Using PUEO to Search for UHE Neutrinos

Or: how to find something thats never been seen before

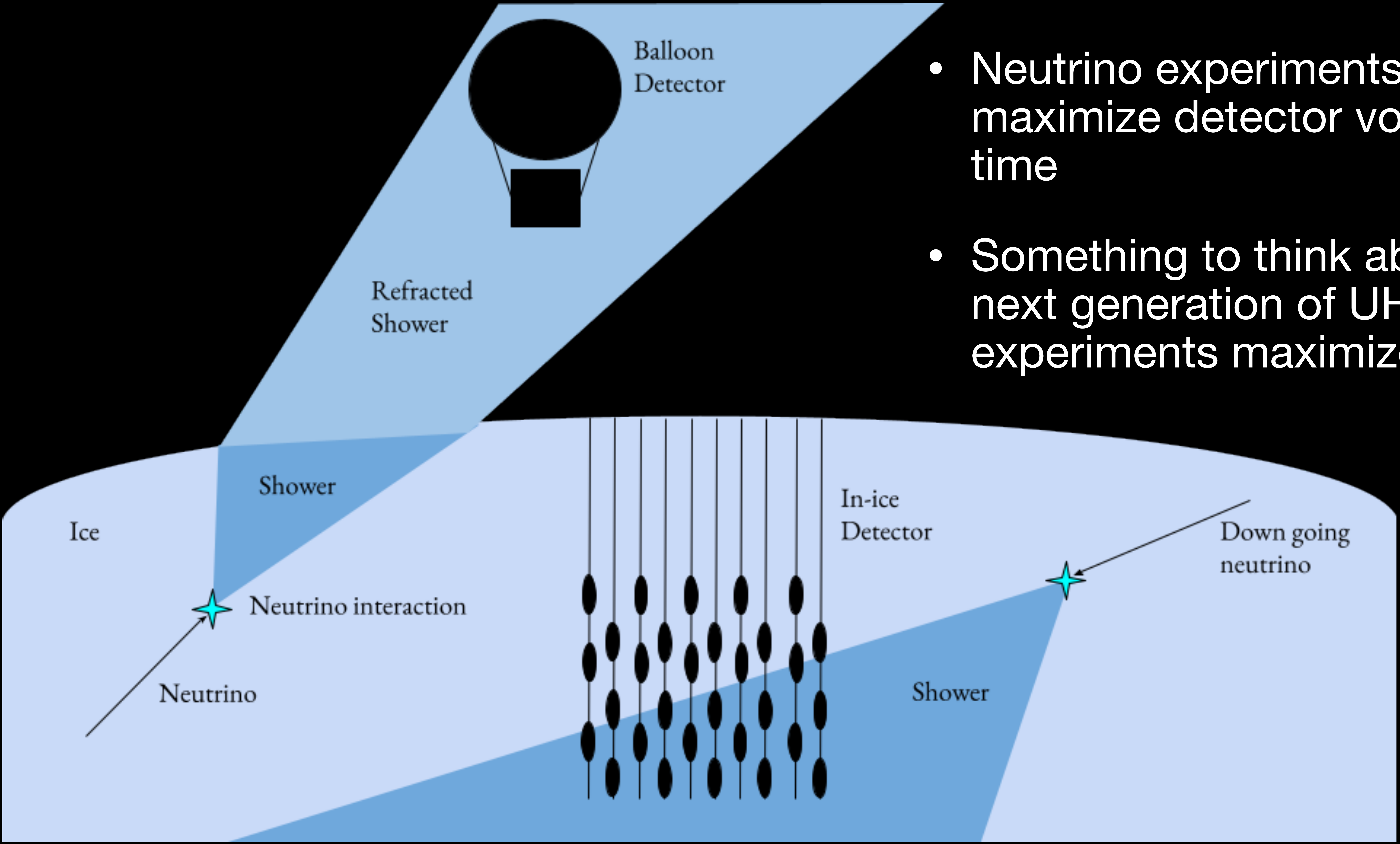
or maybe seen once by KM3Net

Rachel Scrandis, MACROS Workshop 2026

Lessons On How to Design Experiments

- During this talk, will use PUEO as an example of how to tailor your experiment for the science you're looking for
- The next generation of experiments will continue to be the most sensitive thing to ever be built, and thats because we tailor our hardware and analyses as we learn more about our targets
- For all of us (early career scientists), its important we know the strengths and weaknesses of everything we work on, and bring that into our next experiments
- Obviously I'm not an expert. Most of this insight comes from attending to NASA's Astrophysics Mission Design School. If you're interested in designing the world's next generation astrophysics experiments, I'd recommend this program!

