Radio Detection of Neutrinos and Cosmic Rays: ANITA and ARA

Ryan Nichol

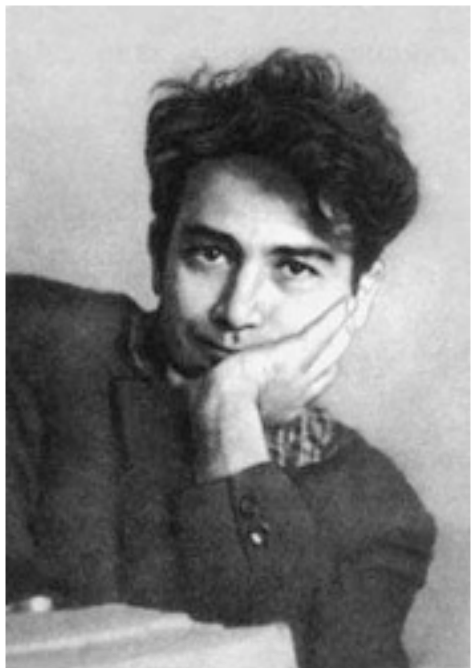
16th Lomonosov Conference on Elementary Particle Physics

Outline

UCL

- Historical Context
- GZK Mechanism
- Radio Emission Mechanisms
  - In Dense Media
  - In Air
- Earlier Experiments
- ANITA
  - Neutrino Search
  - Cosmic Ray Air Shower Detection
- ARA
  - Design
  - Sensitivity
- Summary

(Selected) Radio Detection Timeline

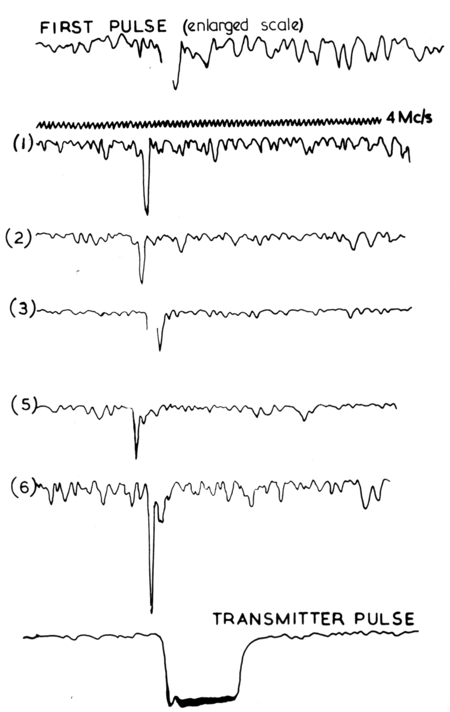


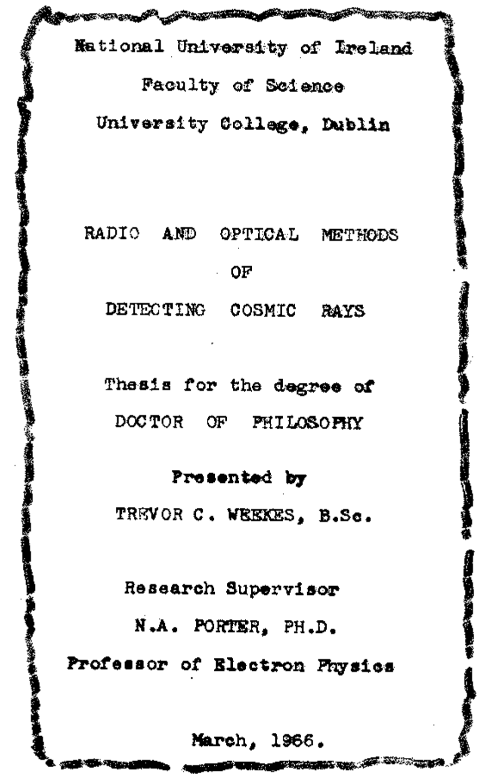
1962

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

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.

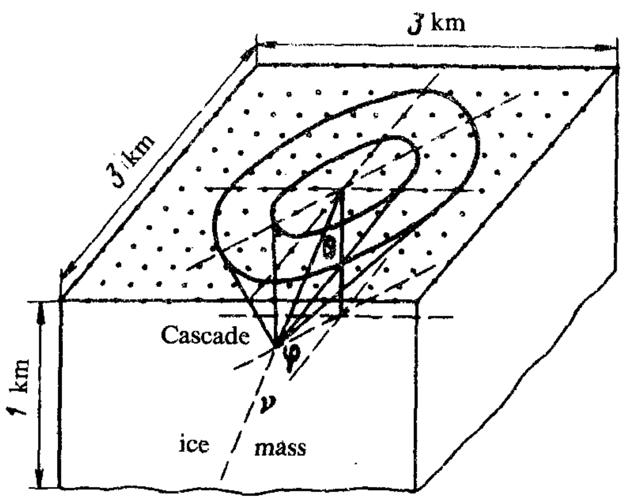
1966

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

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

1966-75

Timeline (continued)



1983

Gusev and Zheleznykh propose constructing a "radio detector for muons and neutrinos" in ice.

1996/7

The first RICE antennas were deployed in conjunction with the AMANDA array

1996-2000

The Parkes and Goldstone radio telescopes stare at the moon (looking for neutrinos).

2002-

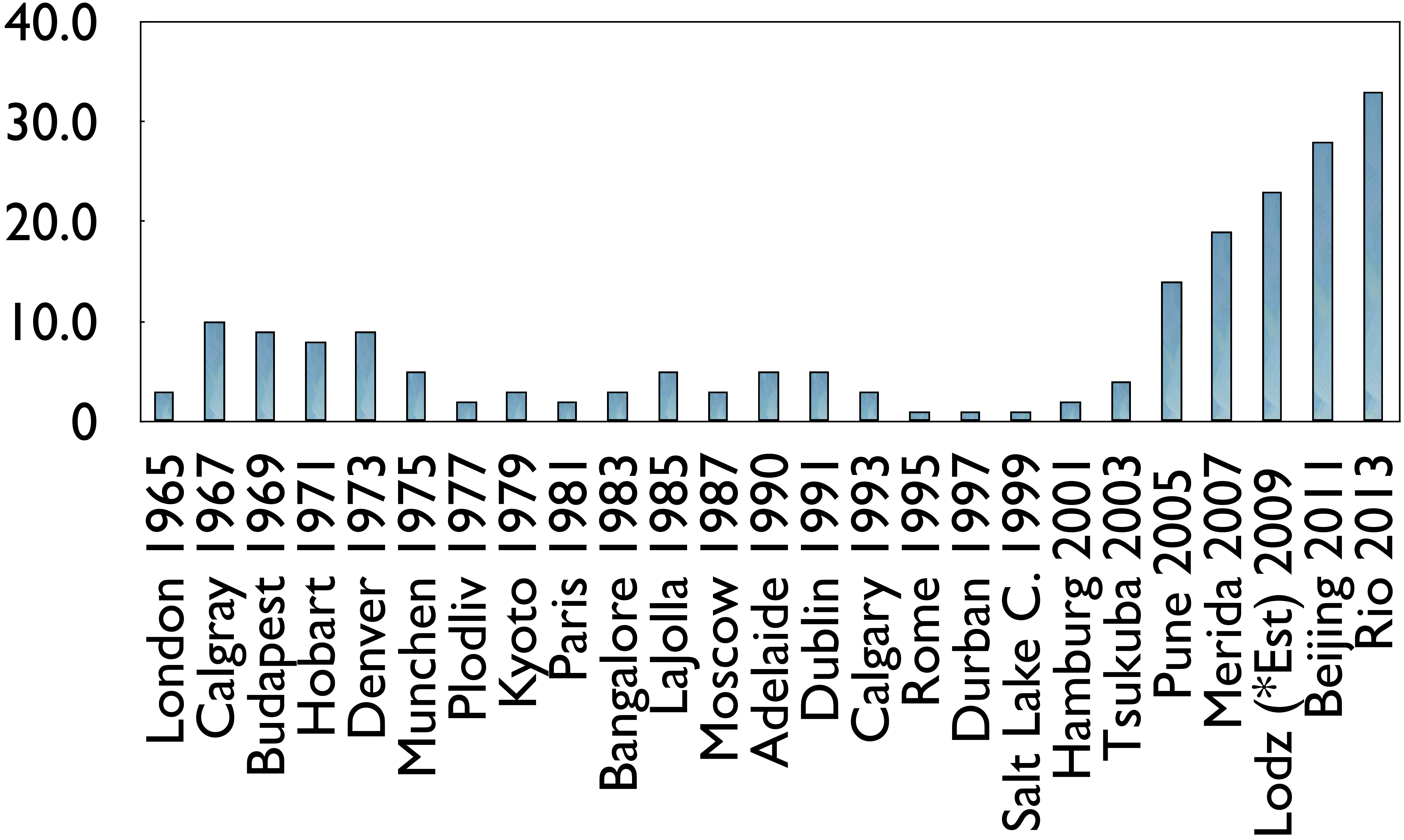
The CODALEMA and LOPES experiments, revisit the radio detection of air showers

2006-

The first ANITA flight launches from Williams Field, Antarctica

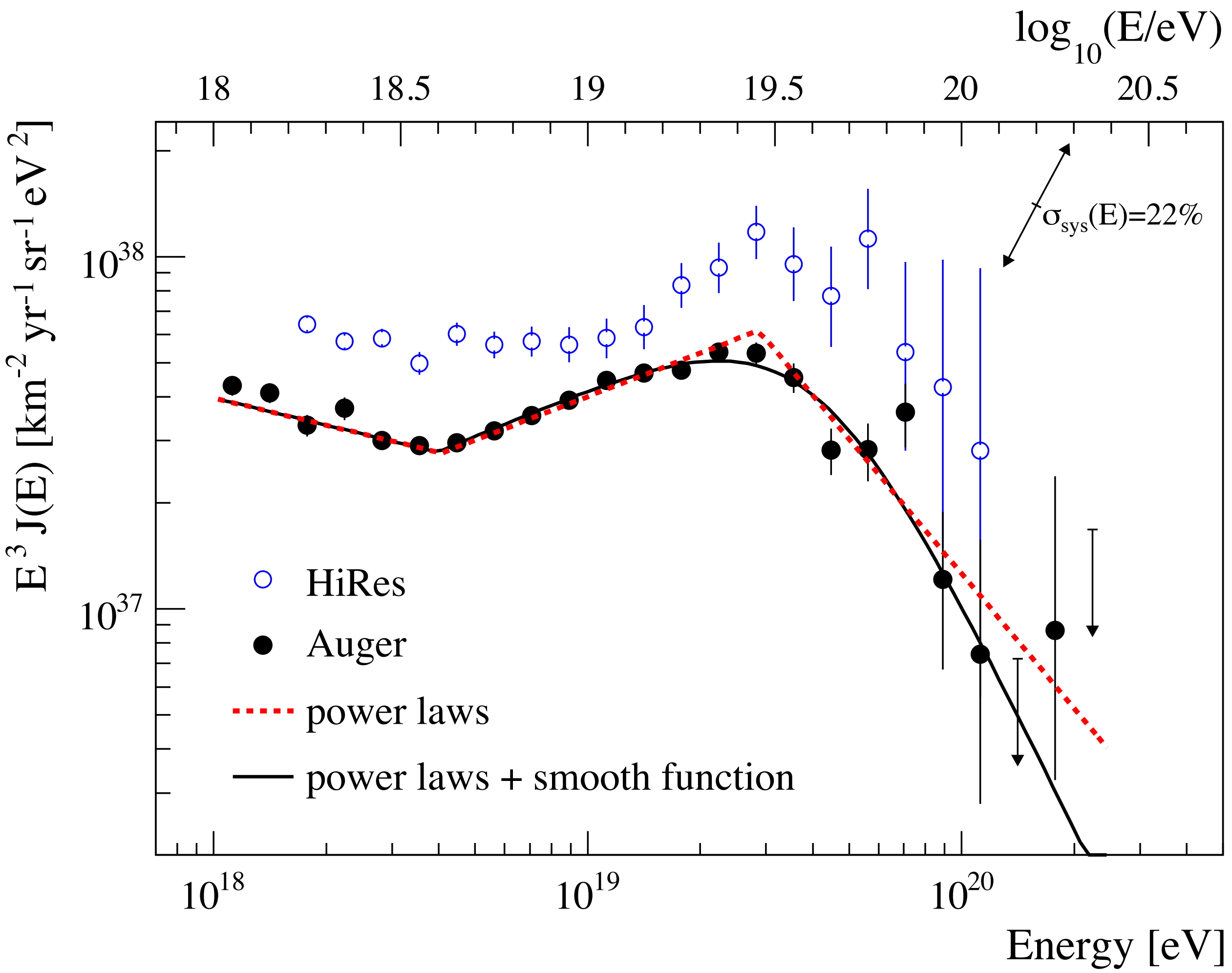
Interest in Radio Detection

- Measured in number of papers presented orally at the International Cosmic Ray Conference.



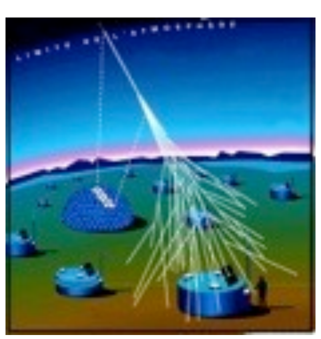
Thanks to T. Weekes and H. Badran, for the 20th century data

Aside -- The GZK Effect



From: Phys.Lett.B685:239-246,2010 (Auger)

- 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



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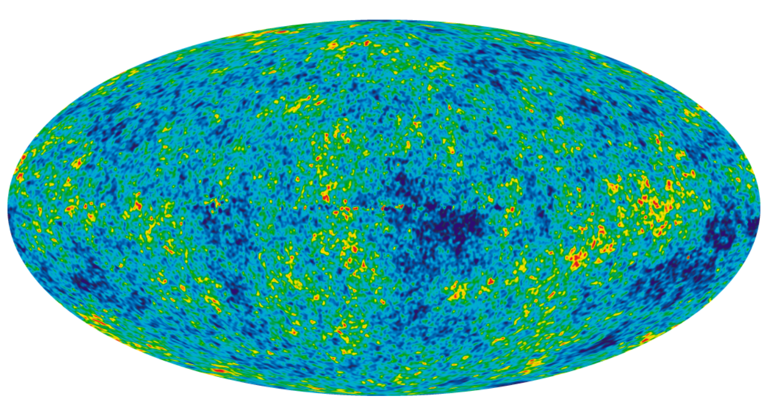
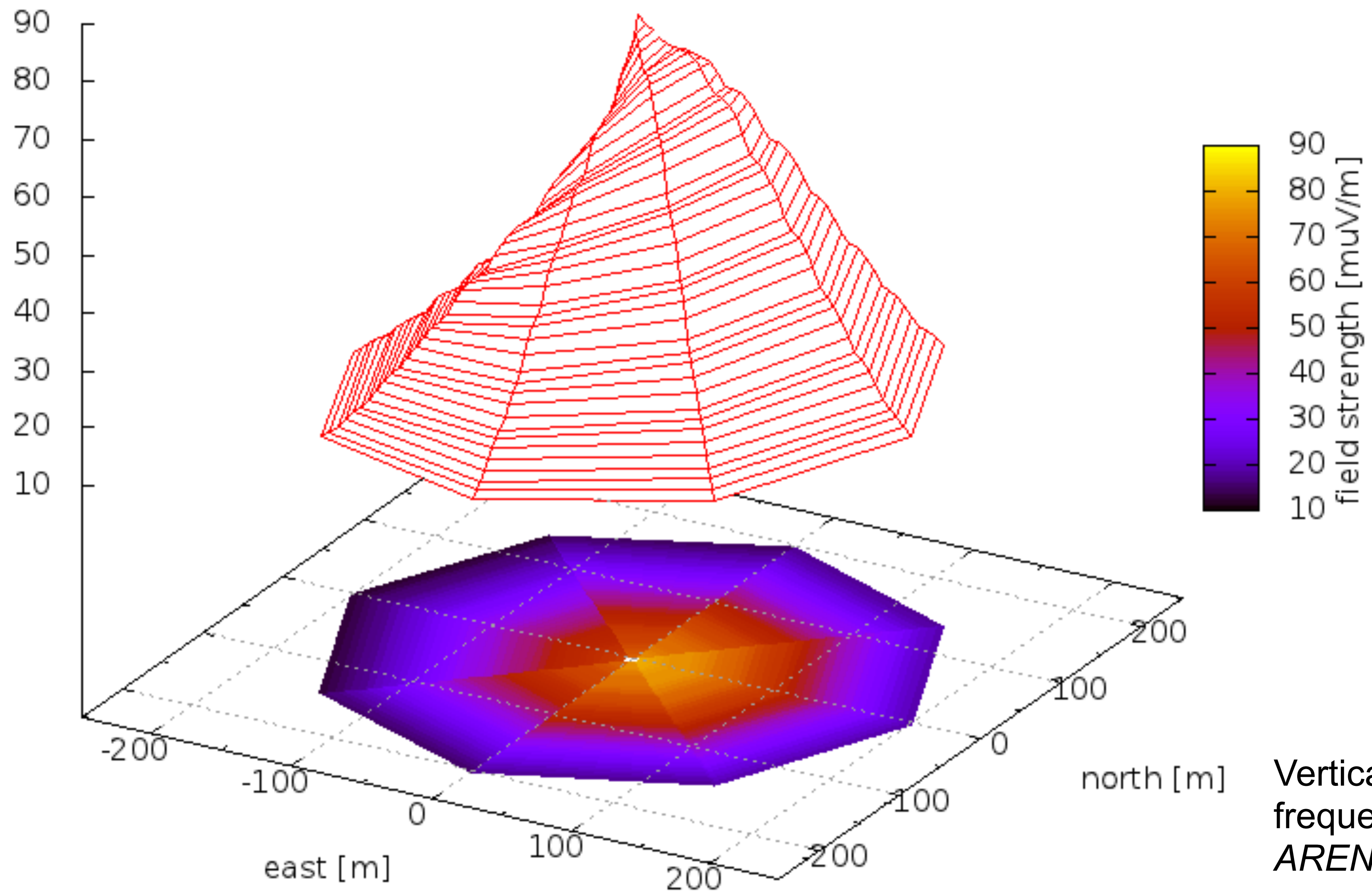


$$p + \gamma_{CMB} \rightarrow \Delta^* \rightarrow n + \pi^+$$
$$\searrow \mu^+ + \nu_\mu$$
$$\searrow e^+ + \bar{\nu}_\mu + \nu_e$$

= "Guaranteed" Neutrino "Beam"!

