# Exploring the Ultrahigh-Energy Universe with the ANITA Long-Duration-Balloon Experiment

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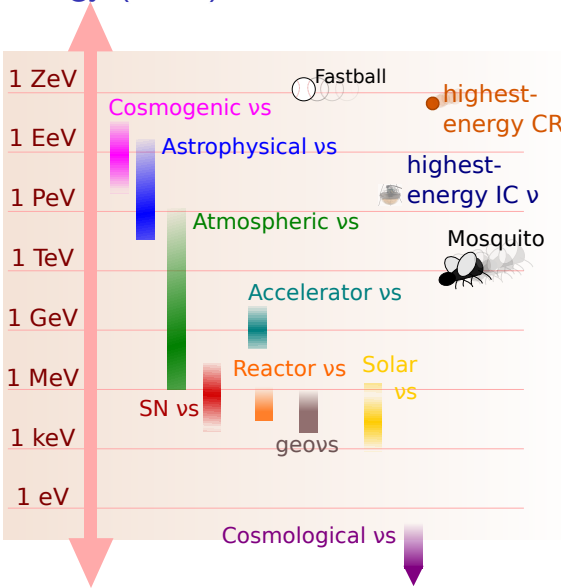
# Outline

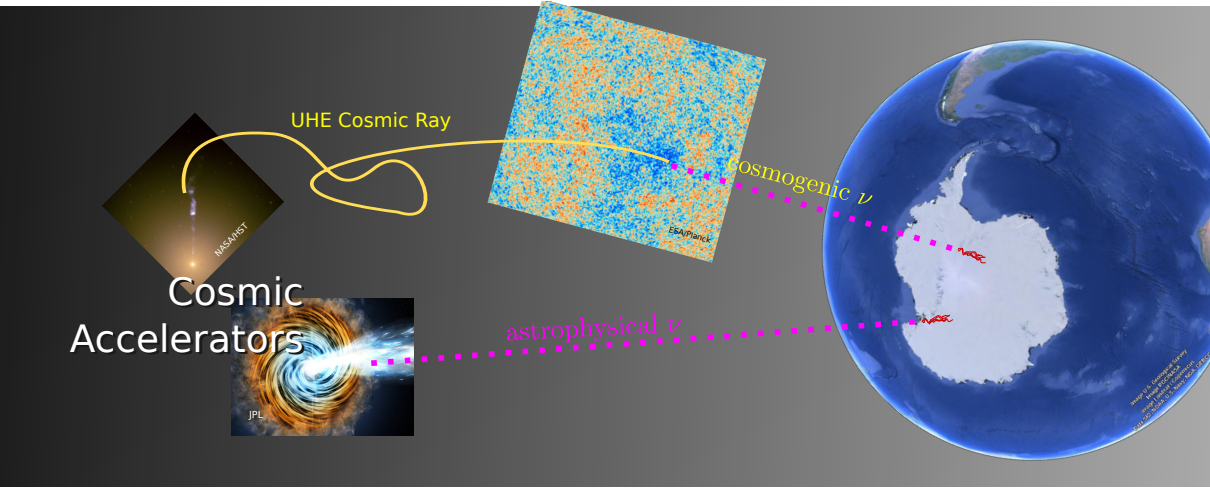
- **Introduction: Ultrahigh energy (UHE) neutrinos and how to detect them**
- The ANITA Experiment
- Results from ANITA
- The future of ANITA (PUEO!)

# What do I mean by Ultrahigh-Energy (UHE)?

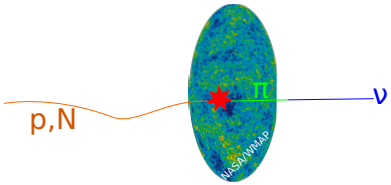
- Neutrinos cover a wide energy range (From $\mu$eV to EeV)
- I'll be talking about looking for neutrinos at energies of $\mathcal{O}(1\mathrm{EeV})$ and higher.
- 1 EeV $= 10^{18}$ eV $= 10^{9}$ GeV $= 10^{6}$ TeV $= 1000$ PeV
- For reference, Most energetic cosmic ray ever detected is 300 EeV.



# Cosmogenic and Astrophysical $\nu$s



# Cosmogenic $\nu$s




- For protons, typically 5% of initial energy goes to $\nu$ in GZK process (threshold $\sim$ 50 EeV).

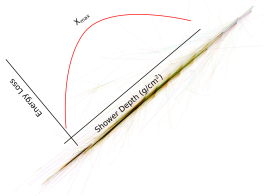
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \pi \rightarrow \nu s \tag{1}$$

- Heavier nuclei also produce $\nu$'s via photodisintegration, but with lower energy yield.
- We know both UHECR and the CMB exist, so these neutrinos are "guaranteed" at some level, although they have not yet been detected.

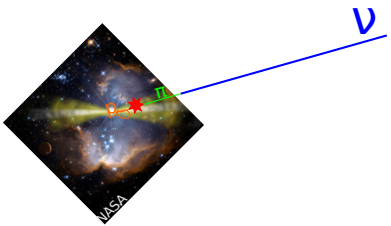
# Cosmogenic $\nu$ flux

Ballpark cosmogenic interaction estimate is $< 1$ / km$^3$ of stuff / century, but large uncertainty.

1. Unconstrained UHECR composition at highest energies
   - TA and Auger measure $X_{max}$, which has a distribution related to the UHECR composition (albeit with large systematics and messy hadronic physics).
   - Auger prefers a heavier CR composition at the highest energies, implying lower UHE $\nu$ flux. TA composition more favorable.
2. Unknown source evolution
   - Since we haven't identified the UHECR sources, don't know how they evolve with redshift.
   - Because of GZK, TA and Auger can only probe the local universe.
   - Some sources classes are much more abundant outside GZK horizon ($z \approx 0.03$).
3. Unknown maximum UHECR energy
   - UHECR get downcoverted by CMB, so cannot constrain $E_{max}$



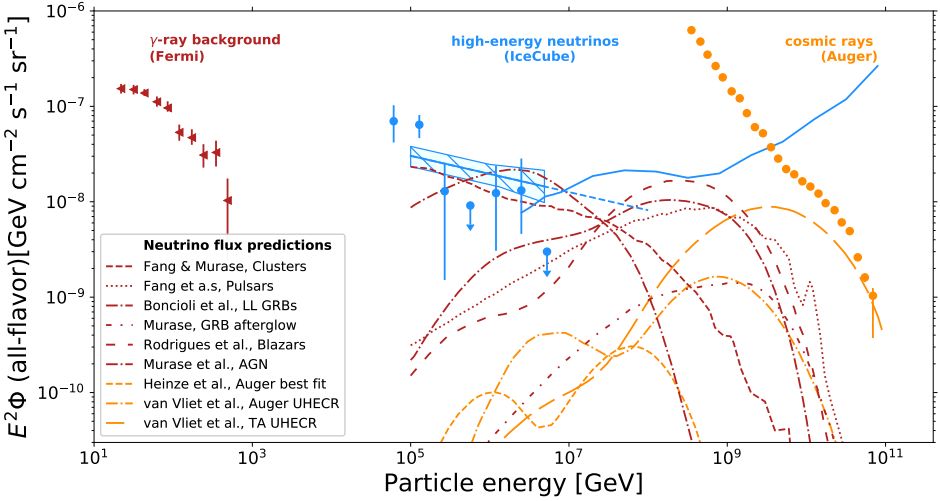
# Astrophysical $\nu$?




