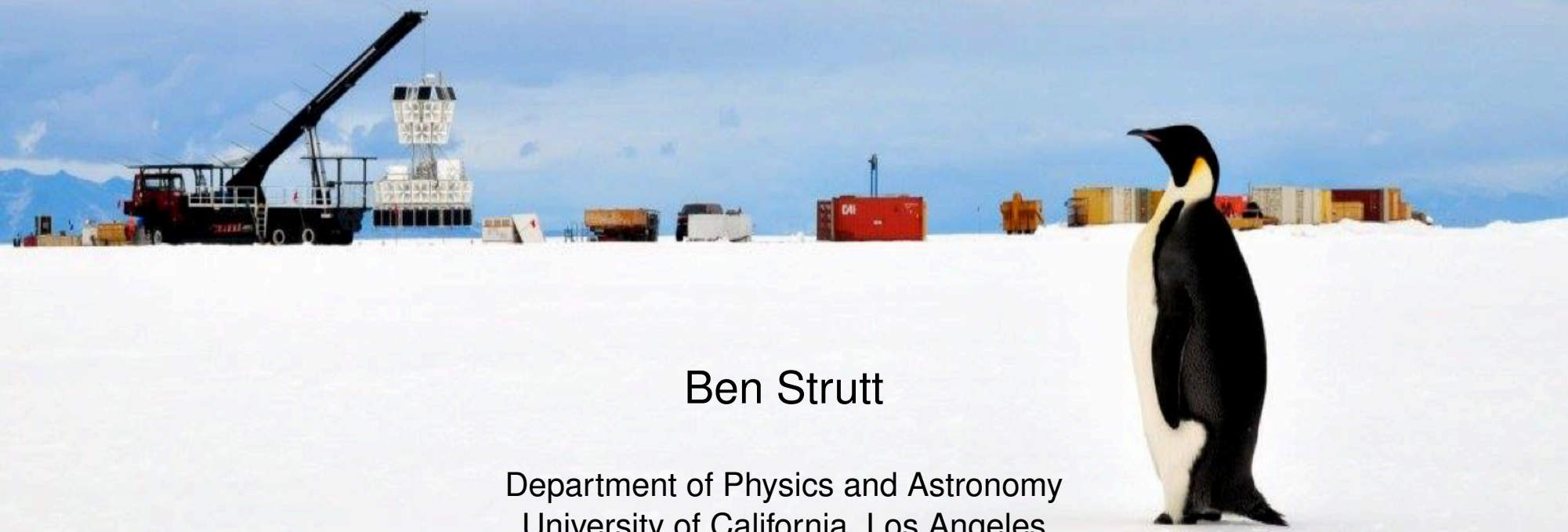
Chasing Ultra-High Energy νs above Antarctica

with the Antarctic Impulsive Transient Antenna (ANITA)



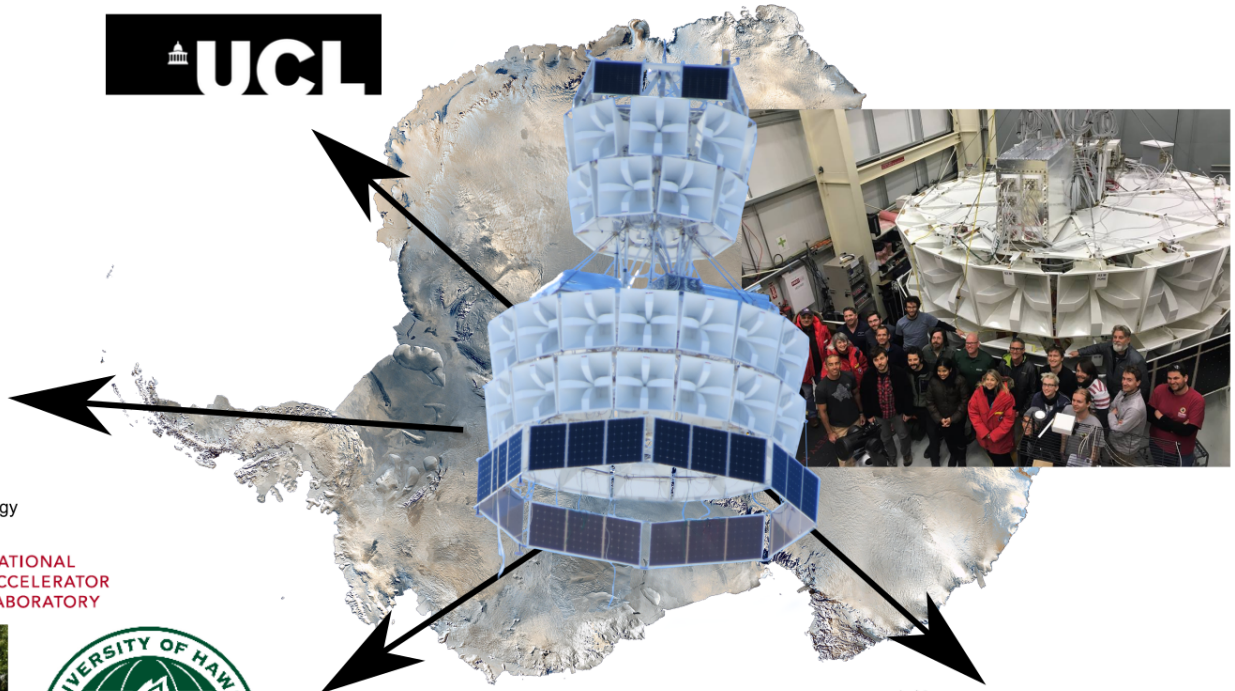
Ben Strutt

Department of Physics and Astronomy
University of California, Los Angeles

16th November 2018

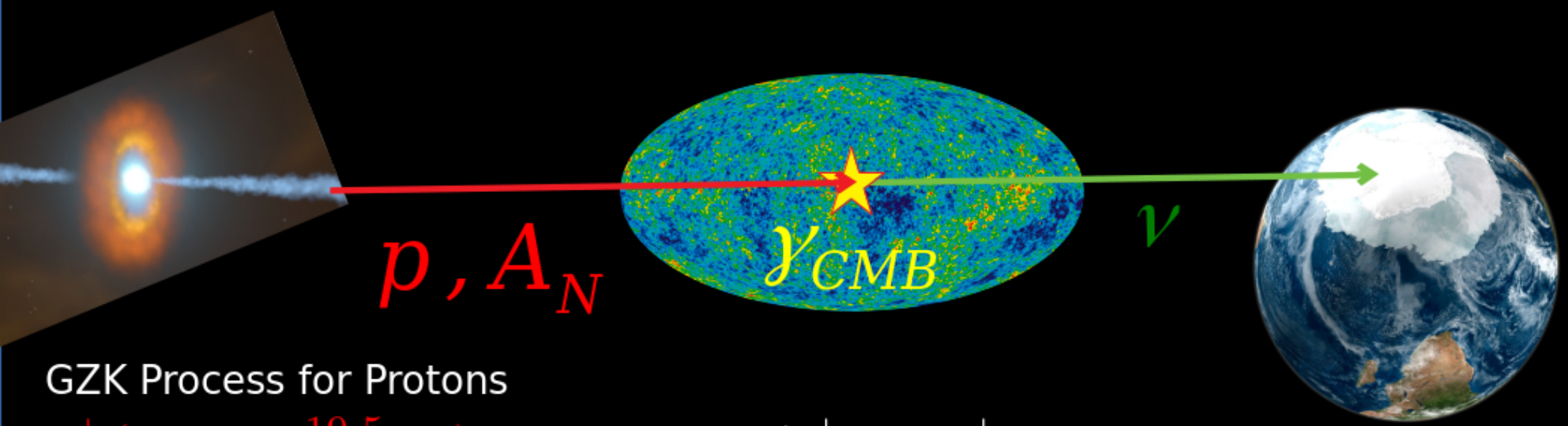
ANITA collaboration

~ 60 people across 11 institutions (9 USA, 1 UK, 1 Taiwan)



Are there cosmogenic neutrinos?

UCLA



GZK Process for Protons

$$p^+(E > 10^{19.5}\text{eV}) + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$\downarrow \qquad\qquad \downarrow$$

$$n \rightarrow p^+ + e^- + \overline{\nu_\mu}$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\downarrow$$

$$\mu^+ \rightarrow \overline{\nu_\mu}\, e^+ + \nu_e$$

Photo-disintegration for heavier nuclei

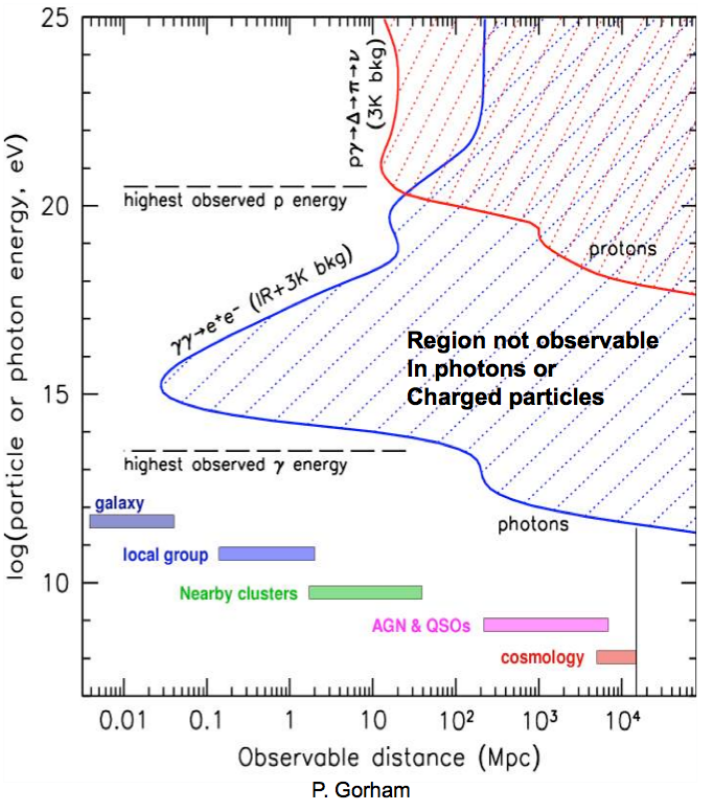
$$A_{\text{N}} + \gamma_{\text{CMB}} \rightarrow A_{\text{N-1}} + n$$

$$\downarrow$$

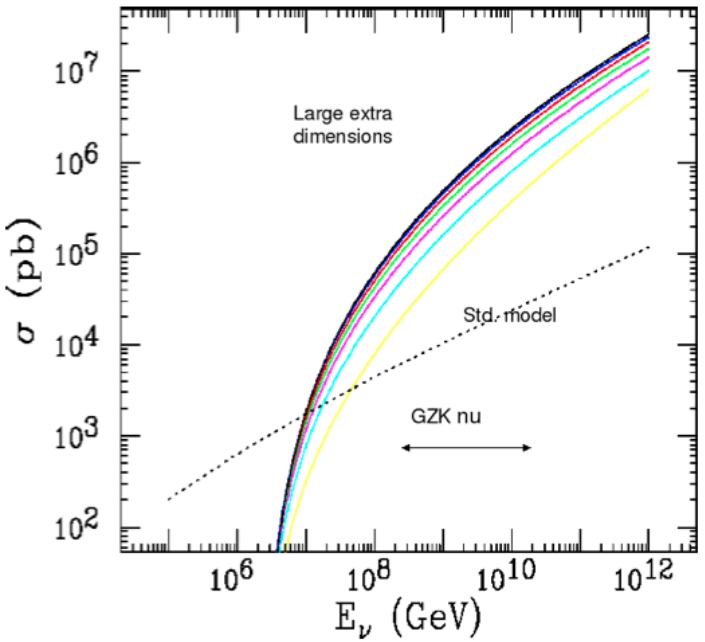
$$n \rightarrow p^+ + e^- + \overline{\nu_\mu}$$

What could they tell us?

- Probe new regions of the universe



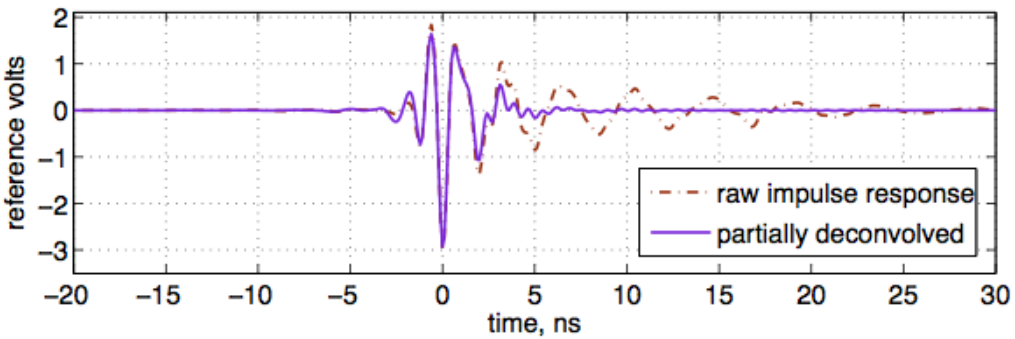
- Use Earth as a shield to measure neutrino cross-section, σ_ν
  - Constrain physics beyond the Standard Model

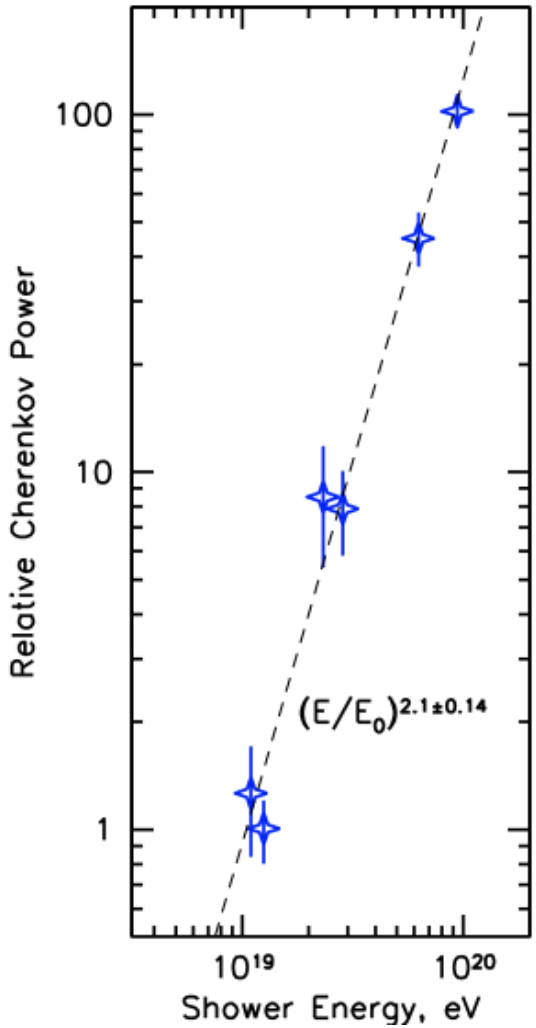


Radio detecion of UHE particles (Askaryan effect)

UCLA

- Interaction in ice creates EM shower
  - ice electrons annihiliate shower positrons
  - ice electrons scattered into shower
  - 20% -ve charge excess
- Charge excess speed > c/n_{ice}:
  - Cherenkov radiation
  - Radio frequencies interfere constructively across shower front
- Impulsive RF signal, a few ns long.
  - Signal power scales $\propto E^2_{shower}$
  - Experimentally verified!
    (Phys.Rev.Lett.99:171101,2007)

