Searches for Ultra-High-Energy Neutrinos with ANITA

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on behalf of the ANITA Collaboration

University of Chicago / Kavli Institute for Cosmological Physics

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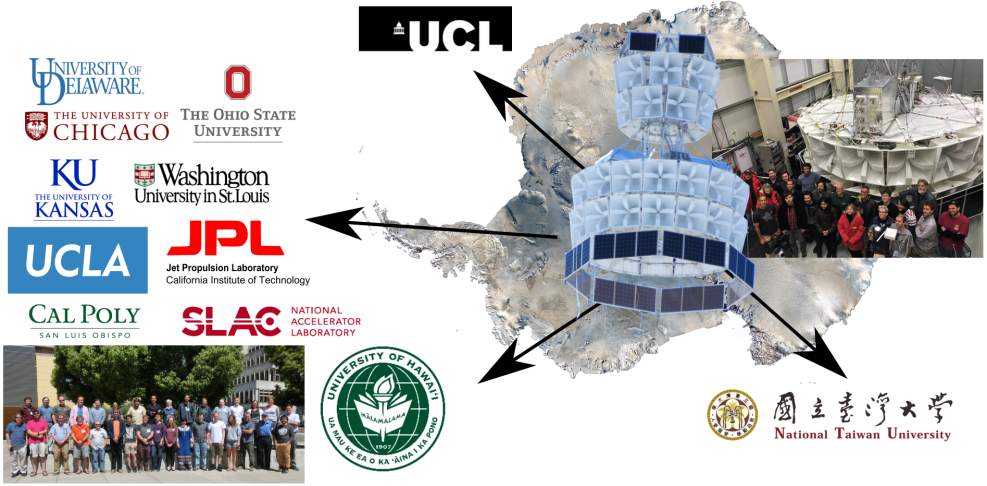
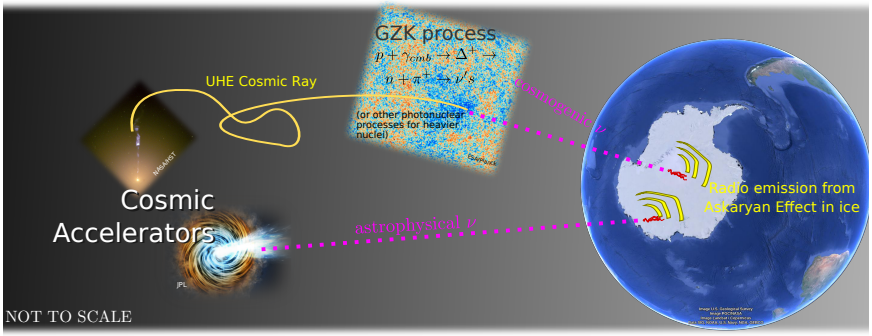
ANITA Collaboration

ANtarctic Impulsive Transient Antenna

12 institutes, 3 countries, 4 continents



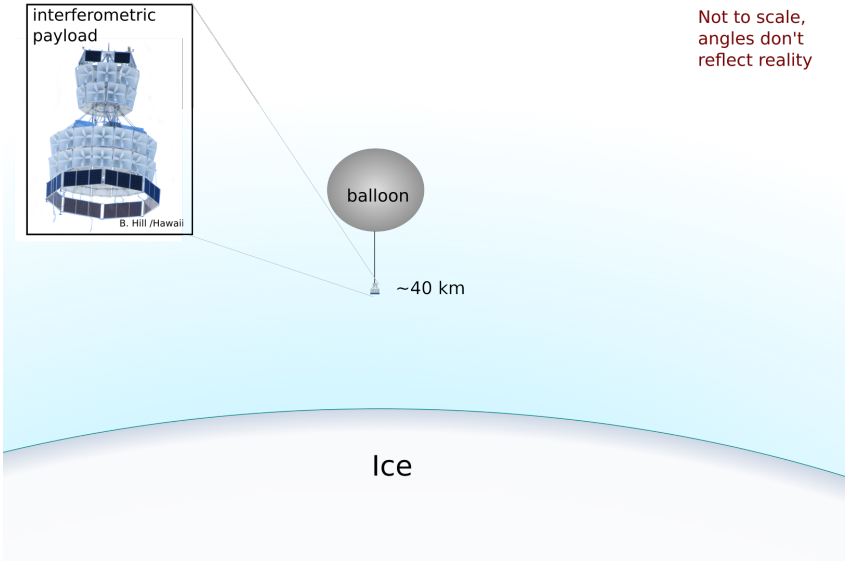
Motivation: Detect UHE ν's (>EeV) using Askaryan Effect in Ice



Both astrophysics (understand sources, composition) and high-energy physics (measure EeV cross-section) motivations.

