Cosmic Ray And Neutrino Astrophysics with the ANITA-III Telescope

PhD Defense

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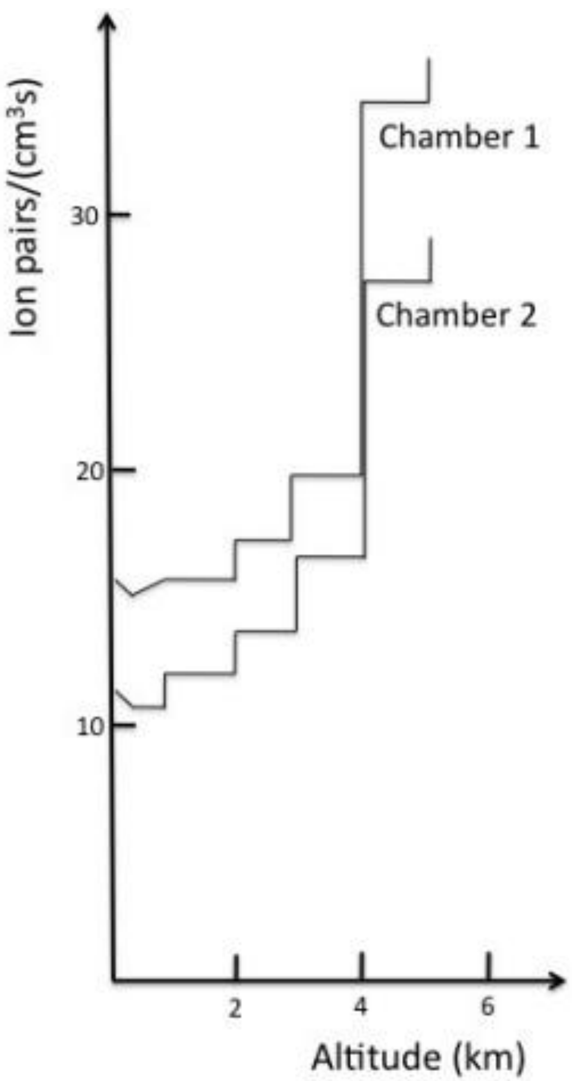
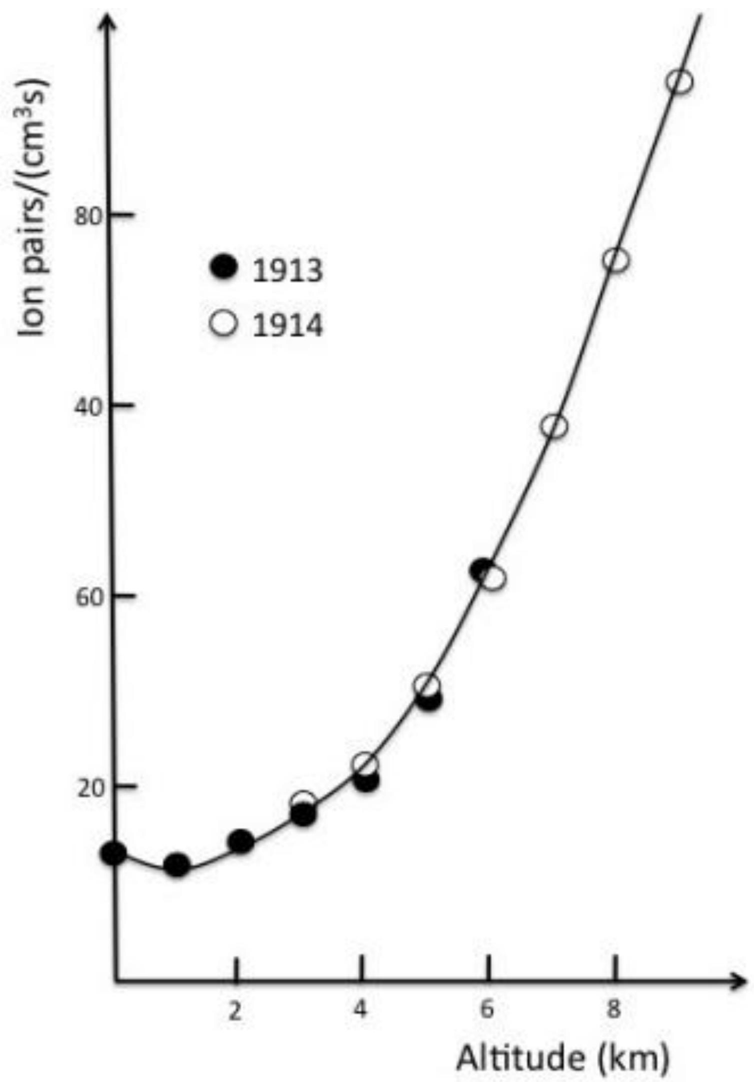
October 20th 2017

Cosmic Rays (CRs)

Astrophysical messenger particles





Discovered over a century ago through measurements of ionizing radiation that increased with altitude

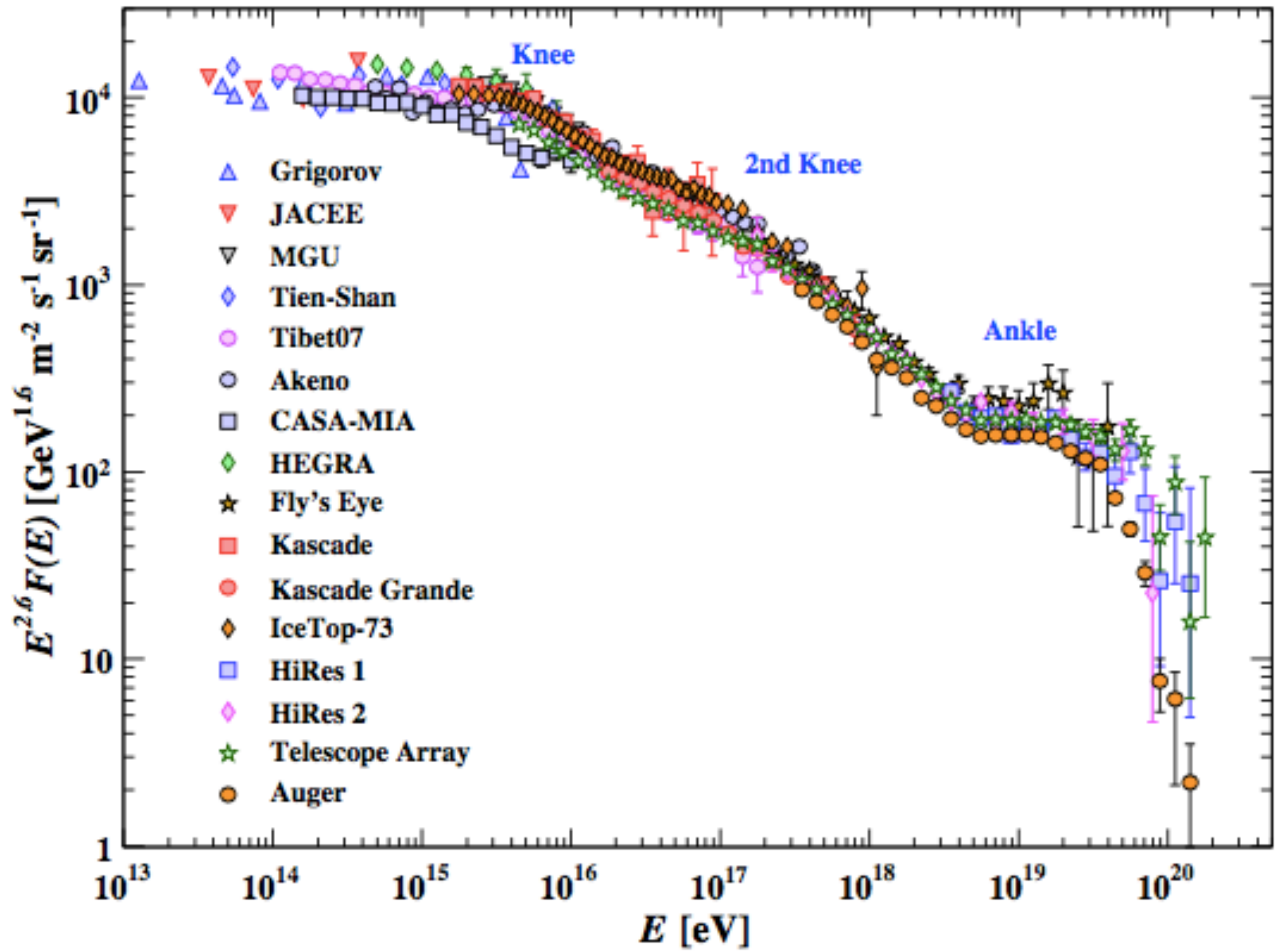
Massive particles, not photons, interacting with the Earth

Contribute additional measurable signals from astrophysical processes

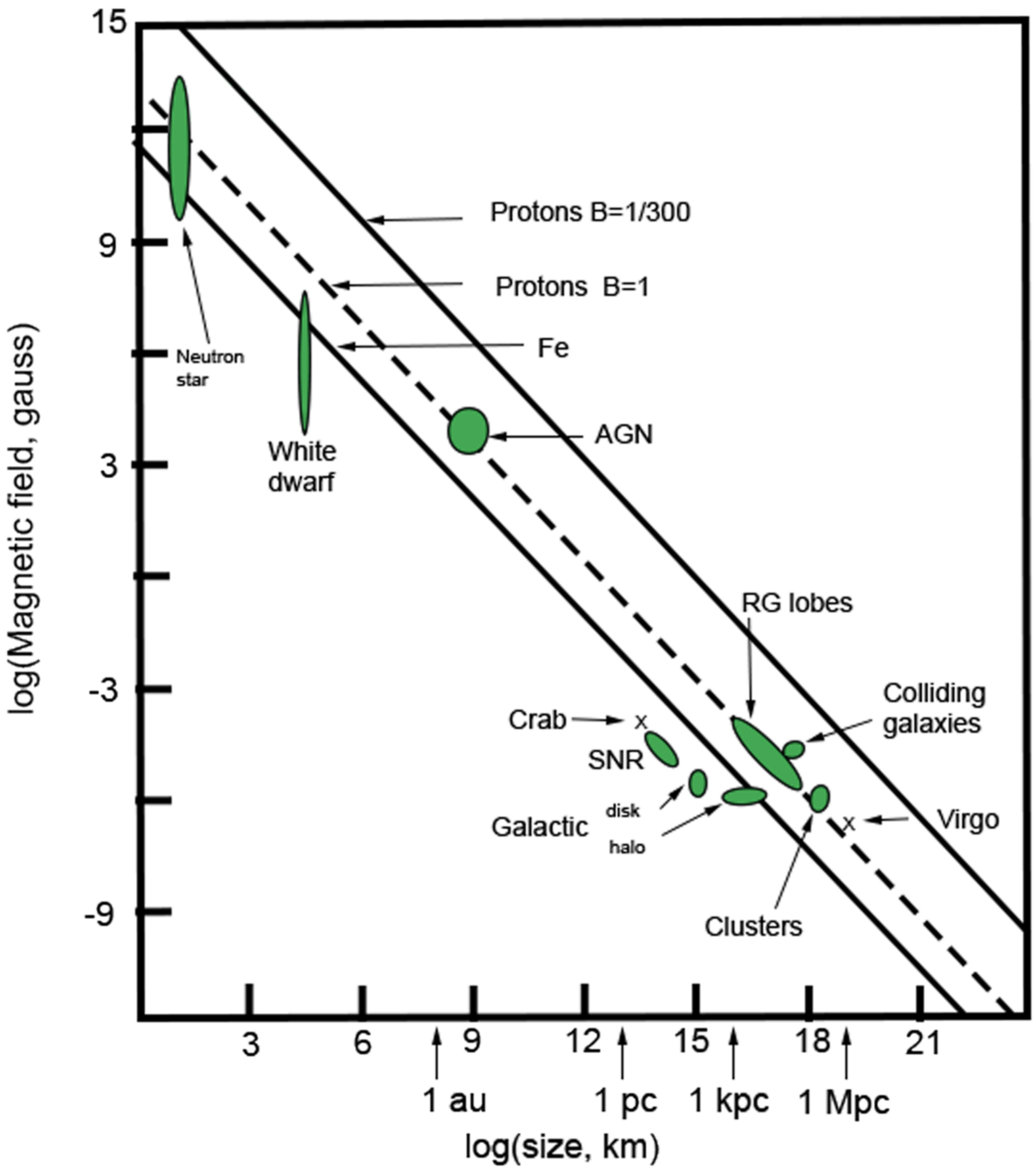
Ultra High Energy CRs (UHECRs)

- Measured spectrum of cosmic rays extends up to Ultra High Energy (UHE) regime

- Above 10^{19}eV, measured flux falls off dramatically, leading to low statistics and high uncertainty



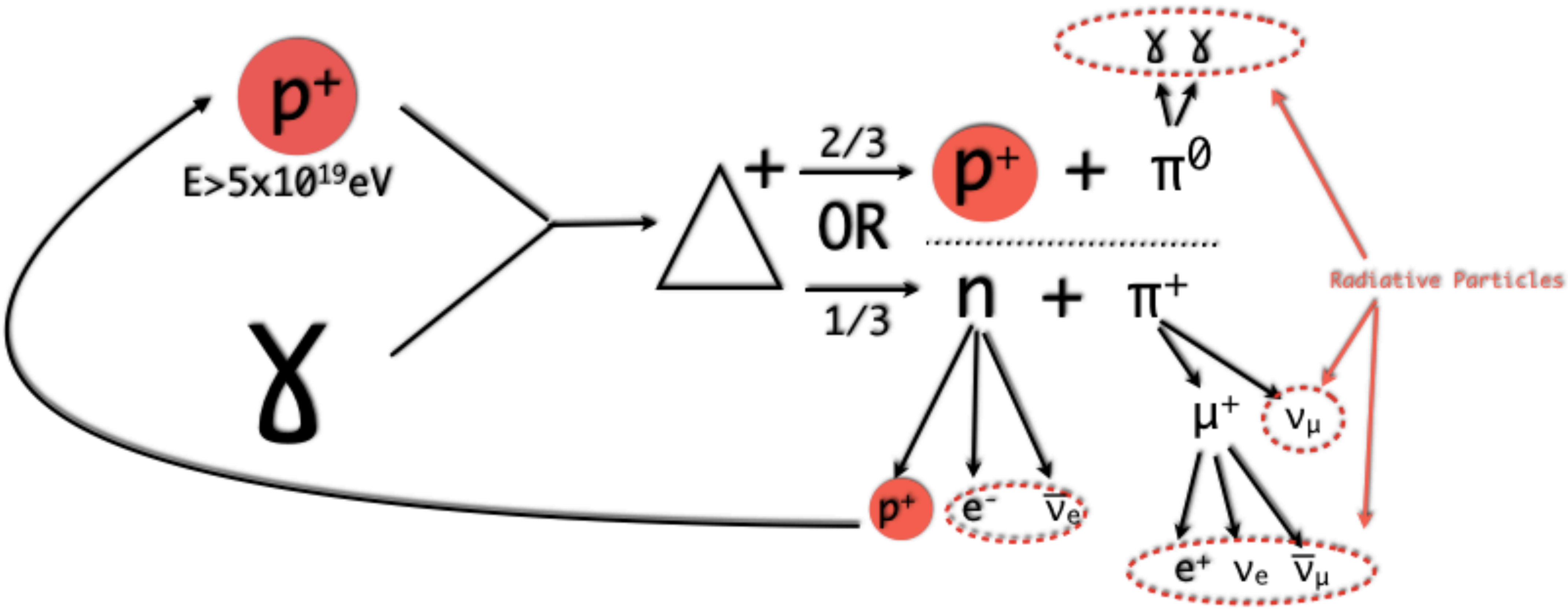
Possible CR source accelerators



Many theories, but UHECR source accelerators are still an unsolved problem in physics.

Lack of observations above 10^{19}eV suggest extra-galactic source accelerator

UHECR limit, and UHE Neutrinos



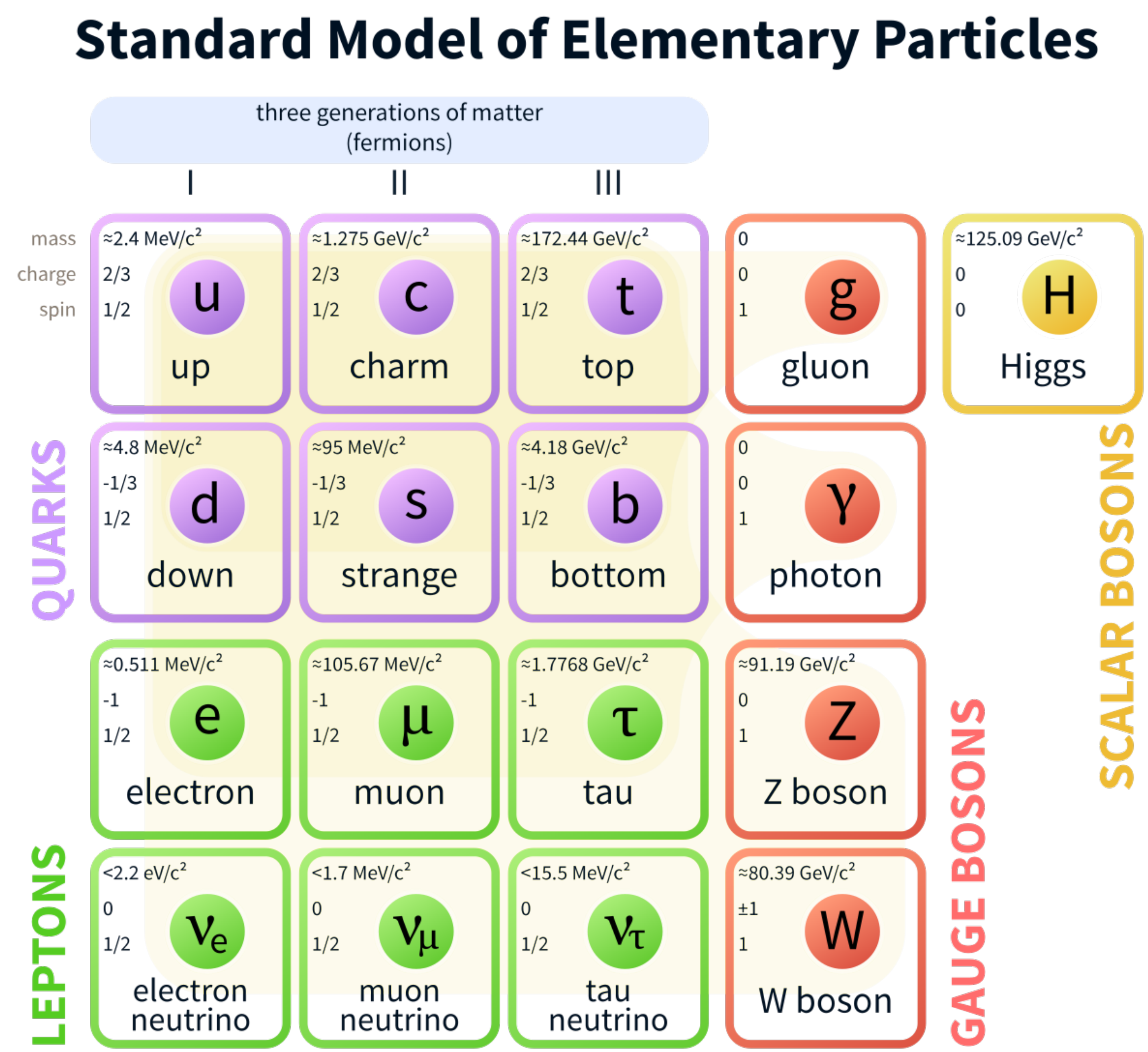
Greisen, Zatsepin and Kuzmin (GZK) process attenuates CRs through delta resonance, suppressing their observed flux on Earth

UHE byproduct of GZK process is a neutrino, which can provide a measurable signal for unexplored regions of the universe.

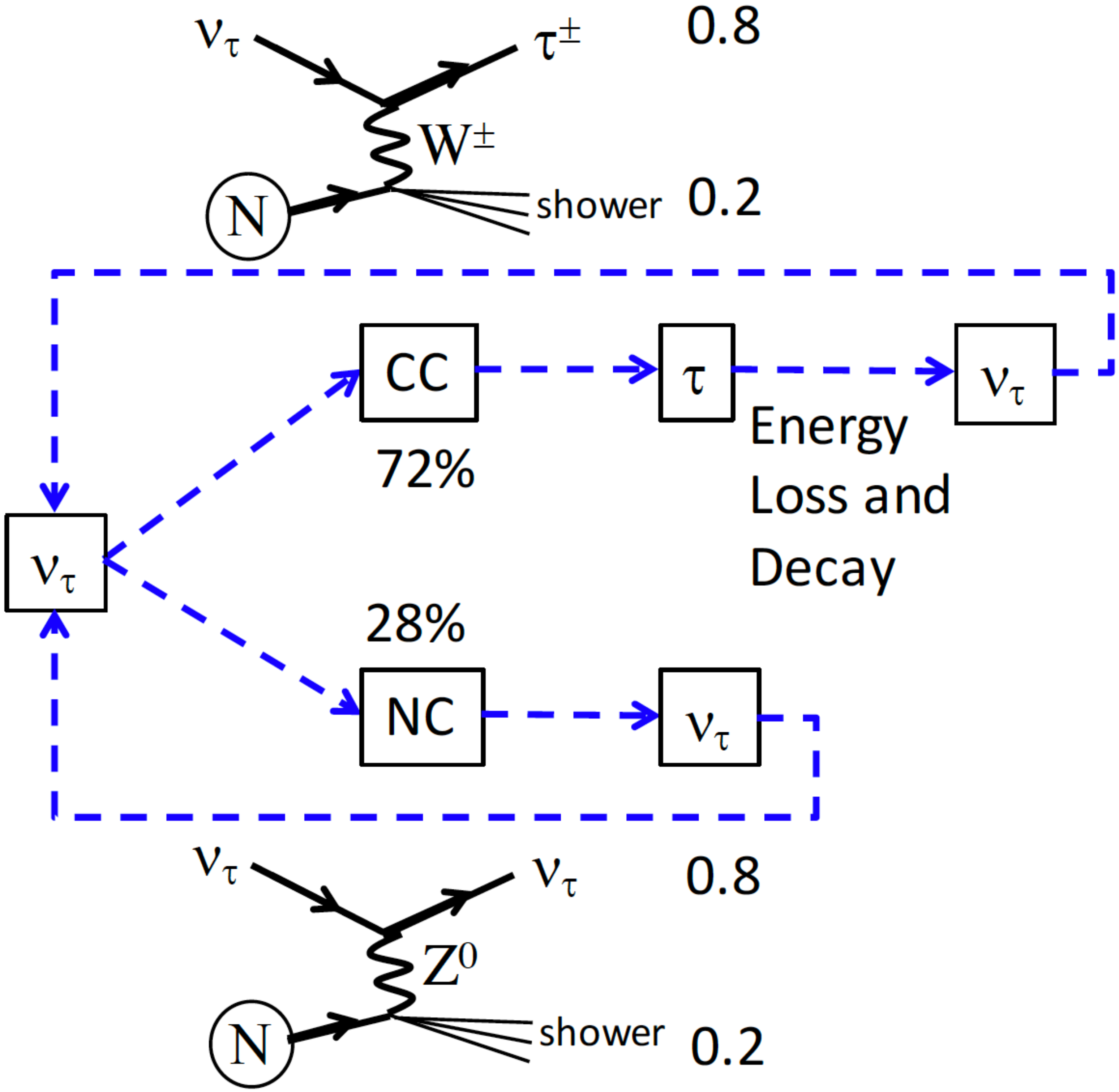
≈30Mpc mean interaction distance: extragalactic

UHE Neutrino Astronomy

- Three types (flavors) of neutrinos that produce signals that neutrinos telescopes researching for
- There have been some detections (IceCube)
- tau produces special signal that is focus
- Though only νe and νu flavors are created in GZK process, enormous universe scale baselines and flavor mixing result in expected 1:1:1 e:μ:τ ratio for detections.



Tau Regeneration



Tau leptons have a very short lifetime (0.29 ps in rest frame), and will decay back to a tau neutrino

Charged current (CC) process in ve or vu results in catastrophic energy loss through extensive multi-particle shower

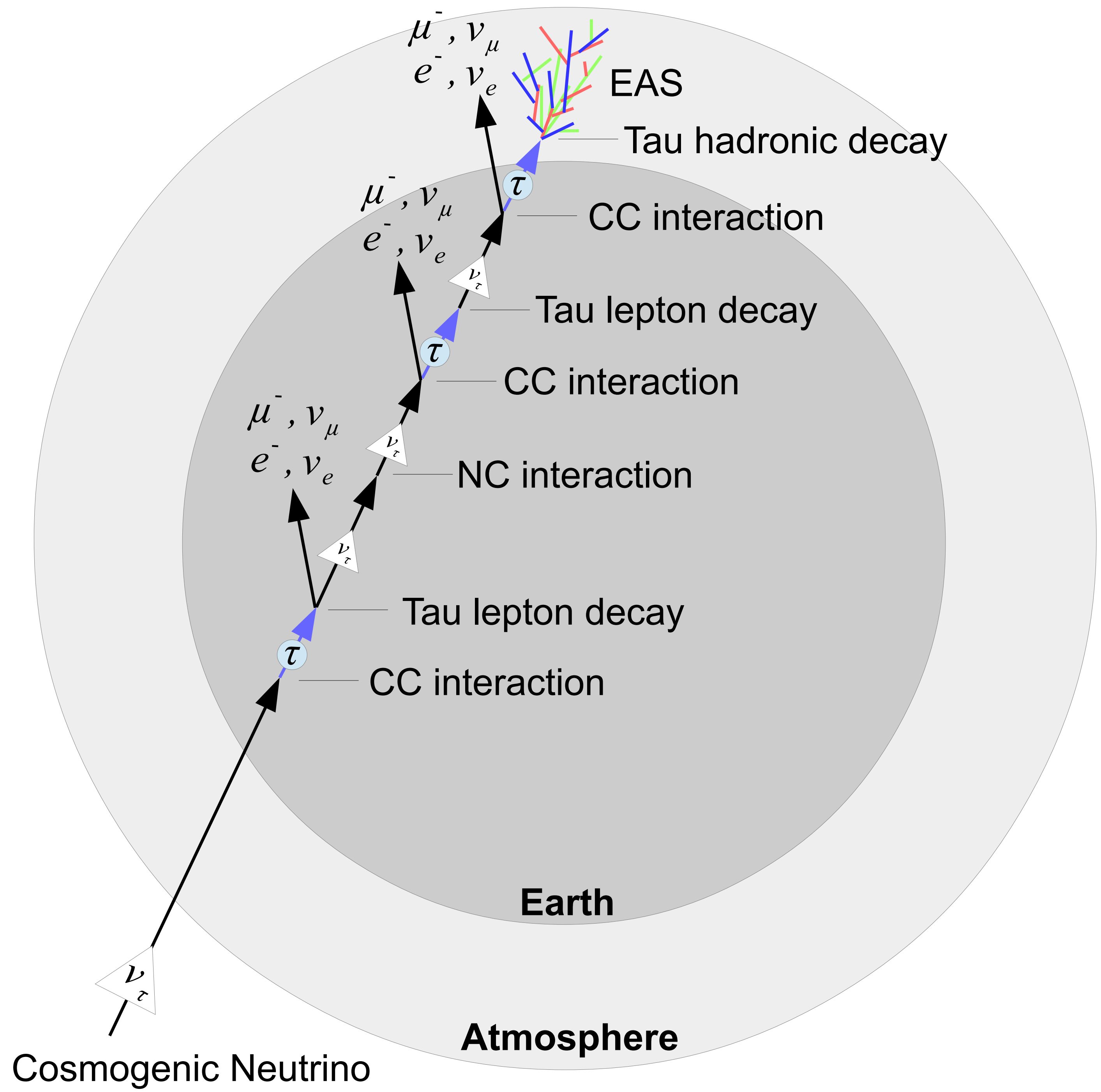
CC in vt however, preserves much of the energy, boosting mean path length. “Regenerated”

Neutral current (NC) process also has small energy losses

arXiv:1707.00334v3

Tau neutrino detection prospects

Extended mean free path allows for increase in detectable incidence angles



Tau signal polarity, observing from high in atmosphere

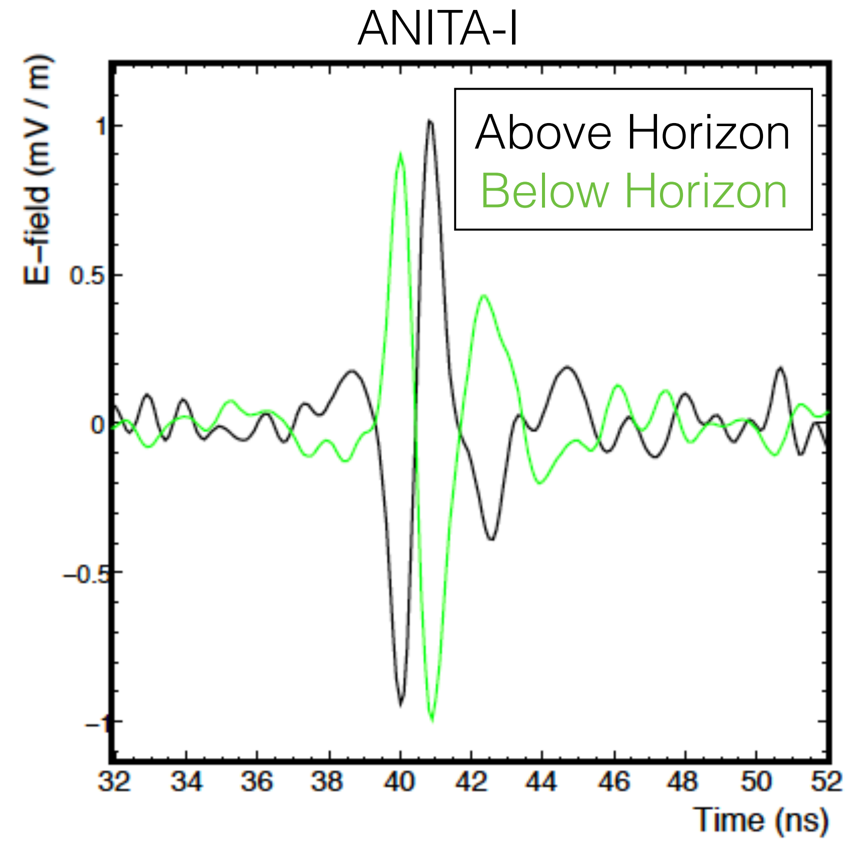
Upgoing Tau initiated shower would have directly viewed radiation