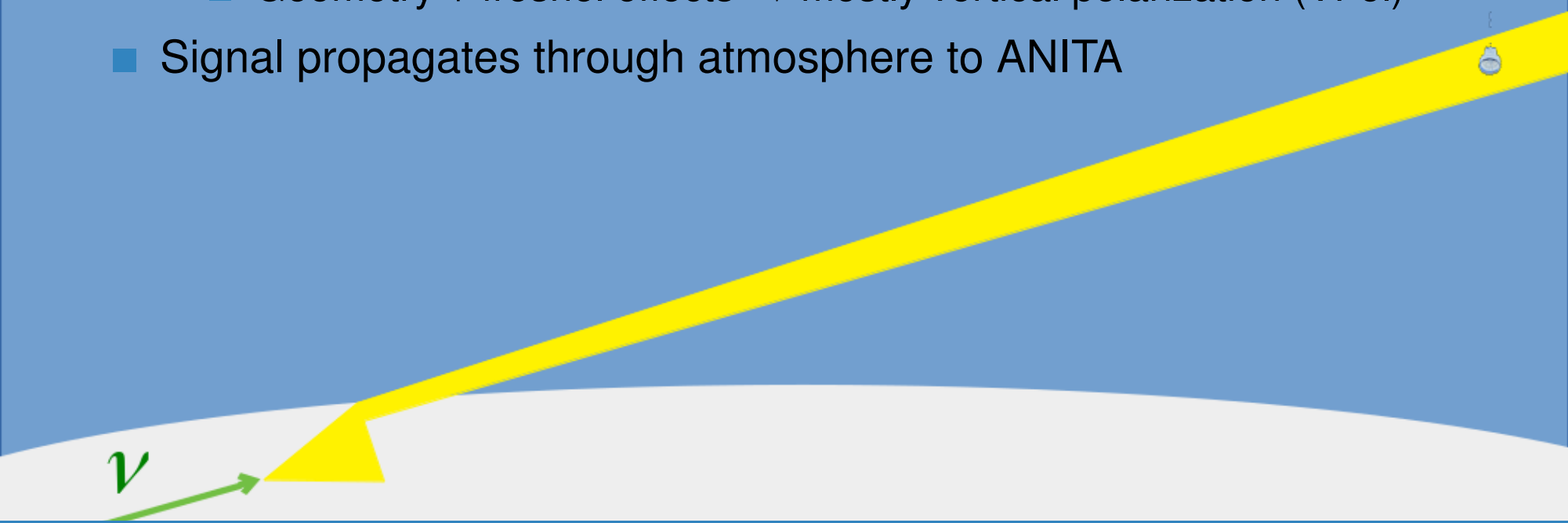




Ultra-high energy neutrinos

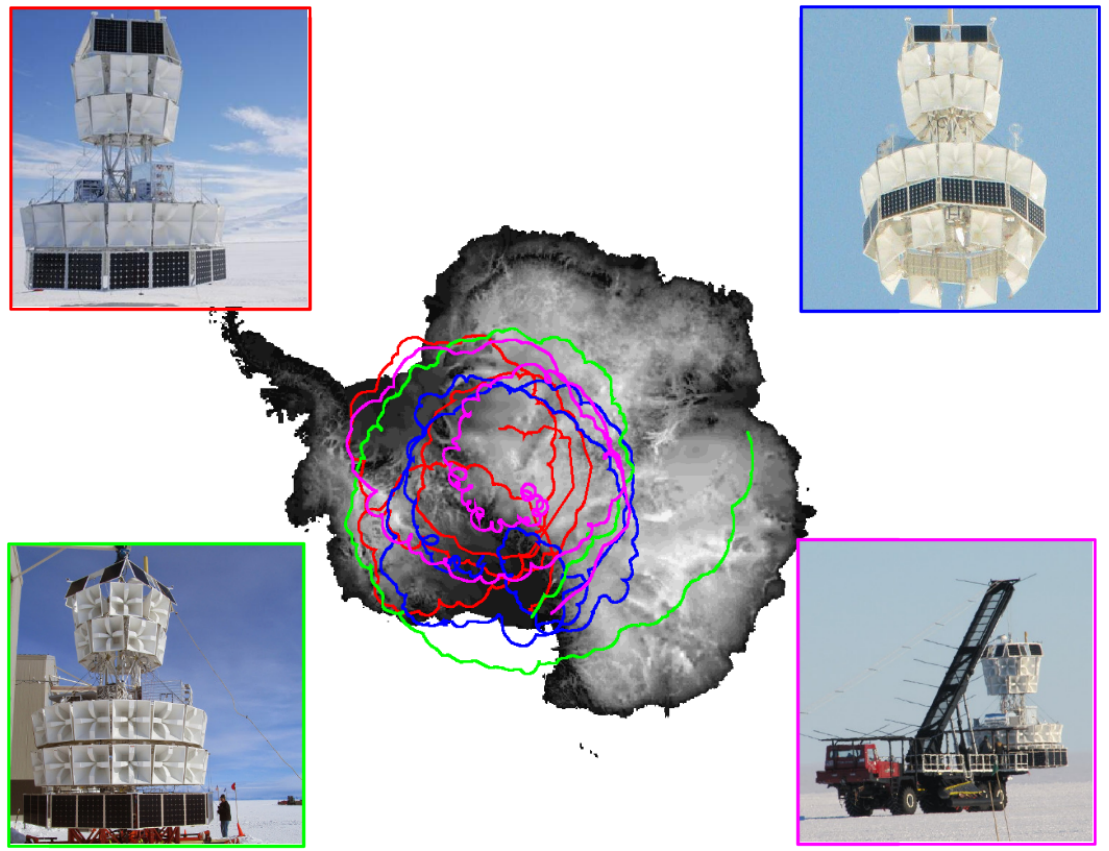
UCLA

- ANITA flies $\sim$ 37 km, horizon is 700km, -6° below the horizontal
- Earth skimming ultra-high energy νs interact in the ice
- Askaryan RF impulse emitted along Cherenkov cone
  - Radio attenuation lenth in ice, $\mathcal{O}$(1km)
  - ANITA observes $\mathcal{O}(10^6)$km^3 ice
- Top of RF cone refracts through the surface of the ice
  - Geometry + fresnel effects $\rightarrow$ mostly vertical polarization (VPol)
- Signal propagates through atmosphere to ANITA



Completed flights of ANITA

- ANITA-1 (2006)
  - 35 day flight
  - Banded linear pol trigger
- ANITA-2 (2008)
  - 30 day flight
  - Banded VPol-only trigger
- ANITA-3 (2014)
  - 22 day flight
  - Single band HPol and VPol trigger
- ANITA-4 (2016)
  - 29 day flight
  - Single band linear pol trigger

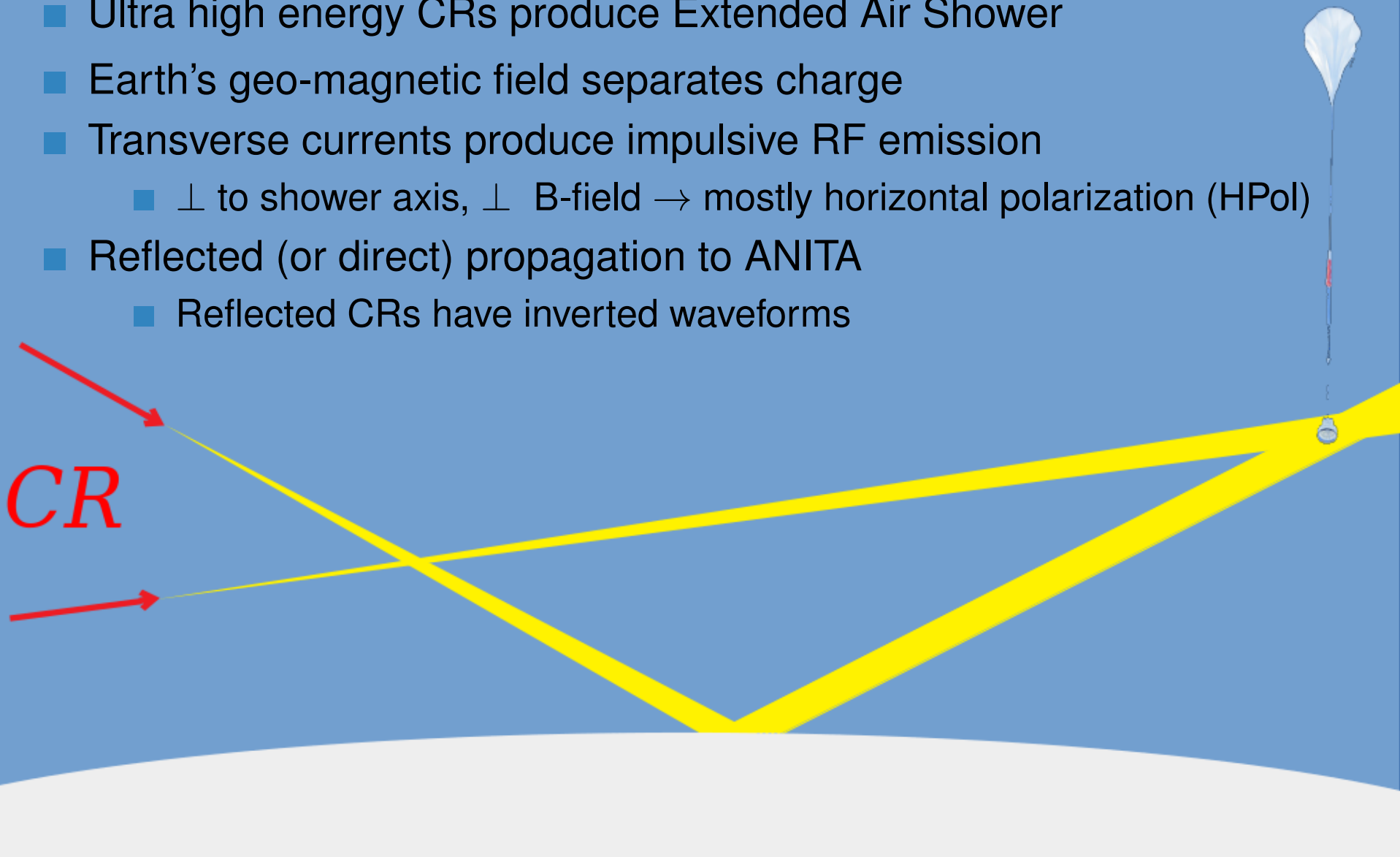


- ANITA-5 (????)
  - Proposal with completely new trigger and digitizer system

Ultra-high energy cosmic rays

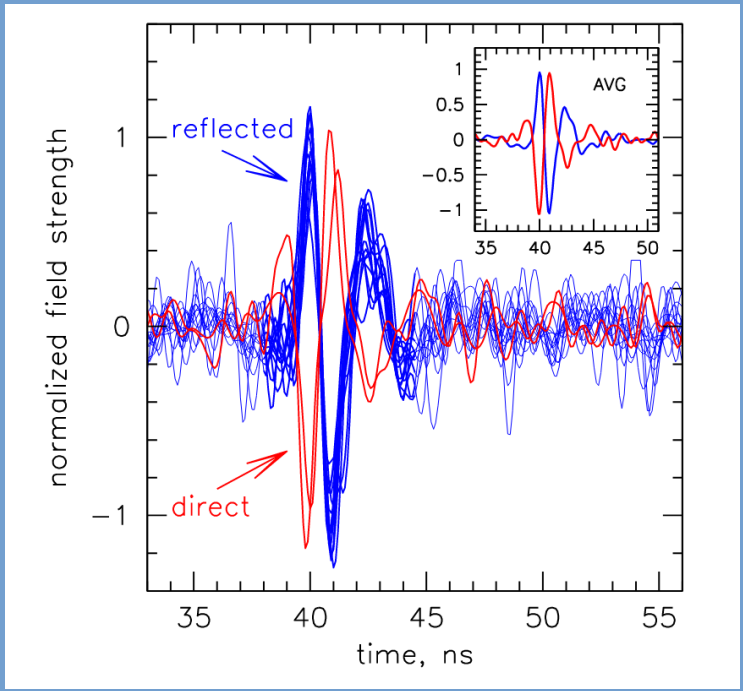
UCLA

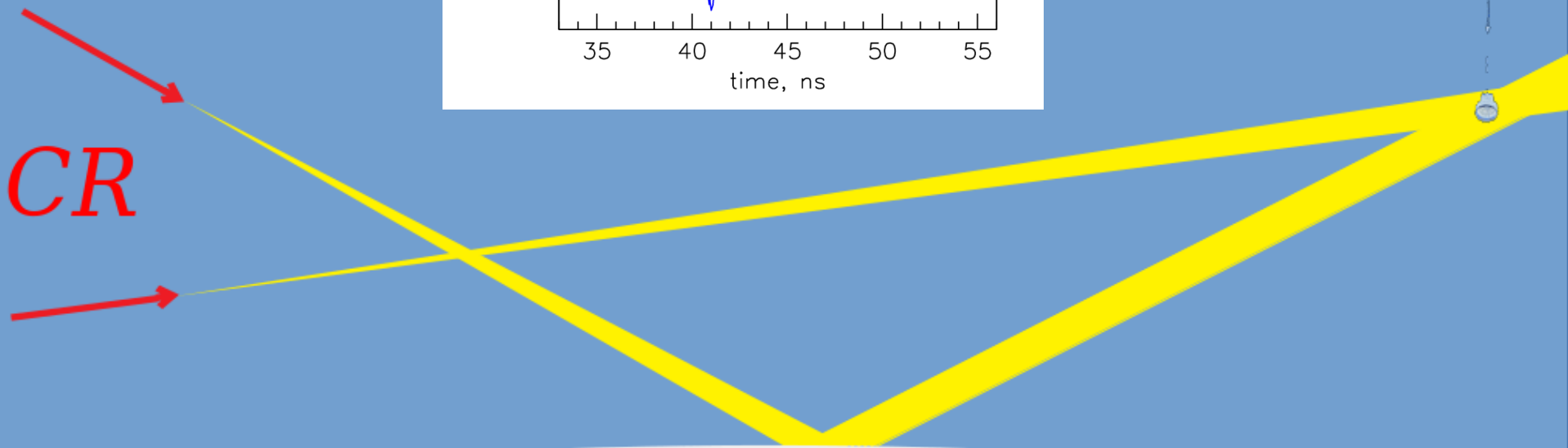
- Ultra high energy CRs produce Extended Air Shower
- Earth's geo-magnetic field separates charge
- Transverse currents produce impulsive RF emission
  - $\perp$ to shower axis, $\perp$ B-field $\rightarrow$ mostly horizontal polarization (HPol)
- Reflected (or direct) propagation to ANITA
  - Reflected CRs have inverted waveforms



Ultra-high energy cosmic rays

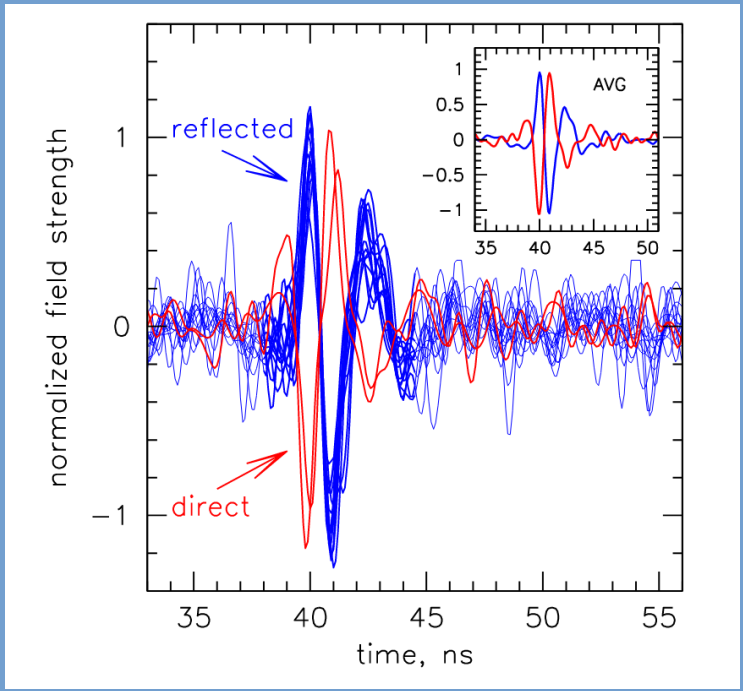
UCLA

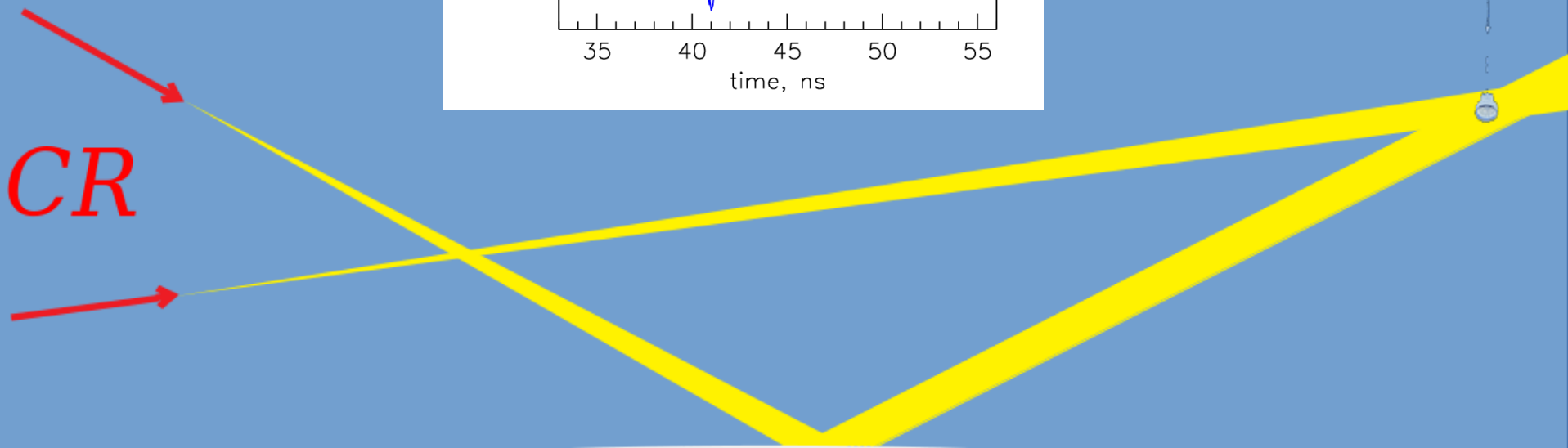




Ultra-high energy cosmic rays

UCLA



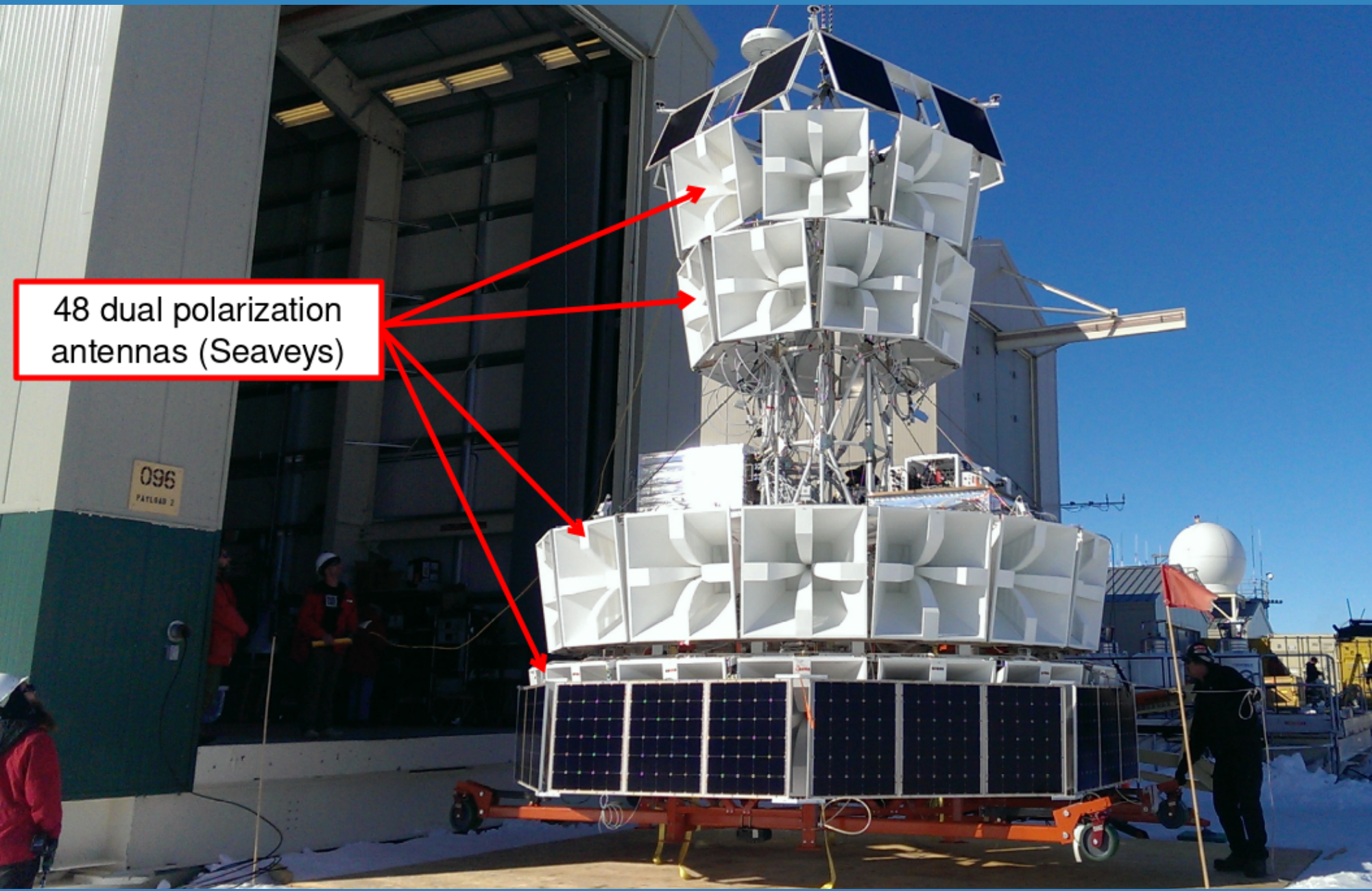


ANtarctic Impulsive Transient Antenna (ANITA)