- These are the neutrinos produced directly in astrophysical sources ($p + \gamma$, $p + p$, etc.), rather than during propagation.
- Have been measured up $\sim$ 10 PeV by IceCube (sources unclear).
- Note that sources of astrophysical $\nu$ not necessarily good sources of UHECR (because the particles can't be accelerated to the highest energy if they produce neutrinos within the source).
  - Typically, need both an acceleration zone and an interaction zone.
  - Usually will also get $\gamma$-rays.
- Some sources (e.g. GRB's, FSRQ) may produce neutrinos at EeV energies.

# Some flux predictions

Note that y-axis is scaled by $E^2$!

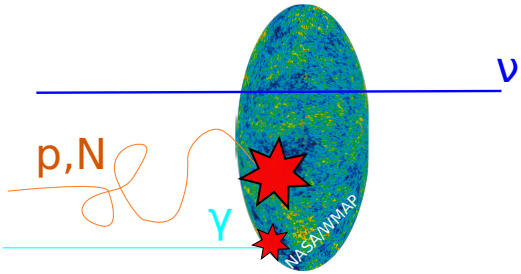



A. Nelles.

# More speculative sources?

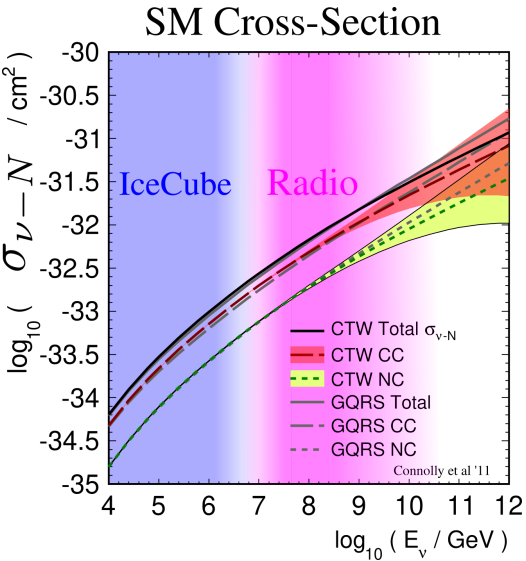
- "Top-down models" (don't accelerate particles, produce them directly):
  - Ultra-heavy dark matter
  - Topological defects
  - Many of these have already been constrained by UHE neutrino data.
- High-redshift-only sources
  - Accelerators outside of GZK horizon ($z \approx 0.03$) largely unconstrained by UHECR or $\gamma$ data (since both downconvert into more abundant lower-energy particles).
  - Not so crazy to imagine some sources just don't exist within our GZK horizon, for example, there are no known FSRQs within GZK horizon.
  - Anything can happen out there and we might only find out through neutrinos.
- ???
  - If found, UHE neutrinos may not be consistent with any of the predictions and suggest something entirely.

# So what? Why bother trying to detect them?

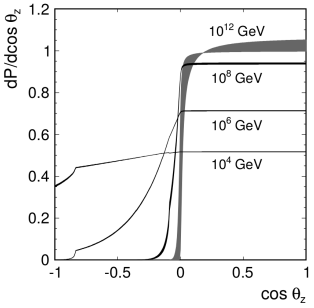



- Because they're (maybe) there!
- To better understand cosmic accelerators:
  - Neutrinos are the ideal messengers since they don't interact or get deflected on the way here.
  - Even though cosmogenics are produced away from the sources, on cosmologlical distances, that's unresolveable, so if there are few enough sources, could find them.
  - Astrophysical $\nu$ may appear coincident with transients from other messengers ($\gamma$s, GW).
  - Even non-detection can provide insight on how cosmic accelerators work (and things like mass composition)

# So what? (for particle physicists): Most energetic neutrinos available!




- Verify Standard Model $\nu - N$ cross-section at a new energy scale by using Earth as a filter.

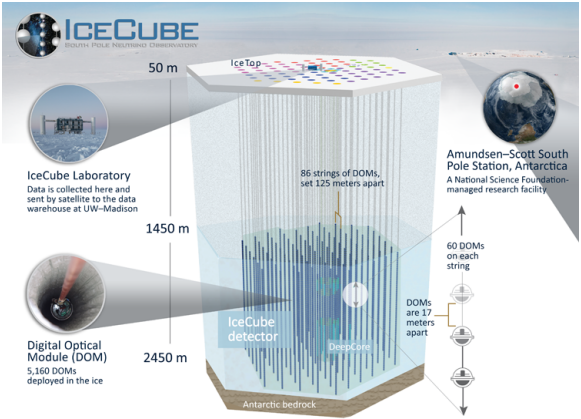



Phys. Rev. D 83, 113009

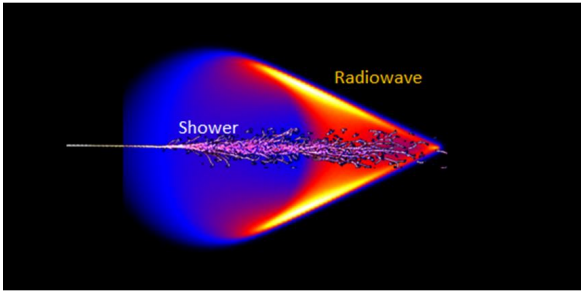
- BSM models could enhance or suppress cross-sections at high energies
- Can also probe Lorentz invariance, sterile neutrinos, etc.

# Problem: how do you build a detector large enough?

- Due to low predicted interaction rate, need to instrument some existing dense volume.
- Optical Cerenkov detectors like IceCube or Km3NeT limited in size by optical transparency of detection medium
  - glacial ice and water have attenuation lengths $\lesssim 100$ m
- Scaling IceCube up by large factors is cost-prohibitive



# Solution: Radio-detection via Askaryan Effect



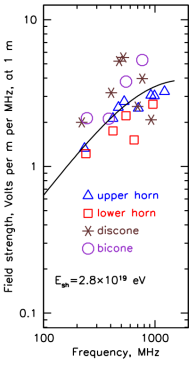

- High-energy cascade in dielectric medium develops $\mathcal{O}(20\%)$ negative charge excess.
- From far away, at wavelengths longer than shower width ($\mathcal{O}(10cm)$, appears as single moving charge going faster than light velocity in medium.
- Potential media: glacial ice, sand, salt, lunar regolith (yes, people have pointed radio telescopes at the moon to look for this!)

# Askaryan Effect in Ice

Demonstrated in SLAC beam test!

