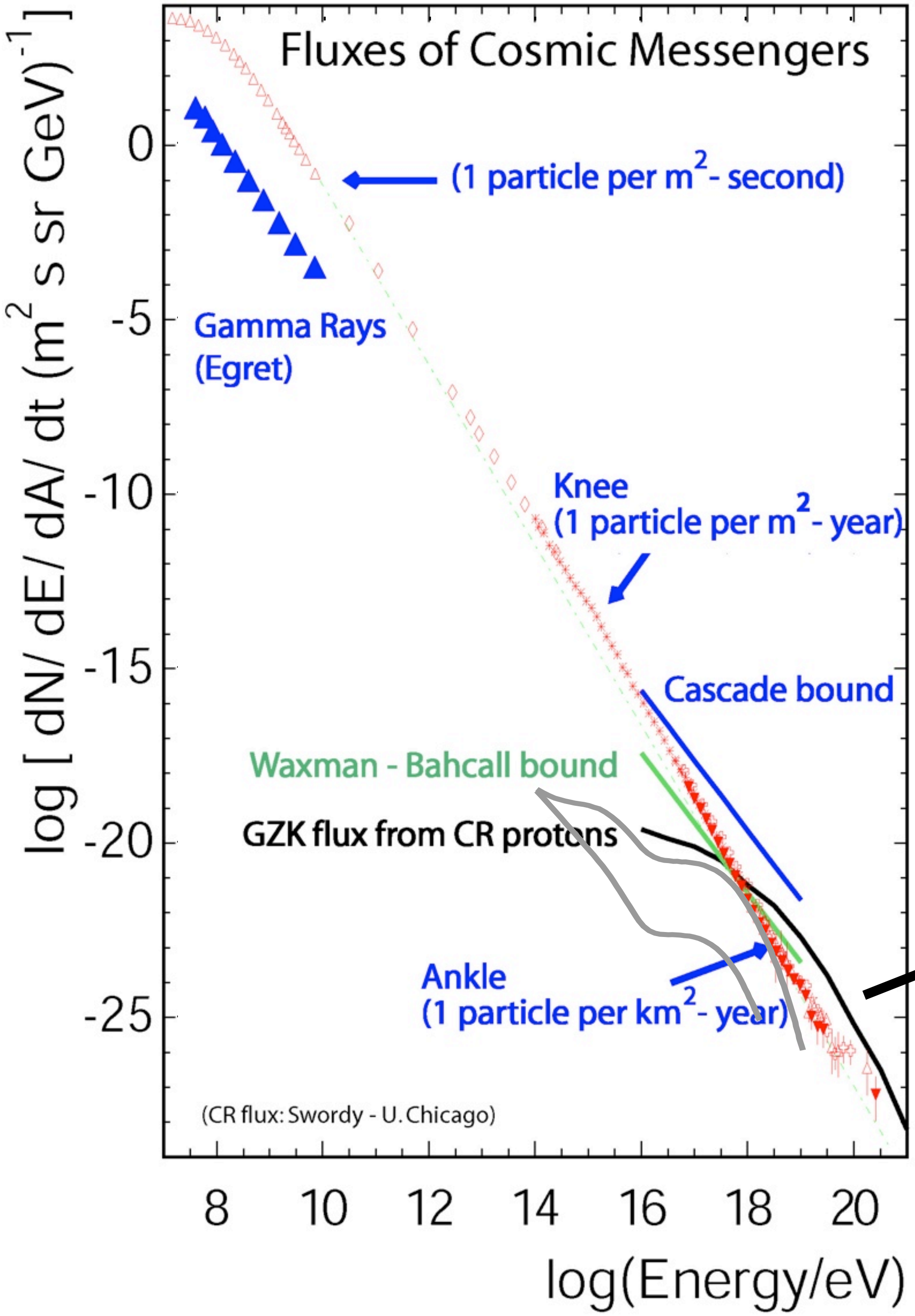
Probing the Ultra-High Energy Universe with Radio and Microwave Signatures: ANITA, AMBER and AERA

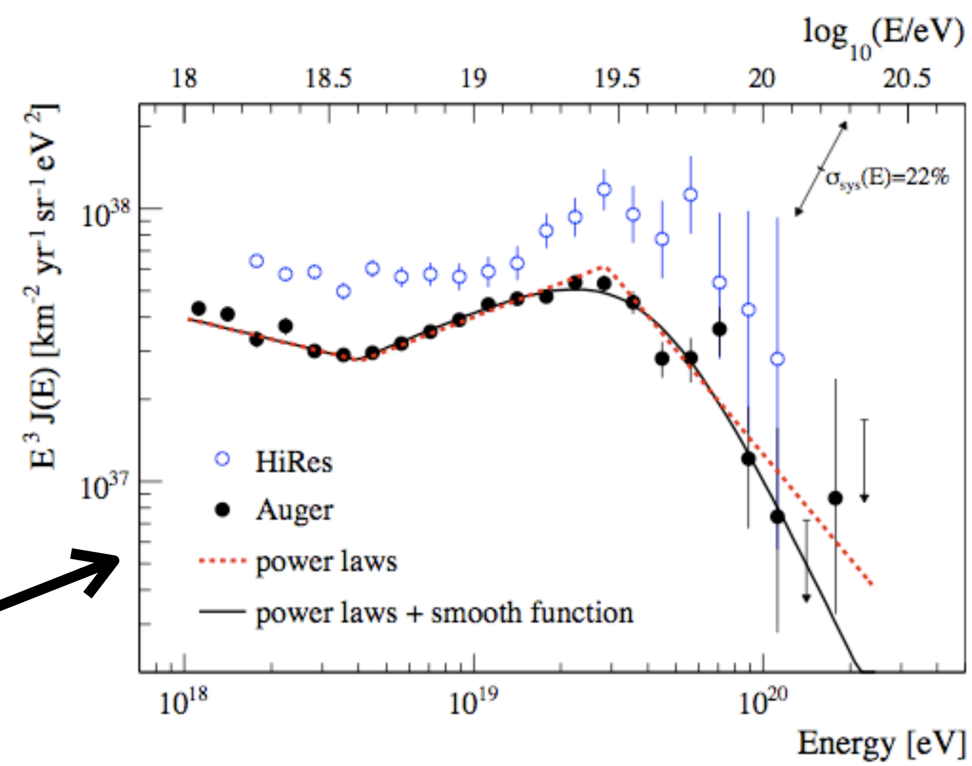
The Symposium on the Recent Progress of Ultra-High Energy Cosmic Ray Observation

Amy Connolly
The Ohio State University
Dec. 12th, 2010

The High Energy Universe



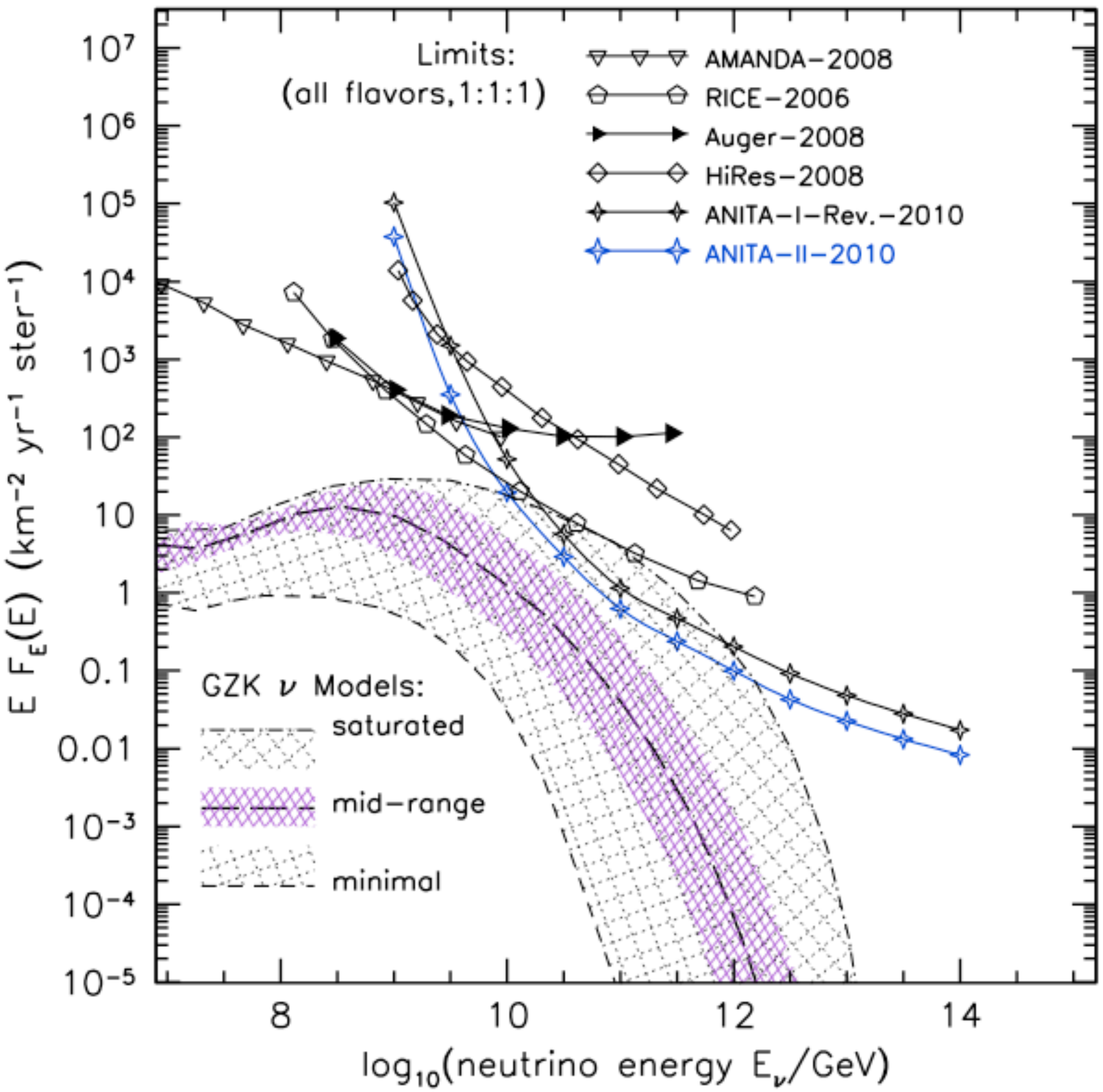
- (Charged) cosmic rays
  - Measured over 14 orders of magnitude
  - Bent by B fields - only highest energy CR's point back
  - GZK cutoff now measured ~$10^{19.5}$ eV



- Gamma rays
  - Point back to their source
  - Attenuated by pair production with CB above ~30 TeV $\gamma\gamma \rightarrow e+ e-$

No cosmic neutrino flux observed

Neutrinos: Current Limits



Expect UHE ν flux from "GZK"

$p+\gamma_{CMB} \rightarrow \Delta^* \rightarrow n\ \pi^+$

AMANDA:

Visible Cerenkov in deep ice

Auger, HiRes:

Search for earth skimming ν_τ

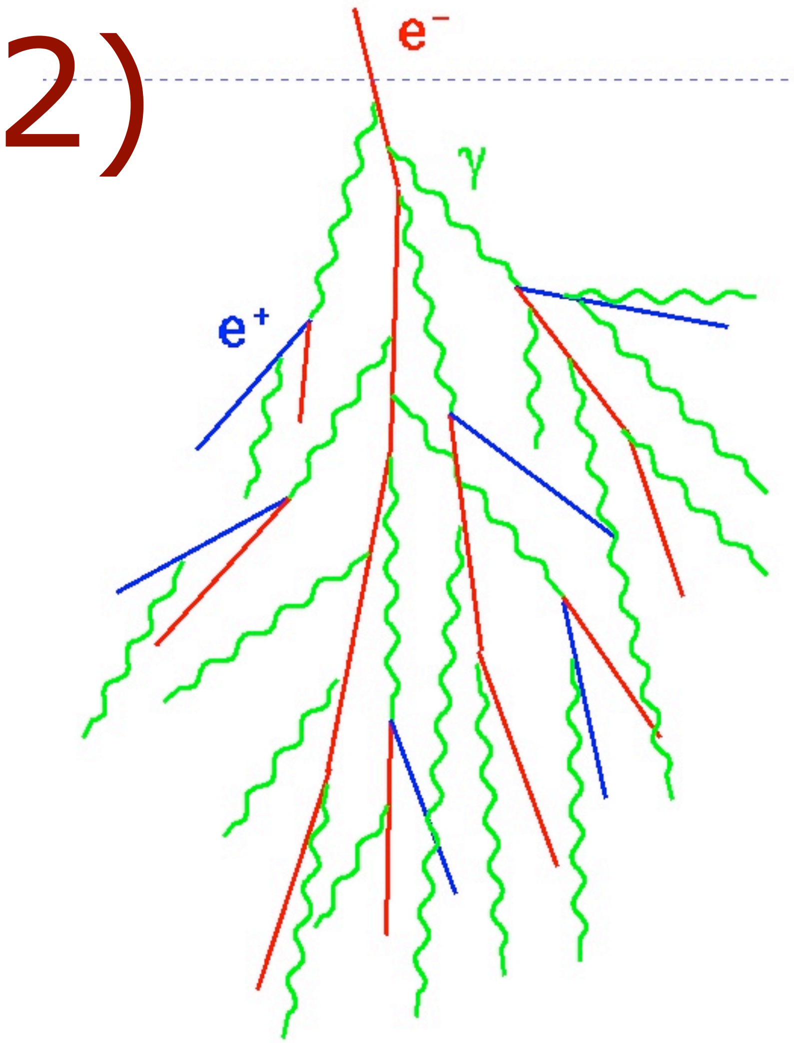
RICE, ANITA:

Radio Cerenkov:

Best limits for energies $>10^{18}$ eV

Radio Cerenkov Technique: Gurgen Askaryan (1962)

- Coherent Cerenkov signal from net "current," instead of from individual tracks
- A ~20% charge asymmetry develops:
  - Compton scattering:
    γ + e-(at rest) → γ + e-
  - Positron annihilation:
    e^+ + e-(at rest) → γ + γ
- Excess moving with v > c/n in matter
  → Cherenkov Radiation $dP \propto \nu\, d\nu$
- If $\lambda >> R_{Moliere}$ → Coherent Emission ~ N^2 ~ E^2
  $\lambda > R_{Moliere}$ → Radio/Microwave Emission

