Building the Payload for Ultrahigh Energy Observations

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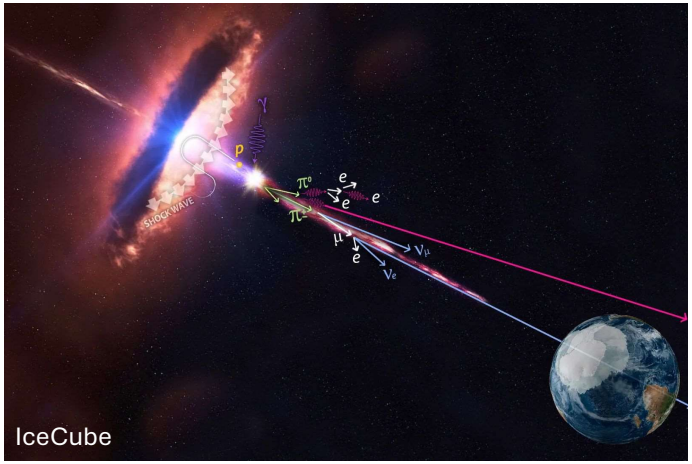
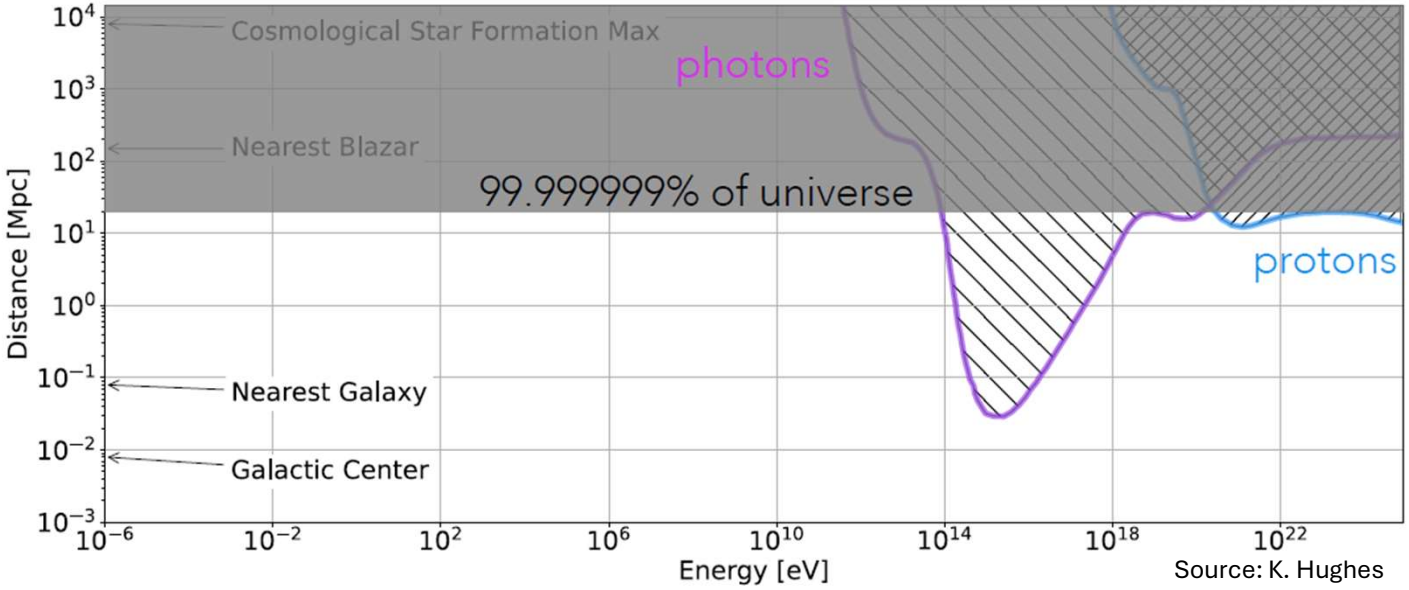
What is PUEO looking for?

We want to study the distribution and nature of the sources of the highest energy particles in the universe!

Neutrinos are uniquely well-suited messengers for this purpose.





Source: K. Hughes

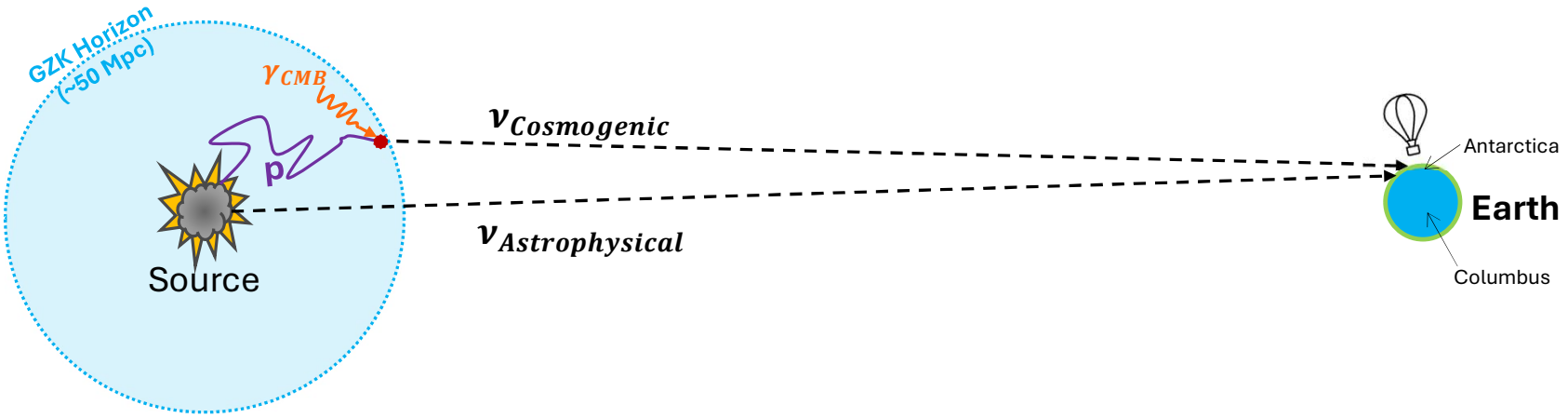
Types of UHE neutrinos PUEO looks for

Astrophysical

UHE neutrinos produced directly by their astrophysical sources.

