Building the Payload for Ultrahigh Energy Observations

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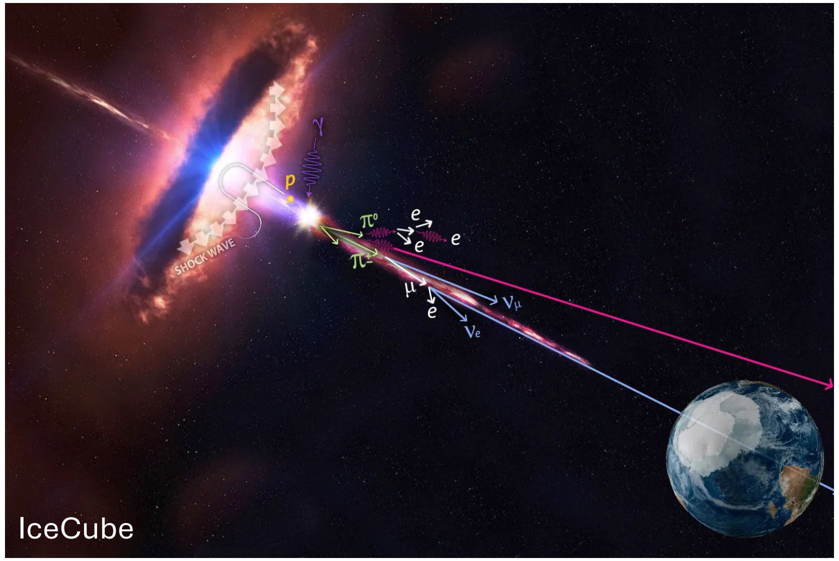
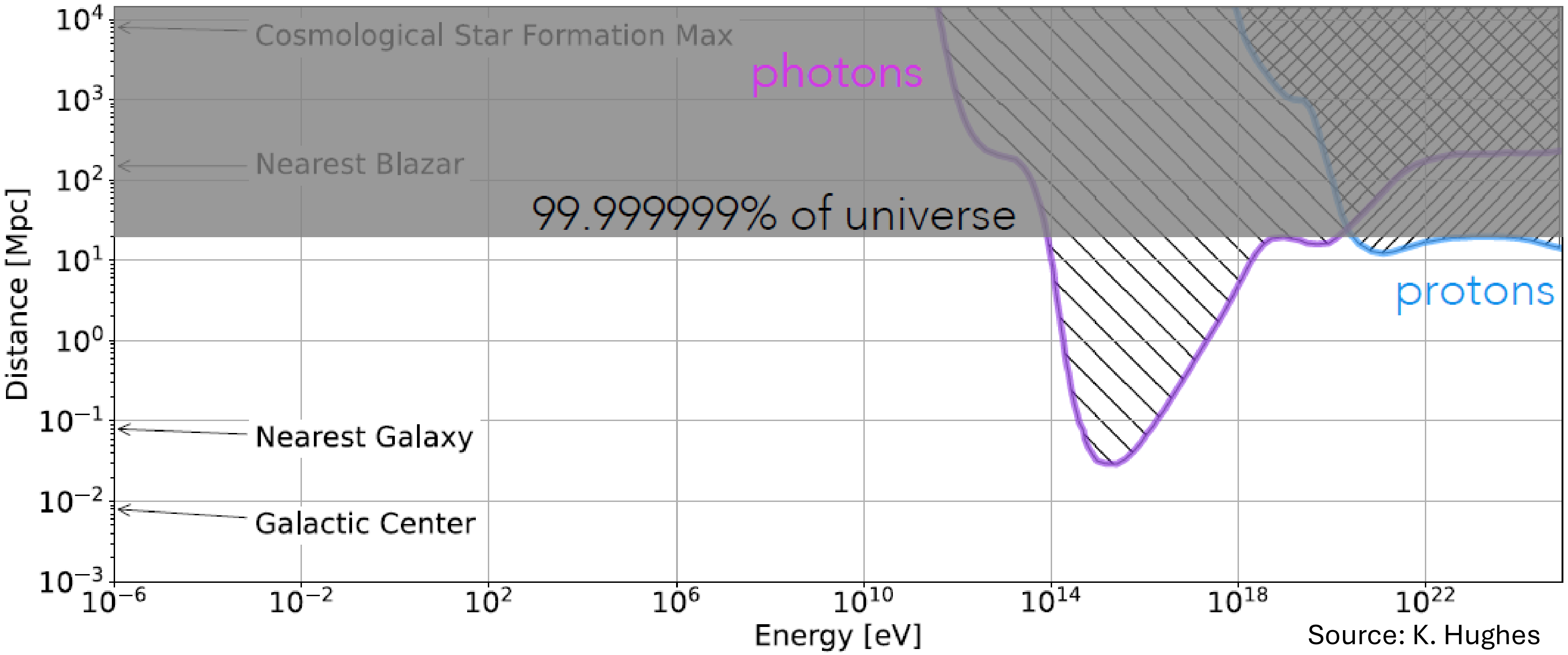
What is PUEO looking for?

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.





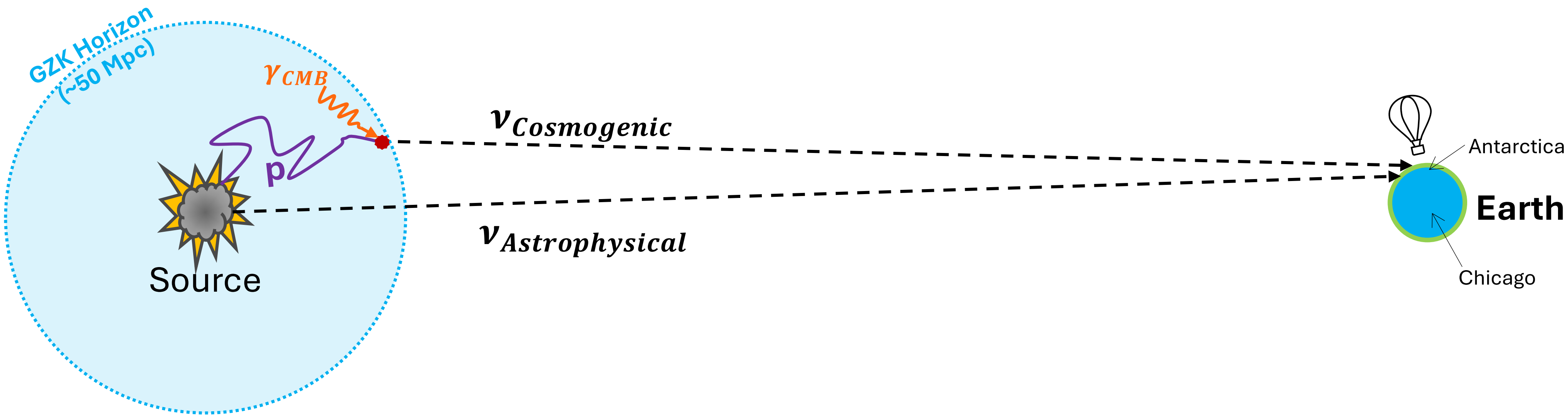
Source: K. Hughes

Astrophysical

UHE neutrinos produced directly by their astrophysical sources.