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

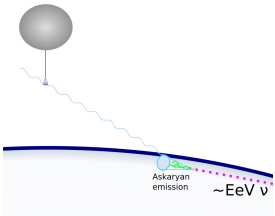
**Observations of the Askaryan Effect in Ice**




Attenuation length $\sim$ 1 km

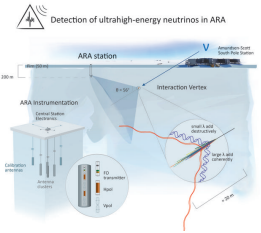
# Some ice-based Askaryan $\nu$ experiments

## ANITA/PUEO*



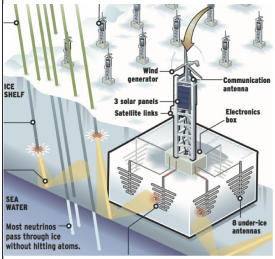

Antennas on a high-altitude balloon over Antarctica

## ARA*



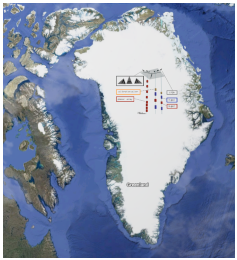

Antennas buried in ice near the South Pole

## ARIANNA




Near surface antennas on Ross Ice Shelf

## RNO-G*

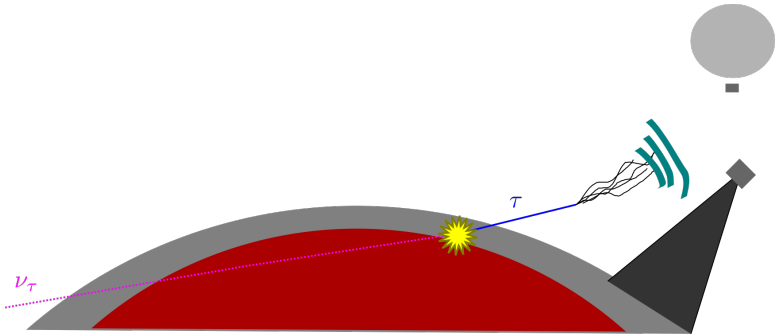


New project in Greenland!

*denotes an experiment I work on.

# Another method (also with radio): Detect upward-going showers from $\nu_\tau$

- Extensive air showers (EAS) also produce radio signal (mostly from charge-separation by Earth's magnetic field, although also an Askaryan component)
- Technique widely used to measure air showers from cosmic rays (e.g. AERA, LOFAR).
- But, a $\nu_\tau$ interacting in the Earth can produce a $\tau$ that escapes the Earth which can then decay in the atmosphere to produce an apparent upward-going air shower.



# Some radio experiments searching for $\nu_\tau$ channel

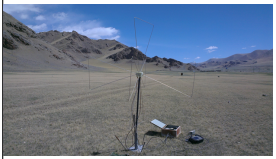
**ANITA***

Antennas on a high-altitude balloon over Antarctica

**BEACON***

Antenna array in White Mountains of California

**GRAND**



(Eventually) thousands of antennas in the Tien Shan Mountains of China

**TAROGE**

Antennas on mountains in Antarctica.

*denotes an experiment I work on.

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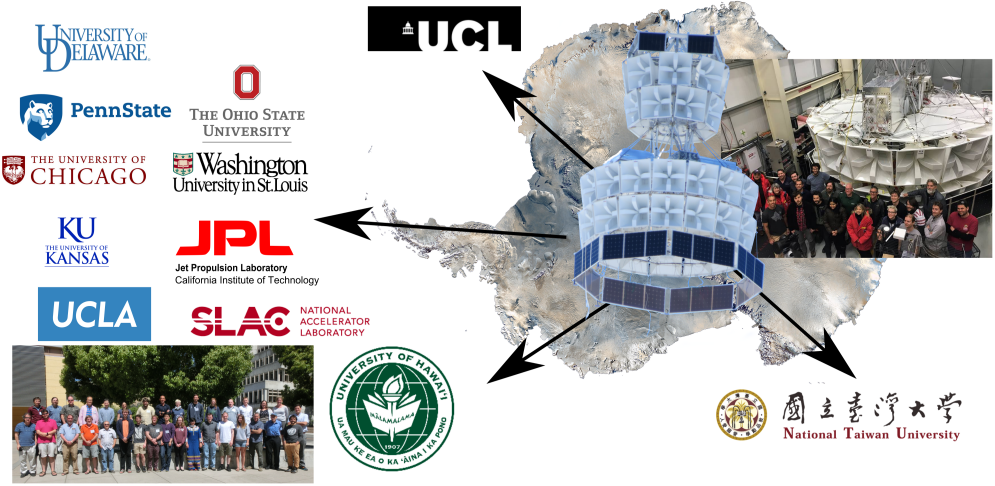
- Introduction: Ultrahigh energy (UHE) neutrinos and how to detect them
- **The ANITA Experiment**
- Results from ANITA
- The future of ANITA (PUEO!)

