Ultra-High Energy Neutrinos and the Radio Detection Technique

Ryan Nichol

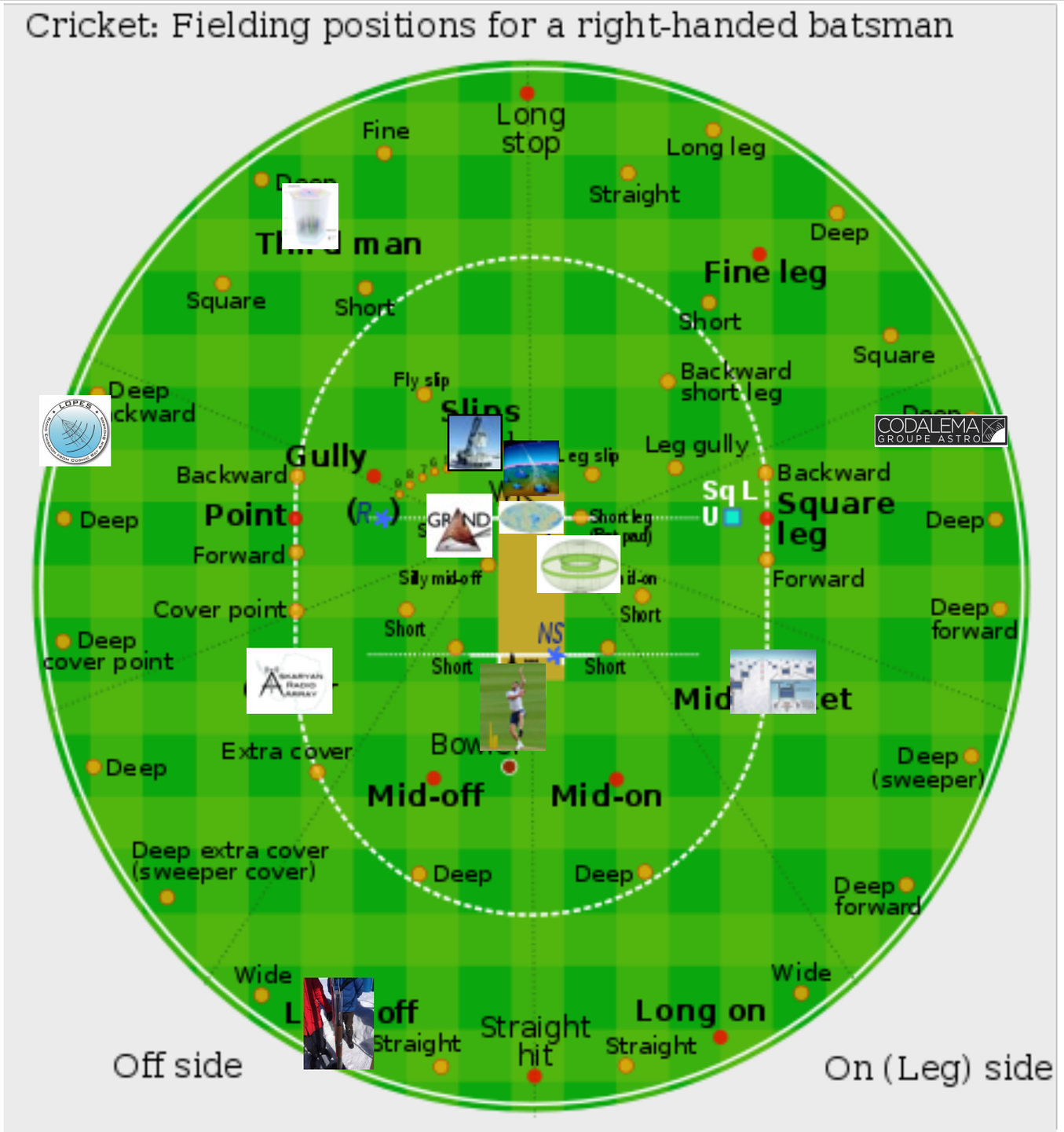
MACROS 2016

The Pennsylvania State University,

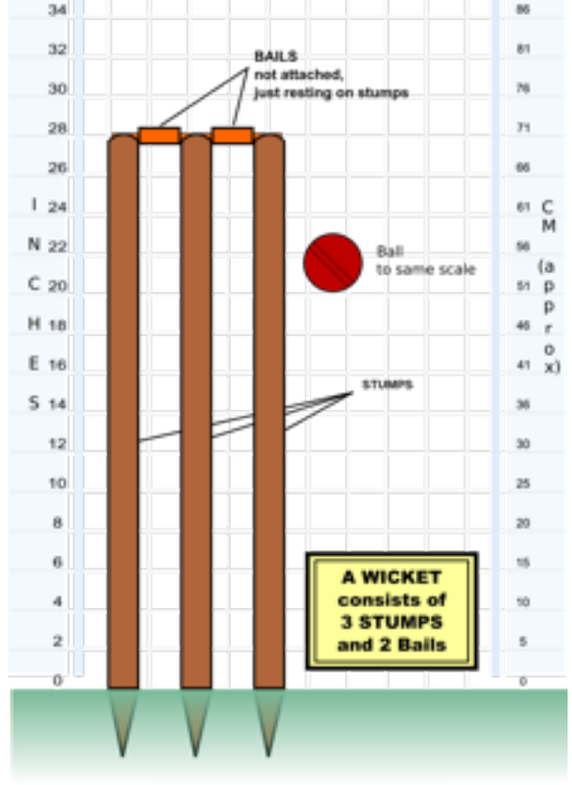
June 20-22 2016

Photo: H. Schoorlemmer , University of Hawaii

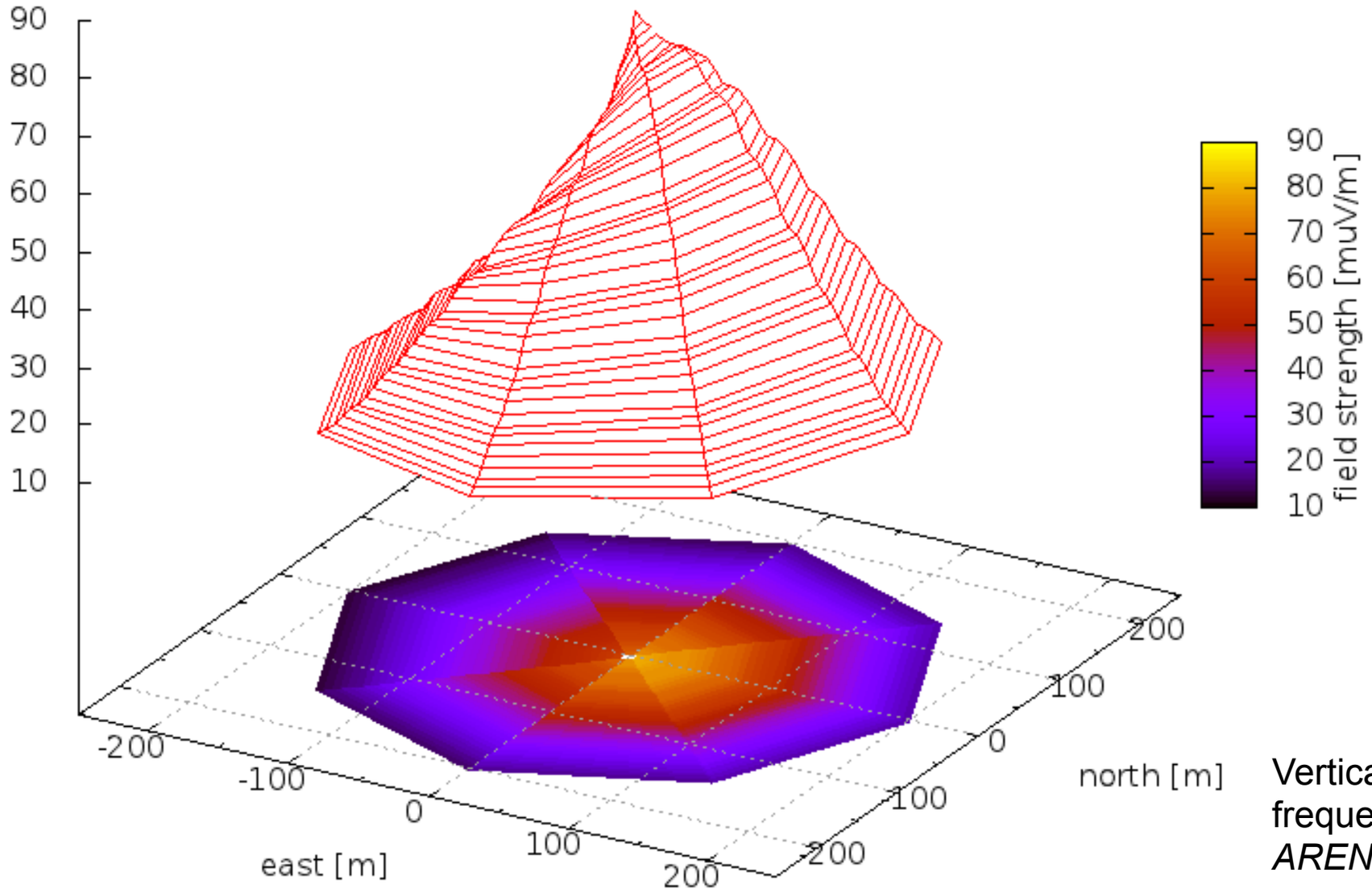
Current and future 11



Substitutes:
NuMoon
Tunka-Rex
AERA
SKA
Radar
Salsa
Taroge
….



Radio Emission Mechanisms

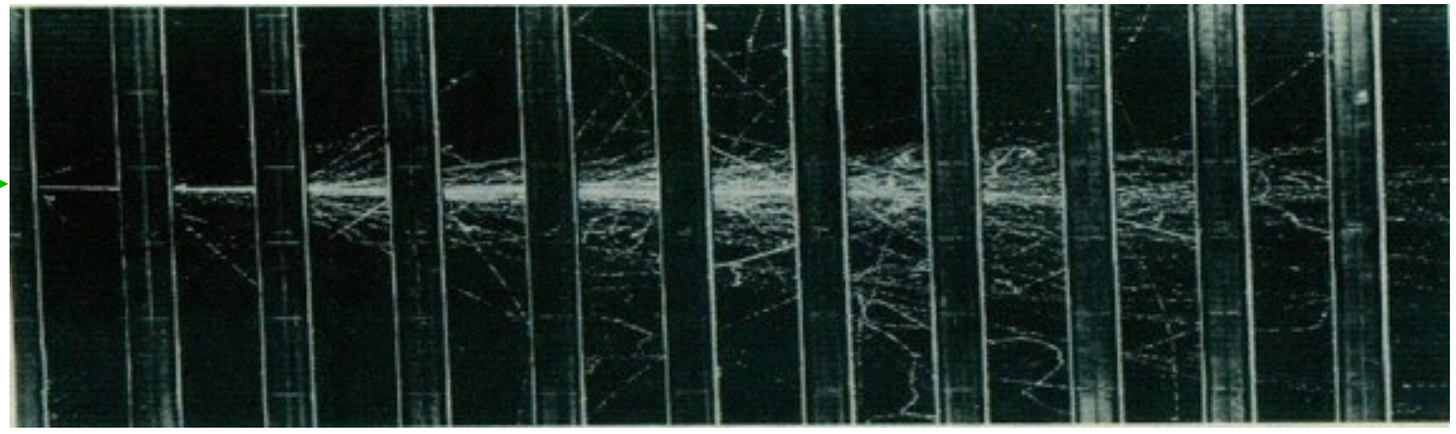


Vertical Iron Shower at LOPES frequencies from T. Huege *et al. ARENA2012*

Radio Cherenkov -- The Askaryan Effect

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

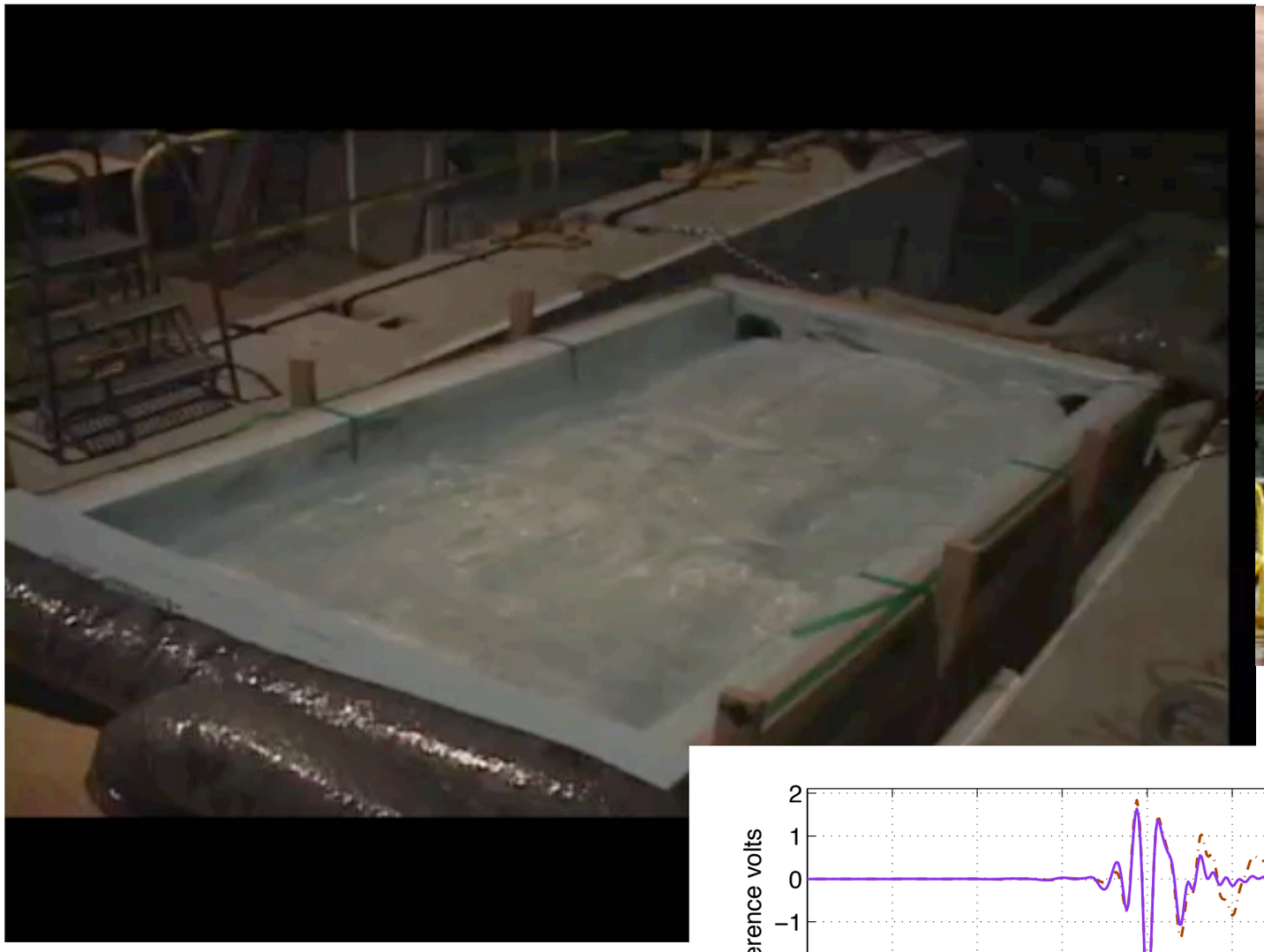
$e^{\pm}$ or γ

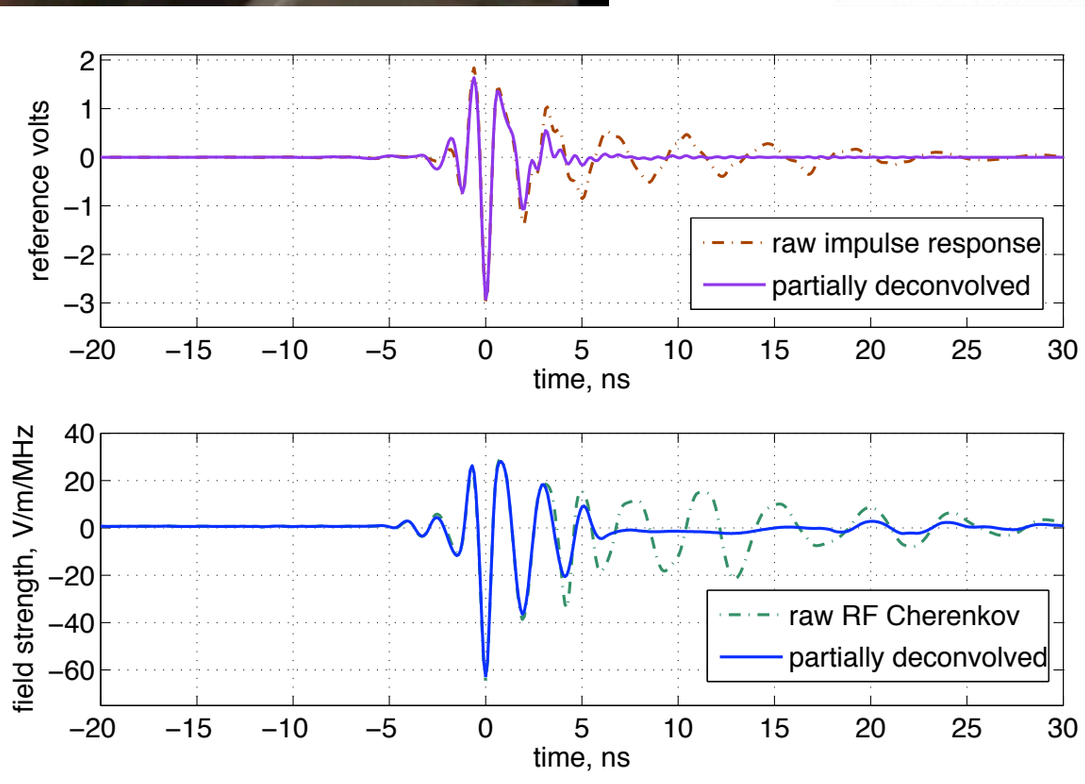


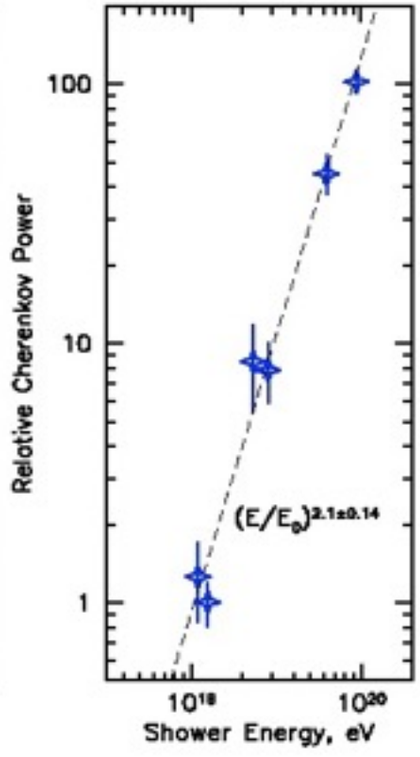
Typical Dimensions:
$L \approx 10$ m
$R_{Moliere} \approx 10$ cm

– 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



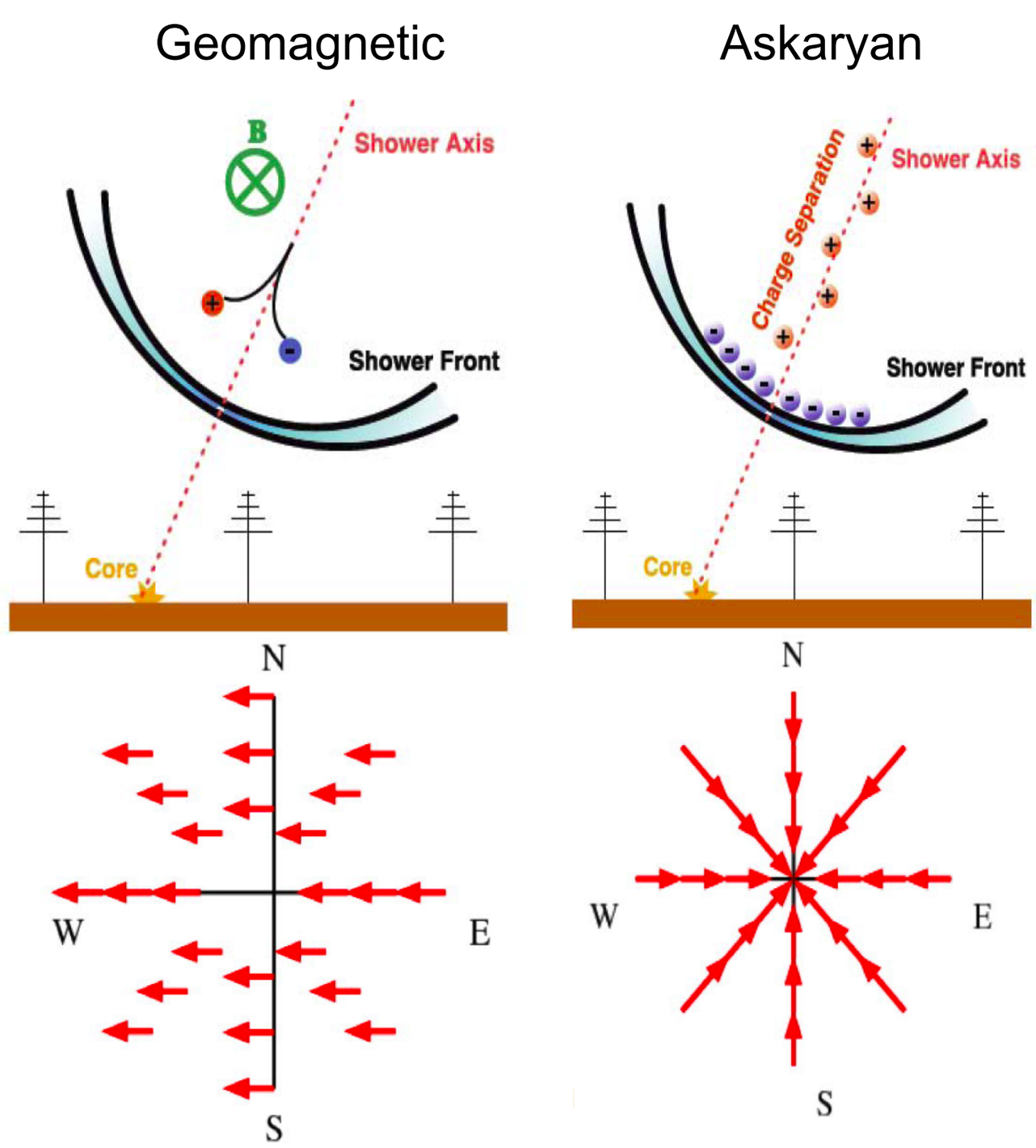




From PRL 99, 171101 (200

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



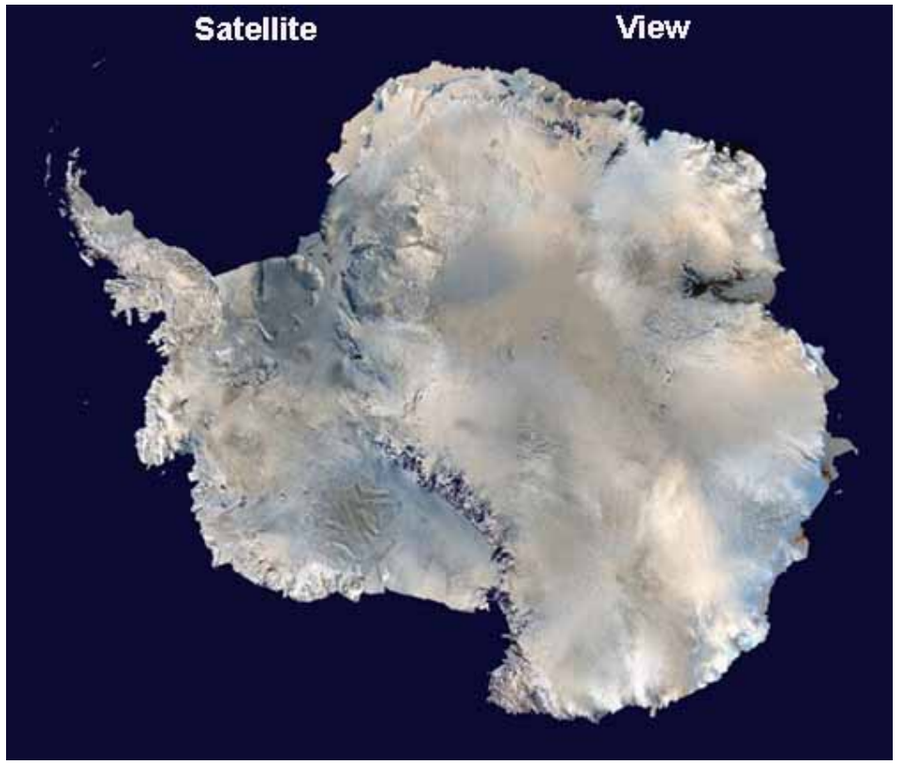
Diagrams from T. Huege, ICRC2013

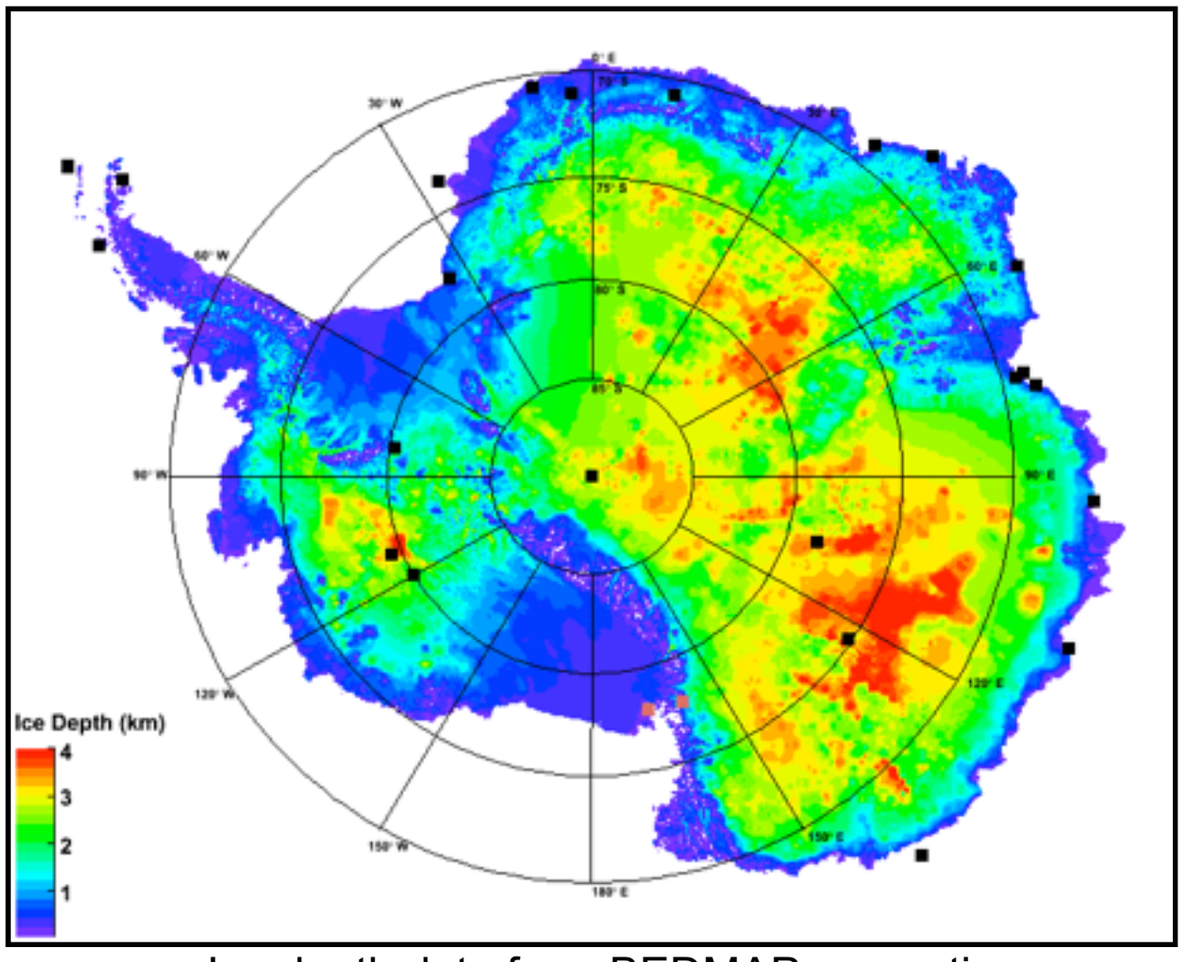
UCL

ANITA

Why Antarctica?

