ANITA: Hunting for neutrinos and new physics

Ryan Nichol

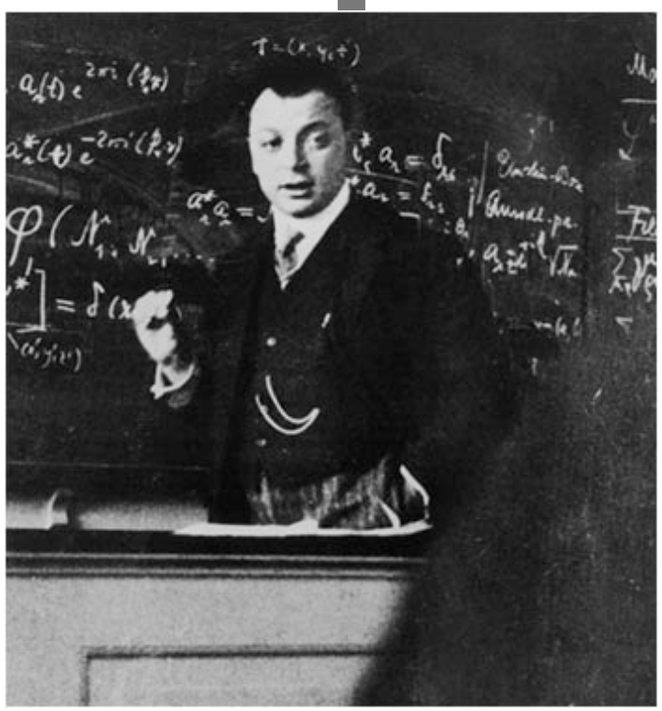
PSI
29th November 2018

LEVERHULME TRUST

Brief scientific timeline leading to ANITA

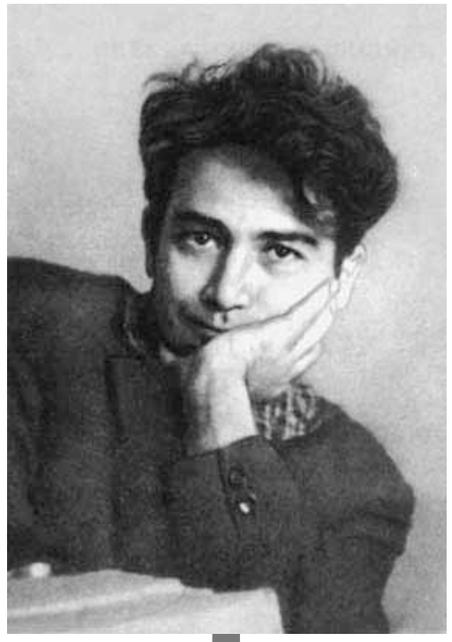
1912

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

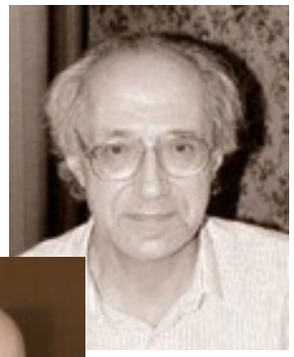


1962

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

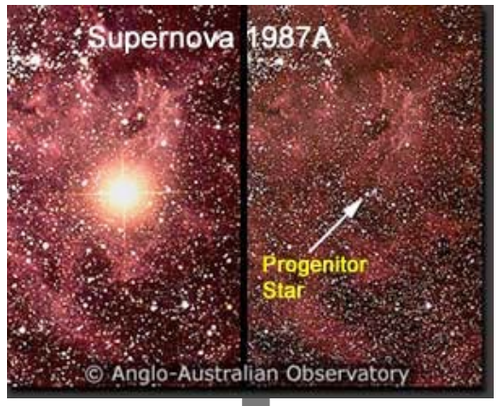
Wilson and Penzias discover the cosmic microwave background

1965



Berezinksy & Zatsepin realise the GZK effect will produce neutrinos

1969



ANITA-I launches from Williams Field in Antarctica

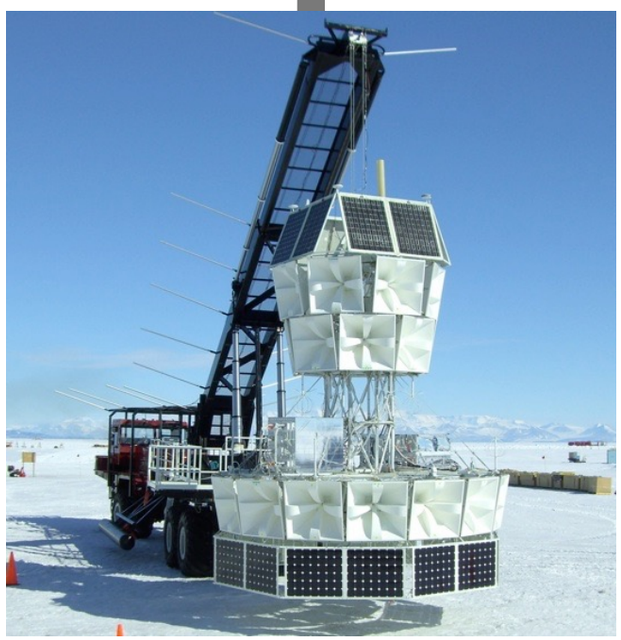
2006

1966

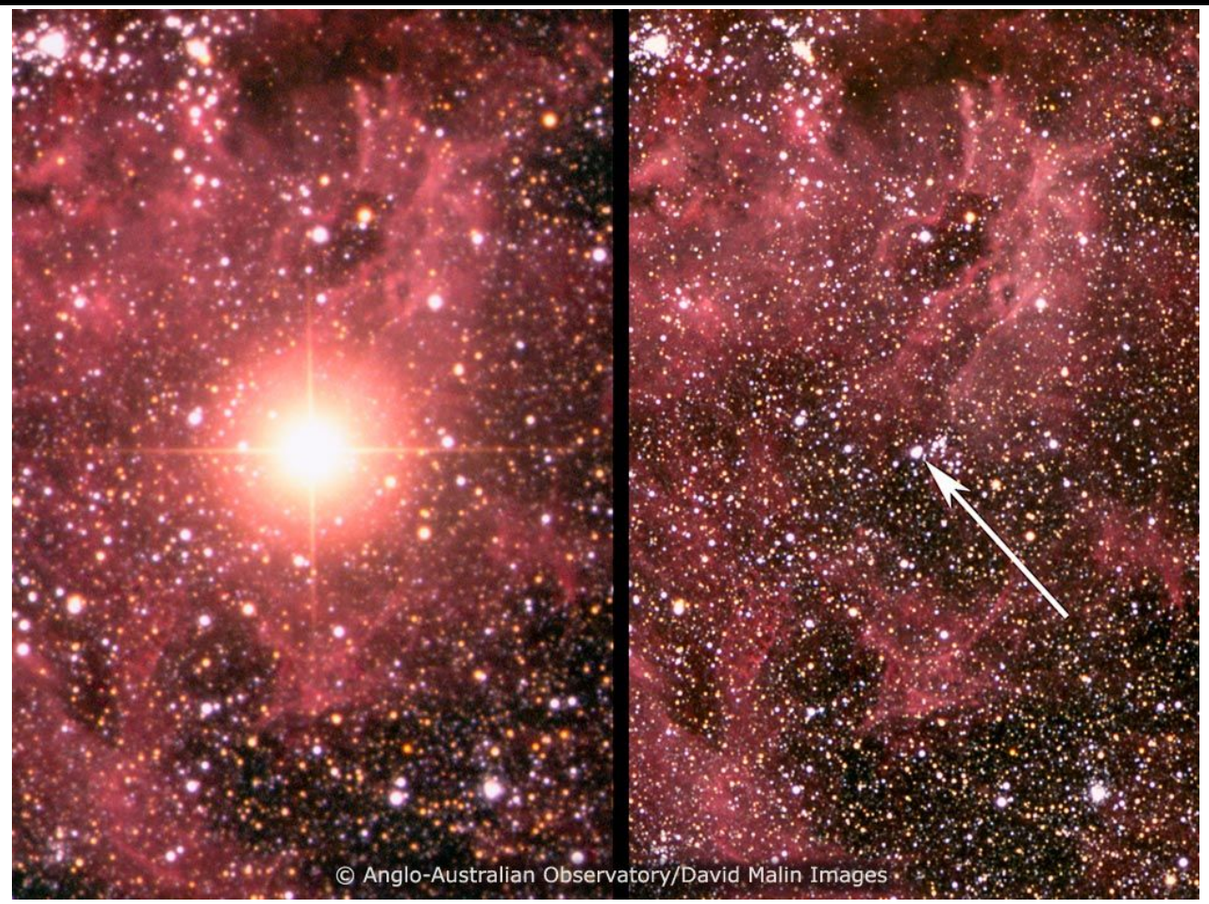
Greisen, Zatsepin & Kuzmin predict the end of the cosmic ray spectrum

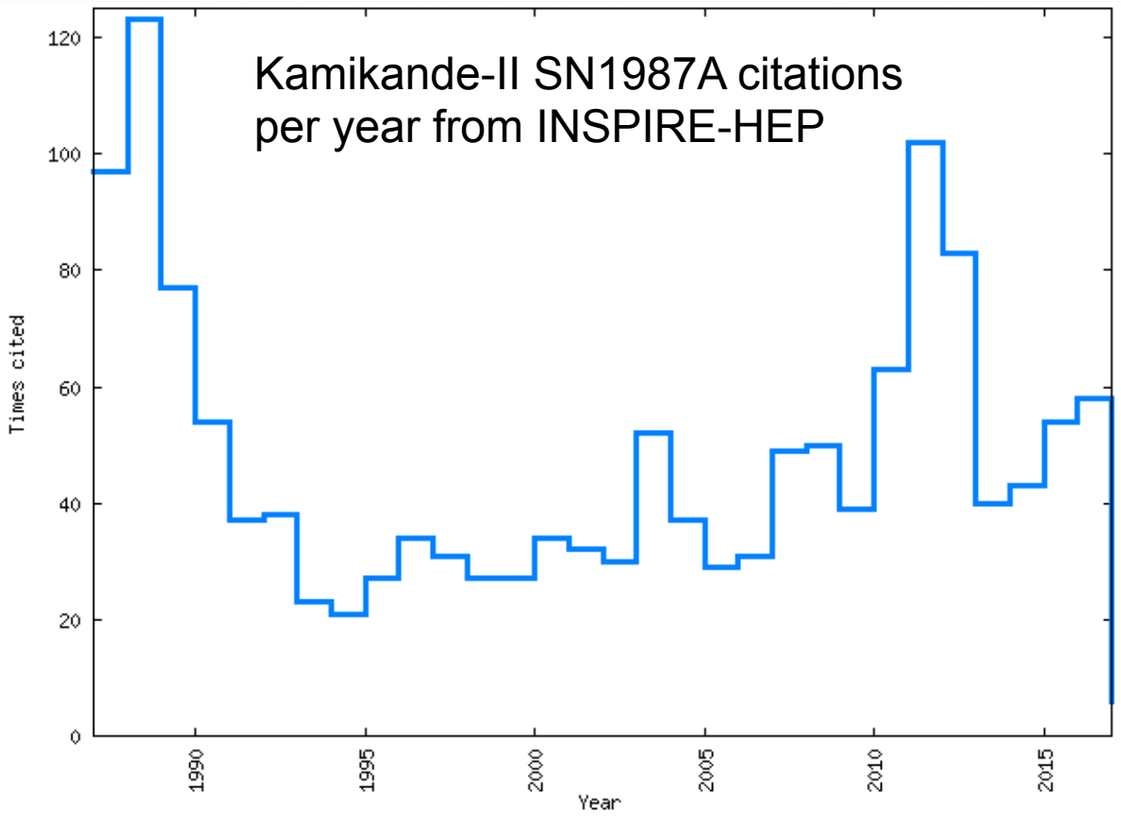
1987

Kamiokande, IMB and Baksan detect neutrinos from a nearby supernova



Complete* History of Neutrino Particle Astrophysics



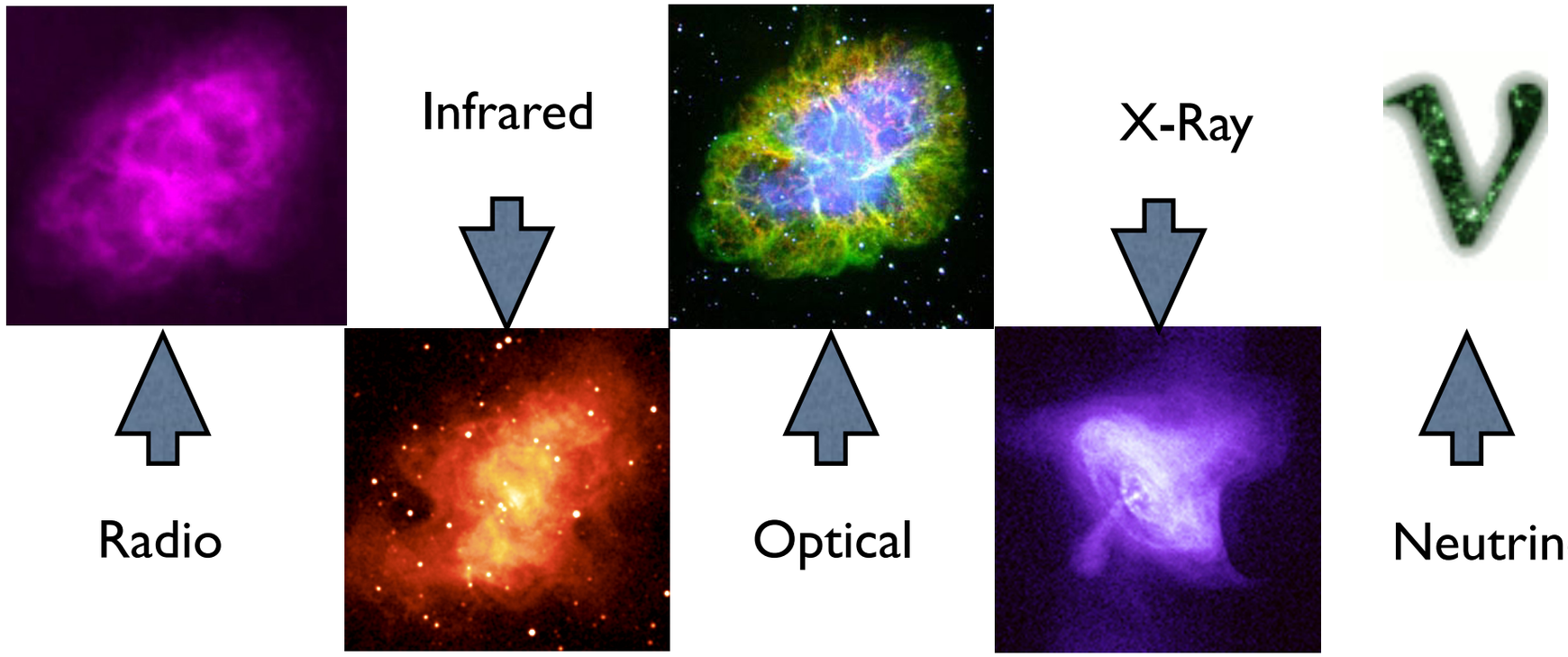


- SN1987A
  - 24 neutrino events detected by Kamikande-II, IMB and Baksan
  - Learned about
    - Supernova collapse mechanisms
    - Neutrinos feel gravity (similarly to photons)
    - Neutrino mass < 23eV from time of flight dispersion
    - Neutrinos are not charged
    - Limits on non-neutrino weakly interacting particles
    - Axion bounds
    - Neutrino mixing and oscillations
    - Exotic neutrino disappearance

* before 2011, excluding solar

Why High Energy Neutrinos?

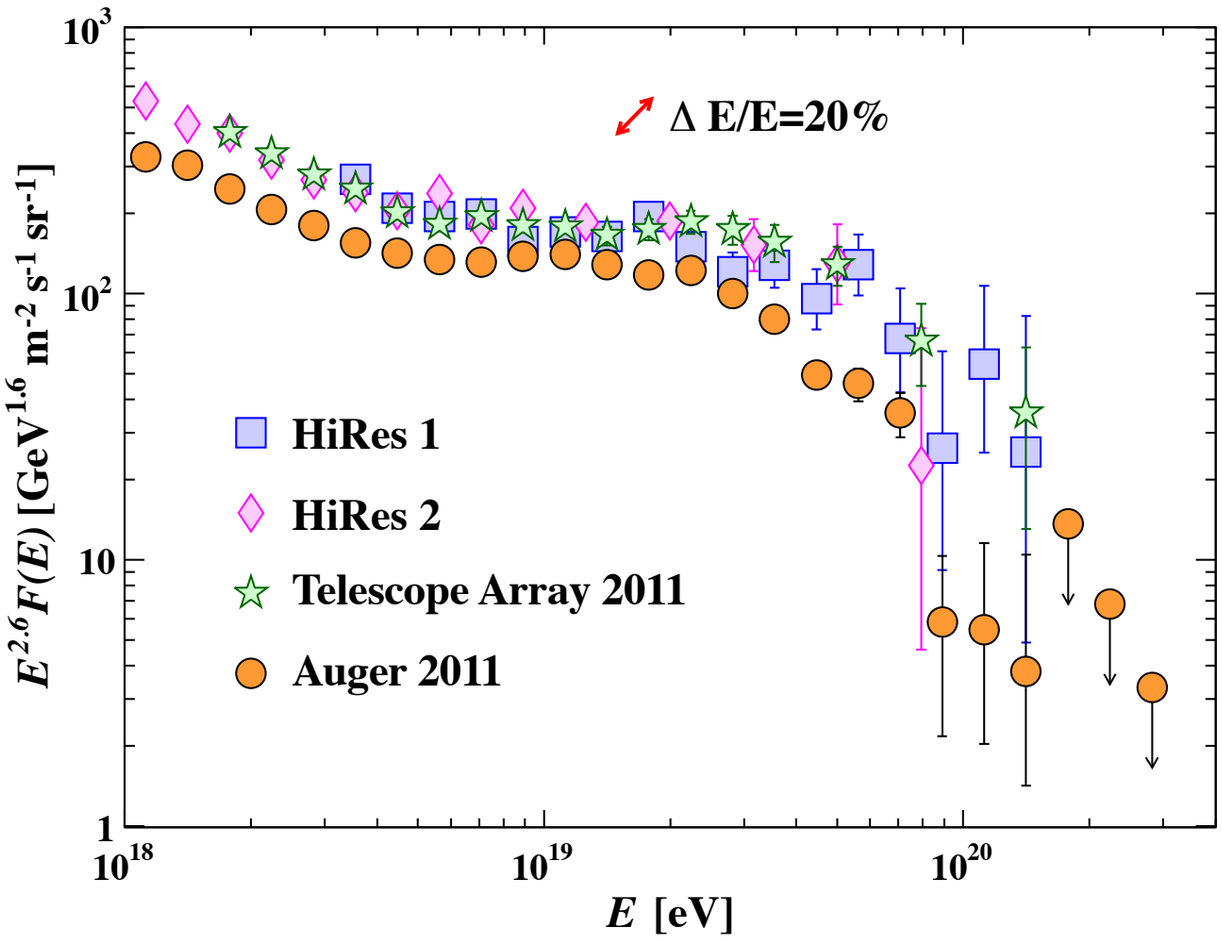
For Astronomers:
The Pretty Pictures Argument



For Particle Physicists:
The 300 TeV (CoM) Neutrino Beam Argument

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

Aside: The GZK Effect



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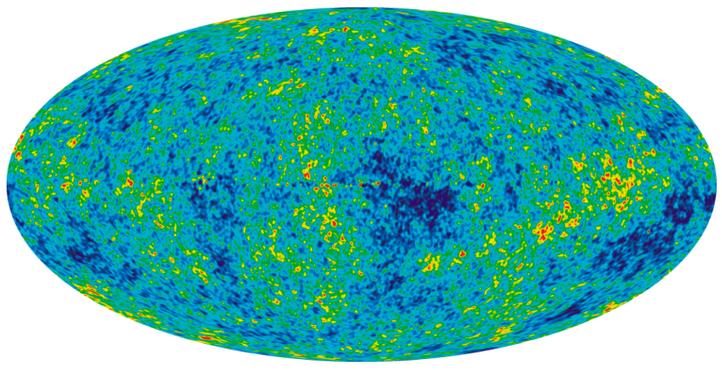


- Greisen-Zatsepin-Kuzmin (GZK) calculated cosmic rays above $10^{19.5}$eV should be slowed by CMB within 50MPc.
- Berezinksy and Zatsepin realised this would produce a flux of neutrinos

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

= “Guaranteed” Cosmogenic Neutrino “Beam”!

UCL

physicsworld

BREAKTHROUGH OF THE YEAR

2013

IceCube

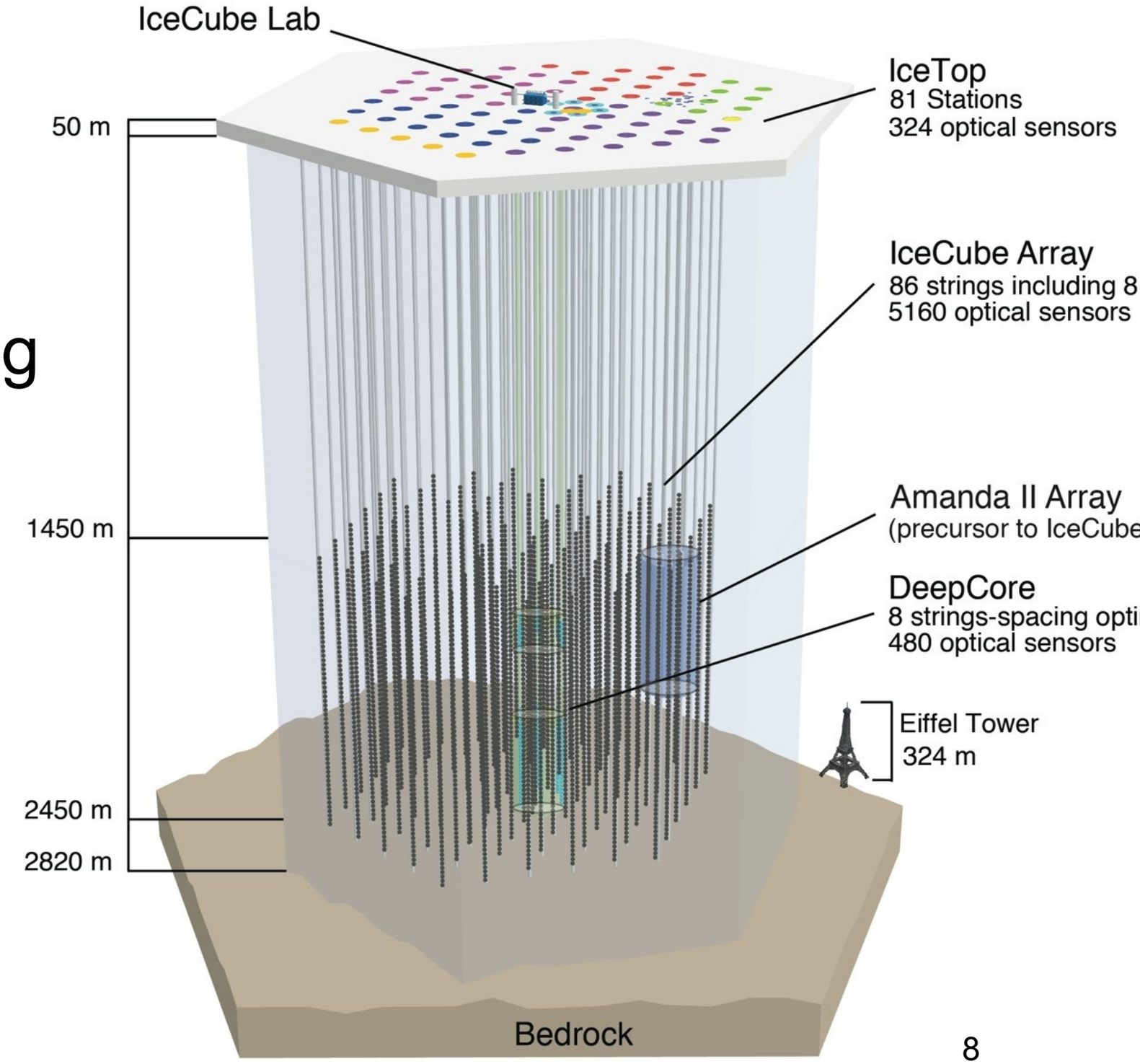
NSF

IceCube

IceCube

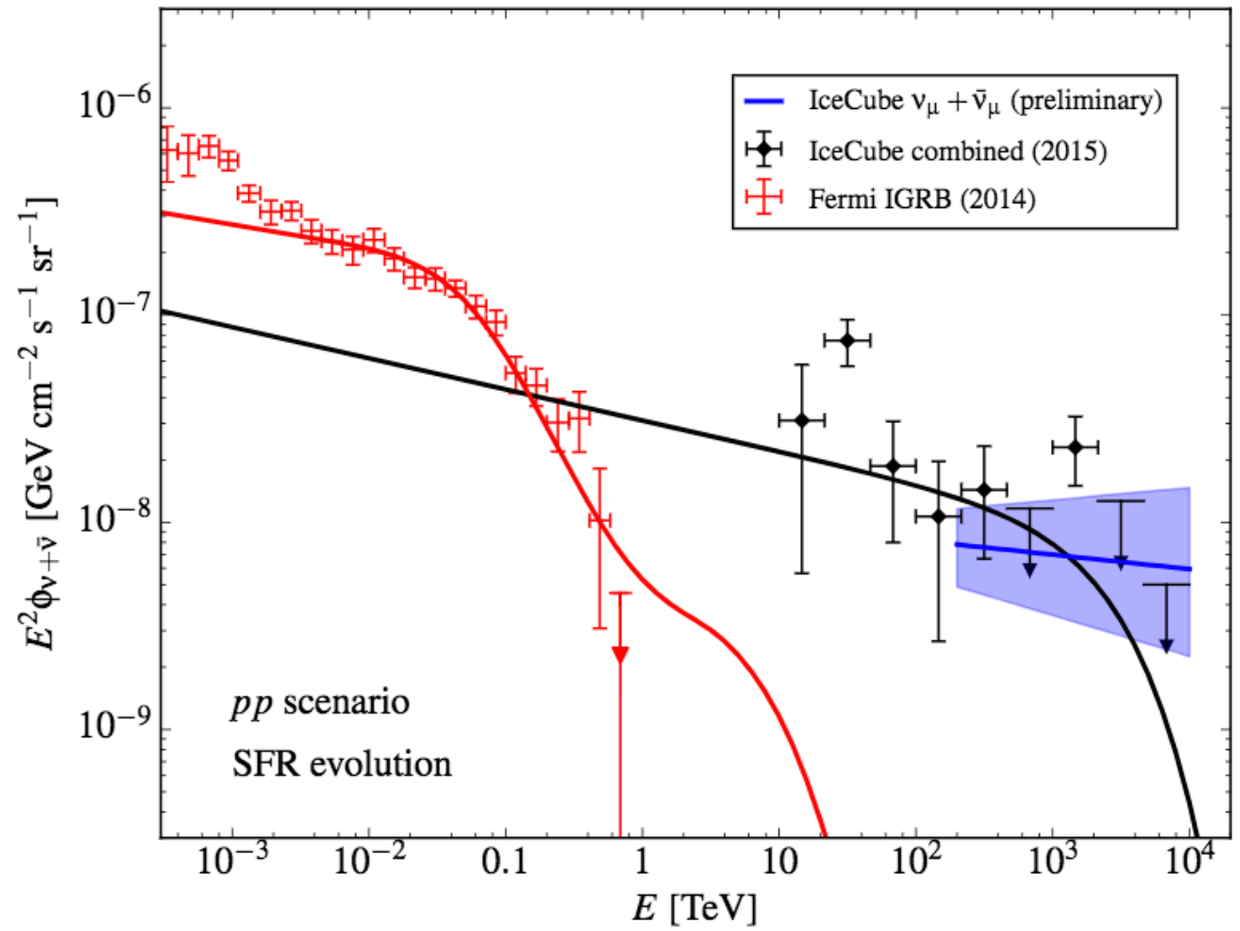
- Completed in 2010
- 1km^3 of ice at the South Pole
- 5160 PMTs
- 86 strings
- 17m vertical spacing
- 125m horizontal spacing

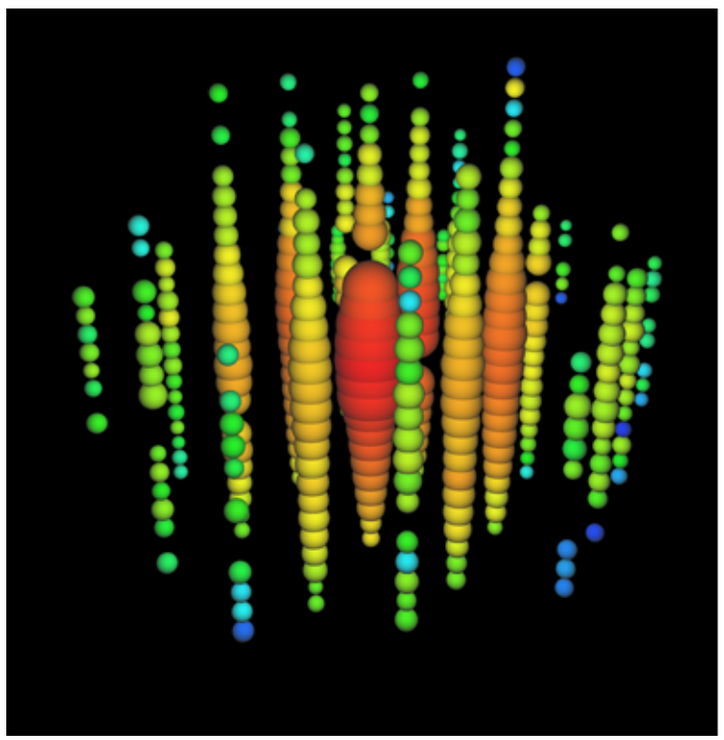
- DeepCore
  - Densely instrumented array of 8 strings in deep good ice

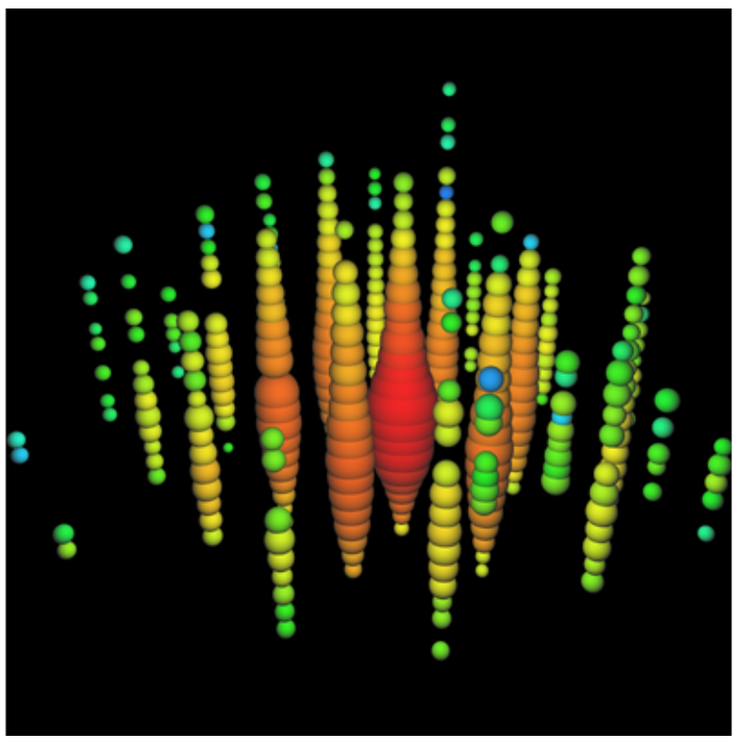


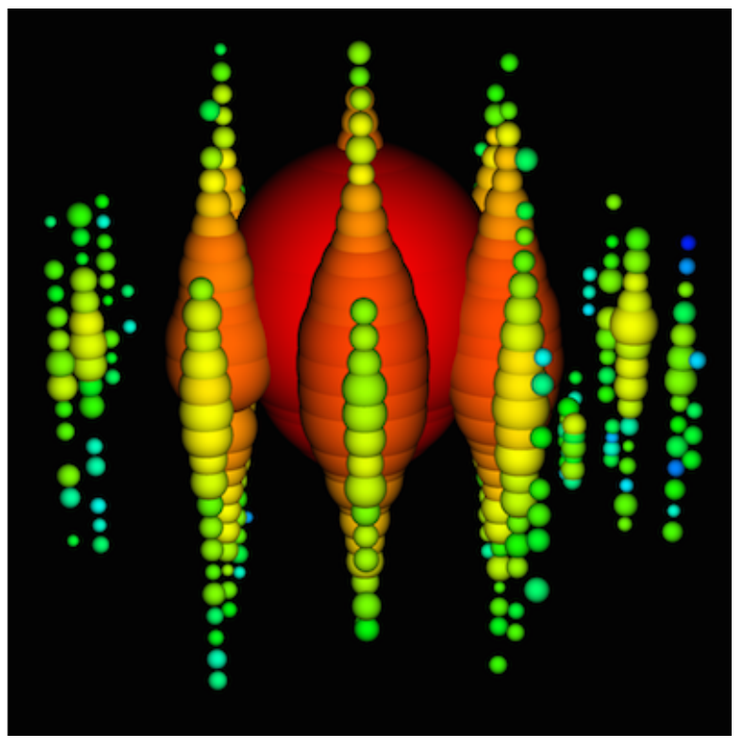
IceCube Results

- IceCube have definitively observed an excess of high energy neutrino events above the atmospheric neutrino prediction









IceCube is too small!