Radio Emission Mechanisms



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

Radio Emission -- Early Theory

- Early theoretical work by Gurgen Askaryan predicted coherent Cherenkov radiation from air showers.

COHERENT RADIO EMISSION FROM COSMIC SHOWERS IN AIR AND IN DENSE MEDIA

G. A. ASKAR'YAN

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editors January 8, 1965

J. Exptl. Theoret. Phys. (U.S.S.R.) 48, 988-990 (1965)

- The geomagnetic contribution was first proposed by Kahn and Lerche in 1965.

Radiation from cosmic ray air showers

BY F. D. KAHN AND I. LERCHE

Astronomy Department, University of Manchester

(*Communicated by Sir Bernard Lovell, F.R.S.—Received* 16 *February* 1965)

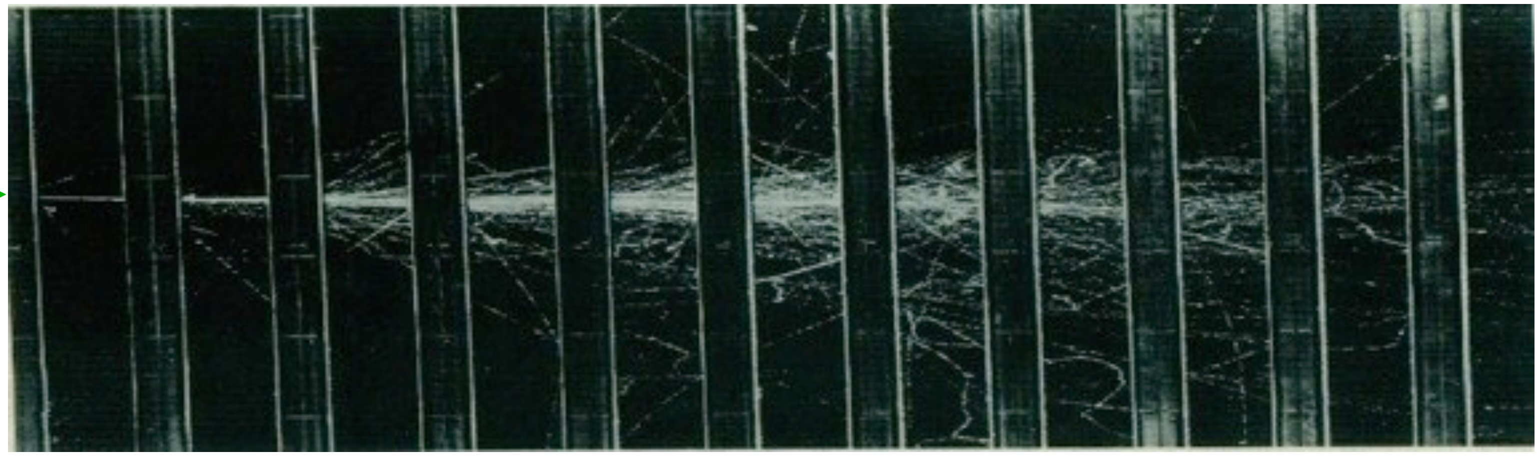
Cosmic ray showers passing through the atmosphere produce electromagnetic disturbances. It has been suggested that these can be detected by means of a radio telescope. We set up a simple model for a shower and find that the time-integrated energy flux in its radiation field, at say 45 Mc/s, is of the order of 60000 flux units × microseconds, when the shower contains 10^6 electrons and 10^6 positrons. The radiation pattern depends on the decay rate of the shower. We have done this calculation in order to give some guidance to experimentalists who are planning to observe cosmic ray showers by radio means.

(1 flux unit = 10^{-26} Wm^{-2} (c/s)$^{-1}$.)

Radio Cherenkov -- The Askaryan Effect

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

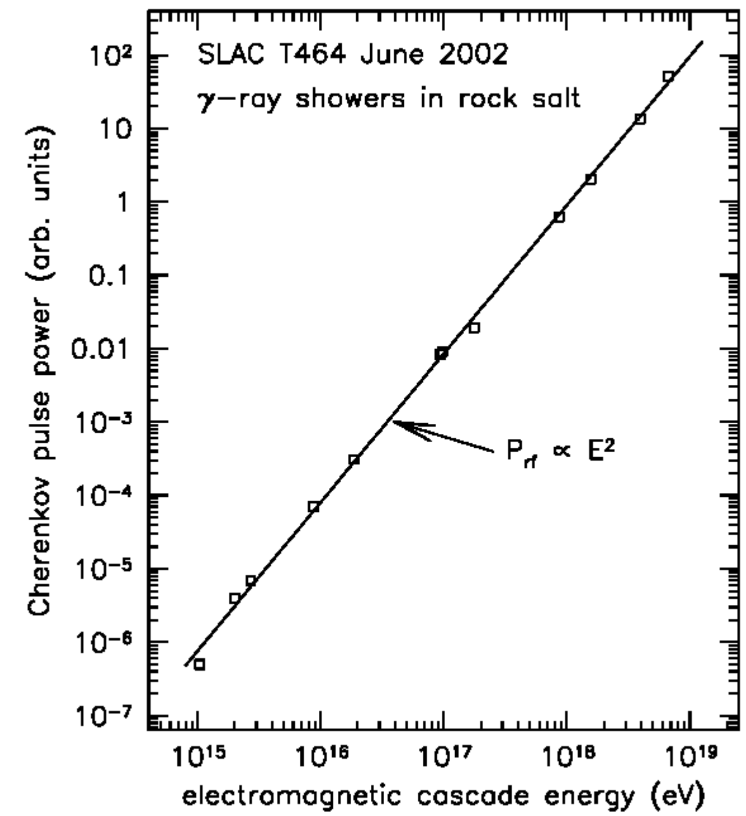
$e^{\pm}$ or γ



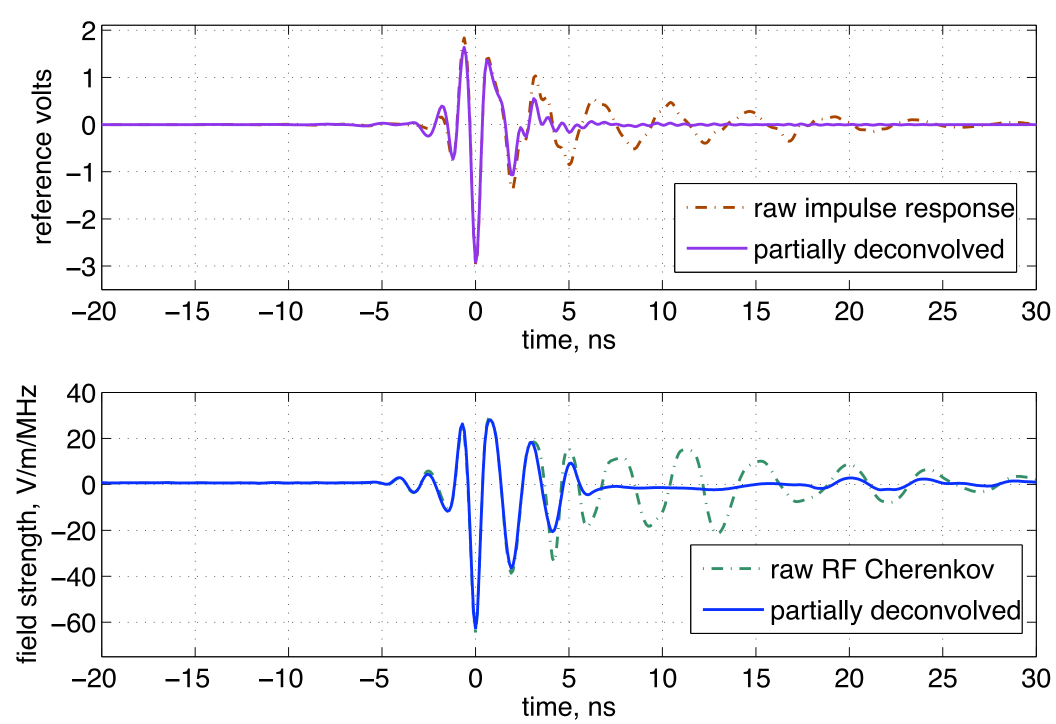
Typical Dimensions:
$L \approx 10$ m
$R_{Moliere} \approx 10$ cm

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

Askaryan Effect in the Laboratory

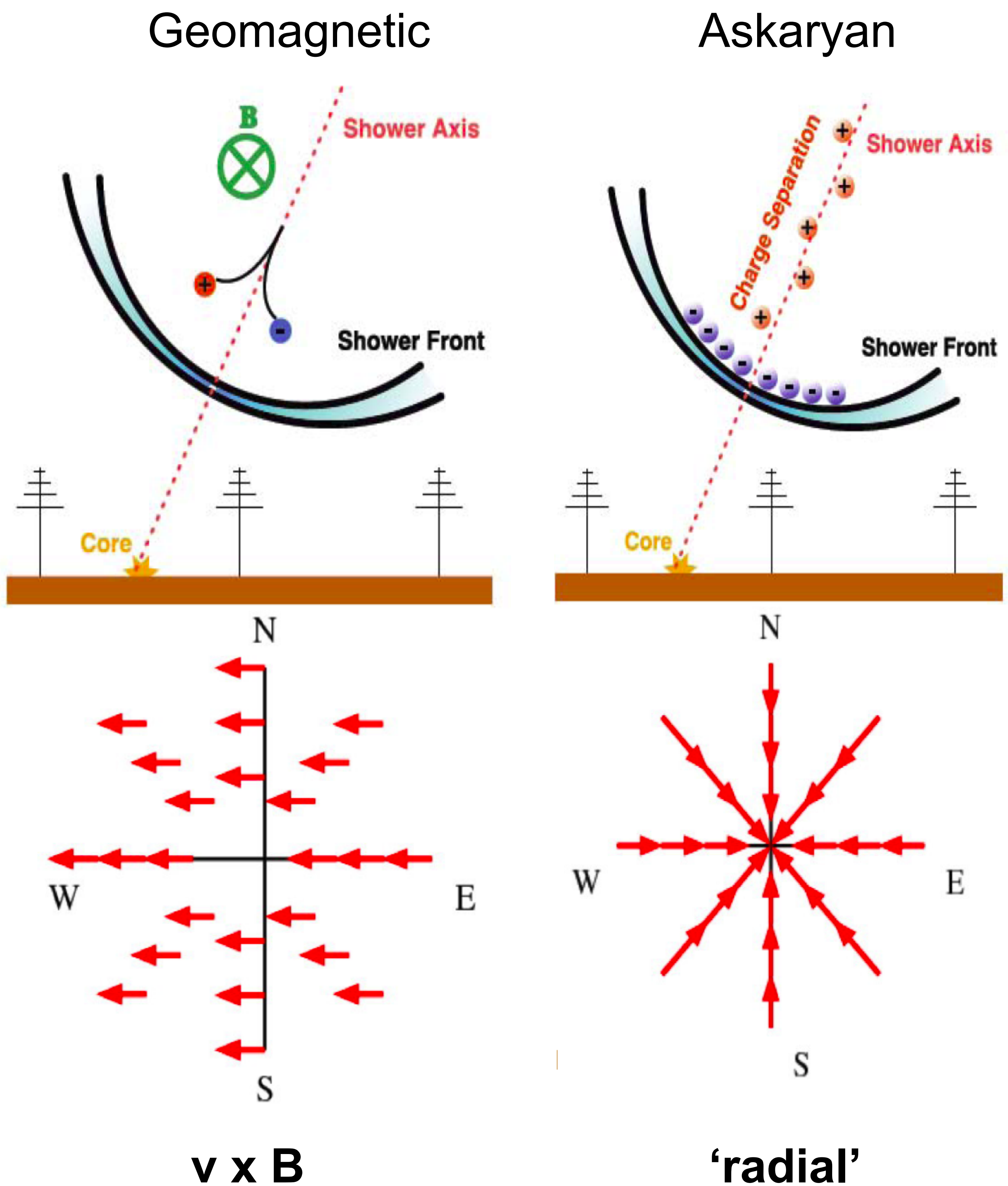


PRL 99, 171101 (2007)
see also:
PRE 62, 8590 (2000),
PRL 86, 2802 (2001),
PRD 72, 023002 (2005)
PRD 74, 043002 (2006)