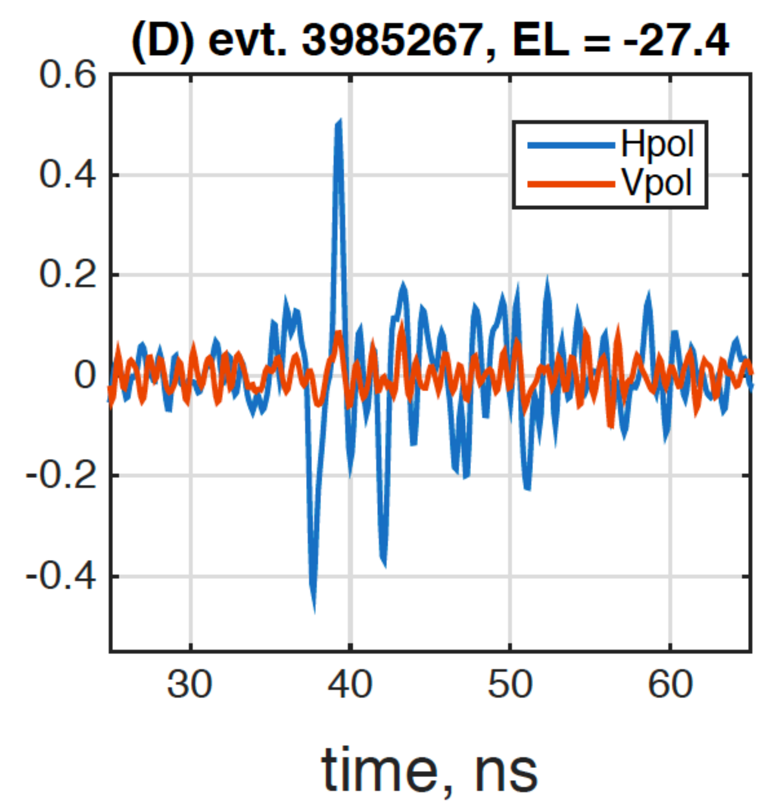
Above horizon CR initiated showers would also be viewed directly

Below horizon reflected CR radiation would have polarity inverted

ANITA-I detected 16 below horizon showers with matching polarity, and 2 above horizon with matching inverted polarity

Also observed one below horizon event matching a “directly” observed shower



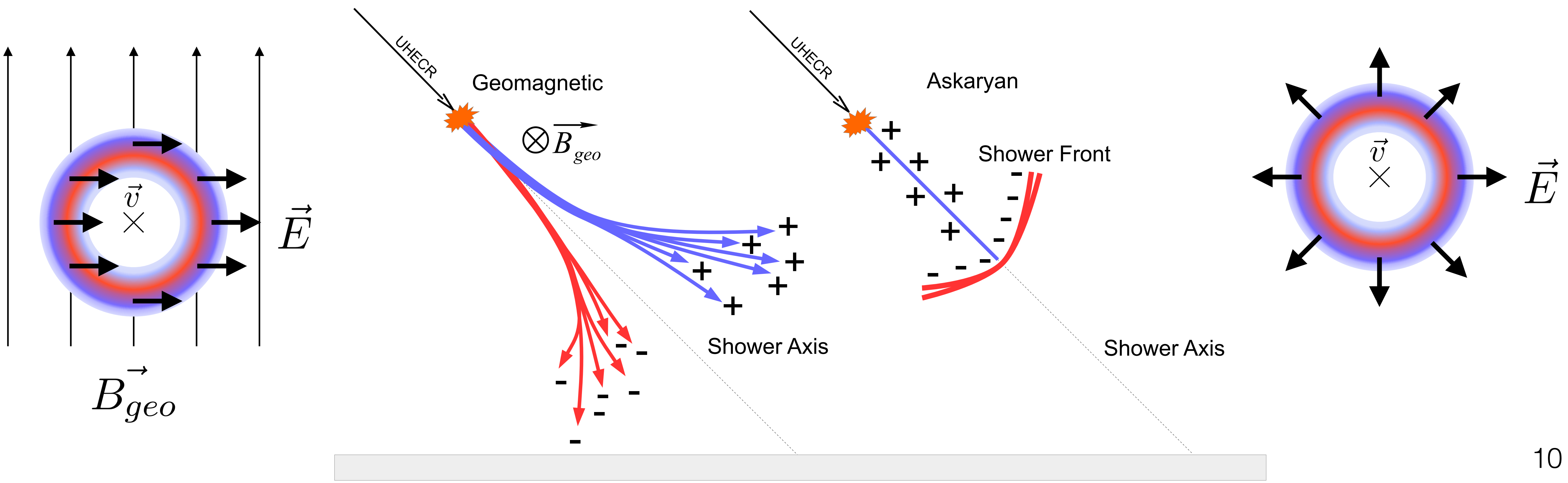


Electromagnetic Radiation From UHECRs

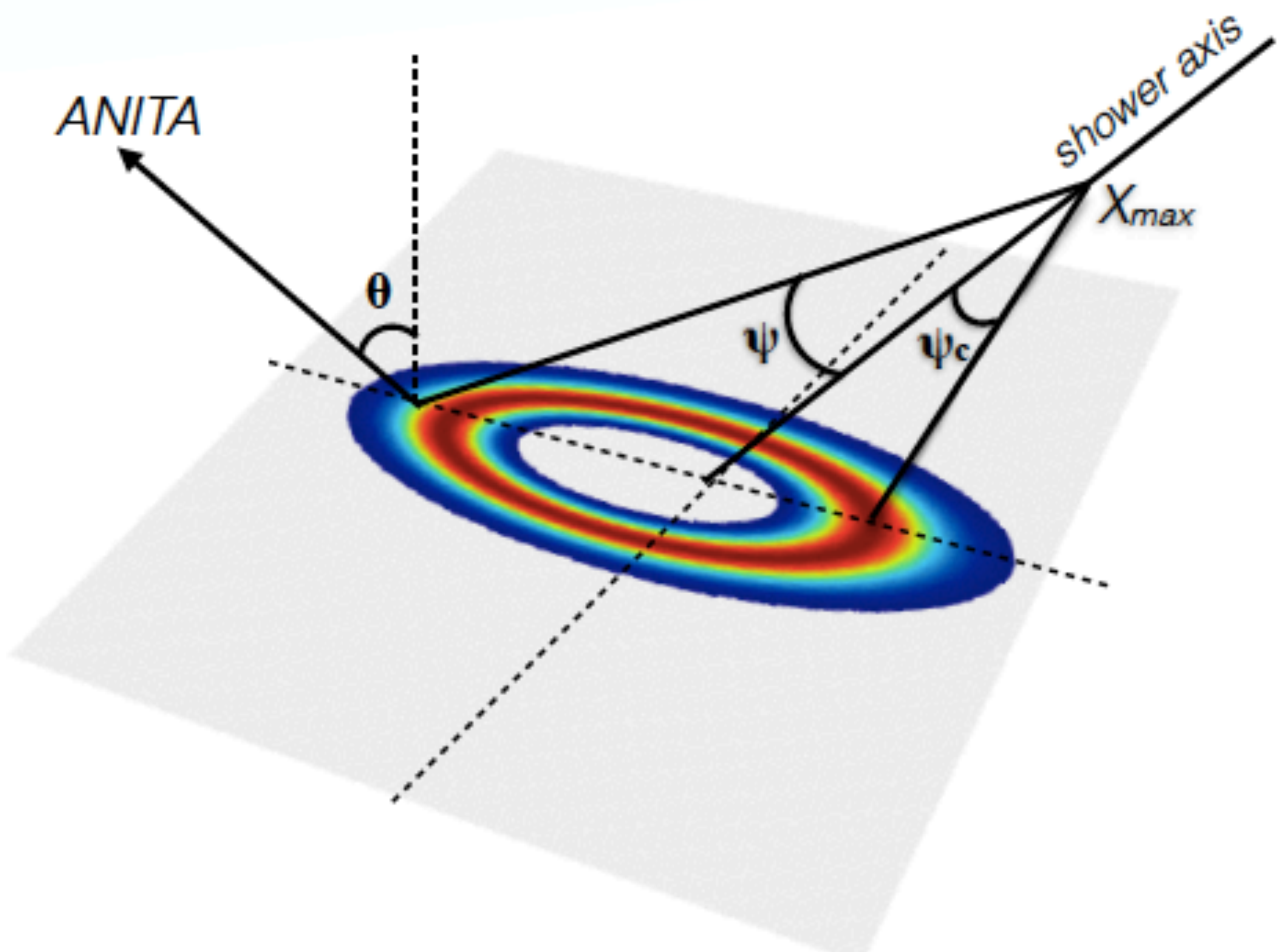
Two major contributors to emitted radiation from EAS interactions:

Geomagnetic: Dominant radiative compc $\vec{E}_{induced} = q\vec{v} \times \vec{B}_{geo}$ ration induced by Earth's magnetic field. Electric field is given by:

Askaryan: Charge separation induced by positron annihilation in shower core. Polarization points radially outwards from shower axis



Cherenkov-like Coherence Angle



Superluminal particle effect that creates signal boost at critical off angle

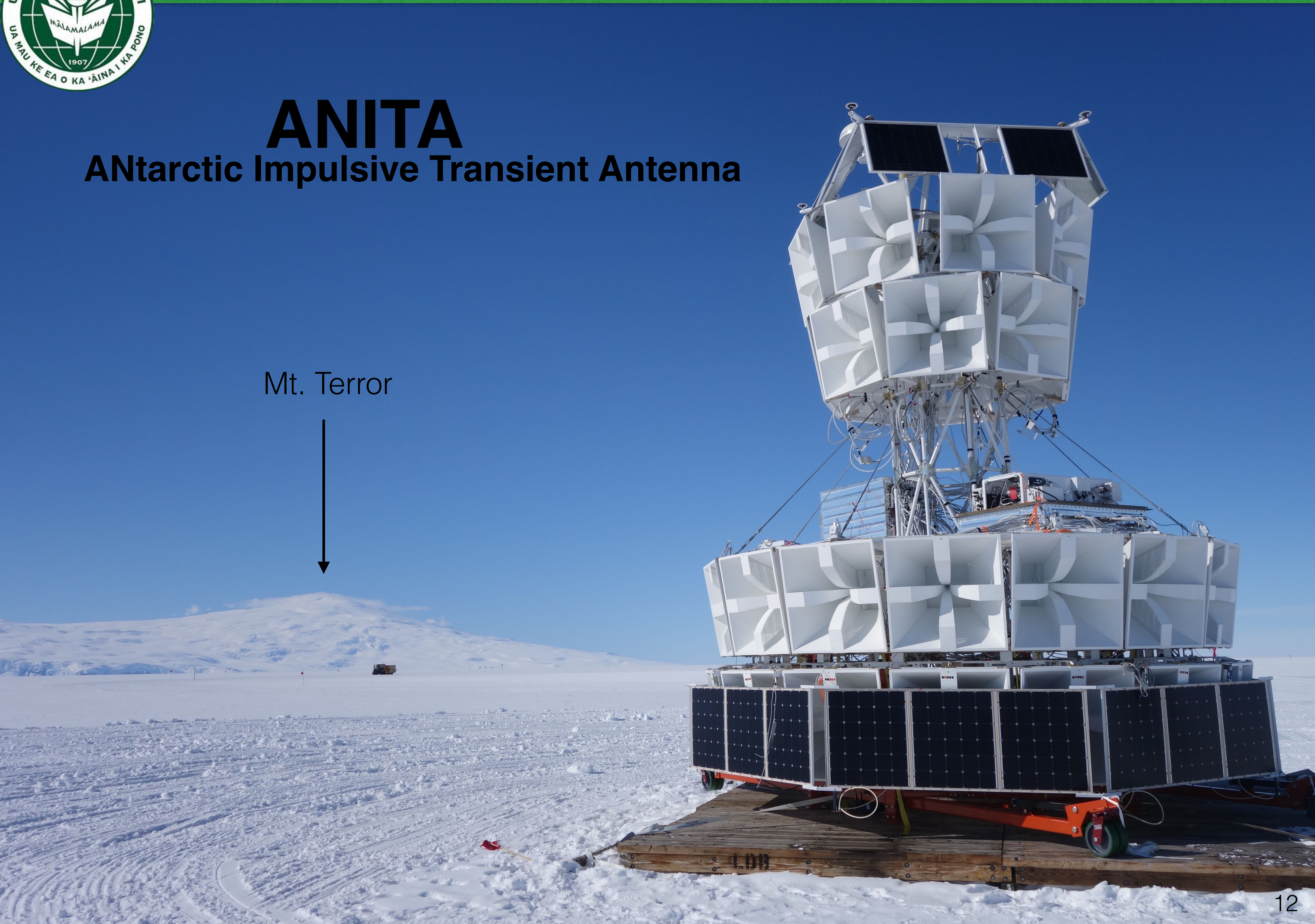
Not Cherenkov light, but at the same angle

Waveforms “stack up”, creating detectable coherent signal

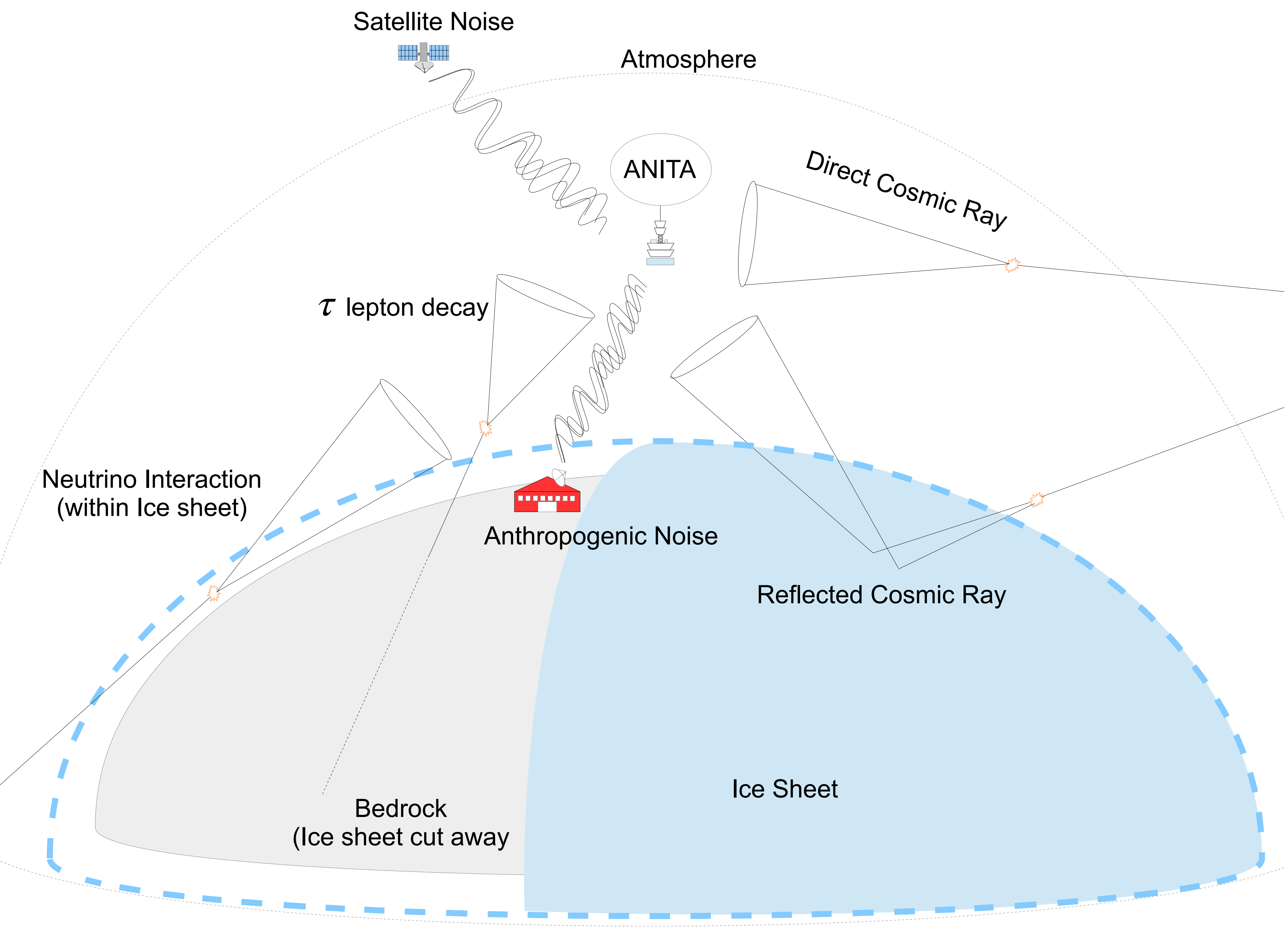
Creates cone where signal strength is highest, and observation most likely.

ANITA

ANtarctic Impulsive Transient Antenna



UHE Detection at earth



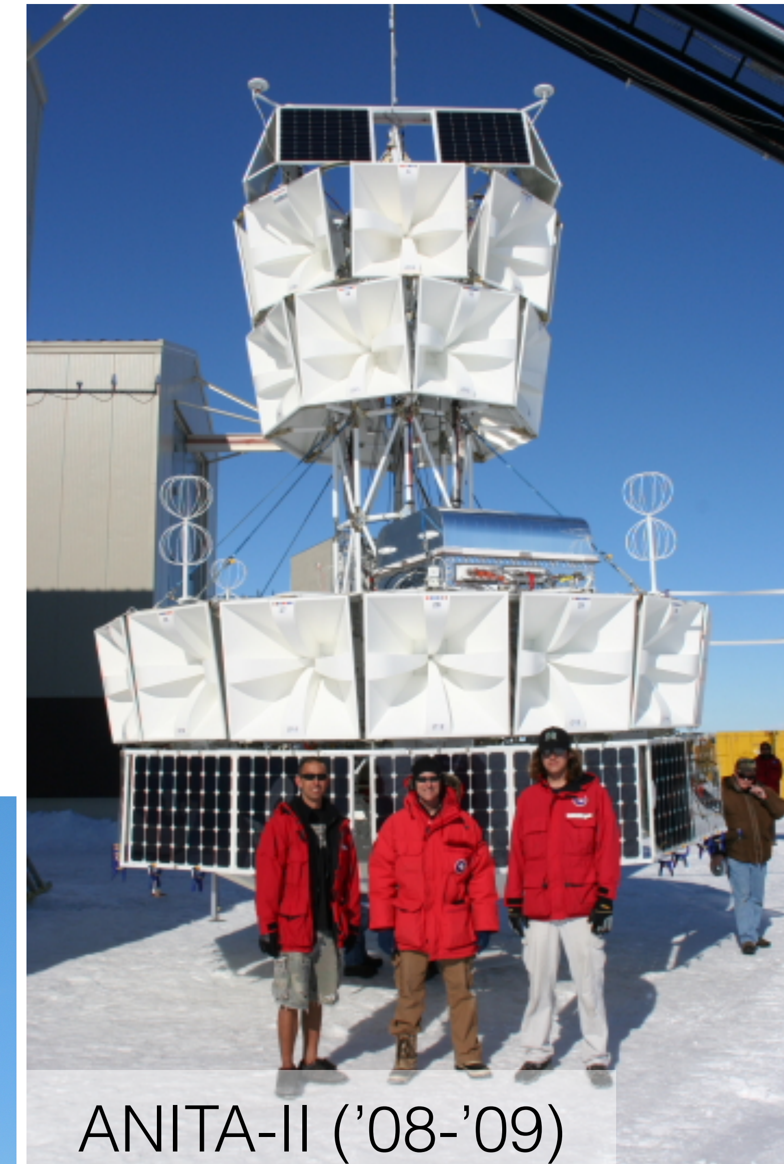
Many different UHE messenger particles that can be measured on Earth with detector positioned in atmosphere over Antarctica

Large field of view from a high altitude would aid in measurements of low flux astrophysical particles

ANITA Past and Present

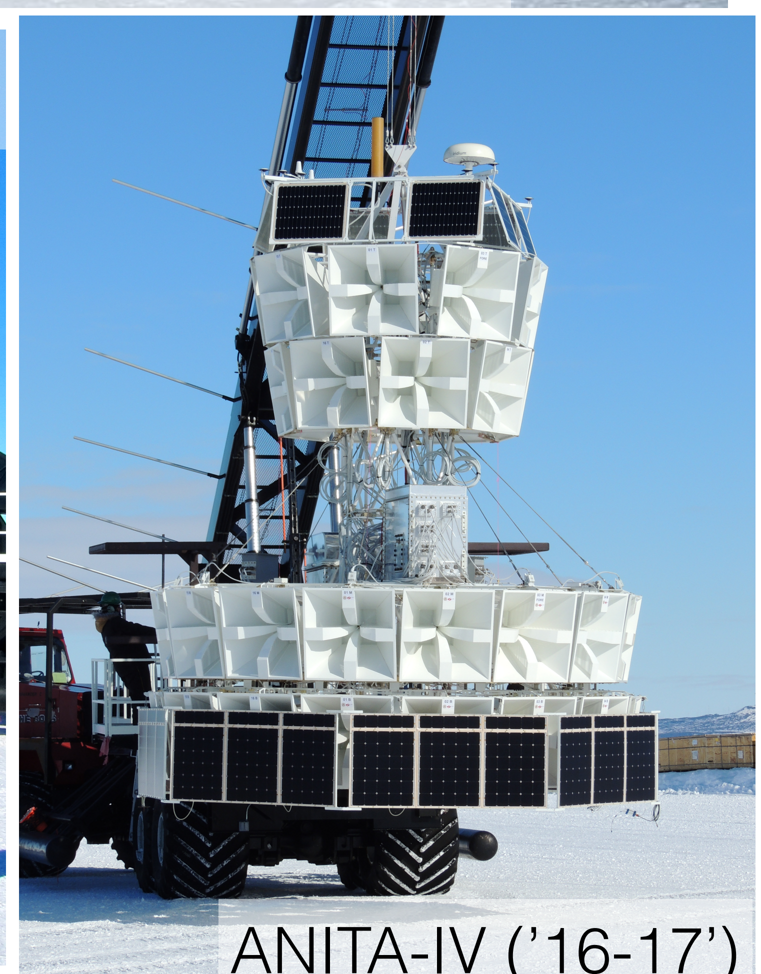
ANITA-LITE ('03-'04)

ANITA-I ('06-'07)



ANITA-II ('08-'09)

ANITA-III ('14-'15)

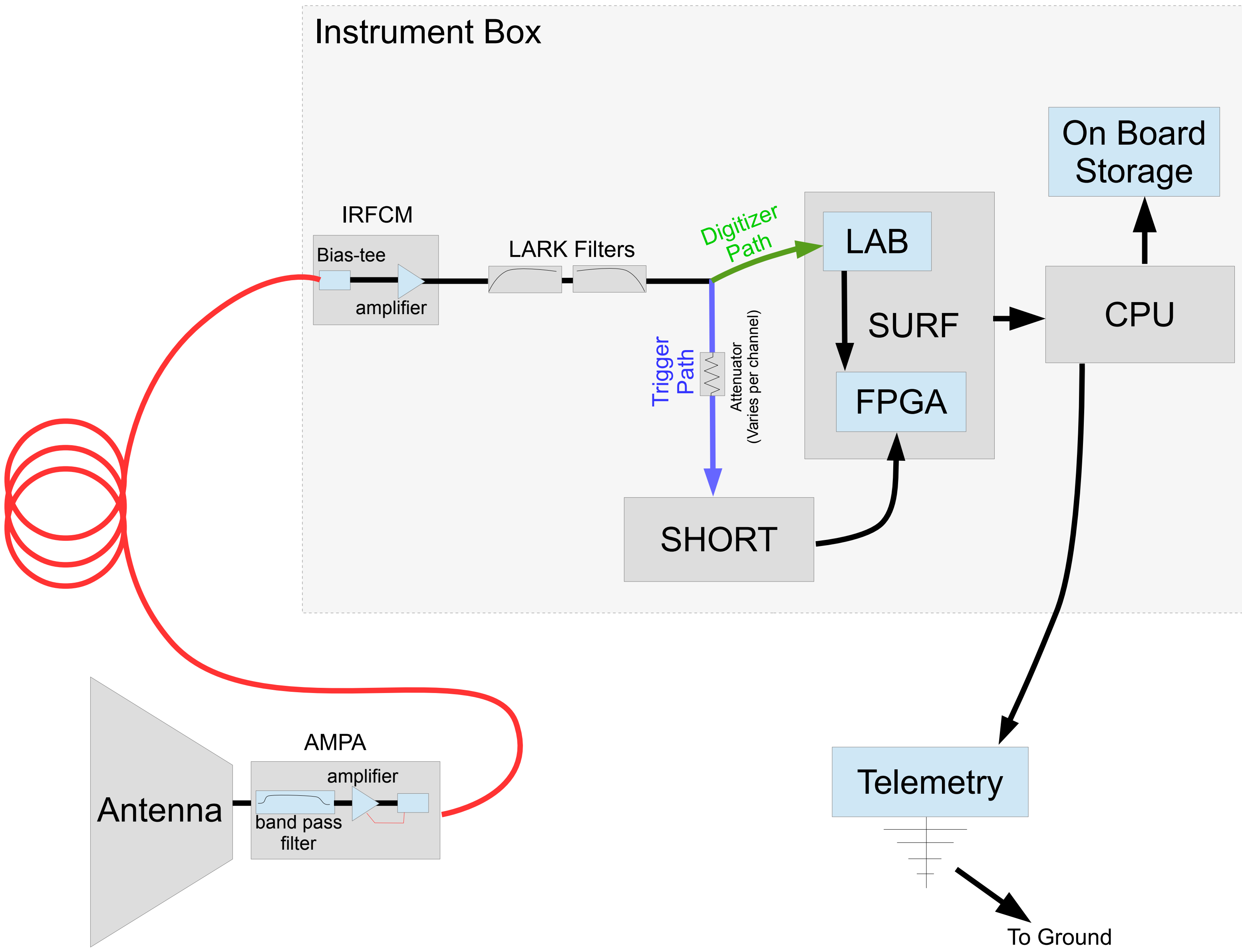


ANITA-IV ('16-17')

Five total flights over 13 years

ANITA-V (??)

ANITA-III Instrument



In essence: a 96 channel, high gain self-triggering oscilloscope

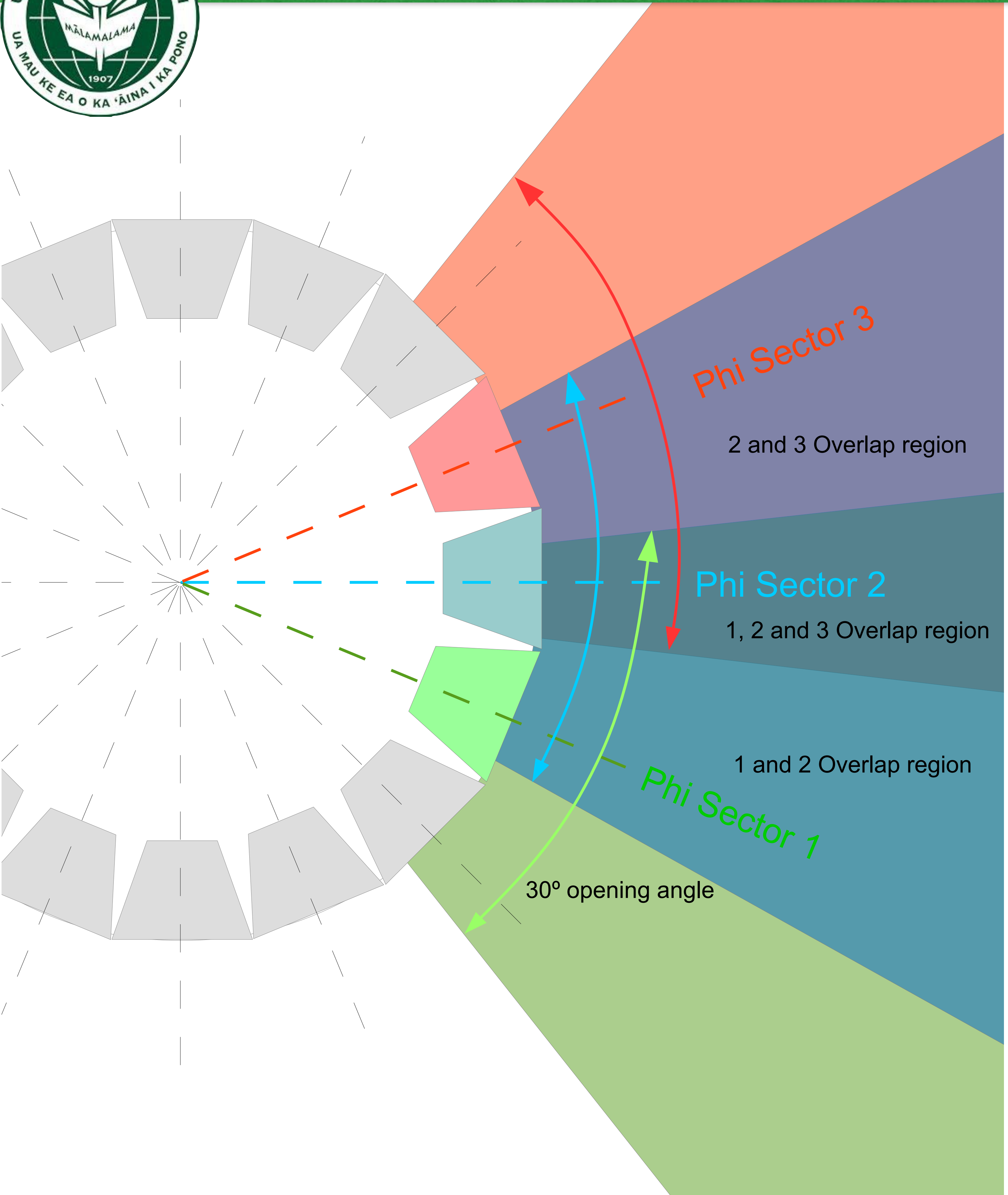
Incident E-field is coupled to antennas, filtered, and amplified in multiple stages

Digitization is performed by LABRADOR3 ASIC developed by the UH IDL

Data is stored on redundant storage devices for recovery

Control and command is done via a telemetry downlink

ANITA-III Instrument Layout

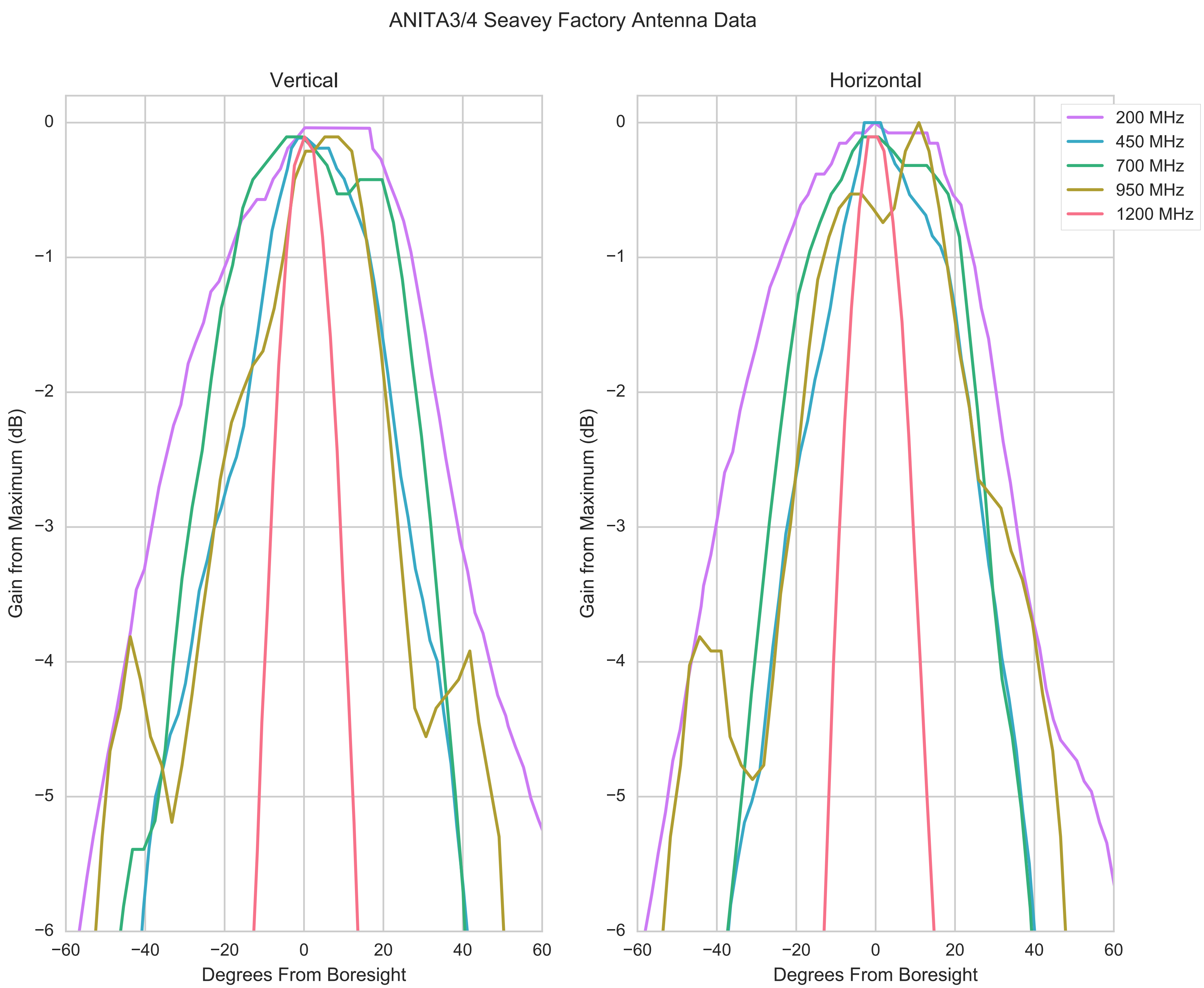


48 antennas grouped into 16 “phi sectors”