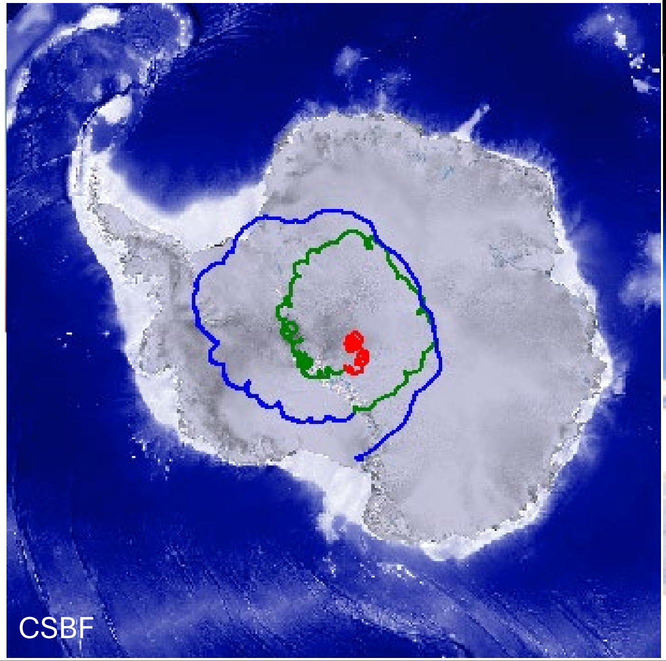
Cosmogenic

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

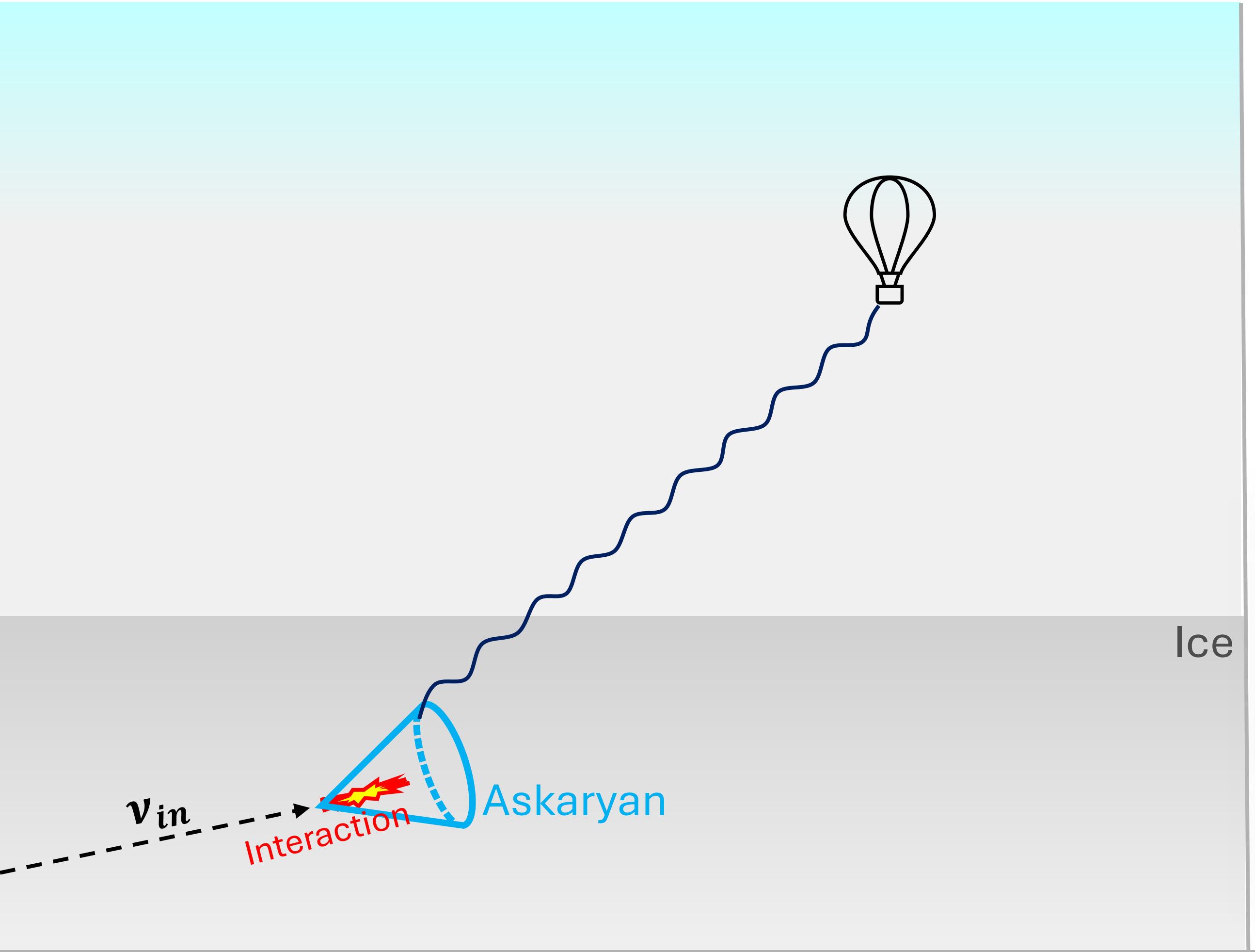


Payload for **U**ltrahigh **E**nergy **O**bservations

- 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)!



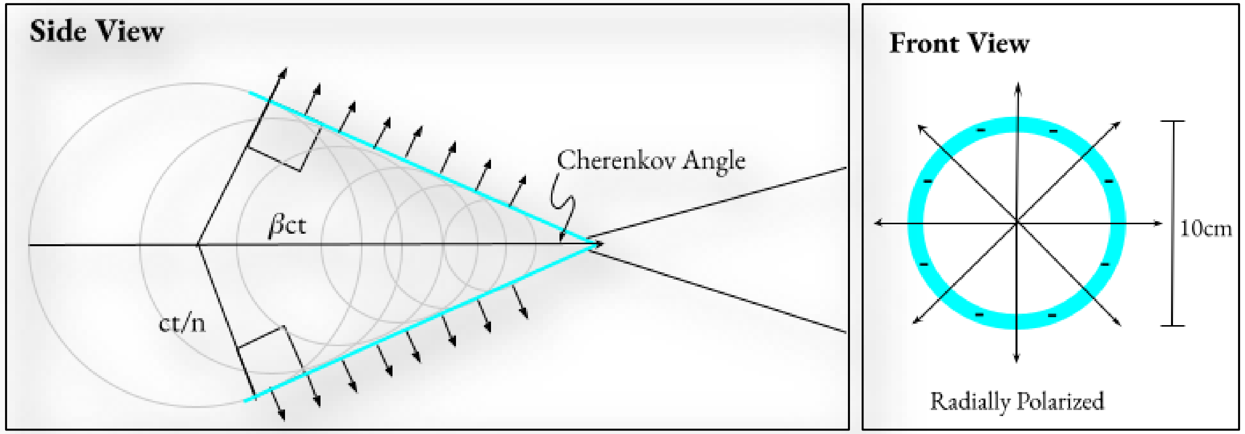
Method 1: Askaryan emission in ice



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

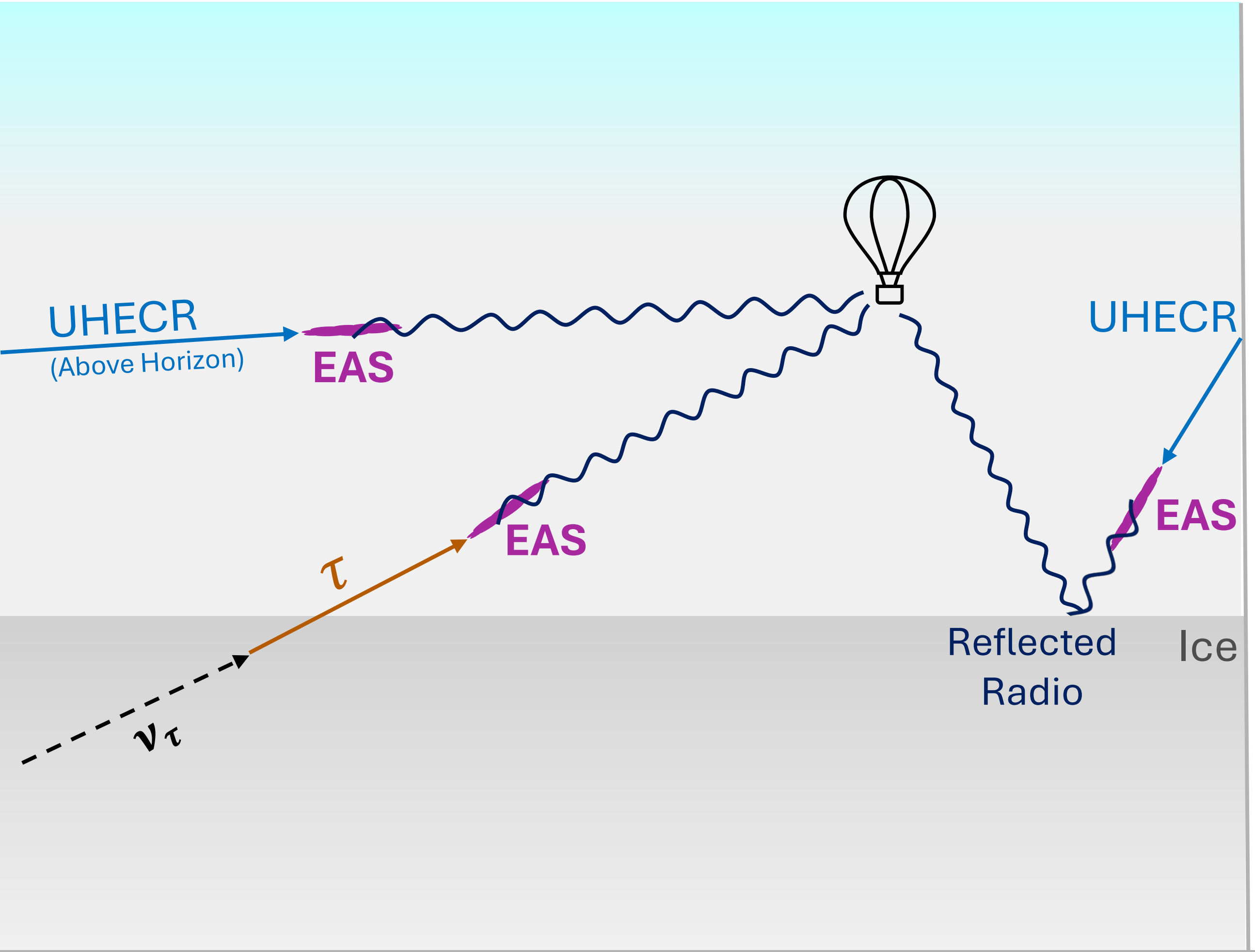
This radiation will add coherently in radio (with power ~ E^2) if the width of the shower is less than radio wavelength.

