Ultra-High Energy Neutrino Astronomy in Antarctica

Ryan Nichol

Neutrinos go Bang**...
...in Ice

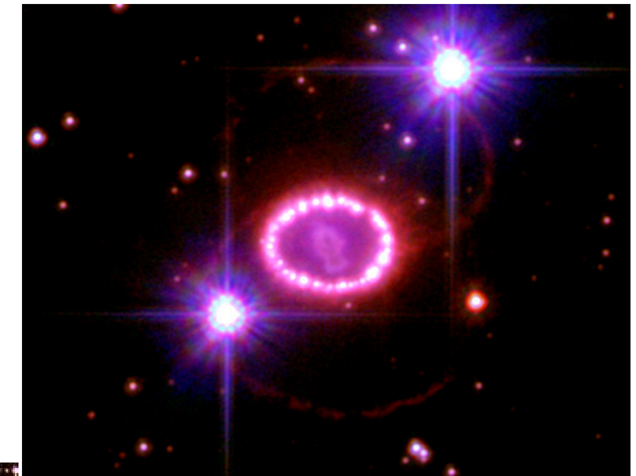
Ryan Nichol

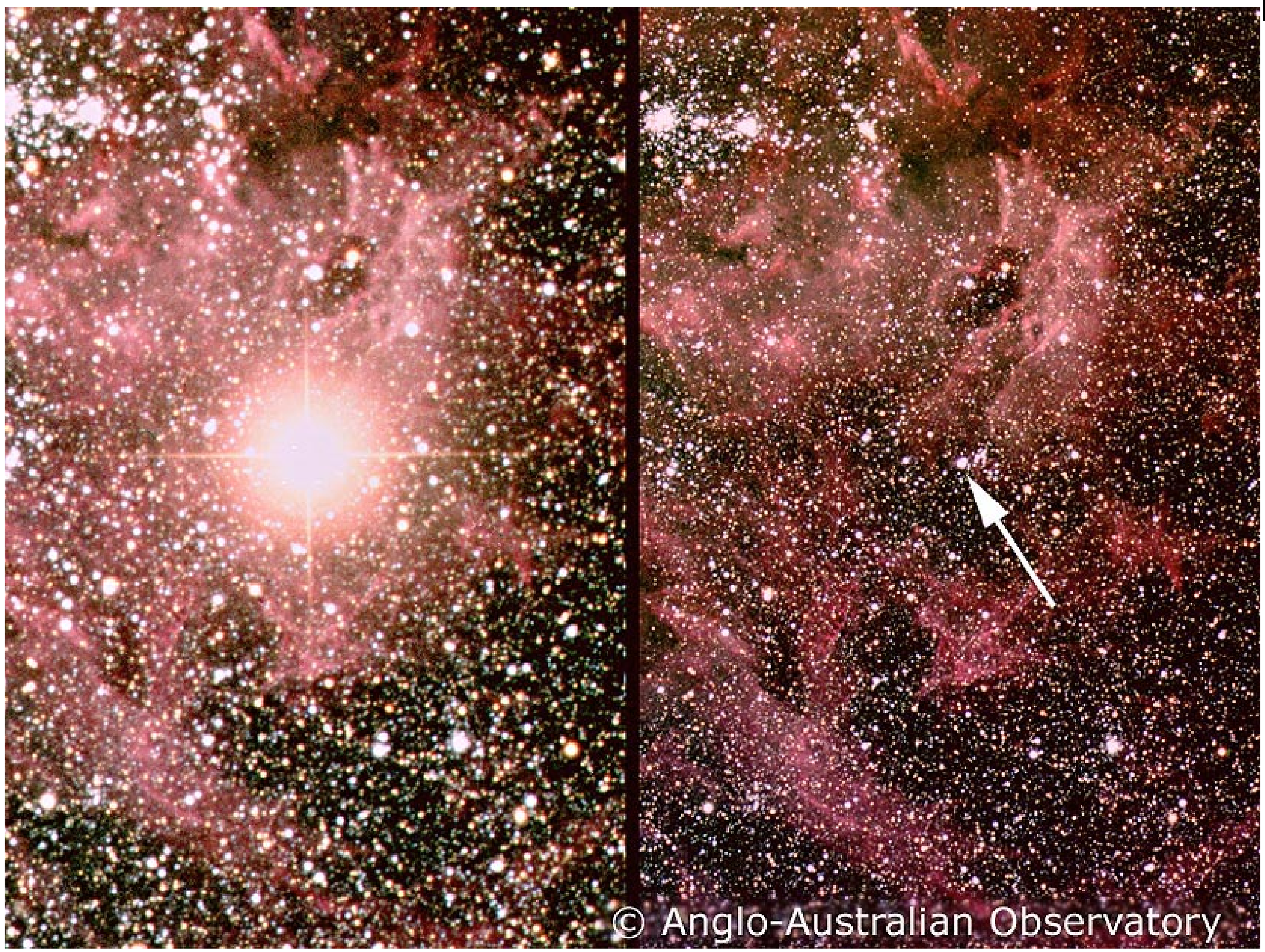
** Hopefully

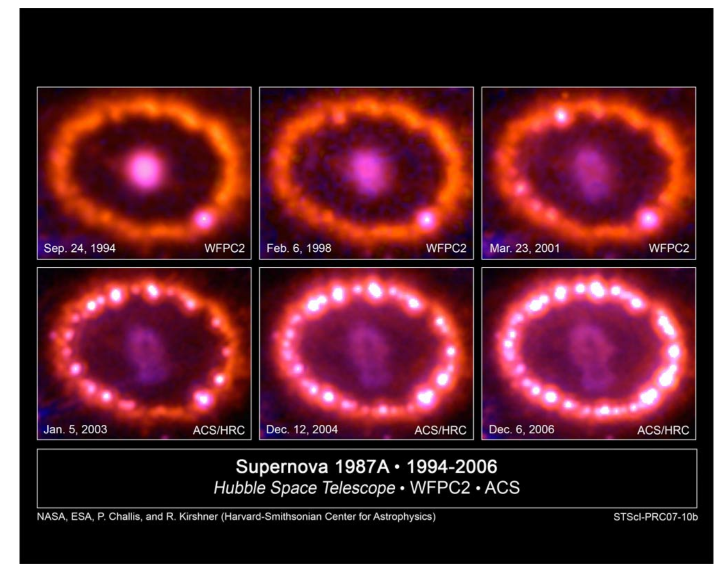
- Abbreviated History Lesson
- Motivation for Ultra-High Energy Neutrino Astronomy
  - For Astronomers, Astrophysicists and Particle Physicists
- Detection Methods
  - Radio
- Why Antarctica?
- Current Experiments
  - ANITA
    - Featuring Ryan’s Antarctic Adventure
- Proposed Experiments
  - ARIANNA, AURA, etc.

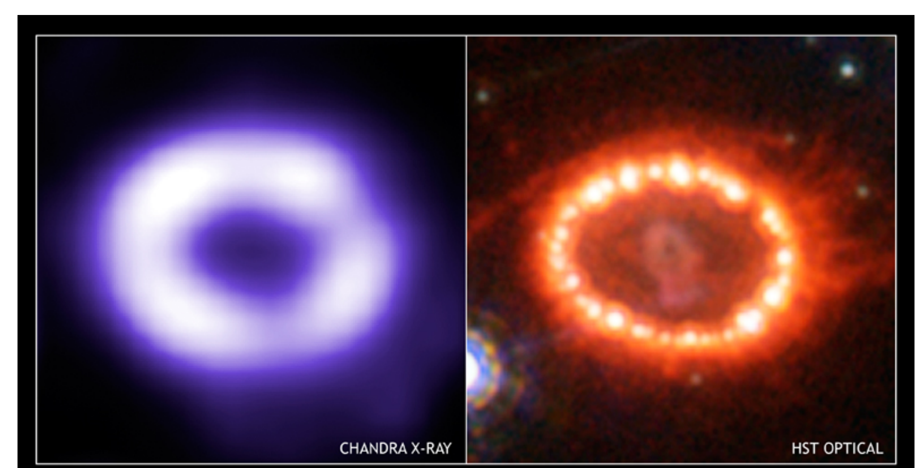
Why?

- Skewed History Lesson
  - Neutrino Astronomy started with a bang...



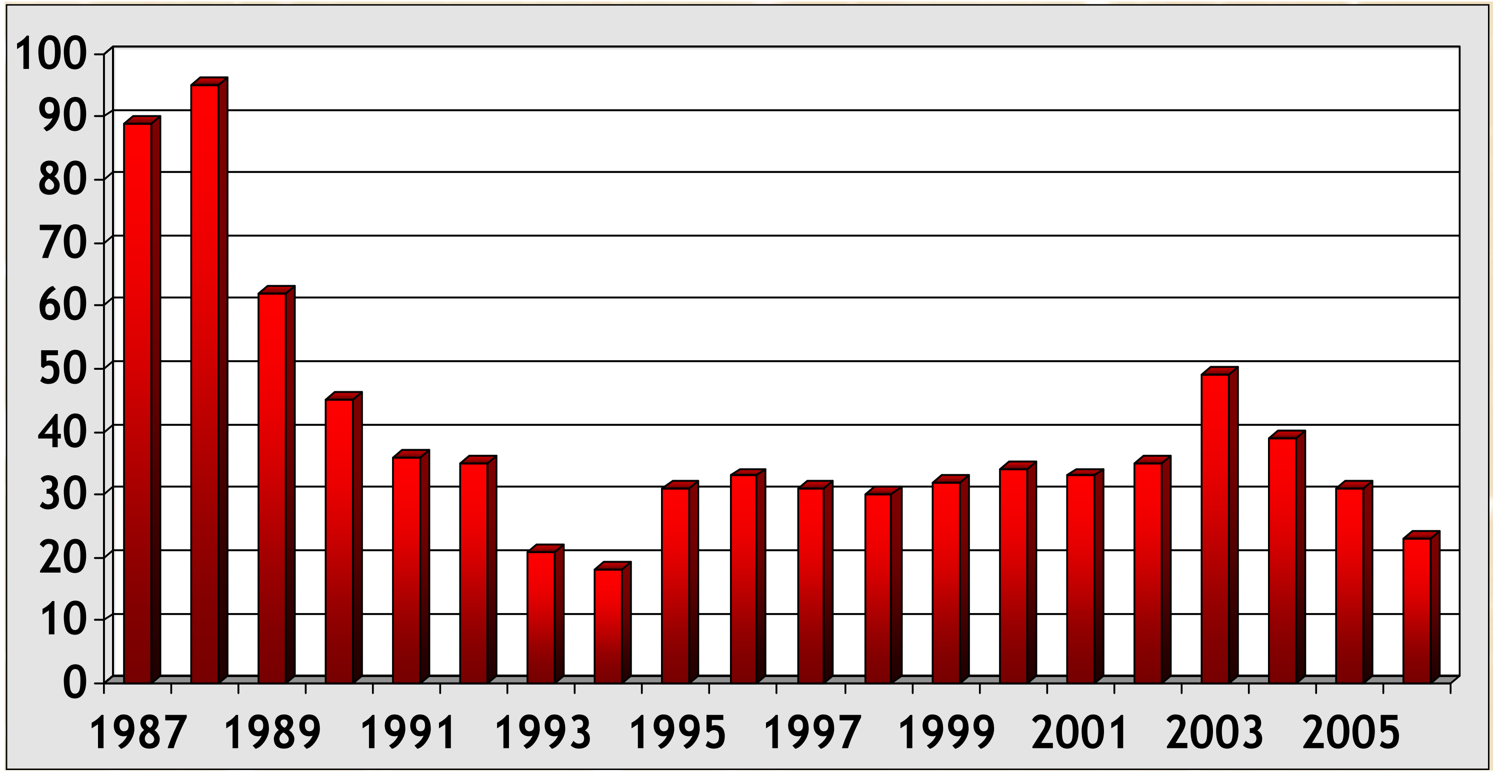




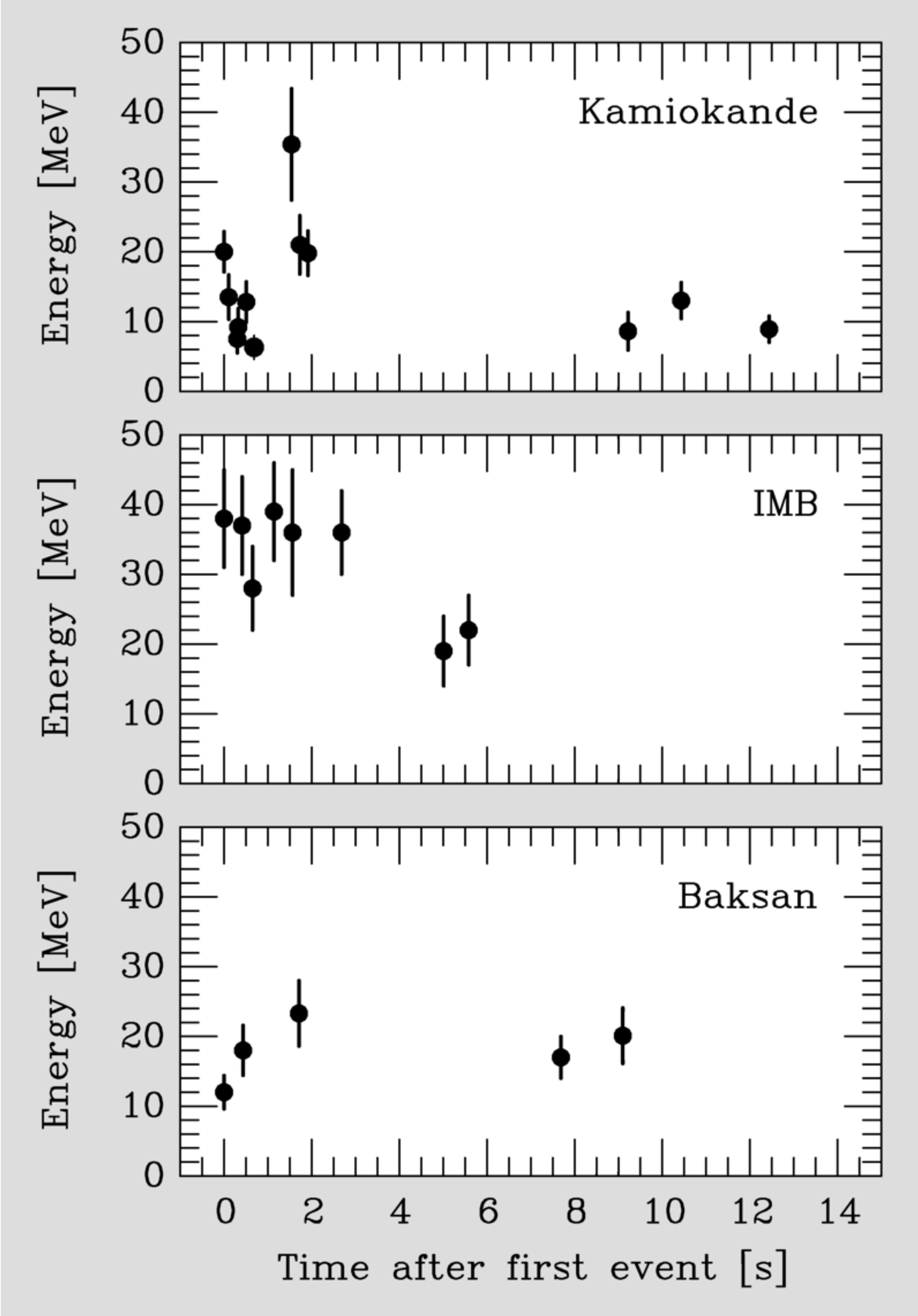


Pretty pictures from Hubble, Chandra (X-ray) and AAO

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

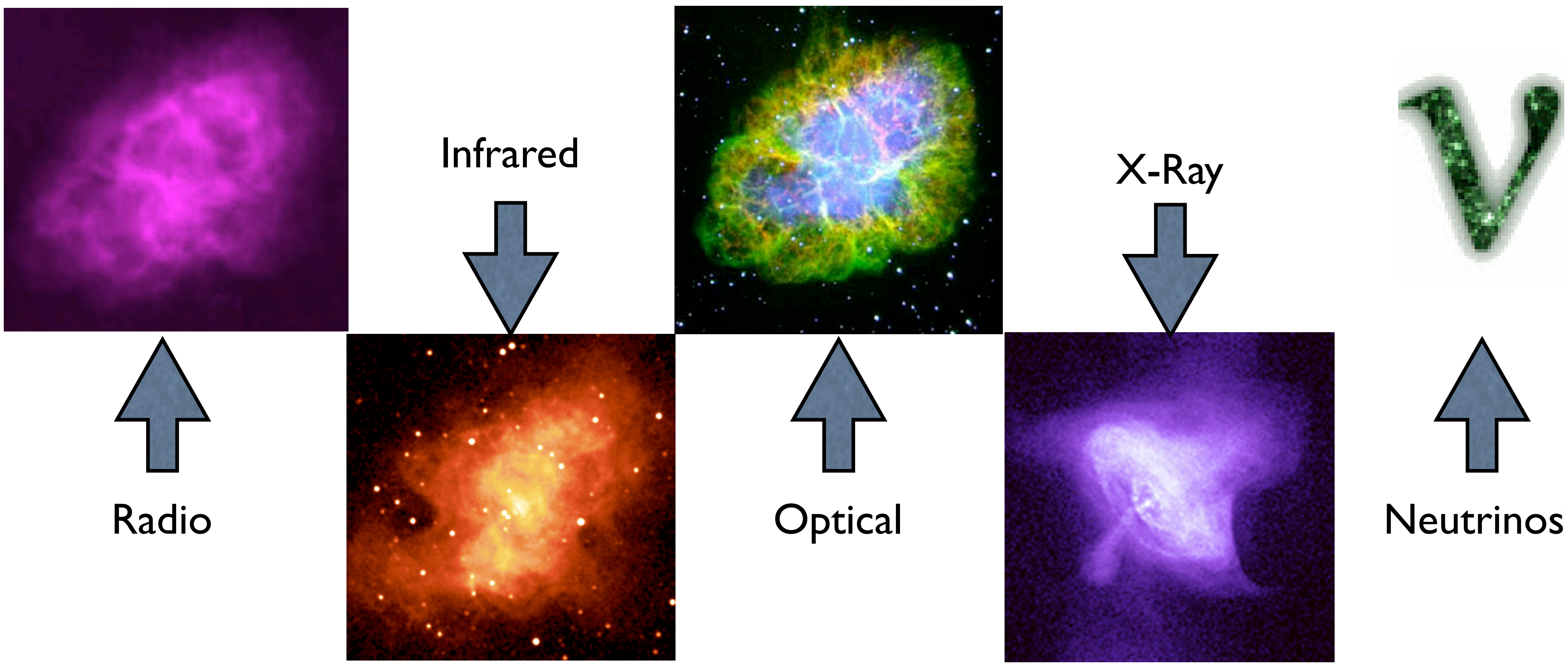


Annual Citations (from SPIRES) of SN 1987A Papers



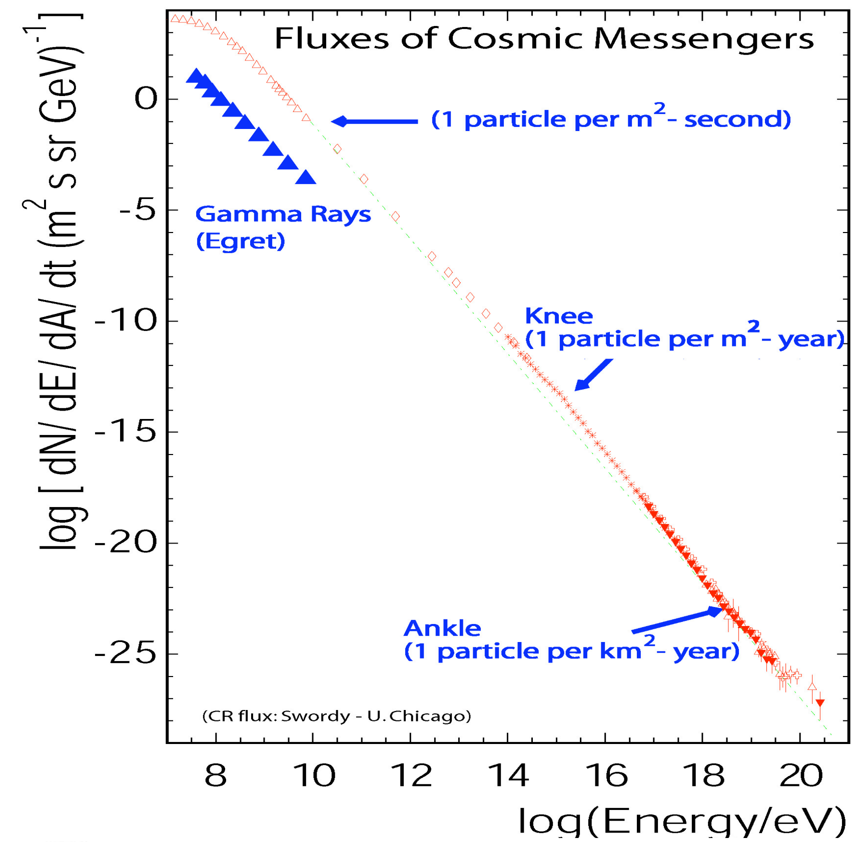
Plots stolen from Georg Raflett

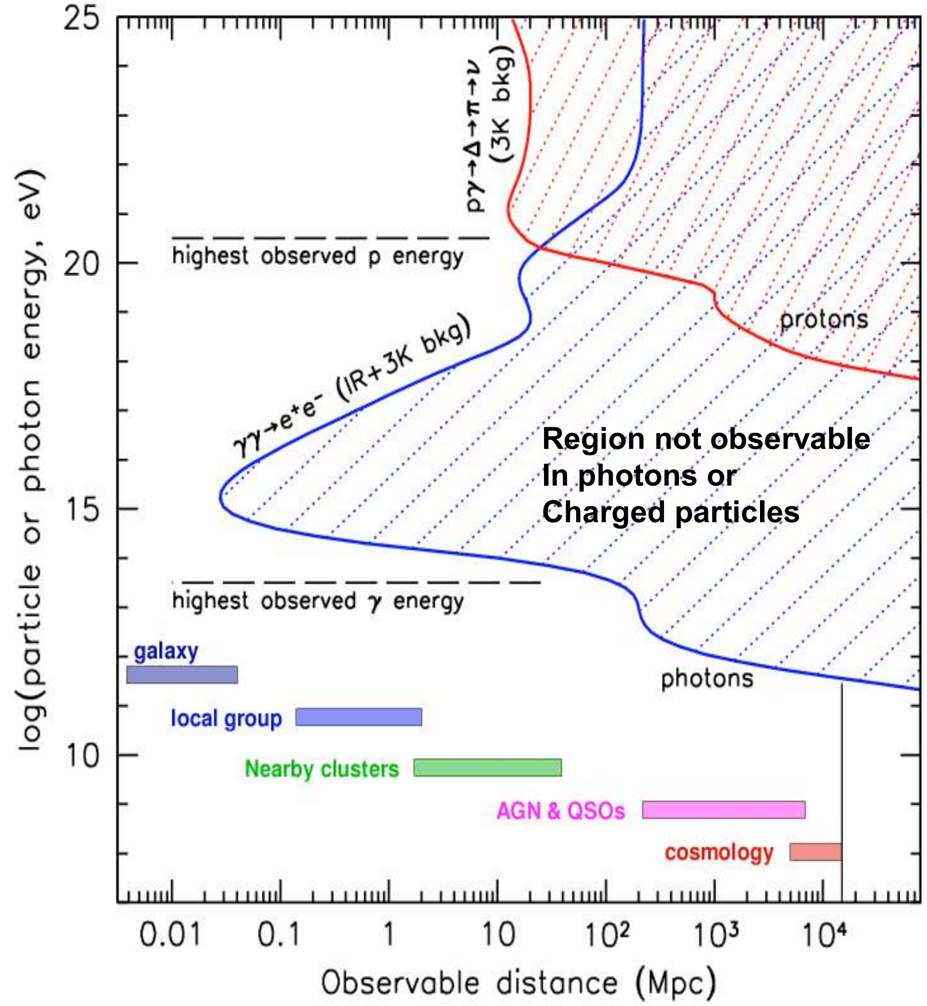
- Why is neutrino astronomy interesting?
  - The Astronomer's (pretty pictures) answer.