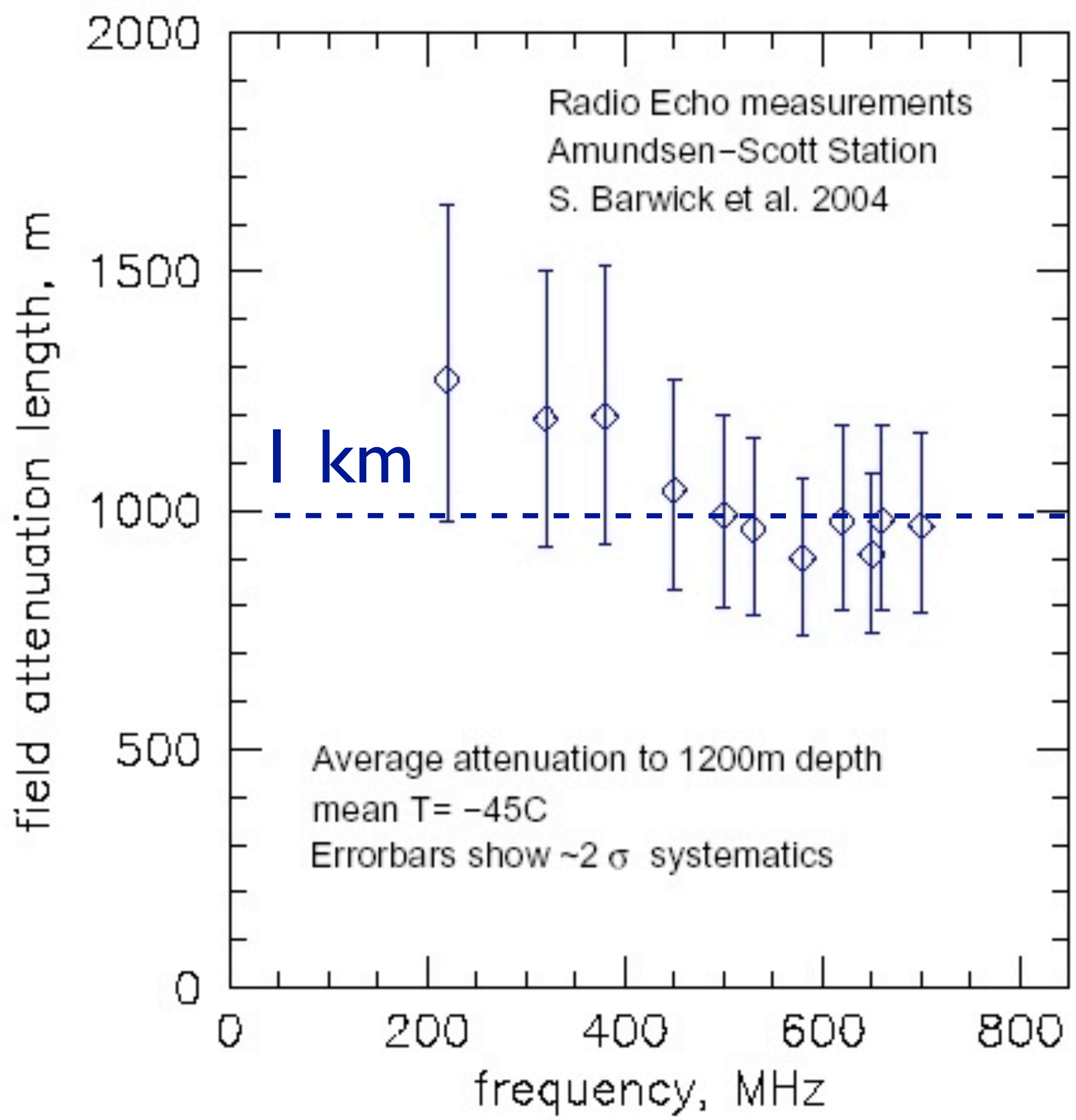


This effect has been confirmed experimentally
PRL 86, 2802 (2002)
PRD 72, 023002 (2005)
PRD 74, 043002 (2006)
PRL 99, 171101 (2007)

Macroscopic size: $R_{Moliere} \approx$ 10 cm, L ~ meters

Long Attenuation Lengths

Askaryan also suggested three radio-clear detection media: ice, salt, sand

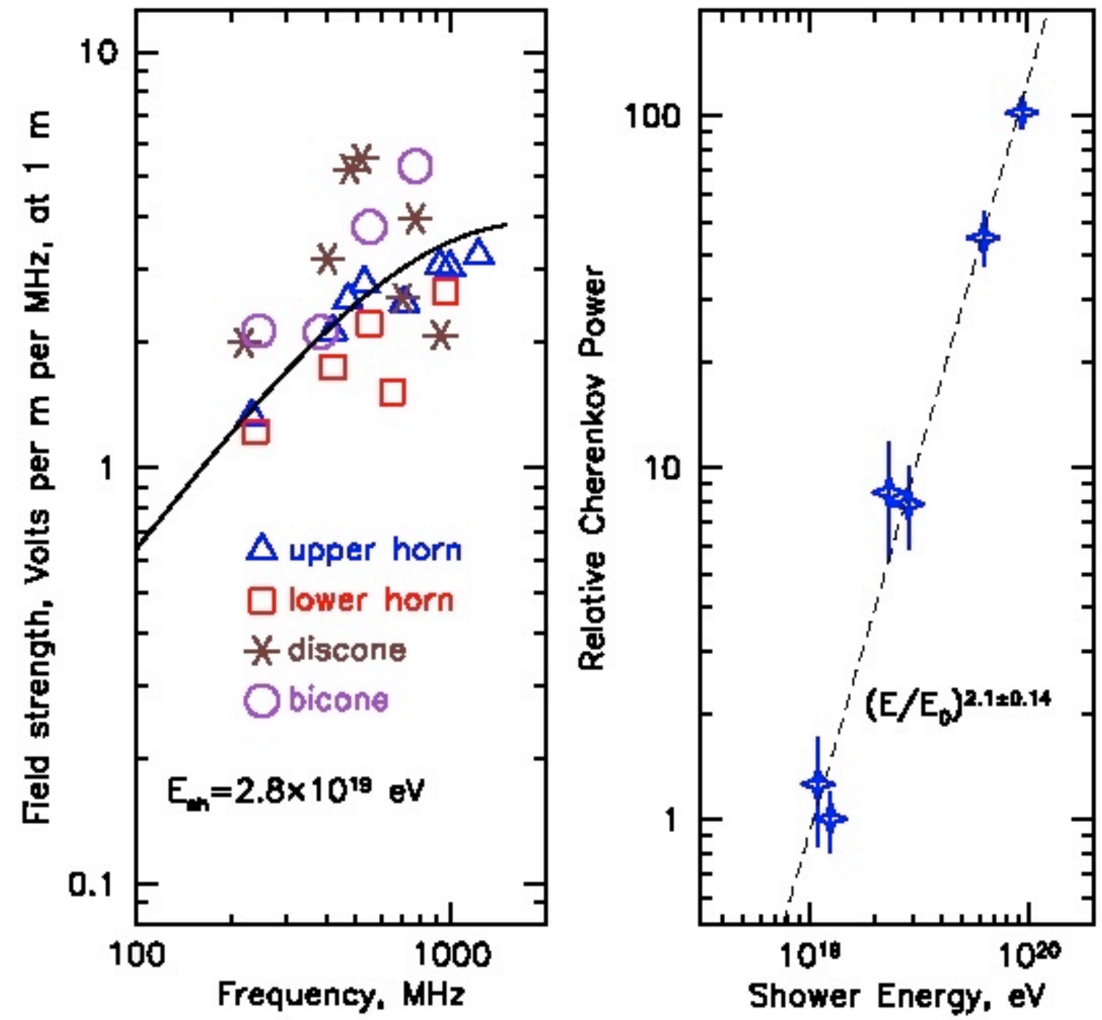


South Pole Ice

Measurement of Radio Cerenkov Emission

Produced Askaryan pulses in ice from 28.5 GeV electron beam at SLAC

~10^9 particles per bunch
→ 10^{19}- 10^{20} eV showers



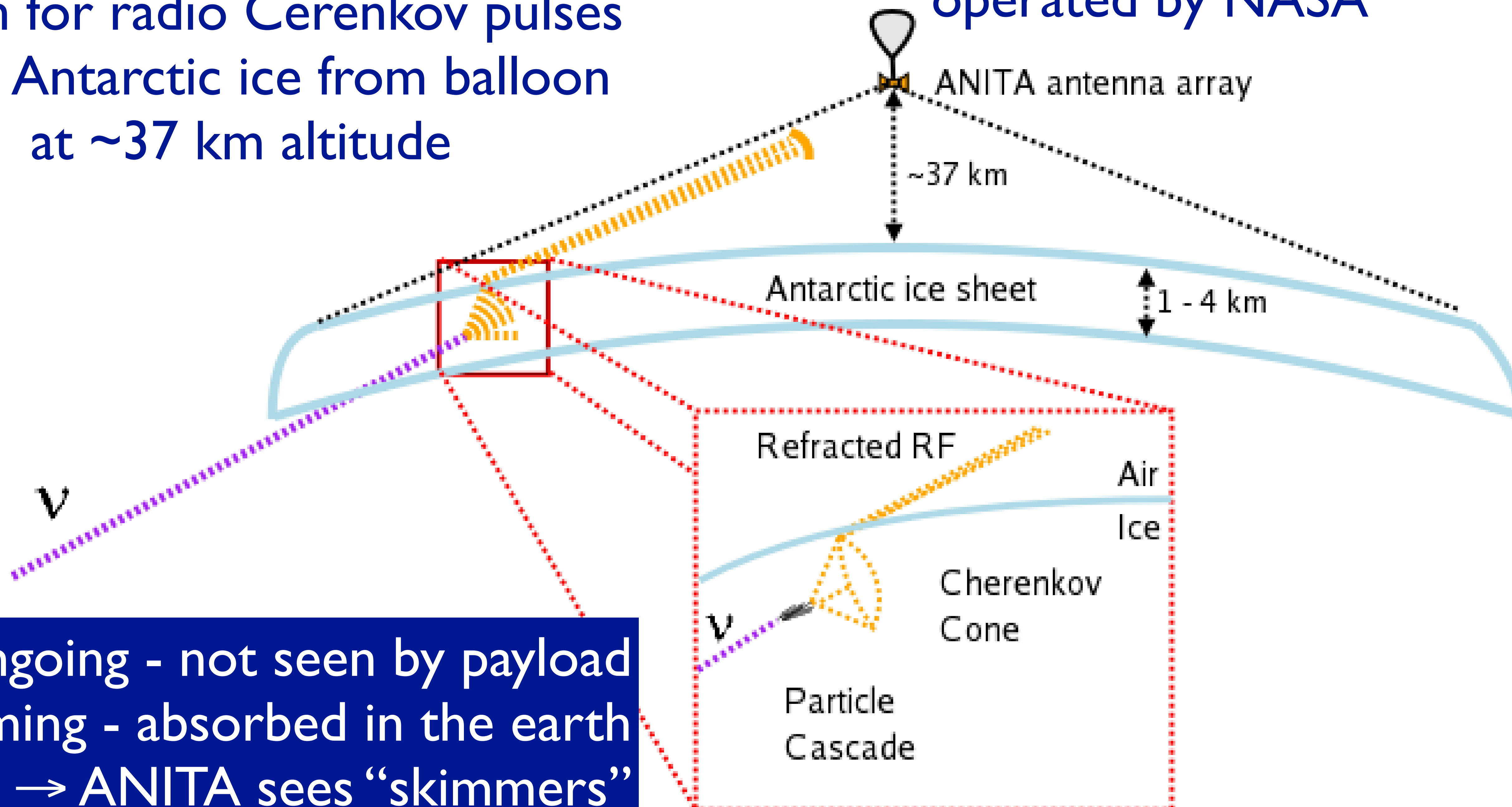
ANITA Collaboration (P.W. Gorham et al.)
hep-ex/0611008

From there, ANITA was off to Antarctica…

ANITA: The Detector Concept

Long duration balloon program operated by NASA

Search for radio Cerenkov pulses in the Antarctic ice from balloon at ~37 km altitude



Downgoing - not seen by payload
Upcoming - absorbed in the earth
→ ANITA sees "skimmers"

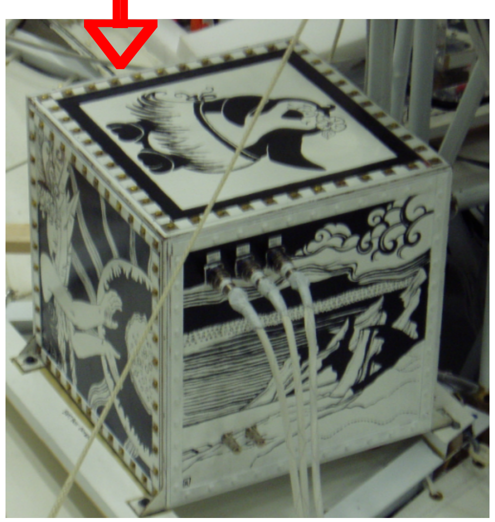
ANITA observes ~1.5 x 10^6 km^2 of ice at once!

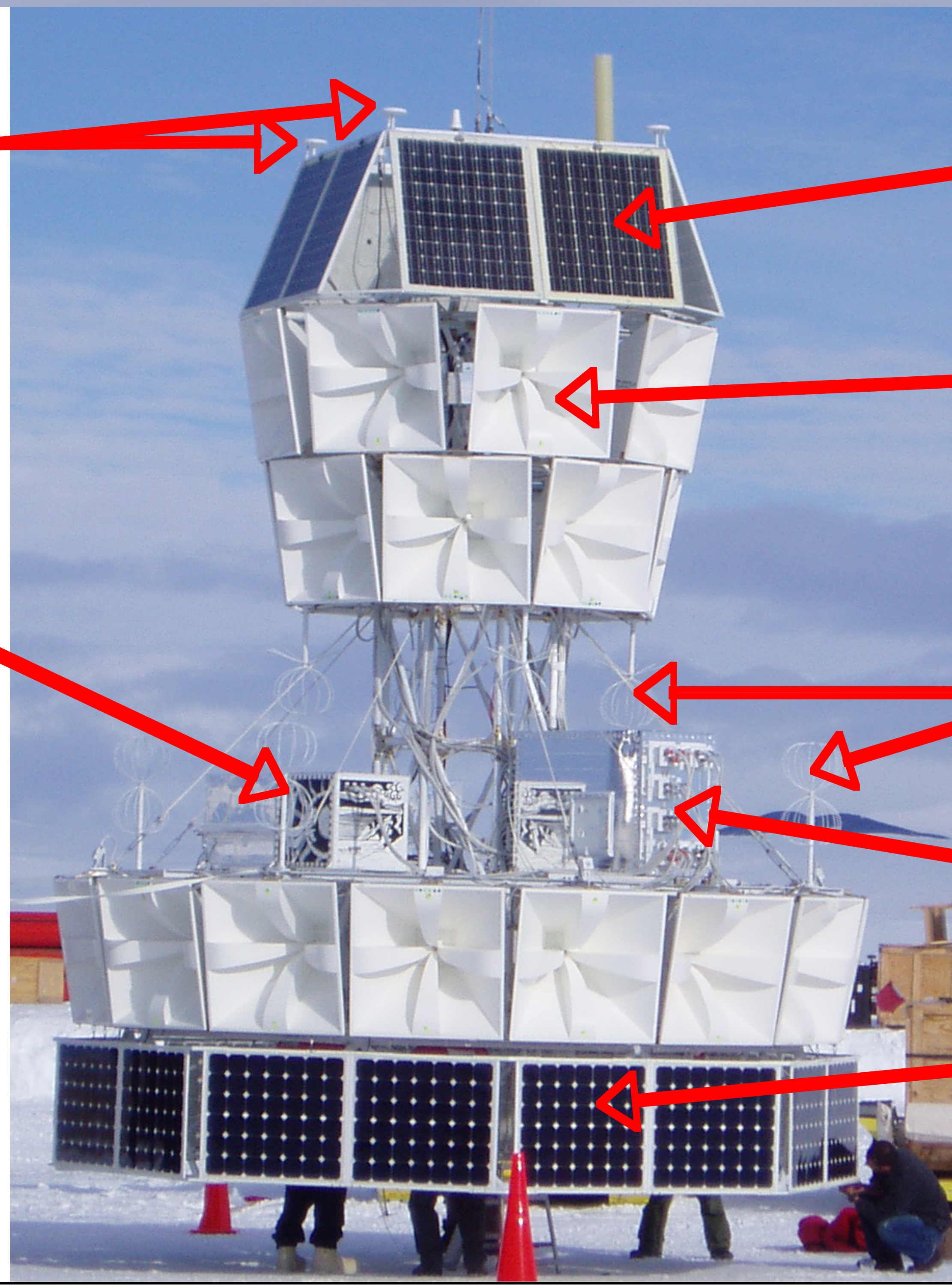
ANITA 1: 2006-2007 ANITA 2: 2008-2009 ANITA 3: 2012-2013