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



Credit: Rachel Scrandis

Method 2: Geomagnetic emission in air showers



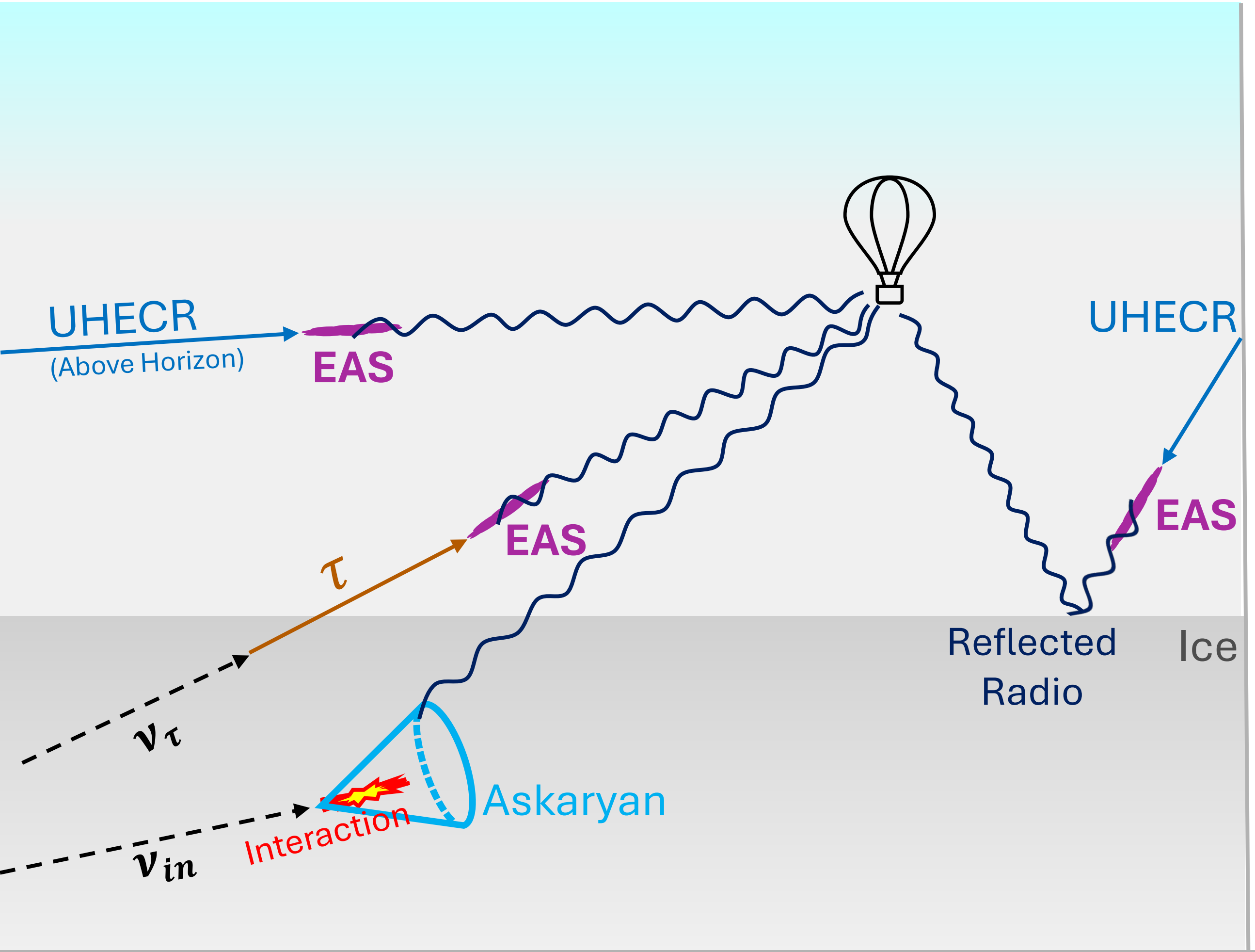
PUEO can also detect the radio that is produced by geomagnetic emission in air showers.

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?

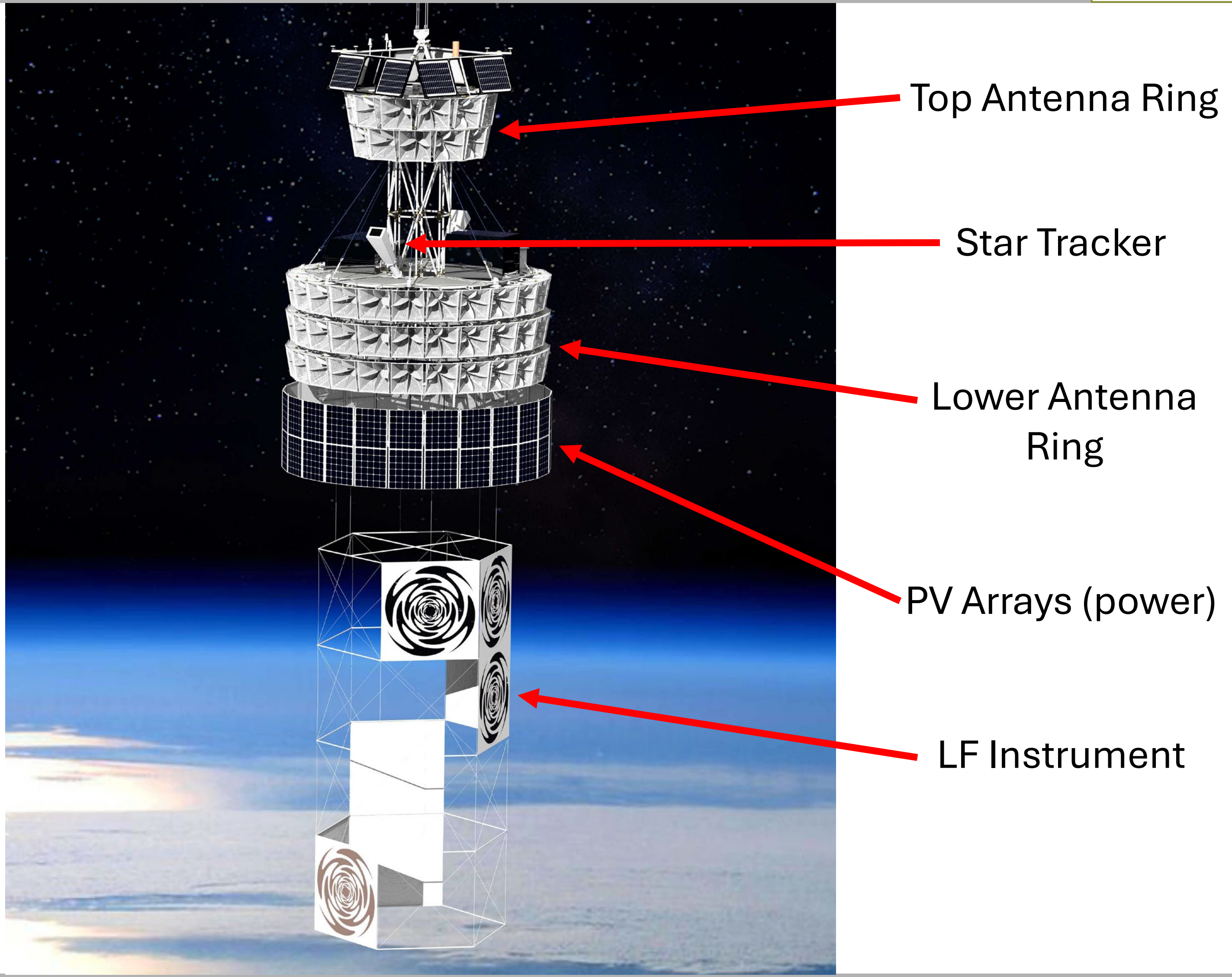
Differentiation Between Radio Sources



- **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

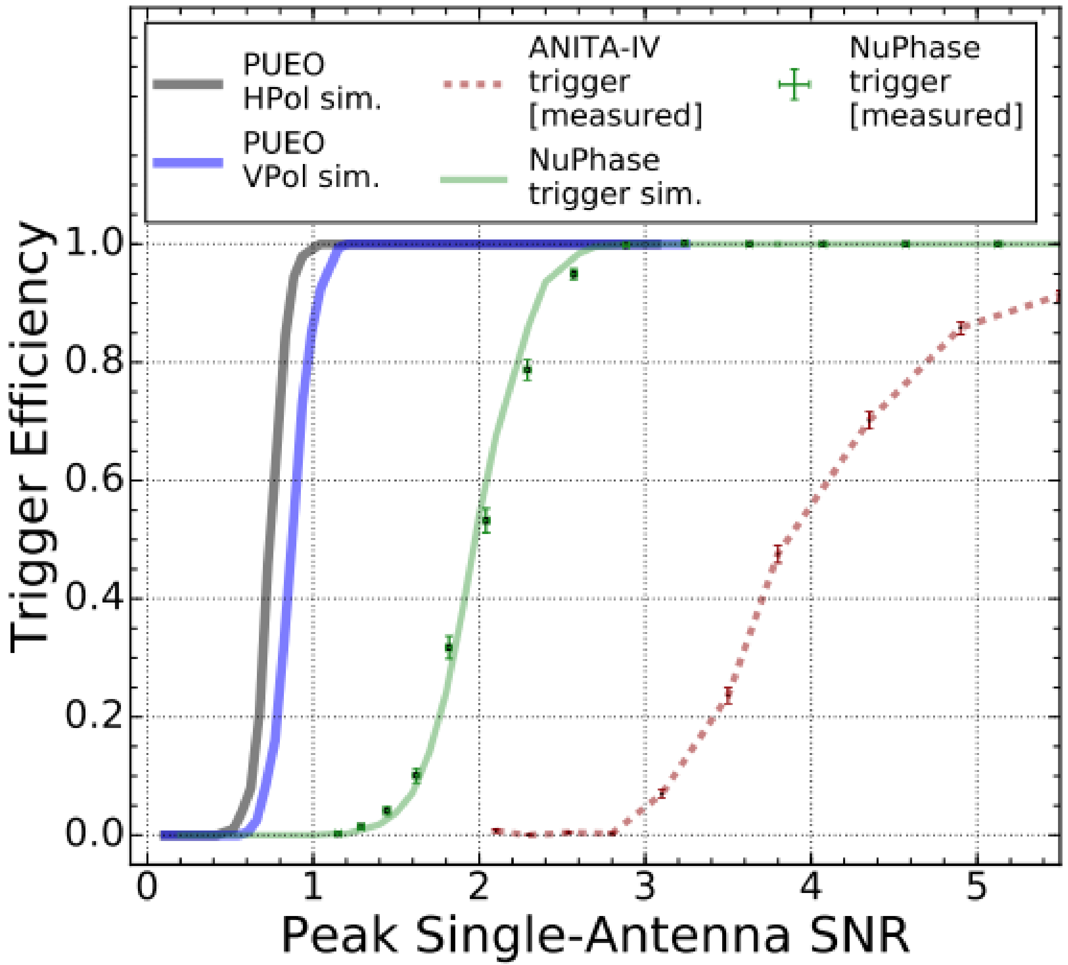


Improvements over ANITA

- 300 MHz high-pass antennas vs 200 MHz
  - Anthropogenic noise below 300 MHz
  - Smaller antennas → more collecting area
- Longer baselines between antennas
  - Improved pointing and background rejection
- Improved DAQ and trigger system
  - Phased array trigger → higher effective SNR
  - Enabled by use of RFSoCs (8 channels @ 3 GHz)
- LF instrument
  - Better sensitivity to air showers from CRs or taus
- Improved navigation/orientation suite

