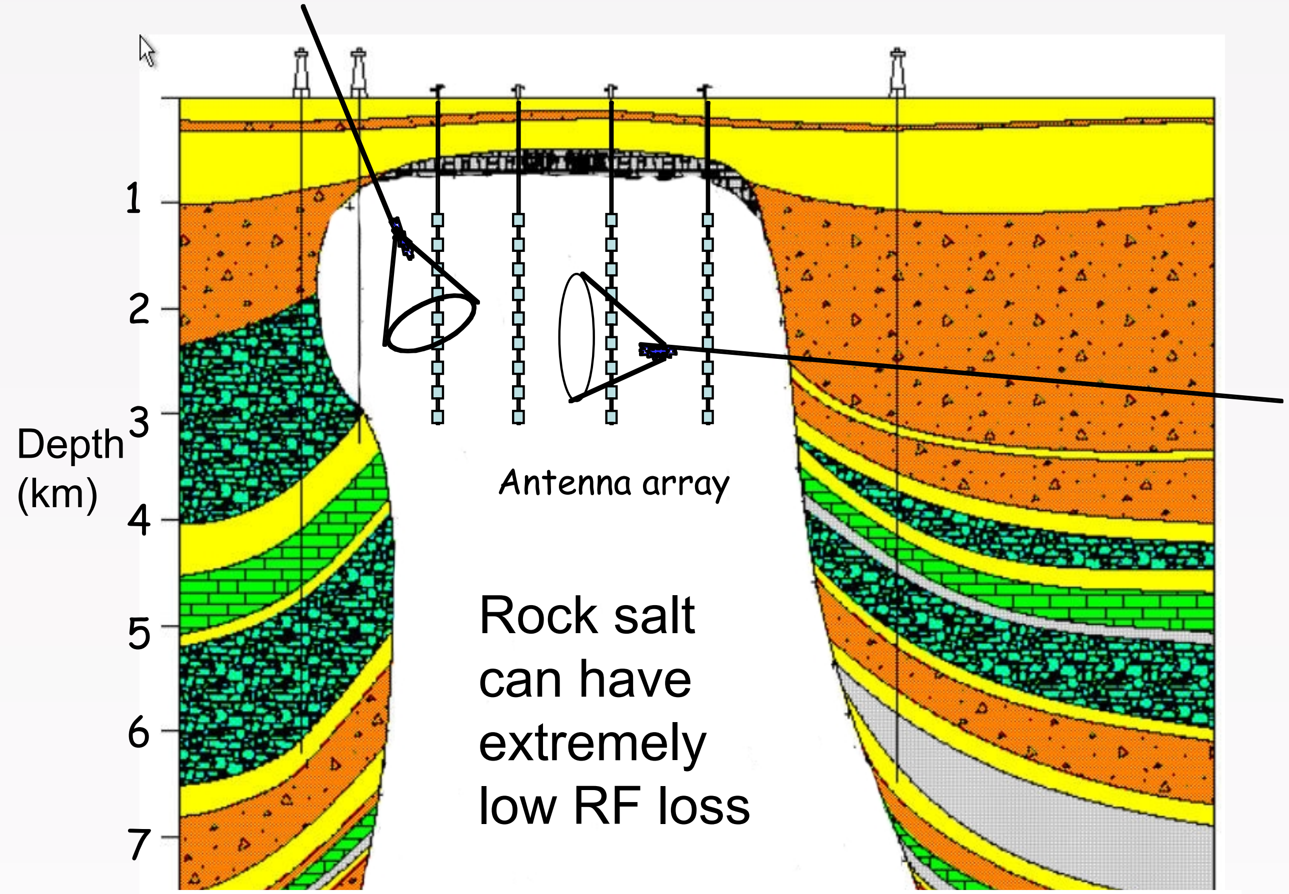
Gives: $\Delta E_\nu / E_\nu \sim 1.9$ (60% of which is intrinsic from y)