Each phi sector has three antennas, each in a different ring

360˚ azimuthal field of view with azimuthal symmetry

Antennas



Quad ridge horn antennas

Two orthogonal polarizations, providing 2 channels per polarization

Flat gain from 180MHz to 1.2GHz and minimal dispersion

10dBi of gain, with a ~30° opening angle in both E-plane and H-plane

First Stage Amplification: AMPA and DDAMPA

Antenna Mounted Pre-Amplifier (AMPA) and Drop-Down AMPA (DDAMPA)

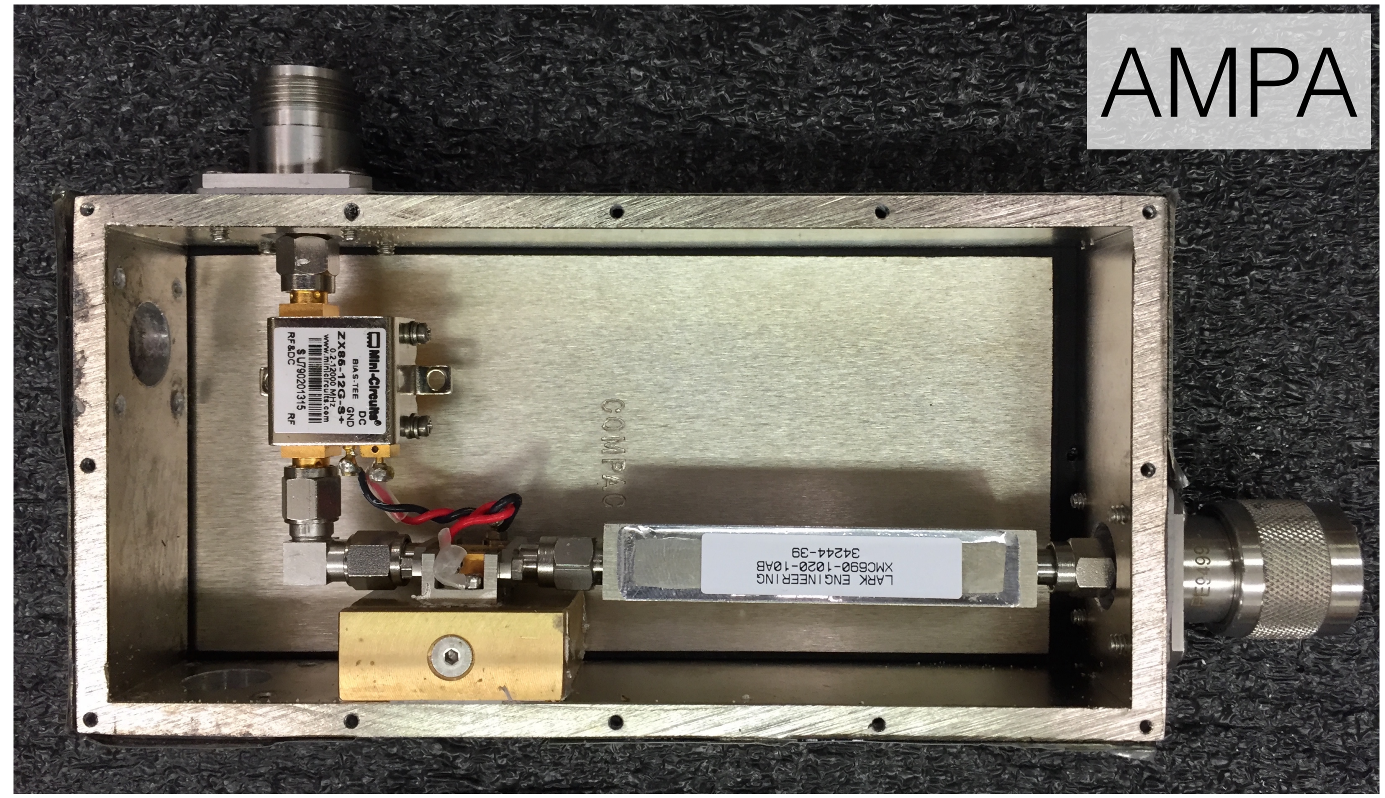
Pre-amplifies and filters signal, immediately after coupling to antenna

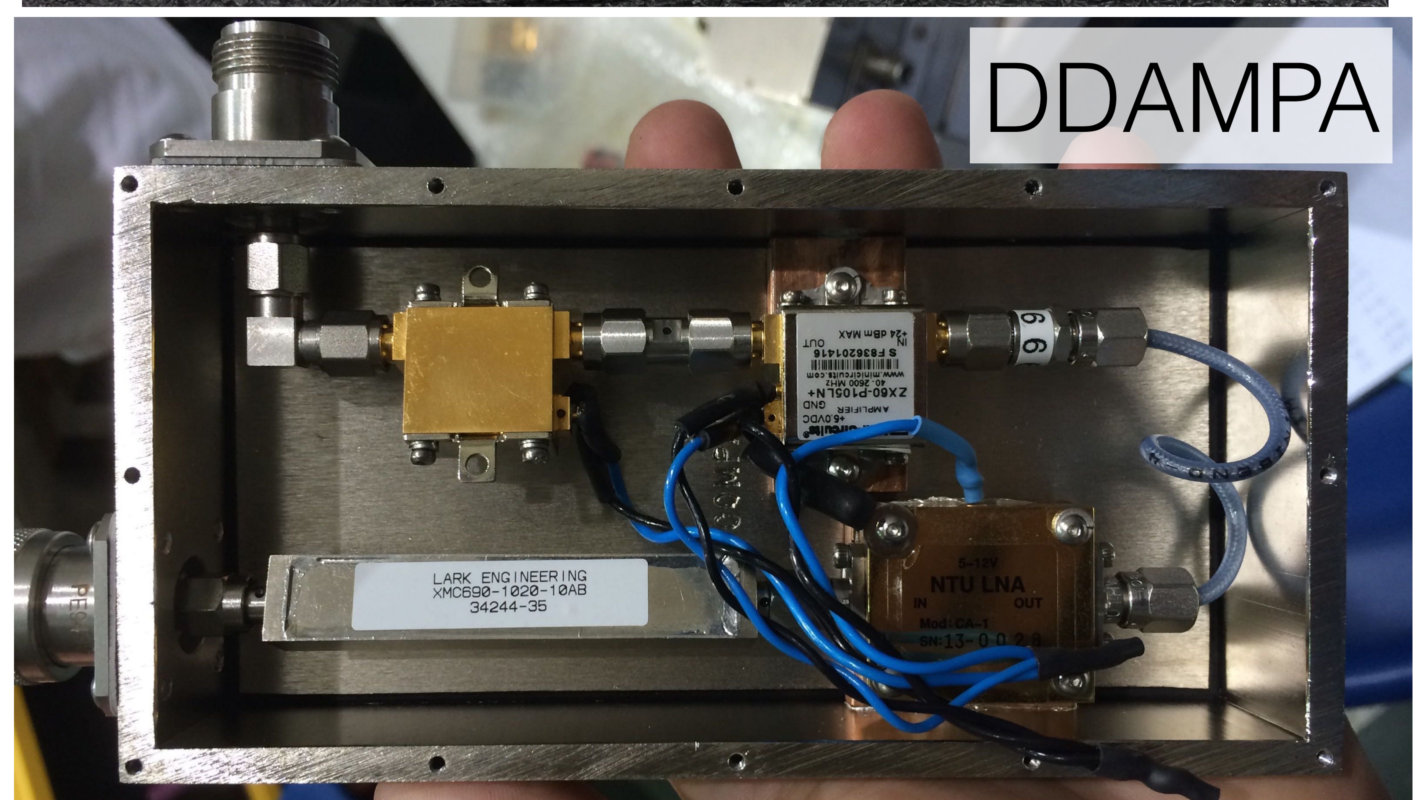
First stage band-limiting filter from 180MHz to 1.2GHz

Provide 40dB of flat spectrum gain

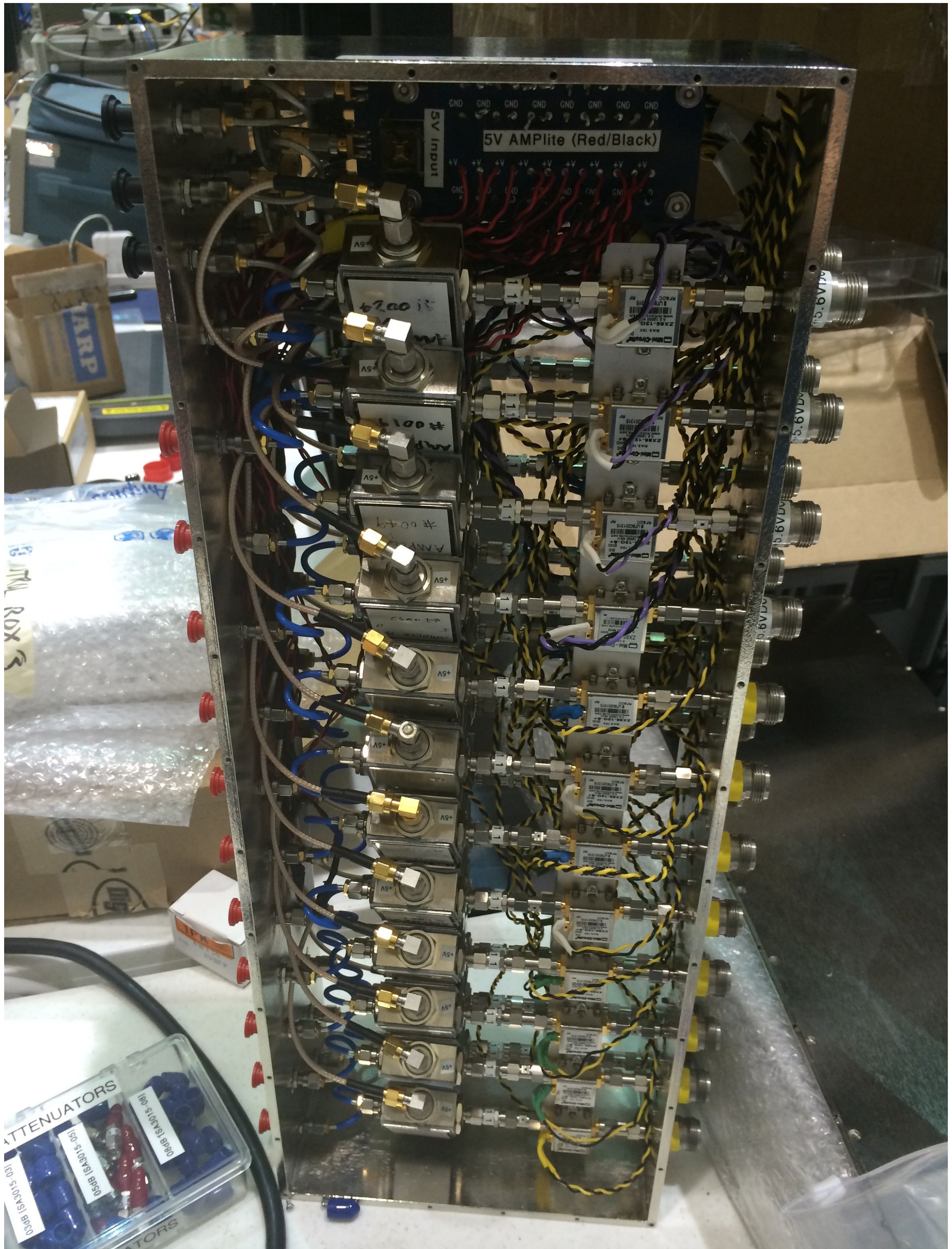
Noise temperature of ~100K

Powered via bias network on coaxial signal cable





IRFCM



Internal Radio Frequency Conditioning Module (IRFCM)

2nd Amplifier stage after pre-amplifier, providing an additional 38dB of gain

Internal to instrument box, and supplies bias network that powers pre-amplifiers

SURF board, TURF board, and CPCI crate

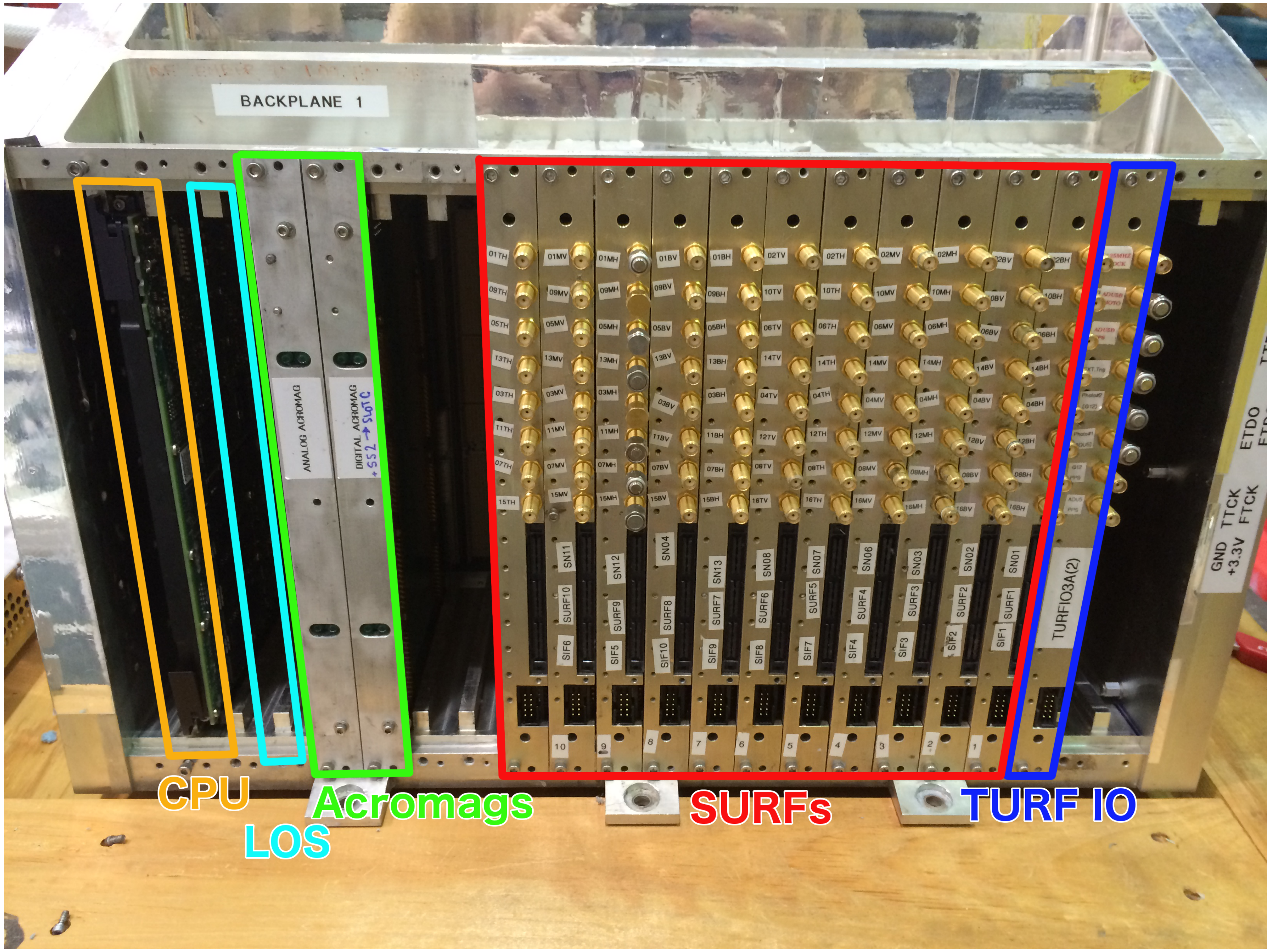
(Signaling Unit for Radio Frequency) (Triggering Unit for Radio Frequency) (Compact Peripheral Component Interconnect)

Houses flight CPU (Central Processing Unit), which reads out digitized signals from SURF boards and stores them to hard disks

FPGA (Field Programmable Gate Array) on backplane generates trigger and controls readout

Additional subsystems for instrument

ANITA's "brain"



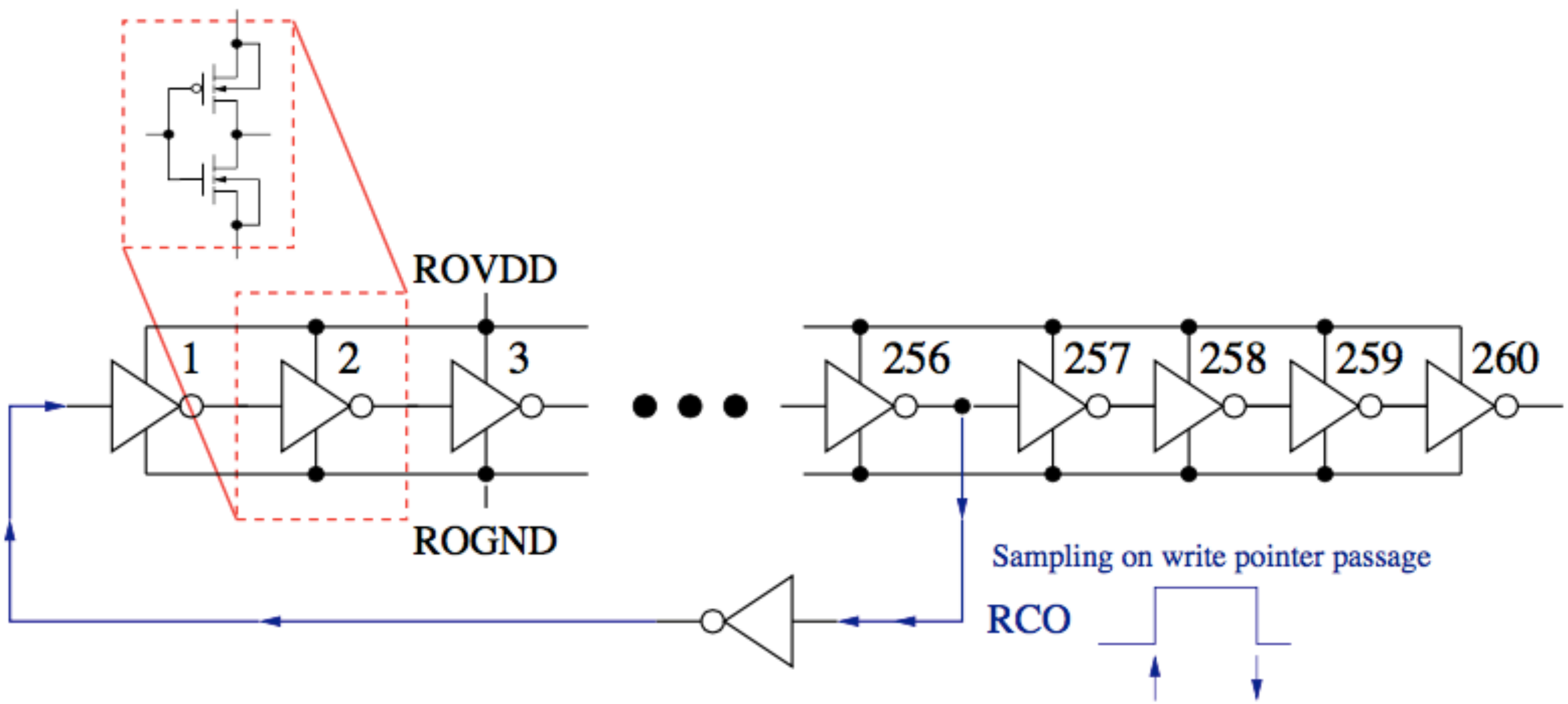
Digitizer: LABRADOR3

Large Analog Bandwidth Recorder And Digitizer with Ordered Readout version 3 (LABRADOR3)

Ring buffer allows constant sampling until digitization

Measures voltage per time. 12-bit (10 effective) readout with 2.6GS/s sampling rate.

One per channel, 96 total. 800MHz analog bandwidth, ~100ns record length



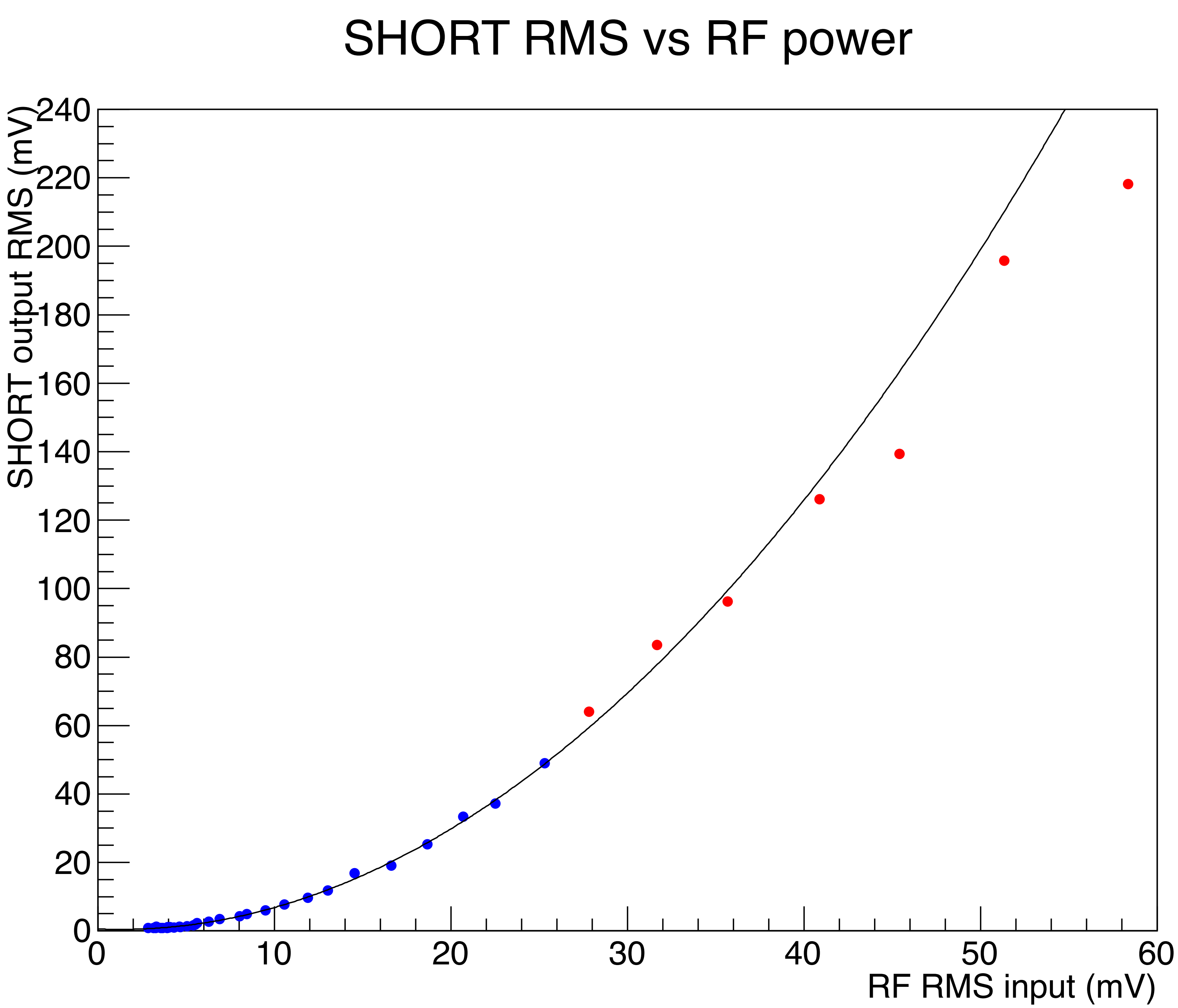
Analog Triggering: SHORT board

SURF High Occupancy RF Trigger (SHORT)

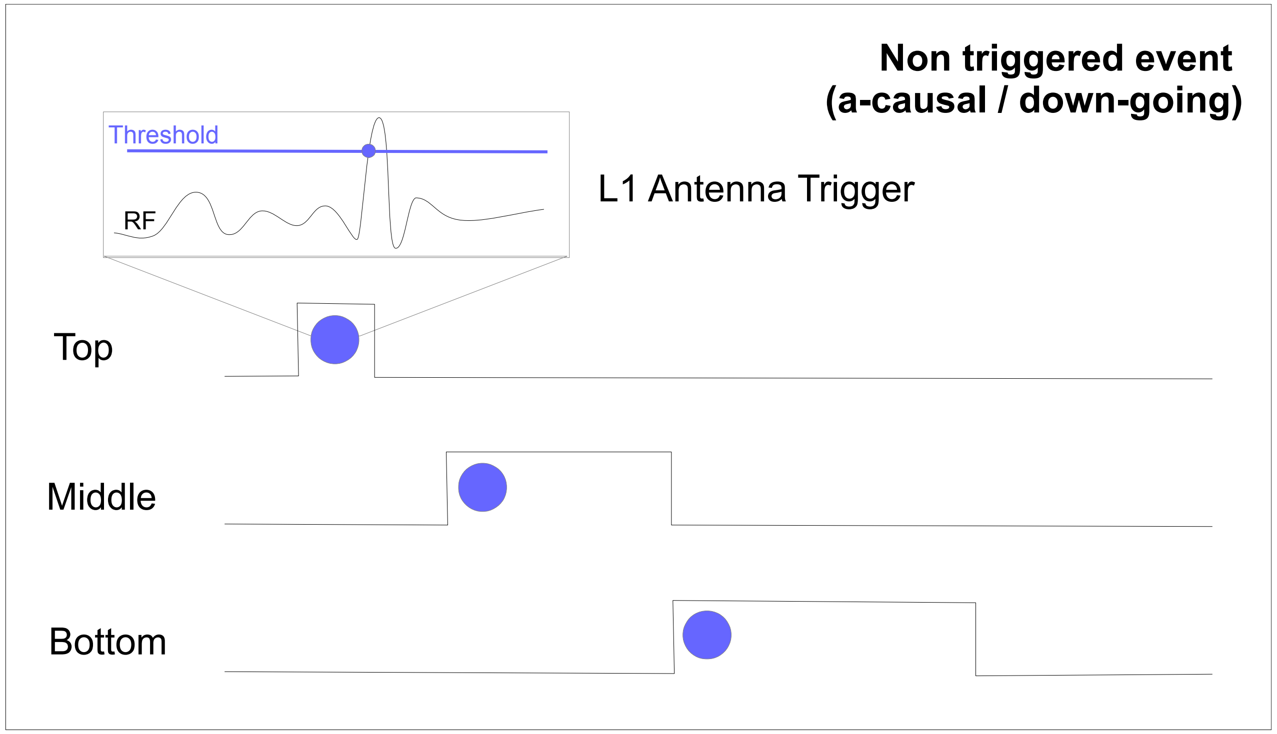
8 channels per SURF, 12 SURFS

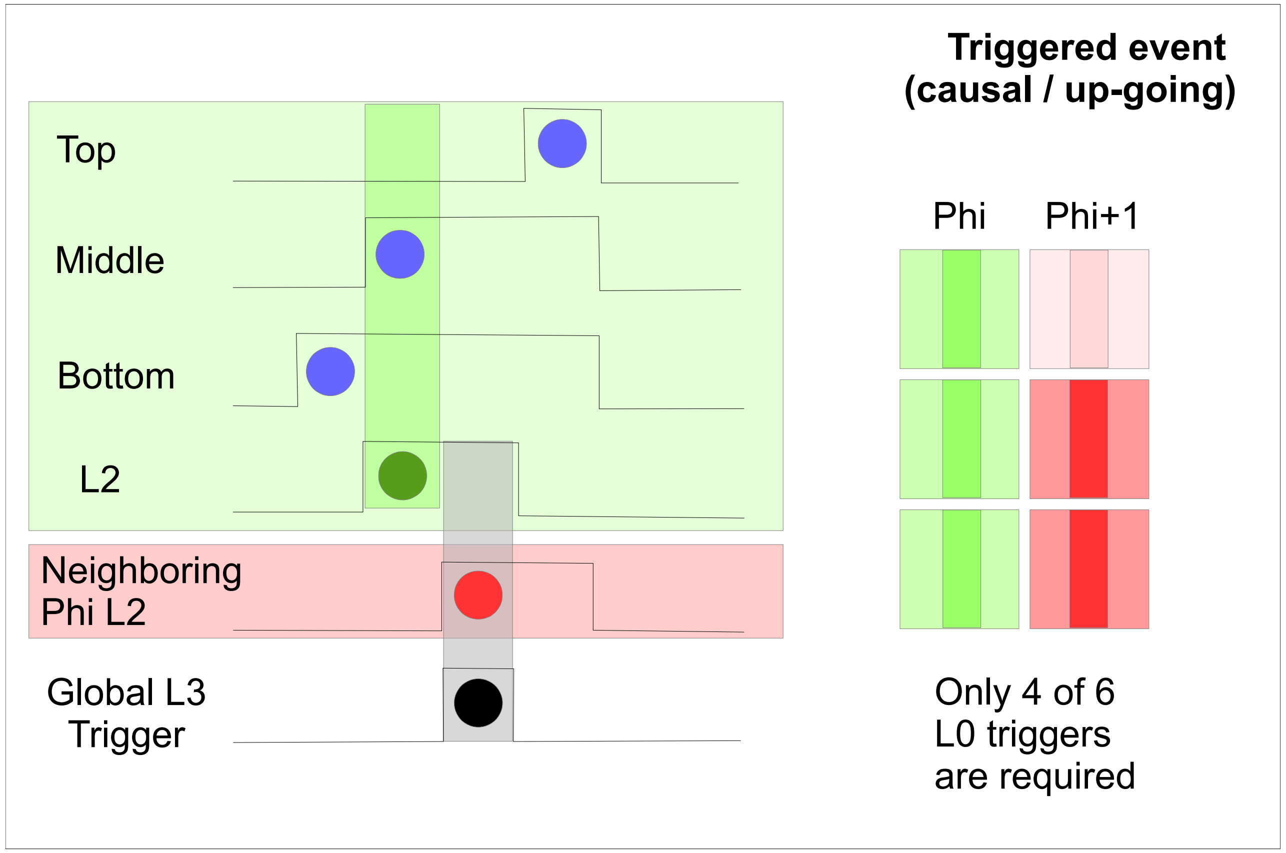
Ezaki (tunnel) diode: rectifies and integrates incident RF power.

