

CRSIG within NASA's Physics of the Cosmos

and the Payload for Ultrahigh Energy Observations

Stephanie Wissel, Penn State, CRNSIG Co-Chair, PhysCOS Mini-Symposium, APS Global Summit 2025

Cosmic Ray and Neutrino Science Interest Group

A horizontal banner featuring a vibrant, multi-colored cosmic scene with stars, nebulae, and galaxies in shades of blue, purple, and orange. The text is overlaid on the left side of the banner.

Physics of the Cosmos

Exploring fundamental questions regarding the physical forces of the universe

- Community-led forum to address open science questions related to the Physics of the Cosmos and Cosmic Rays and Neutrinos
- **Goals:**
 - provide quantitative metrics and assessments to NASA of current and future needs of the cosmic-ray astrophysics community
 - Assess science gaps and technology gaps related to CRs and Neutrinos
 - Provide input from the science community to the Physics of the Cosmos Program

CRNSIG Webinars

Goal: Identify Science Drivers & Connections

- Recent Topics:
 - Galactic PeVatrons
 - On the Origin of Heavy Elements
 - Ultrahigh Energy Cosmic Rays and the Snowmass Study
 - Ultrahigh Energy Neutrinos with Balloon-Borne Missions

Upcoming:
Indirect dark matter searches with cosmic antinuclei

Heavy Element Production Models

How and where are the heaviest elements created?

- TIGERISS's absolute and relative abundances of r- & s-process elements will probe NSM physics and contributions to GCRs
- TIGERISS will observe transition region between SN and NSM production at $Z \sim 40$ ($A \sim 90$)
- In an extended mission (~ 3 yr), TIGERISS will reach Pt-Pb region and constrain NSM production models

Supernova (SN) production relative to solar composition (Woosley & Heger, 2007, PhysRev 442, 269-283)

Neutron star merger (NSM) production model compared to solar composition (open circles) (Just et al., 2015, MNRAS 448, 541-567)

Crab Nebula

LHAASO 2021: <https://www.nature.com/articles/s41586-021-03498-z>

Probe of Extreme Muons

- Fluorescence detection from
- Two science cases: UHECR and
- Complementary to ground array

POEMMA-Stereo

POEMMA-Limb

UHECR EAS

Tau-decay EAS

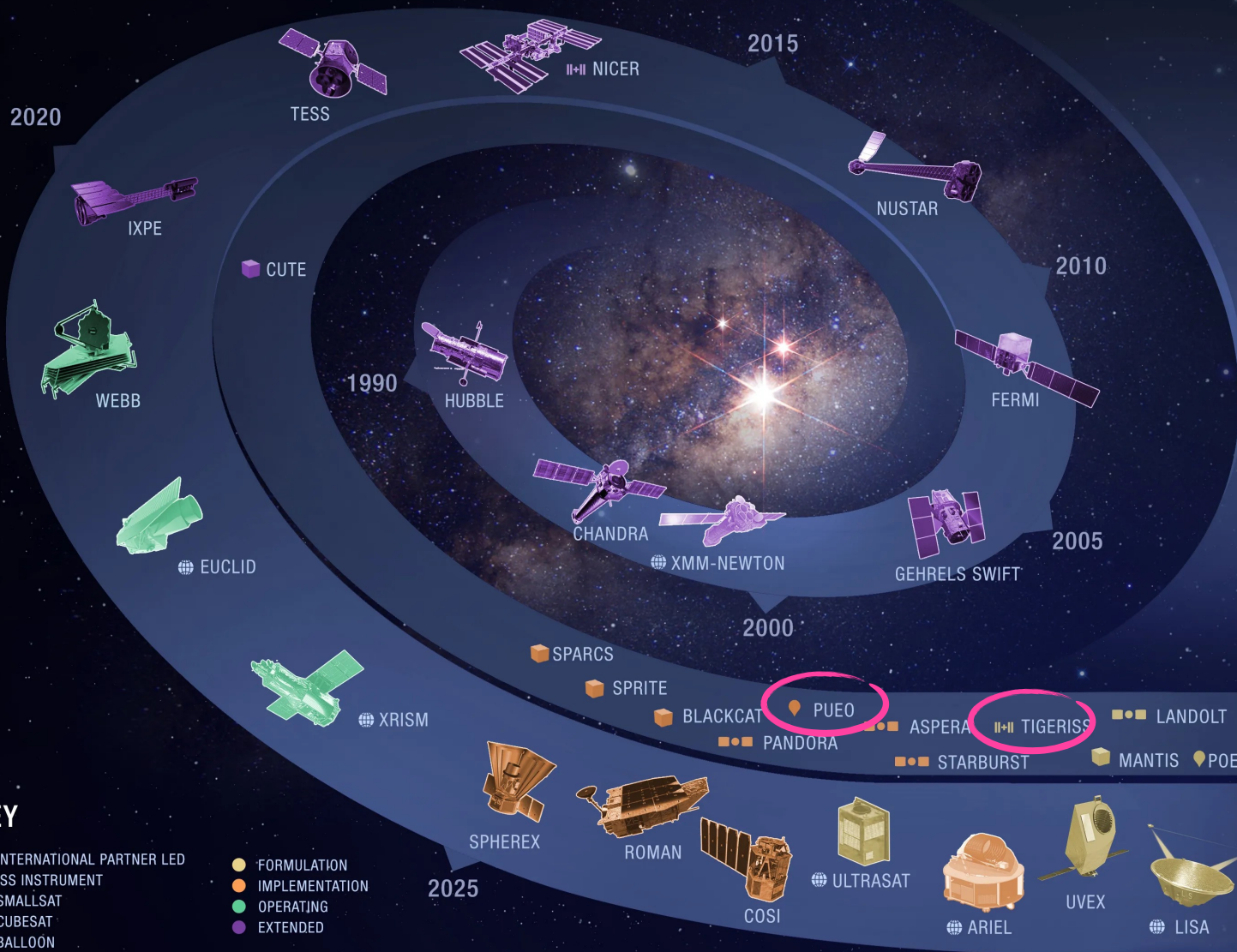
NASA CR SIG Seminar
Snowmass UHECR White Paper
fgs@udel.edu

0:47:54 | 1:11:52

Participants: Narayan, Clark, TP, Tom Hill, A, Athina...



ASTROPHYSICS FLEET



KEY

- 🌐 INTERNATIONAL PARTNER LED
- II-II ISS INSTRUMENT
- SMALLSAT
- 📡 CUBESAT
- 🎈 BALLOON

- FORMULATION
- IMPLEMENTATION
- OPERATING
- EXTENDED

PIONEERS & CUBESATS

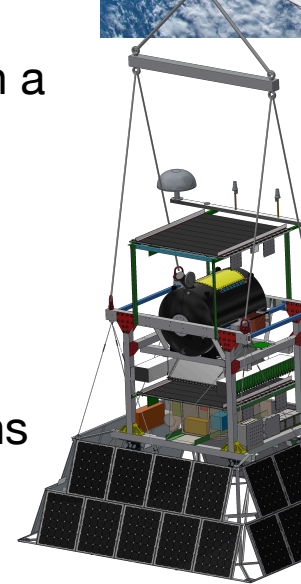
TRADITIONAL MISSIONS

NASA Platforms

relevant for Cosmic Rays & Neutrinos

- Cosmic ray and neutrino observatories have been very successful with space-based instruments with a variety of platforms
 - Balloons: long-duration, superpressure
 - International Space Station
 - Pioneers missions: balloons & ISS
- CRN experiments can be standalone small missions or stepping stones to larger probe class missions
- Maintaining and strengthening small missions (balloons, APRA missions, Pioneers) is vital to our SIG

Example study from Scientific Balloon Roadmap Program Analysis Group (Balloon Roadmap PAG): A Roadmap For Scientific Ballooning 2020–2030 [arXiv:2210.01198](https://arxiv.org/abs/2210.01198)



Cosmic Ray & Neutrino NASA Missions

Recent & Ongoing

- Balloons:
 - EUSO-SBP
 - HELIX
- ISS:
 - AMS-02

Upcoming

- Balloons:
 - PUEO
 - PBR
 - GAPS
 - GRAMS
- ISS:
 - TIGRESS

Planned

- Satellites:
 - POEMMA
 - Community roadmap





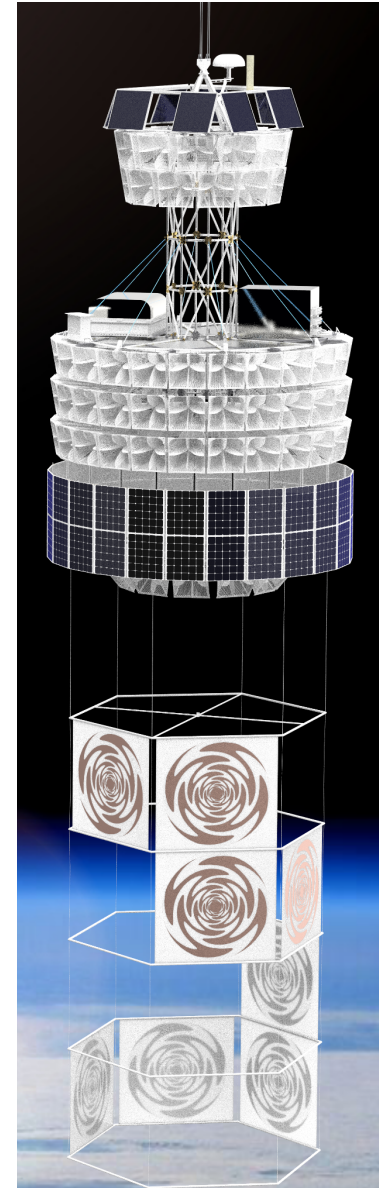
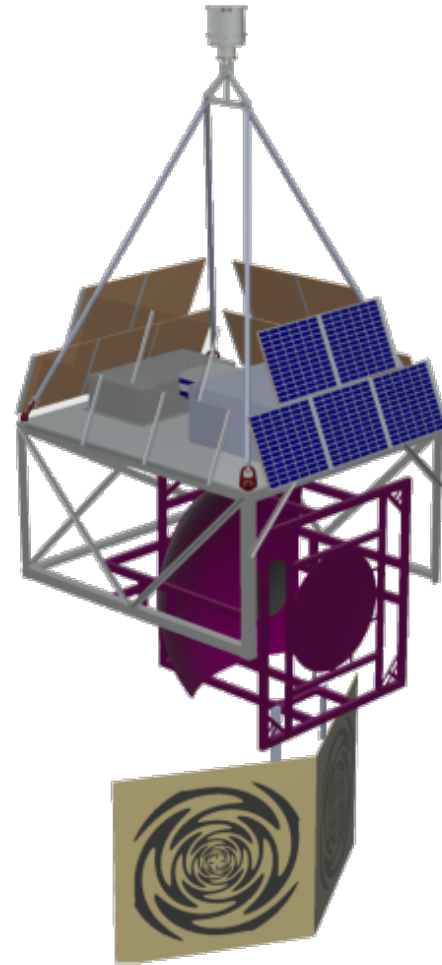
Observations from Space

in concert with ground observations

..in CRNSIG we aim to understand the unique role that space-based observatories play