Expected flux is very low, so need big detector $\rightarrow$ Use Antarctic ice sheet as target and try to detect the coherent radio emission produced via the Askaryan Effect.

ANITA Experiment Concept



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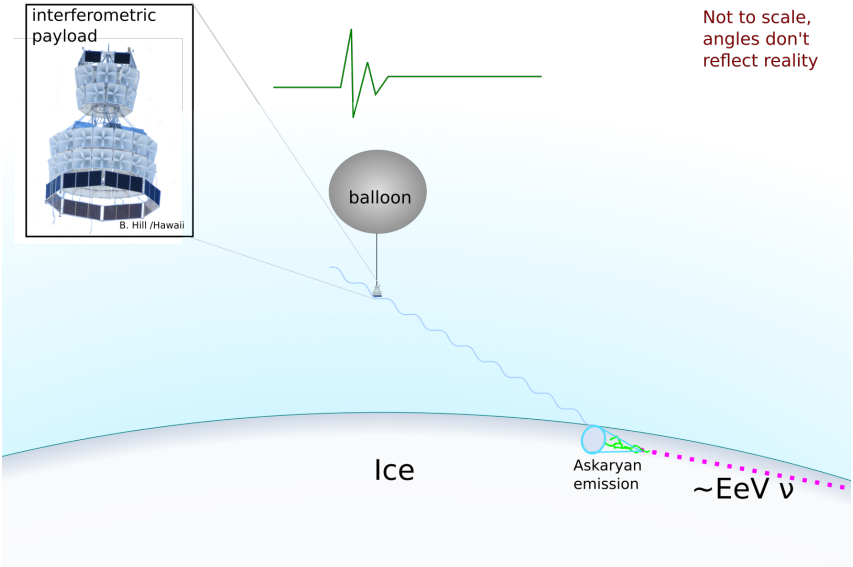
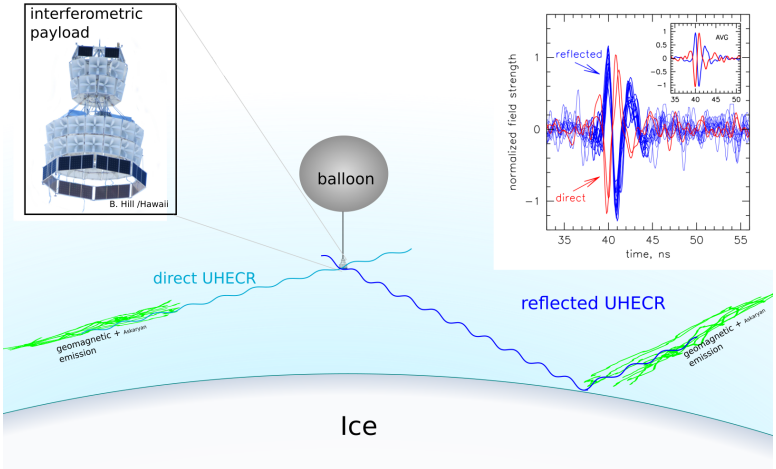


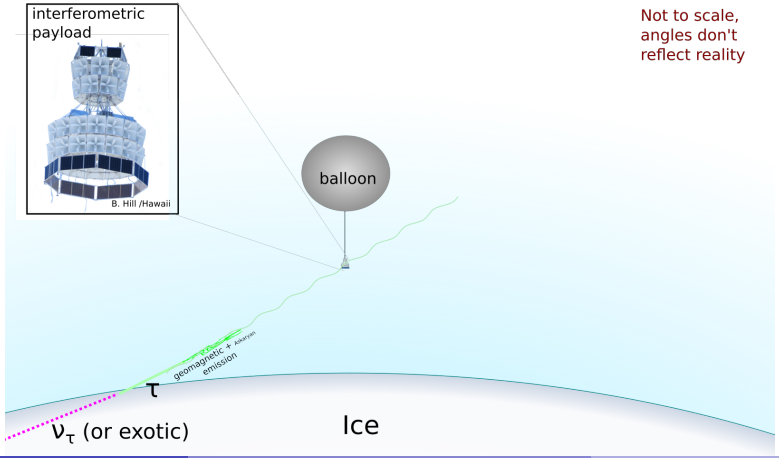
Additional signal: Radio Emission from Extensive Air Showers (EAS)

- Earth's magnetic field separates charges in EASs, produces radio emission
  - "Direct" ∼horizontal CR's: miss ground.
  - "Reflected" down-going CR's: point to ground, **opposite polarity**

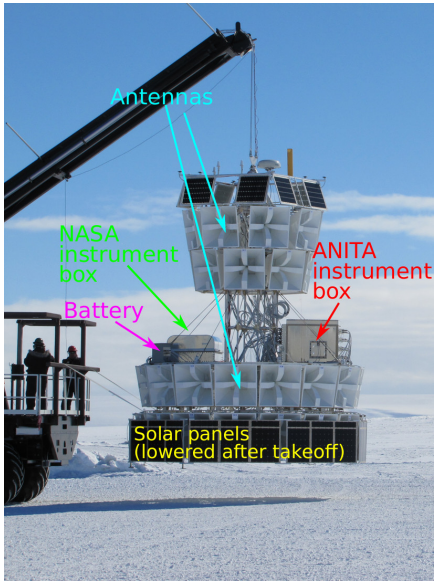


Sensitivity to Upward-Going Showers?