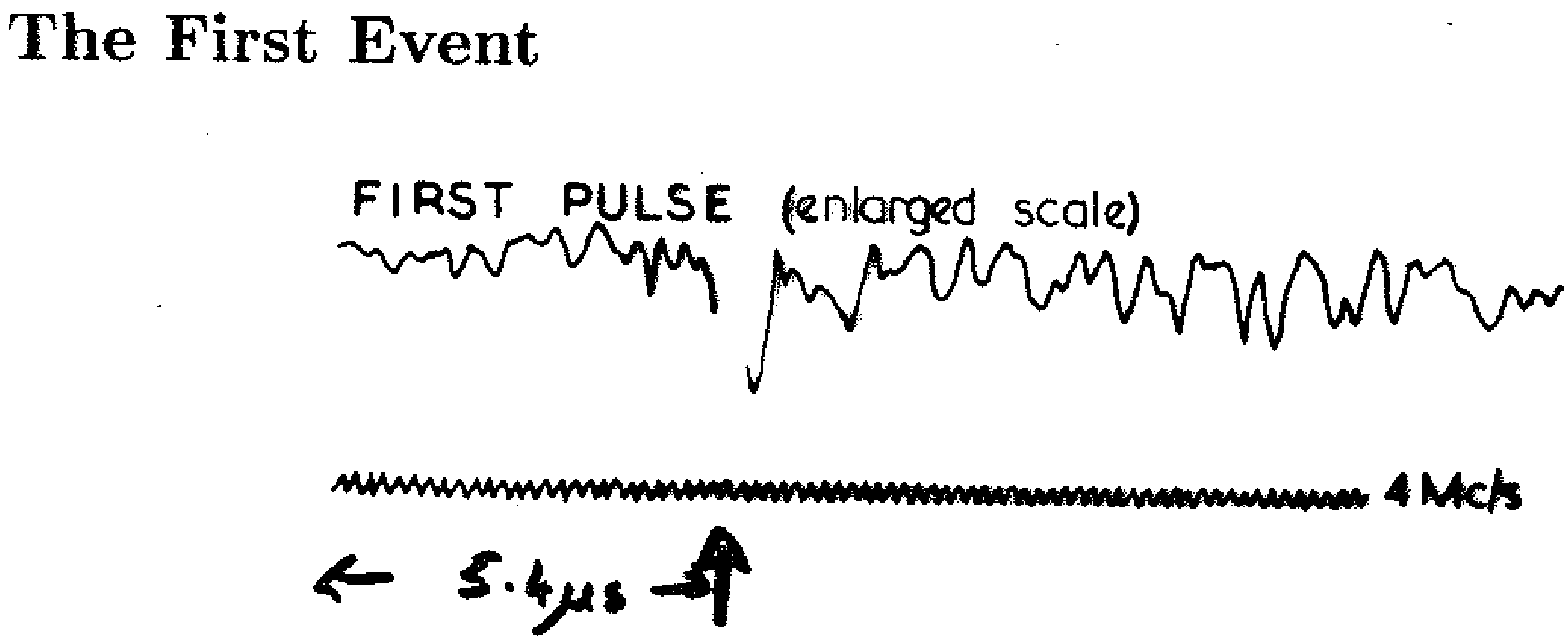
Radio Emission from Air Showers

- 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

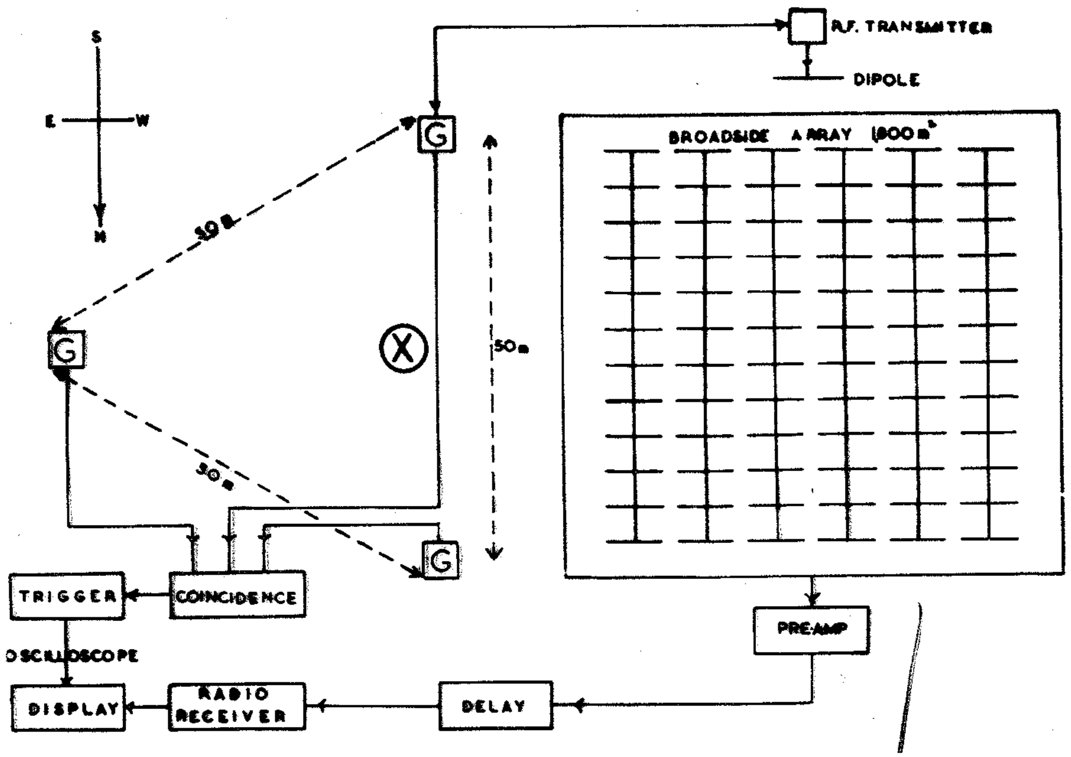
Earlier Experiments



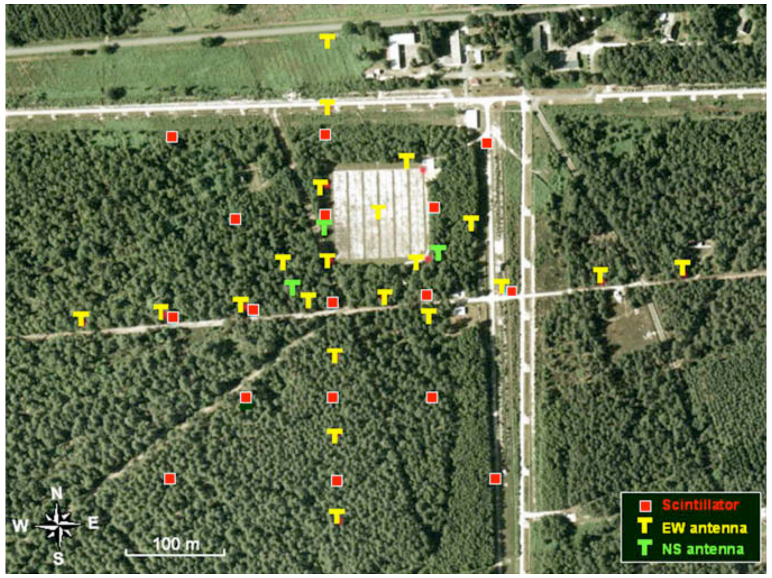
From T. Weekes,
RADHEP2000

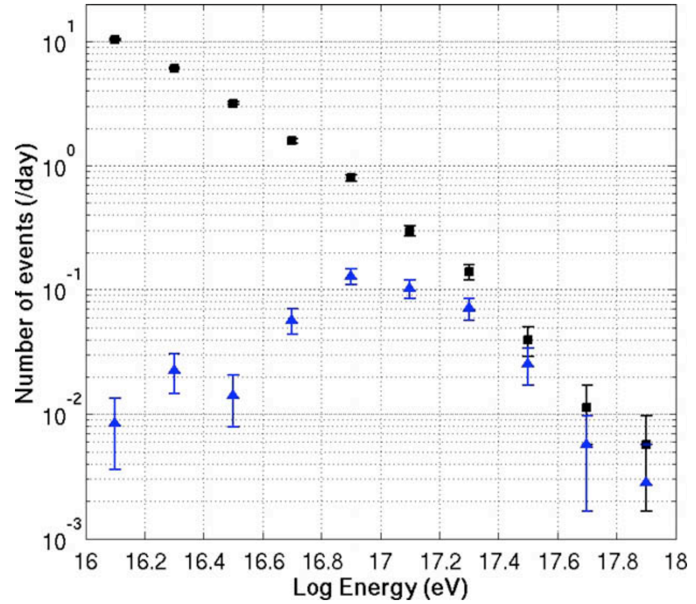
A few of the radio detection experiments

