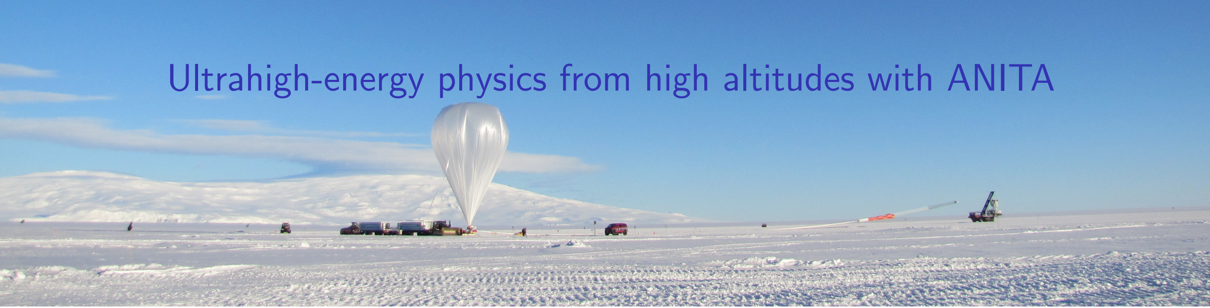
Ultrahigh-energy physics from high altitudes with ANITA



Cosmin Deaconu
on behalf of the ANITA Collaboration

University of Chicago / Enrico Fermi Institute / Kavli Institute for Cosmological Physics

PANIC 2021
“Lisbon”, September 8, 2021

ANITA Collaboration

ANtarctic Impulsive Transient Antenna

12 institutes, 3 countries, 4 continents

UCL

University of Delaware

The University of Chicago

The Ohio State University

KU The University of Kansas

Washington University in St. Louis

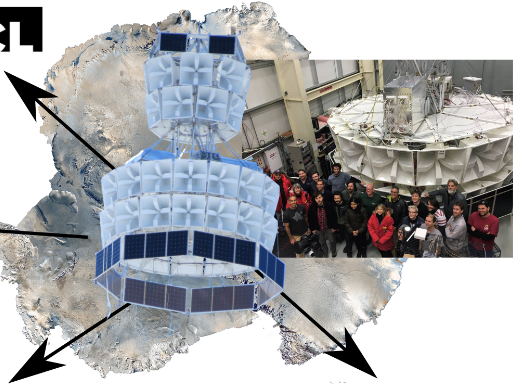
UCLA

JPL Jet Propulsion Laboratory California Institute of Technology

Cal Poly San Luis Obispo

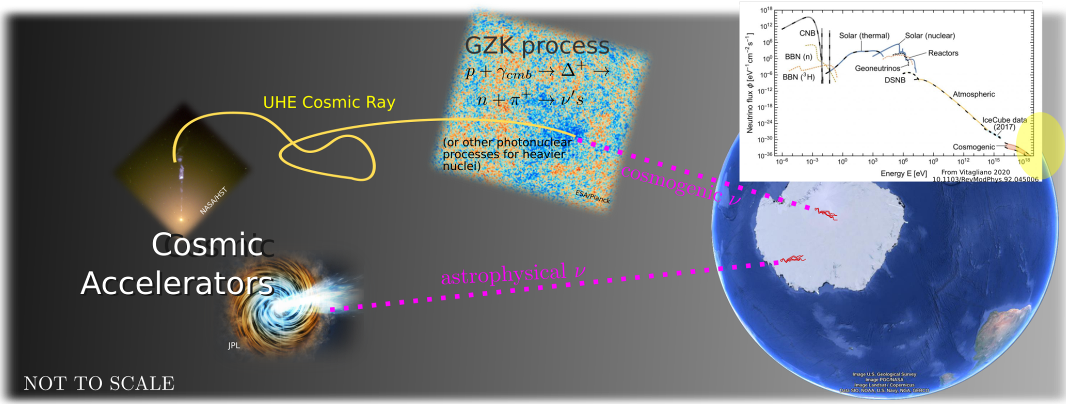
SLAC National Accelerator Laboratory

University of Hawai'i



國立臺灣大學 National Taiwan University

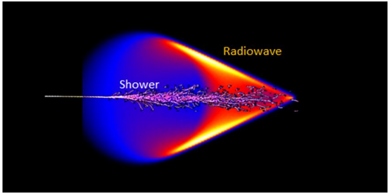
ANITA's Motivation: Detect UHE ν's ($>$EeV)



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

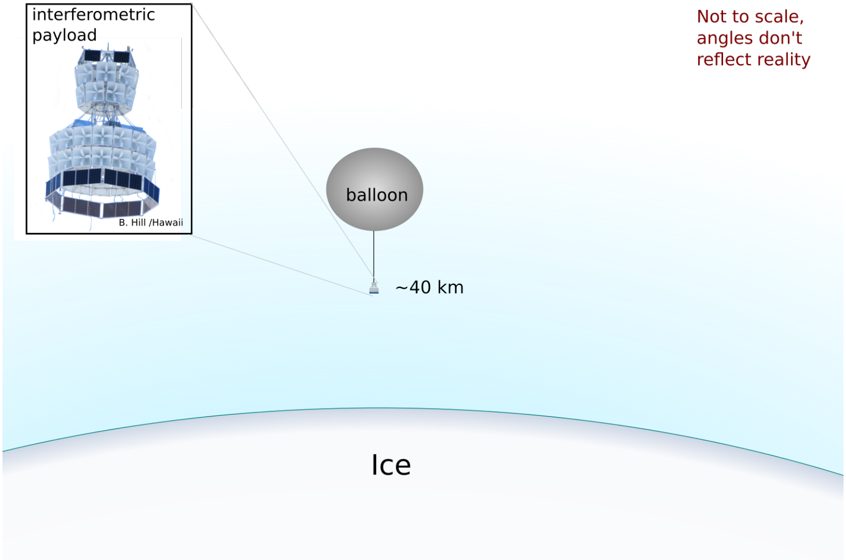
Expected flux is unknown but very low, so need big detector