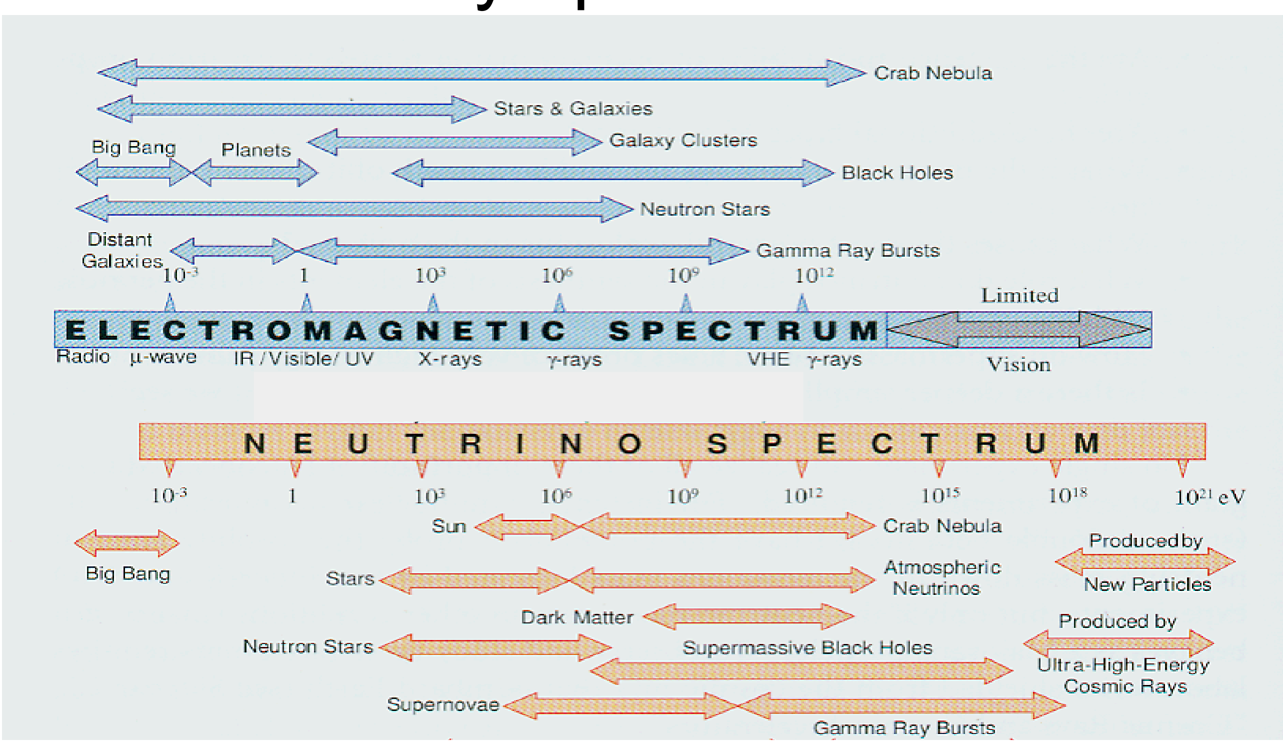


"The real voyage of discovery consists not in seeking new landscapes, but in having new eyes." **Marcel Proust**

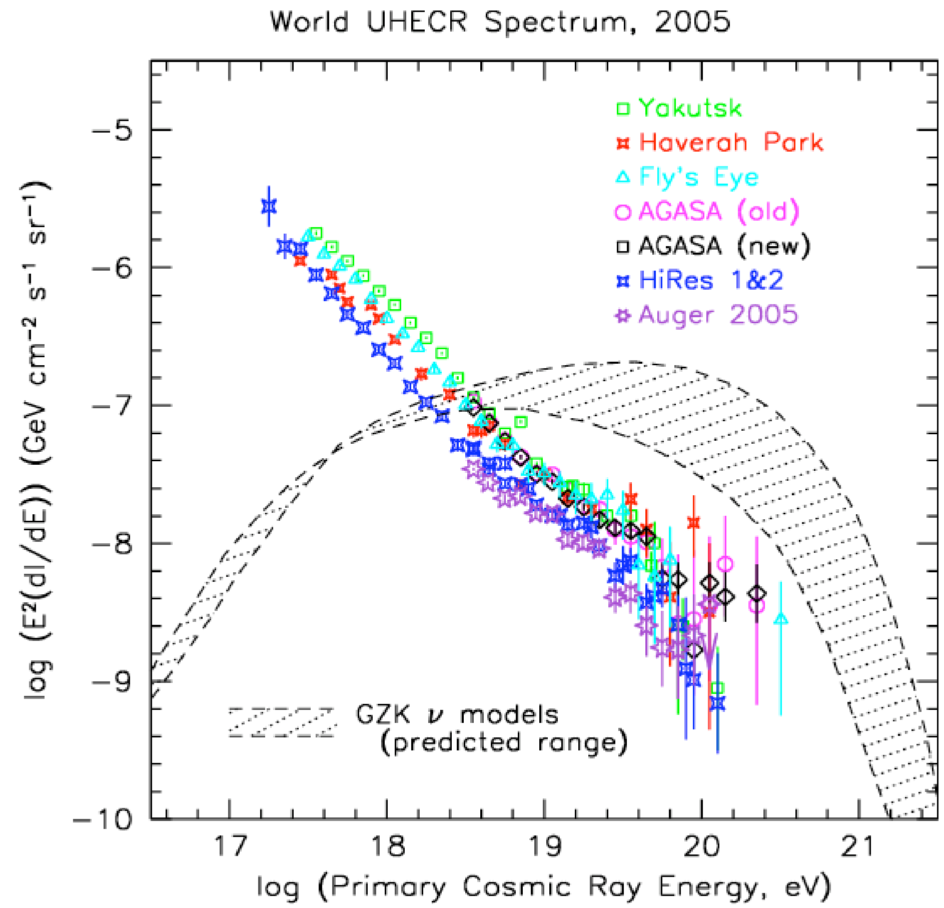
- Cosmic Messengers:
  - Photons
    - Absorbed > 30 TeV
  - Protons/Ions
    - Deflected by B-fields
    - Interact with CMB
  - Neutrinos
    - No diffuse flux detected
    - Only option $E>10^{20}$ eV







- The Ultra-High Energy Cosmic Ray Puzzles
  - Acceleration mechanism not understood
  - Mass Composition (protons or ions) not well measured
  - No point sources found
  - Is there a cut off?
    - Should interact with CMB within 50Mpc
    - If source is within 50Mpc of Earth we should see source.

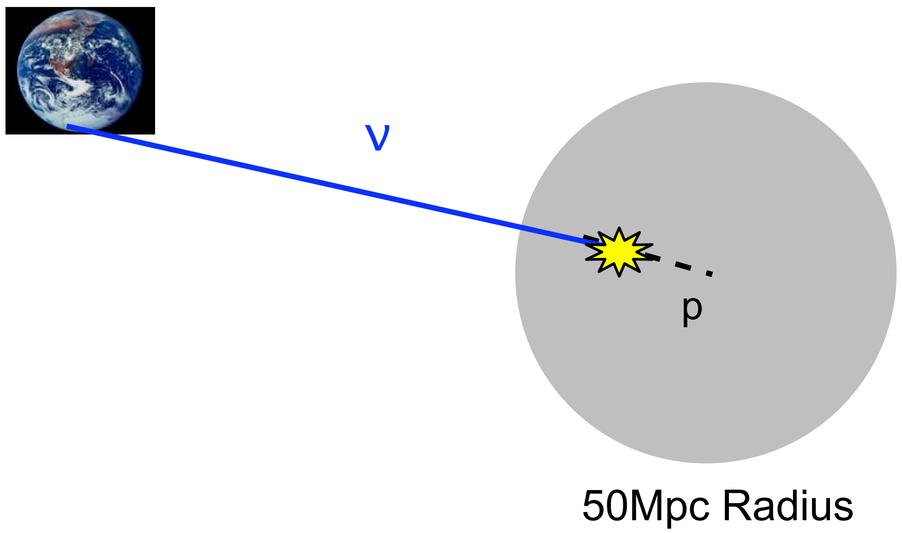


- The highest recorded energy of a cosmic ray is roughly equivalent to a cricket ball at 54 MPH

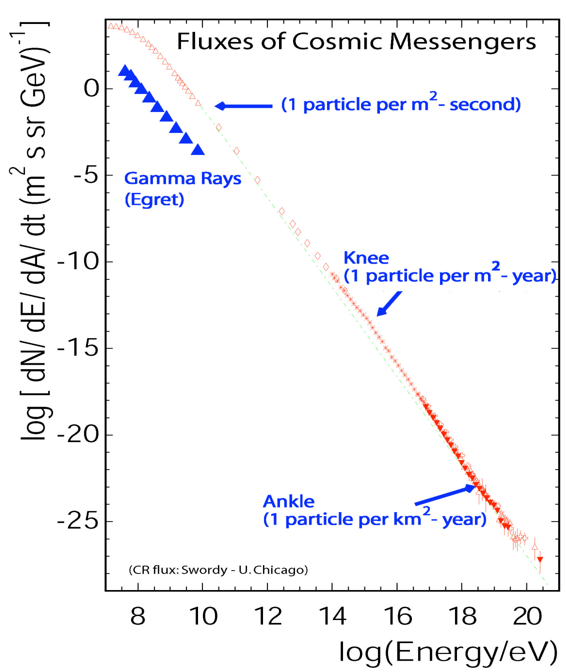
- Greisen-Zatsepin-Kuzmin (GZK) calculated that cosmic rays > $10^{19.5}$eV should be slowed by CMB within 50Mpc.

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

- Neutrinos are produced in GZK interactions
  - point back to source



- So:



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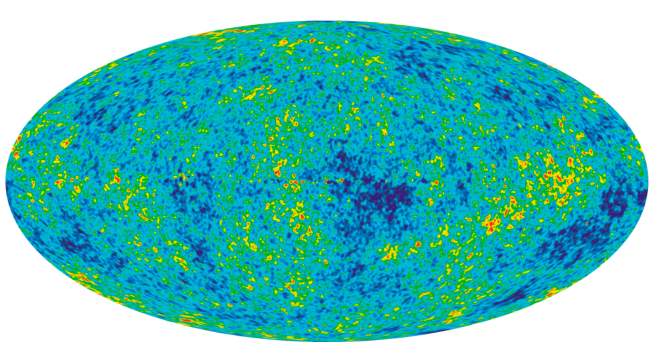
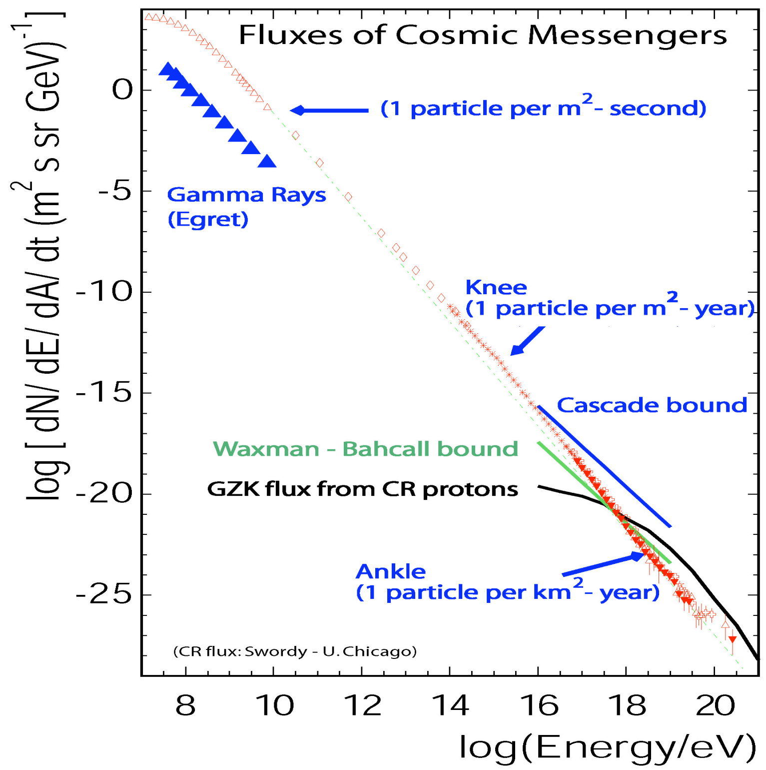
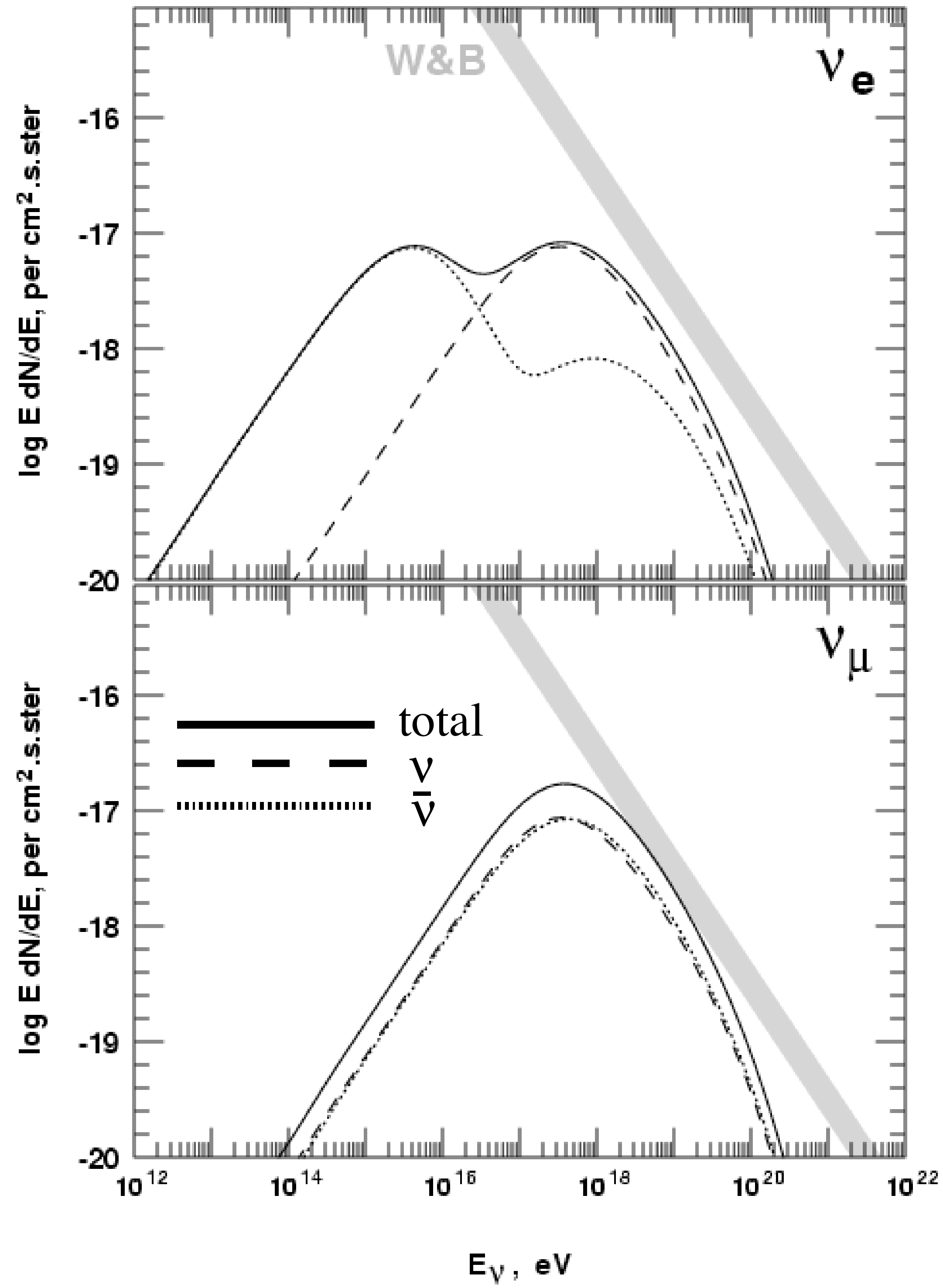


= Neutrino Beam!

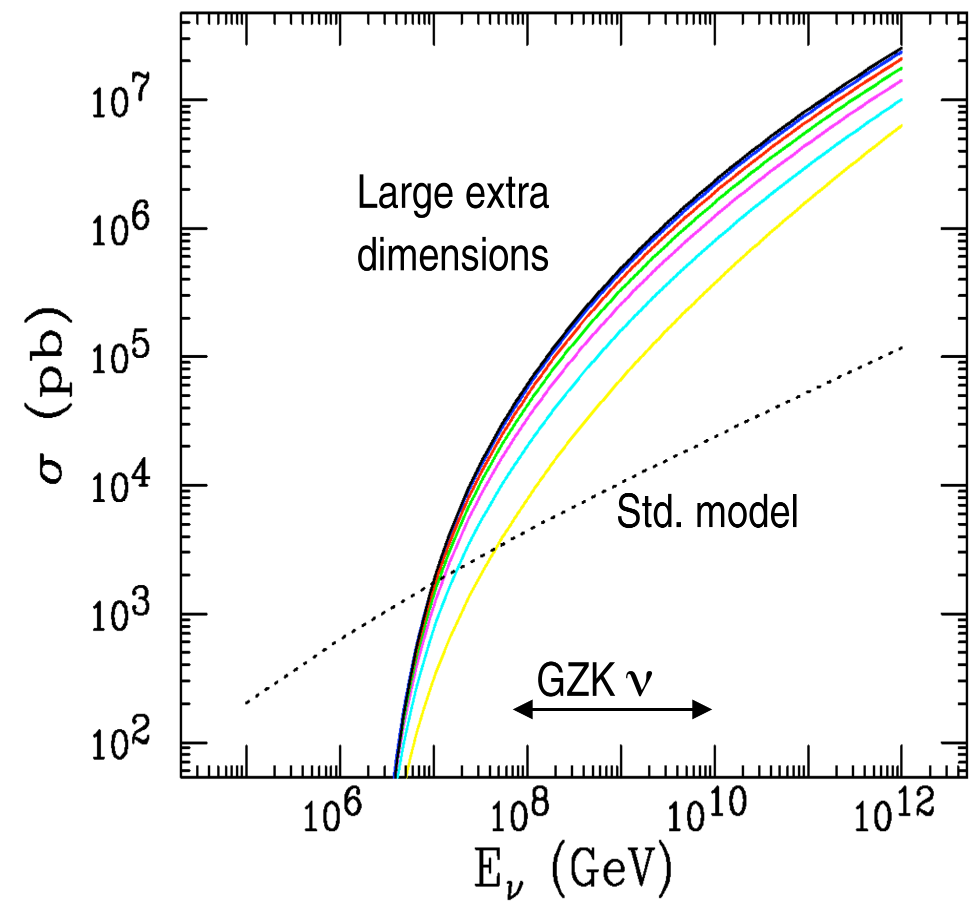
- GZK Flux calculation contains many assumptions
  - Earth CR flux only
  - Injection Spectrum
  - Cosmological Evolution
  - Optical Density of Source