UCLA

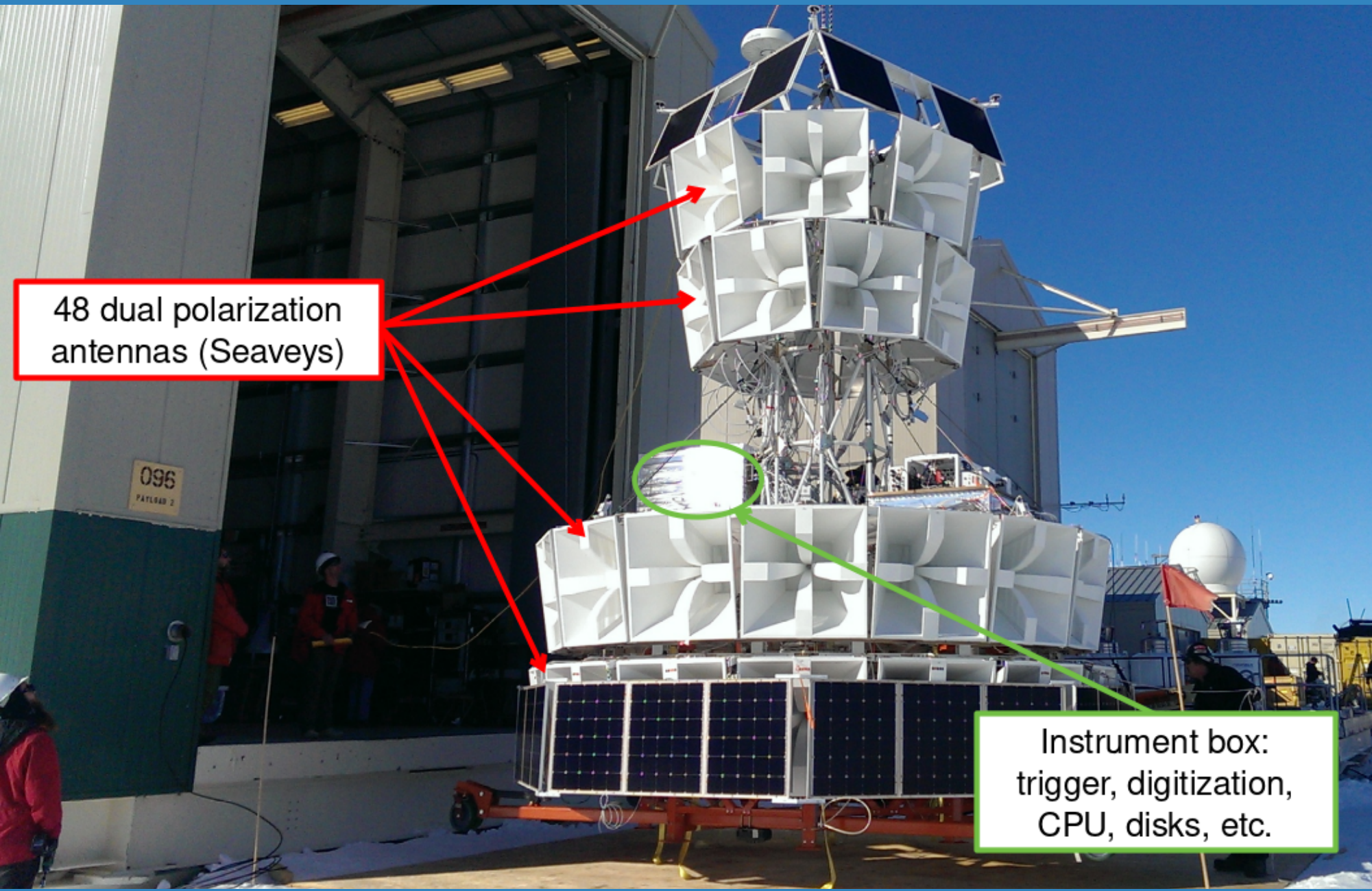
ANtarctic Impulsive Transient Antenna (ANITA)

UCLA



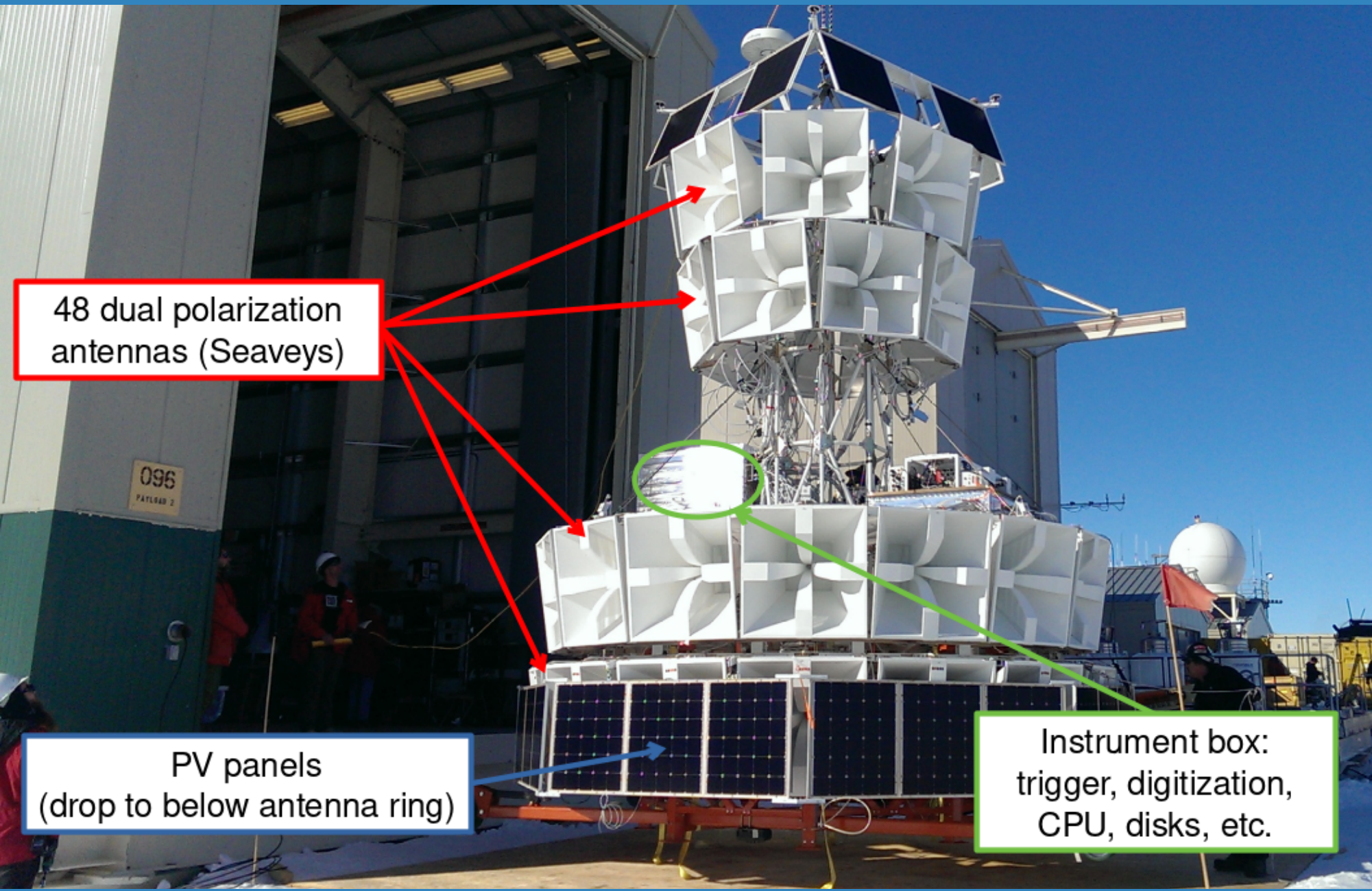
ANtarctic Impulsive Transient Antenna (ANITA)

UCLA



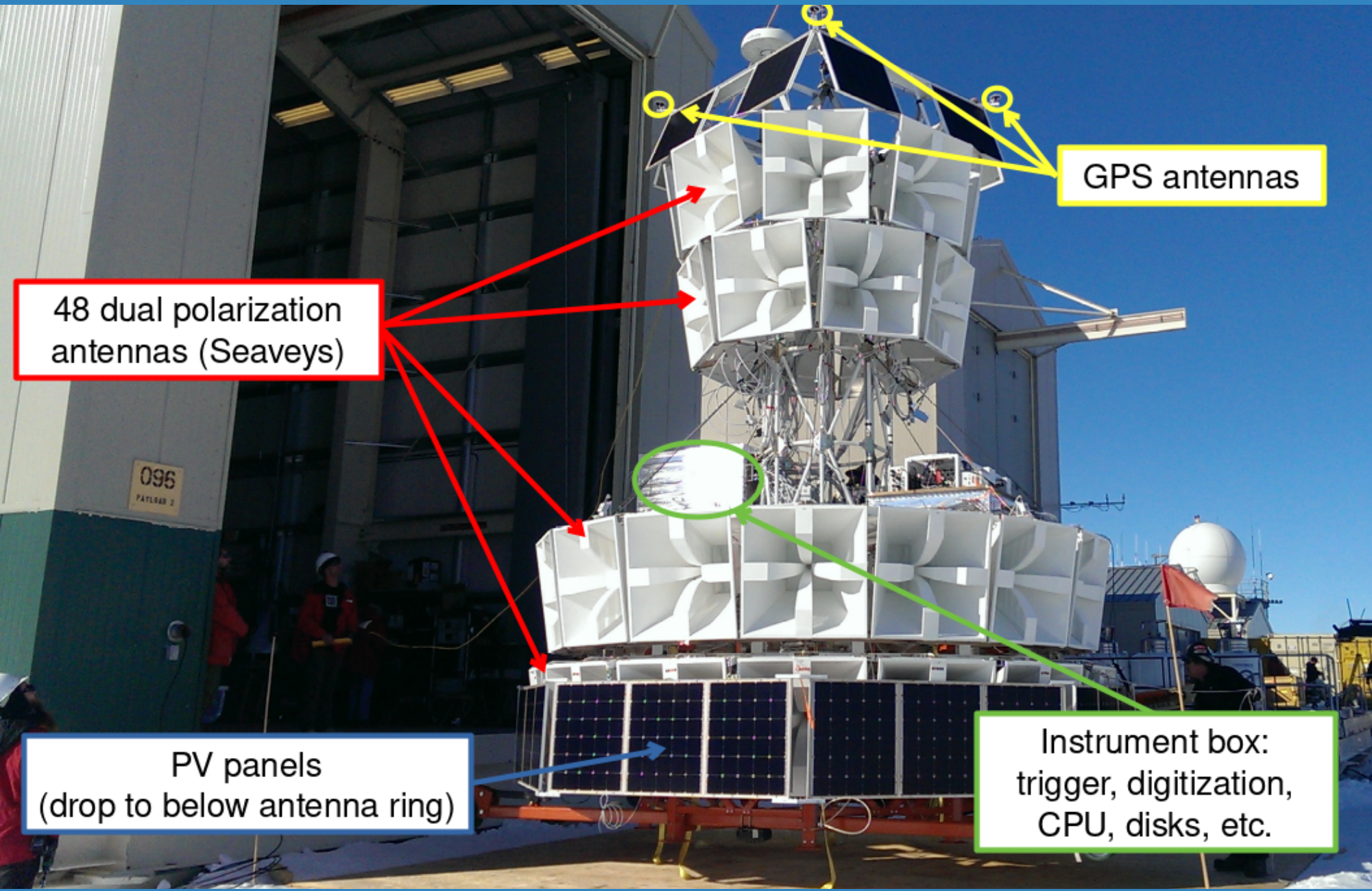
ANtarctic Impulsive Transient Antenna (ANITA)

UCLA



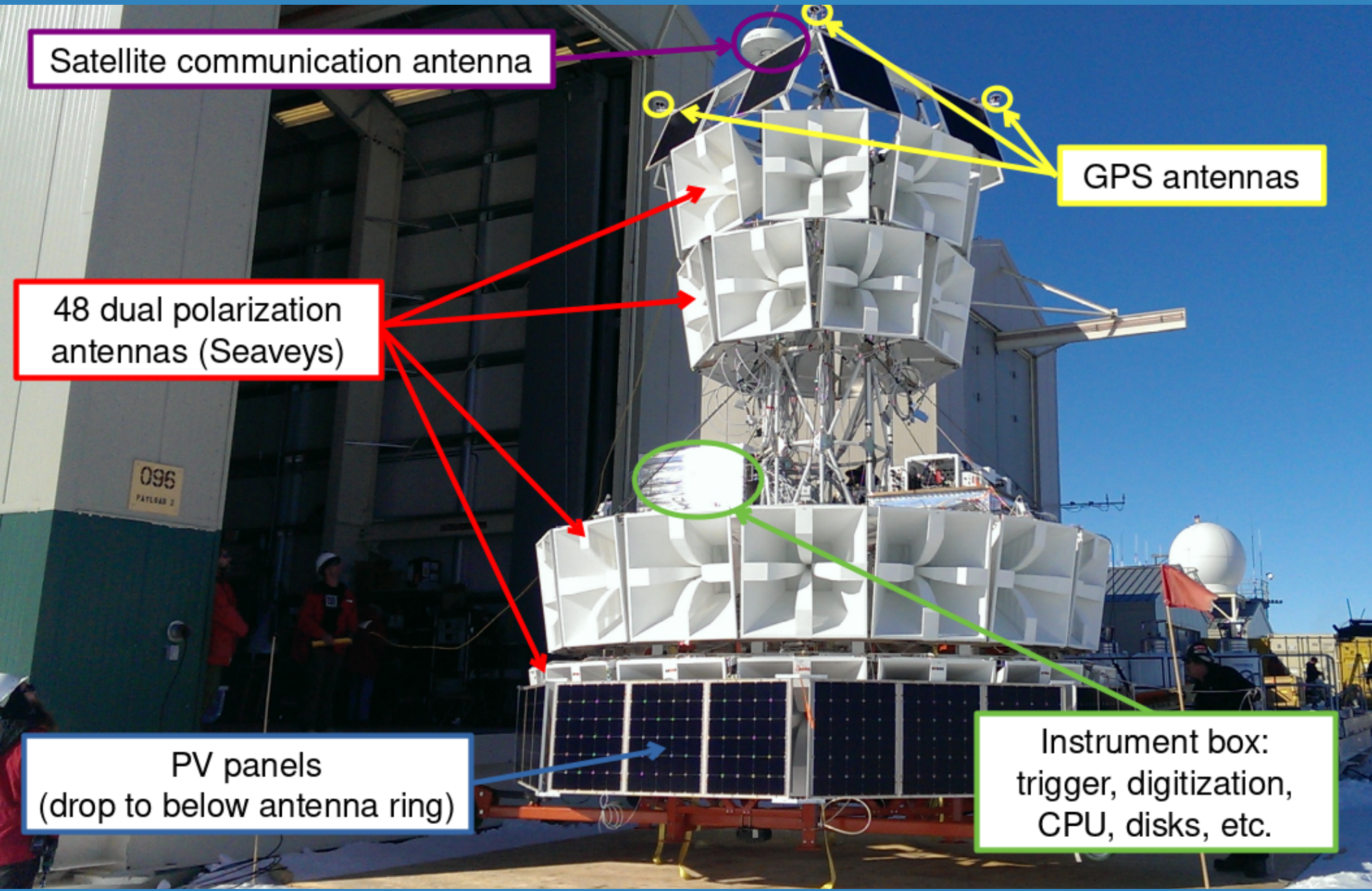
ANtarctic Impulsive Transient Antenna (ANITA)