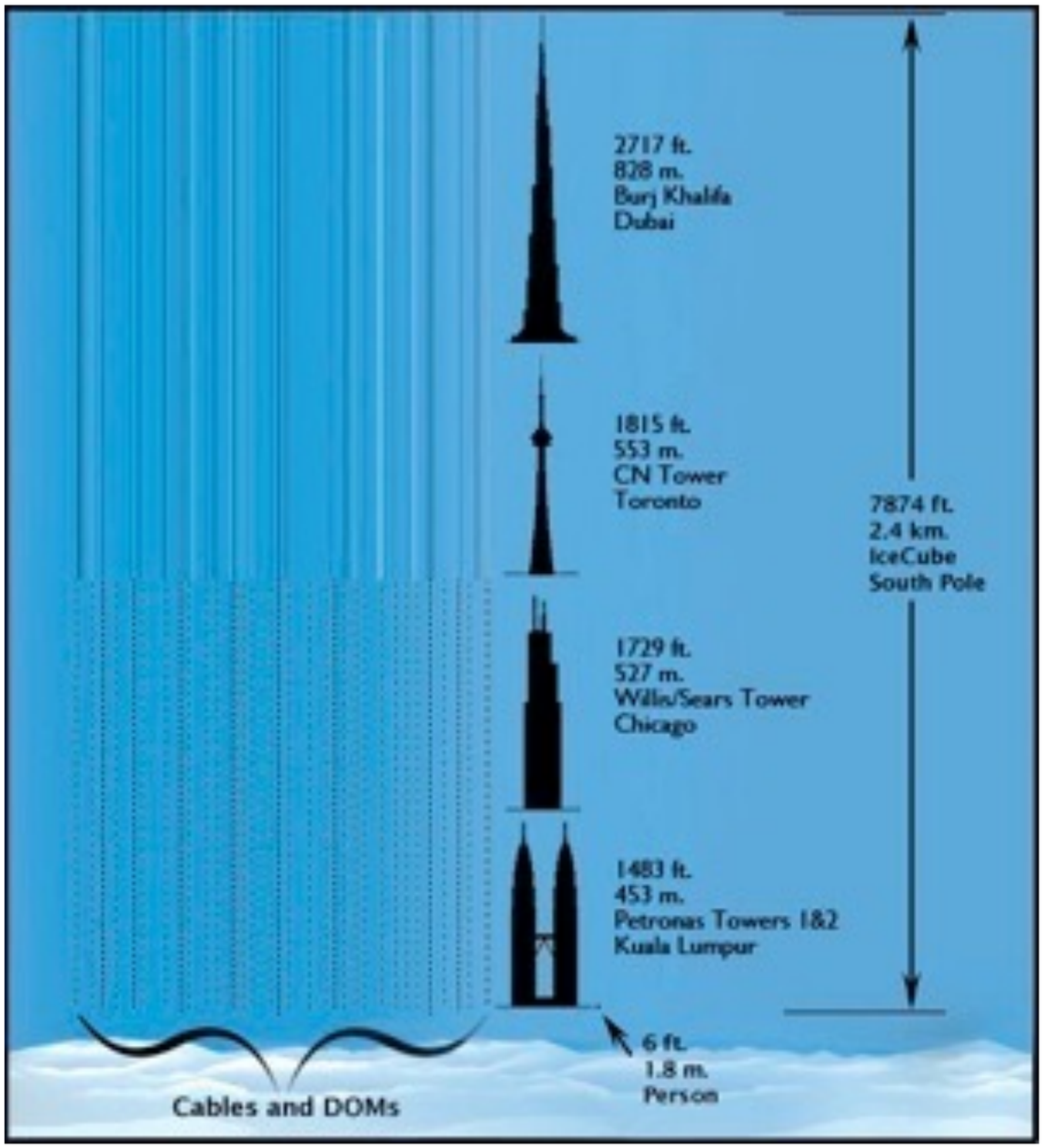
- Some Numbers:

  ~1 cosmogenic neutrino/km^2/yr

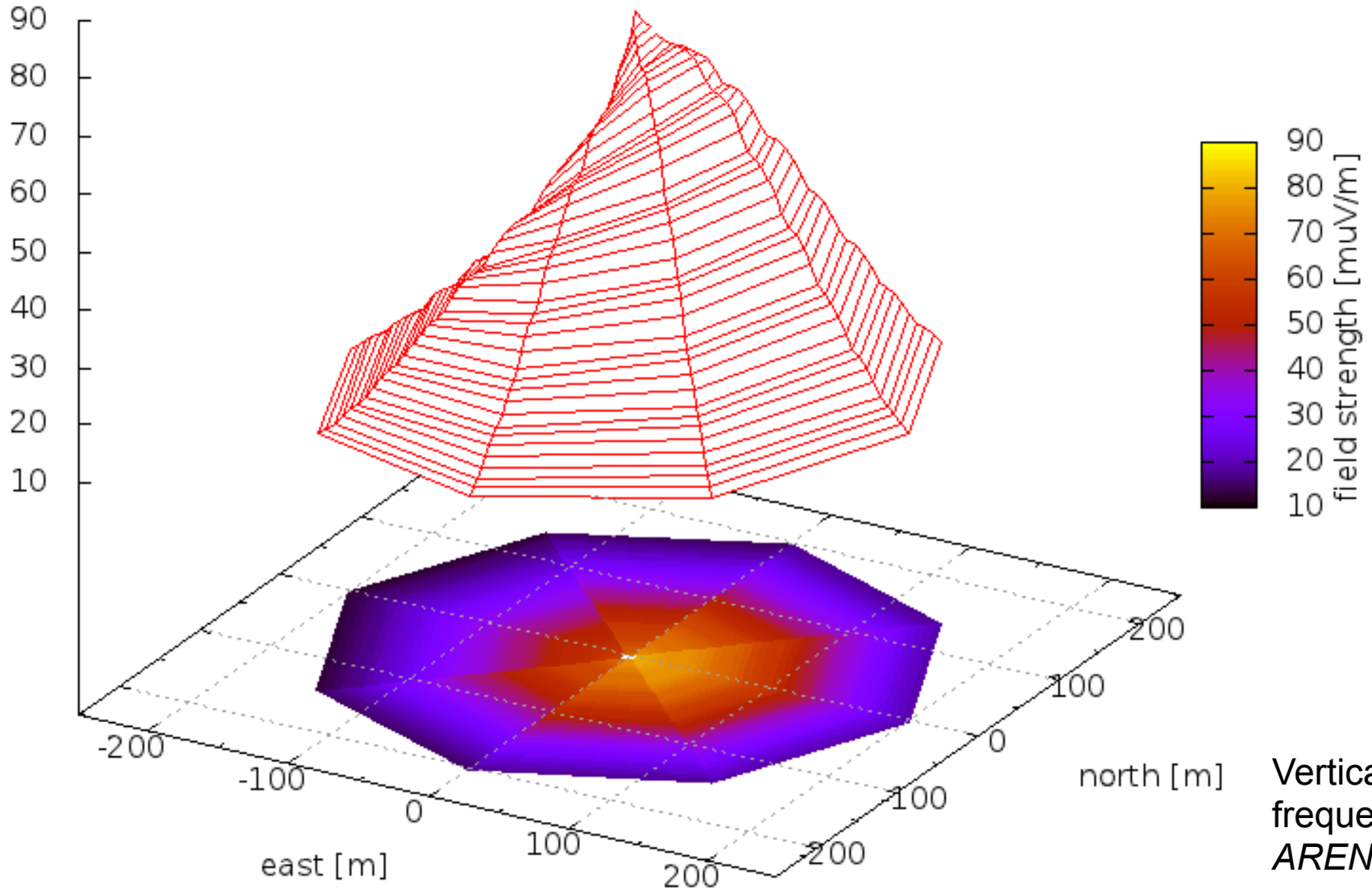
  @ 10^{18} eV the ν-N interaction length ~ 300km

  $\therefore$ 0.003 neutrinos/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



Radio Emission Mechanisms

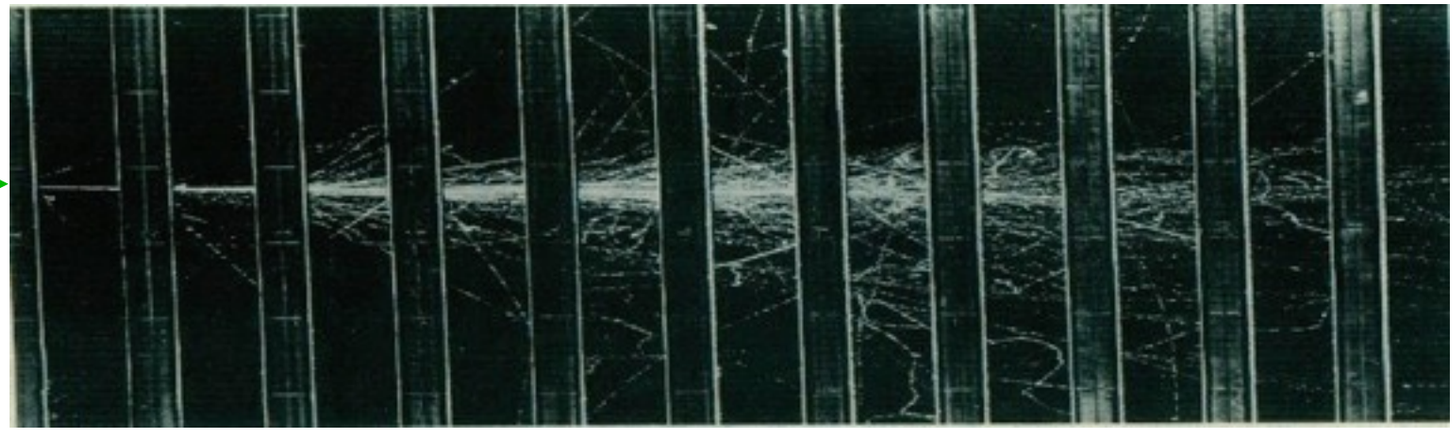


Vertical Iron Shower at LOPES frequencies from T. Huege *et al. ARENA2012*

Radio Cherenkov -- The Askaryan Effect

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

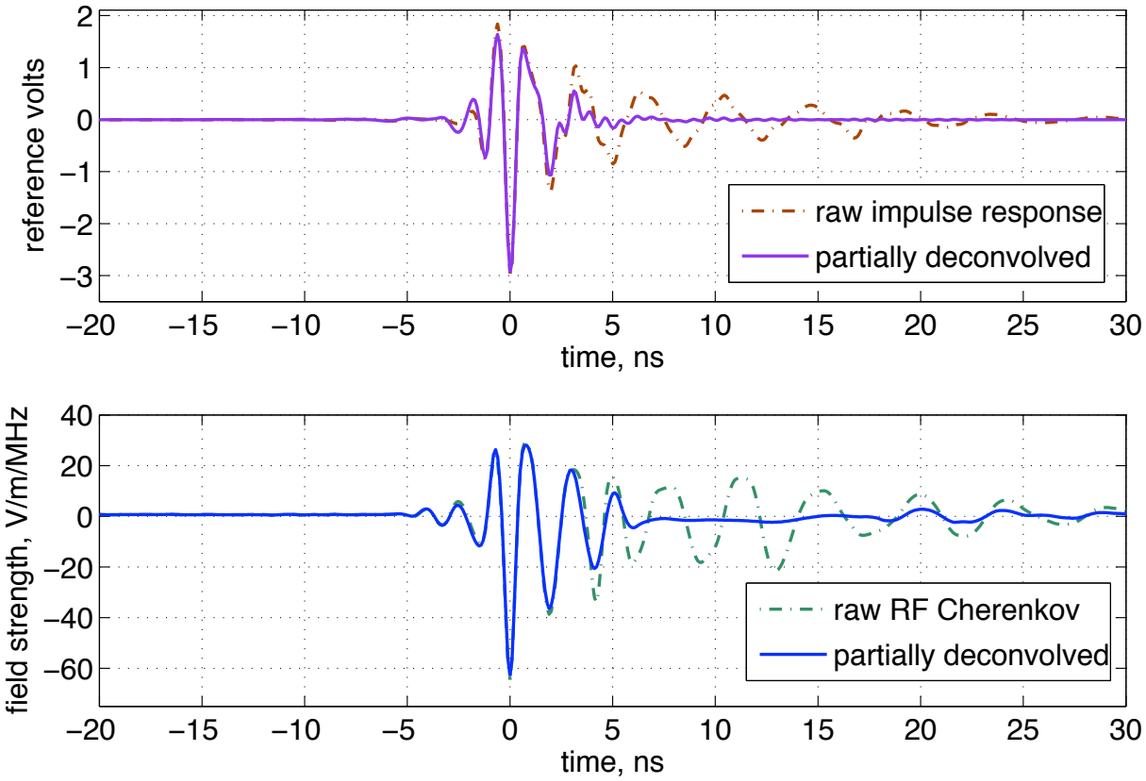
$e^{\pm}$ or γ



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

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

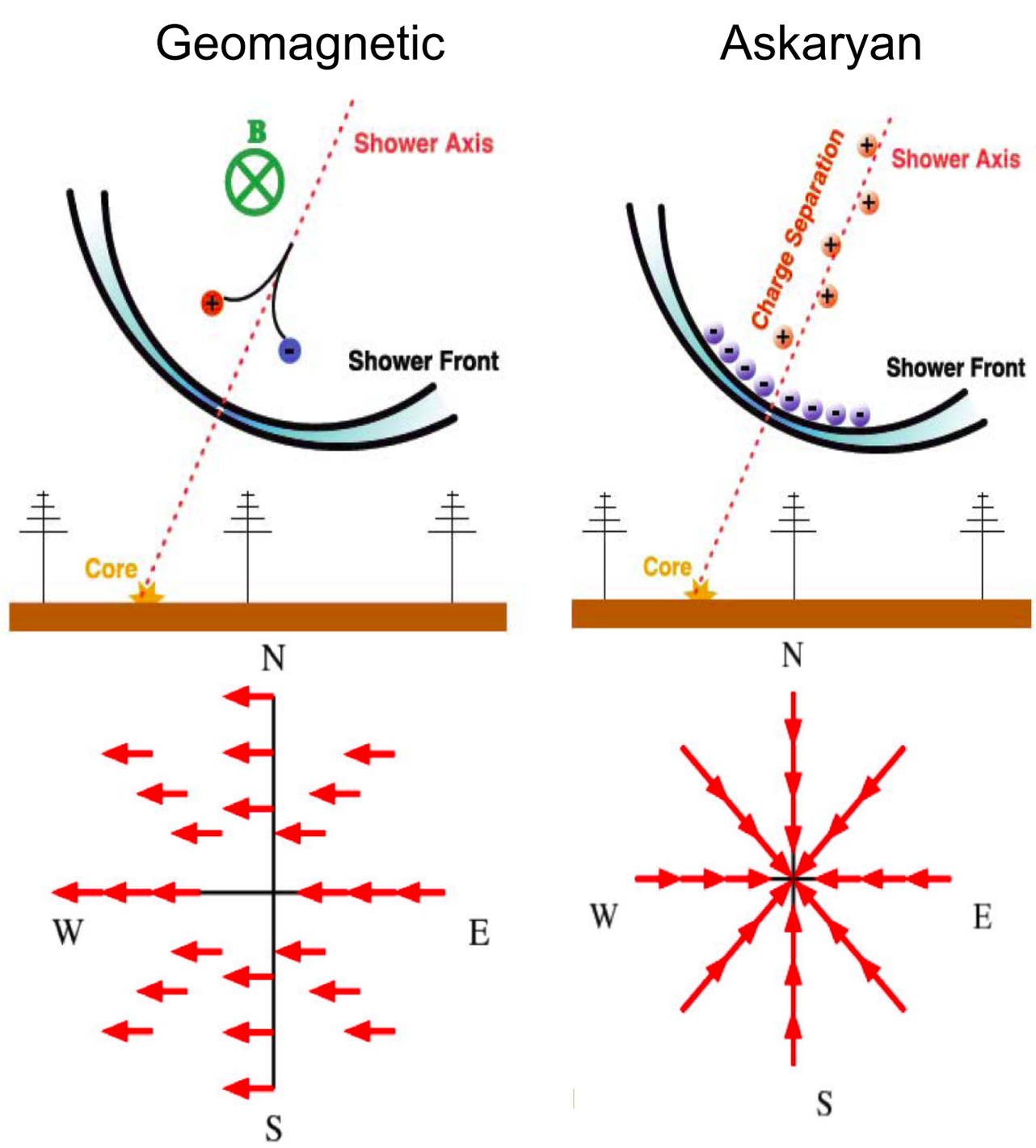
Flashy Ice



From PRL 99, 171101 (2007)

Radio Emission from Air Showers

- Air shower emission is complicated
  - Geomagnetic component from positron-electron separation
  - Askaryan component
  - Cherenkov effects from the varying refractive index of air, compresses pulse giving high frequency component
- T-510 experiment at SLAC tried to disentangle these



v x B **'radial'**

Diagrams from T. Huege, ICRC2013

T-510: Phys.Rev.Lett. 116 (2016) no.14, 141103

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ANITA

ANITA Collaboration

Ohio State University

University of Kansas

Washington University in St. Louis

University of Delaware

University of California, Los Angeles

University of Hawaii at Manoa

National Taiwan University

University College London

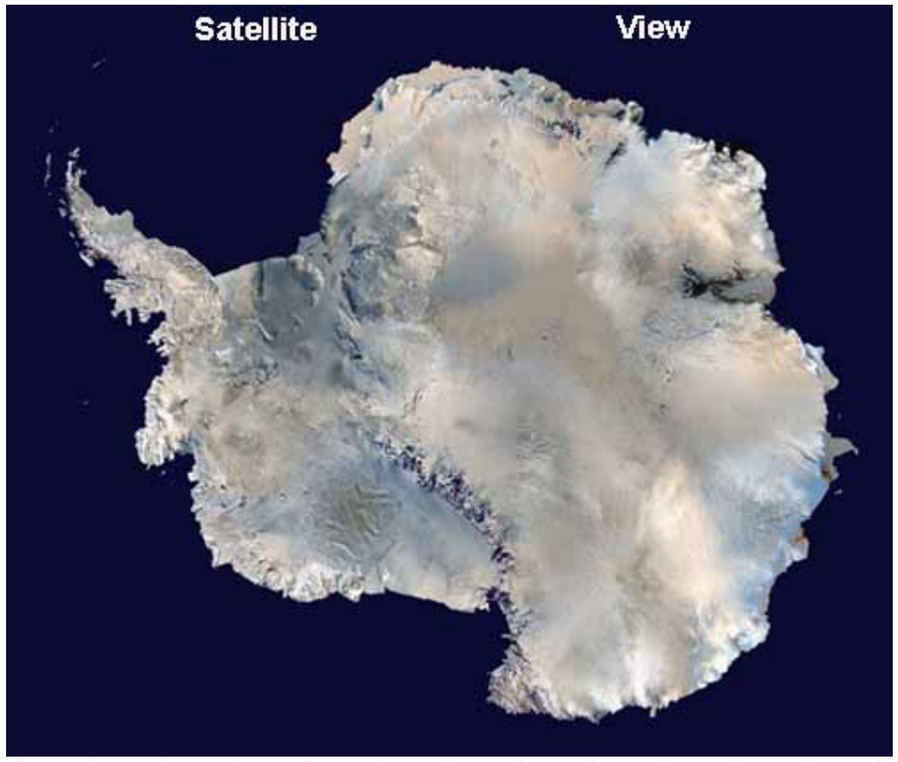
Jet Propulsion Laboratory

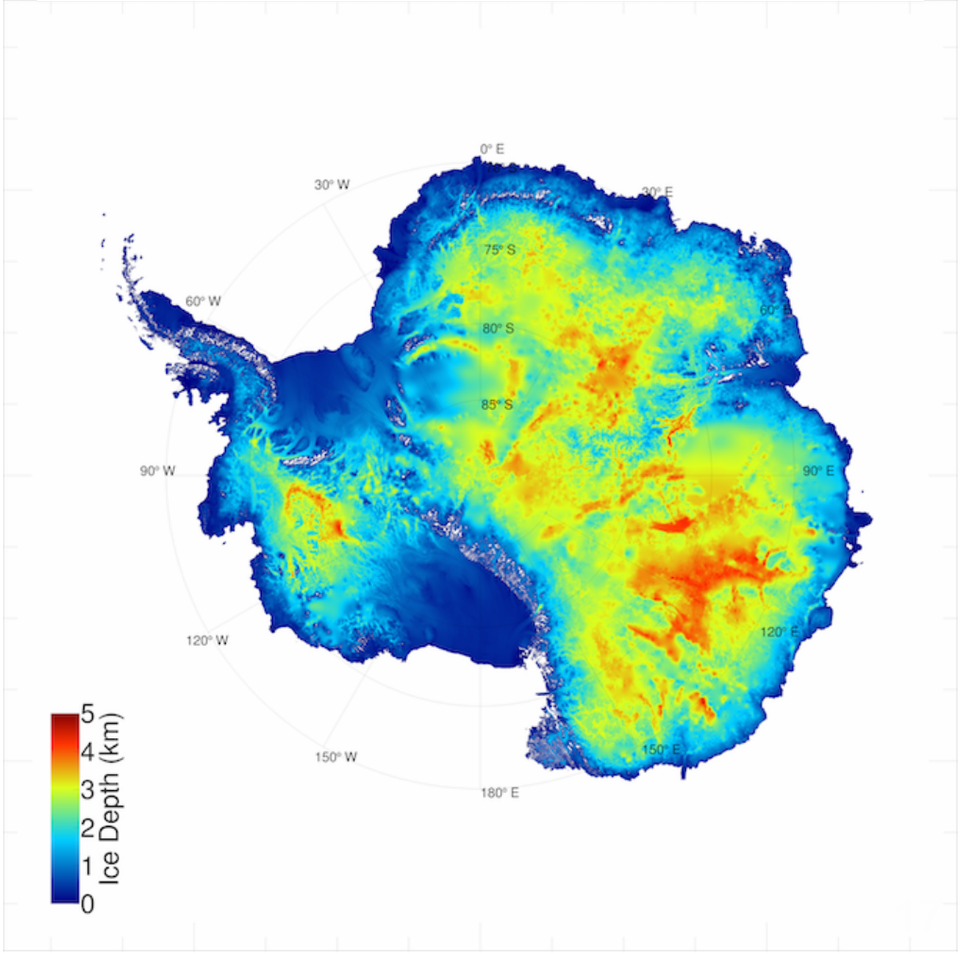
Stanford Linear Accelerator Center

University of Chicago

Need the world's largest detector

- Let's go to 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
    - Home of NASA's long-duration balloon program

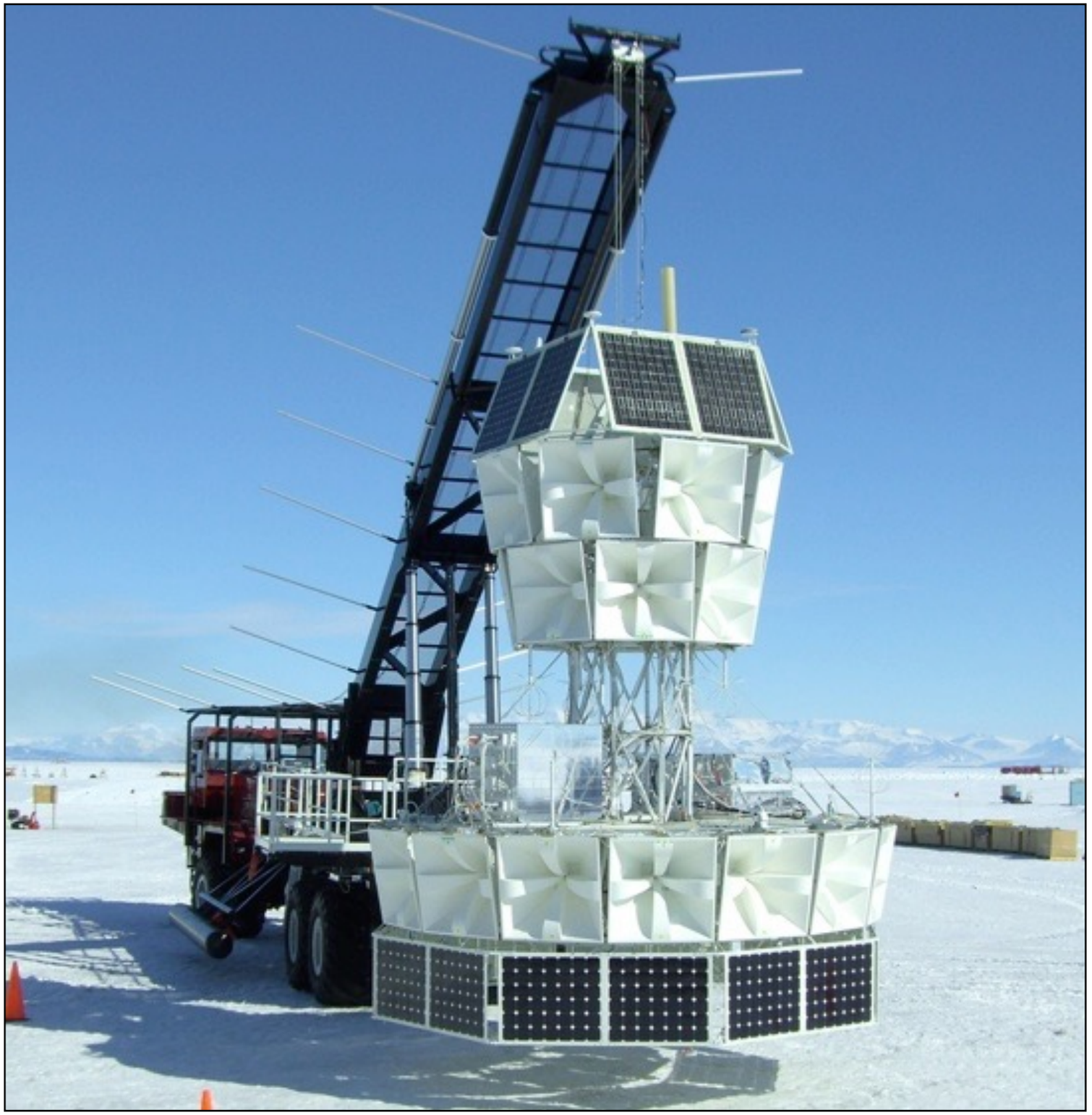




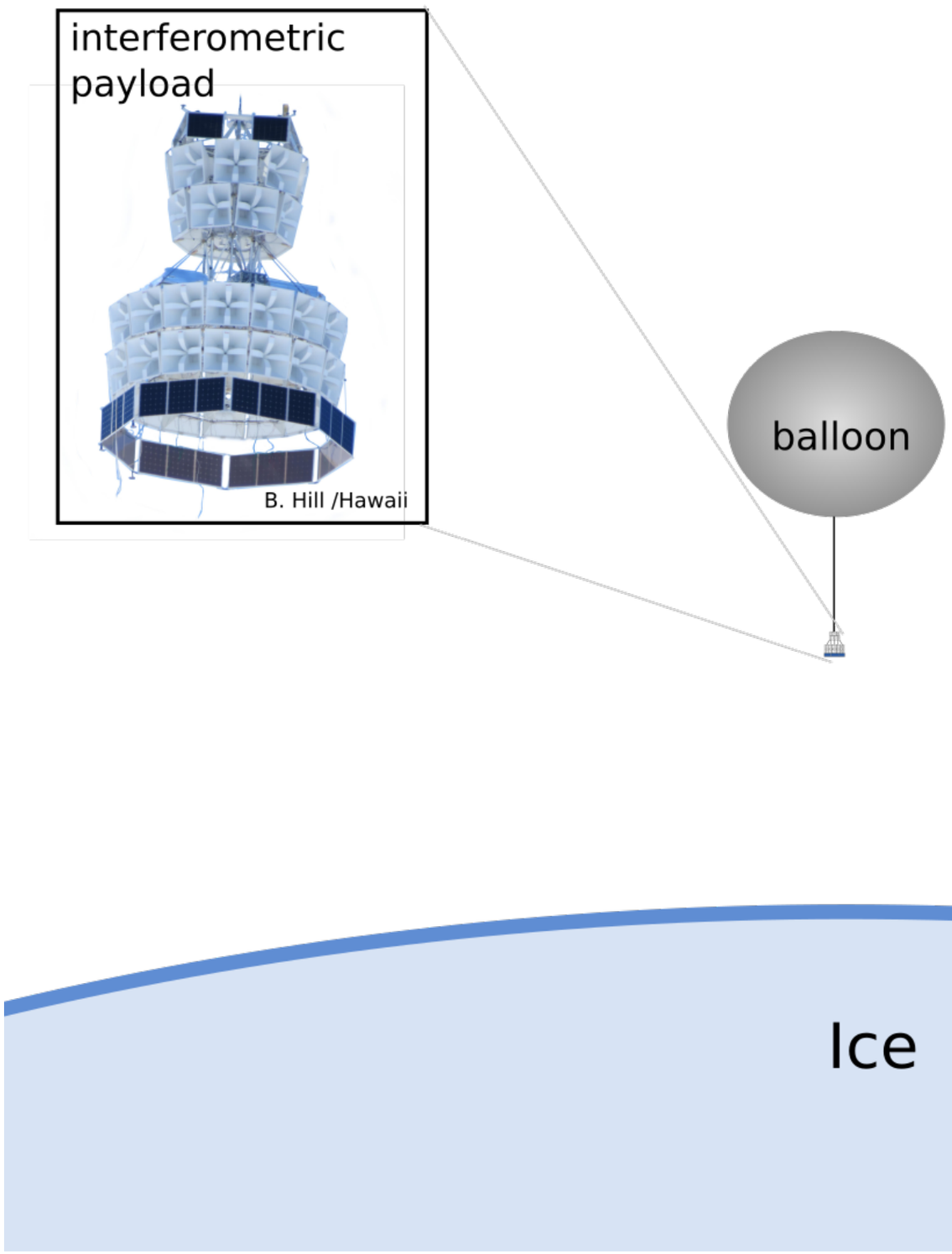
Ice depth data from BEDMAP consortium

ANITA

- The ANtarctic Impulsive Transient Antenna
  - A balloon borne experiment
    - Grown from 32 to 48 dual polarisation antennas
    - Altitude of 37km (120,000 ft)
    - Horizon at 700km
    - Over 1 million km^3 of ice visible