Connections with CRNSIG

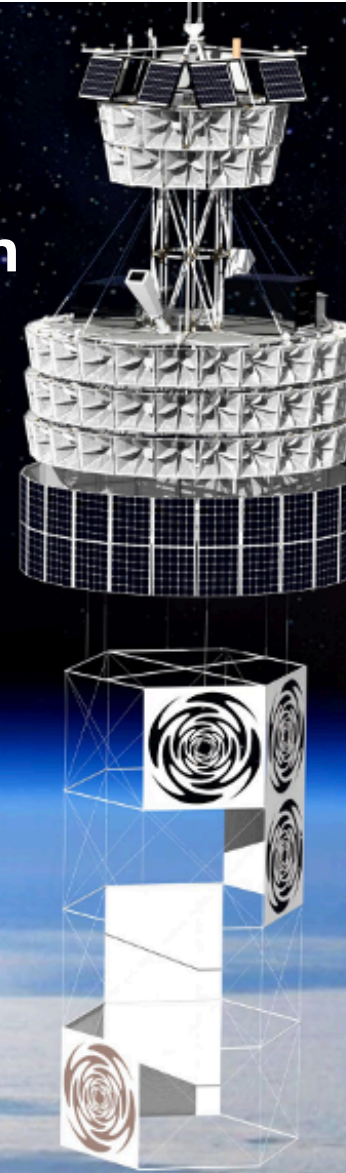
Example of PUEO and PBR



PUEO

Payload for Ultrahigh Energy Observation

See also Abby Vieregg's talk

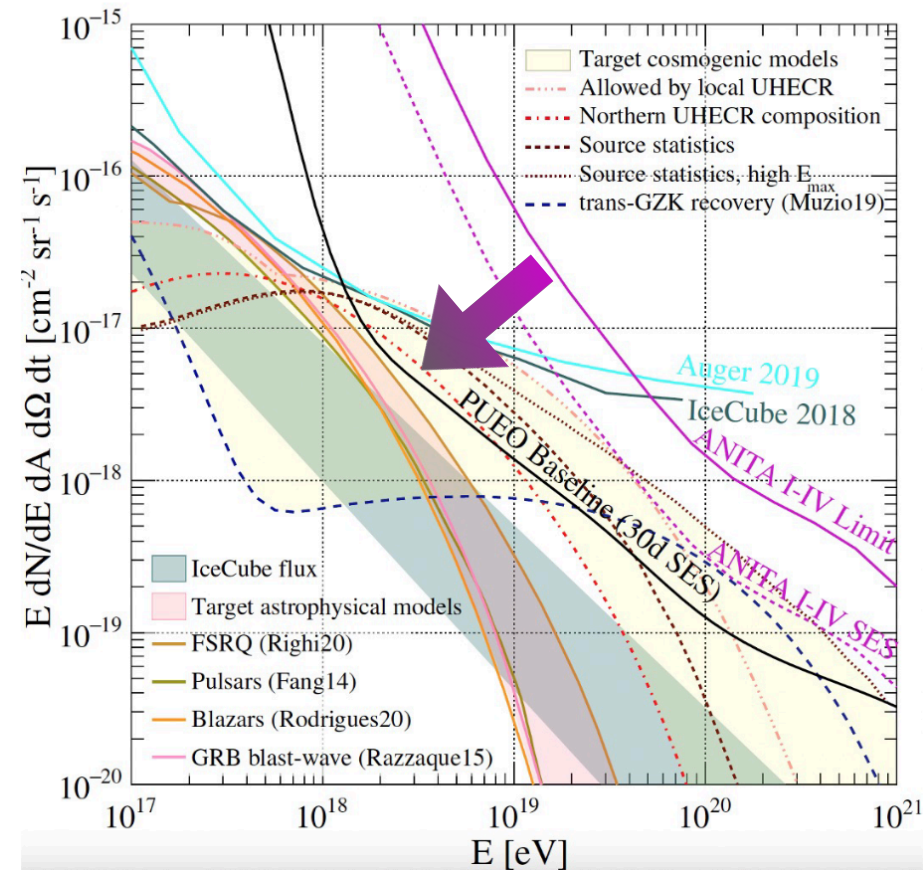


Science Goals of PUEO

Discover UHE Neutrinos

- Origin of UHECRs: cosmological history of UHE CR accelerators
- Hadronic acceleration in astrophysical sources: compact objects, GRBs, AGN
- Sensitivity enhanced over four flights of predecessor ANITA

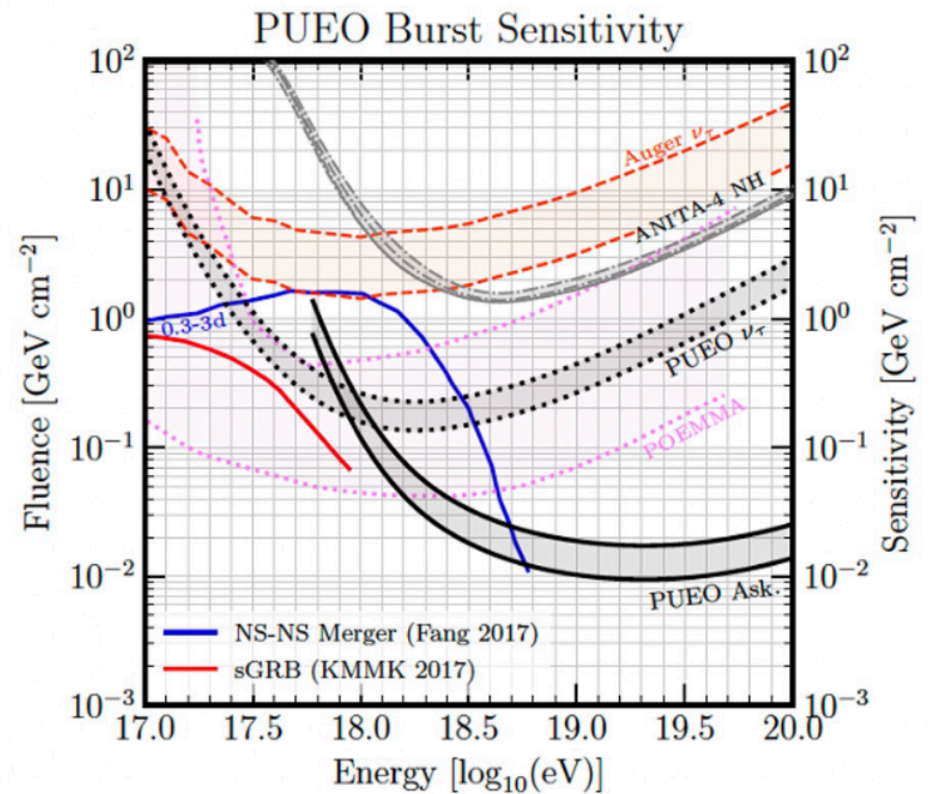
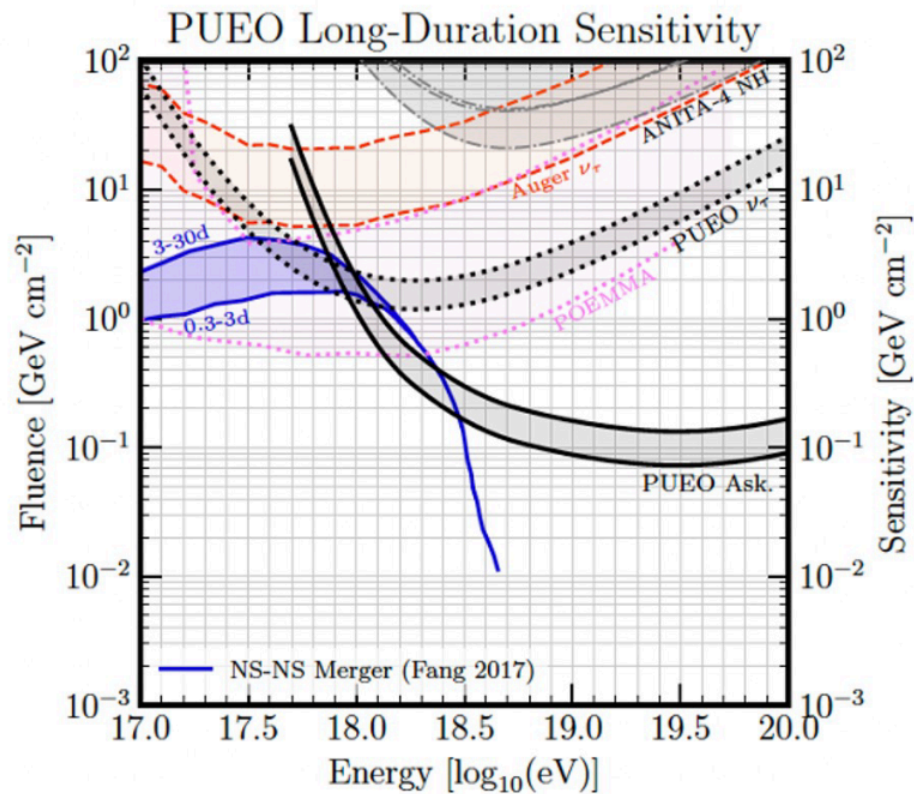
Diffuse Flux Sensitivity of PUEO



PUEO Whitepaper [arXiv:2010.02892](https://arxiv.org/abs/2010.02892)

Science Goals of PUEO

Large Effective Area \rightarrow Deep sensitivity to Neutrino Transients

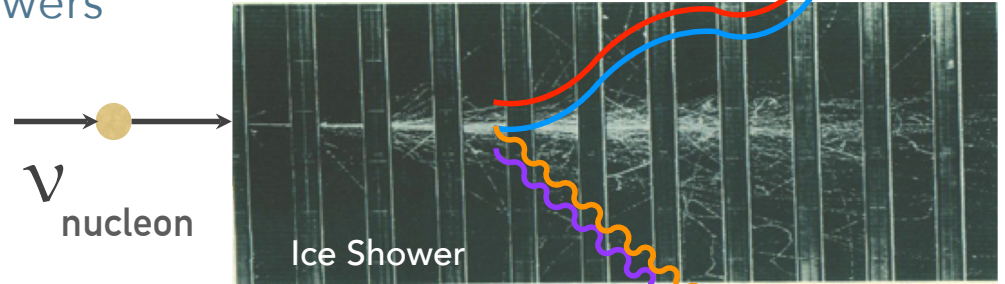


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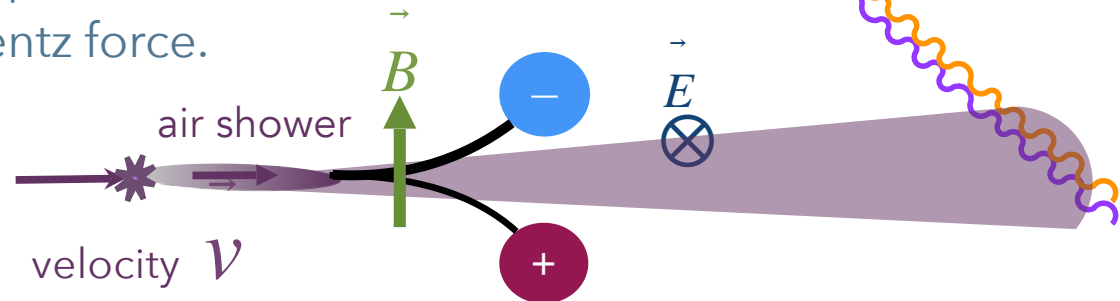
RADIO EMISSION FROM PARTICLE SHOWERS

Askaryan 1969,
Saltzberg, PRL, 2001

- **Askaryan emission:** radiation from net negative charge excess in shower. Dominant for *in-ice* showers