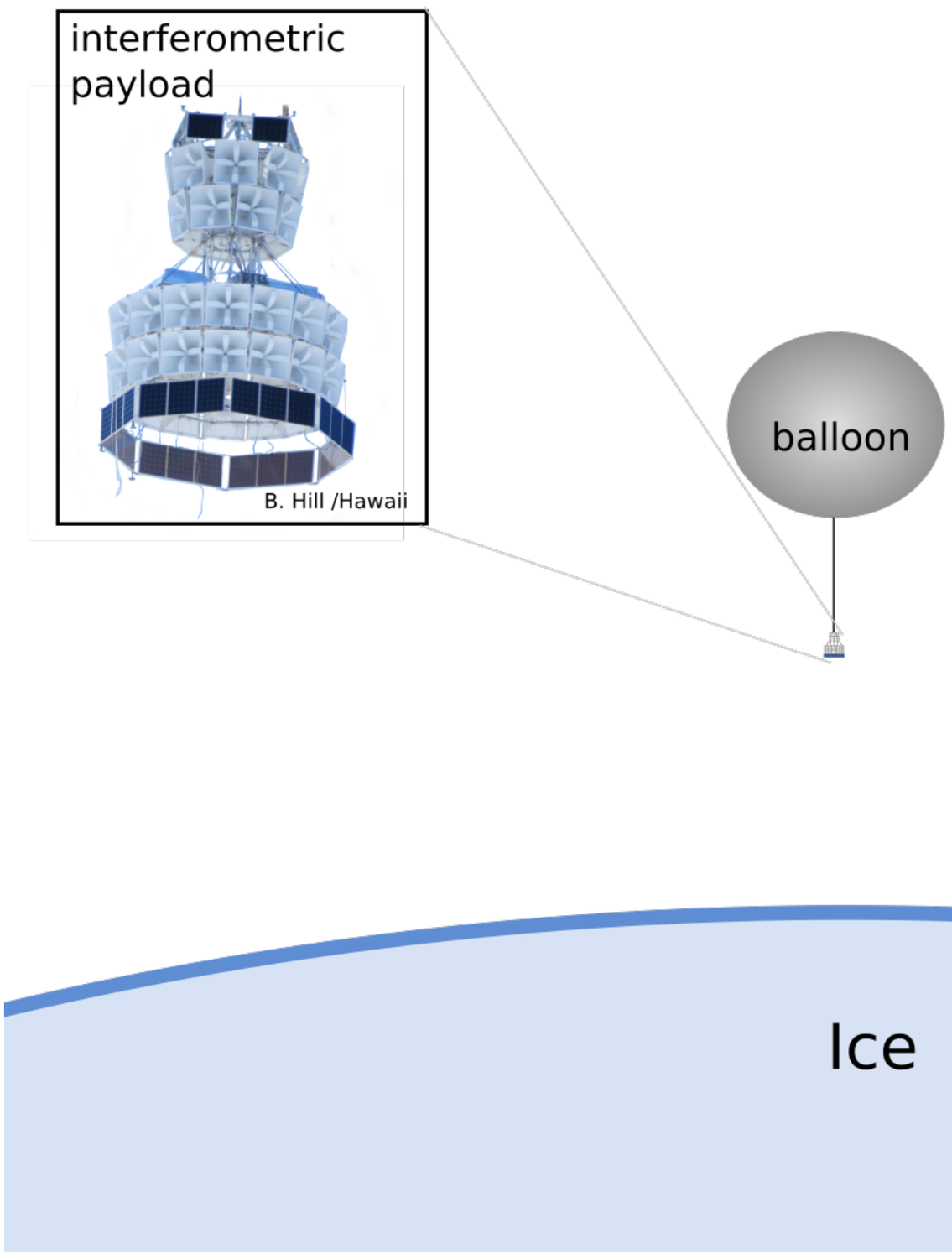
- It is the coldest, driest, windiest place on Earth
- But...
  - Lots of Ice
    - Despite our best efforts
    - Over 4km thick in places
  - Also:
    - The only continent exclusively dedicated to scientific research
    - No indigenous (human) population
    - Home of NASA's long-duration balloon program





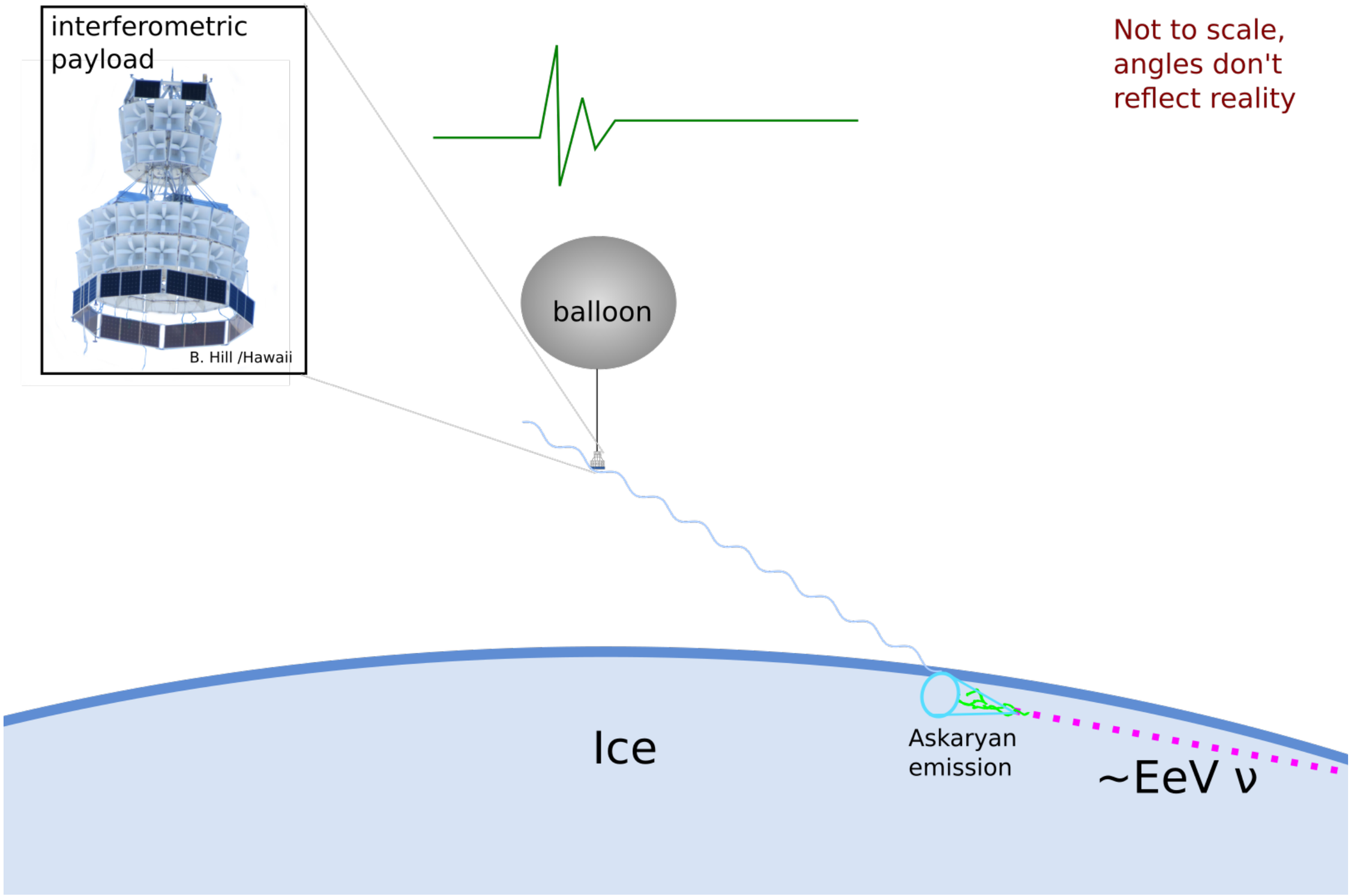
Ice depth data from BEDMAP consortium

Concept



Not to scale, angles don't reflect reality

Concept



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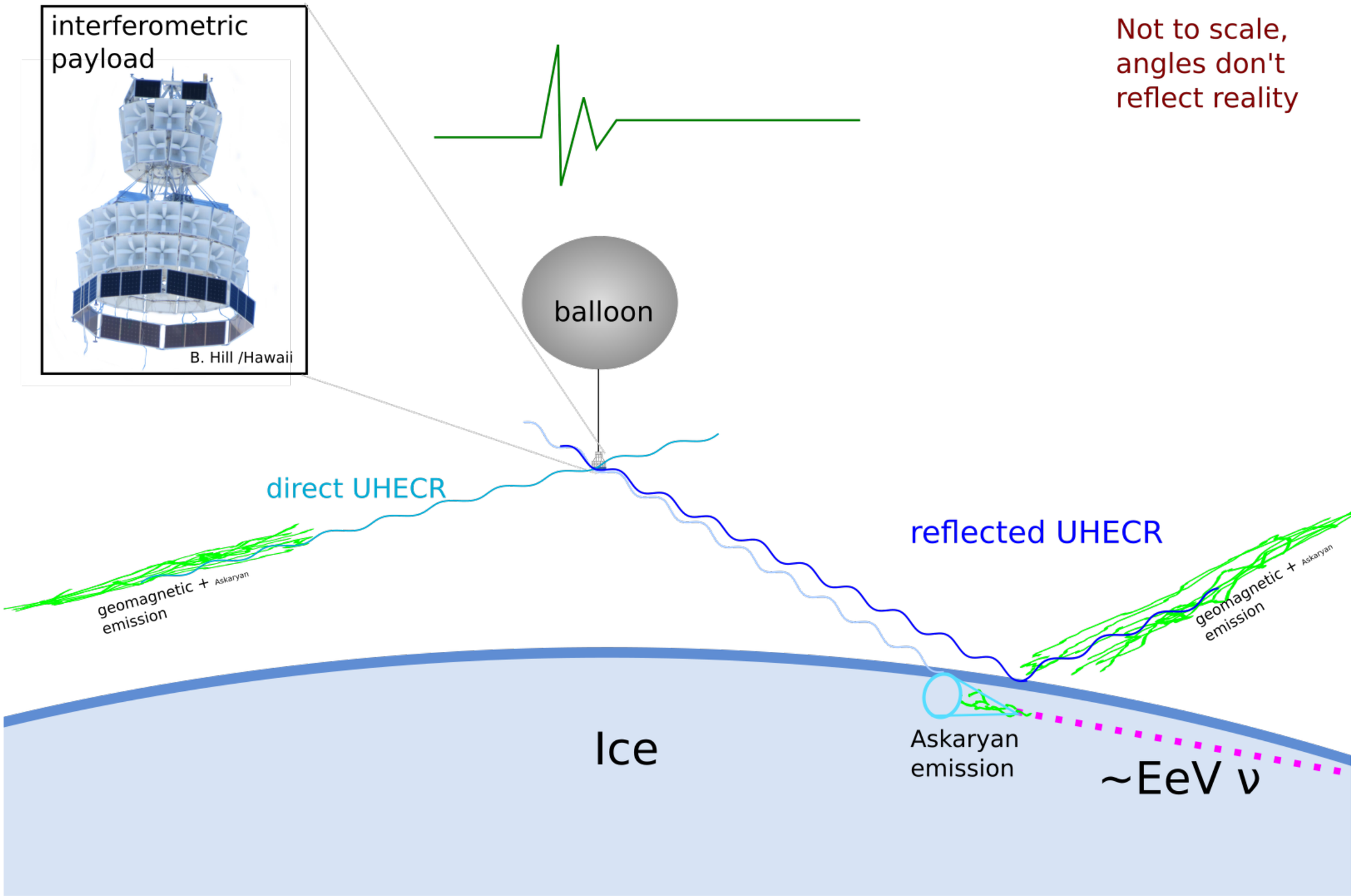
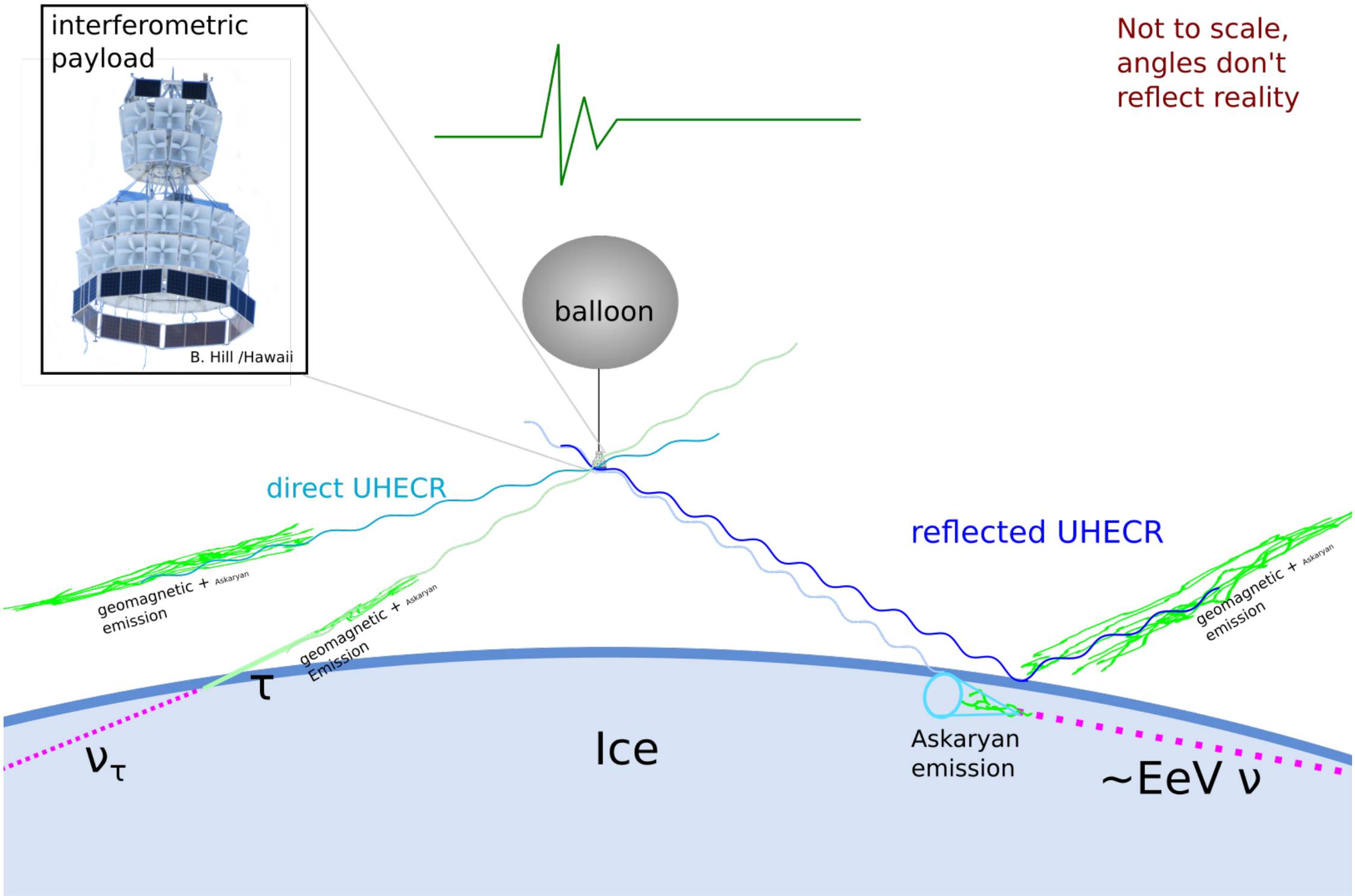


Not to scale, angles don't reflect reality

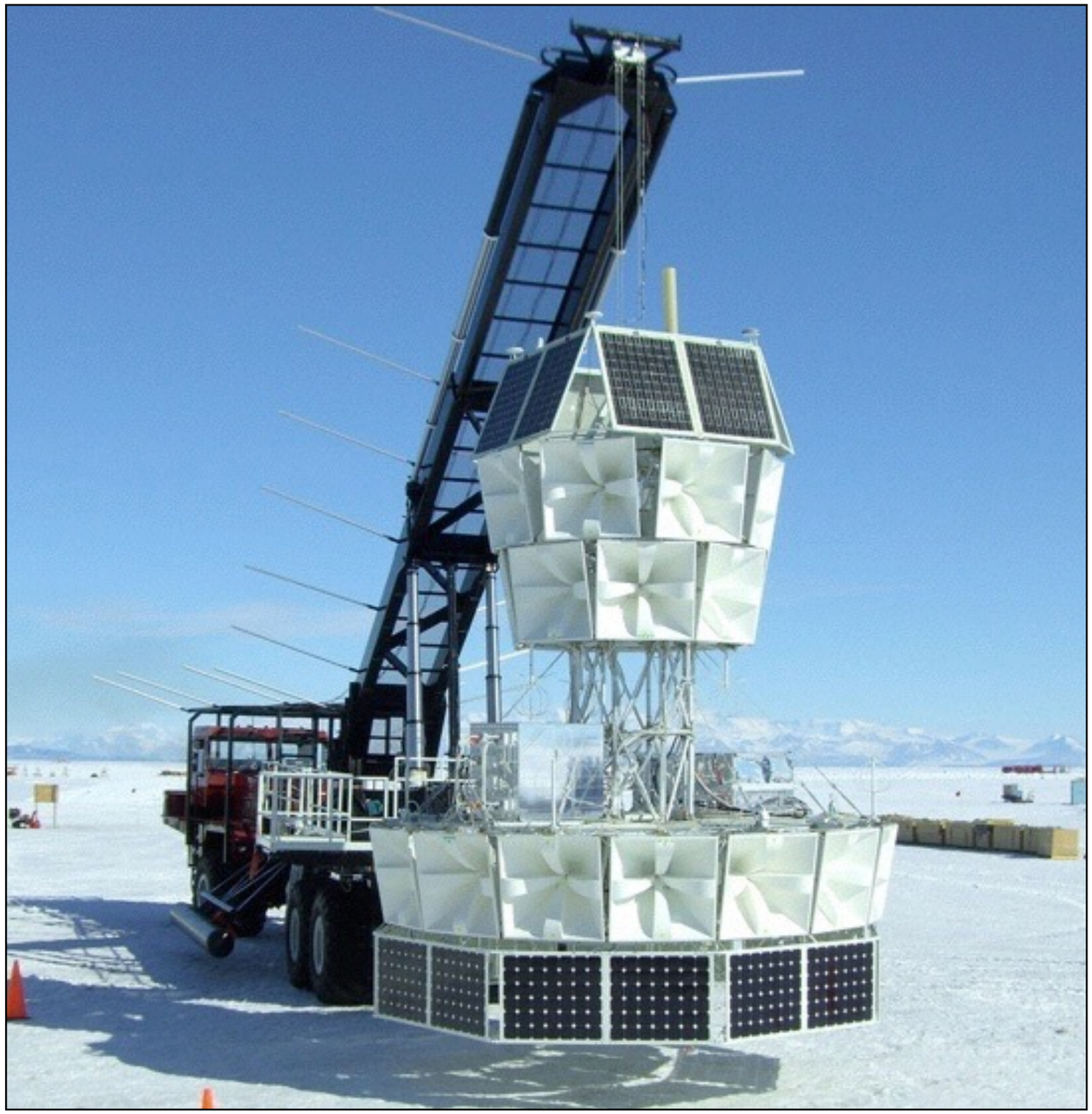
Concept



Not to scale, angles don't reflect reality

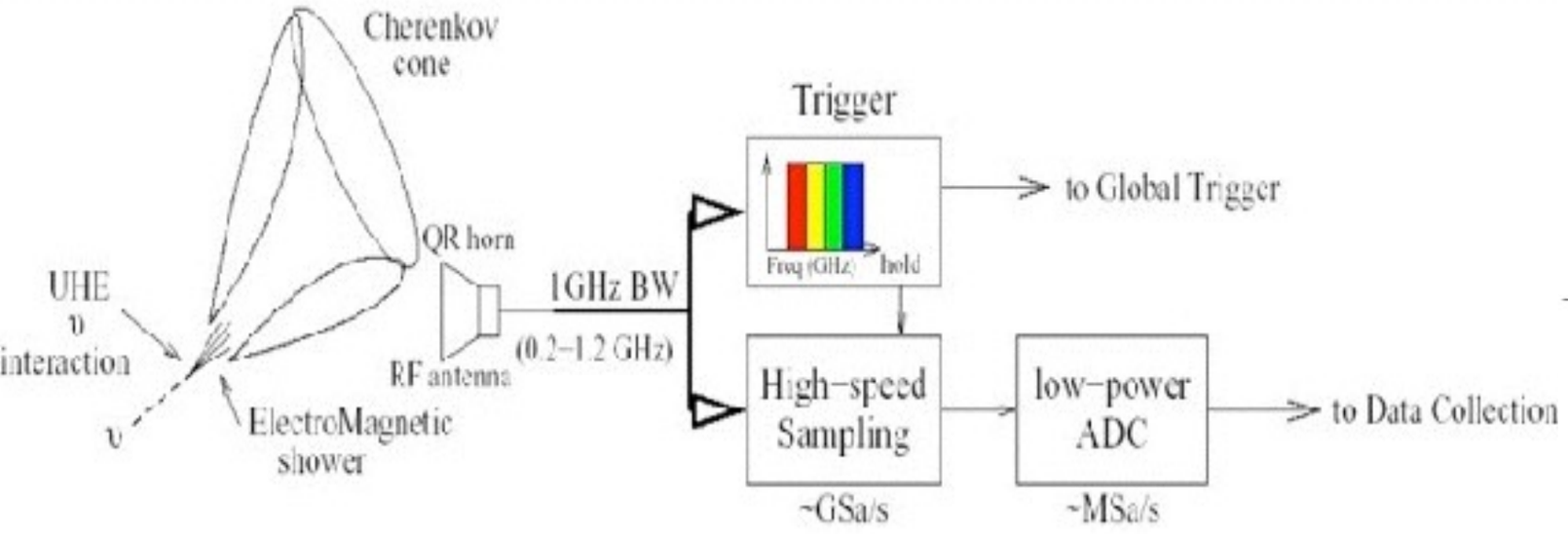
ANITA

- The ANtarctic Impulsive Transient Antenna
  - A balloon borne experiment
    - 32-48 dual polarisation antennas
    - Differential GPS for positioning and orientation
    - Altitude of 37km (120,000 ft)
    - Horizon at 700km
    - Over 1 million km^3 of ice visible

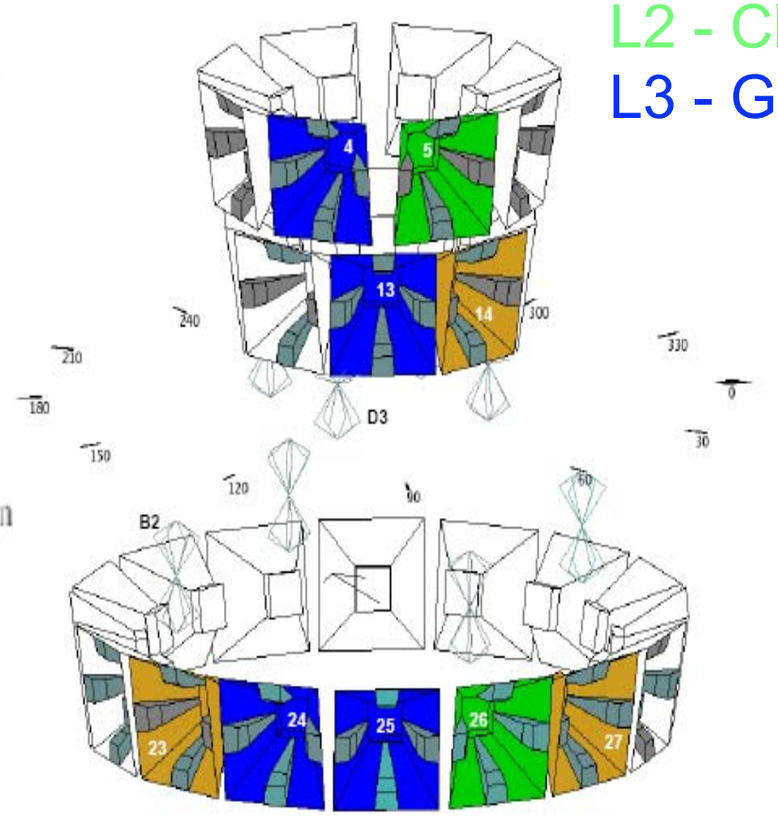


ANITA Electronics and Trigger

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

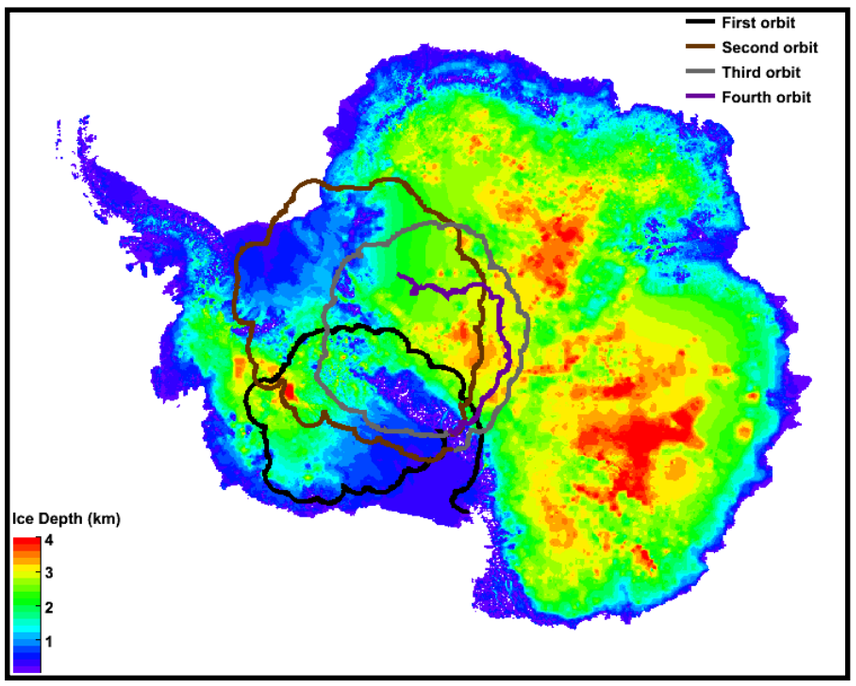


L1 - Antenna
L2 - Cluster
L3 - Global

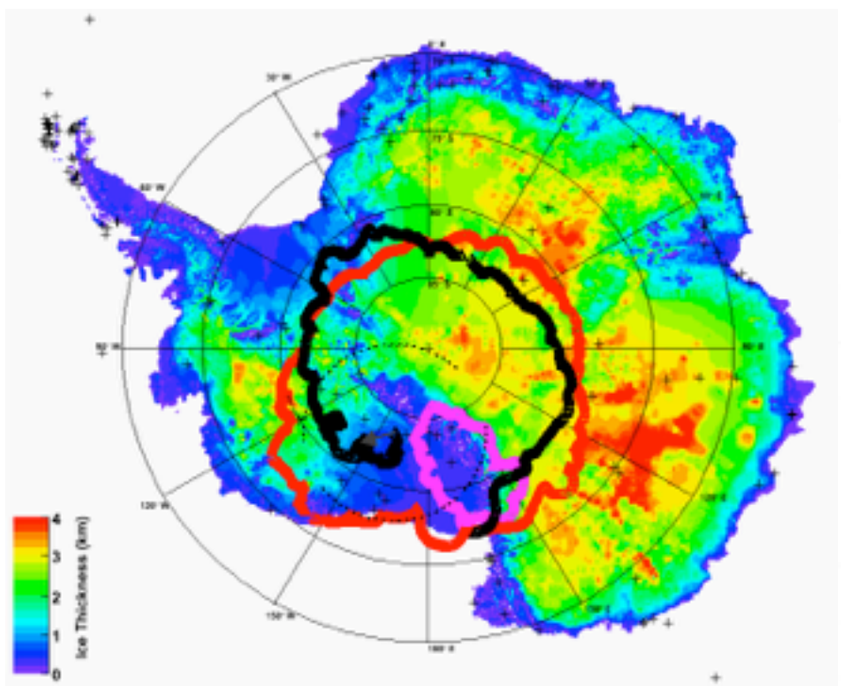


- Split trigger and waveform paths
- Use multiple frequency bands for trigger
- ‘Buffer’ waveform data in switched capacitor array
- Only digitise when we have a trigger