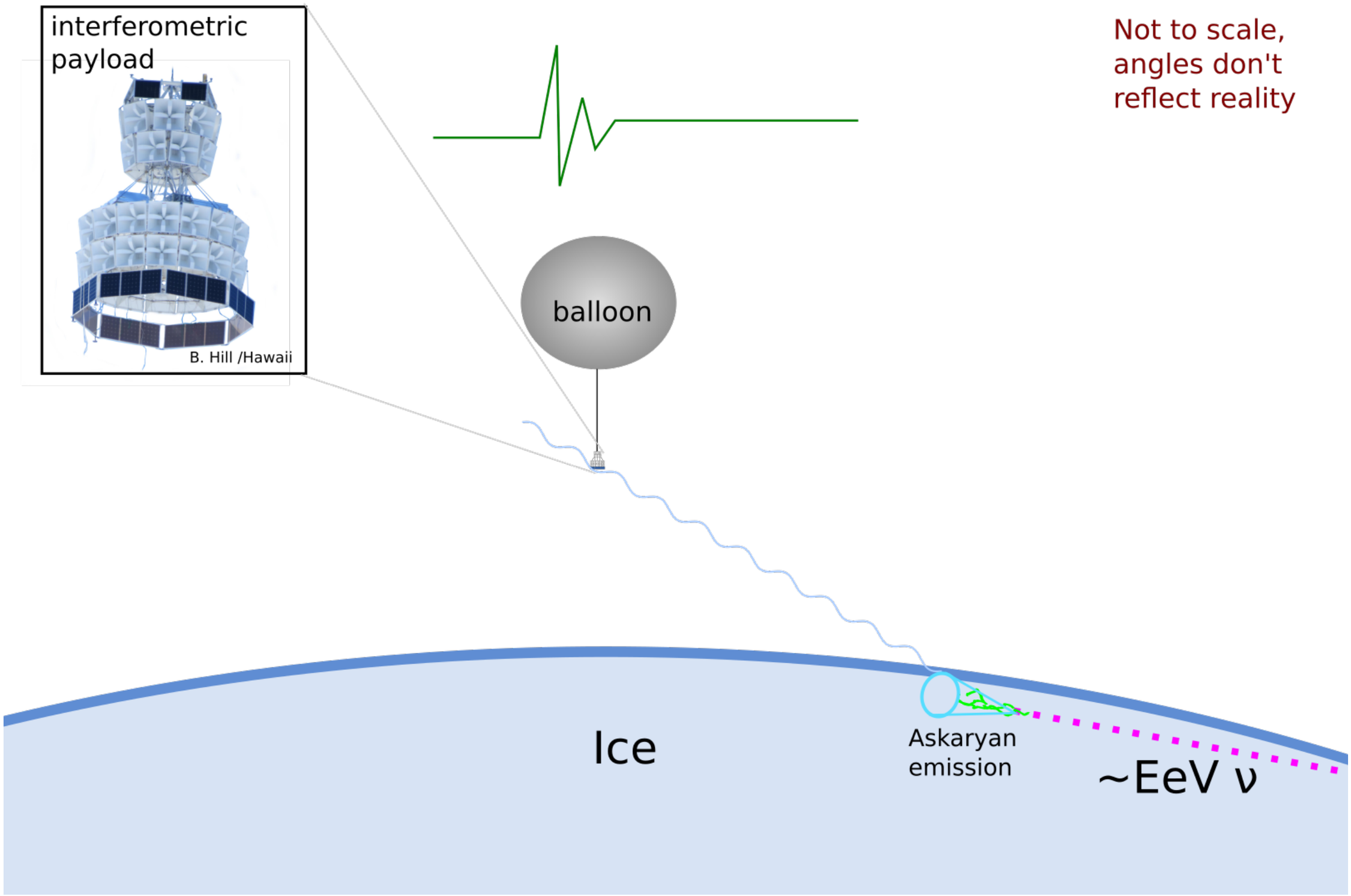


Concept



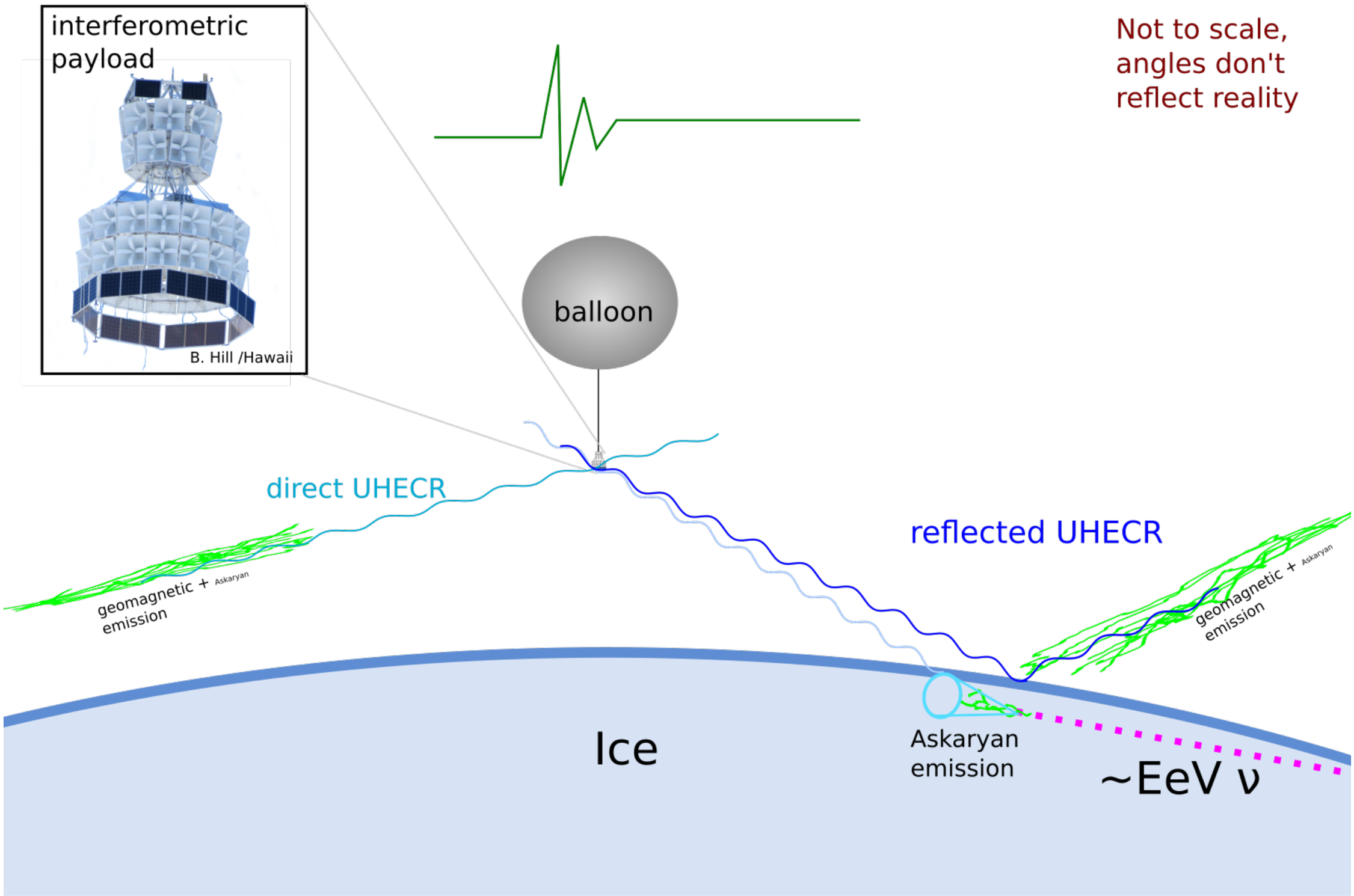
Not to scale, angles don't reflect reality

Concept



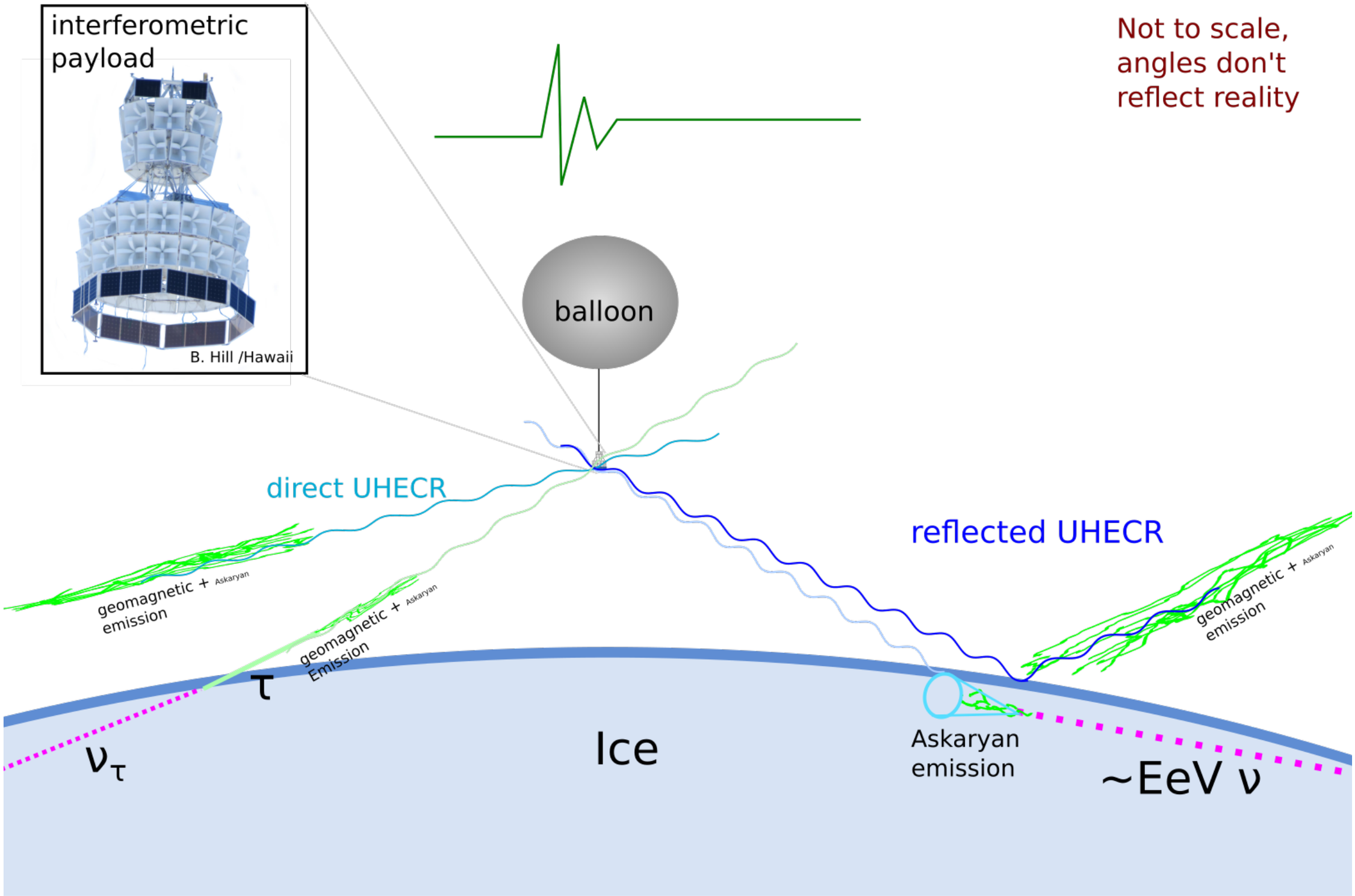
Not to scale, angles don't reflect reality

Concept



Not to scale, angles don't reflect reality

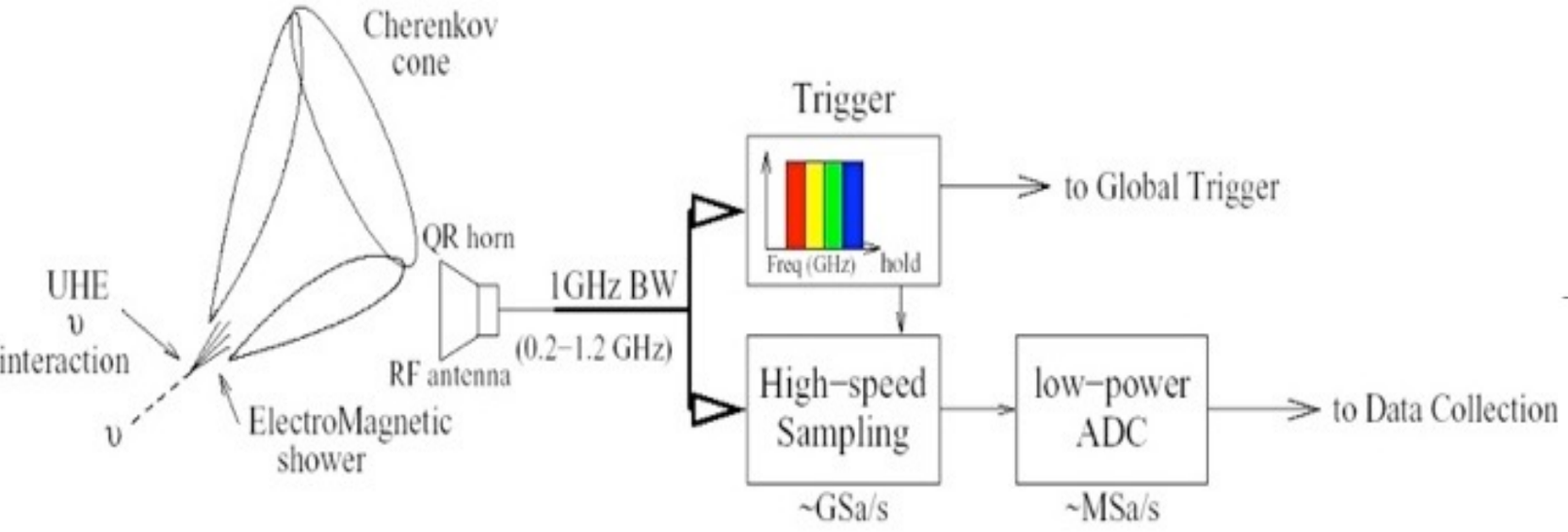
Concept



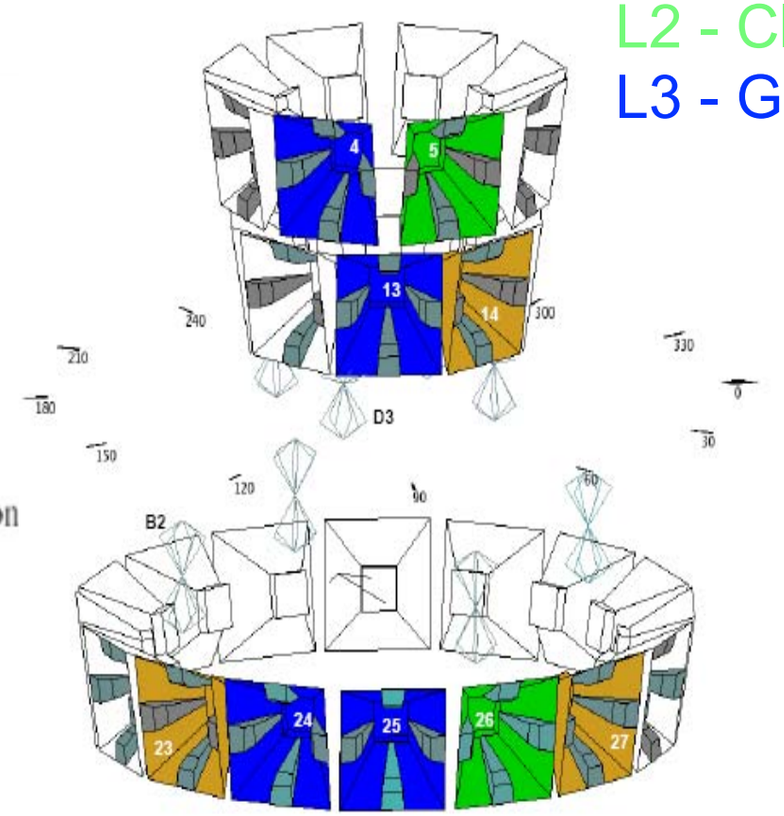
Not to scale, angles don't reflect reality

ANITA Electronics and Trigger

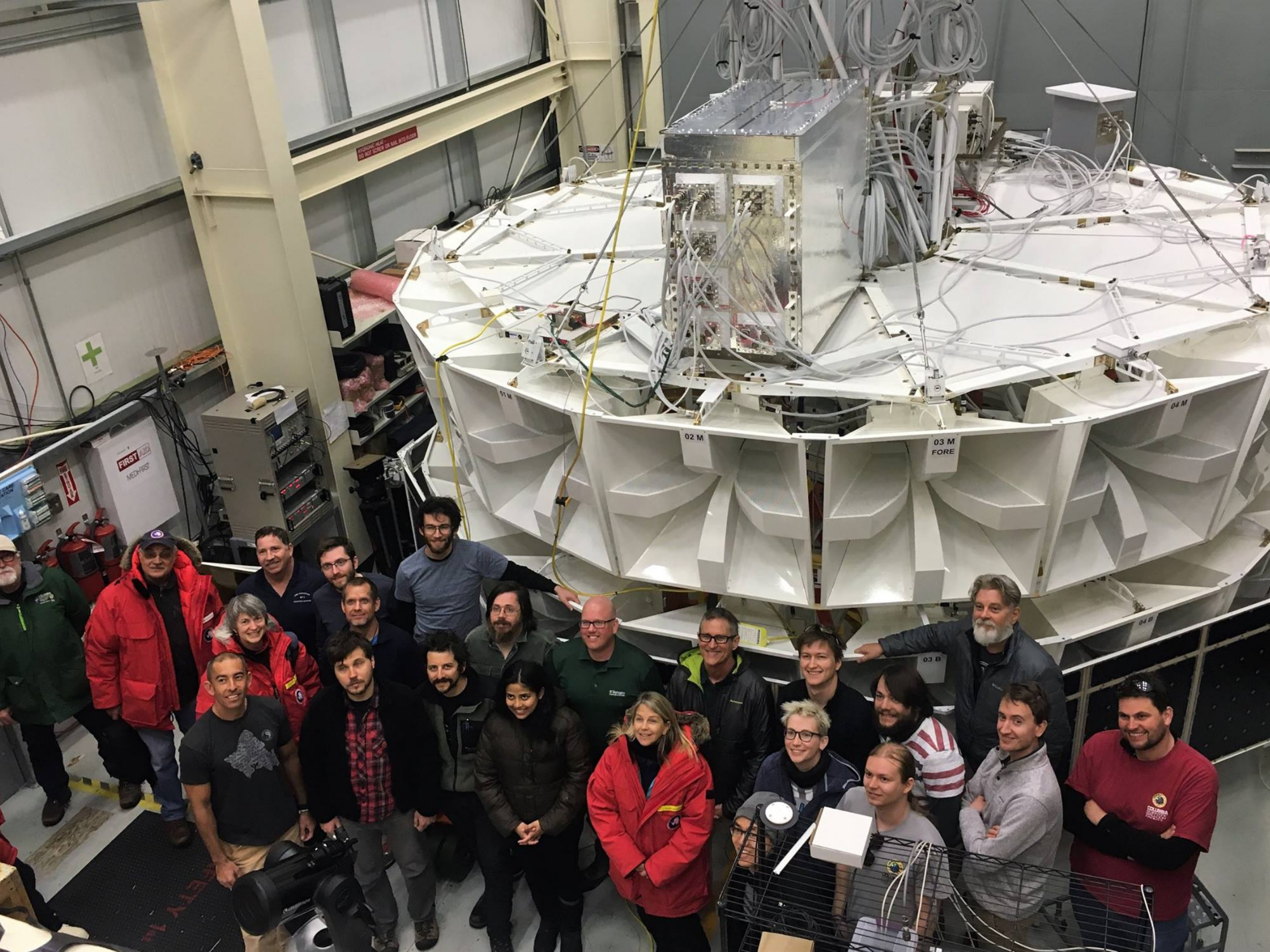
- Need a low power (only solar energy), 90 channel, multi-GHz bandwidth oscilloscope.



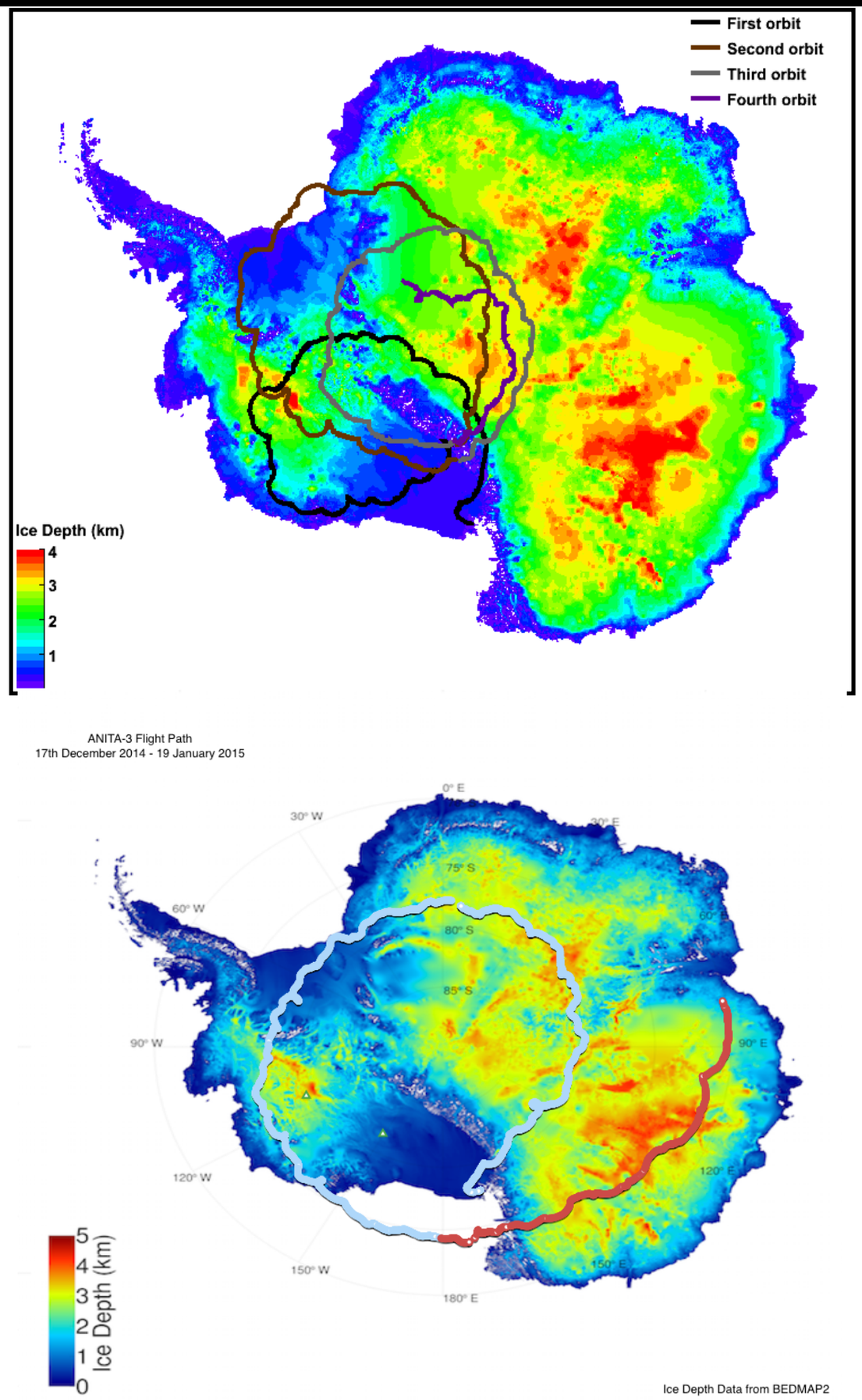
L1 - Antenna
L2 - Cluster
L3 - Global

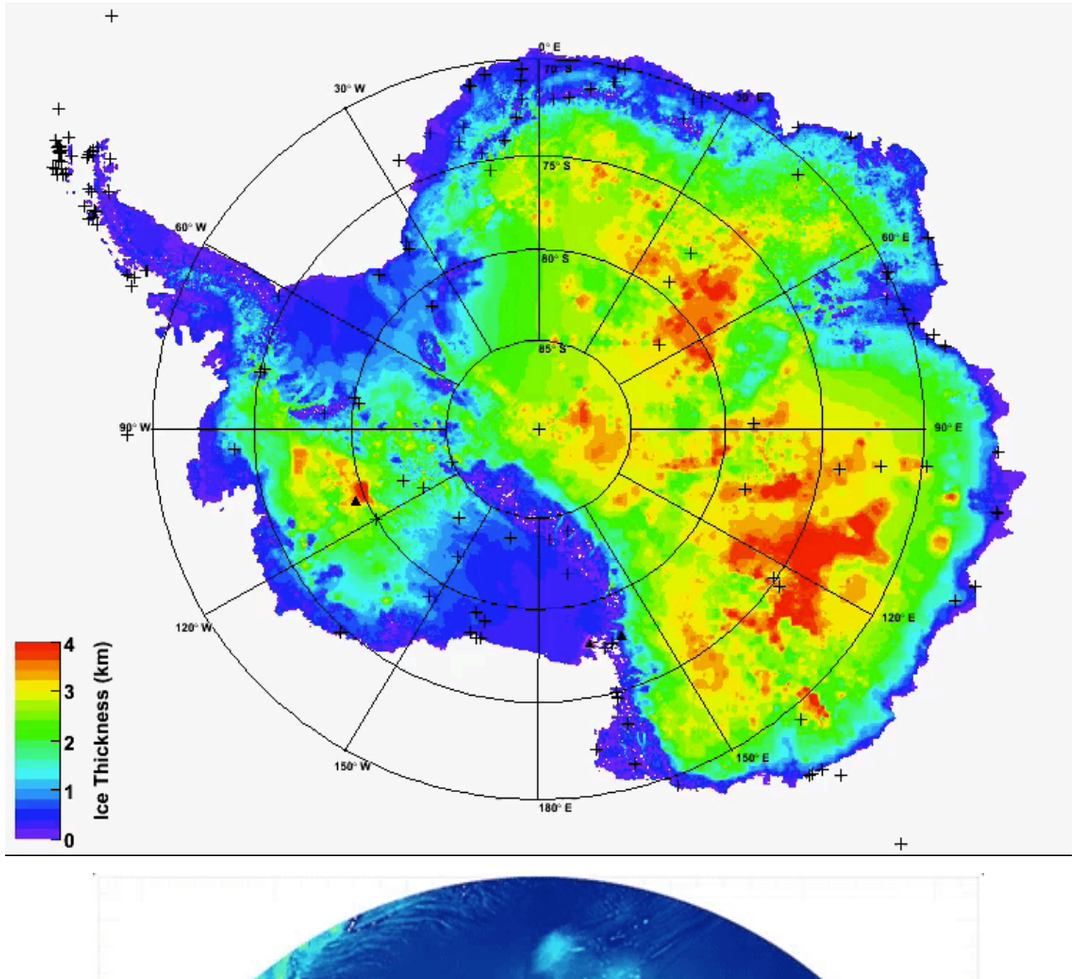


- Split trigger and waveform paths
- Use left and right circular polarisation for linear polarised trigger
- ‘Buffer’ waveform data in switched capacitor array

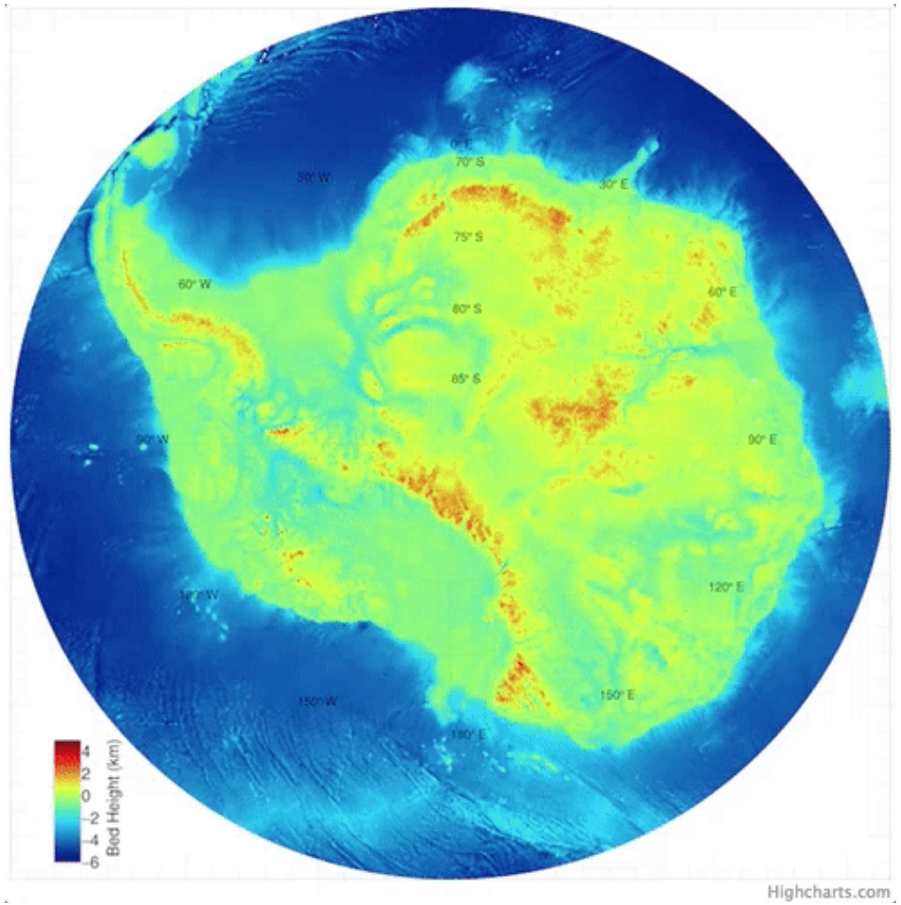

01 M
02 M
03 M
FORE
04 M
04 B
03 B
FIRST
MED-FIRST

ANITA 1-4





Ice Depth Data from BEDMAP2



Ballooning in Antarctica

- Balloons launched from Williams Field since 1988

'Fits' inside the balloon at altitude

ANITA-1 End of Flight

UCL

Image: Dana Braun, Wash. U.

ANITA-2 End of Flight

UCL

Image: Matthew Mottram, UCL

ANITA-3 End of Flight

UCL

Image: Josh F., Australian Antarctic Division

ANITA-4 End of Flight

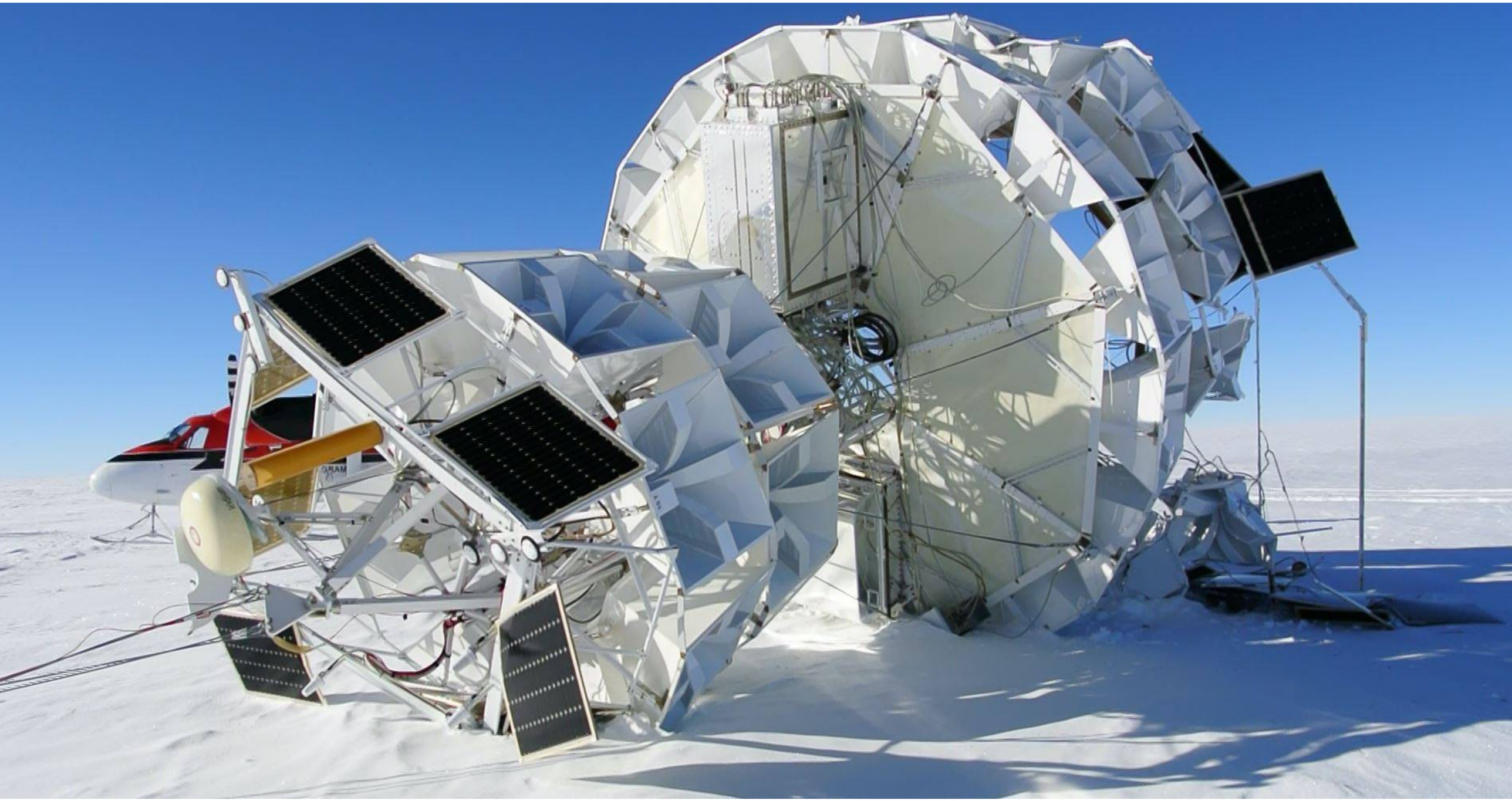
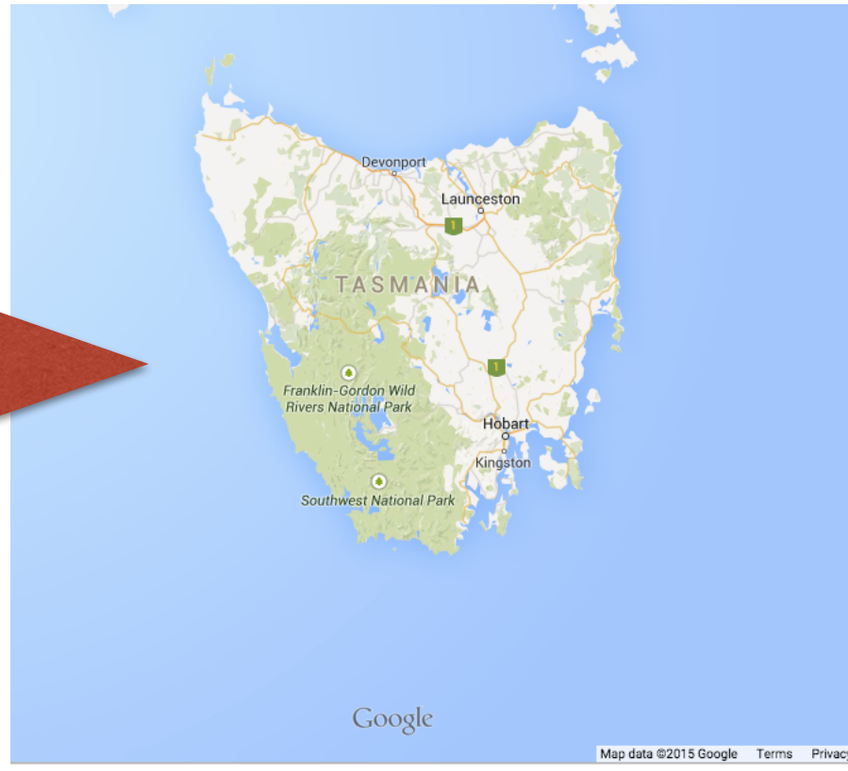


Image: Christian Miki, University of Hawaii

How did we get the data back?