Detection Mechanism: Askaryan Effect



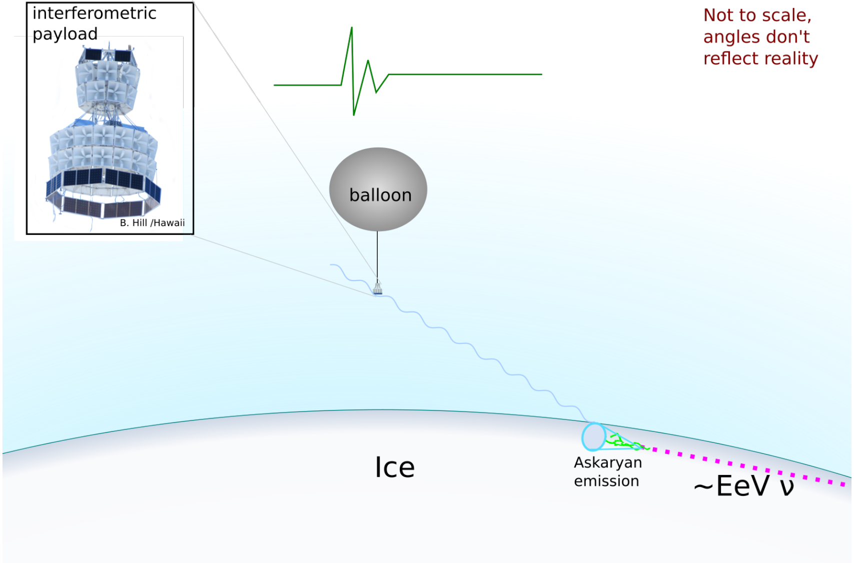
- UHE particle shower in dense dielectric results in fast-moving charge excess due to presence of electrons in the material $\rightarrow$ coherent Cerenkov emission at wavelengths larger than apparent size of shower (i.e. radio!).
- Experimentally confirmed in beam tests in various dielectrics, including glacial ice (abundant, long radio attenuation lengths)
- Other experiments using this technique for Neutrino detection include RICE, ARA, ARIANNA, RNO-G, IceCube Gen2Radio