Cosmogenic

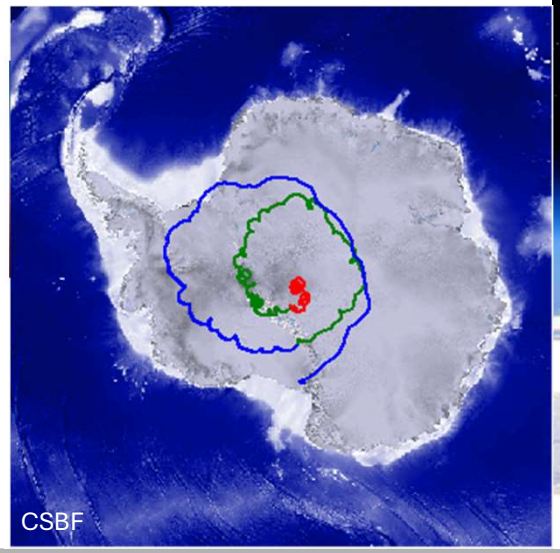
UHECR with energies above ~50 EeV interact with the CMB, producing neutrinos.

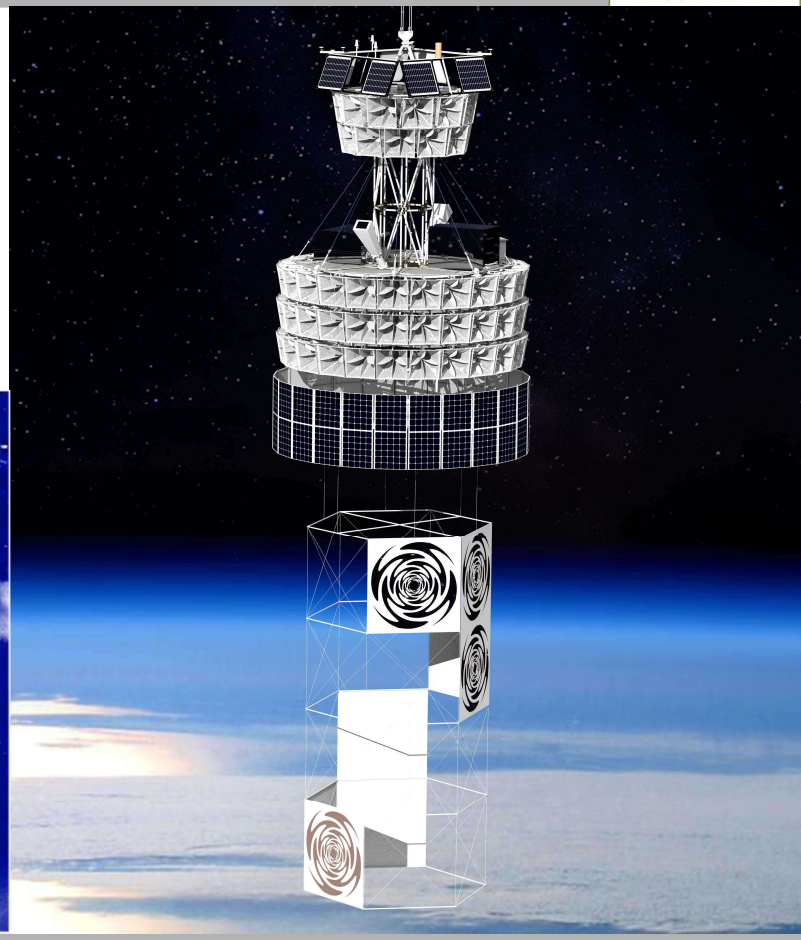


PUEO: A Brief Introduction

Payload for **U**ltrahigh **E**nergy **O**bservations

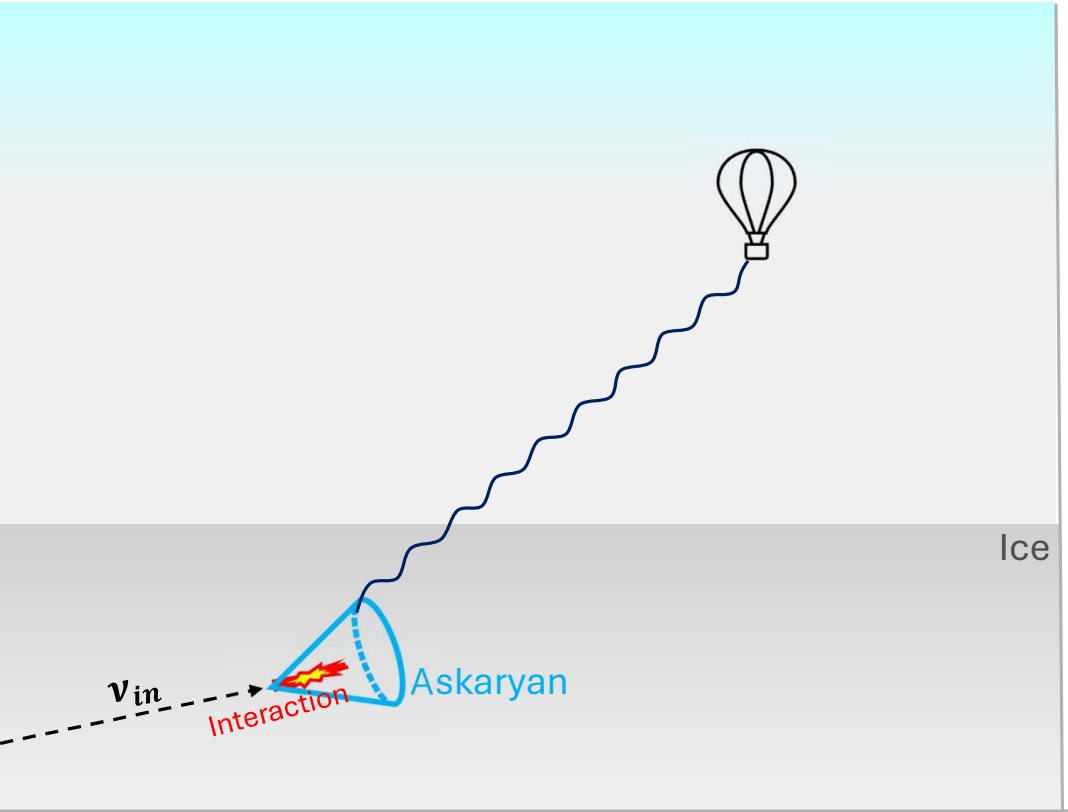
- Radio detection experiment
- NASA Long Duration Balloon flight over Antarctica
- Will measure the ultrahigh energy neutrinos' interactions with the Earth
  - >1 EeV (10^{18} eV)!