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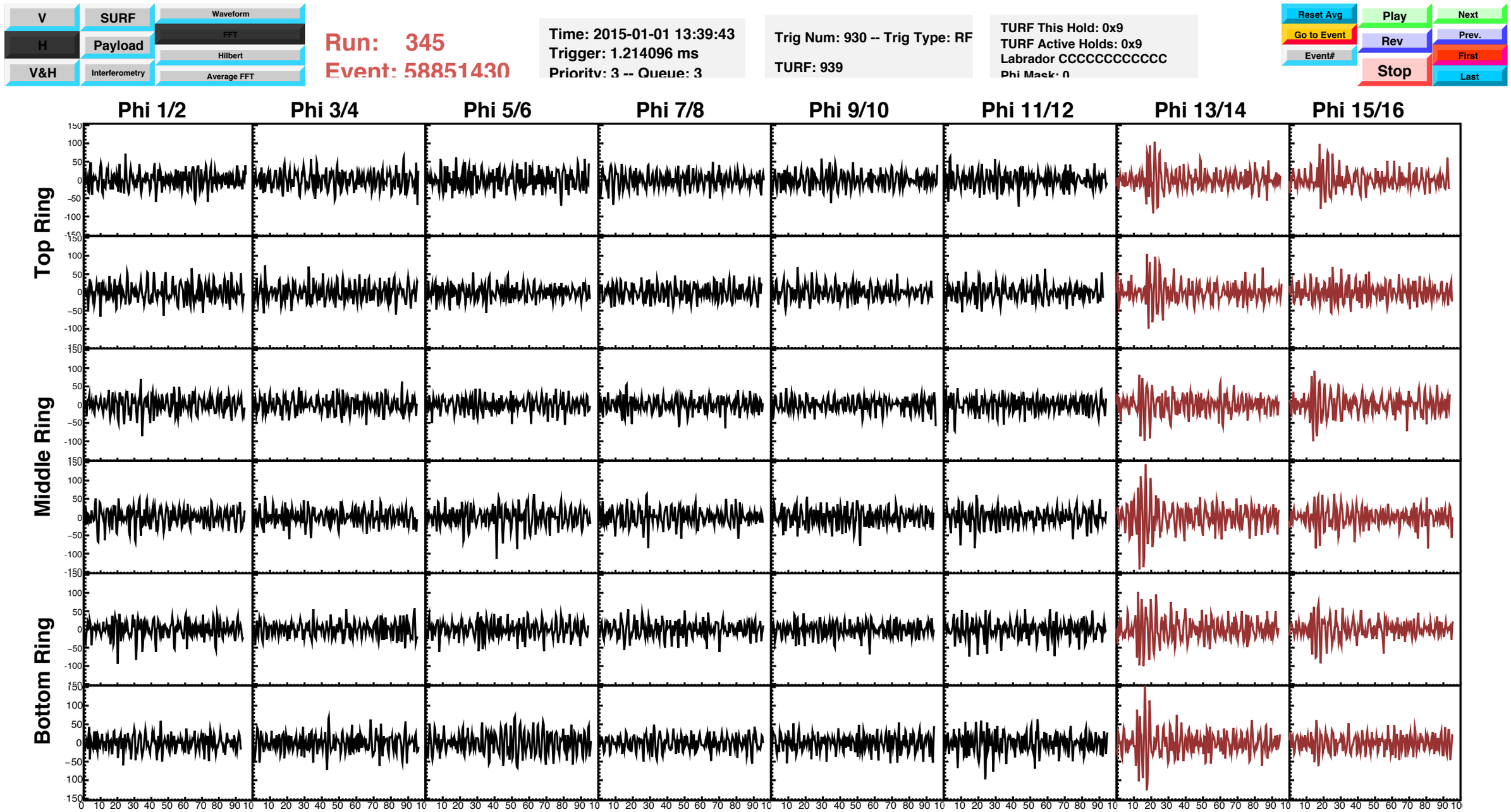
ANITA Analysis

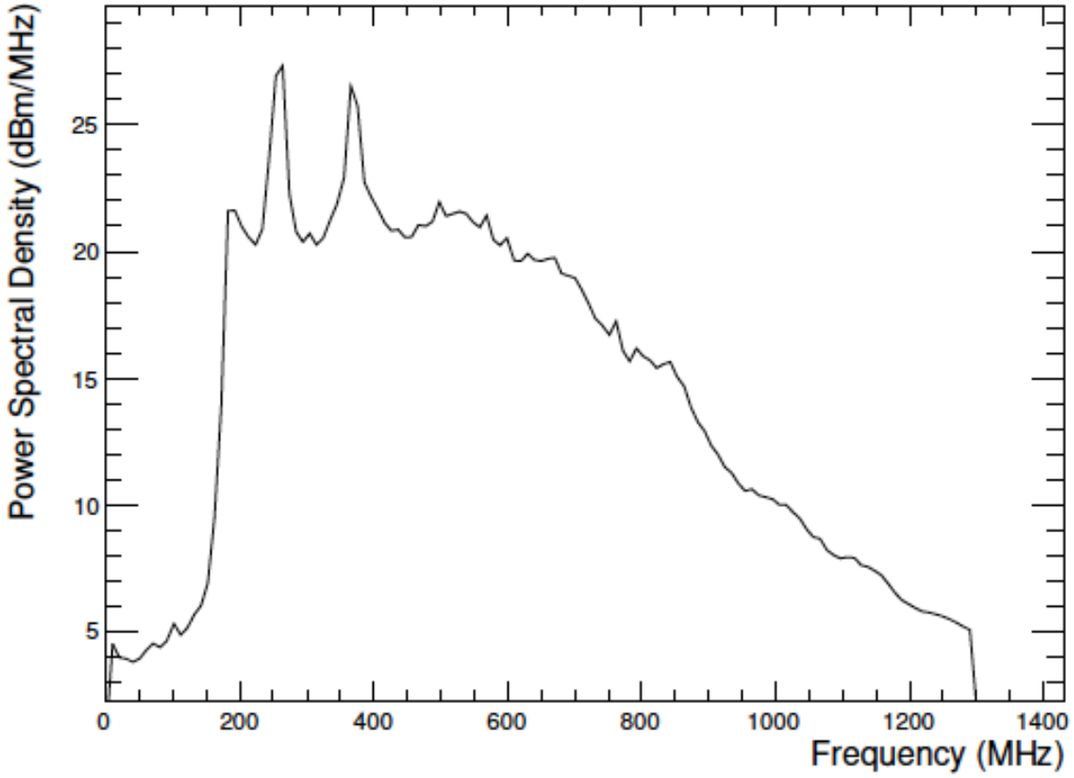
Image: Dana Braun, Wash. U.

How ANITA sees the world

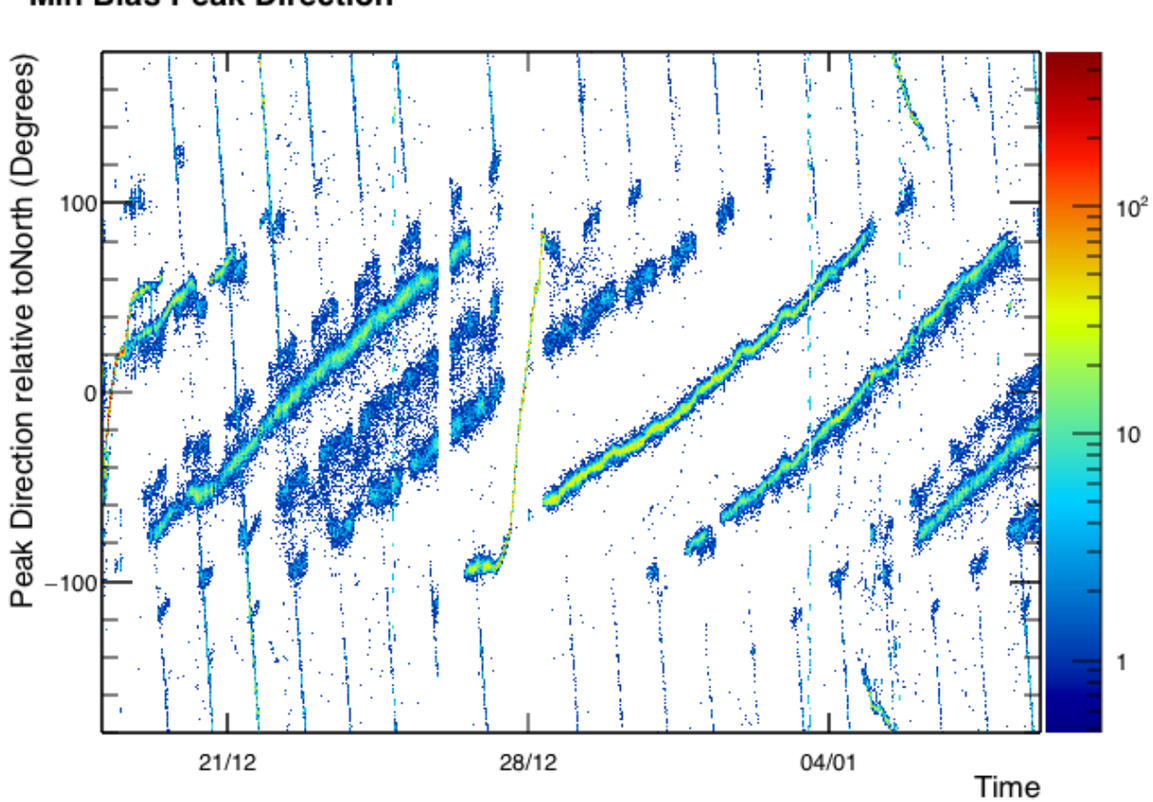


Narrow band noise

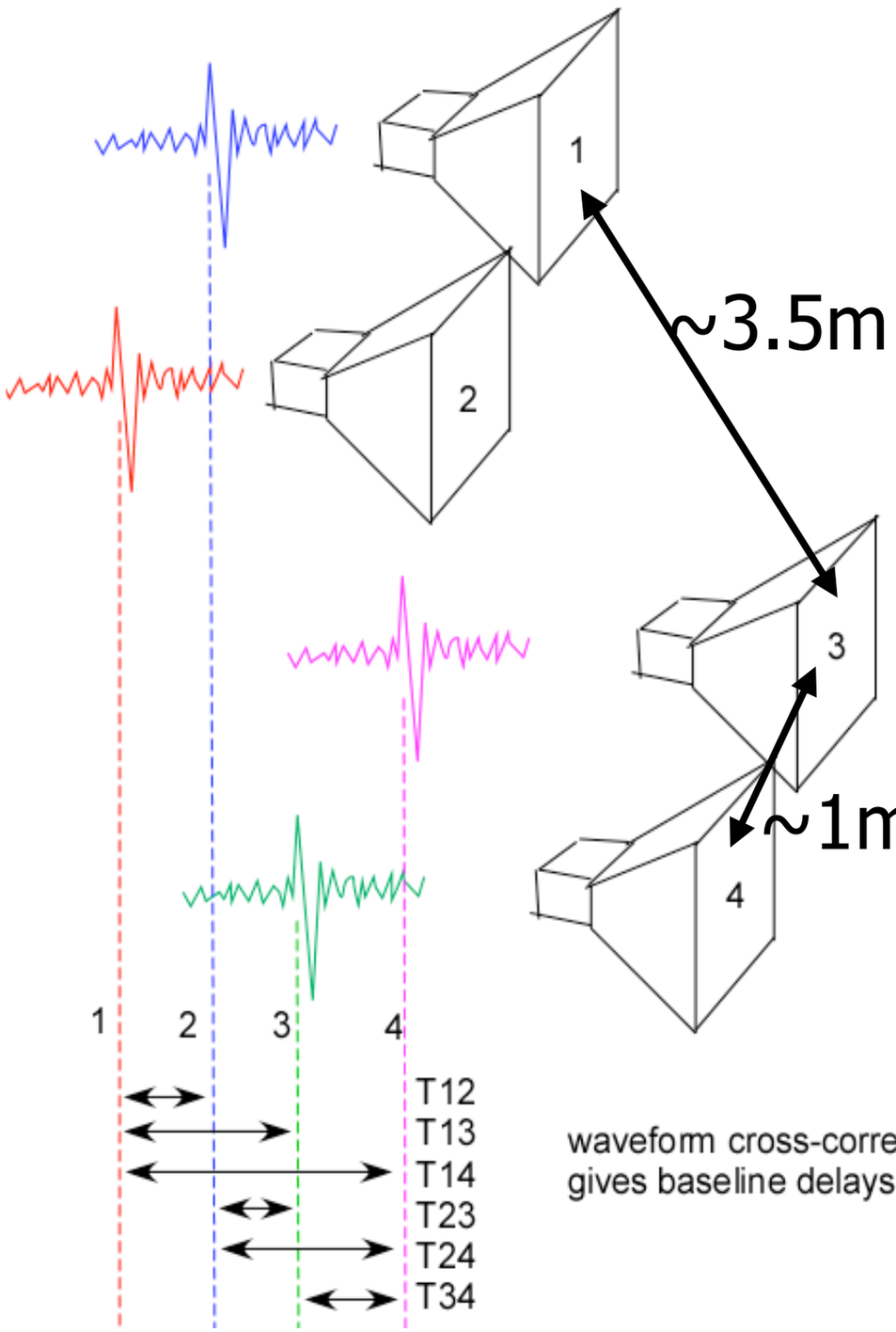
- Satellites and human bases using communications in the bands:
  - 260 MHz
  - 380 MHz



- How to get rid of this?
  - ANITA 1-3: software
  - ANITA 4: hardware

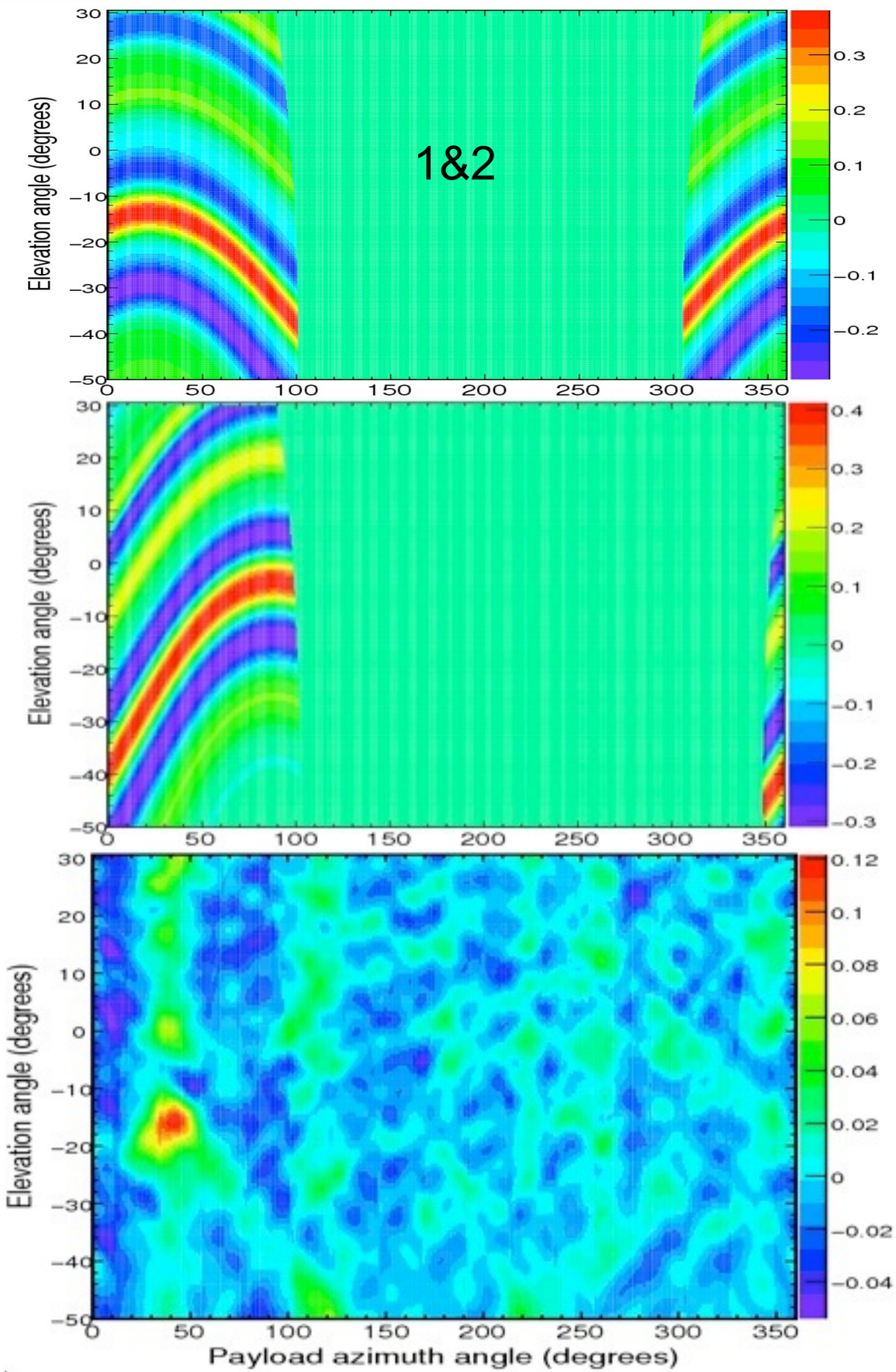


Analysis -- Cross Correlation

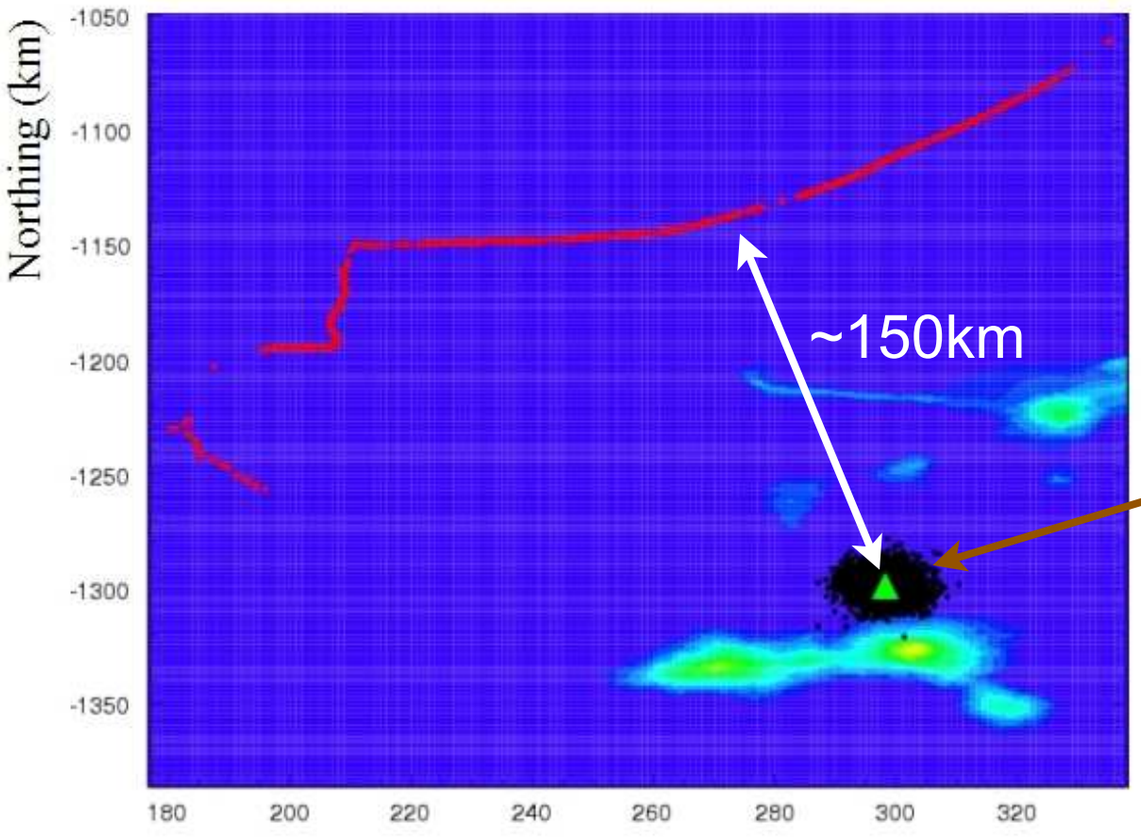


from A. Romero Wolf, Neutrino 2008

http://dx.doi.org/10.1016/j.astropartphys.2014.06.006



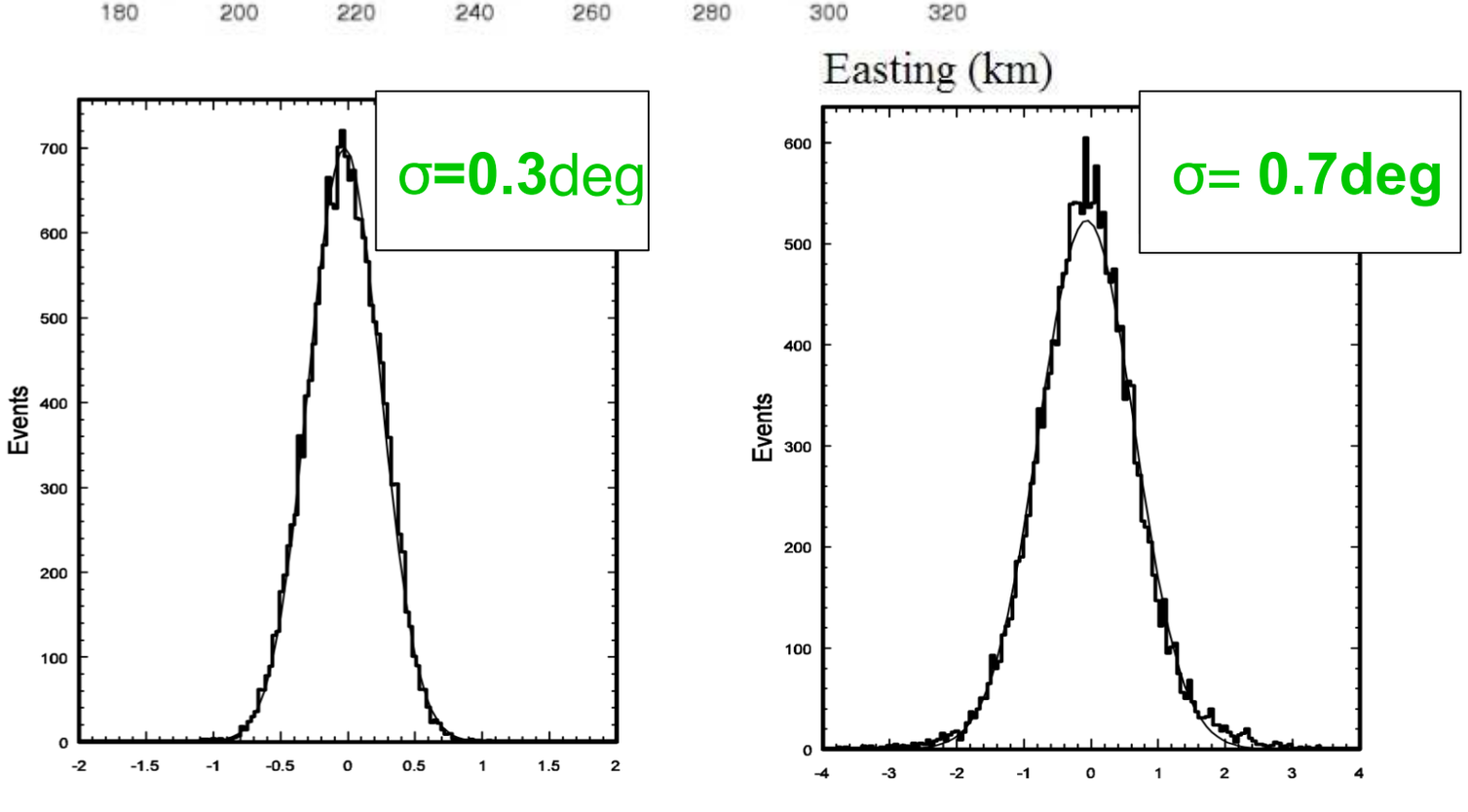
Calibration



Reconstructed event locations

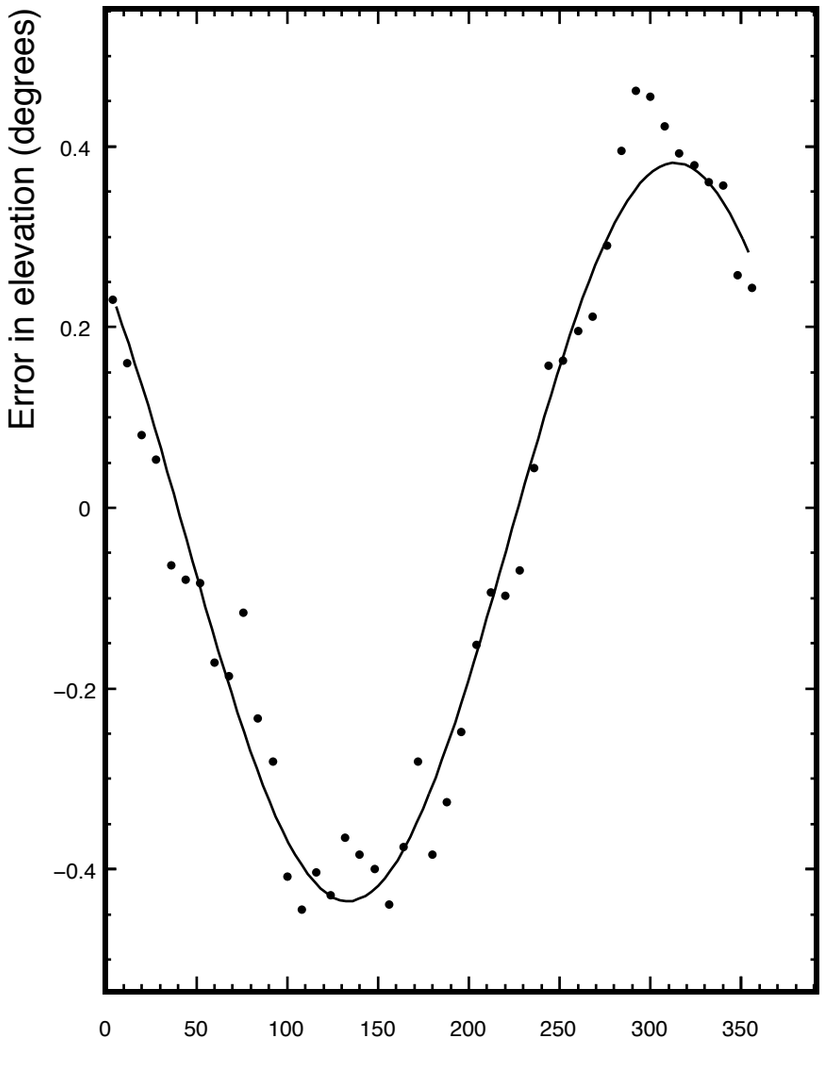
Use ground and borehole calibration pulsers to calibrate antenna positions and time offsets.

