Particle Astrophysics with the ANITA Long Duration Balloon Payload

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University of Chicago / Kavli Institute for Cosmological Physics

ICHEP 2016

ANITA: ANtarctic Impulse Transient Antenna

Jet Propulsion Laboratory
California Institute of Technology

THE OHIO STATE UNIVERSITY

THE UNIVERSITY OF CHICAGO

國立臺灣大學
National Taiwan University

CAL POLY
SAN LUIS OBISPO

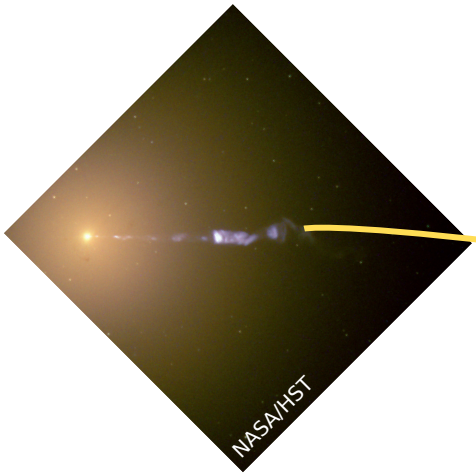
Washington University in St. Louis

NATIONAL ACCELERATOR LABORATORY

WestVirginiaUniversity.

Purpose: To Detect Cosmogenic ν's via Askaryan Effect

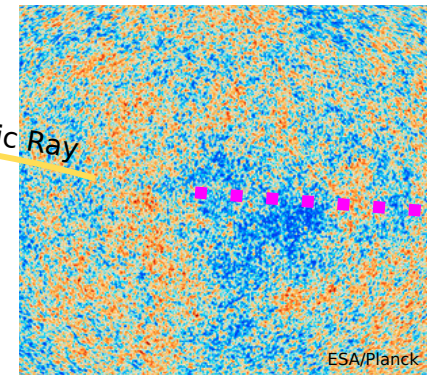
Cosmic Accelerator



UHECR Cosmic Ray

GZK Process

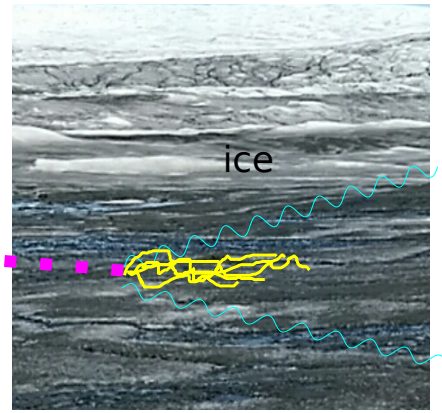
$$p + \gamma_{\mathrm{CMB}} \to \underset{(1)}{\Delta^+} \to p + \pi^0 \to p + 2\gamma$$
$$\to \underset{(2)}{n} + \pi^+ \to (p + e^- + \bar{\nu}_e) + (\nu_\mu + e^+ + \nu_e)$$



"guaranteed" source of extremely-high-energy neutrinos

~EeV ν

Askaryan Effect



High-energy cascade in dielectric produces coherent RF emission below ~ 1 GHz

Both astrophysics (understand sources) and high-energy physics (measure cross-section at 1 EeV) motivations