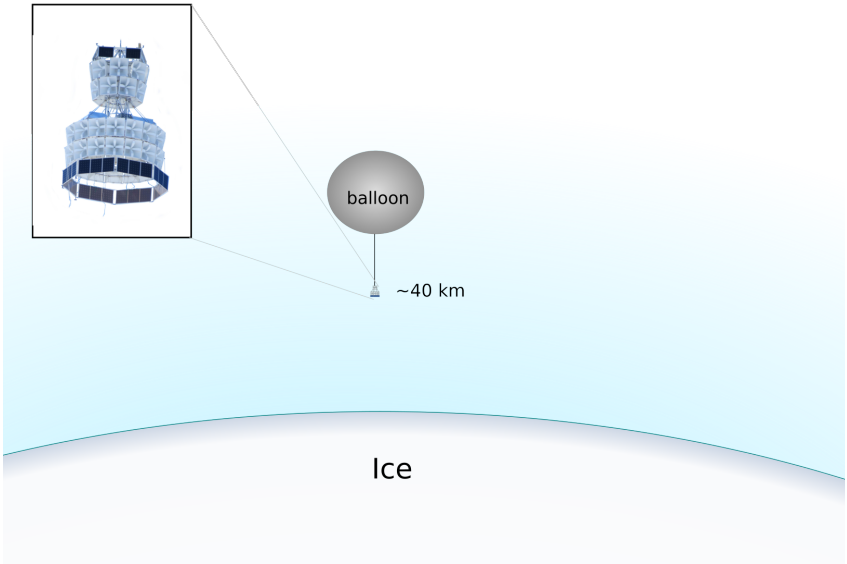
# ANITA Collaboration

**ANtarctic Impulsive Transient Antenna**

12 institutes, 3 countries, 4 continents



# ANITA experiment concept



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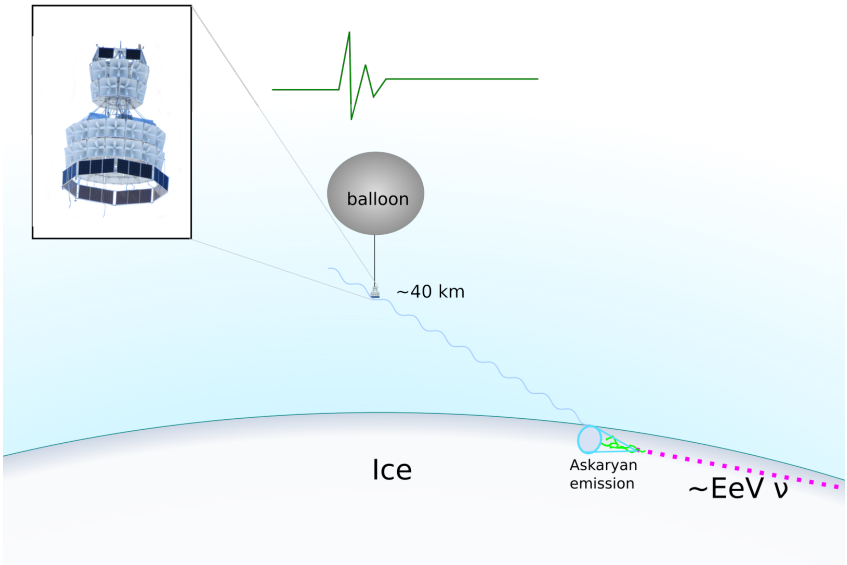
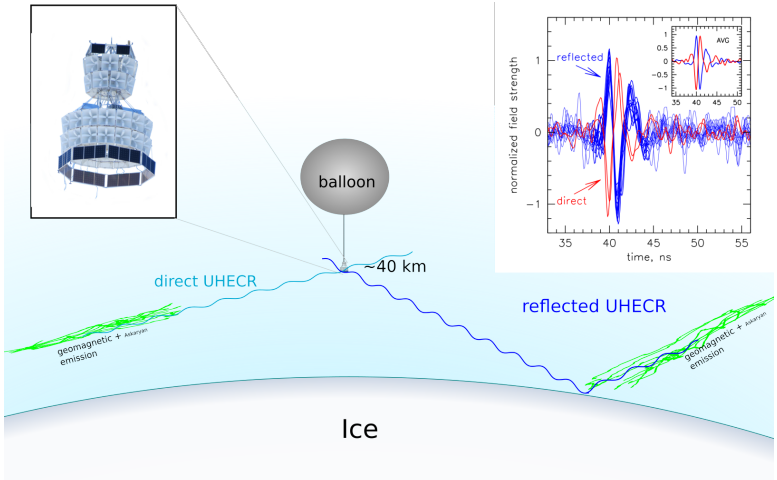


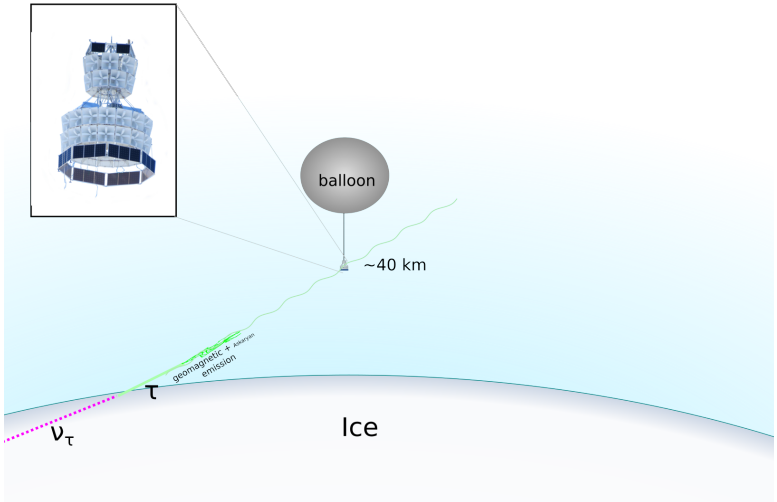
# The UHECR EAS signal

- 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 (phase)**



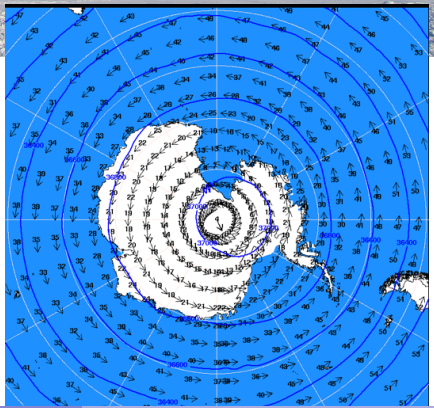
# The $\nu_\tau$ EAS signal

- Can tell apart from UHECR because direction consistent with reflected UHECR, but phase with direct UHECR

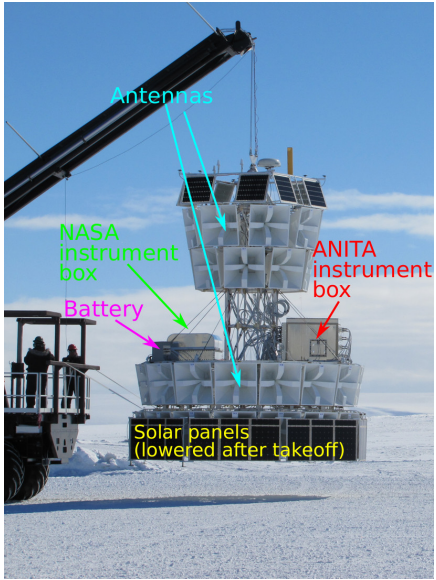


# Ballooning in Antarctica

- 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.

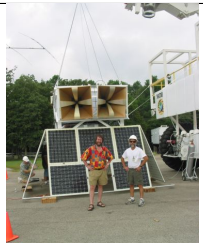
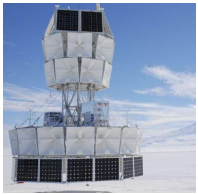
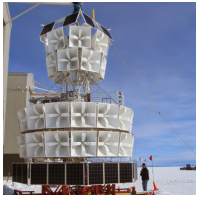


# The ANITA instrument

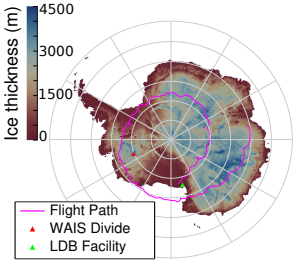


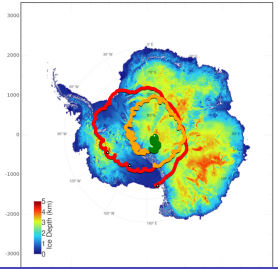

- ANITA is an oscilloscope connected to a bunch of antennas dangled from a balloon
- ANITA's antenna layout is driven by the launch envelope.
- 0.18-1.2 GHz signal split into digitizer and trigger path
  - Tunnel diode square-law detector first-level trigger. Combinatorics between channels take $\mathcal{O}(10^{5-6}$ Hz) singles rate $\rightarrow \mathcal{O}(50$ Hz) global rate that we can reasonably record
  - Switched capacitor array digitizers for high sampling rate and low power consumption.
- Telemetry via line-of-sight and satellite, but mostly rely on recovering payload for data.
  - On-board prioritizer does try to telemeter the "best" events, but fortunately we've never had to rely on it.