How does PUEO see these particles?

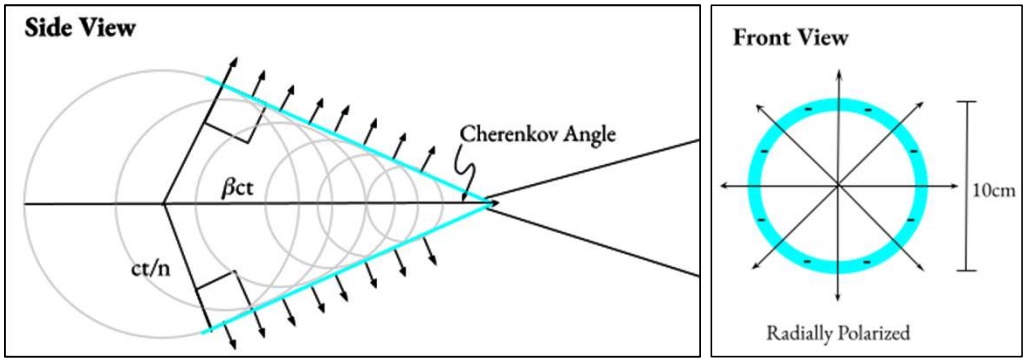
Method 1: Askaryan emission in ice



When an UHE neutrino interacts in the ice, the resulting shower emits Askaryan radiation at the Cherenkov angle.

This radiation will add coherently in radio (with power ~ E^2) if the width of the shower is less than radio wavelength.

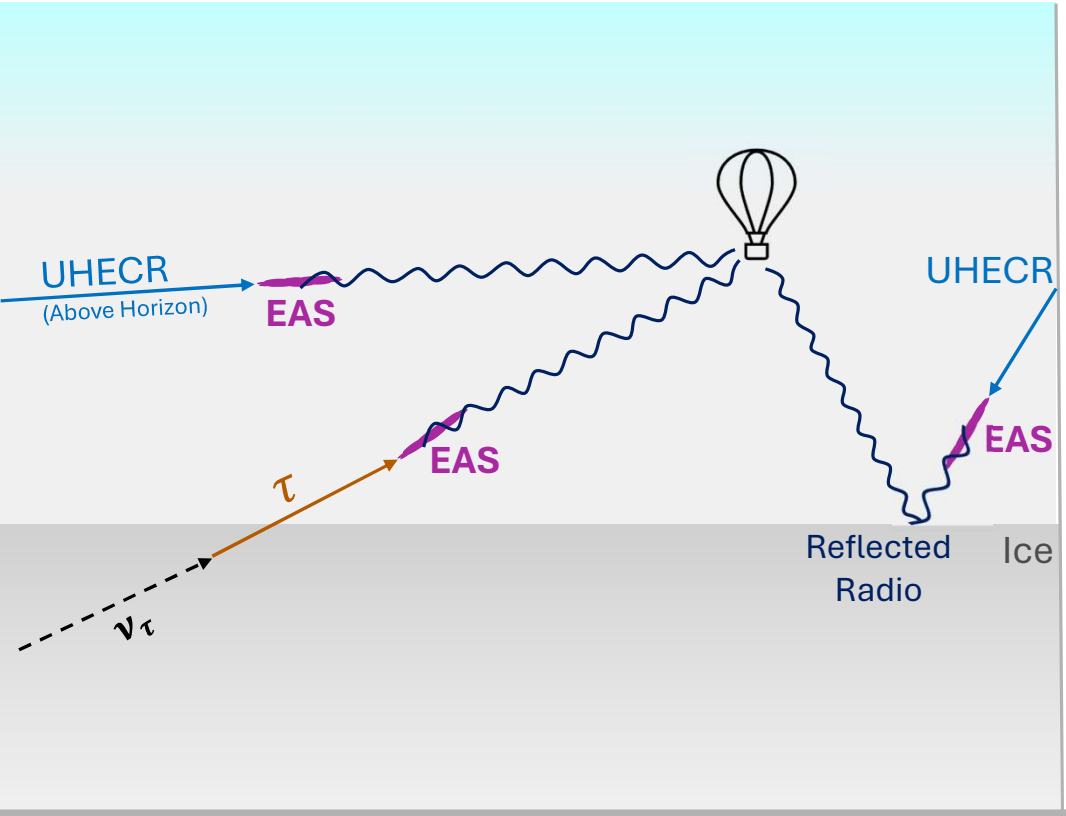
The radio emission is radially polarized, which is useful for reconstructing the direction of the shower.



Credit: Rachel Scrandis

How does PUEO see these particles?