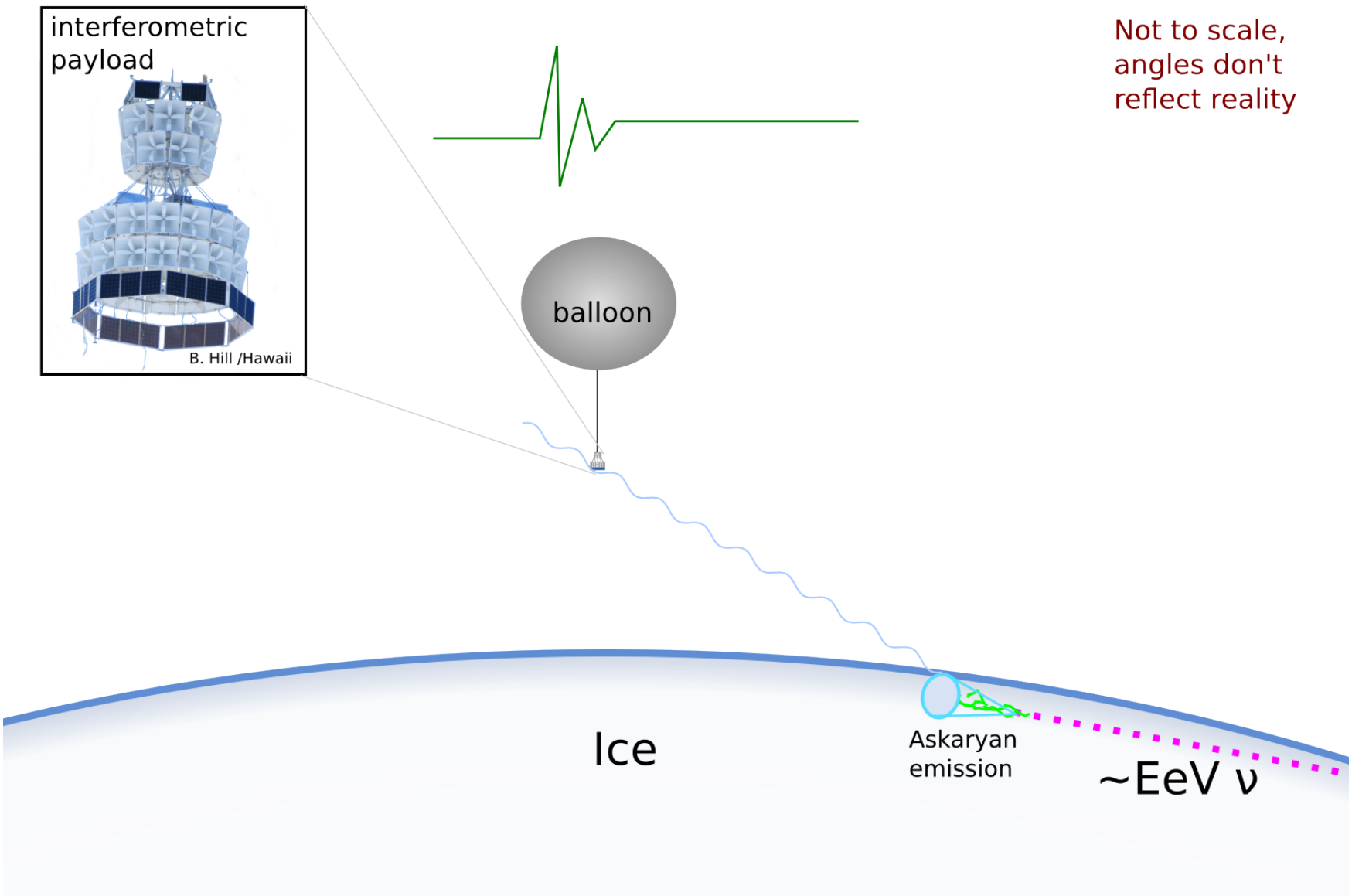
Concept

balloon

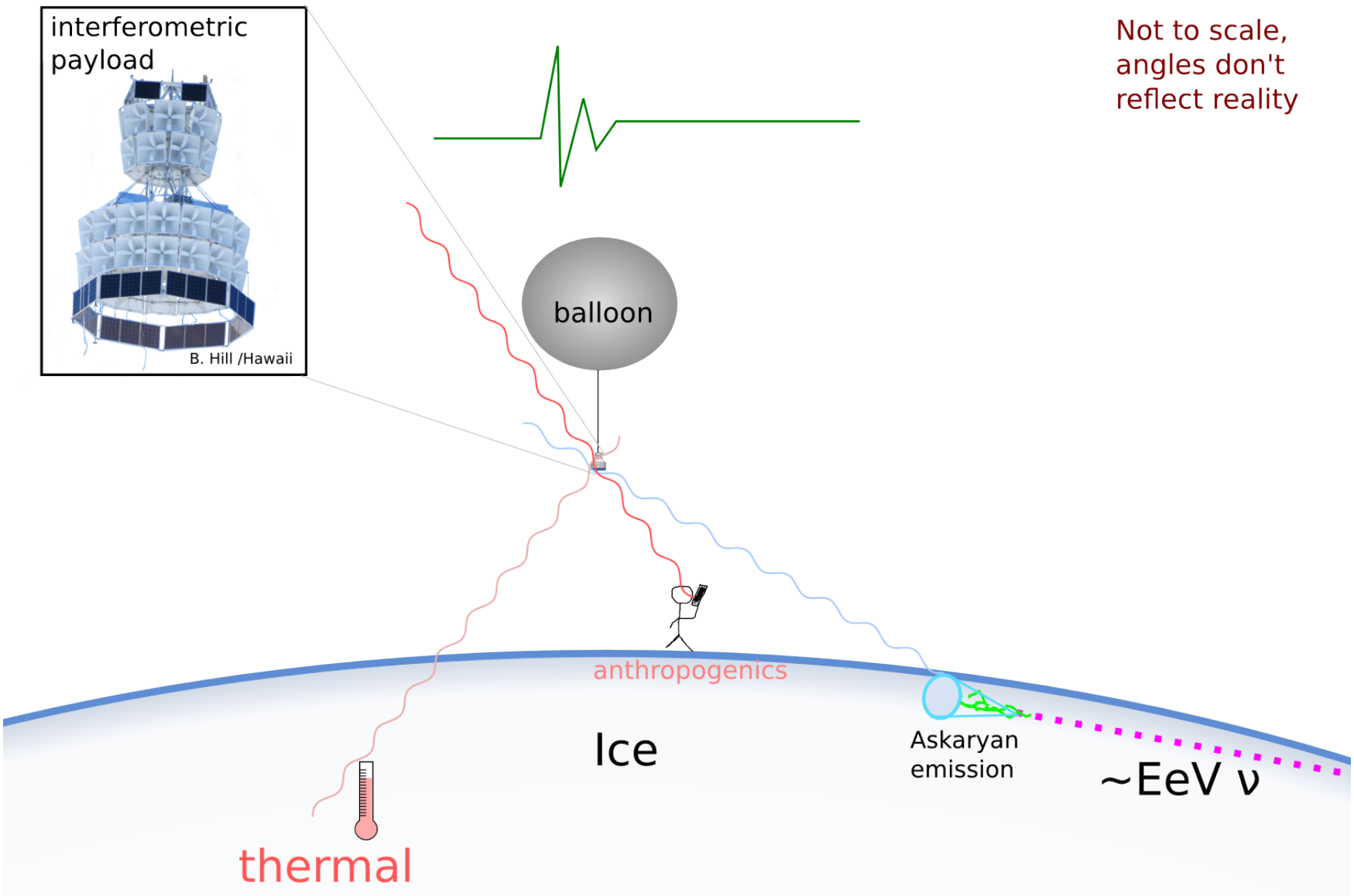
Not to scale,
angles don't
reflect reality

Ice

Concept

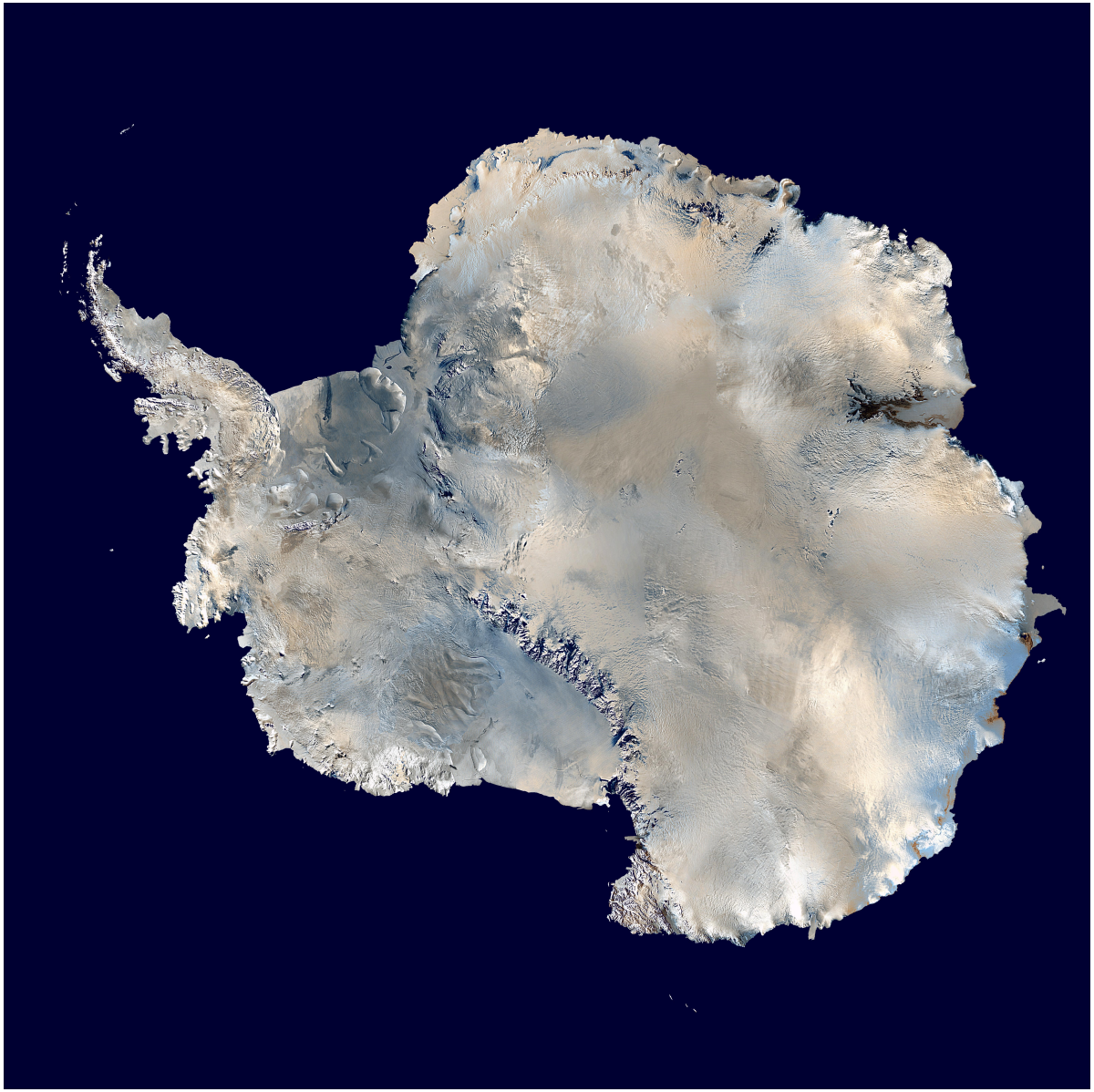

interferometric payload
B. Hill /Hawaii
balloon
Not to scale, angles don't reflect reality
Ice
Askaryan emission
~EeV ν

Concept



Not to scale, angles don't reflect reality

Why Antarctica?

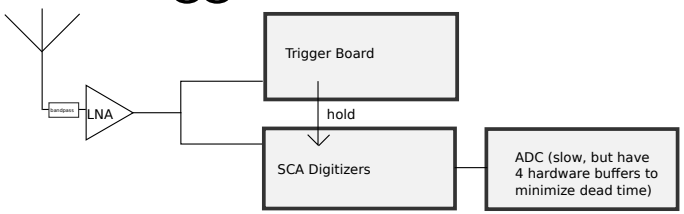


NASA/BlueMarble

- Few people
- Lots of ice, average depth > 1 km
- Wind patterns in summer support long duration balloon flights without spiraling off continent.
- We fly at 37 km, large instantaneous neutrino target volume (> 1 million km^3) but high (10^{17} eV) threshold.