- Angle consistent with reflected UHECR, but polarity of direct
- Could be produced by a ν_τ-induced τ which escapes atmosphere and decays, producing shower. Or by exotics.

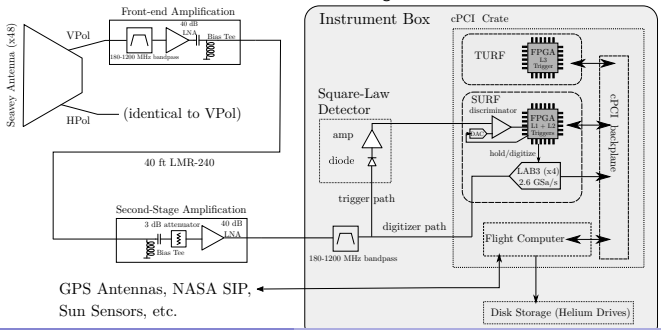


ANITA Instrument

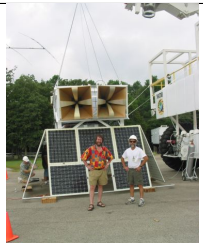
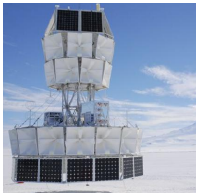
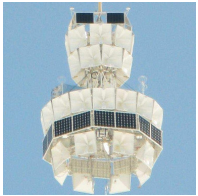
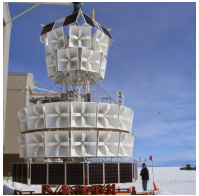


- Signal ($\sim$ 180-1200 MHz) split into digitization and trigger paths
  - Tunnel diode first-level trigger. Combinatorics between antennas take $\mathcal{O}(10^{5-6}$ Hz) singles rate $\rightarrow \mathcal{O}(50$ Hz) global rate
  - Switched Capacitor Array digitizers, $\sim$2.6 GSa/s, $\mathcal{O}(100$ ns).

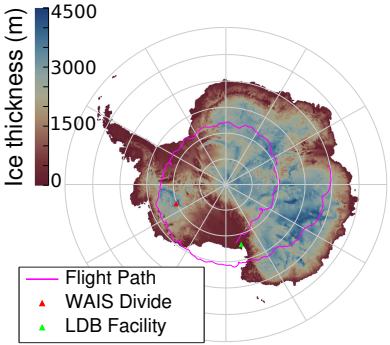
ANITA-III block diagram:



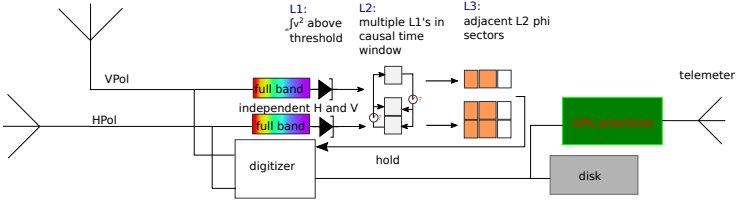
Timeline of Completed ANITA flights

ANITA-Lite	ANITA-I	ANITA-II	**ANITA-III**	**ANITA-IV**
				
2003-2004	2006-2007	2008-2009	2014-2015	2016
18 days, 2 antennas	35 days, 32 antennas	30 days, 40 antennas	22 days, 48 antennas	29 days, 48 antennas
Piggy-back on TIGER	Multi-band, Pol-independent trigger	Multi-band, VPol trigger	Full-band HPol + VPol trigger	Full-band, Lin-Pol trigger

ANITA-III Flight (2014-2015)

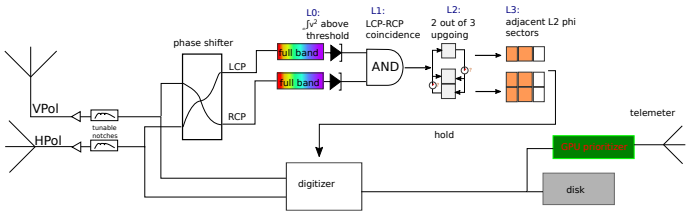


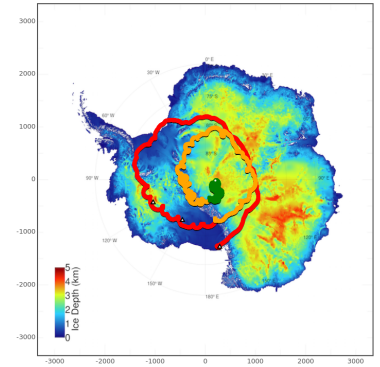
- Independent H + V trigger
- ∼70 million events recorded
- Complications from new military comm satellites → loss of volume, significant improvements to data analysis required.