ANITA Experiment Concept

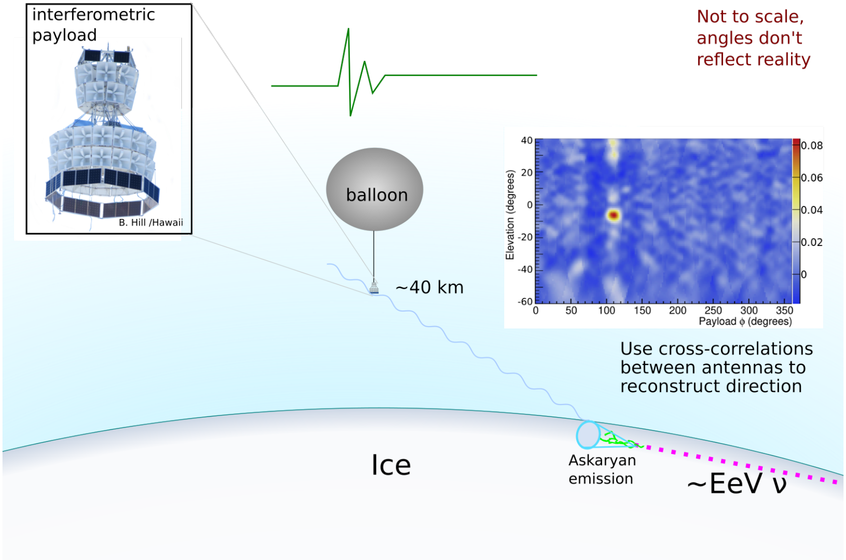


Not to scale,
angles don't
reflect reality

ANITA Experiment Concept

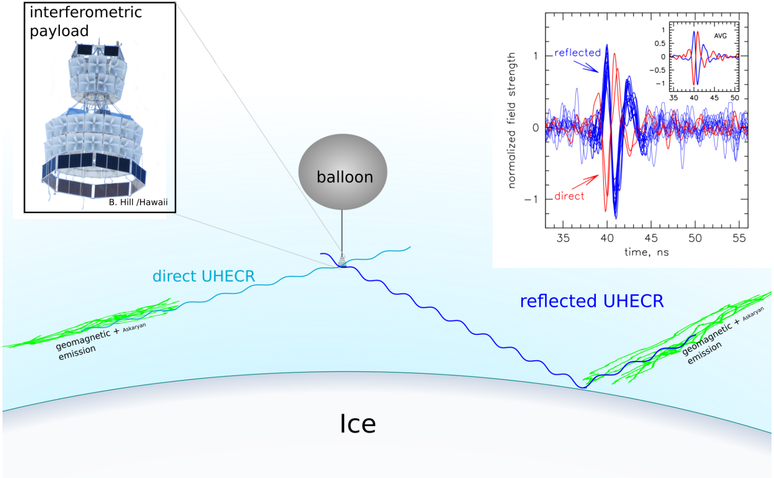


ANITA Experiment Concept



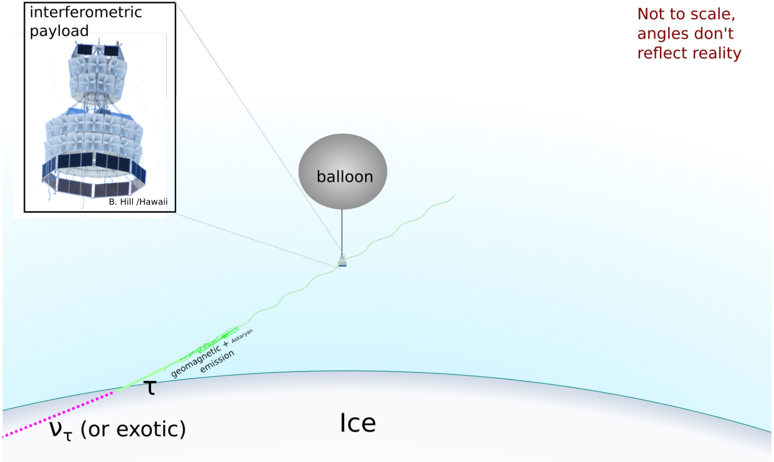
Another signal: Radio Emission from Extensive Air Showers (EAS)

- 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**

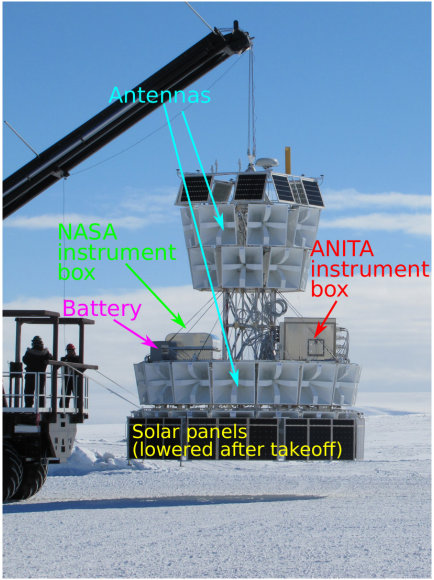


Sensitivity to Upward-Going Air Showers?

- Direction consistent with reflected UHECR, but polarity of direct
- Could be produced by a ν_τ-induced τ which escapes atmosphere and decays, producing shower (subdominant in exposure to Askaryan above a few EeV). Or ... exotics ?

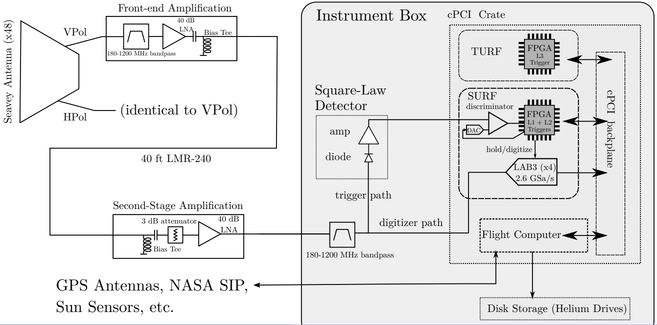


ANITA Instrument

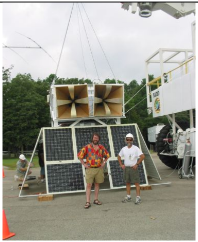
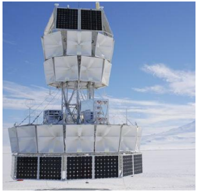
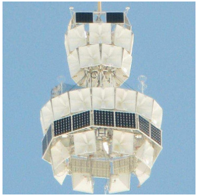
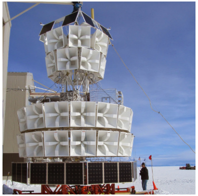


- Signal ($\sim$ 180-1200 MHz) split into digitization and trigger paths
  - Tunnel diode noise-riding first-level trigger. combinatorics between antennas take $\mathcal{O}(10^{5-6}$ Hz) singles rate $\rightarrow \mathcal{O}(50$ Hz) global rate
  - Switched Capacitor Array digitizers, $\sim$2.6 GSa/s, $\mathcal{O}(100$ 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 New Milsats with lots of narrowband noise	Full-band, Lin-Pol trigger Tunable notch filters to fight milsats

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

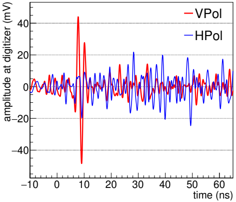
Impulsive Anthropogenic Emission

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

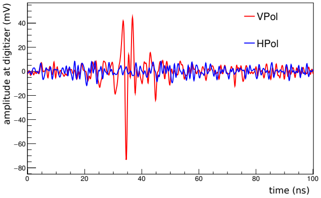
Askaryan ν Results

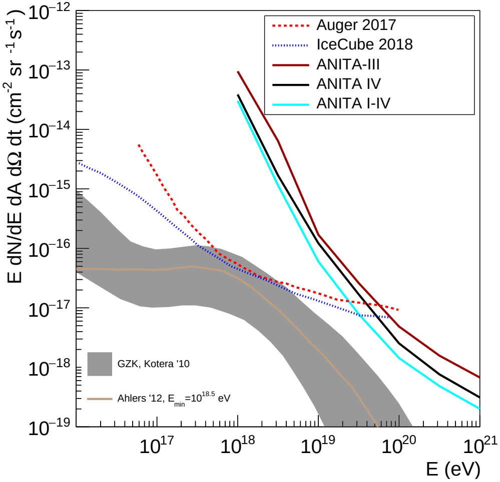
- ANITA-III: Most sensitive diffuse search found one candidate on a background of $0.7^{+0.5}_{-0.3}$ events (arxiv:1803.02719). Also non-diffuse results finds no significant associations (arxiv:2010.02869).
- ANITA-IV: Most sensitive search found one candidate on a background of $0.64^{+0.69}_{-0.45}$ events (arxiv:1902.04005)