- Still 'best known' neutrino flux



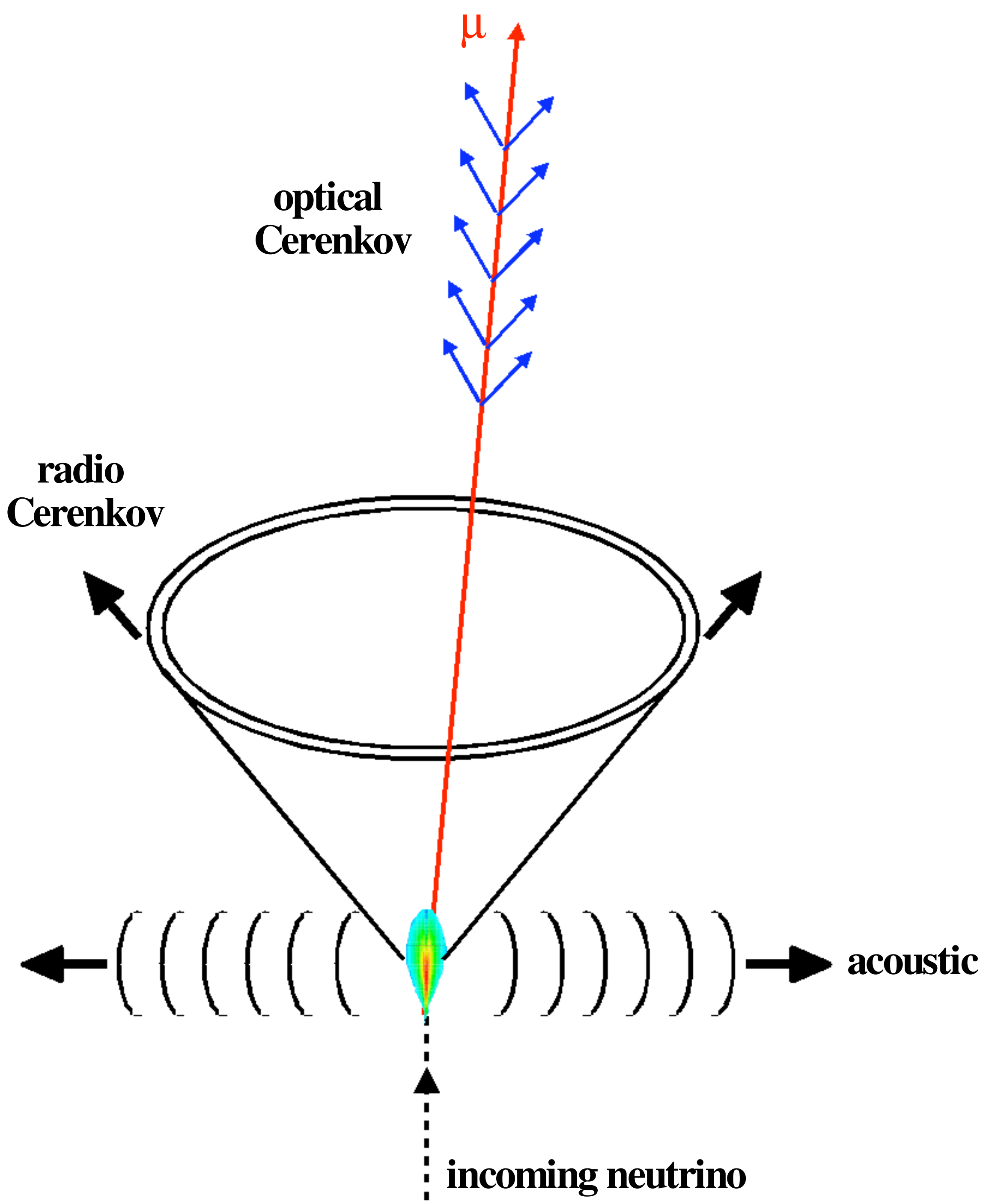
- ‘Guaranteed’ neutrino beam at 10-300 TeV
  - Measure neutrino-nucleon cross section in new regime
  - With flavour tagging can probe:
    - Neutrino Oscillations
    - Neutrino Decay
    - Quantum Decoherence
  - Large extra dimensions
  - Micro blackholes
  - Other Exotic:
    - Super heavy relics
    - Topological Decay
    - Q-balls
    - Magnetic Monopoles



Anchordoqui et al. Astro-ph/0307228

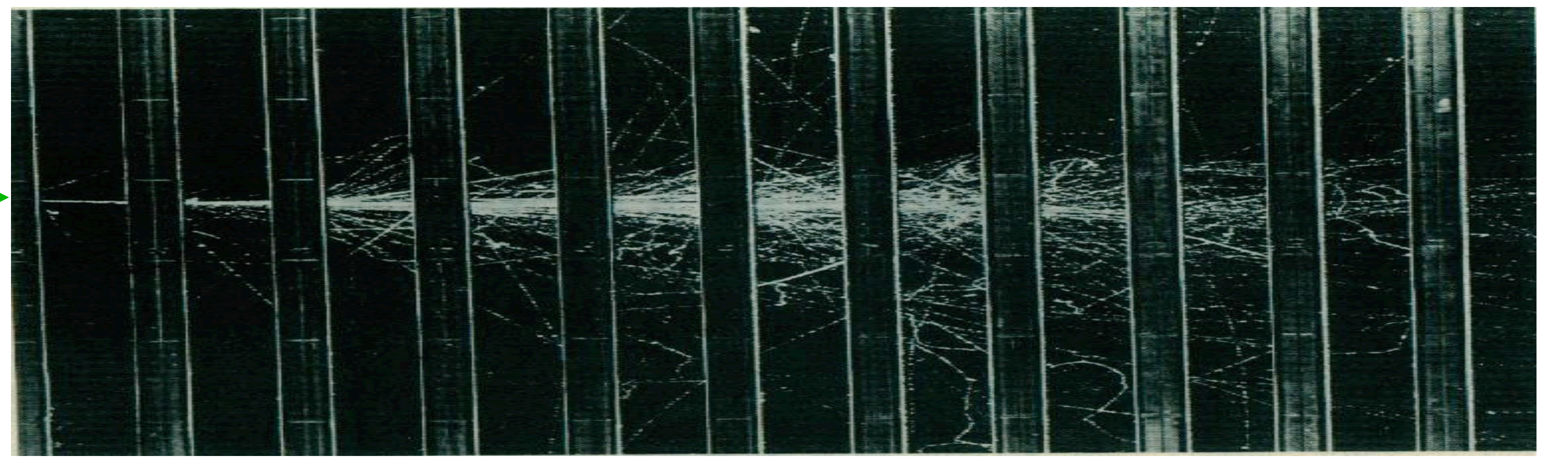
How can you do it?

- Detection Methods
  - Optical Cherenkov
  - Radio Cherenkov
  - Acoustic
- Optical is most mature
  - Baikal
  - Amanda
  - Antares/Nestor/Nemo
  - IceCube
- I will concentrate on Radio Cherenkov



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

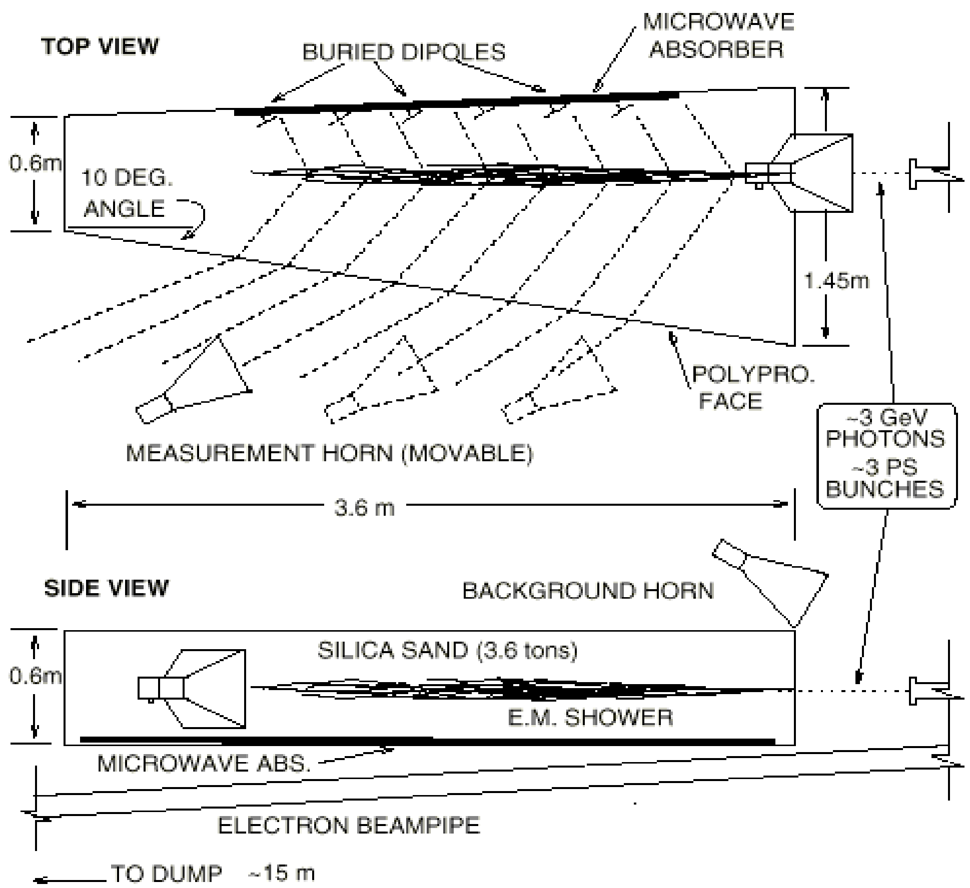
$e^{\pm}$ or Υ



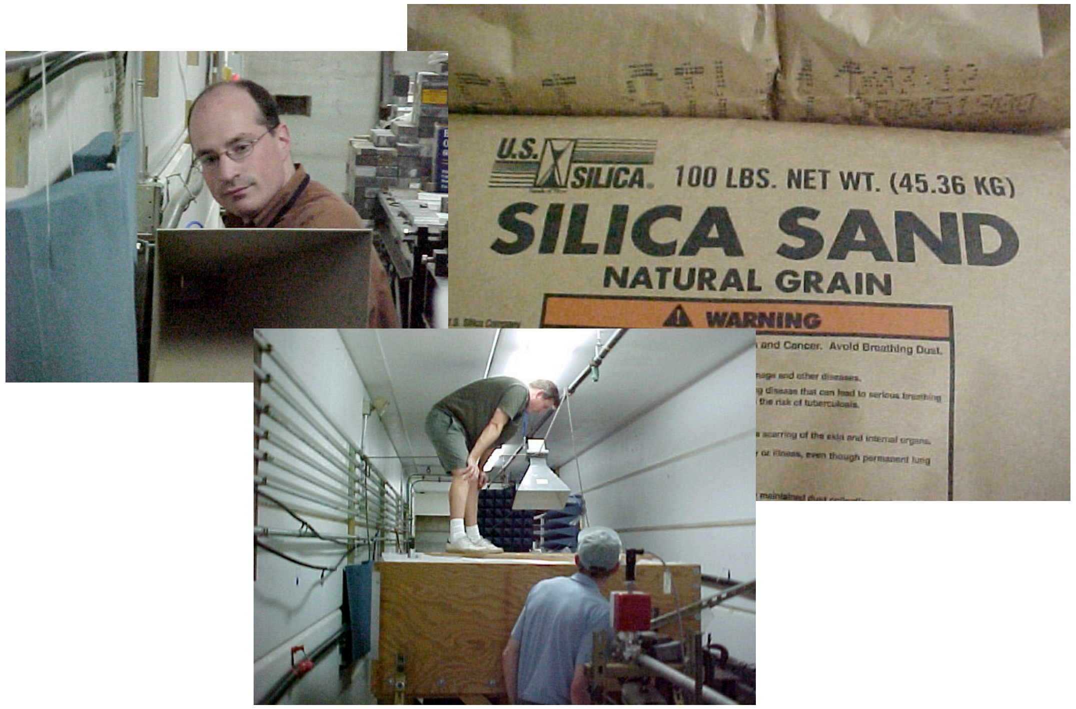
Typical Dimensions:
$L \approx 10$ m
$R_{Moliere} \approx 10$ cm

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

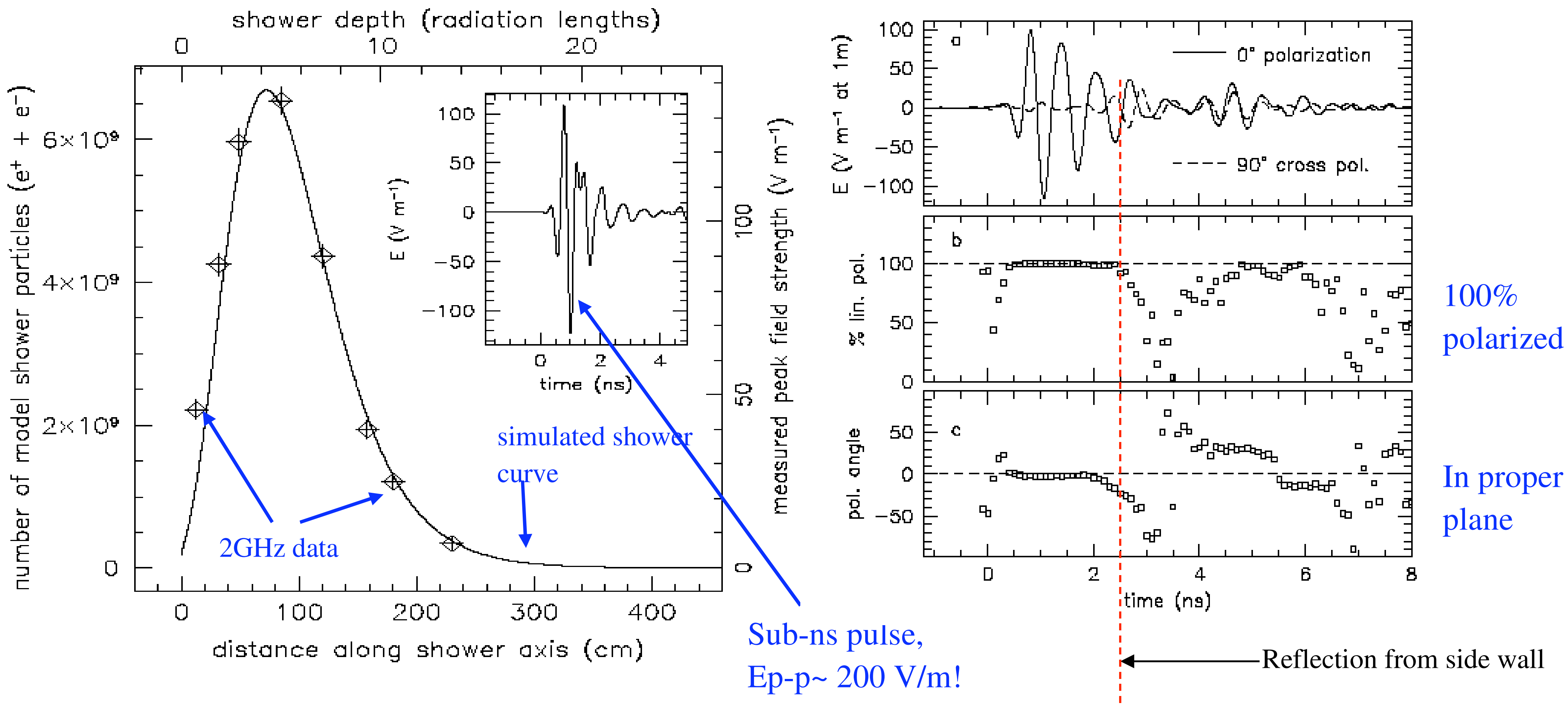
- Askaryan effect experimentally confirmed in 2000



From Saltzberg, Gorham, Walz et al PRL 2001

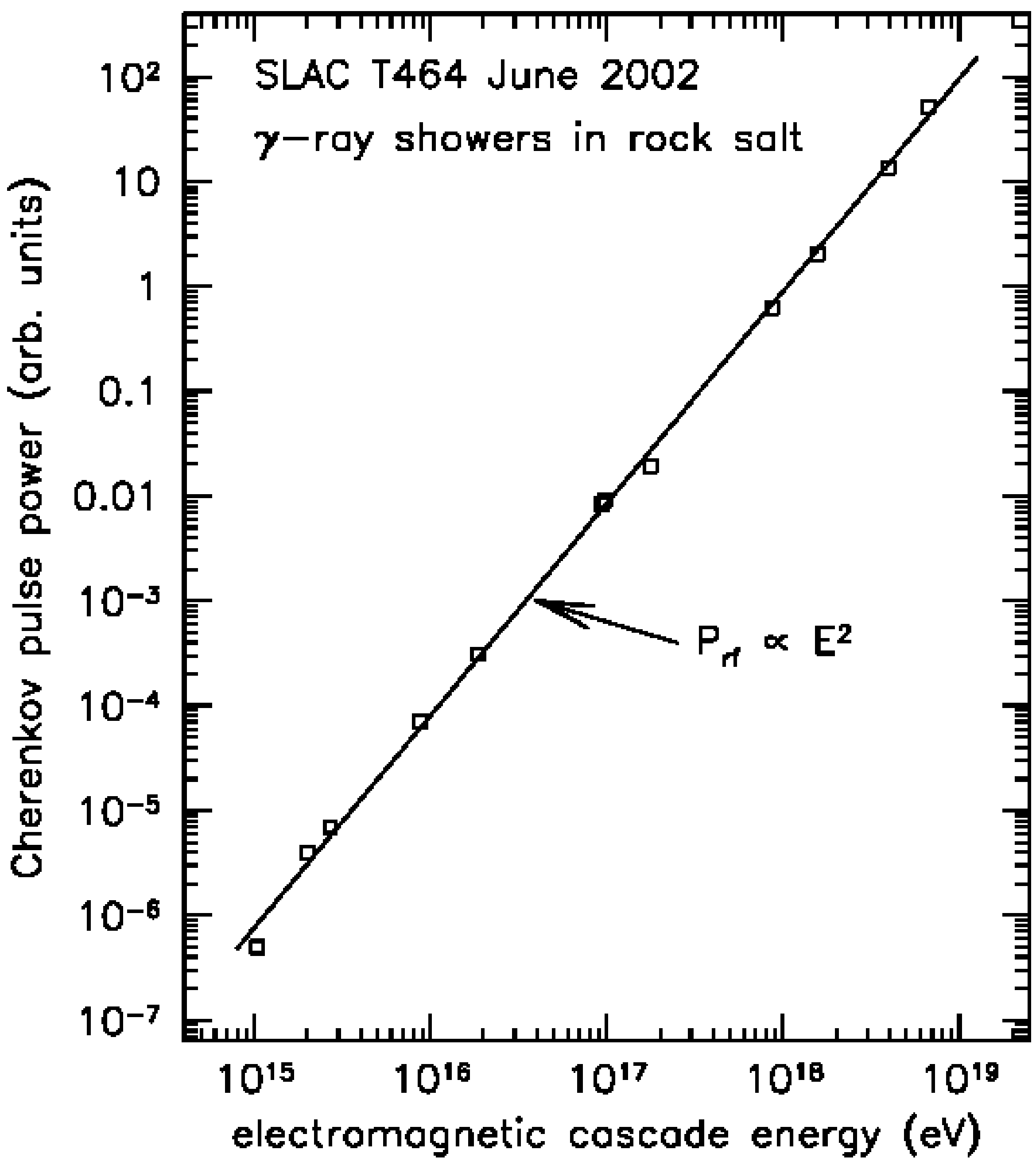


- Using 3.6 Tonnes of sand
  - (like a big cat's litter box)

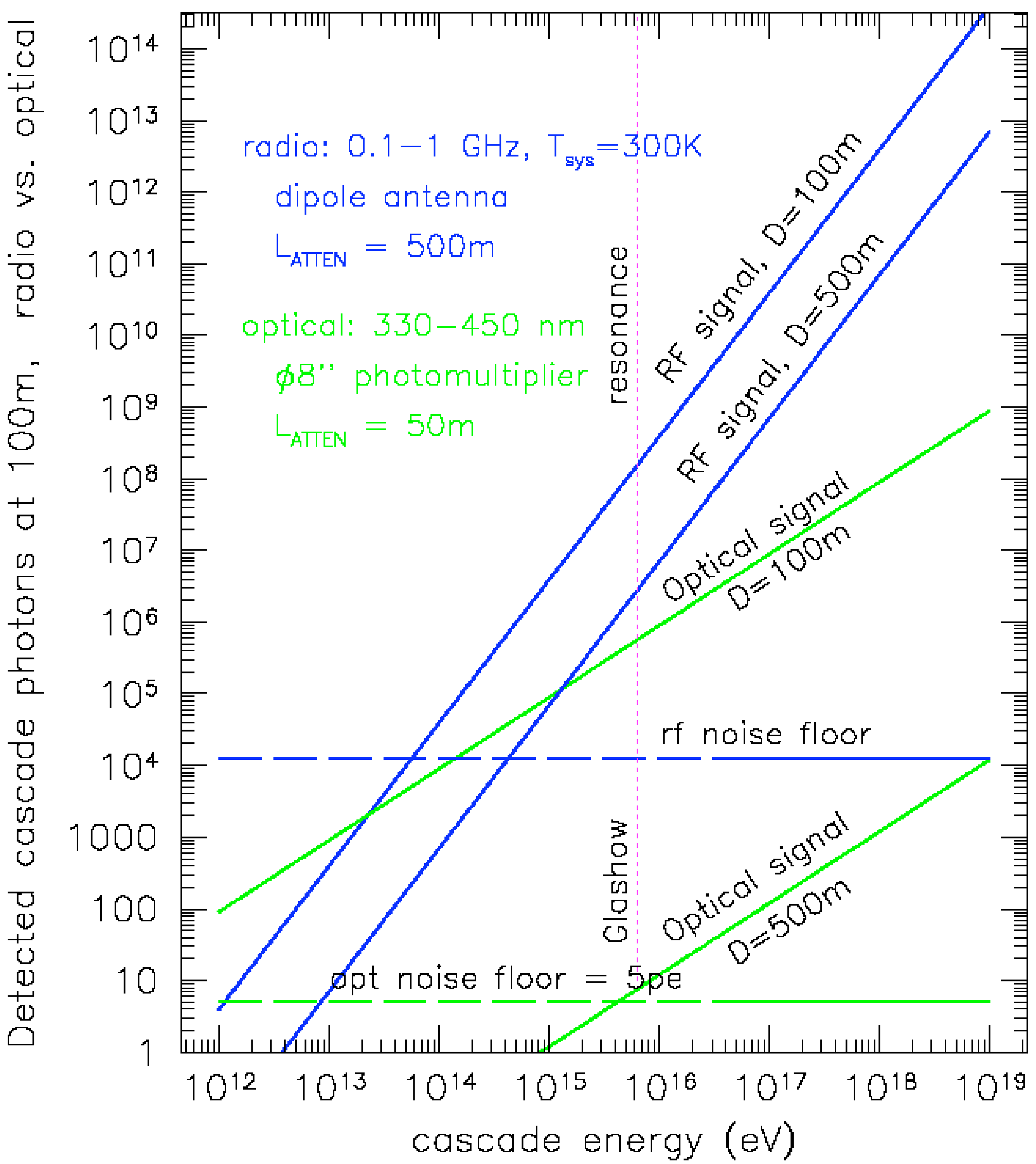


- Sub nanosecond pulse
- Excellent agreement between data and simulation of number of particles in shower
- Linearly polarised as expected
- Further measurements in 2004 with salt as the medium