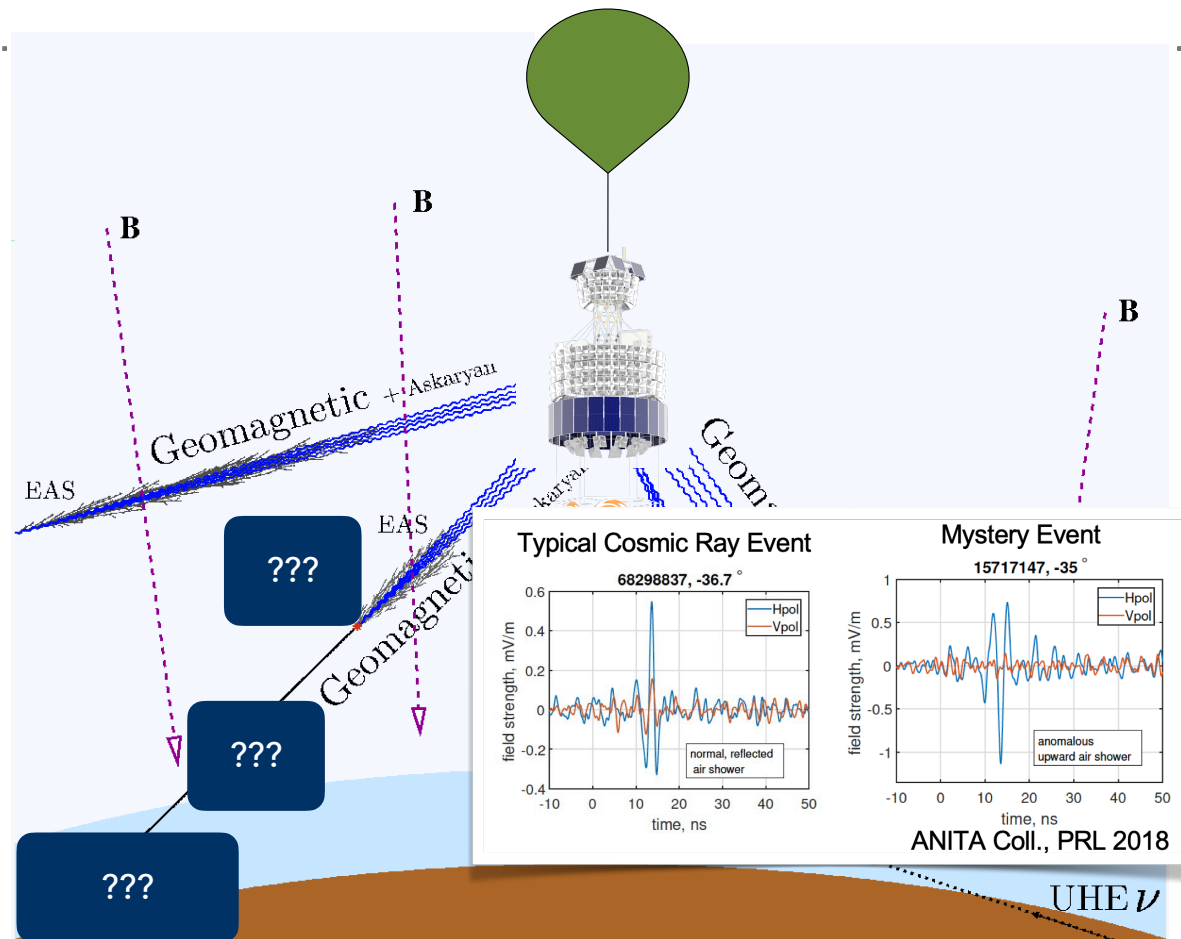
- **Geomagnetic emission:** separation of positive and negative charges in shower due to Lorentz force. Dominant for *air* showers



- Both benefit from boost due to coherence effects near the Cherenkov angle

AIR SHOWERS IN PUEO

- Targets **air shower** events in PUEO
 - **Cosmic rays**
 - Direct, stratospheric
 - Reflected
 - **Tau Neutrinos**
 - Tau lepton air shower decay
 - **Anomalous ANITA events**
 - Upgoing air showers
 - Near horizon (~few deg.)
 - Steep (30° below horizon)



Cosmic rays validate the instrument's performance and help understand sidebands for neutrino backgrounds

POEMMA-Balloon with Radio (PBR)

Ultra-High-Energy Cosmic Rays (UHECRs)
UV Fluorescence

High Altitude Horizontal Airshowers (HAHAs)
Optical+Radio

UHECR

Cosmic Rays $E > \text{PeV}$

Cherenkov Emission

EAS

Atmosphere

EAS

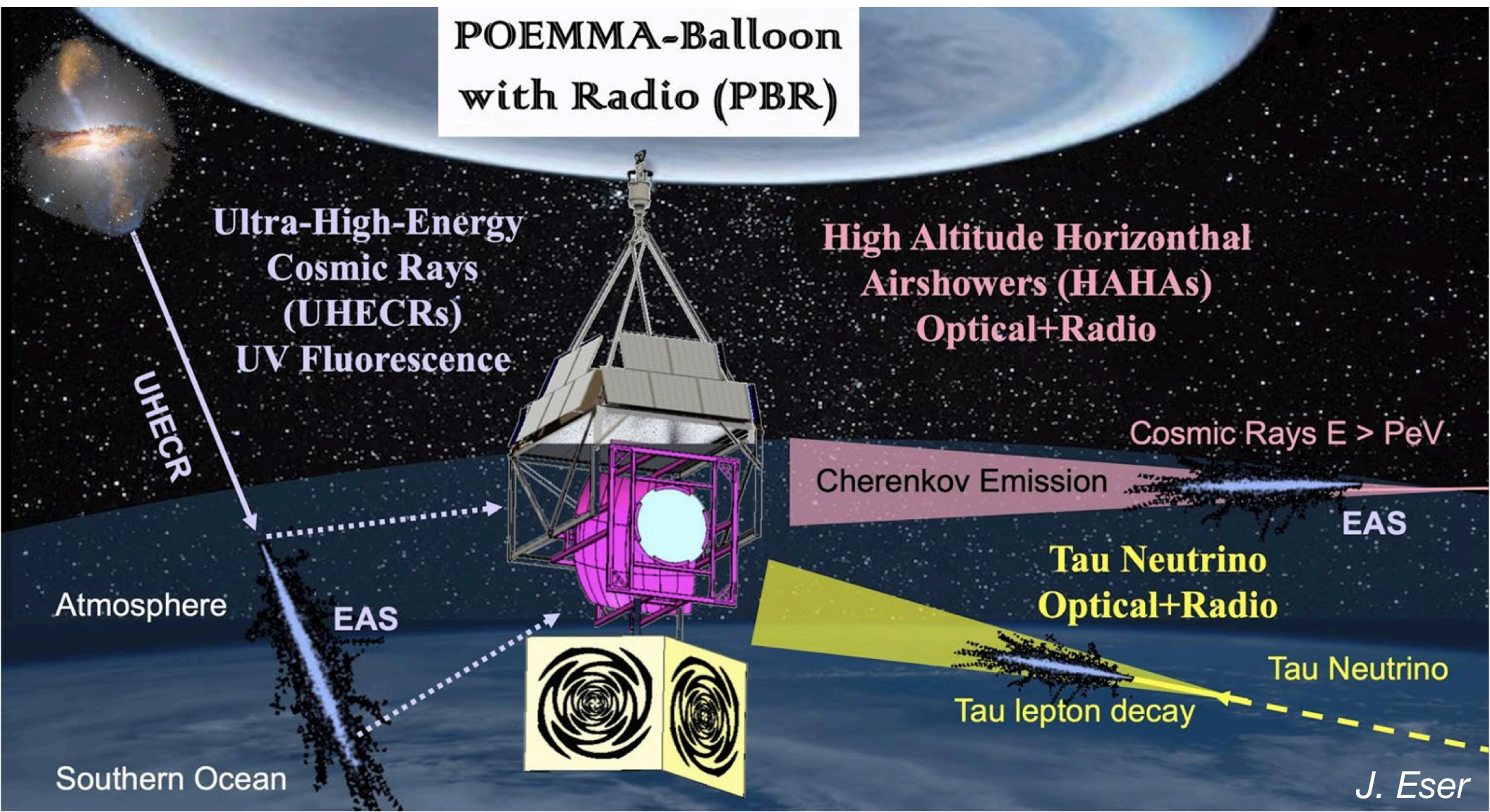
Tau Neutrino
Optical+Radio

Tau Neutrino

Tau lepton decay

Southern Ocean

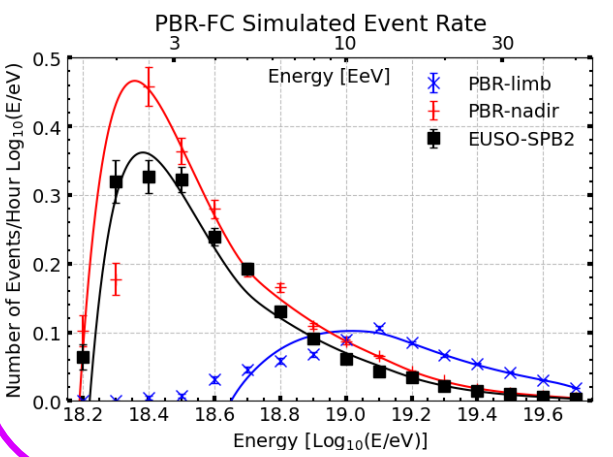
J. Eser



PBR Science

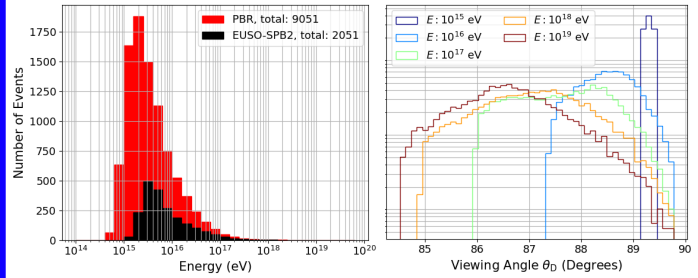
Fluorescence Camera Science:

- Nadir mode: 2.5EeV peak sensitivity
0.23 events/hr
- Validation of technique for space based mission: reconstruct Xmax
 - <10% of events satisfy necessary geometry
 - Observation time: ~14d

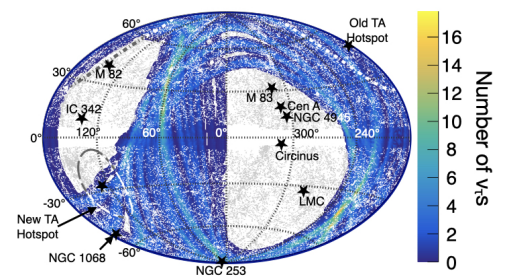


Cherenkov Camera Science:

- Horizon mode: 3PeV peak sensitivity, ~1event/min
 - Validation for τ detection
- Use high statistics to reconstruct direction, energy, composition of CR near the knee