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

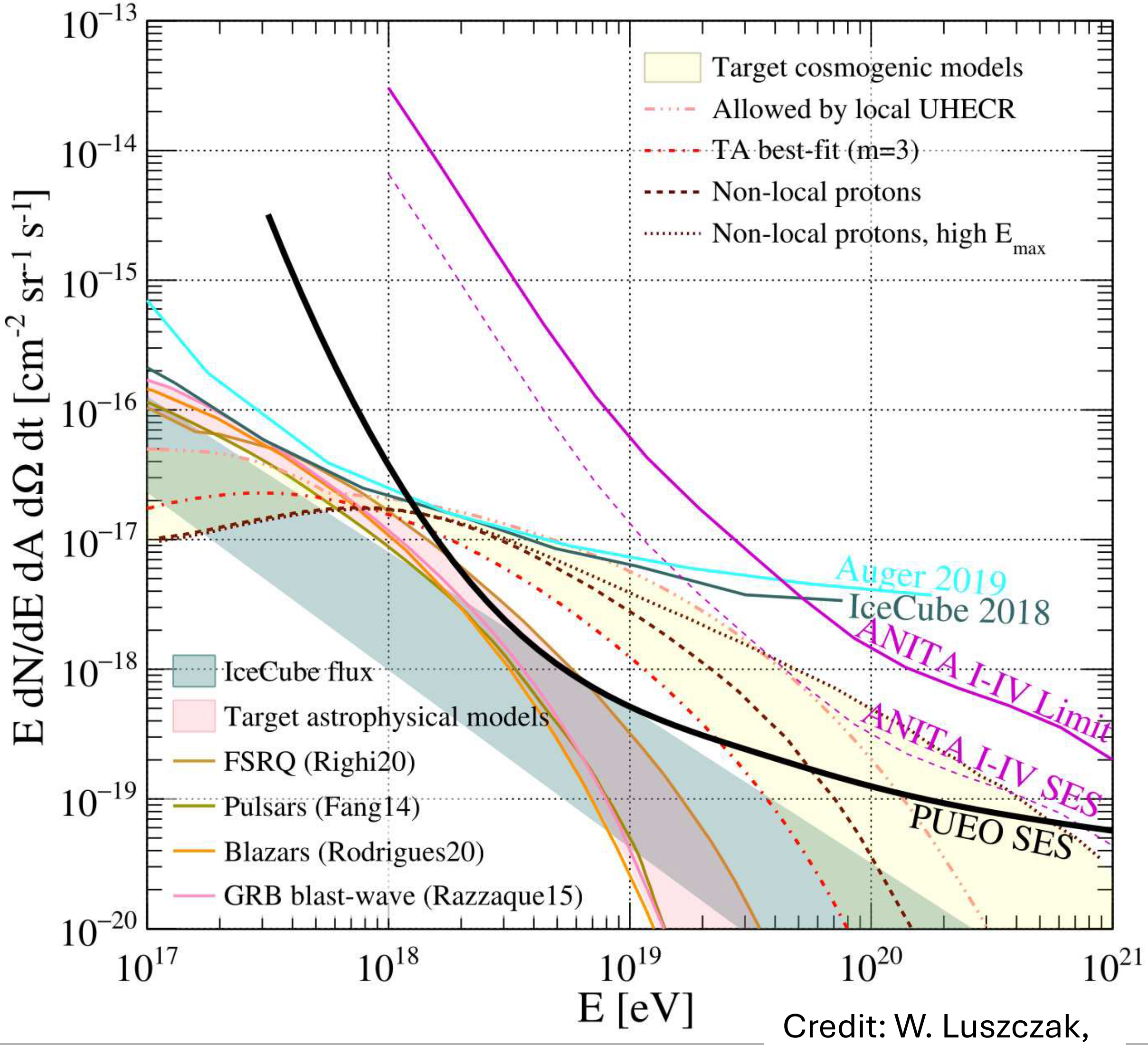


Pueo Whitepaper

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

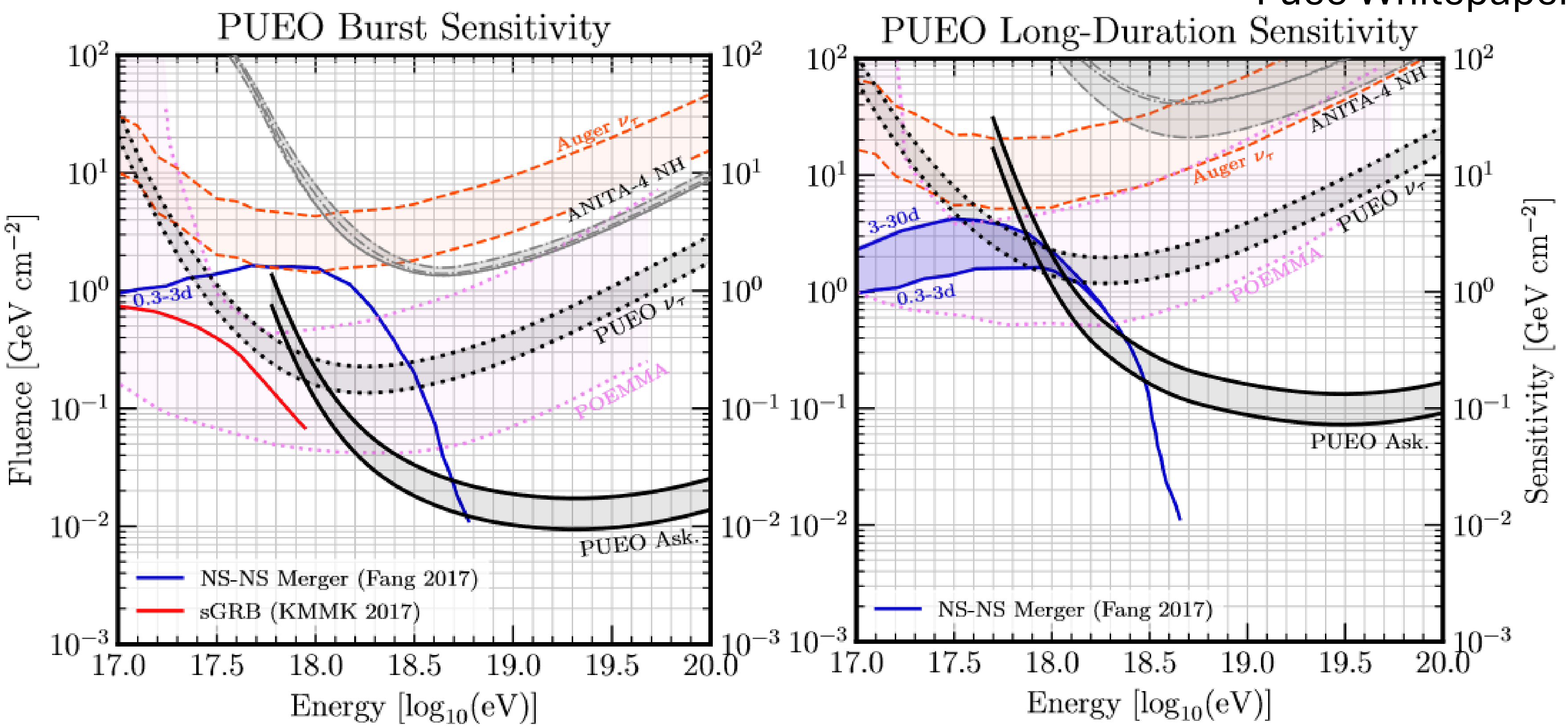


Credit: W. Luszczak, ICRC 2023

PUEO Transient Sensitivity

Pueo Whitepaper

PUEO's large instantaneous aperture makes it ideal for transient searches within its field-of view!