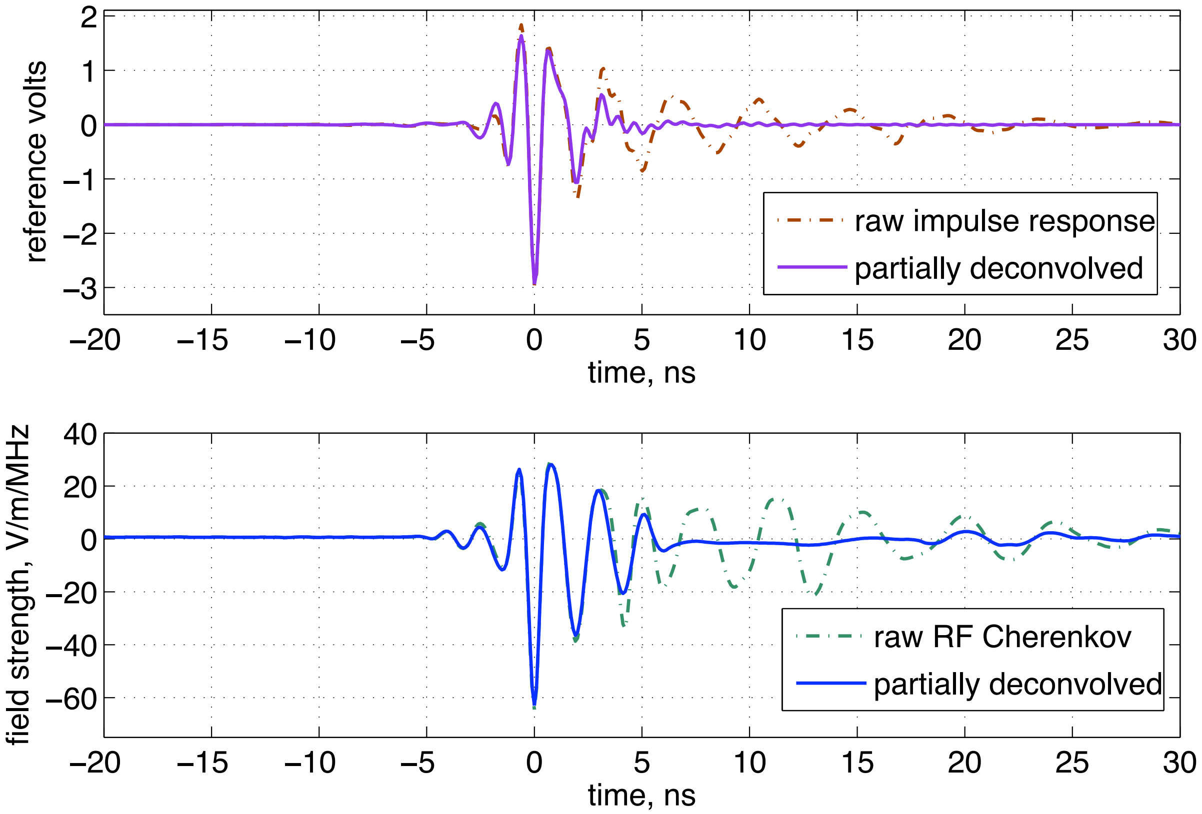
Coherent signal over 4 orders of magnitude

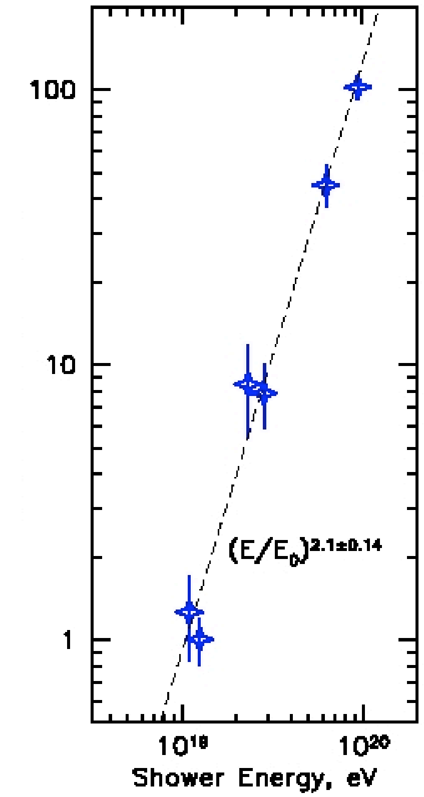


SNR dominant for E > 10 TeV



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





From: ANITA SLAC test beam paper submitted to Physics Review Letters

Where can you do it?

- What do you need for a GZK neutrino detector?

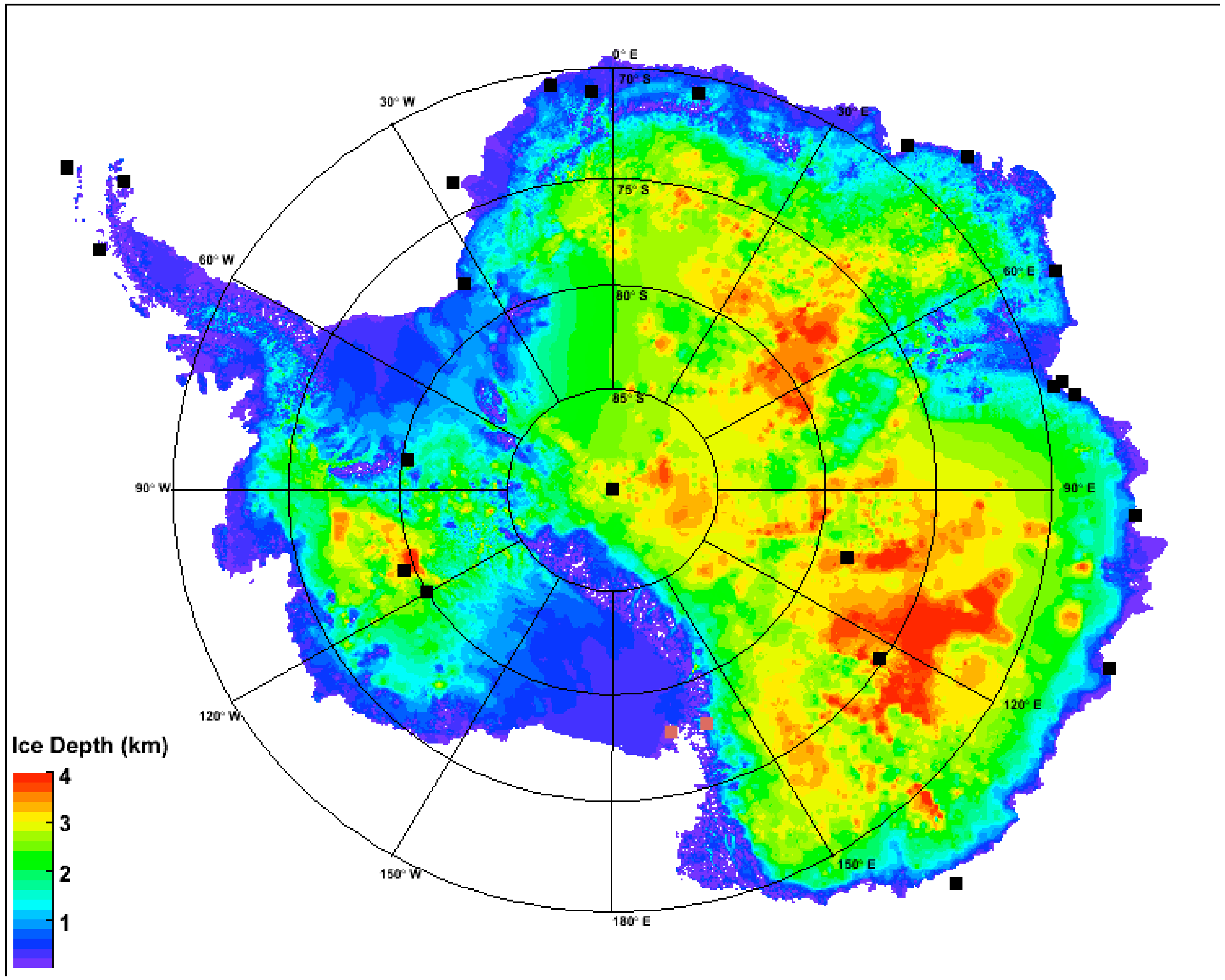
  ~ 10 GZK neutrinos per km^2 per year

  @ 10^{18} ev the ν-N interaction length ≈ 300 km

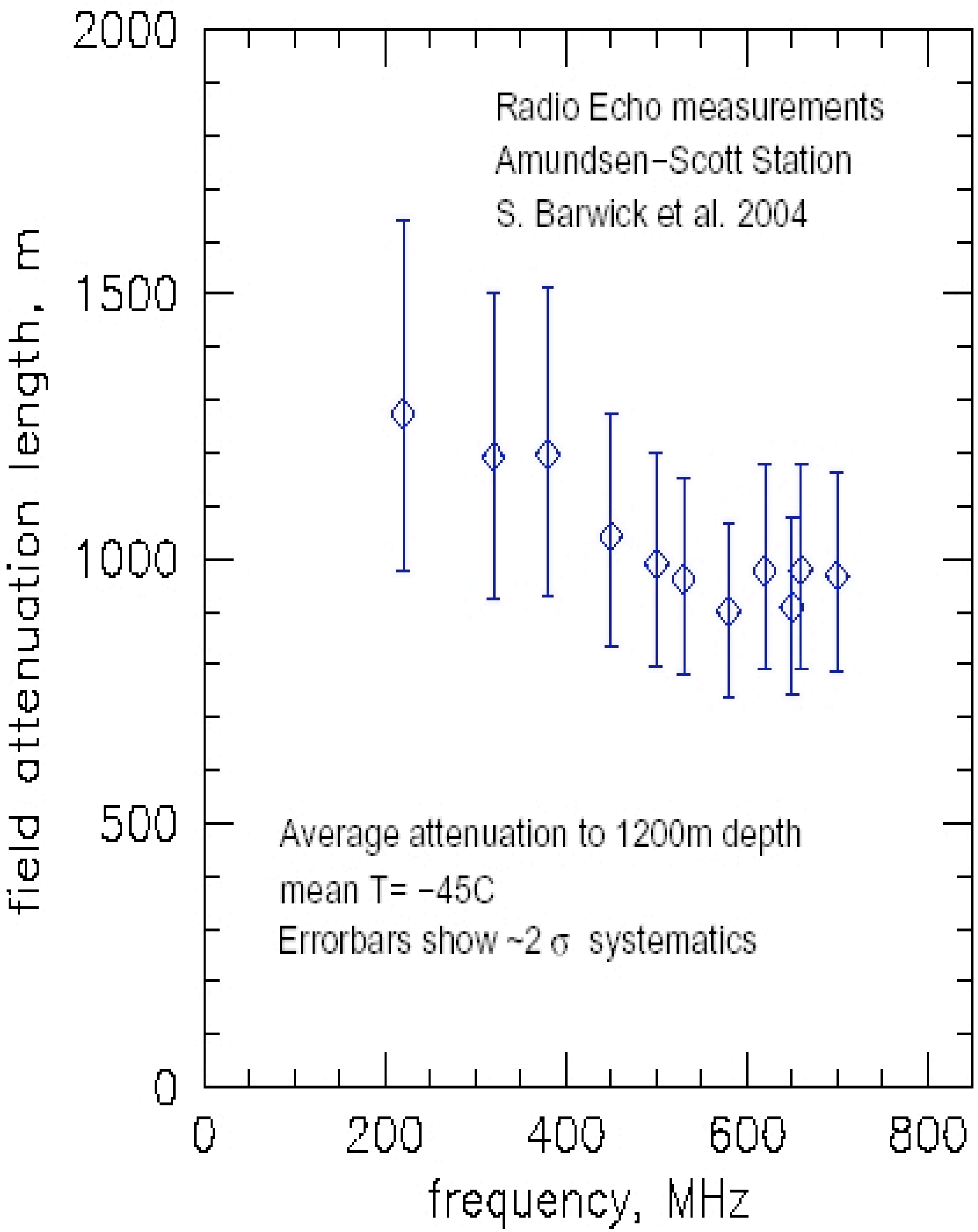
  → 0.03 neutrinos per km^3 per year

- Need a huge detector volume to ensure a likely neutrino detection
  - Where can you find a large volume of matter that is:
    - Optically ‘transparent’, or
    - Radio ‘transparent’, or
    - Acoustically ‘transparent’, or
    - ideally all three
  - The answer is, of course,...

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

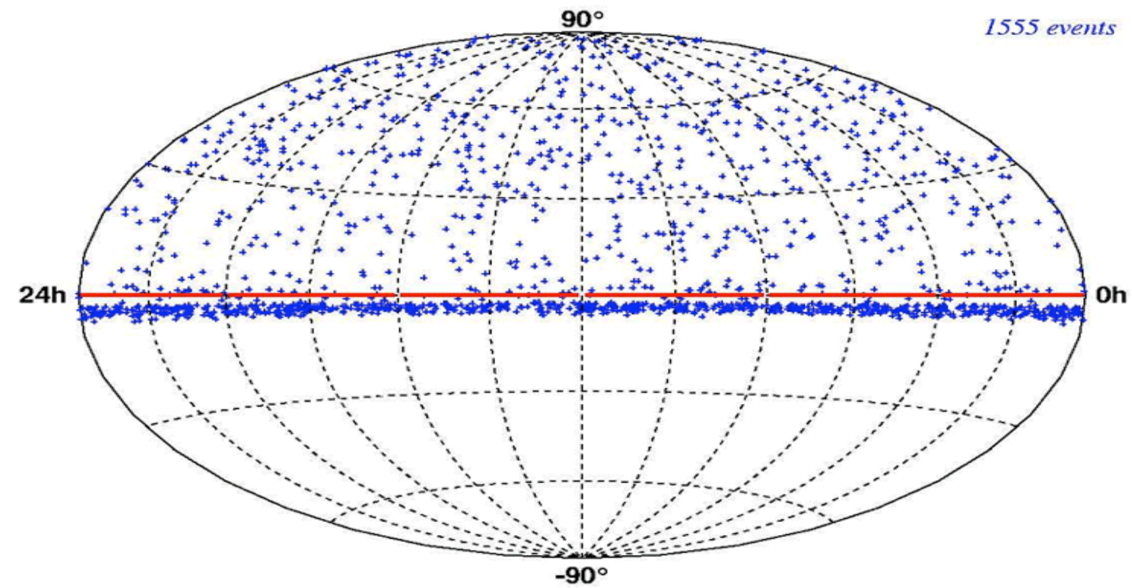


- There are numerous *in situ* measurements of the attenuation length of Antarctic ice, they show:
  - Attenuation length is greater than 1km
  - Limits set on the birefringence
  - Many GPR measurements also

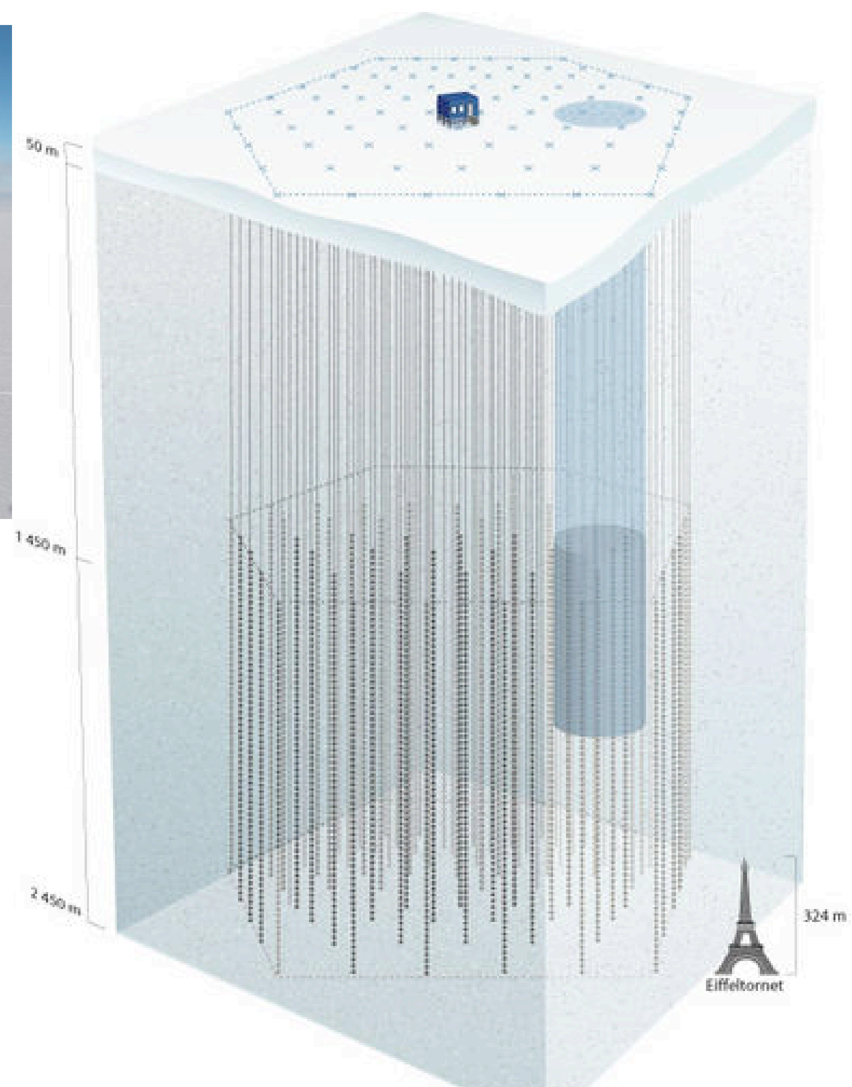


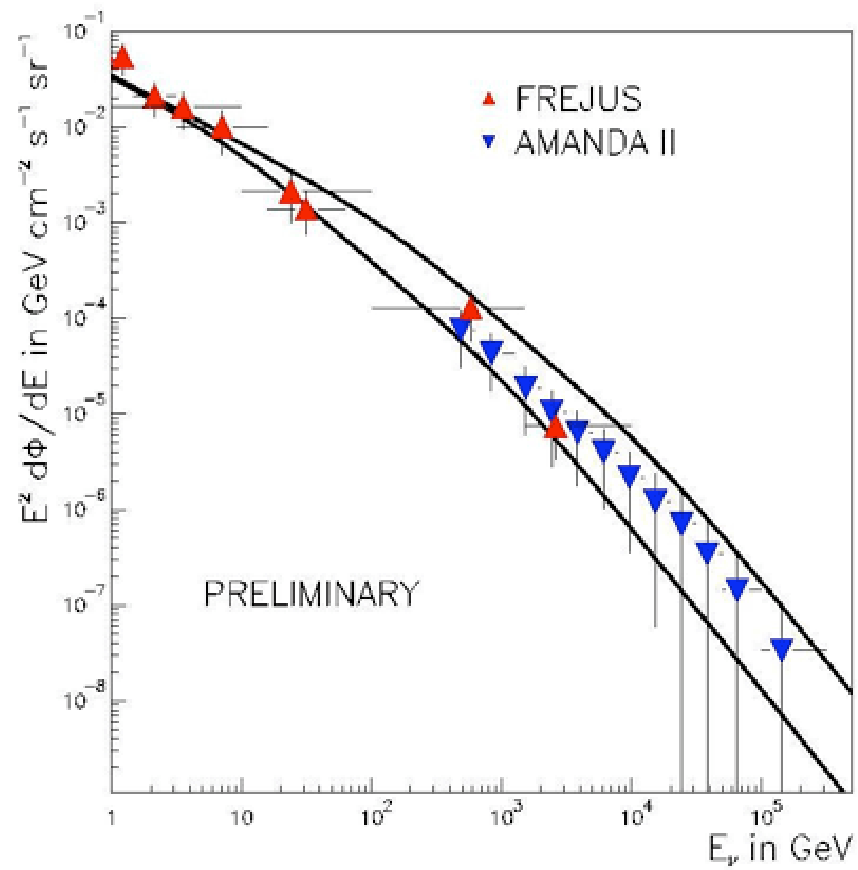
What with?