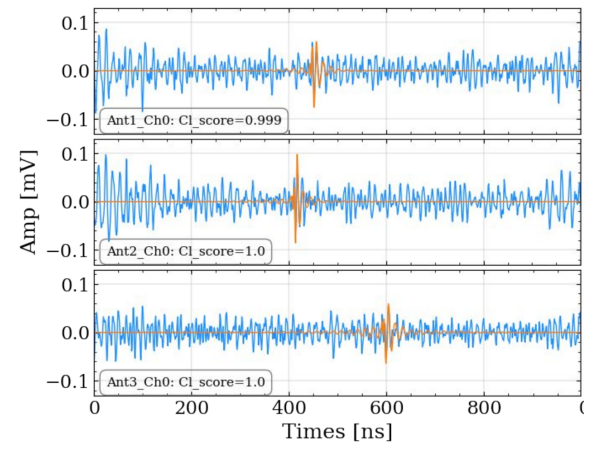
Transient neutrino search



ANITA anomalous event search

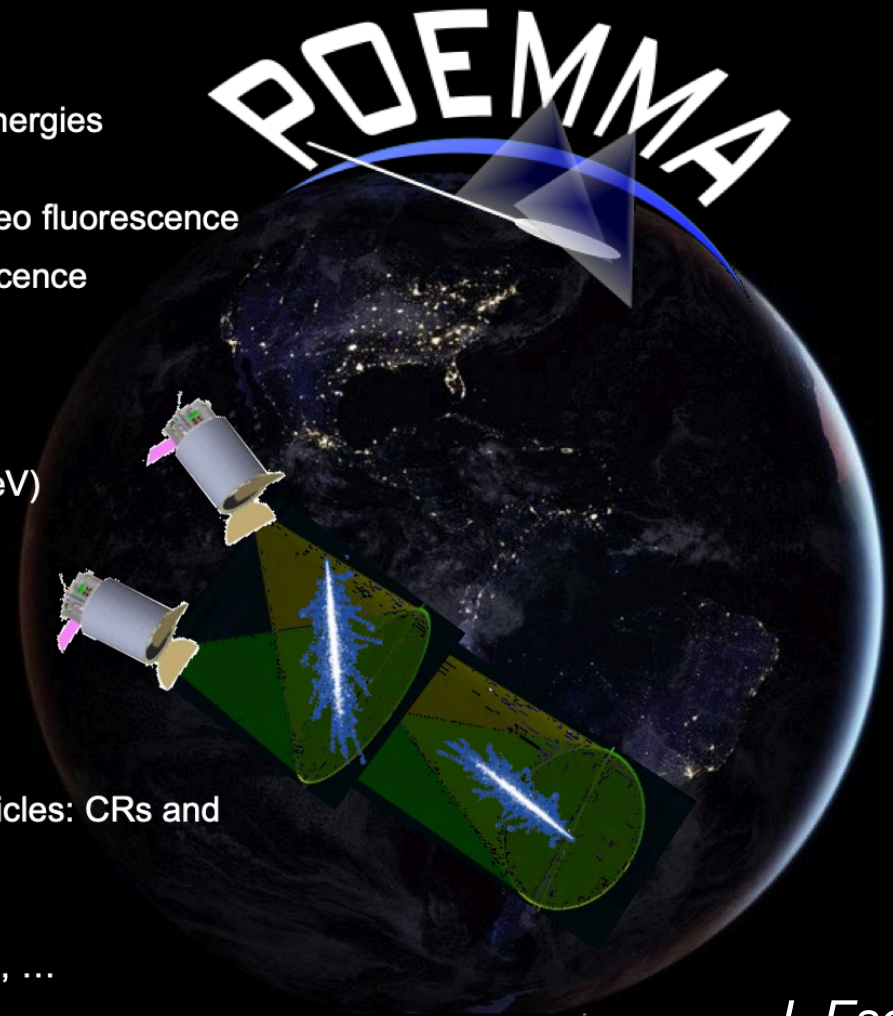
Radio Instrument Science:

- Coincident measurements of >PeV CR with CC
- Use ML techniques to denoise CC-triggered radio signals



- Use radio characteristics to help constrain CR properties
 - Spectrum → energy
 - Beamforming → direction
 - Polarity → reflections
 - Polarization → Xmax

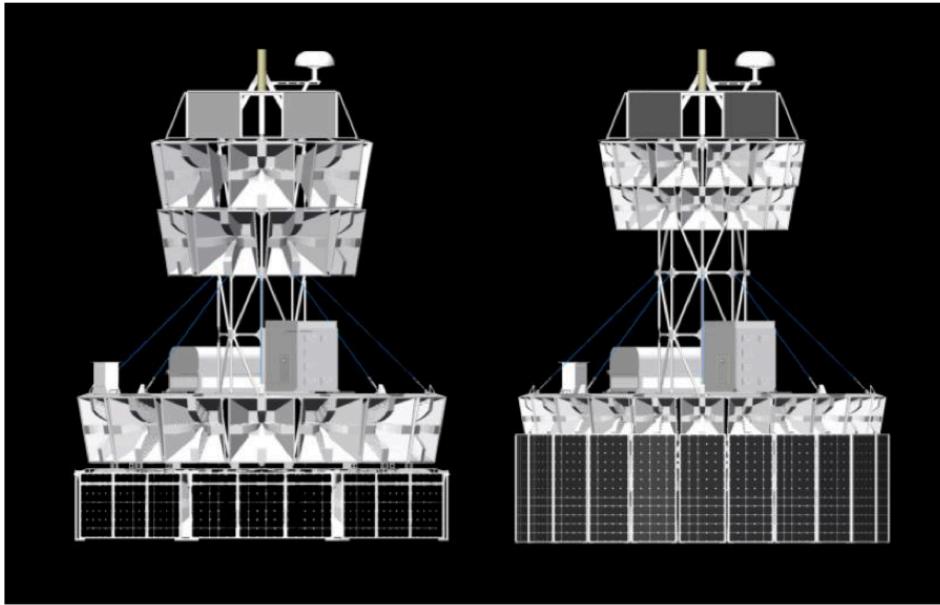
- Discover the origin of Ultra-High Energy Cosmic Rays
 - Measure Spectrum, composition, Sky Distribution at Highest Energies ($E_{\text{CR}} > 20 \text{ EeV}$)
 - Requires very good angular, energy, and X_{max} resolutions: stereo fluorescence
 - High sensitivity UHE neutrino measurements via stereo fluorescence measurements
- Observe Neutrinos from Transient Astrophysical Events
 - Measure beamed Cherenkov light from upward-moving EAS from τ -leptons source by ν_{τ} interactions in the Earth ($E_{\nu} > 20 \text{ PeV}$)
 - Requires tilted-mode of operation to view limb of the Earth & $\sim 10\text{ns}$ timing
 - Allows for tilted UHECR air fluorescence operation, higher GF but degraded resolutions
- Secondary goals
 - study fundamental physics with the most energetic cosmic particles: CRs and Neutrinos
 - search for super-Heavy Dark Matter: photons and neutrinos
 - study Atmospheric Transient Events, survey Meteor Population, ...



Conclusion

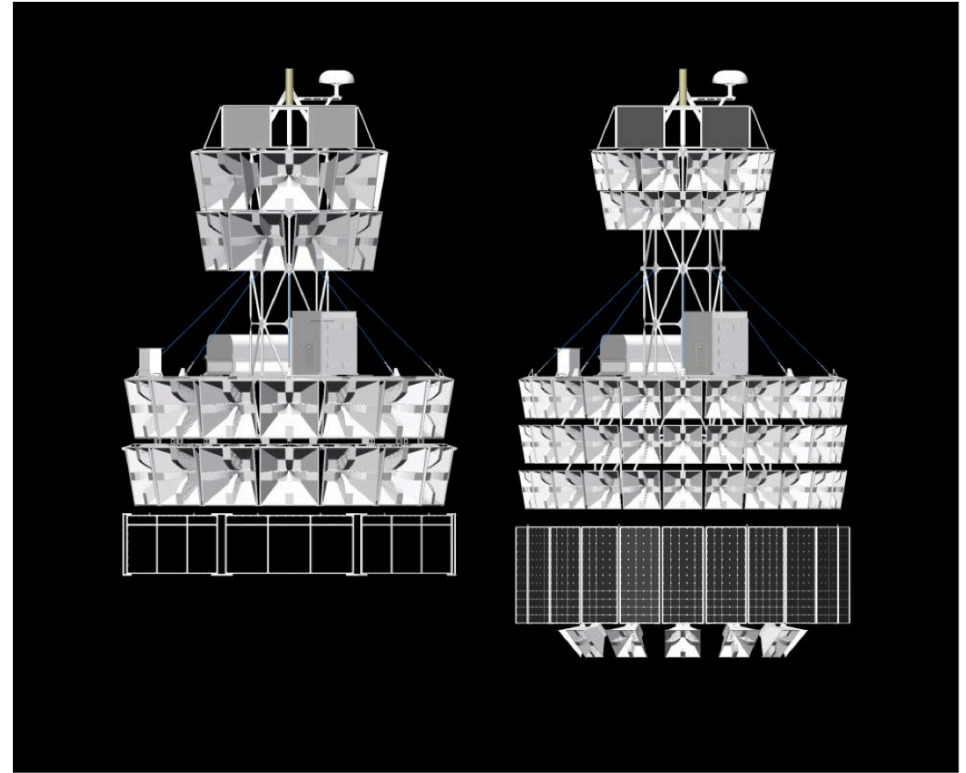
CR N SIG

- Welcoming community forum related to CRNSIG missions within PhysPAG
- Webinars offer opportunity to explore science topics across the broad energy spectrum of CRs
- Many of our CR missions are small, but play an important role in advancing science
- Science and technology gaps serve as important mechanisms for the community to motivate future missions