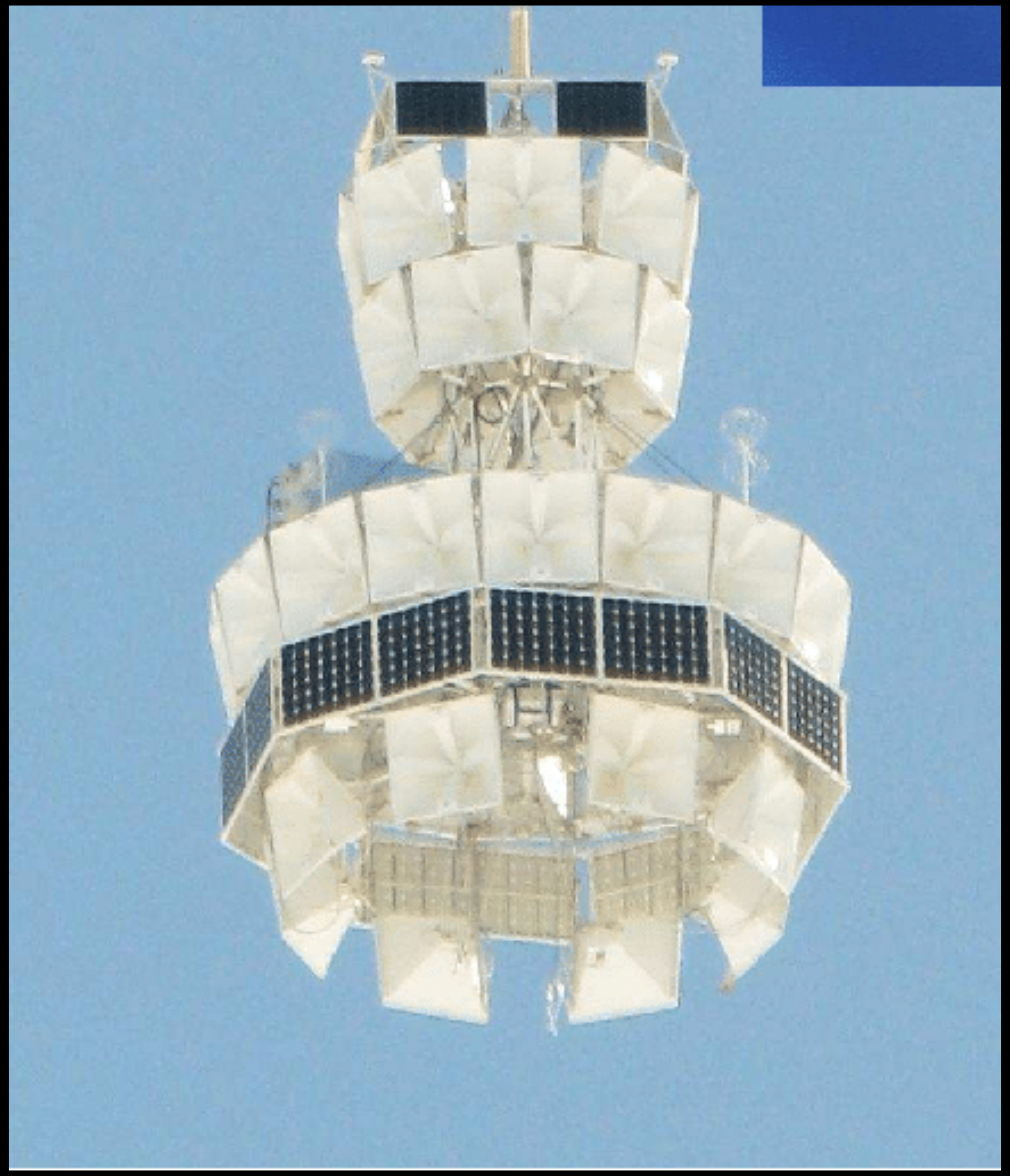
Why Use Balloons?