The Face of ANITA

GPS Antennas

Battery box
(Art by residents of McMurdo)





Solar cells for NASA equipment

Anita I:

32 Quad-ridge horn antennas in 3 layers
- 200 MHz to 1200 MHz
- 10 degree down angle

Anita 2: 40 horns in 4 layers

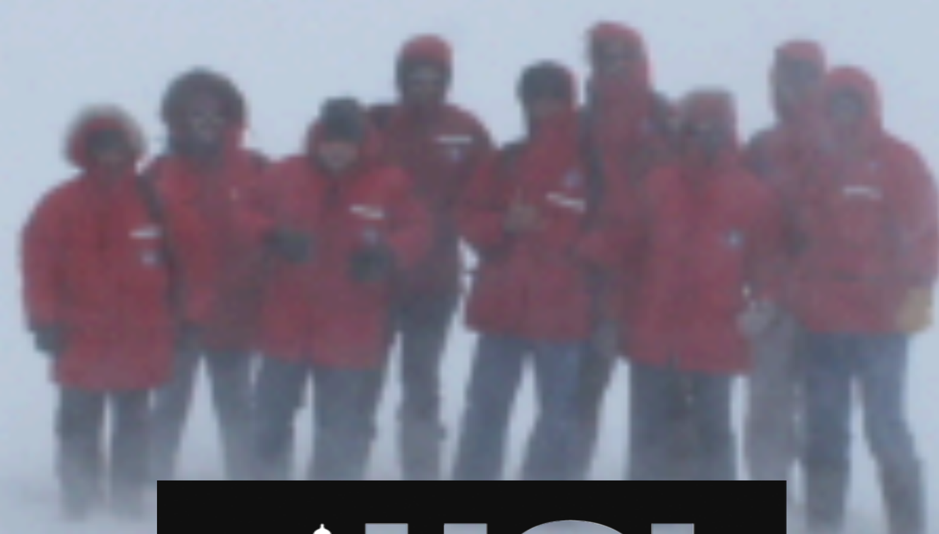
8 low gain antennas to monitor payload-generated noise

ANITA electronics box (mirrored to minimize solar heating)

Power for science mission

"instrument paper": arXiv:0812.1920 [astro-ph]

ANITA Collaboration



University of California, Irvine

Ohio State University

University of Kansas

Washington University in St. Louis

University of Delaware

University of Minnesota

University of California, Los Angeles

University of Hawaii at Manoa

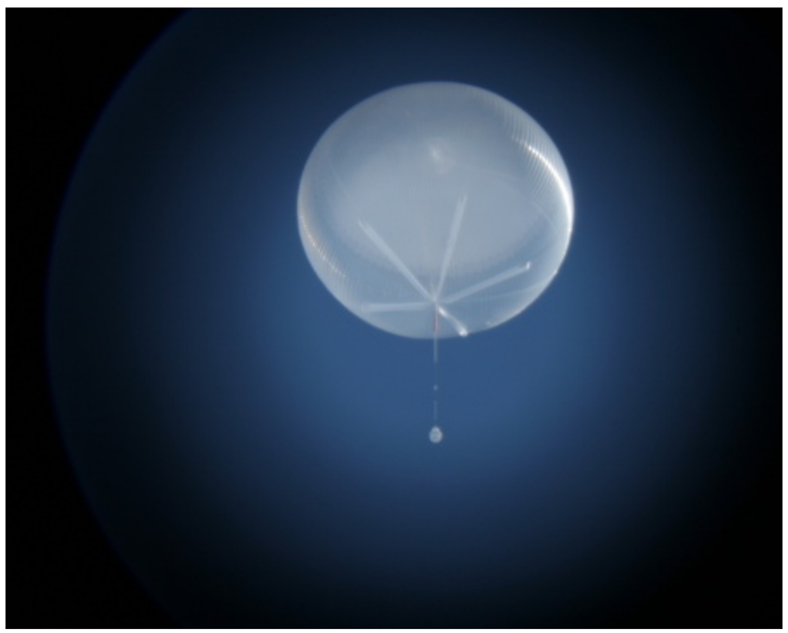
National Taiwan University

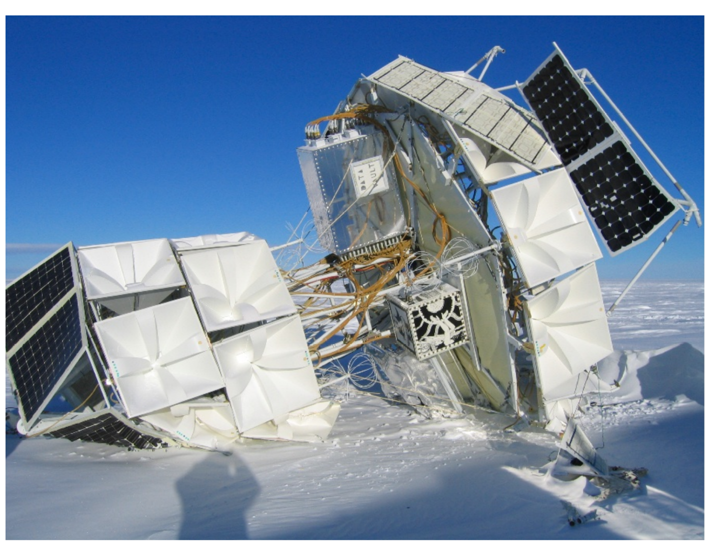
University College London

Jet Propulsion Laboratory

Stanford Linear Accelerator Center

ANITA Flights



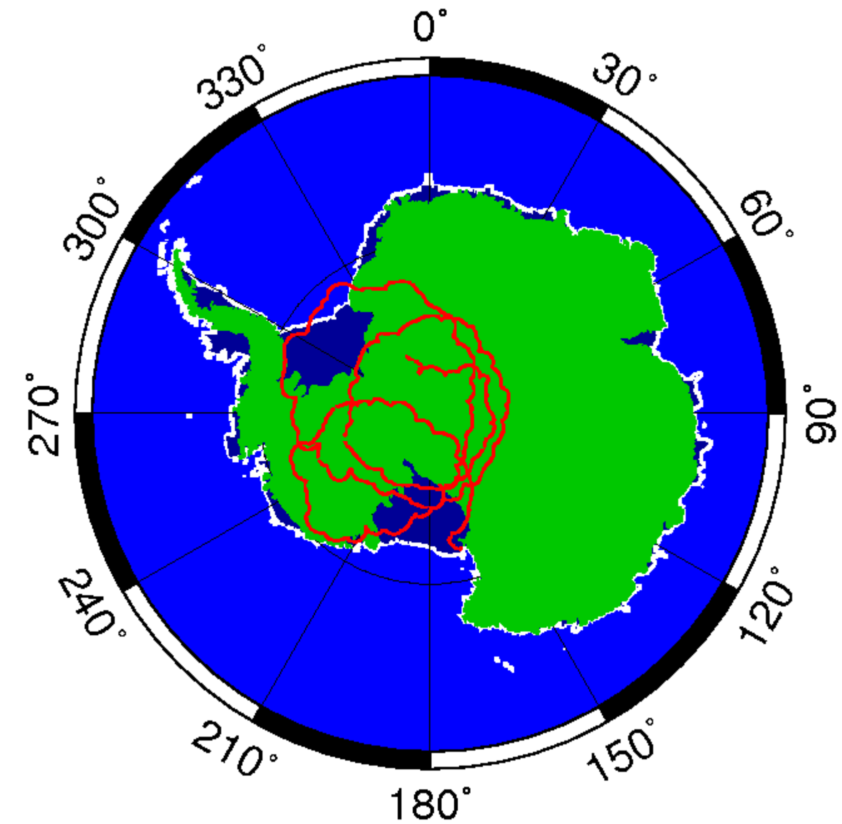


ANITA 1:

2006 - 2007

18 days good livetime

1.2 km average depth



ANITA 2:

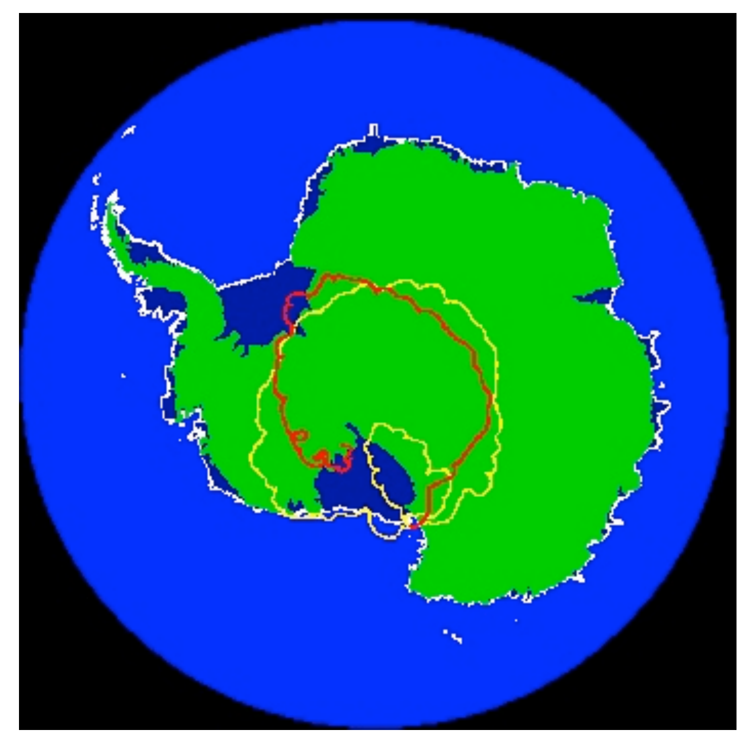
2008-2009

8 more antennas

Lower noise amplification

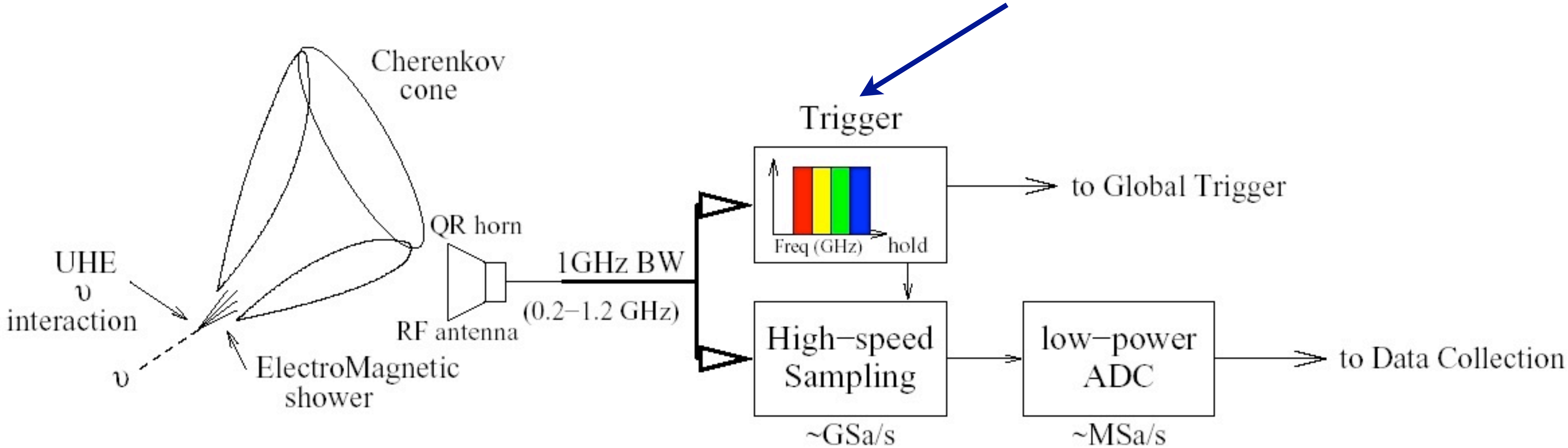
Directional mask

Optimized trigger



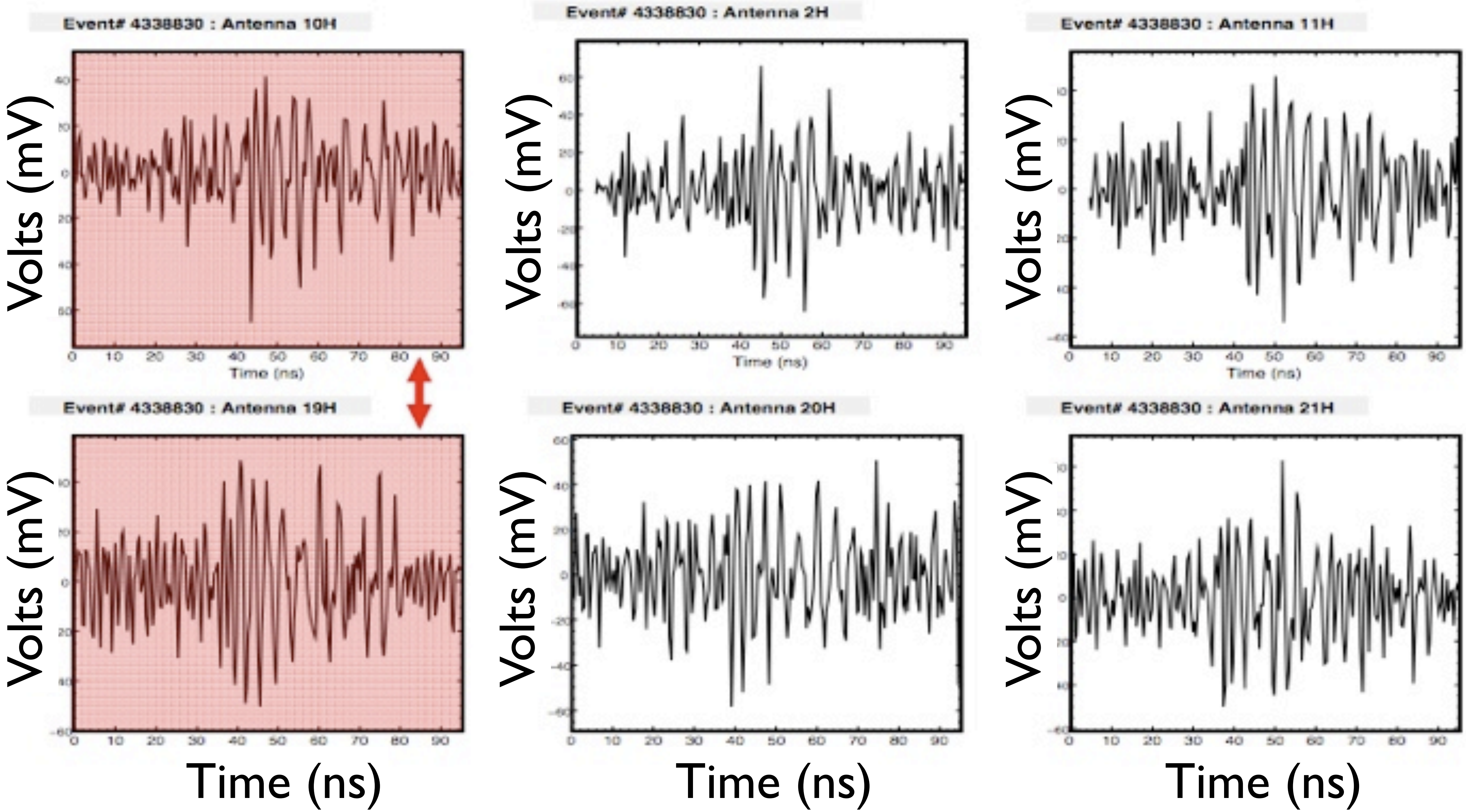
Signal Acquisition

ANITA II: Full band + L, M, H bands



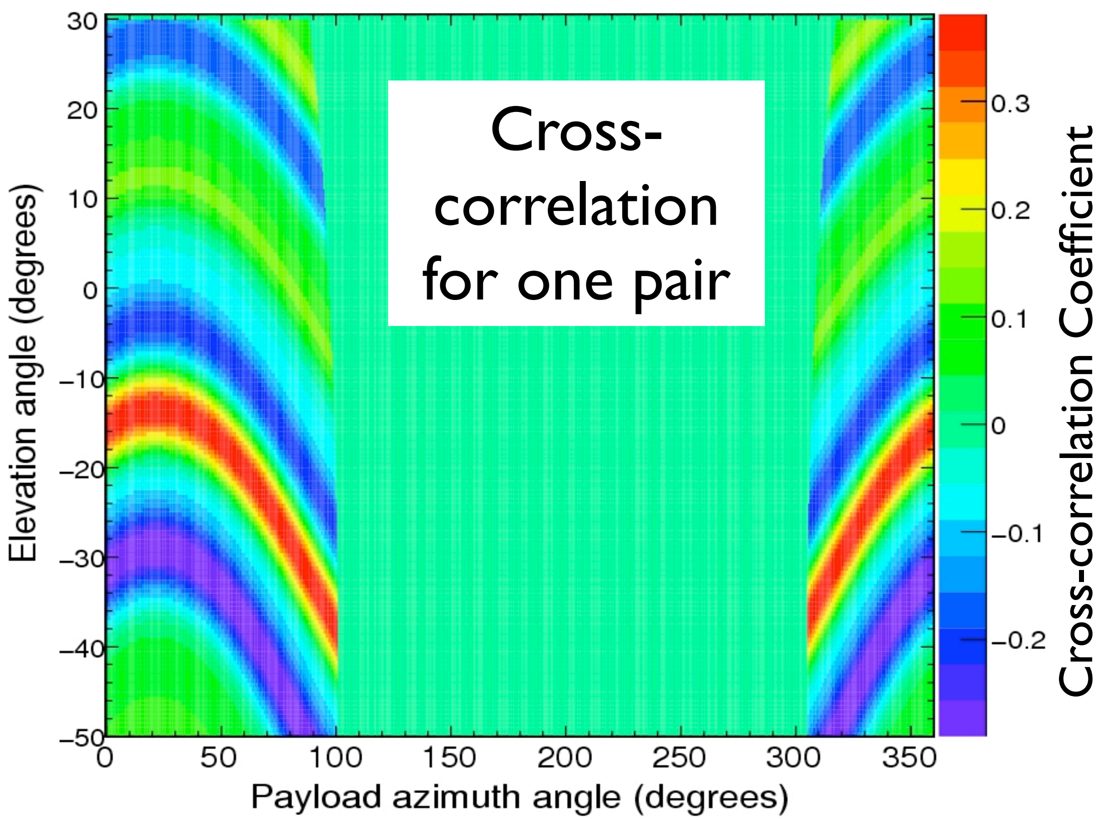
- Trigger: Signal divided into frequency sub bands (channels)
  - Powerful rejection against narrow bandwidth backgrounds
  - Multi-band coincidence allows better noise rejection
- 8 channels/ antenna
- Require 3/8 channels fire for antenna to pass L1 trigger (~150 kHz)
- Global trigger analyzes information across antennas (~5-10 Hz)

Event Reconstruction: Cross-Correlation



slide 18

Reconstruction



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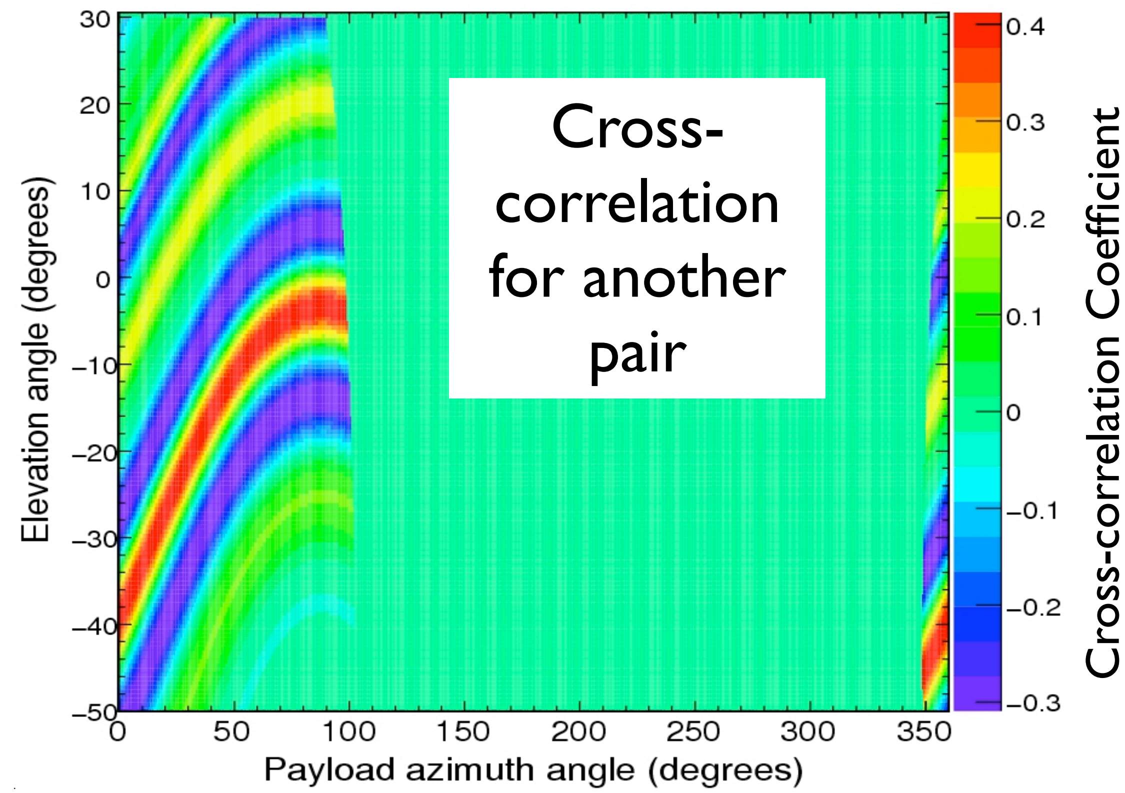
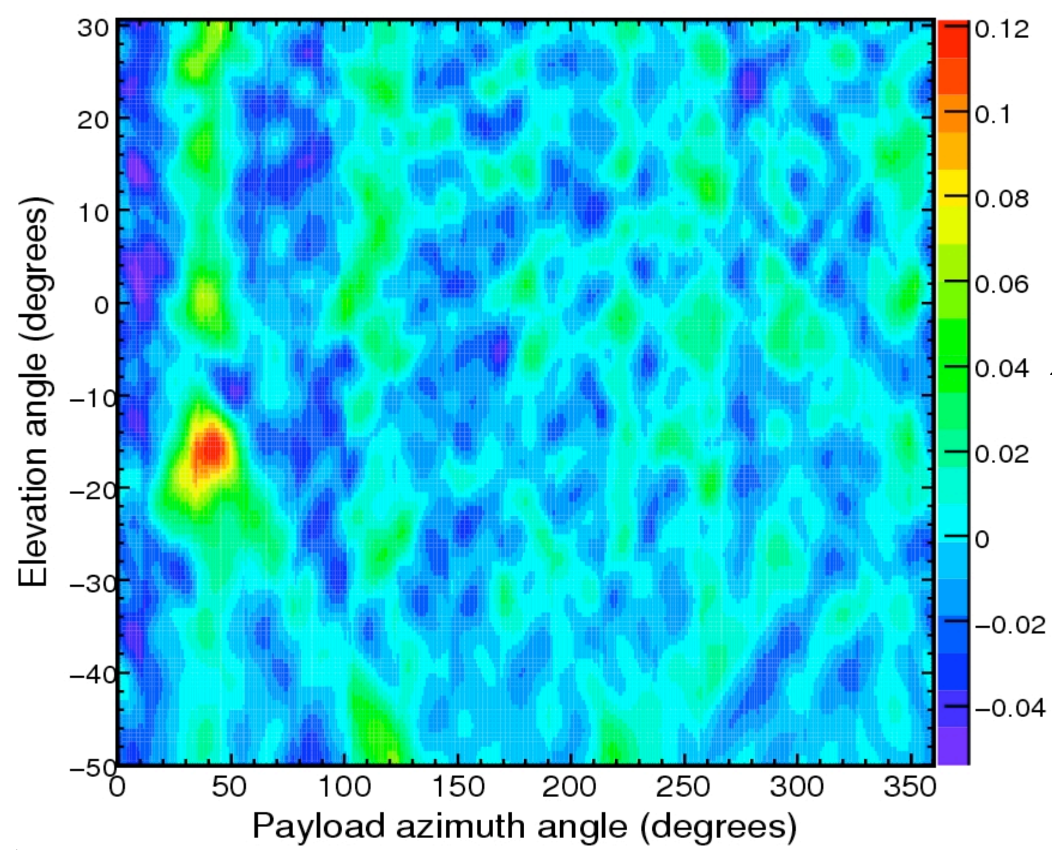


+ ...