ANITA-III candidate:



ANITA-IV candidate:

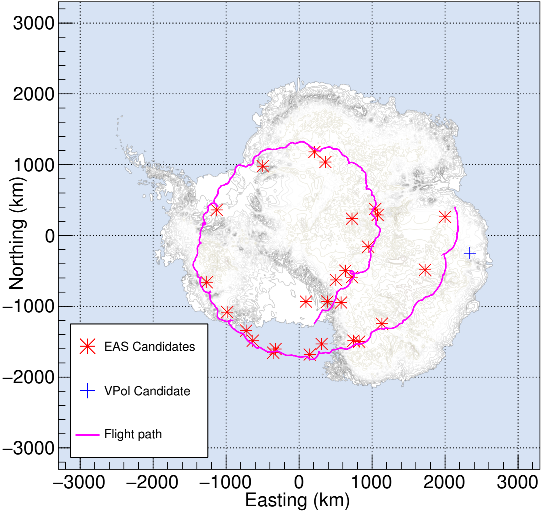




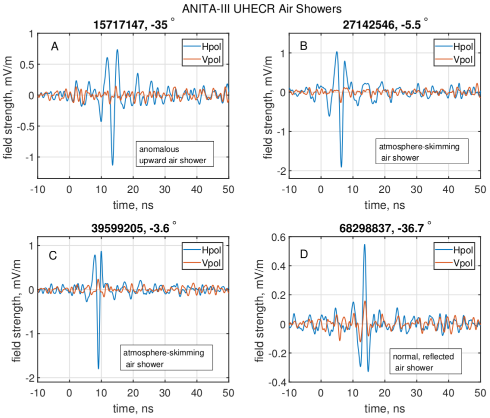
EAS Searches

- 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.

ANITA-III event map:



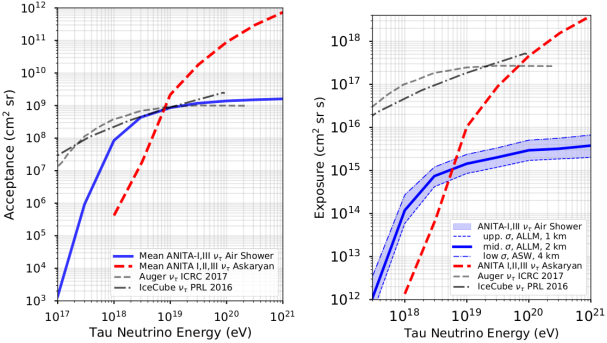
Upward-going showers?



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

- An anomalous event found in ANITA-III (arxiv:1803.05088), similar to event found in ANITA-I (arxiv:1603.05218).
- 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.
- Each event is $\sim 3\sigma$ unlikely to be an anthropogenic background.
- Phenomenologically "looks like" a $\nu_\tau \to \tau$ candidate, but **it can't be an SM neutrino**.

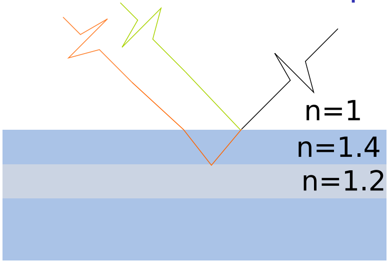
Why these can't be a ν_τ

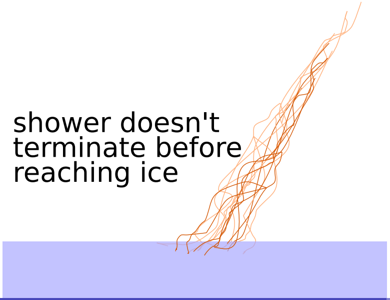


- Auger, IceCube have much larger exposures at implied energy of $\mathcal{O}(1\text{ EeV})$.
- Due to Earth opacity at UHE, not even self-consistent for diffuse flux
- Very hard to produce a transient flux that IceCube or Auger would not have seen.
  - IceCube not running during ANITA-I event, and had a run change at time of ANITA-III event, and Auger wasn't sensitive to that part of the sky at the time, but... how lucky could we get?

These “ANITA anomalous events” have generated a bit of interest

Some Mundane-ish explanations





- Funny ice reflections (Shoemaker et al, arxiv:1905.02846)
  - Possible, but ice would need to have special structure over a large area (Fresnel zone convolved with beam pattern on ground)
  - Would likely need unexpected ice properties, since dielectric constrast from "normal" underice layers would have a very hard time explaining the observations.
  - Lack of non-inversion from HiCal trailing calibration payload suggests that any such reflection can't be common (arxiv:2009.13010).
- Funny EAS emission
  - Maybe there is a class of atypical EAS that look different
  - In particular, some air showers may not terminate before hitting the ice (de Vries and Prohira, arxiv:1903.08750), which could potentially modify shape of the signal.
  - More detailed simulations needed to see if viable.