Also calibrate out the tilt of the payload



ELEVATION ANGLE

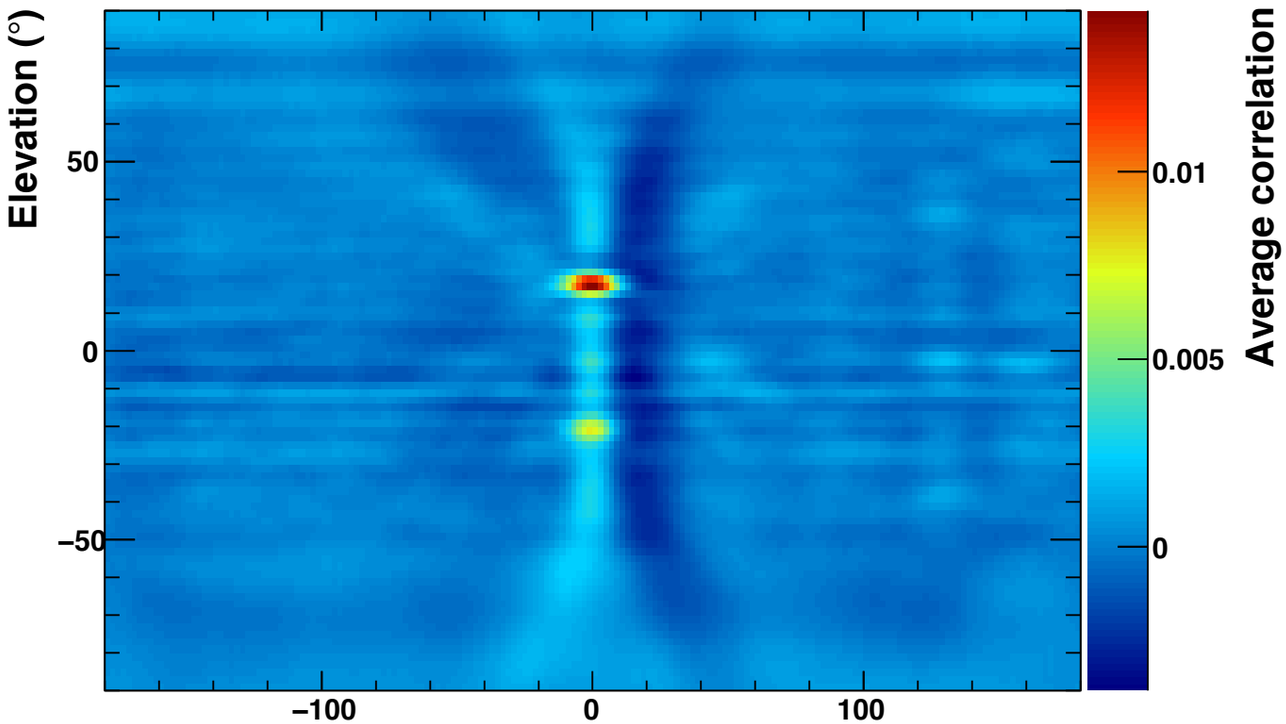
AZIMUTH ANGLE

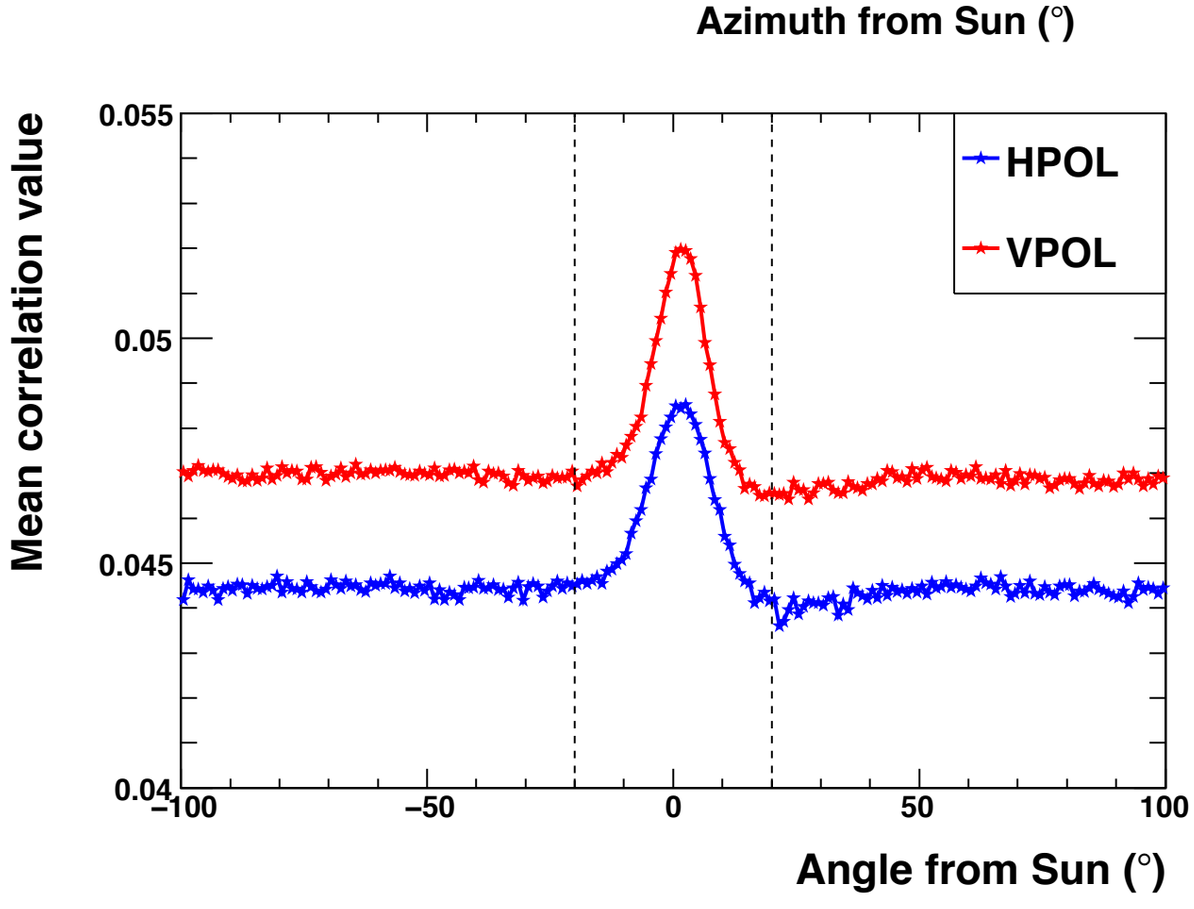


from S. Hoover

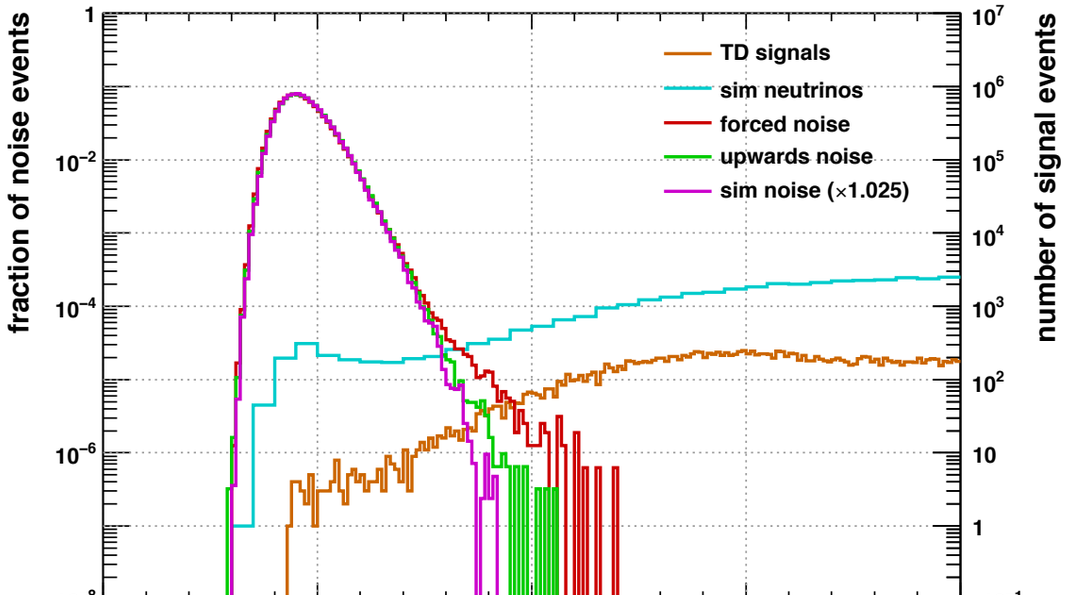
Thermal Noise

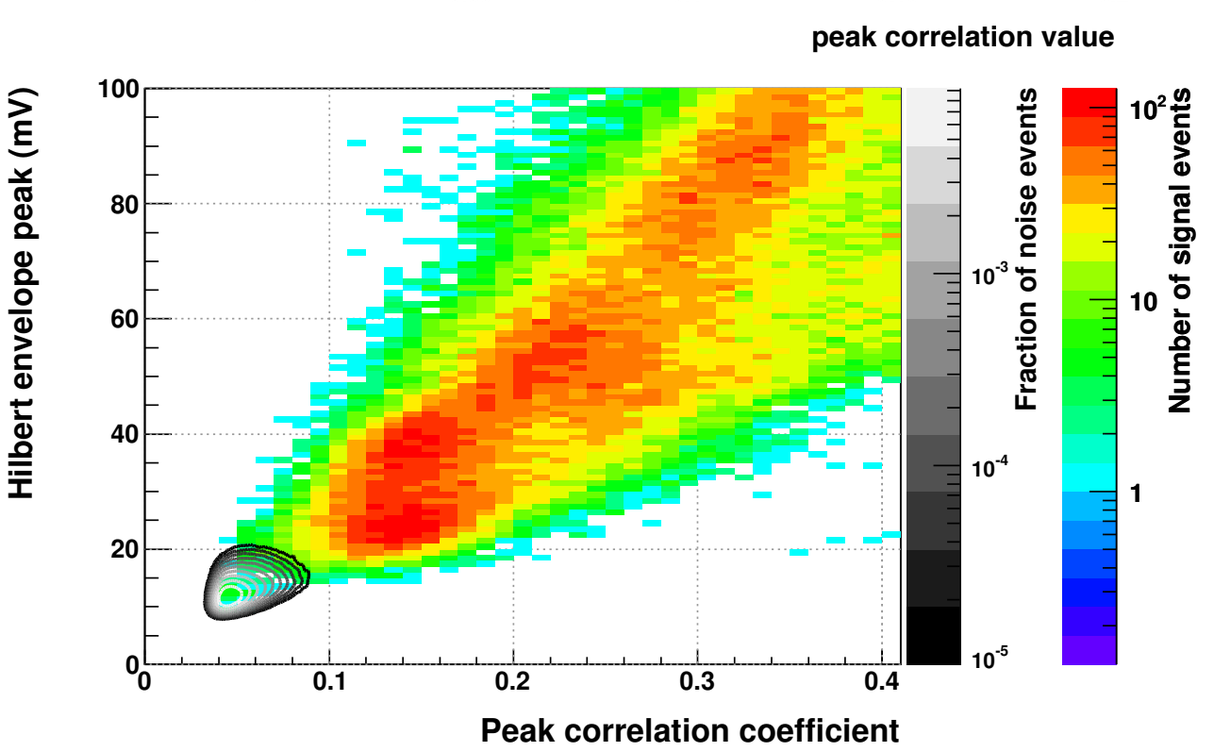
ANITA can “see” the Sun



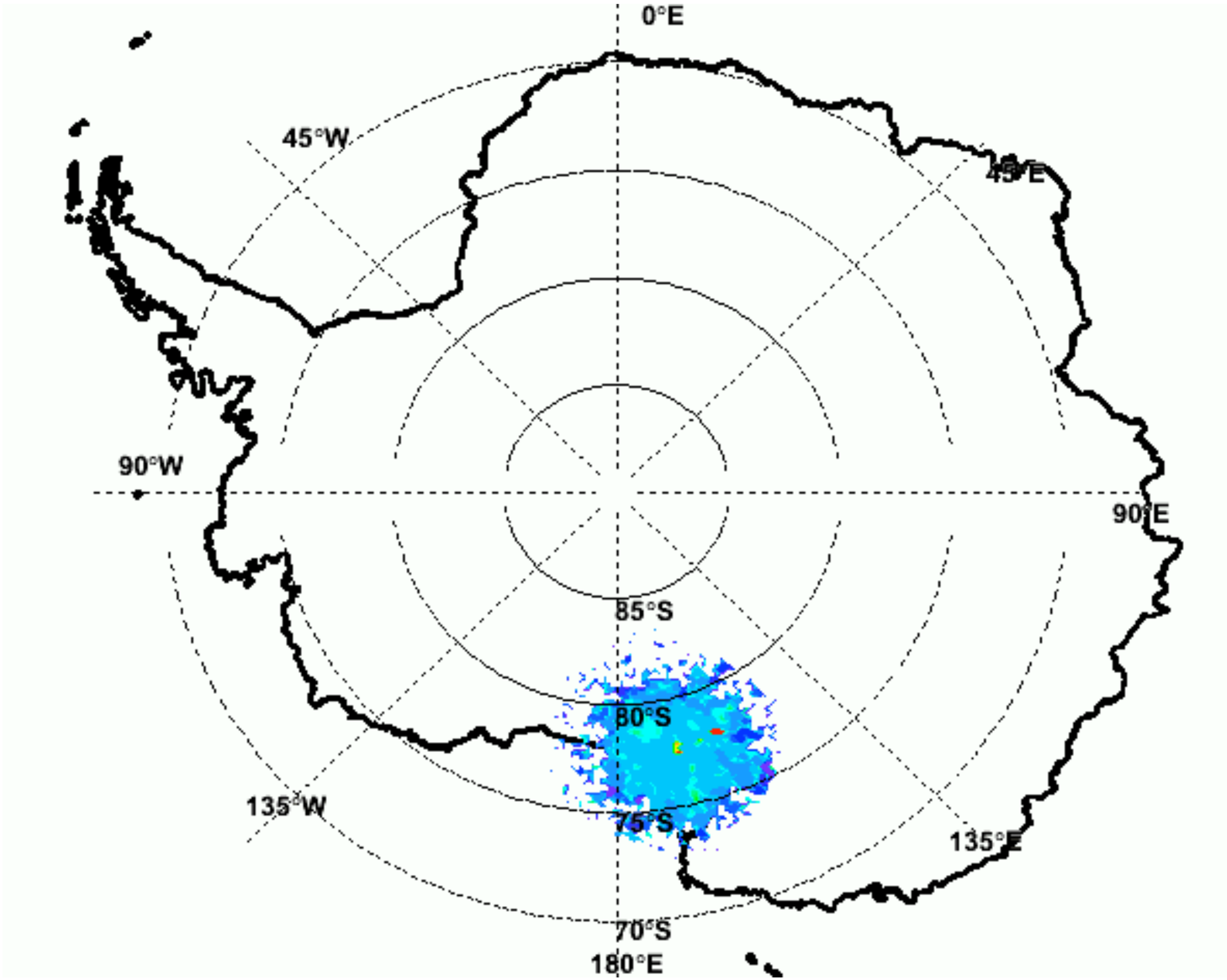


Thermal noise is the dominant source of noise in the data sets.



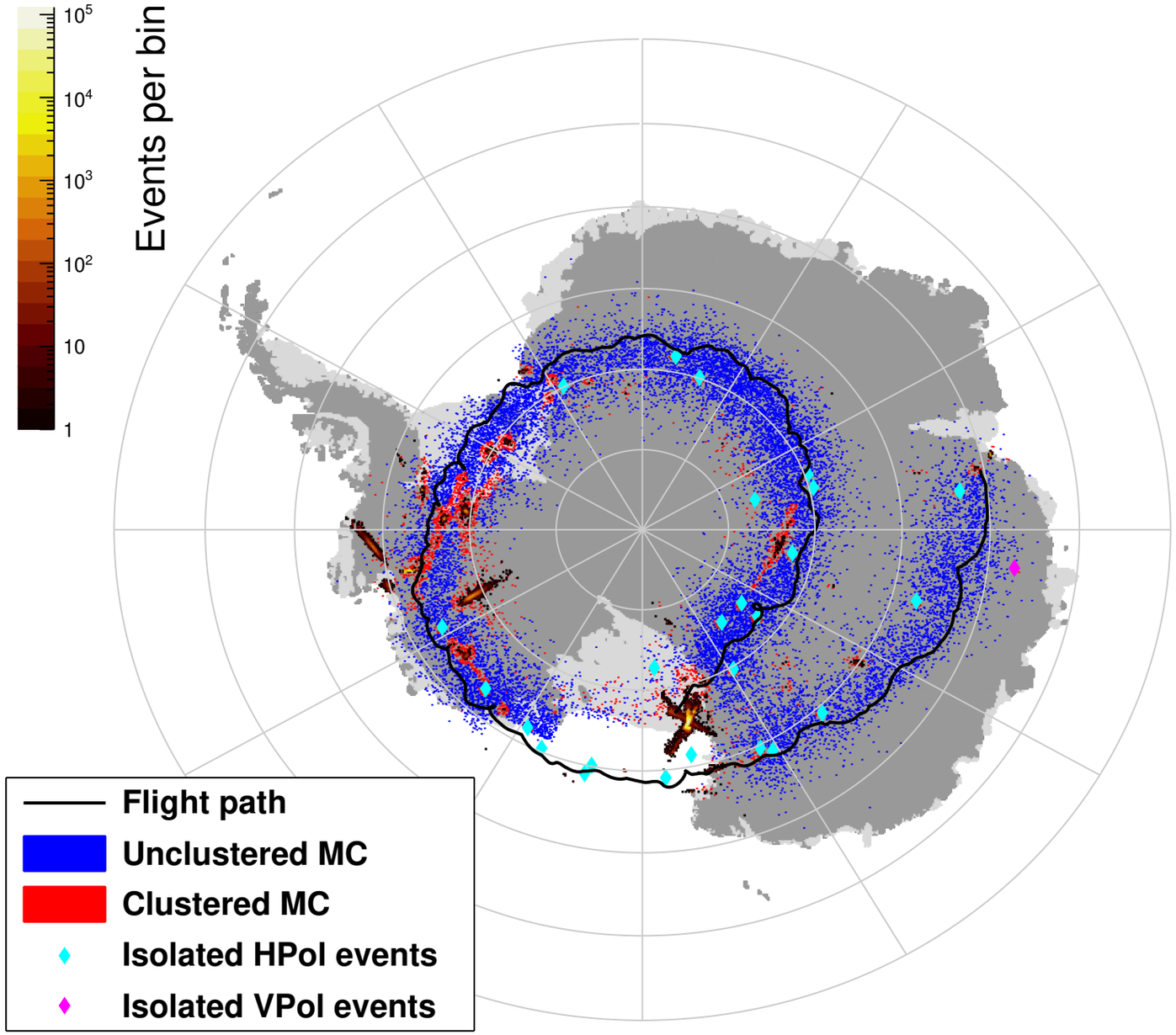


ANITA-2



Clustering

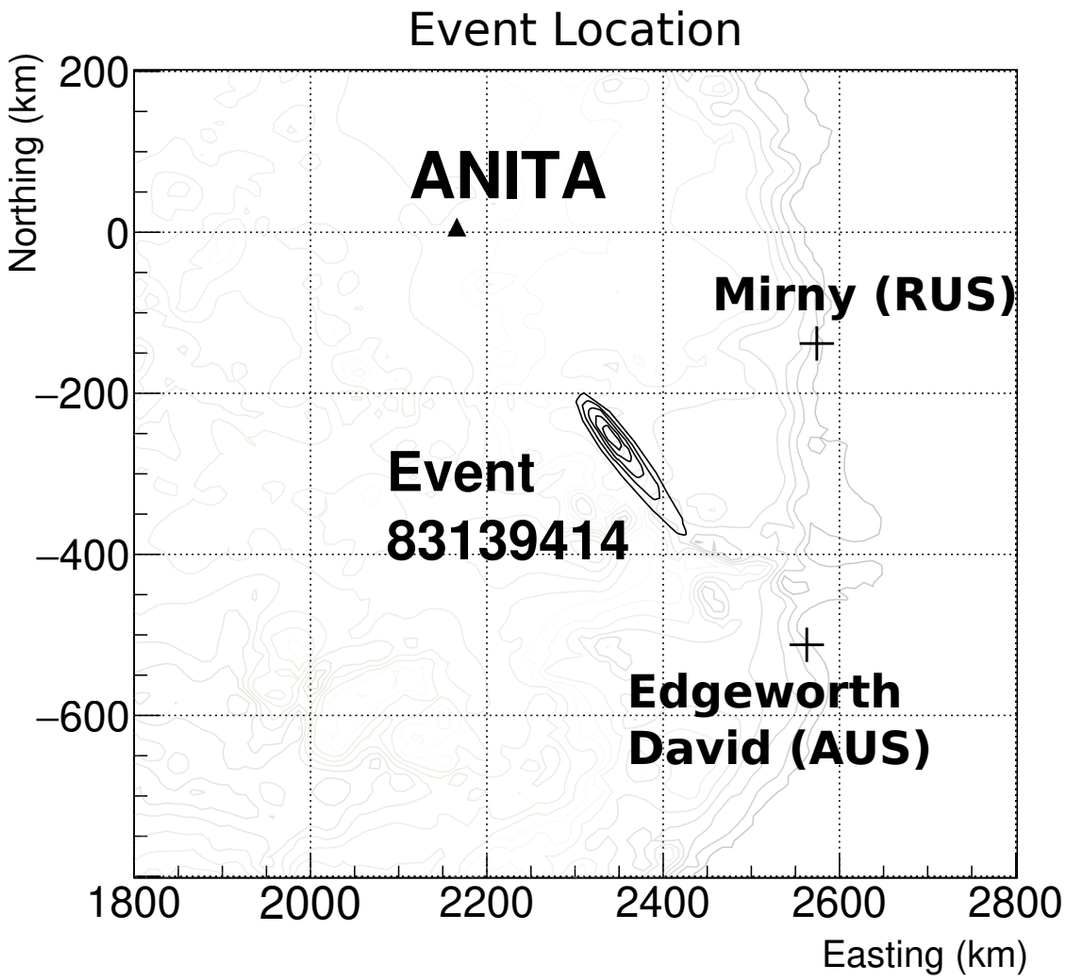
- From previous cuts, ~500k events

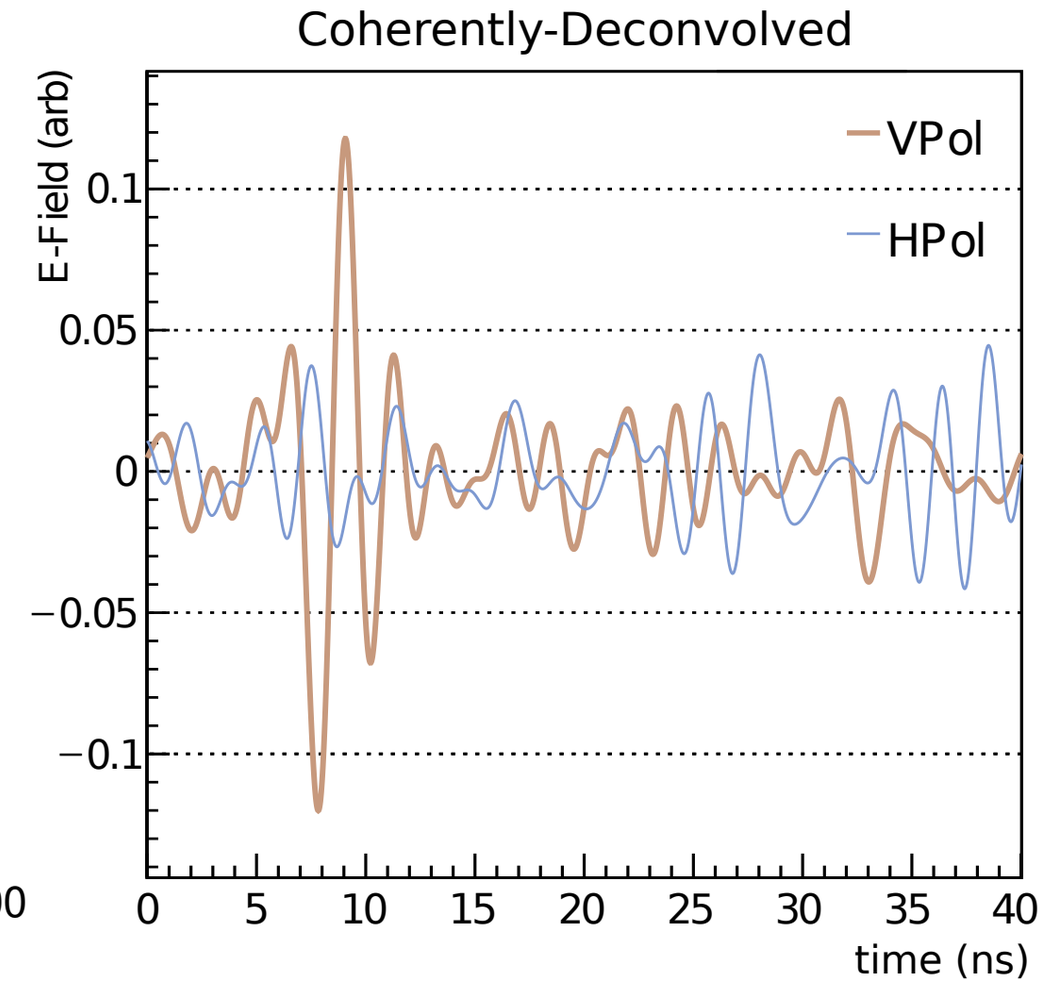


- Look for isolated singlets and doublets
- Remove anything that clusters with human bases
- Remove anything which forms a cluster of 3 or more

What's left?

- One V-POL candidate
- Background estimate: $0.7^{+0.5}_{-0.3}$ per polarisation
- No known human activity within 260km

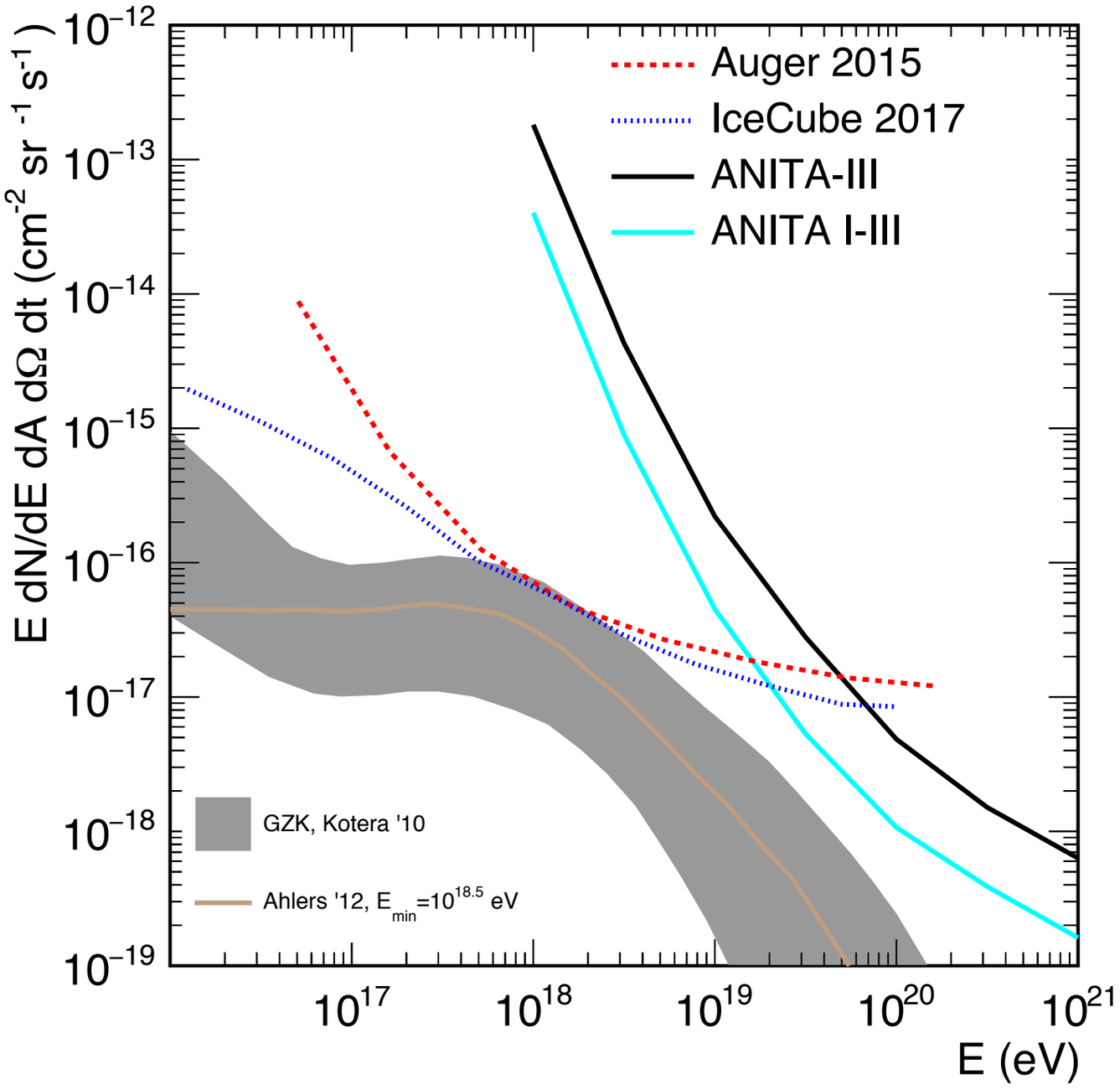




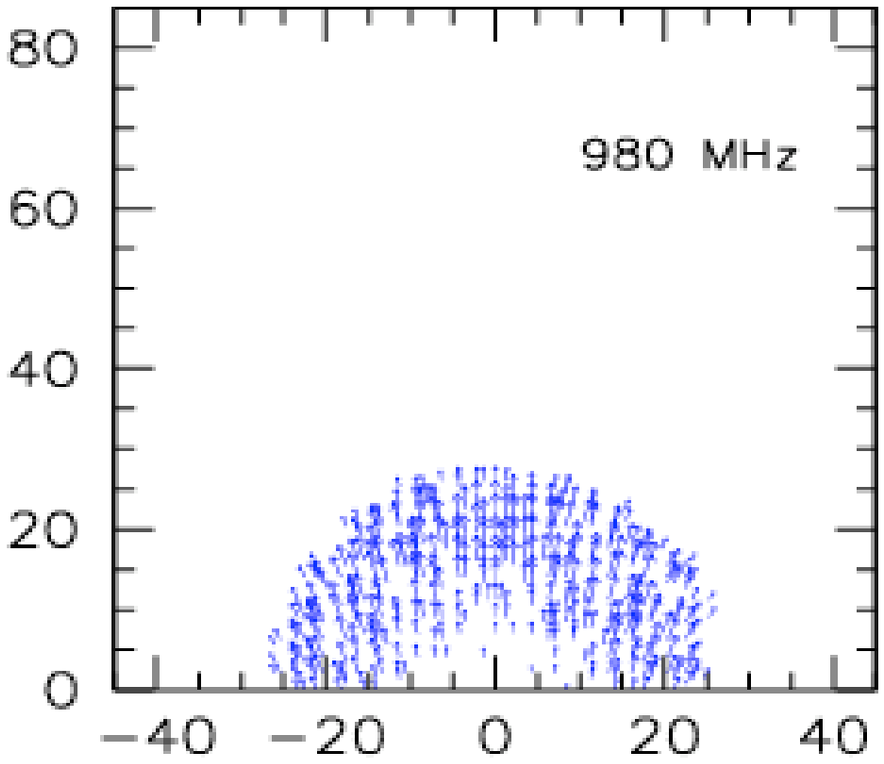
Neutrino limit

- From previous cuts, ~100k events

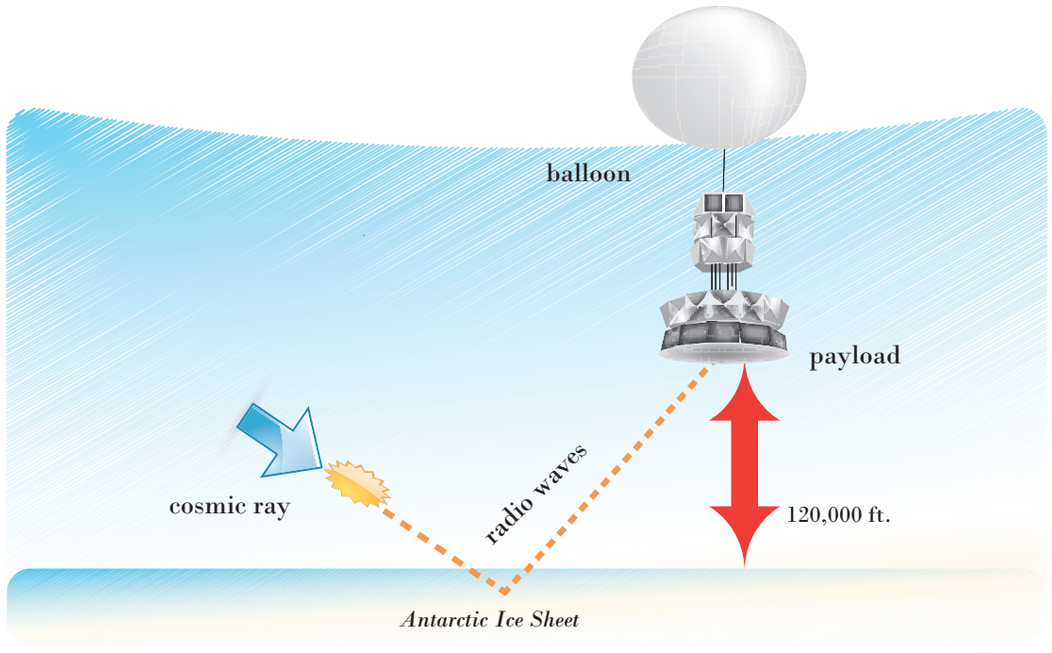
Limit on all-flavour-sum diffuse UHE neutrino flux



What about Horizontal Polarisation?



- Askaryan signals from neutrinos 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
- What could the signal be?