ANITA-IV Flight (2016)

- Key upgrades:
  - Dynamic, tunable hardware notch filters to reduce CW, greatly increasing livetime
  - New trigger uses hybrid phase shifters to convert H+V to LCP and RCP; requires coincidence between LCP and RCP, ensuring linear polarization
  - Lower noise figure front-end design
- ∼100 million events recorded





Signal and Backgrounds (Fake νs)

Askaryan Emission from ν's

- Impulsive signal (few ns)
- Broadband
- Linearly polarized; mostly vertically-polarized (VPol) due to interaction geometry (Earth opaque to EeV ν's) and transmission through air-ice boundary (Fresnel coefficients).

Geomagnetic Emission from EAS

- Impulsive signal
- More low-frequency weighted
- Linearly polarized; due to Earth's magnetic field, primary horizontally-polarized (HPol)

Continuous Wave (CW) Signals

Anthropogenic narrow-band signals (from satellites and bases) contaminate most data

Thermal Noise

Incoherent random noise, that sometimes by chance looks impulsive (but not correlated between antennas)

Self-triggered "payload blasts"

RF emission produced on payload; does not satisfy plane wave condition

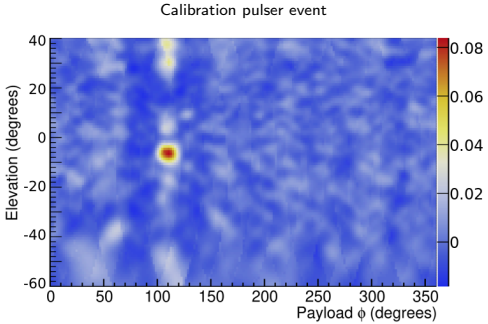
Impulsive Anthropogenic Emission

Transformers, engines, etc. produce broadband impulsive emission that can mimic ν's. These are the most difficult.

Sketch of analysis

Three independent blind ν analyses for ANITA-III, two for ANITA-IV. Basic flow:

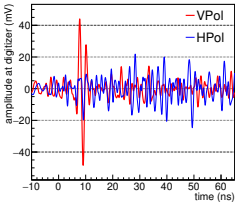
1. Filter waveforms (reduce CW) and remove events failing quality cuts
2. Form correlation map, where we calculate channel cross-correlations with different direction assumptions
3. From peaks of correlation map, form coherent waveforms, generate features (e.g. impulsivity, linear polarization fraction) used to cut out thermal noise
4. Use pointing information to point to continent; select regions with little anthropogenic activity.



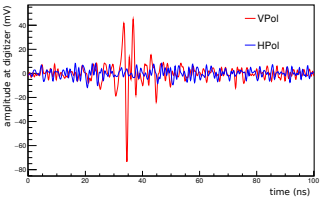
Diffuse Askaryan ν Results

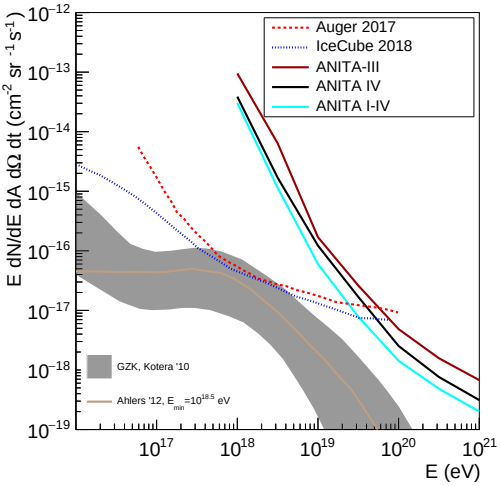
- ANITA-III: (Phys.Rev. D98 (2018) no.2, 022001)
  Most sensitive search found one candidate on a background of $0.7^{+0.5}_{-0.3}$ events.
- ANITA-IV: (Phys.Rev. D99 (2019) no.12, 122001)
  Most sensitive search found one candidate on a background of $0.64^{+0.69}_{-0.45}$ events.