On-board amplifier increases signal strength, then signal is fed into Field Programmable Gate Array comparator which propagates digital signal to trigger logic



Trigger Hierarchy





Logic signal from SHORT input generates L1 trigger.

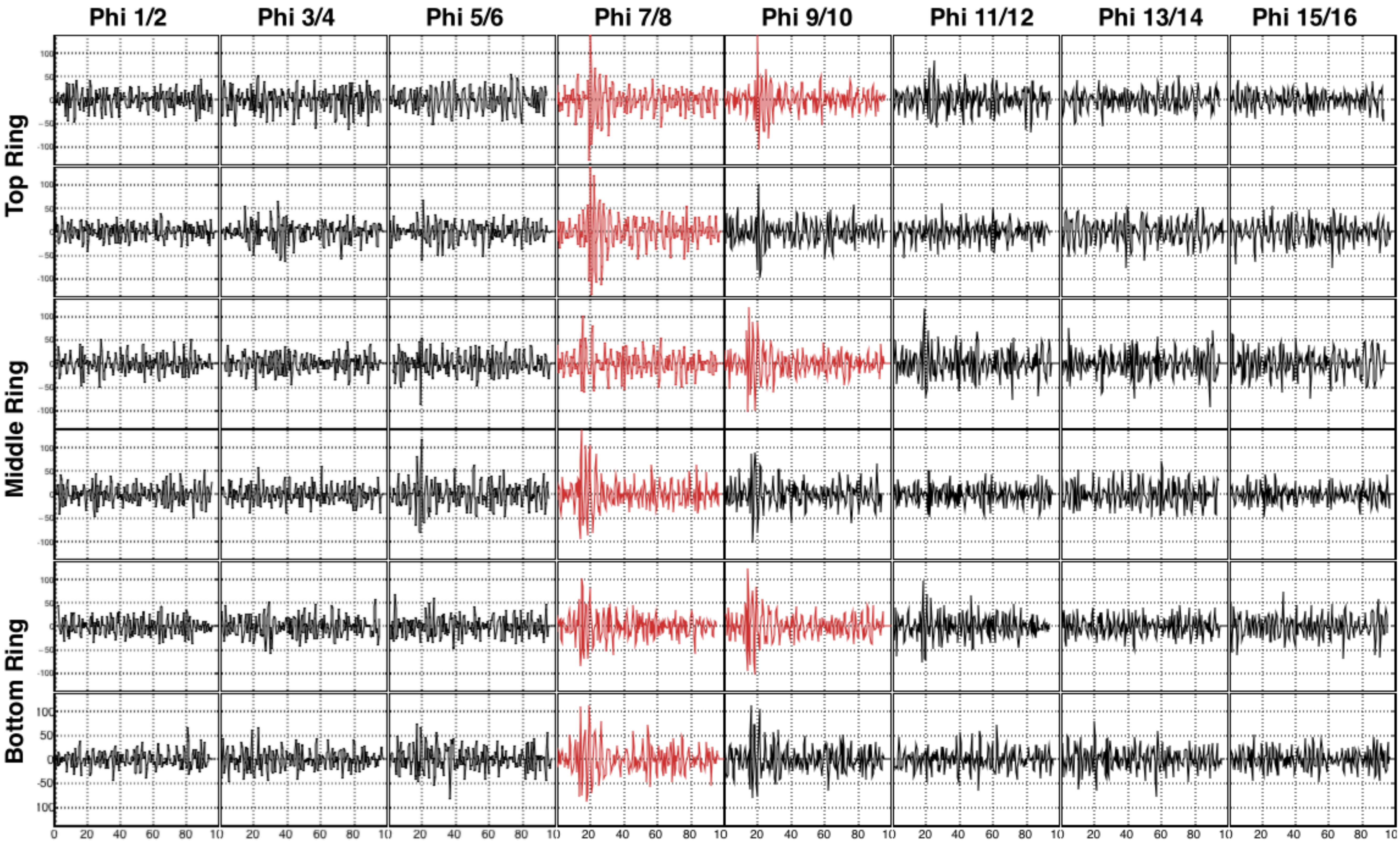
Trigger requires upward propagating plane wave signatures with course pattern matching

L1 triggers are required to be causal between antennas within single phi sector

L2 trigger fires if 2/3 L1s are within causal window

L3 (global) trigger fires if two neighboring phi sectors report an L2 trigger. Global trigger which initiates digitization.

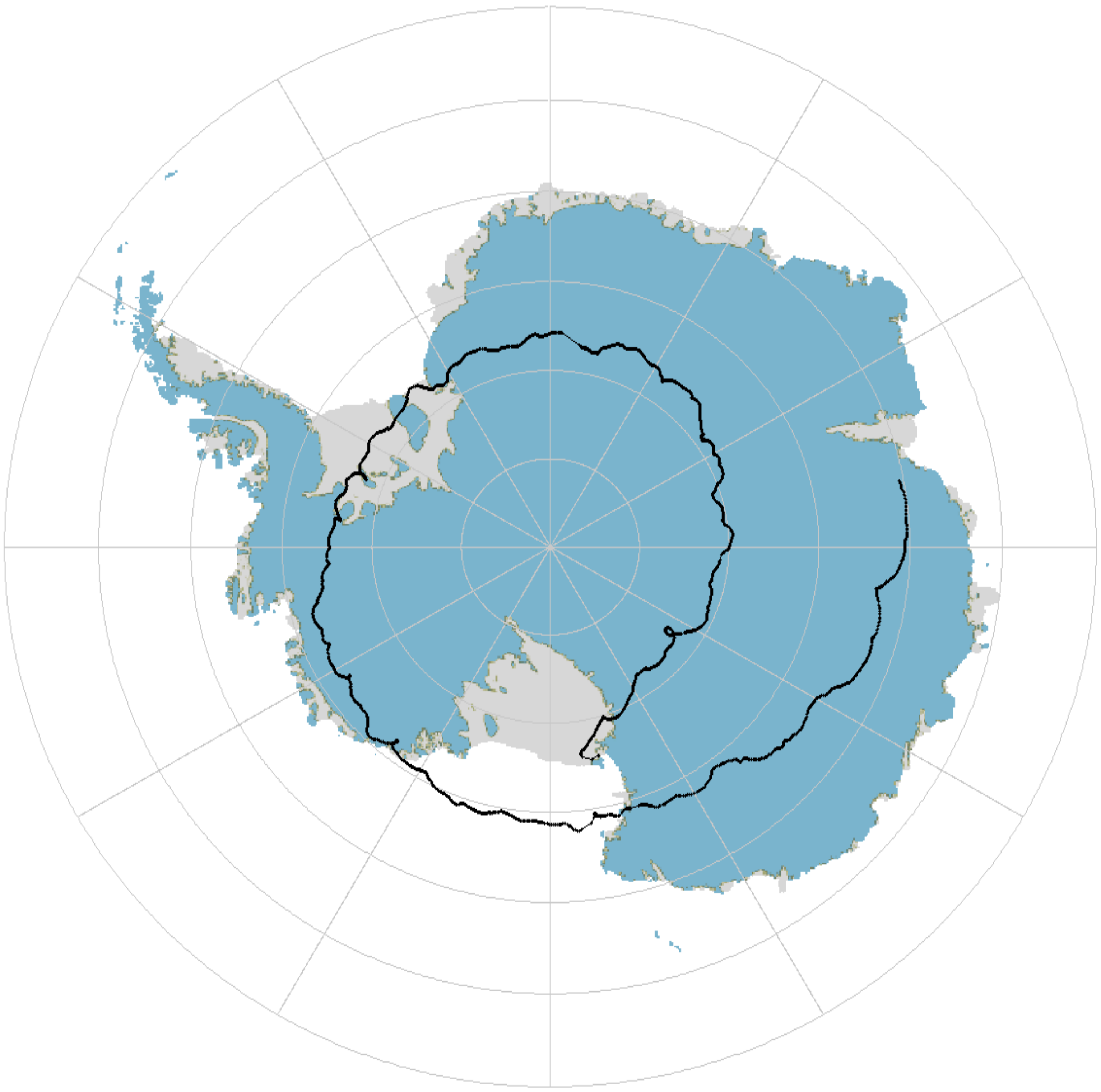
Example recorded signal event



WAIS pulser signal

Red denotes triggered phi sector

ANITA-III flight



Launched on December 17th 2014

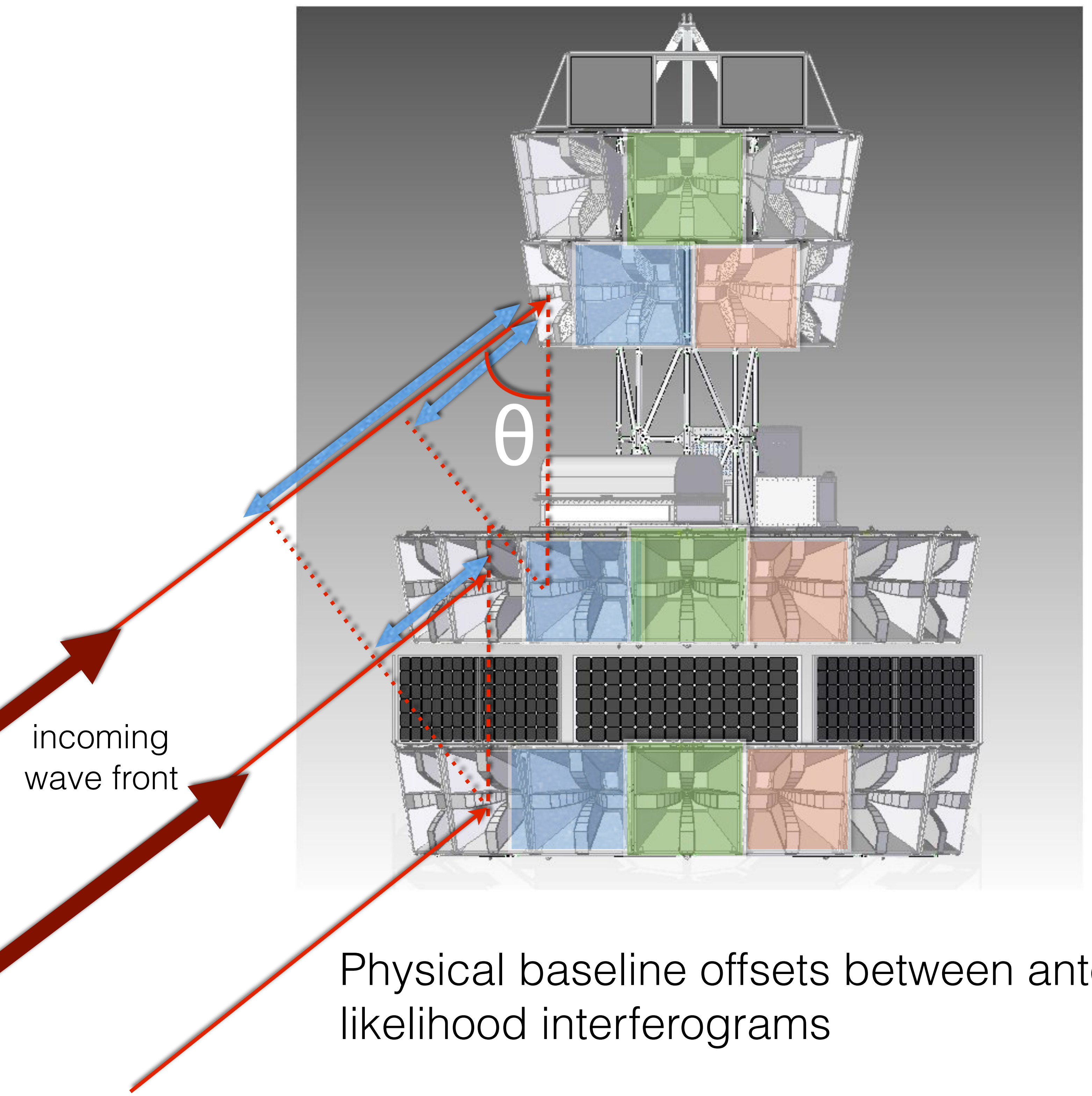
Flew for 22 days before landing near Davis station

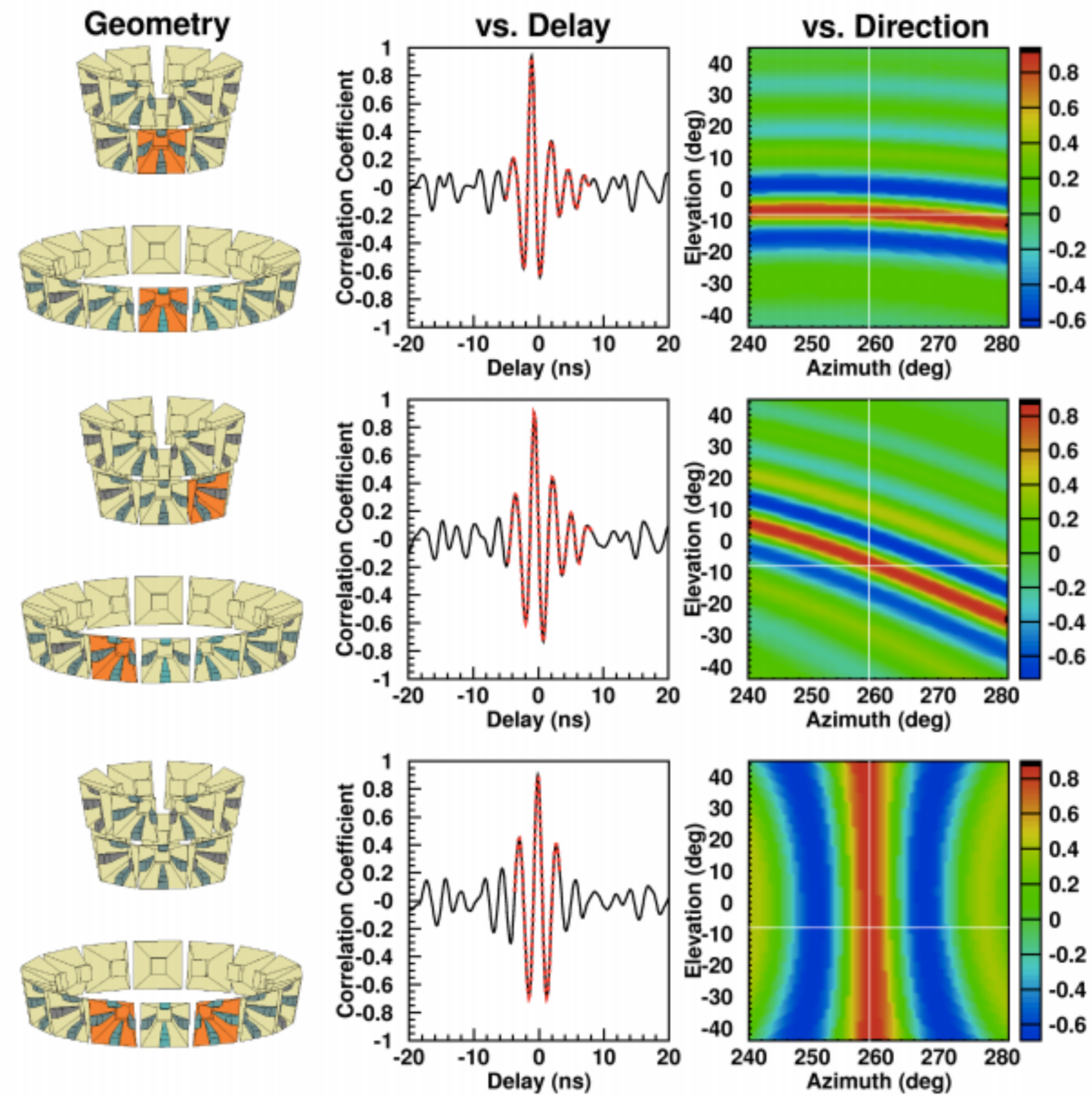
Captured ~84,000,000 events

ANITA-III Launch

ANITA-III Landing

Radio Interferometry



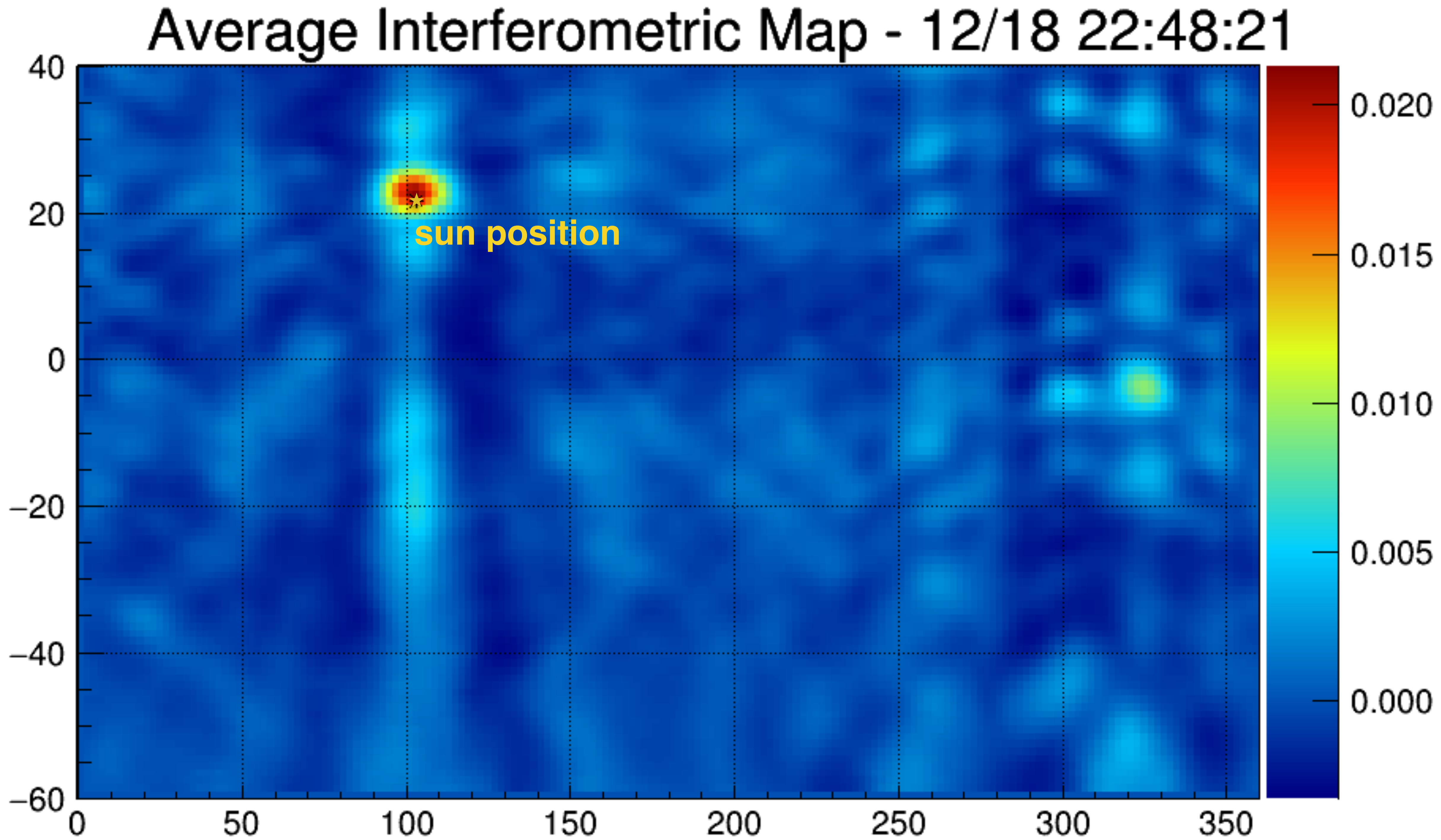


Physical baseline offsets between antenna pairs create incident angle likelihood interferograms

ANITA has better elevation angle uncertainty due to the longer baselines

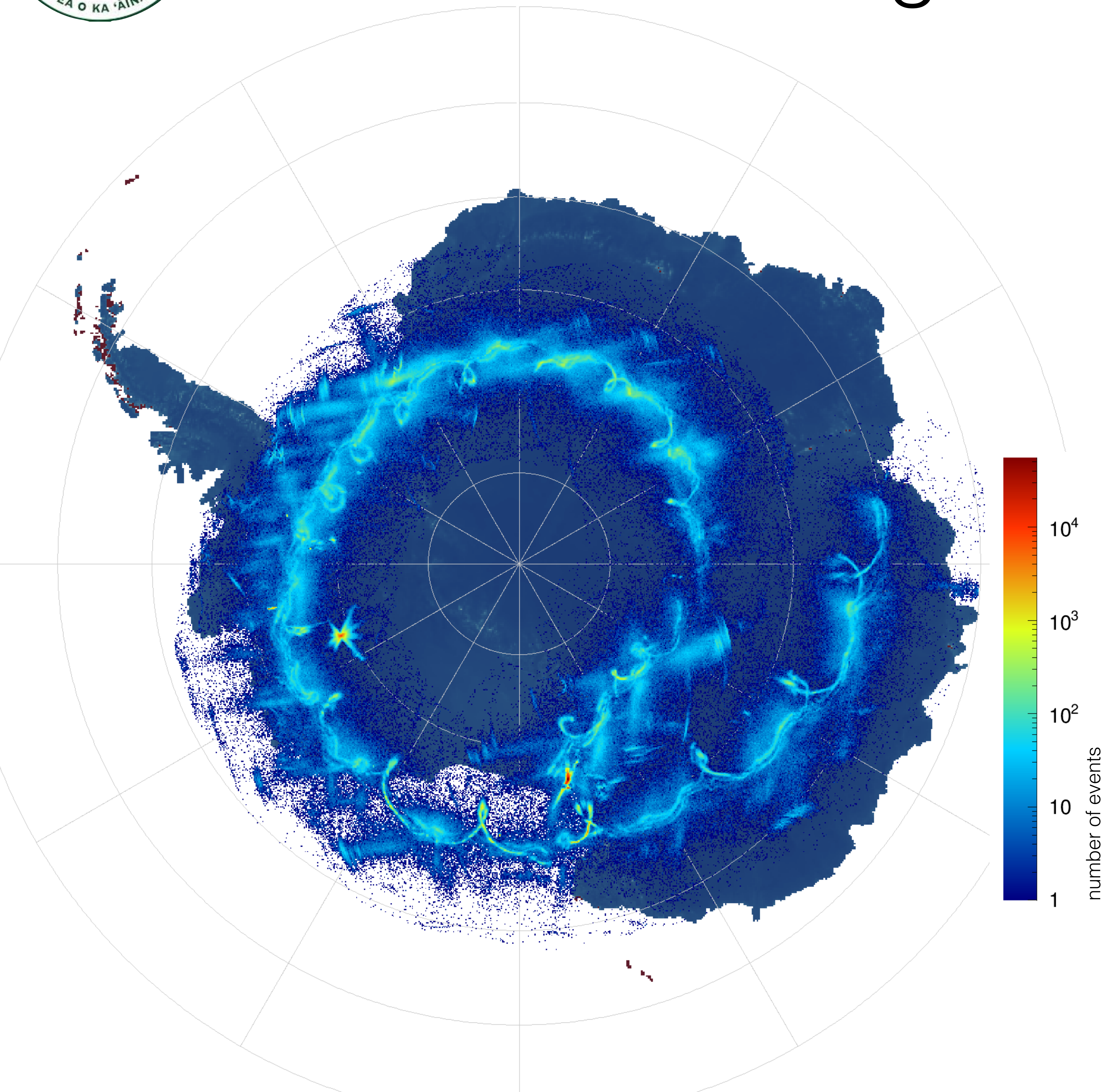
Radio Interferometry

Overlaying multiple baseline pairs can be used to create an "image" of the incident signal



Stack enough maps and you can see the sun

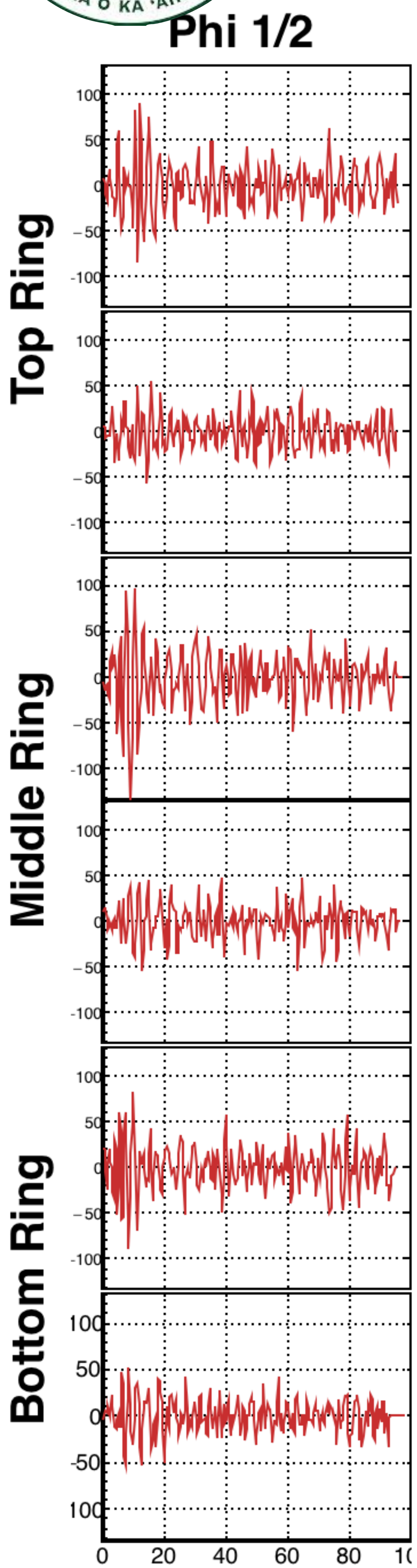
Pointing event to continent

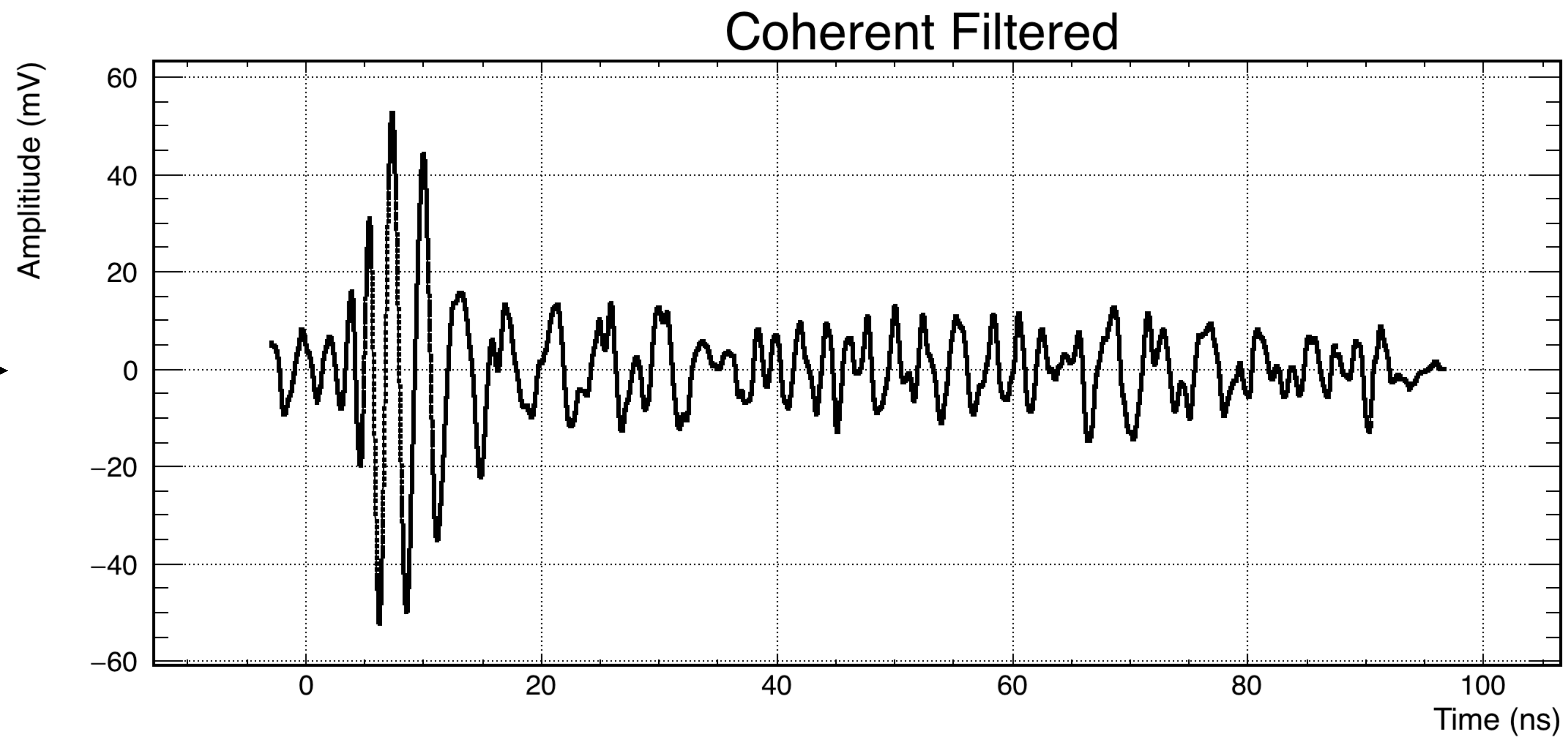


Once incident signal direction is determined, geolocate it to the continent.