Jelley *et al*



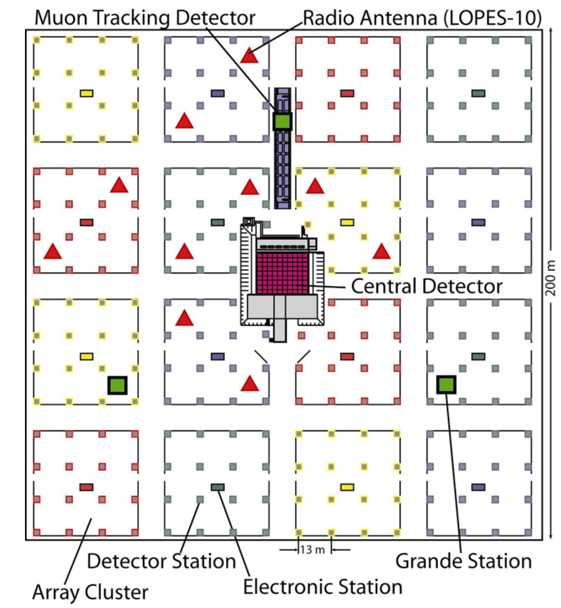
CODALEMA

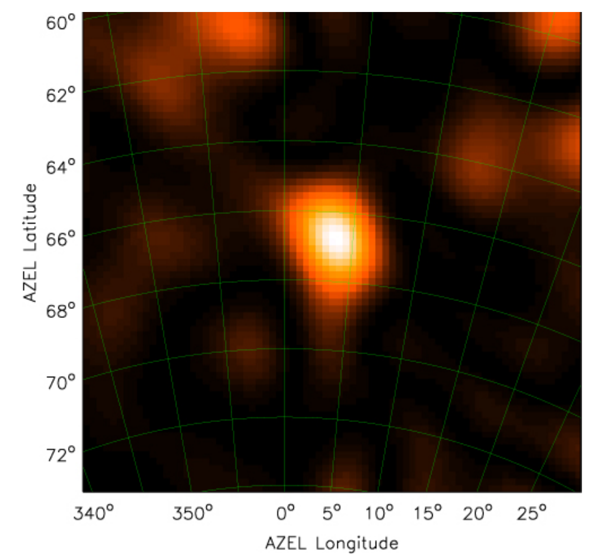




From: D. Ardouin et al. / Astroparticle Physics 31 (2009) 192–200 193

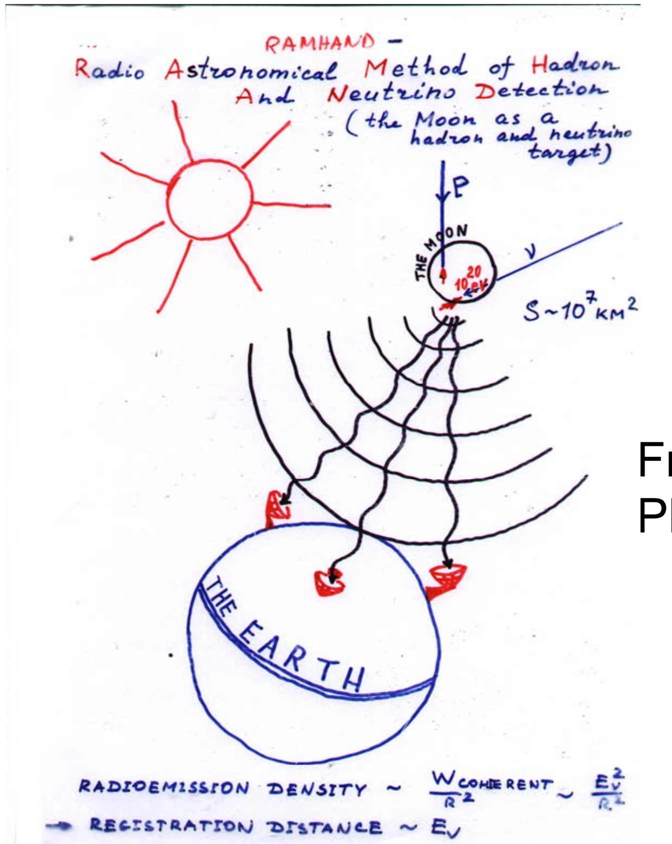
LOPES





LOPES collaboration, Nature 425 (2005) 313

RICE



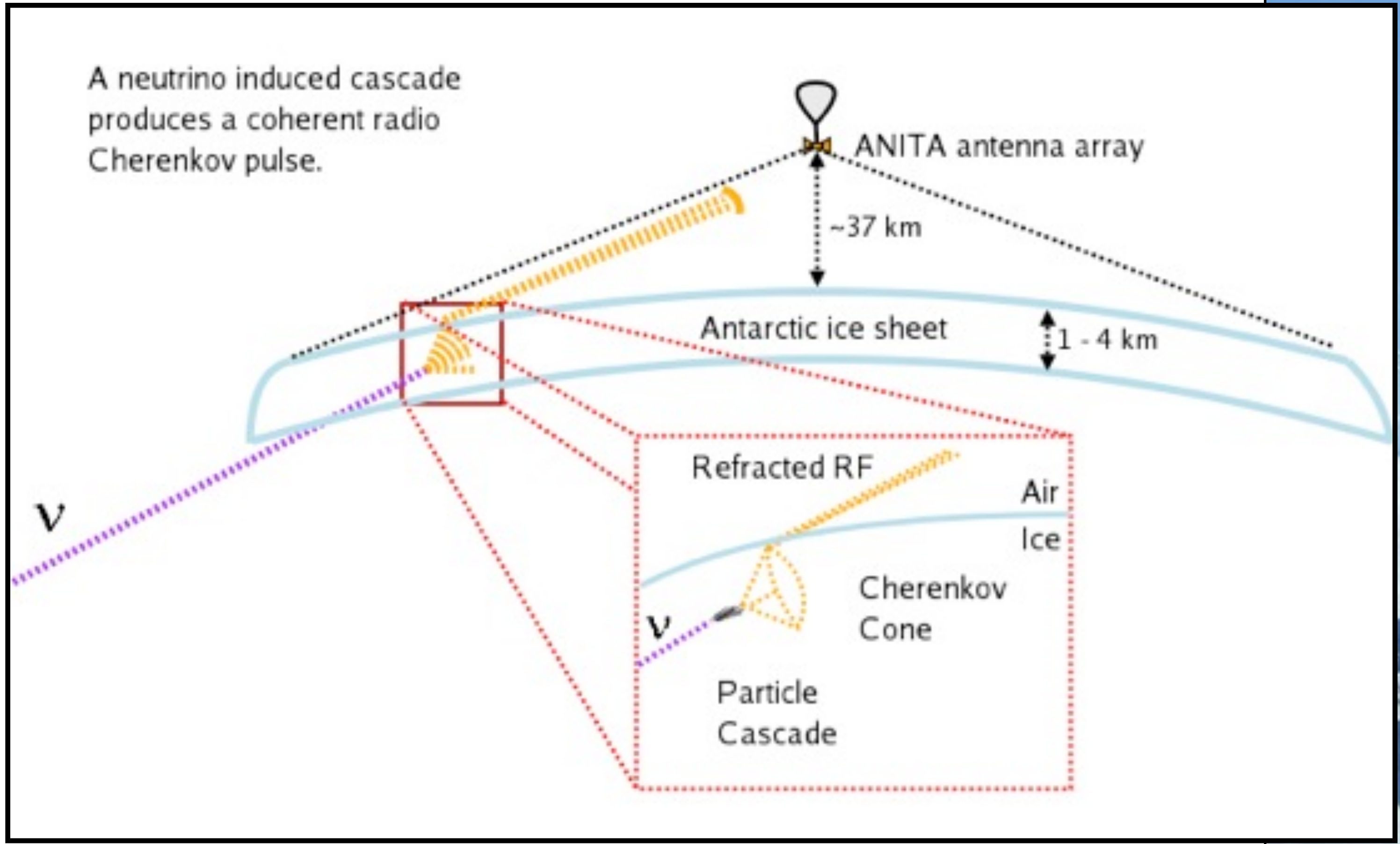
From I. Zheleznykh, ARENA 2008

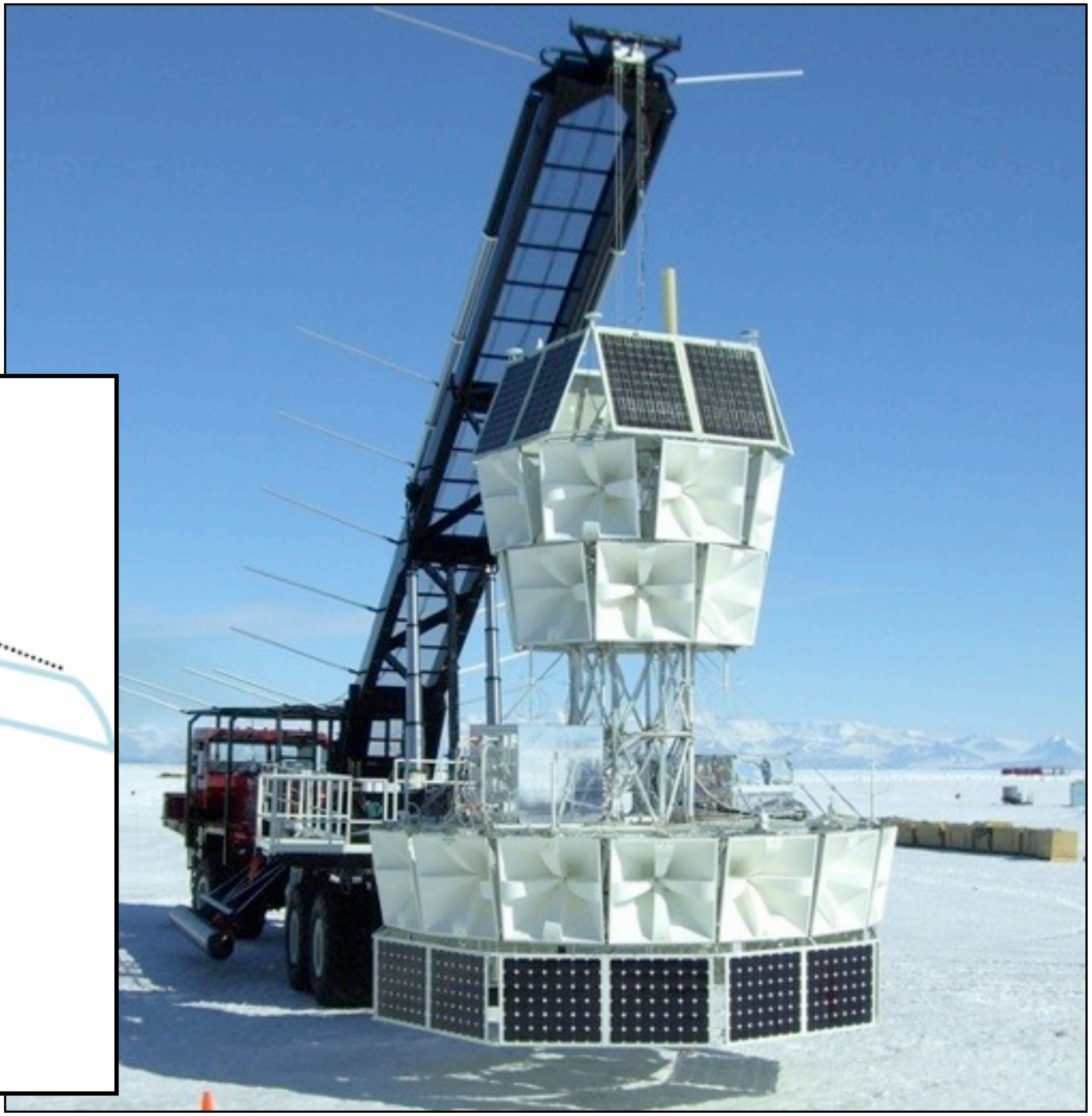
LOFAR

ANITA

ANITA

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

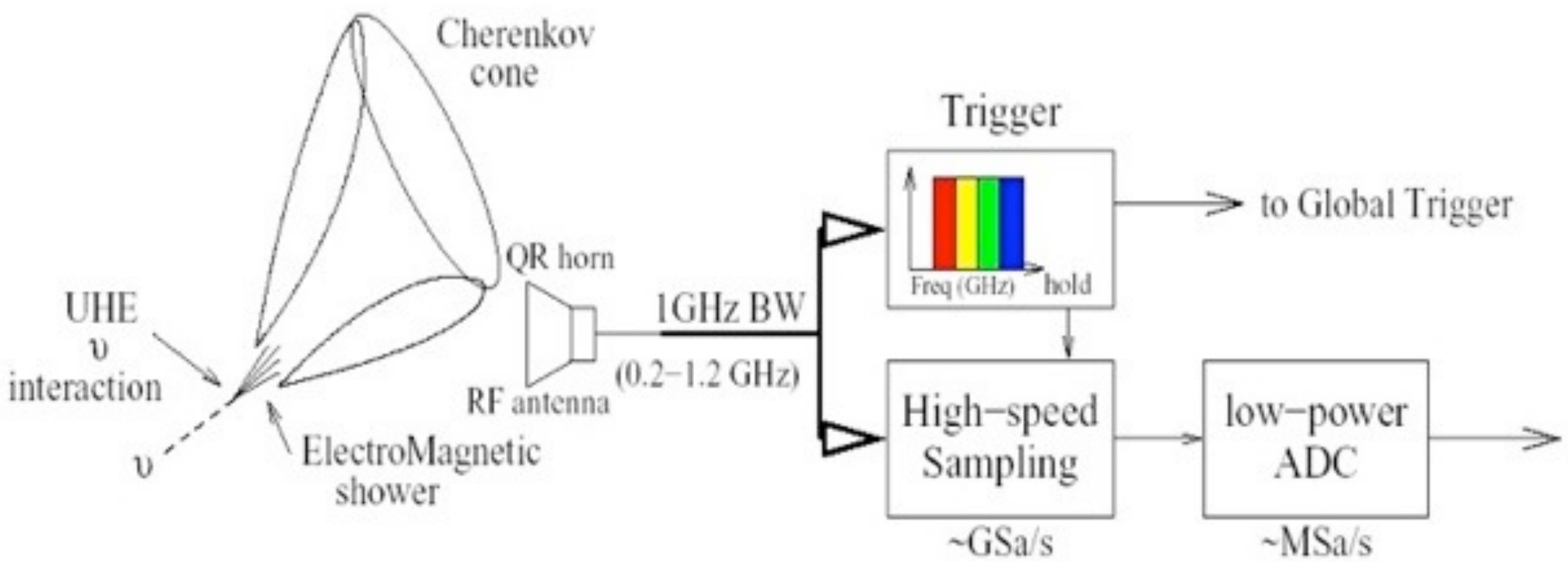


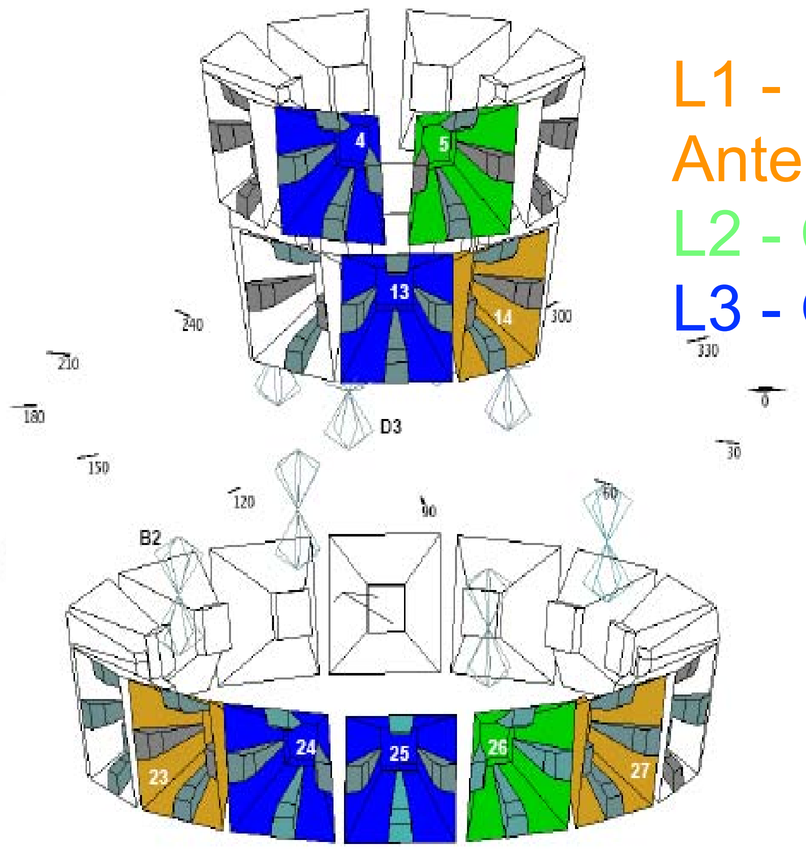


Only top of Cherenkov cone escapes ==> vertically polarised E-field at payload

ANITA Electronics and Trigger

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



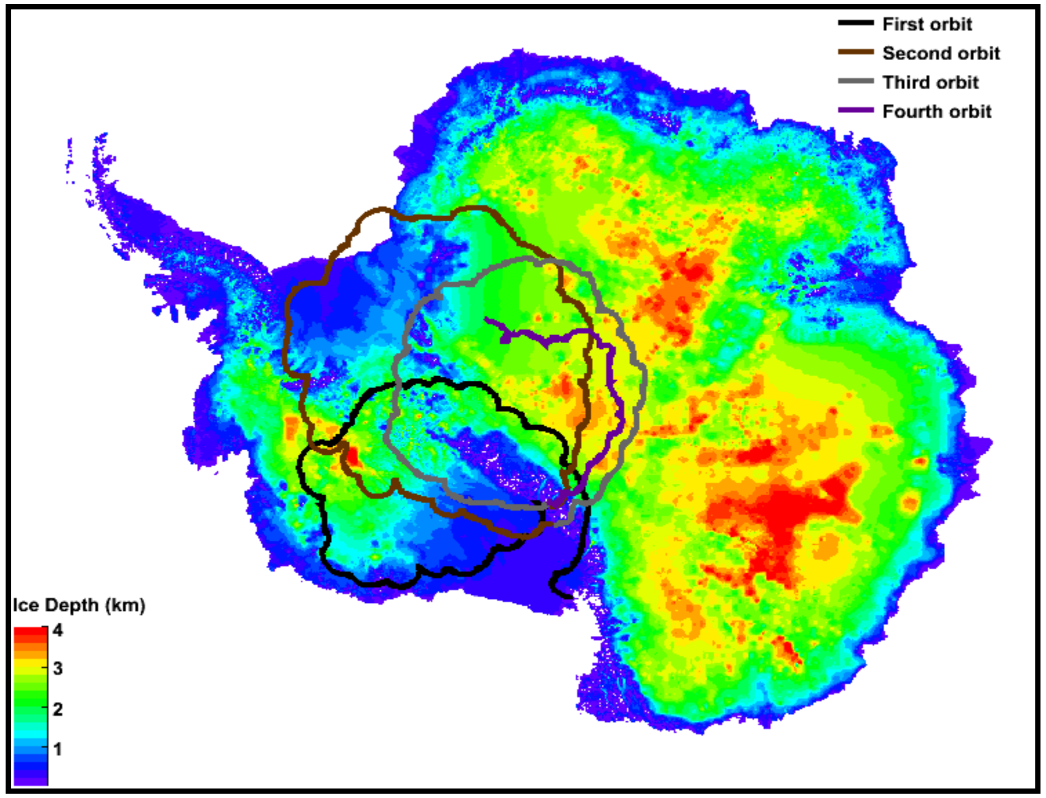


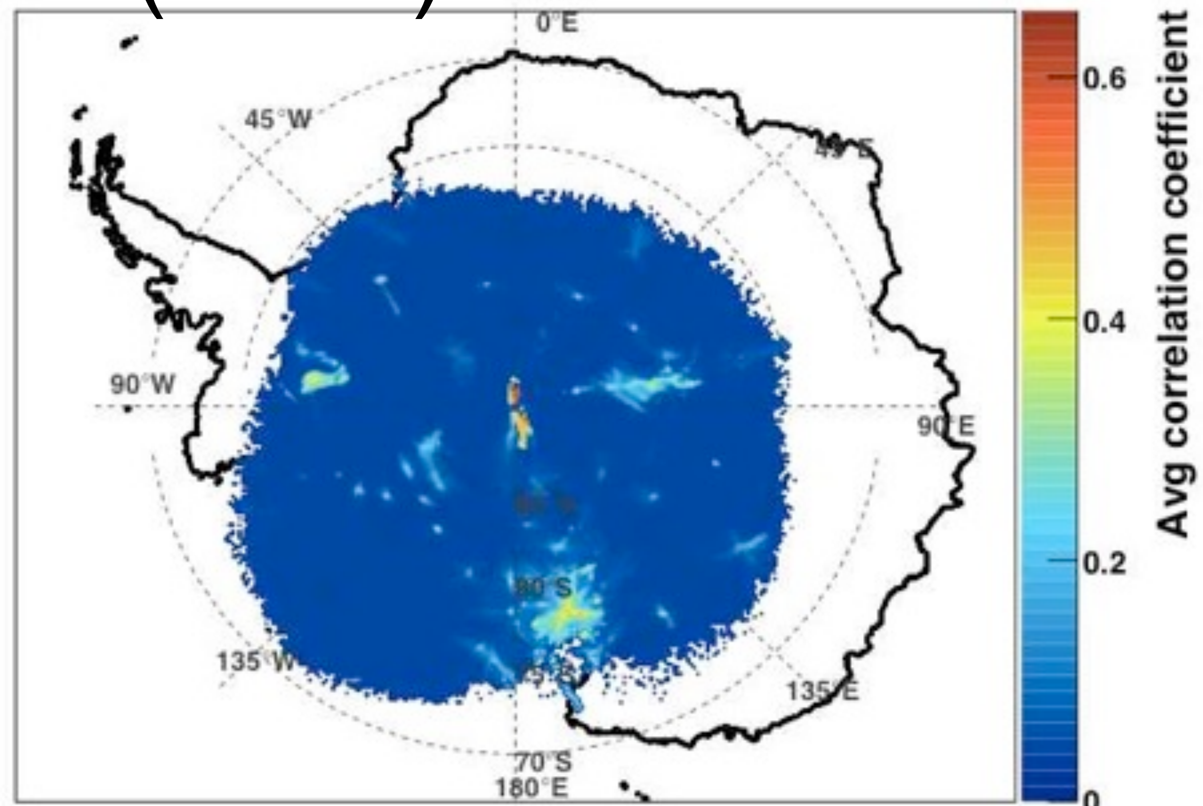
L1 - Antenna
L2 - Cluster
L3 - Global

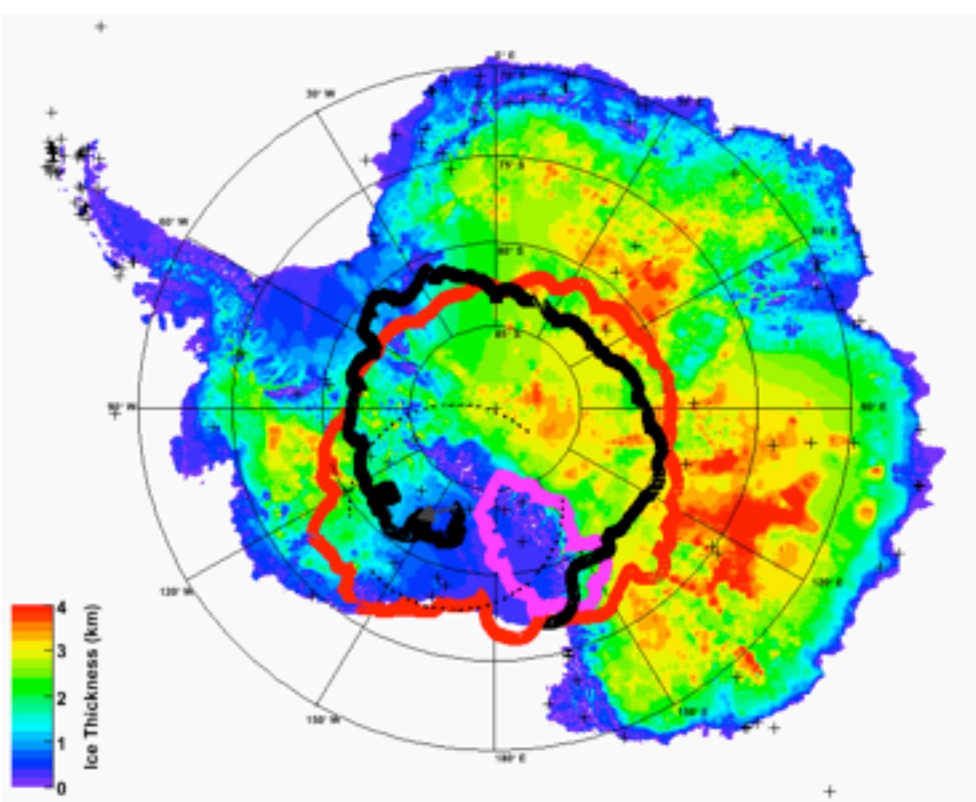
- Split trigger and waveform paths
- Use multiple frequency bands for trigger
- ‘Buffer’ waveform data in switched capacitor array
- Only digitise when we have a trigger

ANITA I&II

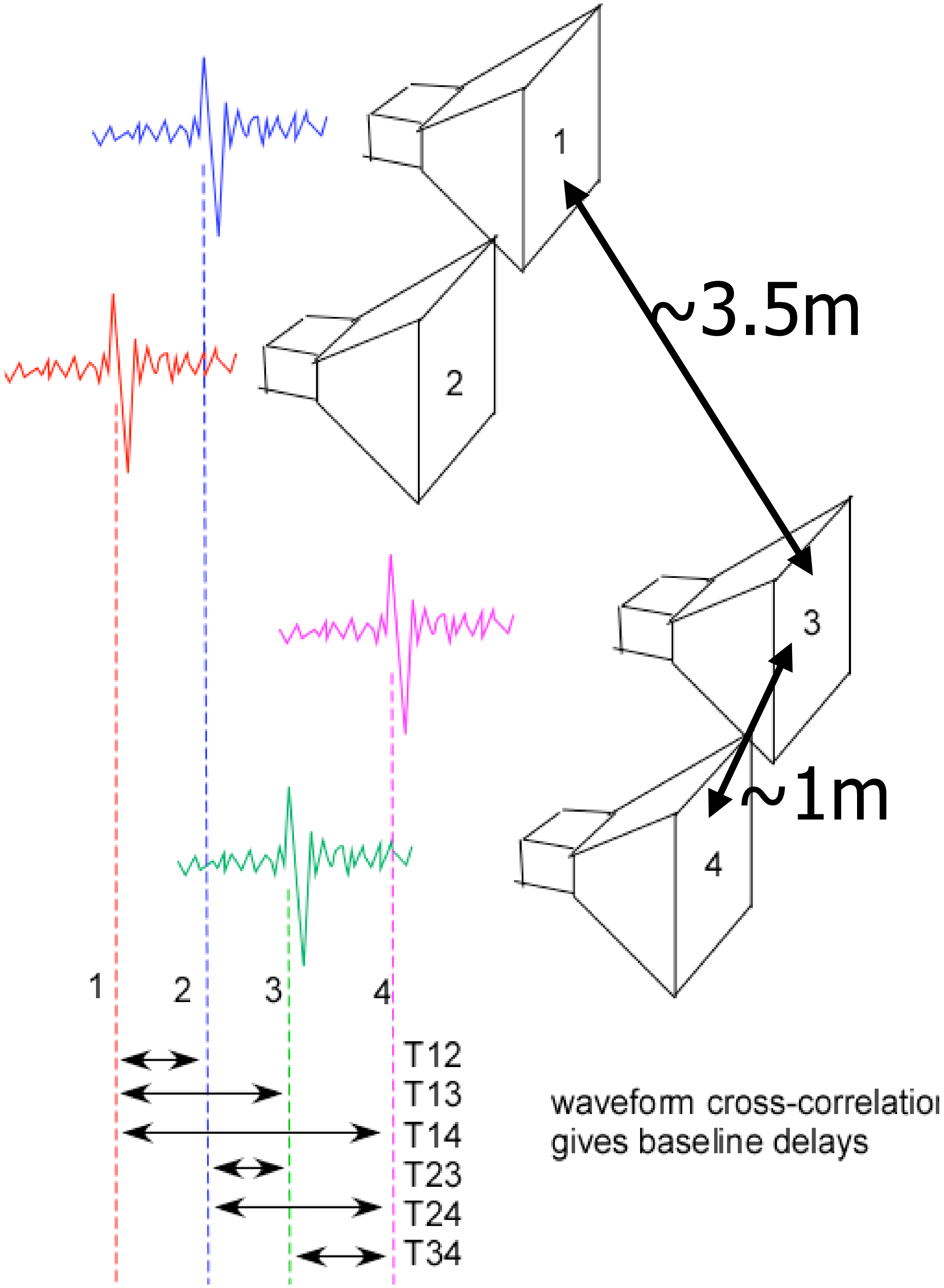
- Over 65 days of flight over Antarctica
- Over 35 million triggered (noise) events