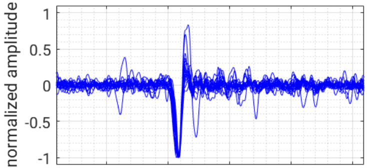
More fun explanations: new physics! (not justified by current significance)

- Many exotic particle or exotic neutrino explanations that eventually produce a τ-induced EAS (See Anchordoqui et al. arxiv:1907.06308 for a summary)
  - +Compatible with observed effect
  - -Non-trivial to evade IceCube or Auger bounds
- Maybe it's actually Askaryan emission from something other than neutrino (e.g. Hooper+CD+Vieregg, arxiv:1904.12865)
  - +Not in tension with other experiments
  - +Observed polarization and polarity possible if Askaryan shower from some deeply penetrating particle (not a ν).
  - -But the observed polarization and polarity would be a coincidence
- Some other radio emission mechanism entirely (e.g. axions in ionosphere, Esteban et al. arXiv:1905.10372).
  - +Not in tension with other experiments
  - +Testable by looking for other evidence of same mechanism in existing data
  - -Unclear if could produce observed signal without more work.

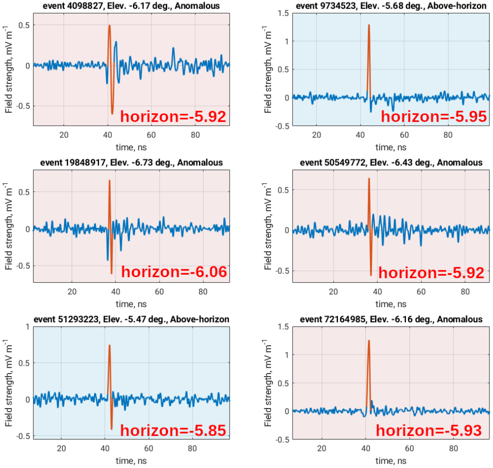
Meanwhile, ANITA-IV results (arxiv:2008.05690)

- Time-dependent filters introduced to mitigate satellite noise in ANITA-III made polarity determination more complicated in ANITA-IV.
- **4 upward-shower candidates identified**
- But... all very near horizon ($\sim -6^{\circ}$)
- $\sim 3.2\sigma$ that ensemble not explained by:
  - mispointed above-horizon air shower (including systematics!)
  - anthropogenic background (est. $0.37^{+0.27}_{-0.17}$)
  - misidentified polarity

21 reflected, below-horizon events (CLEAN-deconvolved):



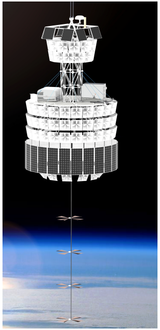
6 unreflected events, 4 (barely) below-horizon (CLEAN-deconvolved):



Interpretation of ANITA-IV events

- These are qualitatively different than previous apparent upward showers (very close to horizon rather than steeply upgoing).
  - The fact that we didn't see any new steep events is not enough to rule those out (in fact there were two events with indeterminate polarity we could not confidently classify one way or another, including one that was steep)
  - No easy way to combine significances across flights.
- Still evaluating if tau neutrino hypothesis could be viable (paper soon)
  - Not obviously self-inconsistent like it was for steep events, due to less Earth absorption and ANITA's large instantaneous exposure, but inconsistent with IceCube, Auger for a diffuse flux.
- Some proposed mundane explanations are harder to invoke:
  - Much larger ice reflection area, would require greater conspiracy of ice effects
  - Grazing air showers don't hit ice
- But, near-horizon radio propagation is complex and hard to model. Possible that more detailed future modeling will reveal additional systematics in addition to the ones we are already considering.

Future of ANITA: Payload for Ultrahigh Energy Observations (PUEO)

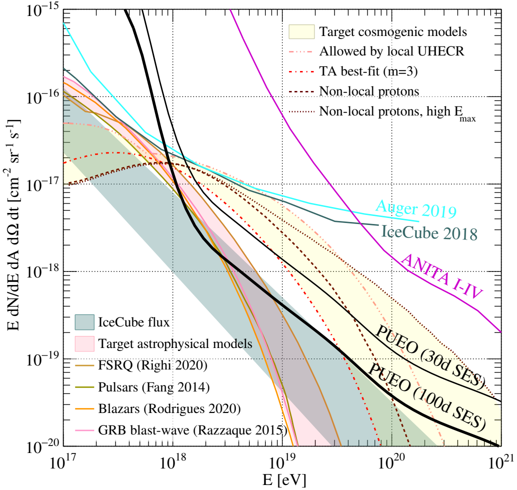


PUEO

pueo

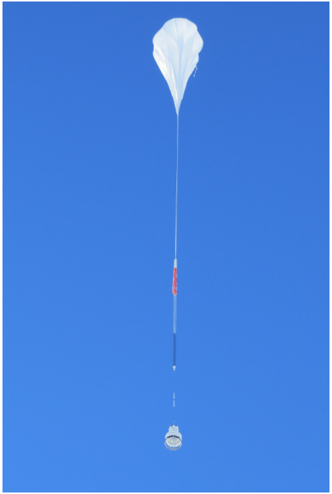
- More antennas but a higher cutoff frequency (300 vs. 180 MHz).
  - Also includes low-frequency array (50-300 MHz) for EAS events and downward antennas for steep events.
- More than an order of magnitude more sensitive than ANITA-IV for Askaryan channel
  - Much lower trigger threshold
  - Improved electronics
- Could fly as soon as 2024.
- White paper: arxiv:2010.02892.
- Best diffuse sensitivity above a few EeV, very large instantaneous sensitivity for transients.