- Amanda/IceCube
  - Neutrino telescope at South Pole
  - Uses optical Cherenkov method

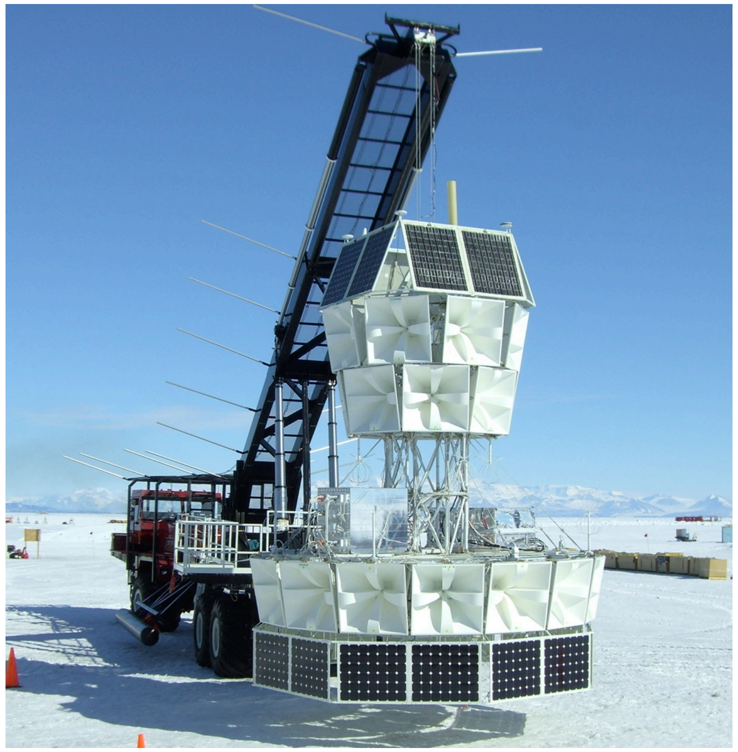


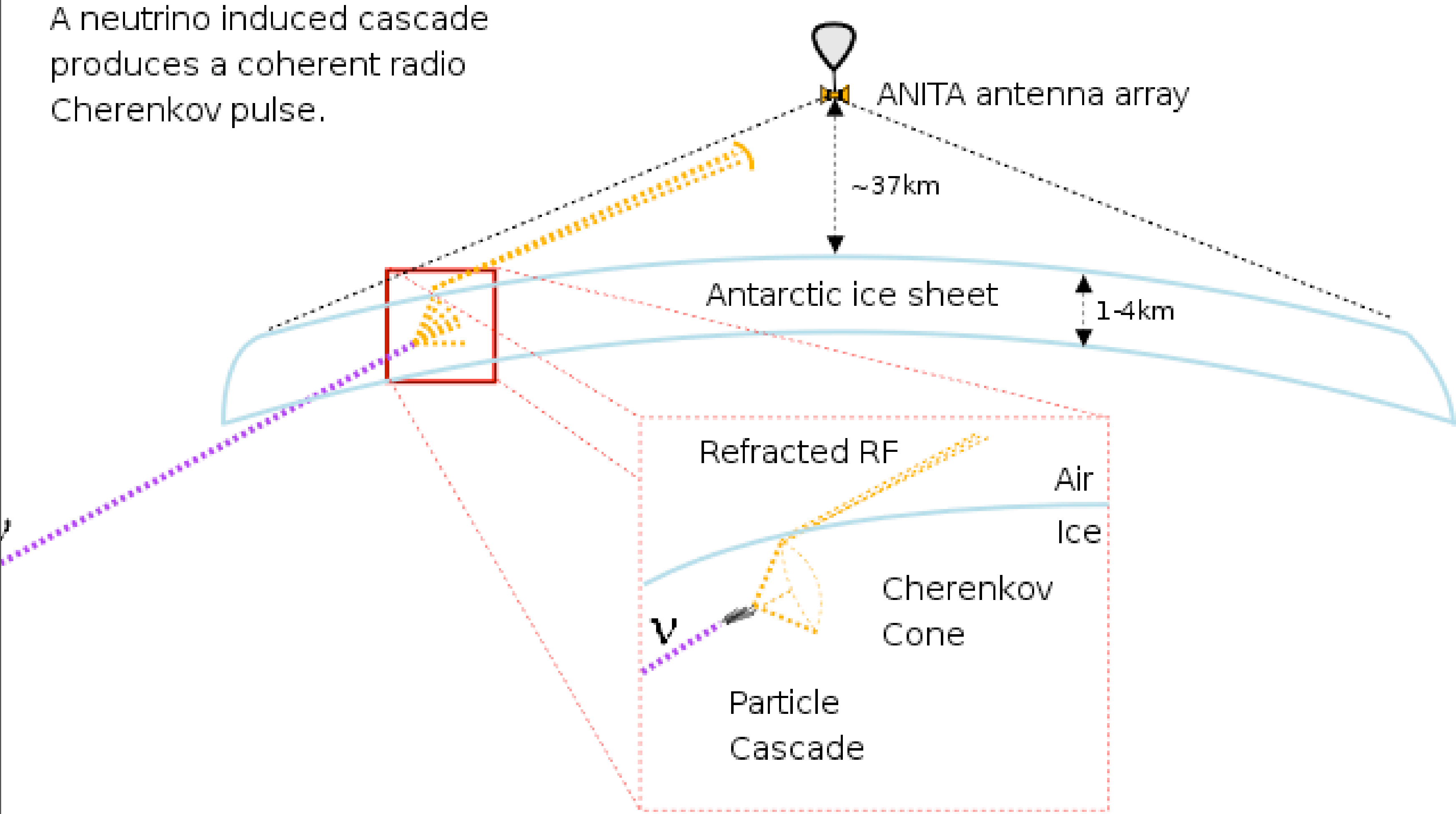
No excess above atmospheric neutrinos

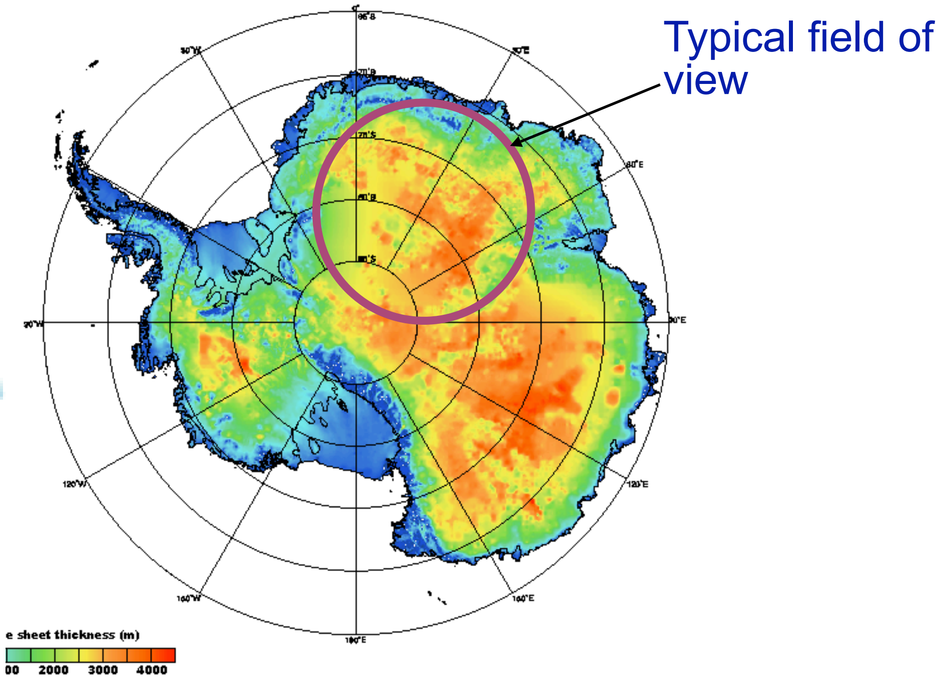




- The ANtarctic Impulsive Transient Antenna (ANITA)
  - A more elegant solution?
  - A balloon borne experiment
    - 32 dual polarization antennas
    - Altitude of 37km
    - Horizon at 700km
    - Over 1 million km^3 of ice visible





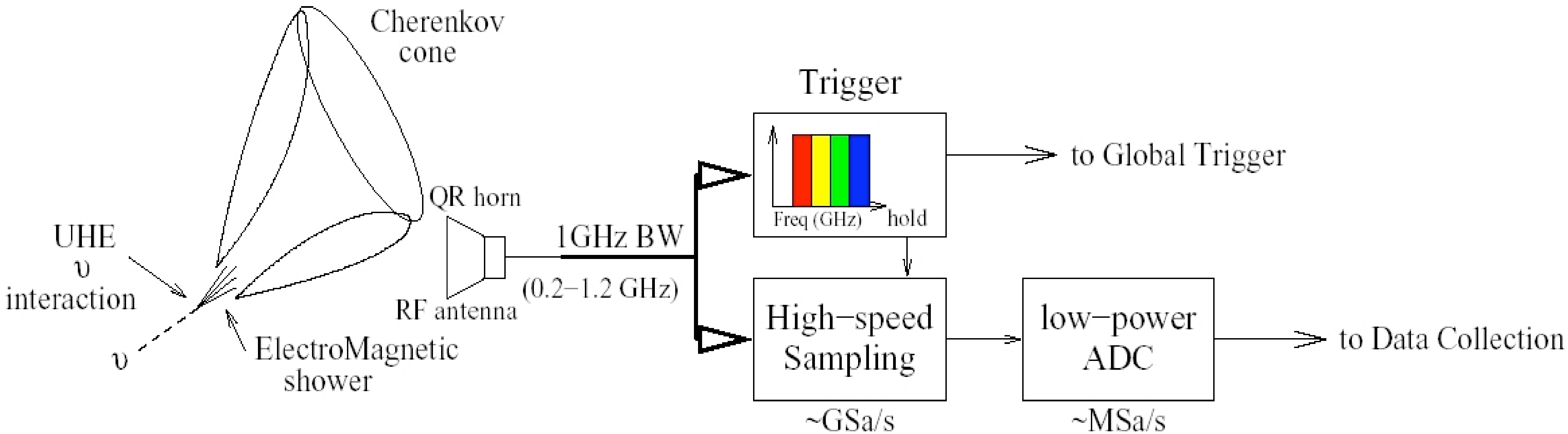


The ANITA Collaboration

- 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
- Washington University in St. Louis
  St. Louis, Missouri, USA

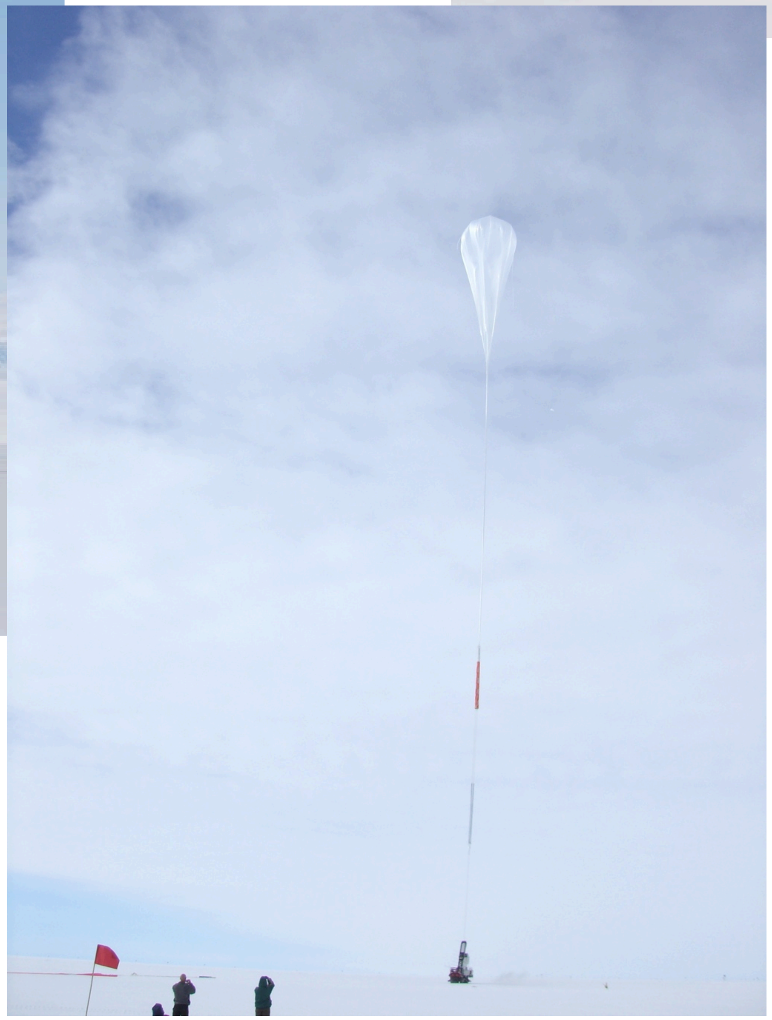
ANITA Electronics

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

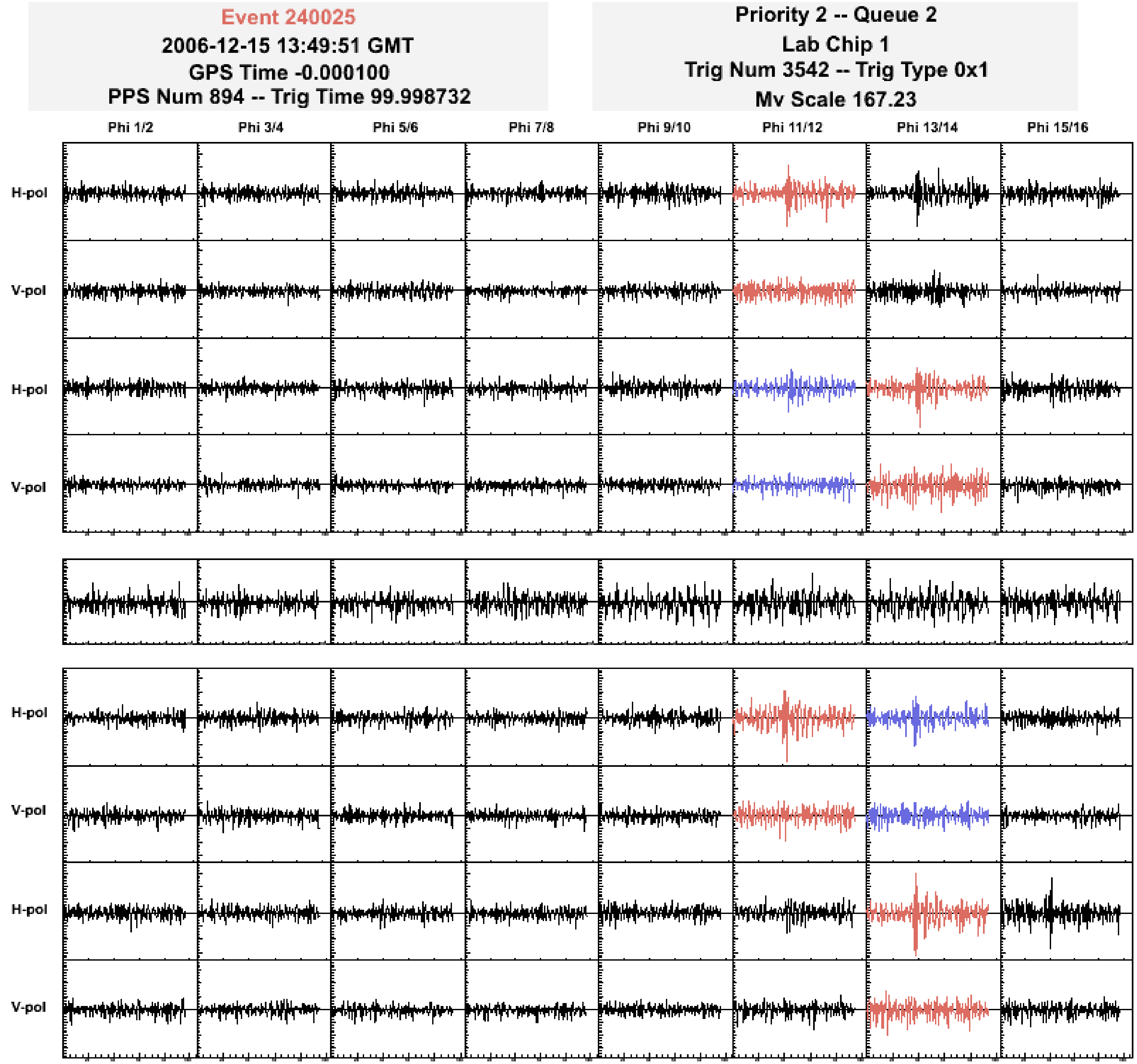


- Split trigger and waveform paths
- Use multiple frequency bands for trigger
- 'Buffer' waveform data in switched capacitor array
- Only digitise when we have a trigger

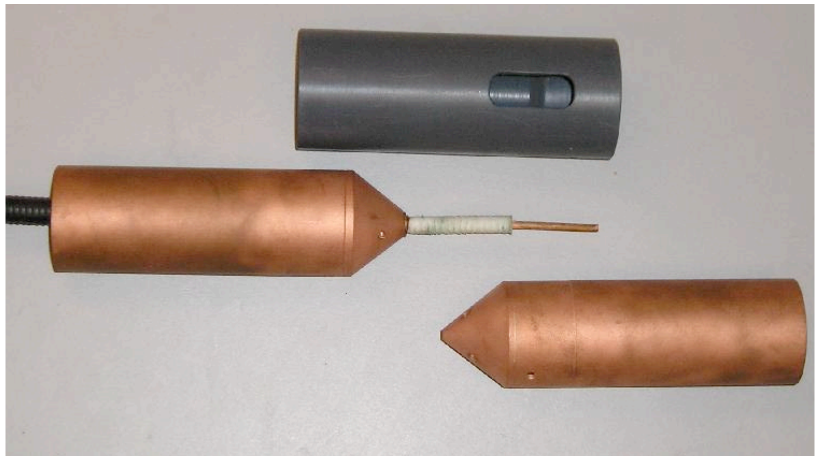
- Balloon Launch
  - Just 0.02mm thick
  - Takes 100 million litres of helium (and several hours) to fill