The Balloon Payload

- Severe weight and power limitations – 48 dual-pol high-gain antennas, 96 scope channels, housekeeping, telemetry, etc. with 600 W and 4000 lb
- Signal (ANITA band is $\sim$ 200-1200 MHz) from antennas split into digitizer and trigger circuits.



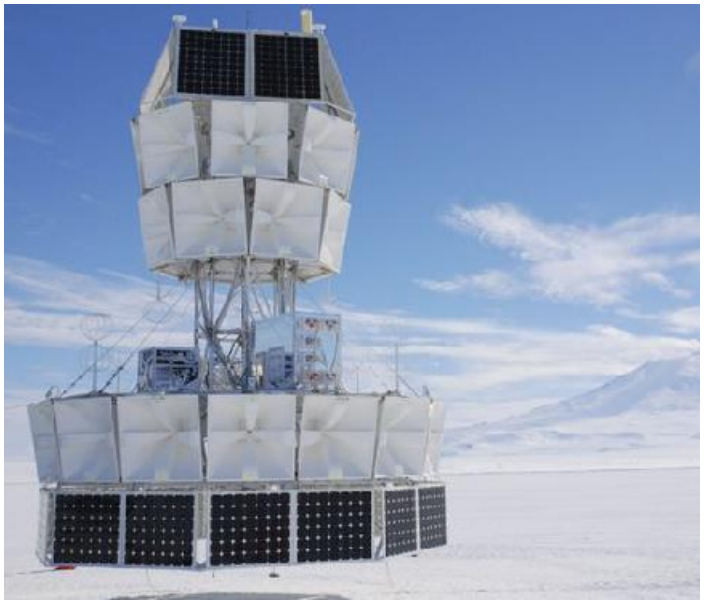
  - Switched Capacitor Array digitizers for $\sim$2.6 GSa/s digitization of $\mathcal{O}(100$ ns).
  - Square-law diodes for trigger. FPGA reduces $\mathcal{O}(10^5 - 10^6$ Hz) singles rate to $\mathcal{O}(10$ Hz) global rate.

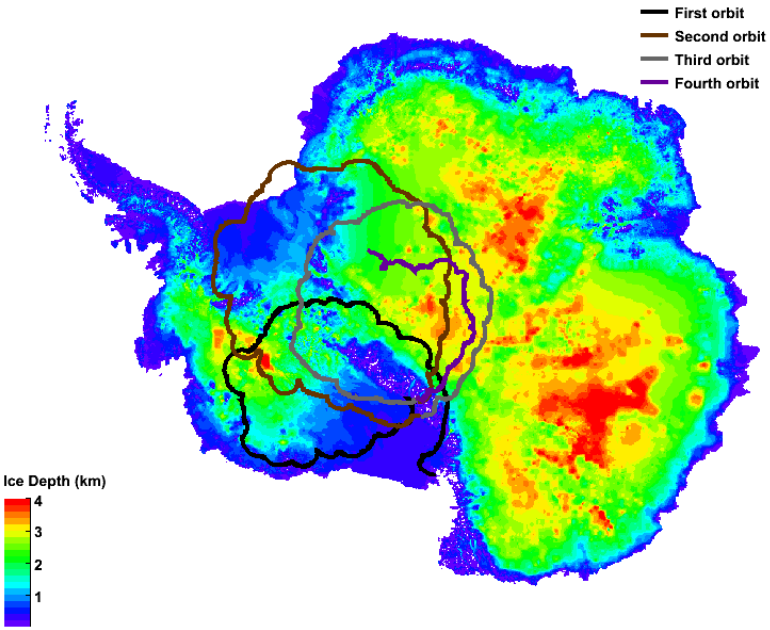
- Telemetry limited, must prioritize as data might not be recovered

ANITA Instrument Box and PI (Photo: C. Miki/Hawaii)

ANITA-3 landing site. (Photo: Josh F/Australian Antarctic Division)

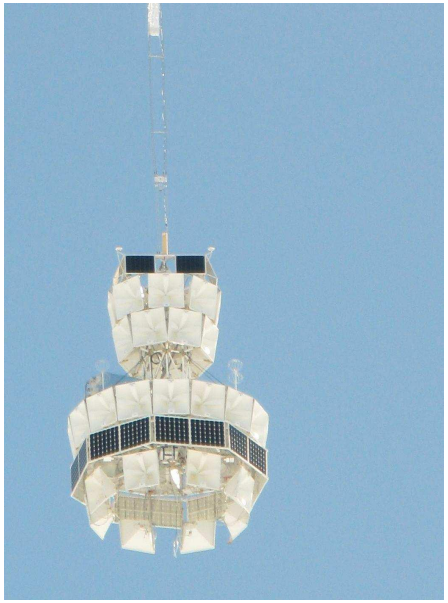
ANITA-1 (2006-2007)

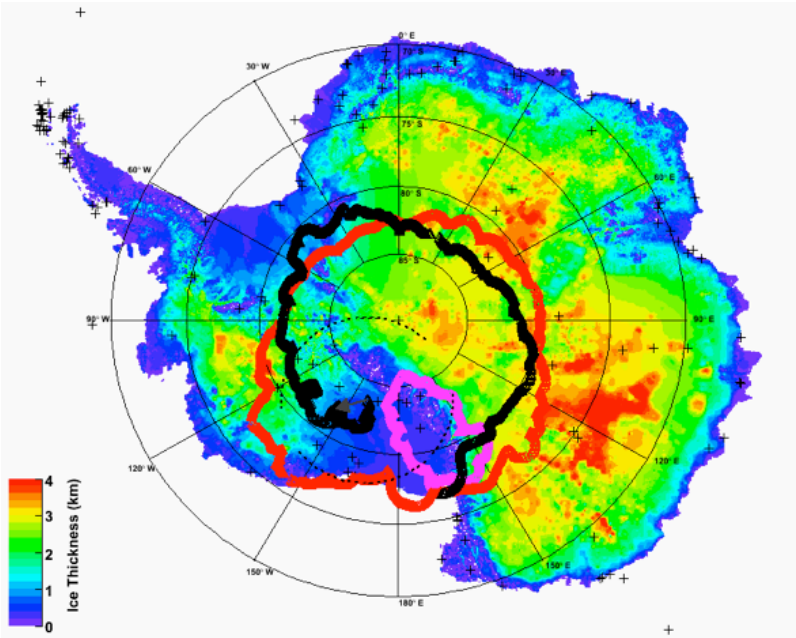




- 35 days in-air (ANITA record)
- Trigger used 90° phase shifters to convert linear to circular polarization for trigger. Requirement of both LCP and RCP selects linear polarization while avoiding polarization plane bias. Banded trigger to reject continuous wave (CW).
- 8 million events recorded

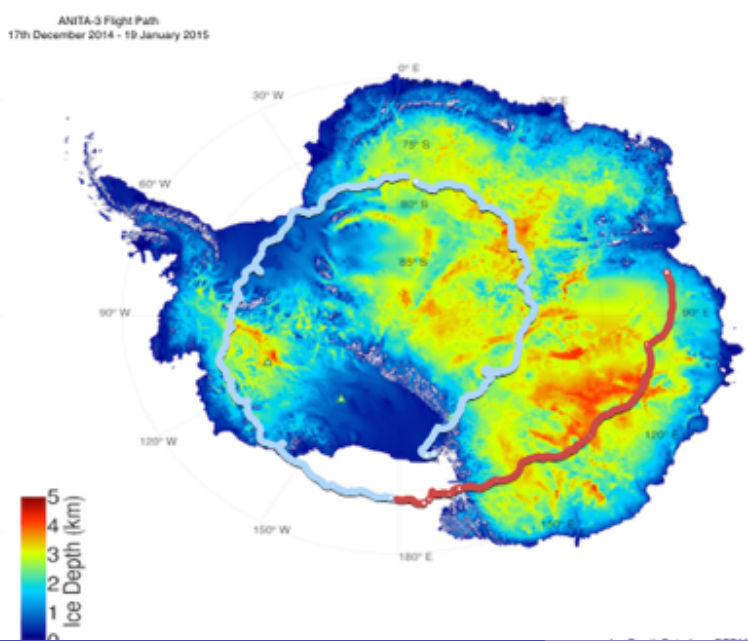
ANITA-2 (2008-2009)