ANITA-III candidate:



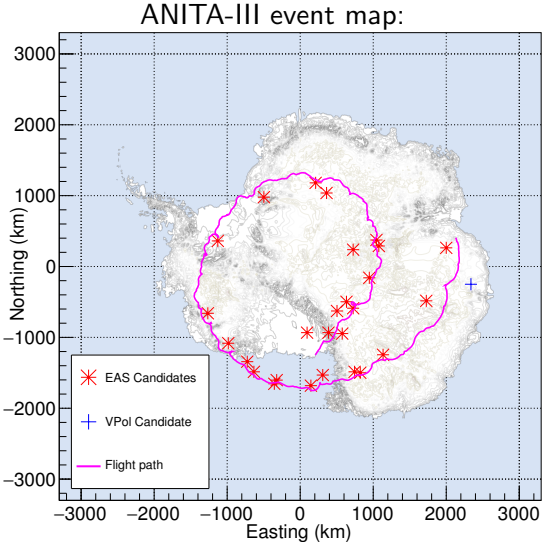
ANITA-IV candidate:



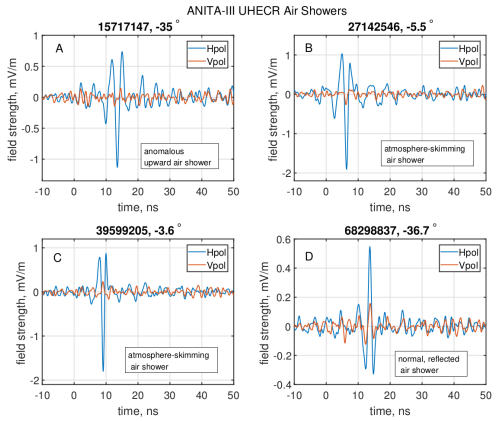


EAS Searches

- Due to potential for upgoing showers, searches performed blind to polarity.
- To be an air shower candidate, in addition to being isolated, impulsive and primarily HPol, must:
  - Match expected air shower shape (which we know, since we've detected EAS before)
  - Have polarization angle consistent with local magnetic field
- $\mathcal{O}$(20-30) EAS candidates identified in each of ANITA-III and ANITA-IV.



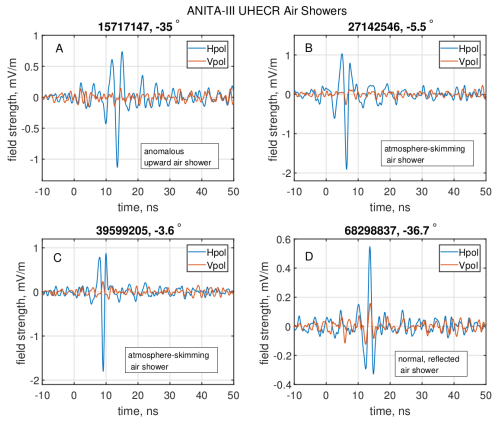
Upward Shower Searches



Top-Left: Anomalous A-III event
Top-Right, Bottom-Left: Direct UHECR candidates
Bottom-Right: A reflected UHECR candidate

- An anomalous event found in ANITA-III (Phys.Rev.Lett. 121 (2018) no.16, 161102), similar to event found in ANITA-I.
- Mostly HPol, matches UHECR template, polarity consistent with direct cosmic ray event, but clearly points to ice, so consistent with an upward going air shower.
- ""Looks like" a $\nu_\tau \to \tau$ candidate, but chord length through Earth in tension with SM cross-section and flux in tension with Auger and IceCube limits; a number of other explanations have been proposed.

Upward Shower Searches



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- **ANITA-IV unblinded polarity not ready yet (sorry!).**

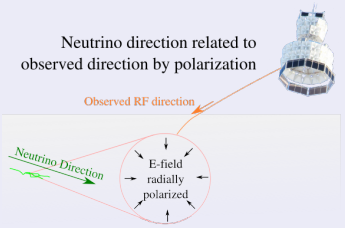
Ongoing ANITA searches

ANITA-IV upward air shower search (i.e. polarity unblinding)

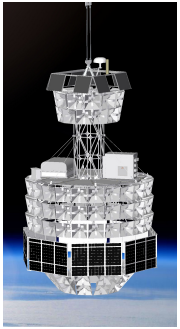
- Holdup is calibration of impulse response, which is more complicated in ANITA-IV due to the programmable notch filters and changes to frontend design.
- Because different filter configurations during flight, must take responses into account when comparing polarity! Lots of work on deconvolution.