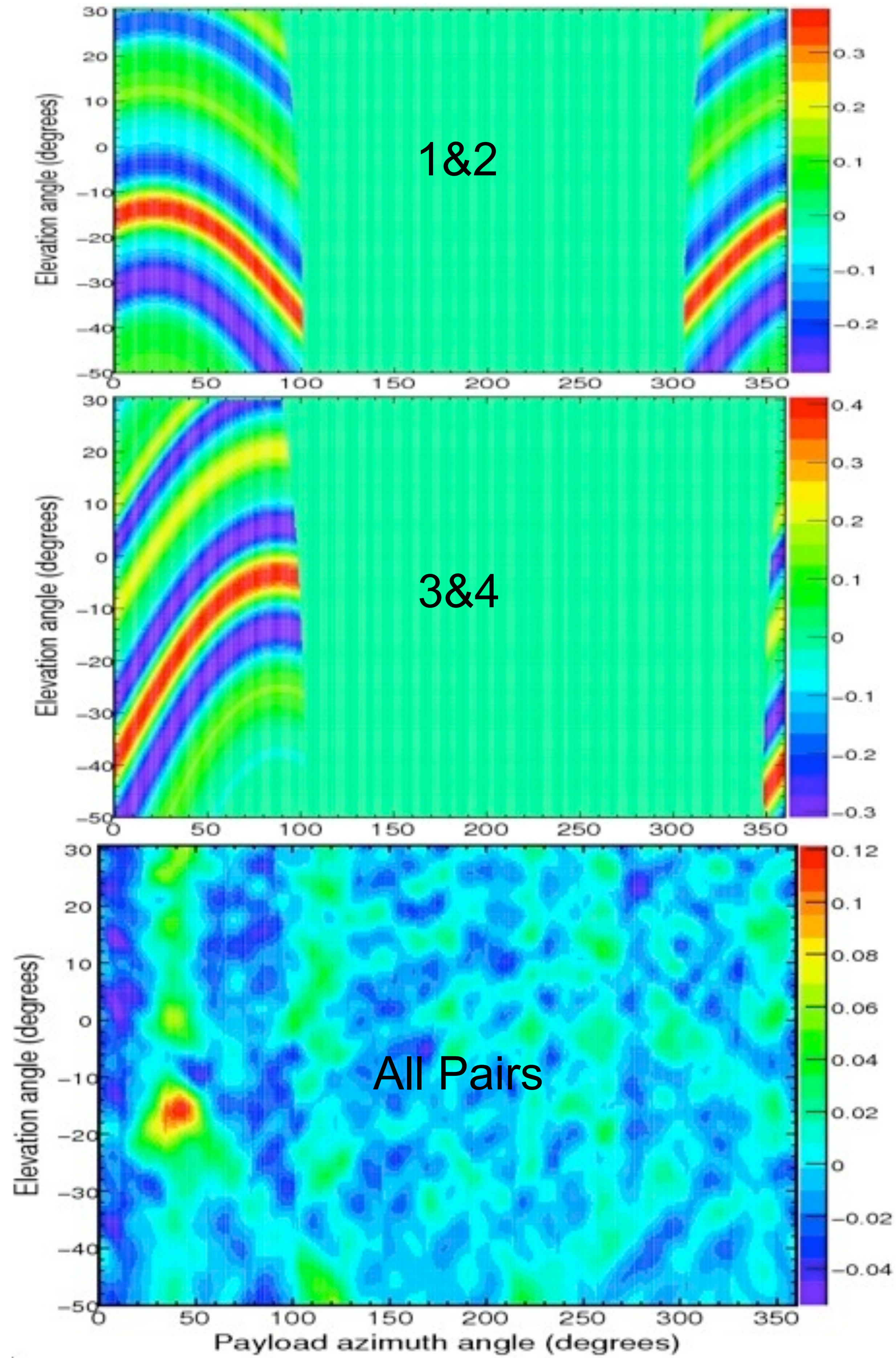






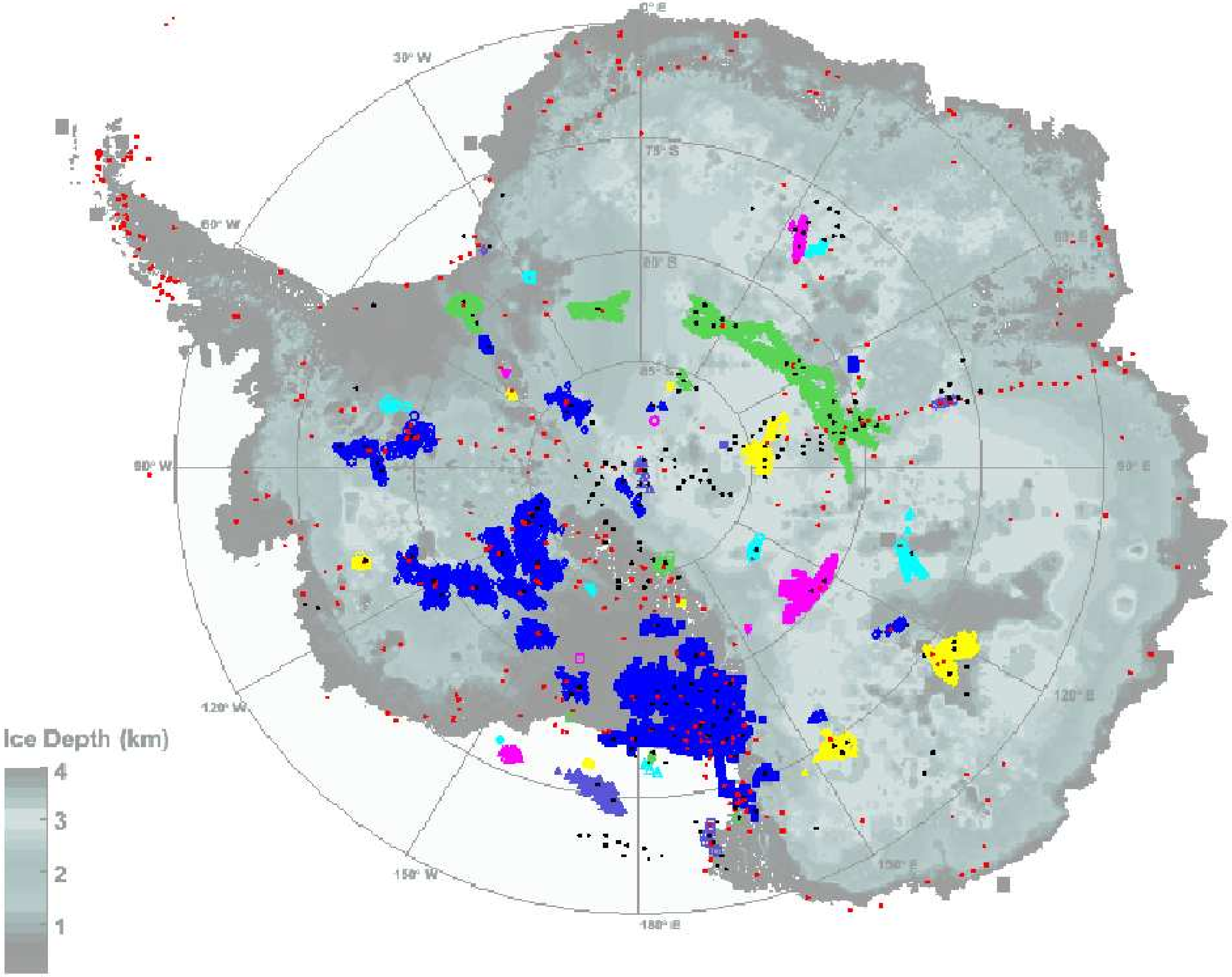
Analysis -- Cross Correlation





from A. Romero Wolf, Neutrino 2008

ANITA-II Results

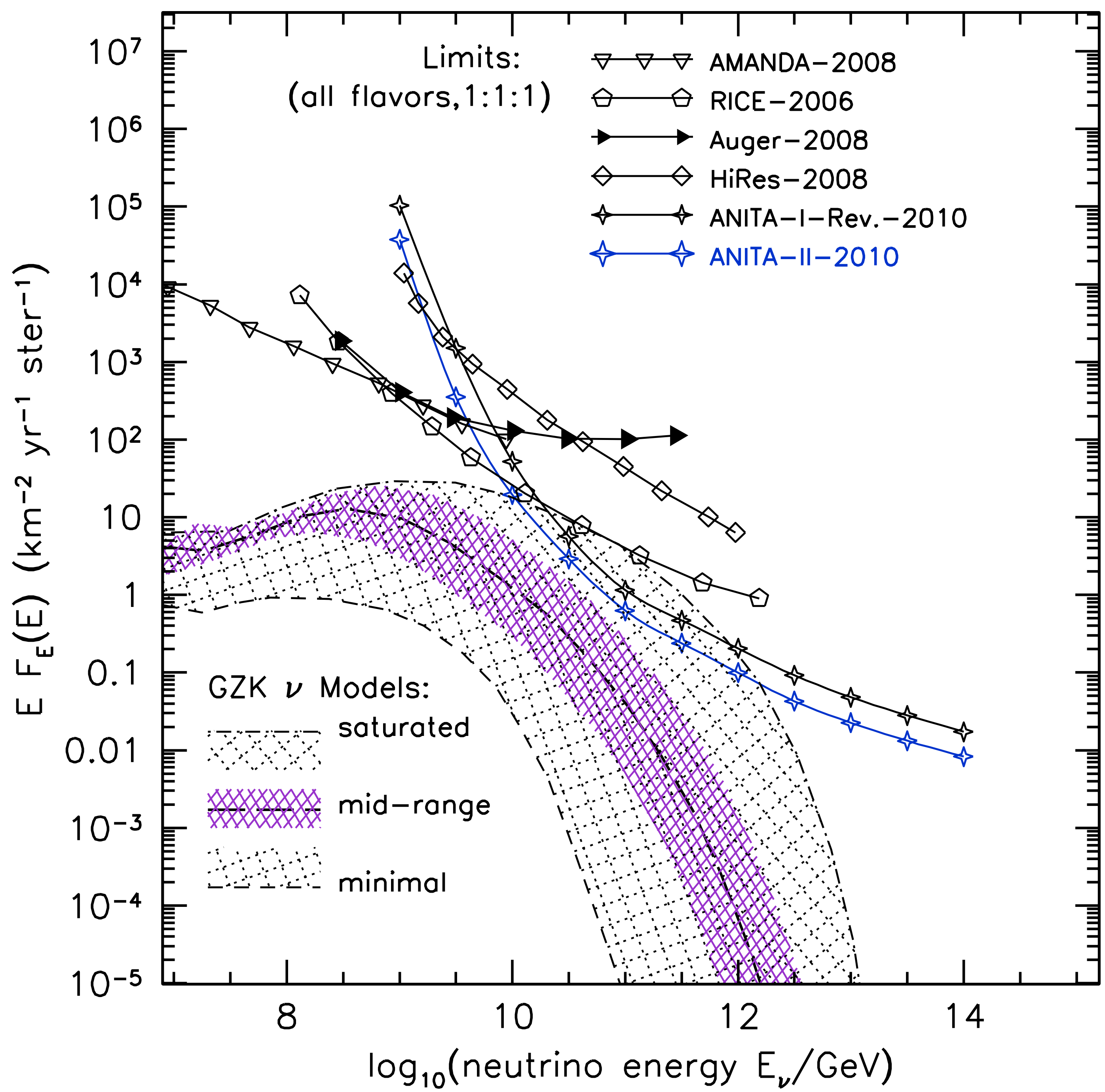


Neutrino Limits

- ANITA-II Results

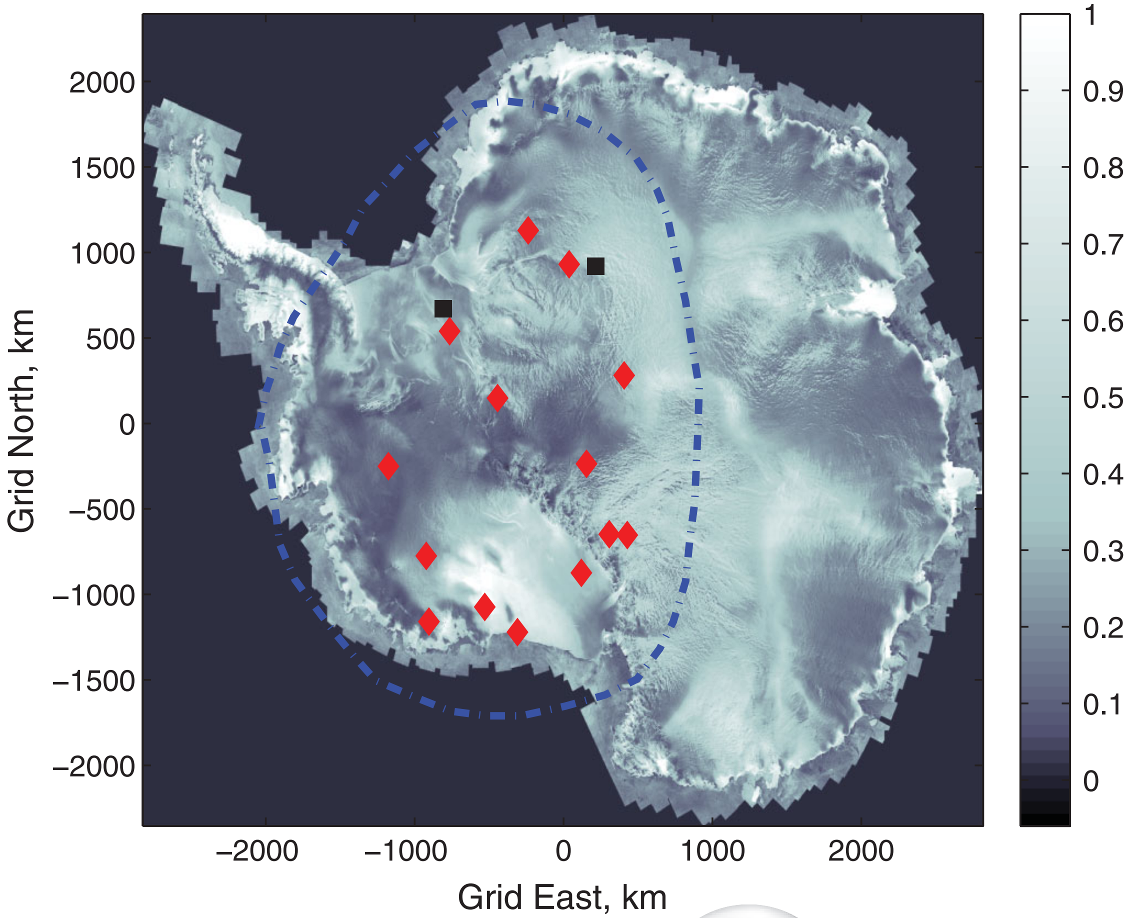
Isolated v-pol events	1
Expected background events	0.97 ± 0.42

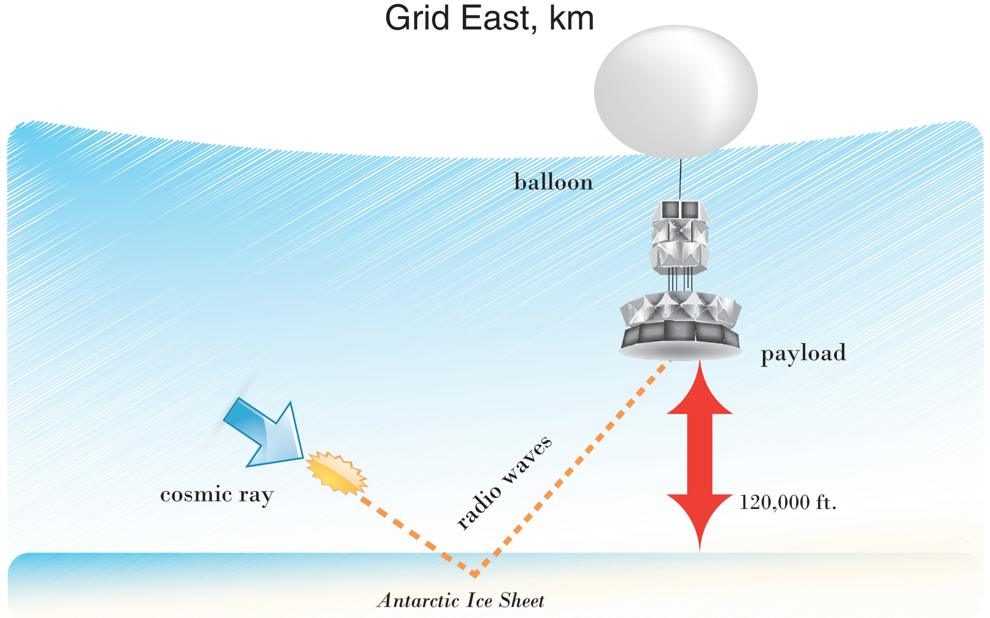
- Combine with efficiency to extract world's best limit on UHE neutrino flux above 10^{19}eV



ANITA-I H-Pol Results

PRL **105**, 151101 (2010)

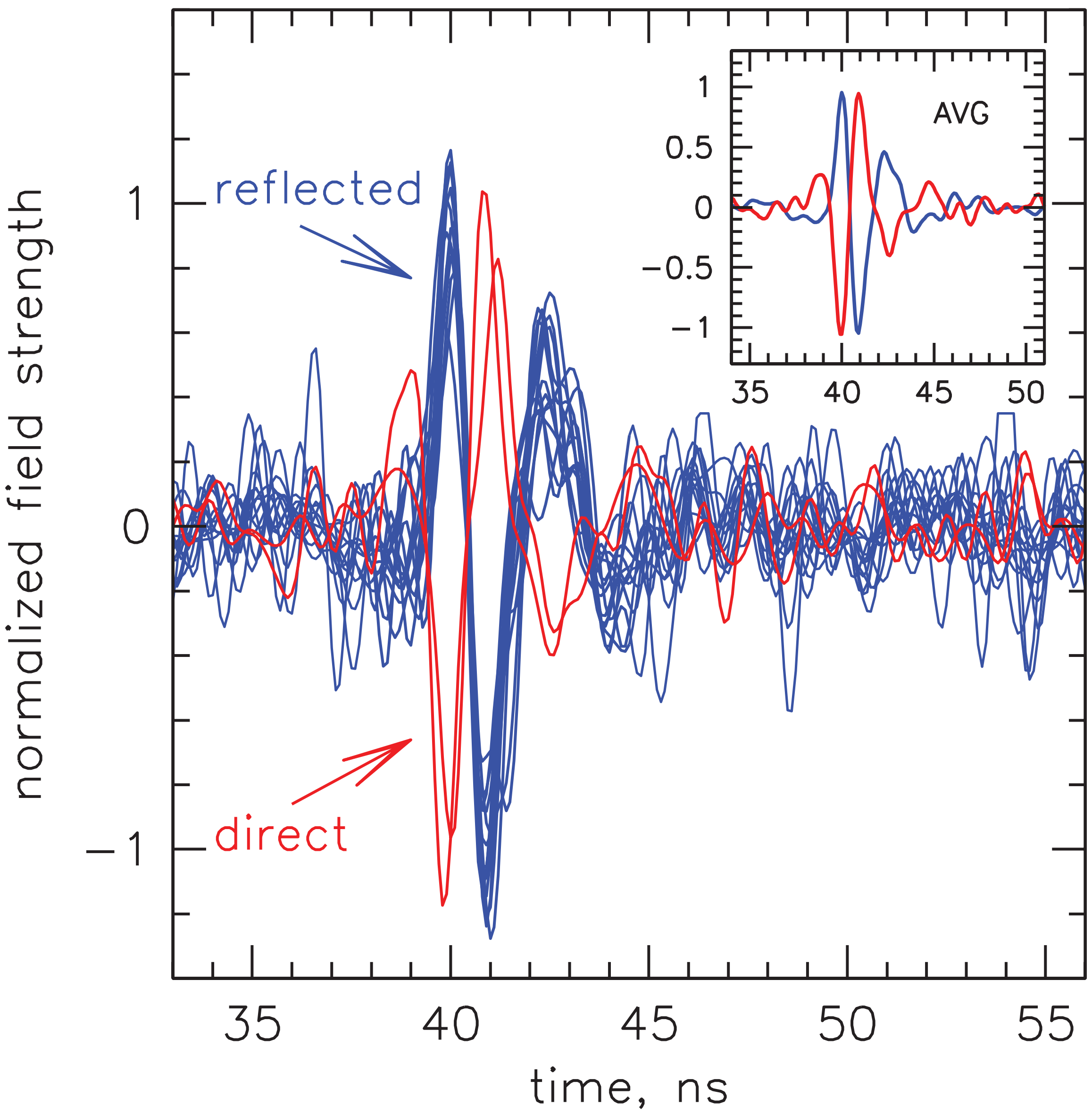




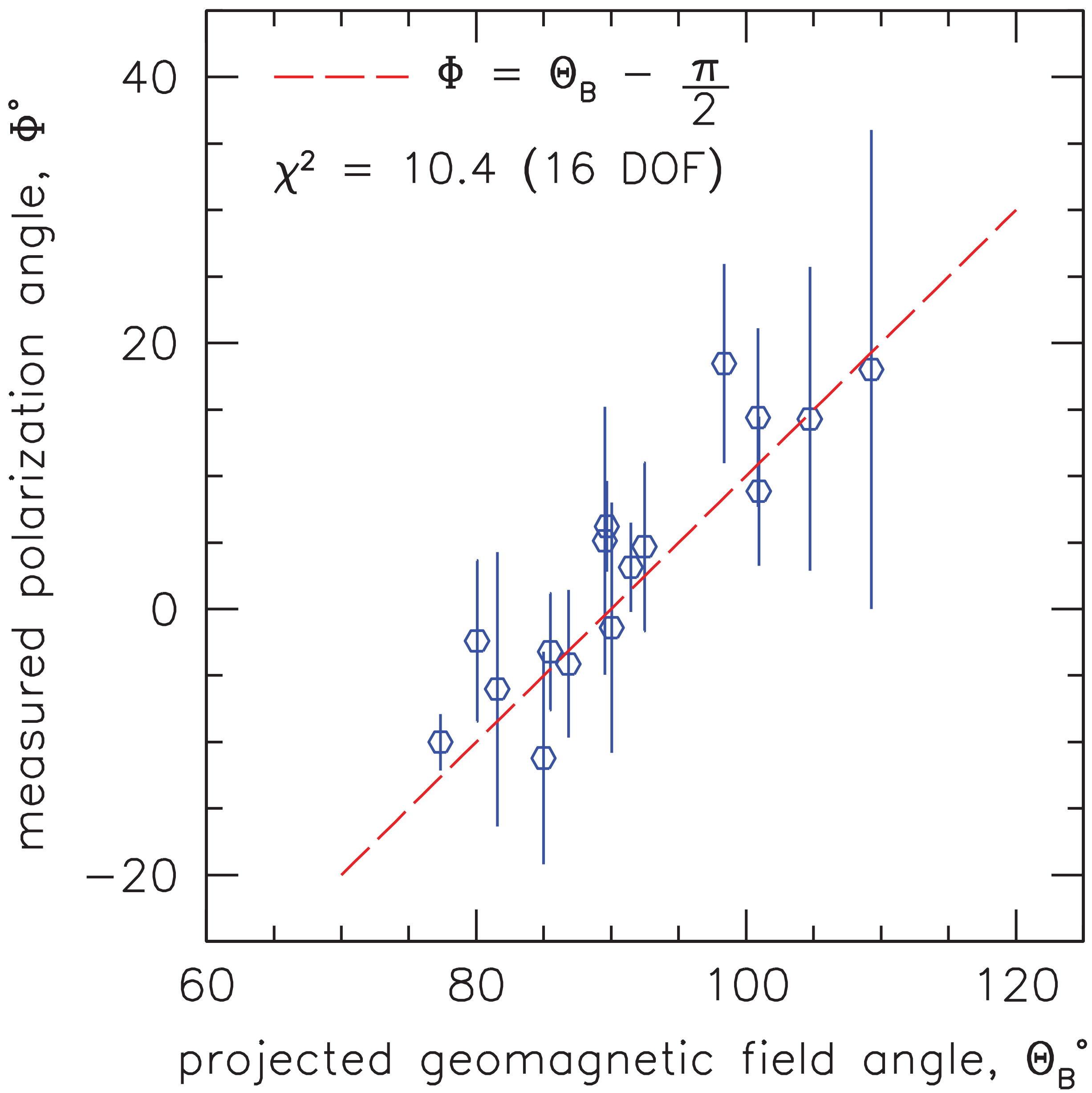
- A combination of **vxB** and Fresnel coefficients result in air shower emission being horizontally polarised at the payload
- ANITA-I detected 16 isolated H-pol candidate UHECR events
- ANITA-II did not trigger on the H-pol channels
  - Doh!!
- Still detected 5 UHECR candidate events

Are they really cosmic ray signals?