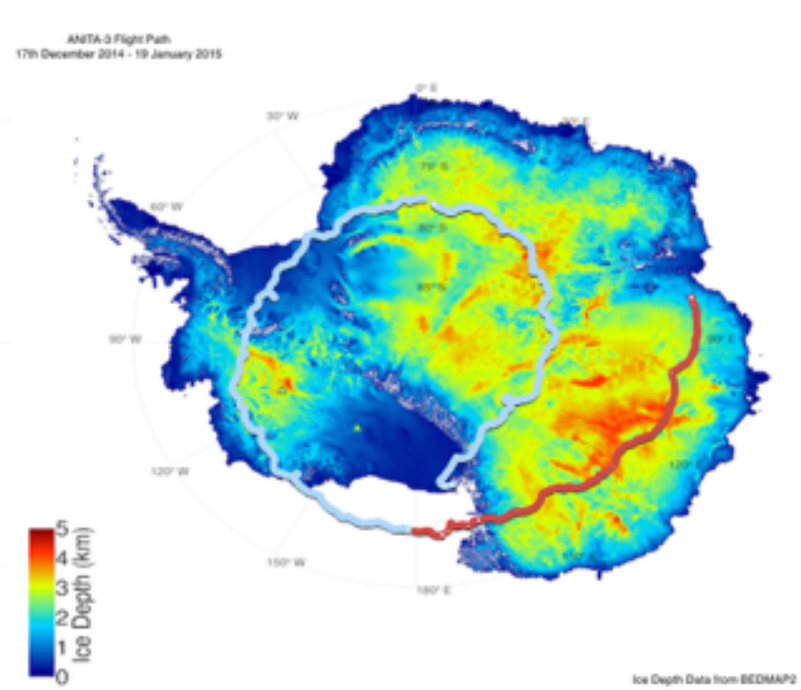
ANITA Flights



ANITA-1: 2006/7



ANITA-2: 2008/9



ANITA-3: 2014/15

Photo: J. Roth, U. Delaware

Photo: M. Mottram, UCL

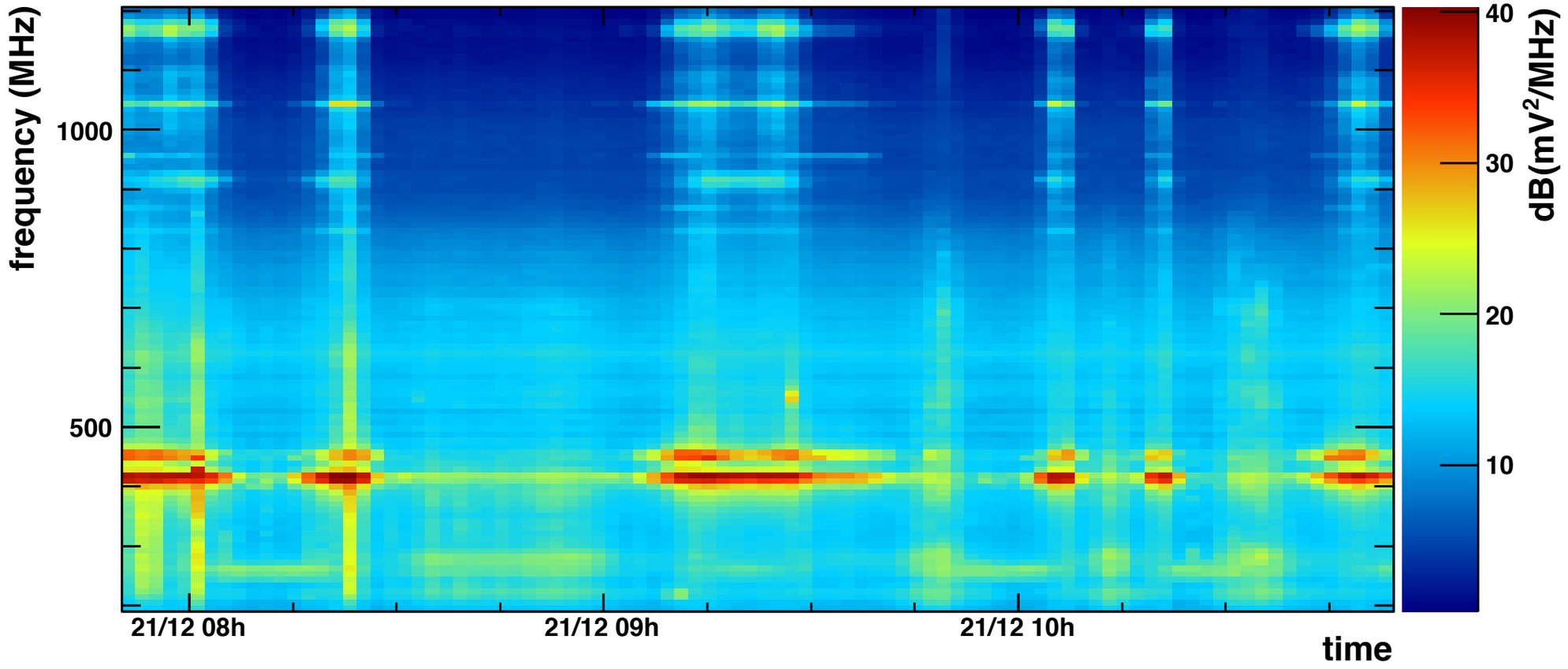
Photo: B. Hill, University of Hawaii

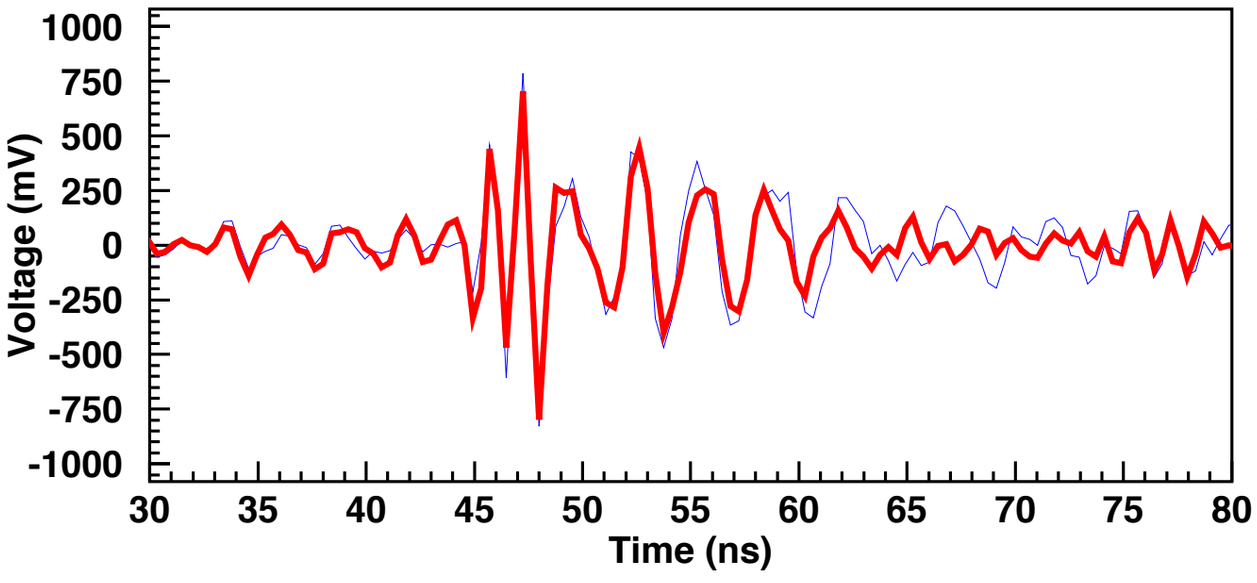
ANITA-3 End of Flight

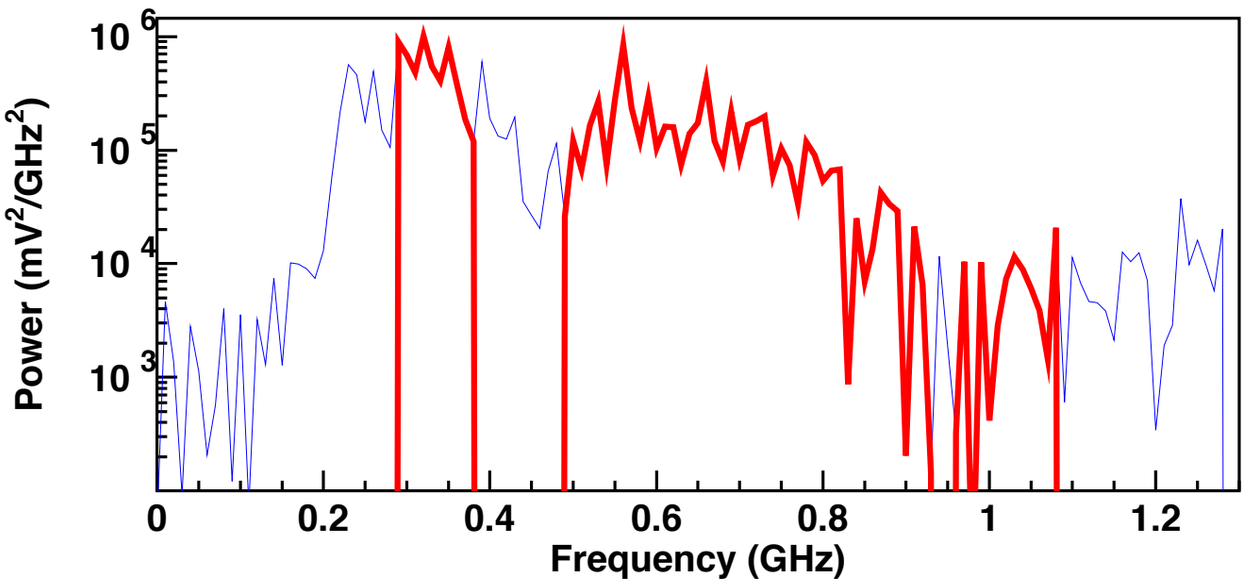
UCL

Image: Josh F., Australian Antarctic Division

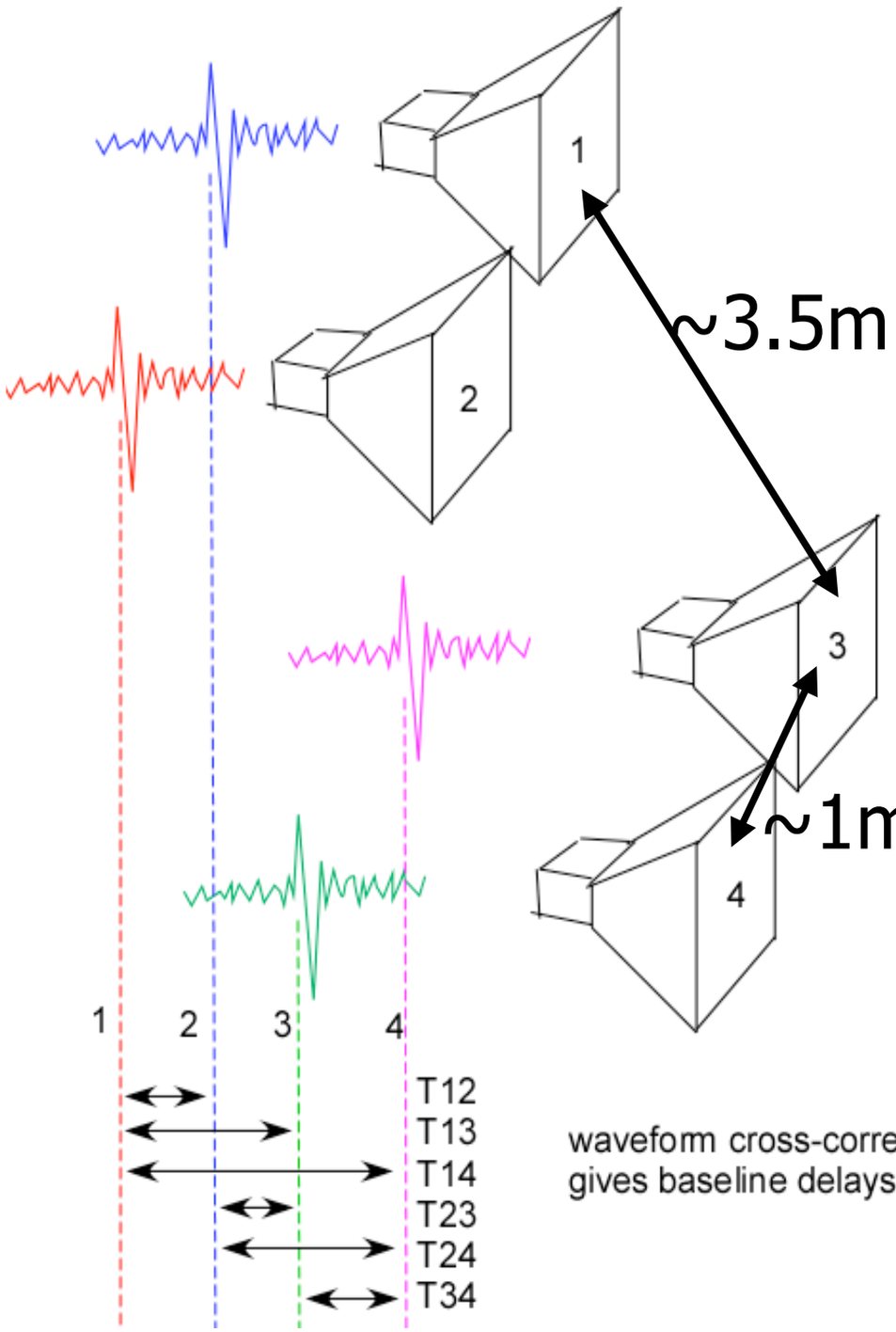
Analysis Step 1: Narrowband Noise





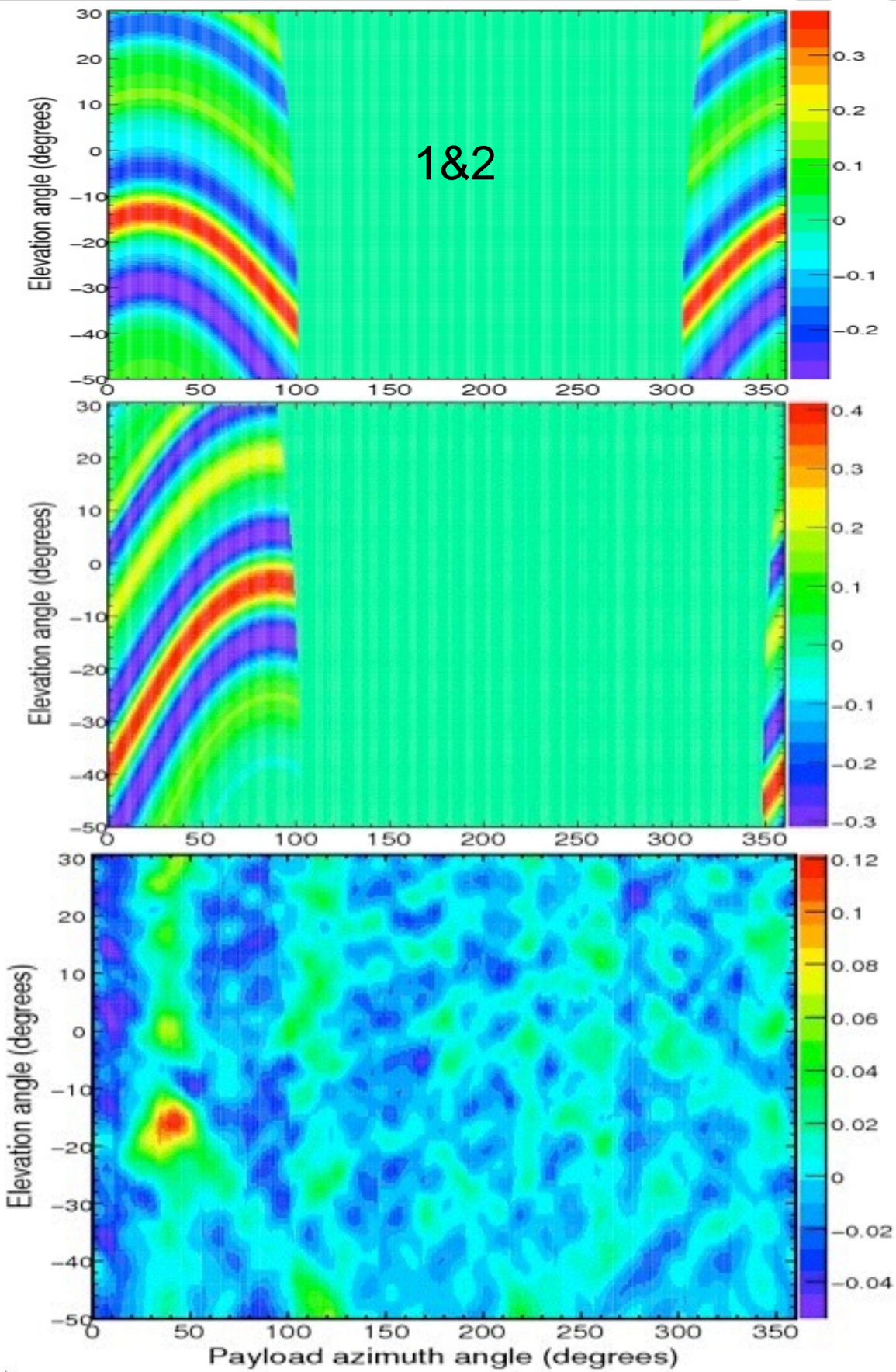


Analysis Step-2: Reconstruction

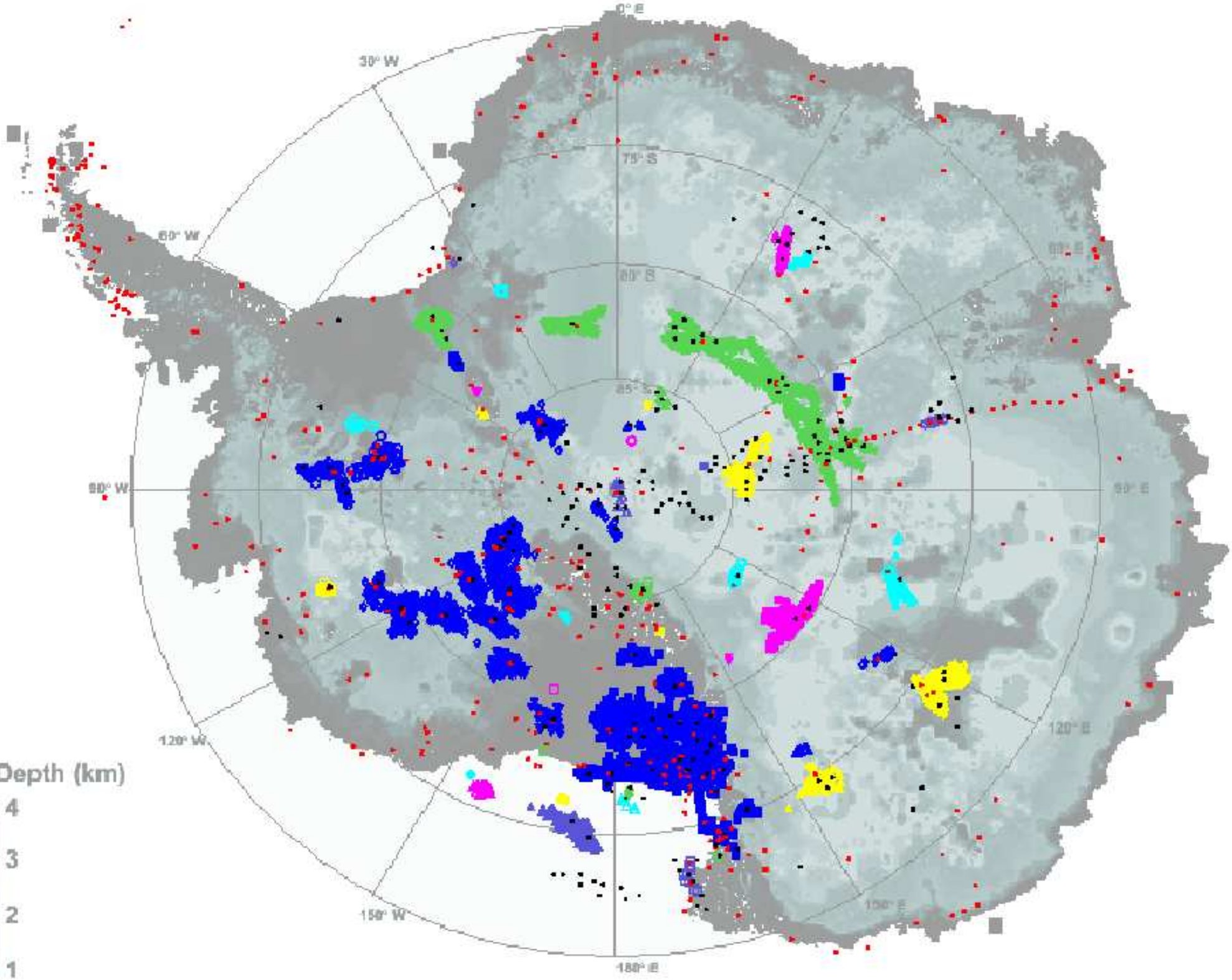


from A. Romero Wolf, Neutrino 2008

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



ANITA-2 Results



Neutrino Limits

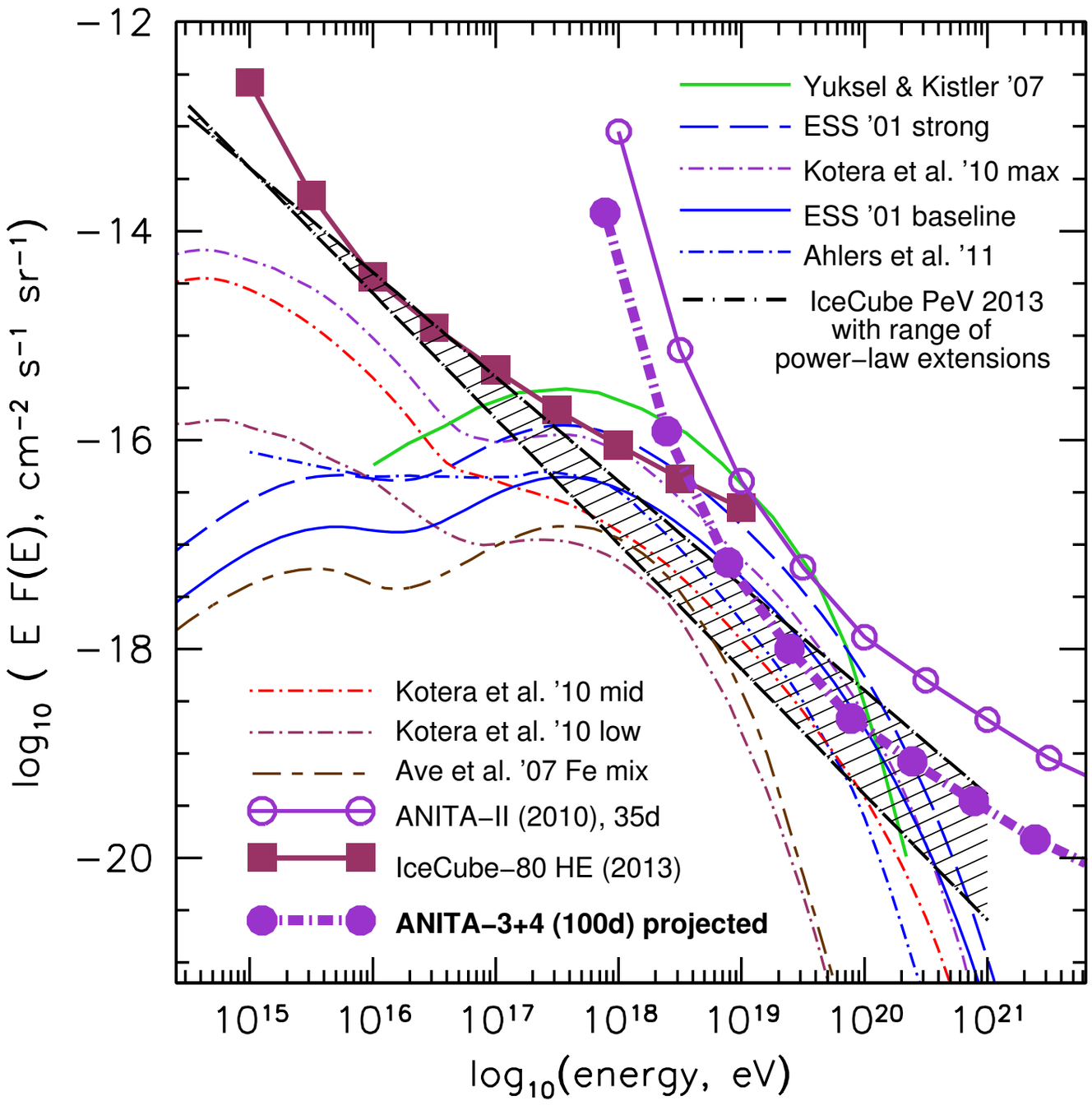
- ANITA-2 Results

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

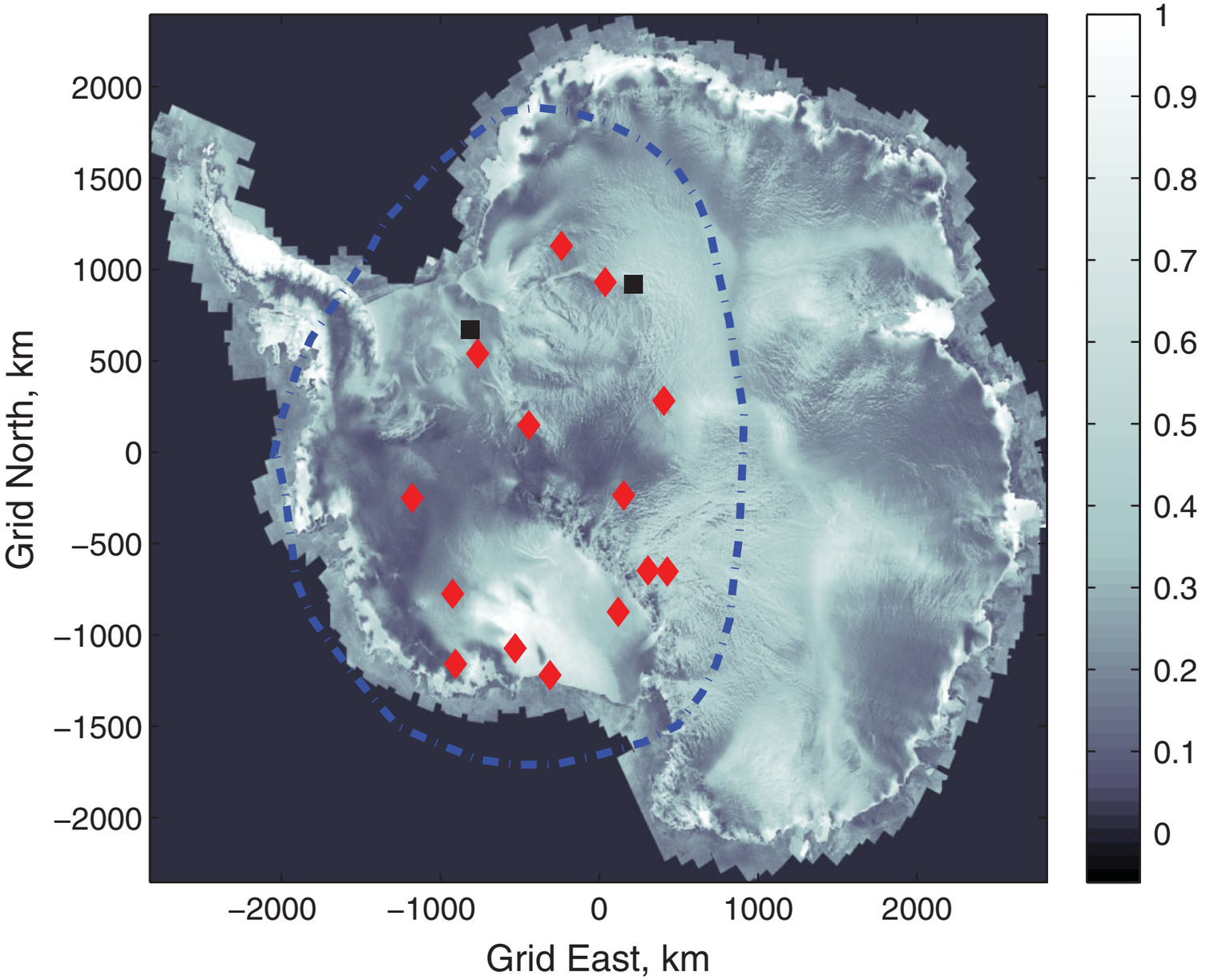
- Use calibration pulser and simulation to determine efficiency and set the best limit on UHE neutrino flux.

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

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



ANITA-1 H-Pol Results

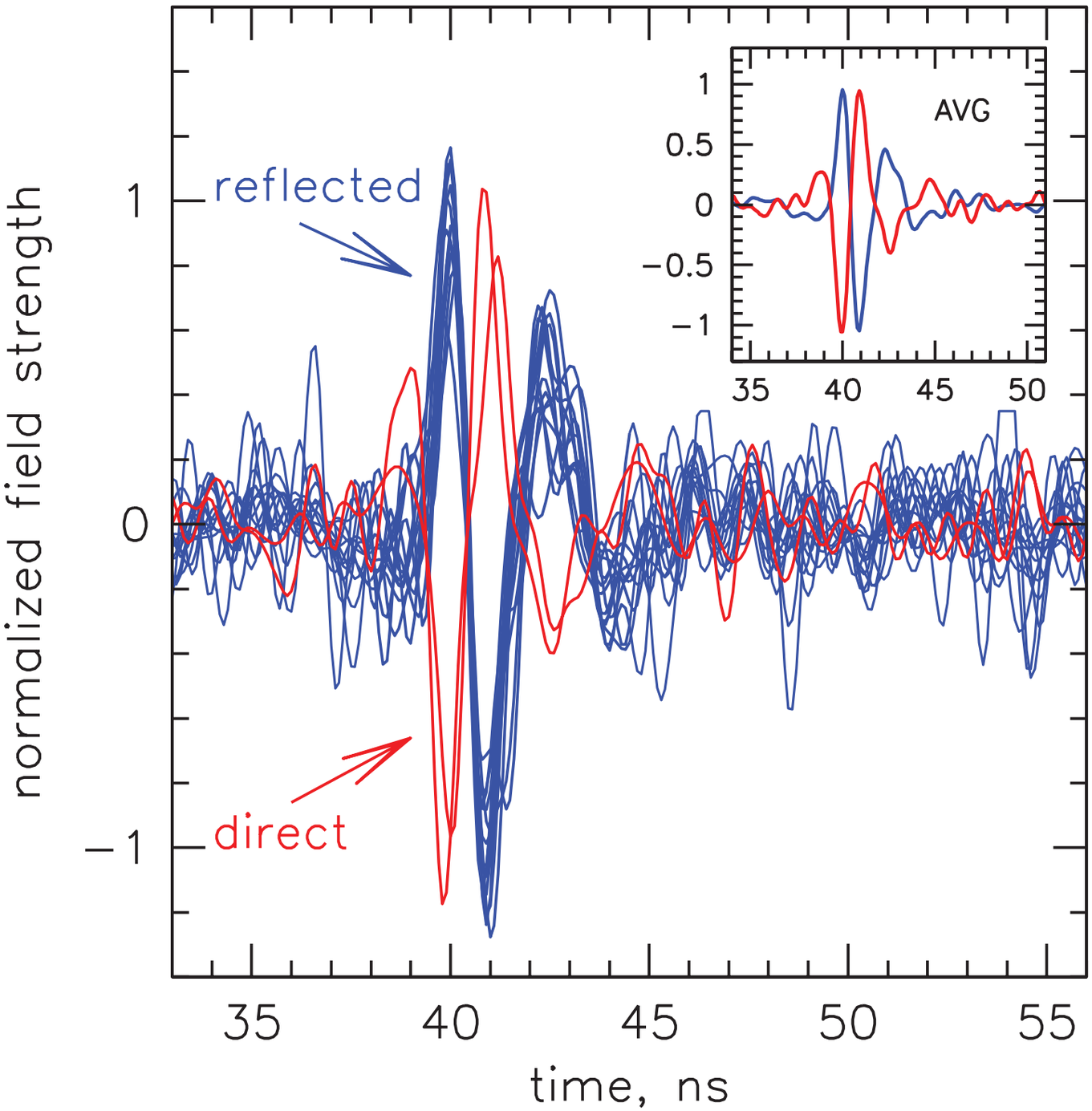


PRL **105**, 151101 (2010)

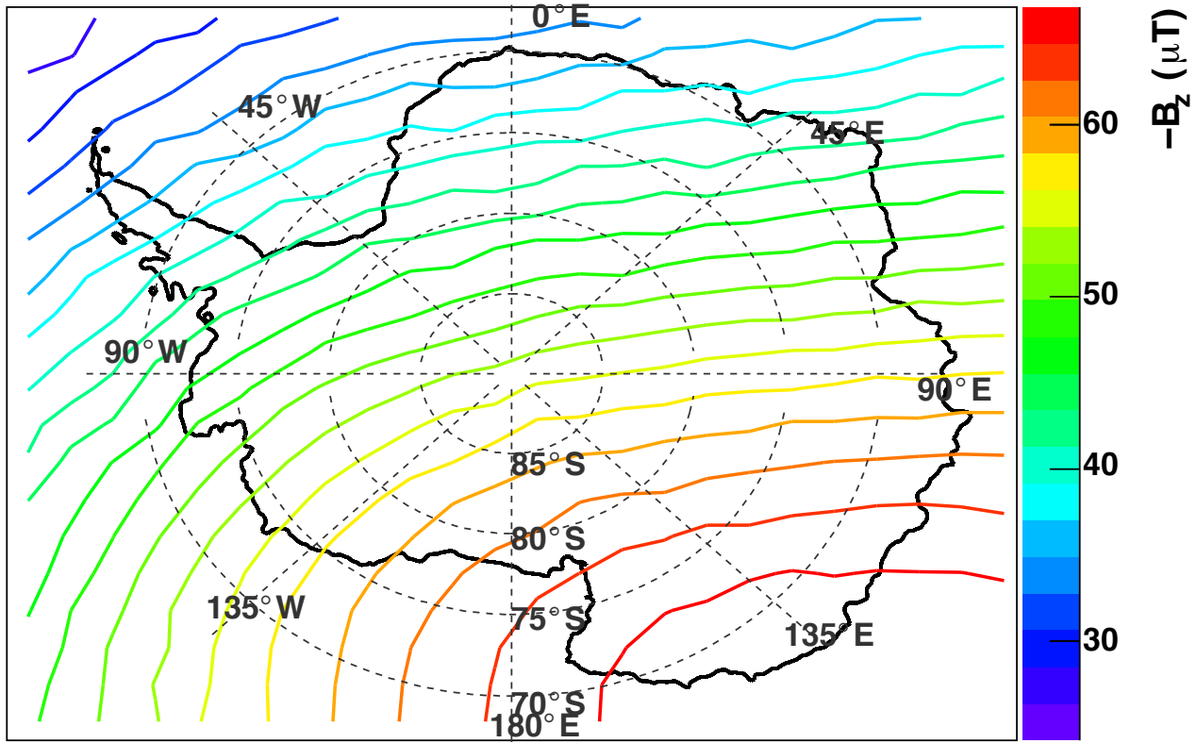
- Neutrinos signals are vertically polarised
  - Top of Cherenkov cone
- ANITA-1 detected 16 isolated H-pol candidate UHECR events
- ANITA-2 did not trigger on the H-pol channels
  - Doh!!
- Still detected 5 UHECR candidate

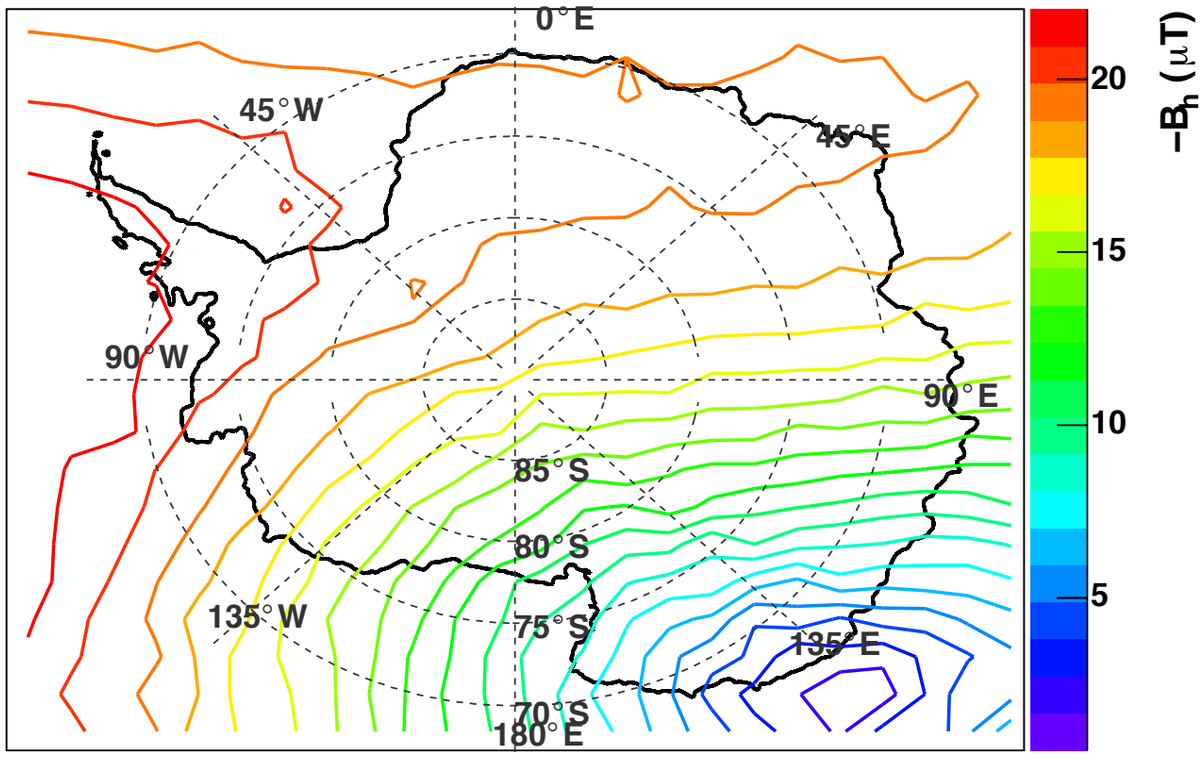
Are they really cosmic ray signals?