ΔΦ=0.7°
Δθ=0.3°
from calibration pulses from within ice

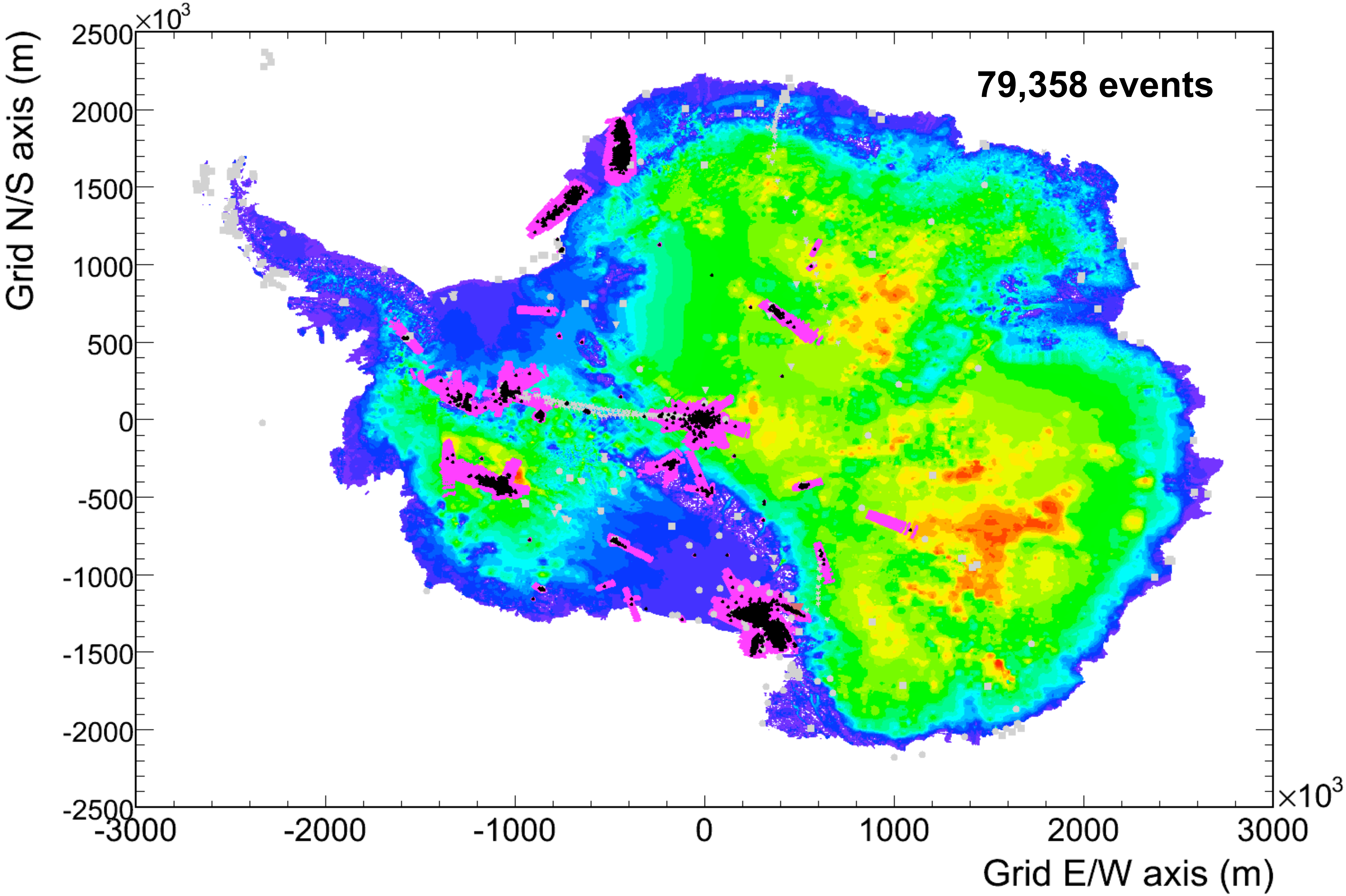
Combine ~50 pairs

=



Locate origin of the signal in elevation, azimuth

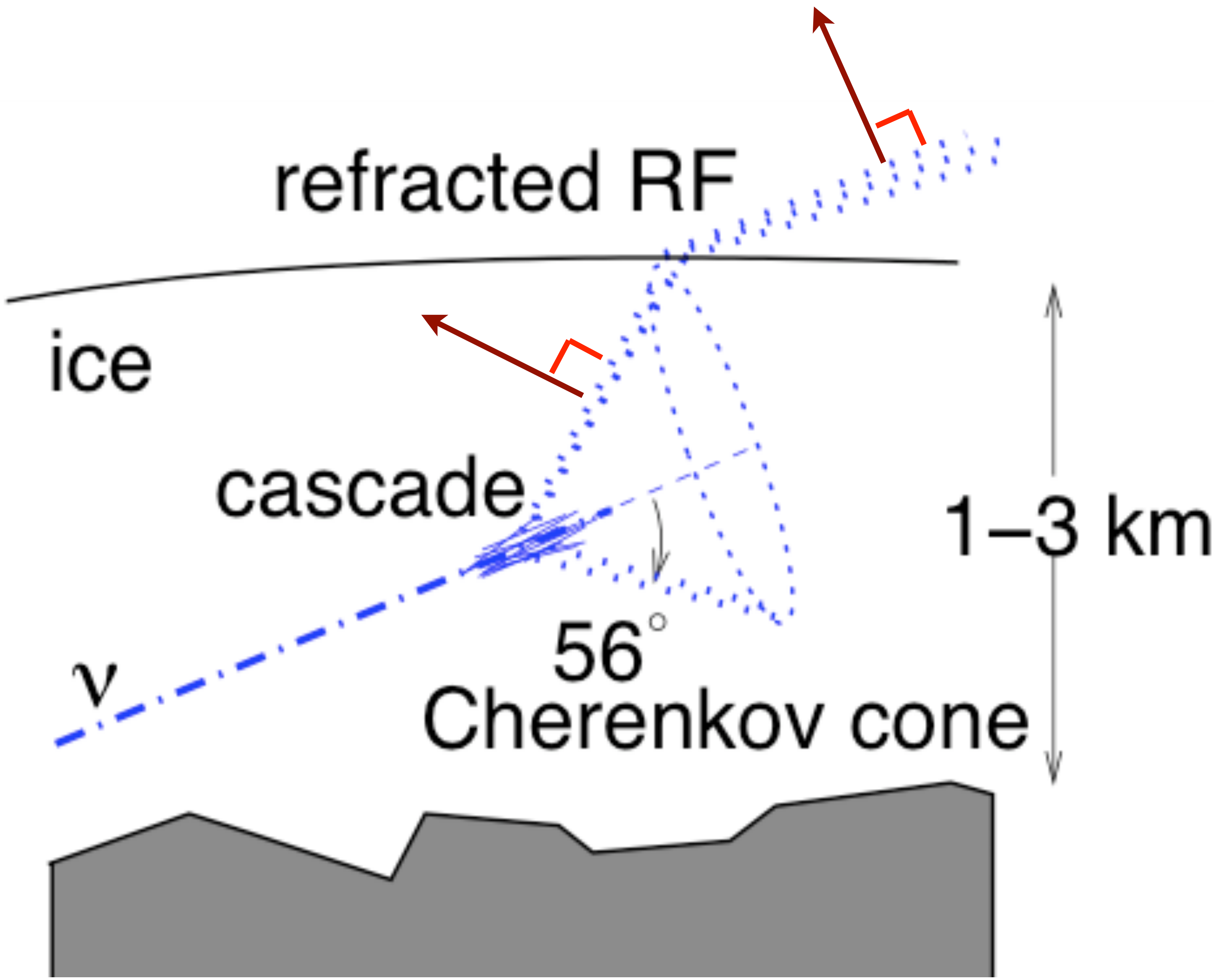
Anita 1: Reconstructed Events



Analysis Cuts

- To reduce backgrounds:
  - Quality cuts
  - Cuts to reduce misreconstructions
  - Thermal noise reduction
  - Not associated with a base or another event

Neutrino Signals are Nearly V-pol



Anita Results

Vertical Polarization (neutrino search)

	Expected Background	Observed Events
Anita 1:	1	1
Anita 2:	1	1

Horizontal Polarization (cosmic rays)

	Expected Background	Observed Events
Anita 1:	2	16

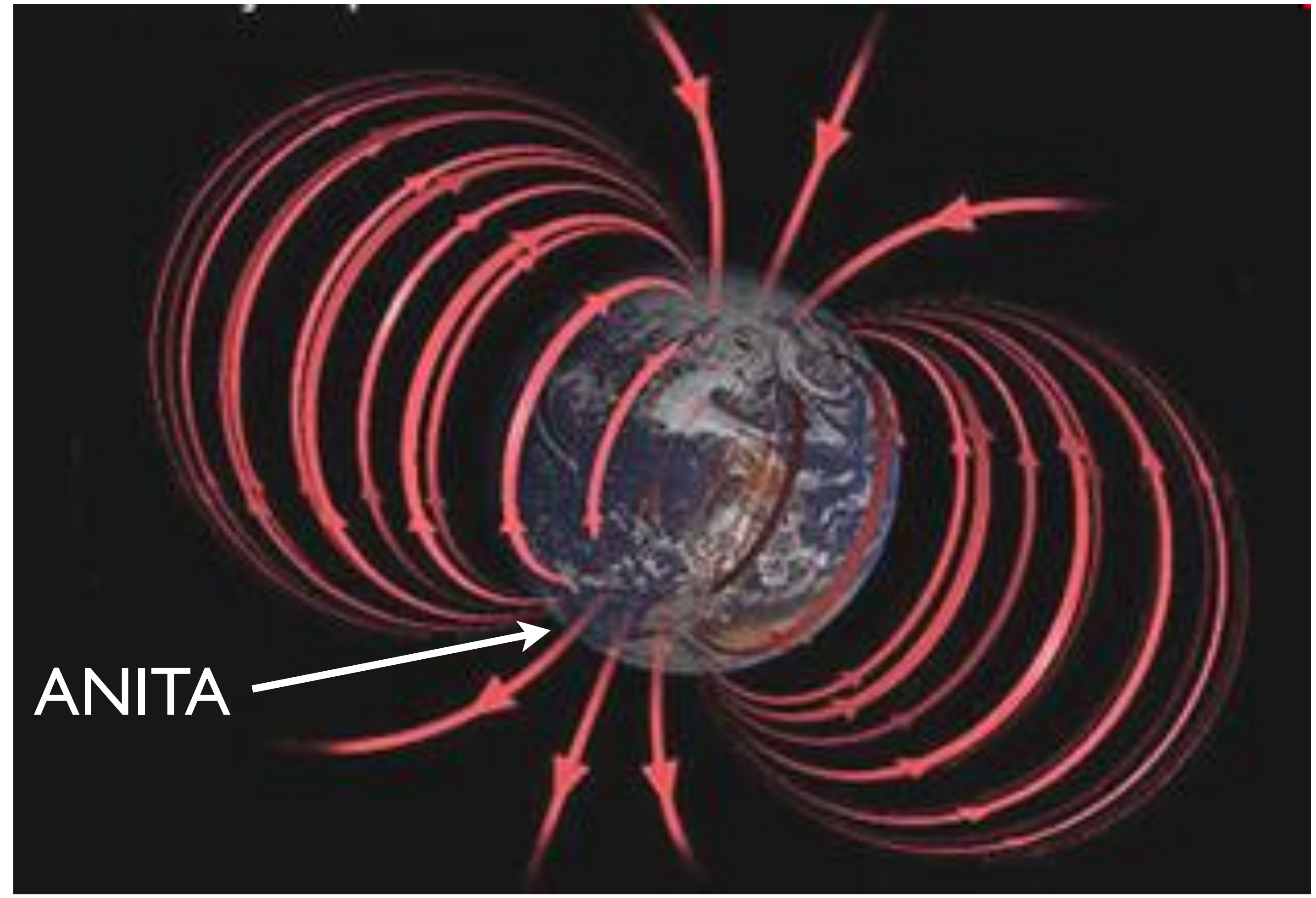
Anita 2: no H-pol trigger

Geosynchotron Emission of CRs

Charged particles in cosmic ray showers:

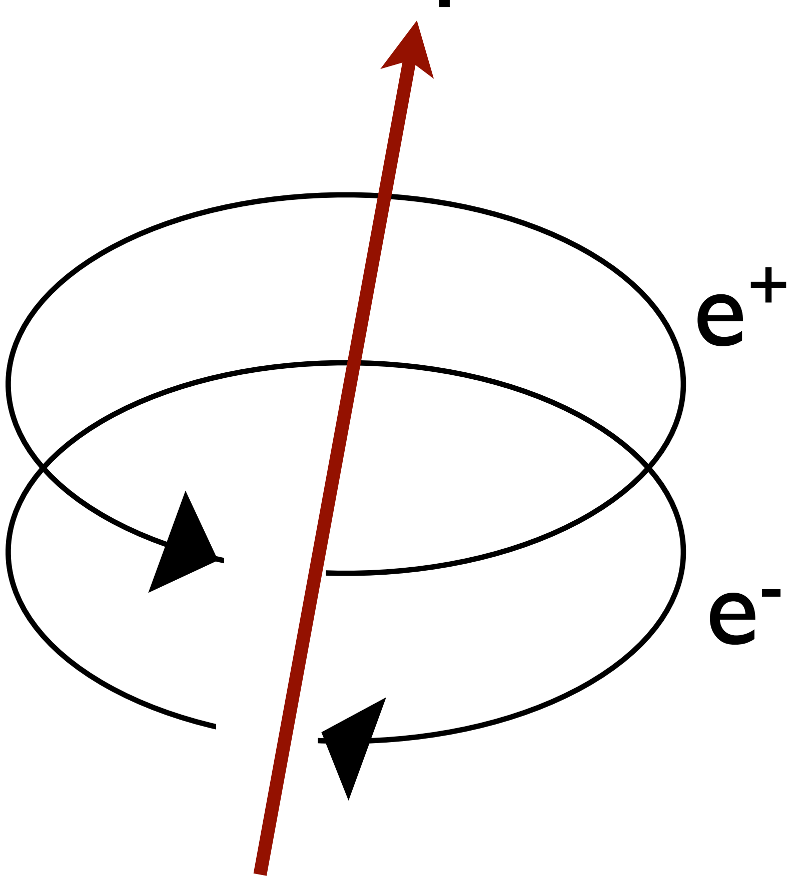
$$F = qv \times B$$

Near South magnetic pole → field points "up"