UCLA



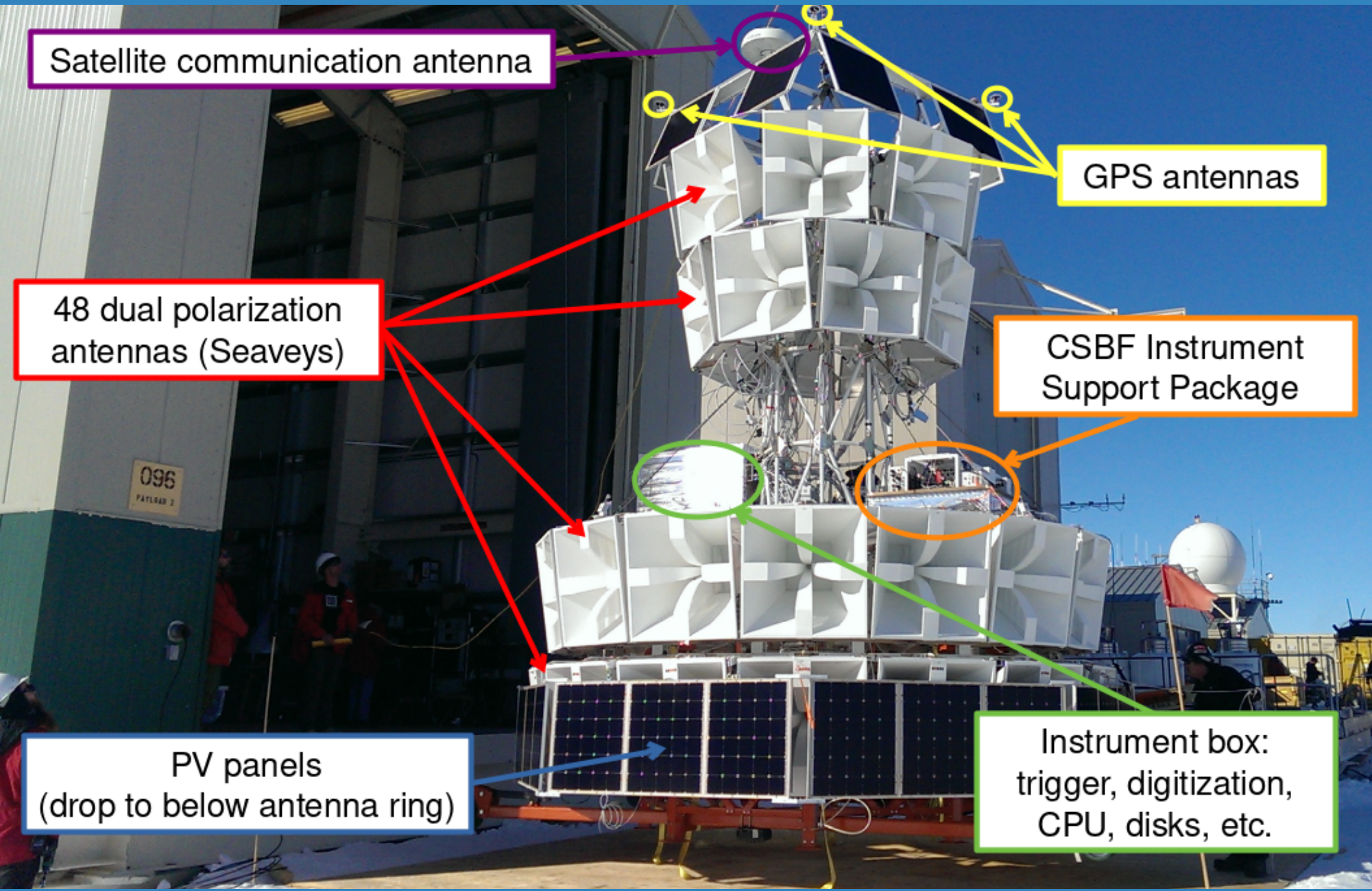
ANtarctic Impulsive Transient Antenna (ANITA)

UCLA

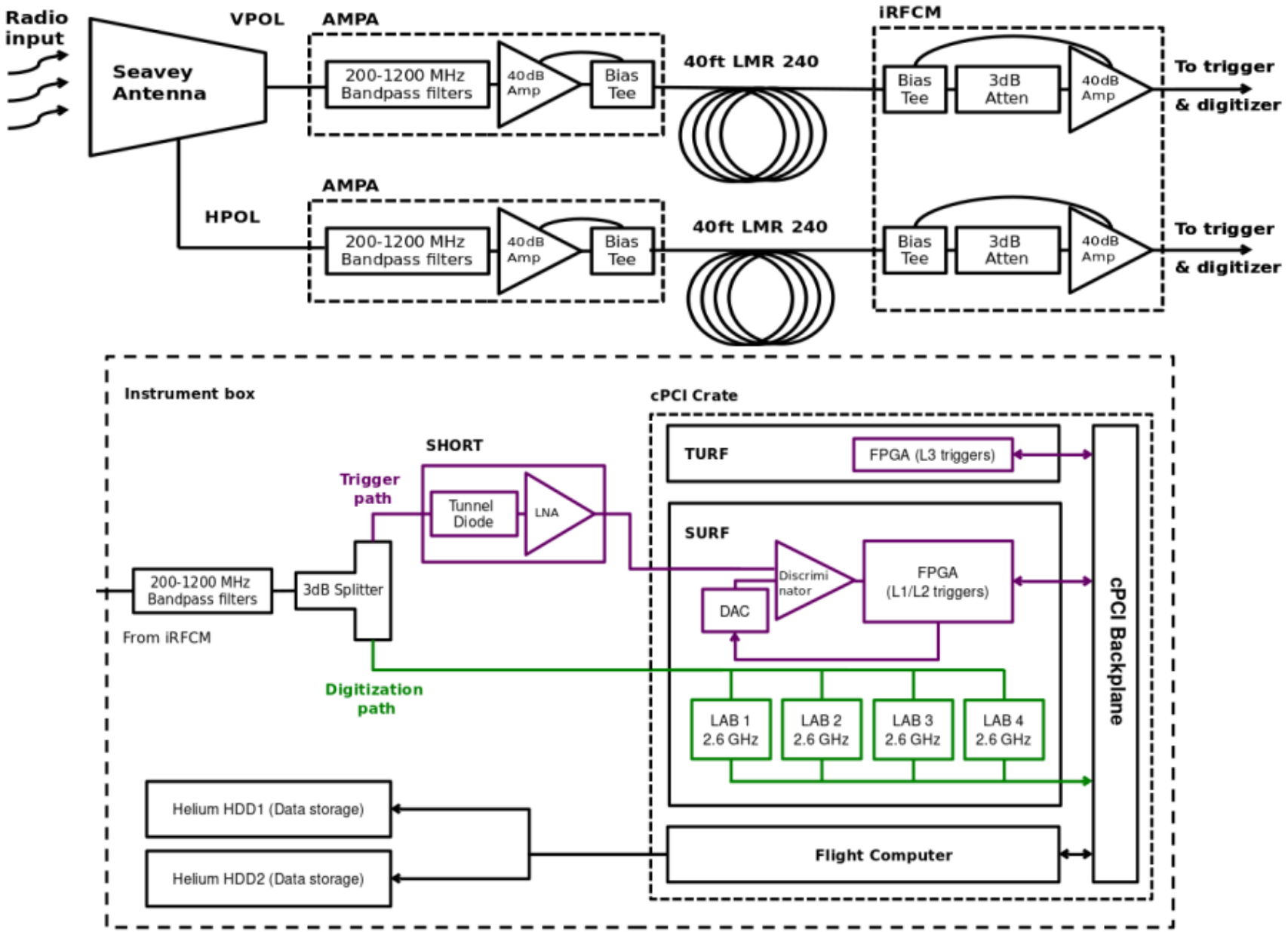


ANtarctic Impulsive Transient Antenna (ANITA)