- 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

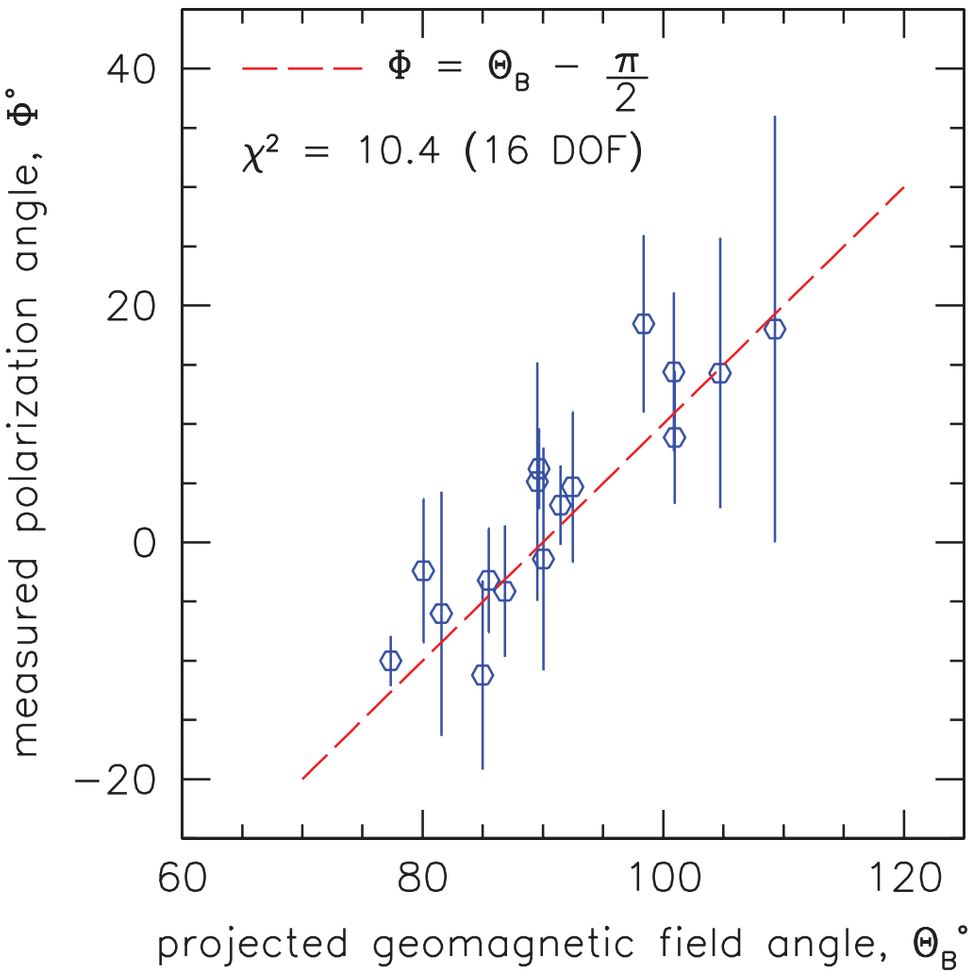


Are they really cosmic ray signals?



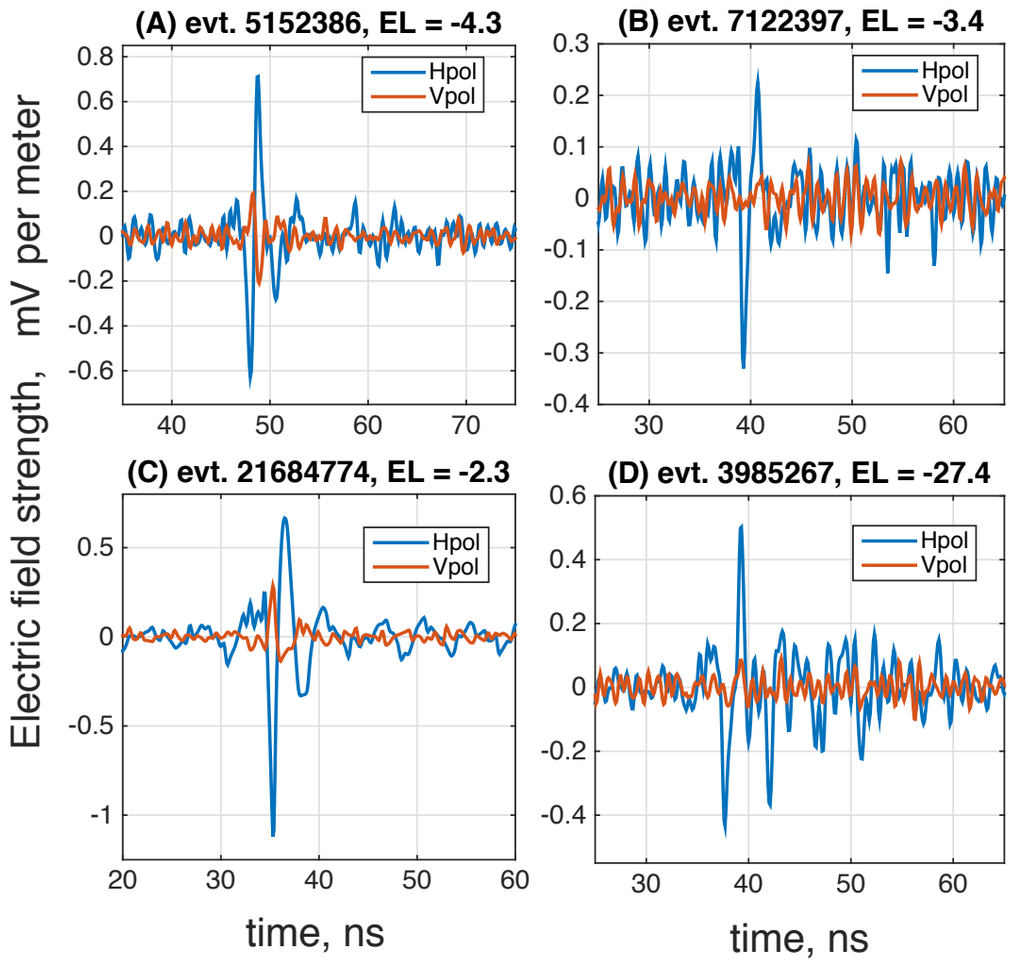


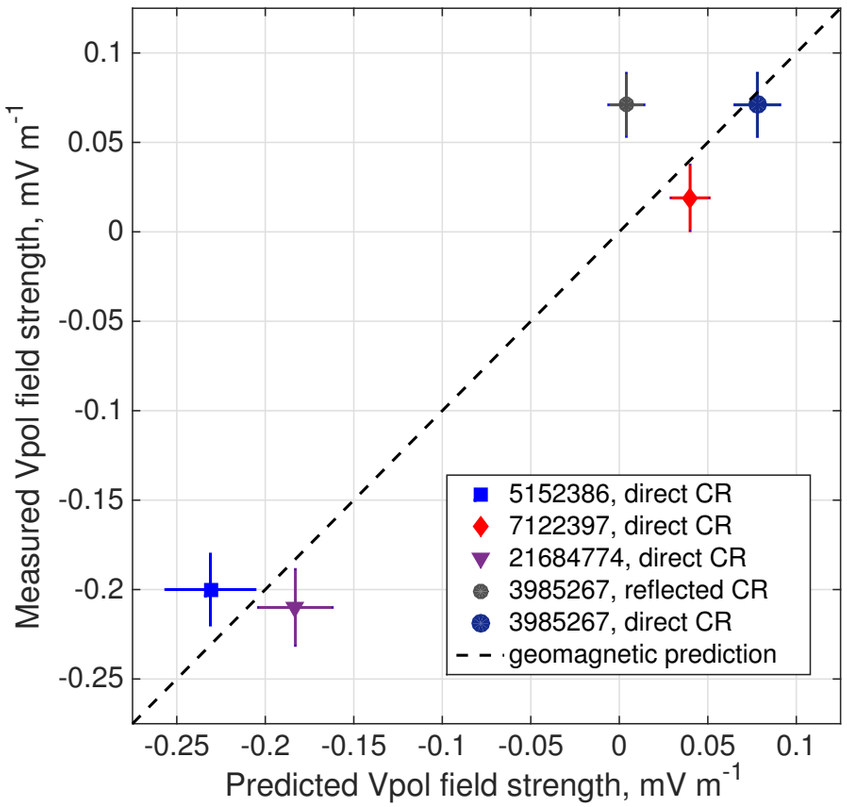
- Magnetic field is nearly (but not) vertical in Antarctica
  - **F**=q **v** x **B**



New mystery event (arxiv:1603.05218)

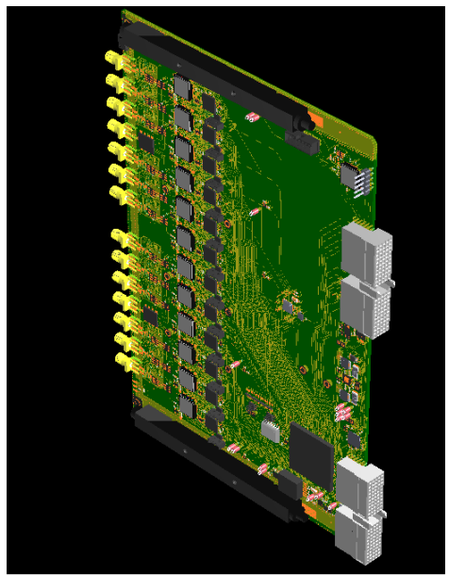
- Recent paper from ANITA discussing the direct cosmic ray signals in the 1st flight
- Uncovered one extra event that clearly points to the ice, but looks very similar to the direct h-pol waveforms
- The measured polarisation is consistent with a shower emerging from the ice
  - Could this be a tau neutrino candidate event?
    - Would require a significant change to the standard model cross-section?
      - 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-4

- Will fly in Antarctica this year
- Upgrading the digitiser and the trigger
- Most of the ANITA term are converging in Palestine, Tx
- Busy times ahead



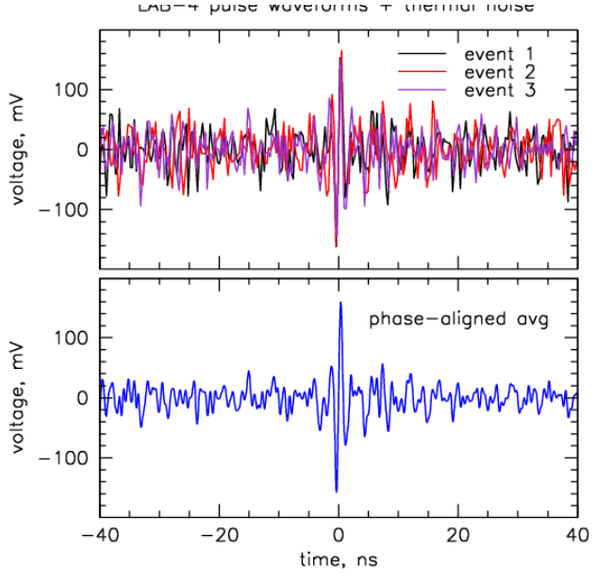
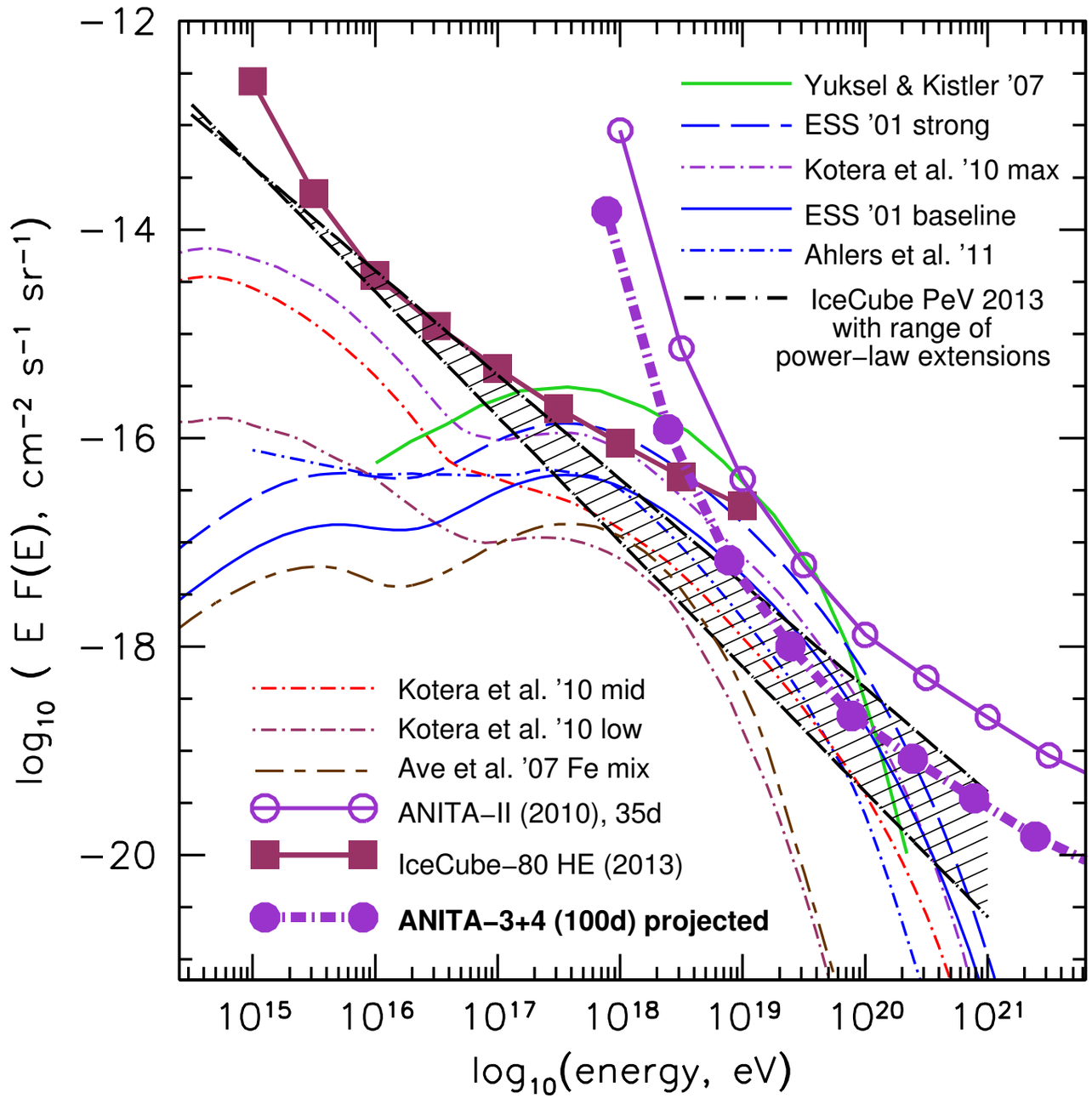


Figure 10: *Left: 3D CAD model of the new digitizer cPCI board for ANITA-3 & 4. Right: ANITA receiver chain test impulse waveforms captured with the LAB4 prototype board, along with phase-aligned average waveform.*

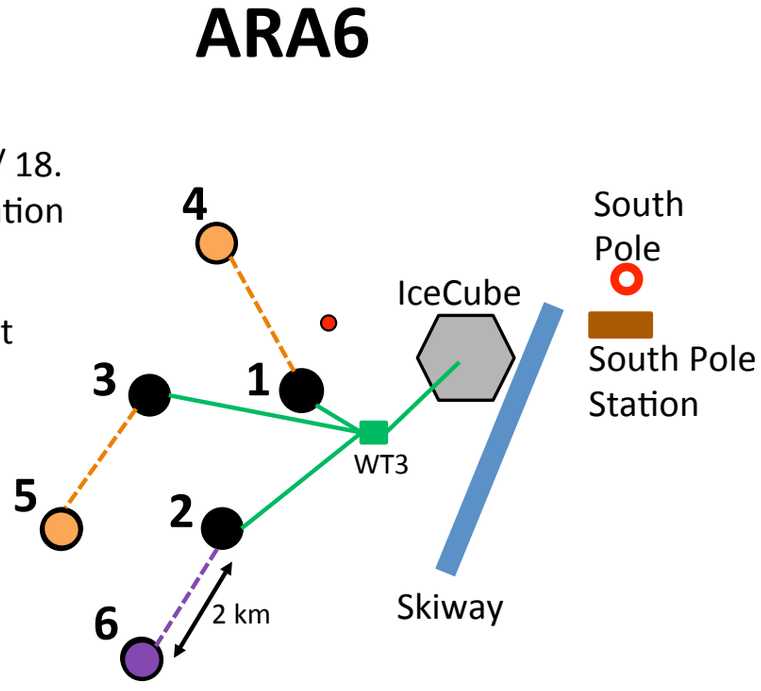


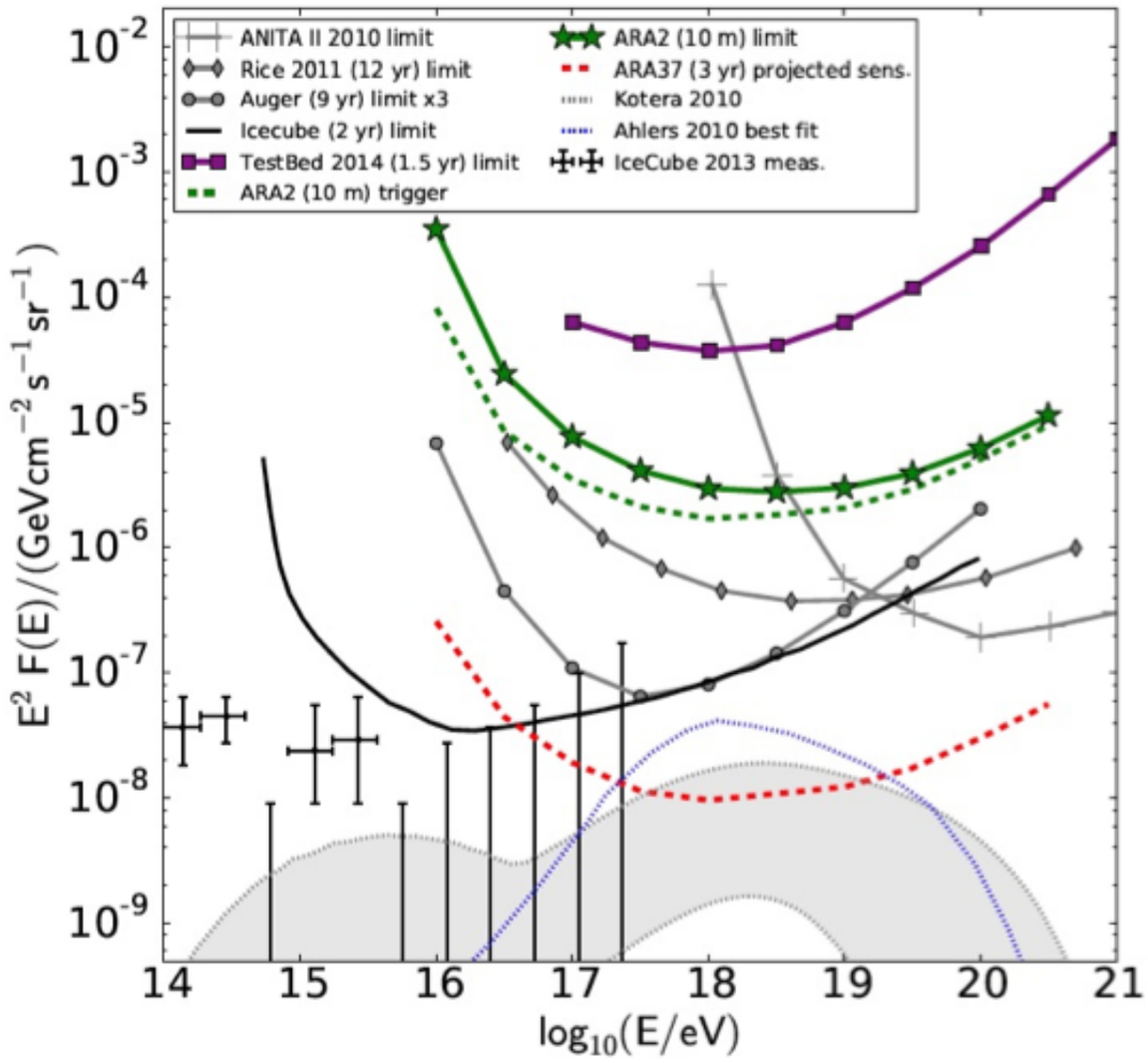
Future projects

Deployed ARA Station

Instrumentation deployment in 17 / 18. Site / road preparation in 16 / 17.

Potential if support is available



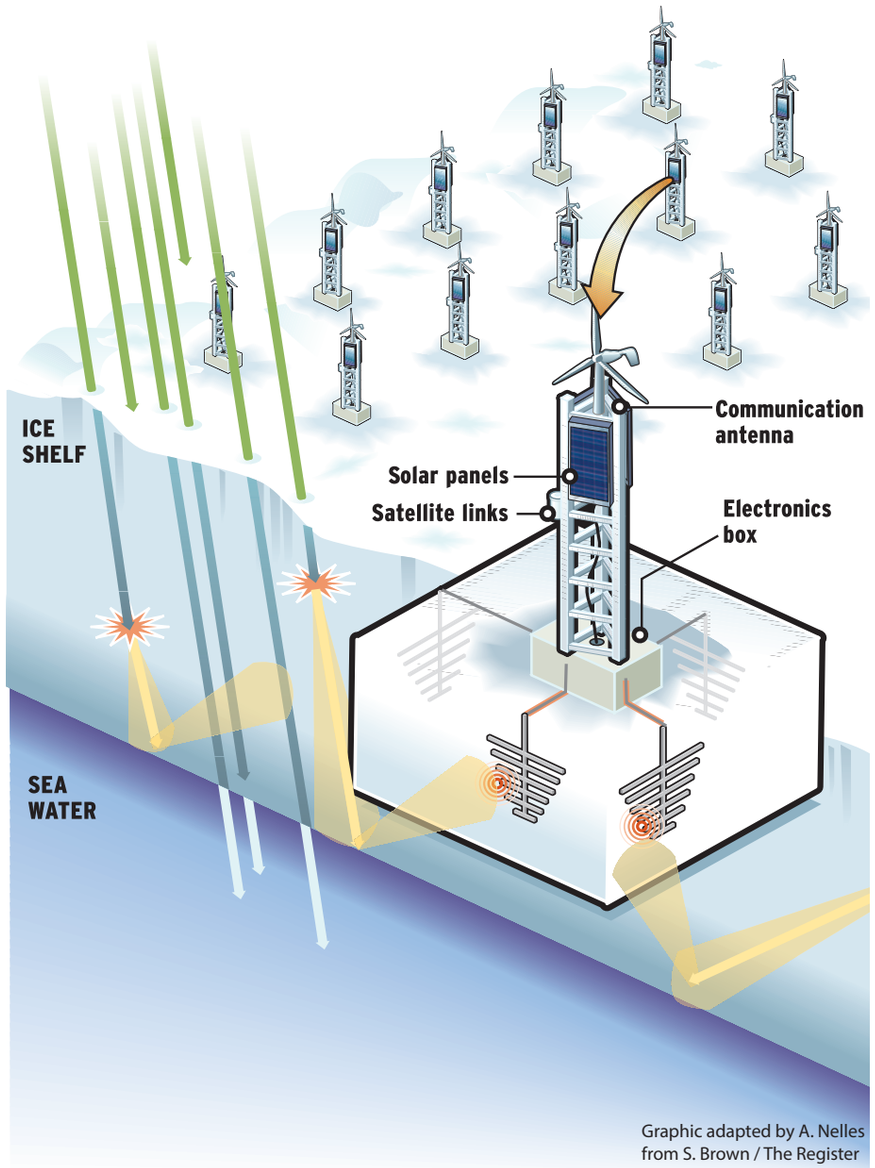


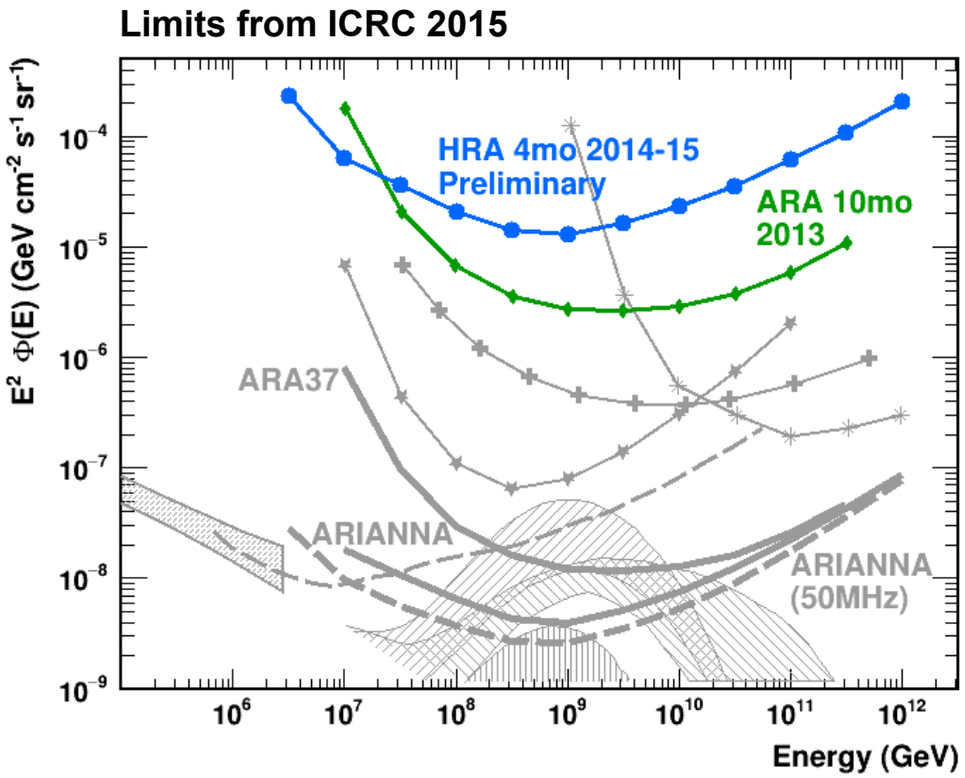
- ARA has three operating deep stations at the South Pole.
  - Another 3 stations already constructed
  - Approval to install two stations in season 17/18
  - Several analysis improvements on the way (see ARENA talks)

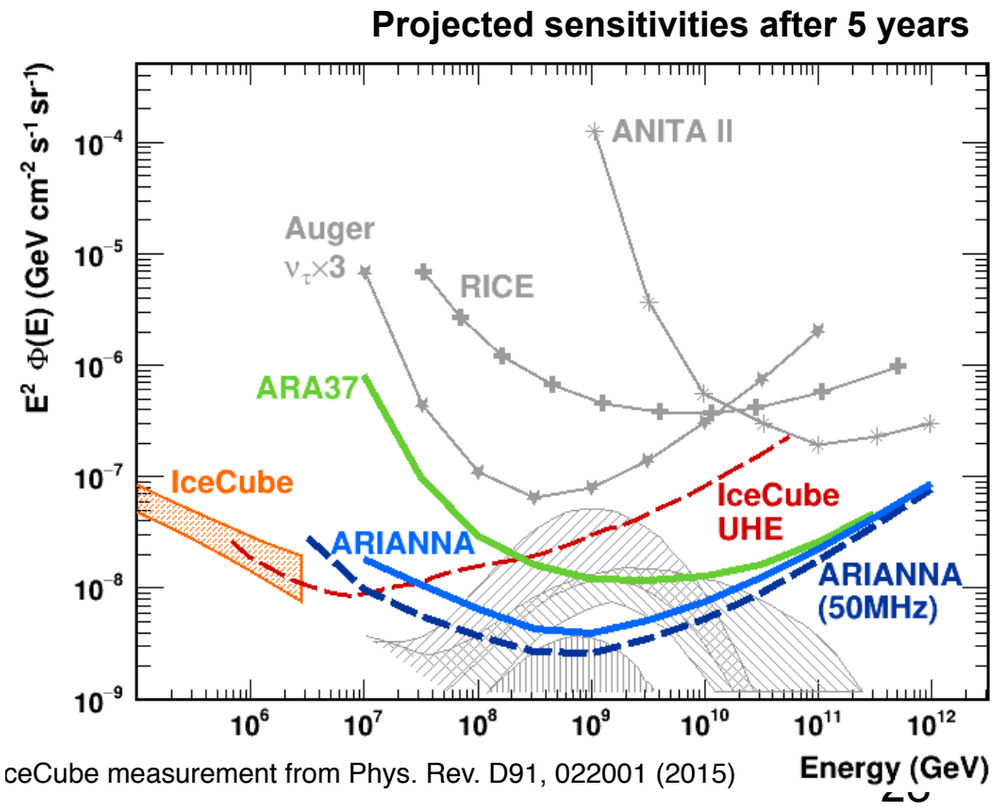
from C. Pfender, ARENA2016

ARIANNA

- Proposed array of antennas on the Ross Ice Shelf
- Currently running the hex station since 2015