Searches for neutrinos in coincidence with sources ongoing in ANITA-III and ANITA-IV

- Consider e.g. putative IceCube sources, flaring blazars, and GRB's
- By constraining time and direction, lower backgrounds and analysis threshold
- Using polarization information, simulations preliminarily indicate RA and dec resolution of a few degrees.
- Intriguingly, the IceCube "neutrino burst" from TXS 0506+056 occured during ANITA-III flight



Future: Payload for Ultrahigh Energy Observations (PUEO)

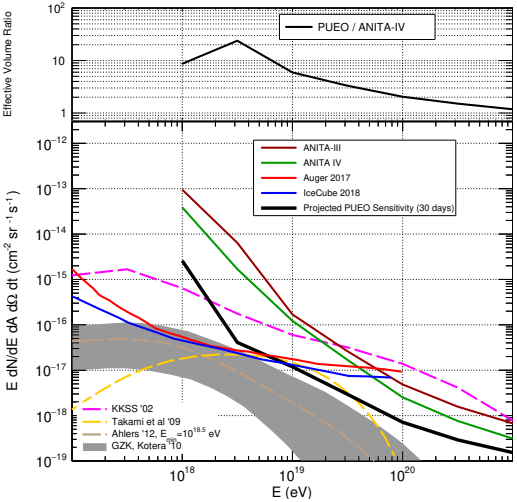


PUEO

pueo

- Additional antennas (120 instead of 48), but with a higher cutoff frequency (300 vs. 180 MHz).
- Beamforming trigger using few-bit streaming digitizers to lower trigger threshold
- 24 antennas canted down to fill gap in ANITA elevation coverage (and further investigate steep air shower events)
- Improved digitizers with better response at high frequencies
- Up to 10X more sensitive than ANITA-IV

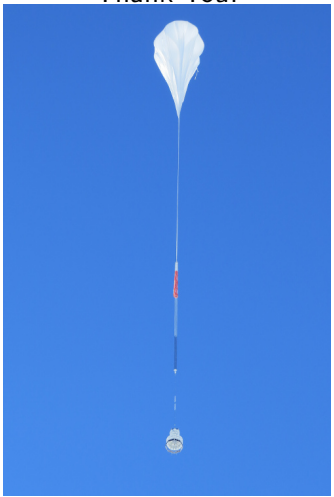
Projected PUEO sensitivity:



Conclusion

- ANITA I-IV combined set the best limits on UHE ν flux above $10^{19.5}$ eV.
- Many EASs detected in ANITA-III and ANITA-IV.
- One of the ANITA-III EAS has anomalous polarity, consistent with an upward-going air shower.
- Stay tuned for ANITA-IV polarity unblinding and ANITA-III and ANITA-IV source searches!
- The proposed PUEO will have substantial hardware and sensitivity improvements.

Thank You!

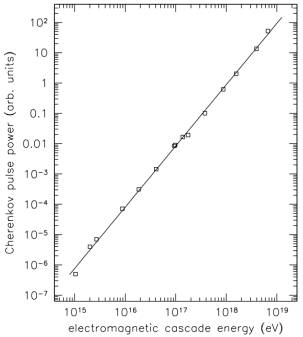


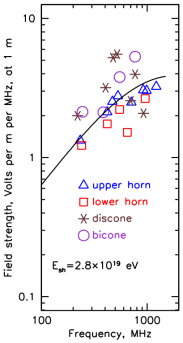
Questions?

Backup Slides

Detection Mechanism: Radio Emission from Askaryan Effect in Ice

- **Askaryan (charge-excess) radiation**: Fast-moving charge density in dielectric → coherent emission ($\propto E^2$) at long (radio) wavelengths
  - Charge excess from annihilation of positrons with electrons in material
  - At wavelengths larger than lateral width, don't resolve individual charges
- Confirmed in ice with SLAC beam test (Phys.Rev.Lett.99:171101,2007)
- Radio attenuation length in ice is $\sim$ 1 km





(Some) Upward Shower Explanations

ν_τ-induced EAS

- \+ Would produce upward-going EAS
- \- Chord through Earth not compatible with SM cross-section
- \- Tension with IceCube and Auger results

Funny reflection of UHECR EAS

- \+ Apparent upward-going EAS shower
- \- Hard to invert polarity but maintain coherence
- \- Would likely have seen effect in data from HiCal (trailing balloon with HV pulser)

Anthropogenic Background

- \+ No physics to explain
- \- We consider it unlikely

Transition Radiation from UHECR EAS

- \+ Could produce impulsive emission with right polarization
- \- Work needed to see if can mimic signal

Exotics (e.g. heavy ν DM, sterile ν)