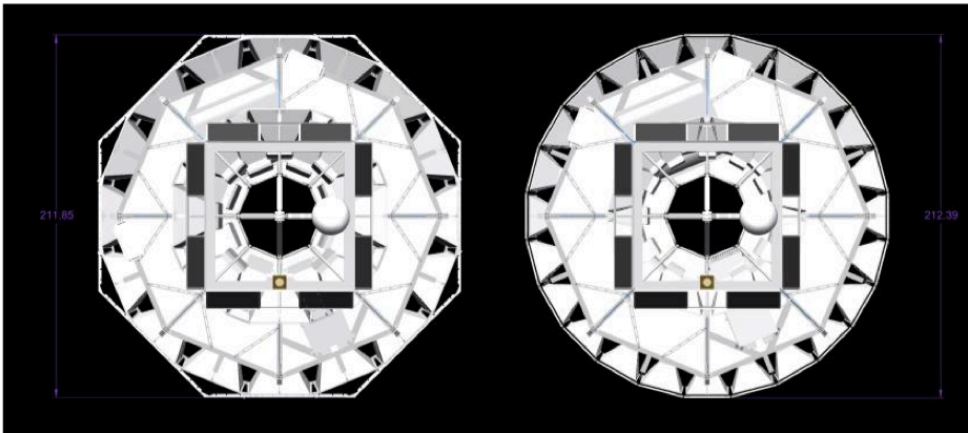
ANITA

PUEO



ANITA

PUEO

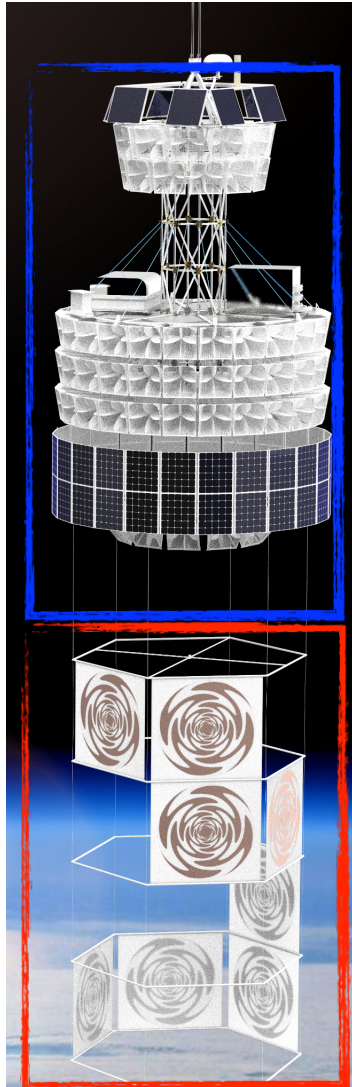


PUEO: PAYLOAD FOR ULTRA-HIGH ENERGY OBSERVATIONS

Main Instrument

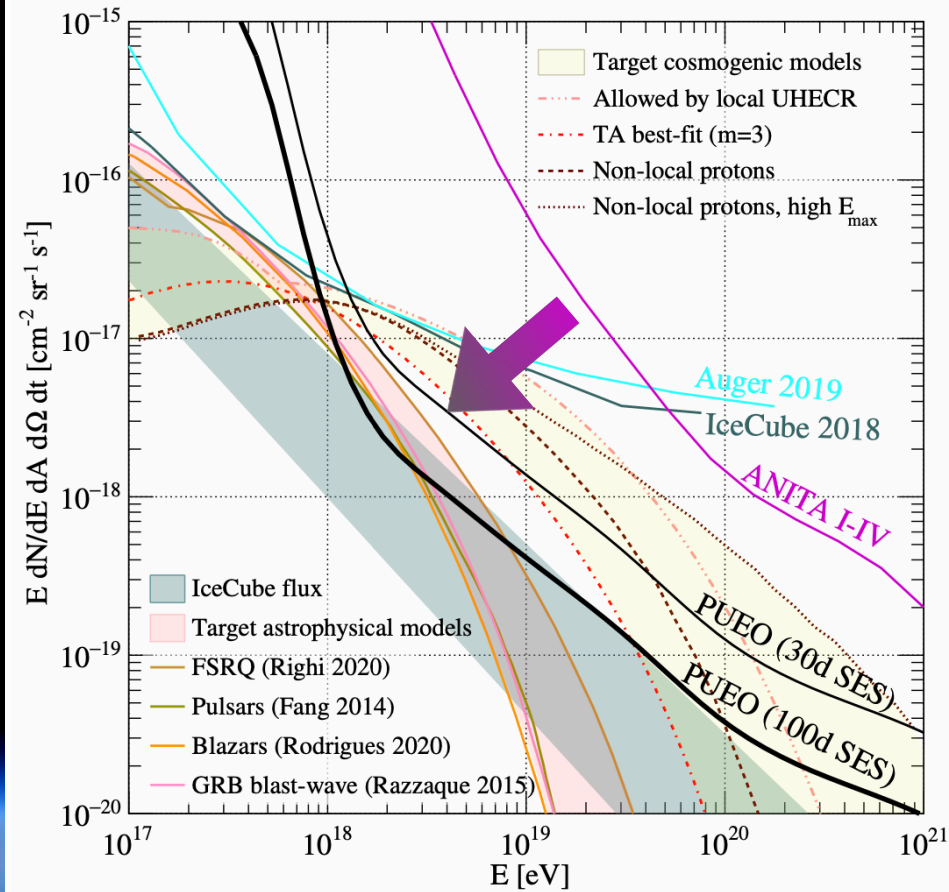
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1. Double the number of antennas
2. Improved RF signal chain
3. Phased arrays via RFSocS



Low Frequency Instrument

1. New!
2. Designed for air showers

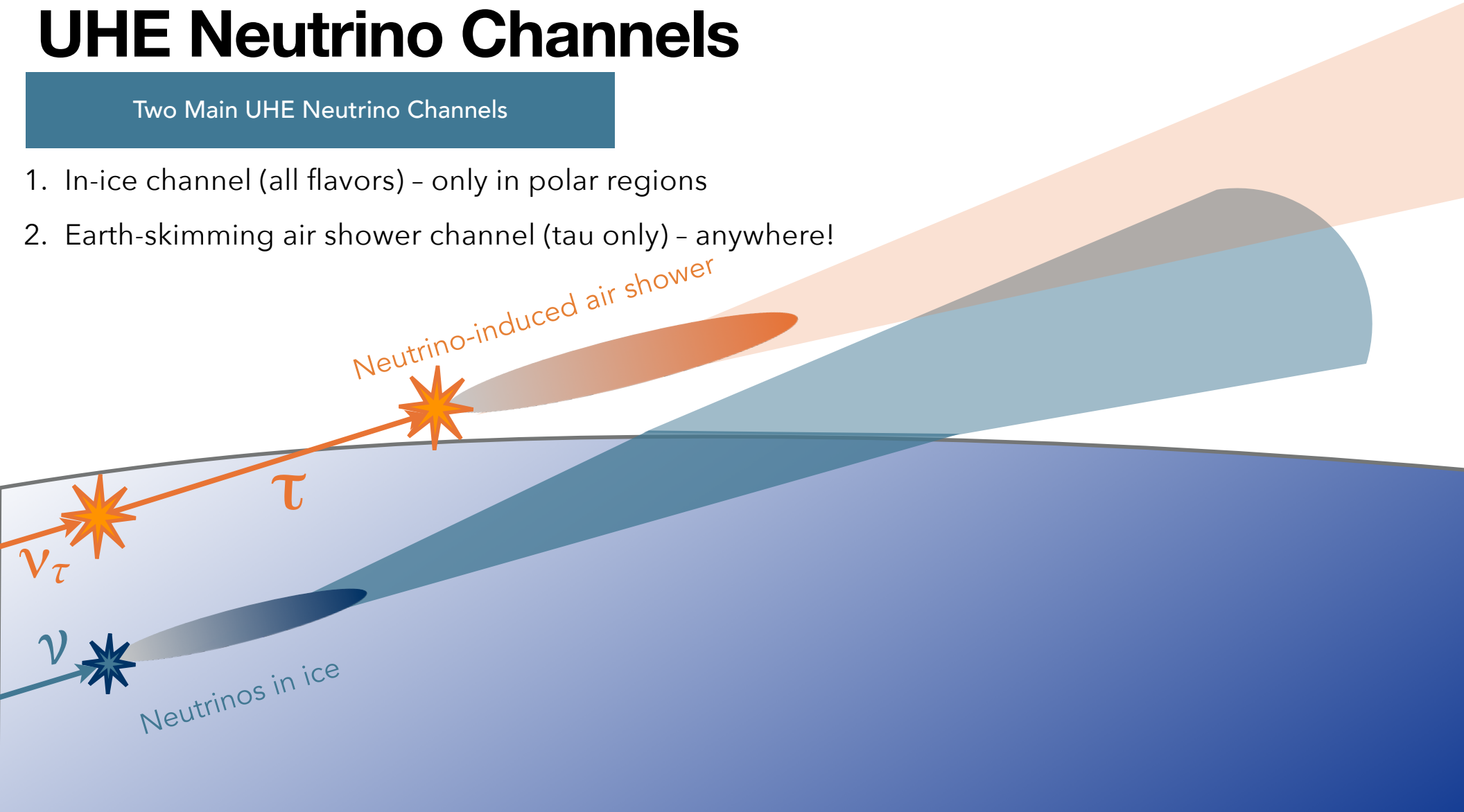


PUEO Whitepaper [arXiv:2010.02892](https://arxiv.org/abs/2010.02892)

UHE Neutrino Channels

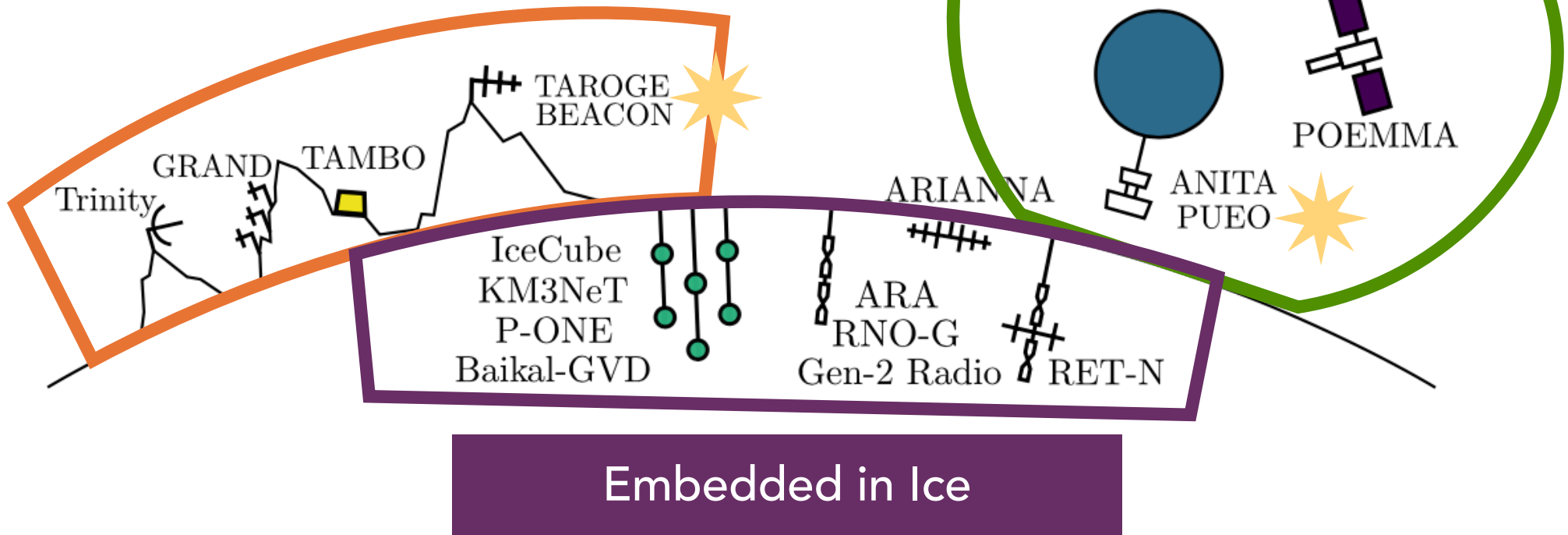
Two Main UHE Neutrino Channels

1. In-ice channel (all flavors) - only in polar regions
2. Earth-skimming air shower channel (tau only) - anywhere!



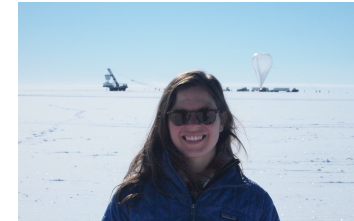
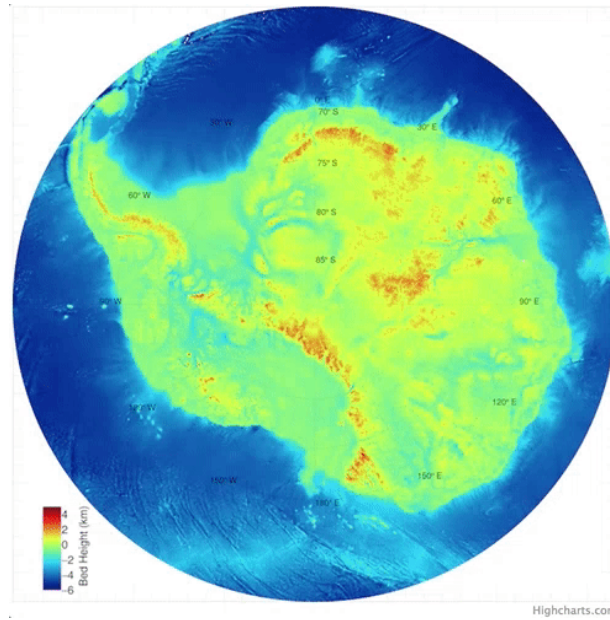
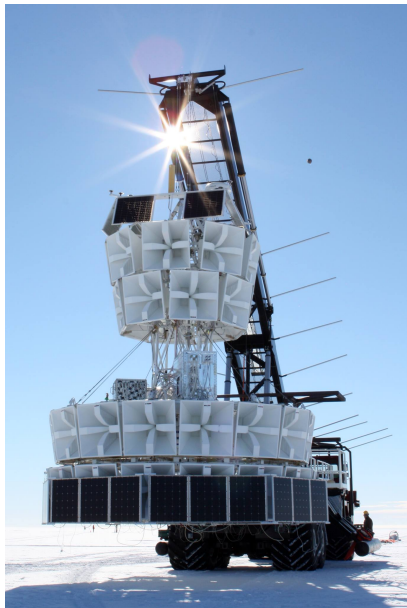
Valleys and Mountains