- 30 days in-air, better flight path
- Triggered only on VPol (expected better sensitivity to neutrinos). Banded trigger to reduce CW.
- 27 million events recorded

ANITA-3 (2014-2015)

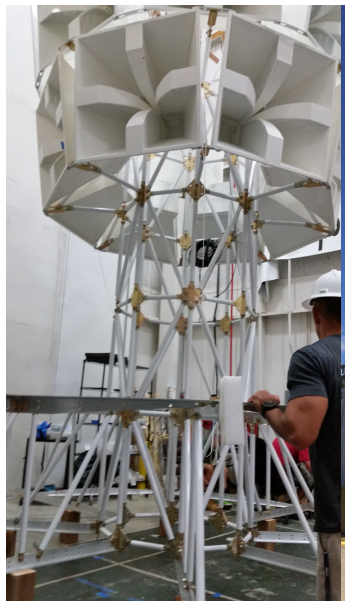


- 22 days in-air
- More antennas
- Got rid of banded trigger (to maximize SNR). Independently trigger on HPol and VPol. Better sensitivity to low SNR, but more susceptible to CW (e.g. satellites) which led to high deadtime.
- GPU prioritizer for telemetry allowed higher event rate
- $\sim$78 million events recorded
- Data analysis still under way

ANITA-4 (2016-2017)

- Scheduled to fly this Austral summer (i.e. 3 months from now)
- Successfully completed hang test at CSBF less than a week ago!
- Upgrades include:
  - New trigger:
    - ★ Restore 90-degree hybrids (convert VPol and Hpol to LCP and RCP) used in ANITA-1; select for linear polarization with no preferred orientation
    - ★ Satellites mostly CP, so will be less likely to trigger
  - Dynamic, tunable, hardware notch filter, along with a spectrum analyzer to guide usage
  - Higher altitude, lighter gondola

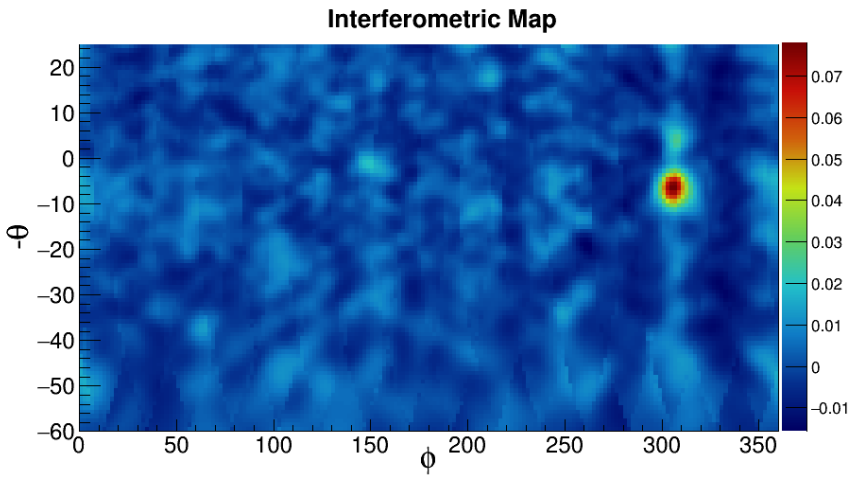
Instrument box in thermal-vacuum chamber (Photo: C. Miki)

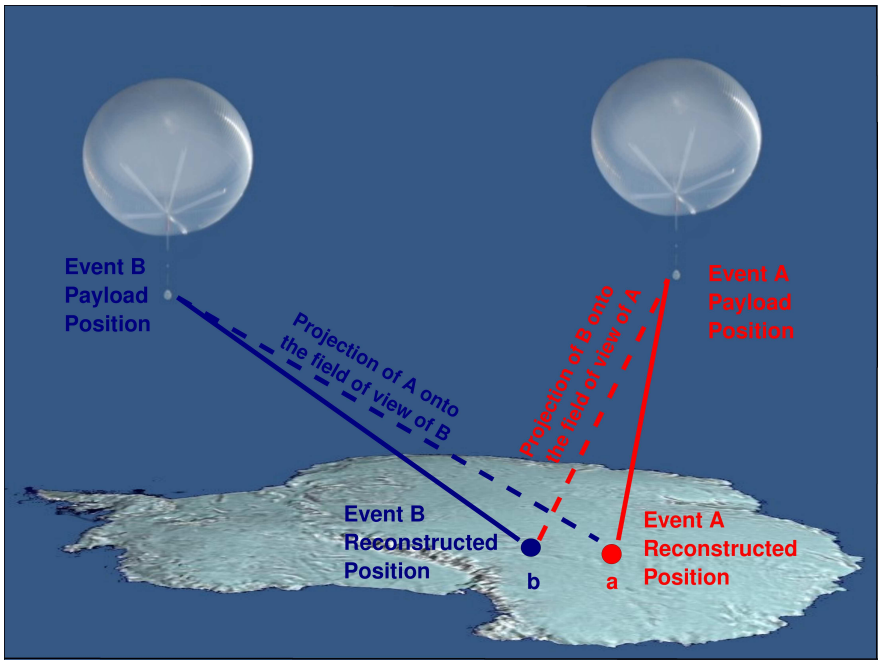


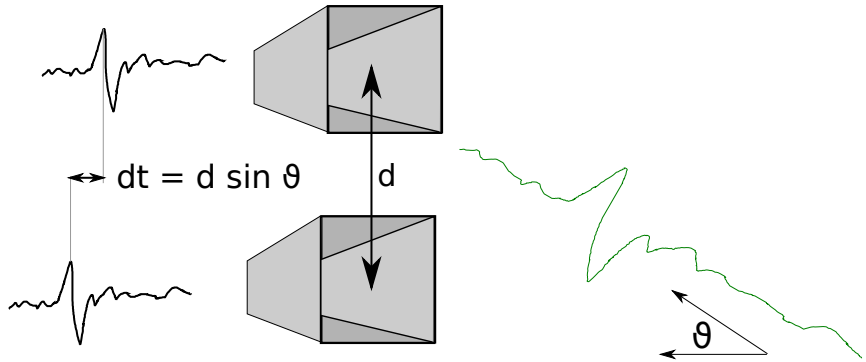
ANITA's skeleton

Hang test (Photo: C. Miki)