No. 4969 January 23, 1965 NATURE

RADIO PULSES FROM EXTENSIVE COSMIC-RAY AIR SHOWERS

By Dr. J. V. JELLEY and J. H. FRUIN
Atomic Energy Research Establishment, Harwell

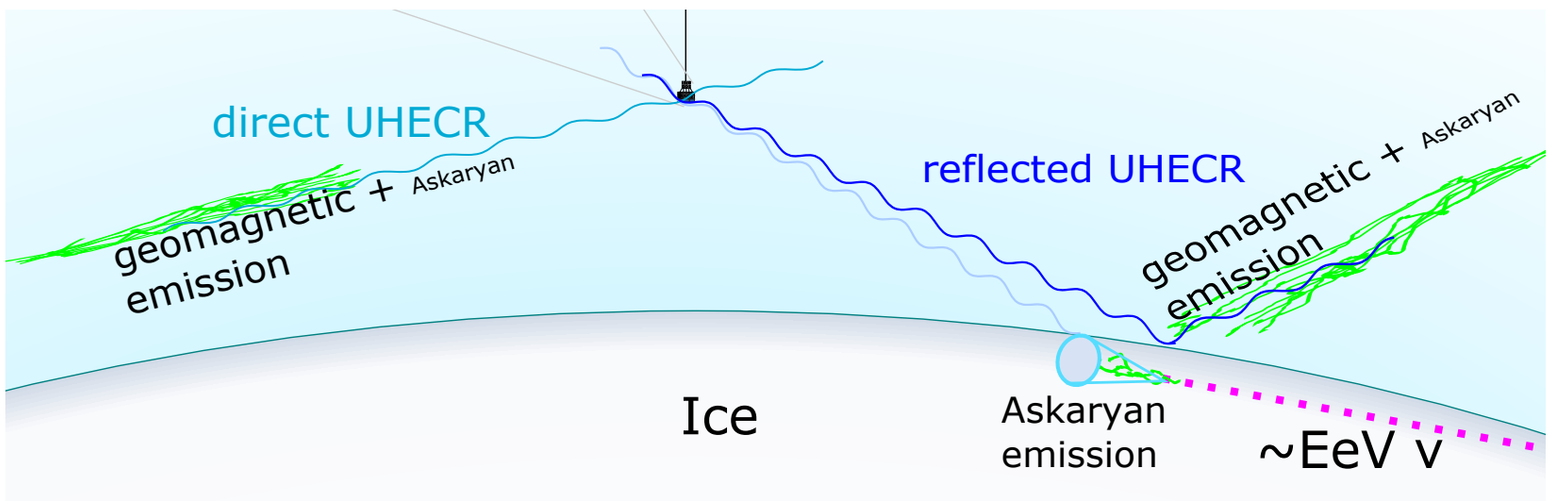
Prof. N. A. PORTER and T. C. WEEKES
University College, Dublin

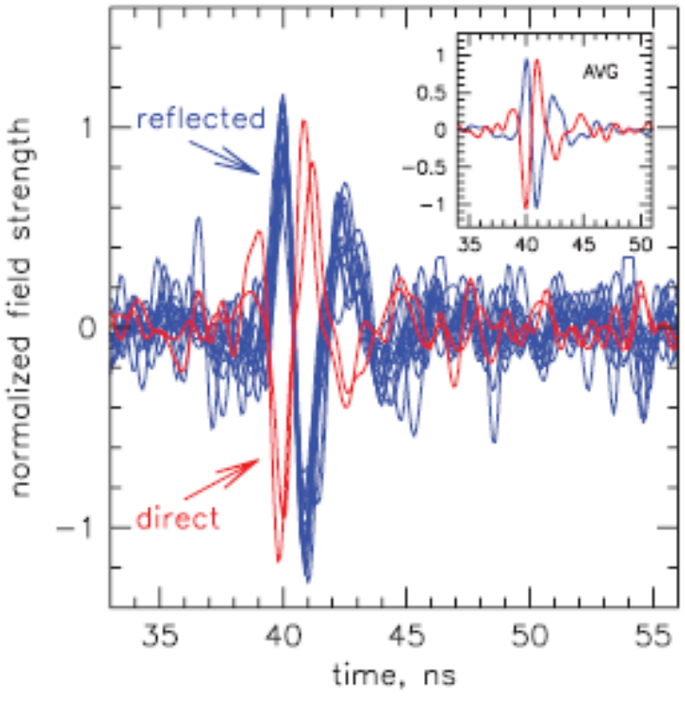
AND

Prof. F. G. SMITH and R. A. PORTER
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank

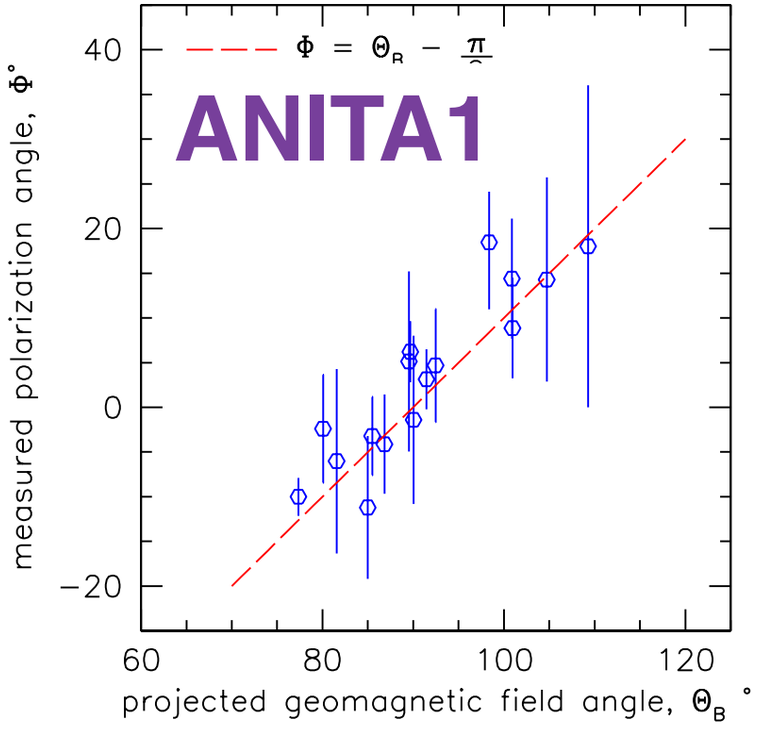
UHECR

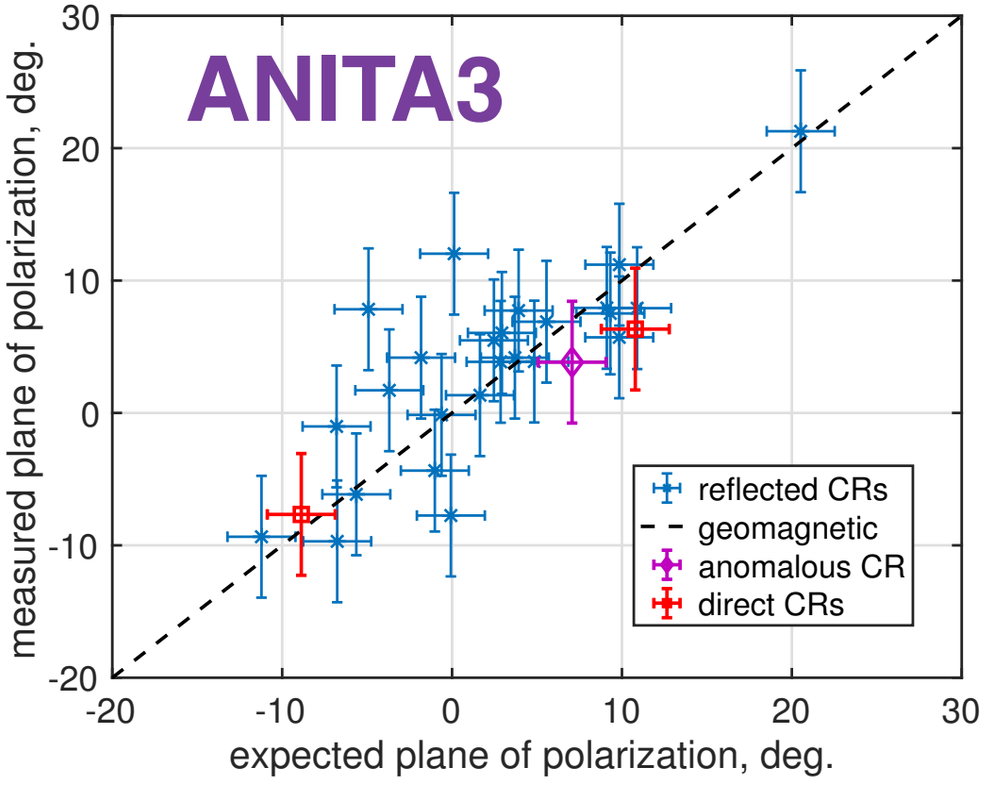
ANITA1: 16 UHECR
 14 reflected + 2 direct
ANITA-2: 2 UHECR
 H-pol trigger was off
ANITA-3: 20 UHECR
ANITA-4: analysis in progress





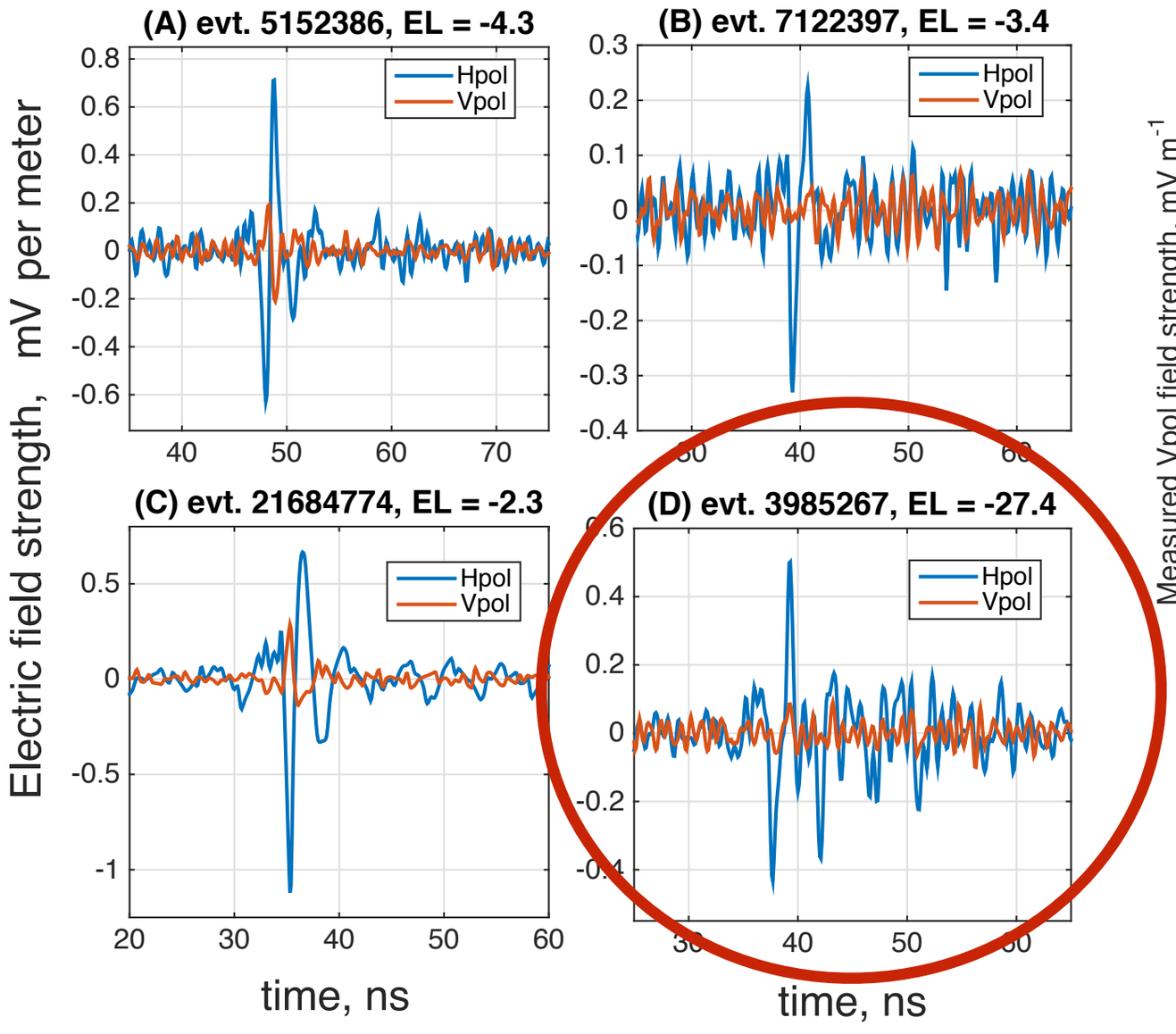
PRL 105, 151101 (2010)

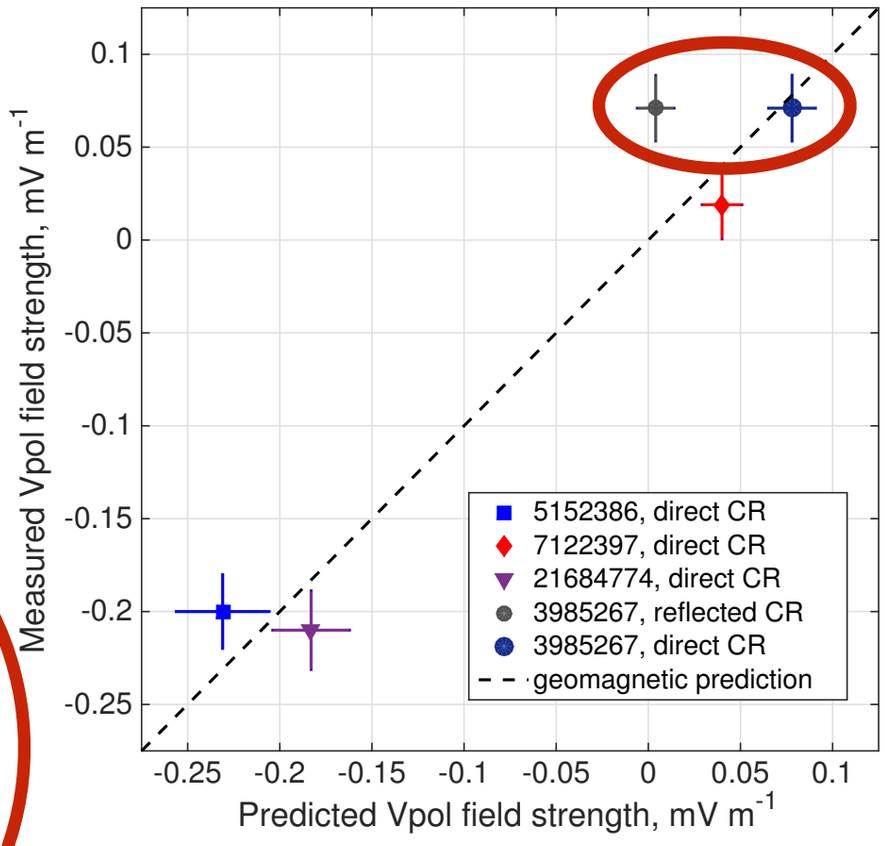




arXiv:1803.05088 [astro-ph.HE]

ANITA-1 mystery event



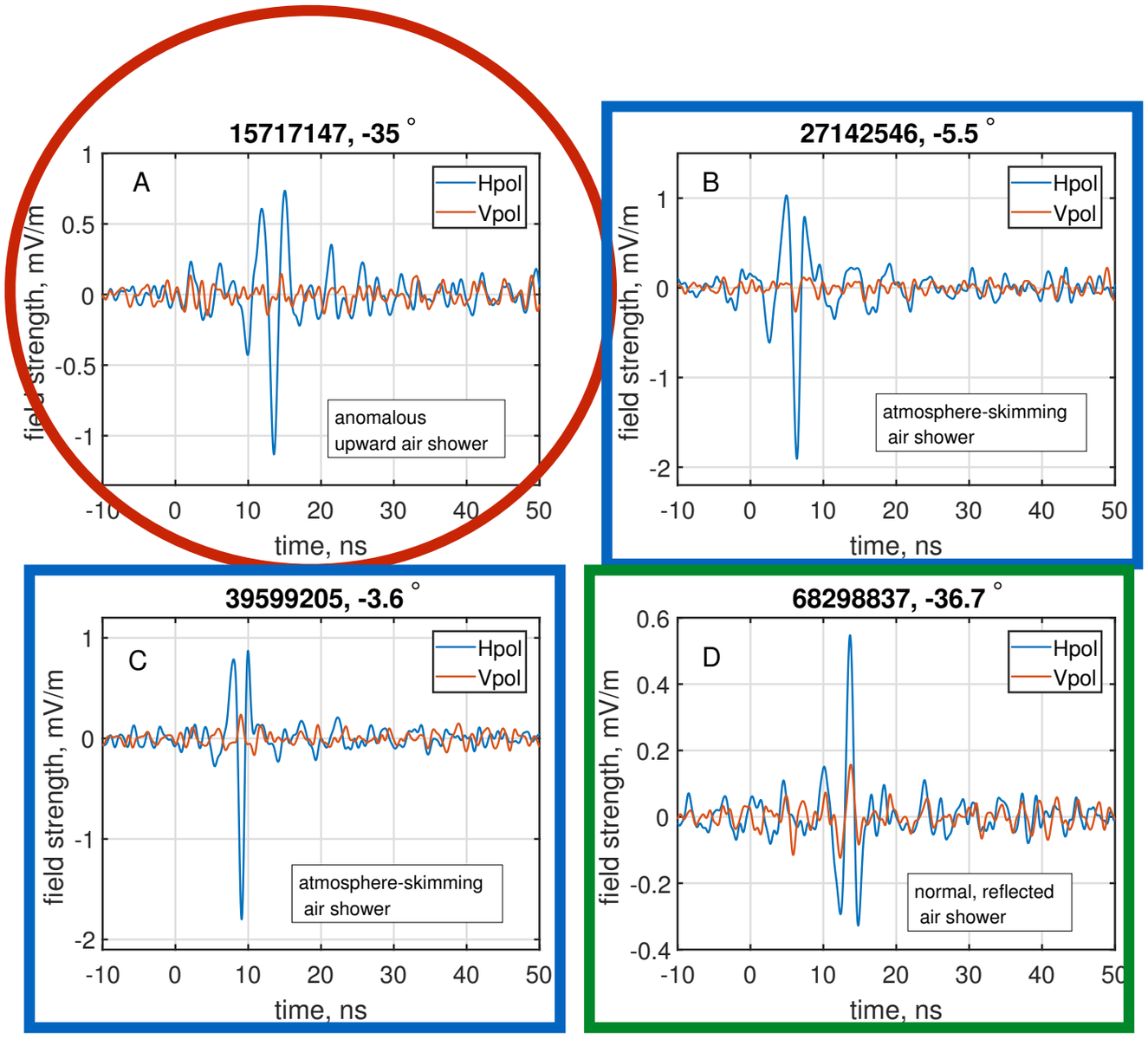


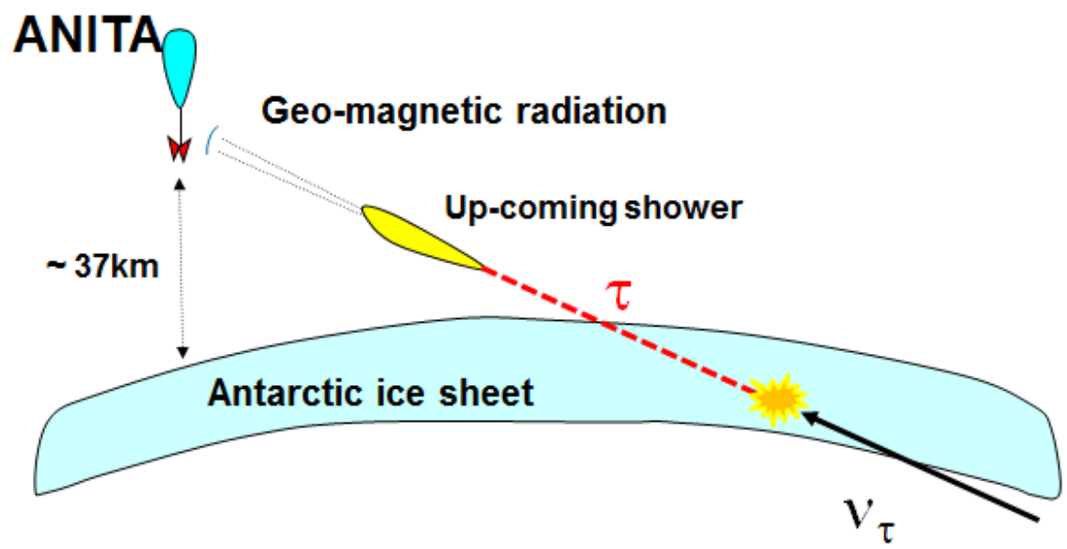
A strong H-pol non-inverted signal seen!

- Expected background events: 4×10^{-4}
- 27.4 deg below horizon, E = 0.6 ± 0.4 EeV

Phys. Rev. Lett. 117, 071101 (2016)

And ANITA-3 mystery event





Direct Cosmic Rays

Reflected Cosmic Rays

NEW PHYSICS ?

Chord length: 5500-7000 km (20-30,000km water equivalent)
1600km SM interaction length @ 1 EeV

Background estimate < 10^{-2}

arXiv:1803.05088 [astro-ph.HE]

All news is good news?

- Diffuse neutrinos:

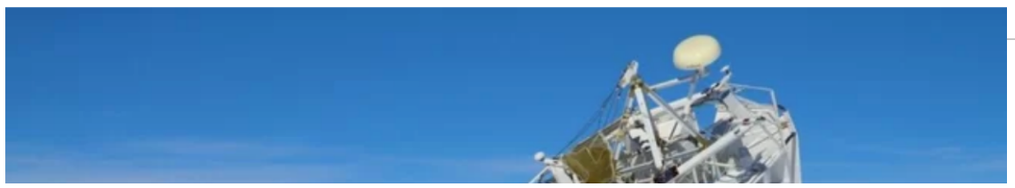
LIVESCIENCE

NEWS TECH HEALTH PLANET EAR

Live Science > Space

Bizarre Particles Keep Flying Out of Antarctica's Ice, and They Might Shatter Modern Physics

By Rafi Letzter, Staff Writer | September 26, 2018 08:16pm ET



IFLSCIENCE!

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Scientists Confirm The Electron Is Truly Round, And It's A Big Deal.

PHYSICS
Dandelion Seeds Reveal A New Form Of Aerodynamics

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An Astonishing Discovery Might Have Just Broken Particle Physics

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Moveable Hacking Environment Space Gaming Health Tech Science

COSMIC MYSTERIES | By Daniel Oberhaus | Sep 28 2018, 6:40pm

Mysterious Cosmic Rays Shooting from the Ground in Antarctica Could Break Physics

NASA went searching for micro black holes in Antarctica. Instead, it detected cosmic rays shooting from the ground and some physicists think it could be evidence of a supersymmetric particle.

DAILY NEWS 28 September 2018

Weird signals in Antarctica could be hints of a new realm of physics

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BY CAROLYN GRAMLING OCTOBER 22, 2018

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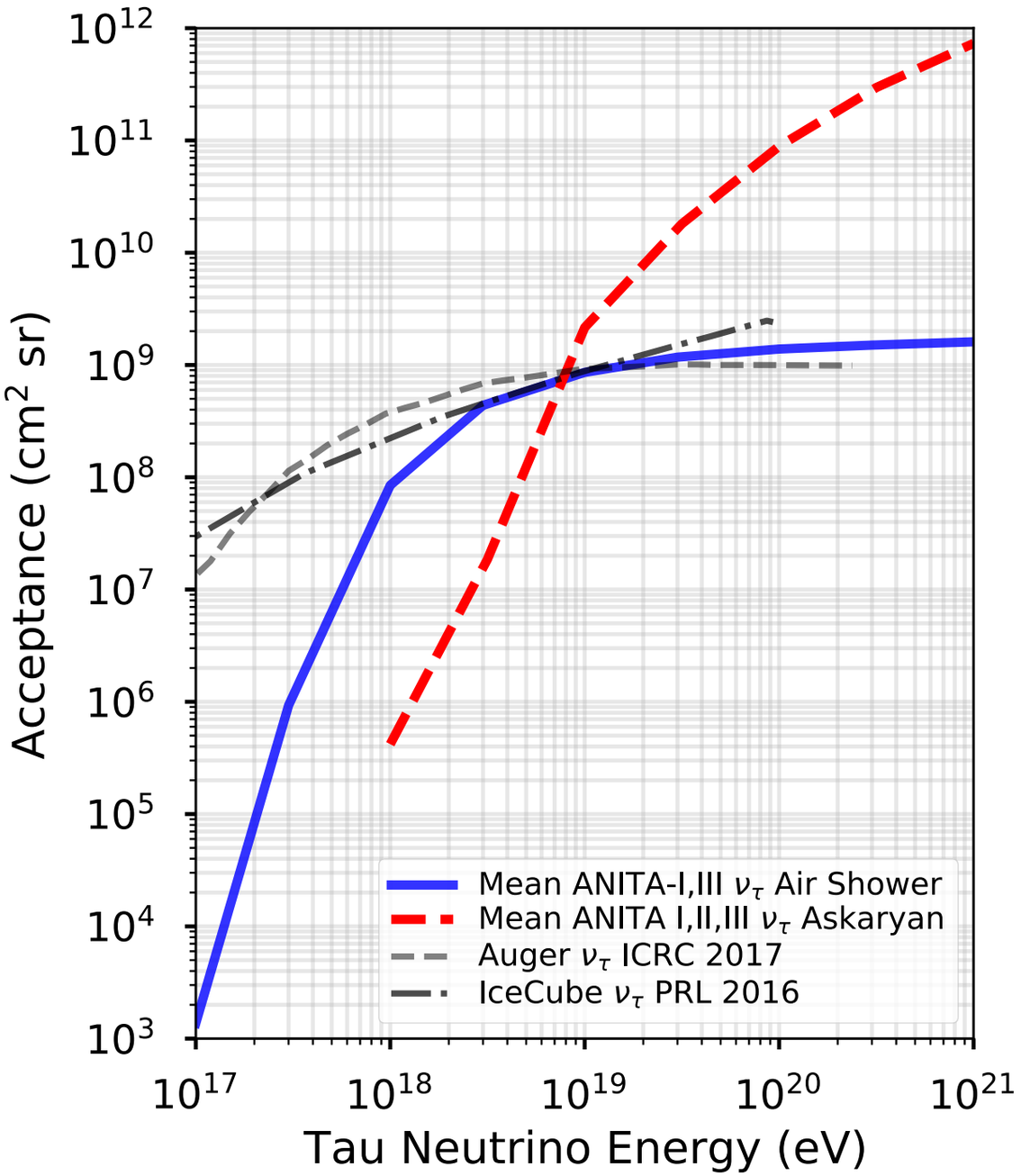
BY AMANDA B. KEENER OCTOBER 22, 2018

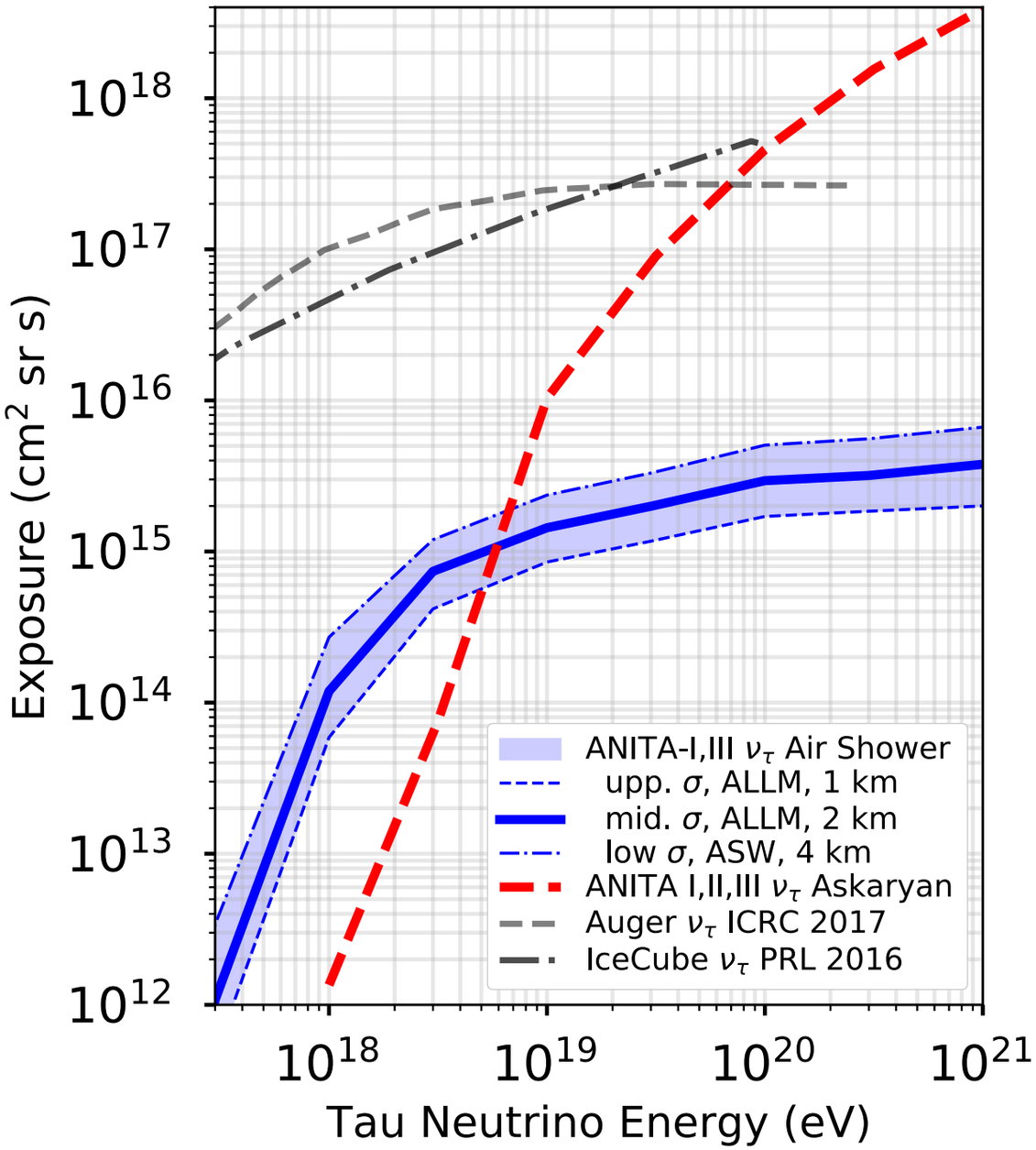
NEWS PARTICLE PHYSICS

Hints of weird particles from space may defy physicists' standard model

Problem 1: ANITA vs IceCube vs Auger

- If these are tau neutrinos why hasn't IceCube seen them?

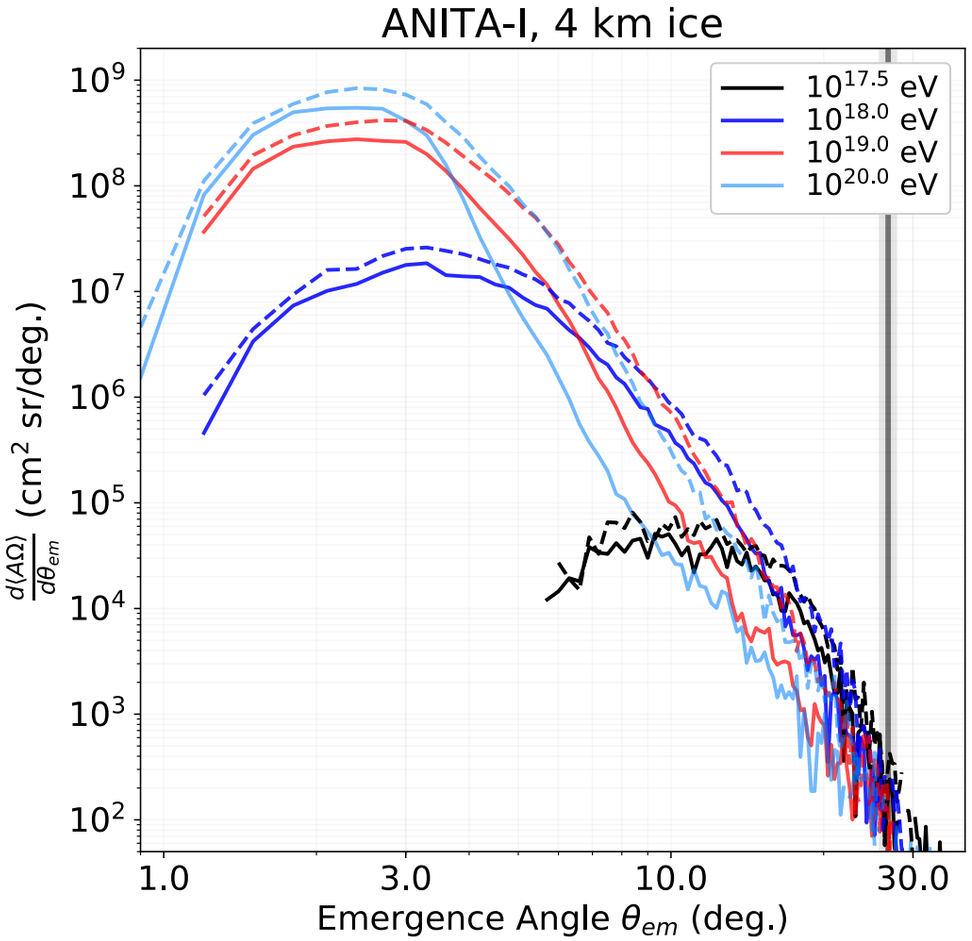


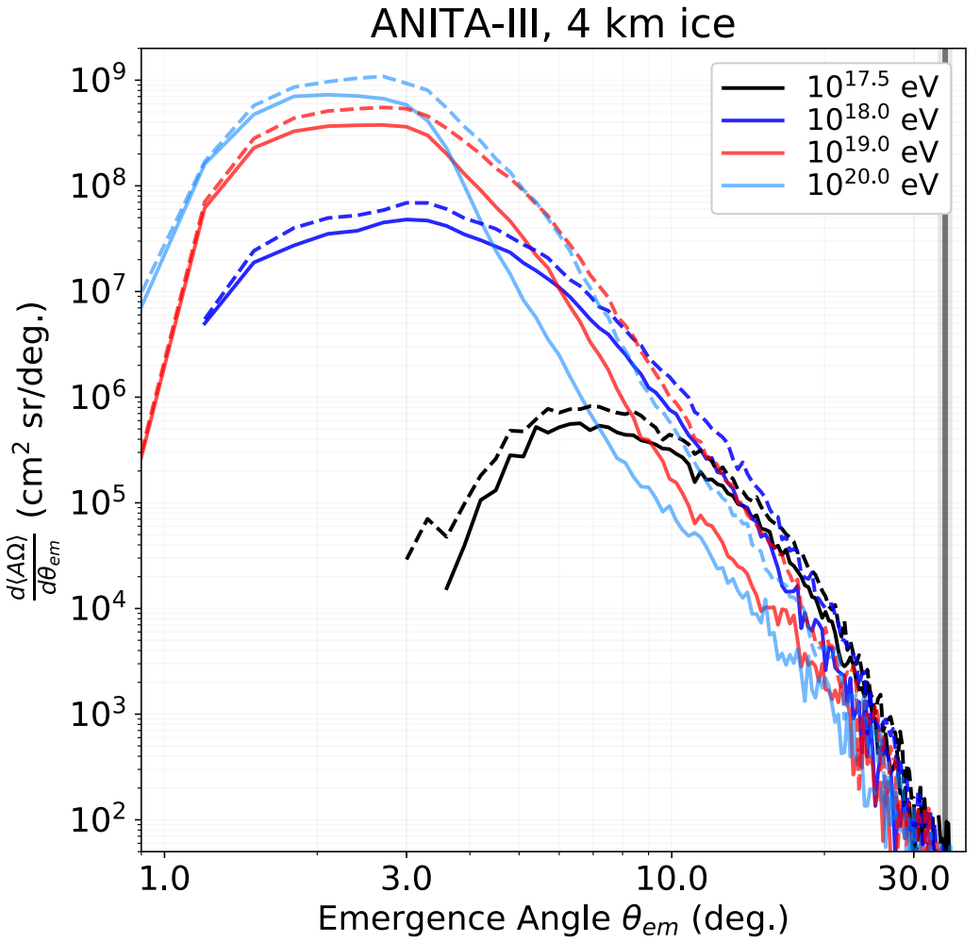


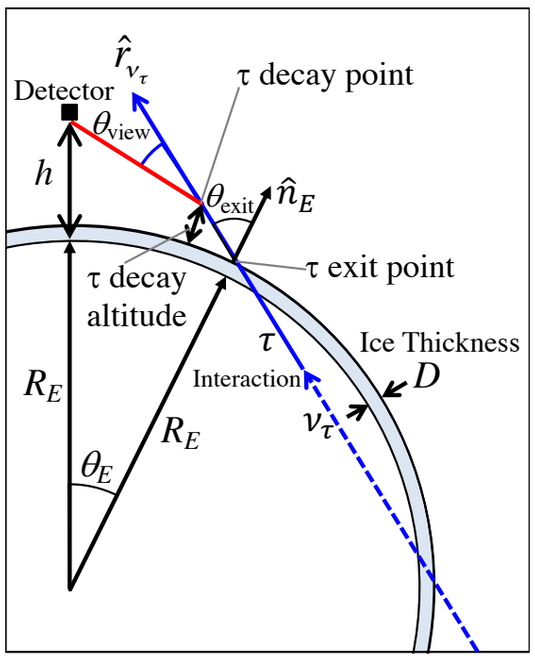
arXiv:1803.05088v1 [astro-ph.HE]

Problem 2: Why didn't ANITA see more?