$B_{vertical}$ = 30-60 μT

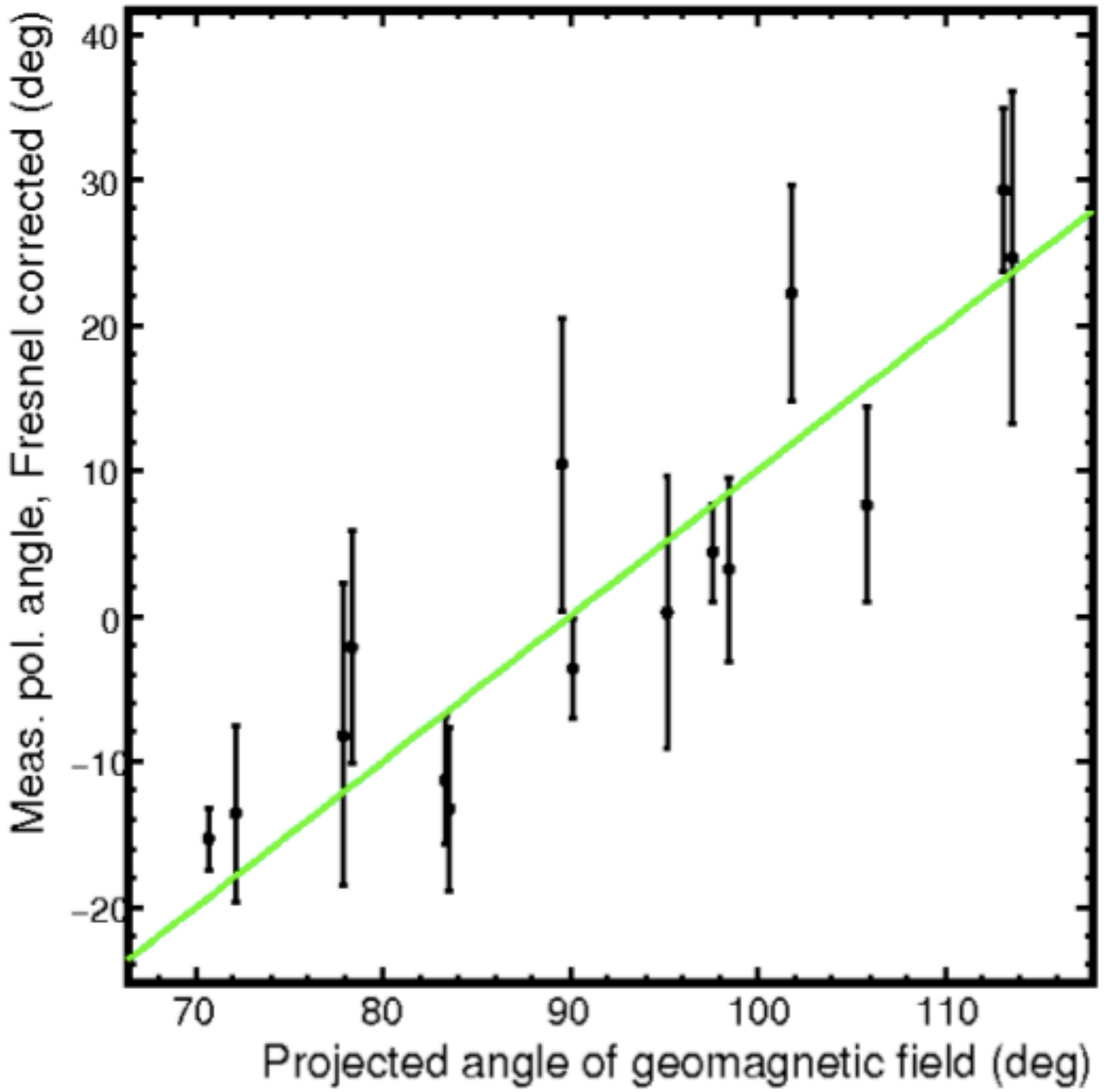
$B_{horizontal}$ = 0-20 μT



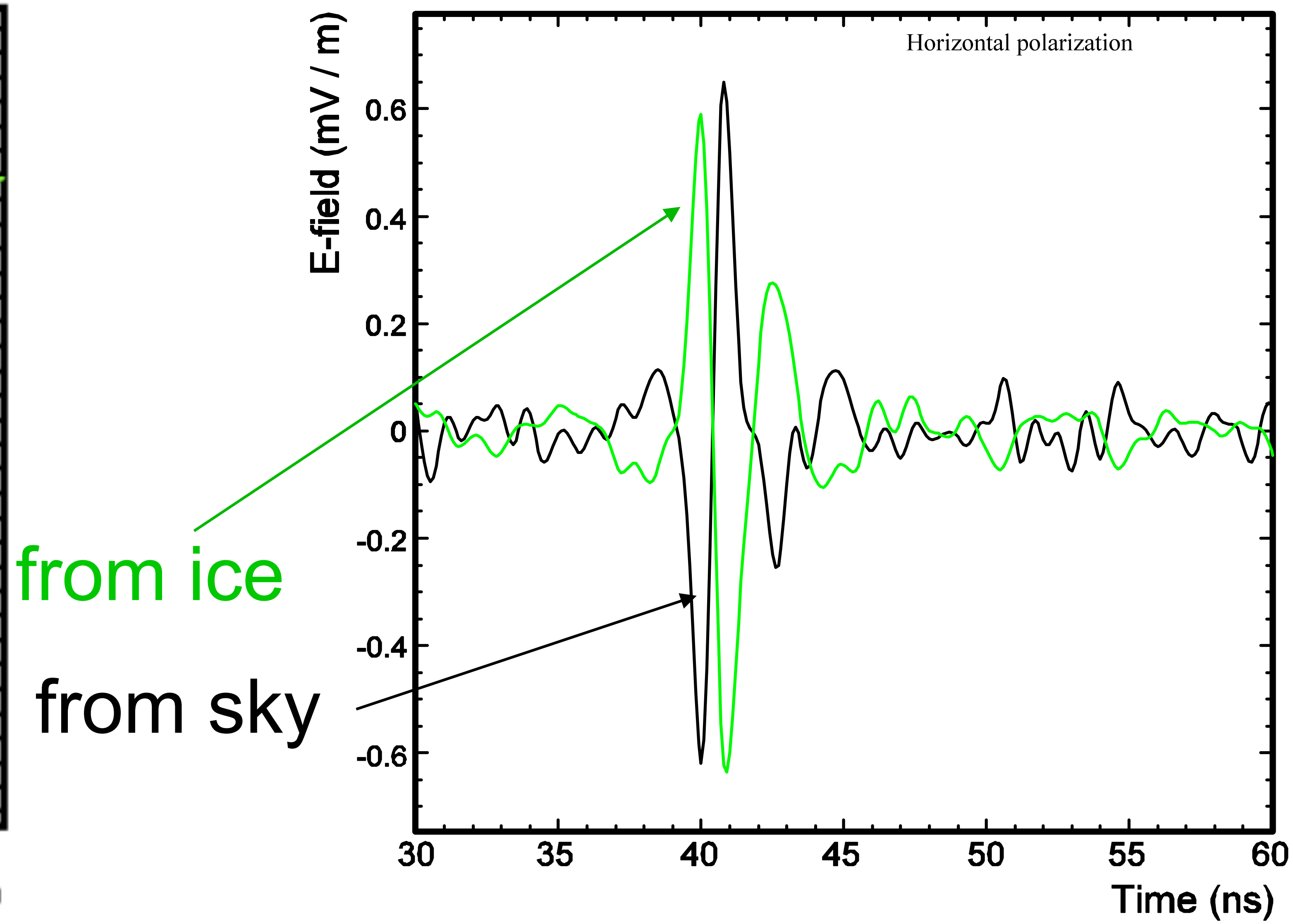
- H-pol emission
- Always the same polarity
- Reflected off snow surface

Evidence for Cosmic Rays

Know B field, direction of CR
→ predict pol. angle of
measured RF



Reflection at the surface
flips the signal



- <E> ~ $O(10^{19})$ eV
- Highest energy cosmic ray sample from radio
- 16 events from 17 live days

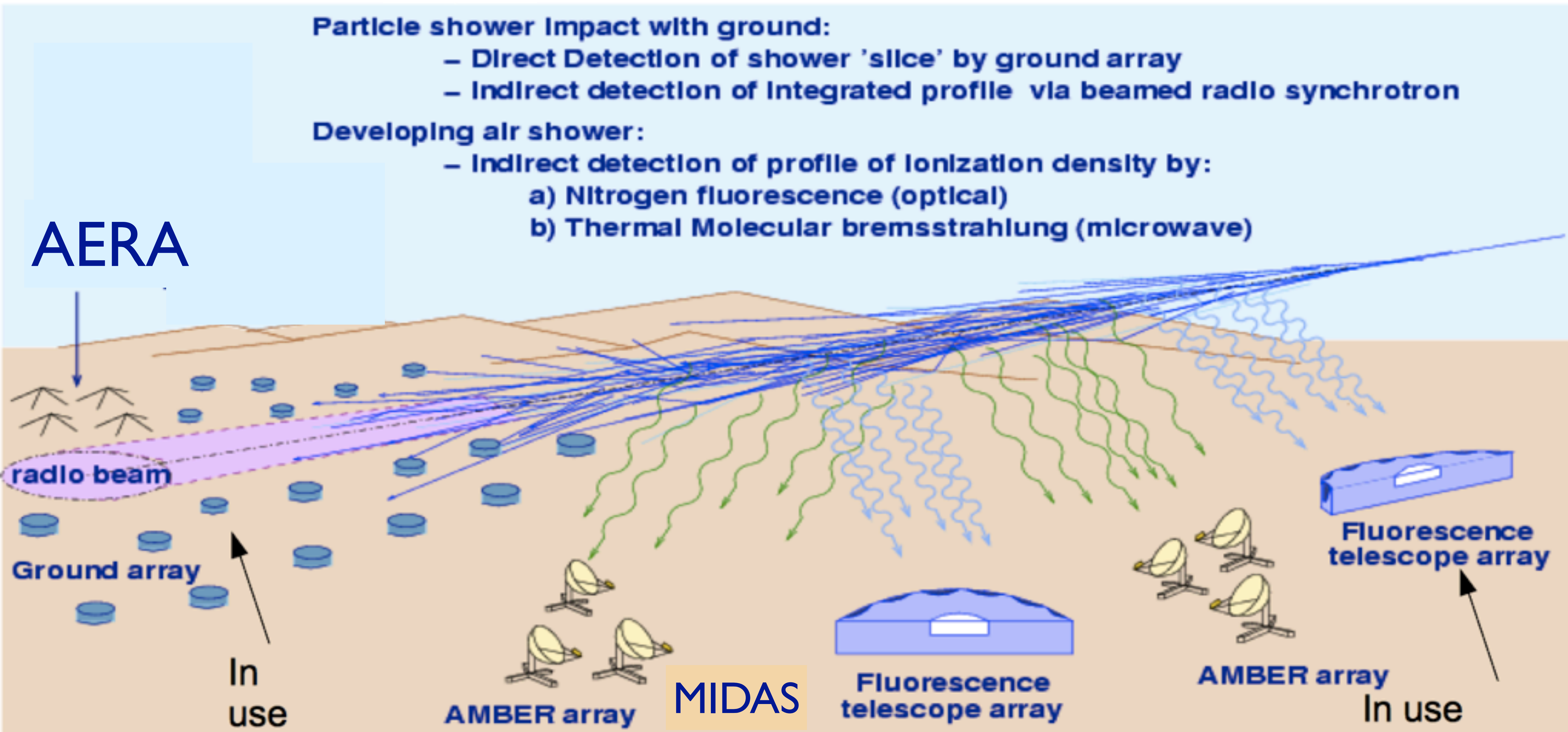
Anita 3

Goals:

- Improve 16→ O(100) UHECR events
- Neutrino events!

- Optimized separate V-pol (neutrino) and H-pol (CR) triggers
- More antennas
- More remote pulsers for calibration

UHECR Detection Methods at Auger



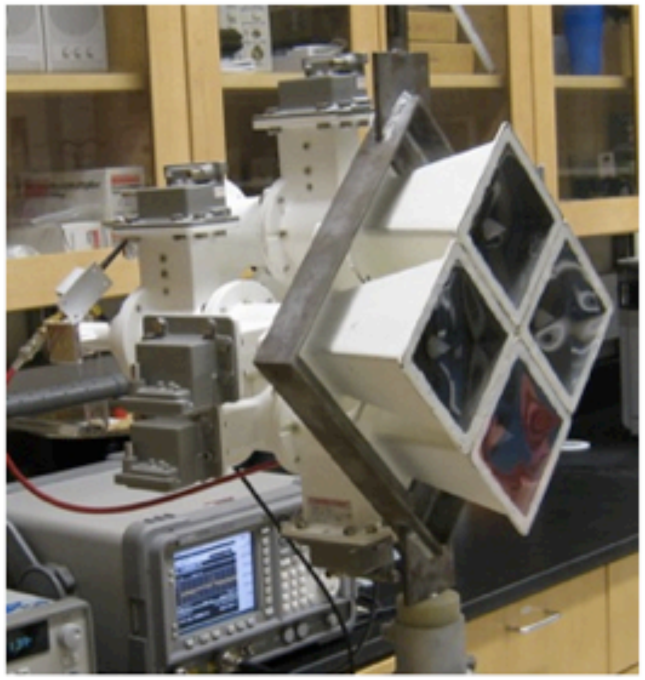
(10% livetime)

Lateral detection (must infer X_{max})

Longitudinal detection (direct measurement of X_{max})

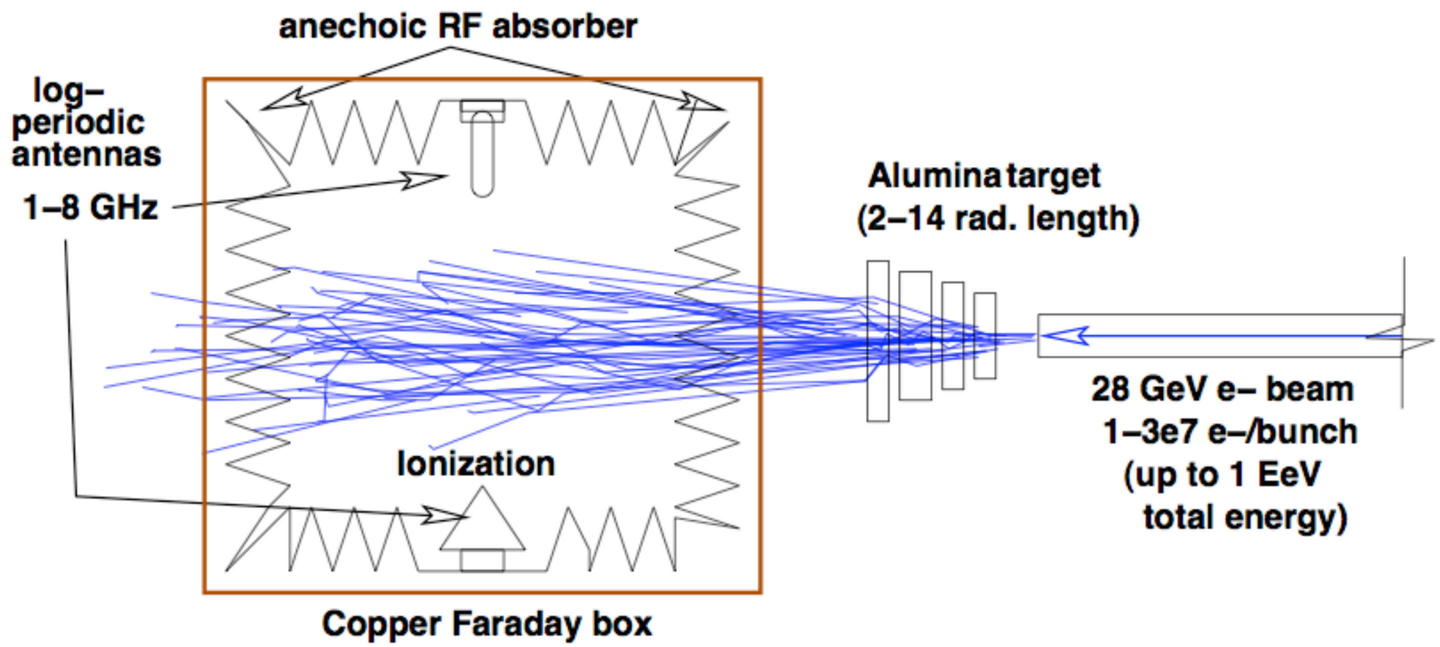
AMBER

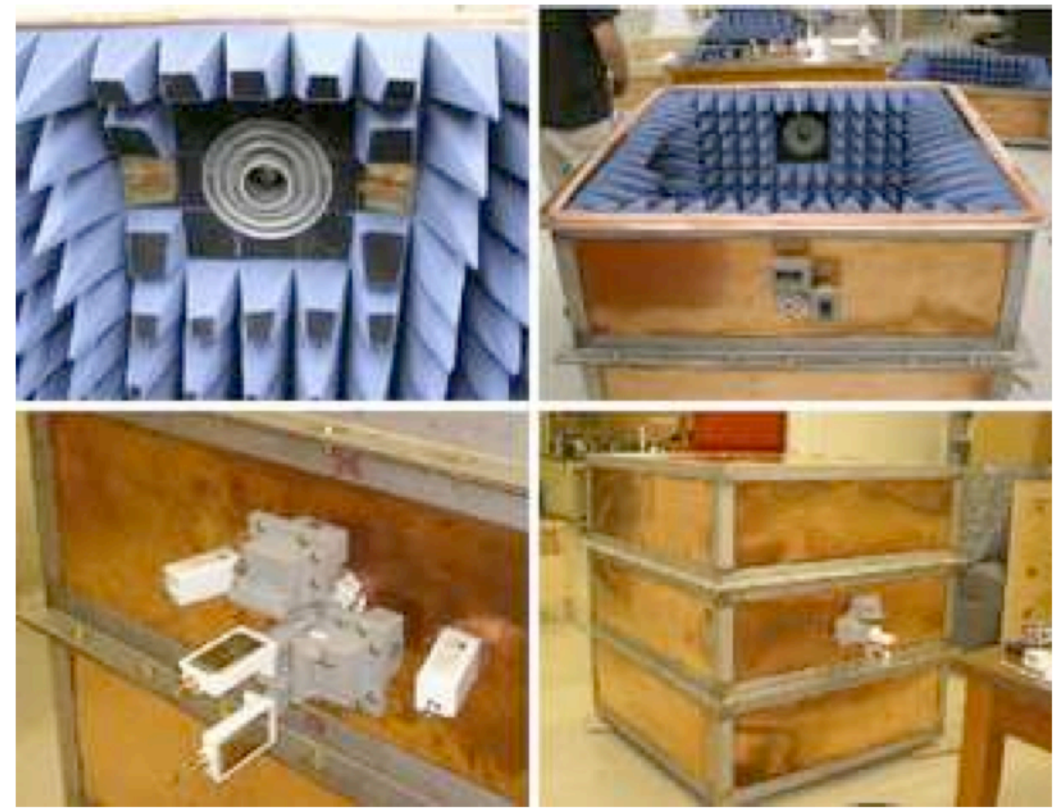
- P.W. Gorham et al., PRD 78, 032007 (2008): Microwave emission from electromagnetic showers at accelerators
- 4-channel prototype built; observed small number of possible sources
- Prototype was expanded to attempt to observe showers in coincidence with Auger