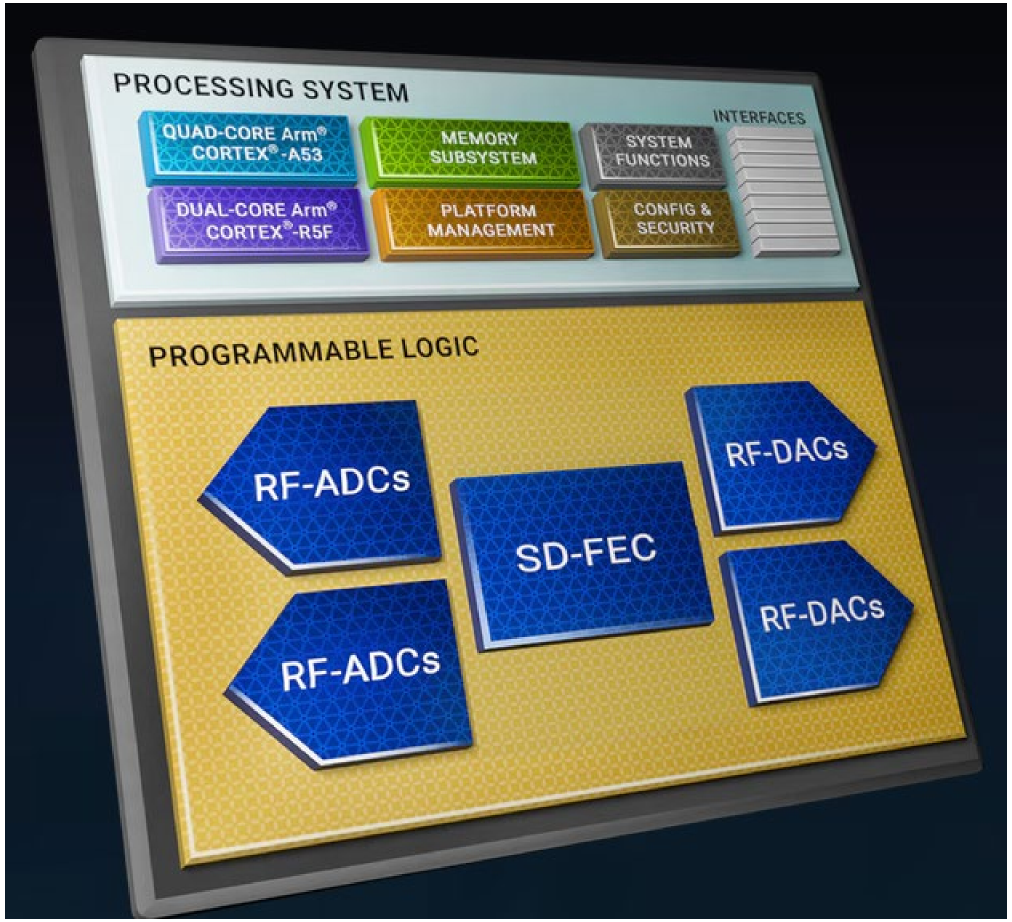
Burst sensitivity is for transients lasting a few hours.

Long duration sensitivity is for transients lasting around the same length as the flight, so effective area is averaged over the full flight.

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

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.

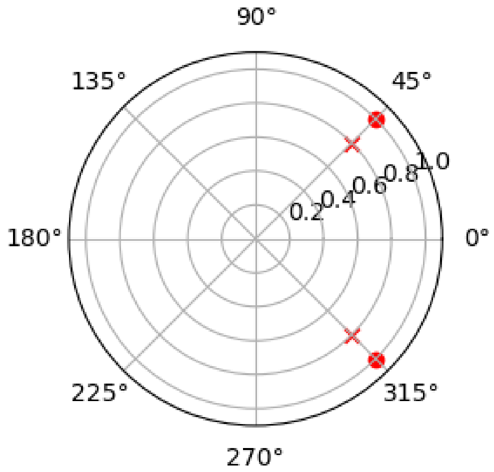


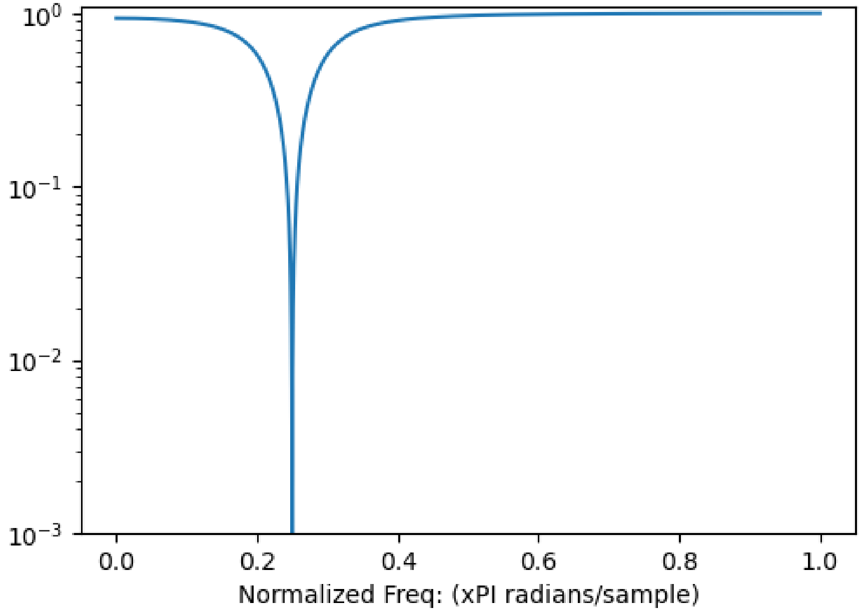
Biquad Reminder

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

Zeros

Poles





Plotting script adapted from Jim Beatty's in pueo-utilities

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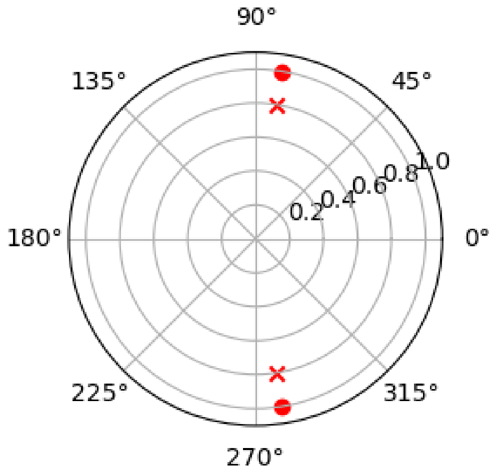

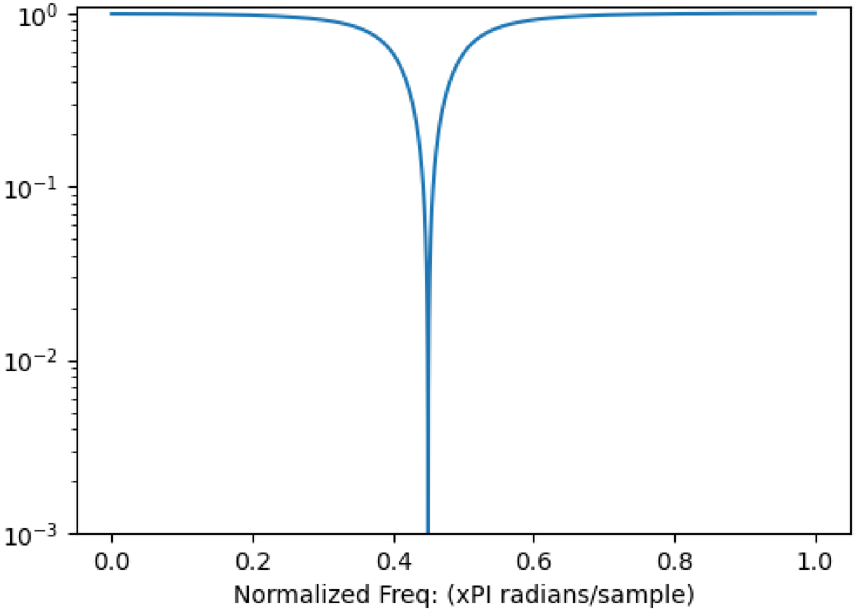

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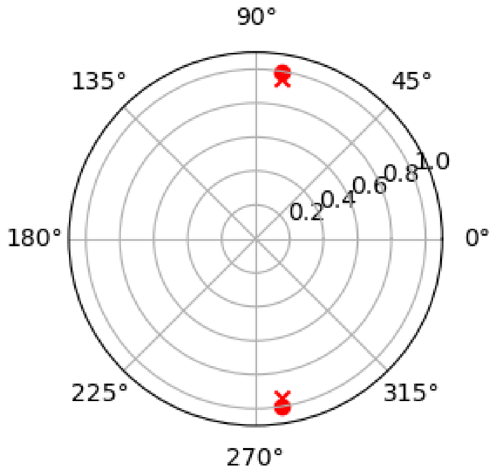

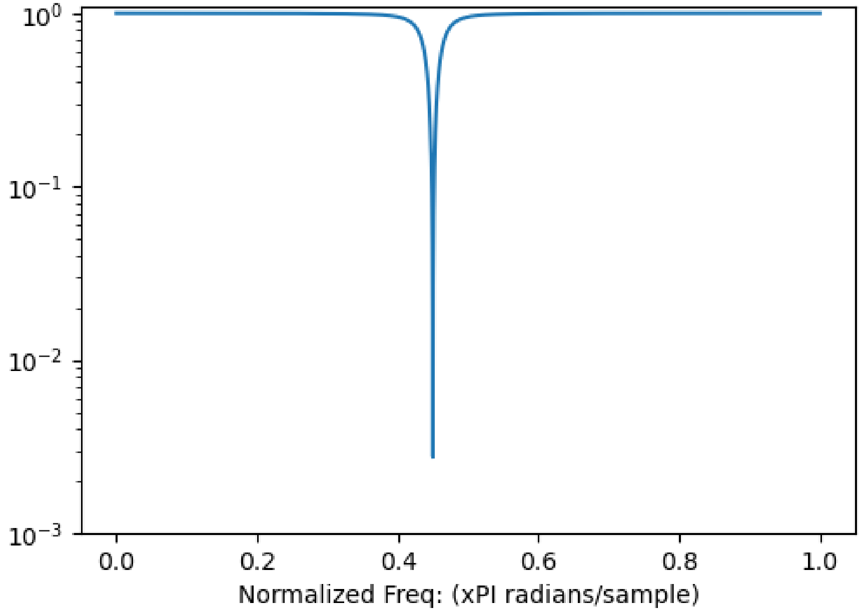

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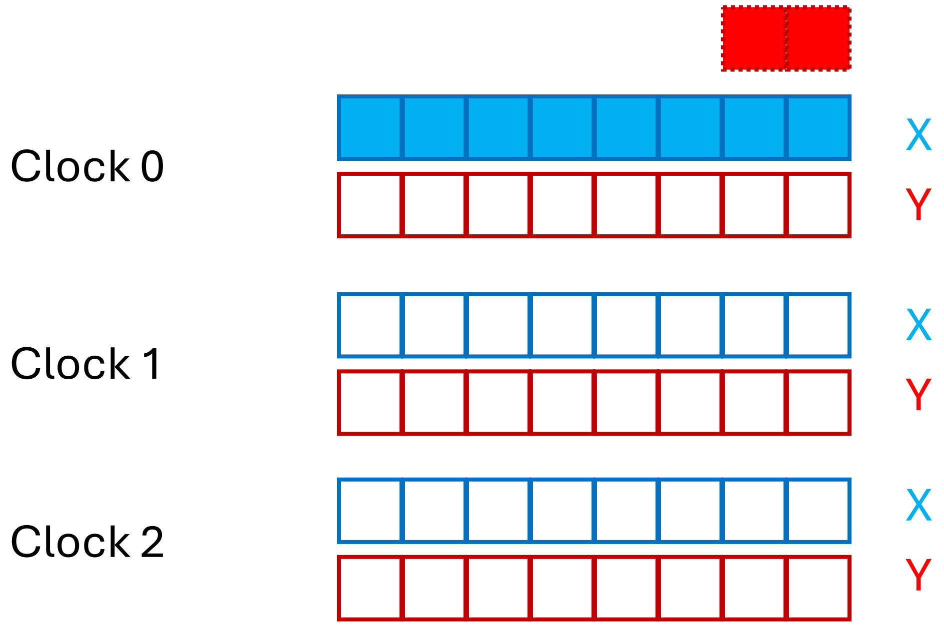
Biquad Reminder – 8 Samples Per Clock