This gives you an idea of where sources are on the continent

Coherently summing waveforms



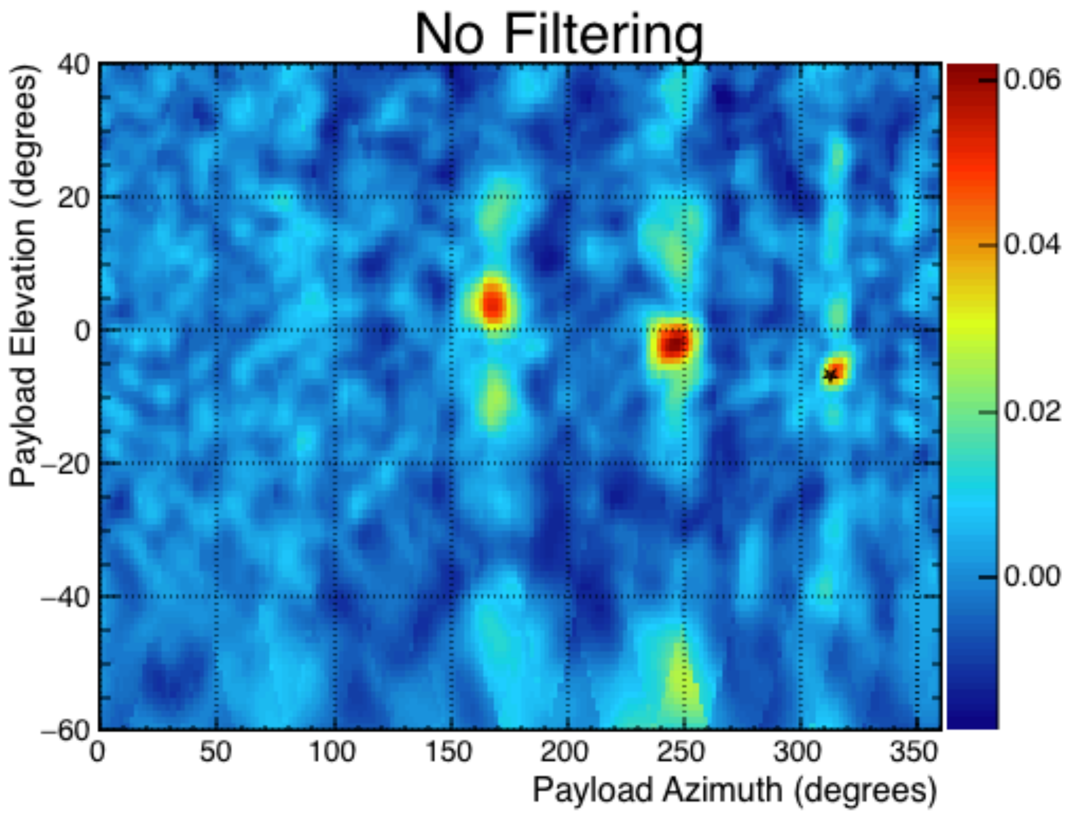


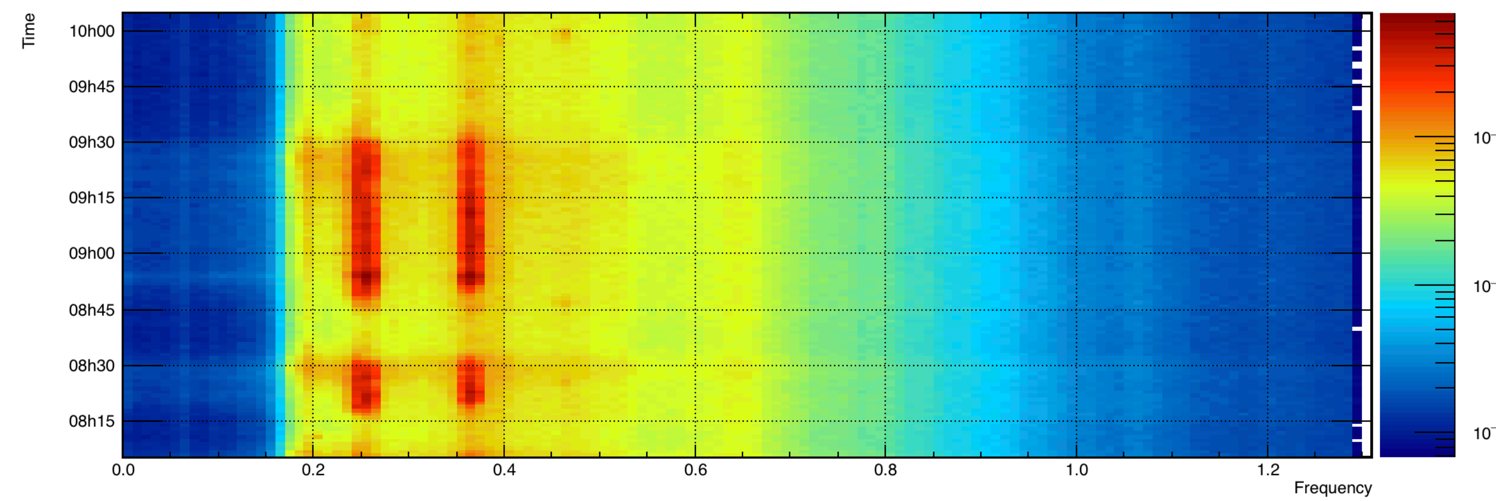
Also known as beam forming

Adding waveforms with timing offsets determined by using the peak of the interferometric map allows signals with low SNR to be found.

15 antennas, 5 phi sectors, are combined in this manner to form each final waveform

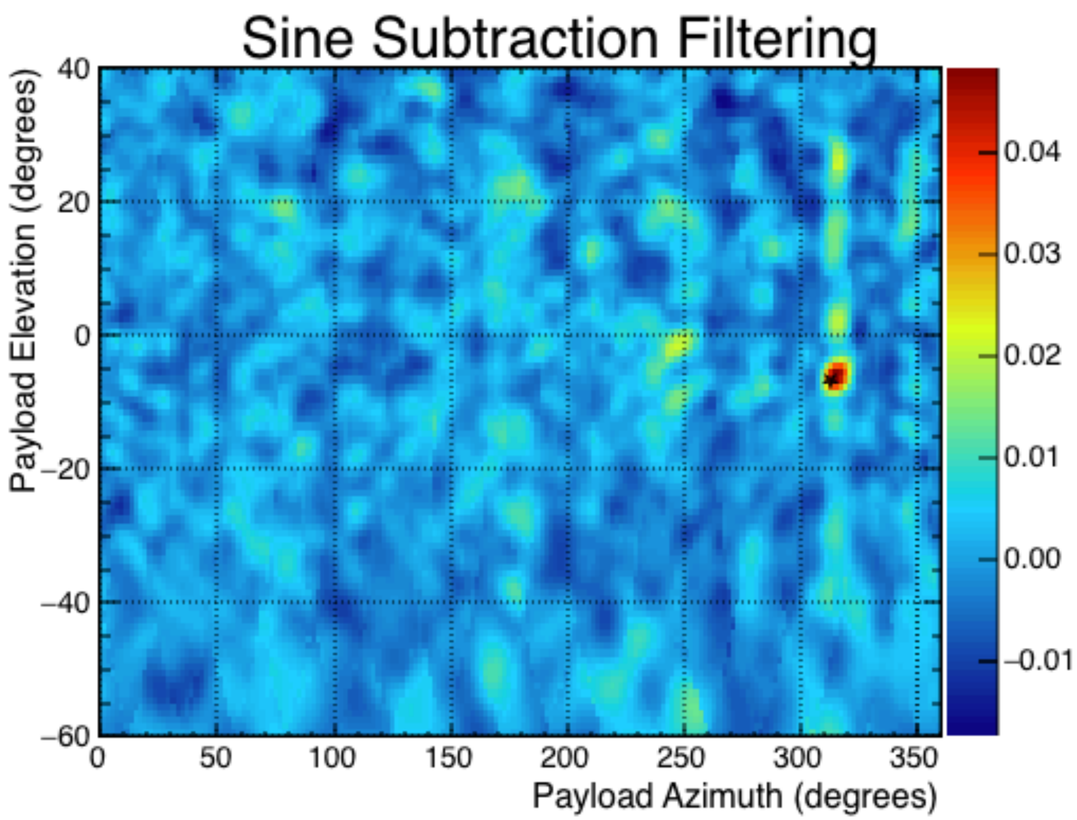
Sine subtract filtering





ANITA-III was plagued by carrier wave (CW) satellite noise at 220MHz and 380MHz

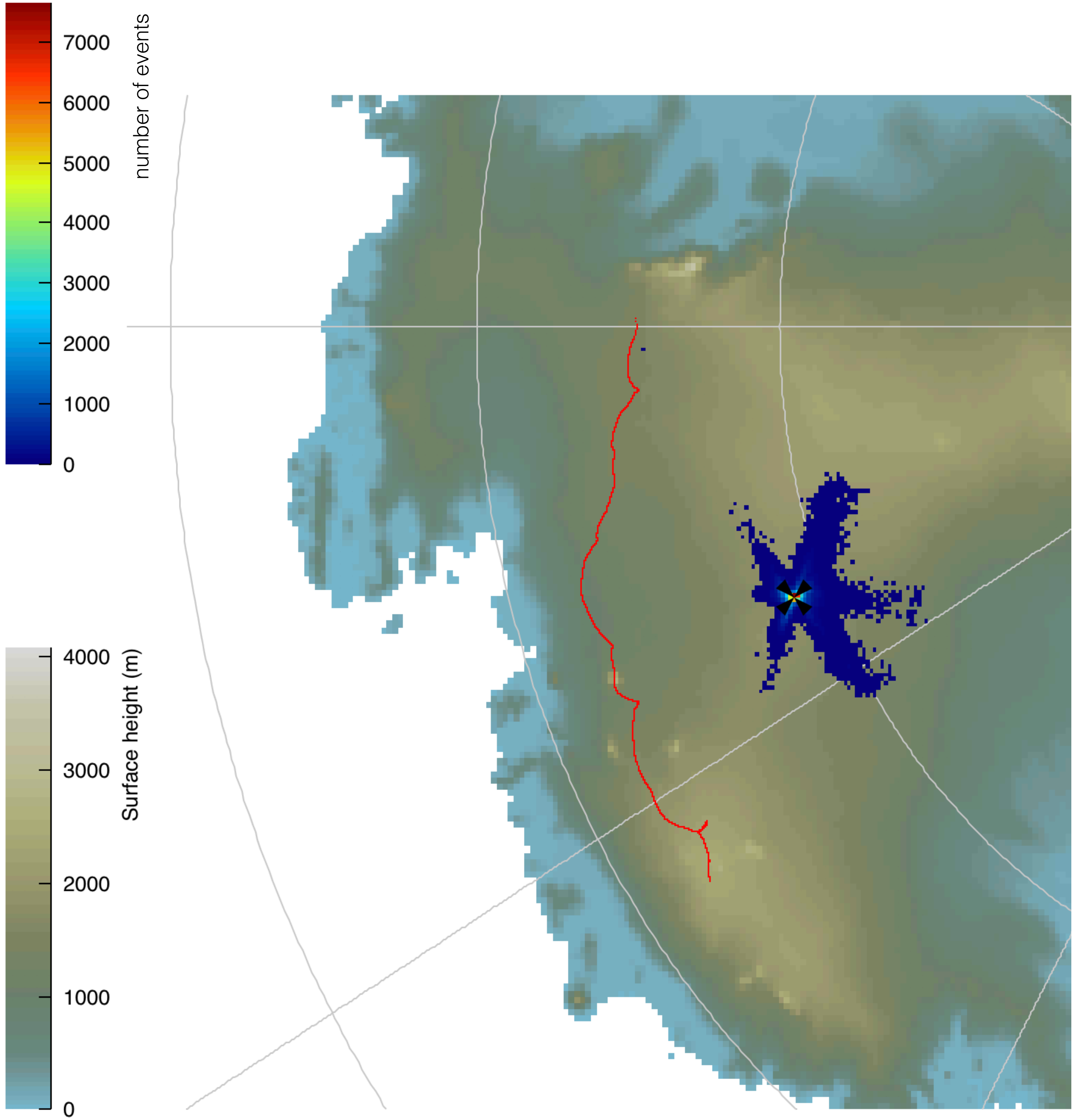
These sources reconstruct, and often are the brightest point in interferometric maps



In place of dispersive digital finite impulse response (FIR) filtering, a novel method of iteratively subtracting sine waves fit to waveforms was developed

Sine wave subtract filtering succeeds at eliminating CW interference while minimally distorting impulsive signals

WAIS calibration pulser



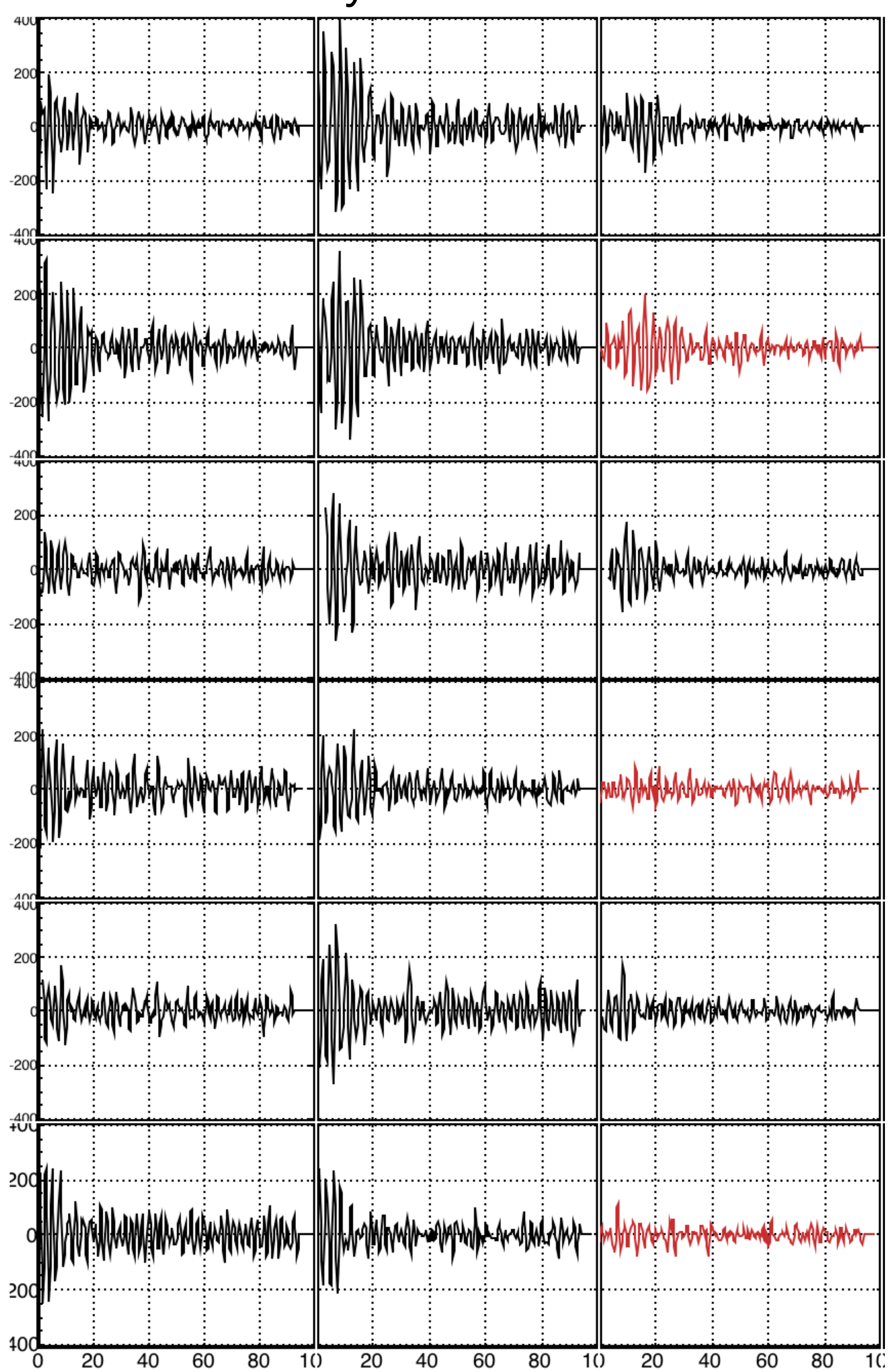
West Antarctic Ice Sheet (WAIS) Divide automated impulsive signal generator.

Synced to pulse on the GPS second for easy identification

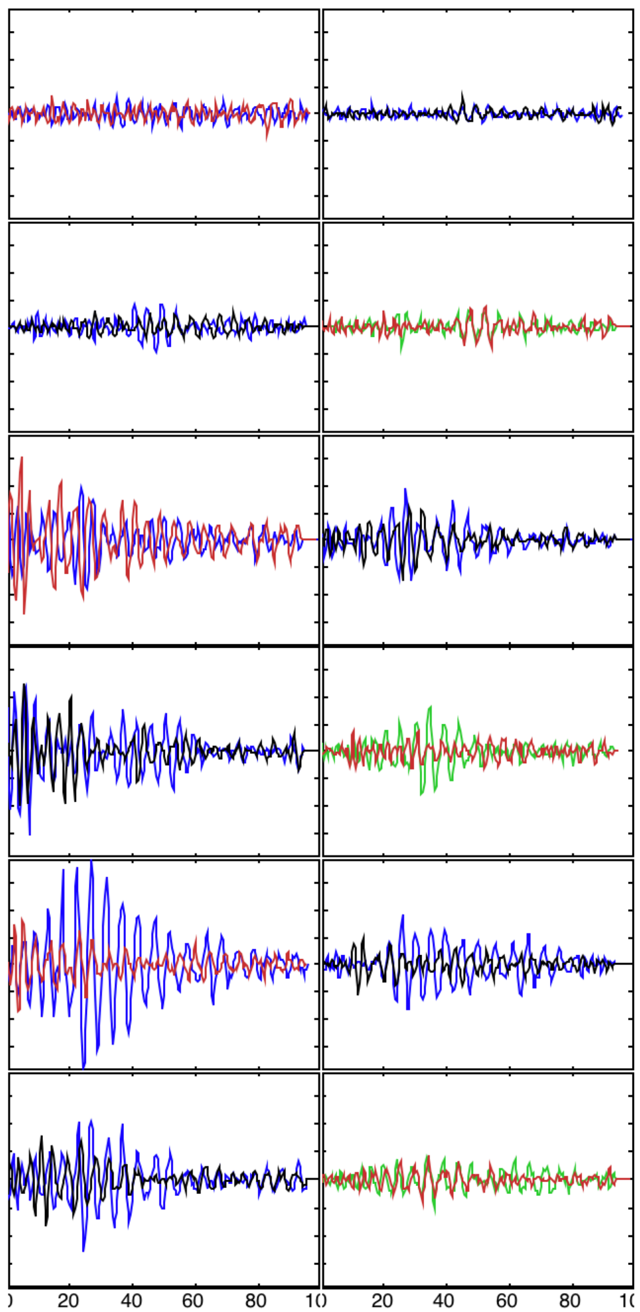
These events serve as our primary calibration source for the instrument

Bad quality events

Early Waveform



Payload Blast

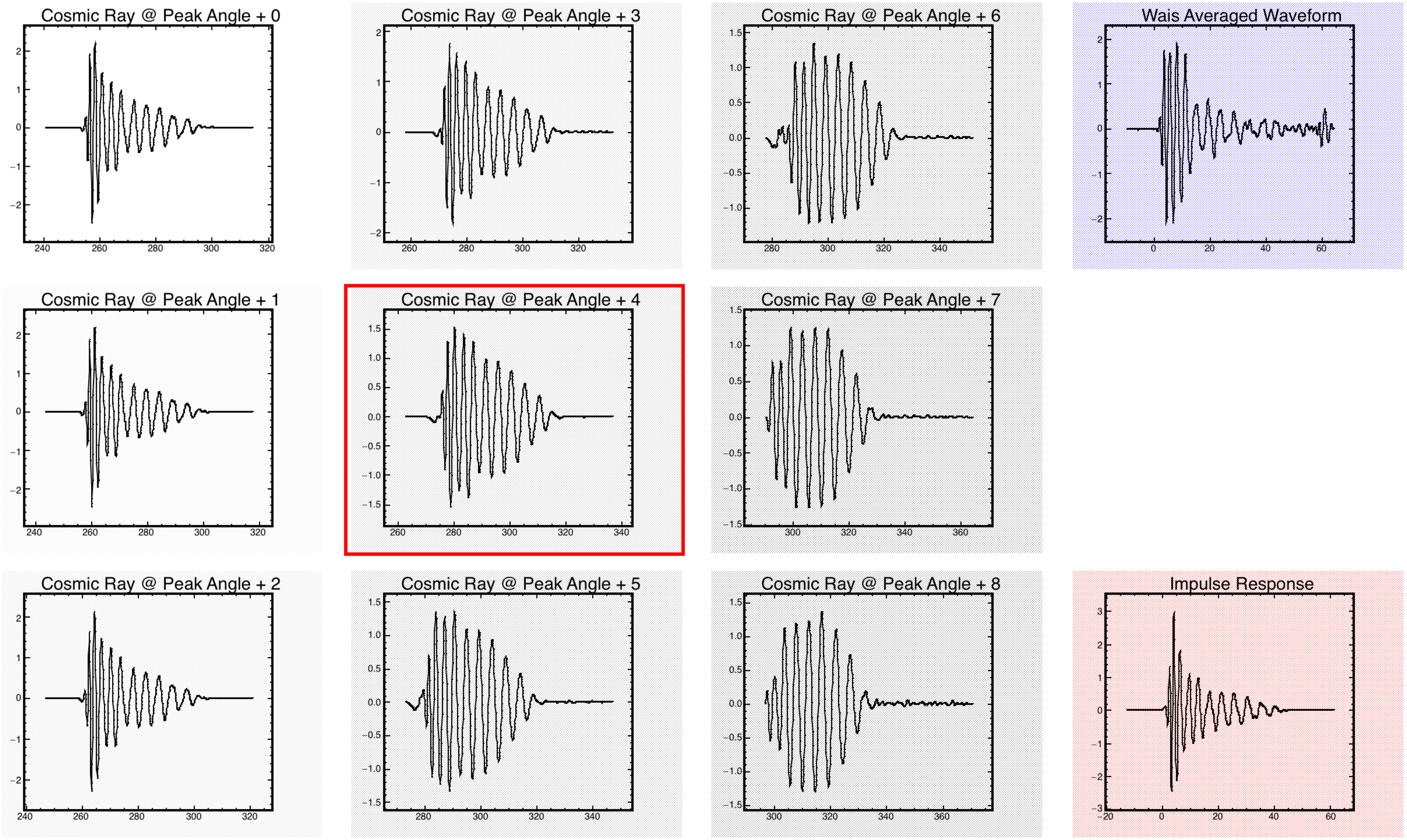


Several signal types were discovered while working through the data cuts that need to be removed.

Early Waveform events come from masked phi-sectors and “wrap” around the payload. Increased trigger latency from physical baseline causes them to be overwritten in the record

Payload Blasts are suspected on-payload transients near the bottom of the payload

Cosmic Ray Template Search



Cosmic ray impulsive signals have been measured extensively and can be reliably simulated

For a CR search, a requirement that signals have high normalized correlations with simulated impulses convolved with the instrument impulse response will eliminate most thermal and anthropogenic events, while being highly efficient on real CR signals

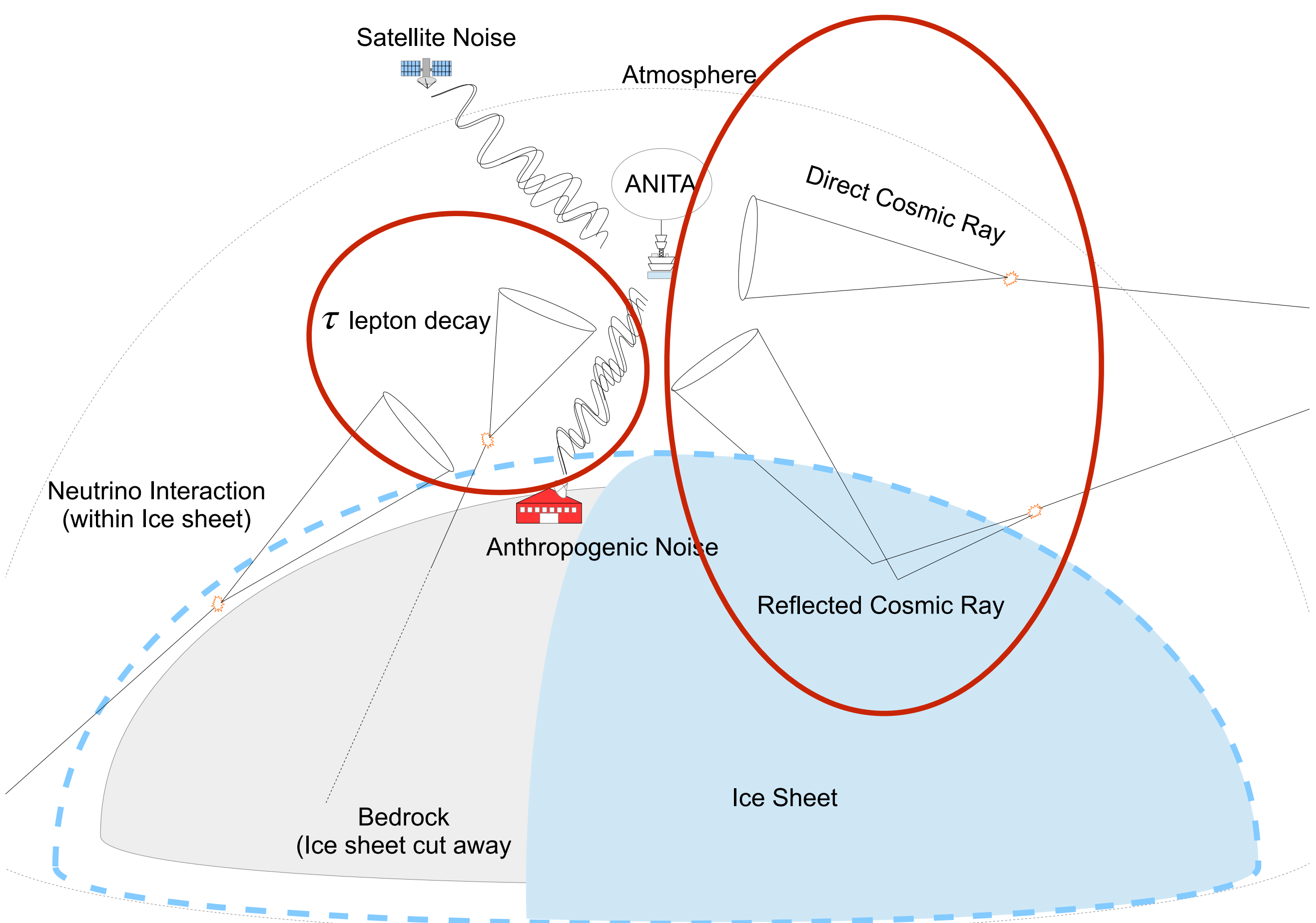
Blind search for taus

Don't want to bias analysis in search for taus

Only absolute peak template, regardless of max or min, is saved

Additional polarity blinding: Signals are inverted randomly by opaque software routine

Do not look in ve or vu channel, which has a dominant vertical polarization

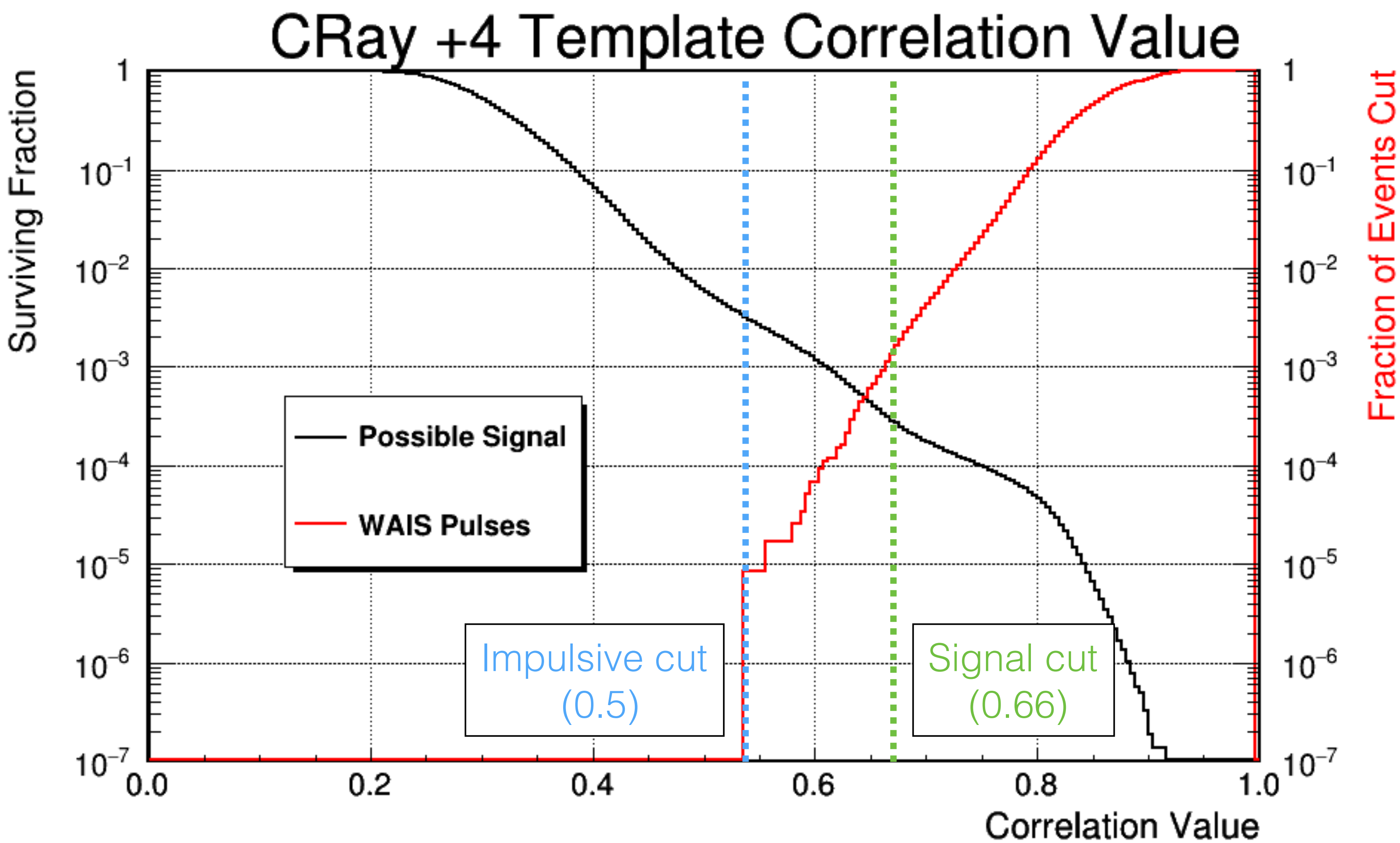


Cut Values

Template correlation value is *extremely* efficient on signal, while anthropogenic and thermal backgrounds are significantly reduced

Cut is so good, a second, lower cut must be established to allow through weak anthropogenic signals for clustering

Additional cuts on signal impulsivity are made to allow through >99.9% of WAIS pulser events