Sketch of Analysis



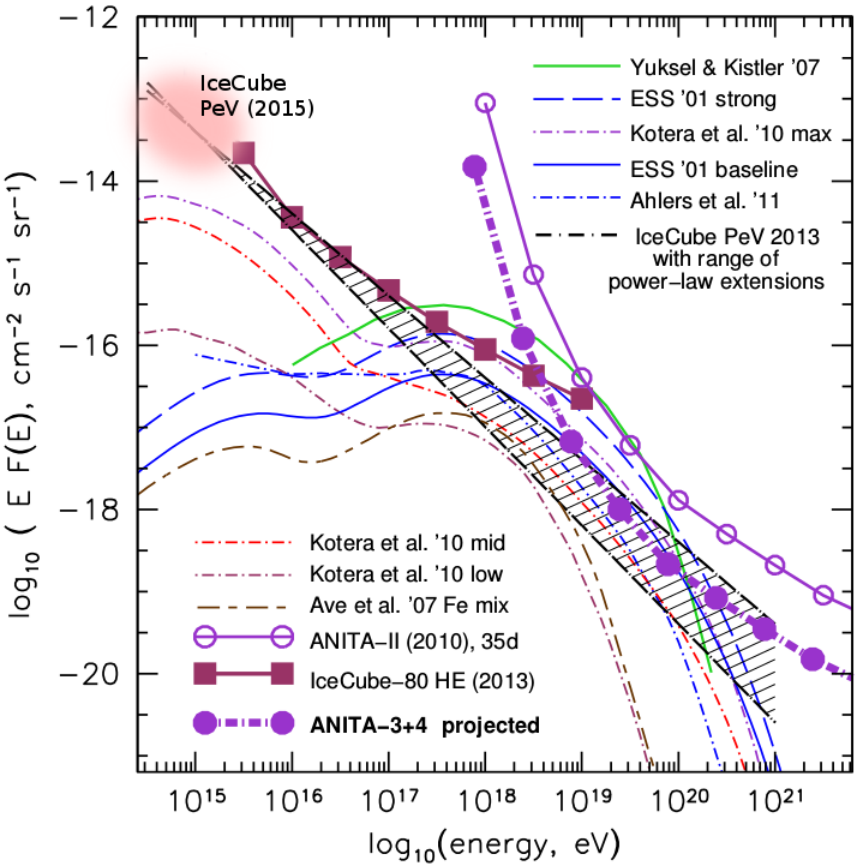


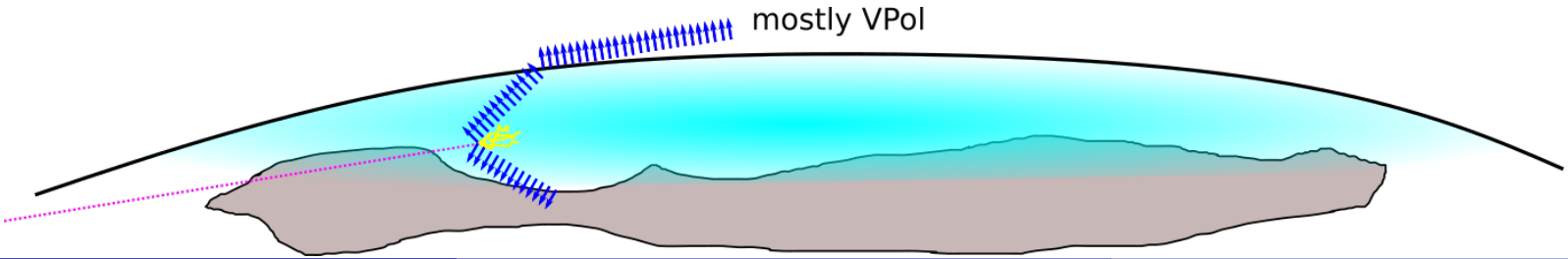


1. Filter out narrow-band continuous transmission from satellites, bases, etc.
2. Construct interferometric "pointing" map
3. Cut out thermal noise, remaining non-impulsive and other pathological waveforms
4. Cluster remaining events. Assume non-isolated events are anthropogenic.

Askaryan Neutrino Search

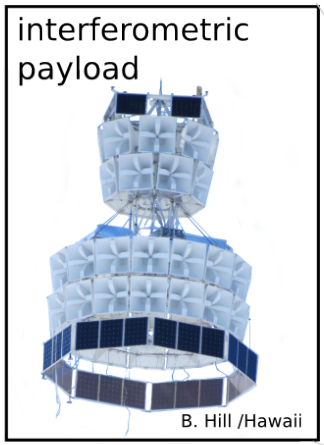
- Look for isolated, impulsive, predominantly VPol events
- VPol due to geometry of emission cone for ice-skimming neutrinos
- For e.g. ANITA-2, expected ~ 1 remaining background, based on number of doubles and triples.
- ANITA-1 saw zero candidates, ANITA-2 saw one.
- Papers:
  10.1103/PhysRevD.85.049901
  10.1103/PhysRevD.82.022004
  10.1103/PhysRevLett.103.051103

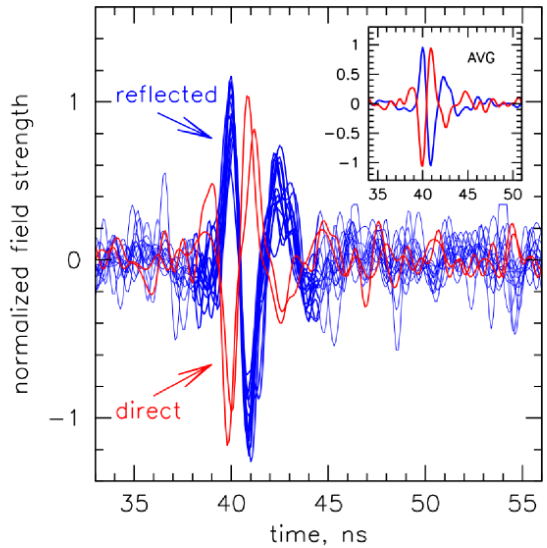




UHE Cosmic Ray Search

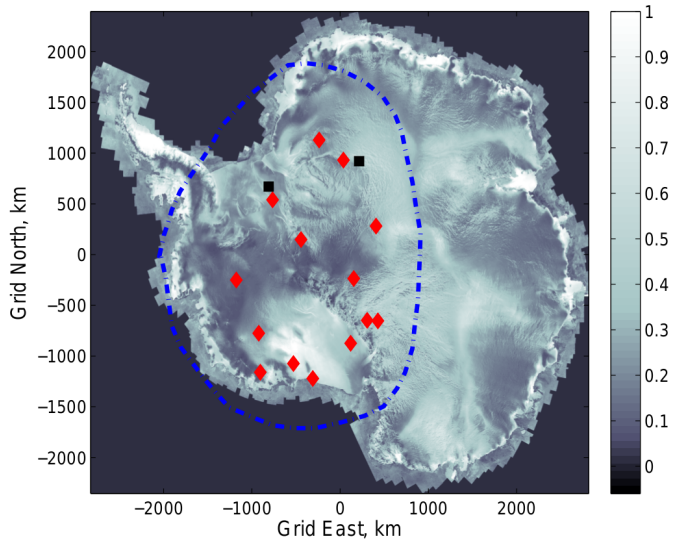
- ANITA-1 saw 16 isolated events in HPol, identified as cosmic rays
  - Reflected cosmic rays: point to ground, Fresnel modifies polarization
  - Direct cosmic rays: miss the ground. **Inverted polarity from reflected**