Projected PUEO sensitivity:



Conclusion

Thank You!



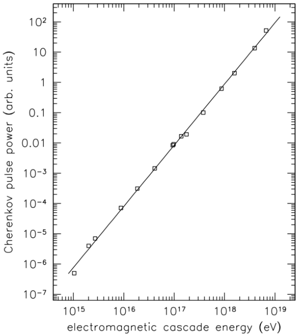
Questions?

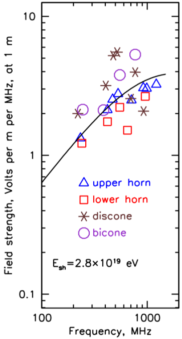
- ANITA I-IV combined set the best limits on UHE ν flux above $10^{19.5}$ eV.
- Many EASs detected in ANITA-III and ANITA-IV.
- Anomalous polarity events still not understood.
- The proposed PUEO will have substantial hardware and sensitivity improvements.

Backup Slides

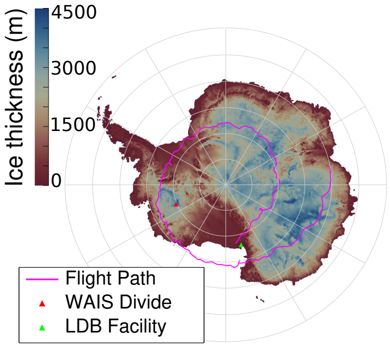
Detection Mechanism: Radio Emission from Askaryan Effect in Ice

- **Askaryan (charge-excess) radiation**: Fast-moving charge density in dielectric $\rightarrow$ 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

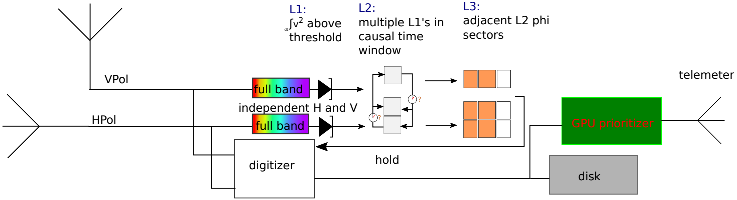




ANITA-III Flight (2014-2015)

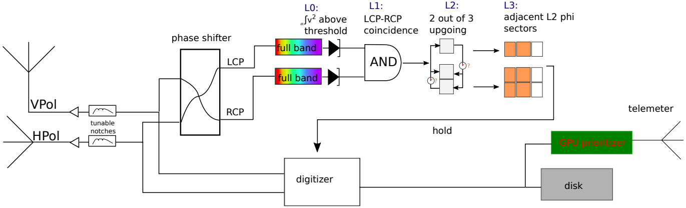


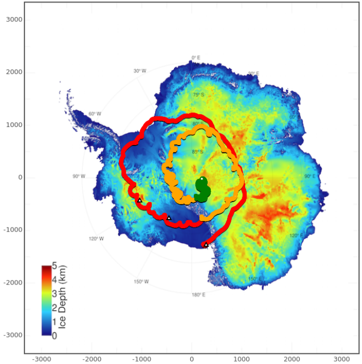
- Independent H + V trigger
- ∼70 million events recorded
- Complications from new military comm satellites → loss of volume, significant improvements to data analysis required.



ANITA-IV Flight (2016)

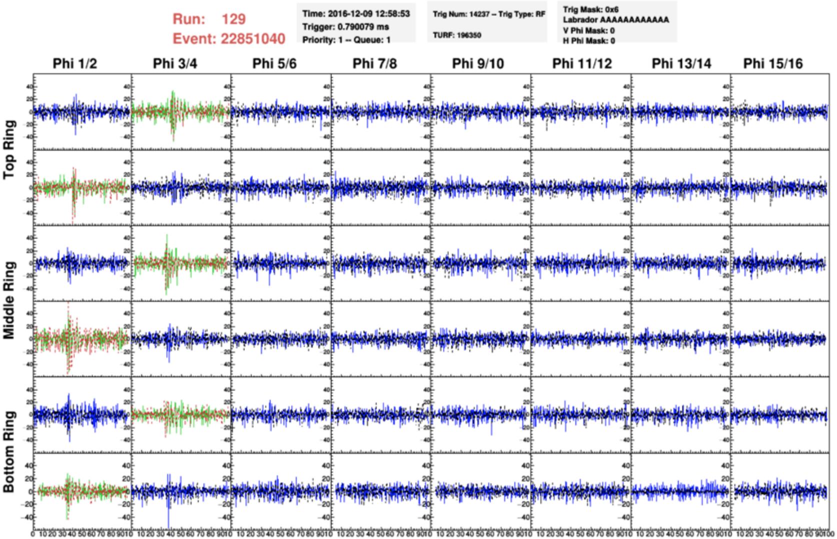
- Key upgrades:
  - Dynamic, tunable hardware notch filters to reduce CW, greatly increasing livetime
  - New trigger uses hybrid phase shifters to convert H+V to LCP and RCP; requires coincidence between LCP and RCP, ensuring linear polarization
  - Lower noise figure front-end design
- ~100 million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