Method 2: Geomagnetic emission in air showers



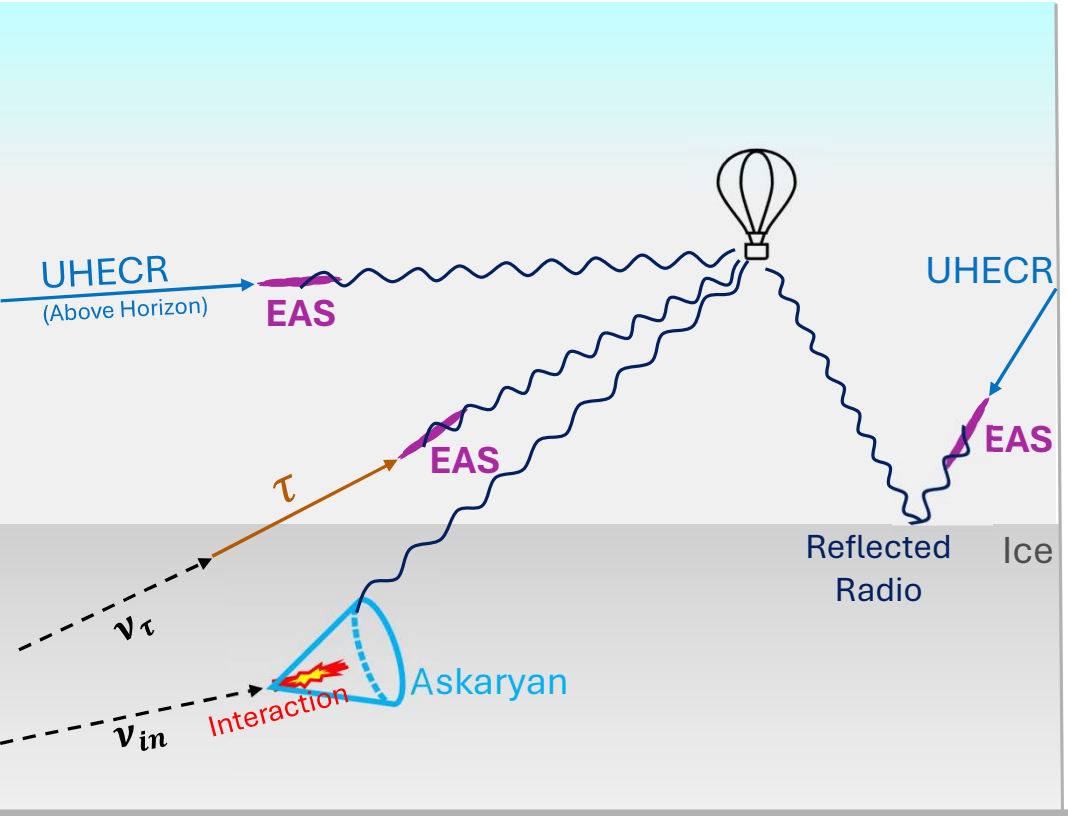
PUEO can also detect the radio that is produced by geomagnetic emission in air showers.

Tau neutrinos interacting in the earth produce tau particles, which then decay and produce an Extensive Air Shower (EAS).

EASs can also be produced by UHE cosmic rays.

How does PUEO see these particles?

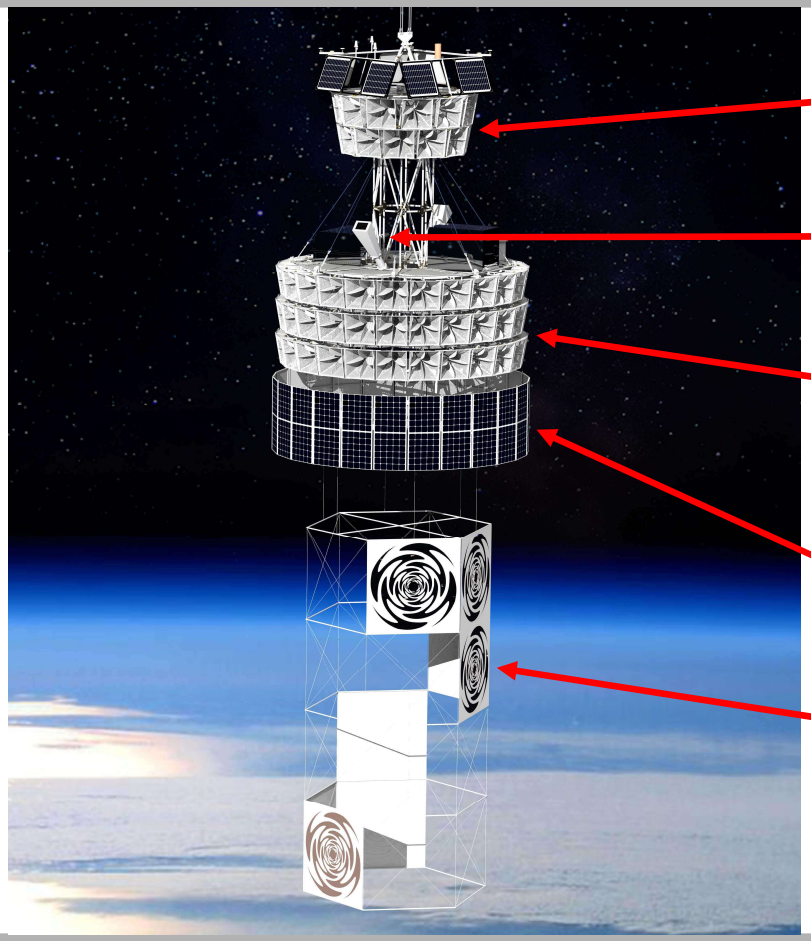
Differentiation Between Radio Sources



- **In-ice Askaryan**
  - Below horizon
  - Vertically polarized
- **Tau-neutrino induced EAS**
  - Below horizon
  - Horizontally polarized
- **UHECR induced EAS**
  - Above horizon
  - Horizontally polarized
- **UHECR induced EAS (reflected)**
  - Below Horizon
  - Horizontally polarized
  - *Polarity flip relative to other EAS showers*