- Neutrino experiments either need to maximize detector volume or integration time
- Something to think about: how can the next generation of UHE neutrino experiments maximize both?

PUEO’s History

ANITA - I
Flew Austral Summer 06/07
for 35 days
32 antennas



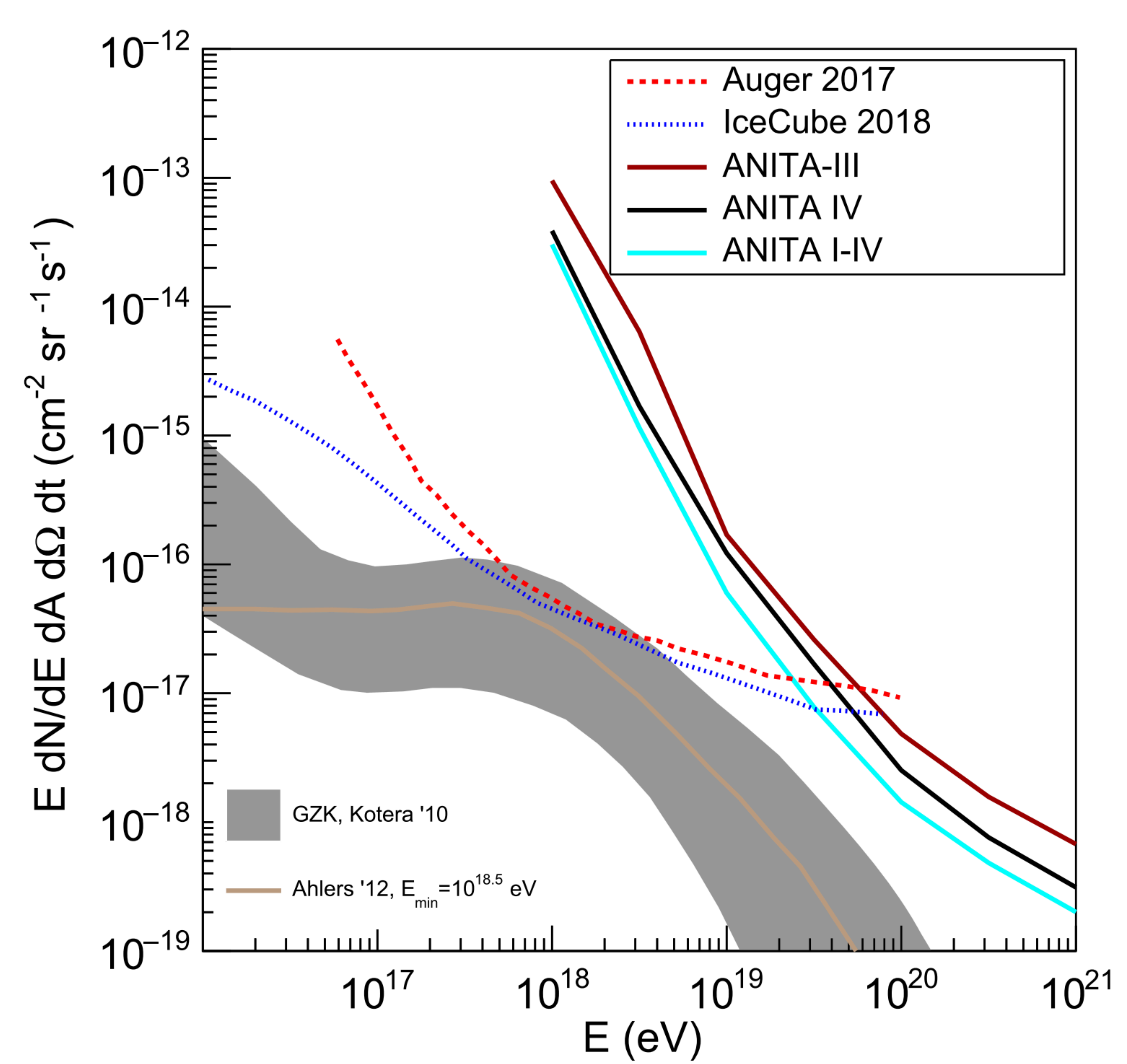
ANITA - II
Flew Austral Summer 08/09
for 31 days
40 antennas