# 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 (2014-2015) and ANITA-IV (2016)




- ANITA-III:
  - Independent H + V trigger
  - Complications from new military comm satellites → loss of volume, significant improvements to data analysis required.
- ANITA-IV:
  - Tunable notch filters to reduce CW, increase livetime
  - New trigger uses phase shifters to convert H+V to LCP and RCP; requires coincidence of LCP and RCP, ensuring linear polarization
  - Lower noise figure front-end design

# ANITA-IV Launch (December 2016, 7 miles from McMurdo)

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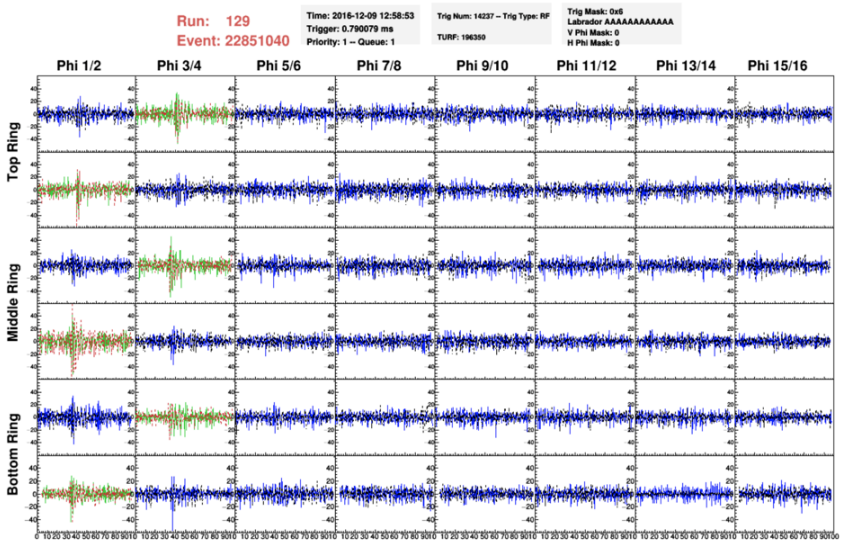
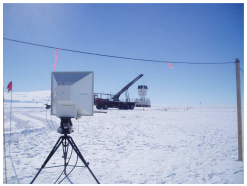
# Example raw data (from calibration pulser)

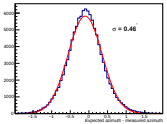
- 48 dual-polarization horn antennas
- Sampled at $\approx$ 2.6 GHz's
- 100 ns per event
- 50 Hz global trigger rate
- $\mathcal{O}(10^7)$ RF triggers per flight (ANITA-III and IV)

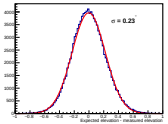


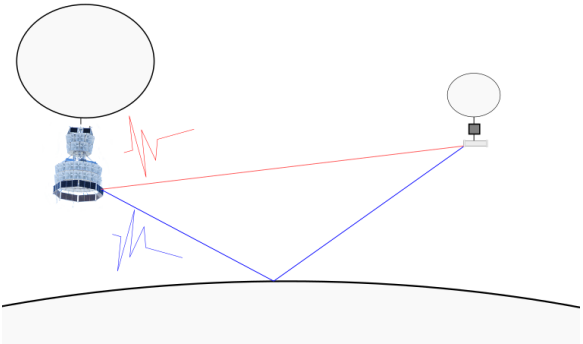
# Calibration

- Use ground-based calibration pulsers in a field camp (WAIS, for ANITA-III and -IV):
  - Calibrate as-flown antenna phase centers (effective positions)
  - Understand efficiency as function of SNR
  - Estimate pointing resolution
  - Measure payload tilt
- Hi-Cal trailing balloon provided balloon-borne calibration signal for part of flight (ANITA-III and -IV)
  - Also better understand ice properties!





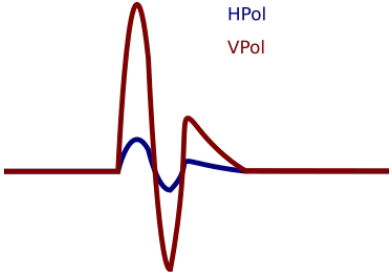



# Signals

## Askaryan emission from $\nu$'s

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



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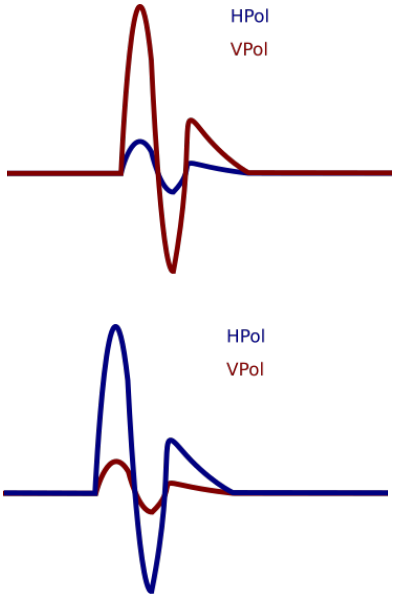
## Geomagnetic emission from EAS

- Impulsive signal
- More low-frequency weighted
- Linearly polarized; due to Earth's magnetic field and $\vec{v} \times \vec{B}$, primarily horizontally-polarized (HPol)



# Signals and backgrounds (fake $\nu$s)

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## Continuous wave (CW) signals

Anthropogenic narrow-band signals (from satellites and bases) contaminate most data so must be filtered.

## RFI from payload ("payload blasts")

Timing between antennas not plane wave-y.

## Thermal noise

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

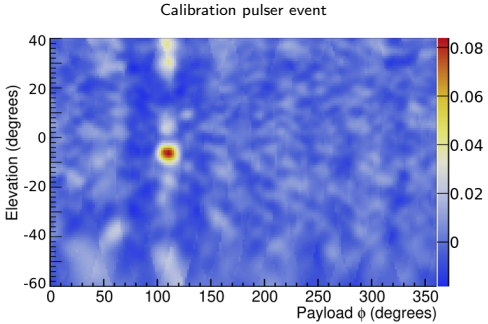
## Impulsive anthropogenic emission

Transformers, engines, etc. produce broadband impulsive emission that can mimic $\nu$'s. **Dominant background**.

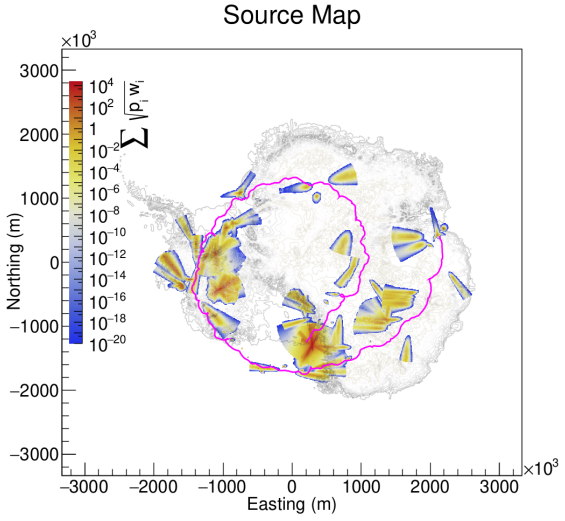
# Sketch of analysis: Part 1, identify impulsive events

Three independent blind $\nu$ 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, payload RFI.



# Sketch of analysis: Part 2, reject 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.

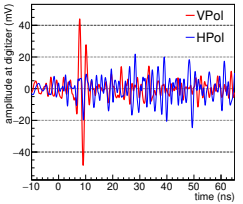
# Outline

- Introduction: Ultrahigh energy (UHE) neutrinos and how to detect them
- The ANITA Experiment
- **Results from ANITA**
- The future of ANITA (PUEO!)