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2] + a_1 y[n-1] + a_2 y[n-2]$$



* Some latency ignored

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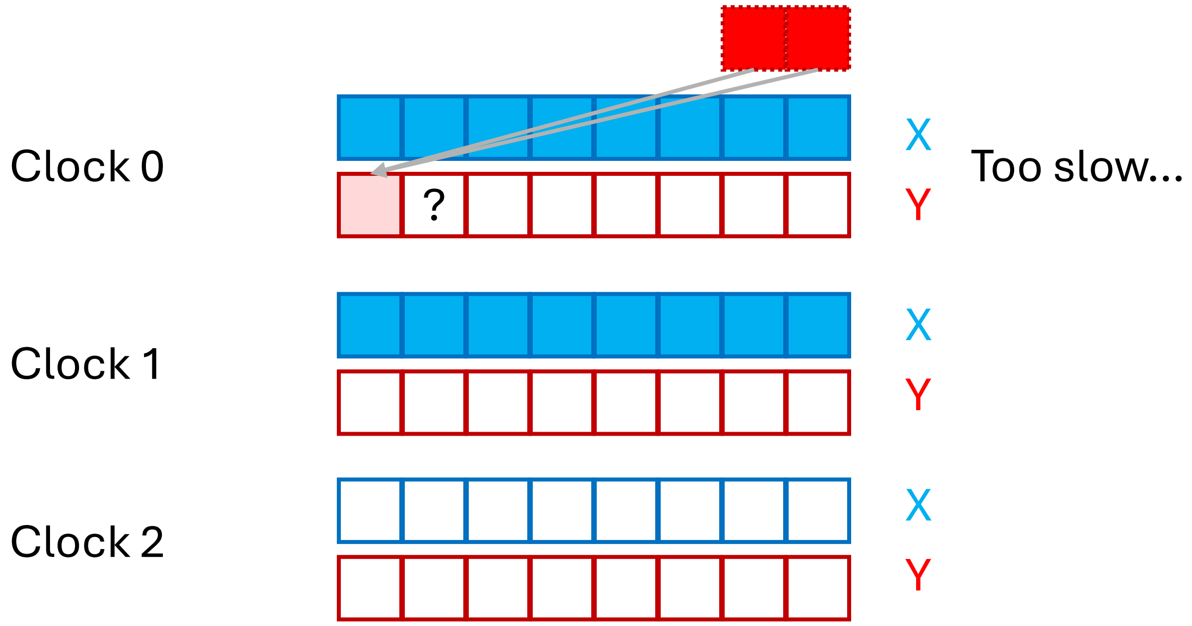

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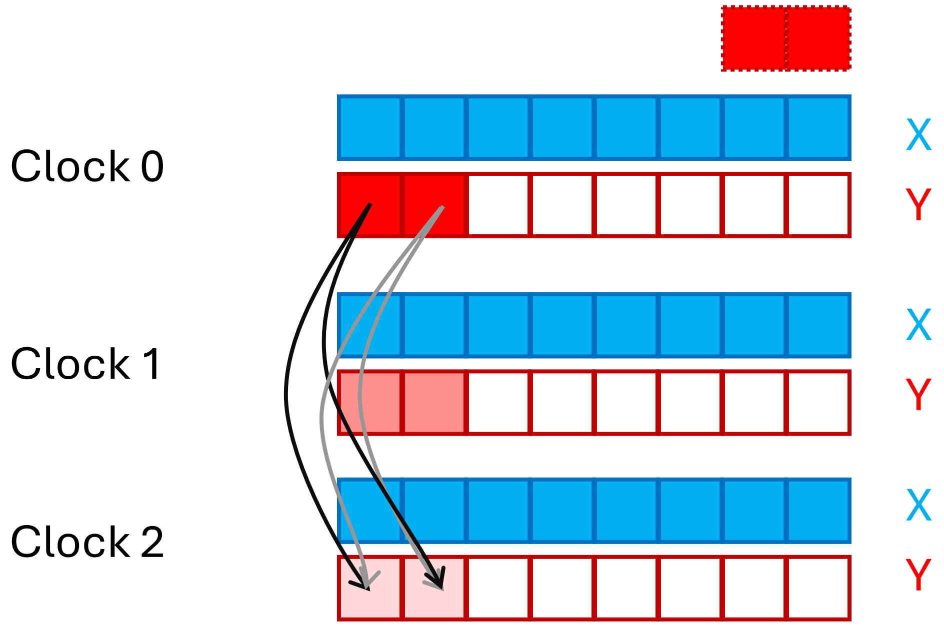
Biquad Reminder – Clustered Look Ahead

Signal Processing, DSP Notes, and Biquad Derivation
DocDB: PUEO-doc-252

$$y_0[b] = P^{M-1}U_{M-1}(\cos\theta)\, y_1[b-1] - P^{M}U_{M-2}(\cos\theta)\, y_0[b-1] + u_0[b] + \sum_{i=i}^{M-2} P^{i}U_i(\cos\theta)\, u_{M-i}[b-1]$$

$$y_1[b] = P^{M}U_{M}(\cos\theta)\, y_1[b-1] - P^{M+1}U_{M-1}(\cos\theta)\, y_0[b-1] + u_1[b] + PU_1(\cos\theta)\, u_0[b] + \sum_{i=2}^{M-1} P^{i}U_i(\cos\theta)\, u_{M-i+1}[b-1]$$



* Some latency ignored

Biquad Reminder – Incremental Computation

Signal Processing, DSP Notes, and Biquad Derivation
DocDB: PUEO-doc-252

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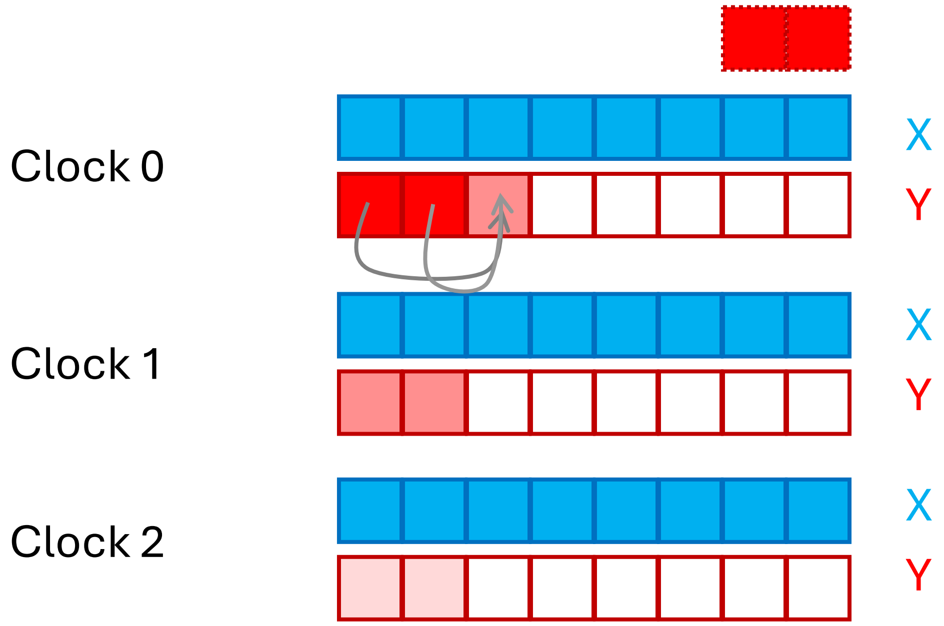
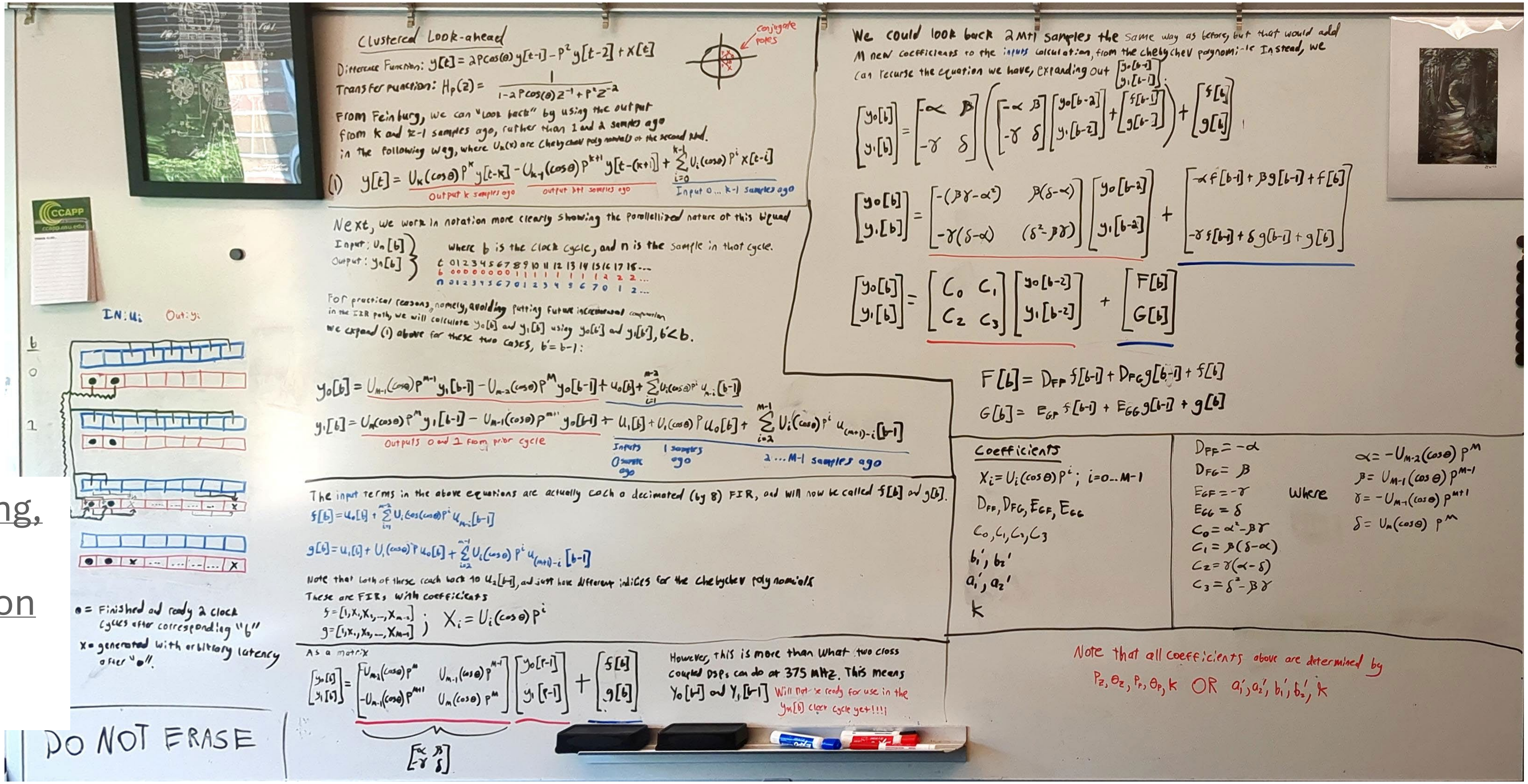