Balloons & Satellites

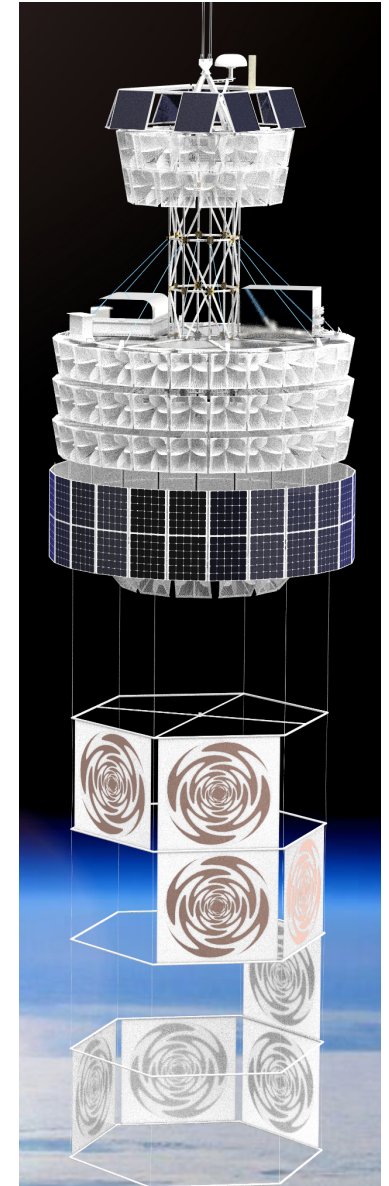


PUEO: Payload for Ultra-High Energies

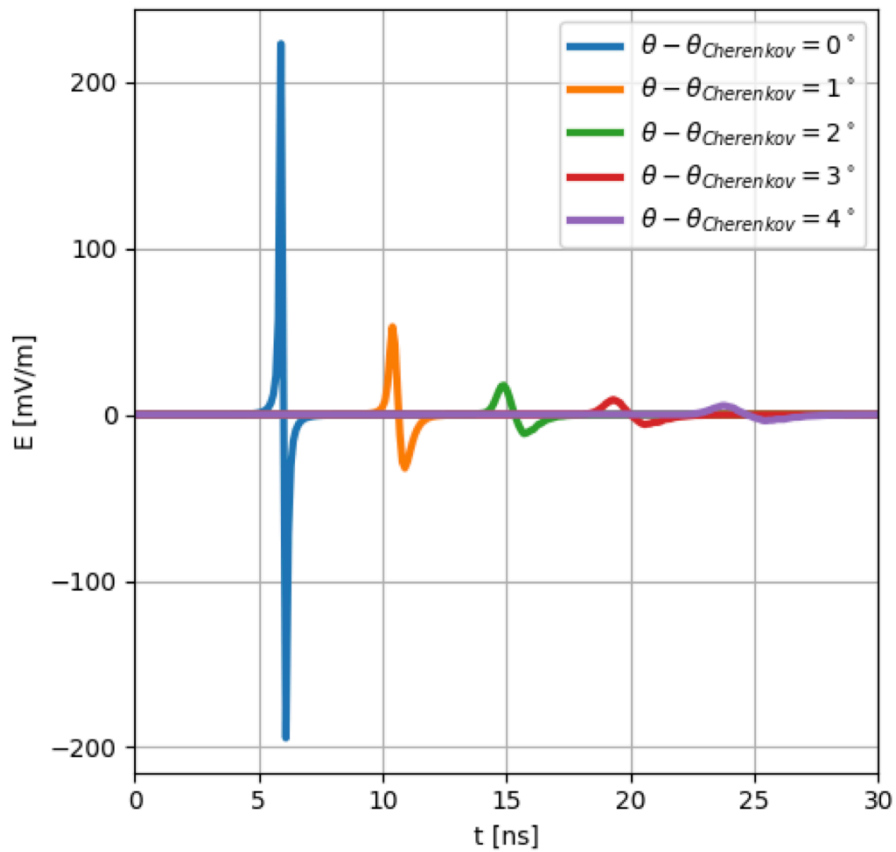
...and its predecessor ANITA



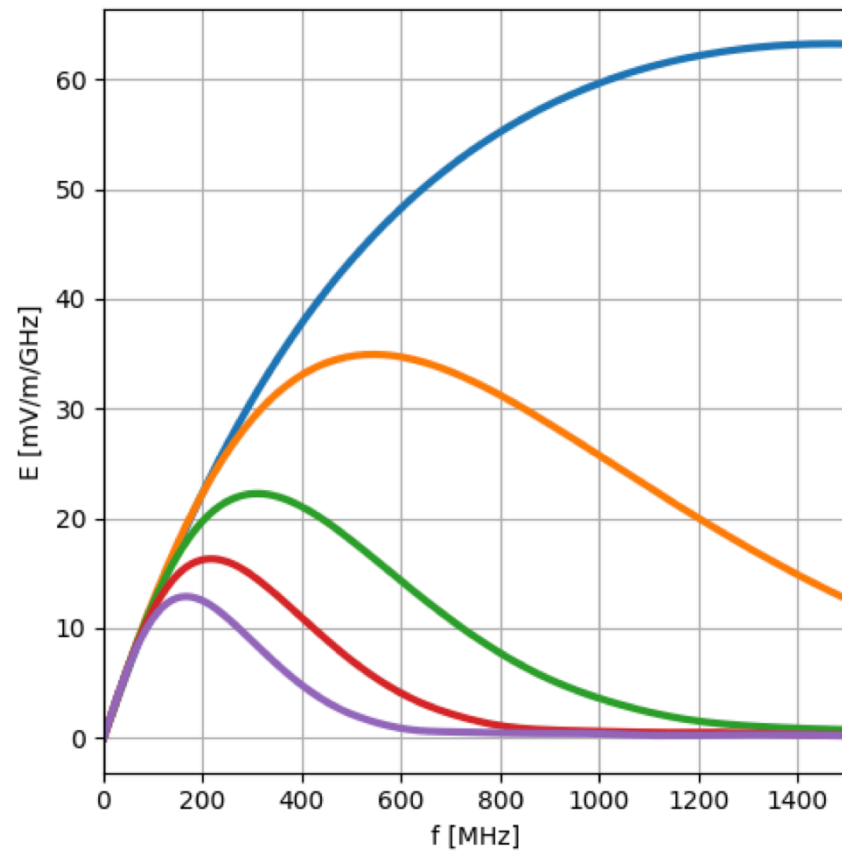
- ANITA: 4 flights 2005-2016
- PUEO Flight in 2025



ASKARYAN SIGNAL



Fast radio spark



Broadband up to ~GHz

POLARIZATION SIGNATURE

- Askaryan neutrinos are **vertically polarized**, because ANITA picks up the top of the cone

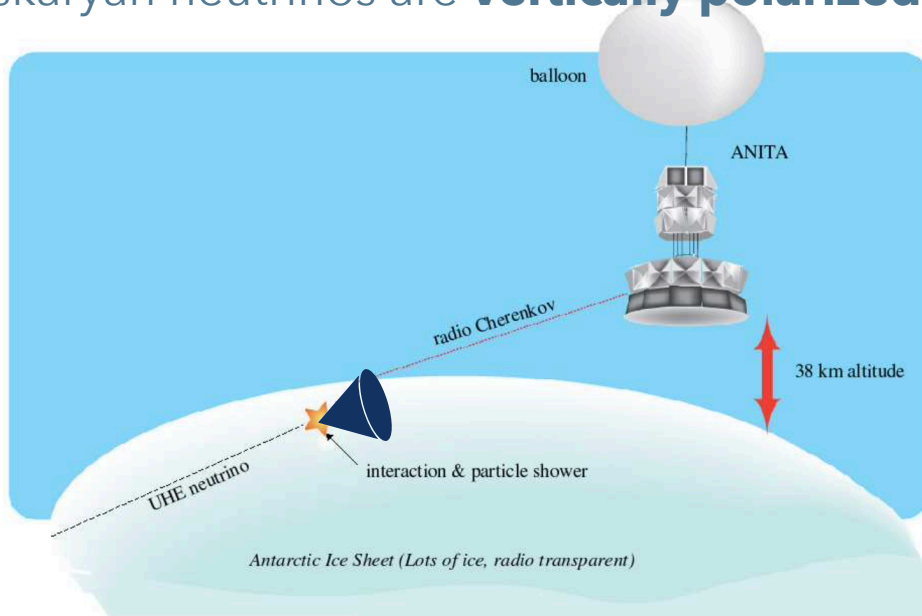
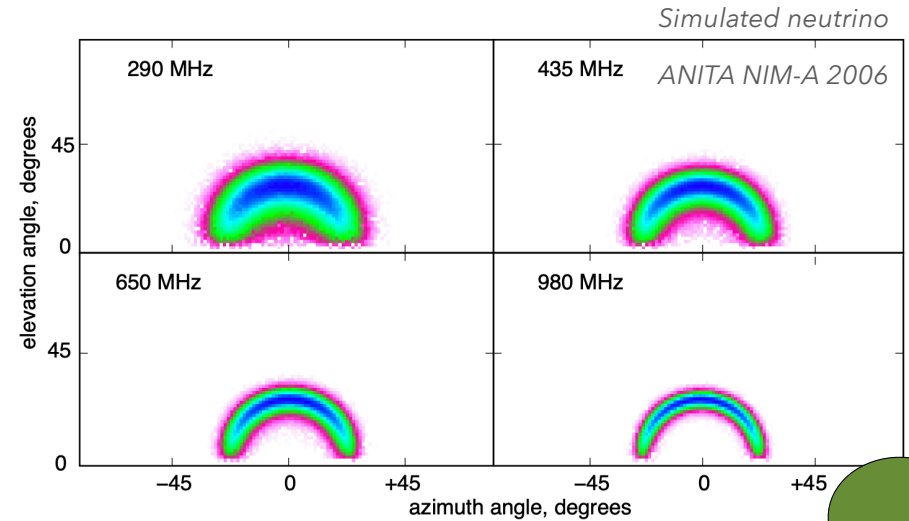
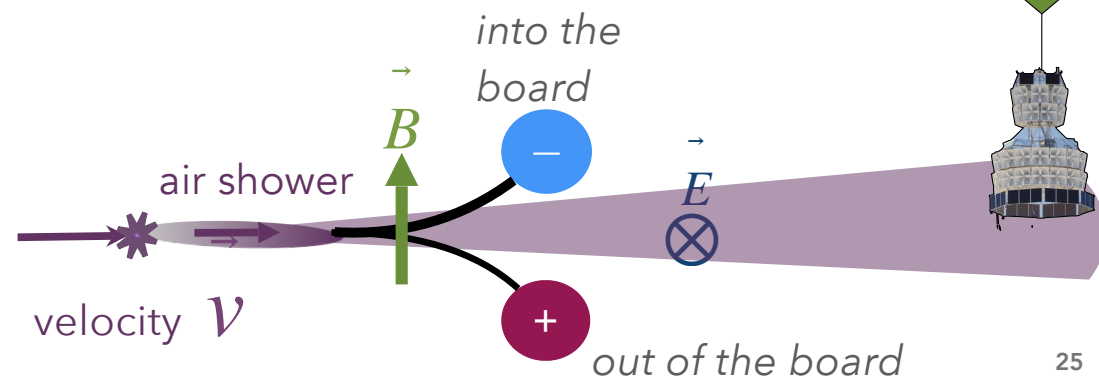
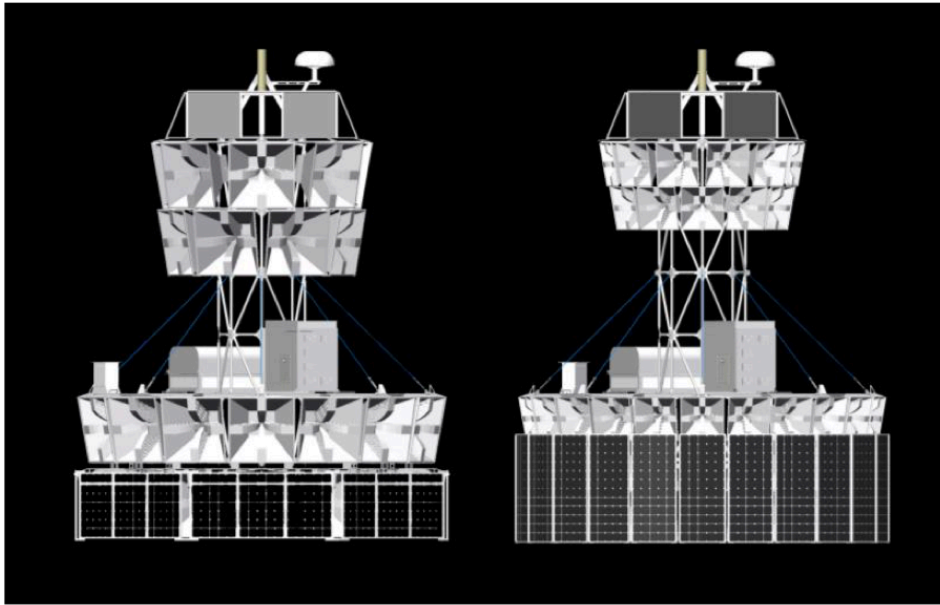