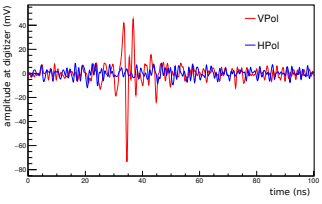
# Diffuse Askaryan $\nu$ results

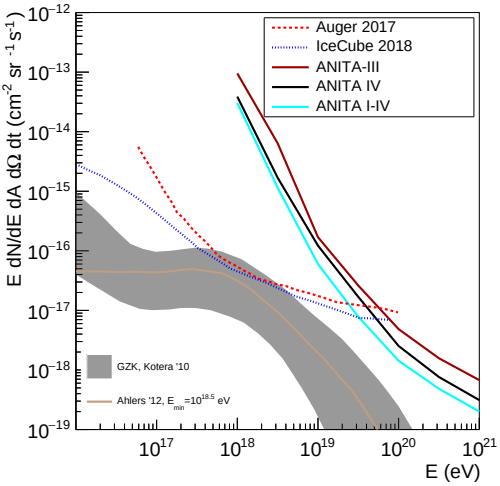
- ANITA-III: (Phys.Rev. D98 (2018) no.2, 022001)
  Most sensitive search found one candidate on a background of $0.7^{+0.5}_{-0.3}$ events.
- ANITA-IV: (Phys.Rev. D99 (2019) no.12, 122001)
  Most sensitive search found one candidate on a background of $0.64^{+0.69}_{-0.45}$ events.

ANITA-III candidate:




ANITA-IV candidate:

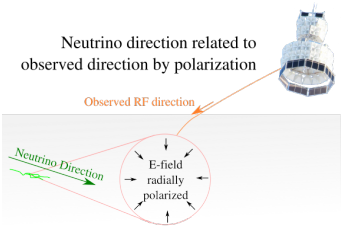


# Work in progress: Non-diffuse Askaryan analyses

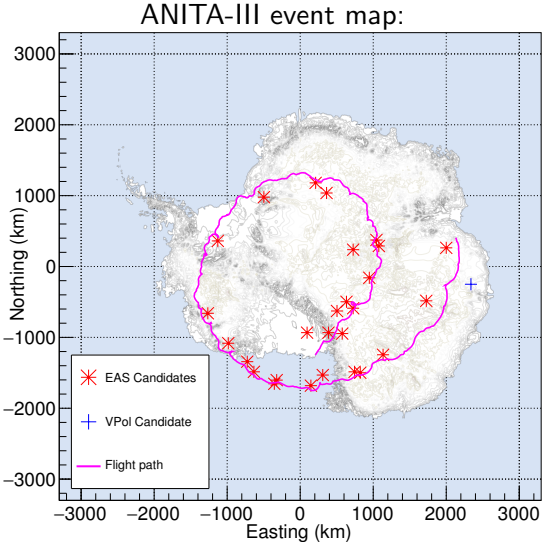
Searches for neutrinos in coincidence with sources ongoing in ANITA-III and ANITA-IV

- Consider e.g. putative IceCube sources, flaring blazars, and GRBs
- By constraining time and direction, reduce backgrounds and analysis threshold. Also set explicit limits on sources.
- 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

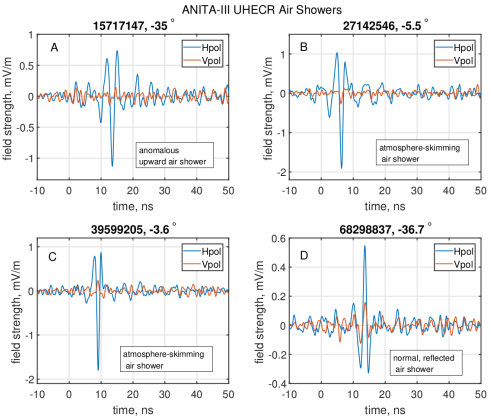


# EAS searches

- 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
- $\mathcal{O}(30)$ EAS candidates identified in each of ANITA-III and ANITA-IV.



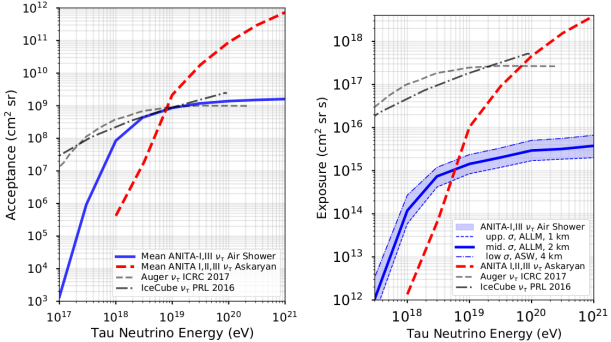
# Upward-going showers?




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 (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.
- 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 $\nu_\tau$

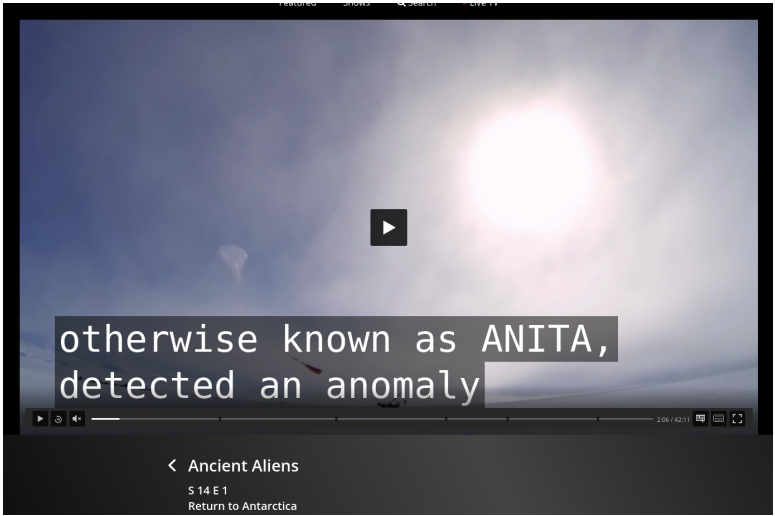



- Auger, IceCube have much larger exposures at implied energy of $\mathcal{O}(1\ \mathrm{EeV})$.
- Due to Earth opacity at UHE, not even self-consistent for diffuse flux, even accounting for $\tau$ regeneration.
- Very hard to produce a transient flux that IceCube or Auger would not have seen.
  - IceCube 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 quite a lot of interest

# Including of the wrong kind (tabloids!)...

# ...and the REALLY wrong kind (*Ancient Aliens*!)



# Some Mundane-ish explanations

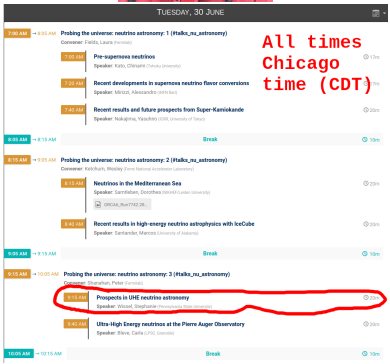
- Funny ice reflections (Shoemaker et al, arxiv:1905.02846)
  - Possible, but ice would need to have special structure over a wide area (Fresnel zone convolved with beam on ground)
  - Would need a massive underice cavern, shallow or surface lake, or something unexpected like that in order to not be overly contrived (dielectric constrast from underice layers would have a very hard time explaining the observations).
  - Lack of non-inversion from HiCal suggests that any such reflection can't be common
- Funny EAS emission
  - Maybe there is a class of atypical EAS that produce signals 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 make an event appear to be non-inverted.
  - Whether or not this works will require more detailed simulations

# More fun explanations: new physics!

- Many exotic particle or exotic neutrino explanations that eventually produce a $\tau$-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, not from an EAS (e.g. Hooper et al., arxiv:1904.12865)
  - +Not in tension with other experiments
  - +Observed polarization and polarity possible if Askaryan shower from some deeply penetrating particle (not a $\nu$).
  - -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.