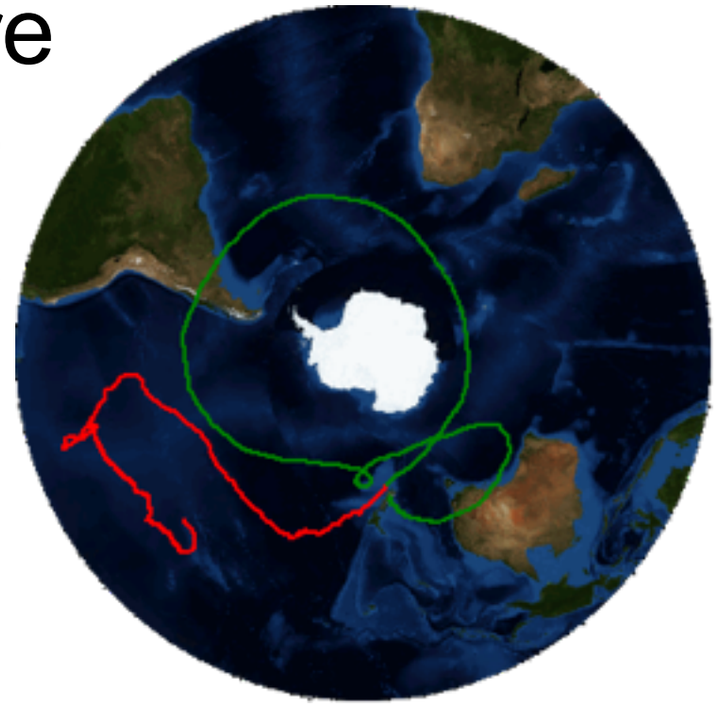


ceCube measurement from Phys. Rev. D91, 022001 (2015)

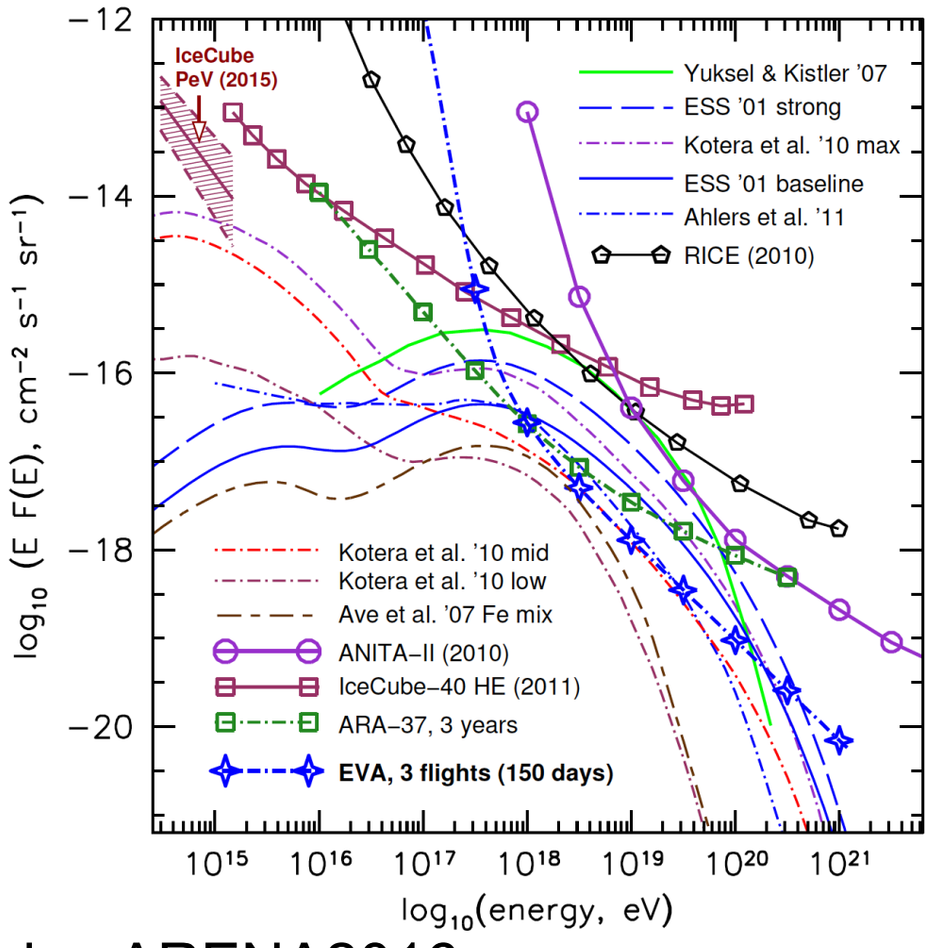
from A. Nelles, ARENA2016

EVA

- Planned super-pressure balloon which uses the balloon as the antenna
  - Increases the antenna gain by 20dB
- Small scale (1/20) test version demonstrated

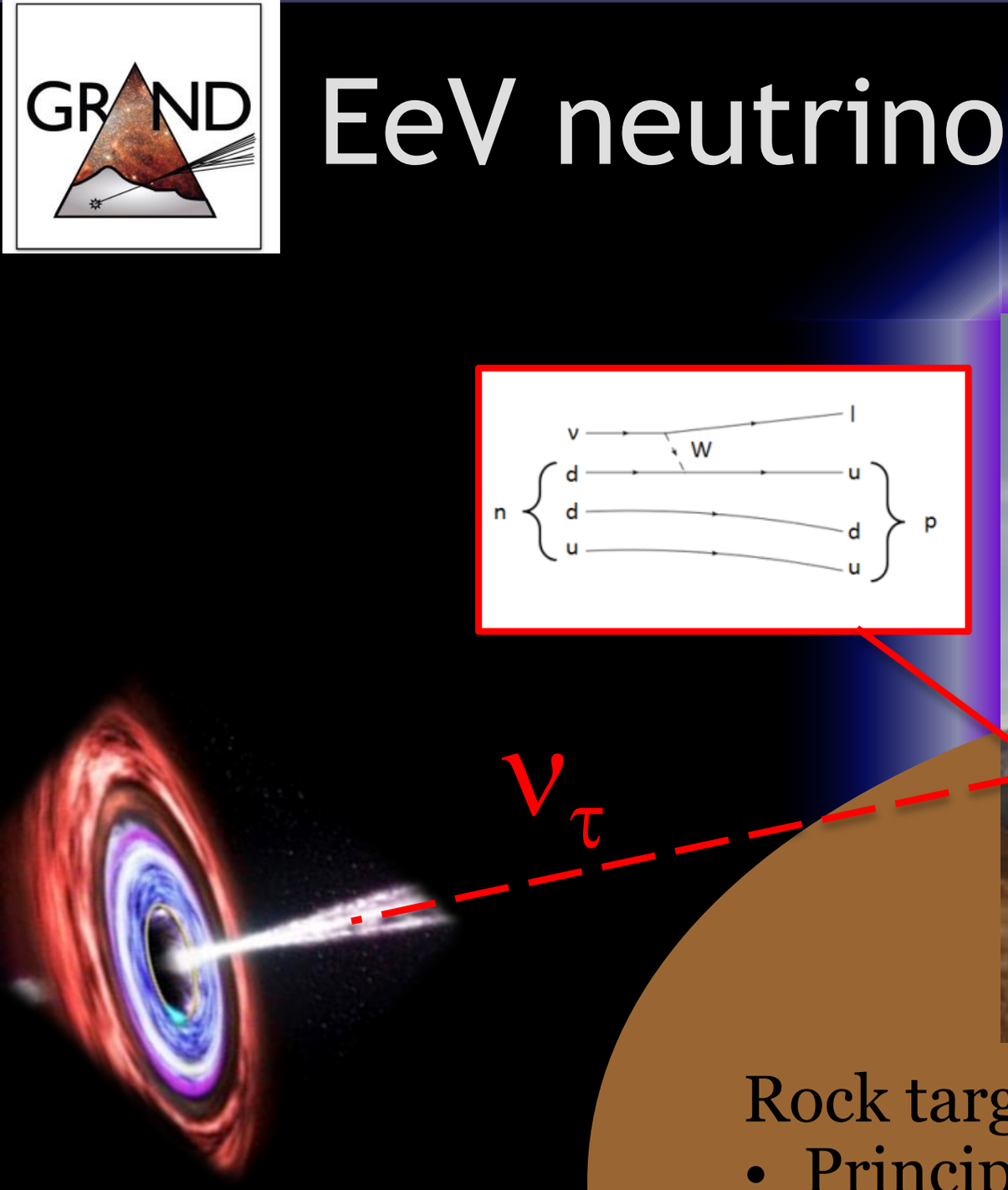


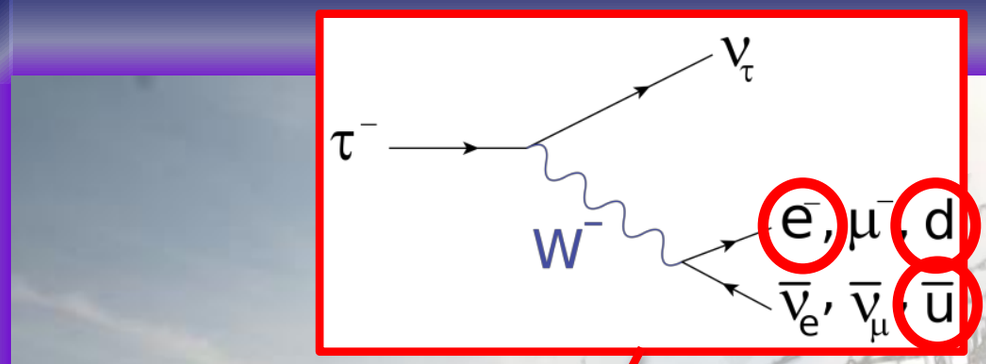
COSI-SPB 36 Days and Counting



from C. Pfender, ARENA2016

EeV neutrino detection





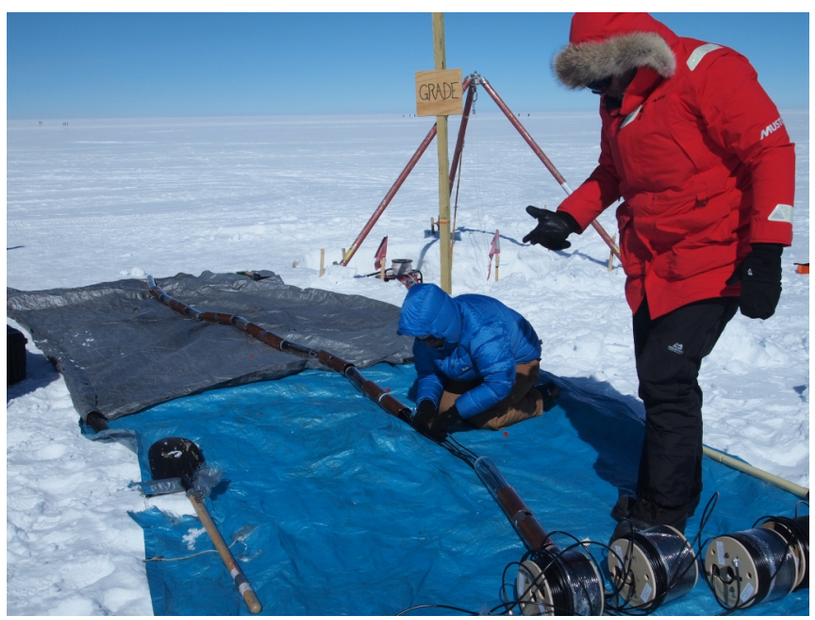
Rock target:

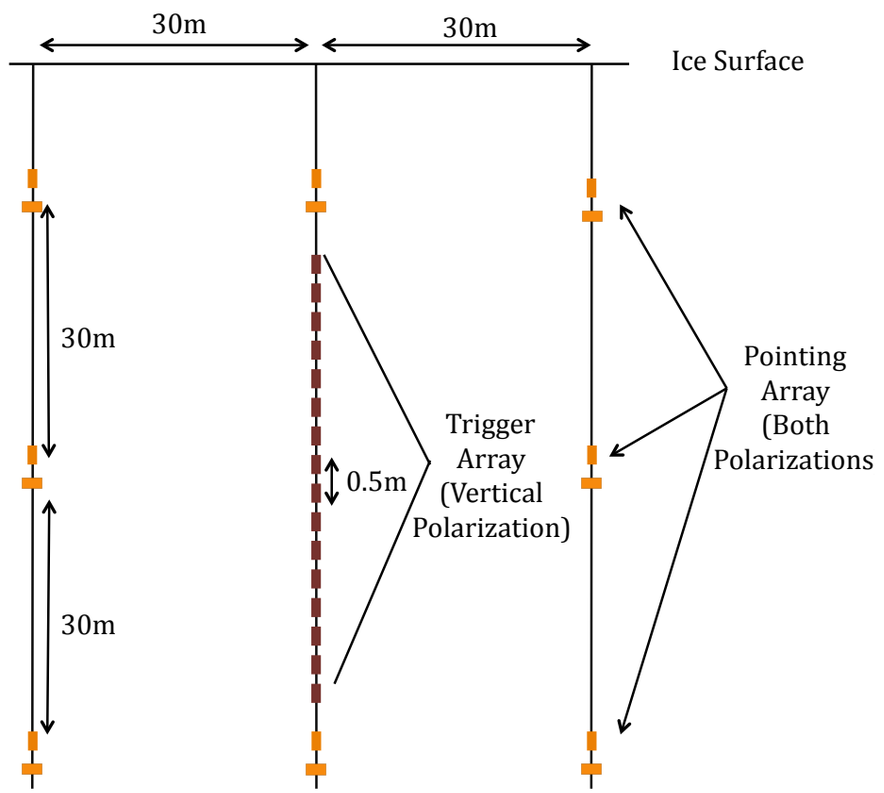
- Principle:
  - ν-induced tau decays in atmosphere generate ~horizontal extensive air showers.
    [Fargion astro-ph/99066450, Bertou astro-ph/0104452]
- Issues:
  - VERY seldom events
  - Earth-skimming trajectories

From: O. Martineau
at ARENA2016

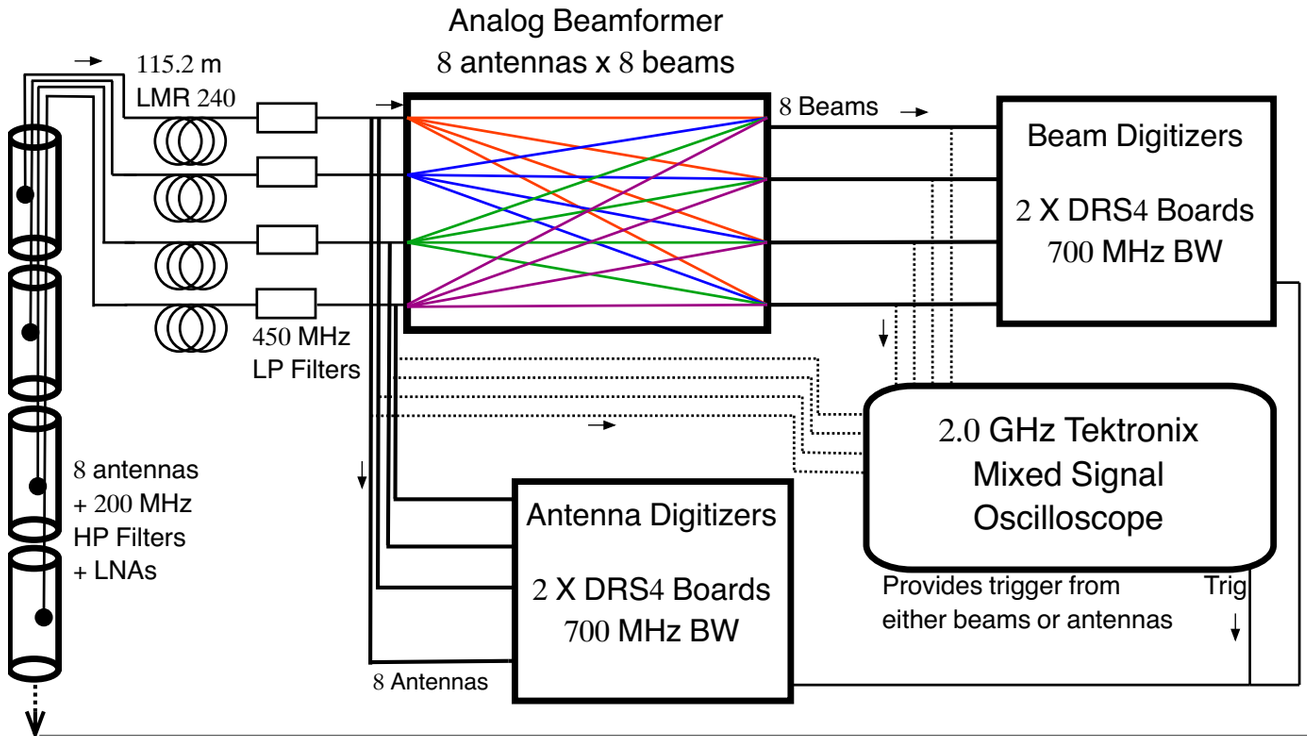
Phased Arrays (e.g. GNO)

- Coherently sum signals to increase gain



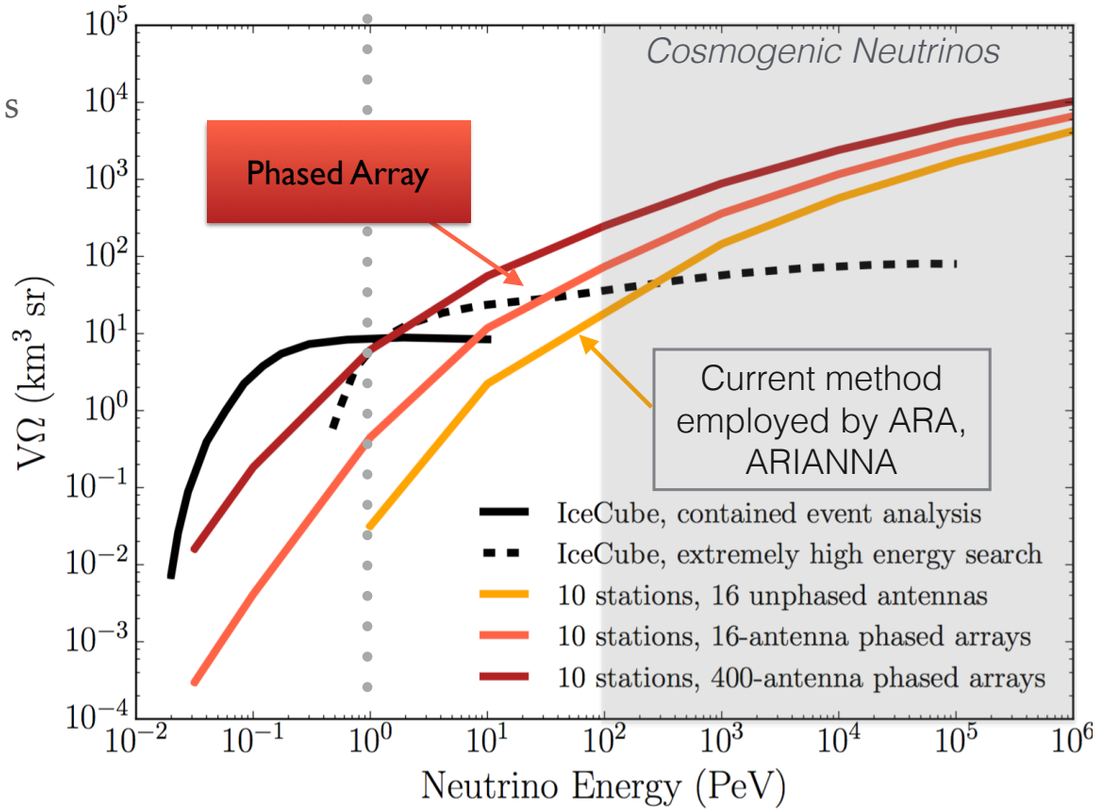


Vieregg, Bechtol, Romero-Wolf JCAP 2016 arXiv:1504.08006v1



Analog Phased Array Prototype at Summit Station, June 2015

From: S. Wissel ARENA2016



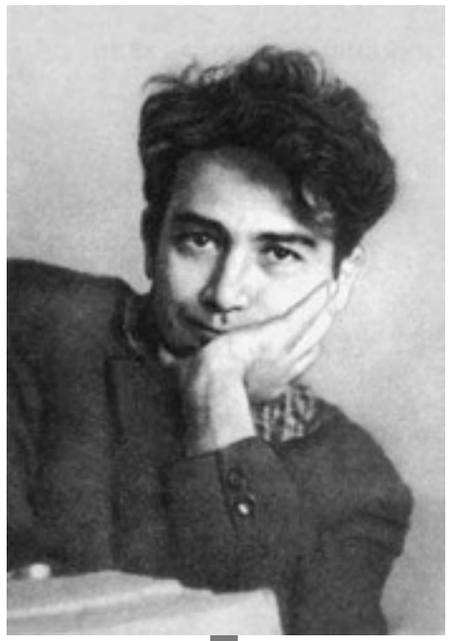
Summary

- The radio detection of high energy particles is undergoing a period of renaissance
- The first two flights of ANITA have been used to set the most stringent limits on the UHE neutrino flux
  - ANITA-1 did detect 16 UHECRs though
  - ANITA-3 should have recorded O(10-100) UHECR events
- 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 UHECR

Me in front of the Royal Society Range

Photo: H. Schoorlemmer , University of Hawaii

Pre-history



John V. Jelley *et al* record first radio pulses associated with high energy particles (from an air shower)

1964/5

National University of Ireland
Faculty of Science
University College, Dublin

RADIO AND OPTICAL METHODS
OF
DETECTING COSMIC RAYS

Thesis for the degree of
DOCTOR OF PHILOSOPHY

Presented by
TREVOR C. WEEKES, B.Sc.

Research Supervisor
N.A. PORTER, PH.D.
Professor of Electron Physics

March, 1966.

Radio experiments at Haverah Park, Jodrell Bank, Mount Chacaltaya, Penticon, Medicini, Dublin and Kharkov

1966-75

1962

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

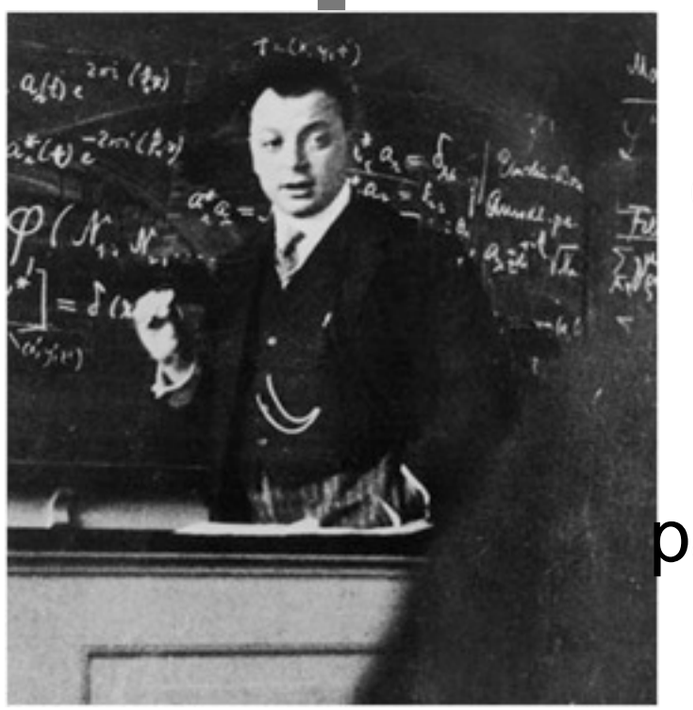
1966

Trevor C. Weekes, who actually recorded the first radio event, is awarded the first PhD for the radio detection of cosmic rays

Brief scientific timeline leading to ANITA

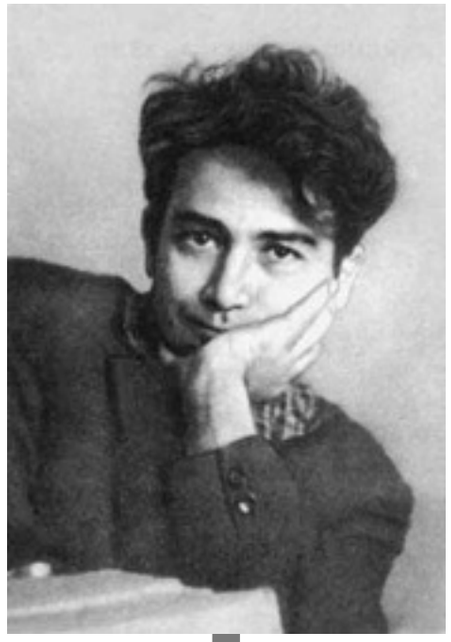
1912

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

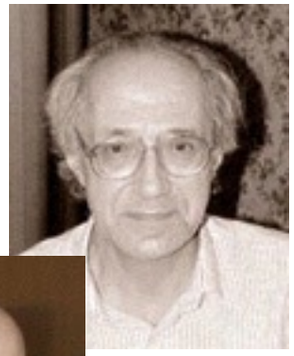


1962

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

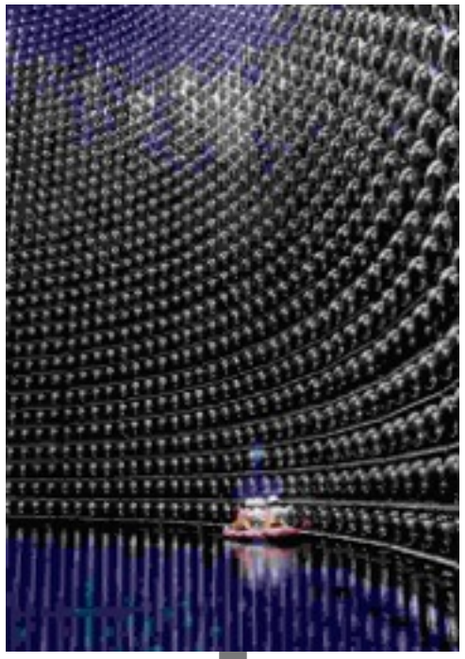
Wilson and Penzias discover the cosmic microwave background

1965



Kamiokande, IMB and Baksan detect neutrinos from a nearby supernova

1987

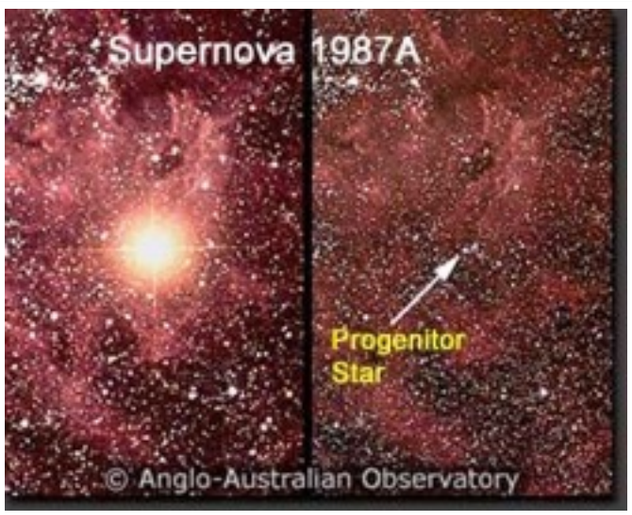


ANITA-I launches from Williams Field in Antarctica

2006

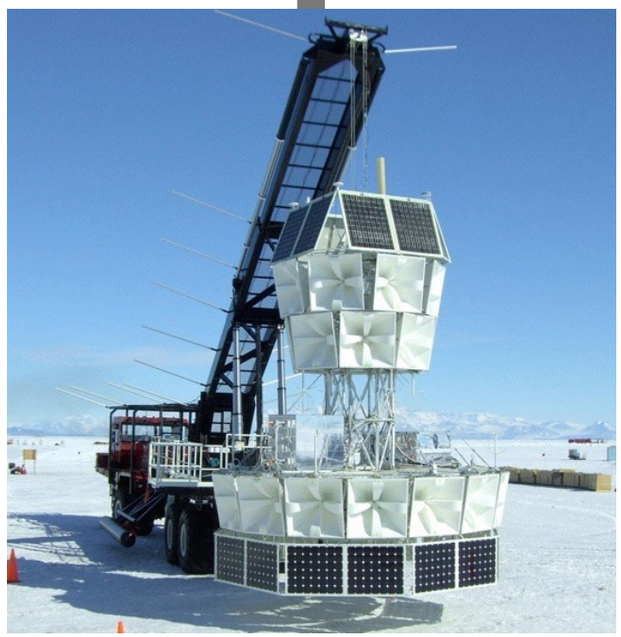
1966

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



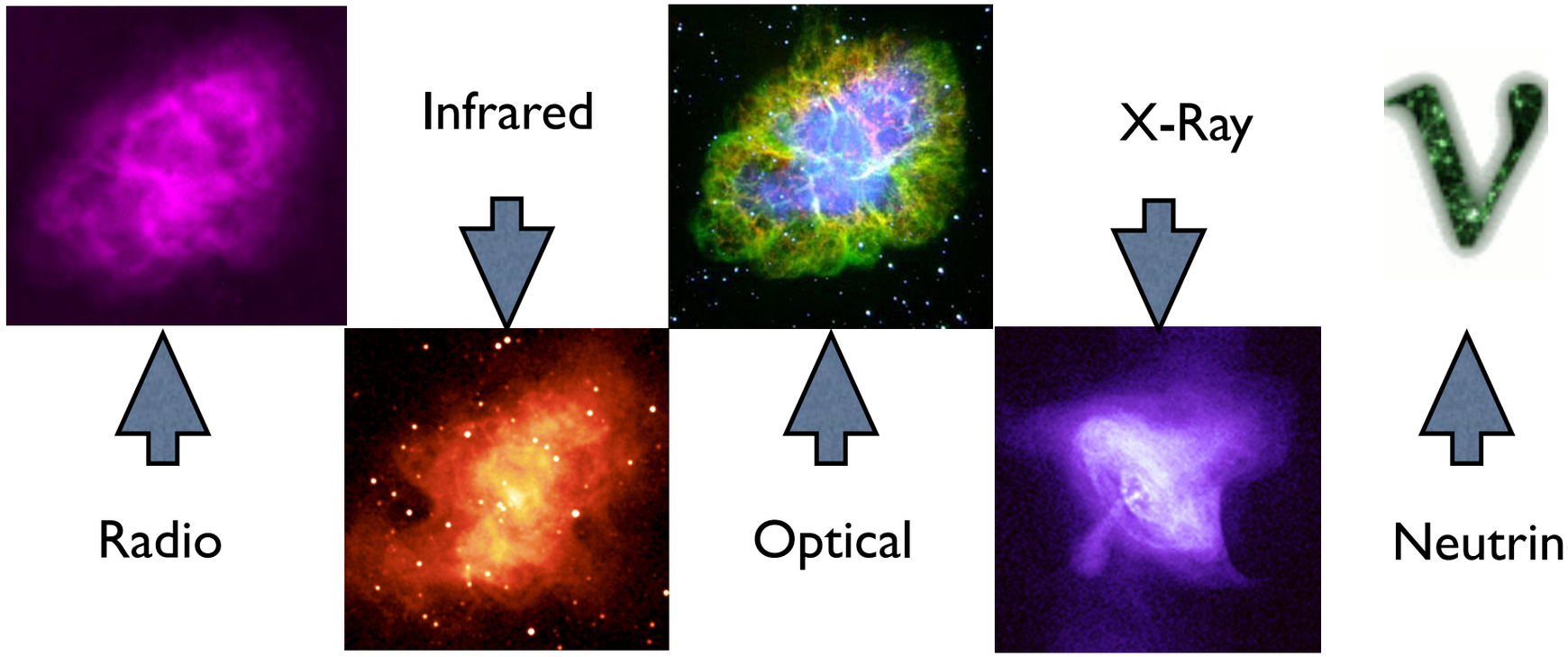
1998

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



Why High Energy Neutrinos?