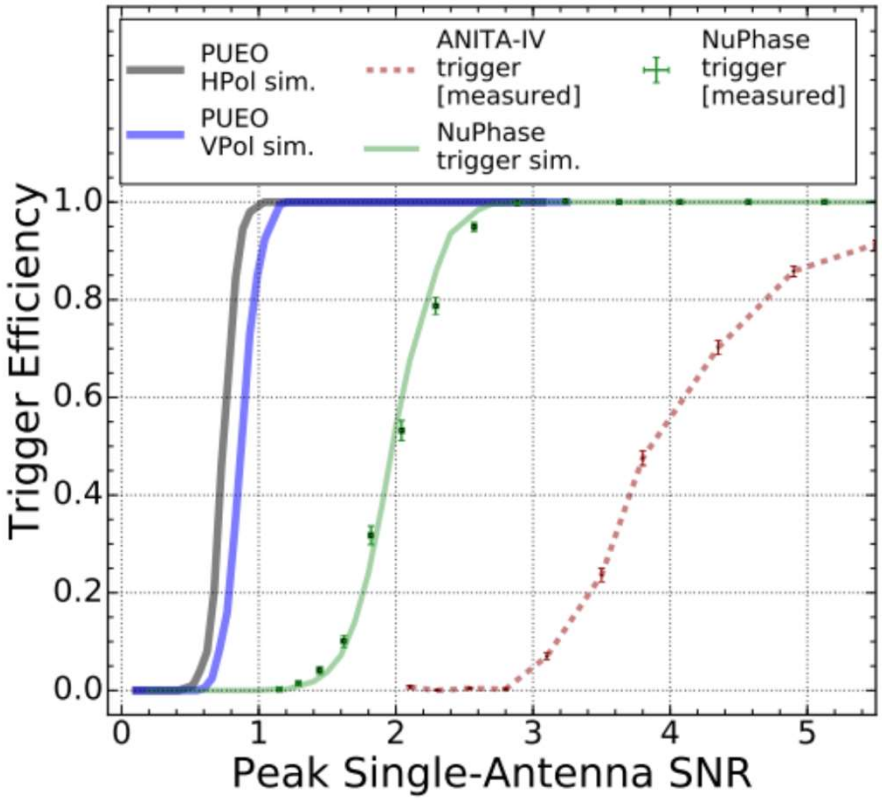
Design of PUEO

- Main instrument antennas
  - 96 Quad-ridged horns
  - Dual polarized
  - Arranged into 4 rings
  - 2π (full) azimuthal coverage
  - 300-1200 MHz band
- Low frequency instrument
  - 8 Sinuous antennas
  - Dual polarized
  - 50-500 MHz band
  - Made of conductive fabric



DAQ and Phased Array Trigger

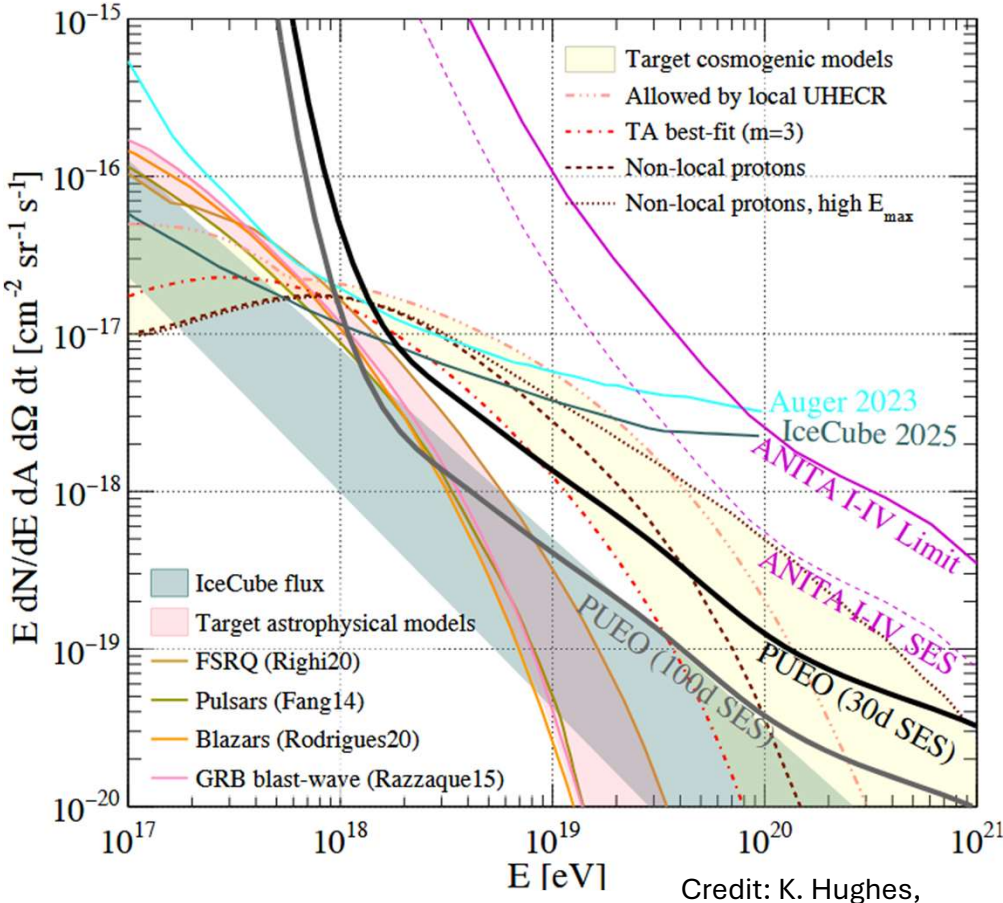
- RFSoCs digitize signals from the antennas to 12 bits
- Real-time digital processing
  - Low-pass filter at ~750 MHz
  - Tunable dual-biquad notch filters
  - Automatic gain control
  - 12-to-5 bits, then beamform
- Trigger thresholds adjust to maintain a constant event rate



Pueo Whitepaper

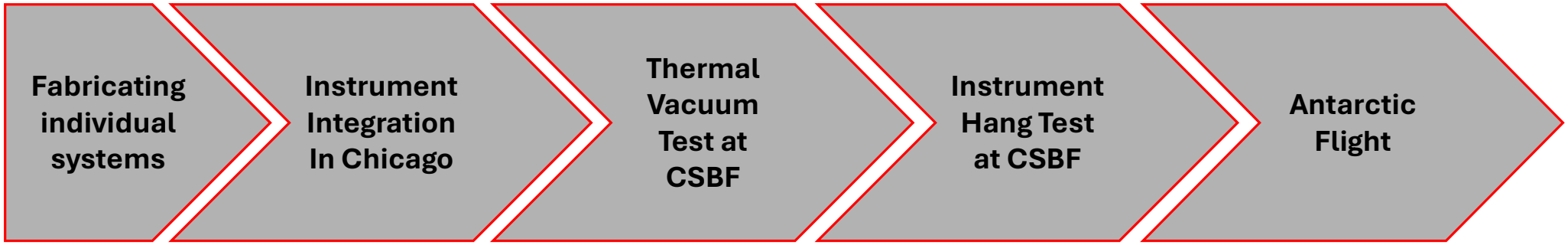
PUEO Diffuse Sensitivity

- PUEO's single-event sensitivity (SES) to diffuse UHE fluxes will outperform the combined ANITA flights
  - Exclude or measure a number of cosmogenic models
- Multiple or longer flights could probe additional phase space
  - Astrophysical production models