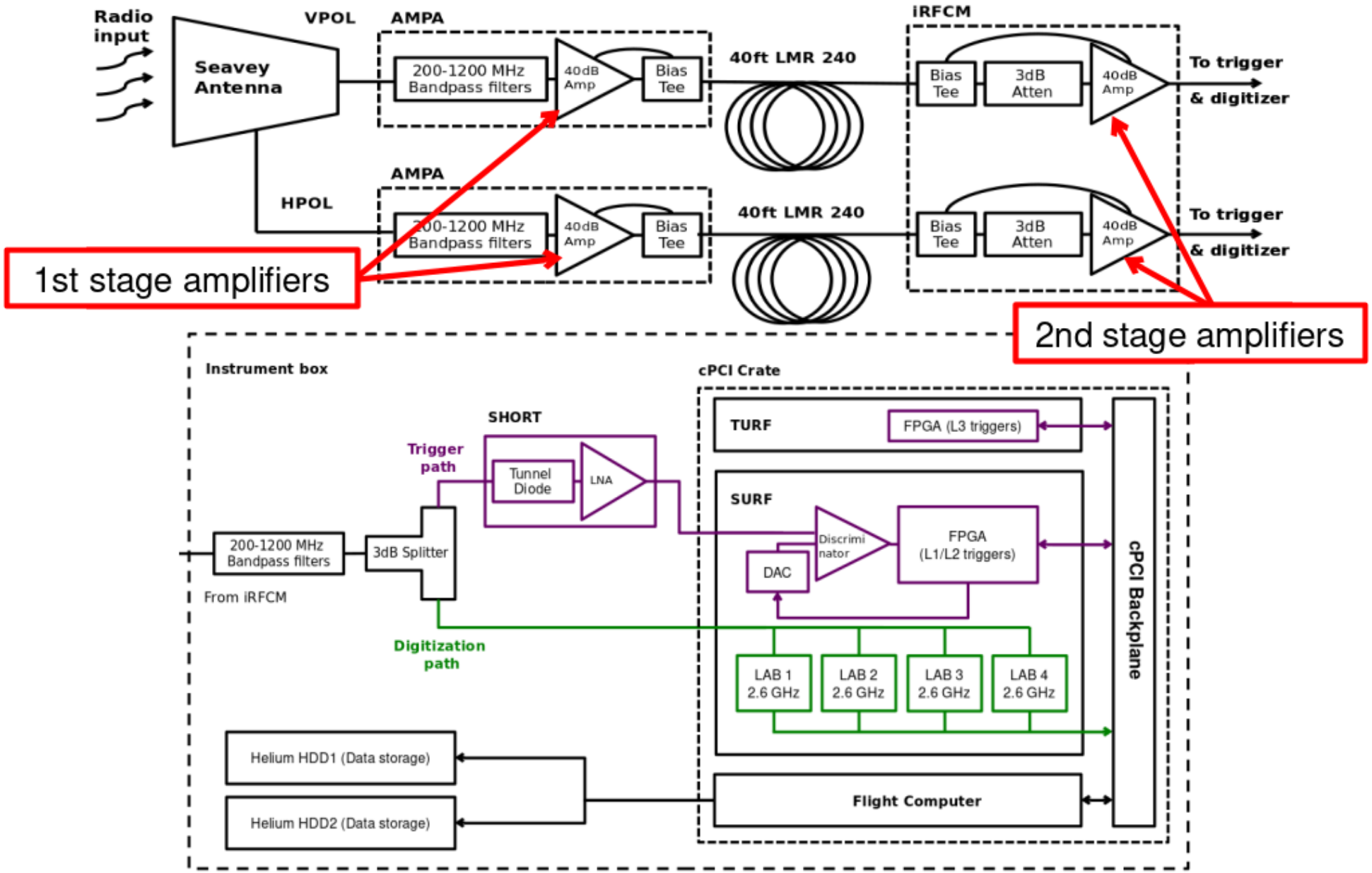
UCLA



Signal chain

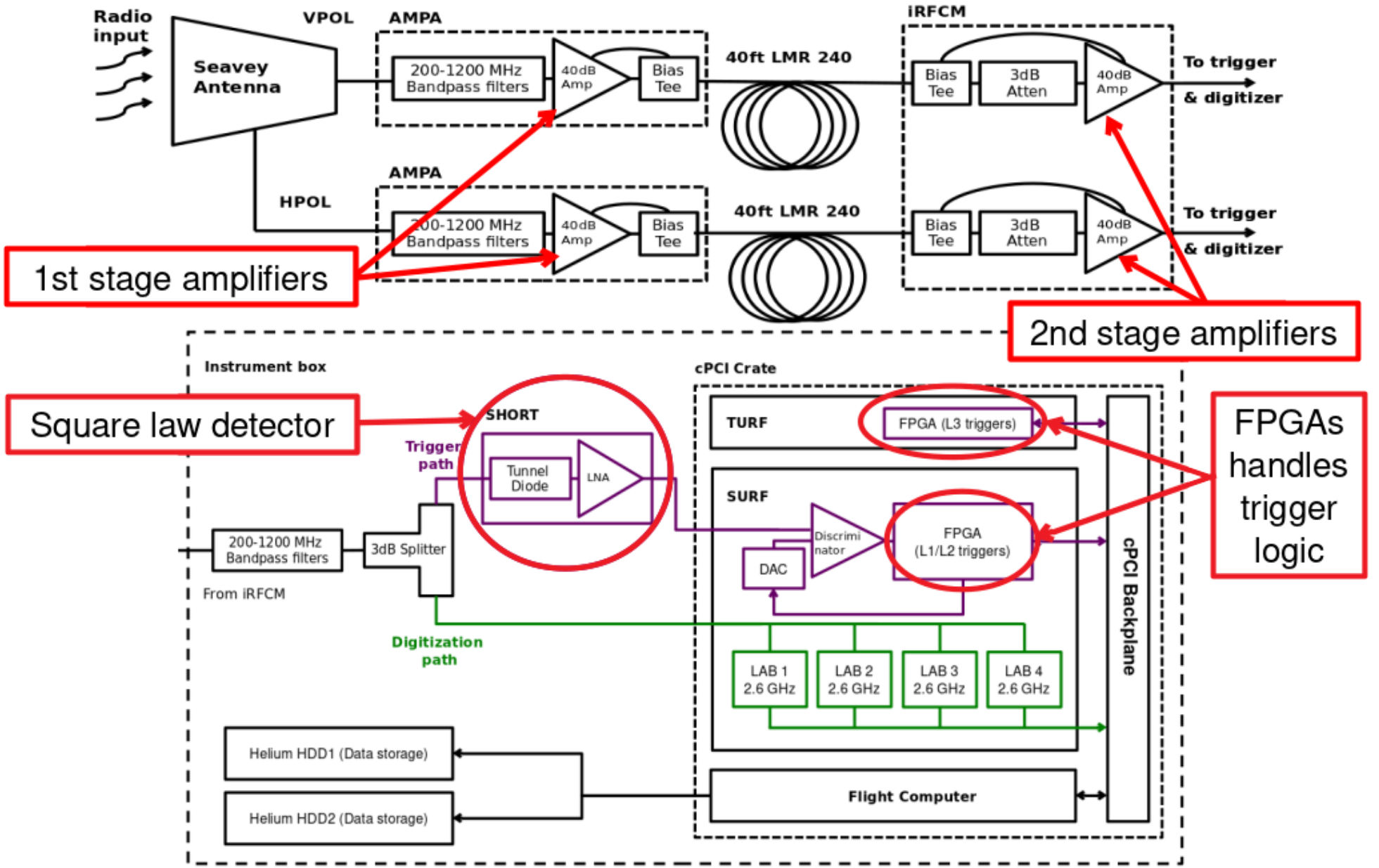


Signal chain

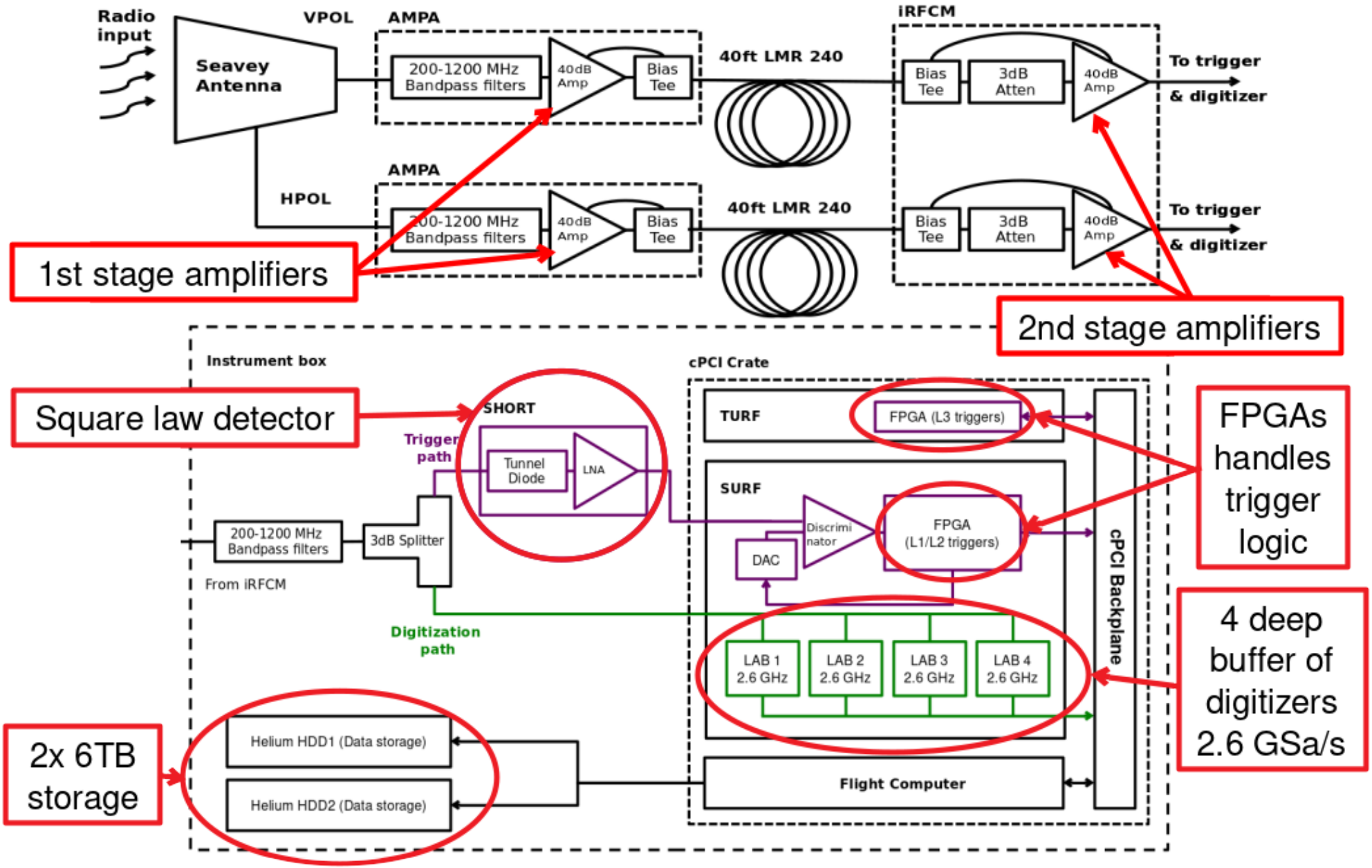


Signal chain

UCLA



Signal chain



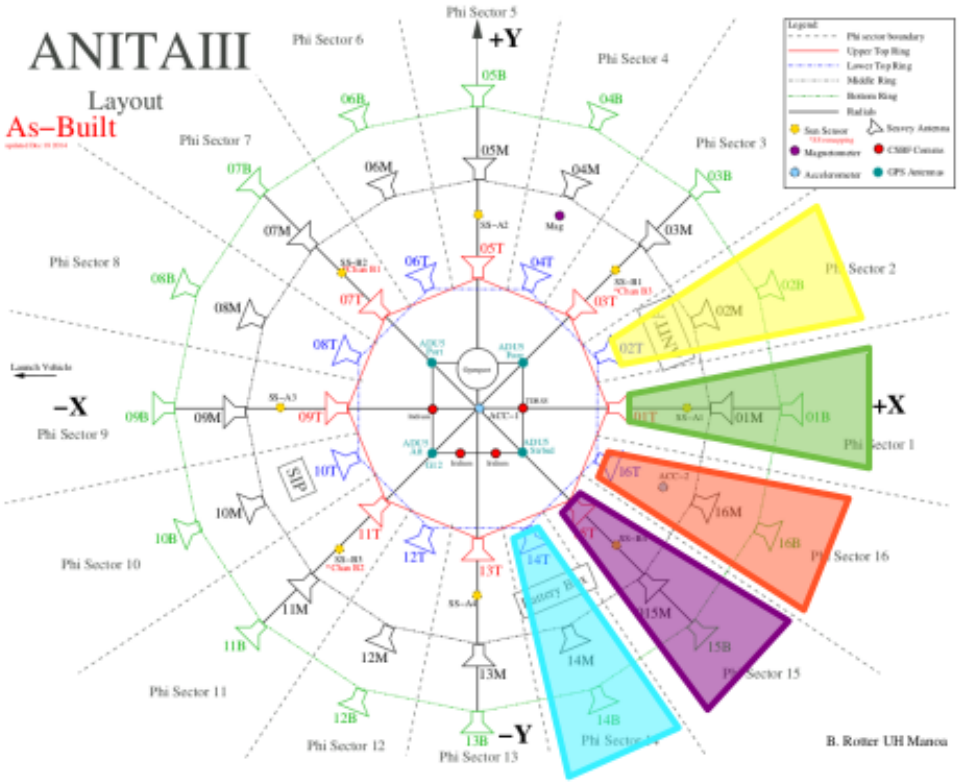
Trigger logic

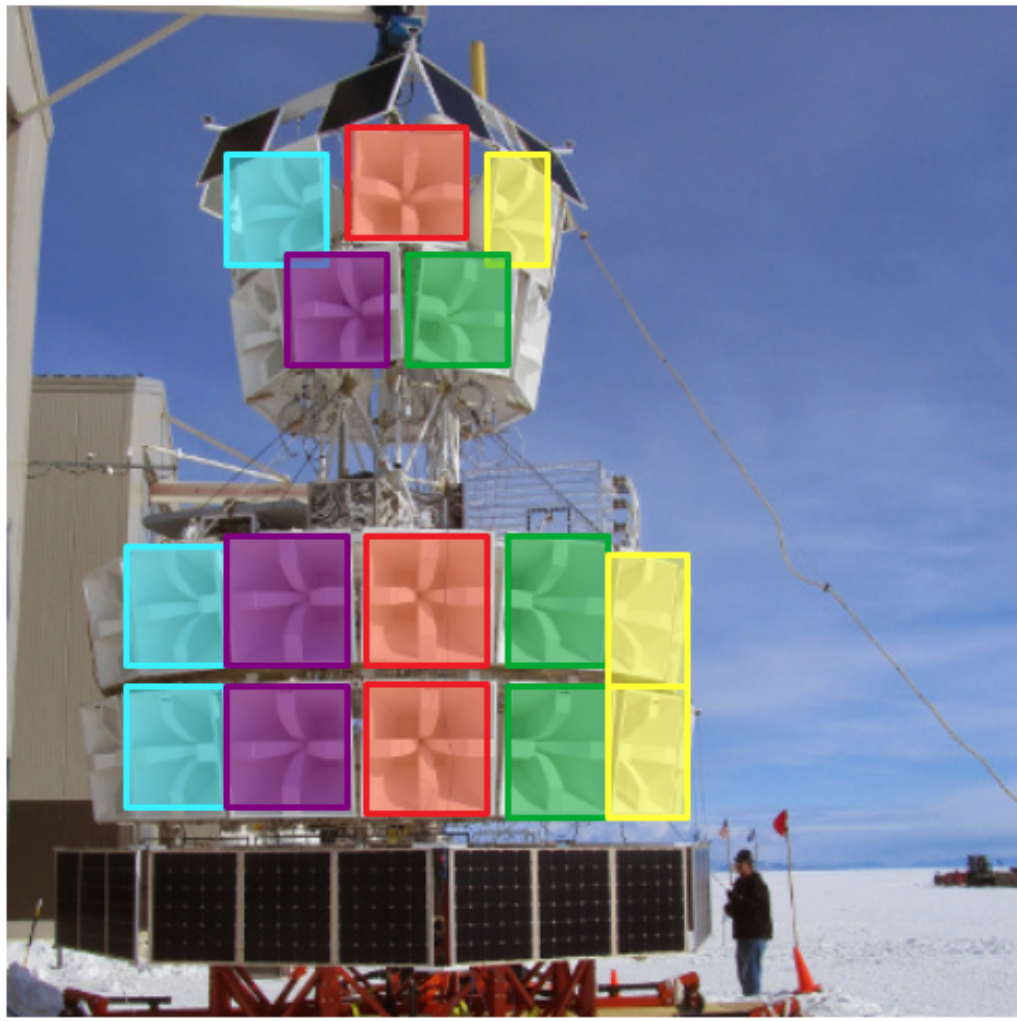
UCLA

- Lower thresholds by requiring multi-channel coincidence in space and time!
  - Bandwidth + power limits $\rightarrow \sim 50$ Hz to disk
  - Single channel scalar rate: $\mathcal{O}\left(5 \times 10^5\right)$ Hz
- For ANITA-3: separate VPol and HPol triggers
  - L1 trigger is single channel above threshold
- For ANITA-4: combine VPol and HPol to make linear pol trigger
  - Mix V+H into left + right circular polarization (LCP+RCP)
  - L0 is either LCP or RCP above threshold
  - L1 trigger is single channel above threshold

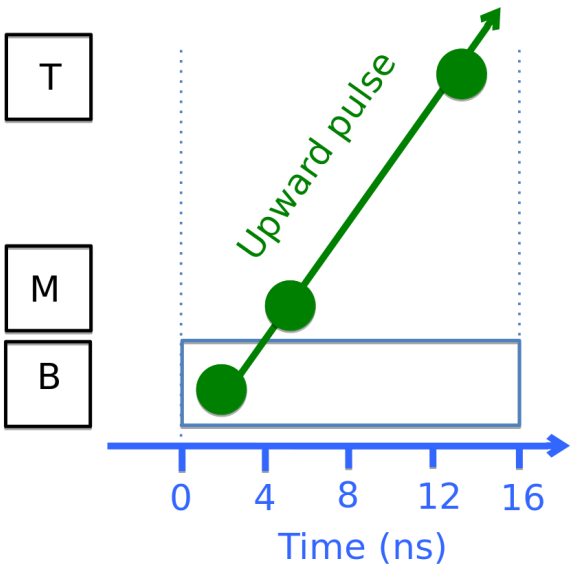
Φ-sectors

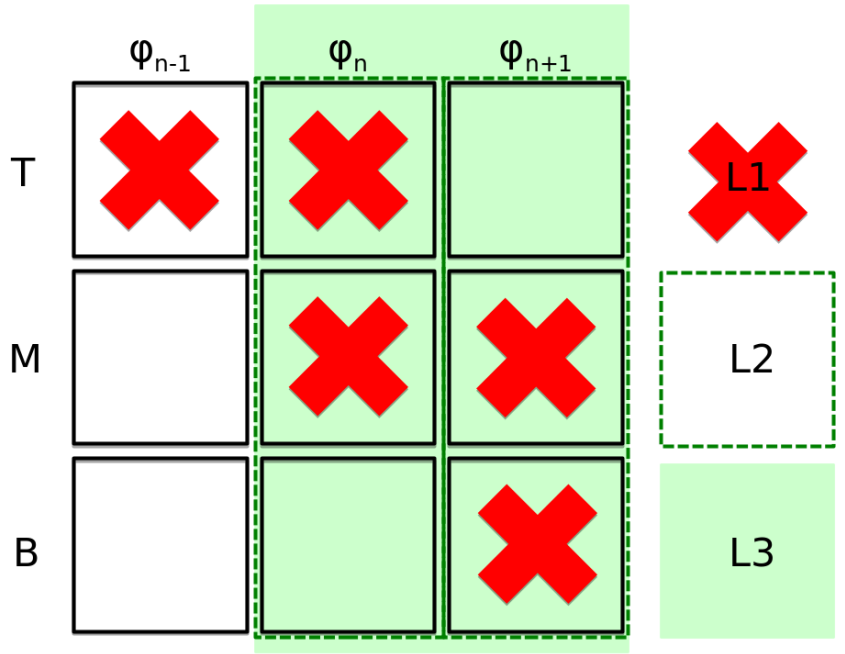
- Group 48 antennas → 16 sets of 3 vertically aligned Φ-sectors





L2 and L3 triggers

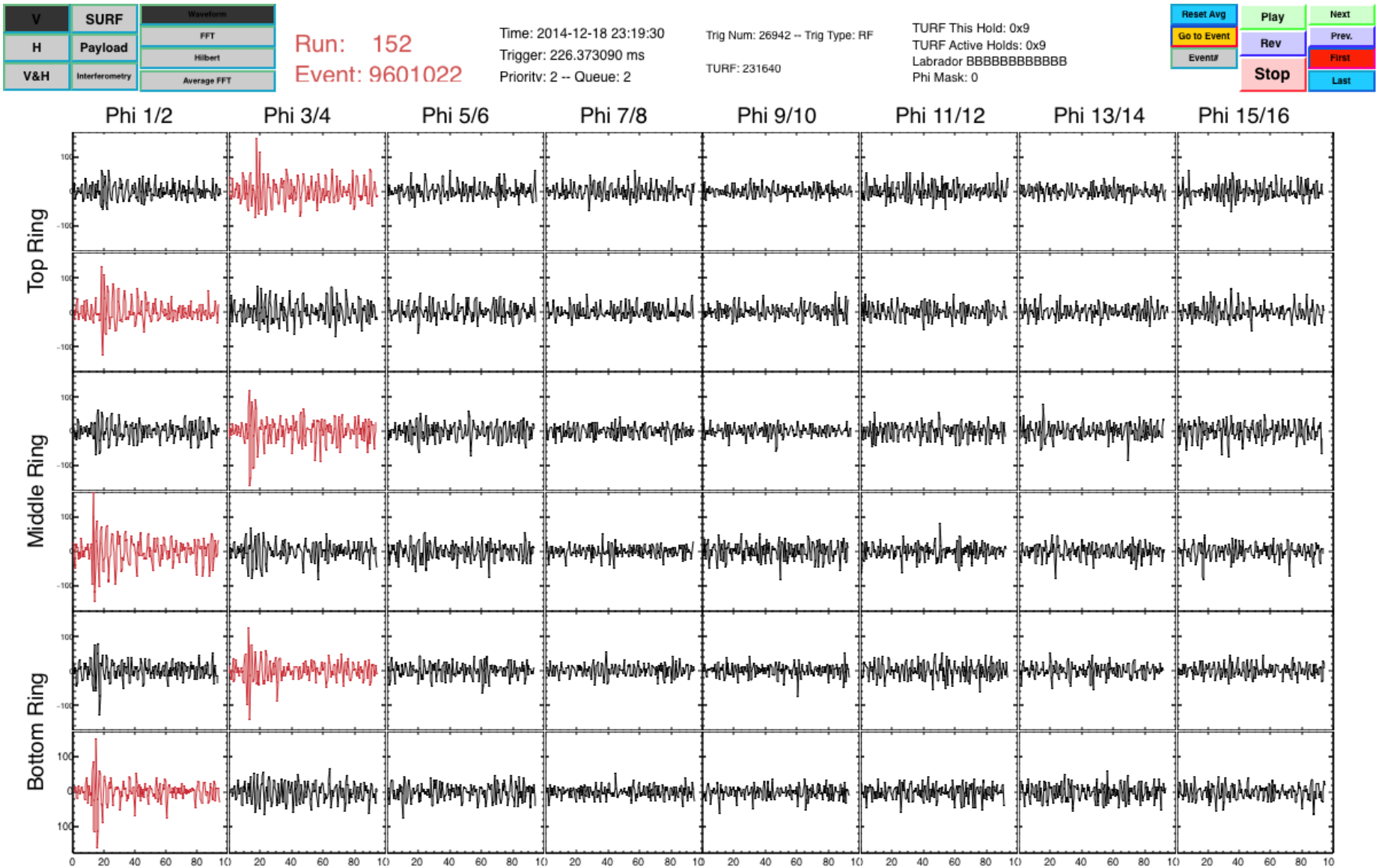




- L2 (Φ-sector) trigger requires 2/3 antennas in a ϕ-sector
- Each L1 trigger opens window:
  - Bottom 16ns
  - Middle 12ns
  - Top 4ns
- L3 (event) requires 2× L2 triggers in adjacent ϕ-sectors within 8ns