For Astronomers:
The Pretty Pictures Argument



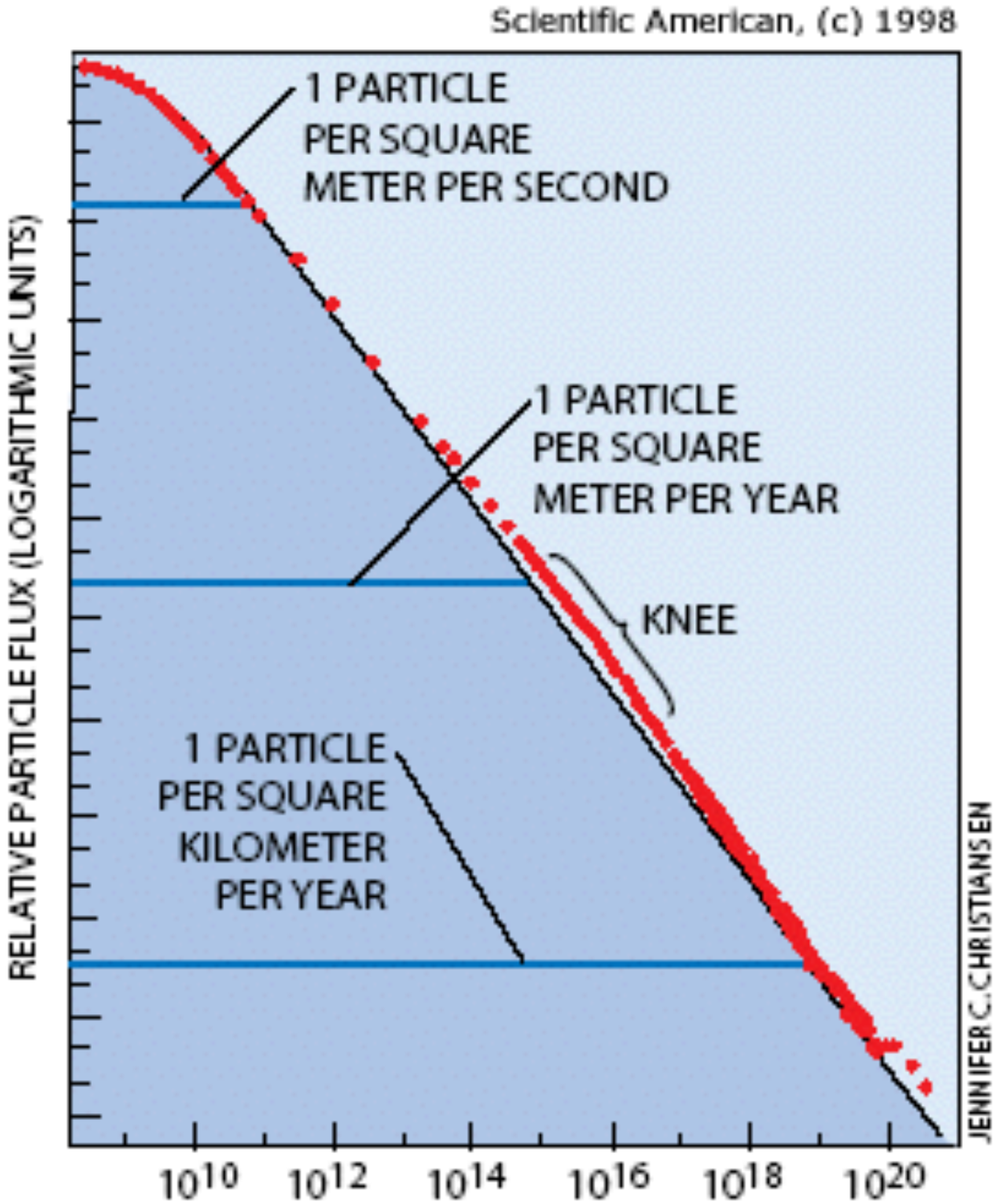
For Particle Physicists:
The 300 TeV (CoM) Neutrino Beam Argument

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

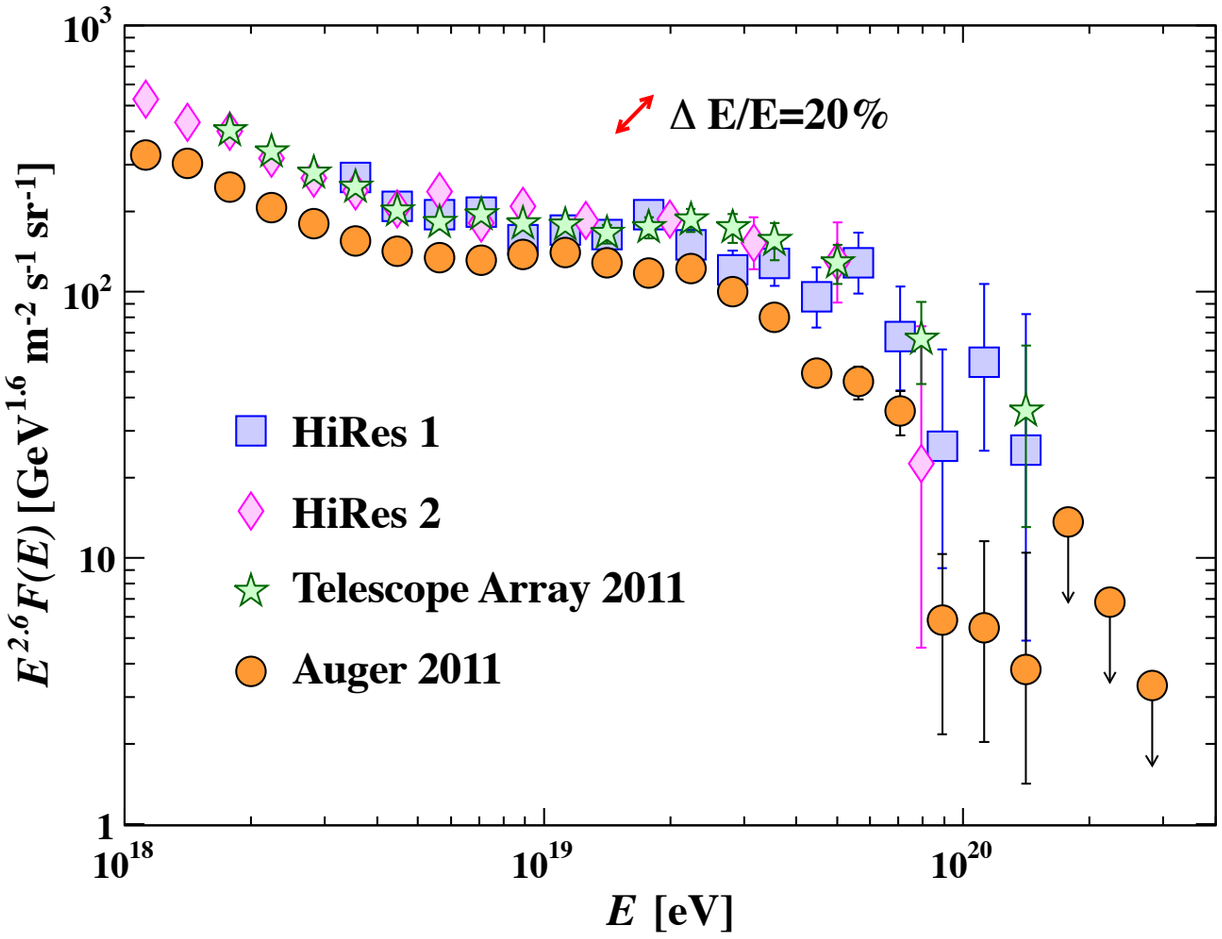
Cosmic Ray Riddle

Symmetry Magazine, Sandbox Studio

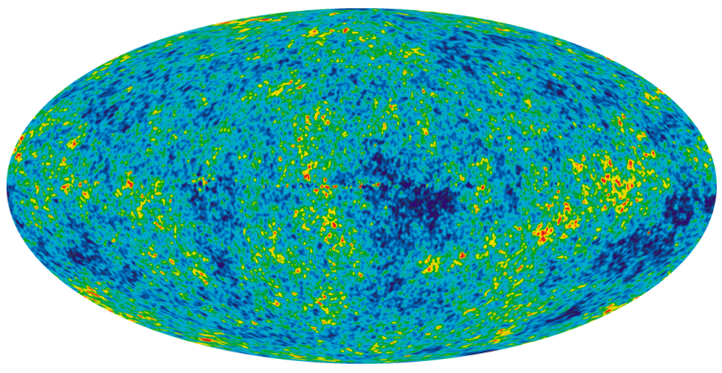
- Where do the highest energy cosmic rays come from?
- Nearby sources should point
- Faraway sources should be attenuated by the cosmic microwave background
- Could neutrinos solve the problem?



Aside: The GZK Effect



+



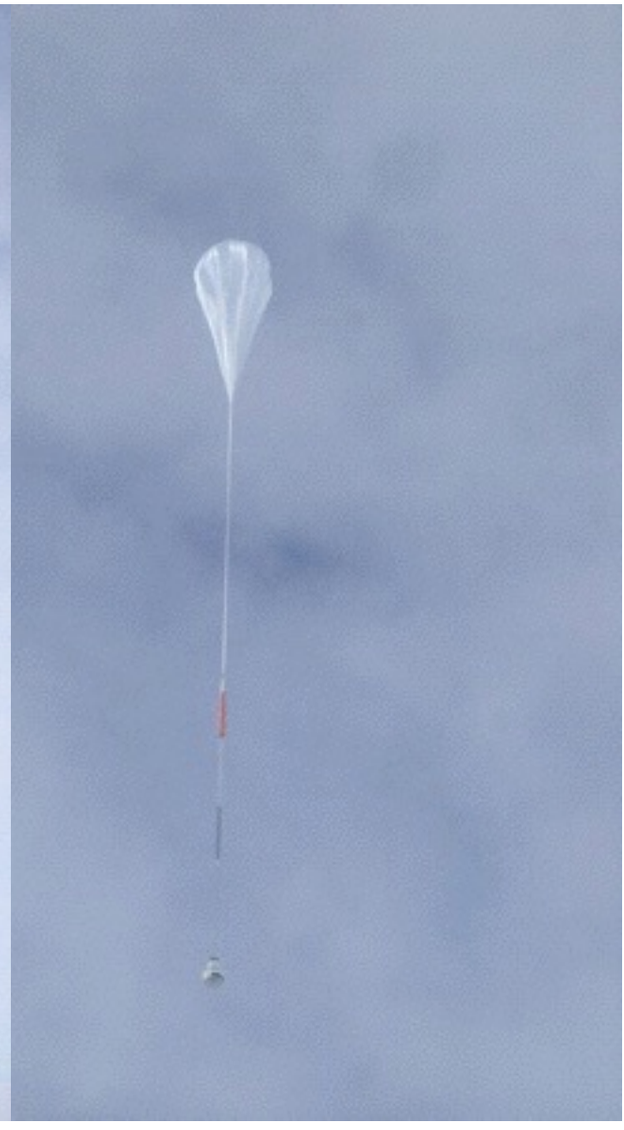
- Greisen-Zatsepin-Kuzmin (GZK) calculated cosmic rays above $10^{19.5}$eV should be slowed by CMB within 50MPc.
- Berezinksy and Zatsepin realised this would produce a flux of neutrinos

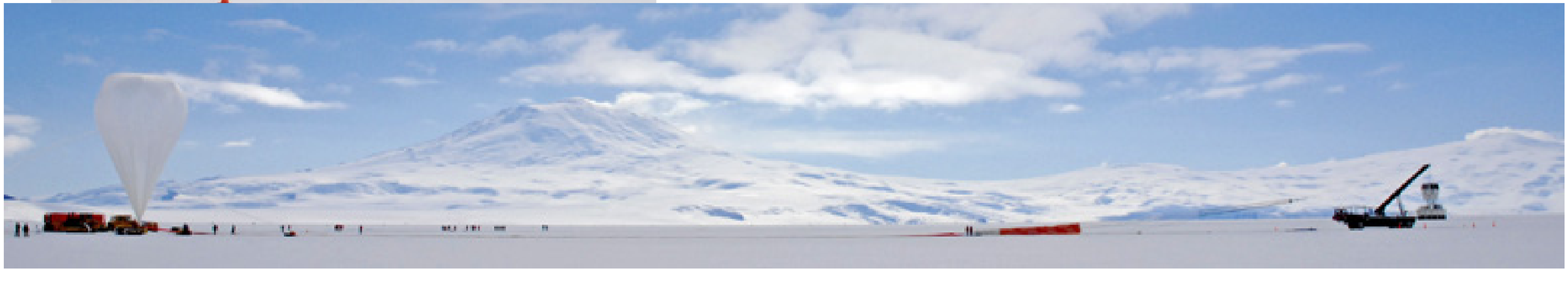
$$p + \Upsilon_{CMB} \rightarrow \Delta^* \rightarrow n + \pi^+$$
$$\searrow \mu^+ + \nu_\mu$$
$$\searrow e^+ + \overline{\nu_\mu} + \nu_e$$

= “Guaranteed” Cosmogenic Neutrino “Beam”!

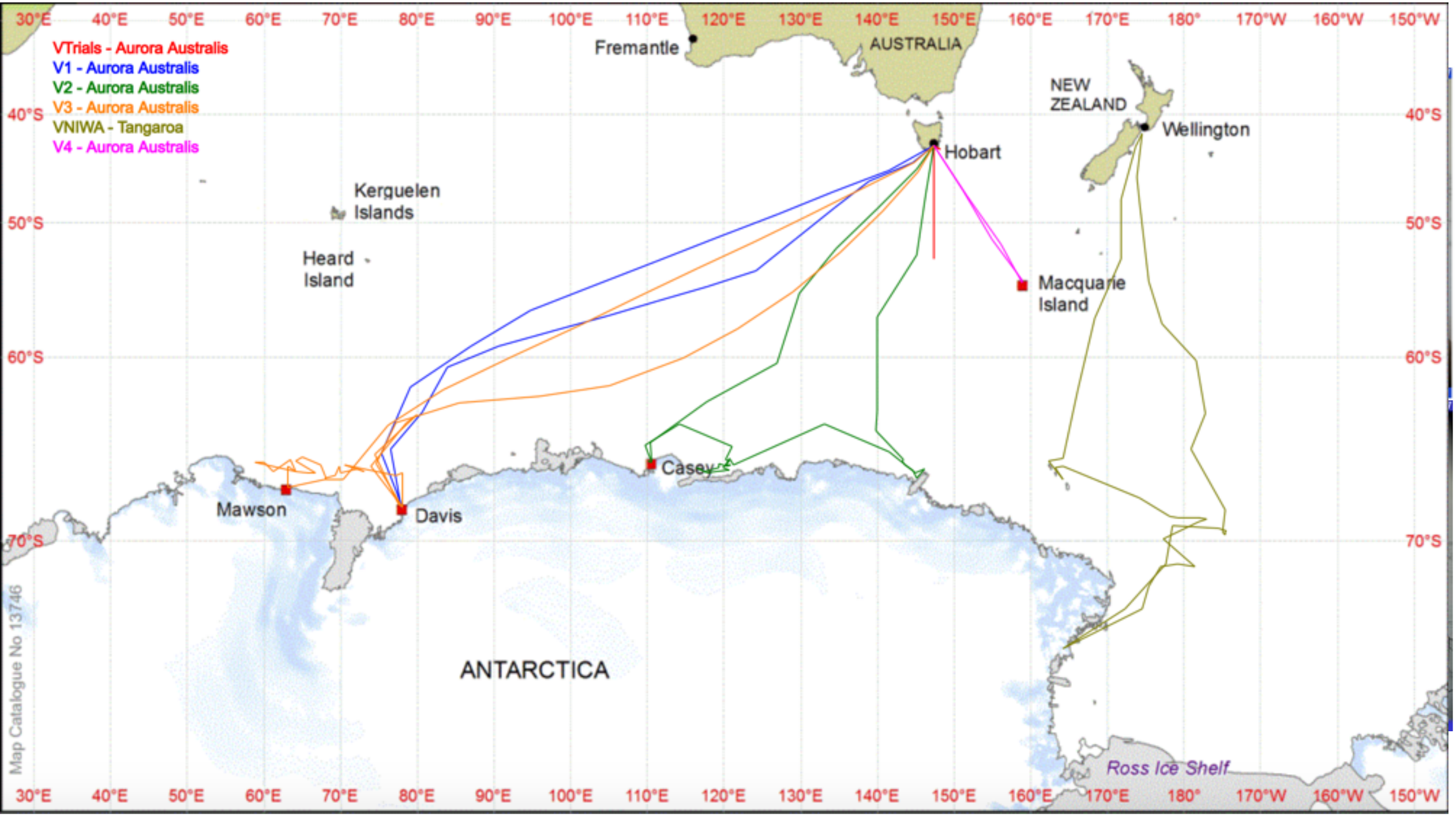
Up, up and away

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





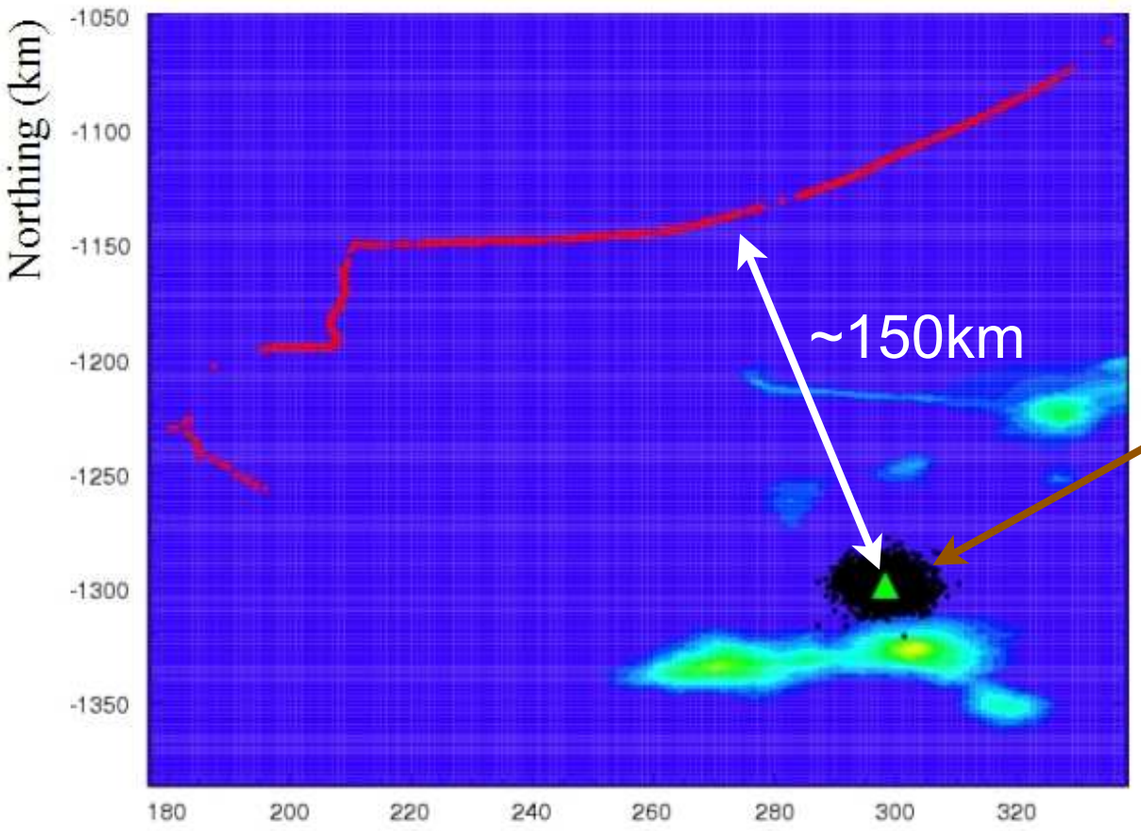
Where is the Aurora Australis?



https://secure3.aad.gov.au/public/schedules/voyageTrack.cfm?season=1415

http://www.antarctica.gov.au/webcams/aurora

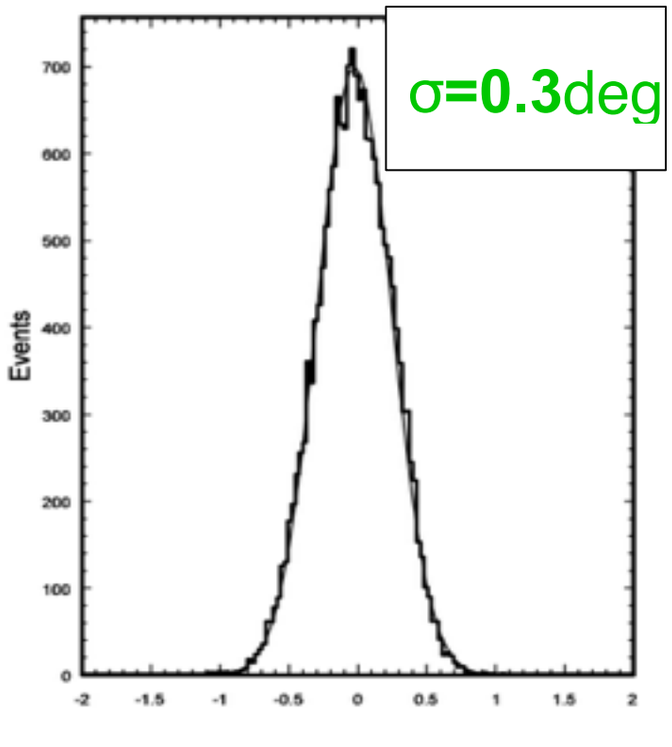
Calibration



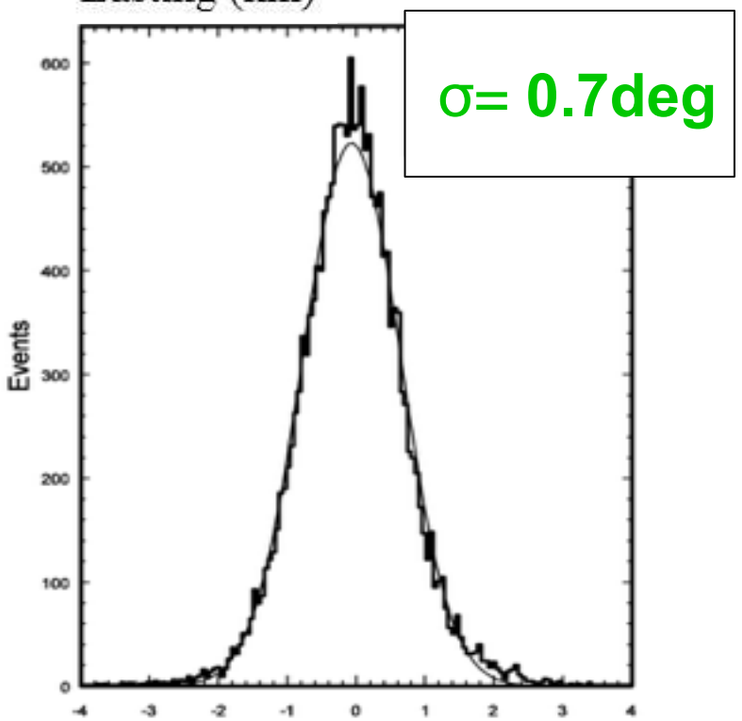
Reconstructed event locations

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

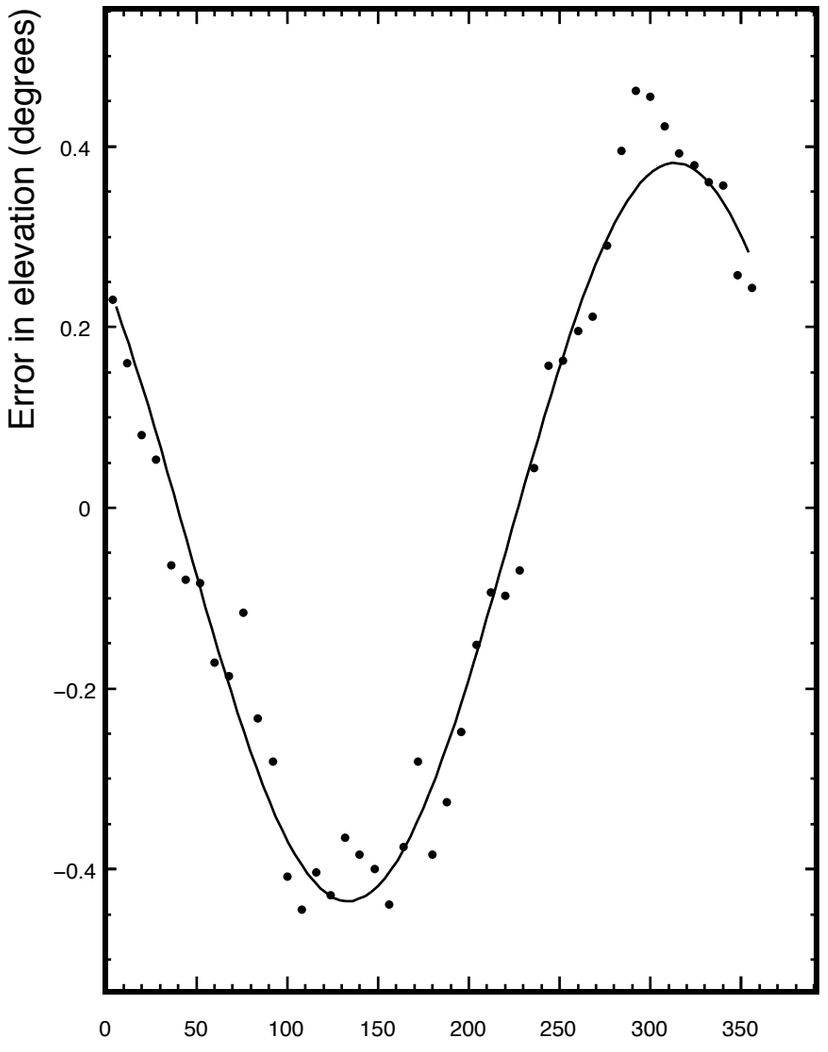
Also calibrate out the tilt of the payload