Additional cut parameters

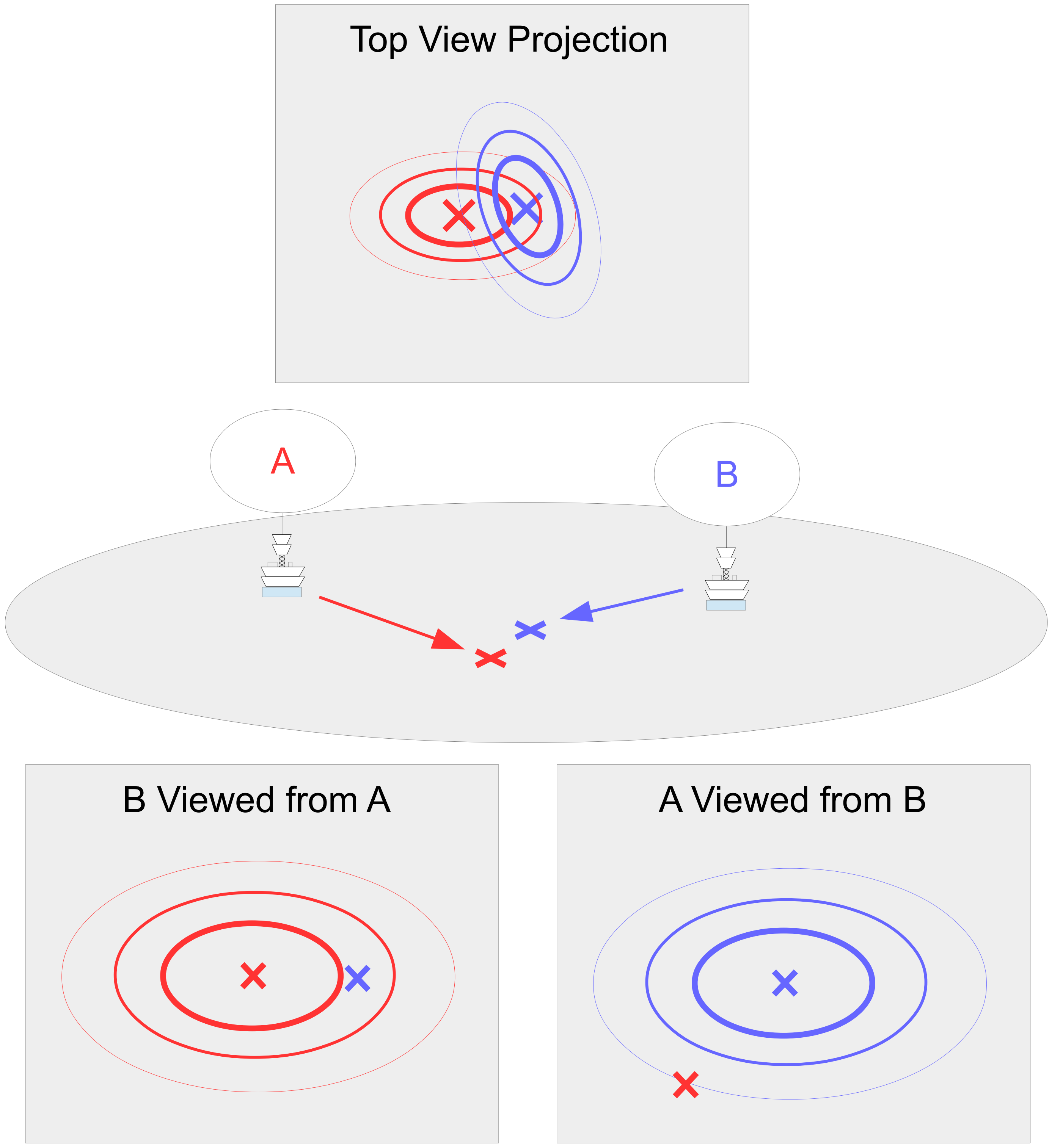
Start with 41,566,966 H-Pol triggered events

Quality Cuts: 2,670,191 remain (6.42×10^{-2})

Impulsivity Cuts: 5997 remain (1.44×10^{-4})

Signal Cuts: 882 events(2.12×10^{-5})

Event Clustering



Candidate physics events will isolated in time and location

Clustered signals are characteristic of anthropogenic background

Log Likelihood event clustering metric

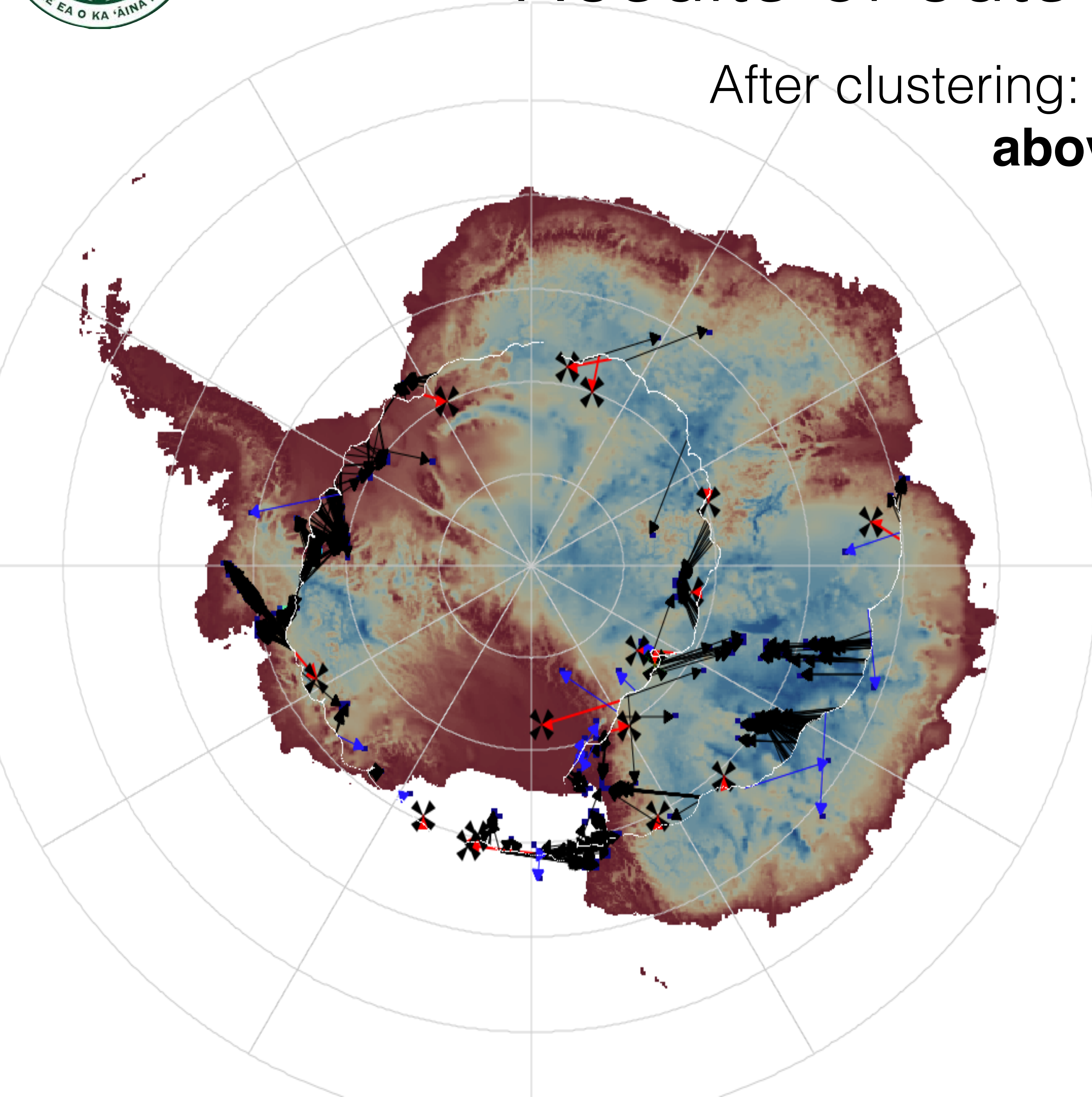
Determines "closeness" of two events by comparing the angular difference from one to the other, and vice versa.

Events that point to the continent with a value L < 40 are considered to have clustered, and removed from the final signal set

$$L = \sqrt{\frac{\Delta\phi_{AB}^2 + \Delta\phi_{BA}^2}{\sigma_\phi(SNR)} + \frac{\Delta\theta_{AB}^2 + \Delta\theta_{BA}^2}{\sigma_\theta(SNR)}}$$

Results of cuts and clustering

After clustering: **18 CR Candidates + 2 above horizon**

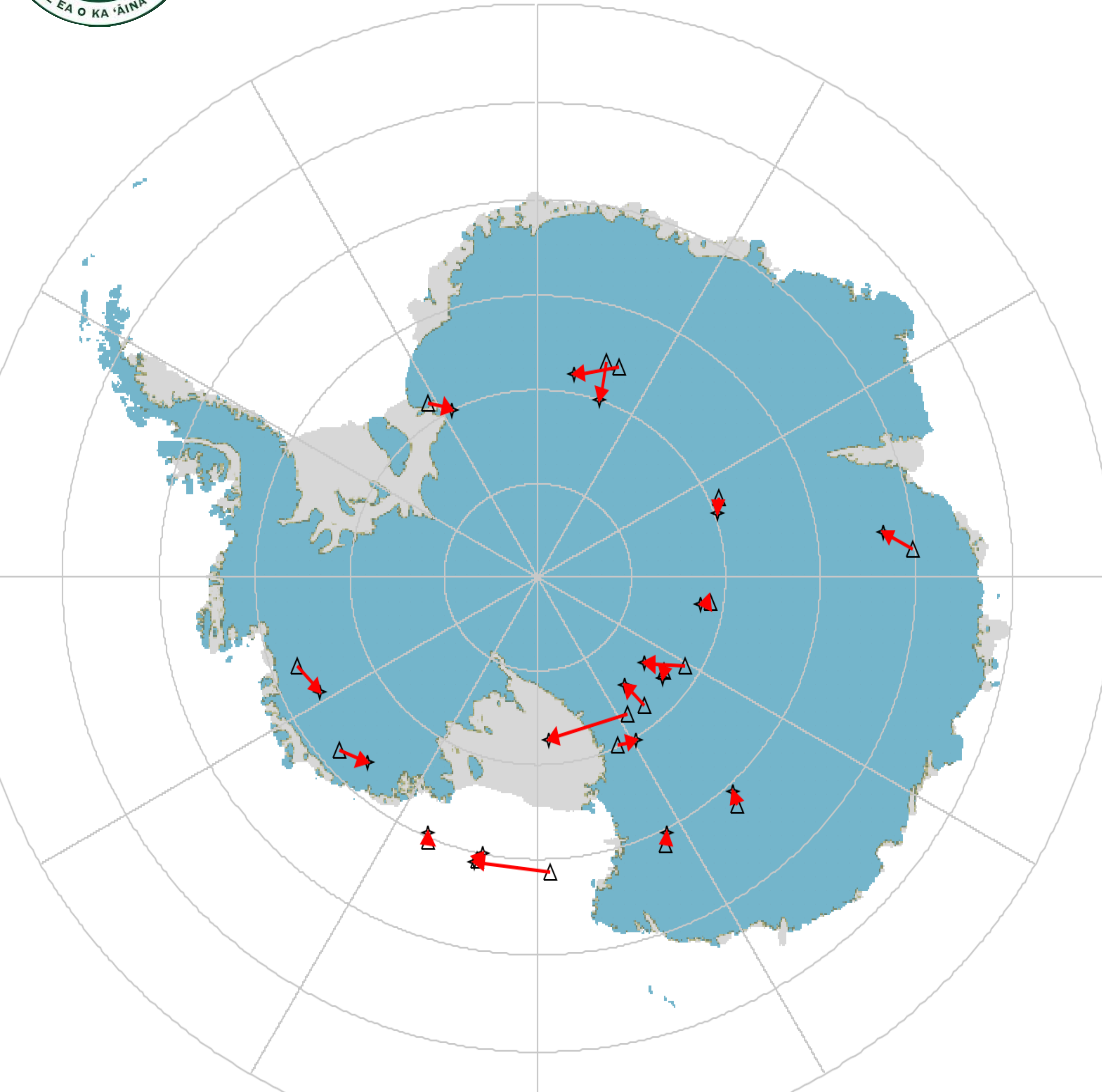


Red arrows to black **X**s denote candidate events that project to the continent

Blue arrows pass impulsivity cuts, but fail signal cuts

Black arrows are events that cluster with at least one additional event

20 Isolated events that pass all signal cuts



With this search, I found 18 CR-like signals that pointed below the horizon onto the continent

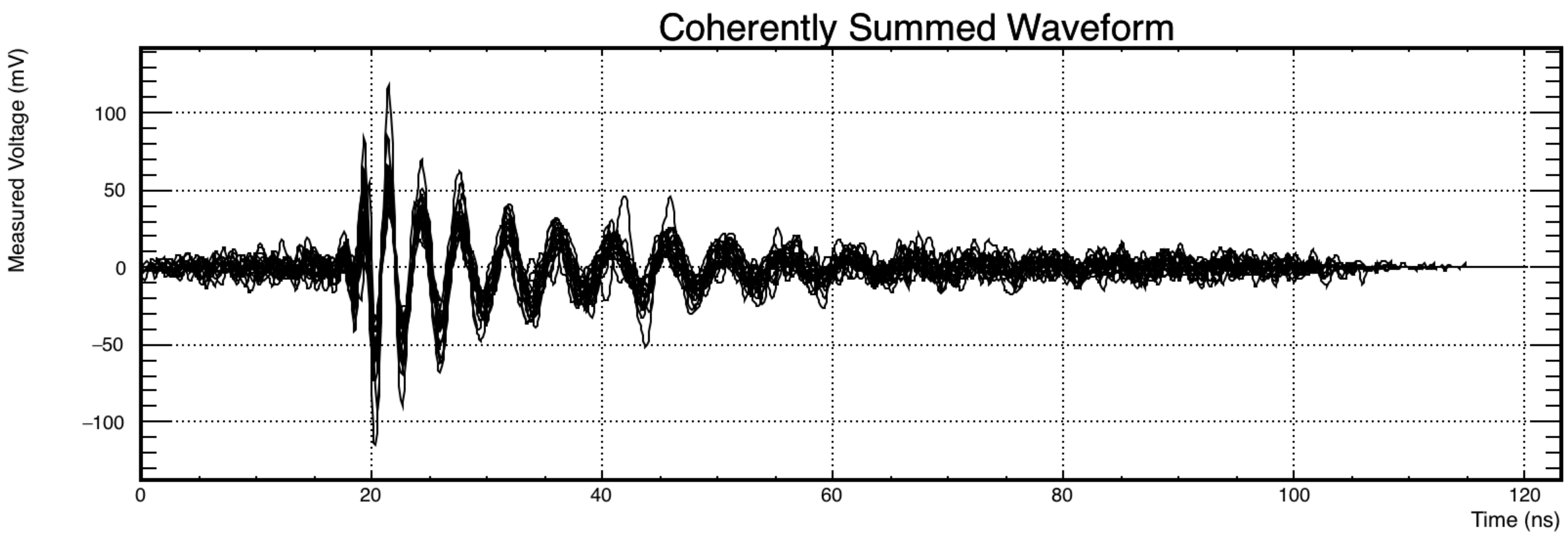
I also found 2 CR-like signals that pointed below the horizontal, but above the horizon

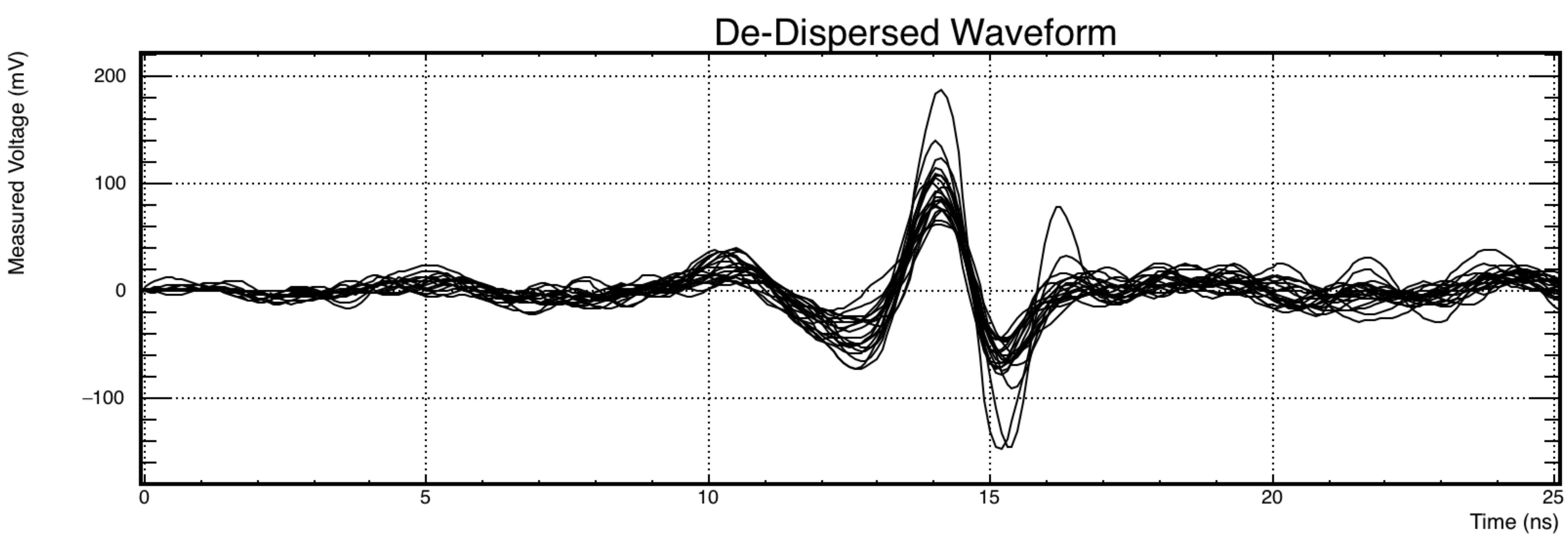
These are candidates for CRs interacting in the atmosphere

Resulting CR Candidates

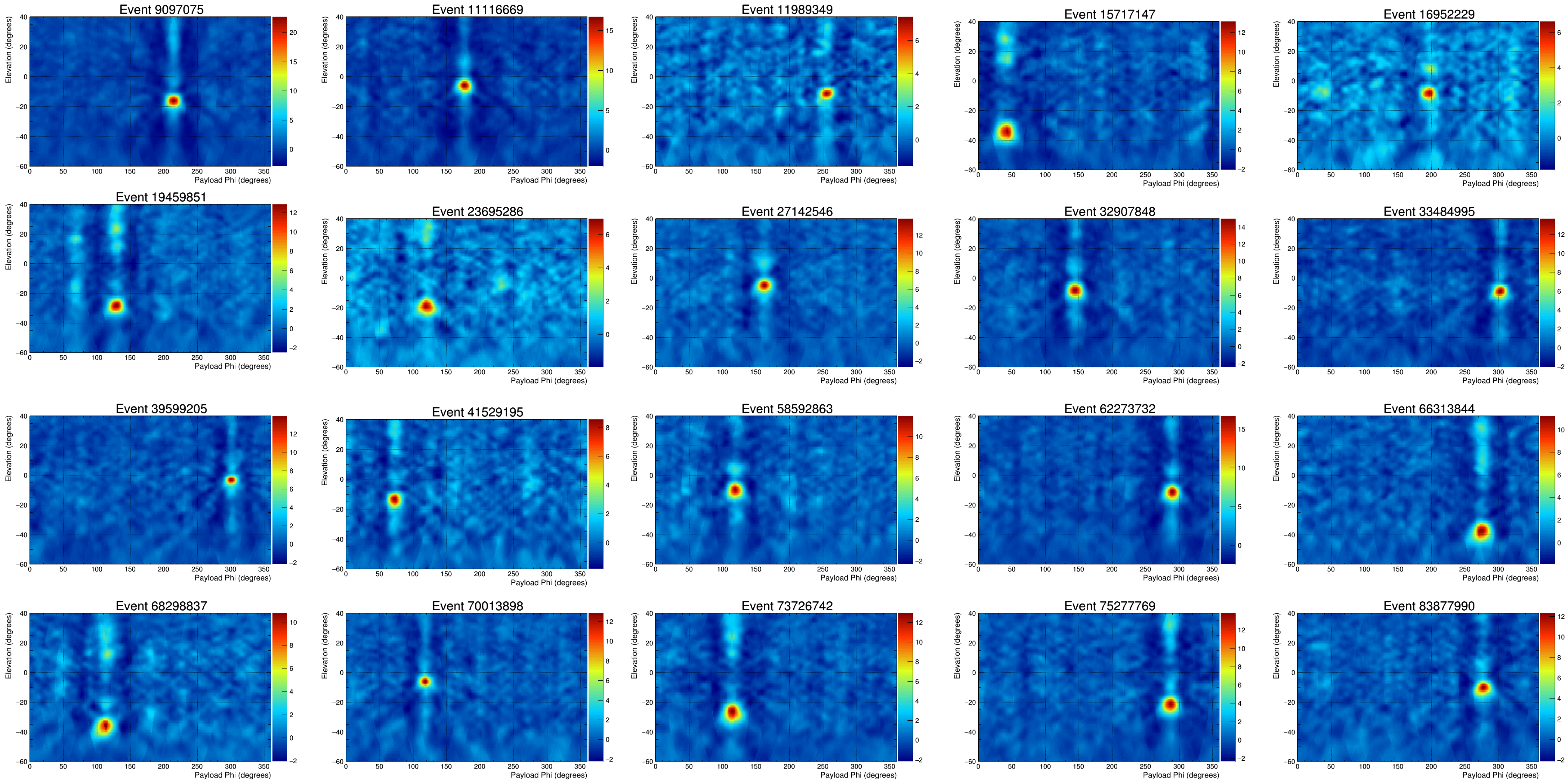
Polarity was blinded for this analysis, to ensure no bias in selecting for signals that matched UHEv

Polarity corrected for this plot according to results of polarization estimator





H-Pol Candidate Maps



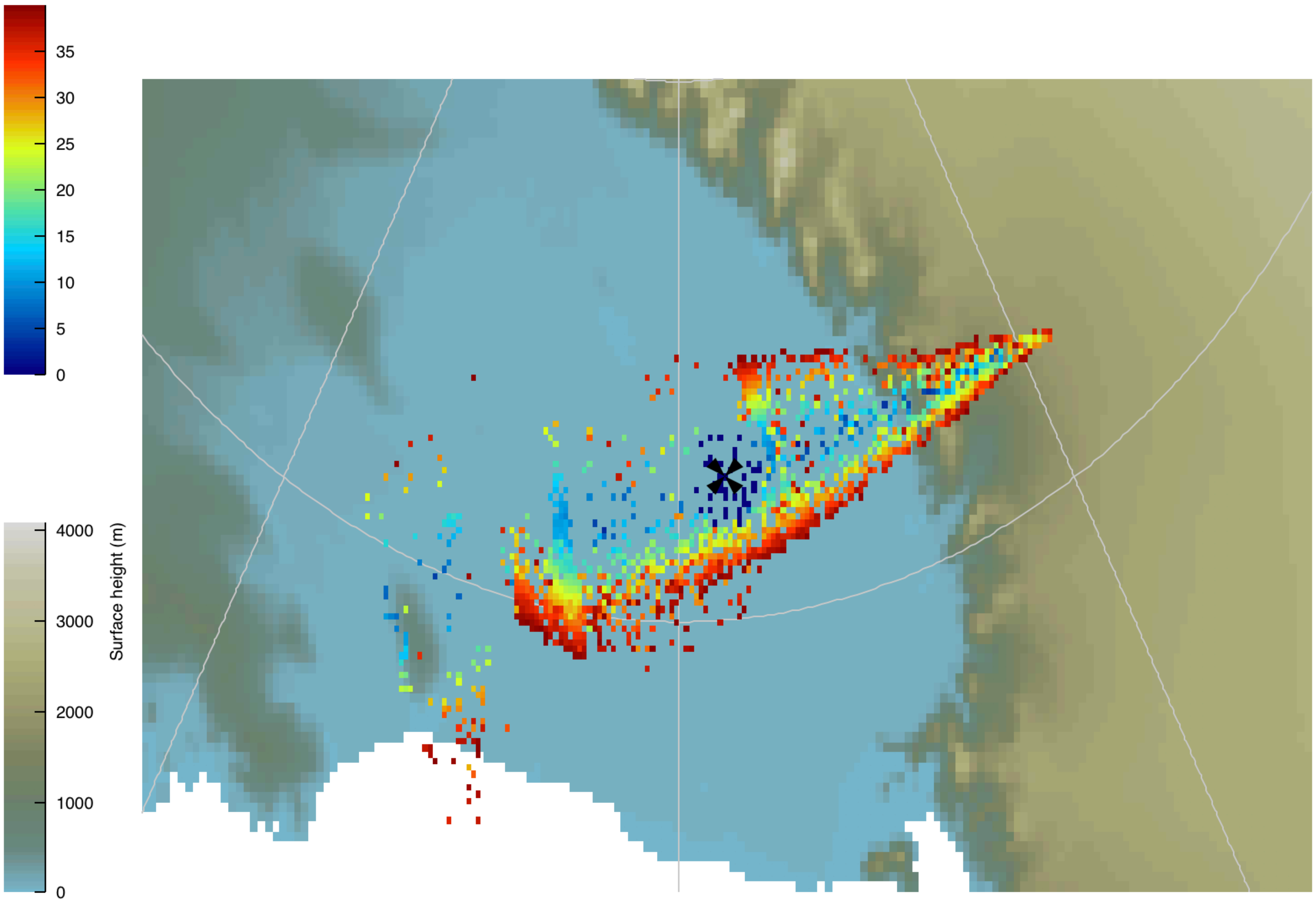
Whats next?

- Polarity unblinding for UHE
- ANITA-IV data is still being analyzed
- A ve and vu blind search
- Graduating!

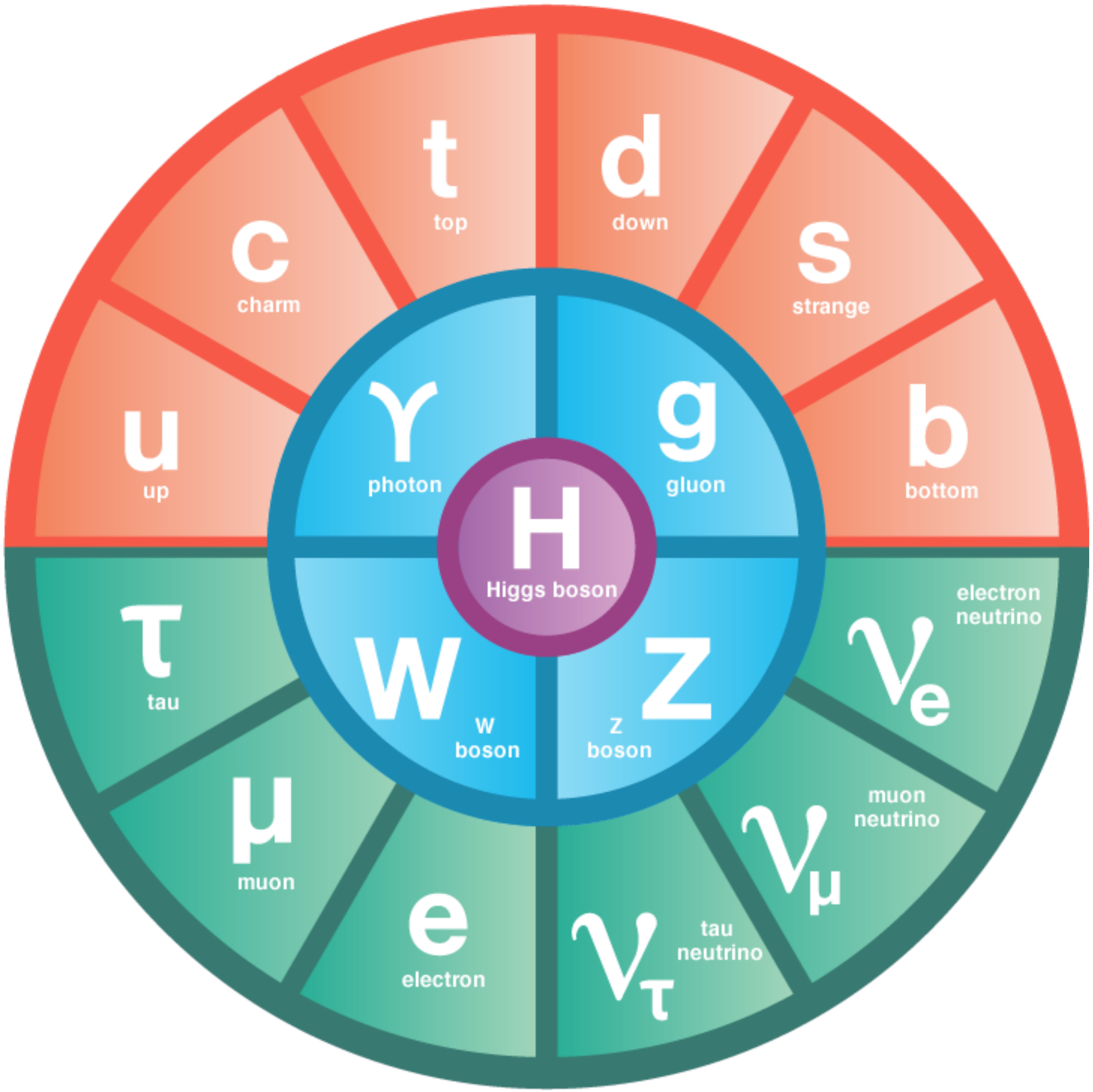



ANITA-III Launch

Extra Slides


35
30
25
20
15
10
5
0
4000
3000
2000
1000
0
Surface height (m)

The Standard Model



- Foundation of particle physics
- CRs are baryons, combinations of three quarks, found in the red section
- Neutrinos are leptons, which are the bottom green section
- This figure is in every talk, so it should at least be a backup slide

Unique UHE Messenger Particles

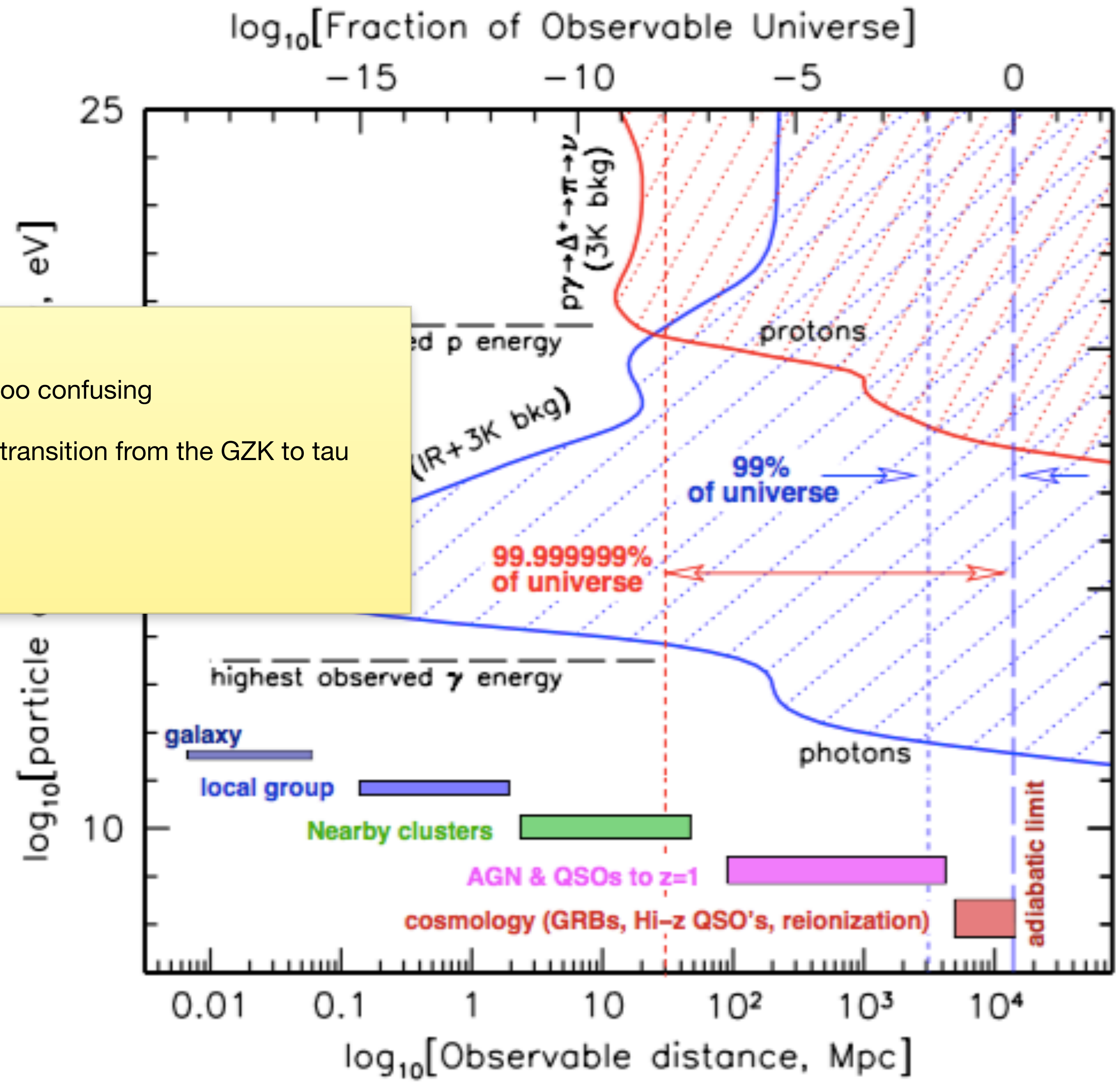
Photons are attenuated through pair production, obscuring most of the UHE universe from traditional astronomy