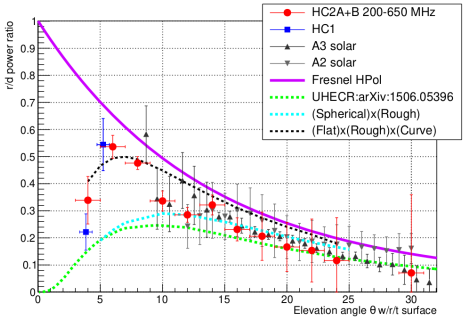
# What about upward showers in ANITA-IV?

- Due to time-dependent system response from tunable notch filters, polarity determination significantly more complicate in ANITA-IV
- We've very recently unblinded polarity ...
  - For real this time! Had to re-blind polarity after significant errors found in determining system response
- ... but I don't have permission to share results with you.
- However, results should be revealed Tuesday at Stephanie Wissel's Neutrino2020 talk!



# Some other things ANITA can measure

- Measure ice reflectivity / roughness (with HiCal, reflection of sun, EAS) (arxiv:1801.08909)
- Look for some other exotics that can produce radio signatures
  - Monopoles (arXiv:1008.1282)
  - Antiquark Nuggets (arXiv:1208.3697)
- Lorentz Invariance (arXiv:1207.6425)




igure 24: *Summary of HiCal results, compared with HiCal-1b results and calculation. As with HiCal-1 and solar measurements, error bars orrespond to the widths of R/D distributions and are taken to be indicative of the scale of inherent systematic errors.*

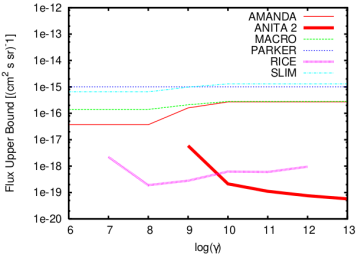



FIG. 12: Comparison of ANITA upper limit on diffuse monopole flux with other results. Save for RICE, other experimental results have been extrapolated up to our sensitive kinematic interval. In performing this extrapolation, the limits for $\gamma \geq 10^9$ have been weakened by a factor of two, to account for increasing Earth opacity.

# Outline

- Introduction: Ultrahigh energy (UHE) neutrinos and how to detect them
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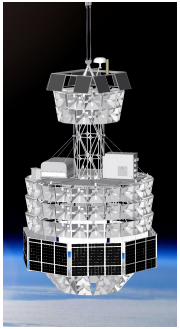
- **The future of ANITA (PUEO!)**

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

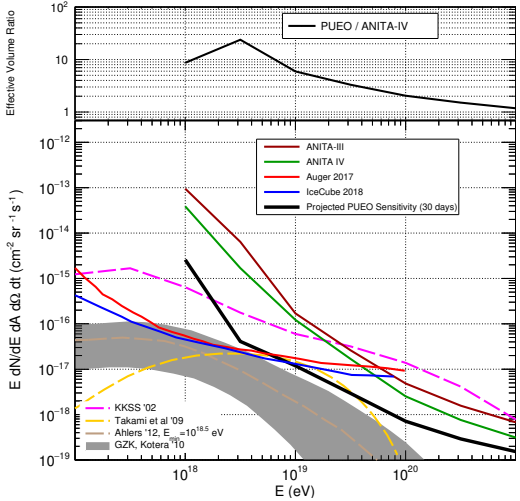


PUEO

*pueo*

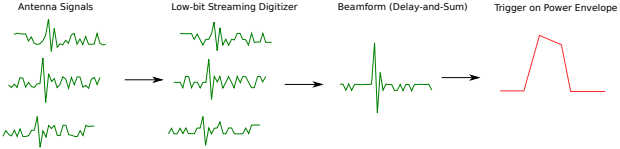
- More antennas (120 instead of 48), but with a higher cutoff frequency (300 vs. 180 MHz).
- Much lower trigger threshold
- 24 antennas canted down to fill gap in ANITA elevation coverage (and further investigate steep air shower events)
- Improved digitizers, front-end electronics
- Up to 10X more sensitive than ANITA-IV

Projected PUEO sensitivity:

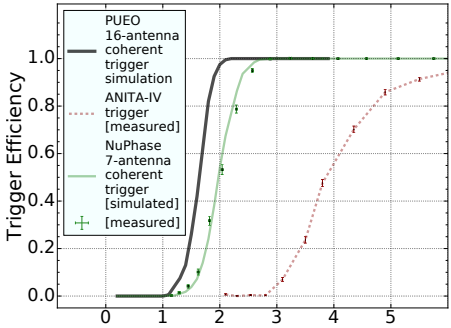


# How to reduce threshold? Beamforming Trigger!

- Abandon analog combinatoric trigger, switch to a digital beam-forming trigger

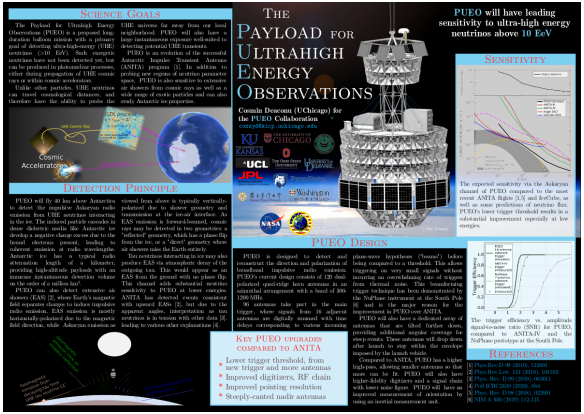



- Use streaming digitizers (mostly likely a low-bit custom ASIC, for power reasons) to record signals from each channel in real time, then delay and sum according to causal plane-wave hypotheses ("beams").
- Technique demonstrated in-situ at the South Pole, this would use more channels and higher-gain antennas to achieve an even lower threshold.