ELEVATION ANGLE



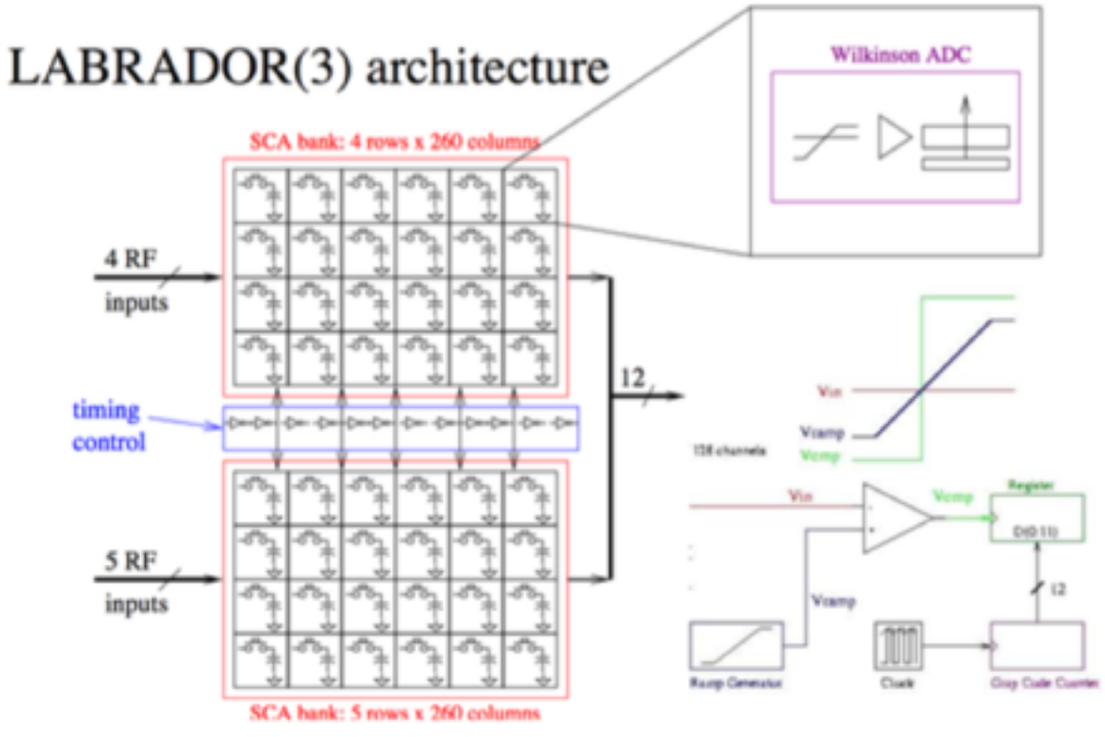
AZIMUTH ANGLE

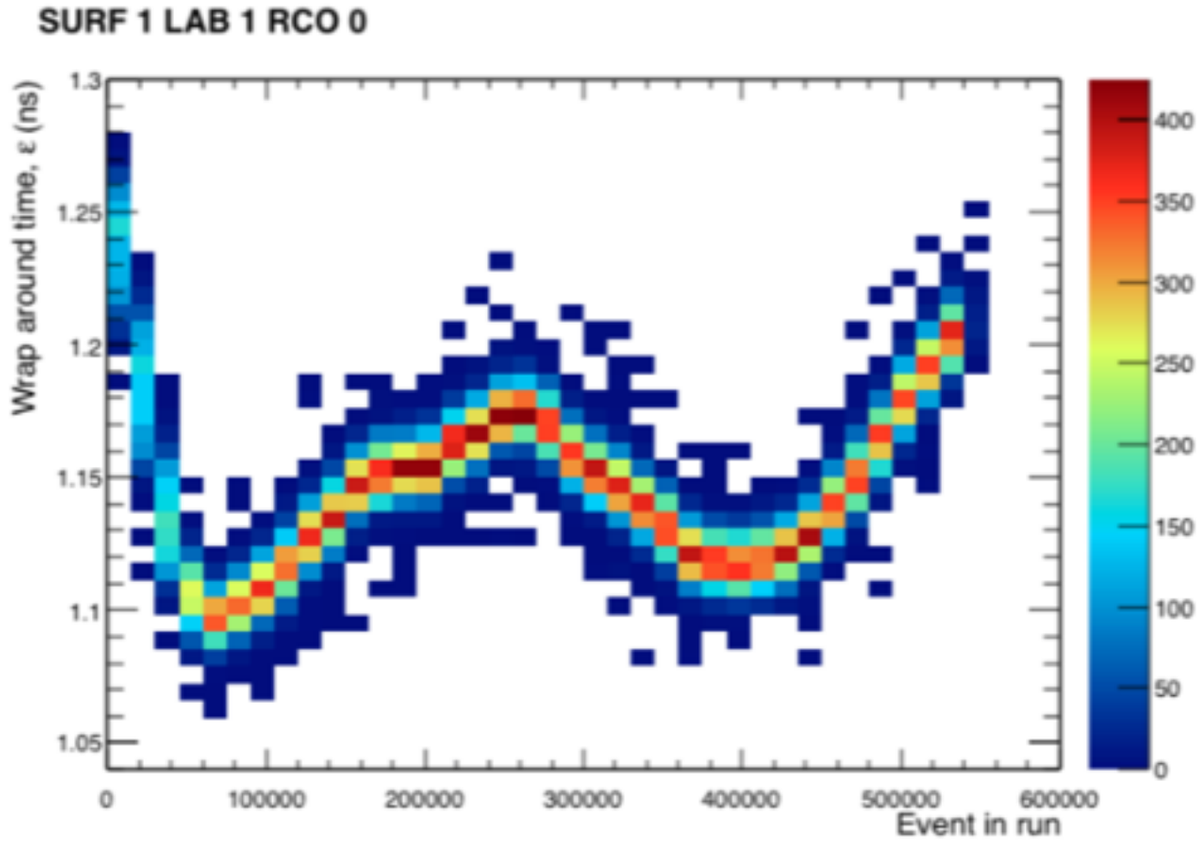


from S. Hoover

ANITA Calibration

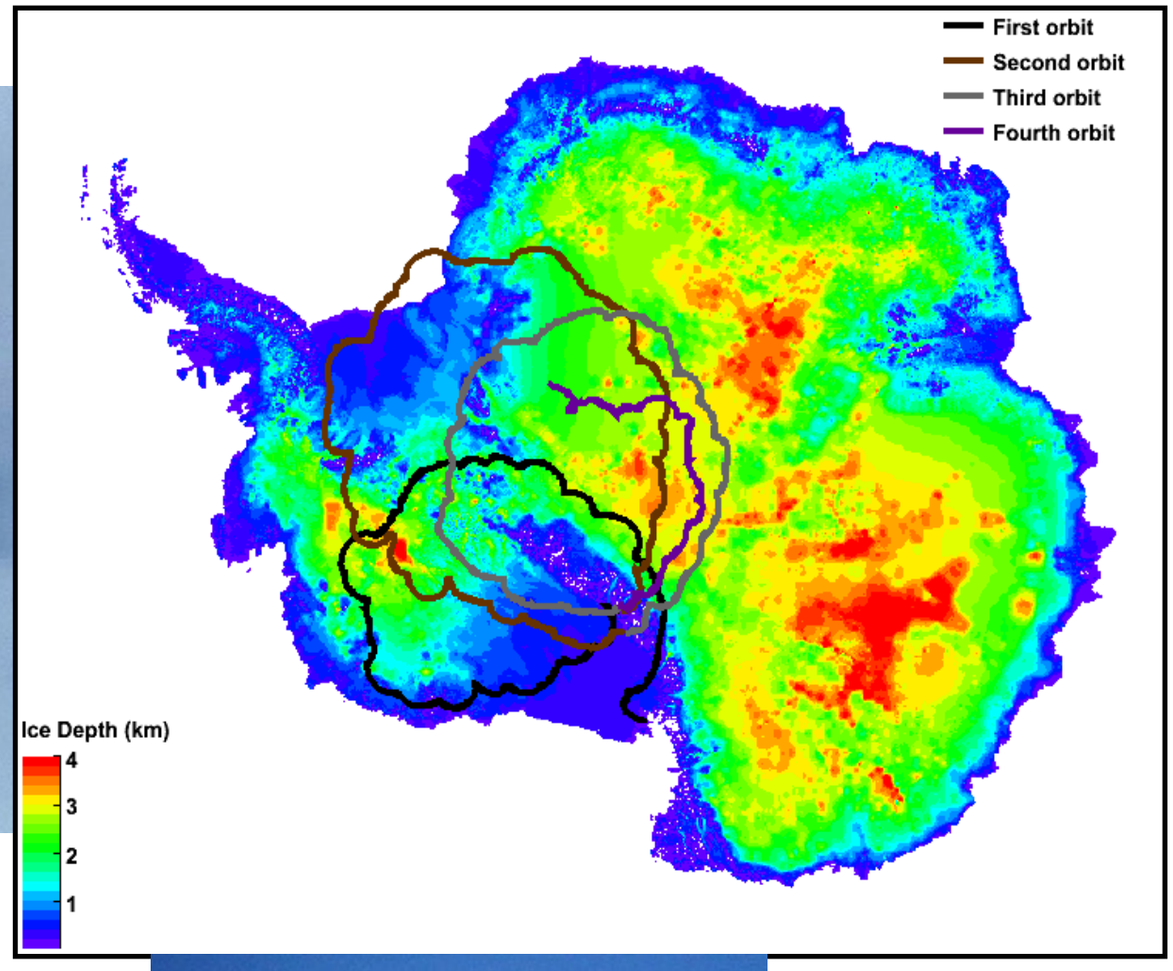
- There are ~12,500 capacitors in the analogue sampling array, each needs to be calibrated
- In addition the timing calibration depends on the temperature, event-by-event trigger jitter, pathologies of the clocks used for the calibration, …



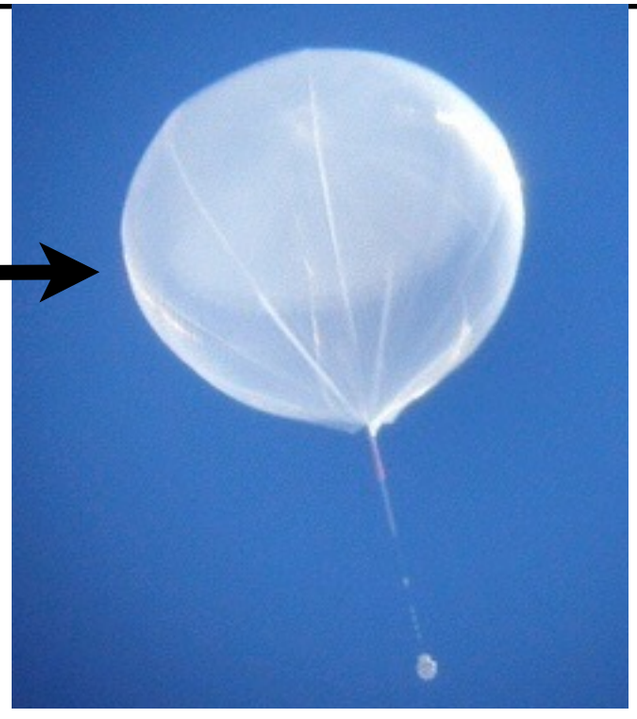


ANITA-1 — 2006/7

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

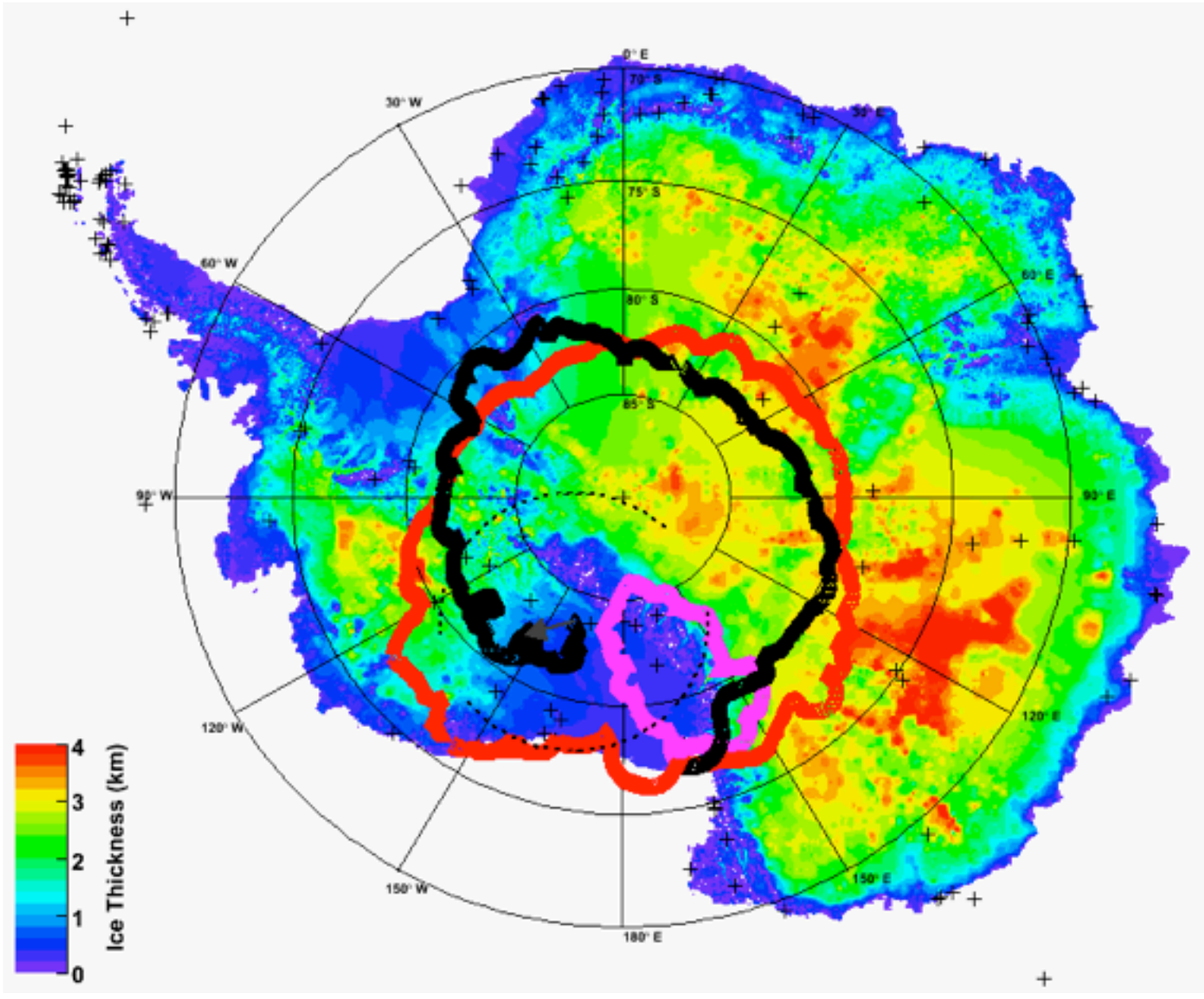


Fits inside the balloon at altitude



ANITA-2 — 2008/9

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



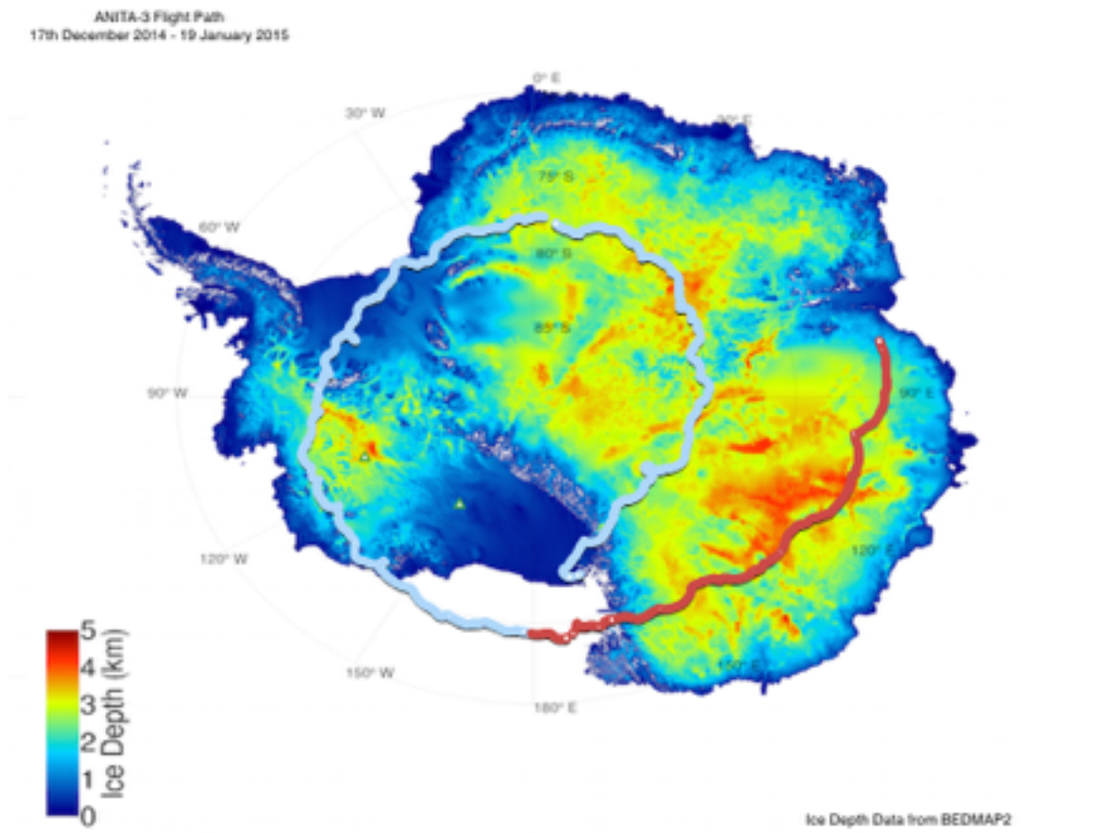
ANITA-3 — 2014/15

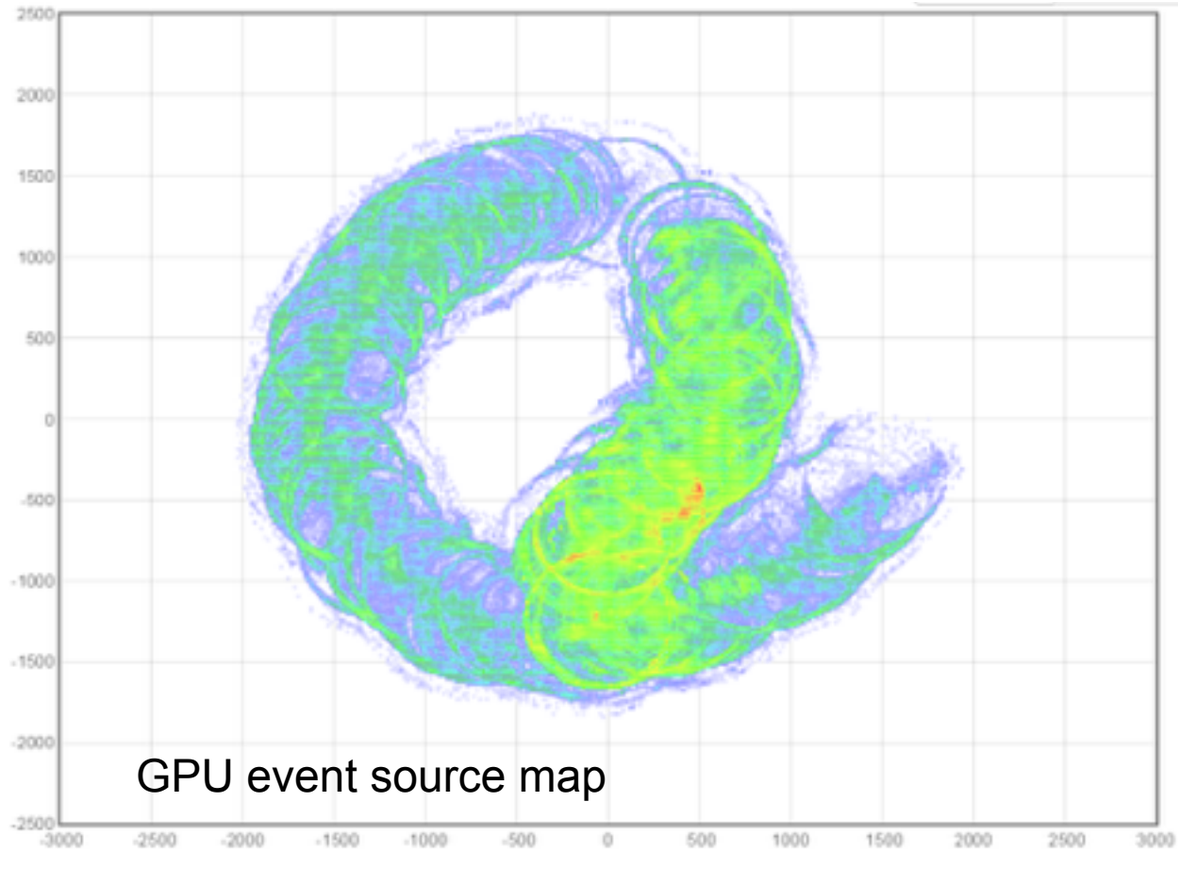
- Added an additional 8 antennas
  - Three equal rings of 16 antennas
- Added a new GPU-based software trigger
  - Allowing us to run at a higher rate with lower threshold
- "Improved" antenna design
- Lower noise RF front-end
- Added a low frequency antenna for cosmic ray characterisation

Photo: B. Hill, University of Hawaii

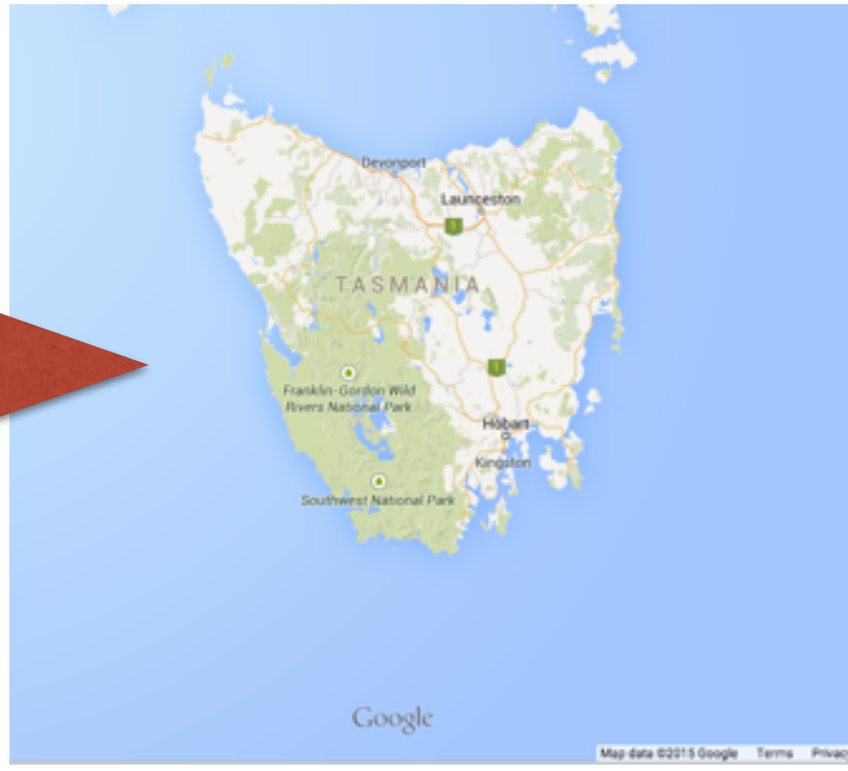
ANITA-3 Flight

- Launched December 17th 2014
- Landed January 9th 2015
- Had to terminate the flight as payload was about to spiral off the continent
- Recorded over 80 million triggered events.
  - Best guess 0-5 neutrinos
  - Best guess O(200) cosmic ray events
- First step of the analysis was to retrieve the data…





What happened to the data?



We got lucky

UCL

Antarctica

Aurora Australis icebreaker runs aground during blizzard in Antarctica

Crew and passengers all reported safe after Australian resupply ship broke free of moorings during storm with winds of more than 130km an hour

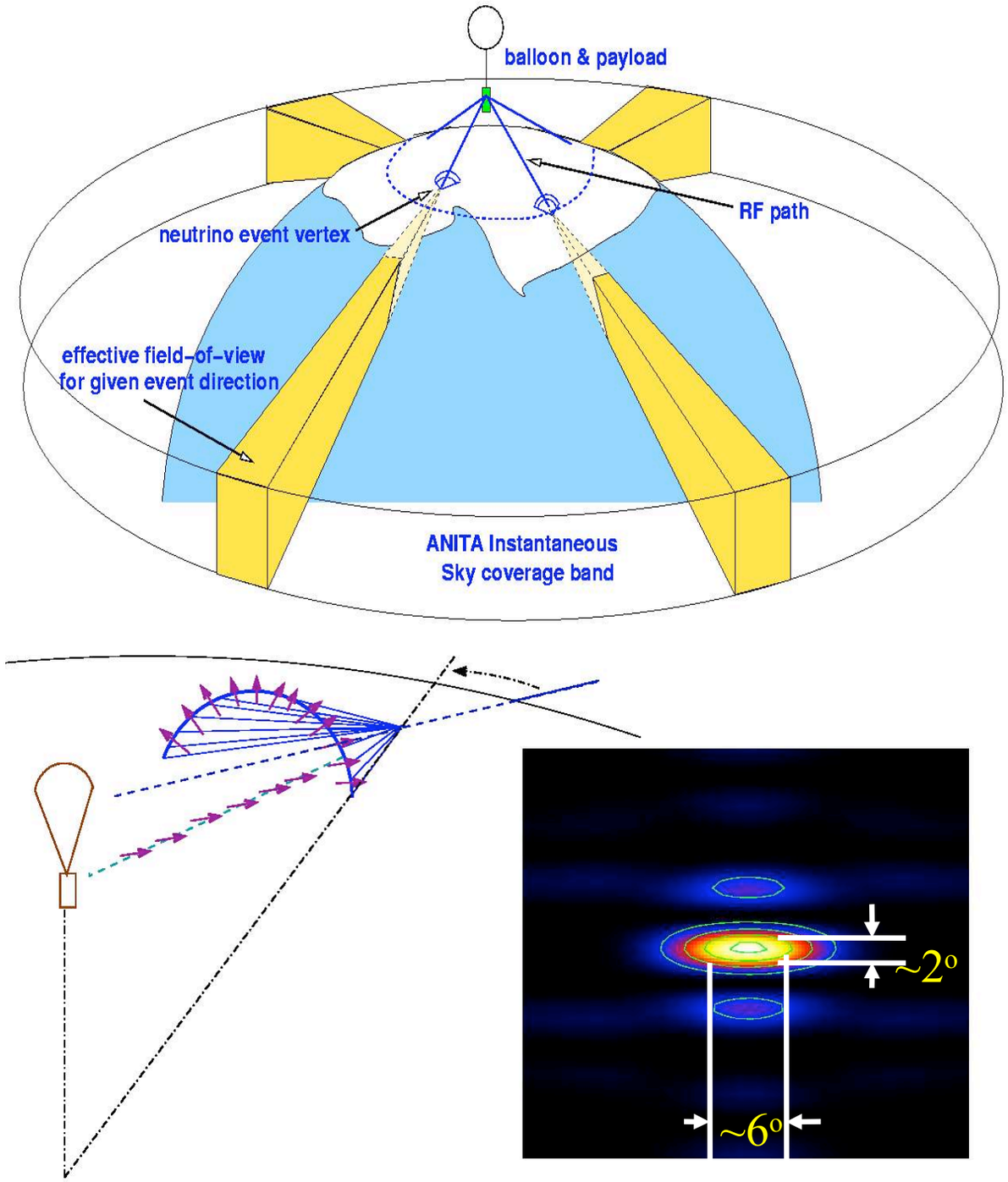
Paul Karp

@Paul_Karp

Wednesday 24 February 2016 17.02 EST

The Australian Antarctic Division's chartered icebreaker the Aurora Australis on a previous mission wedged in ice in Commonwealth Bay 10 nautical miles from Mawson's Hut in Antarctica. The ship has now run aground in Horseshoe Harbour after a blizzard. Photograph: Dean Lewins/AAP

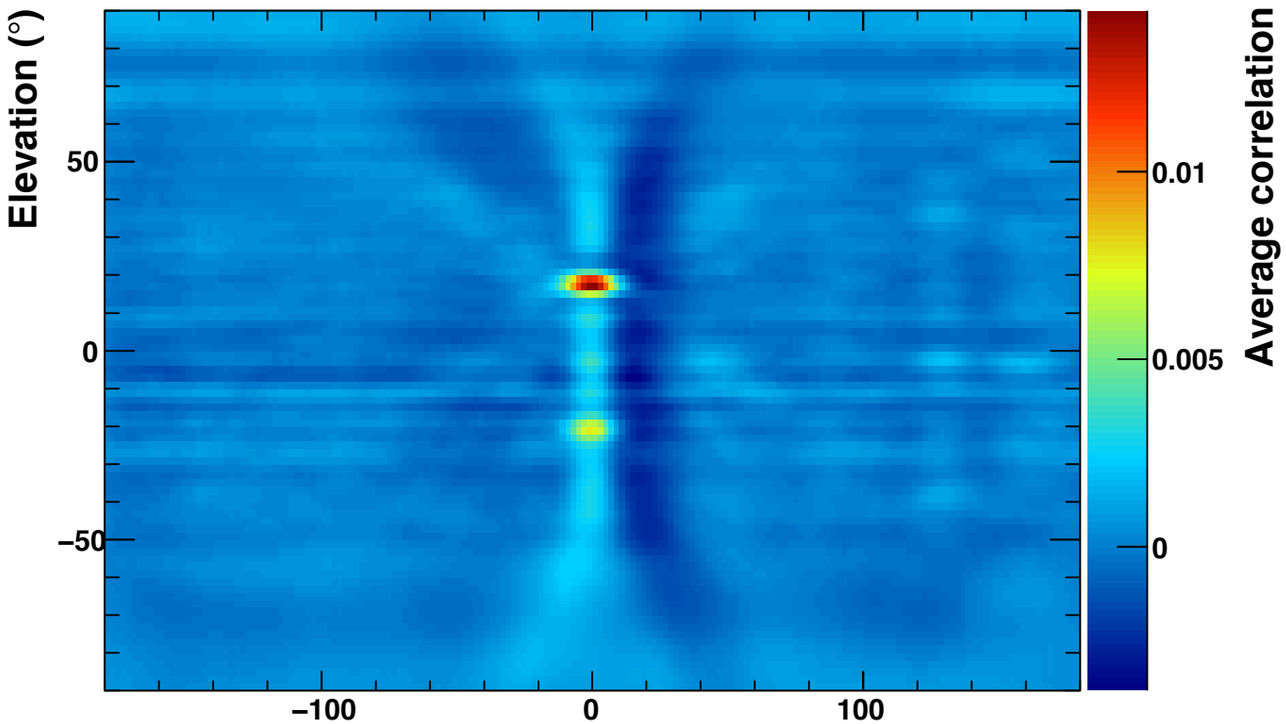
ANITA -- Angular Resolution

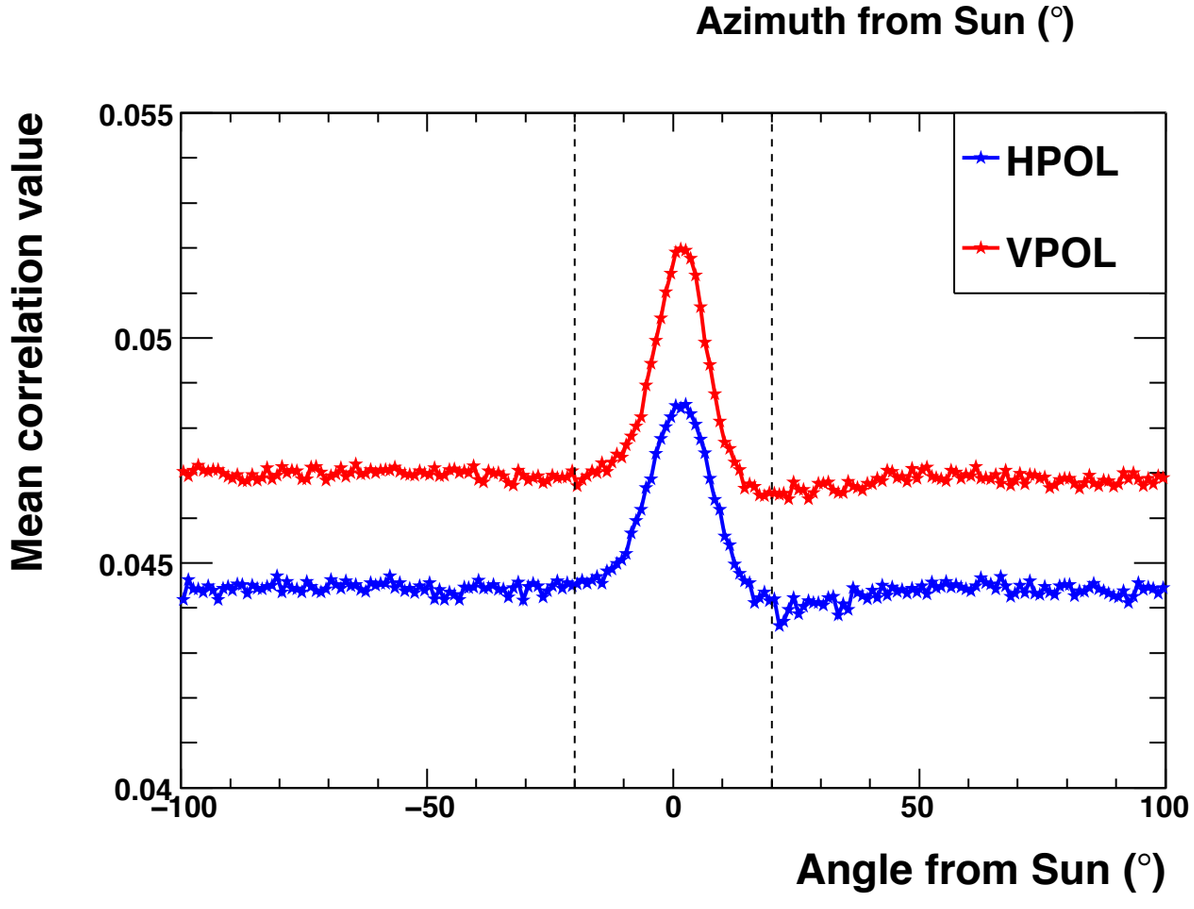


- Using signals from multiple antennas it is possible to measure the direction of arrival of radio pulse to ~0.5° in elevation and ~1.5° in azimuth (based on ANITA-lite calibration data)
- The neutrino direction can vary around radio pulse direction but is constrained to ~2° in elevation and by 3-5°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