Credit: K. Hughes, ICRC 2025

PUEO Approximate Timeline



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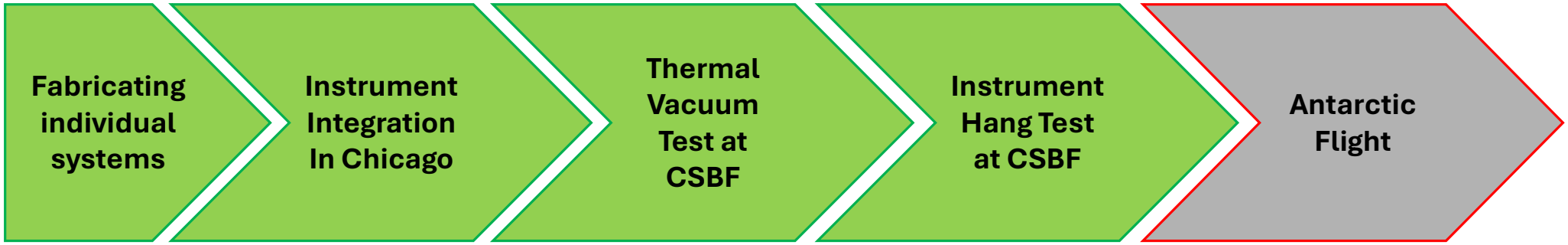


Photos!

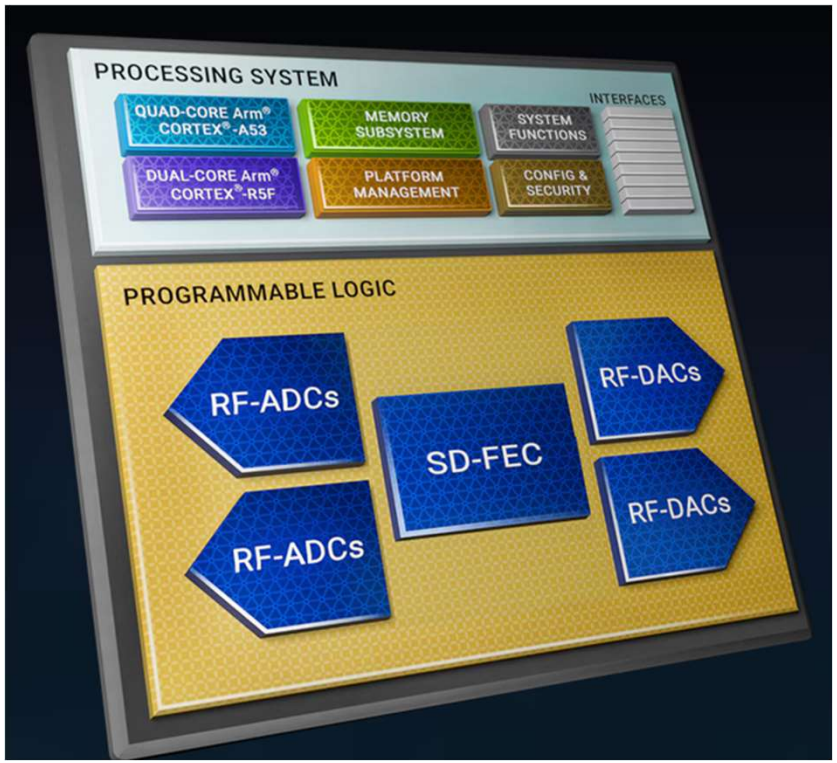
Wait, Lucas, what do you actually do all day?

Something Even More Exciting Than Tornadoes!!!

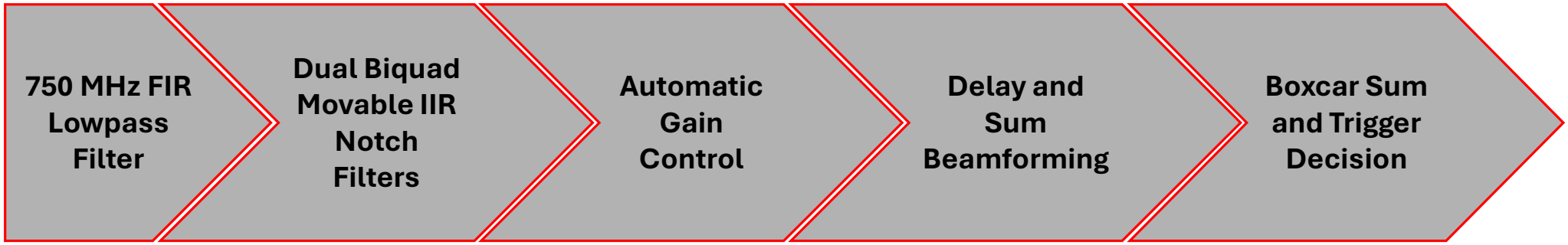

Firmware

Quick intro: Why firmware?

- Firmware, in this context, means FPGAs.
- Why use FPGAs (Field Programmable Gate Arrays)?
  - A serial processor, like the one in your computer, is not ideal for digitizing, filtering, triggering, and buffering a large and fast system!
  - A highly parallel digital circuit is much better suited for these applications.
  - FPGAs can implement these, and they are reprogrammable.