- Both the ANITA-1 and ANITA-3 events were relatively close to the balloon
- There is much more acceptance close to the horizon
- Where are those tau candidate events?





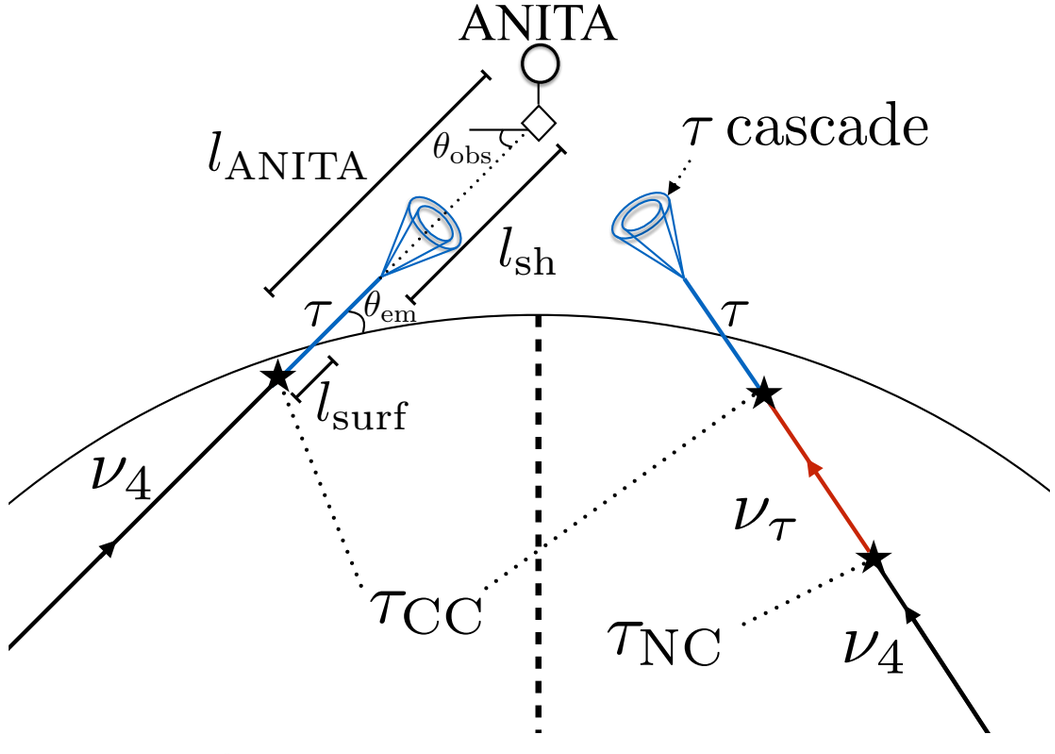


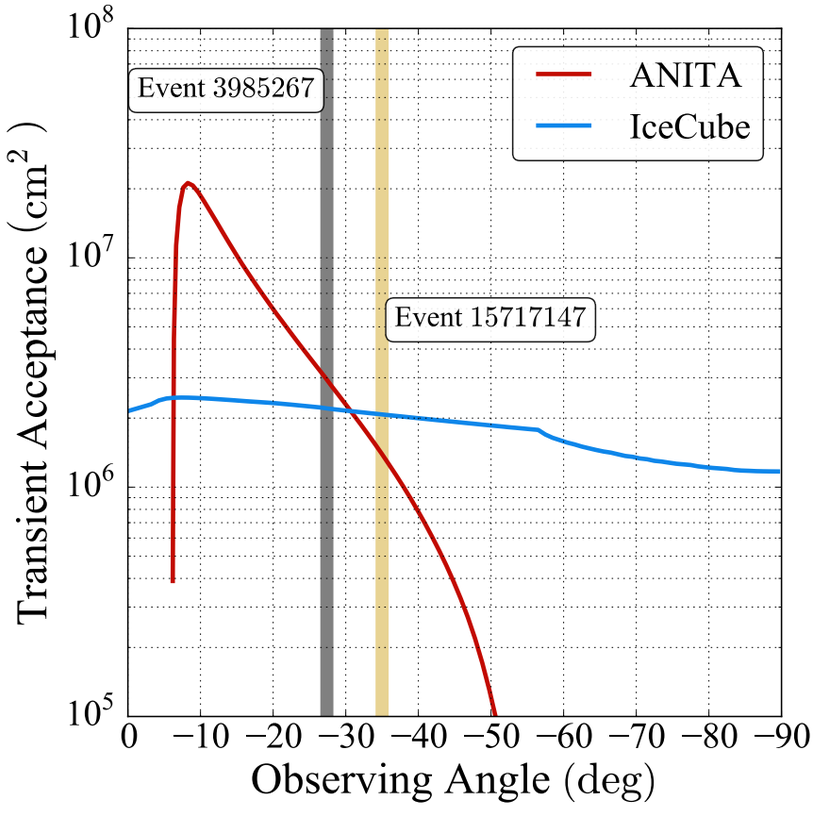
NB: Emergence angle is the complement of exit angle

arXiv:1803.05088v1 [astro-ph.HE]

Solution 1: Sterile Neutrinos?

- Cherry and Shoemaker proposed that the ANITA anomalous events could be explained through sterile neutrino mixing
- To avoid IceCube constraints the source needs to be transient
- To avoid an excess of events in ANITA you need a conspiracy that disfavours events close to the horizon (L/E near the Δm^2 for the active to sterile)

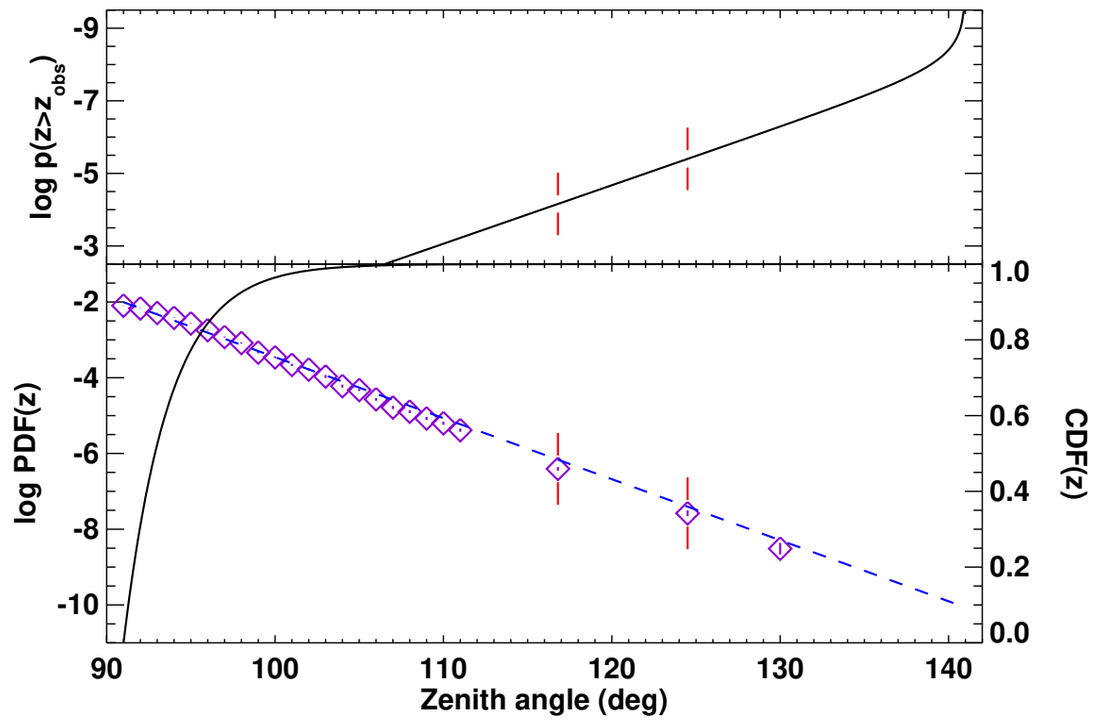




arXiv:1802.01611v2

Solution 2: Supersymmetry?

- Fox *et al* provide further evidence that it is hard to incorporate these anomalous events in the standard model.
  - Goldilocks scenario
    - Horizon disfavoured by long lived BSM particle
    - Upping disfavoured by energy loss / earth attenuation
- Collins *et al* also suggest a BSM particle explanation
  - "It would be remarkable if weak-scale supersymmetry was discovered in such an unexpected way!"



Fox *et al*

arXiv:1809.09615

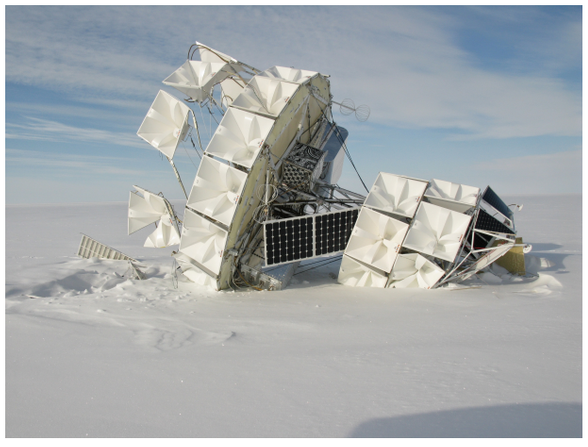
Collins *et al*

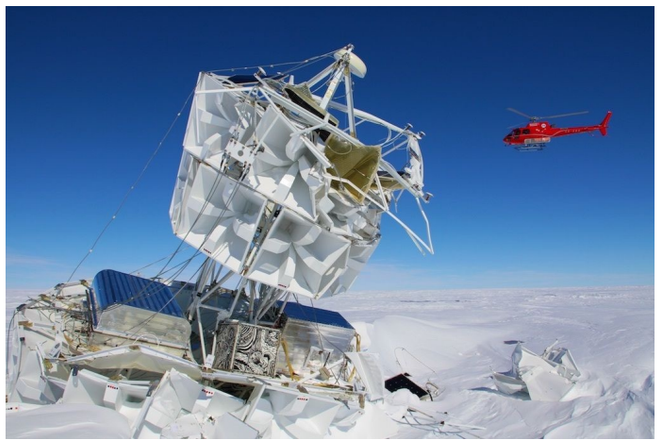
arXiv:1810.08479

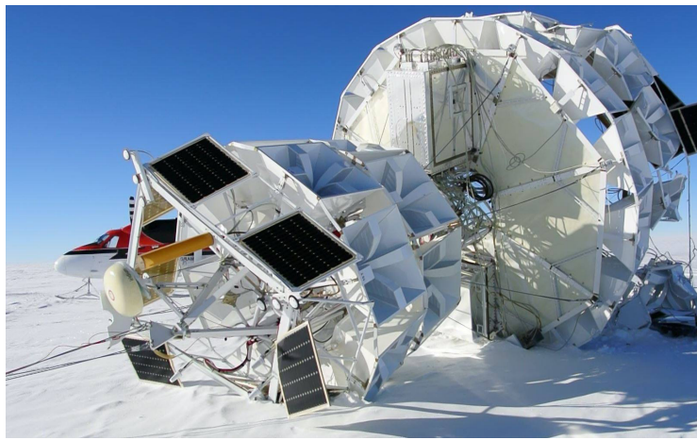
Future?

Image: Dana Braun, Wash. U.

ANITA 1-4: Progress and regress

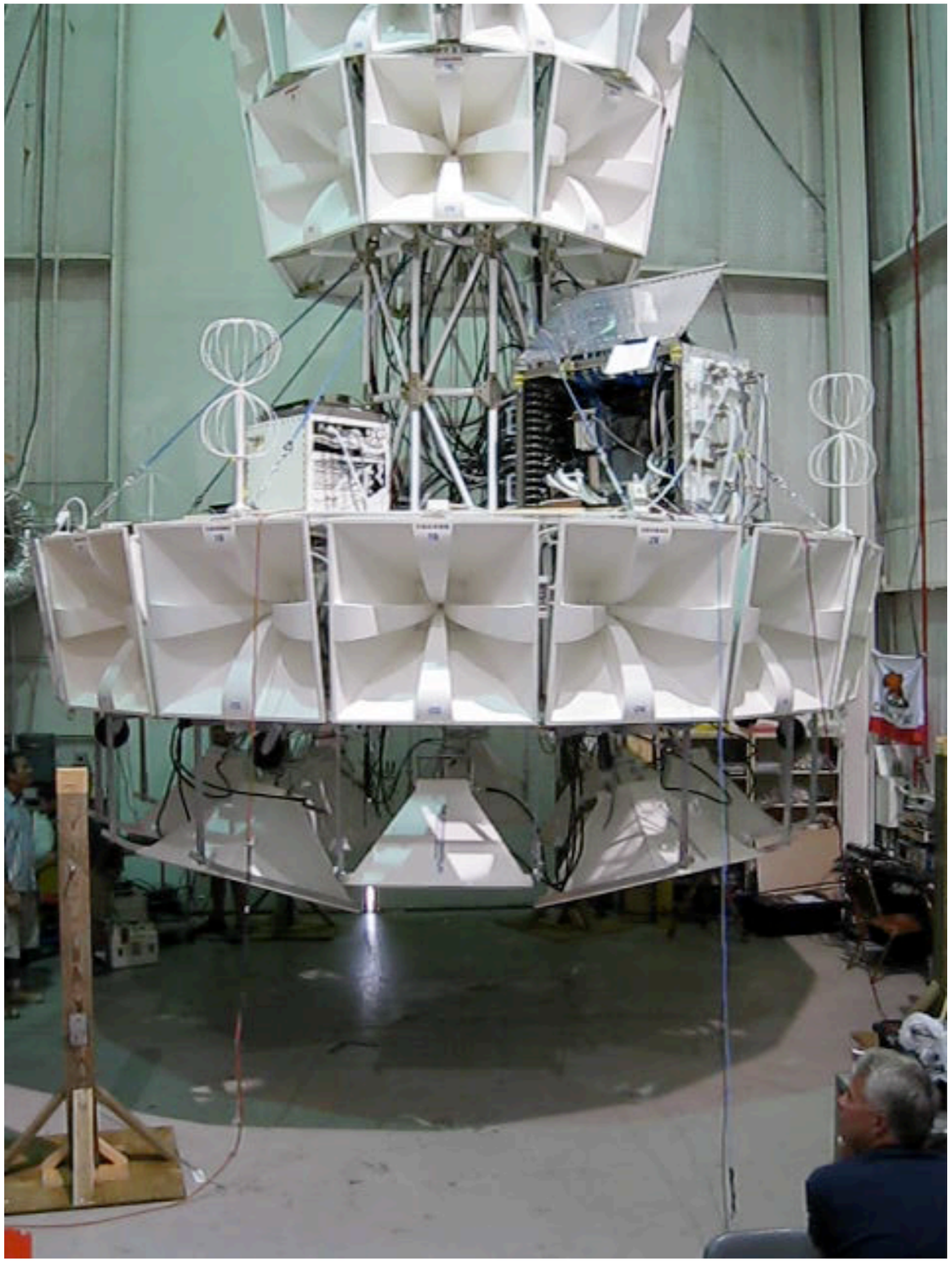






- ANITA-1
  - 2006
  - 32 Antennas
  - Circularly polarised coincidence trigger
  - Frequency banded trigger
- ANITA-2
  - 2008
  - 40 Antennas
  - Vertically polarised trigger
  - Frequency banded trigger
- ANITA-3
  - 2014
  - 48 Antennas
  - Vertically & horizontally polarised triggers
  - ~~Frequency banded trigger~~
  - GPU software filter
- ANITA-4
  - 2016
  - 48 Antennas
  - Circularly polarised coincidence trigger
  - ~~Frequency banded trigger~~
  - GPU software filter
  - Tuneable notch filter

Think smarter not harder



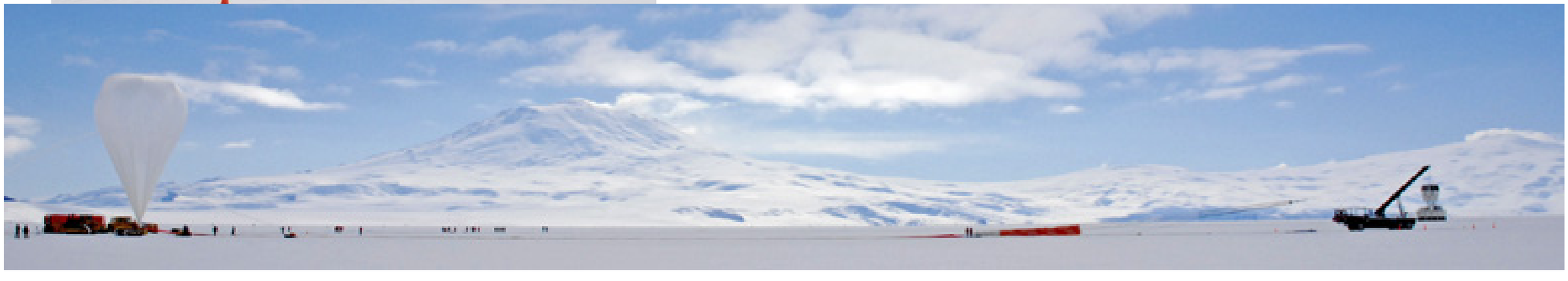
Summary

- Radio detection of high energy particles is a vibrant field
- The first three flights of ANITA have been used to set the most stringent limits on the UHE neutrino flux
  - ANITA has detected over 30 UHECRs
  - There are two interesting events with flipped polarity
- Still analysing ANITA-4 data
- 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 unambiguous detection of an UHE neutrino.
  - But in the mean time there are the anomalous events and UHECR

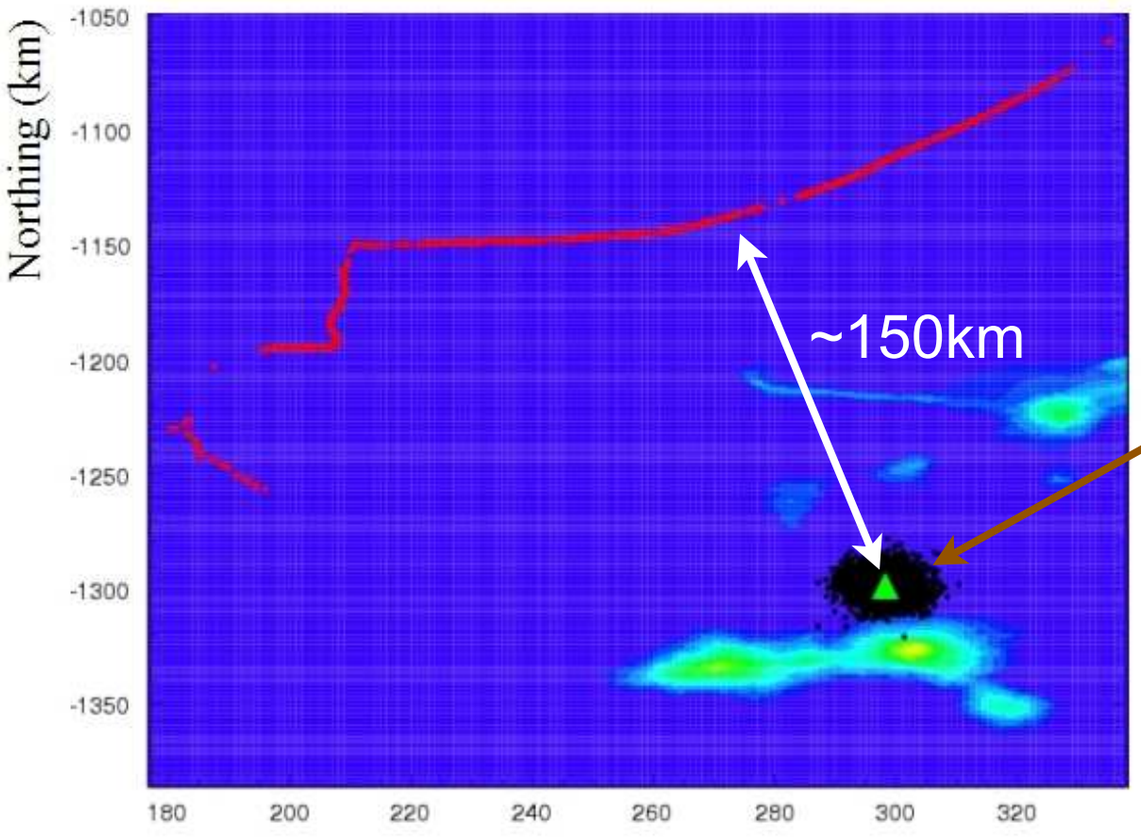
Me in front of the Royal Society Range in 2008? or 2006? or 2014? or 2016?

Up, up and away

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



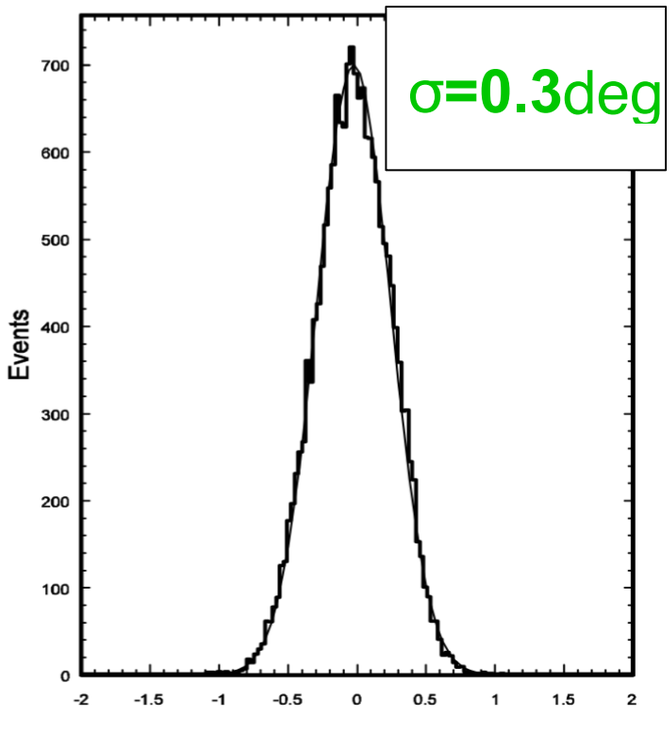
Calibration



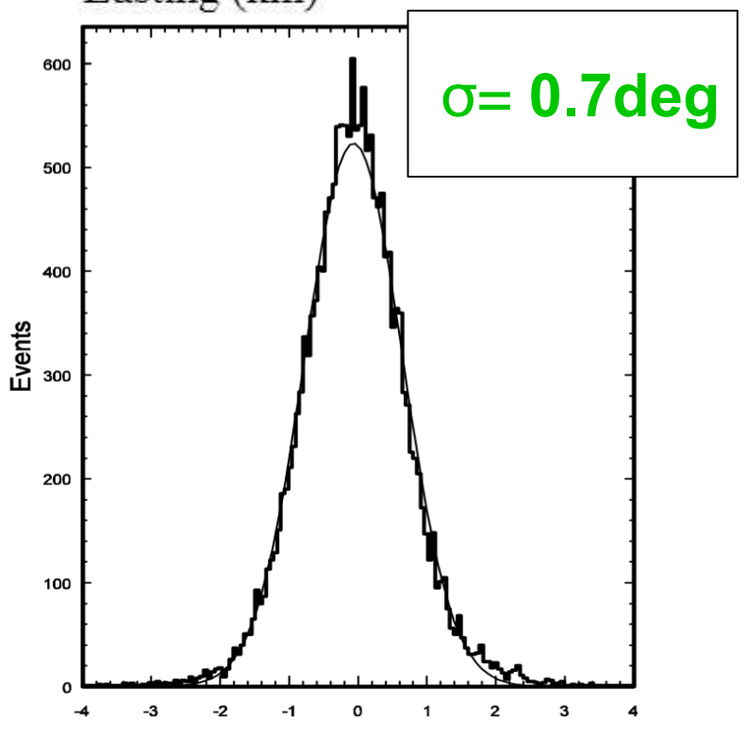
Reconstructed event locations

Use ground and borehole calibration pulsers to calibrate antenna positions and time offsets.

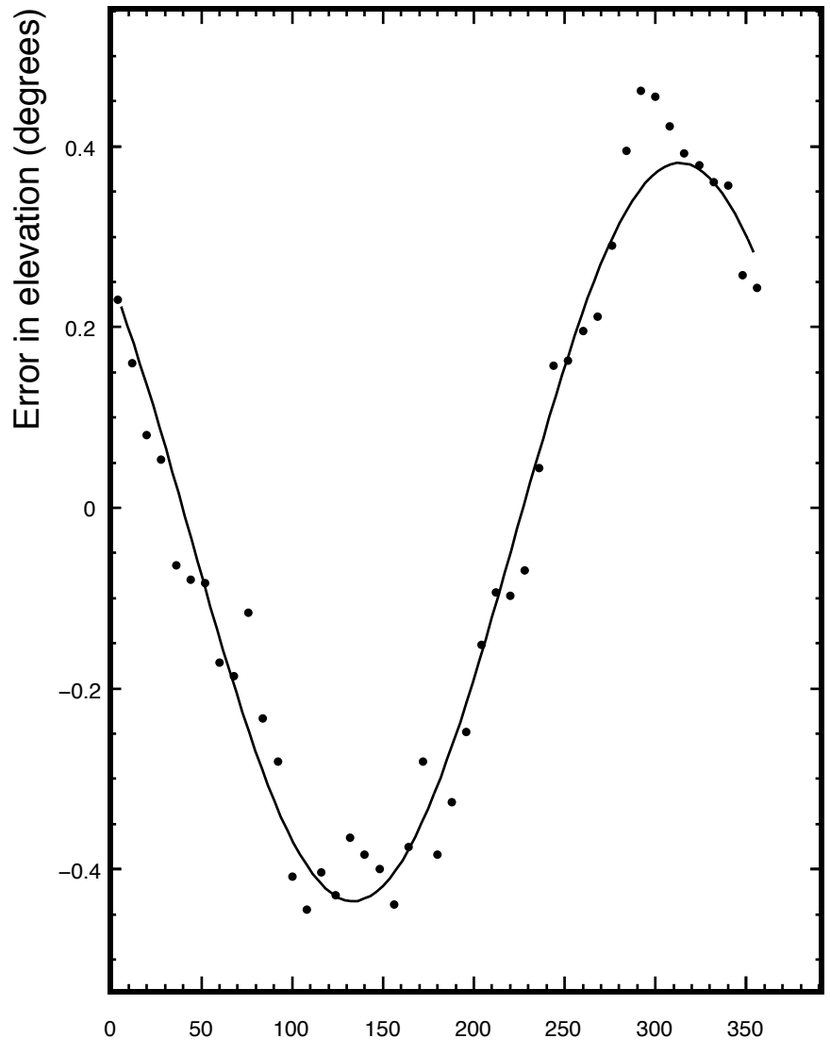
Also calibrate out the tilt of the payload



ELEVATION ANGLE

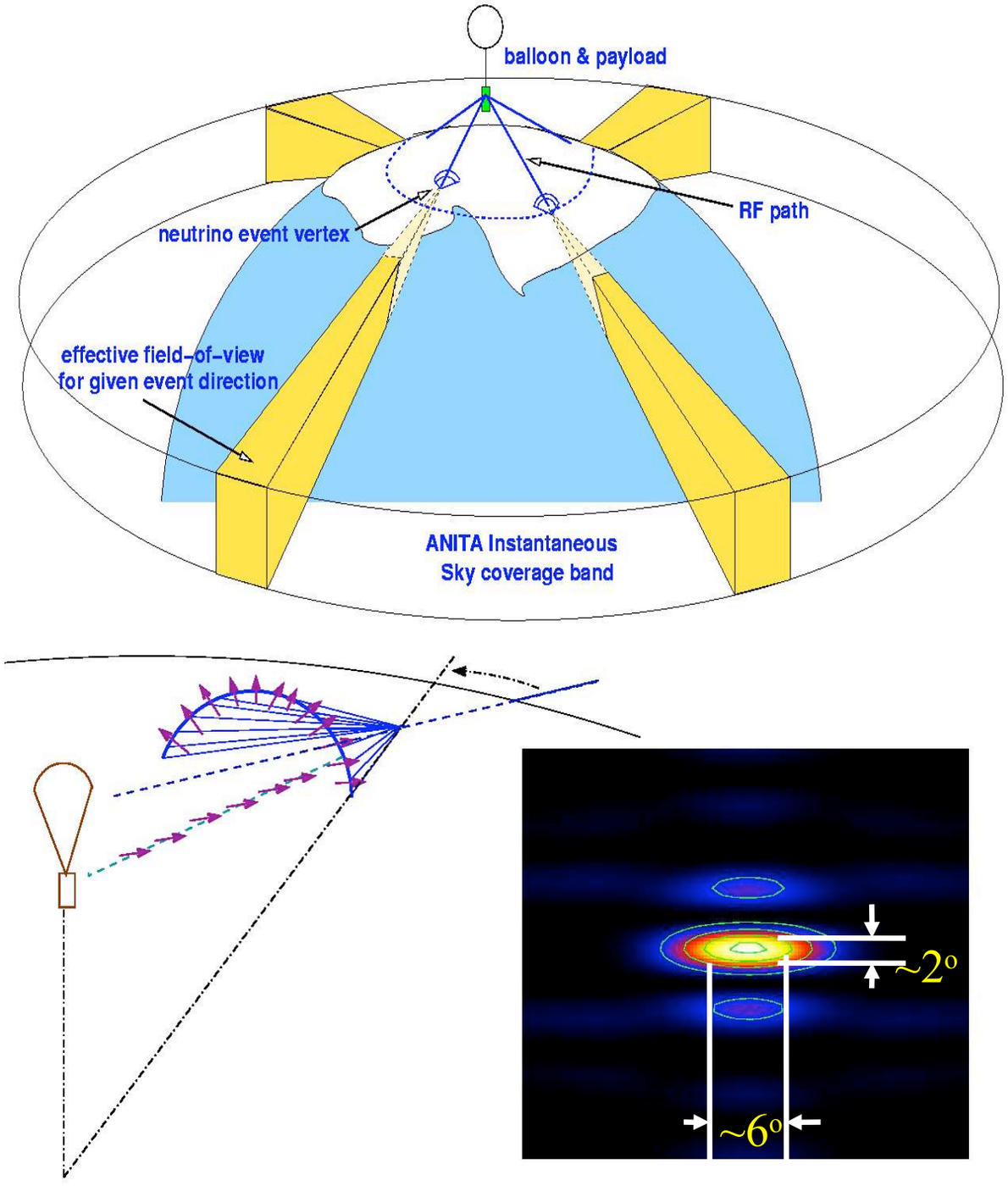


AZIMUTH ANGLE



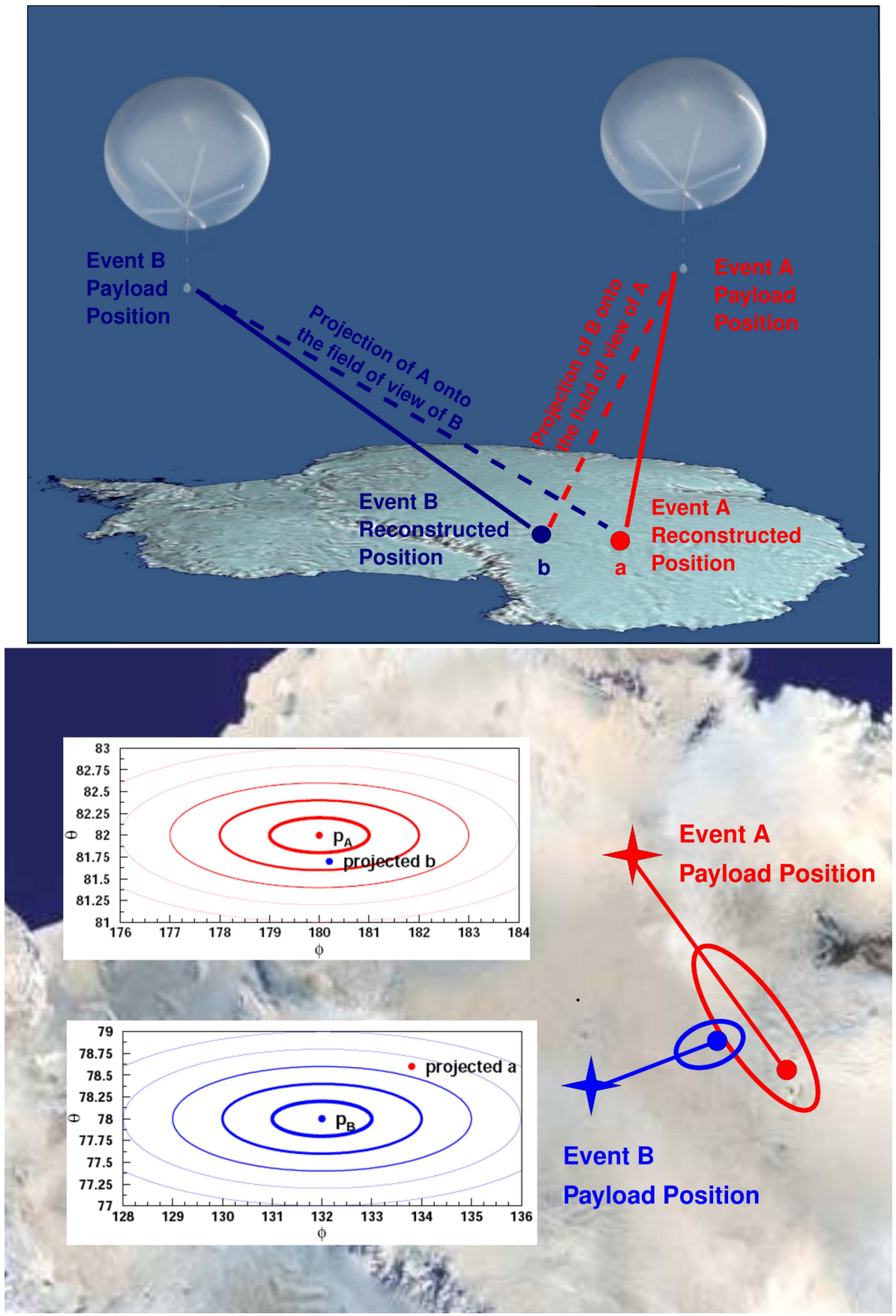
from S. Hoover

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.