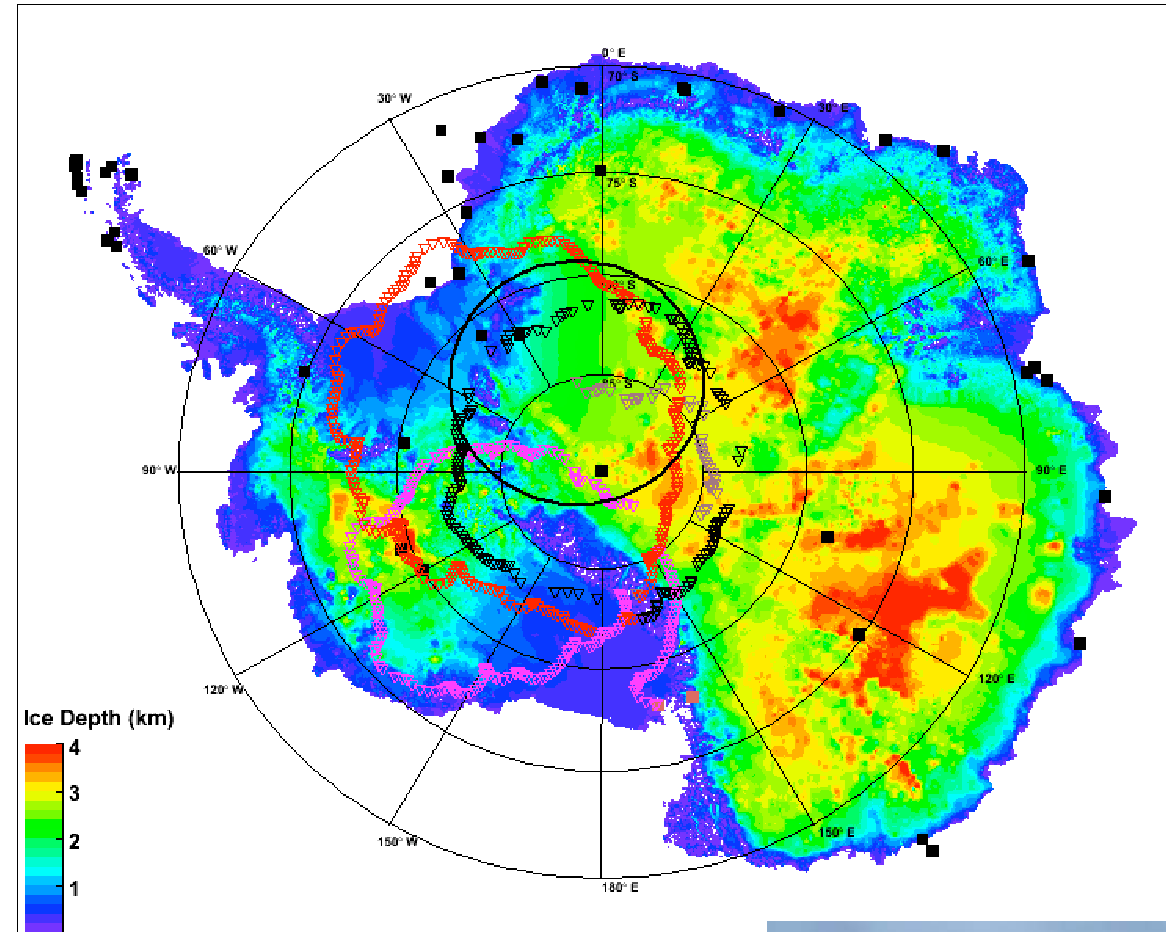
Example Ground Calibration Pulse



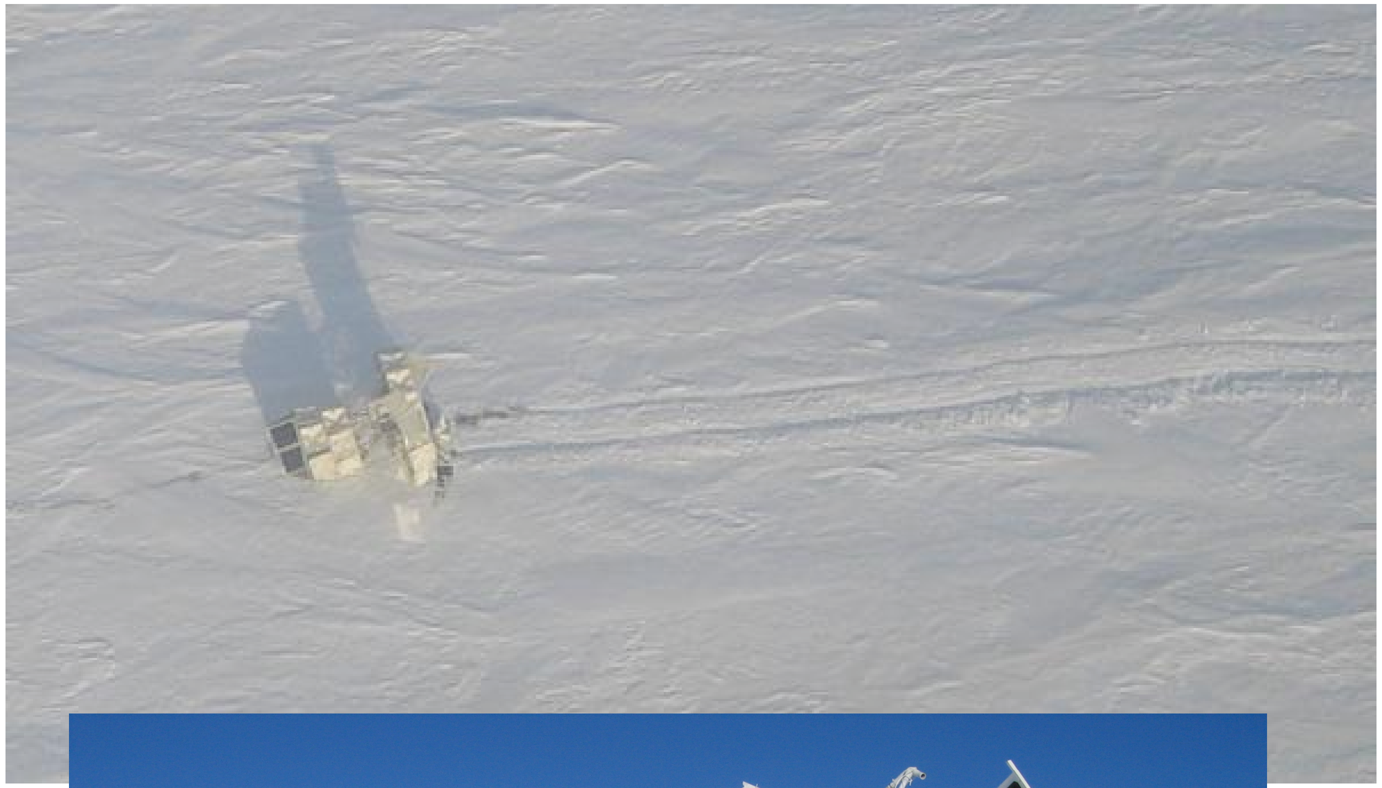
Example Borehole Calibration Pulse

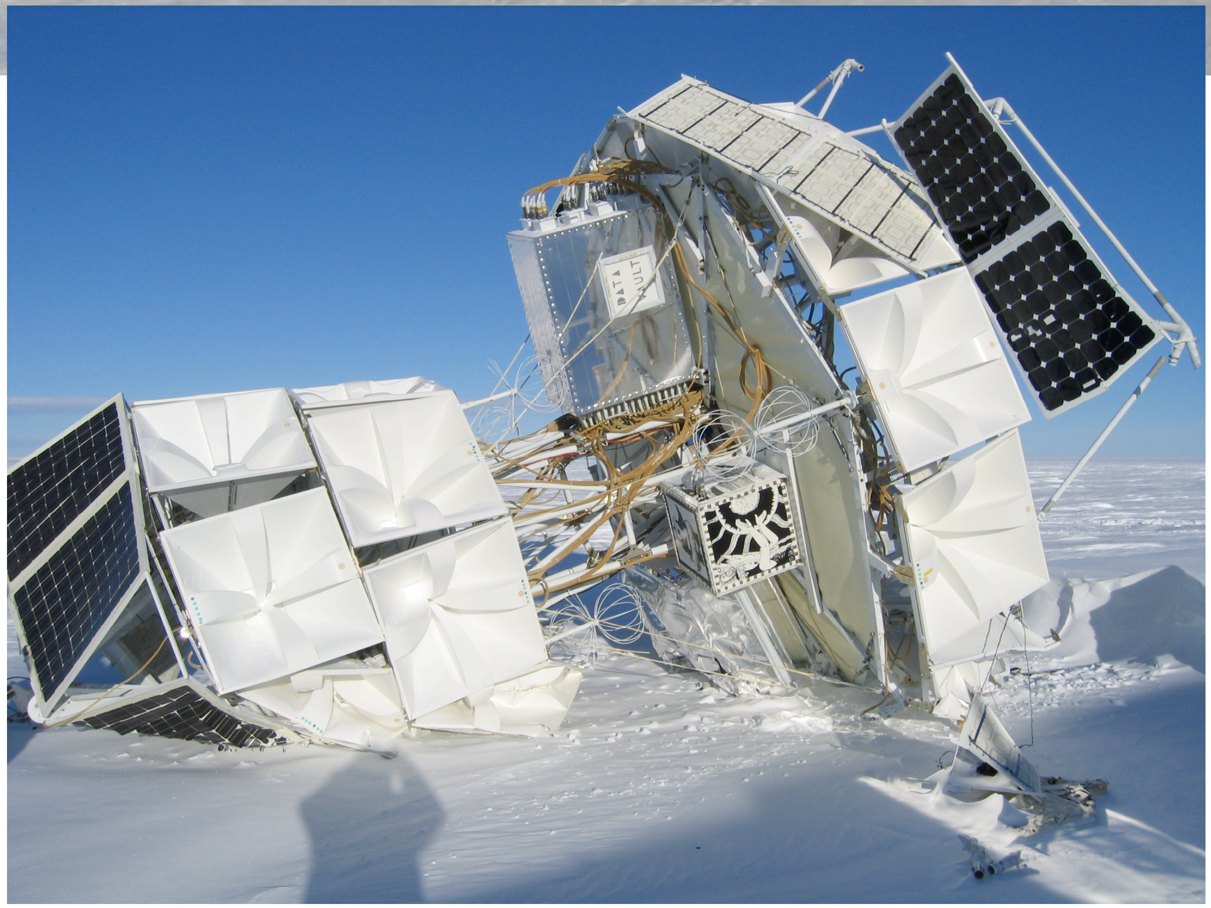


- The flight
  - Lasted 35 days (record is 42)
  - Three and a half sort of polar orbits
  - Took over 8 million events
    - Maybe 1 or 2 neutrinos
  - Flew so close to South Pole, someone took a photo
    - See how shape changes at altitude



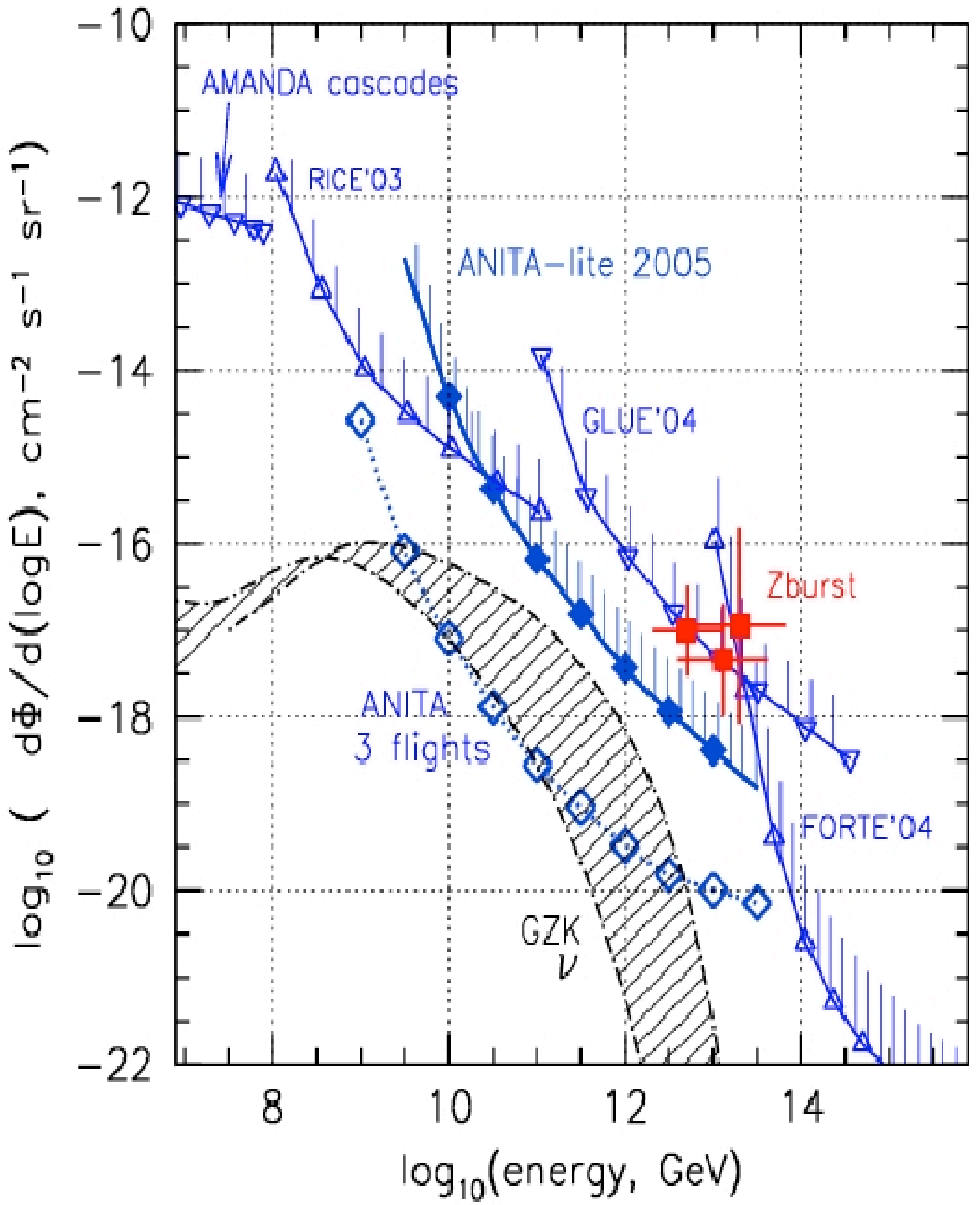
- The Landing:
  - Initiated by detonating small explosive to separate from balloon
  - Descend gently on a parachute to the ground
  - Release parachute to prevent dragging
    - BLAST was dragged for 100 miles this year (ended in a crevice)
    - A few years ago one was dropped from 5000 feet



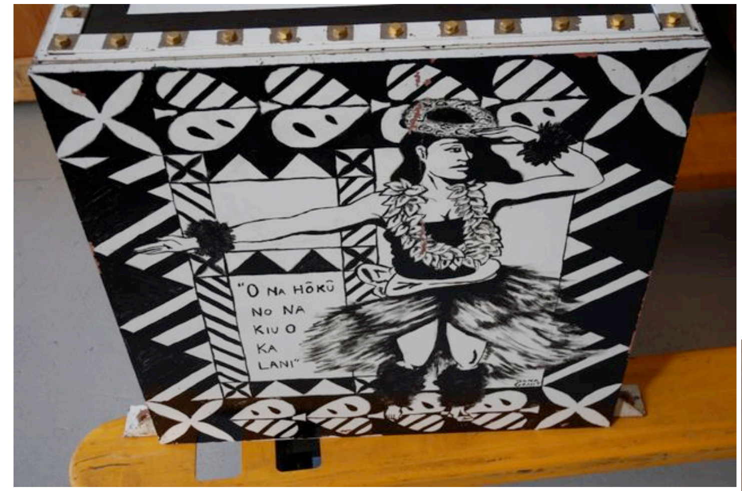


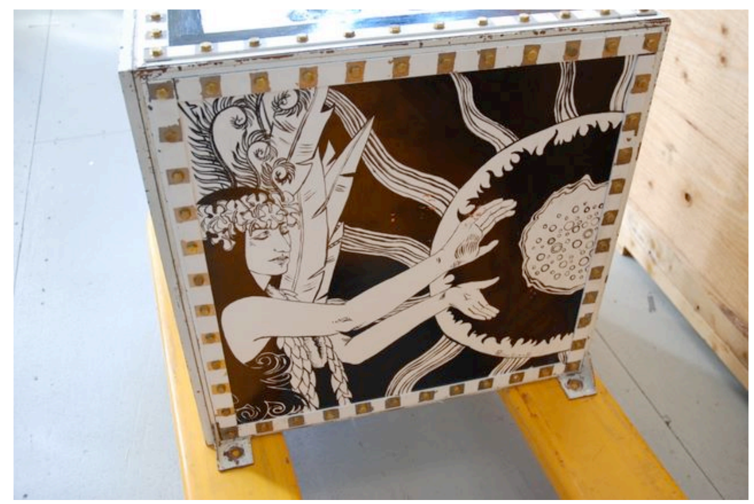
Photos from Dana Braun

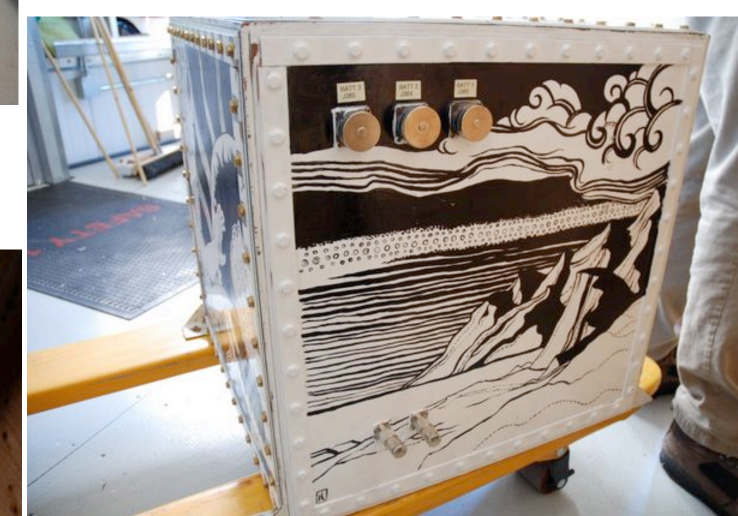
- Analysis is progressing
- Expect to either detect UHE neutrinos or set the world's best flux limit.
- ANITA-lite, the ANITA prototype currently has the best limits over some of the range.



- 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!

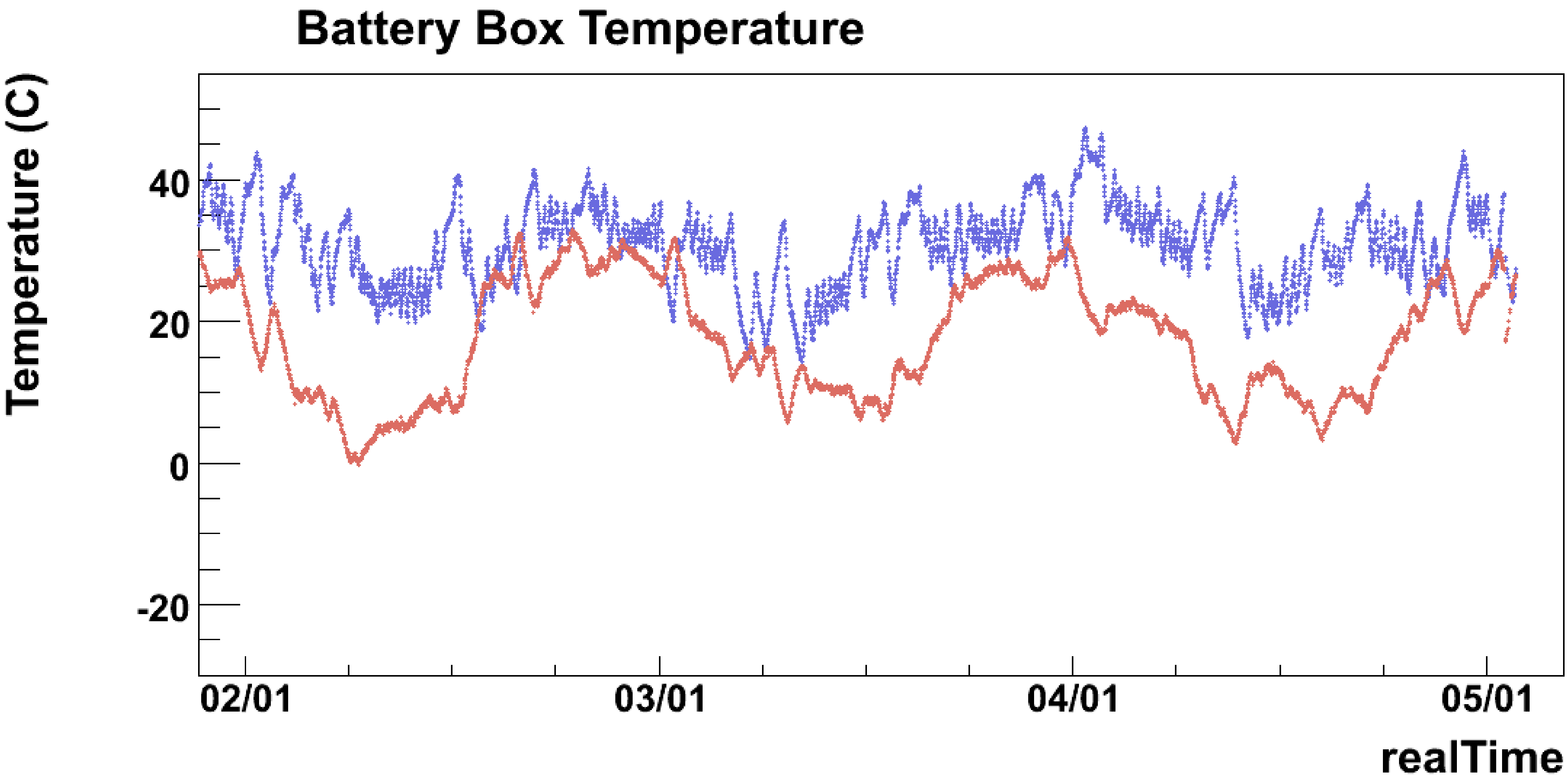




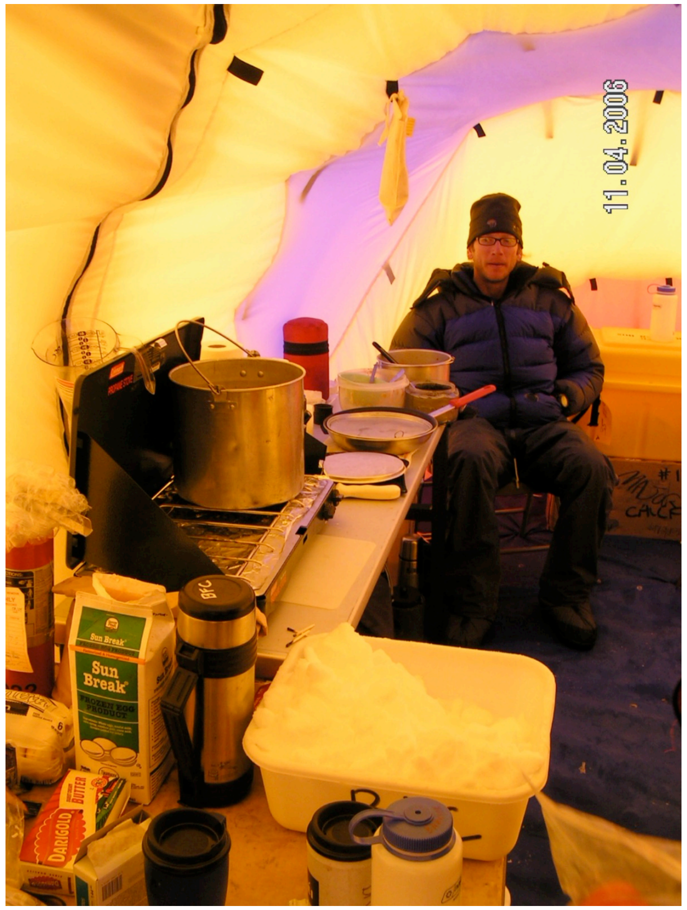


Thanks to the artists: Kai Smart, Dana Grant, Karen Joyce and ??? and Jeff Kowalski for the photographs

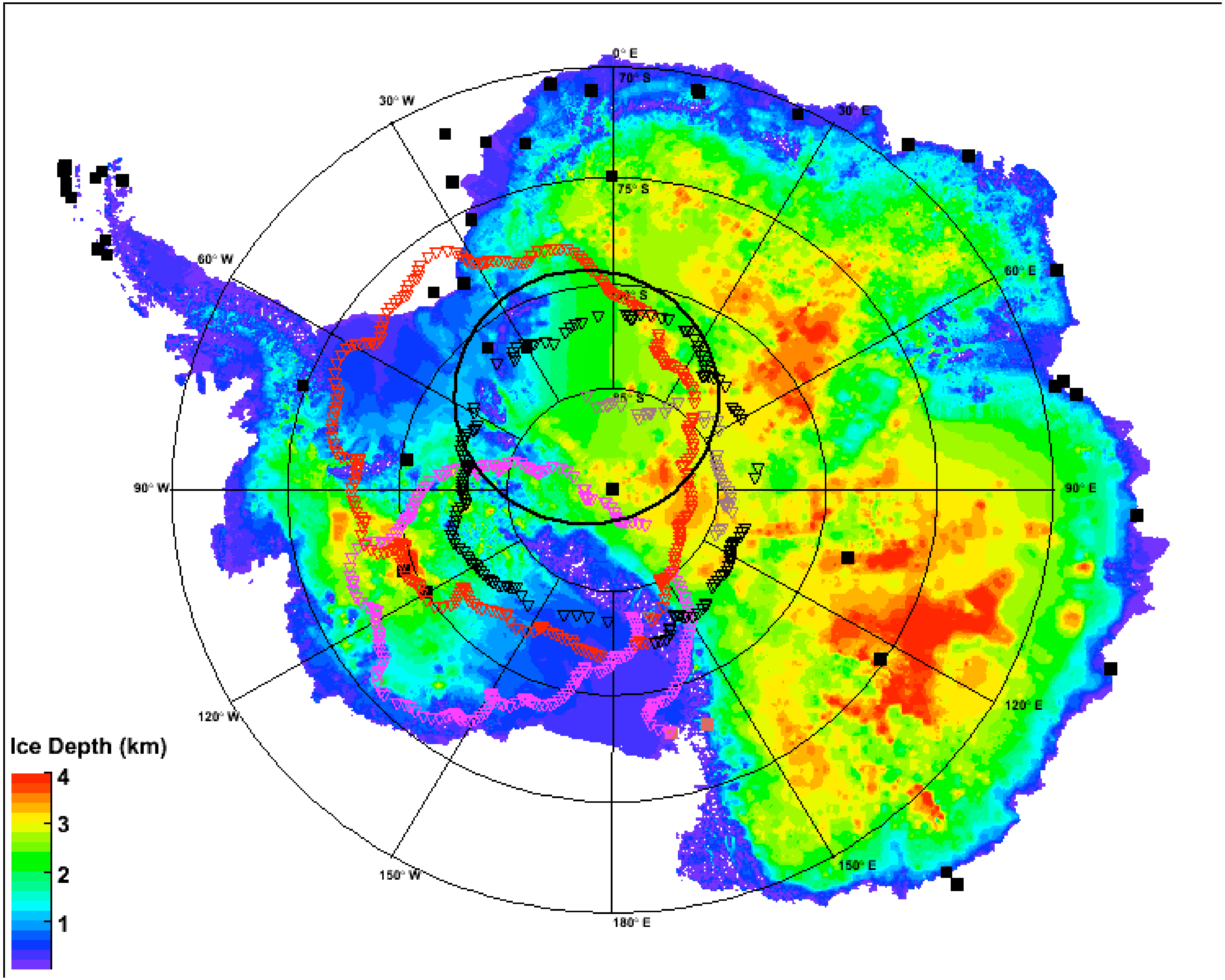
Paint Job Worked?