ANITA - III
Flew Austral Summer 14/15
for 22 days
48 antennas

ANITA - IV
Flew Austral Summer 16/17
for 28 days
48 antennas

ANITA's Limits on UHE Neutrinos

Given the lack of statistically significant results, ANITA was able to set world leading constraints on the expected UHE neutrino flux



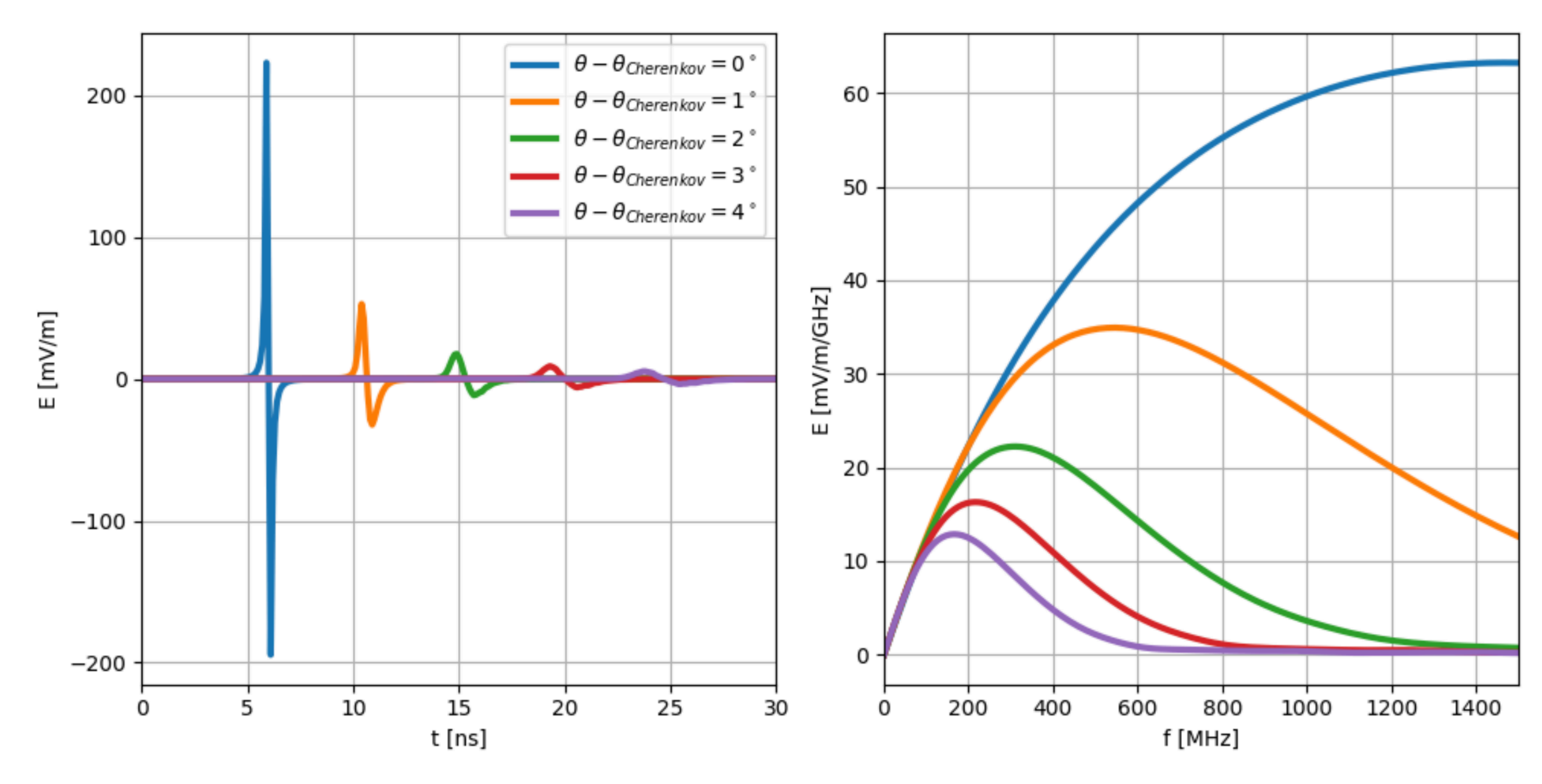
P. W. GORHAM et al. PHYS. REV. D 99, 122001 (2019)