ANITA data

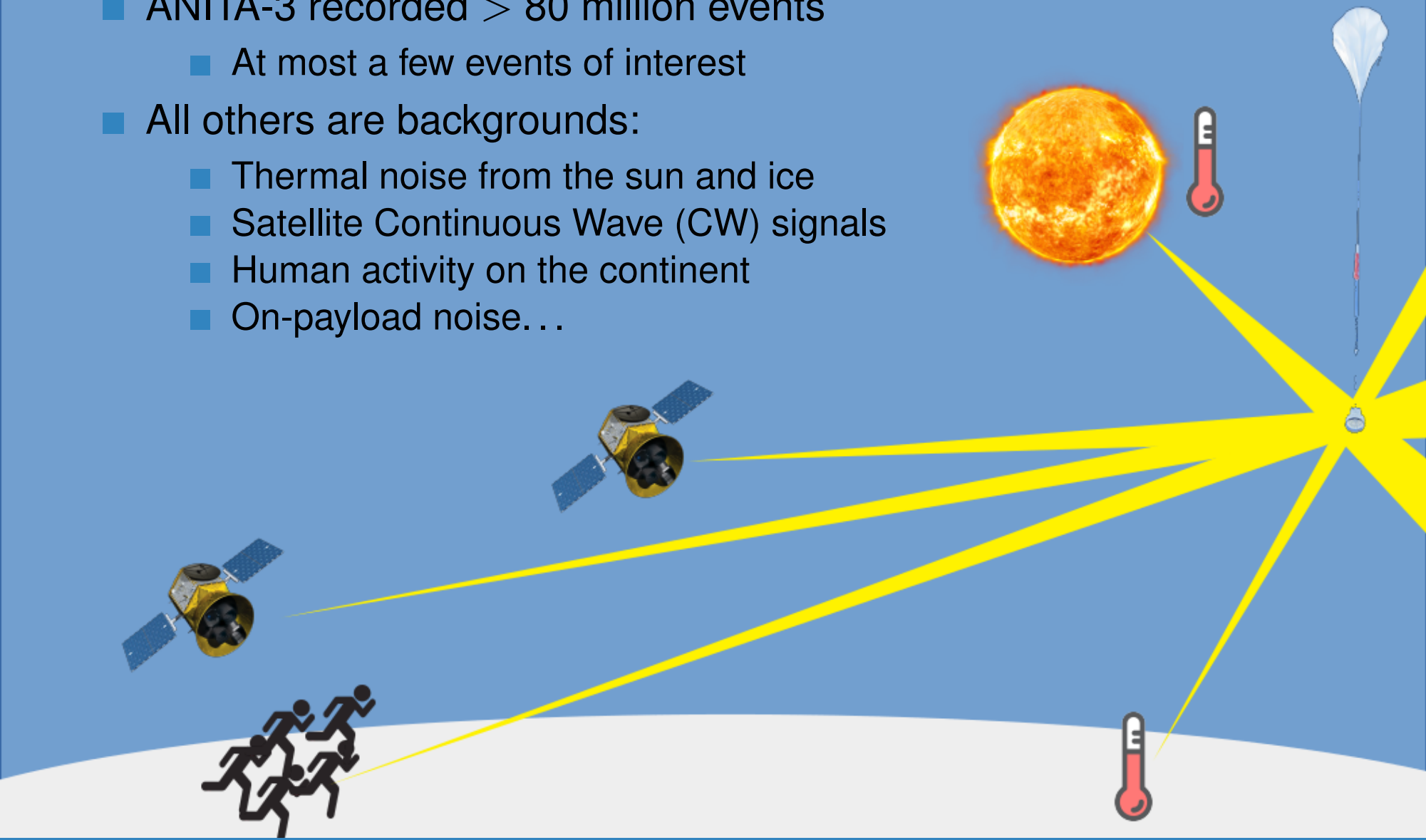
UCLA



ANITA-3 diffuse ν search 10.1103/PhysRevD.98.022001

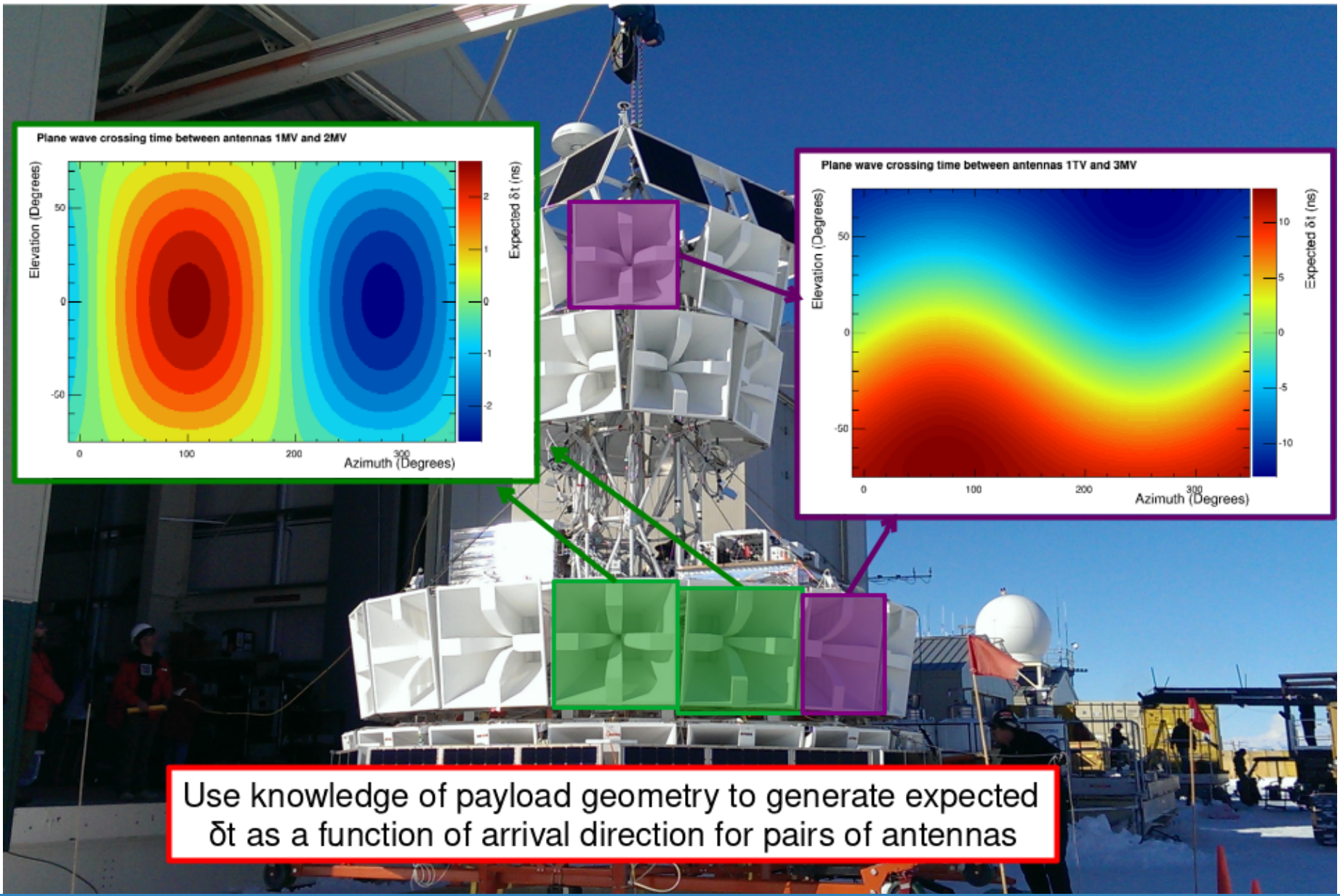
UCLA

- ANITA-3 recorded $>$ 80 million events
  - At most a few events of interest
- All others are backgrounds:
  - Thermal noise from the sun and ice
  - Satellite Continuous Wave (CW) signals
  - Human activity on the continent
  - On-payload noise...



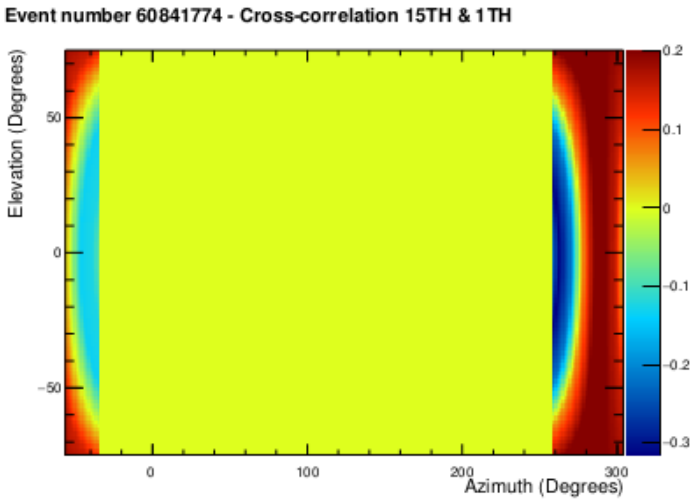
Directional reconstruction

UCLA

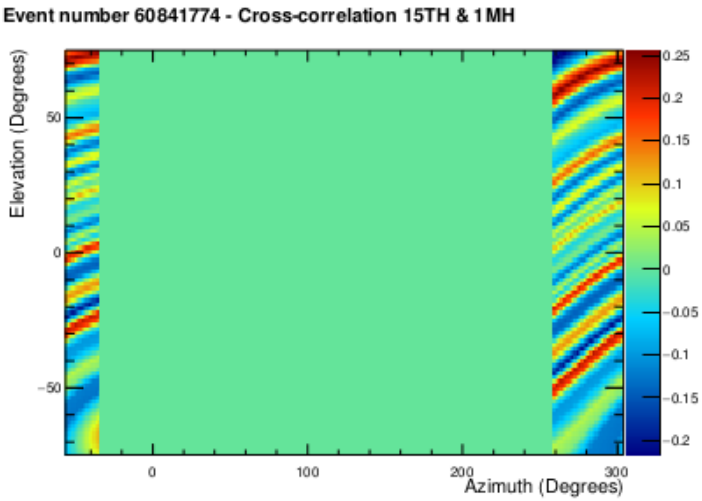


Use knowledge of payload geometry to generate expected δt as a function of arrival direction for pairs of antennas

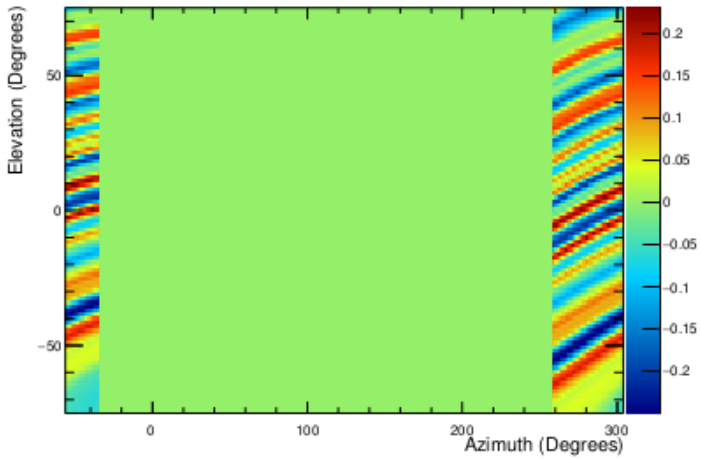
Summing cross-correlations



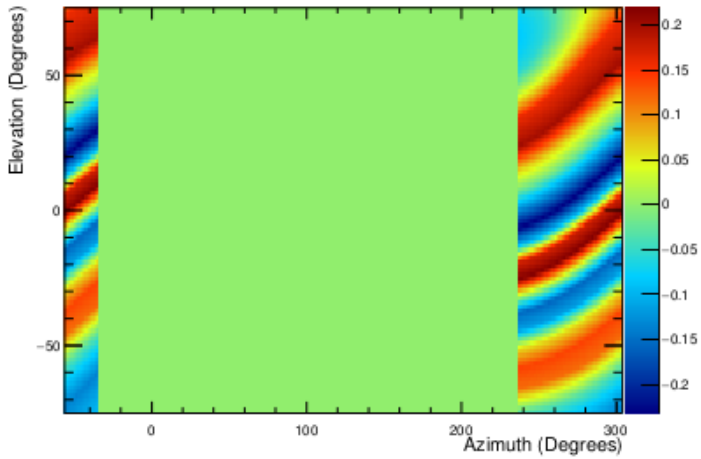
(a) 1TH & 15TH



(b) 1MH & 15TH



(c) 1BH & 15TH



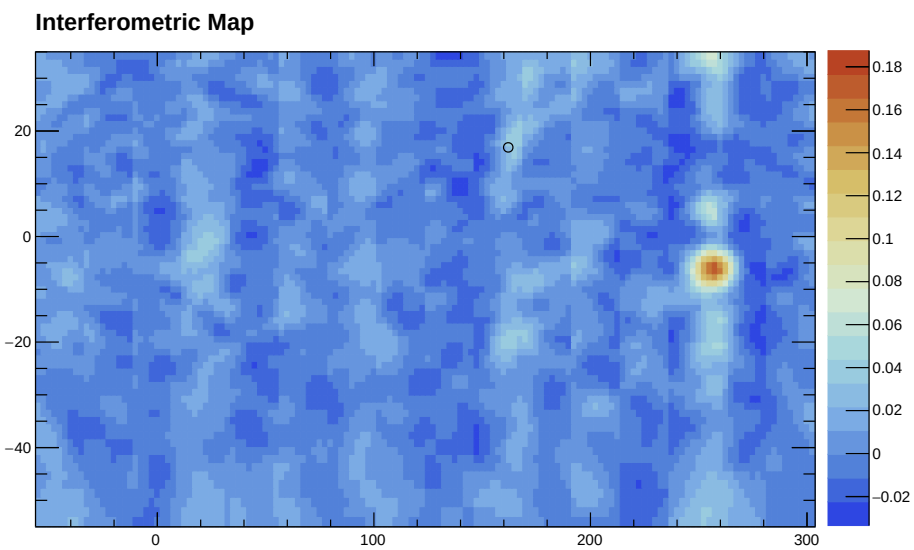
(d) 16TH & 15TH

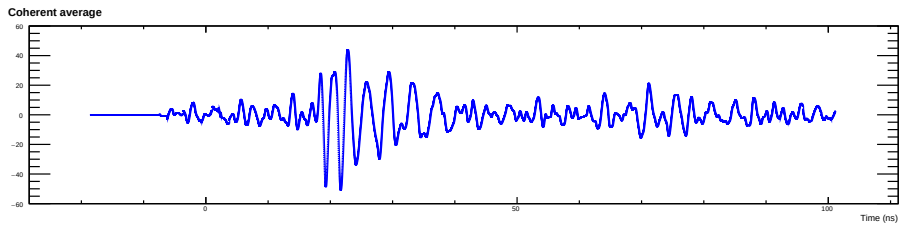
Event reconstruction

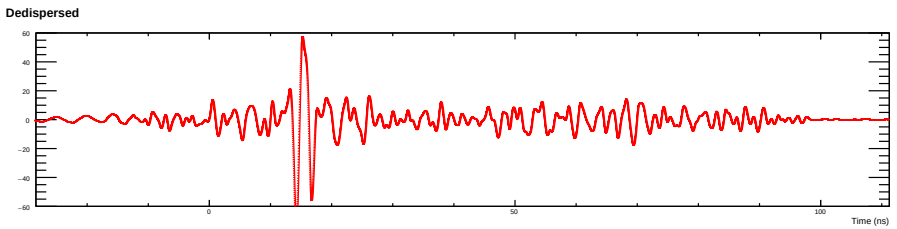
UCLA

1. Iterative sine-wave subtraction (reduce satellite CW)
2. Directional reconstruction*
   - Antenna positions: $\delta t(\phi, \theta)$
   - Inter-channel cross-correlation: $\rho(\delta t)$
   - Interferometric map $\rho(\phi, \theta)$
   - $(\phi_{peak}, \theta_{peak}) \rightarrow$ direction
3. Coherently average: delay channels by $\delta t(\phi_{peak}, \theta_{peak})$ and average
4. Dedisperse: Remove frequency dependent delay introduced by signal chain

*arXiv:1304.5663



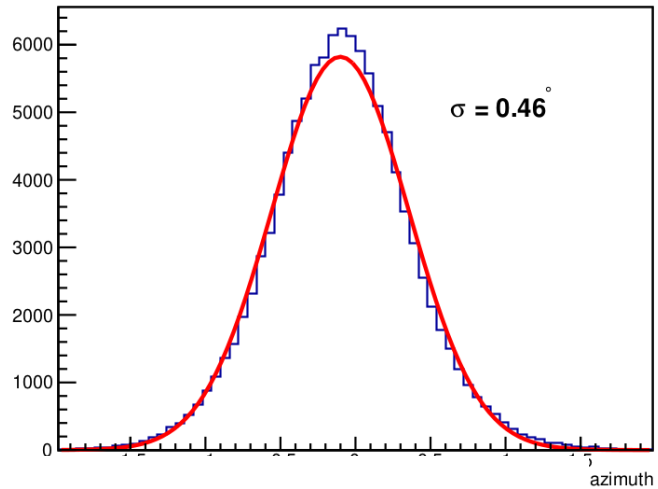


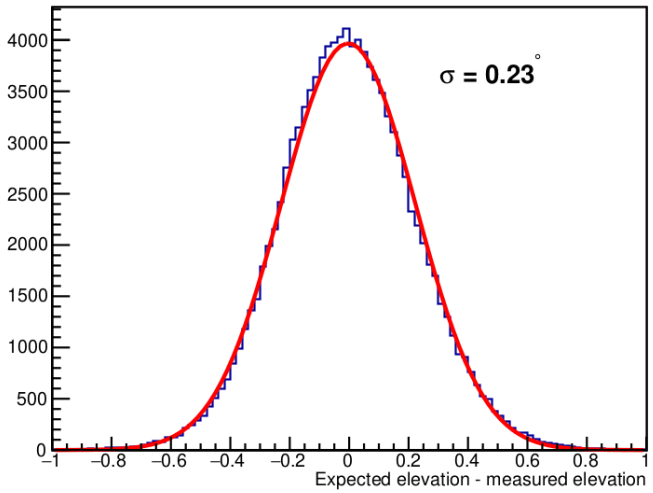


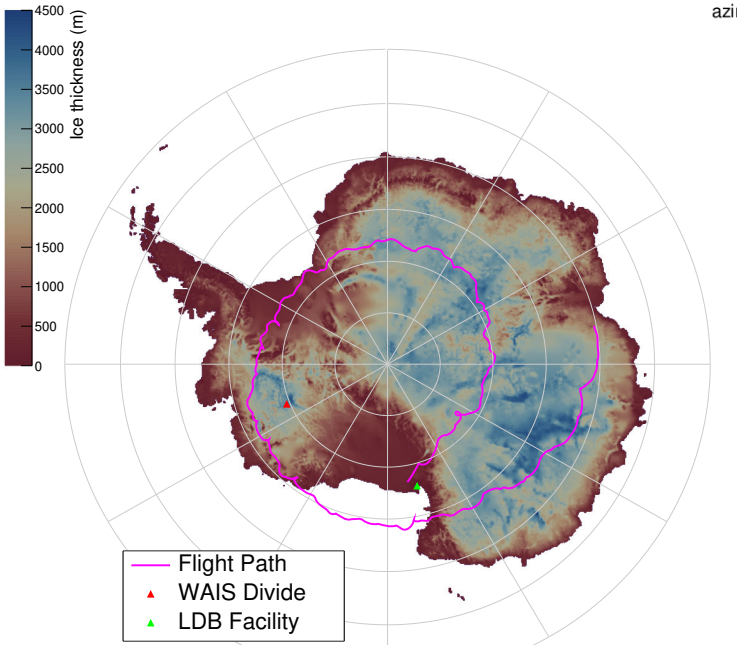
Calibration pulsing

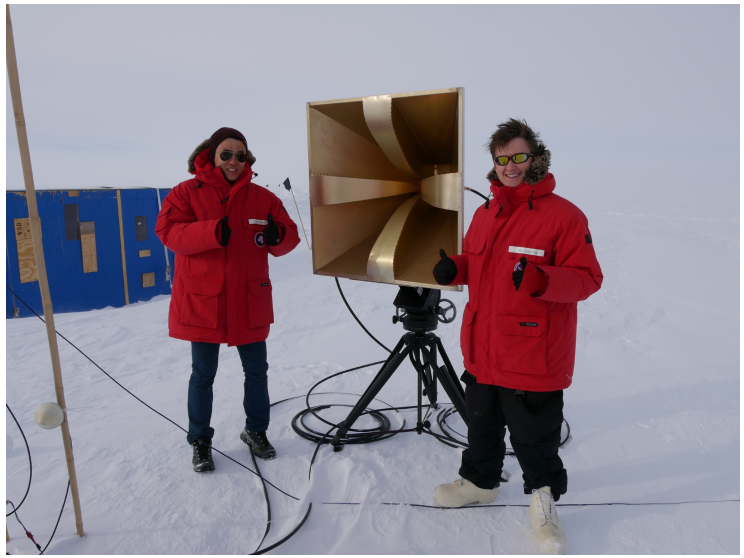
UCLA

- Sub-degree resolution in azimuth (left) and elevation (right)