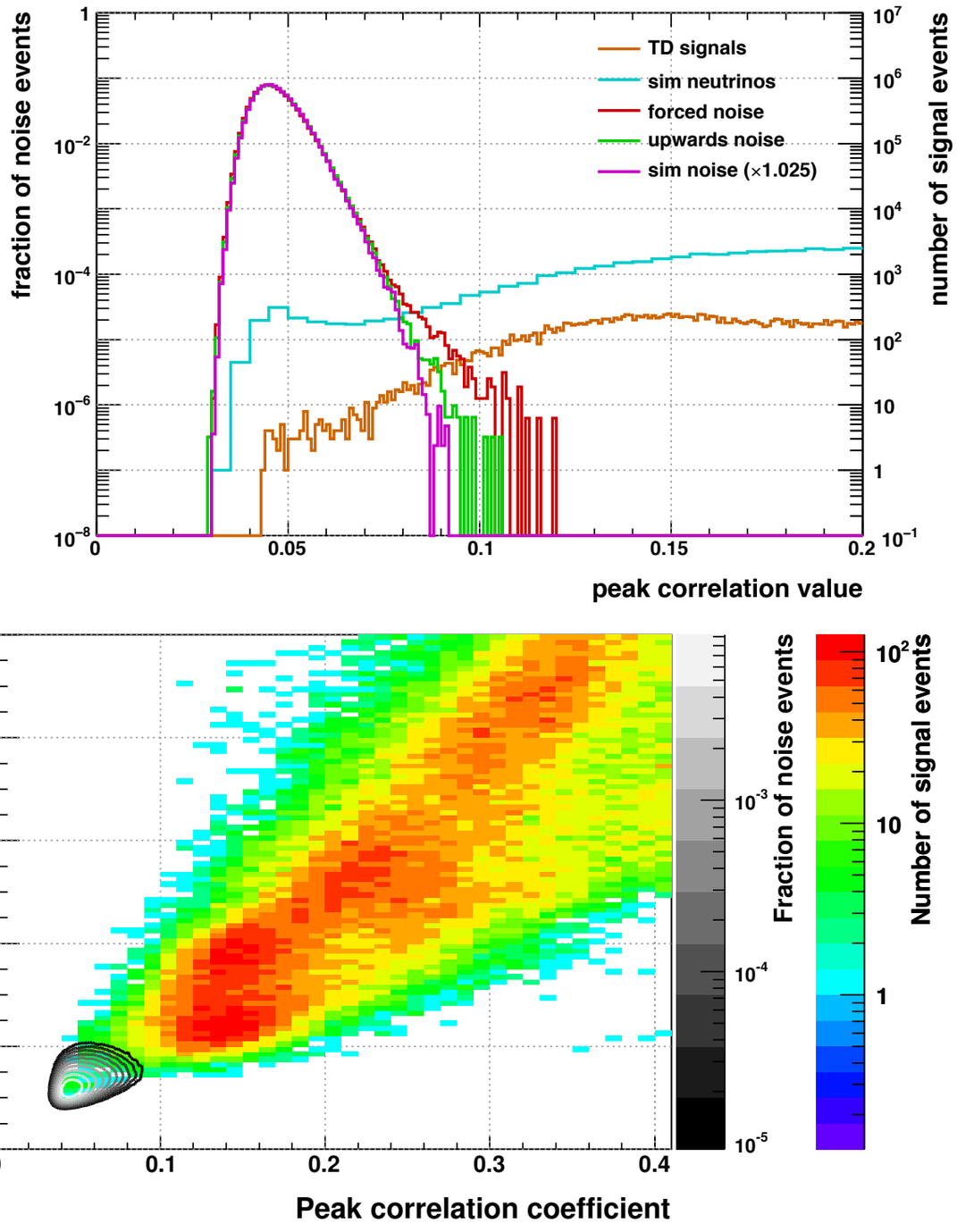
Thermal Noise

ANITA can “see” the Sun



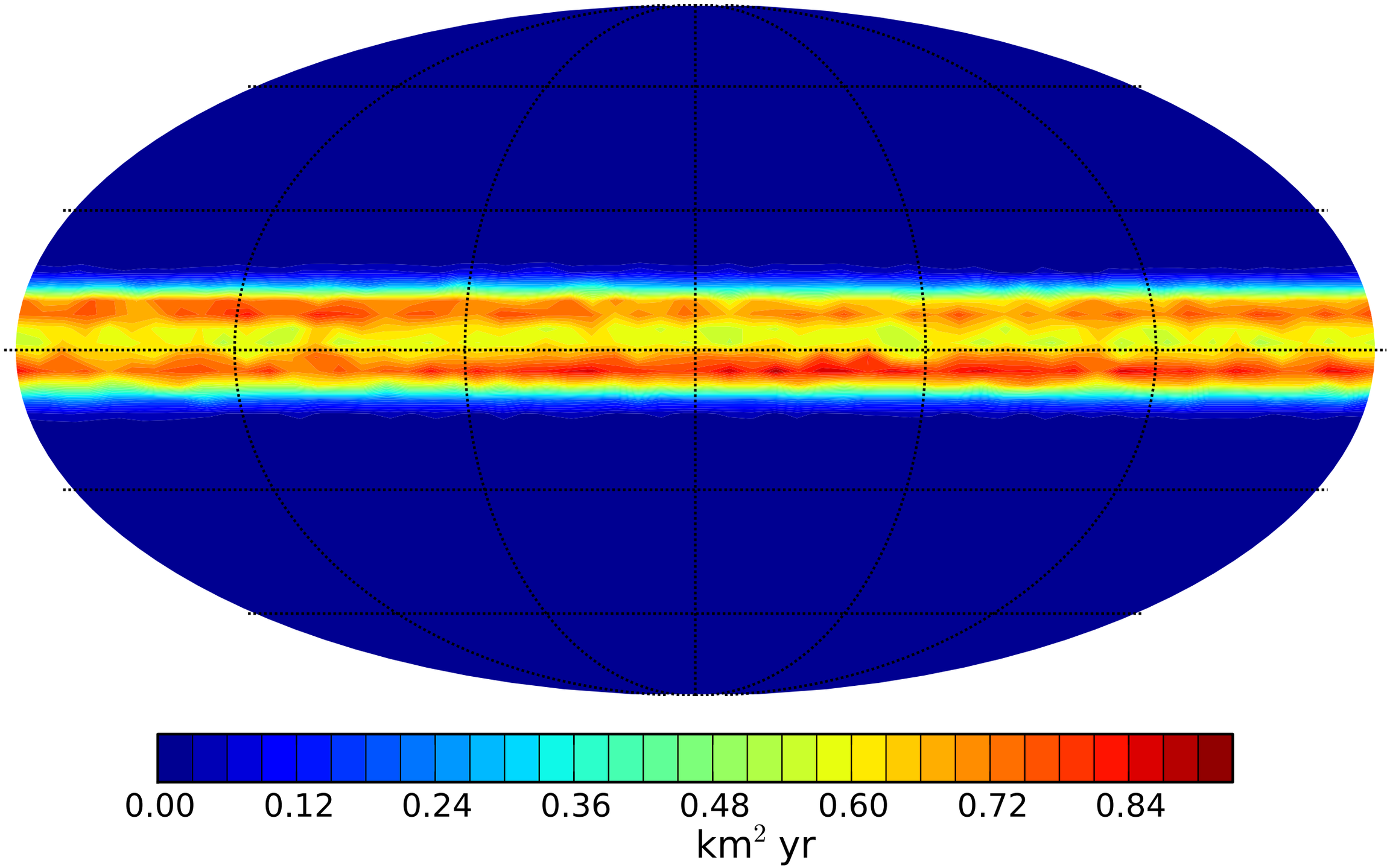


Thermal noise is the dominant source of noise in the data sets.



ANITA-2 Neutrino Sky Map Sensitivity

UCL



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

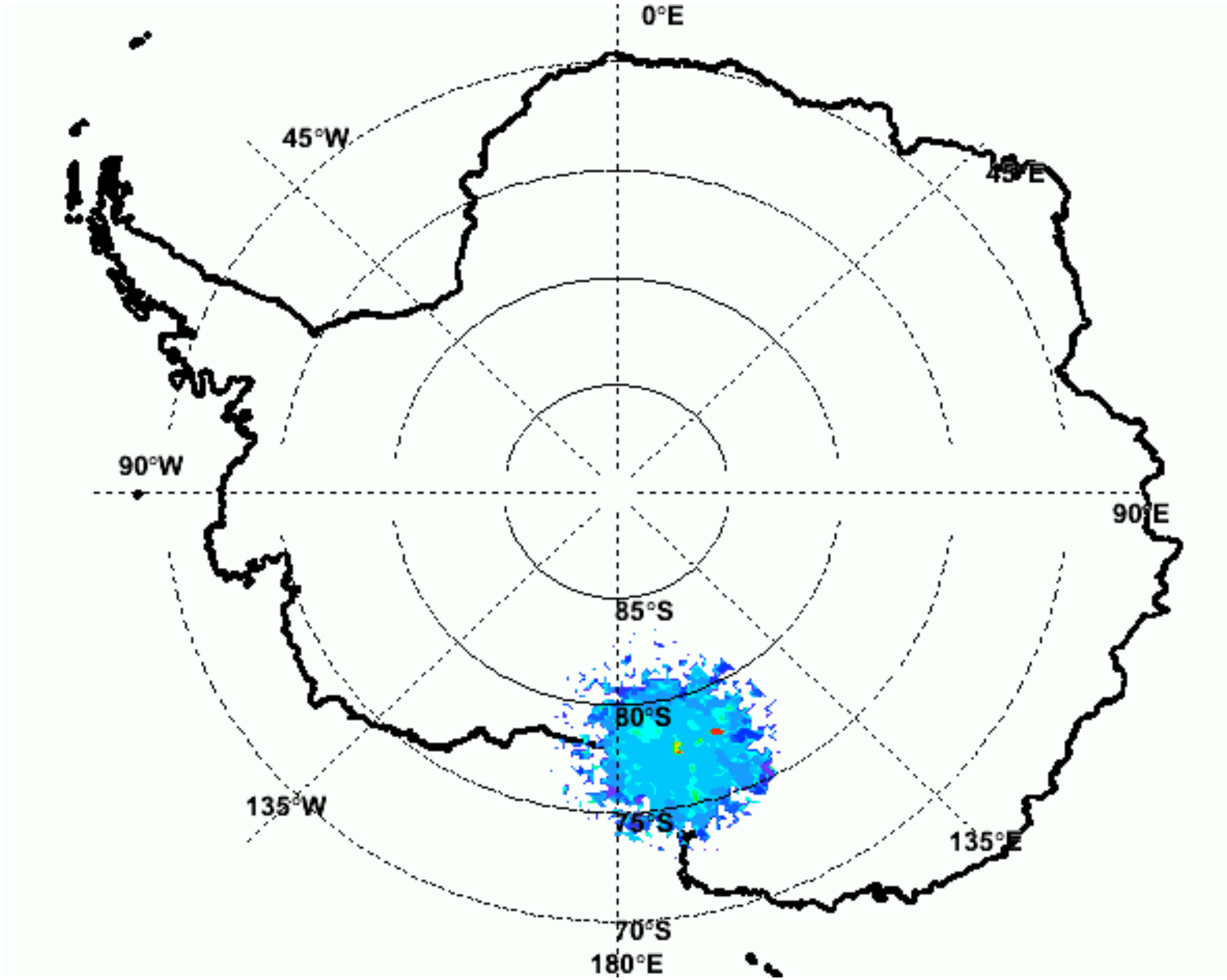
(estimated from RF spectrum)

Exponential is attenuation in ice at depth d.

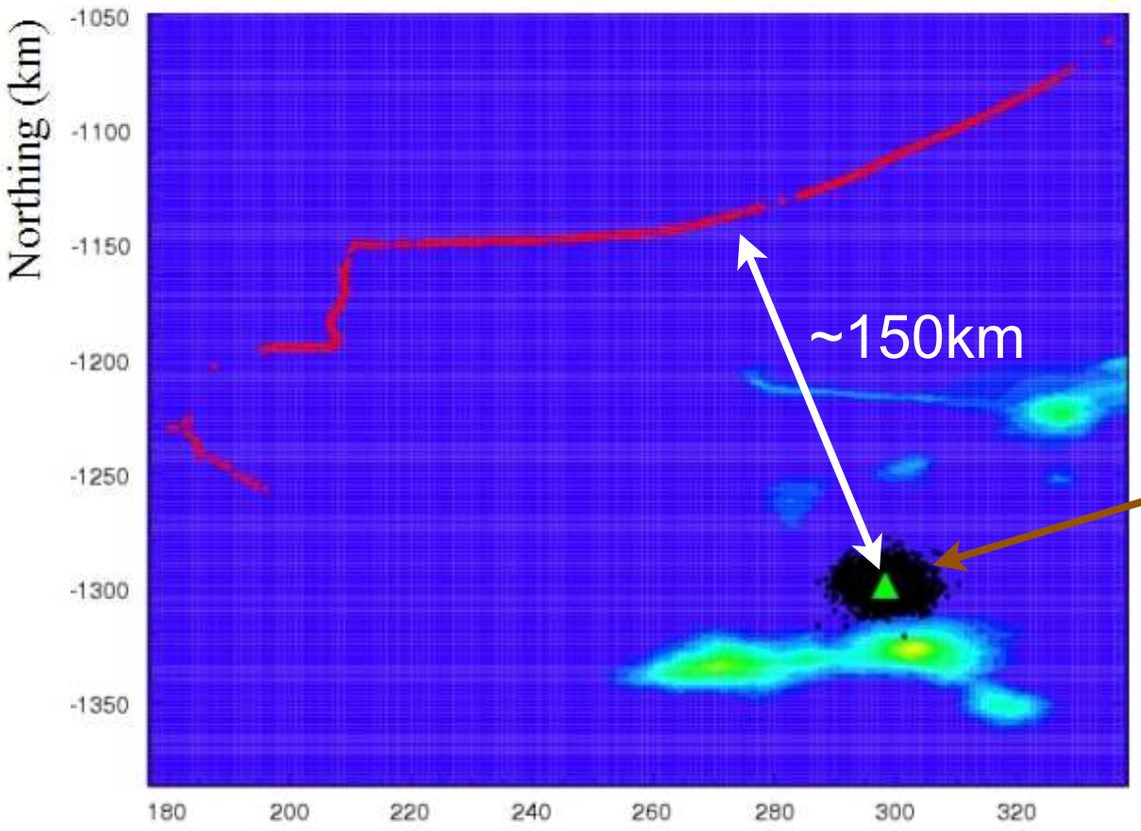
(estimated from RF spectrum and polarization effects)

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

ANITA-2



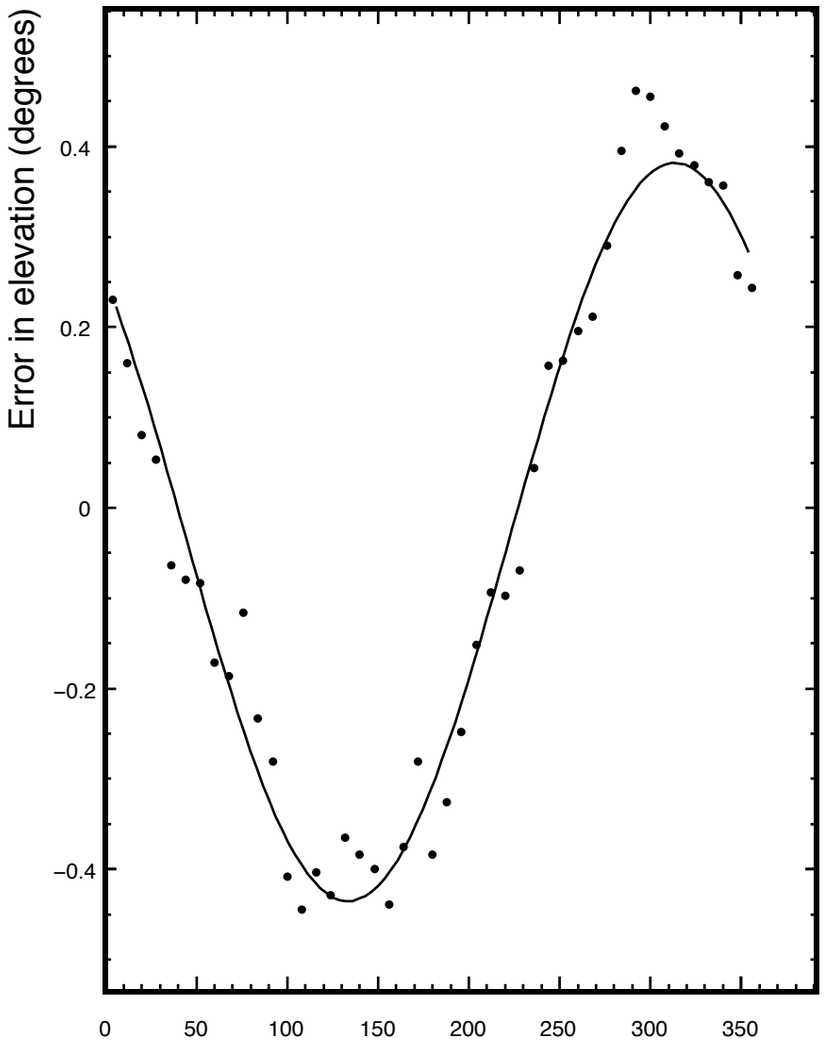
Calibration

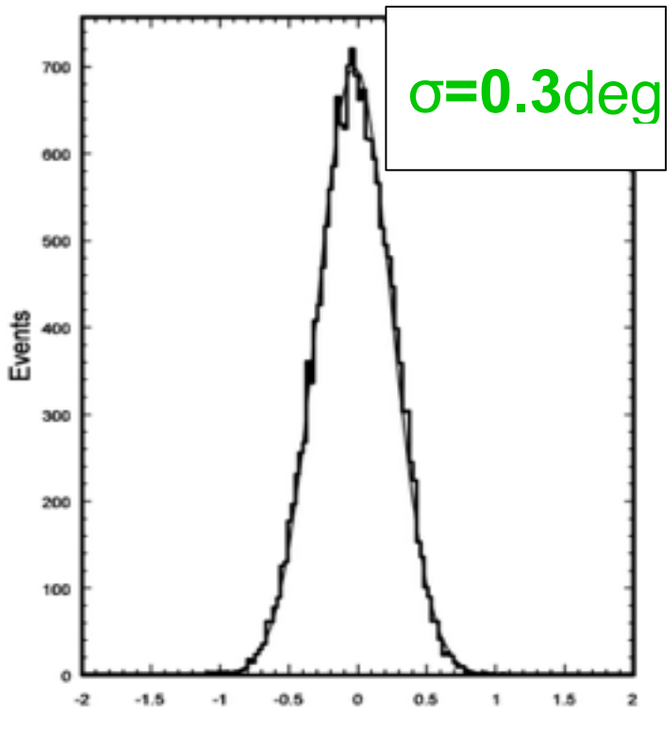


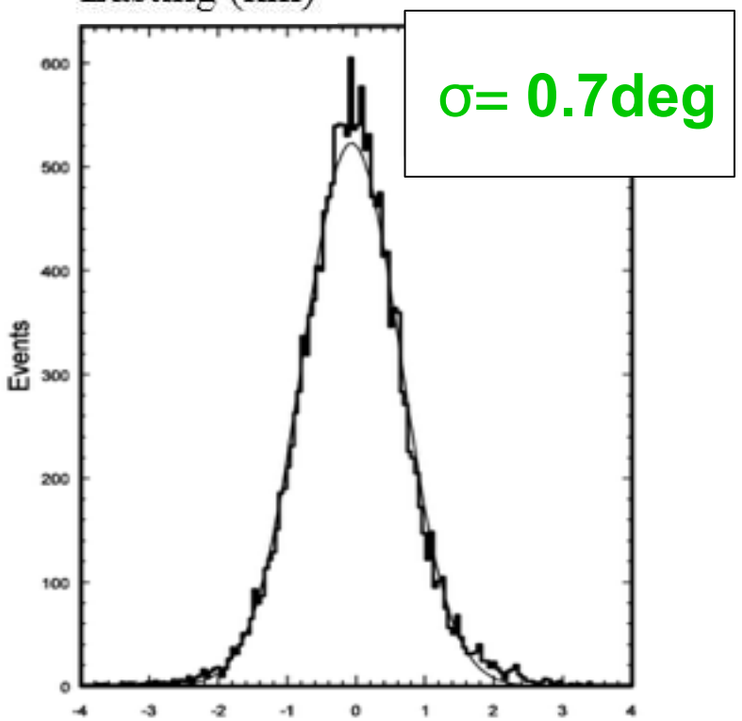
Reconstructed event locations

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

Also calibrate out the tilt of the payload





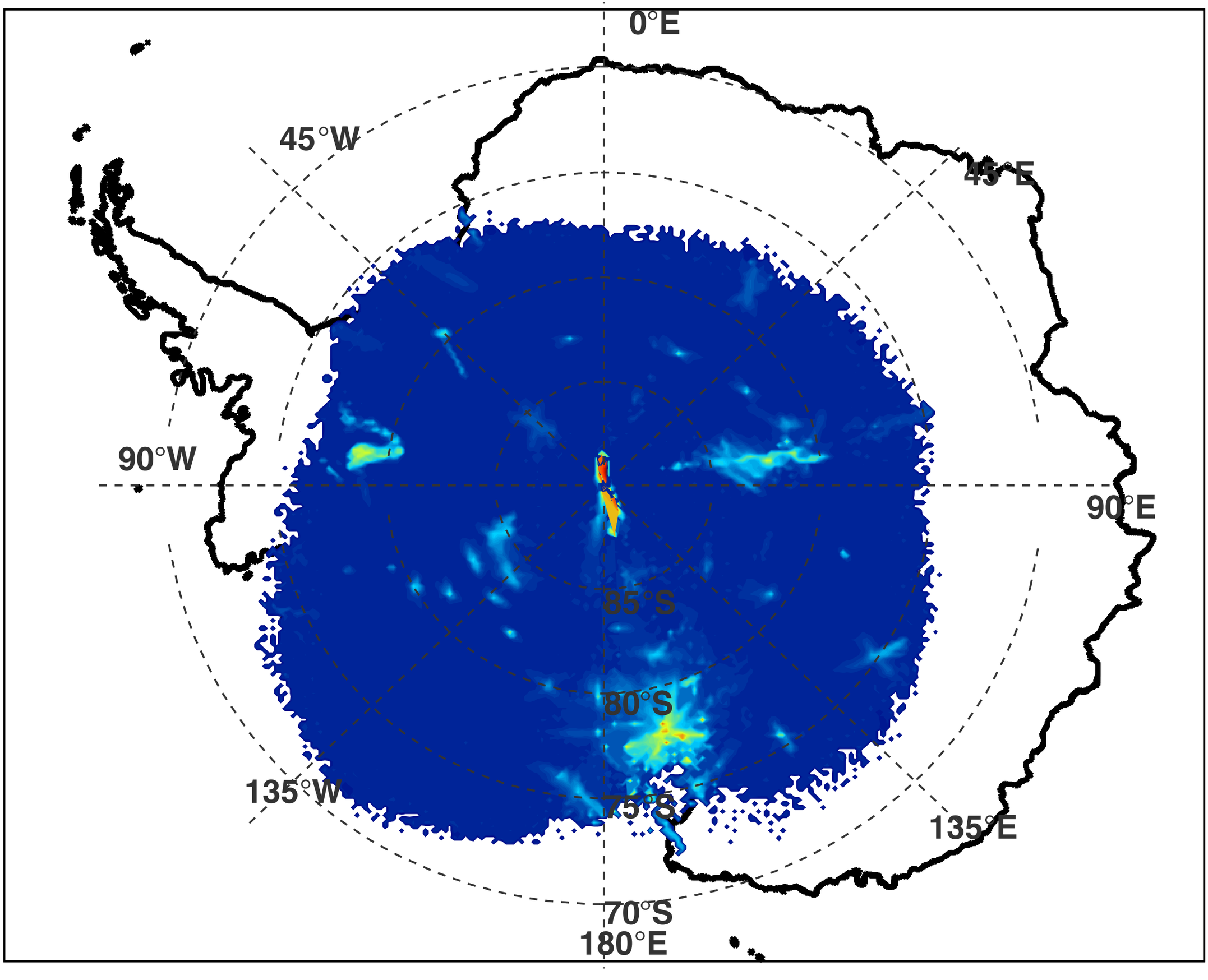


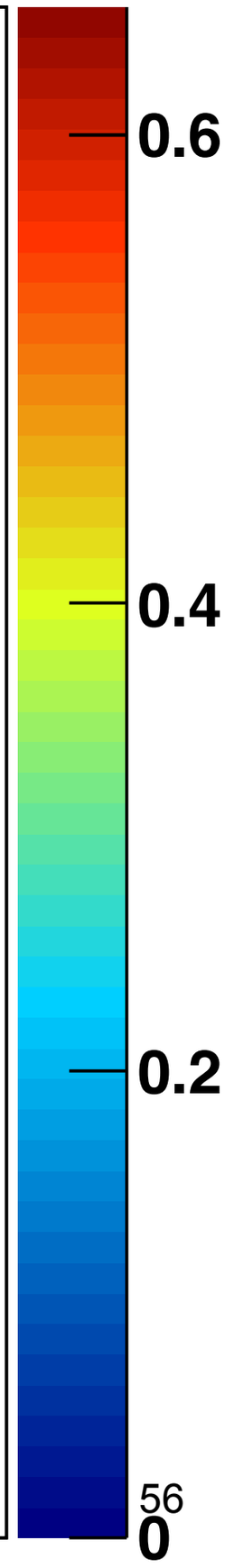
ELEVATION ANGLE **AZIMUTH ANGLE**

from S. Hoover

ANITA-2

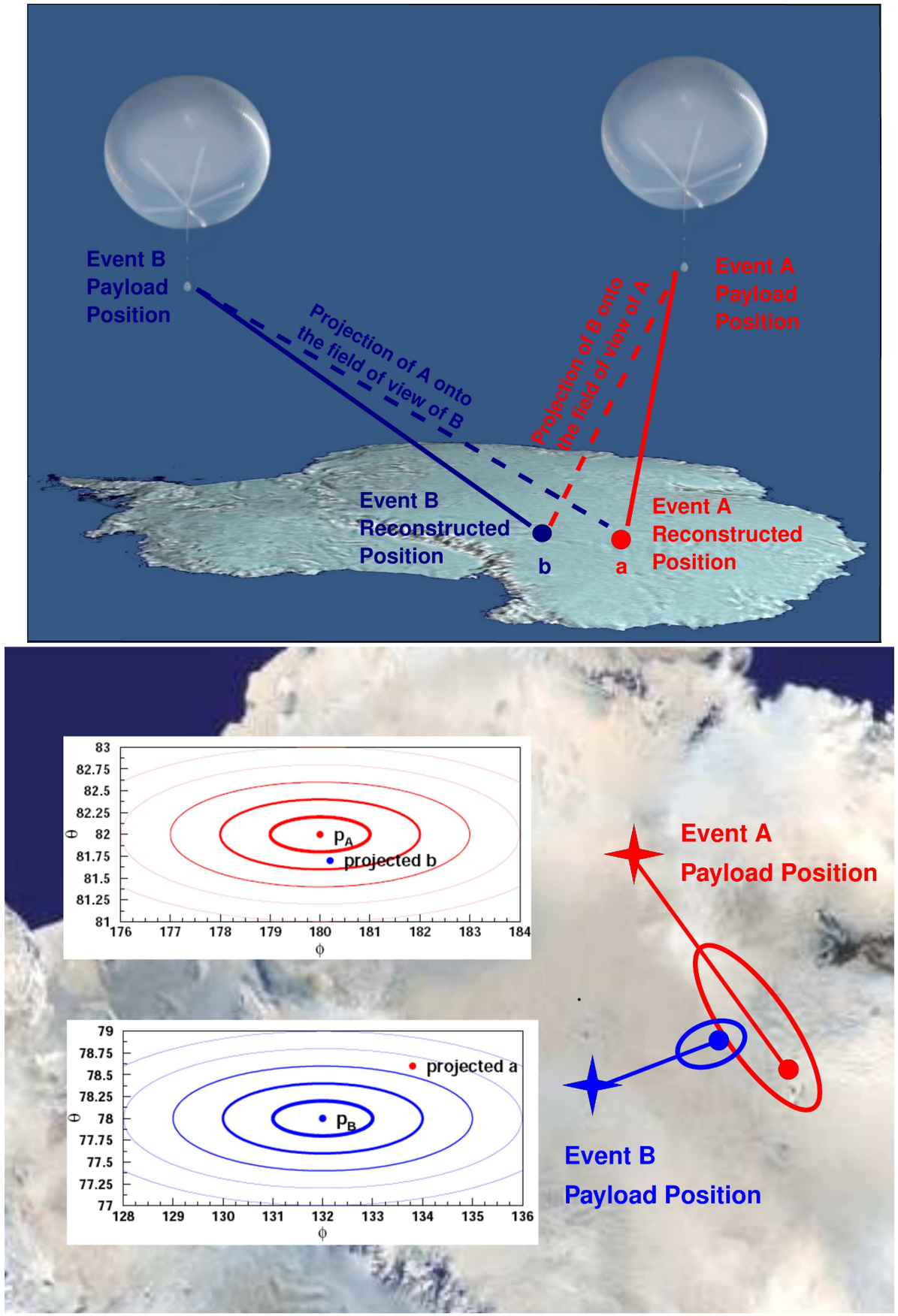
UCL





Avg correlation coefficient

Analysis Step 3: Clustering



- 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

Stokes Parameters