Image Credit: Stephen Hoover



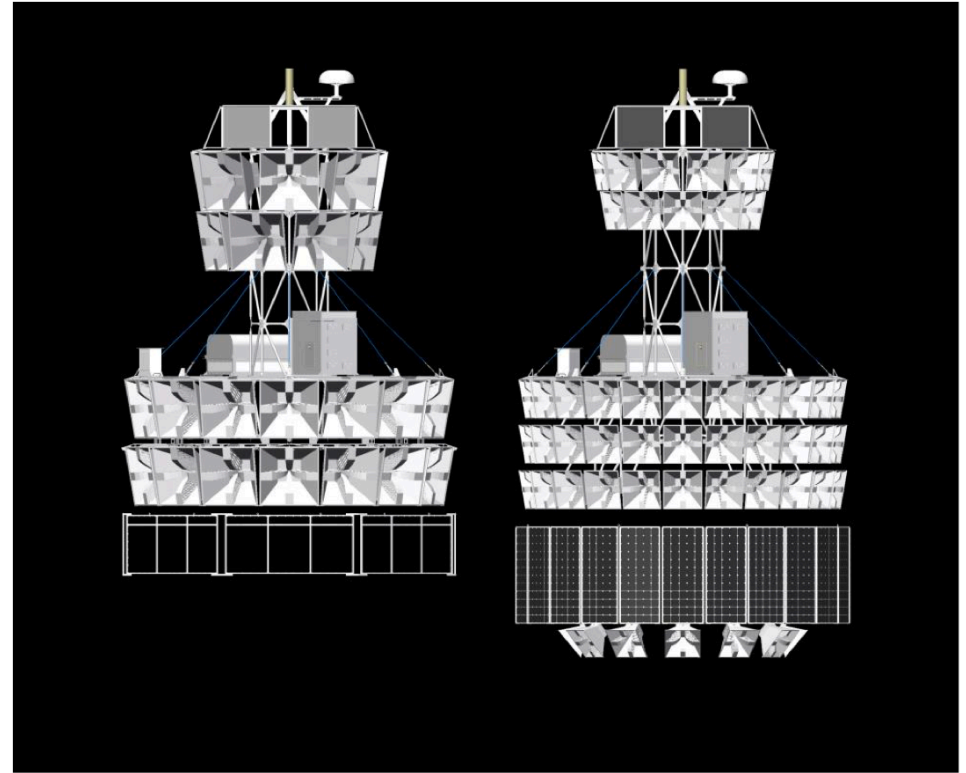
- Air showers are **horizontally polarized**, because the Earth's magnetic field vertical at South Pole





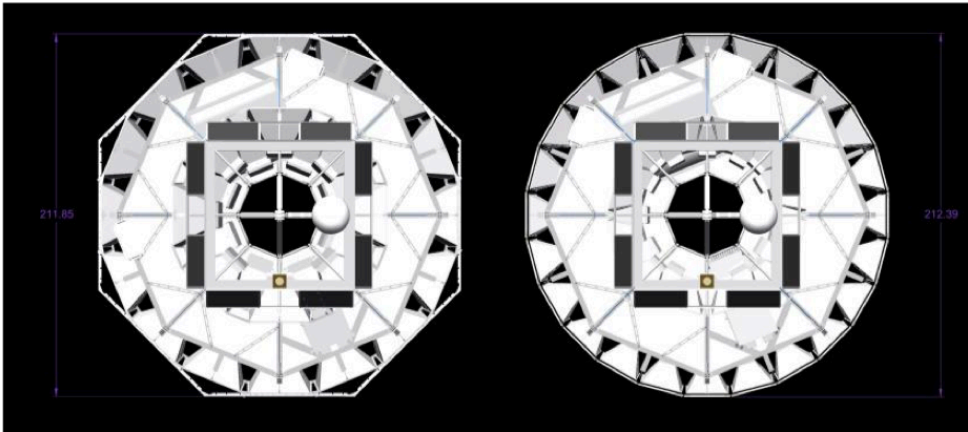
ANITA

PUEO



ANITA

PUEO



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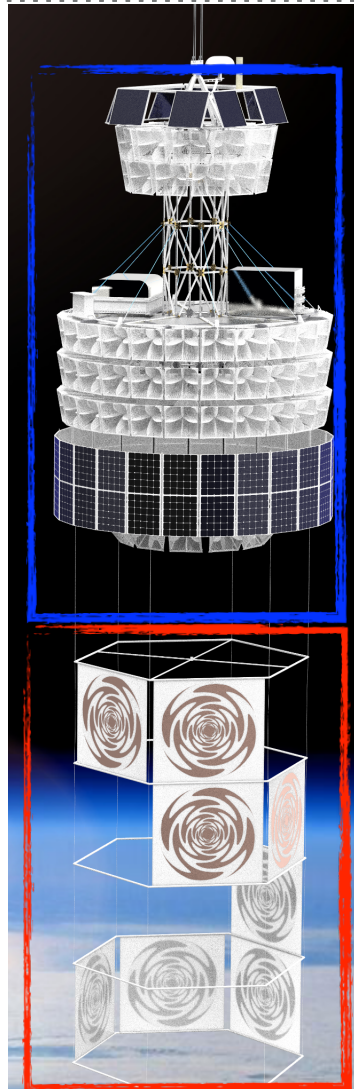
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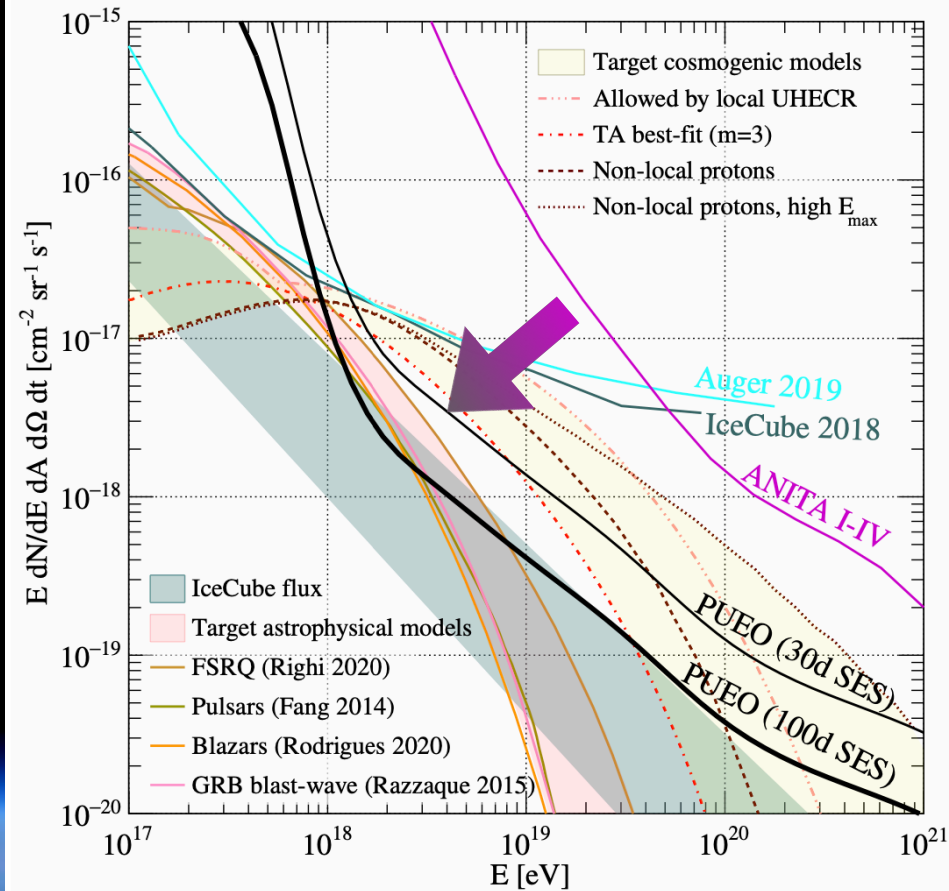
SNR improved with:

1. Double the number of antennas
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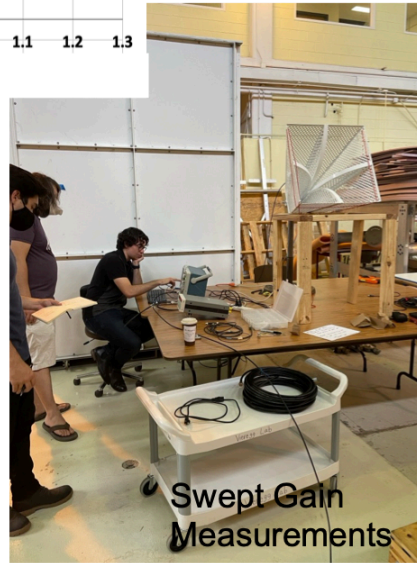
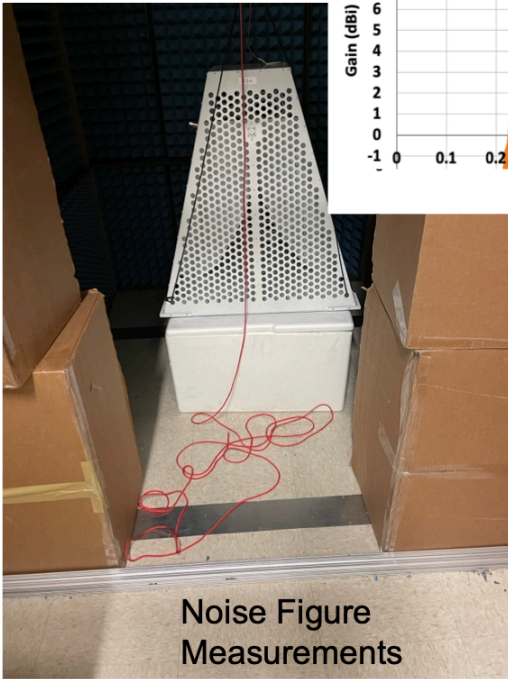
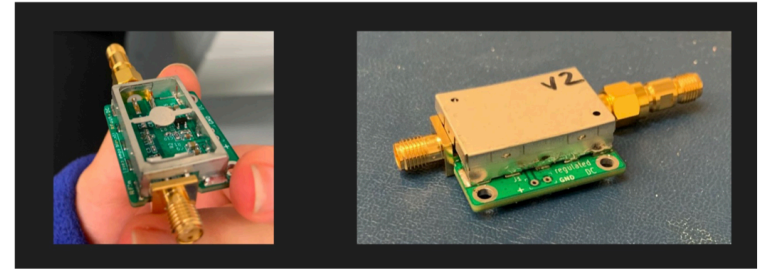
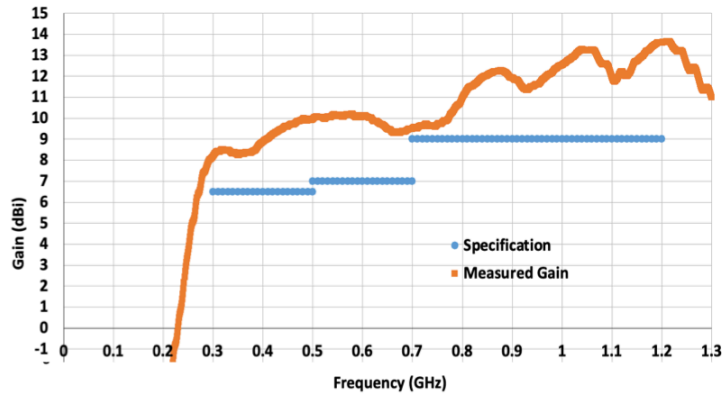
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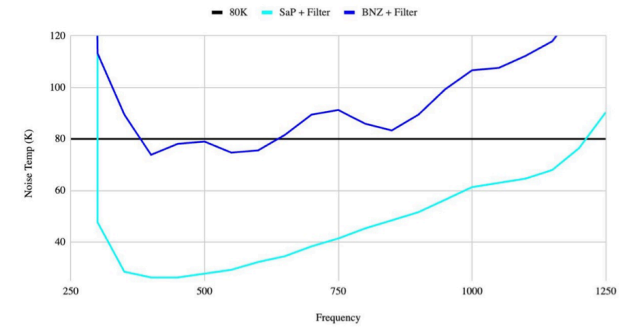
HIGHER SNR: BETTER ANTENNAS AND BETTER RF SIGNAL CHAIN

Boresight Swept Gain



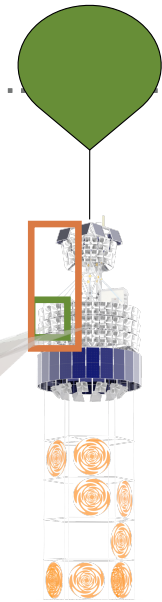
Switching to a new LNA: ~20% more neutrinos over design sensitivity

SaP Noise Temp Comparison

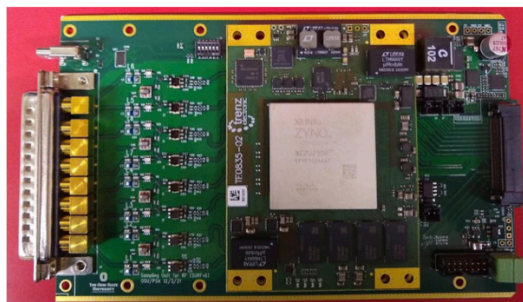


PUEO'S PHASED ARRAYS

- Phasing multiple antennas increases the SNR by \sqrt{N} and the gain by the $\log(N)$
- Multiple beams can cover the full solid angle with a higher gain
- "Tuning into" weaker events



Phased Arrays implemented on novel RFSoCs



Phased Array Lowers Trigger Threshold

Coherent Signal increases by N

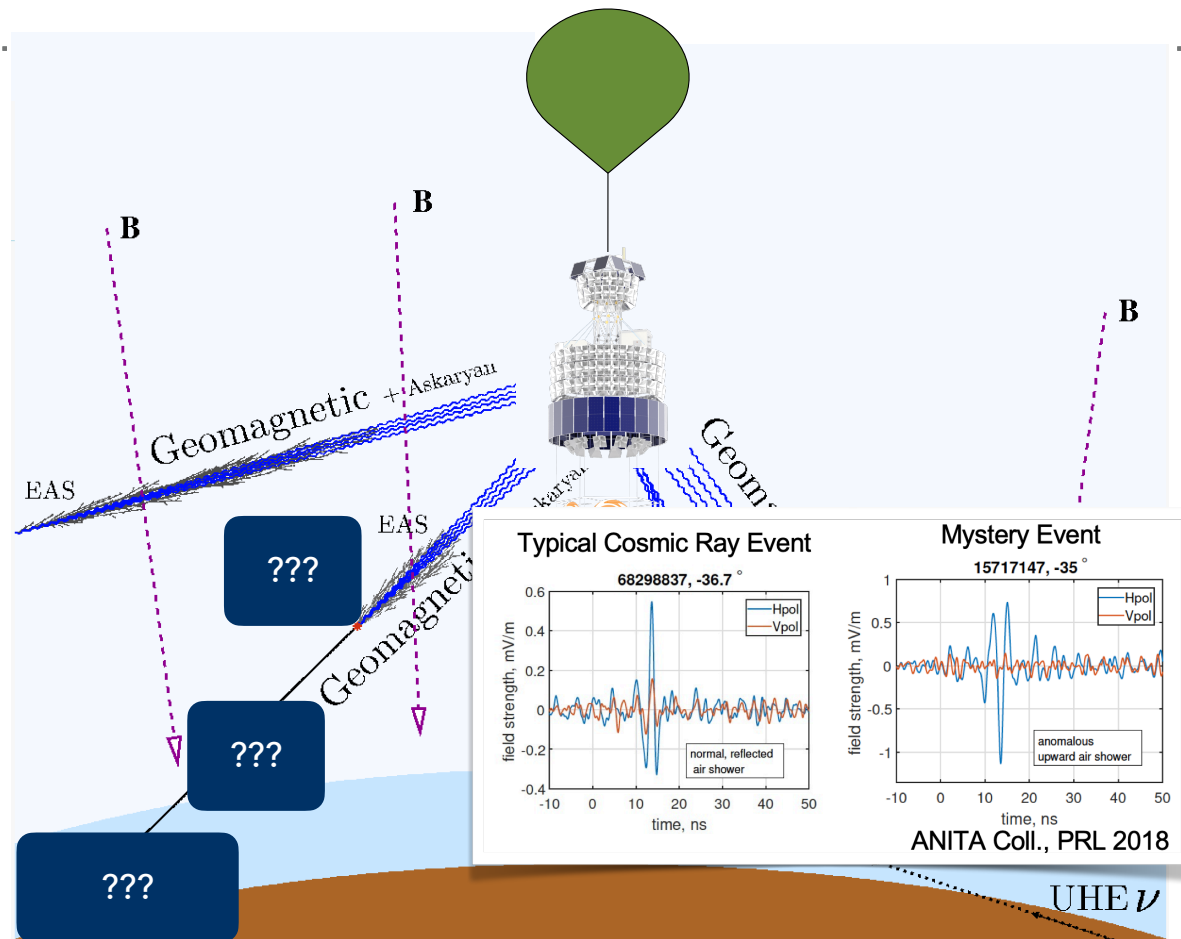
Incoherent Noise reduced by \sqrt{N}

SNR grows with \sqrt{N}

PUEO Whitepaper, 2021

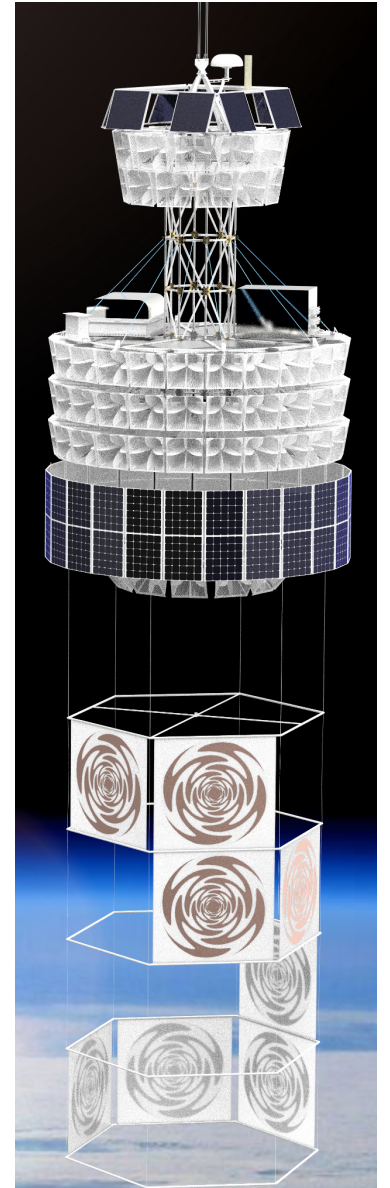
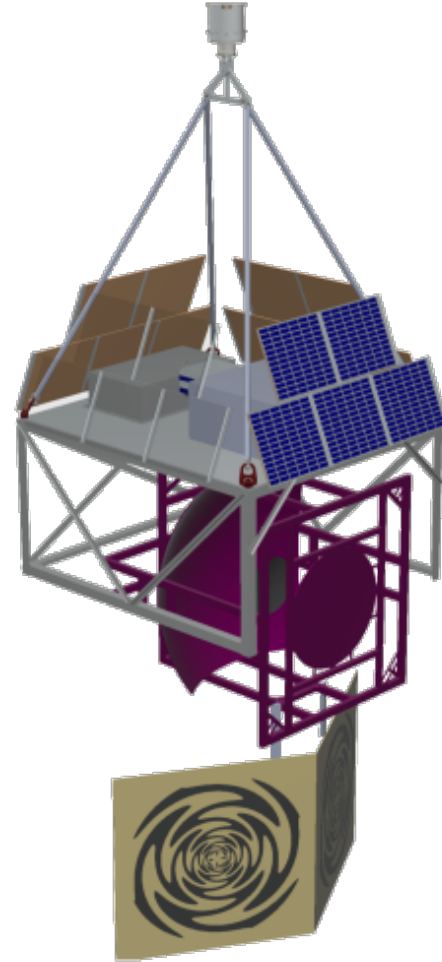
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 - Direct, stratospheric
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Upcoming UHE CR & Neutrino Balloon Payloads



Conclusions

and Discussion Points