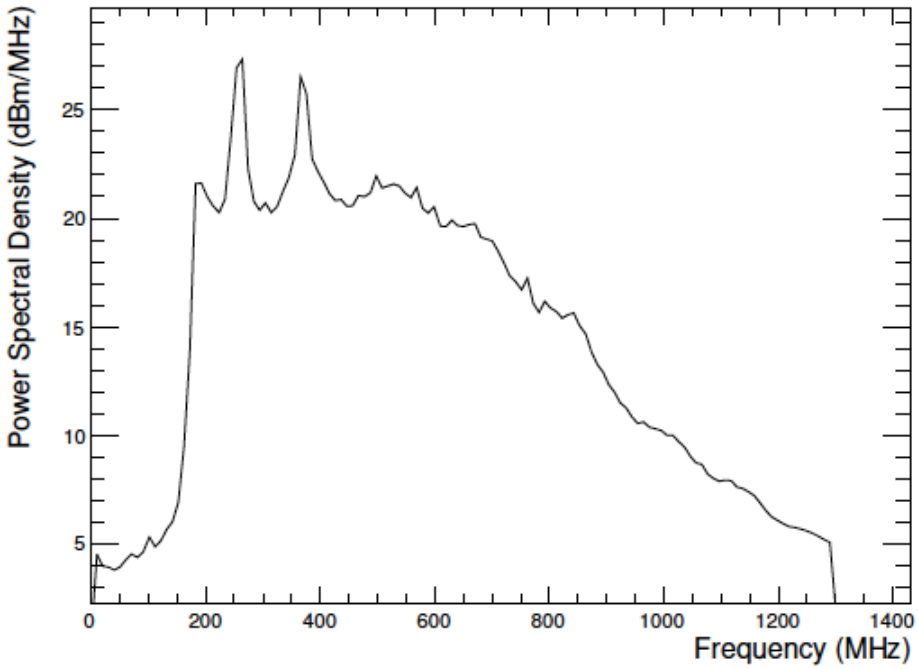




Satellite noise

UCLA

- Satellites use frequencies in the ANITA band (200-1200 MHz)

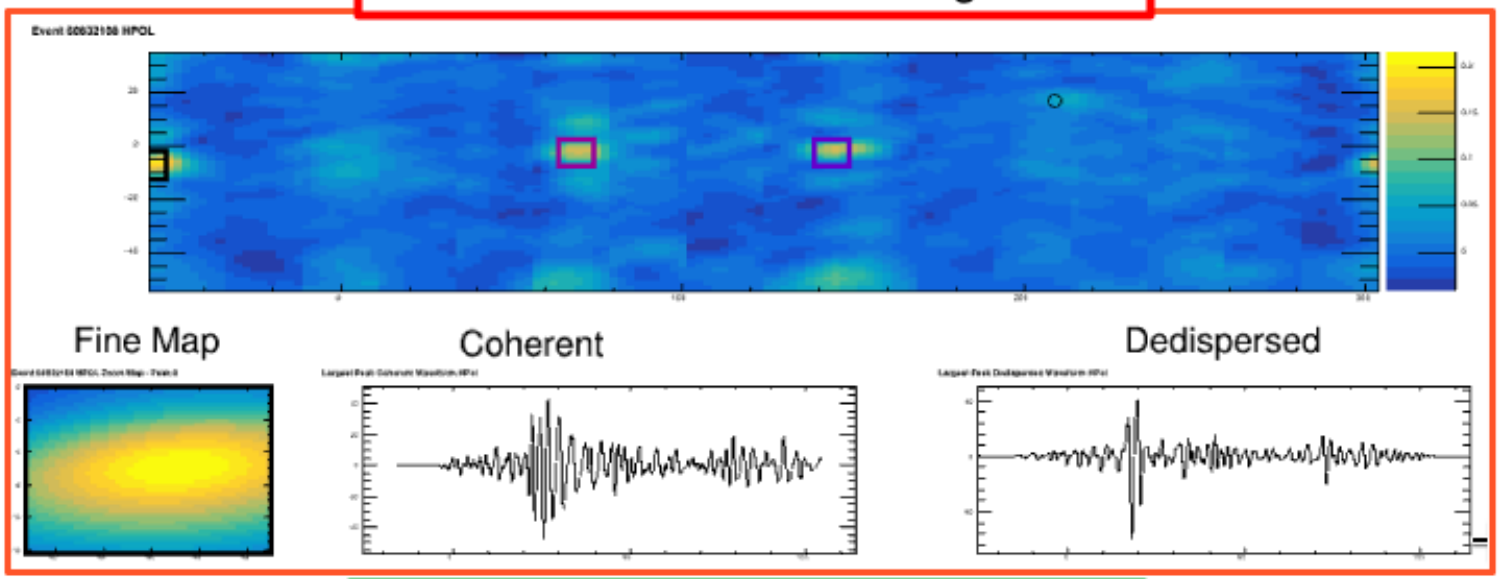


- ANITA-3: remove in software
  - Iterative sine wave fitting and subtraction
- ANITA-4: remove in hardware
  - Installed dynamic narrow band notches

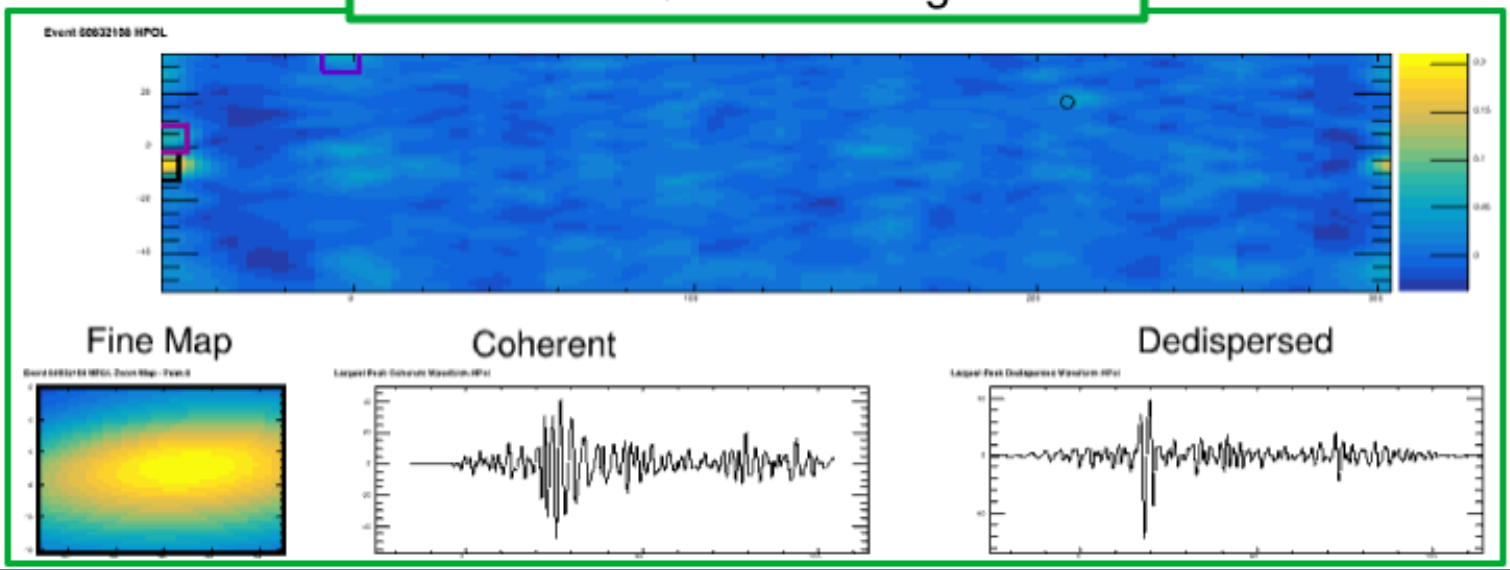
Software filtering

UCLA

Before sine subtraction algorithm



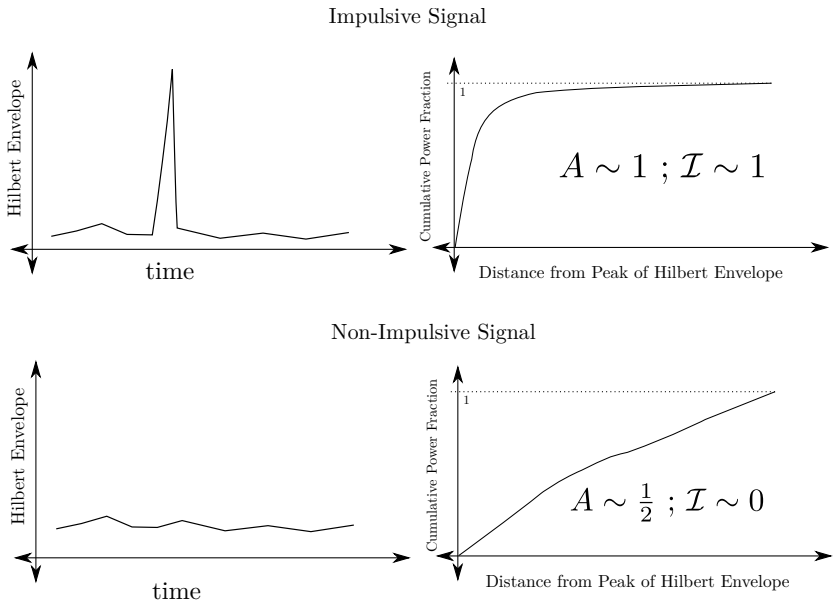
After sine subtraction algorithm



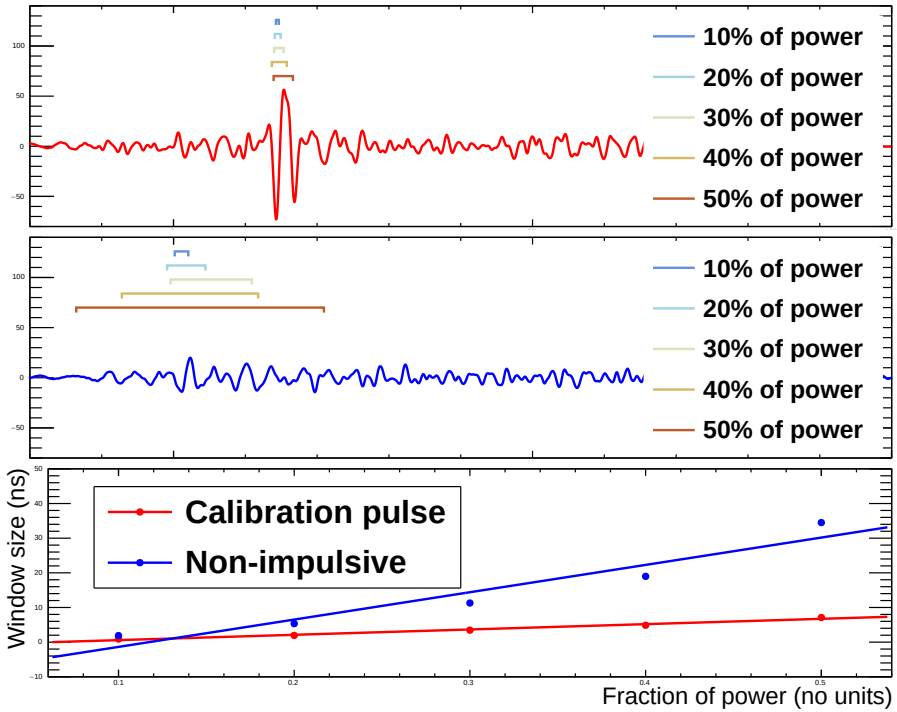
Two Impulsivity metrics $\mathcal{I}$ and $\mathcal{G}$

UCLA

- Compute Hilbert Envelope
  - Normalize area = 1
- Do bi-directional integration out from peak
- $\mathcal{I} = 2\mathcal{A} - 1$, where $\mathcal{A}$ = mean value of integral vs. distance

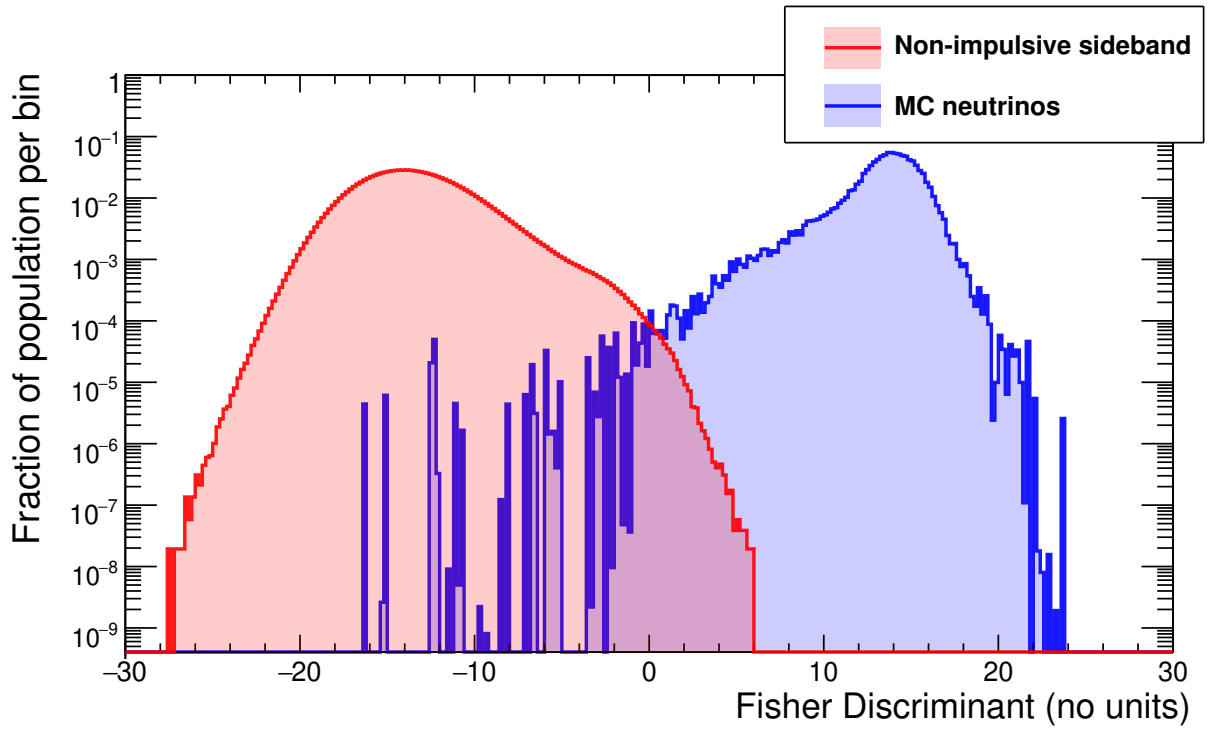


- Find smallest window containing 10%, 20%, . . . 50% of the total power
- $\mathcal{G}$ = gradient of line of best fit
  - Impulsive → small $\mathcal{G}$
  - Non-impulsive → large $\mathcal{G}$



Background separation

- Fisher Discriminant created from map peak, waveform impulsivity metrics (coherent average + de-dispersed)
  - Monte Carlo (MC) neutrinos as signal (`icemc`)
  - Events that point above horizontal as non-impulsive sideband
    - Ionosphere is dispersive in ANITA band

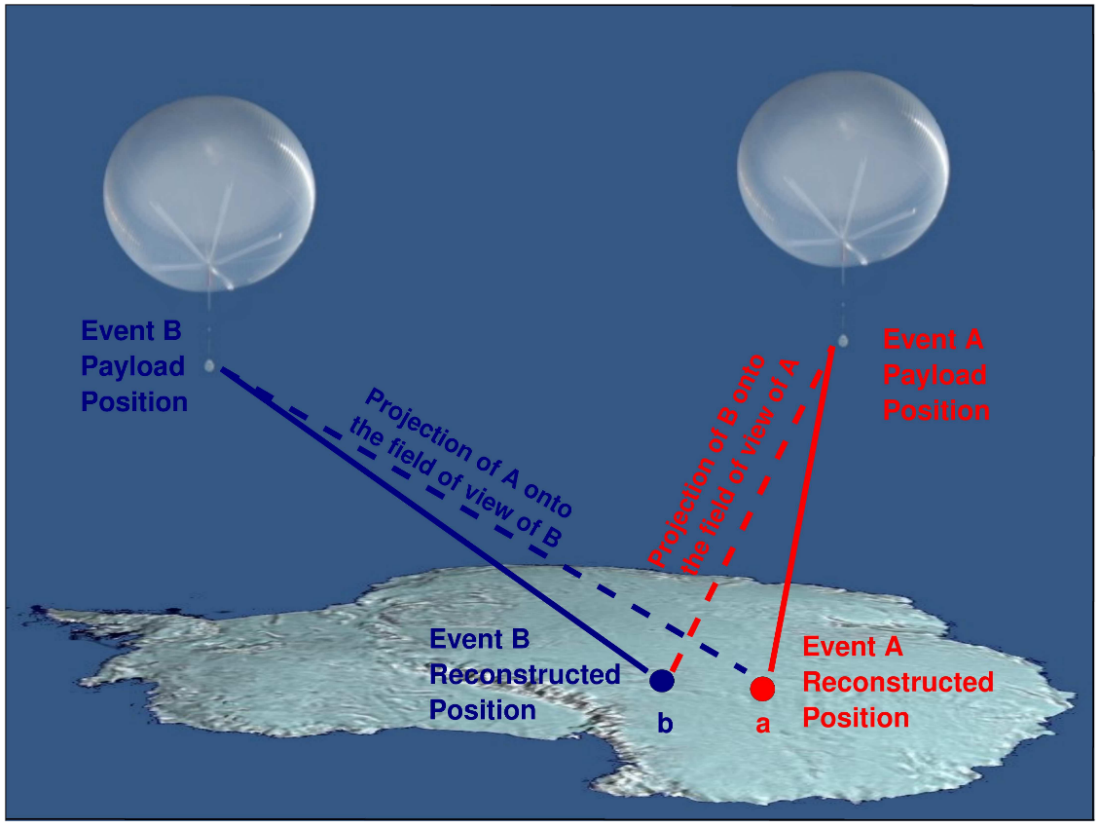


- Keep events with (FD > 5.8)