Cosmic rays can survive to much higher energies, allowing a deeper probe into the universe at low energies

Universe becomes opaque to even CRs at EeV (10^{19}eV) energy scales, once again obscuring much of the universe

drop, too confusing

Add a transition from the GZK to tau



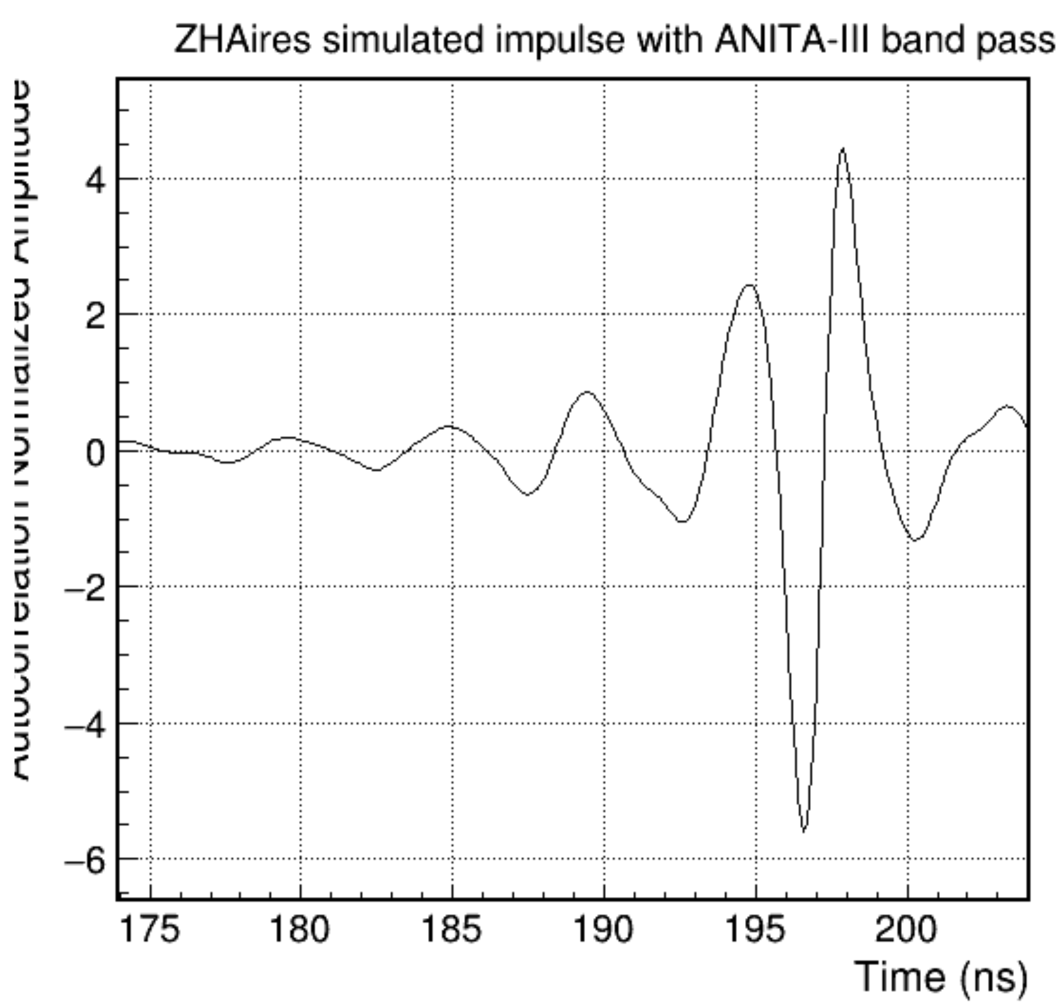
Courtesy of Peter Gorham

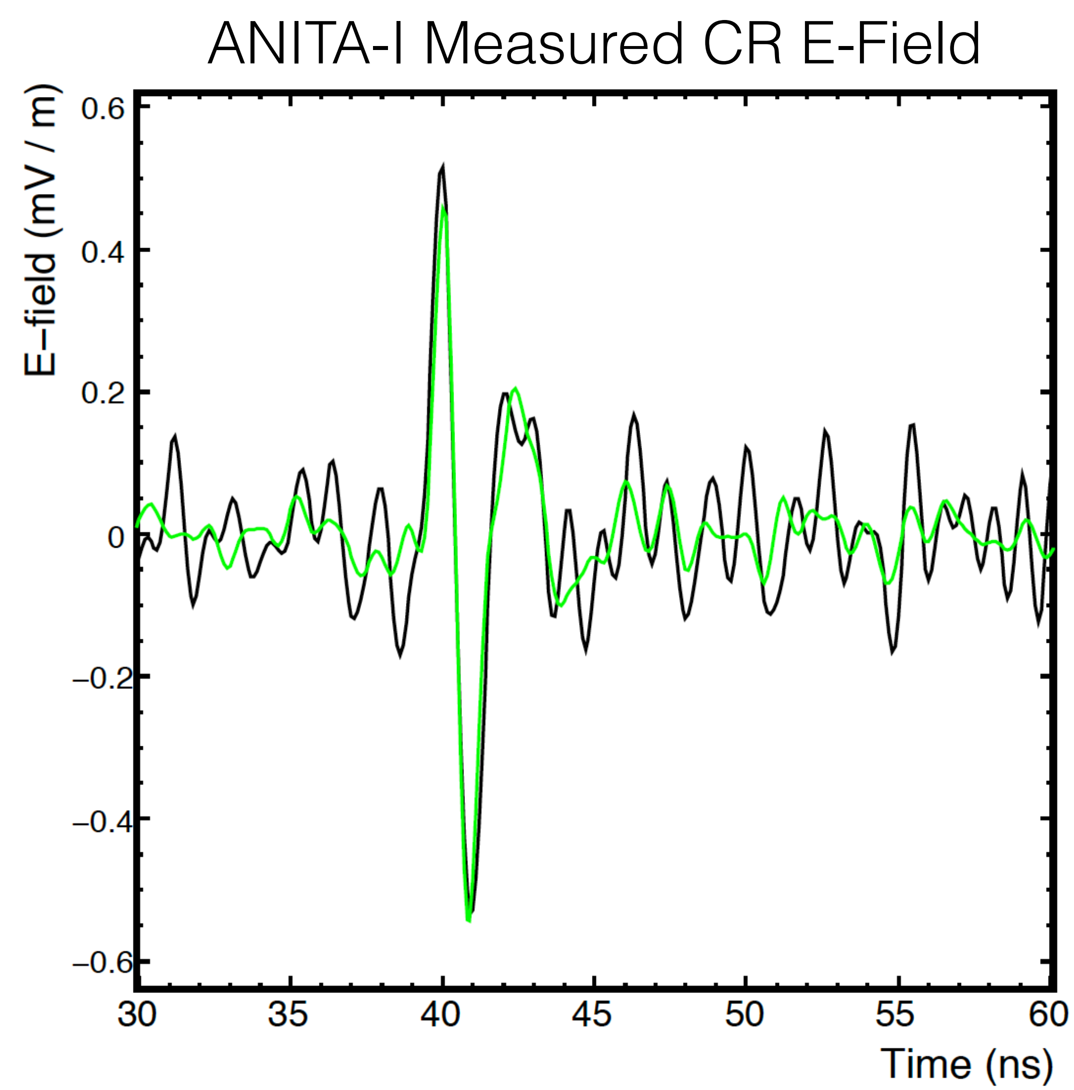
Simulated and Measured Electromagnetic Field Impulse

CR extended air showers (EAS) are expected to produce impulsive radio frequency signals

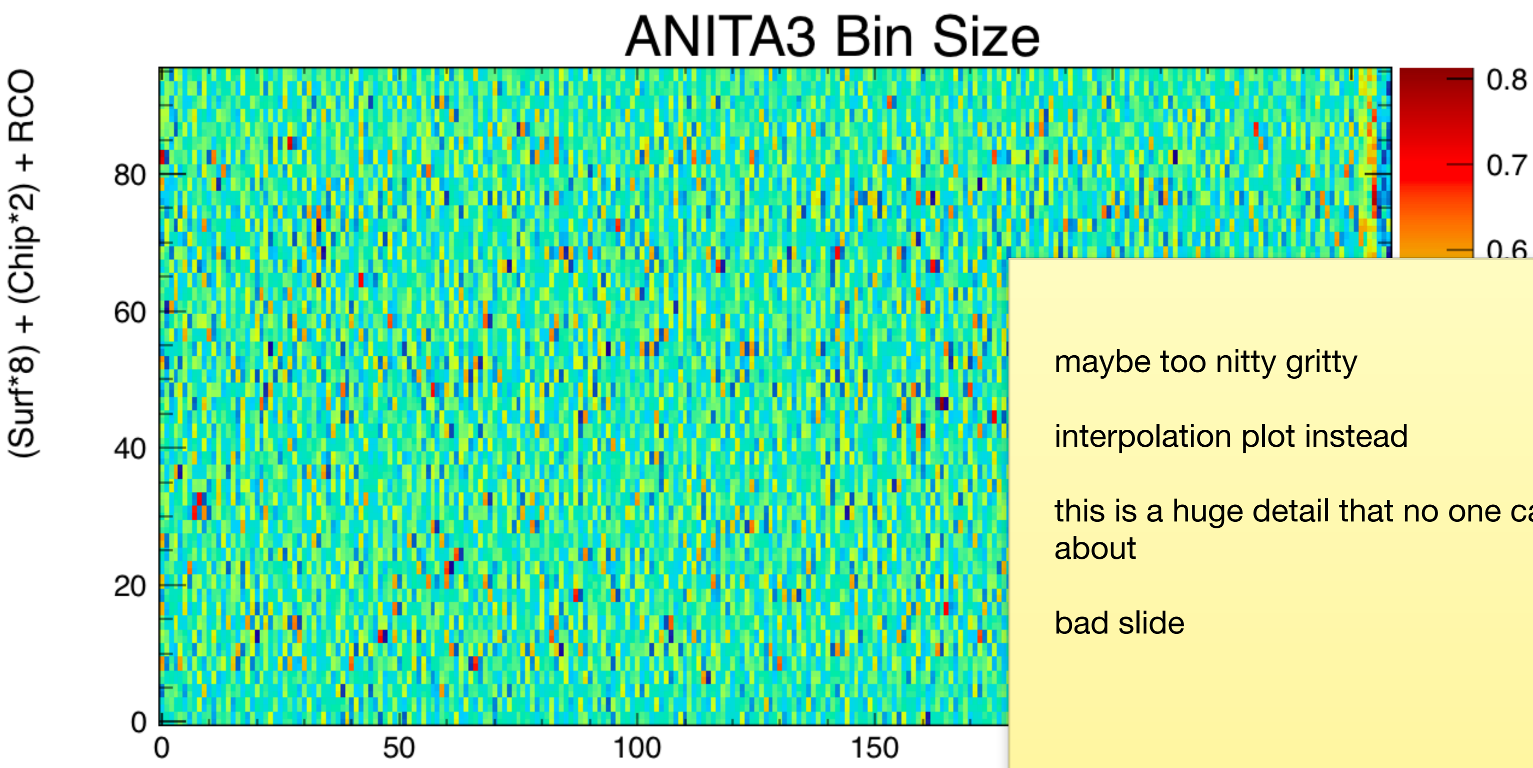
Physics simulation packages exit, such as ZHAires, that model the full shower profile development, and calculate the resulting electric fields

Measurements done by several experiments have validated these simulations





LAB timing calibration

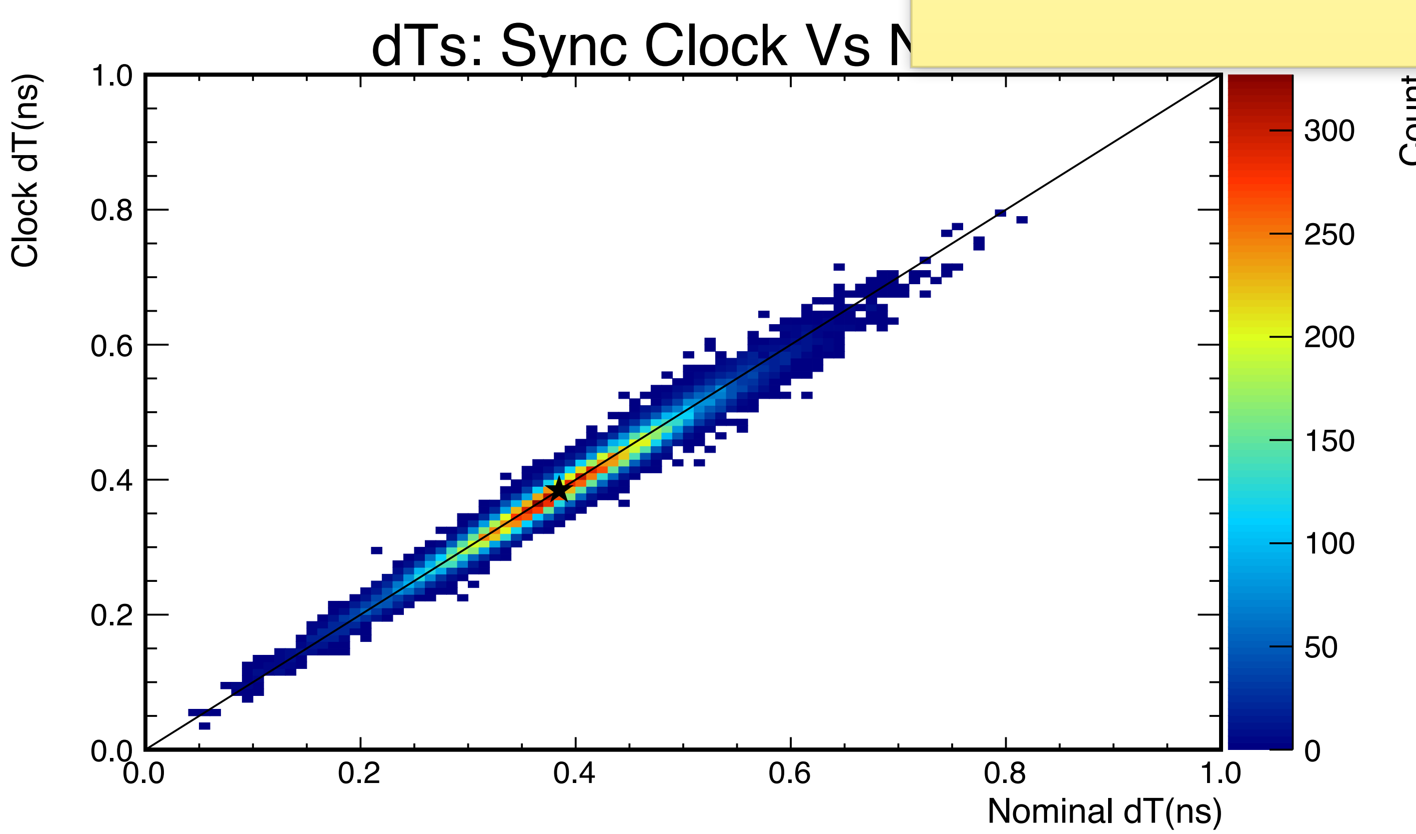


maybe too nitty gritty

interpolation plot instead

this is a huge detail that no one cares about

bad slide



Each time bin must be individually calibrated, as process parameter spread from the ASIC manufacturing creates a variation bin to bin.

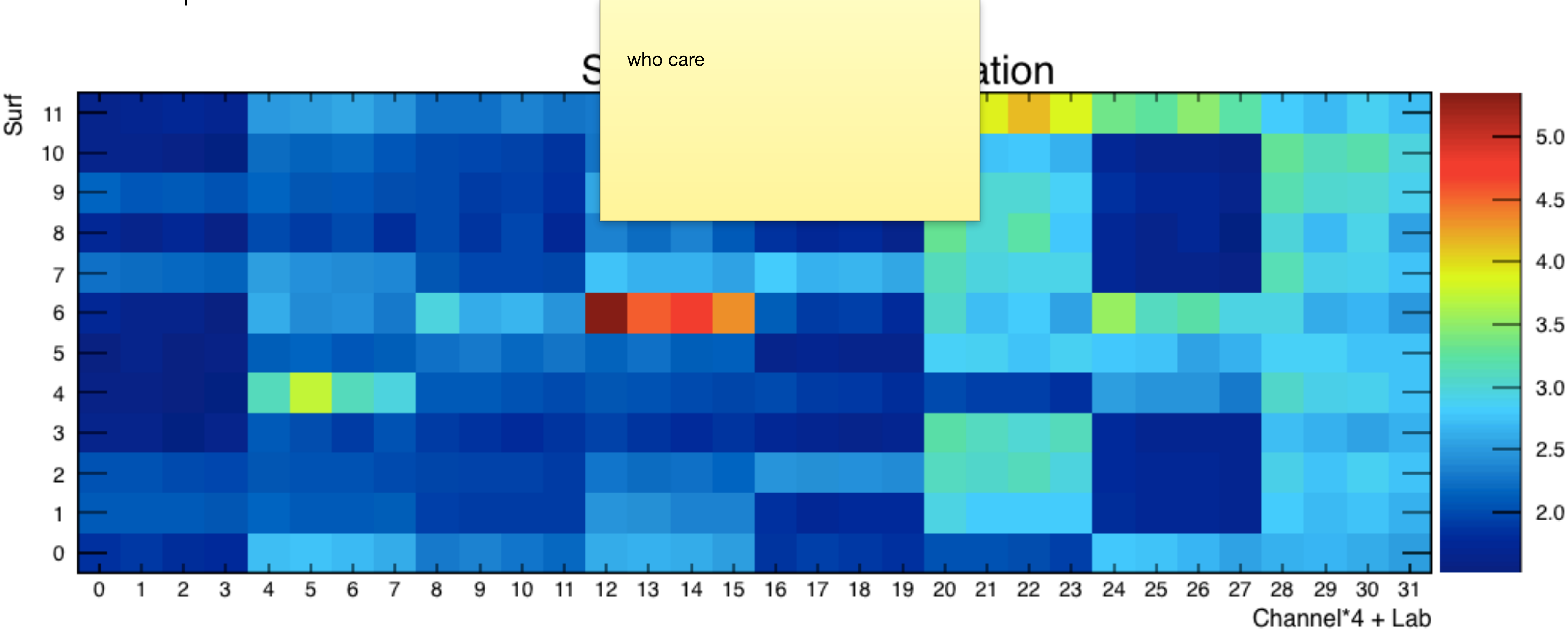
Resulting digitized waveforms are non-uniformly sampled, requiring interpolation

Calibration took place in Antarctica before flight, and was re-done several times with different methods to check for consistency

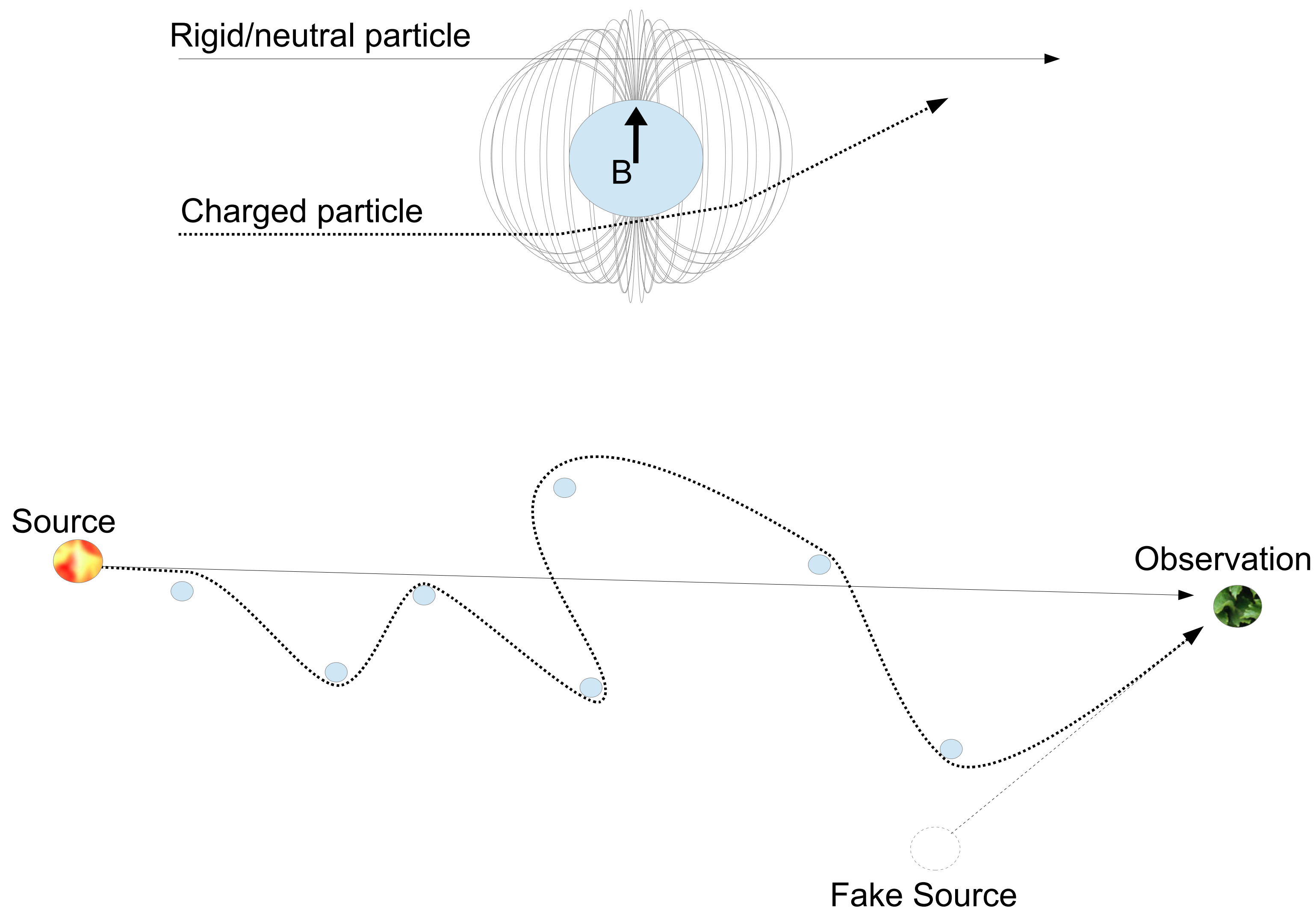
LAB voltage calibration

Recorded digital values must be related back to voltage in order to determine absolute signal strength.

Calibration was done by comparing an impulsive signal input into SURF board and concurrently measured with ANITA DAQ (Digital AcQuisition) and calibrated Tektronix oscilloscope

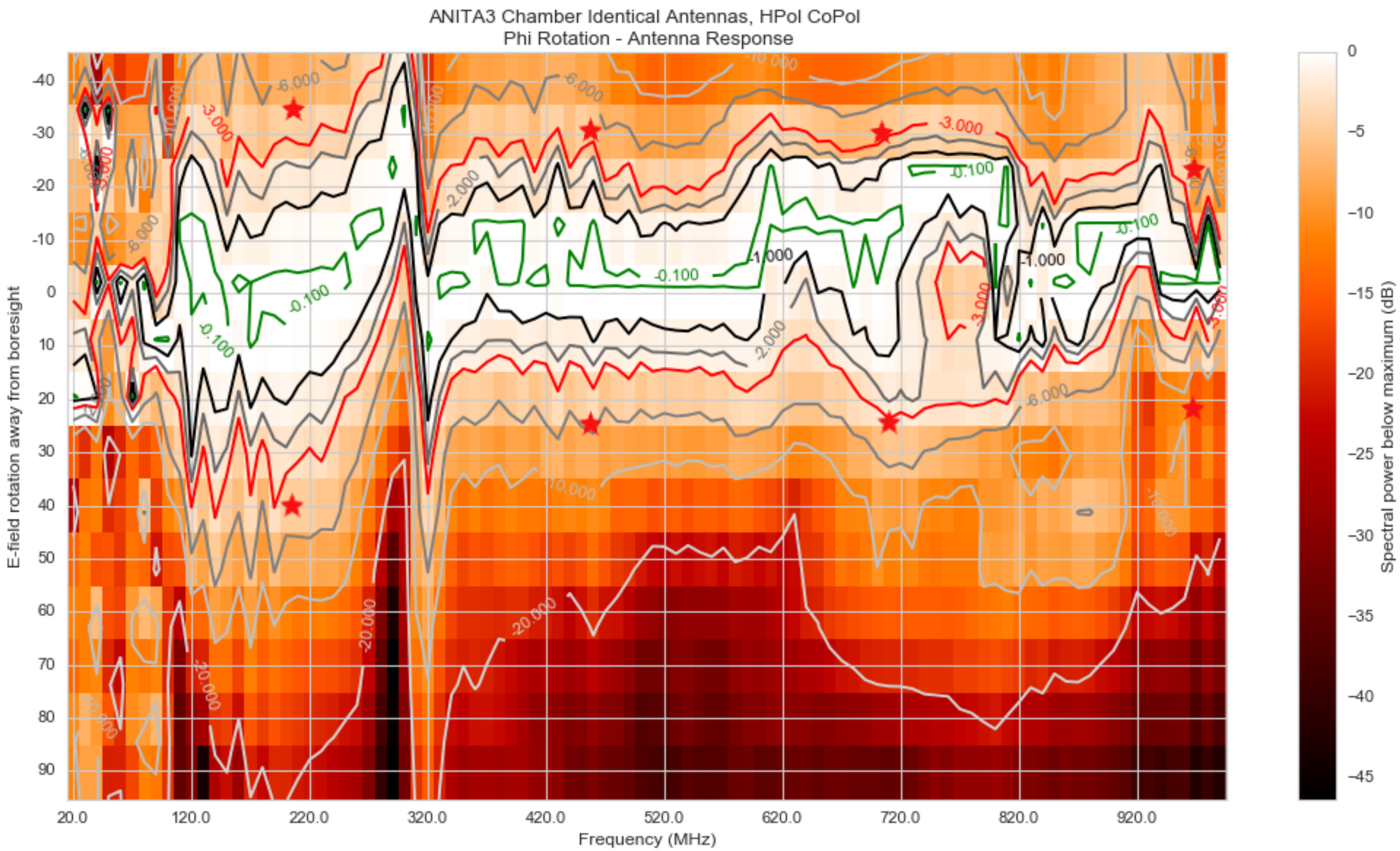


Pointing to UHECR sources

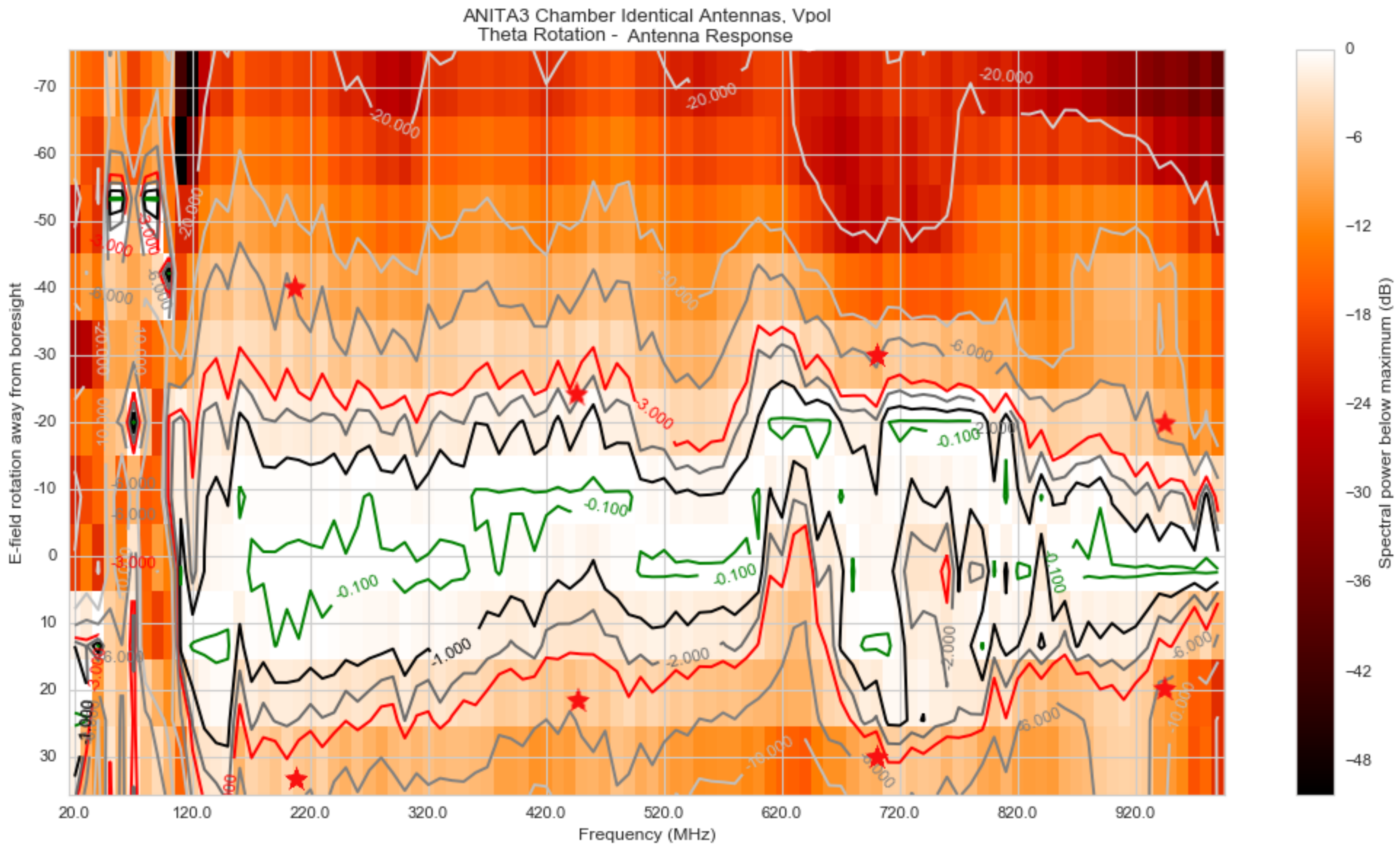


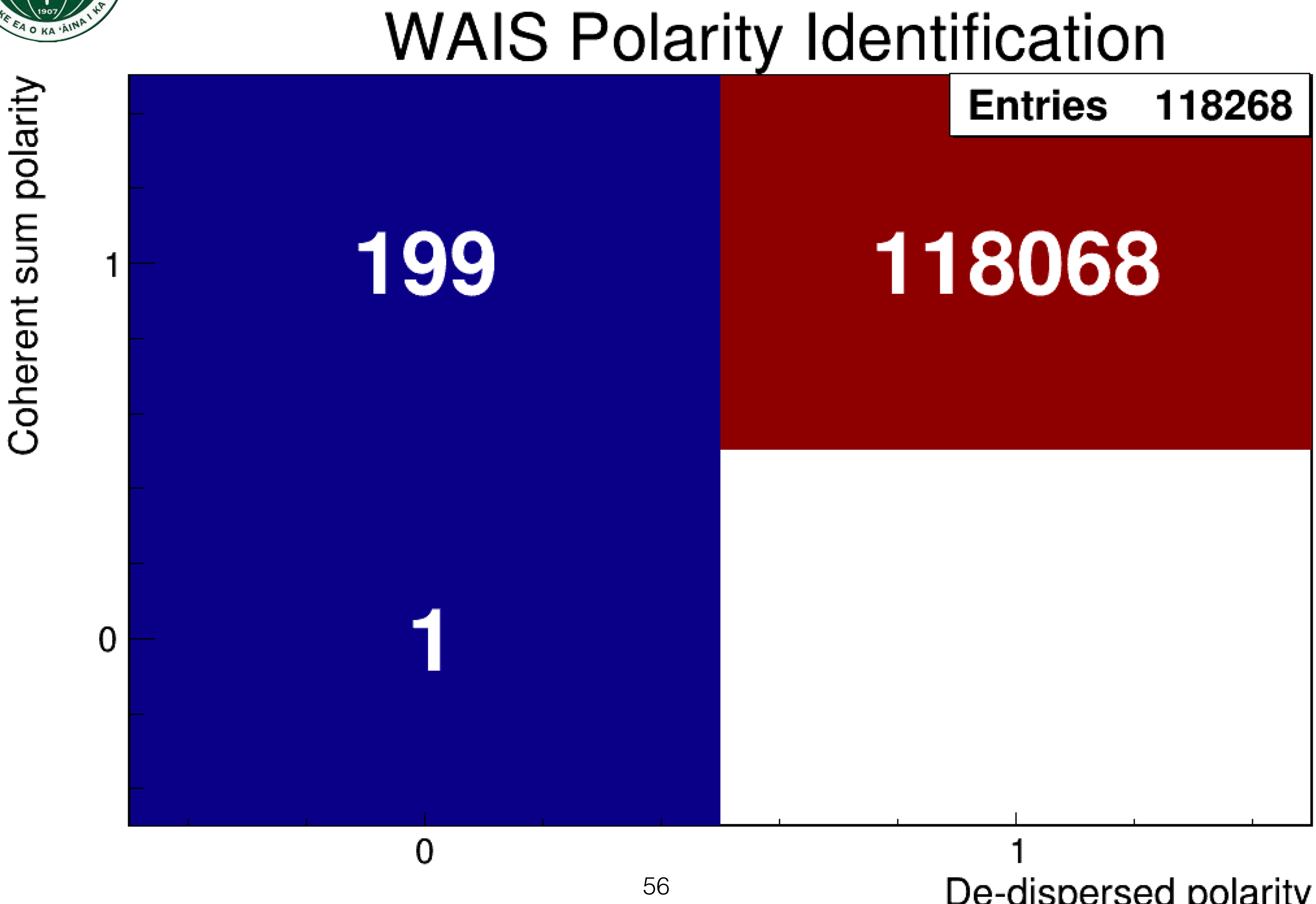
Low energy CRs are bent via the Lorentz force as they traverse the universe