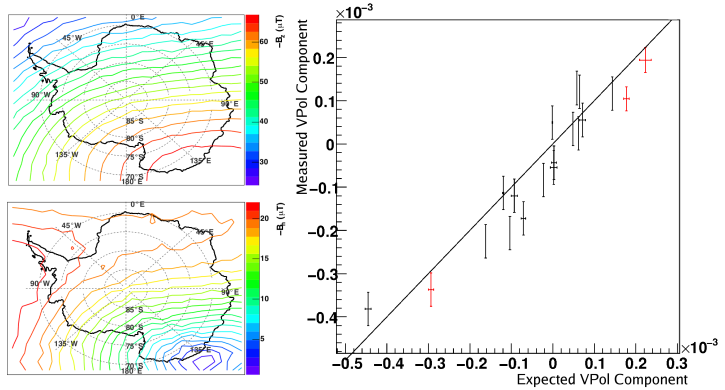




UHE Cosmic Ray Search

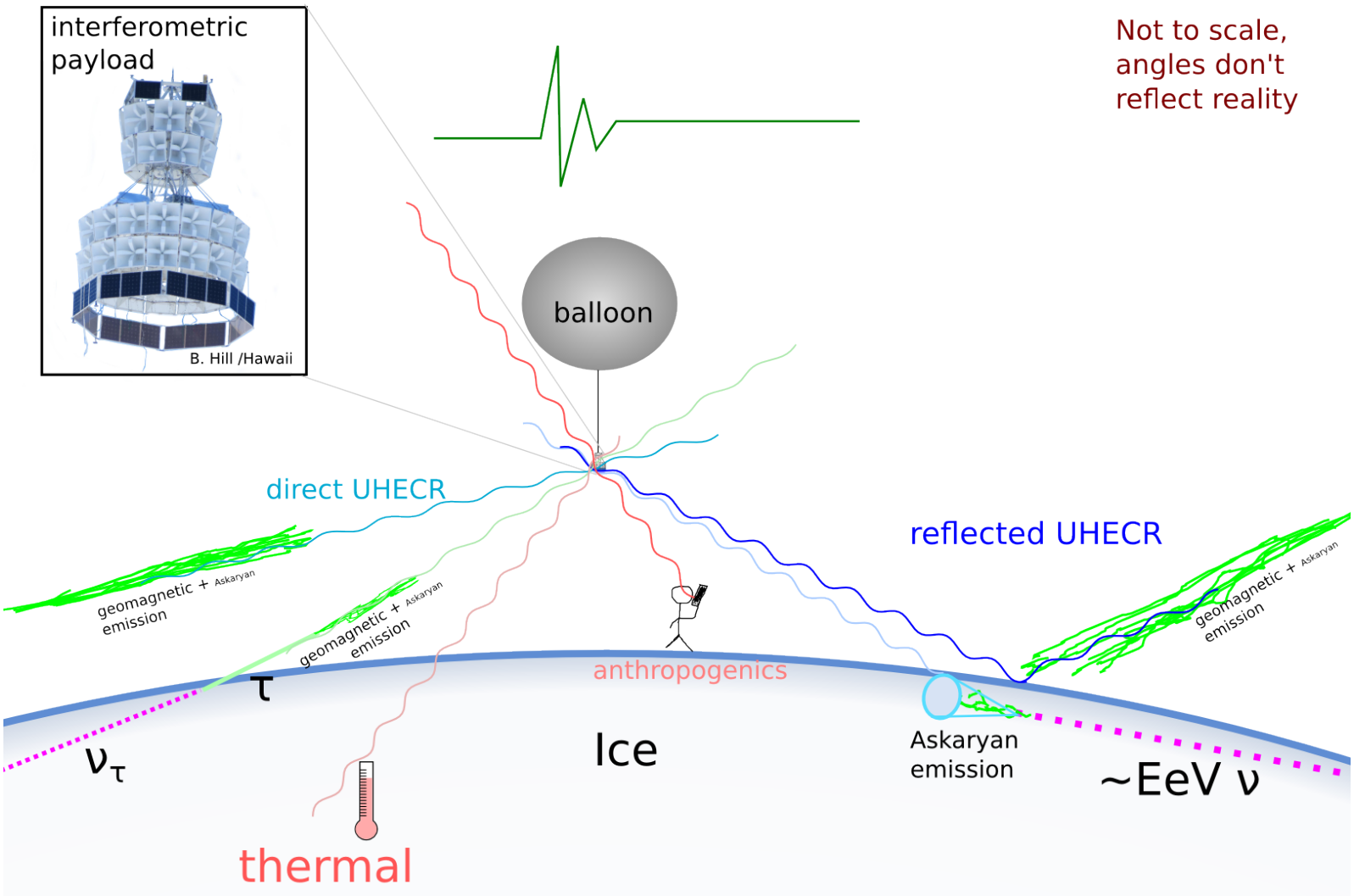
- Dominant RF mechanism from extensive air showers is synchrotron radiation from Earth's magnetic field.
- Polarization from B-field and shower directions. Since B-field in Antarctica mostly vertical, expect mostly HPol.
- Can check geomagnetic hypothesis by looking up local magnetic field and checking polarization angle
- Switch to VPol-only in ANITA-2 made instrument much less sensitive, but still saw 3 CR's that were sufficiently energetic to trigger in VPol.
- 10.1103/PhysRevLett.105.151101





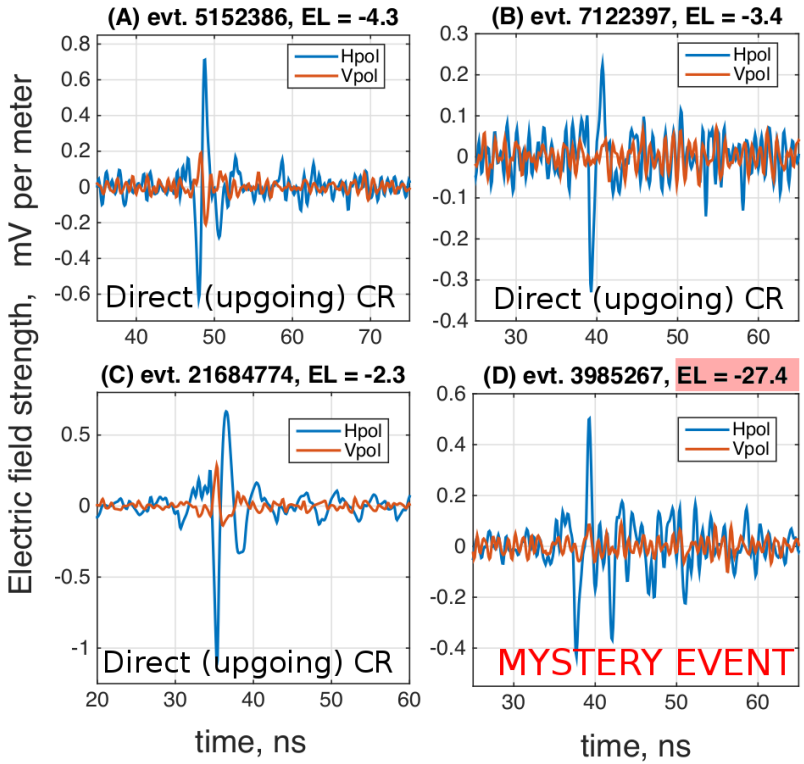
Sensitivity to upward-going τ showers?

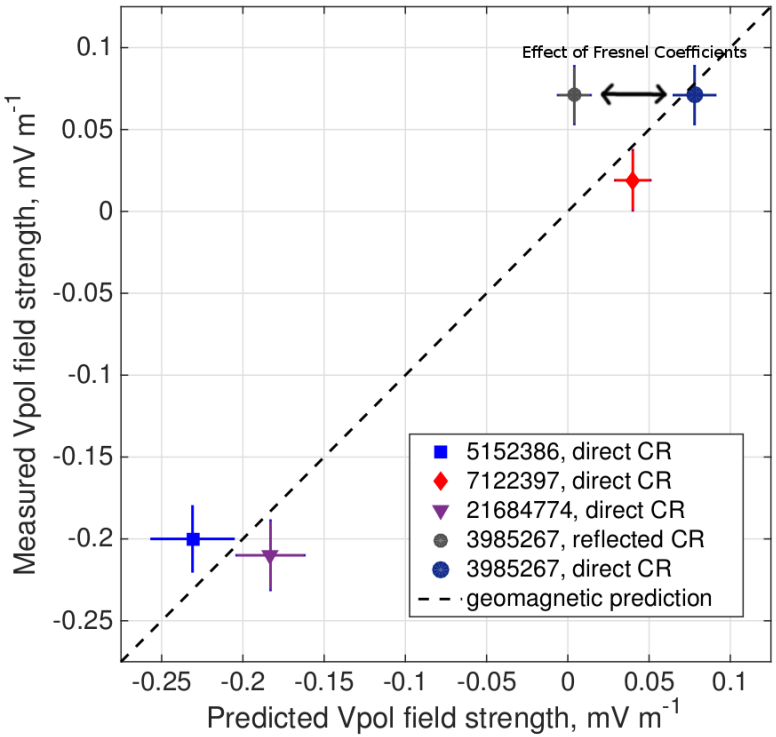
- ν_τ creates τ which escapes atmosphere and decays hadronically



Mystery event

- Mysterious event from ANITA-1 (arxiv:1603.05218, accepted to PRL)
- Mostly HPol, has polarity consistent with direct cosmic ray event, **but clearly points to ice** (27 degrees below horizontal).
- Polarization angle more consistent with unreflected signal (adding Fresnel coefficients worsen agreement with geomagnetic expectation)
- Shower energy estimate is 0.6 $\pm$ 0.4 EeV