Background separation

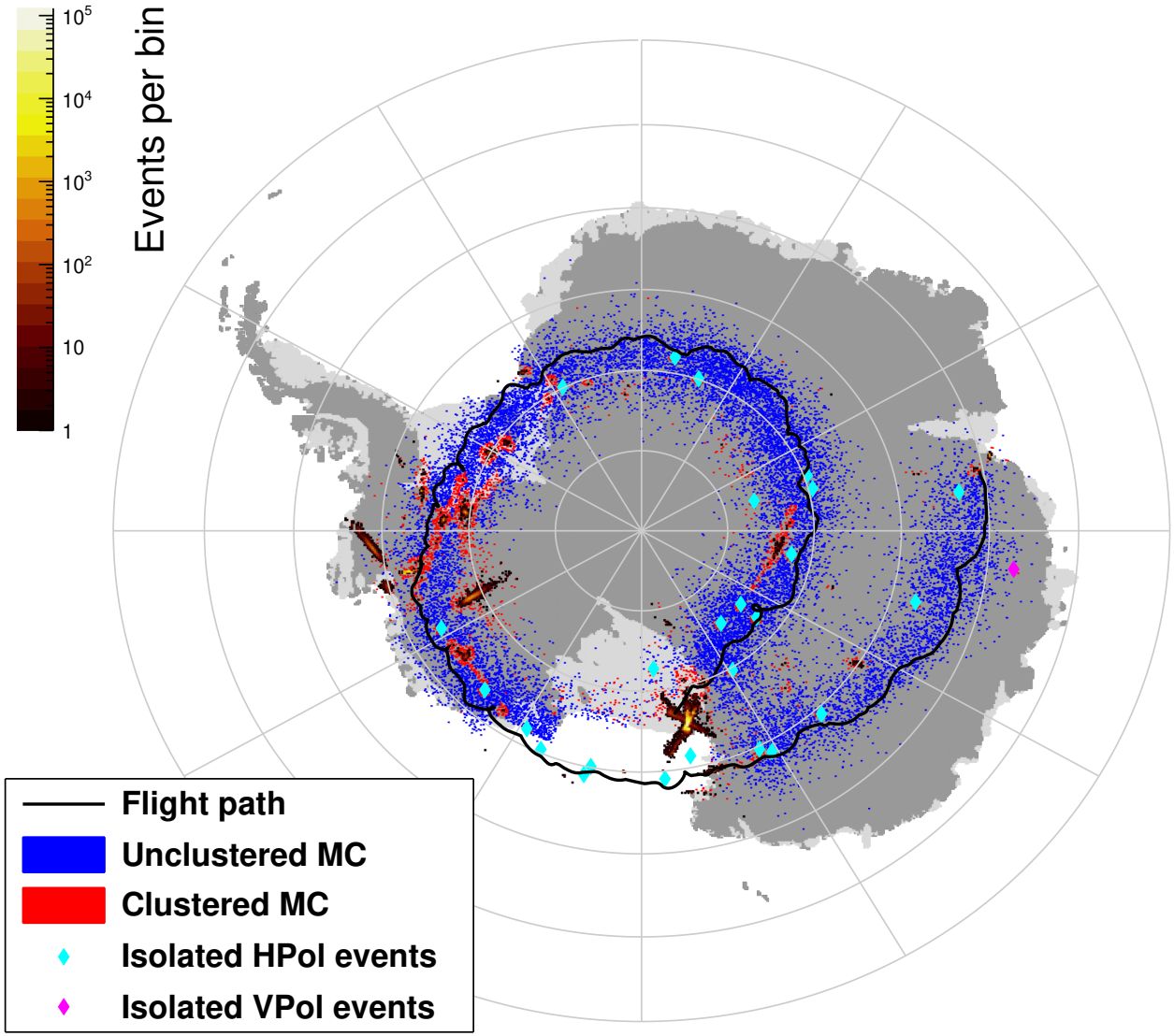
UCLA

- Ray trace $\sim 600,000$ remaining events along $(\phi_{peak}, \theta_{peak})$ onto model of Antarctica
- Diffuse flux of ν and CRs should be isotropic so require isolation
- Reject events near known human activity
- Reject clusters with $N_{events} > 1$



Clustering output

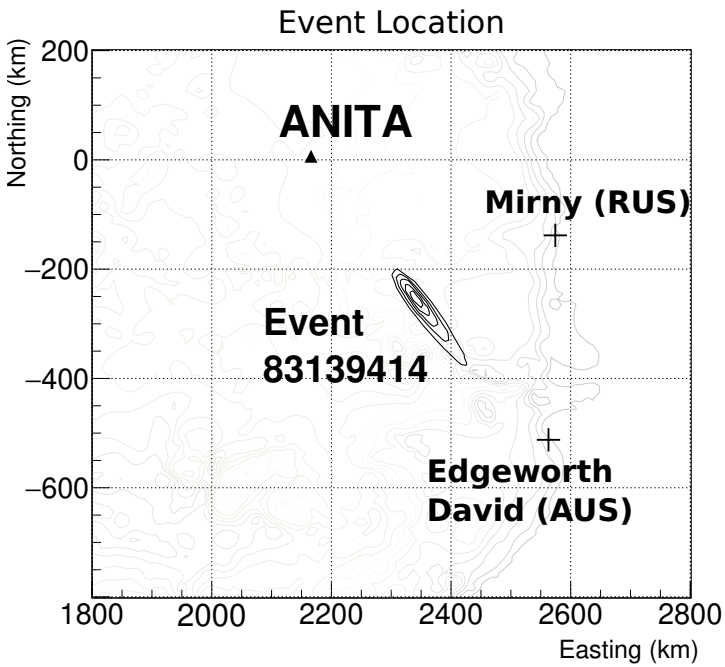
UCLA

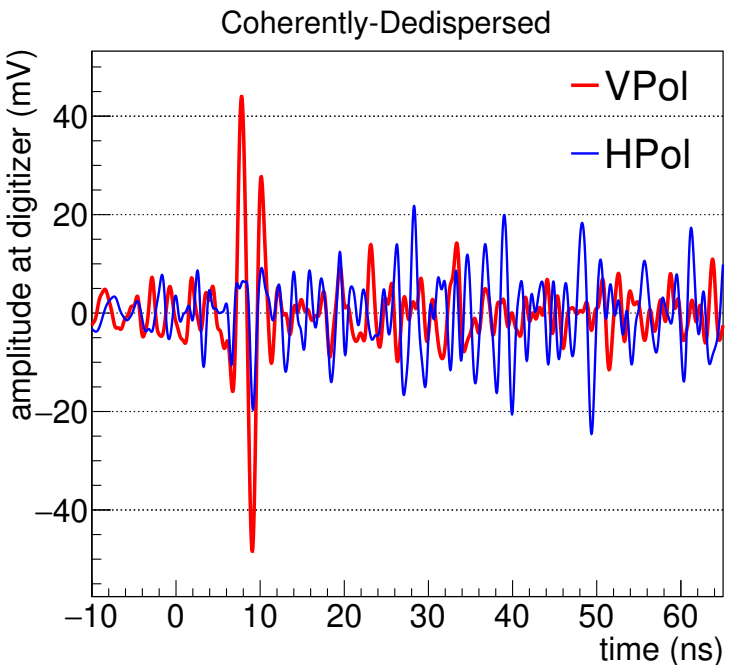


Surviving ν candidate event

UCLA

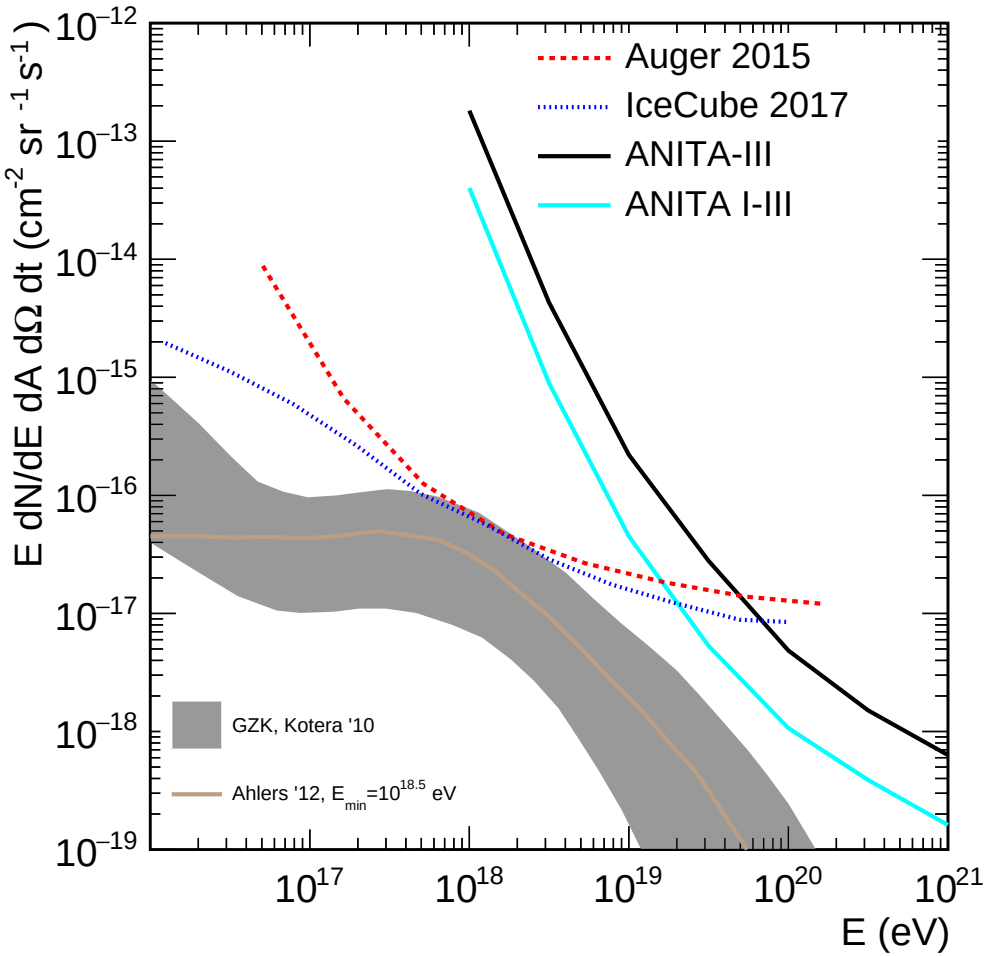
- Find 1 VPol event on expected background of $0.7^{+0.5}_{-0.3}$





- Find 25 HPol events on expected background of $0.7^{+0.5}_{-0.3}$
  - Identified as cosmic rays* by separate, dedicated CR search

Combined Limits



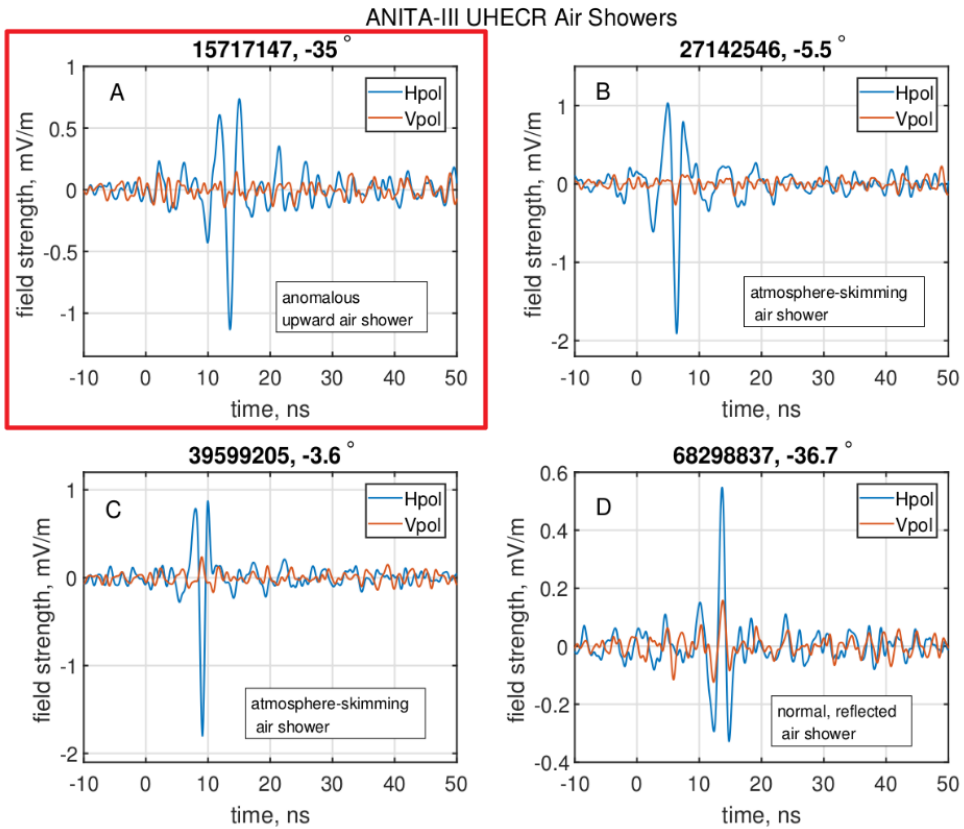
- Combined with ANITA-1 & ANITA-2, set the worlds best limit on diffuse flux of UHEν above $10^{19.5}$ eV

An anomalous event in ANITA-3 data

UCLA

- Second such event
  - ANITA-1 anomaly

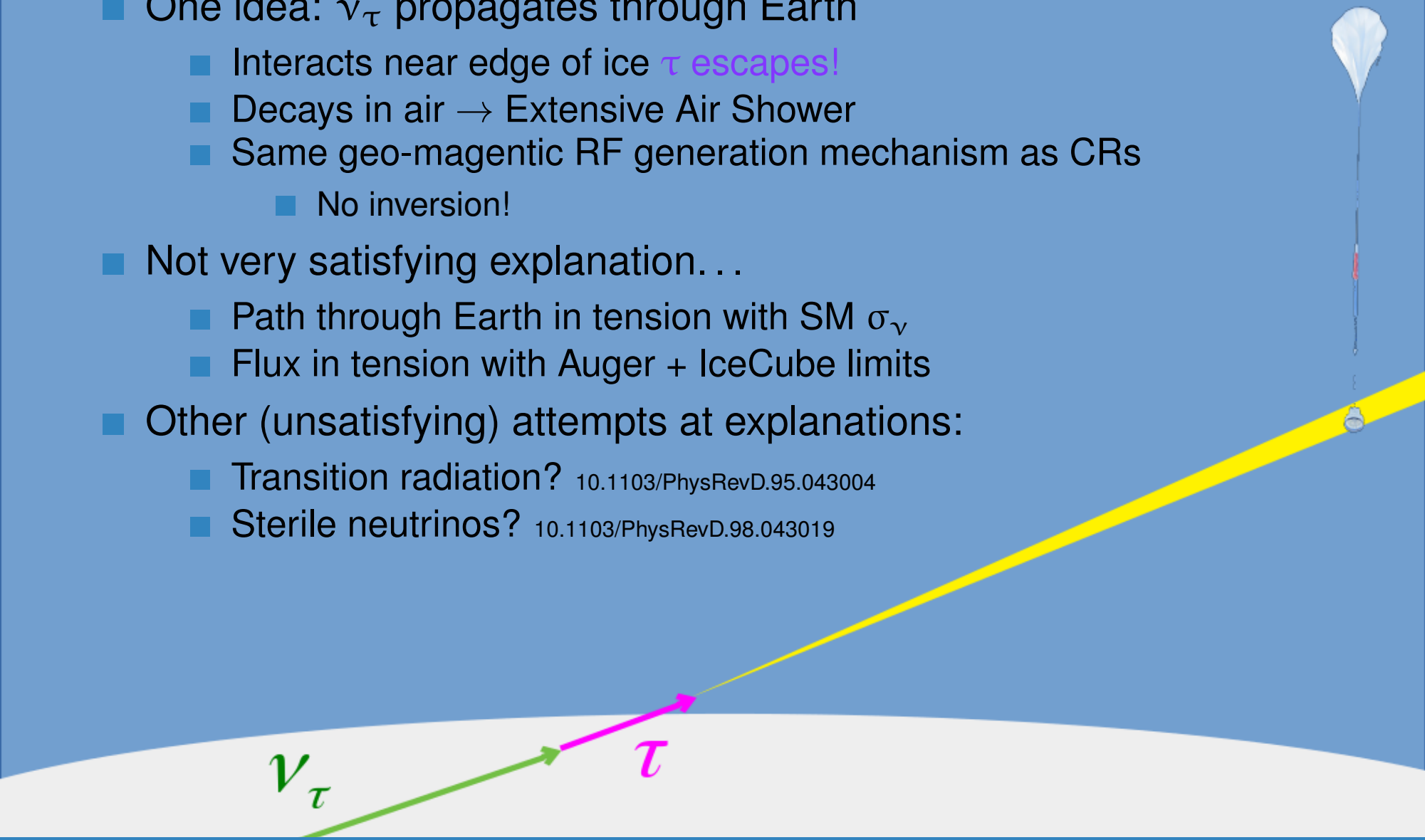
    10.1103/PhysRevLett.117.071101
- Consistent with direct (i.e. *unreflected*) cosmic ray event
- Steeply upcoming angle (-35°), clearly comes from ice *should* be inverted
- Very isolated
  - No nearby humans
  - Nothing subthreshold



Second anomalous event

UCLA

- One idea: ν_τ propagates through Earth
  - Interacts near edge of ice τ escapes!
  - Decays in air $\rightarrow$ Extensive Air Shower
  - Same geo-magentic RF generation mechanism as CRs
    - No inversion!
- Not very satisfying explanation...
  - Path through Earth in tension with SM σ_ν
  - Flux in tension with Auger + IceCube limits
- Other (unsatisfying) attempts at explanations:
  - Transition radiation? 10.1103/PhysRevD.95.043004
  - Sterile neutrinos? 10.1103/PhysRevD.98.043019



Summary

UCLA

- ANITA-3 produced the worlds best limits on the diffuse flux of ultra-high enery neutrinos $E > 10^{19.5}$ eV
  - Over 25 Cosmic Ray like events in ANITA-3 data
  - Second anomalous event also discovered in flight data
    - Ongoing effort to understand these events
- ANITA-4 flight completed in 2016
  - Initial ν and CR analysis nearly complete
  - Expected higher sensitivity than ANITA-3
- ANITA-5 proposal
  - Significant upgrades to trigger and digitizer electronics will increase sensitivity

Thank you for your attention

UCLA