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

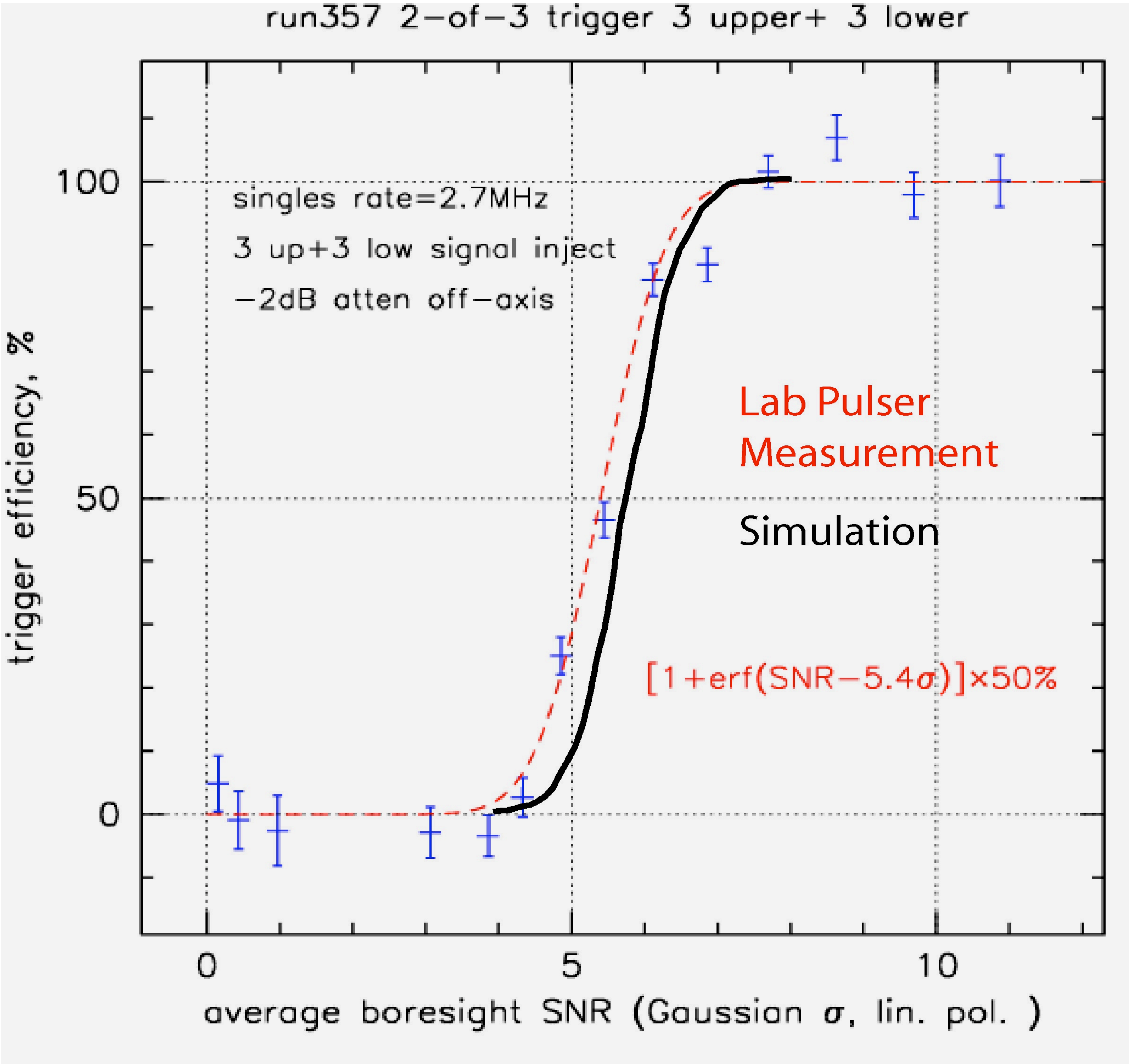


Maybe Next Flight

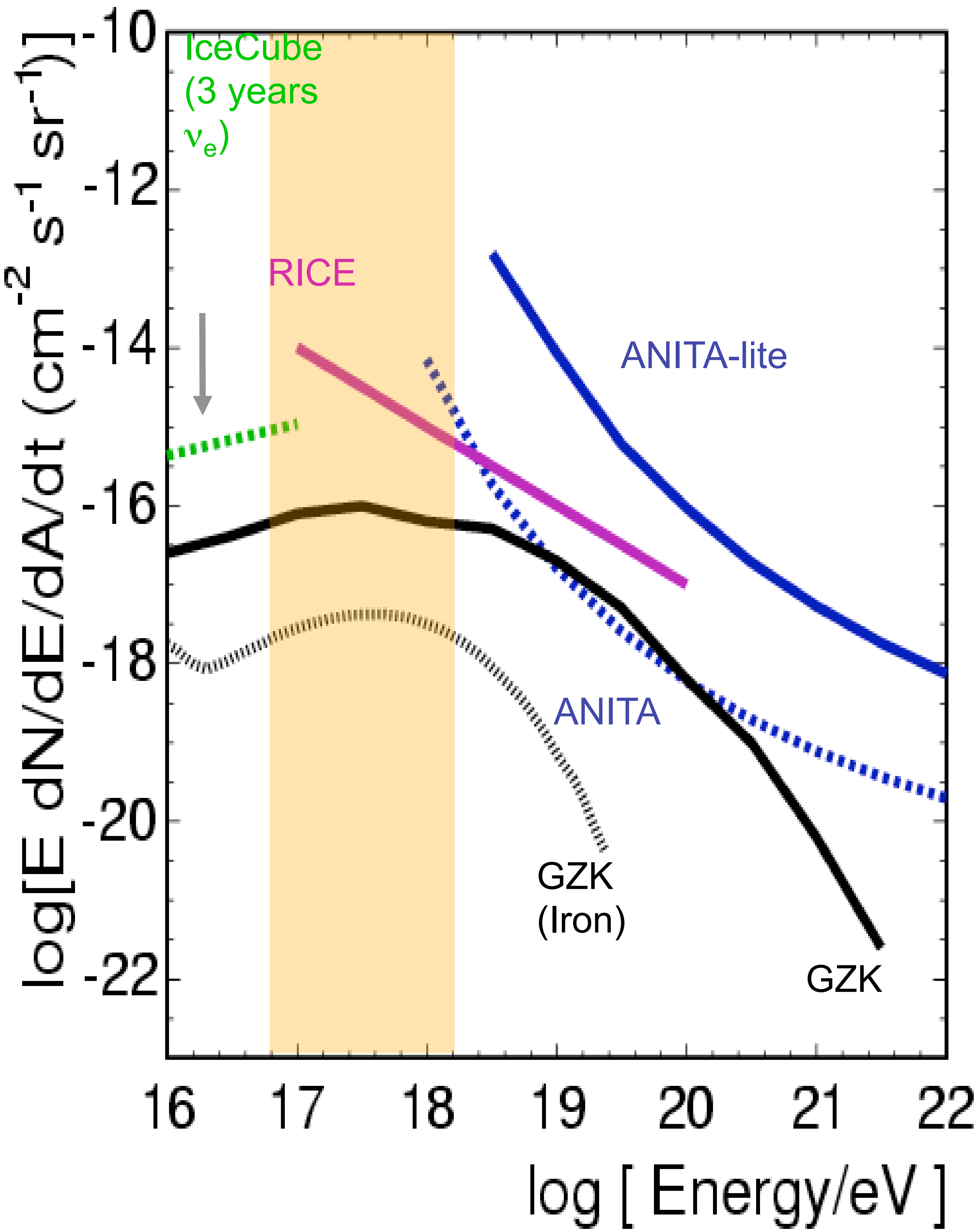


If not now, when?

- Second ANITA flight proposed for 2008/9
- Plan to:
  - Improve trigger efficiency currently need 5.4σ signal to trigger
  - Implement software trigger
- Hope for:
  - Longer flight
  - Better flight path

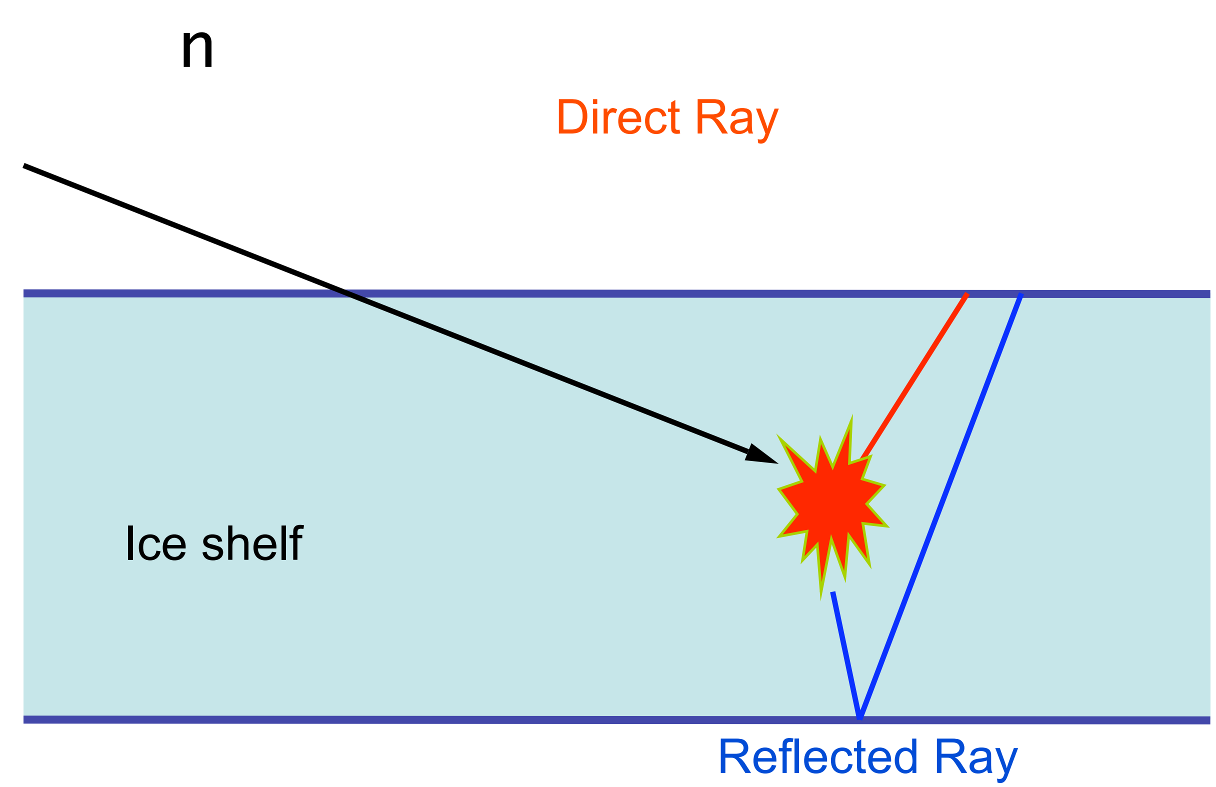


- Need embedded detectors to lower energy threshold
- Two of the ice-based candidates are:
  - ARIANNA
  - AURA
- Also competition from:
  - Auger
  - SalSA
  - Lofar/SKA

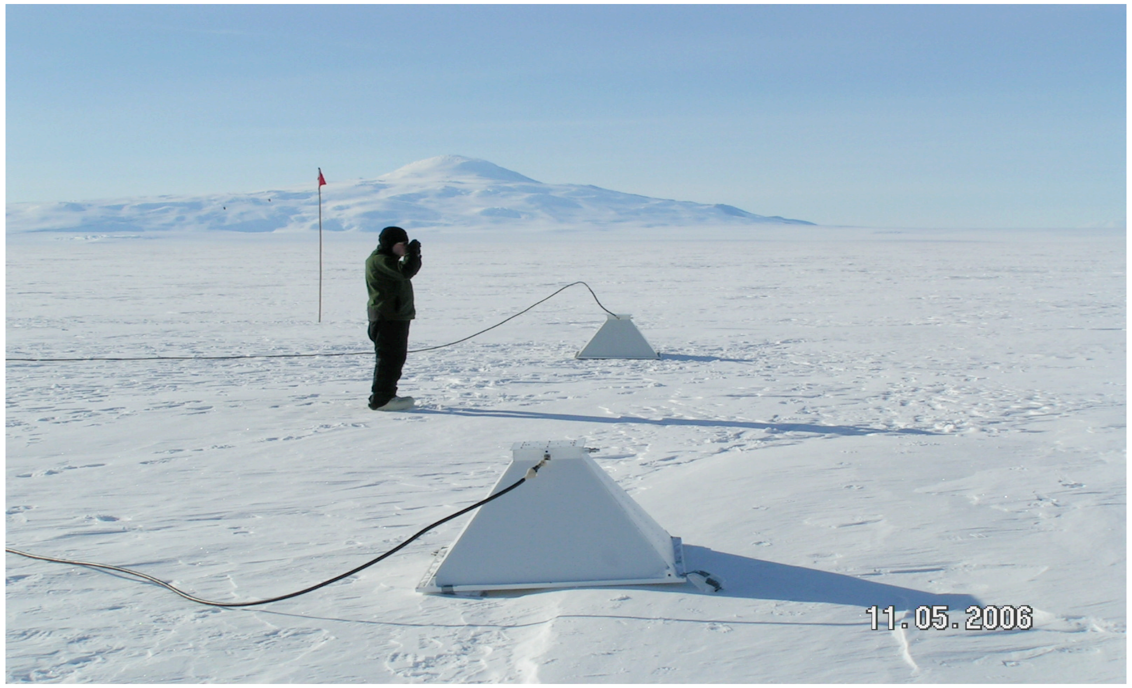


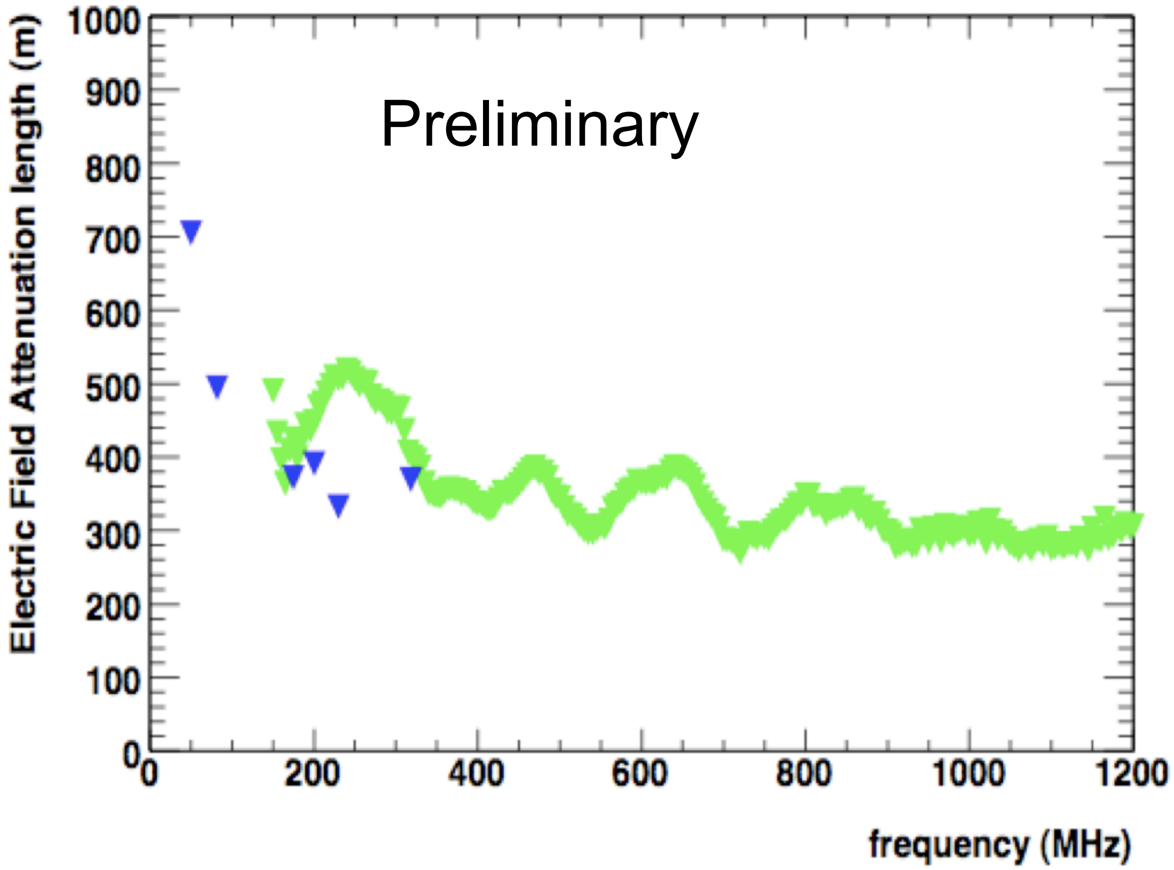
Antarctic Ross Ice shelf ANtenna Neutrino Array

- 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)



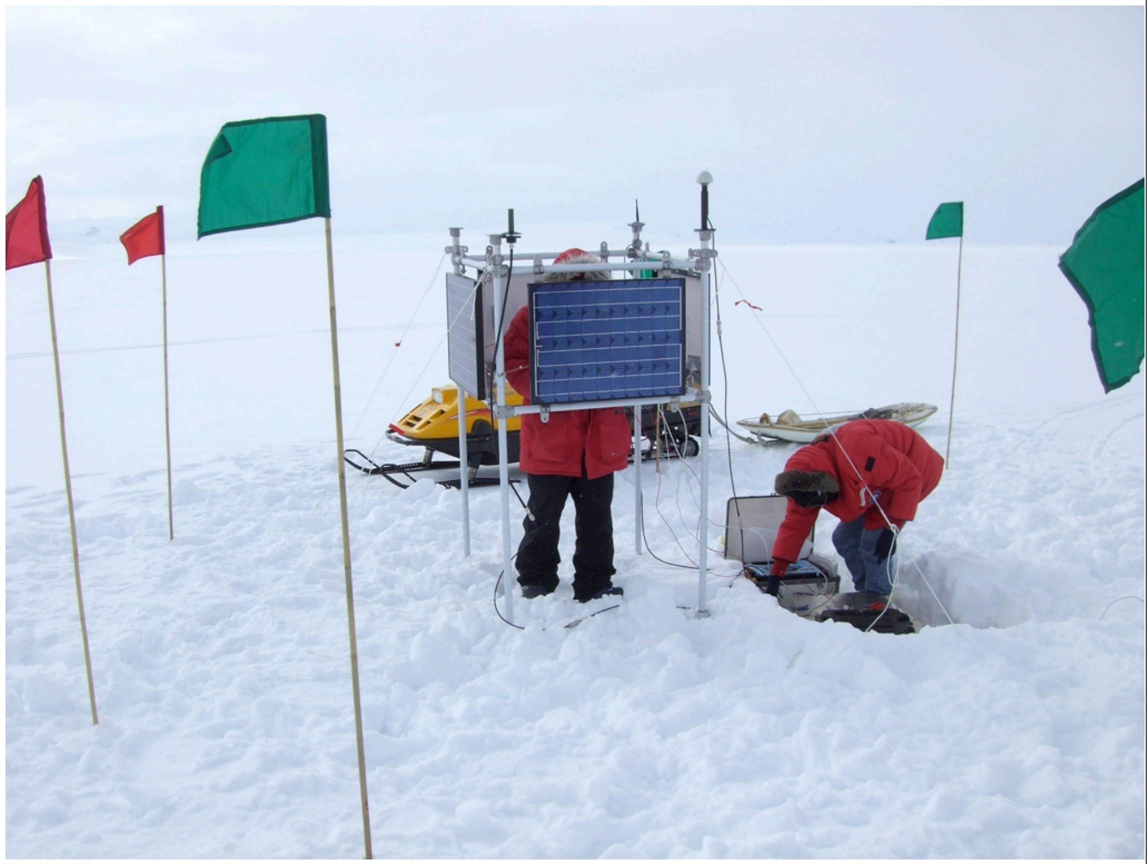
- David Saltzberg and Steve Barwick made attenuation length measurements on the ice shelf this Austral Summer