# See my PUEO poster at Neutrino2020!

Poster 486, presented at poster session that just happened
(so you'll need access to the parallel universe to see it)

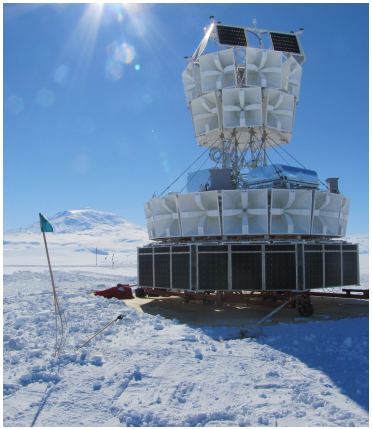



Video: `https://www.youtube.com/watch?v=uCy6mKr_d2E`

# Conclusions

- Ultrahigh-energy (UHE) neutrinos can teach us a lot about the universe and neutrinos.
- Radio detectors can be used to search for UHE neutrinos.
- ANITA I-IV combined set the best limits on UHE $\nu$ flux above $10^{19.5}$ eV.
- ANITA has detected EAS candidates consistent with an upward-going air shower, but unclear intepretation.
- 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.

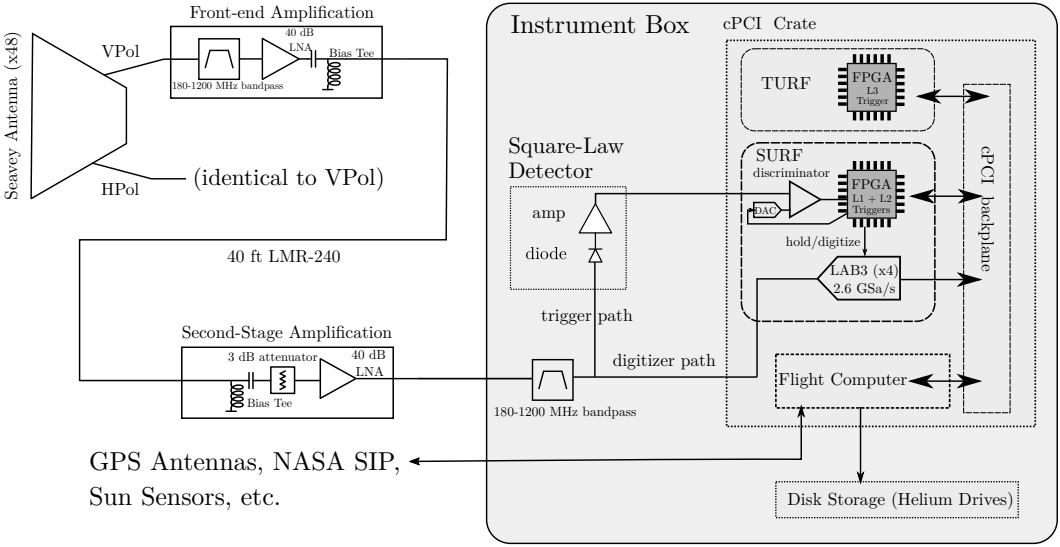
Thank You!



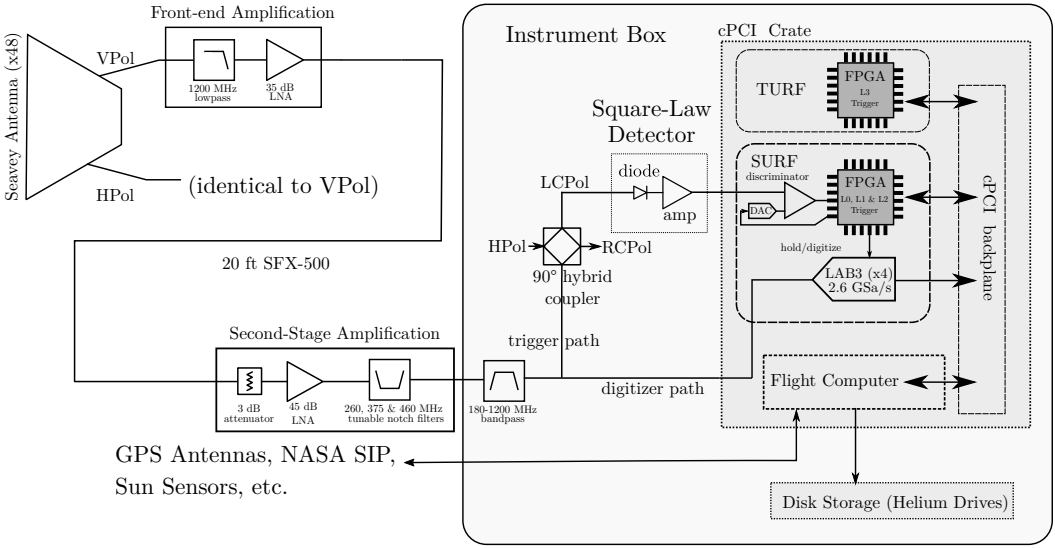
Questions?

# Backup Slides

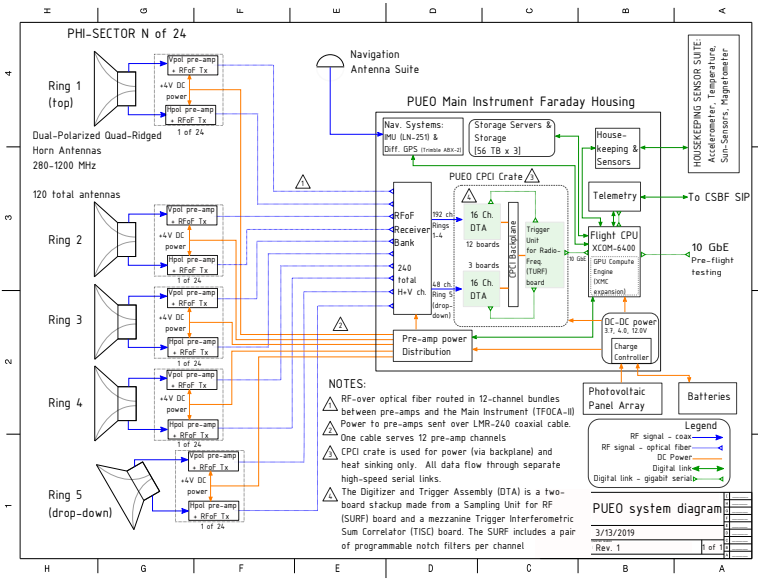
# ANITA-III Block Diagram



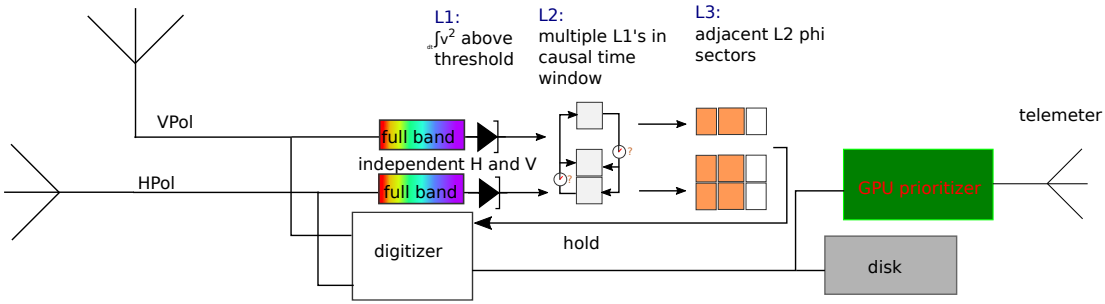
# ANITA-IV Block Diagram



# PUEO Block Diagram



# ANITA-III Trigger



# ANITA-IV Trigger