How do we build the next generation balloon-based neutrino telescope?

Back to the Basics

Askaryan emission's frequency content depends on viewing angle

Peaks at lower frequencies the further off cone you get

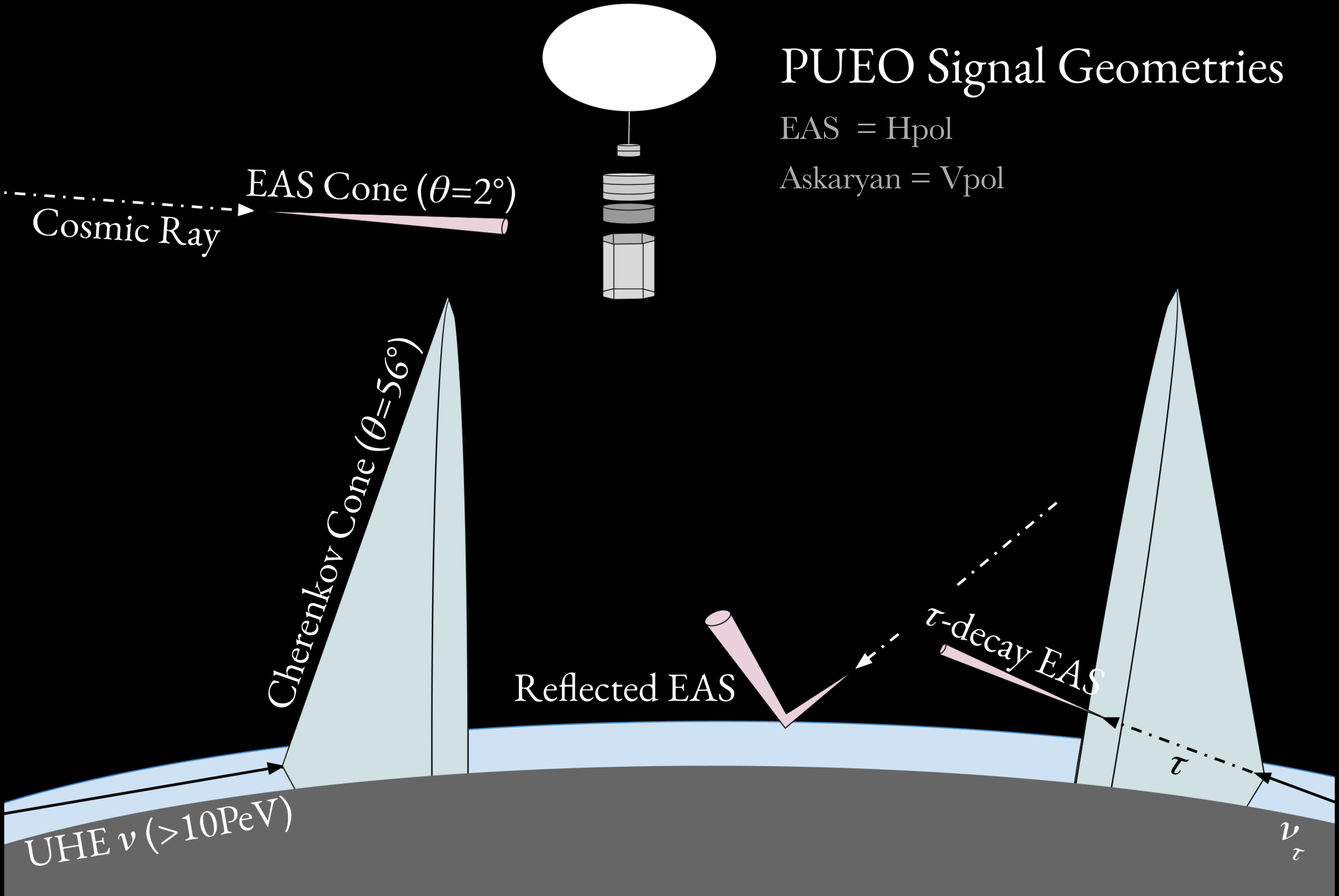