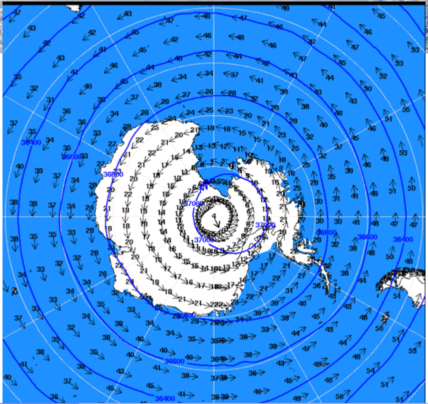
The Raw Data (a Calibration Pulse, Not a ν)

- 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

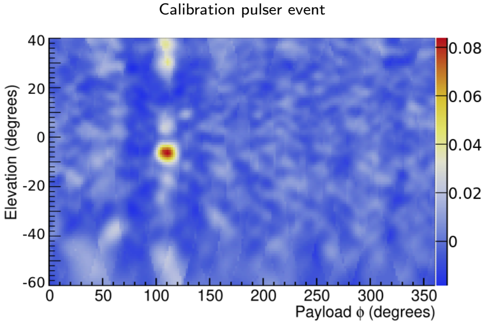
- Antarctica not only has abundant ice but also hosts the NASA long duration balloon program!
- At float (35-40 km), balloon expands to size of football stadium.

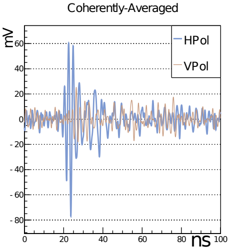


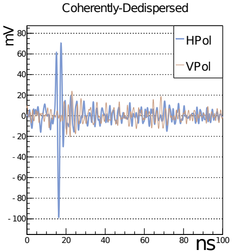
Sketch of analysis

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

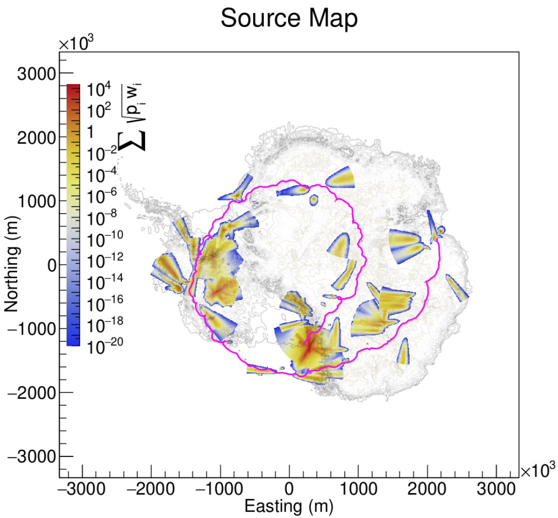
1. Filter waveforms (reduce CW) and remove events failing quality cuts
2. Form correlation map, where we calculate channel cross-correlations with different direction assumptions
3. From peaks of correlation map, form coherent waveforms, generate features (e.g. impulsivity, linear polarization fraction)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