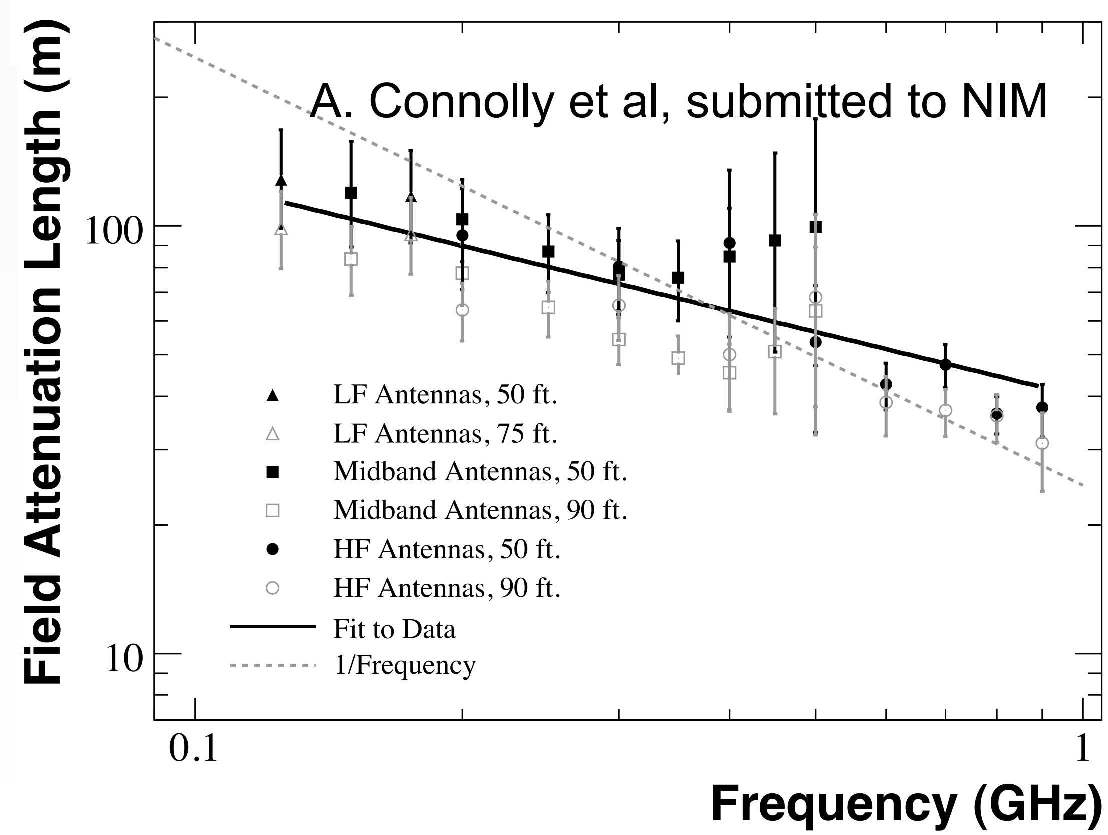
ARIANNA/SalSA

- Two of the proposed next generation radio arrays
  - ARIANNA (Ice Shelf)
  - SalSA (Salt Dome)