UHECRs, with their high rigidity, would not be effected by this, but their low flux prevents source identification



ANITA3 Chamber Identical Antennas, HPol CoPol
Phi Rotation - Antenna Response
E-field rotation away from boresight
Frequency (MHz)
Spectral power below maximum (dB)


ANITA3 Chamber Identical Antennas, Vpol
Theta Rotation - Antenna Response
E-field rotation away from boresight
Frequency (MHz)
Spectral power below maximum (dB)
20.0
120.0
220.0
320.0
420.0
520.0
620.0
720.0
820.0
920.0
-70
-60
-50
-40
-30
-20
-10
0
10
20
30
0
−6
−12
−18
−24
−30
−36
−42
−48
-20.000
-10.000
-6.000
-3.000
-2.000
-1.000
-0.100



WAIS Polarity Identification
Entries 118268
199
118068
1
Coherent sum polarity
1
0
0
1
De-dispersed polarity

Tau branching ratio

Hadronic Decays:

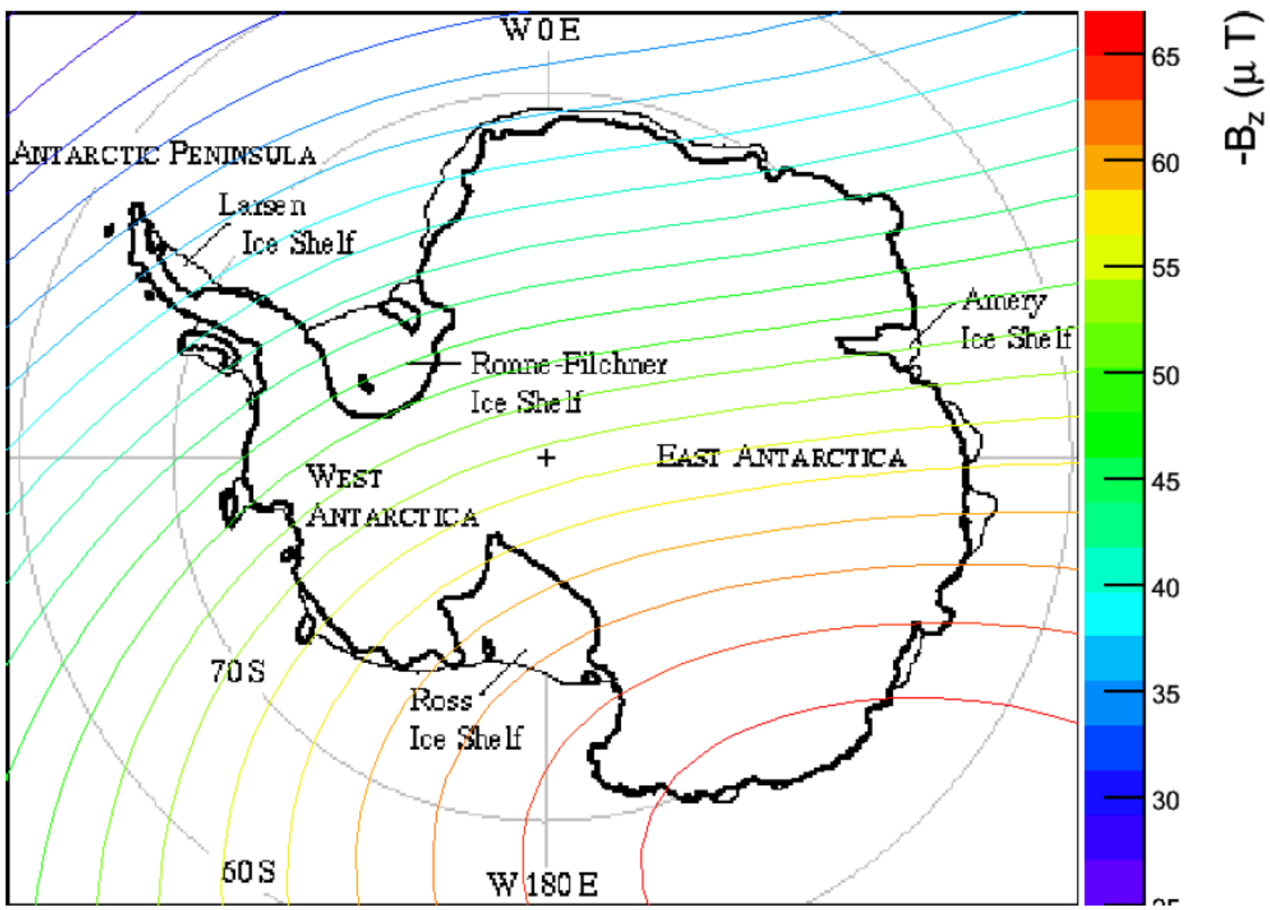
- 25.52% for decay into a charged pion, a neutral pion, and a tau neutrino;
- 10.83% for decay into a charged pion and a tau neutrino;
- 9.30% for decay into a charged pion, two neutral pions, and a tau neutrino;
- 8.99% for decay into three charged pions (of which two have the same electrical charge) and a tau neutrino;
- 2.70% for decay into three charged pions (of which two have the same electrical charge), a neutral pion, and a tau neutrino;
- 1.05% for decay into three neutral pions, a charged pion, and a tau neutrino.

Leptonic Decay:

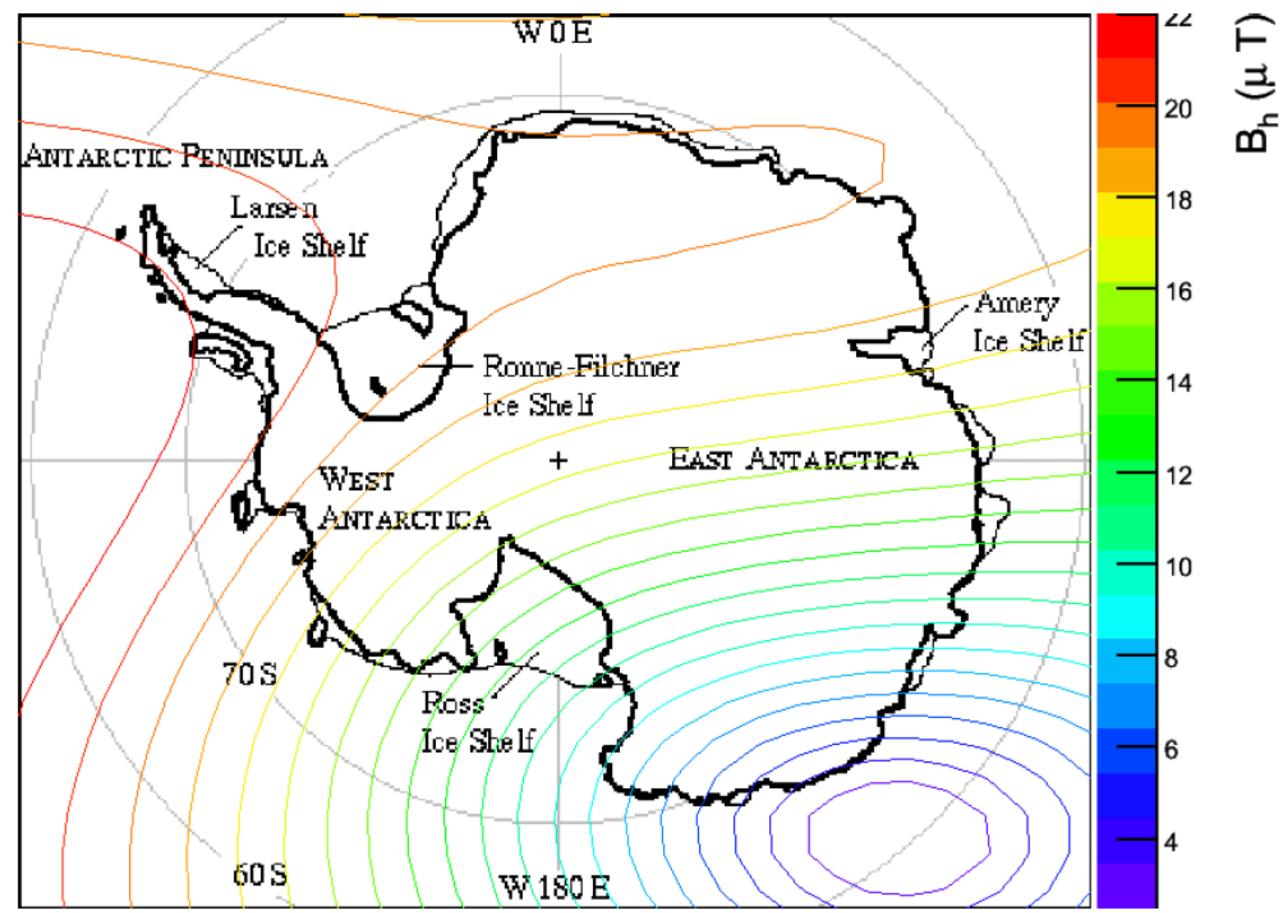
- 17.82% for decay into a tau neutrino, electron and electron antineutrino;
- 17.39% for decay into a tau neutrino, muon and muon antineutrino.

https://en.wikipedia.org/wiki/Tau_(particle)#Tau_decay

Geomagnetic field over Antarctica



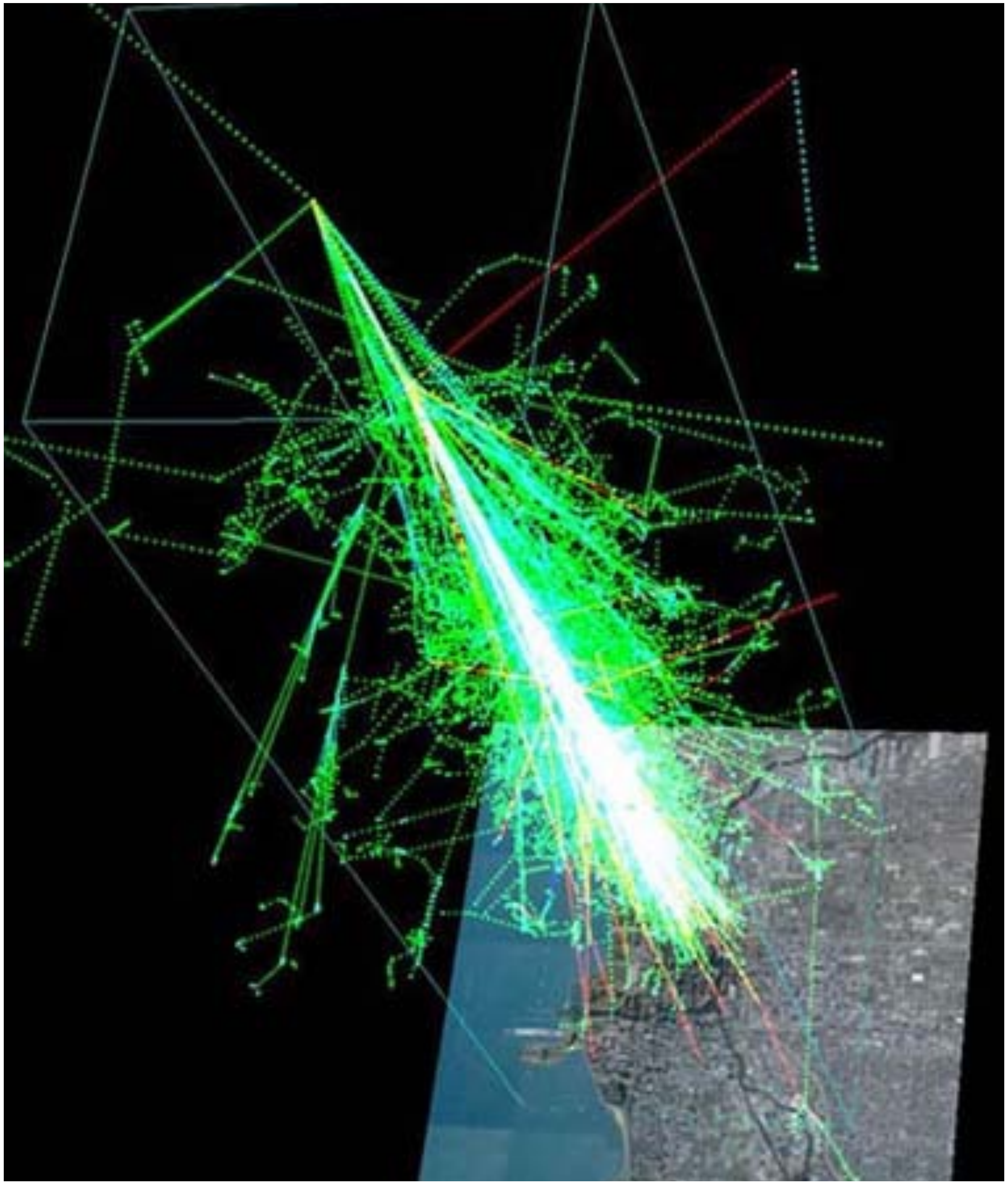
Vertical



Horizontal

[Steven Hoover's Dissertation]

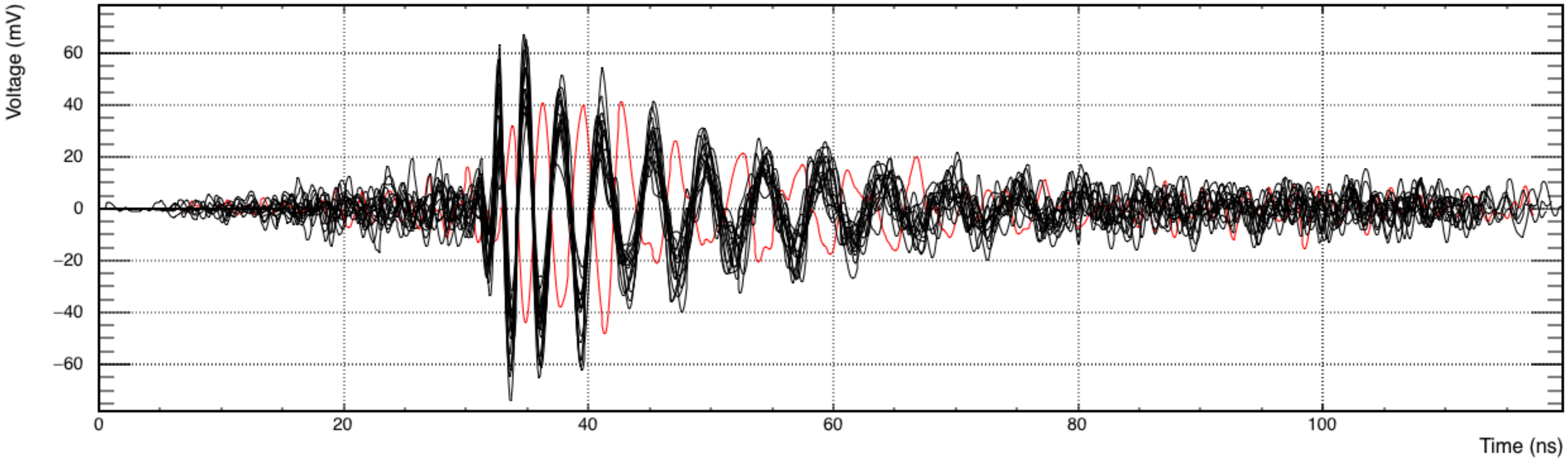
Cool shower visualization

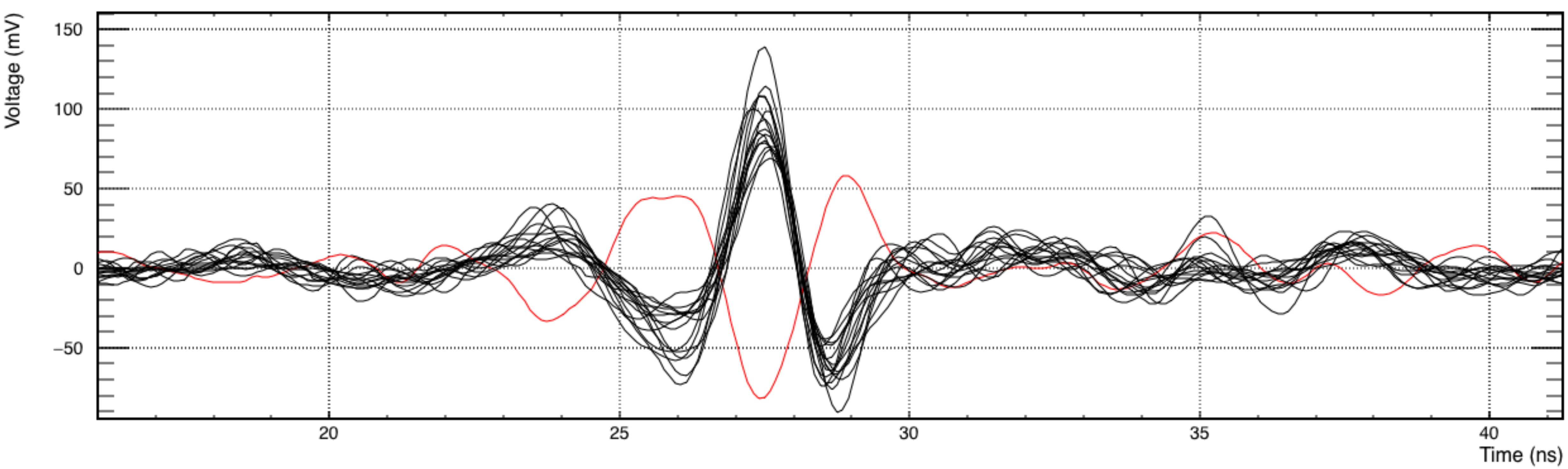


Only the committee allowed past this point

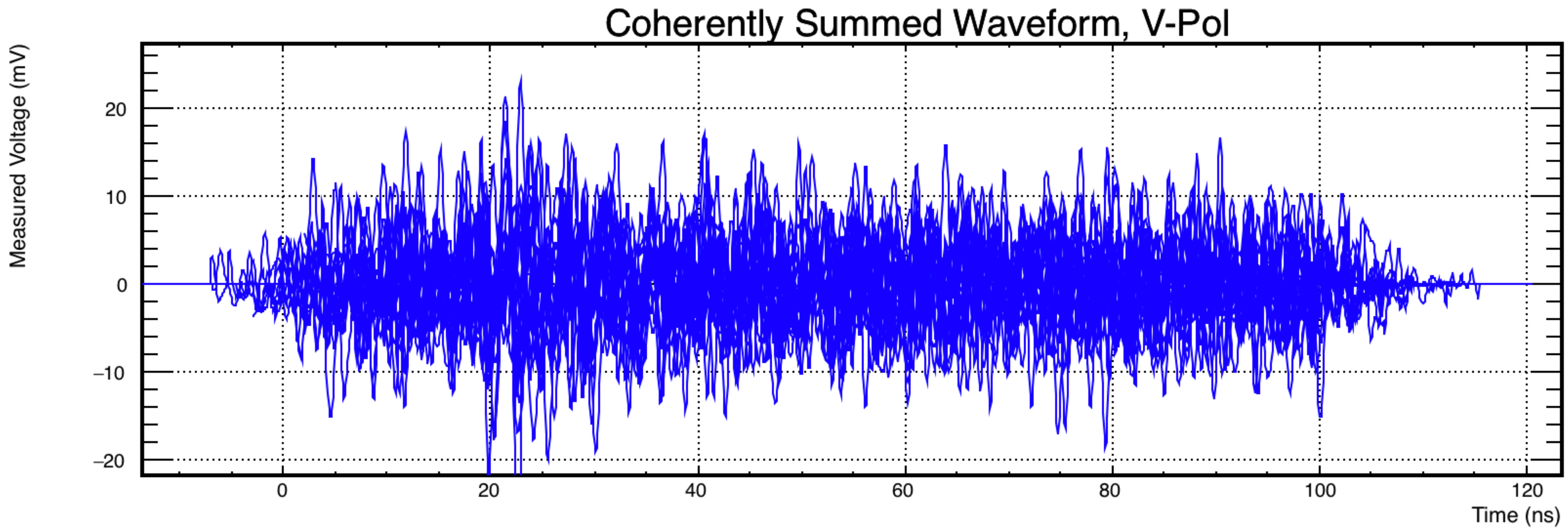
Event Number	Above/Below Horizon	Coherent Polarity	Deconvolved Polarity
9097075	Below	0	0
11116669	Below	0	0
11989349	Below	0	0
15717147	Below	1	1
16952229	Below	0	0
19459851	Below	0	0
23695286	Below	0	0
27142546	Above	1	1
32907848	Below	0	0
33484995	Below	0	0
39599205	Above	1	1
41529195	Below	0	0
58592863	Below	0	0
62273732	Below	0	0
66313844	Below	0	0
68298837	Below	0	0
70013898	Below	0	0
73726742	Below	0	0
75277769	Below	0	0
83877990	Below	0	0

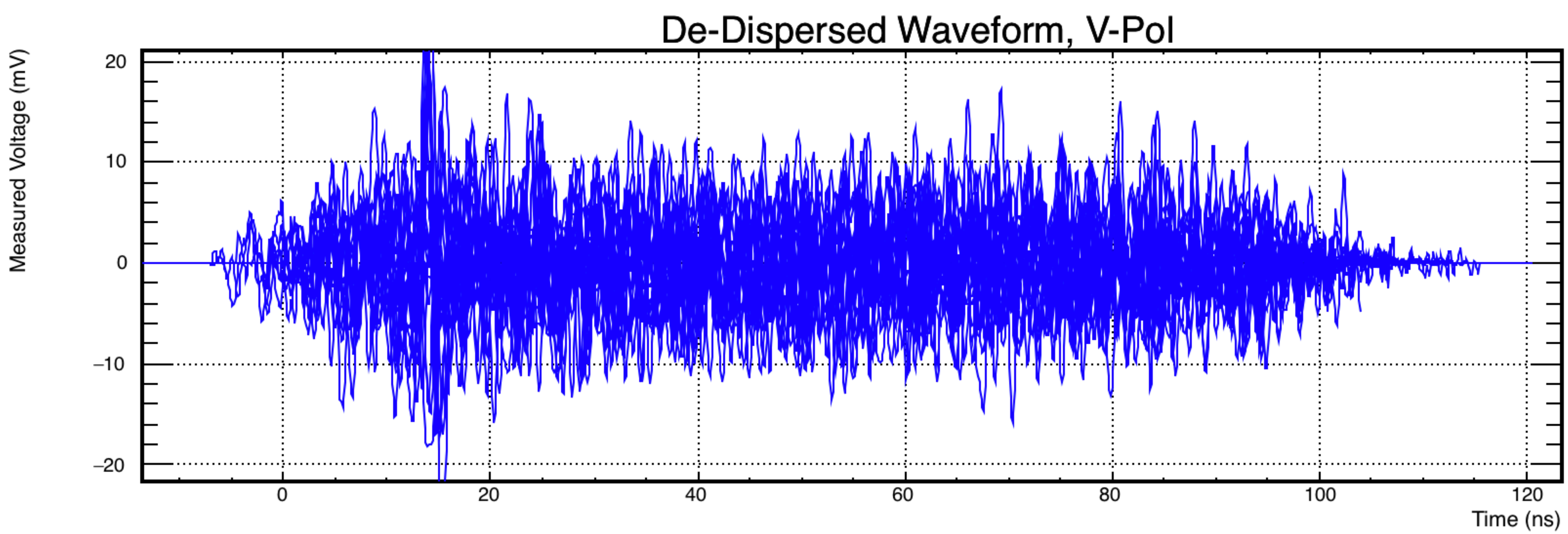
Below Horizon H-Pol



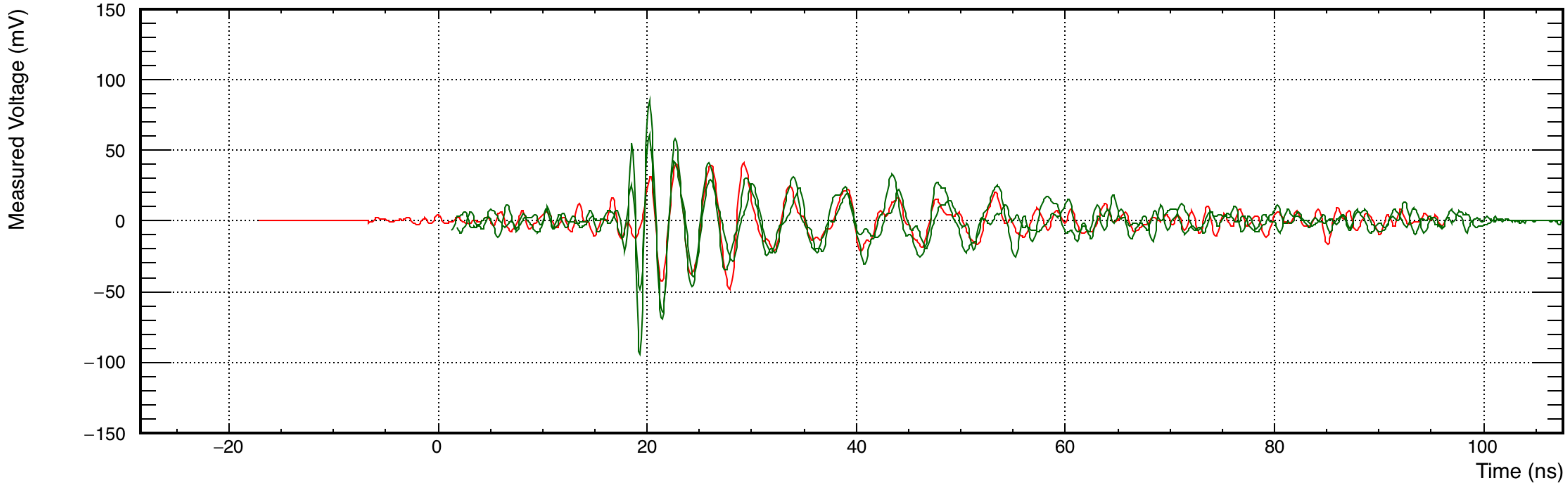


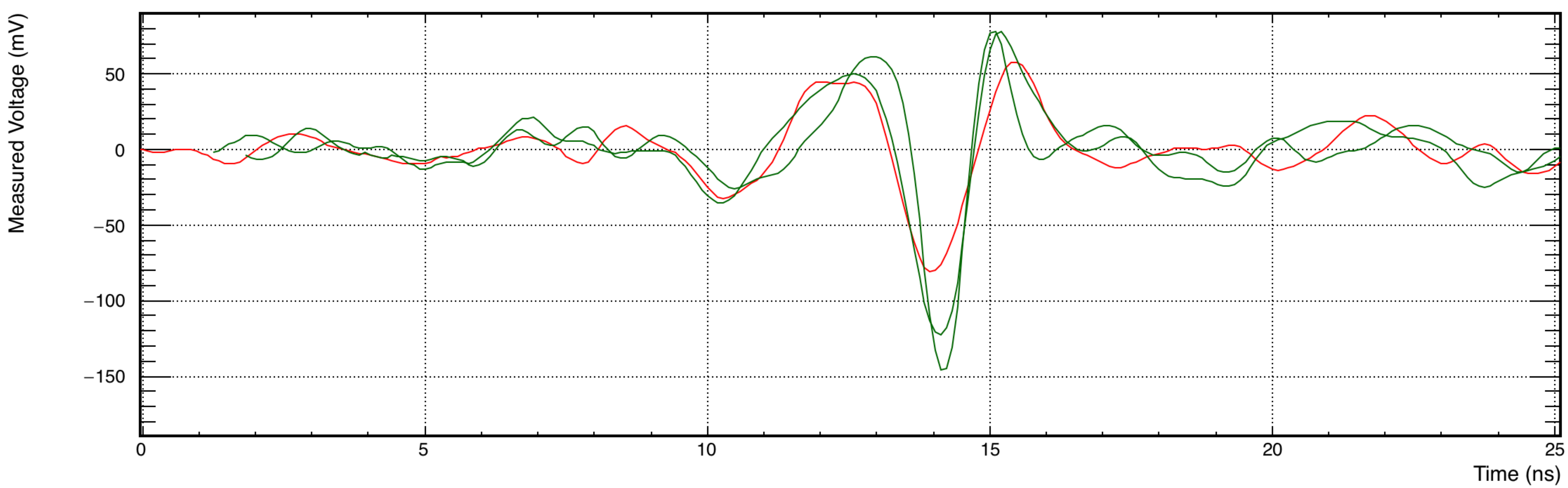
Below Horizon V-Pol





Above horizon (green) and inverted (red)





All coherently summed waveform