Direct vs Reflected flip polarity



Correlation os measured polarisation with local geomagnetic field angle



More data needed to fully understand energy scale. ANITA III will fly in 2014 and should collect 500-1000 UHECR air shower events during its flight.

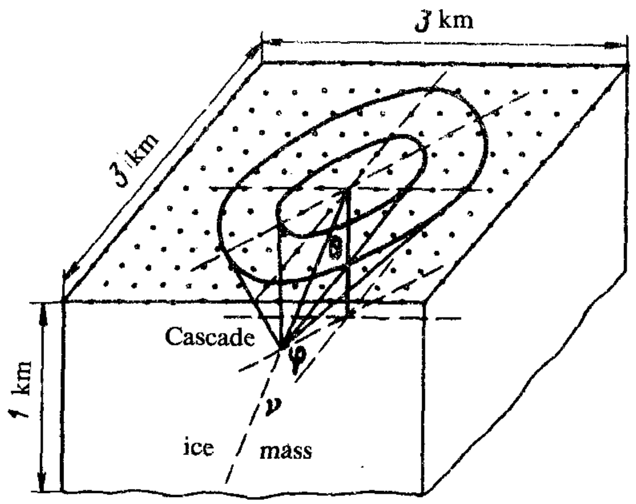
Future Prospects

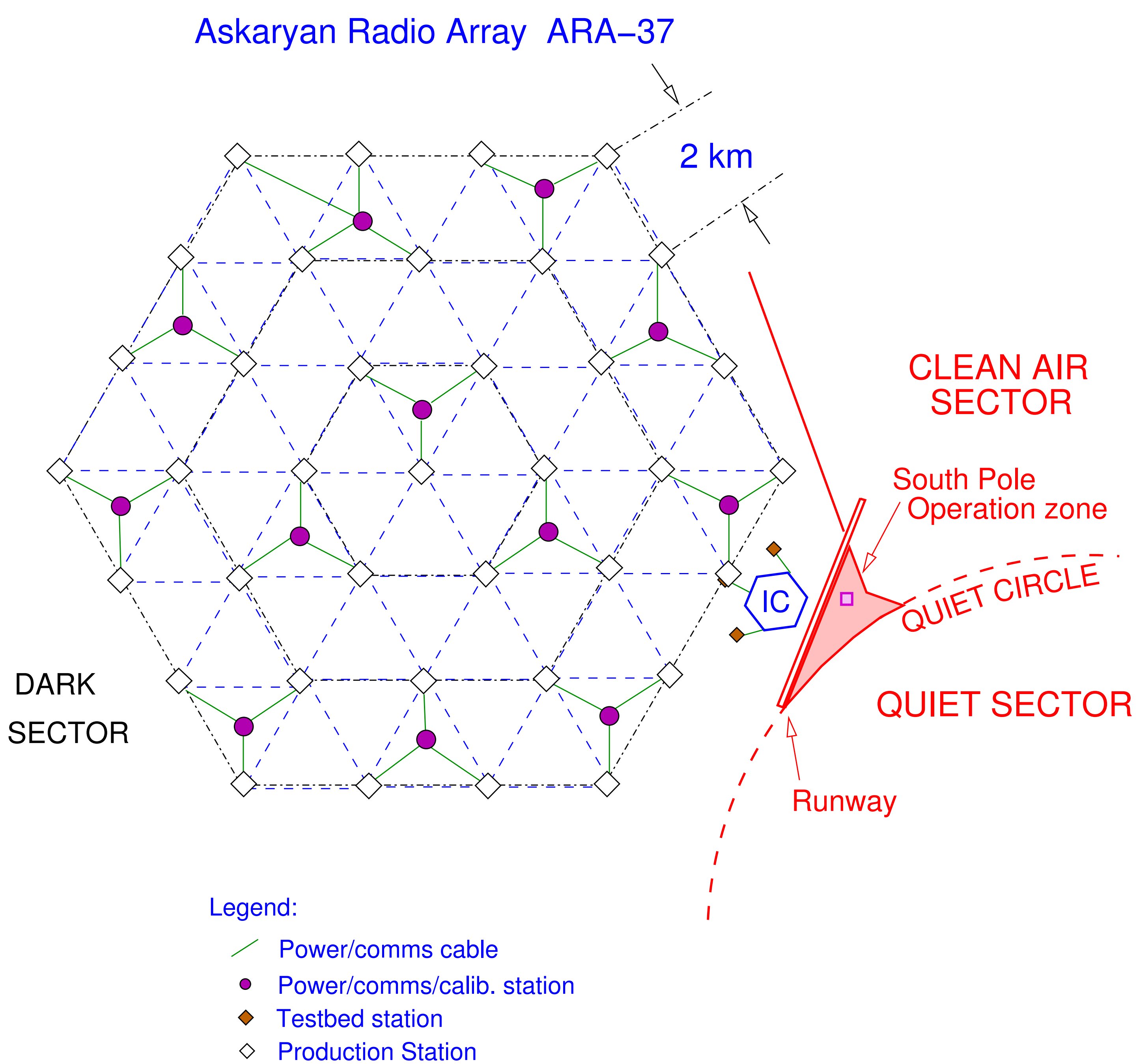
Radio array in Antarctica, proposed in the 1980s

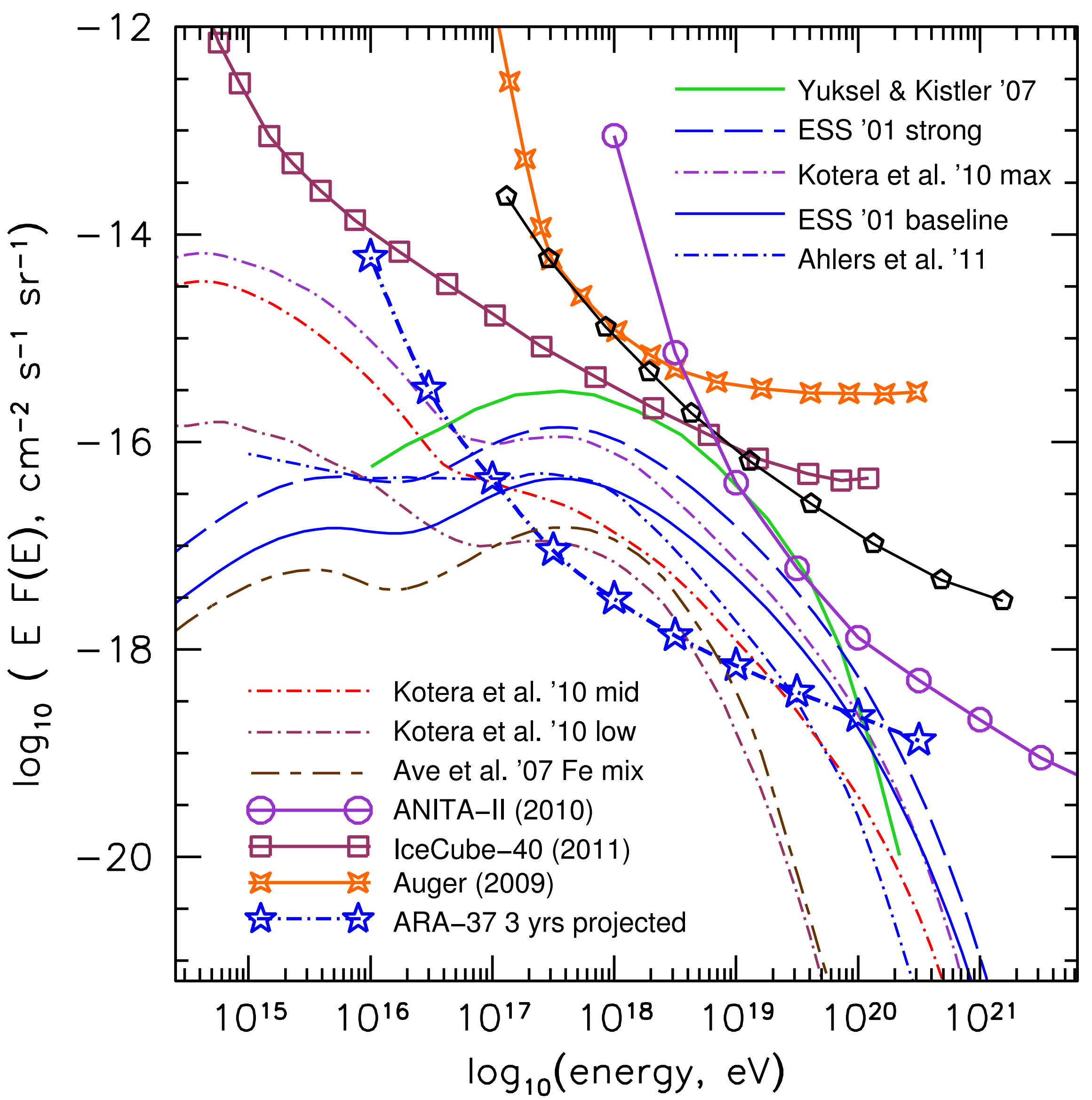
Neutrino and muon detection from the radio-emission of cascades created by them in natural dielectric media

G. A. Gusev and I. M. Zheleznykh
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 27 September 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 10, 505–507 (25 November 1983)