Now that you are free from dependence outside that cycle of 8, latency is no longer an issue. Just keep doing this for the remaining 6 samples.

* Some latency ignored

Easy, right?

Easy, right?

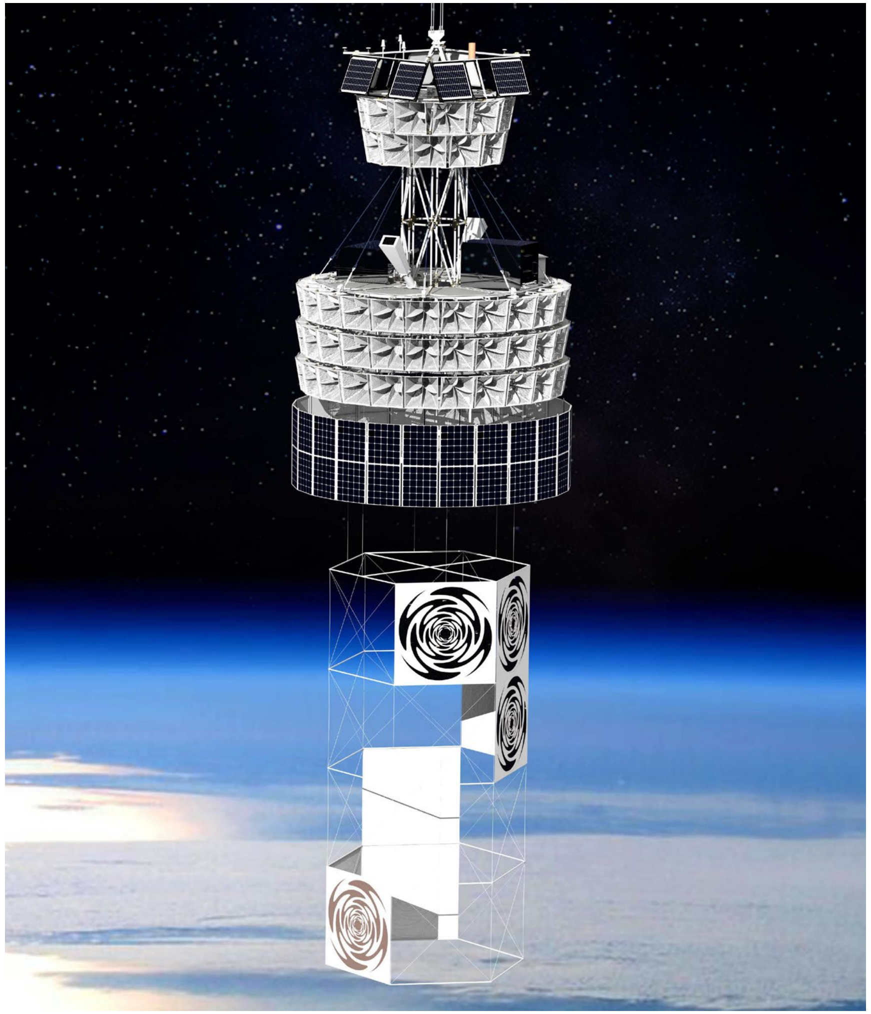


[Signal Processing, DSP Notes, and Biquad Derivation](#)
DocDB: PUEO-doc-252

Well, no.

Conclusion

- PUEO’s fabrication is currently underway!
- Expecting to integrate the instrument here in Chicago early next year
- Plan to launch in December 2025
- Significant improvements to measurement of diffuse UHE neutrino flux
- Well prepared to measure transient sources

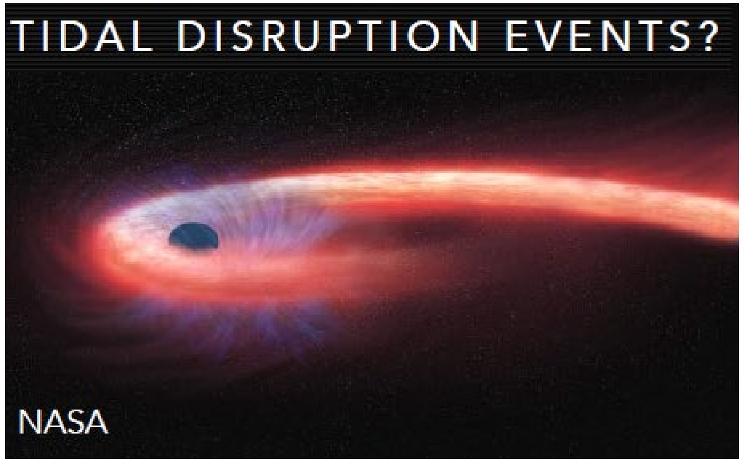


PUEO will probe the some of the highest energy phenomenon in the universe!

Questions?