Credit: RNO-G Collaboration

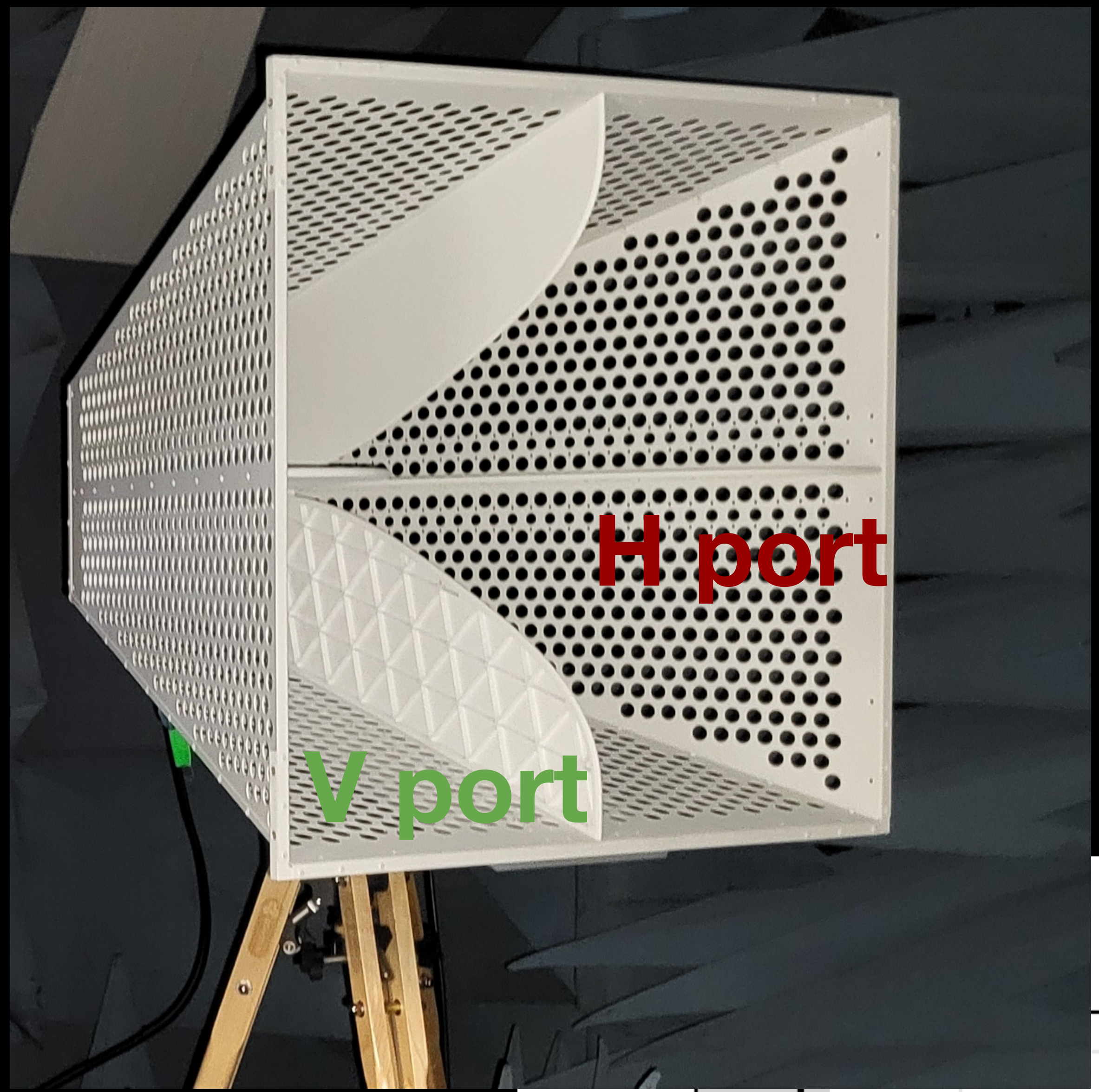
PUEO Signal Geometries

EAS = Hpol