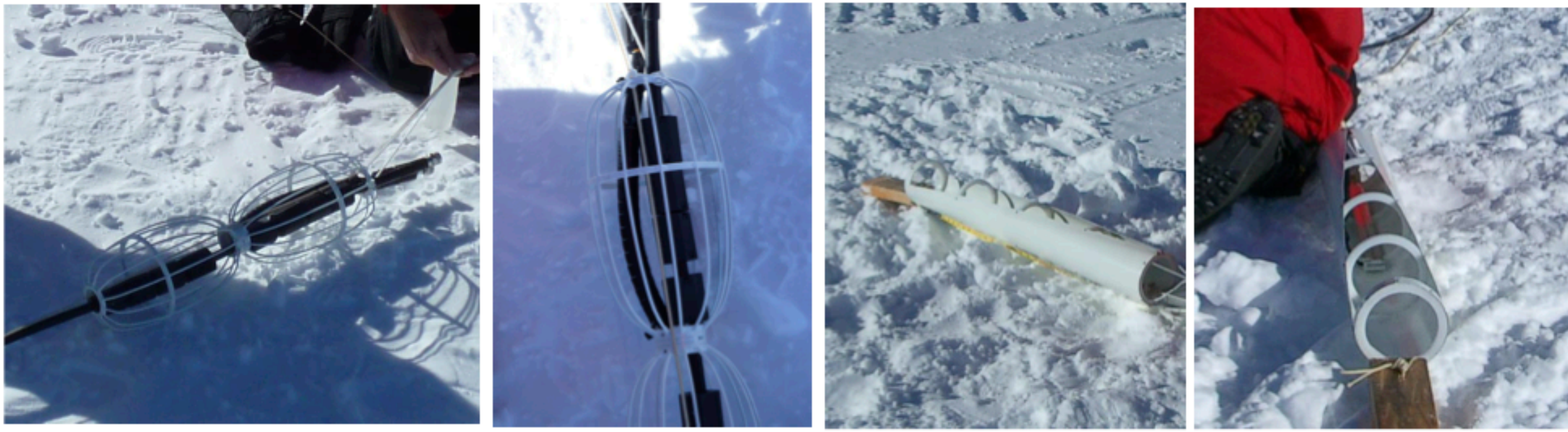


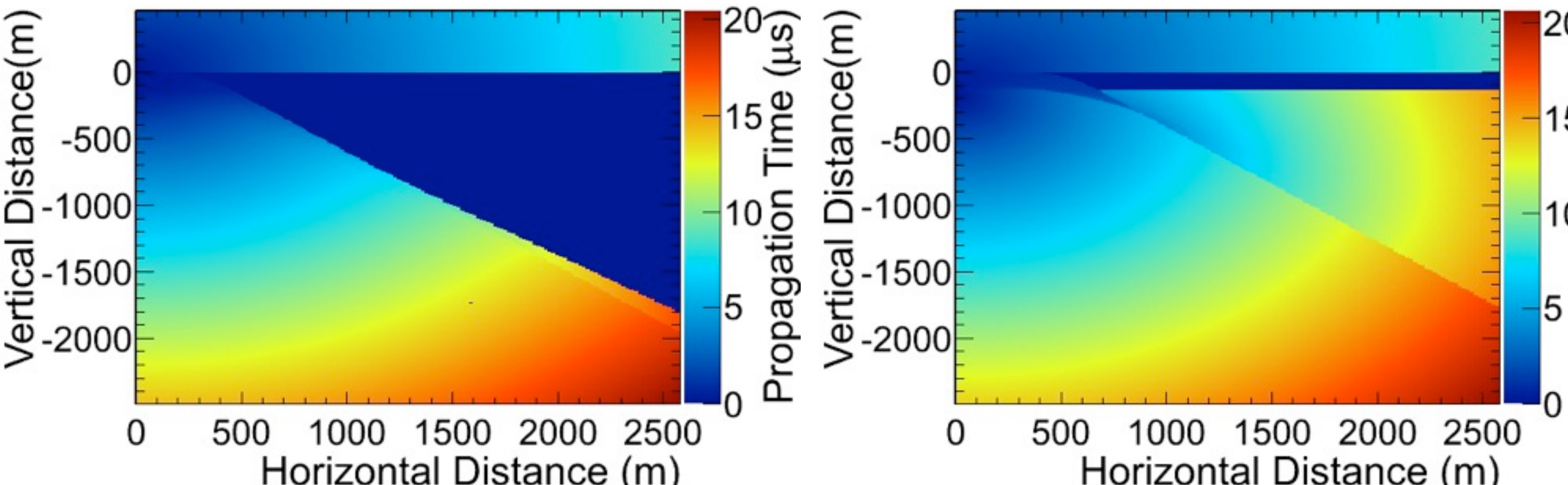




Askaryan Radio Array

- Four stations deployed



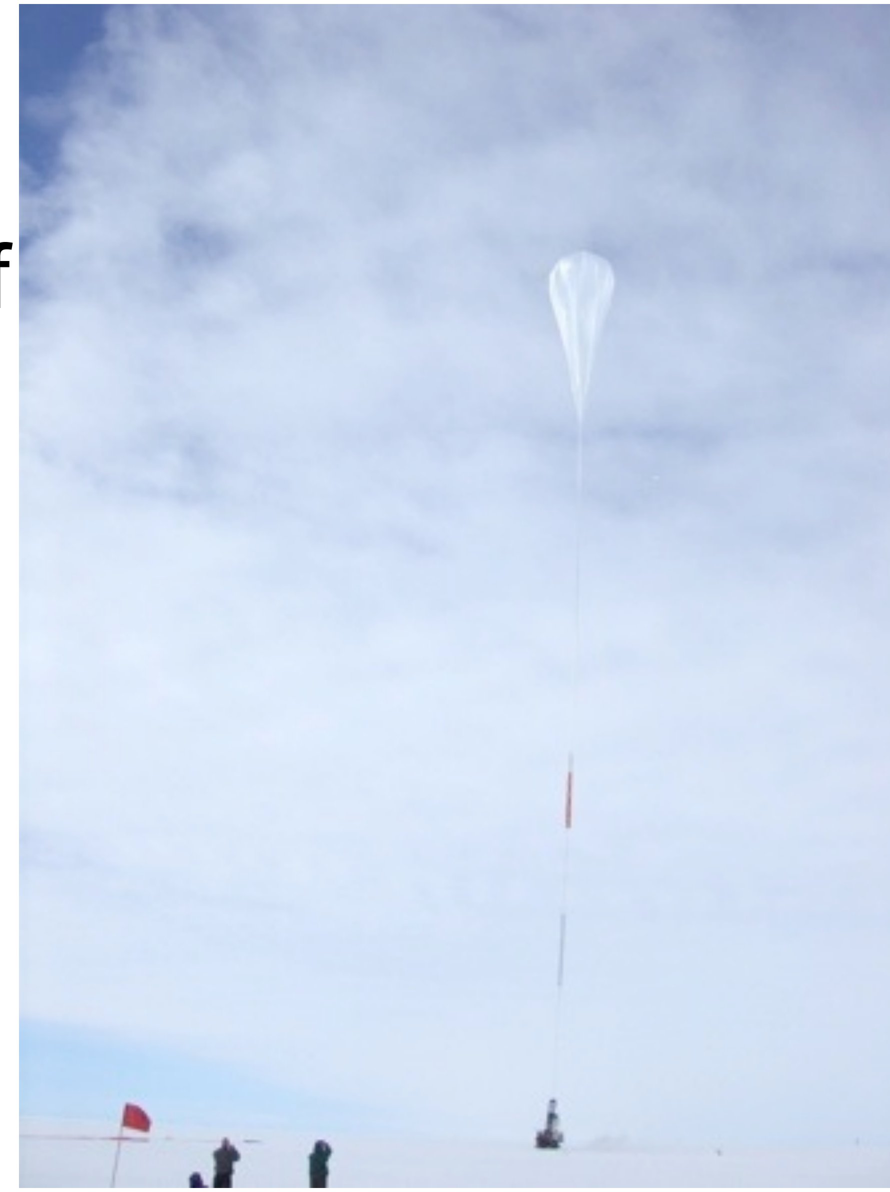


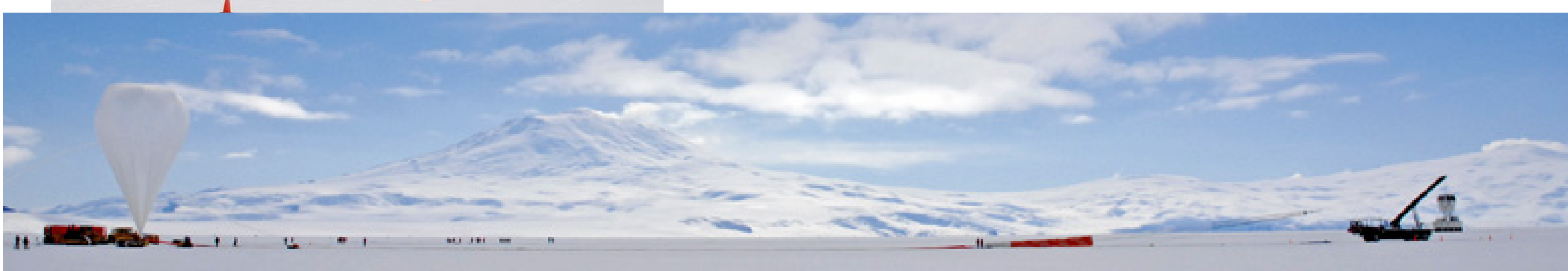
Summary

- The radio detection technique is currently in a renaissance
- Several experiments have detected high energy cosmic ray air showers ($>10^{17}$eV) and several more are in the planning or prototype phase
- The third ANITA flight should detect 500-1000 cosmic rays
  - Such a sample should allow determination of the energy scale by comparison to ground-based spectra
- Both ANITA and ARA are closing in on the elusive goal of detecting BZ neutrinos originating from the GZK interaction of cosmic rays with the cosmic microwave background