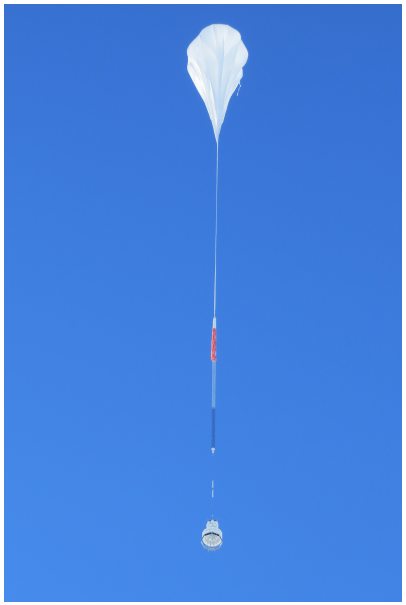




Mystery event interpretations

- **Anthropogenic background:** certainly possible, but:
  - 1.6 events expected to pass clustering cuts.
  - Only a few percent of anthropogenic events detected correlate as well with average CR shape.
  - Only half will have correct polarity.
  - Fewer than 10 percent expected to lie so close to geomagnetic polarization.
- **Mistaken observed polarity?** We think it's excluded:
  - The SNR is too large to accidentally pick wrong polarity
  - Any systematic would have to invert polarity but preserve polarization.
- ν_τ **producing upward shower:** tantalizing, but:
  - Chord through Earth is 5450 km, resulting in a $\mathcal{O}(10^{-4})$ attenuation with SM cross-section.
  - Need at least a factor of 3-5 reduction in $\sigma_{\nu N}(1\text{ EeV})$ to be plausible.
  - **However:** SM cross-section extrapolated over several orders of magnitude from measurements. Different extrapolations can change value by at least factor of 2 (see e.g. 10.1103/PhysRevD.77.013001).
- Interpretations welcome!

Conclusions and Near-Future



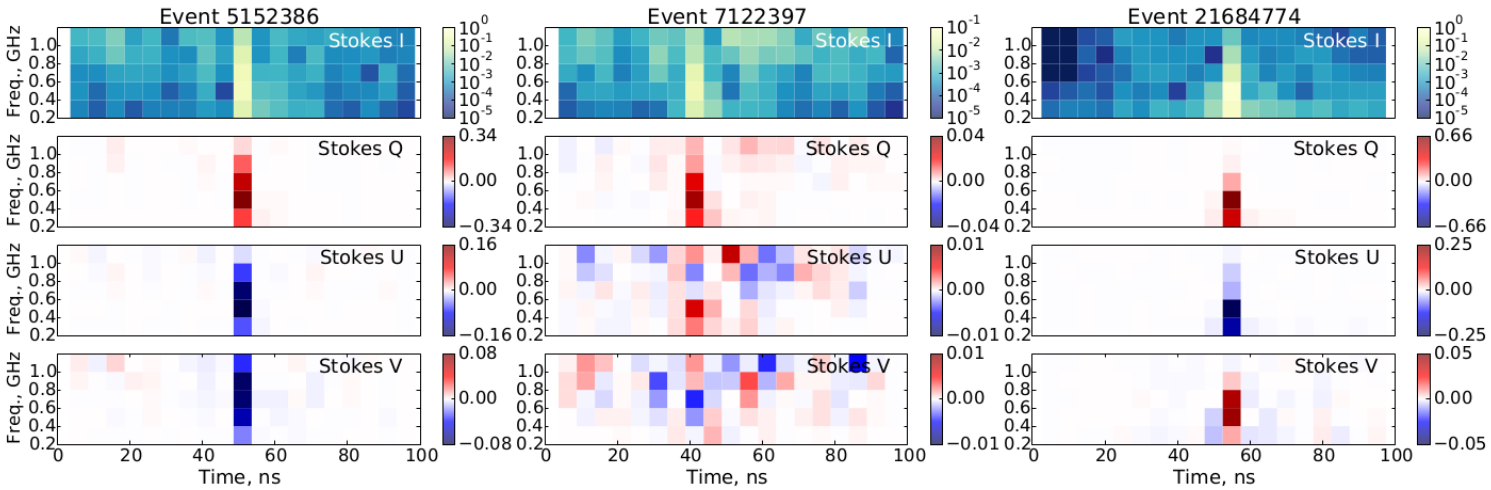
- ANITA-1 and 2 have best cosmogenic neutrino limits in energy range. Also sensitive to UHECR's.
- Mysterious event from ANITA-1 which we don't fully understand. If it is an upward τ shower, we probably require revision of SM cross-section (which affects all limits, sensitivities, etc.).
- Preparing ANITA-4 to launch this December, with a trigger with no preferred polarization angle (this improves acceptance if the cross-section really is lower).
- Simultaneously, working on ANITA-3 analysis, which we hope:
  - will detect many more UHECR's
  - could detect a neutrino candidate
  - will hopefully shed more light on our mystery event.
- Busy, but exciting, times ahead.

Thank you

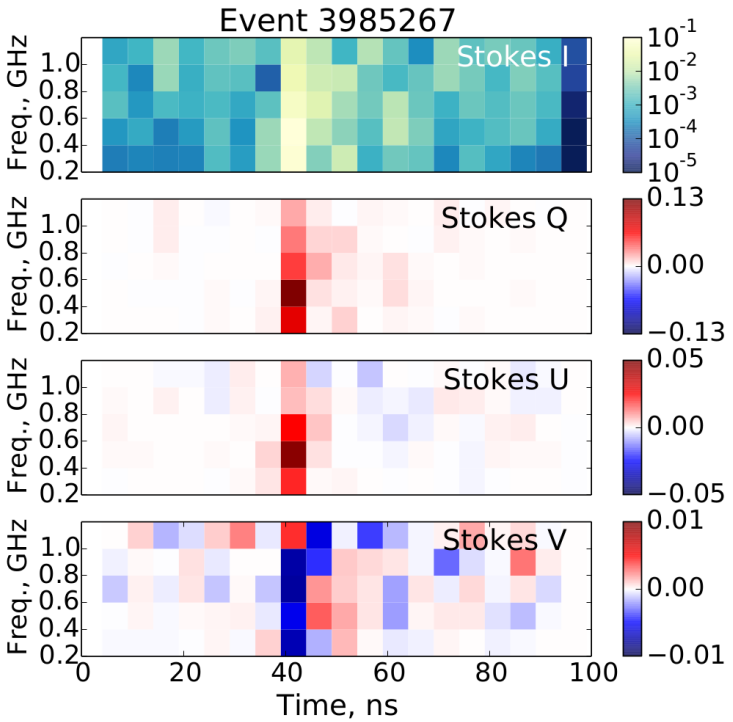
Photo: H. Schoorlemmer, Hawaii/Heidelberg

Backup

Stokes Parameters



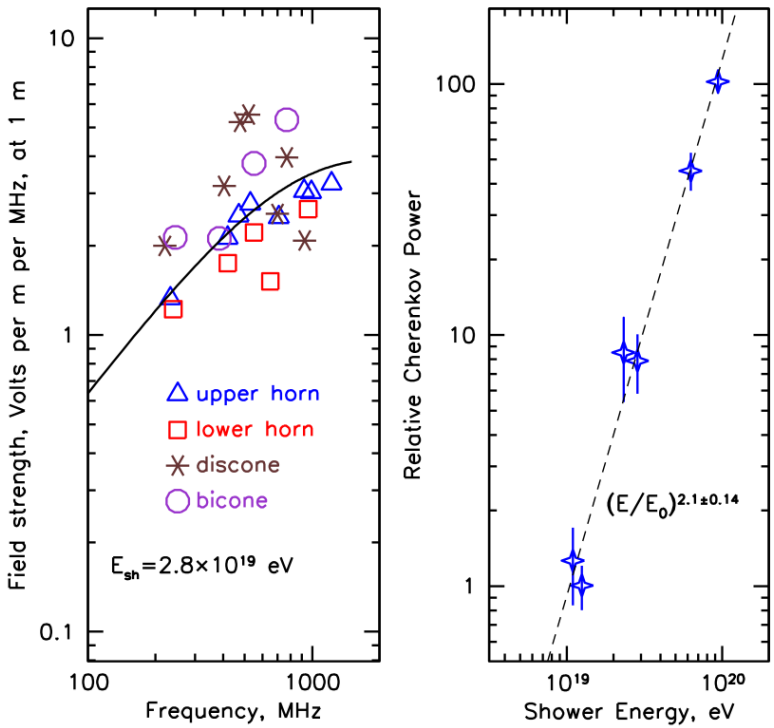
- Stokes parameters of direct CR's (above) and mystery event (right)
- Mystery event and high SNR CR's show higher-than-expected Stokes V (Circular Polarization).
- Could be due to combination of Askaryan and geomagnetic components