Backup

Possible UHE Neutrino Sources



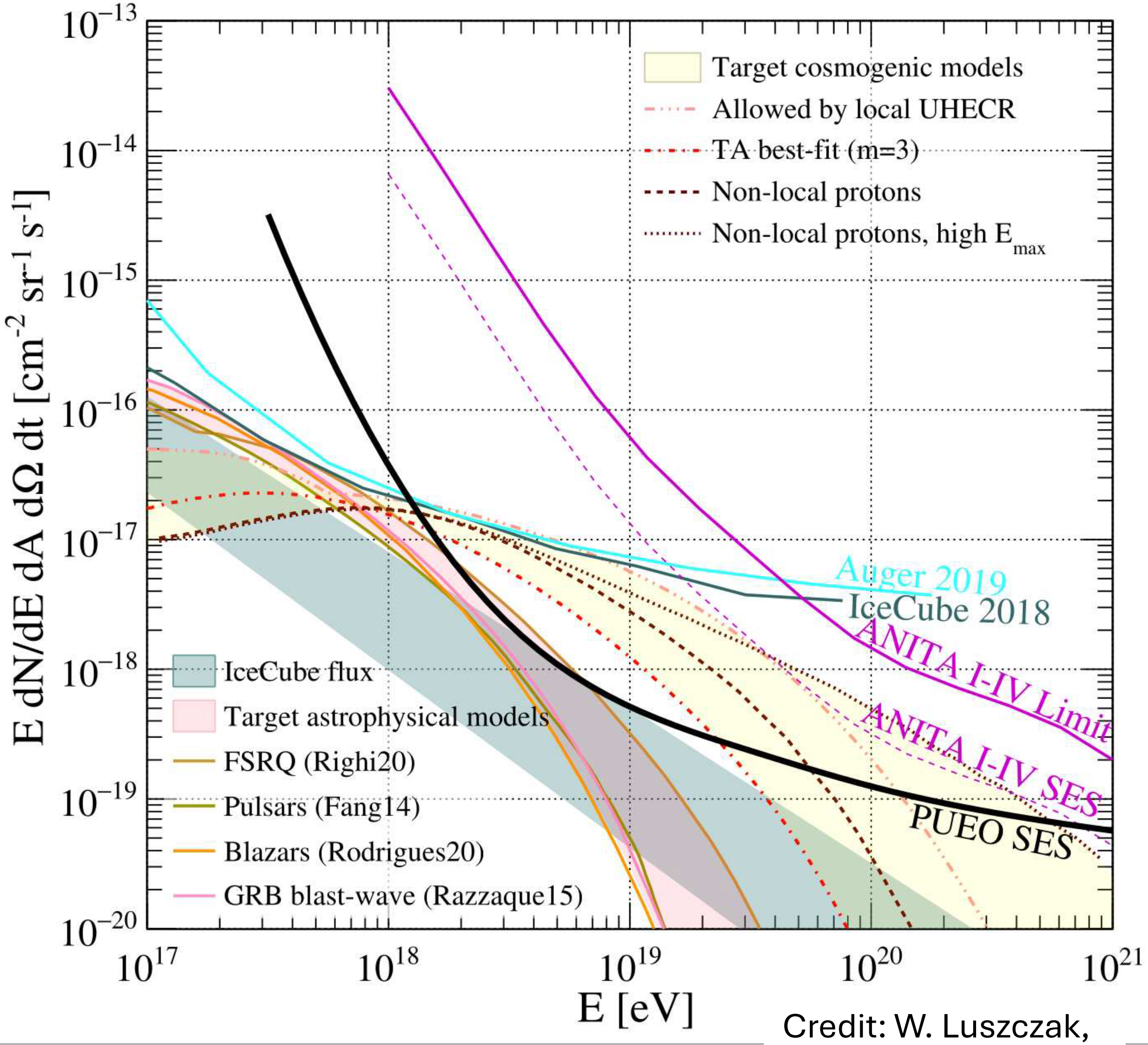
Adapted from K. Hughes

Low Frequency Instrument

- Sensitive to the lower frequency (50-500 MHz) components present in air showers
  - Overlaps frequency range with main instrument, providing independent measurement
- Enhanced measurement of tau-neutrino induced EASs
- Measurements of cosmic ray induced EASs
  - Understanding neutrino signal background
  - Opportunity to better characterize events like the ANITA "mystery events"

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: W. Luszczak, ICRC 2023

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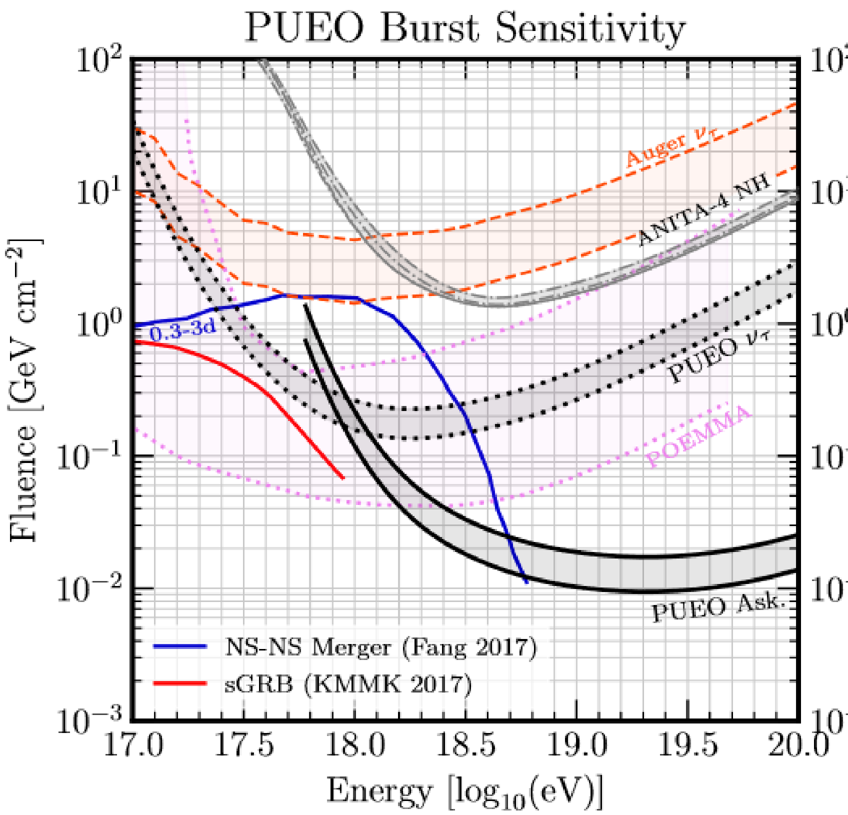

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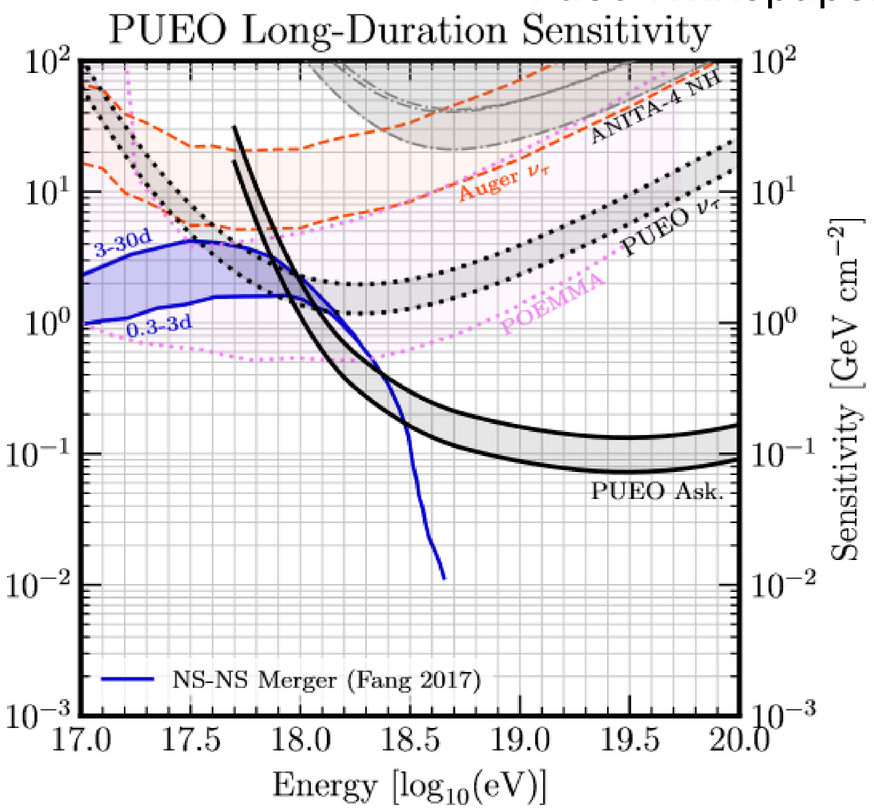
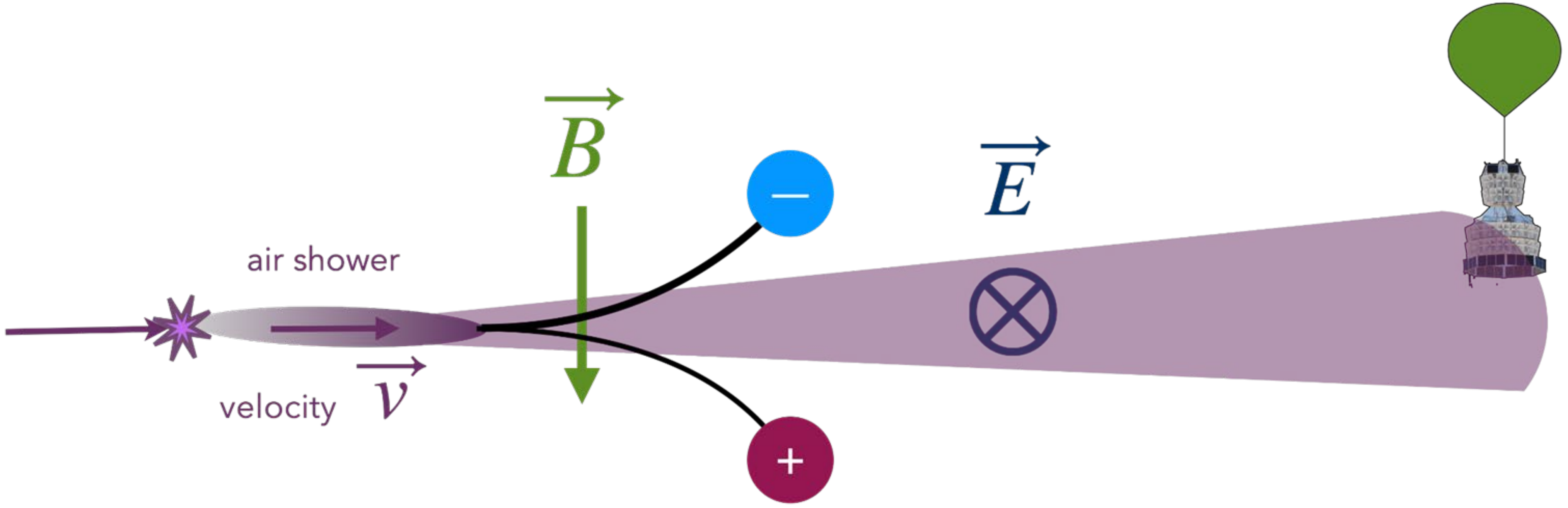


Long duration sensitivity is for transients lasting around the same length as the flight, so effective area is averaged over the full flight.

PUEO Approximate Timeline

Fabricating individual systems	Happenin g now
Instrument Integration In Chicago	January 2025
Thermal Vacuum Test at CSBF	April 2025
Instrument Hang Test at CSBF	July 2025
Antarctic Flight	Winter 2025

Geomagnetic Radiation



Credit: Stephanie Wissel