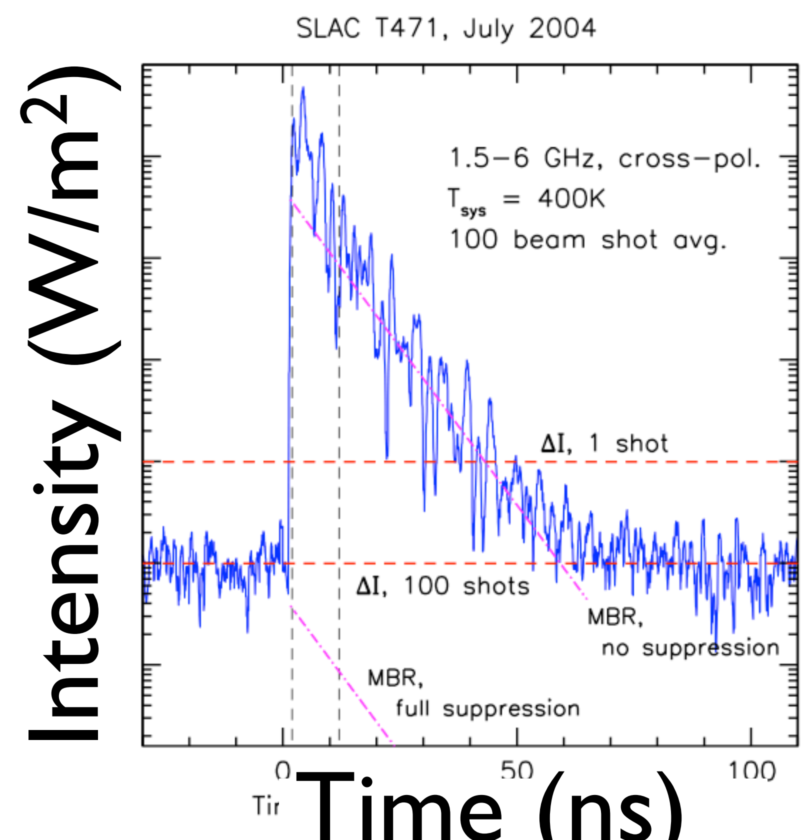
Microwave Bremstrahlung: Beam Experiments

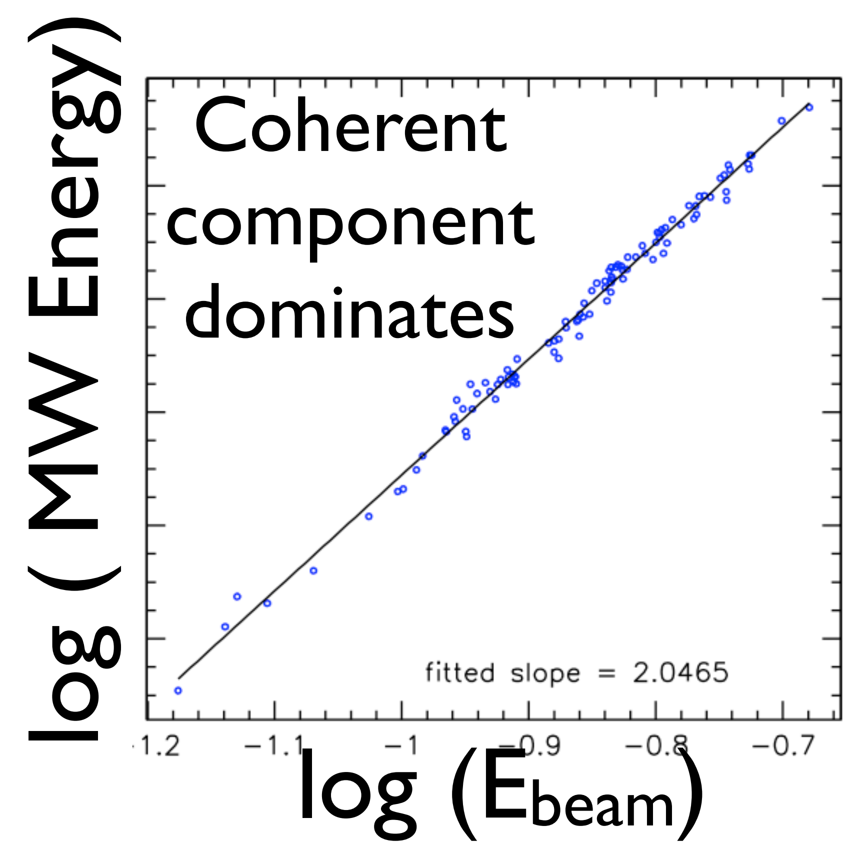
SLAC T471 experiment





- 28 GeV electron beam on 90% Al_2O_3, 10% SiO_2 target producing ion plasma in chamber
- Shower E ~6×10^{17} eV





Similar experiment performed at Argonne (same paper)

AMBER: Collaboration

- Ohio State University
- P.S. Allison, J.J. Beatty, E.W. Grashorn,
N. Griffith, J. Mayer, C. Morris
- University of Hawaii
- X. Gao, P.W. Gorham, J. Kennedy, L. Macchiarulo,
C. Miki, L.L. Ruckman, G.S. Varner
-
- Also thanks to X. Bertou for FastCt at Auger, trigger client, studies regarding maximum latency

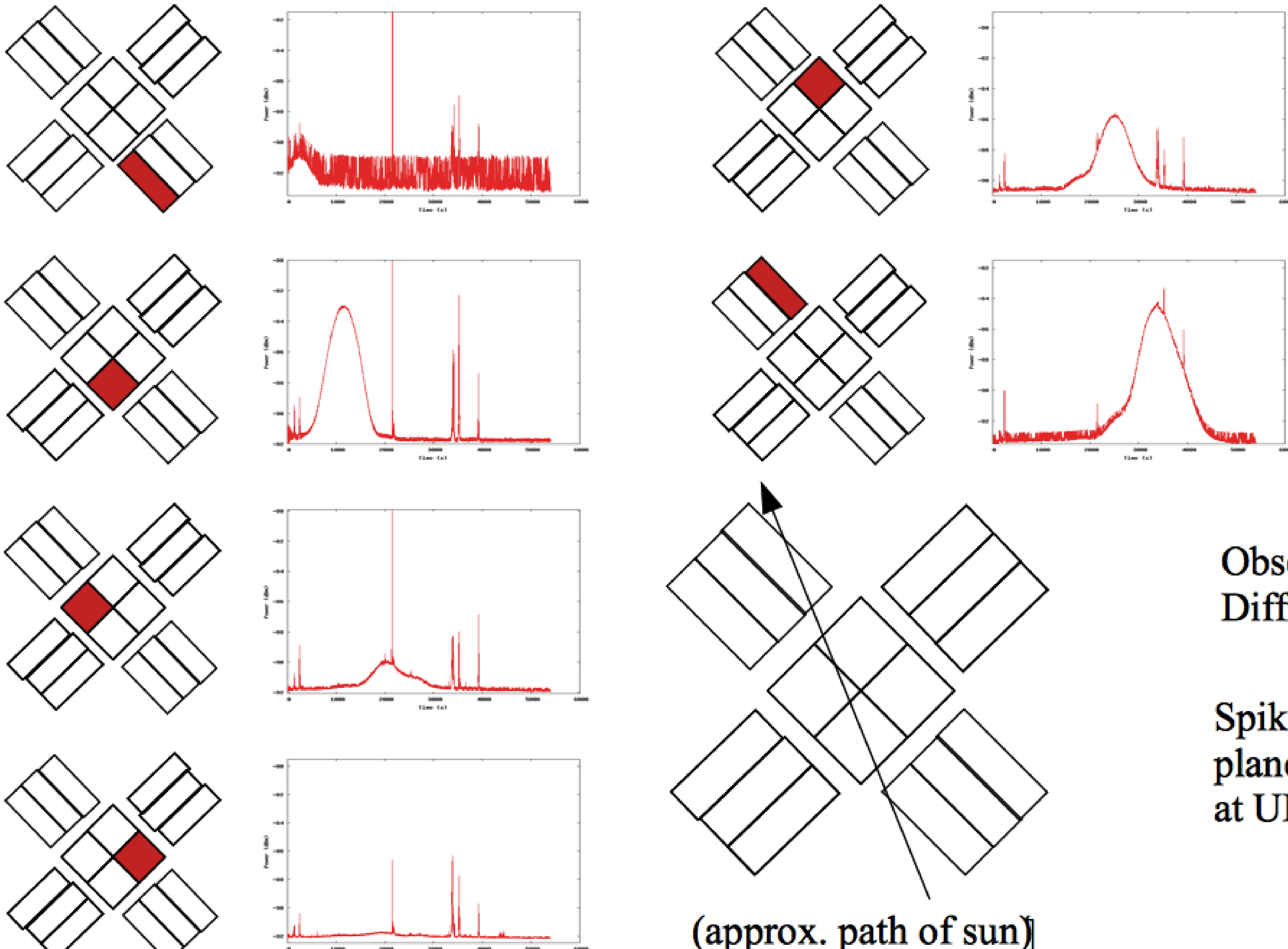
AMBER Configuration

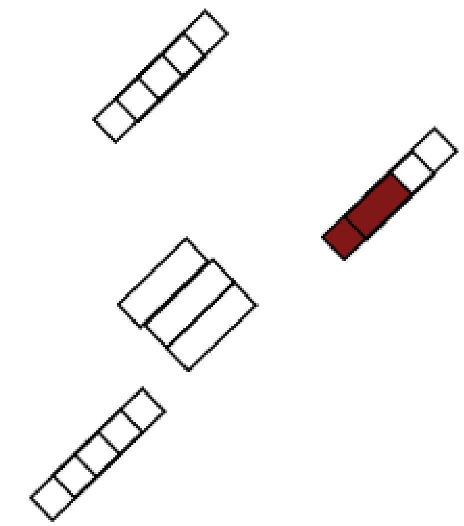
- 2.4 m offset feed paraboloid
  - Minimize matter in beam
  - Cold sky in sidelobes, low emissivity dish
  - 30 degree lookup angle
- 16 Feedhorns
  - 4 C & Ku band dual polarization
  - 12 C band single polarization
- Deep buffer- cross triggering from Auger Surface Detector

C band: 4-8 GHz
Ku band: 12-18 GHz

slide by Patrick Allison

AMBER Sun Transit Observation



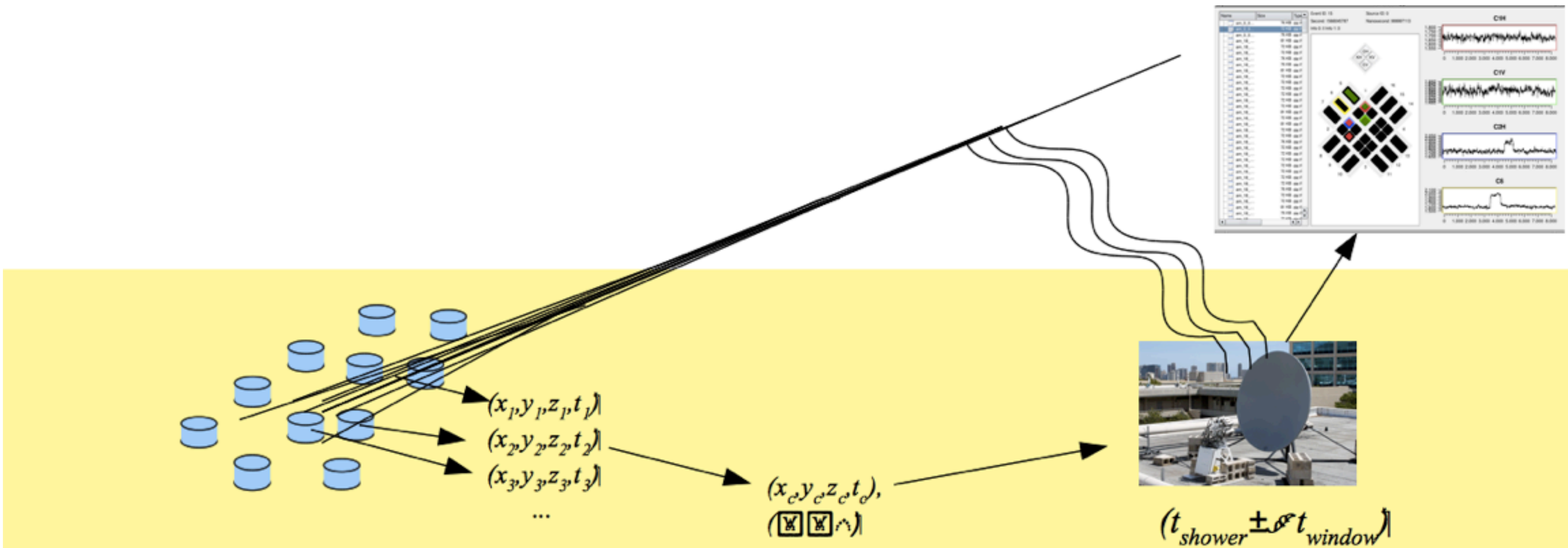


Observed FWHM: ~2.4 deg.
Diffraction limit: ~2.3 deg

Spikes/noise due to planes/nearby RF sources at UH

slide by Patrick Allison

AMBER/Auger UHECR Detection



Particle cascade detected at ground by Auger surface detectors
Trigger is formed when 3 nearby stations register a certain trigger type within ~few μs
Times, locations of stations sent to AMBER from Auger (after ~ 3 seconds)
AMBER software computes estimate of incoming shower direction, core location/time
From core location/time + direction, software then computes when shower was in field of view
AMBER hardware then extracts that time window from a ~5 second data buffer

slide by Patrick Allison

AMBER Current Status

- UH rooftop setup taken down after ~1 month of stable, final operation
  - No real candidates – noise environment worse than previous years
  - Completed several observations of sun transit, scans of C-band satellites, and astronomical source observations
    - Astronomical sources (non-Sun) need better averaging/filtering – currently in progress
- Auger first-step integration basically done
  - FastCt interface ~done (just need to wrap network transport)

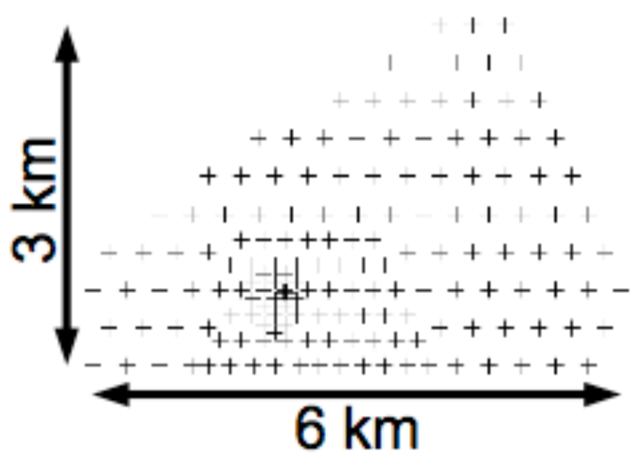
AMBER hardware shipped to Argentina for data taking