Askaryan Effect in Ice

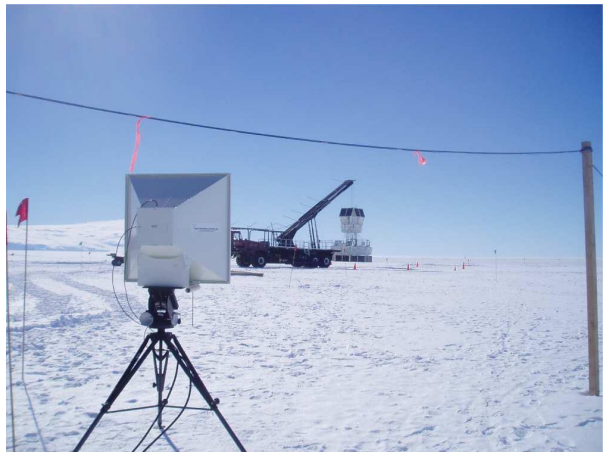
PRL 99, 171101 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007

Observations of the Askaryan Effect in Ice

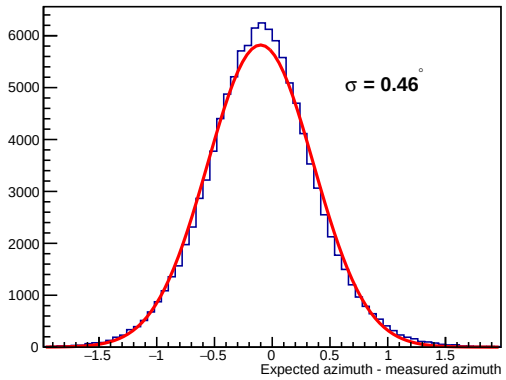


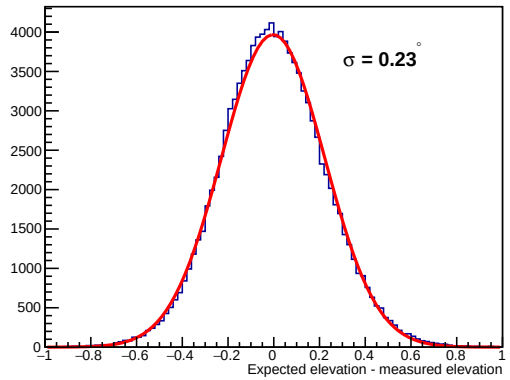
Calibration

- Use ground (or in borehole) calibration pulsers
  - Calibrate antenna positions
  - Understand efficiency as function of SNR
  - Estimate pointing resolution
  - Measure payload tilt
- For ANITA 3 and 4, Hi-Cal trailing balloon provides calibration signal for part of flight

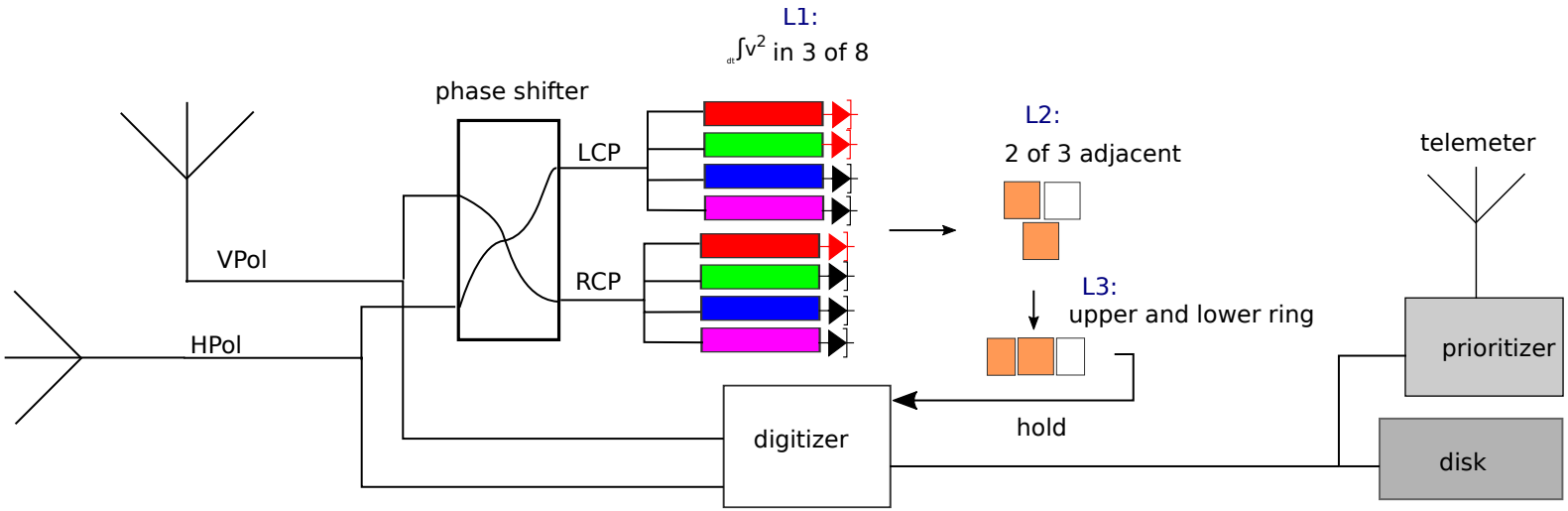


Preliminary ANITA-3 pointing:

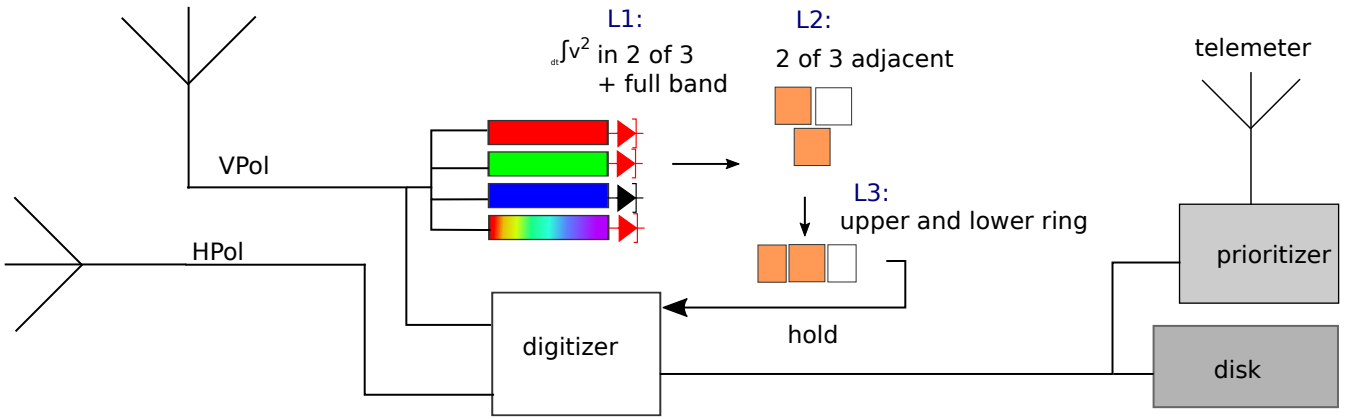




ANITA-1 Trigger



ANITA-2 Trigger



ANITA-3 Trigger