Anthropogenic Backgrounds



- Use clustering algorithms to associate events with known bases and with other events
- Remove all events that cluster leaving only isolated events
- Remaining background is the number of unknown sites of anthropogenic noise which we have not identified... hard to quantify

Neutrino Limits

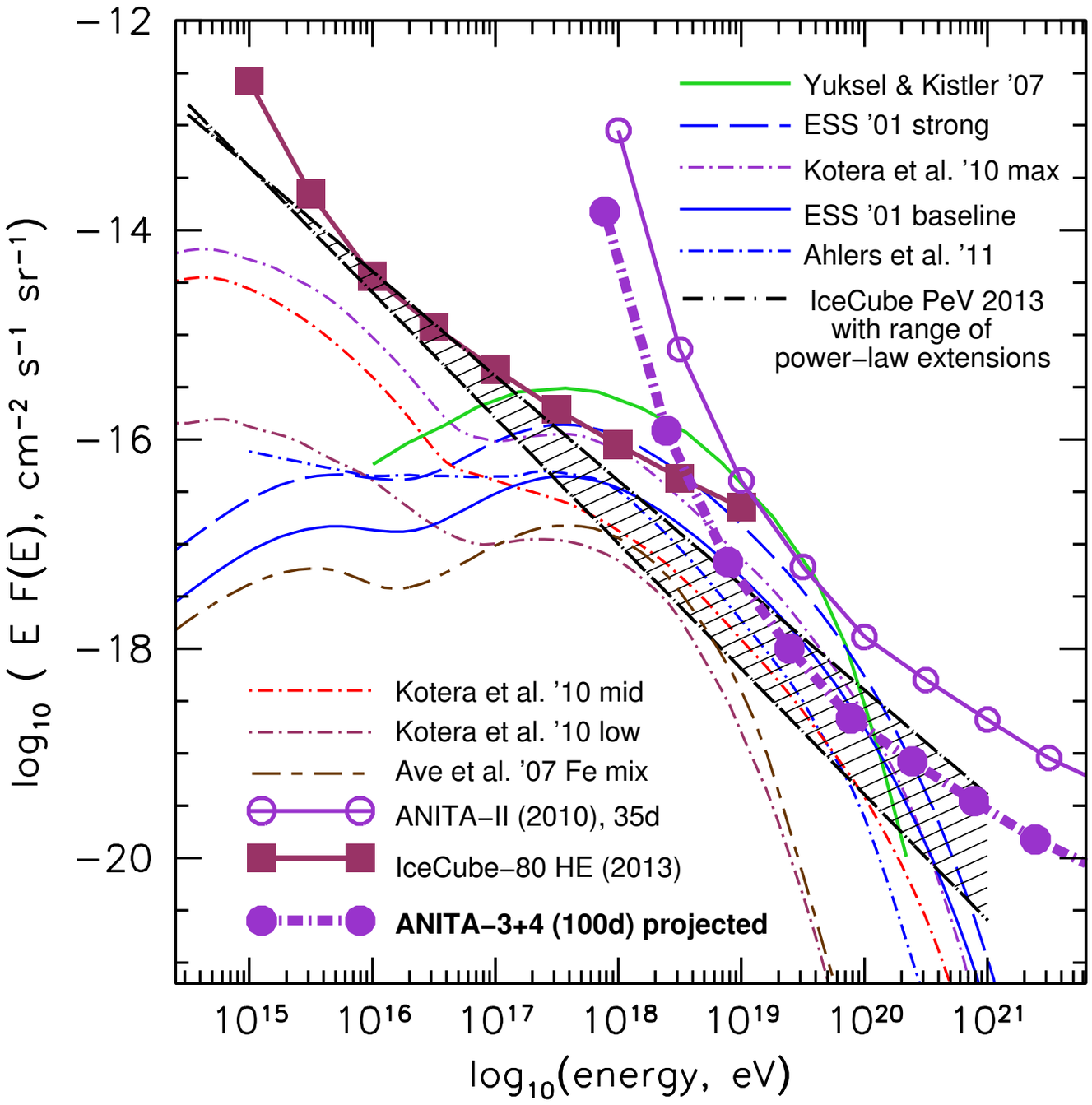
- ANITA-2 Results

Isolated v-pol events	1
Expected background events	0.97 ± 0.42

- Use calibration pulser and simulation to determine efficiency and set the best limit on UHE neutrino flux.

DOI:
10.1103/PhysRevD.85.049901
10.1103/PhysRevD.82.022004

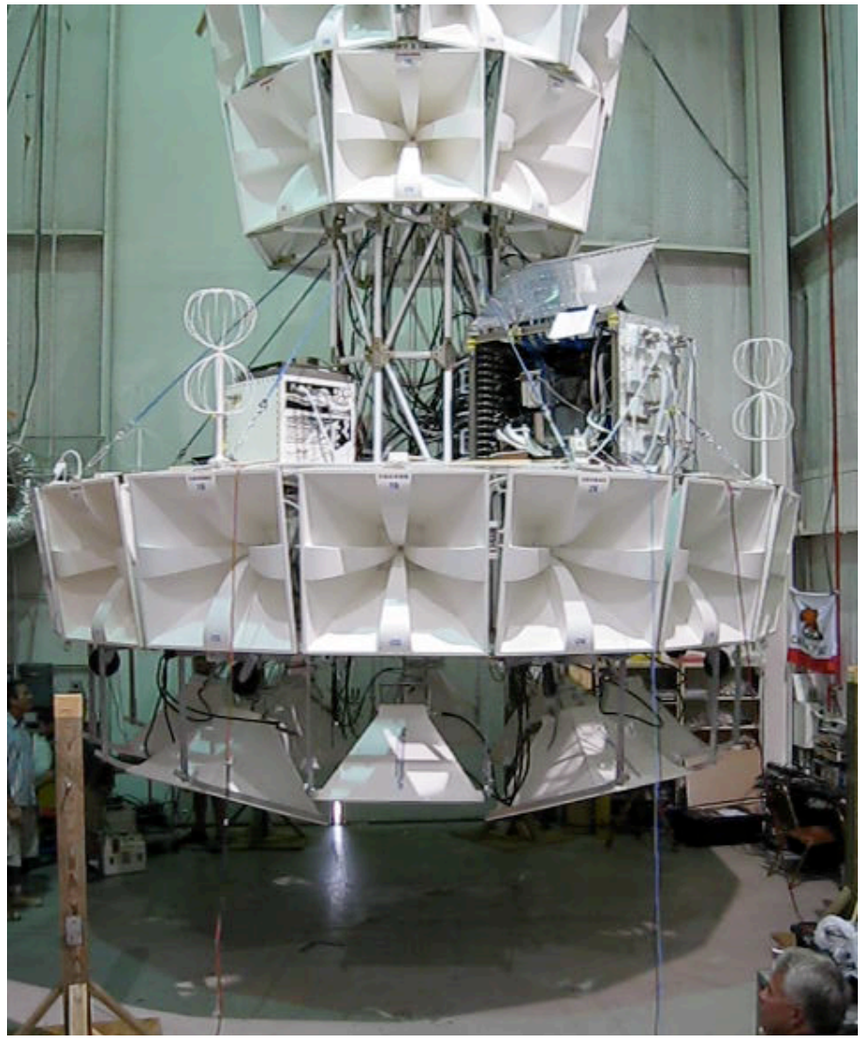
Also limits on magnetic monopoles and neutrinos from gamma-ray bursts

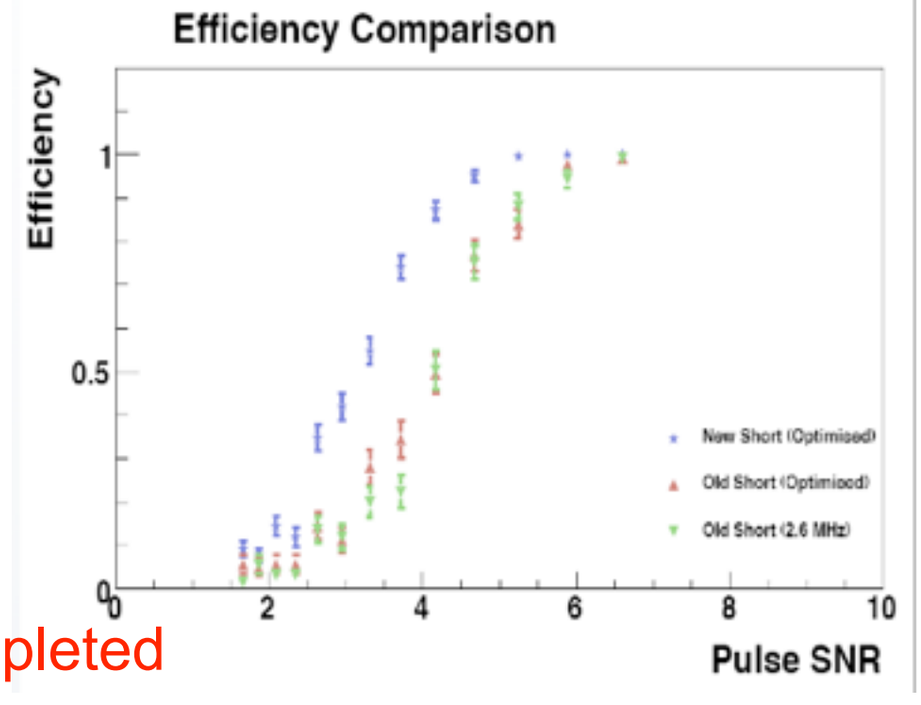


ANITA-II

- Additional ring of antennas
- Lower noise amplifiers
- Trigger only on vertical polarisation**
- Directional trigger masking

- Net improvement:
  - Factor of 1.7 in threshold --> x3 in event rate
  - Up to 30% in exposure (flight path dependent)
  - Up to 40% in live time
  - Total factor > 5 in neutrino sensitivity

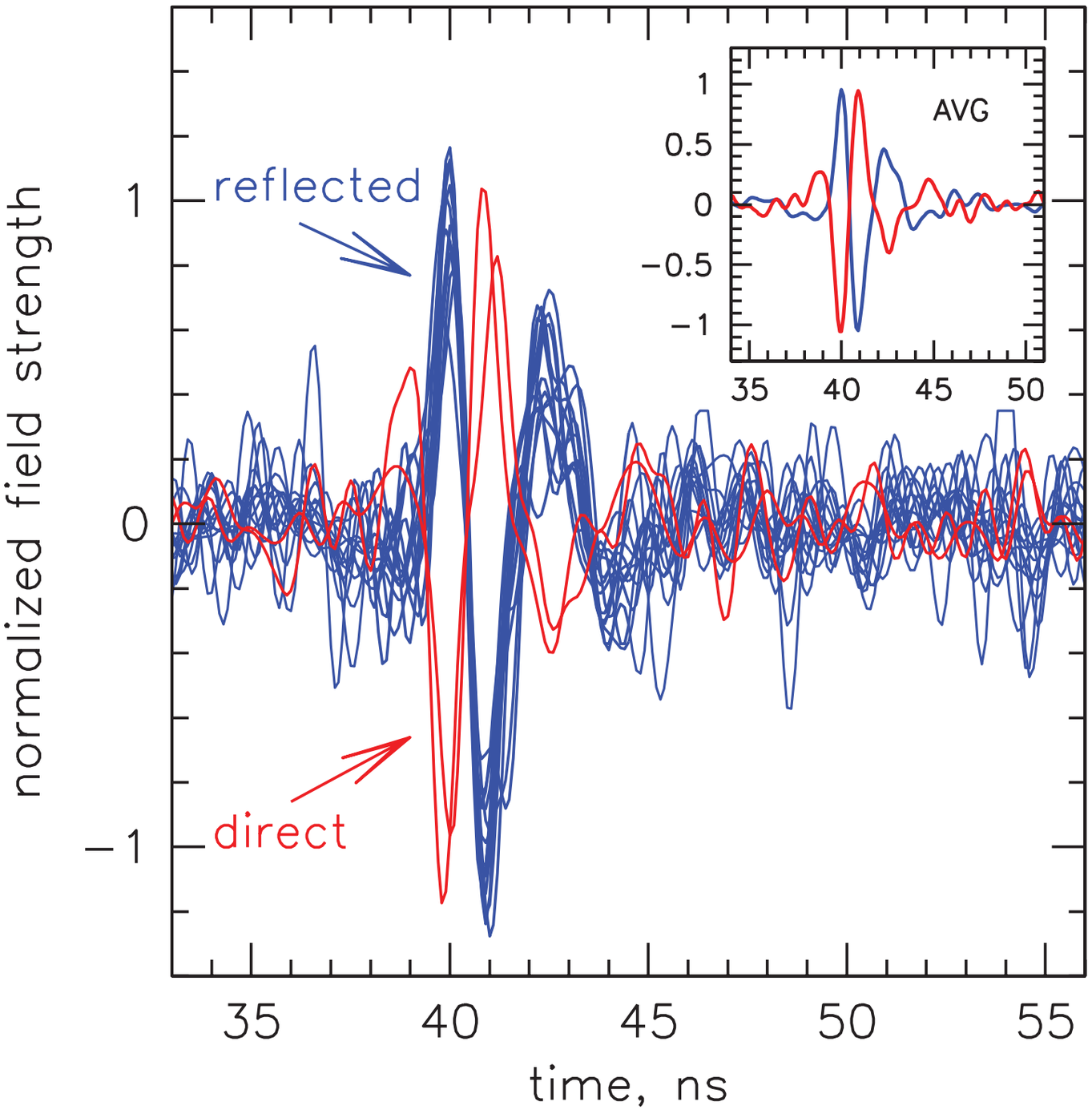




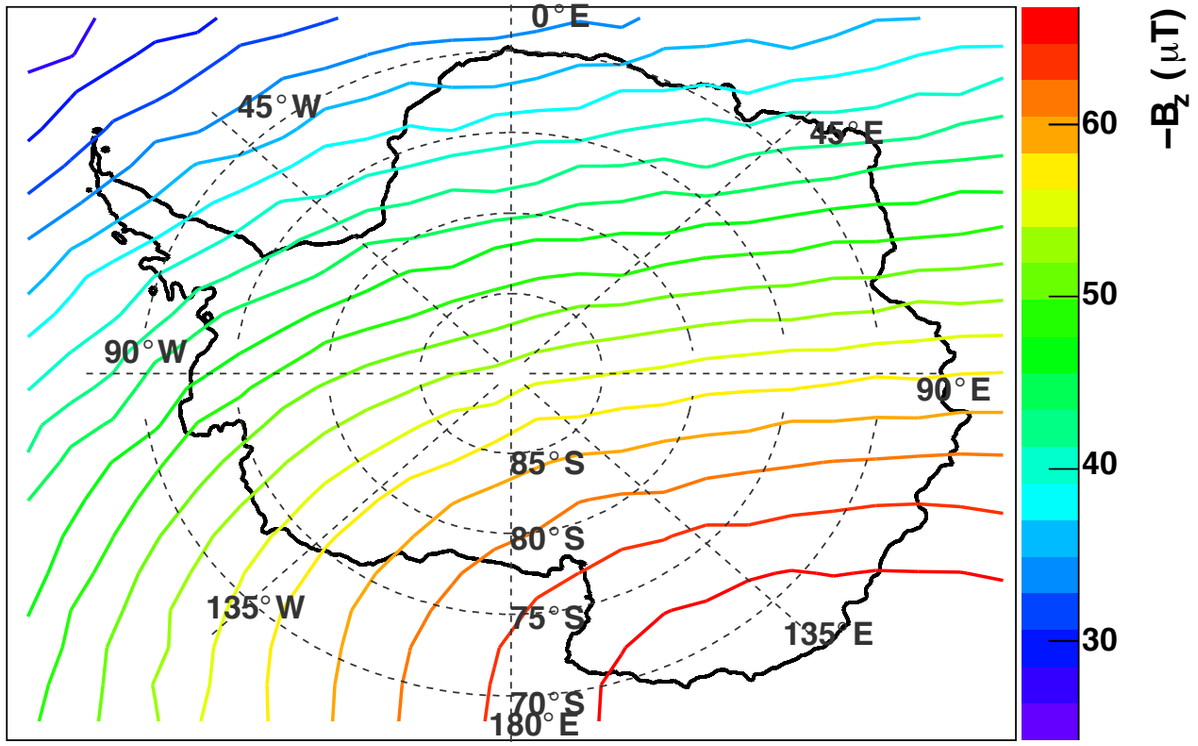
** Decision made before the ANITA-I analysis was completed

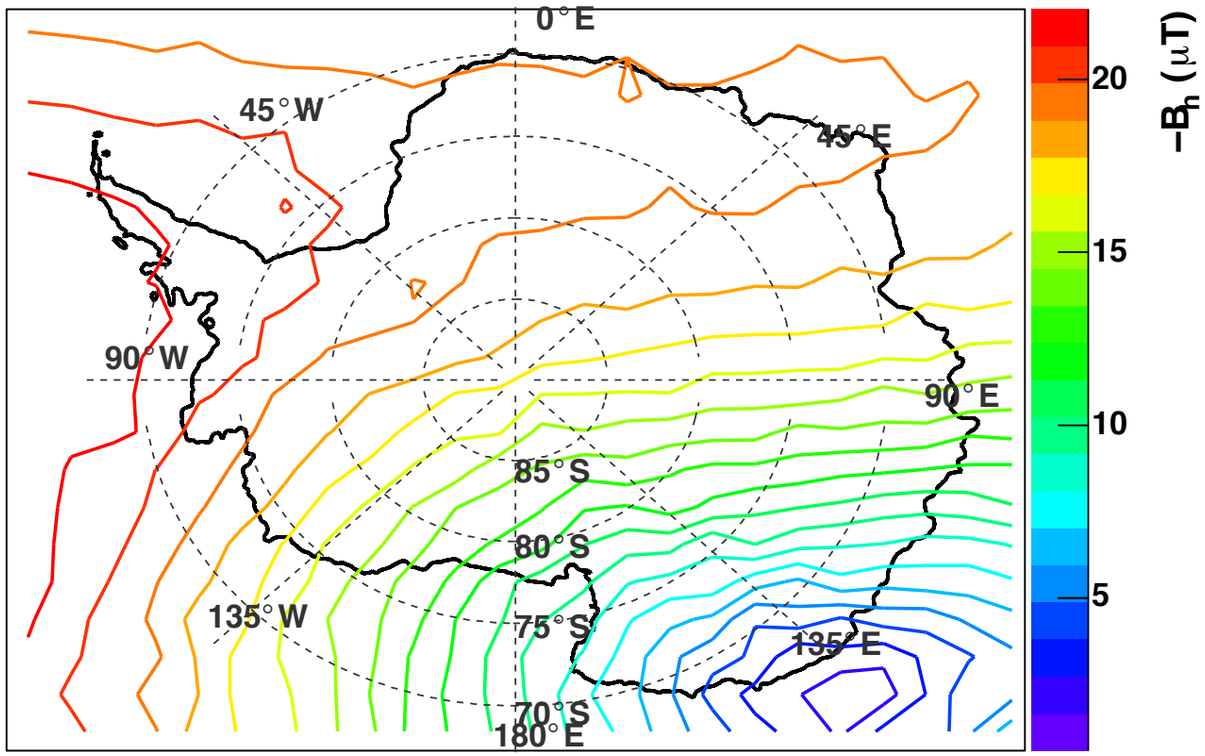
Are they really cosmic ray signals?

- The 14 events that reconstruct to the surface (i.e. are reflections) have very similar waveforms
- The 2 events that reconstruct above the surface have the opposite polarity
- Consistent with some signal that is generated above the surface

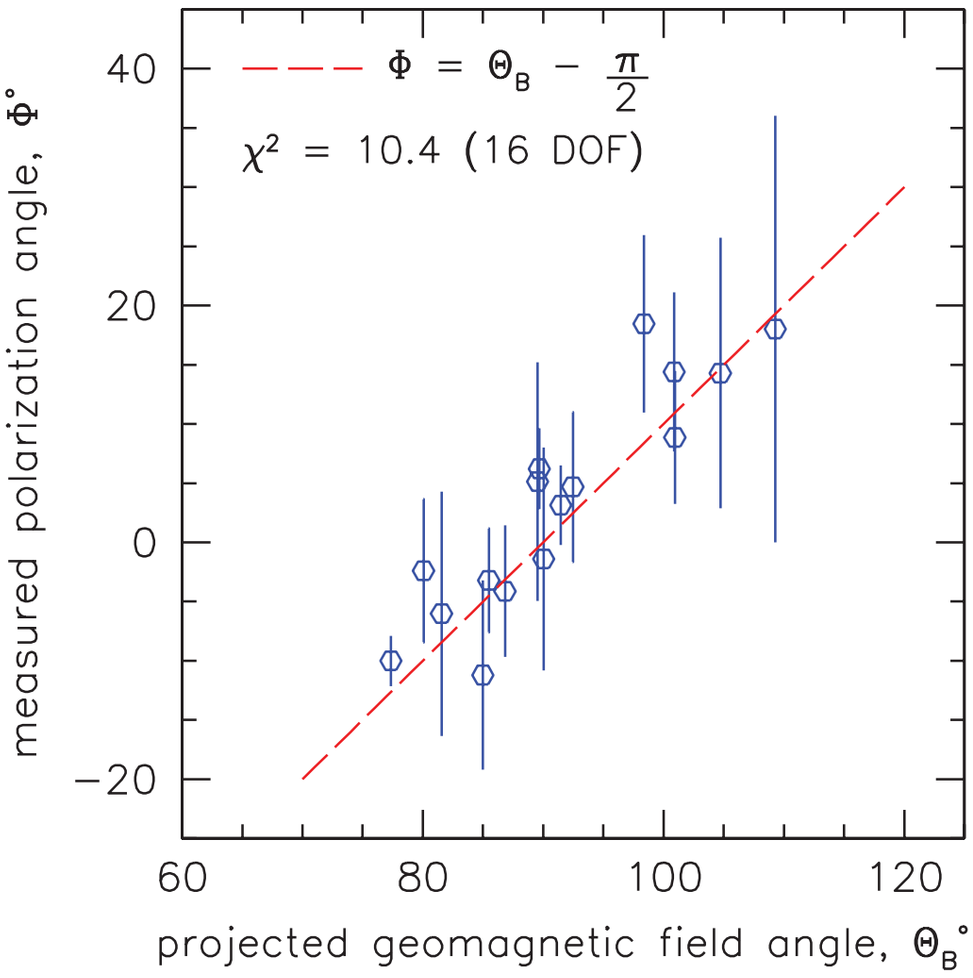


Are they really cosmic ray signals?



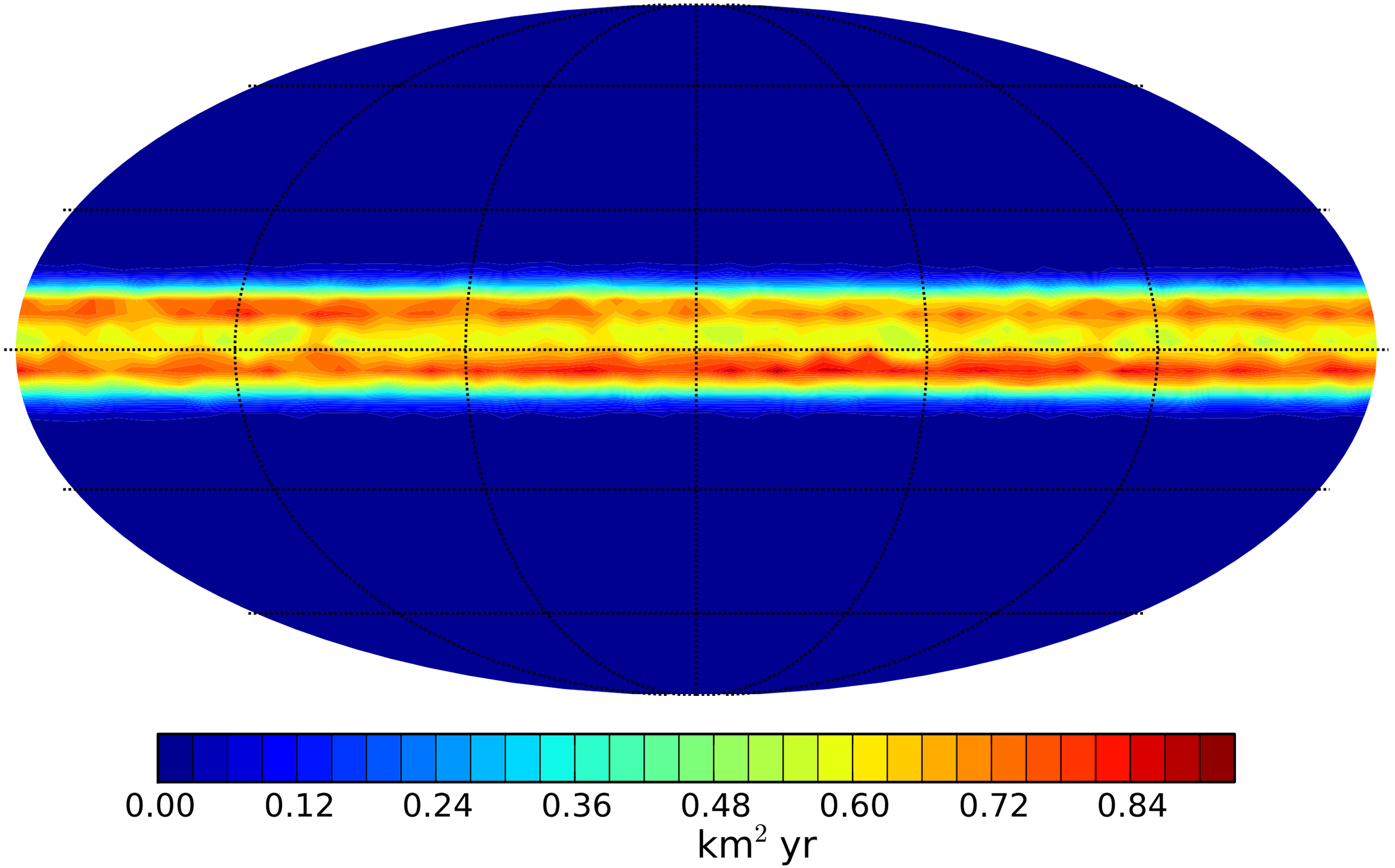


- Magnetic field is nearly (but not) vertical in Antarctica
  - **F**=q **v** x **B**



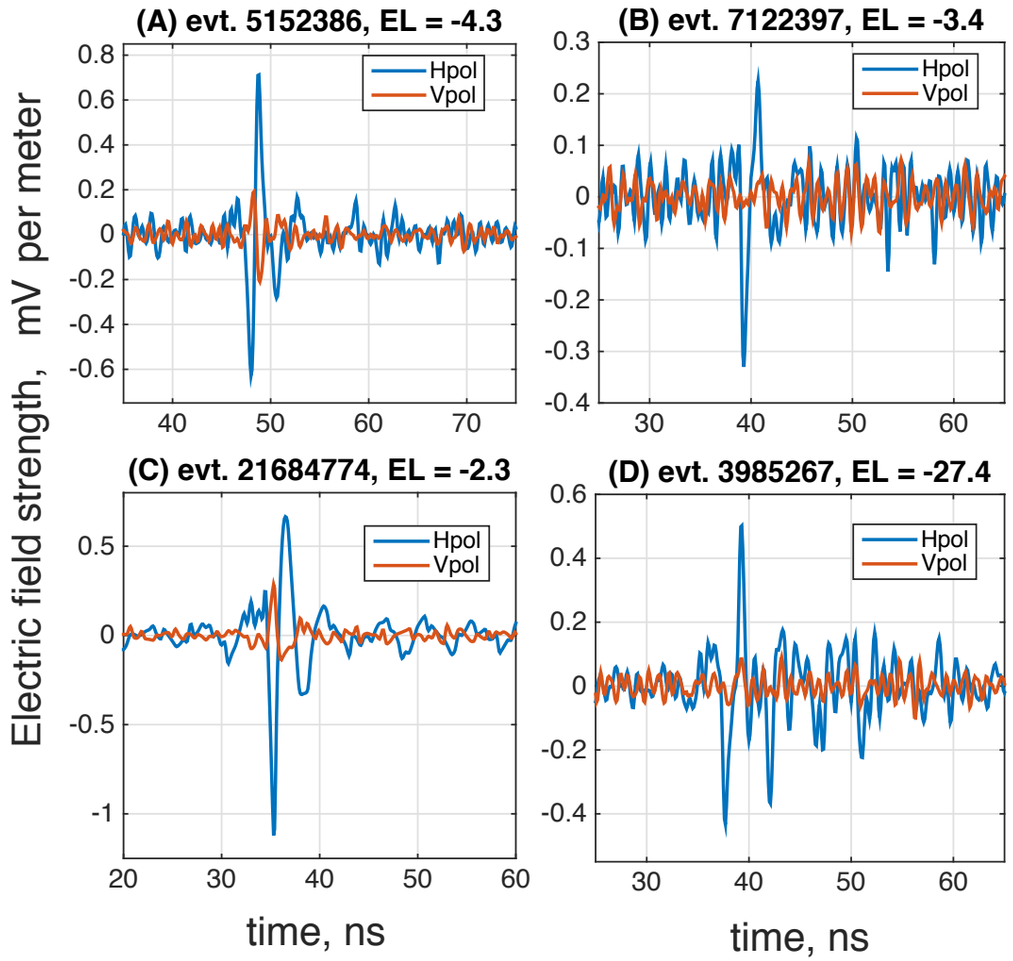
ANITA-2 Neutrino Sky Map Sensitivity

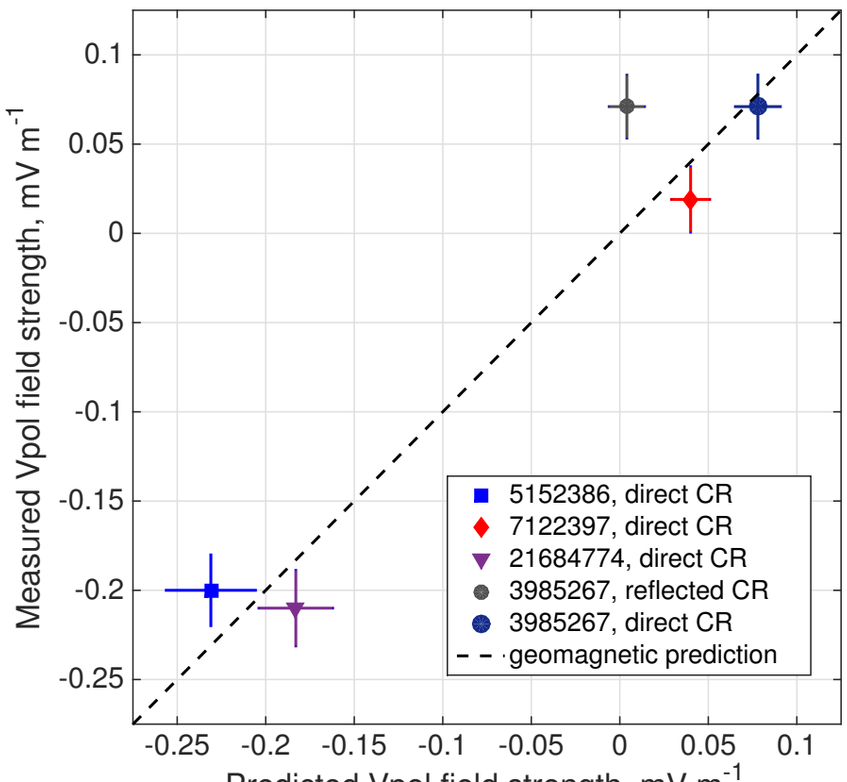
UCL



ANITA-1 mystery event (PRL 117 071101)

- Recent paper from ANITA discussing the direct cosmic ray signals in the 1st flight
- Uncovered one extra event that clearly points to the ice, but looks very similar to the direct h-pol waveforms
- The measured polarisation is consistent with a shower emerging from the ice
  - Could this be a tau neutrino candidate event?
    - Would be unlikely to survive given standard cross-section extrapolation
      - Should be attenuated by the Earth over the 5500km chord length
  - Could this be a cosmic ray with inverted polarity?
  - Could this be anthropogenic noise?





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)