AERA

Science Goals

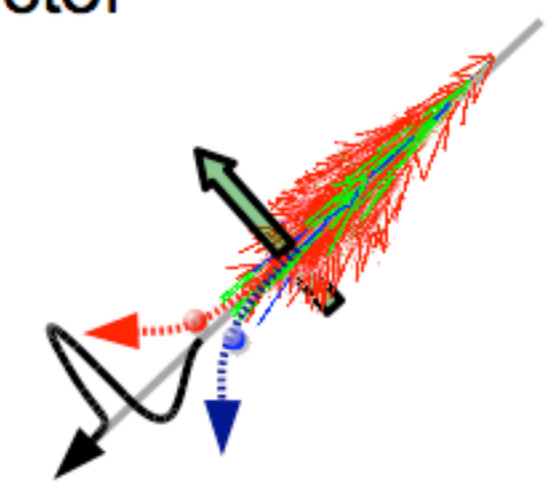
Probe the nature of cosmic rays at the transition region
with a novel independent detection technique

Realize a large scale Radio Detector



Understand the details of the
radio emission processes

Explore the Potential of the
Radio Detection Technique



Realize combined detection of air showers at Auger
„Super-Hybrid“: Radio + SD + FD

AERA Auger Engineering Radio Array

slide by Stefan Fliescher

The AERA Group

Bergische Universität, Wuppertal
KIT, Campus North, IK, Karlsruhe
IMAPP, Radboud University, Nijmegen
KIT, Campus North, IPE, Karlsruhe
KVI, University of Groningen, Groningen
LPSC, Grenoble
Nikhef, Amsterdam & Nijmegen
RWTH Aachen University, Aachen
SUBATECH, Nantes
KIT, Campus South, EKP, Karlsruhe

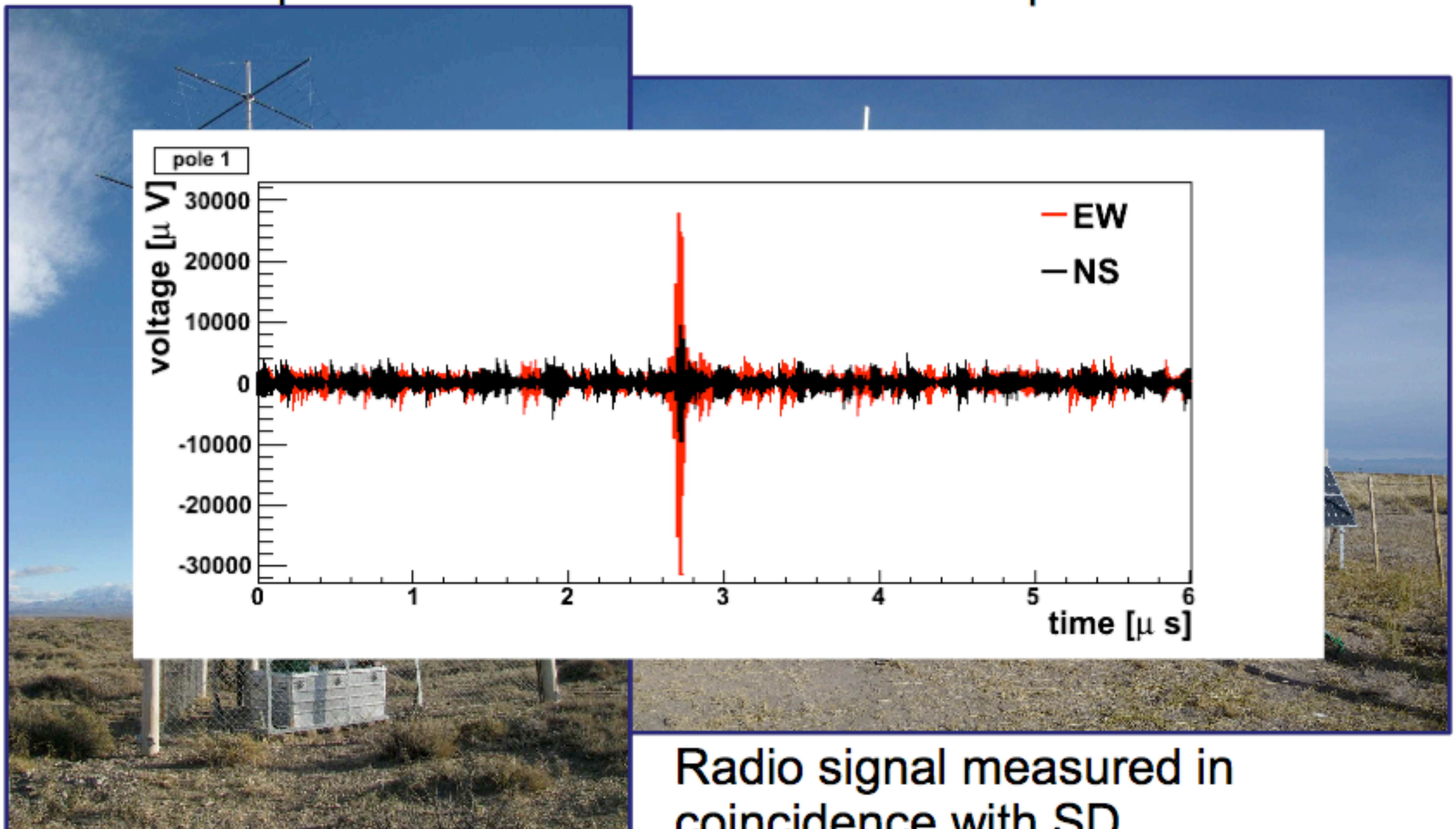
AERA Auger Engineering Radio Array

Stefan Fliescher

Recent Radio Setups at Auger

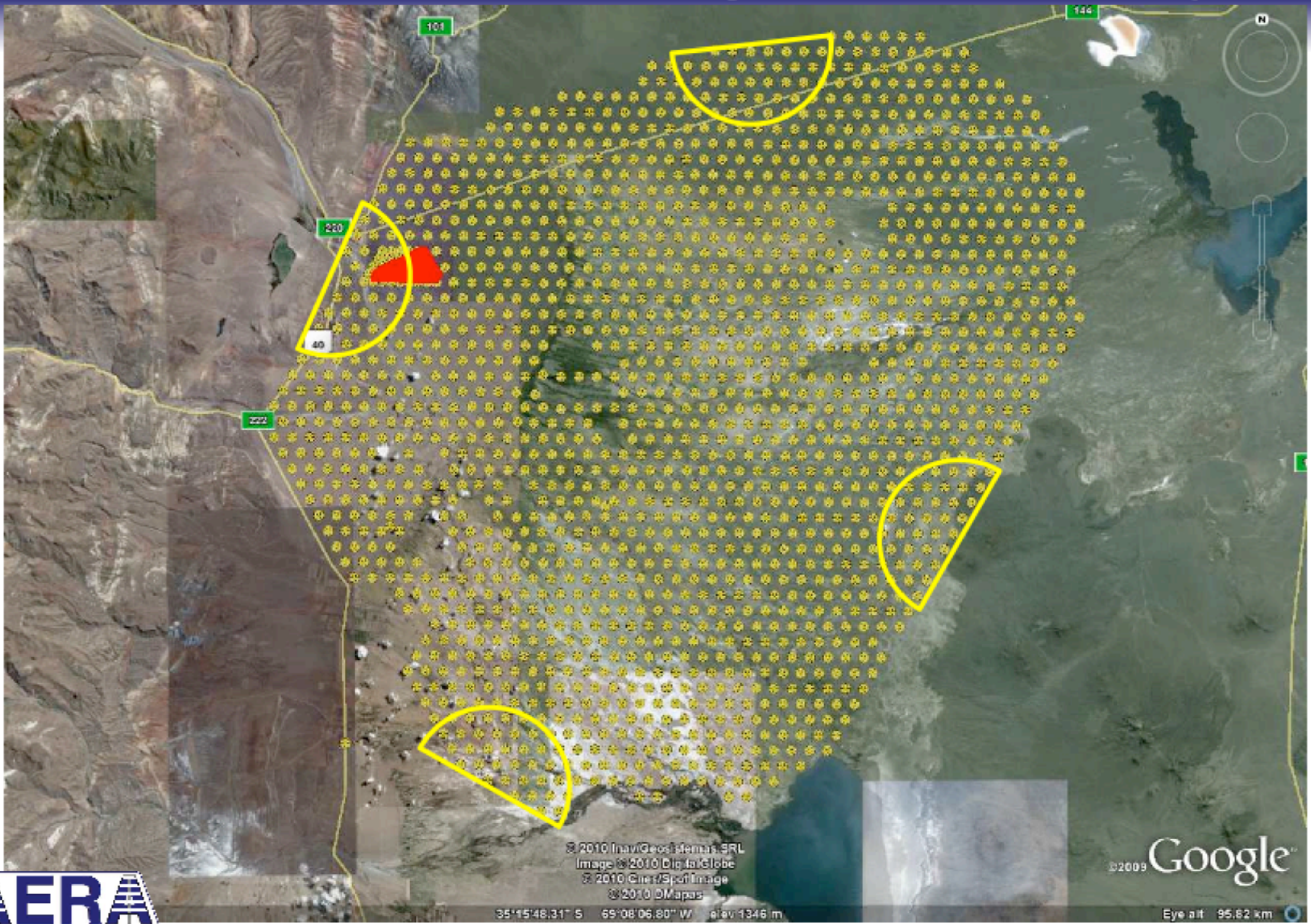
Setup at BLS

Setup at CLF



Radio signal measured in coincidence with SD

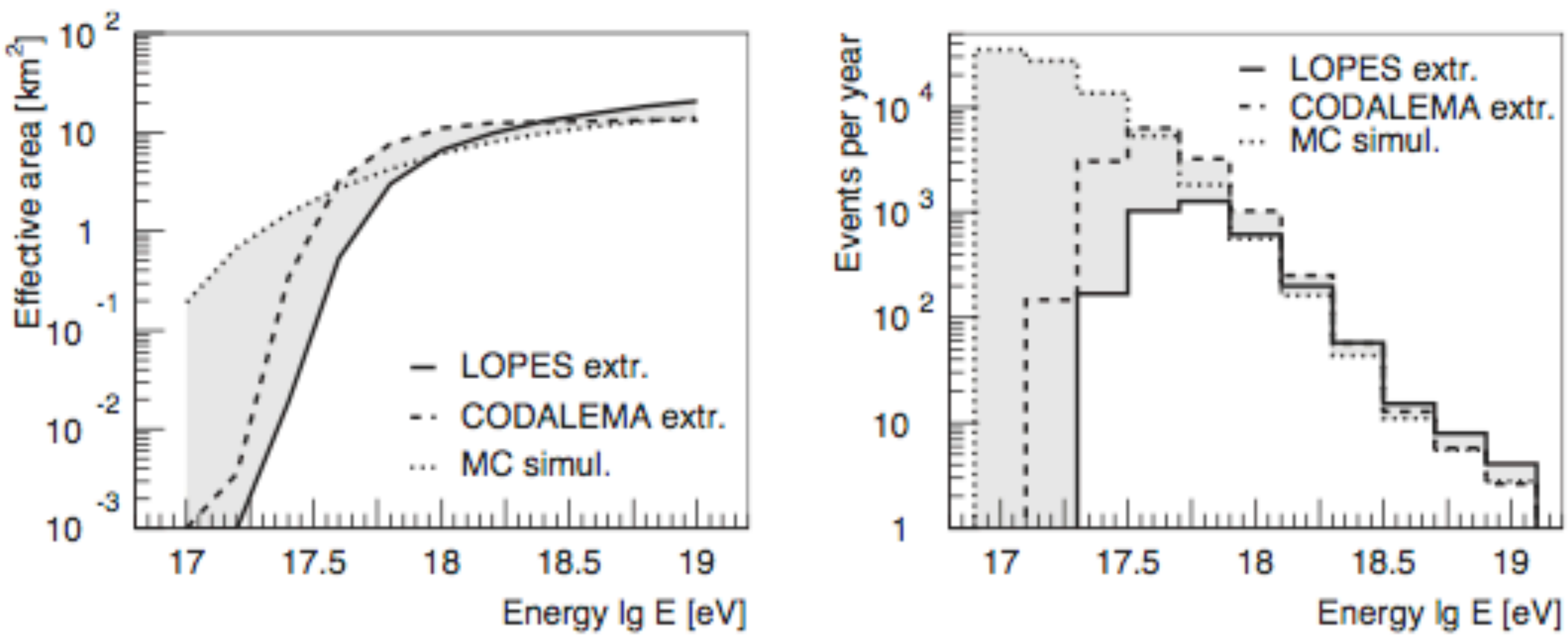
Overview: Pierre Auger Observatory



AERA
Auger Engineering Radio Array

Impressions from the AERA Site

Event Rates



Conservative energy threshold: log(E / eV) ~ 17.2

5000 events / year with E > 3×10^{17} eV
800 events / year with E > 1×10^{18} eV

slide by J. Kelley

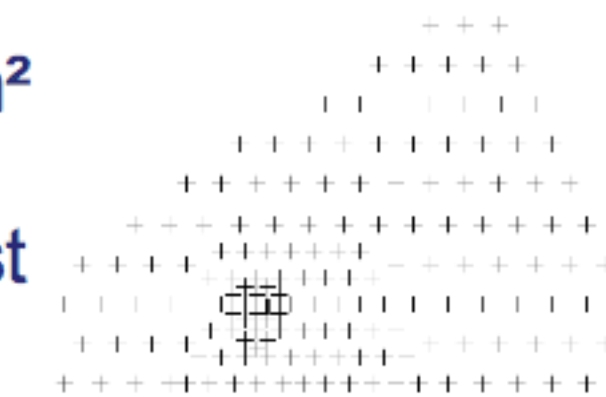
Summary & Outlook

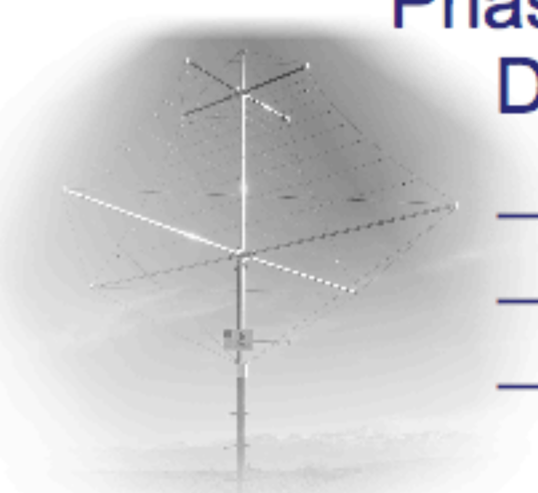
Large Radio efforts at Auger

Midas & Amber have approval to set up at the Auger site and start first coincident measurement with SD and FD

Auger Engeneering Radio Array

10 Institutes
161 Radio Detector Stations, 20 km²
Phase 1: 24 stations
Data taking scheduled for August





→ Details of Radio emission
→ Potential of Radio
→ Nature of cosmic ray at the transition region

' Super-Hybrid ': Unique possiblity to study UHECRs

AERA Auger Engineering Radio Array

Conclusions

- Radio Cerenkov technique well established for neutrino searches, ANITA sets world's best limits $>10^{18}$ eV
- Geosynchotron technique coming on the scene for UHECR detection
- Microwave Bremstrahlung also promising technique for UHECR detection, first AMBER, MIDAS stations ready for data taking

Radio/Microwave techniques could provide much needed data complementary to other techniques