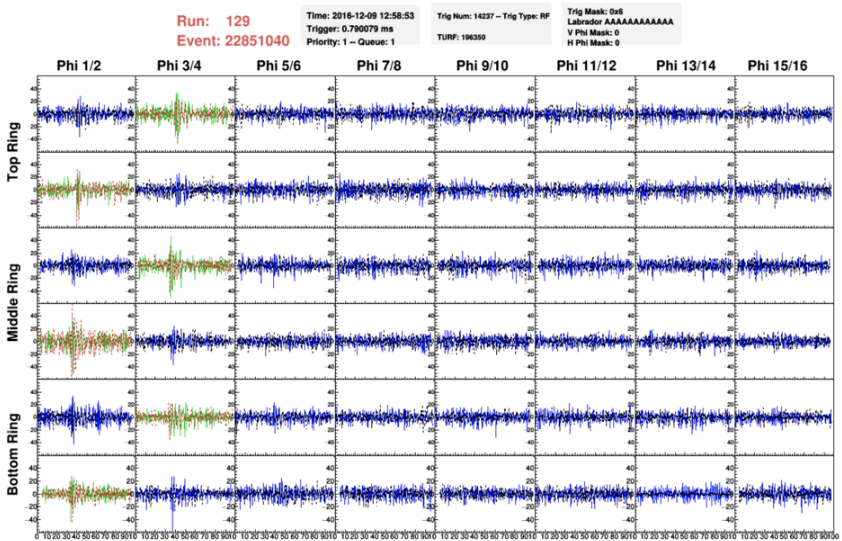
- \+ Could produce upward-going EAS
- \- New physics
- \- Tension with IceCube and Auger

Not geomagnetic, instead Askaryan

- \+ Could produce impulsive emission
- \+ Not in tension with other experiments
- \- If from ν, observed polarization unlikely
- \- If from some exotic, need new physics.

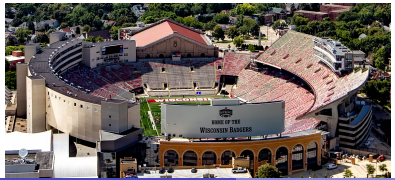
The Raw Data (a Calibration Pulse, Not a ν)

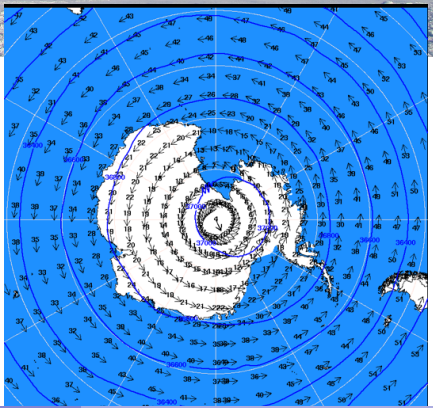
- 48 dual-polarization horn antennas
- Sampled at $\approx$ 2.6 GHz's
- 100 ns per event
- 50 Hz global trigger rate
- $\mathcal{O}(10^7)$ RF triggers per flight (ANITA-III and IV)



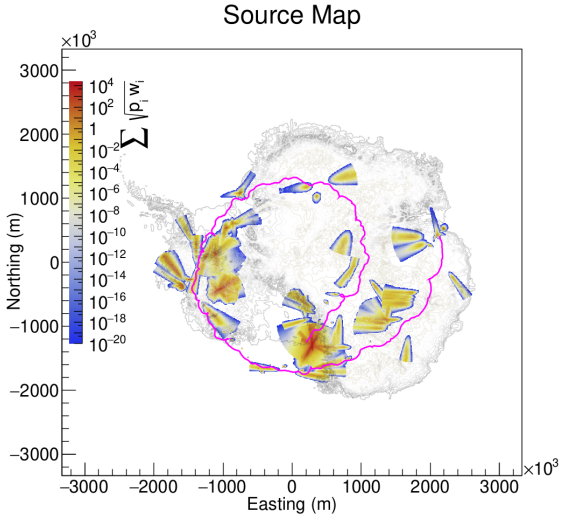
Ballooning in Antarctica

- Antarctica not only has abundant ice but also hosts the NASA long duration balloon program!
- At float (35-40 km), balloon expands to size of football stadium.