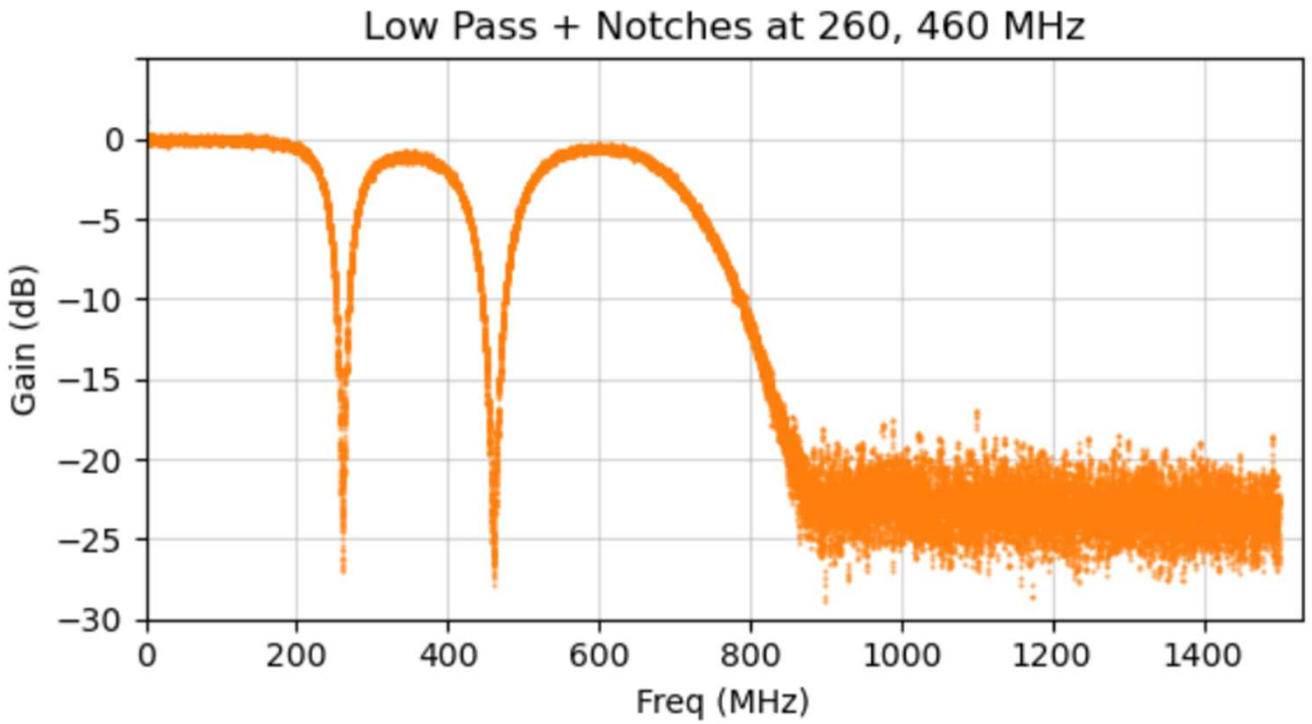
L1 Trigger Chain



Band limiting	CW Noise (satellites)	Balance SNR	Add signals constructively	Lowpass filter and trigger threshold

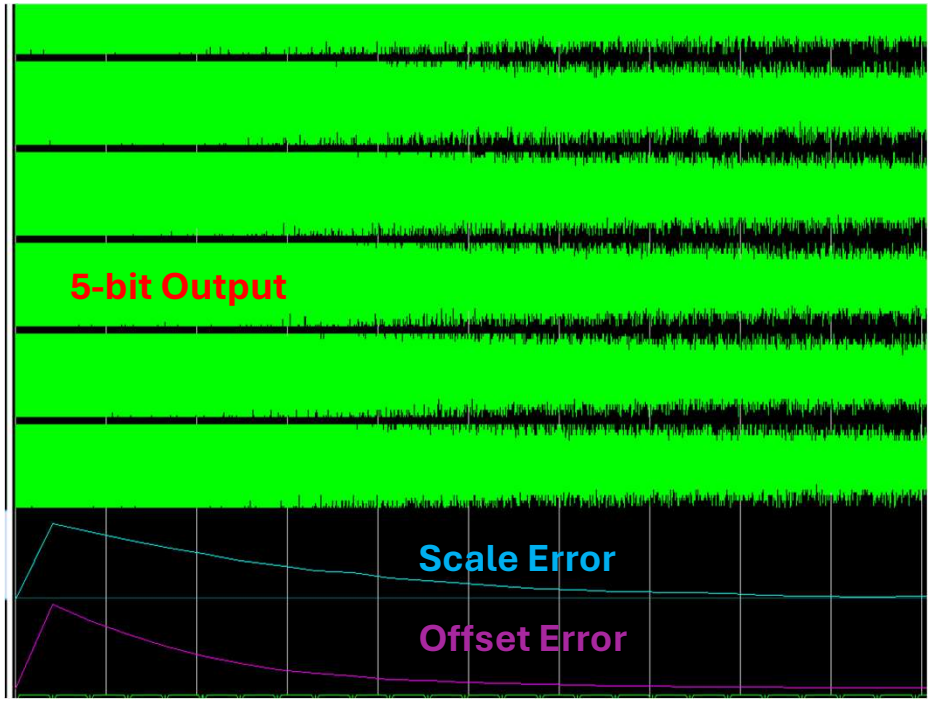
Lowpass + Notch Filters

Lowpass Filter | **Notch Filters** | Automatic Gain Control | Delay and Sum Beamforming | Boxcar Sum and Trigger Decision