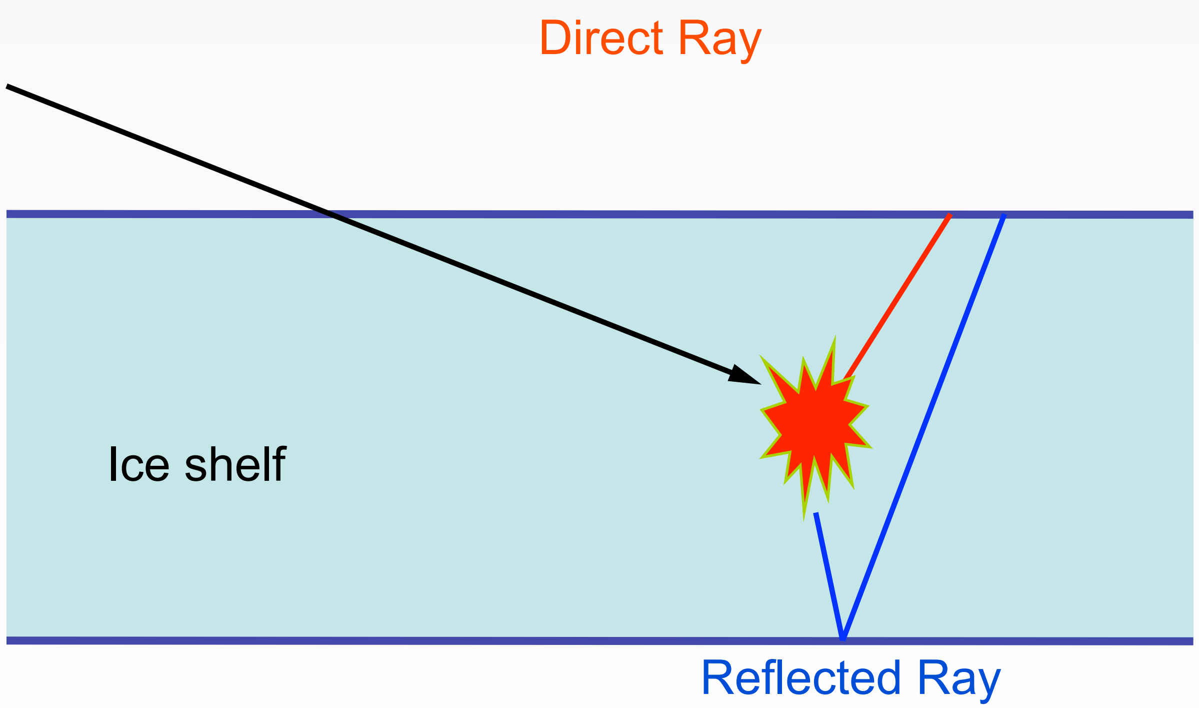






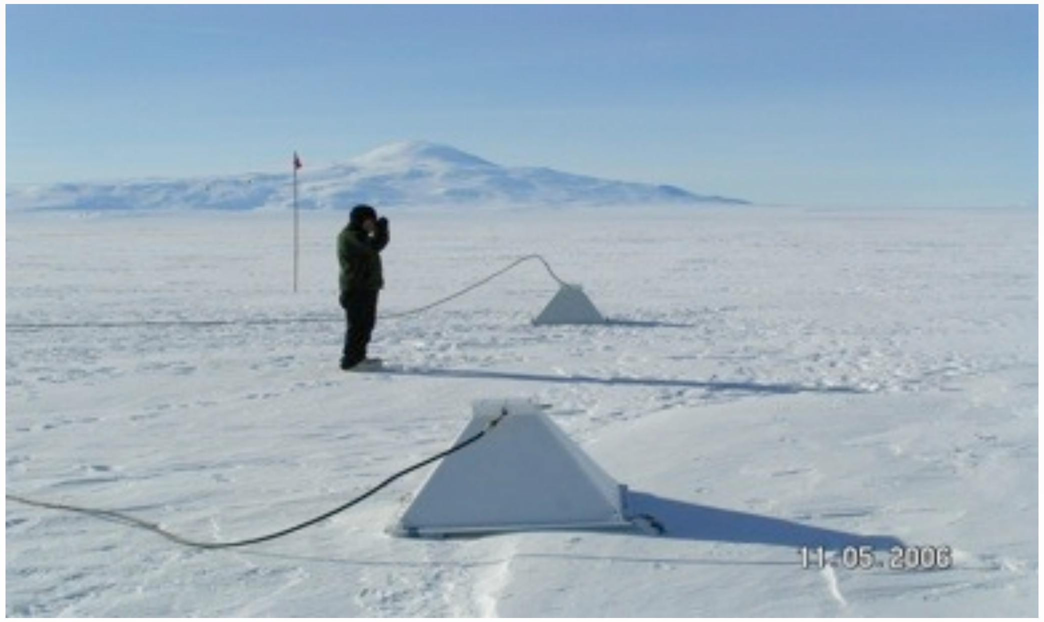
Ice Shelf Neutrino Array

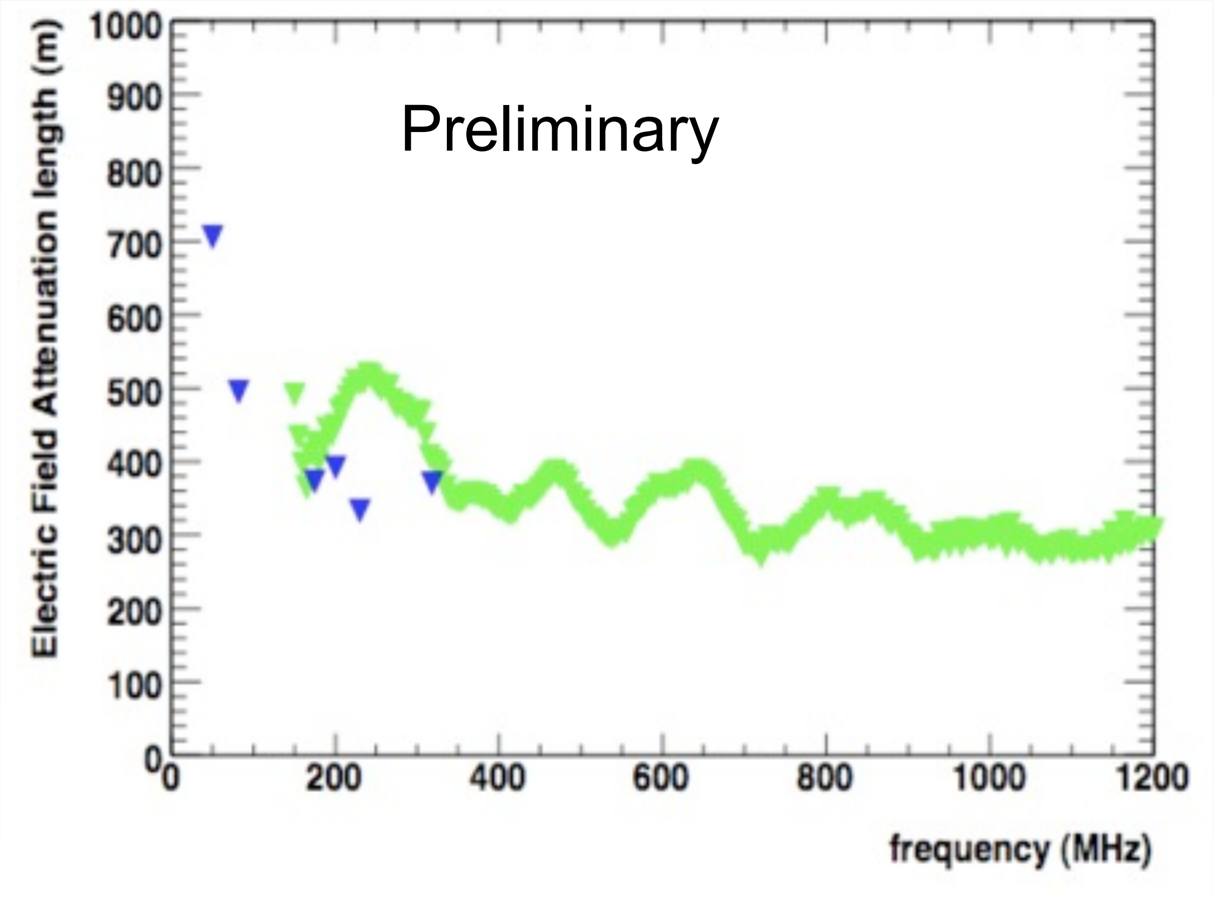
- ARIANNA
  - Array of antennas on top of the Ross Ice shelf
    - Lower threshold
    - More solid angle coverage
  - Advantages:
    - No need for deep holes
    - Cost effective?
    - Near McMurdo (logistics)



Ice Shelf Attenuation Measurements

- David Saltzberg and Steve Barwick made attenuation length measurements on the ice shelf in December 2006.





Better than 300m across the band

Fun Slides

Ryan Nichol

- Alternative Titles:
  - "Call that an accelerator?"
    - Let me tell you about a real particle accelerator, just as soon as we work out where it is, how it works and what exactly it is accelerating.
  - "World's largest scientific experiment?"
    - Our detector is the size of a continent, of course we haven't actually detected anything yet (but hey, neither have you).
  - "Call that a long-baseline neutrino experiment?"
    - We measure our baseline in Mpc, or we will if we find one of the little blighters.
  - "Yet more stuff that might happen before the ILC"


CARHART, JACKET
CARHART, PARKA
PARKA, RED
ATTENTION
WHEN RETURNING OR EXCHANGING
CLOTHING YOU MUST BRING YOUR
CLOTHING ISSUE FORM WITH YOU


UNITED STATES ANTARCTIC PROGRAM
PASSENGER TERMINAL


U.S. AIR FORCE

- McMurdo Facts:
  - Established 1937
  - Takes its name from McMurdo Sound (named after Lieutenant Archibald McMurdo of the *Terror*
  - Near Scott's Hut
  - Food is inedible 363 days a year
    - Christmas
    - Thanksgiving
- Facilities:
  - Harbour (two weeks a year)
  - 3 Airfields
  - 1 bowling alley
  - 3 bars

- Williams Field Facilities
  - Own galley (so edible food)
  - Three payloads in 2006
  - No indoor plumbing though