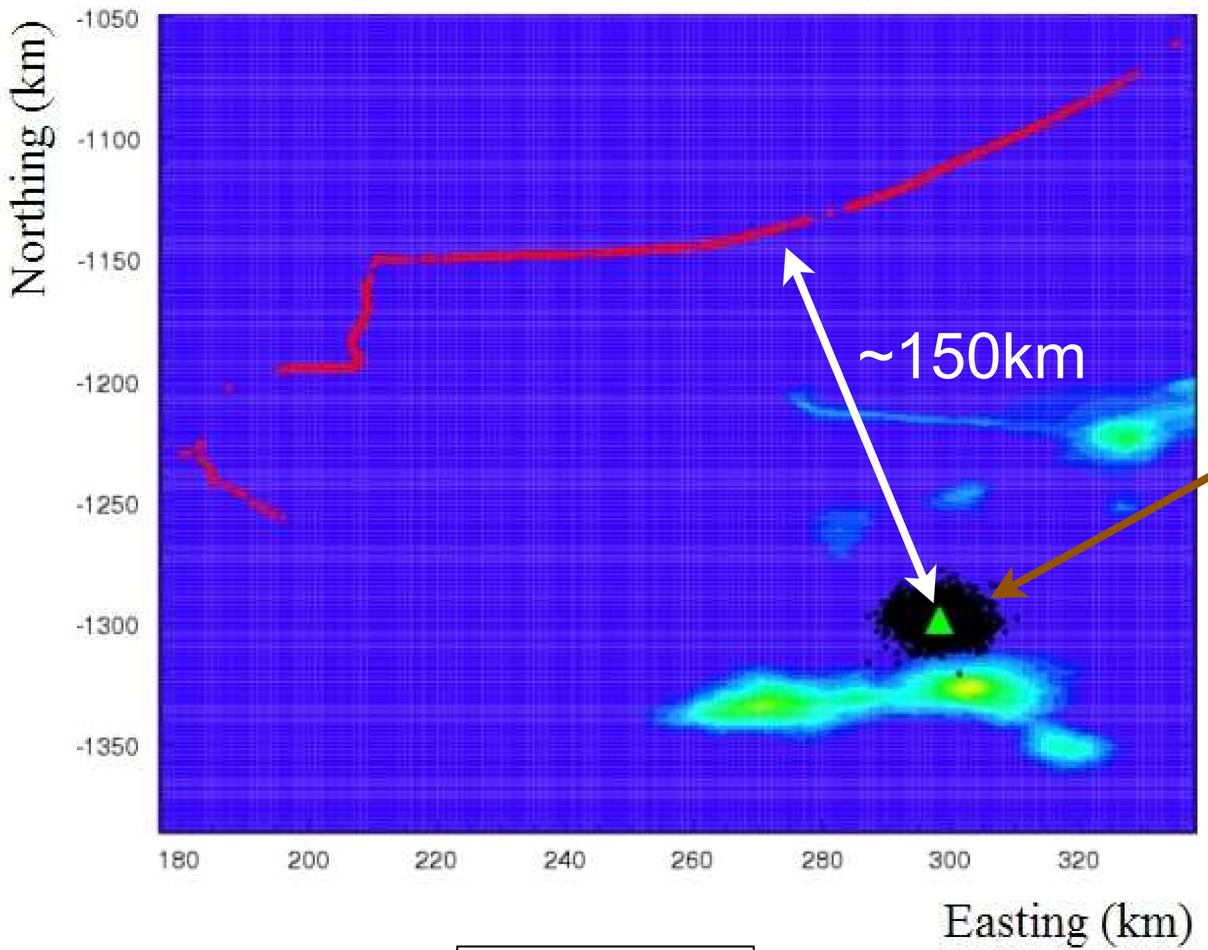
Up, up and away

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





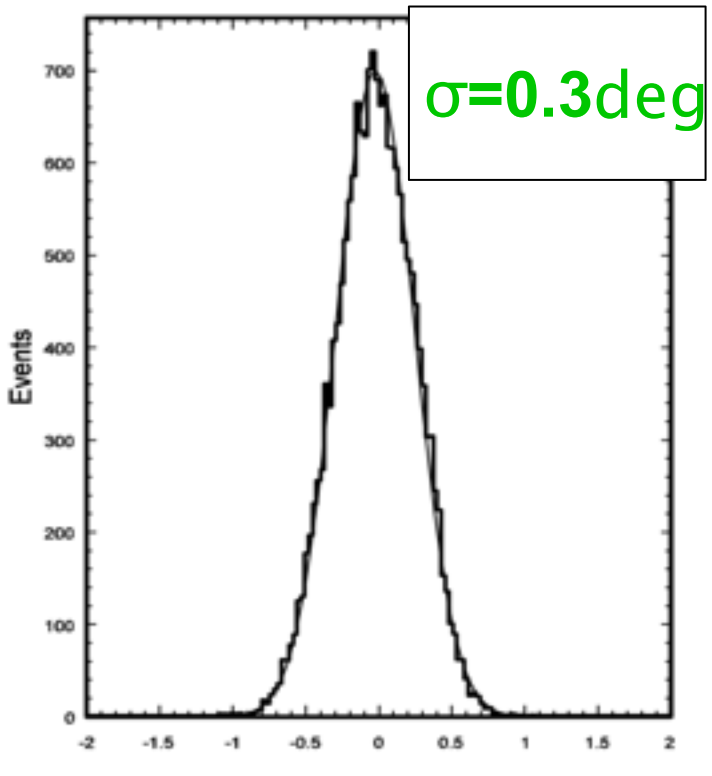
Calibration

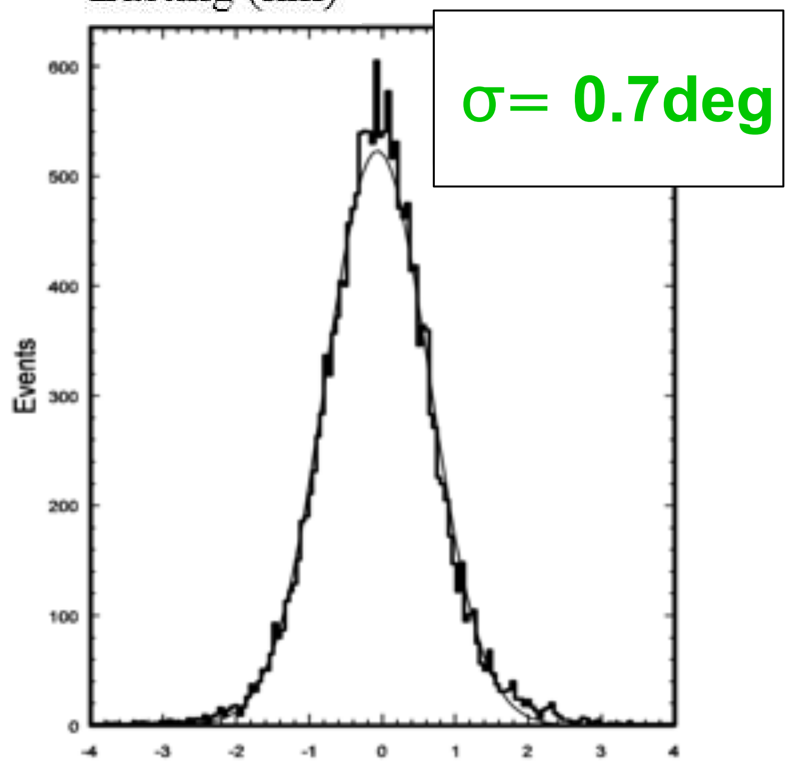


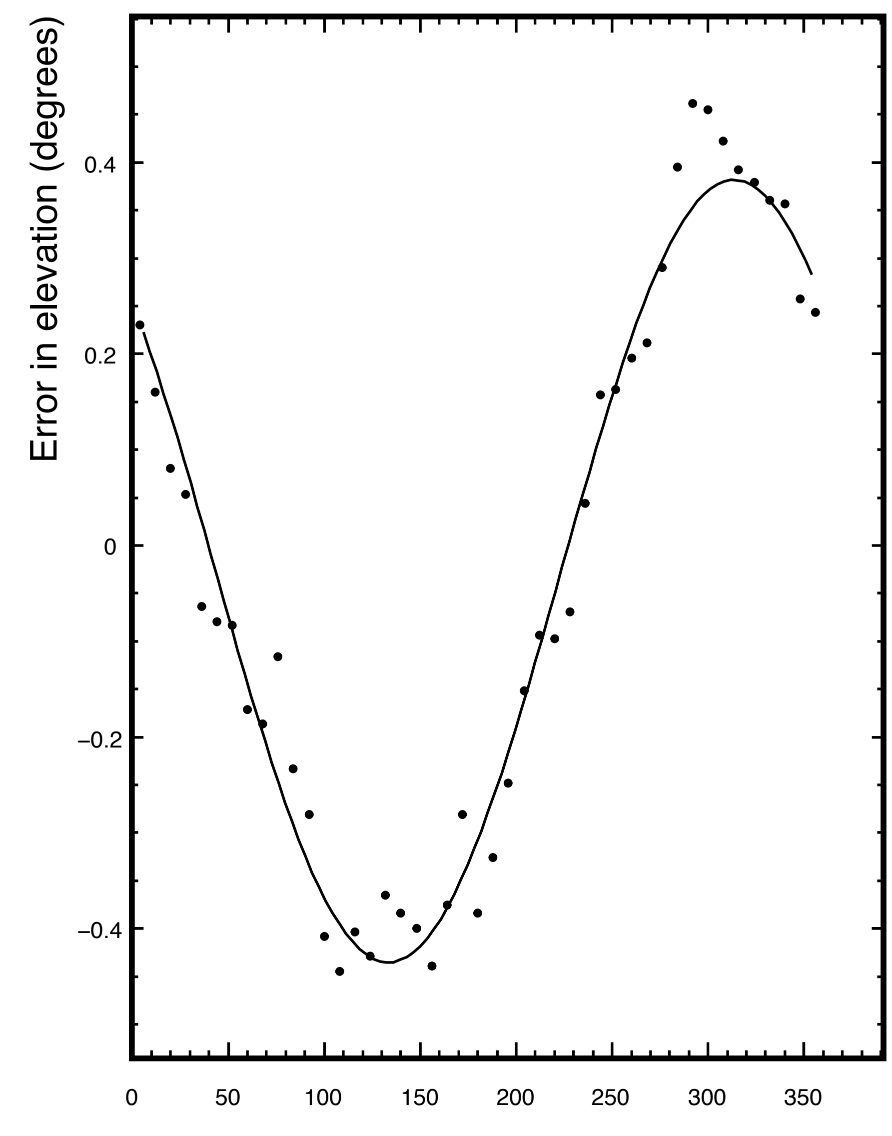
Reconstructed event locations

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

Also calibrate out the tilt of the payload





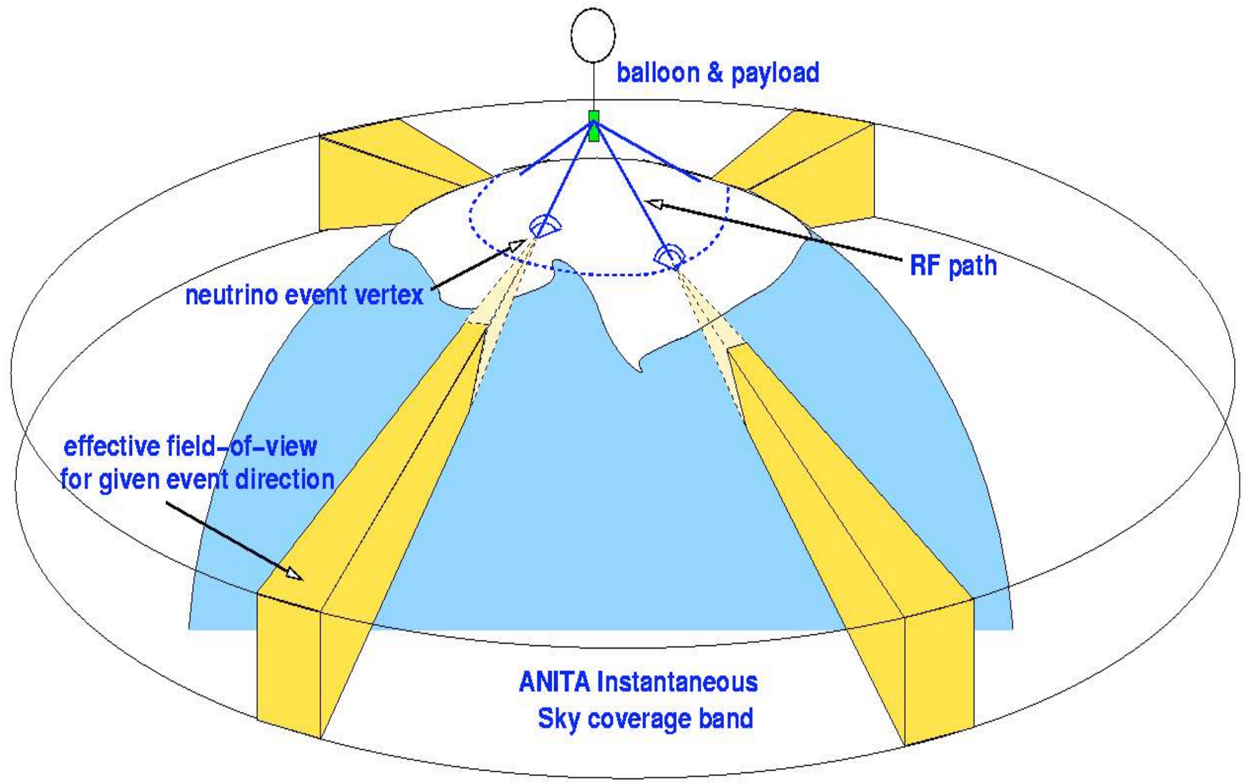


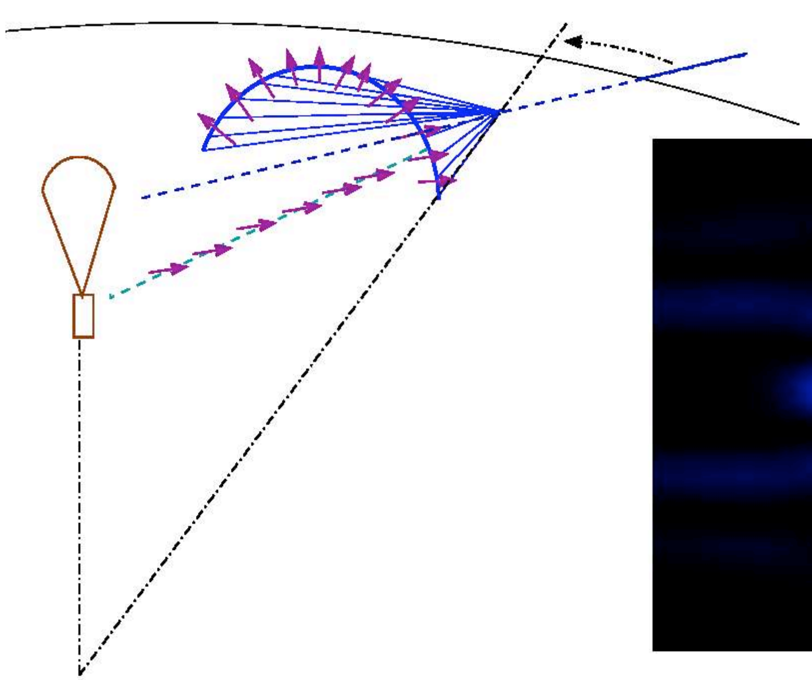
ELEVATION ANGLE

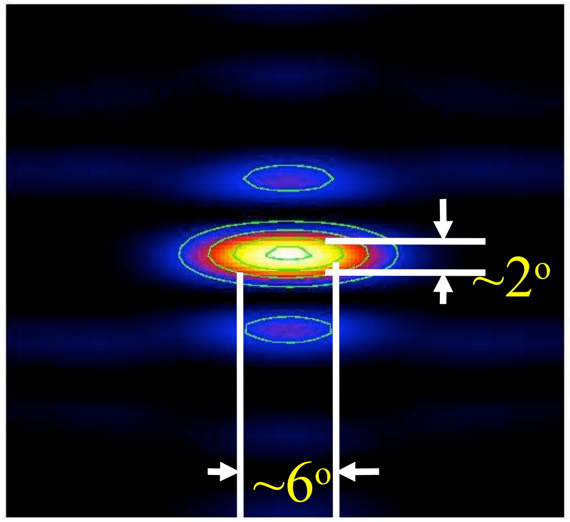
AZIMUTH ANGLE

from S. Hoover

ANITA -- Angular Resolution



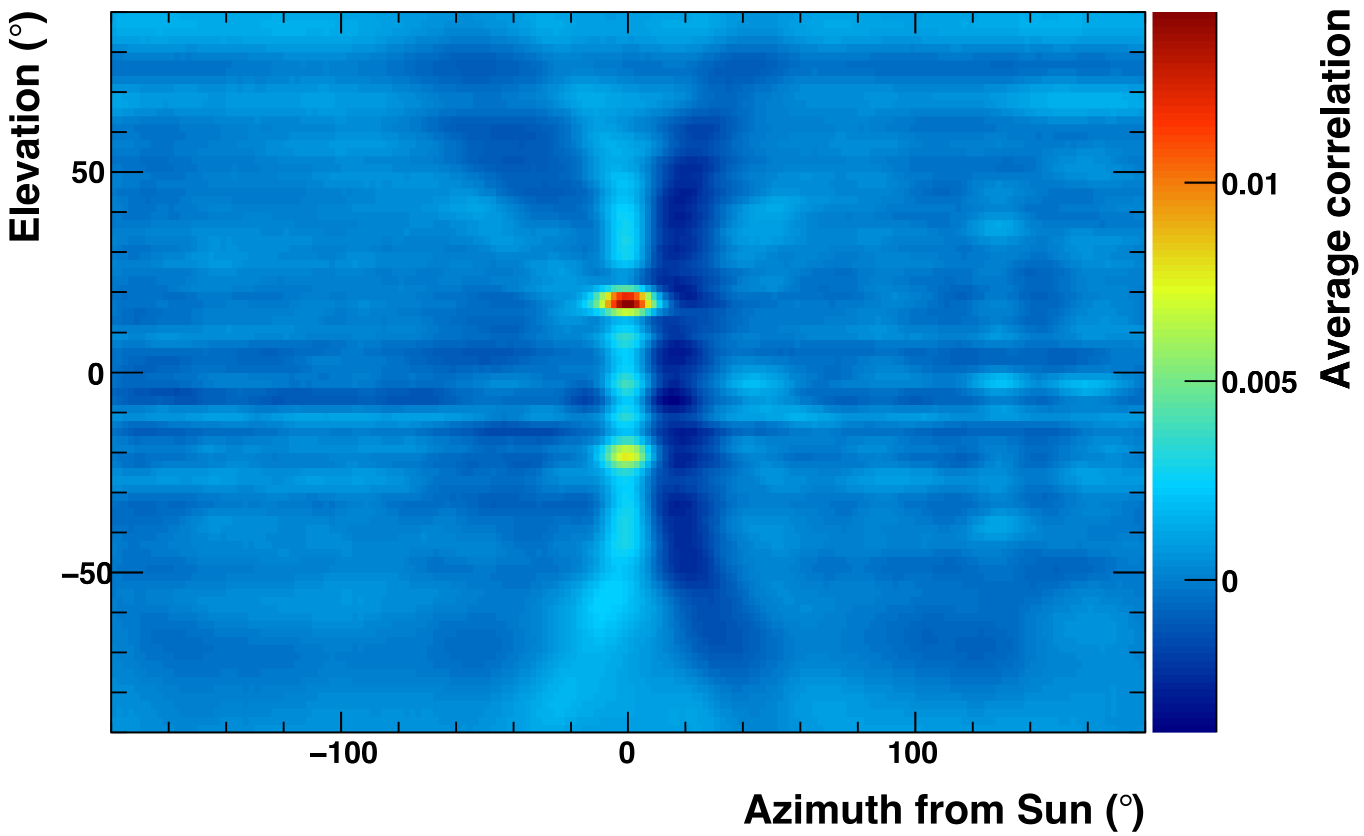




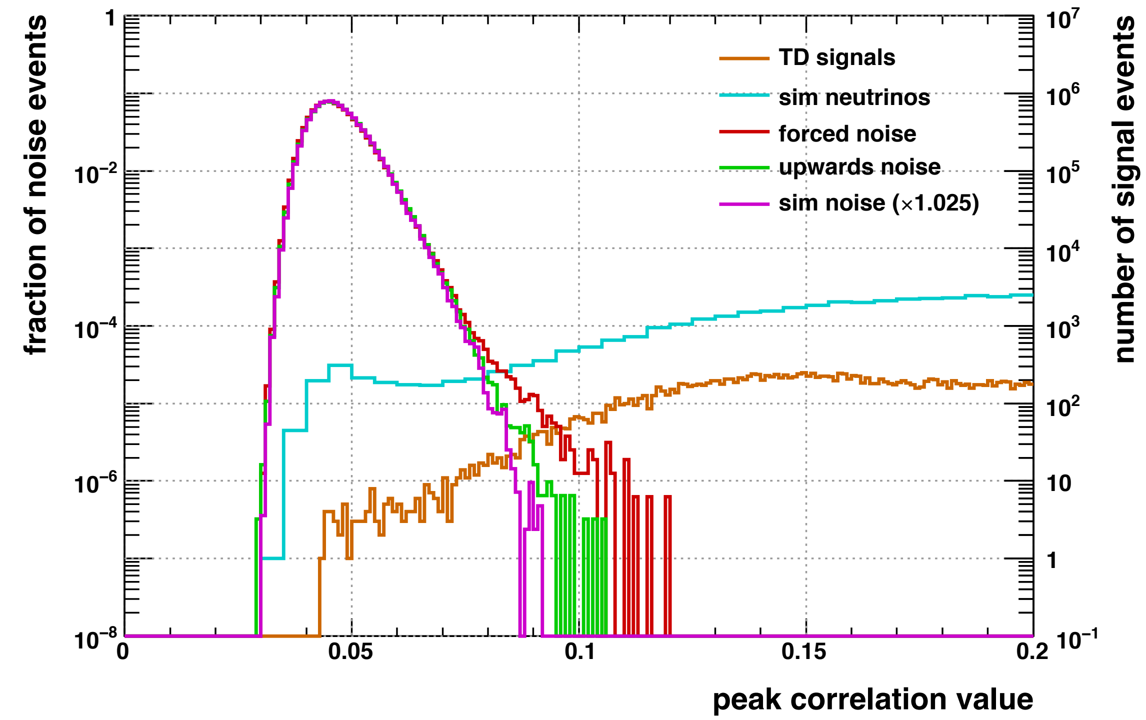
- Using signals from multiple antennas it is possible to measure the direction of arrival of radio pulse to ~0.5° in elevation and ~1.5° in azimuth (based on ANITA-lite calibration data)
- The neutrino direction can vary around radio pulse direction but is constrained to ~2° in elevation and by 3-5°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

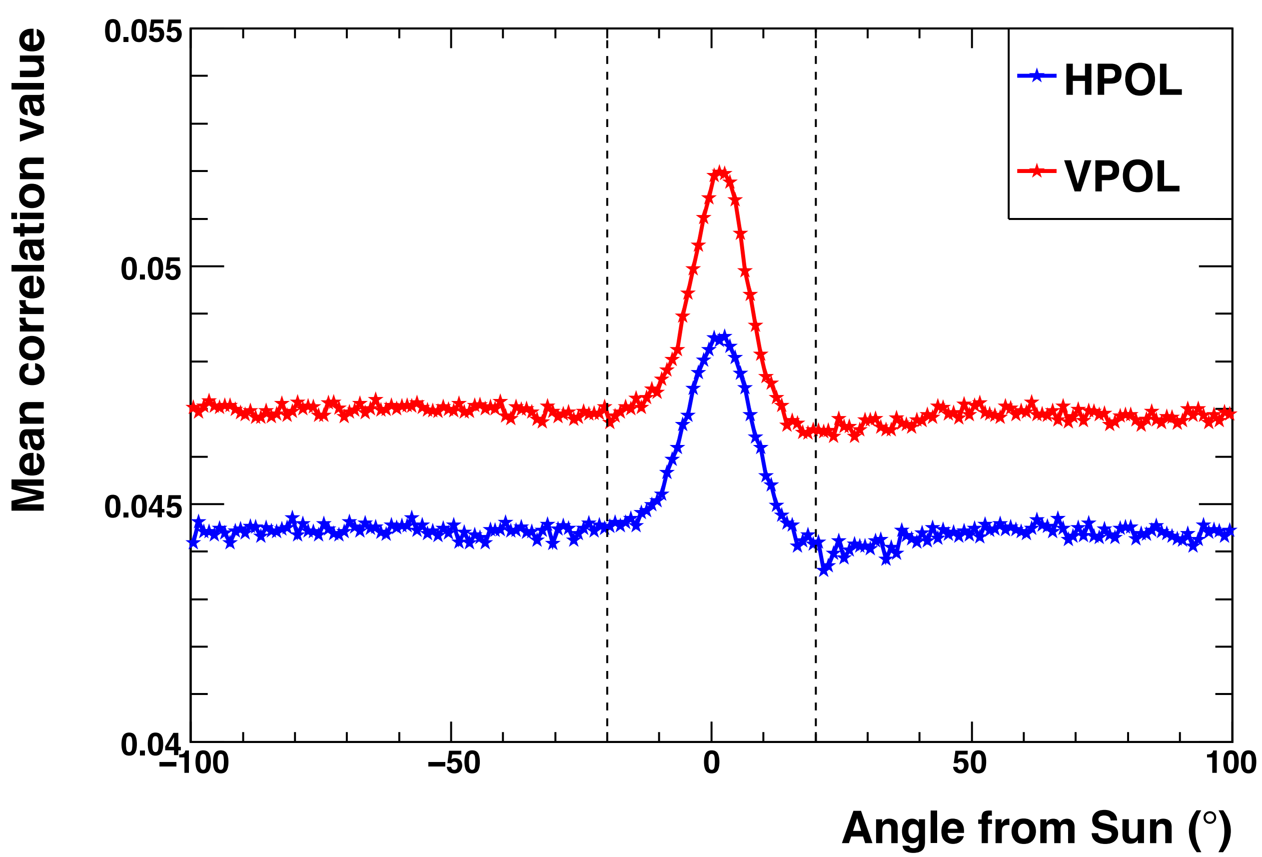
Thermal Noise

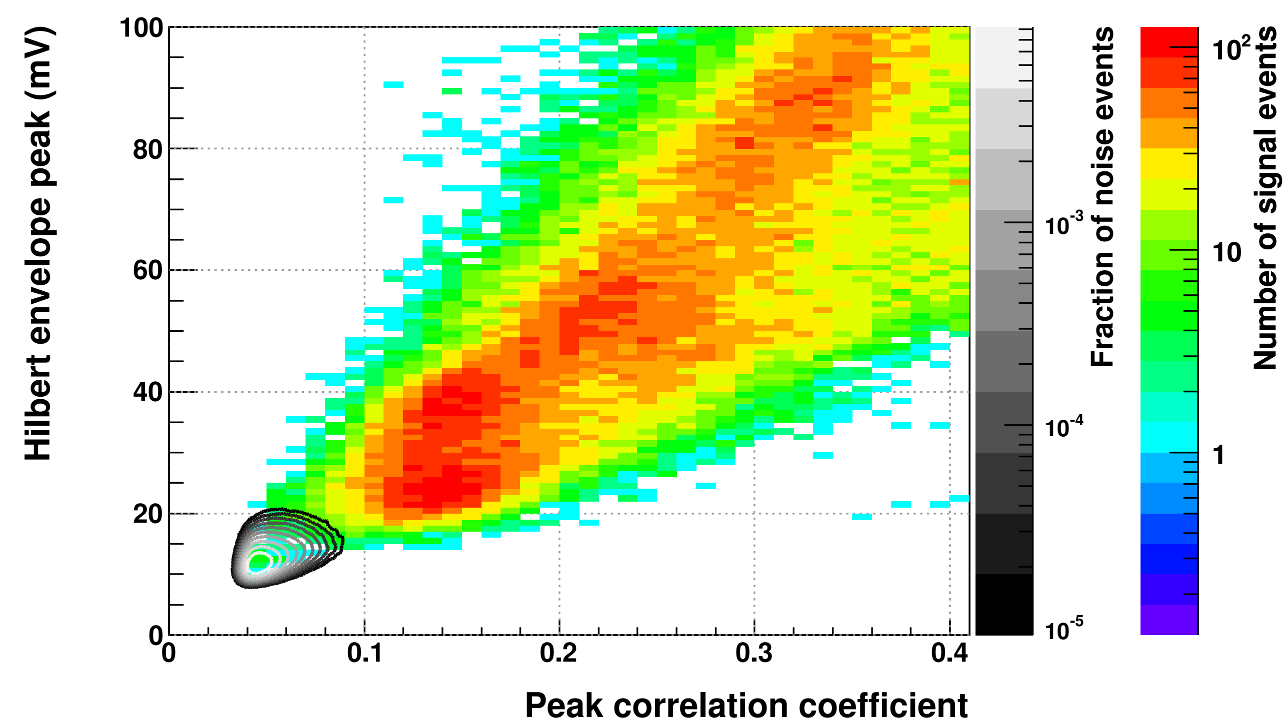
ANITA can “see” the Sun



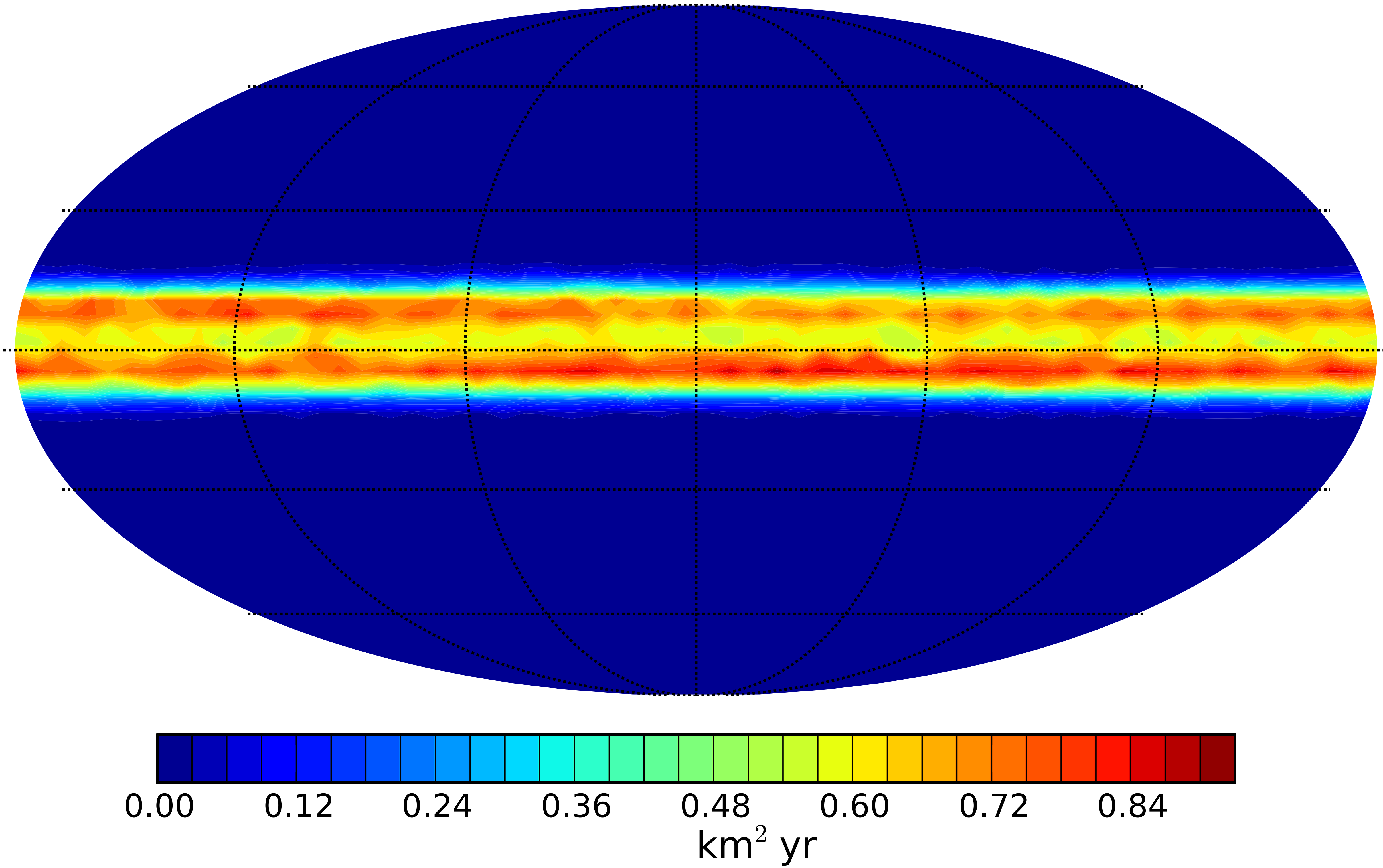
Thermal noise is the dominant source of noise in the data sets.







ANITA-2 Neutrino Sky Map Sensitivity



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)

Energy and Pointing

- Energy determination is tricky, depends on
  - Exact radio production contribution
  - Modelling of electrons and positrons in shower
  - Distance from balloon to X_{max} (via surface reflection)
  - Angle relative to shower direction
  - Losses at reflection (Fresnel, roughness, obliquity)
  - etc.
- Probably good to within a factor 3
  - More data will help us understand several of these processes