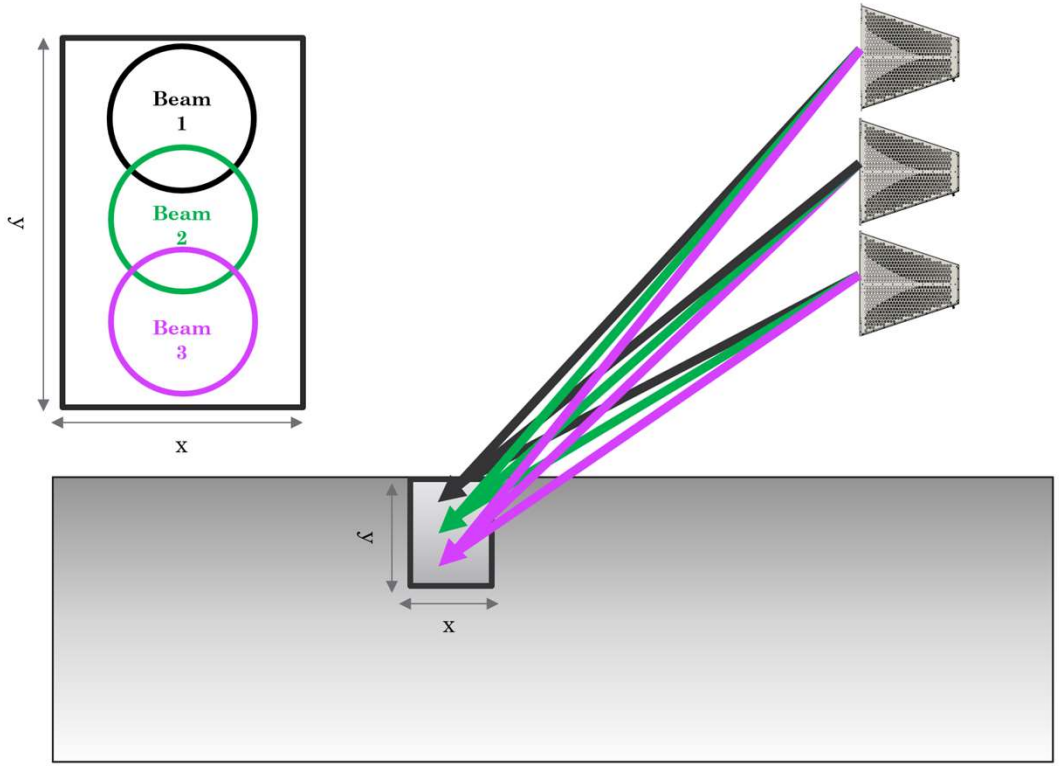
Automatic Gain Control

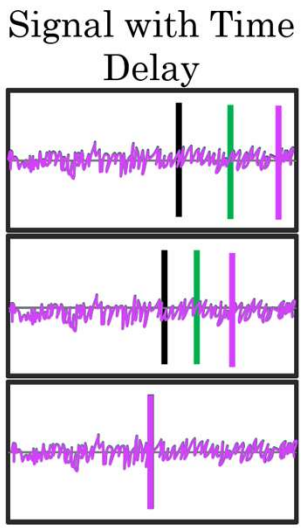
- With our newly filtered signals, we now want to beamform for the trigger. But wait!
  - We have 12 bits per measurement – do we really want that many?
  - Do all the channels have the same gain? If not, the trigger will suffer.
- In firmware, we convert 12->5 bits.
  - Scale thermal noise to be a specific RMS.
  - Subtract an offset to get equal tail fractions on each side.



AGC on ZCU111

Beamforming Basics

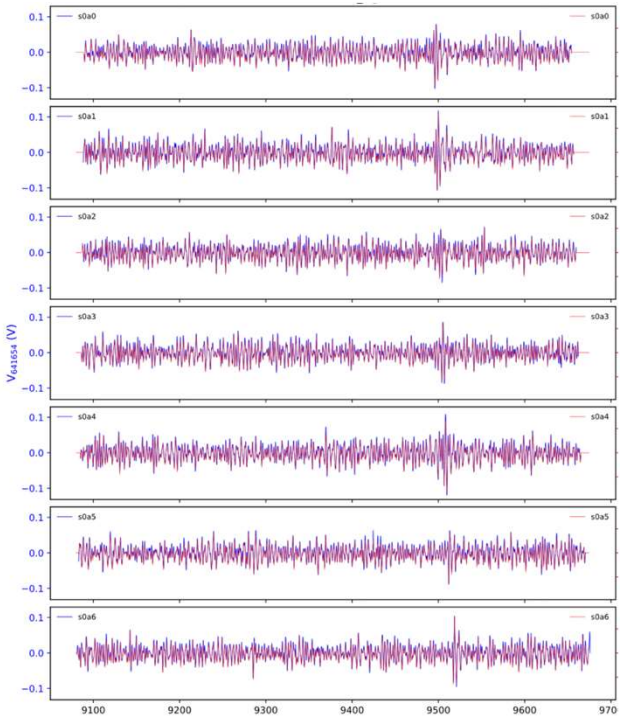


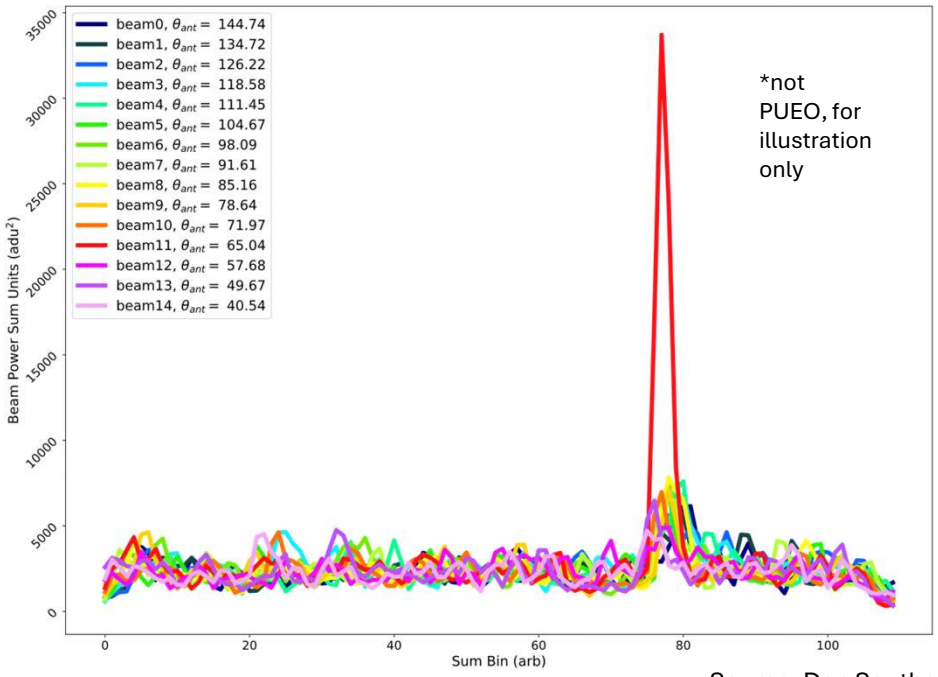


Source: Taylor Coakley

Beamforming Basics

Lowpass Filter → **Notch Filters** → **Automatic Gain Control** → **Delay and Sum Beamforming** → **Boxcar Sum and Trigger Decision**





Source: Dan Southall

- We delay the samples, sum them, and square.
- Boxcar of 8 samples every 4, then check threshold.

Conclusion

- PUEO's DAQ System is taking data
- PUEO passed the integration and "hang" test at NASA CSBF over the Summer
- On its way to Antarctica!
- Significant improvements to measurement of diffuse UHE neutrino flux
- Well prepared to measure transient sources

PUEO will probe the some of the highest energy phenomenon in the universe!

Questions?