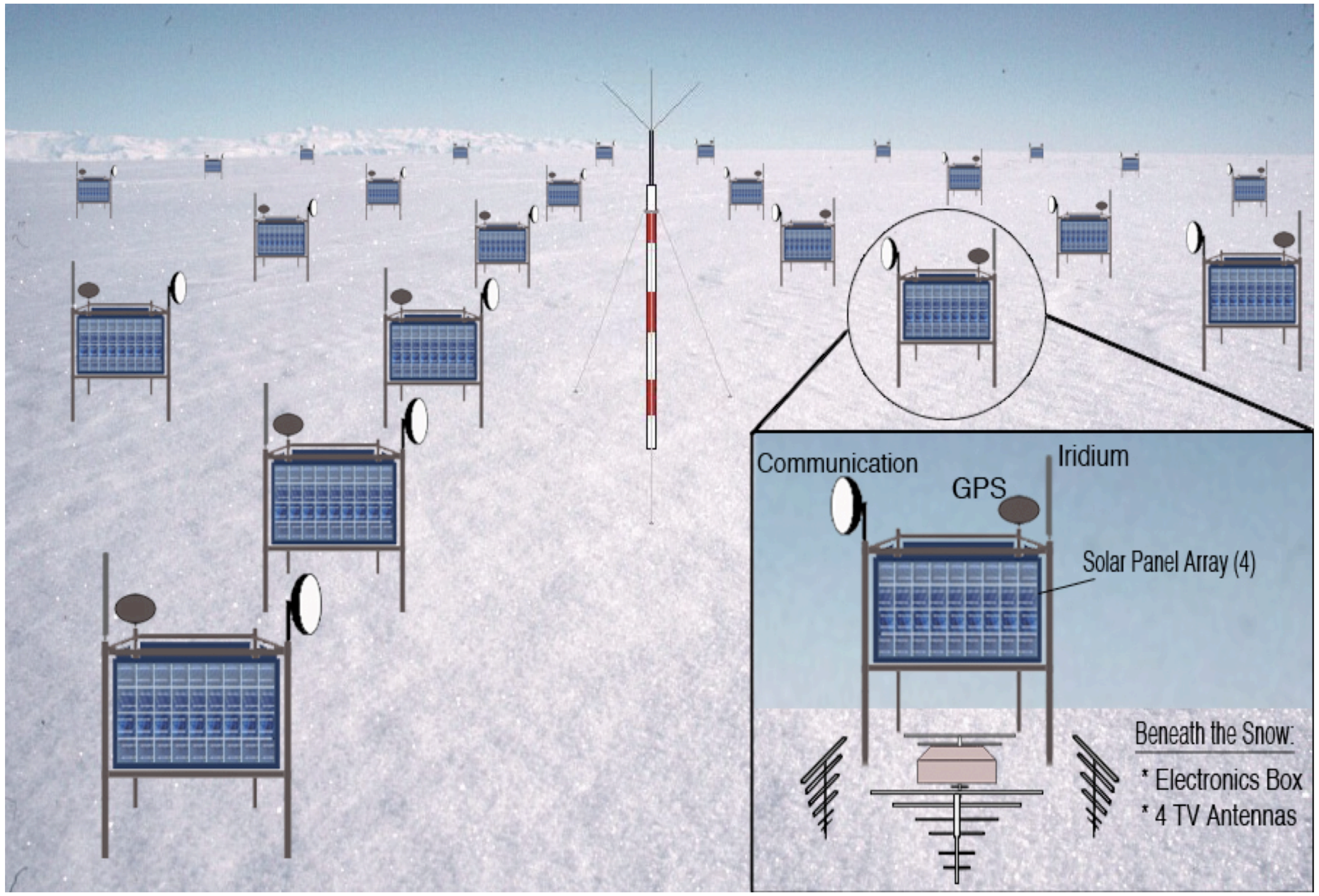




Better than 300m across the band

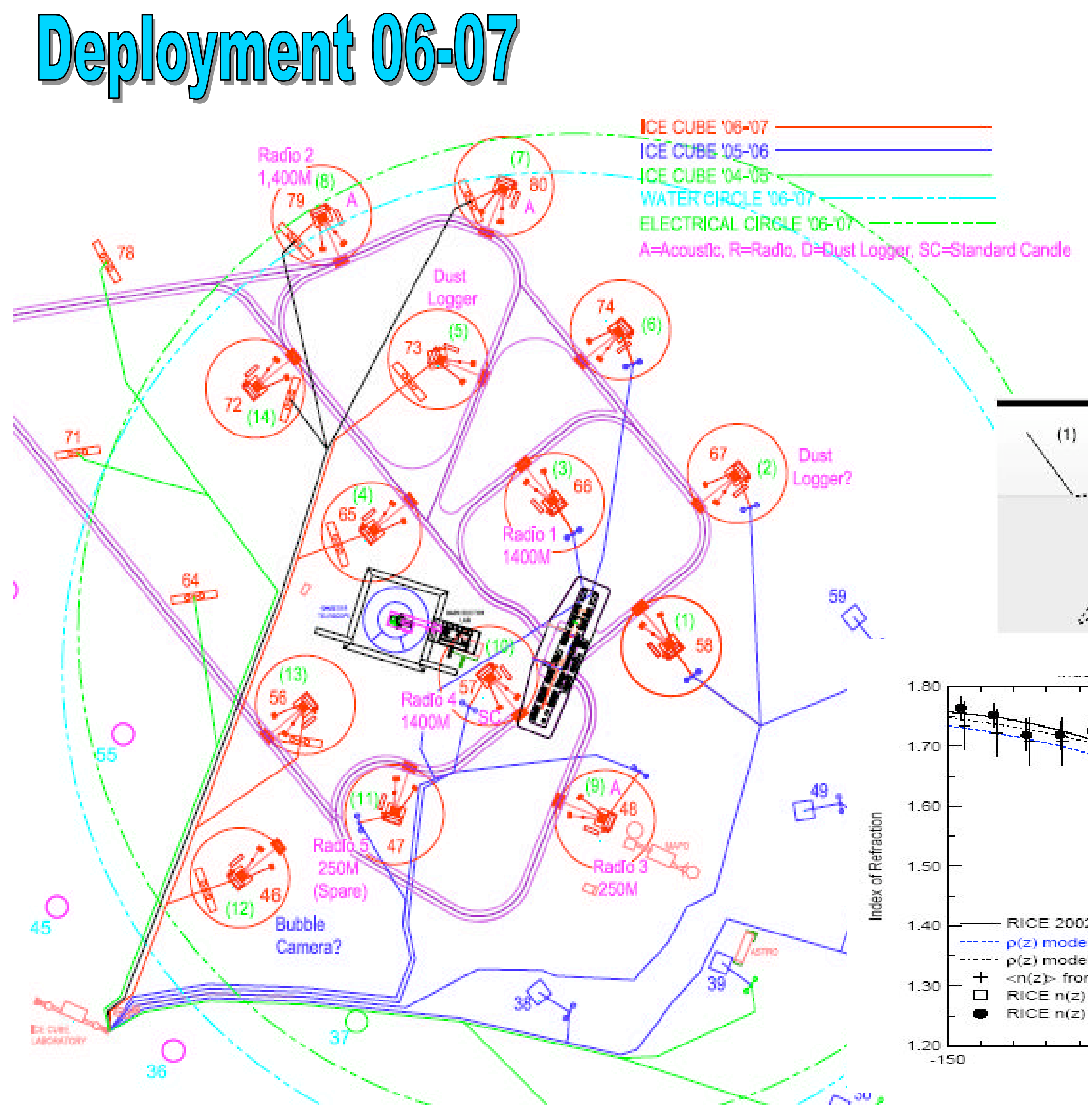
- Prototype station deployed 2006/7
  - Communicated for two months with iridium modem



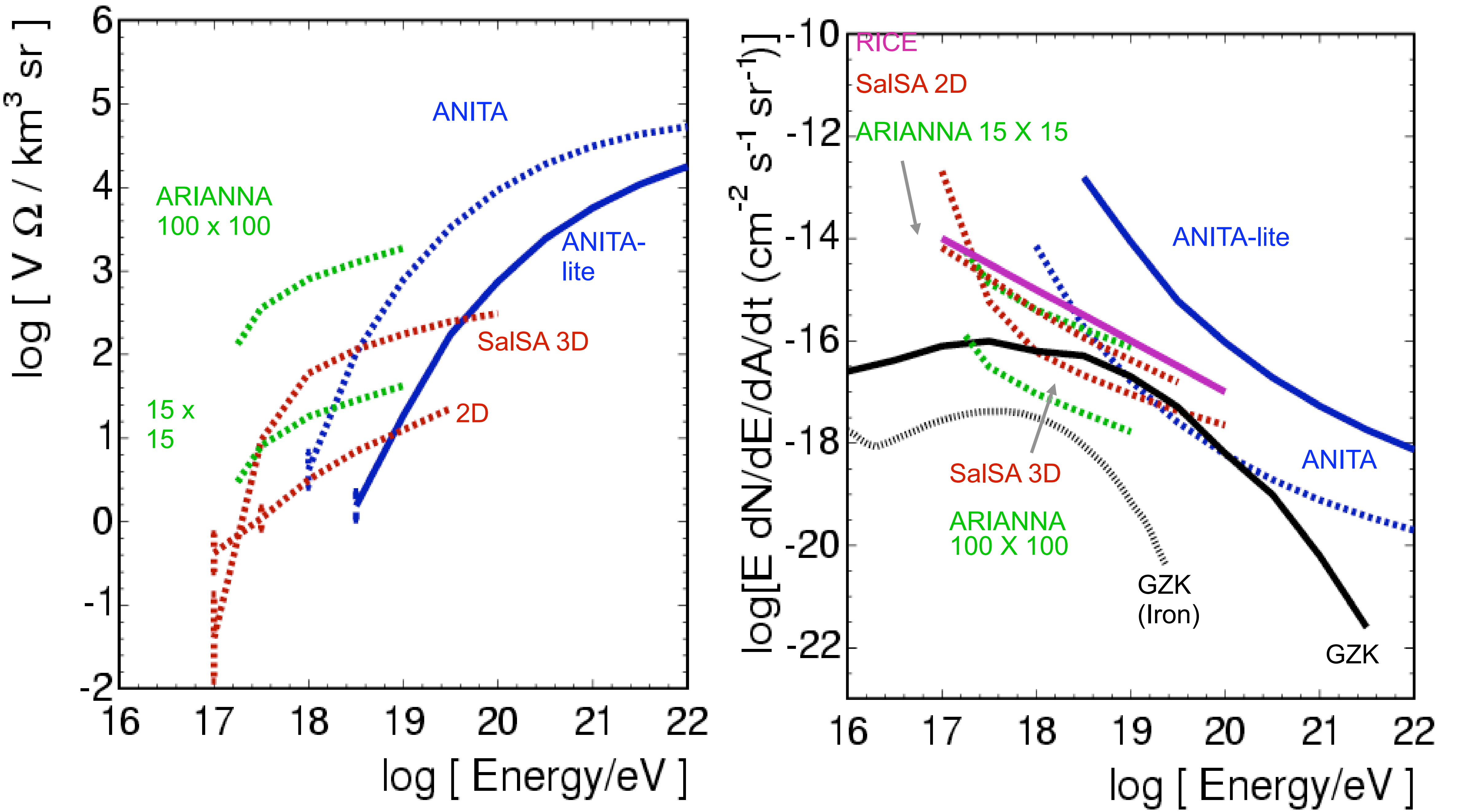


  - Now it’s gone quiet (and dark) down there
  - Plans for 15x15 array

- AURA/SPATS
  - Deploy acoustic and radio detectors in conjunction with IceCube
  - Possibility to measure neutrino with all three detection methods simultaneously
  - Successor to the RICE experiment



Sensitivities



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)

Summary

- Neutrino Astronomy is really frontier physics
  - Radio detection technique allows fro vast detection volumes of >100km^3
- ANITA completed its first full flight and analysis is underway
  - Will either detect UHE neutrinos or set best limit
- The next generation of neutrino astronomy facilities may finally realise the ambition of probing the universe with “new eyes”
  - An ultra-high energy neutrino beam for studying fundamental physics
- Hopefully soon we will have a UHE neutrino

Fun Slides

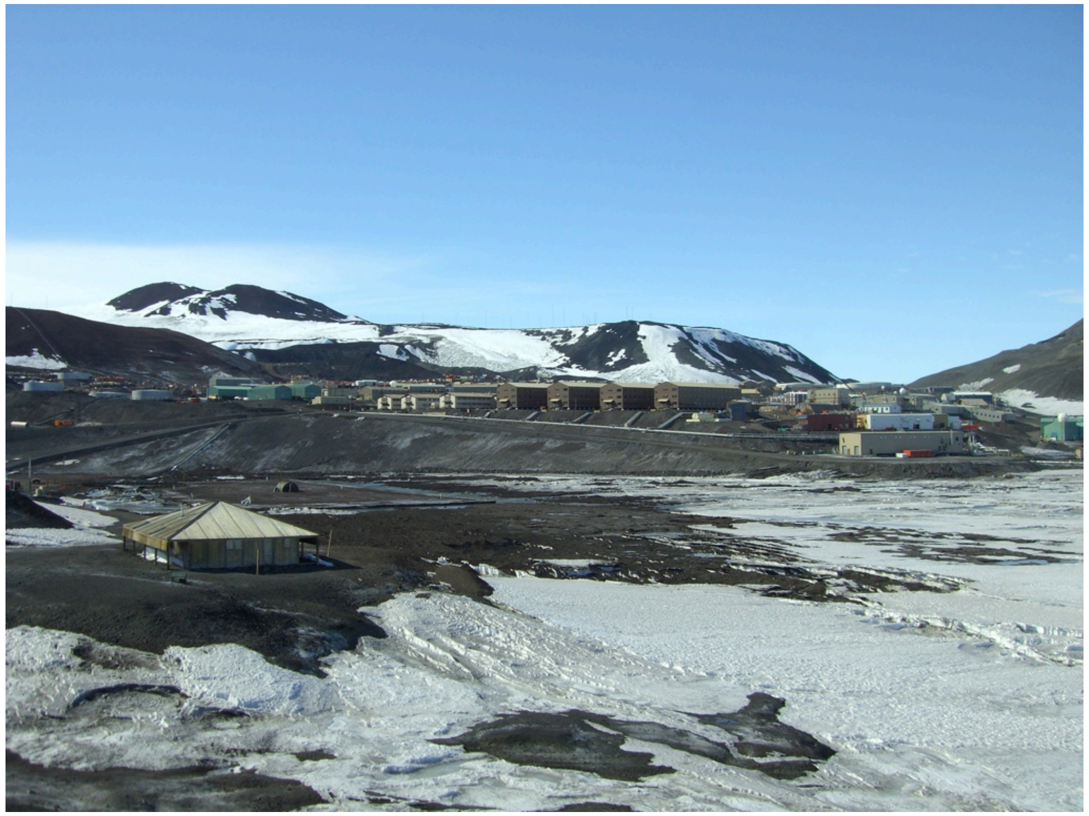
Ryan Nichol

- 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"


PARKA, RED
CARHART JACKET
CARHART PARKA
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



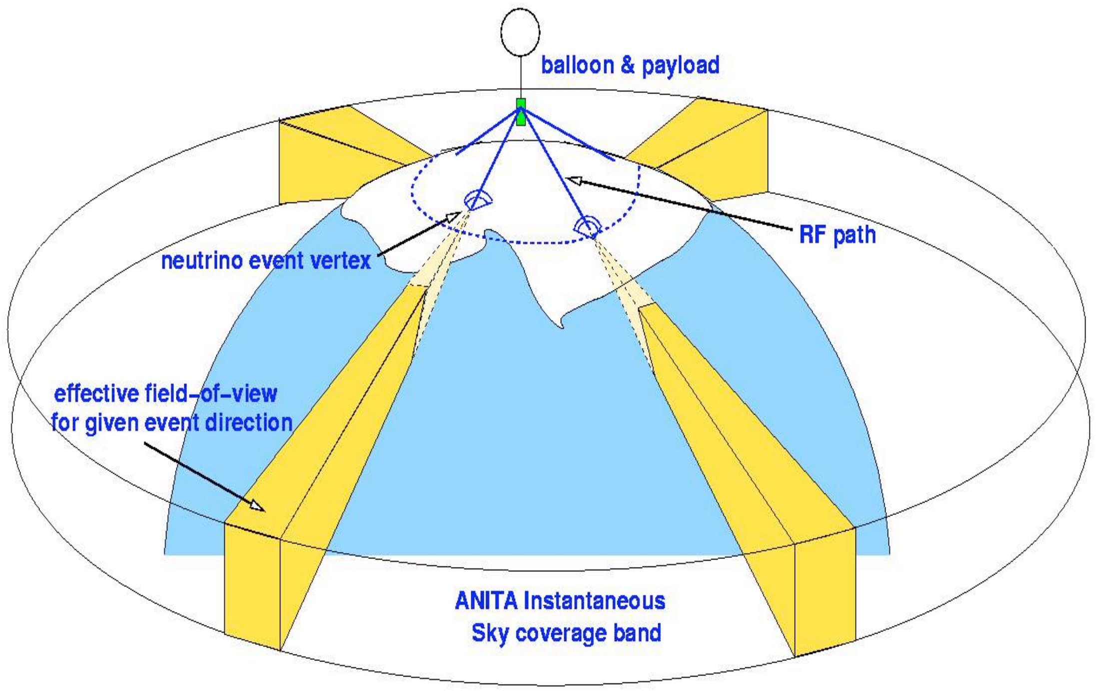
- McMurdo Facts:
  - Established 1937
  - Takes its name from McMurdo Sound (named after Lieutenant Archibald McMurdo of the *Terror*
  - Near Scott's Hut
  - Food is inedible 363 days a year
    - Christmas
    - Thanksgiving

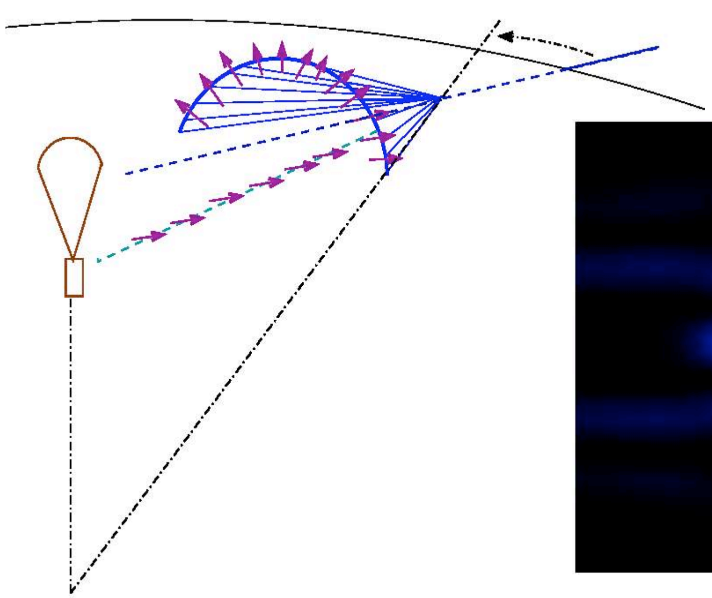
- Facilities:
  - Harbour (two weeks a year)
  - 3 Airfields
  - 1 bowling alley
  - 3 bars

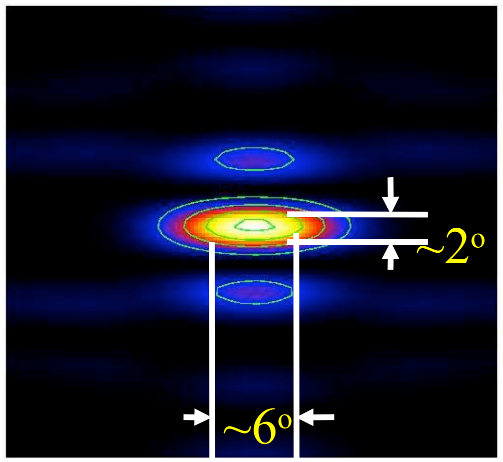
- Williams Field Facilities
  - Own galley (so edible food)
  - Three payloads this year
  - No indoor plumbing though

Backup Slides

- Angular Resolution

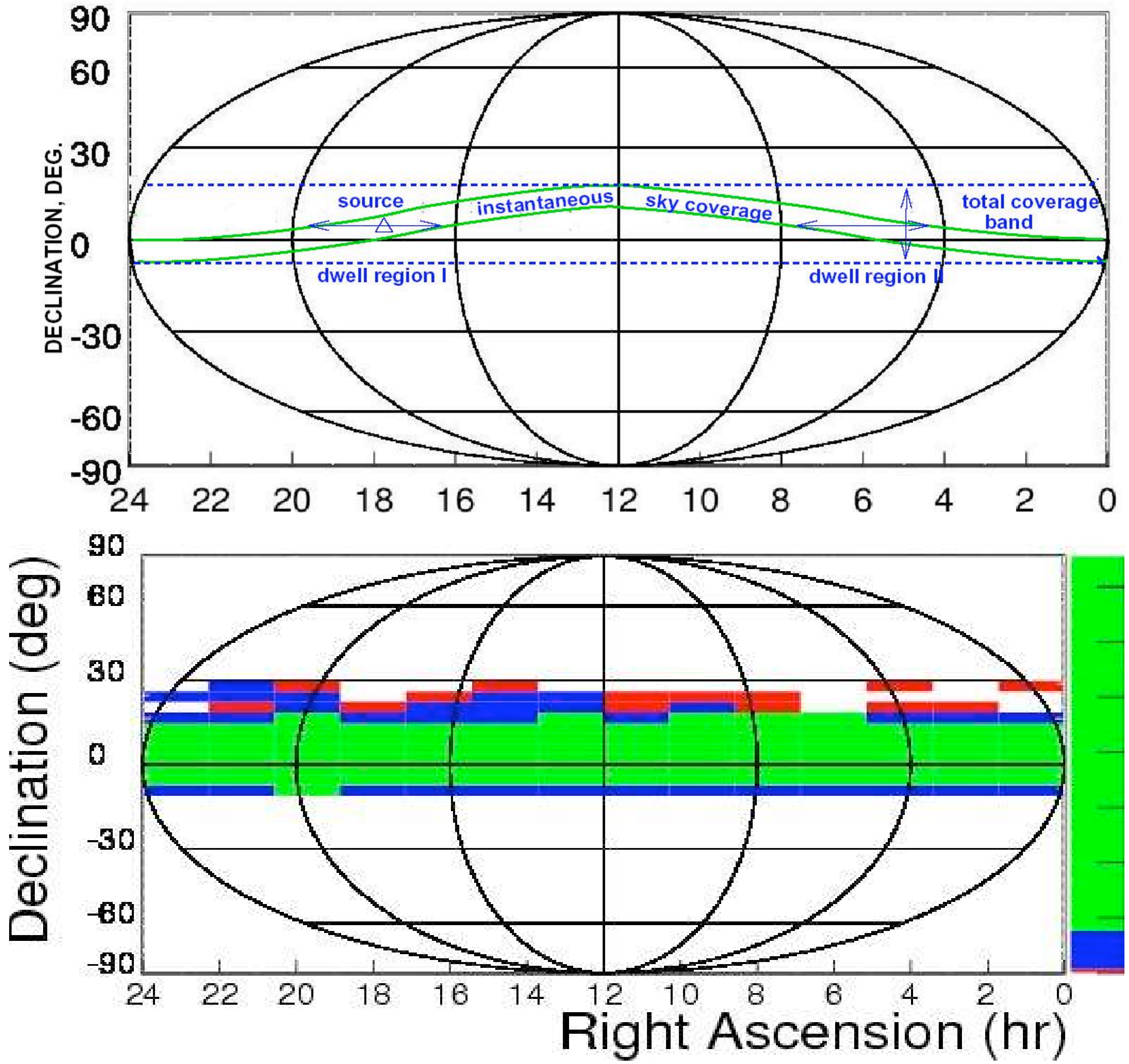






- Using signals from multiple antennas it is possible to measure the direction of arrival of radio pulse to ~0.5° in elevation and ~1.5° in azimuth (based on ANITA-lite calibration data)
- The neutrino direction can vary around radio pulse direction but is constrained to ~2° in elevation and by 3-5°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

- # Point Source Sensitivity



- ANITA is sensitive to sources with declination between -10 and 20 degrees.
- The actual dwell time over a particular source is less than the flight time.
  - So exposure for a point source is a factor 4-5 less than a diffuse source.

- 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)