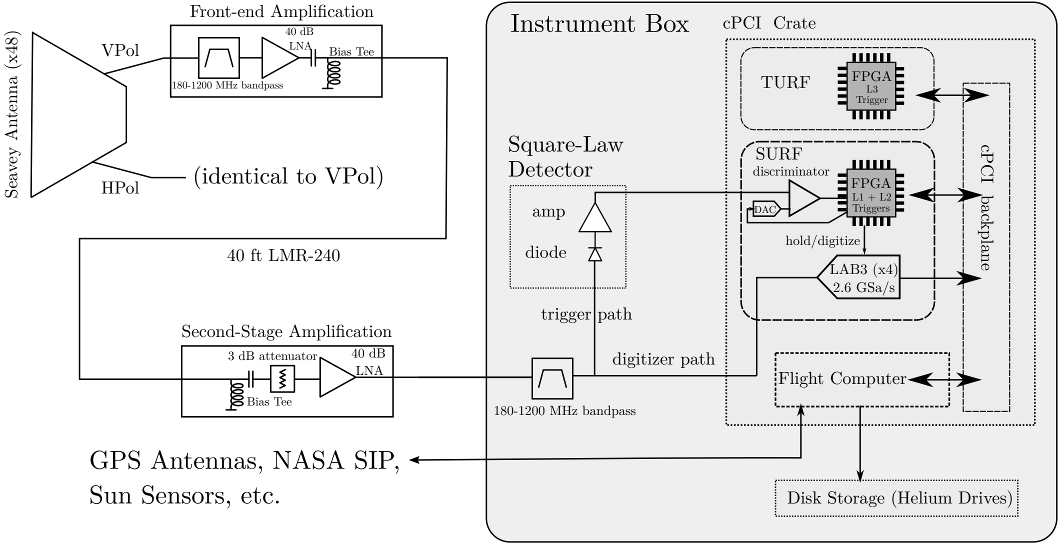


Using Spatial Information to Remove Anthropogenics

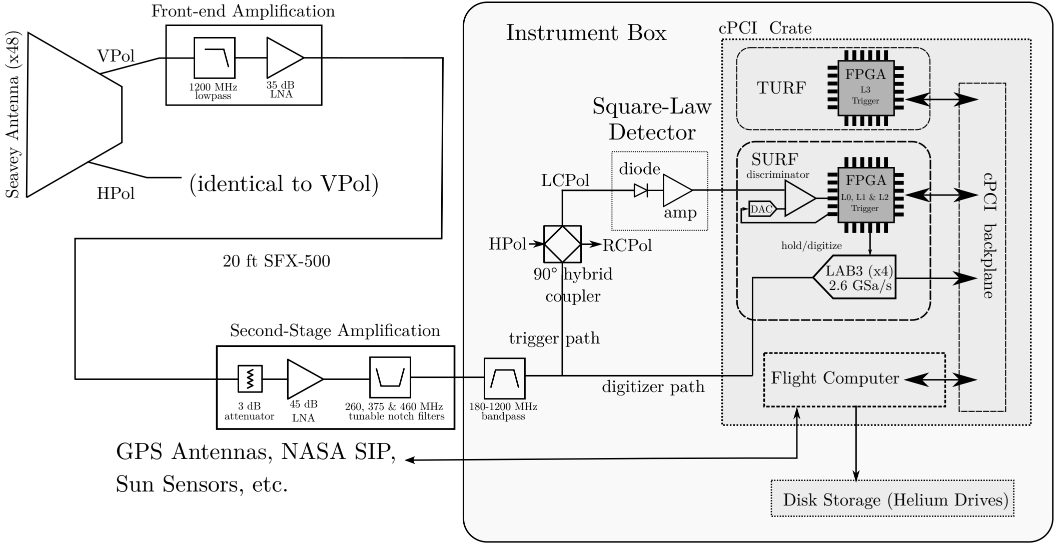


- We assume anthropogenic emission is spatially clustered on the continent, so we only consider isolated events as candidates.
- For each signal-like event, we measure a direction with some pointing resolution.
- One example clustering algorithm:
  - Project all interesting events to continent and accumulate 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.

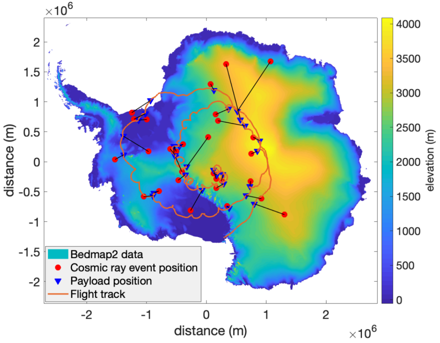
ANITA-III Block Diagram

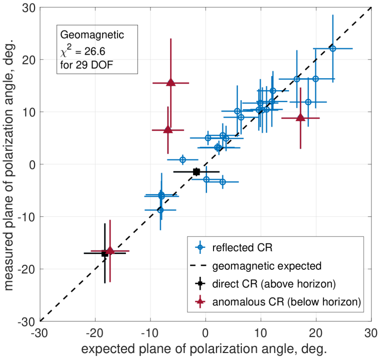


ANITA-IV Block Diagram



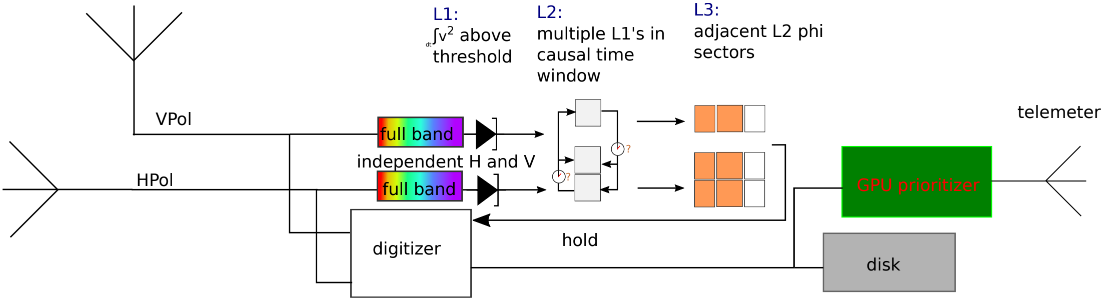
More details on the ANITA-IV events





event #	mm dd hh mm ss UTC 2016	Apparent source location Lat.°,Lon.°, alt., m	elev. angle degrees	horizon angle degrees	azimuth degrees	Payload location Lat.°, Lon.°, alt., km	Type	Energy EeV
4098827	12 03 10 03 27	-75.71, 123.99, 3184	-6.17 ± 0.21	-5.92 ± 0.02	337.70	-80.157, 131.210, 38.86	NI	1.5 ± 0.7
9734523	12 05 12 55 40	-71.862, 32.61, 19000[b]	-5.64 ± 0.20	-5.95 ± 0.02	2.01	-80.9, 31.6, 39.25	AH	...
19848917	12 08 11 44 54	-80.818 , -79.87, 758	-6.71 ± 0.2	-6.06 ± 0.02	194.34	-76.66, -72.86, 38.97	NI	0.9 ± 0.5
50549772	12 16 15 03 19	-83.483, 14.73, 2572	-6.73 ± 0.2	-5.92 ± 0.02	234.08	-81.95, 47.29, 38.52	NI	0.8 ± 0.3
51293223	12 16 19 08 08	-74.800, 11.43, 18600[b]	-5.38 ± 0.24	-5.85 ± 0.02	306.45	-81.7, 39.2, 37.53	AH	...
72164985	12 22 06 28 14	-86.598, 0.35, 2589	-6.12 ± 0.10	-5.93 ± 0.02	140.03	-86.93, -104.29, 38.58	NI	3.9 ± 2.5

ANITA-III Trigger



ANITA-IV Trigger