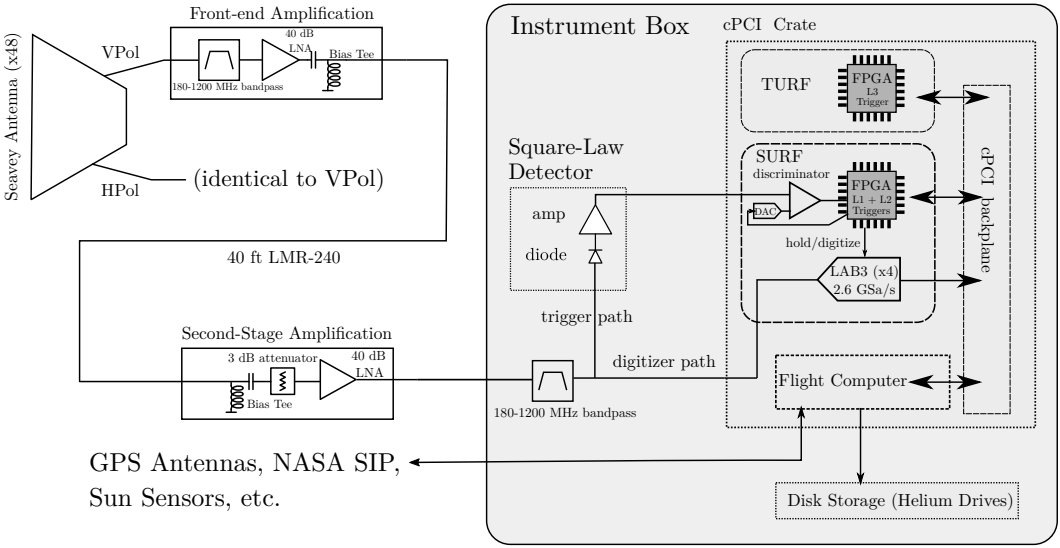


Using Spatial Information to Remove Anthropogenics

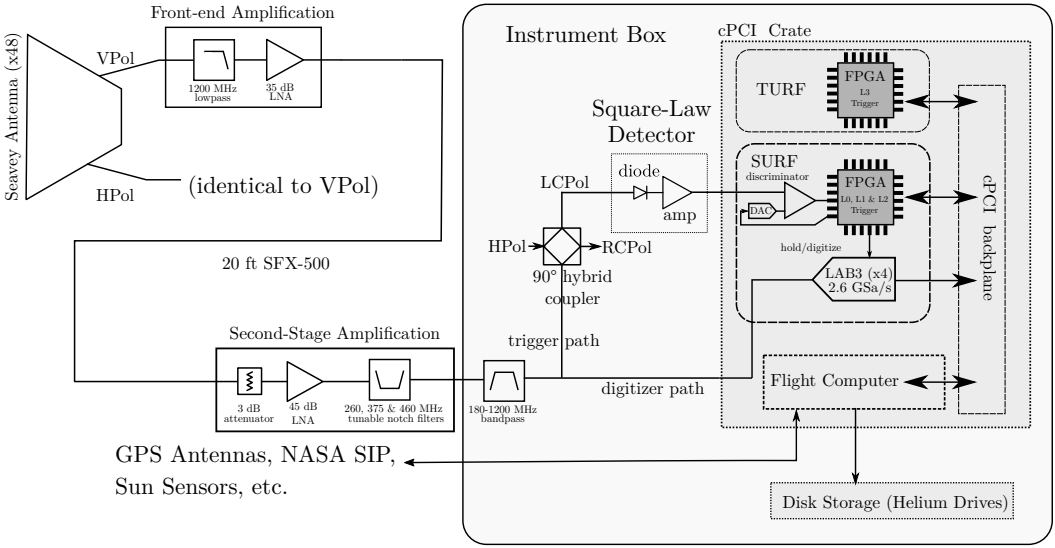


- We assume anthropogenic emission is spatially clustered on the continent, so we only consider isolated events as candidates.
- For each signal-like event, we measure a direction with some pointing resolution.
- One example clustering algorithm:
  - Project all interesting events to continent and accumulate to form a "clustering map." Use to compute overlap integral of each event with all other events.
  - Isolated events will have overlap integrals close to zero
- Other methods to tackle anthropogenics include pairwise event clustering or a binned continent analysis.

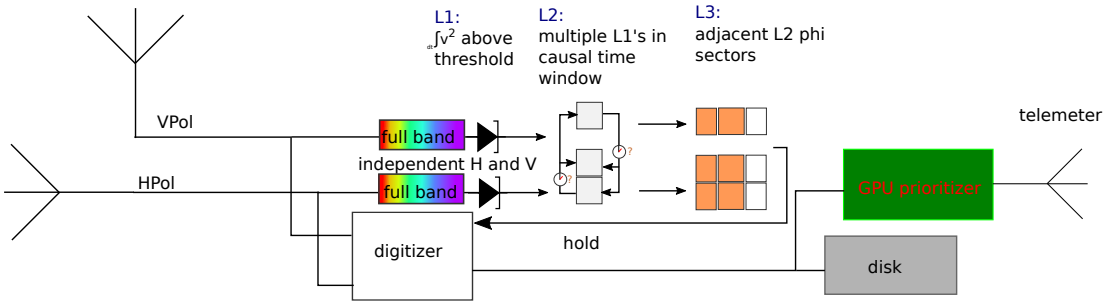
ANITA-III Block Diagram



ANITA-IV Block Diagram



ANITA-III Trigger



ANITA-IV Trigger