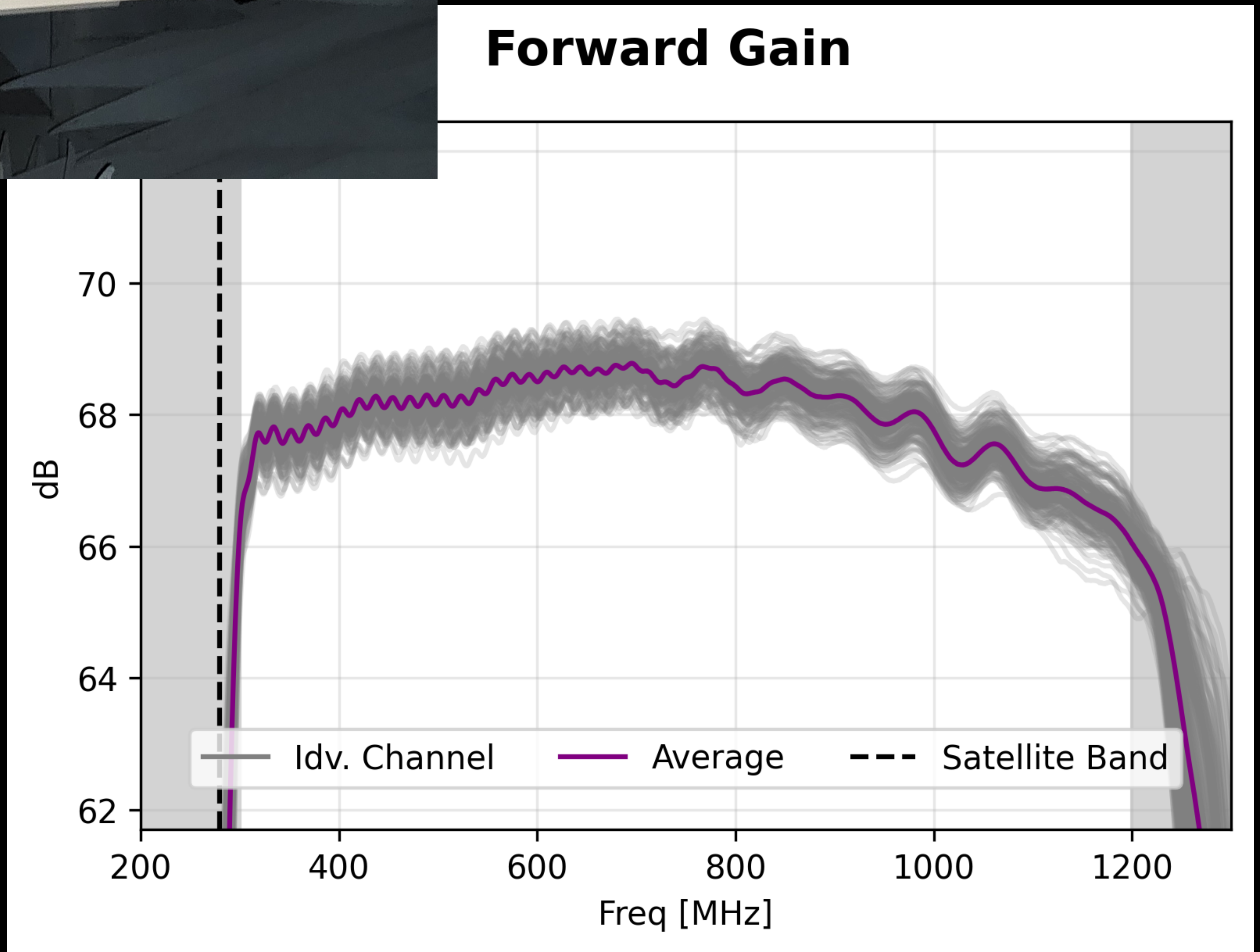
Askaryan = Vpol

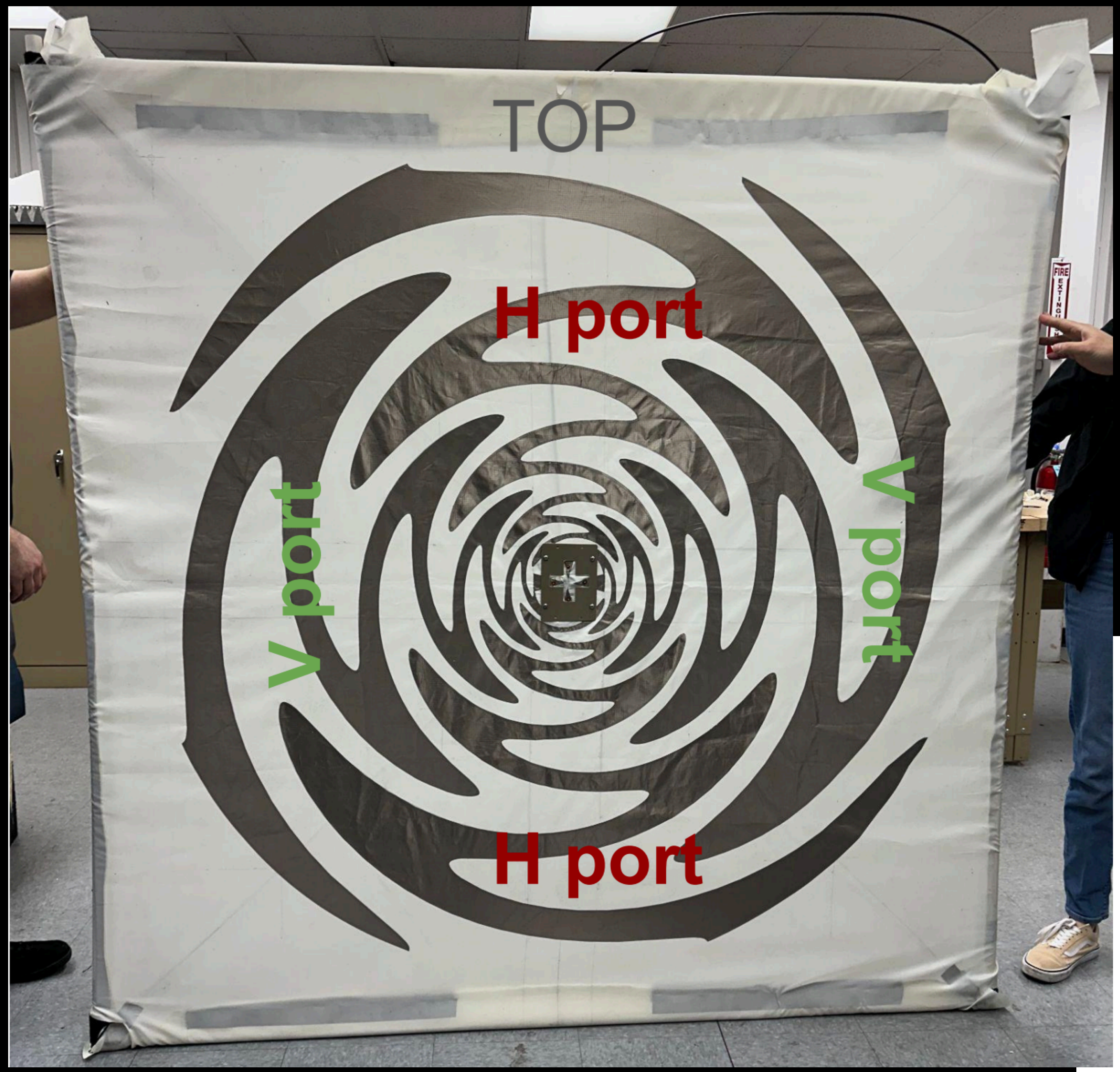


Designing PUEO Around Science Goals

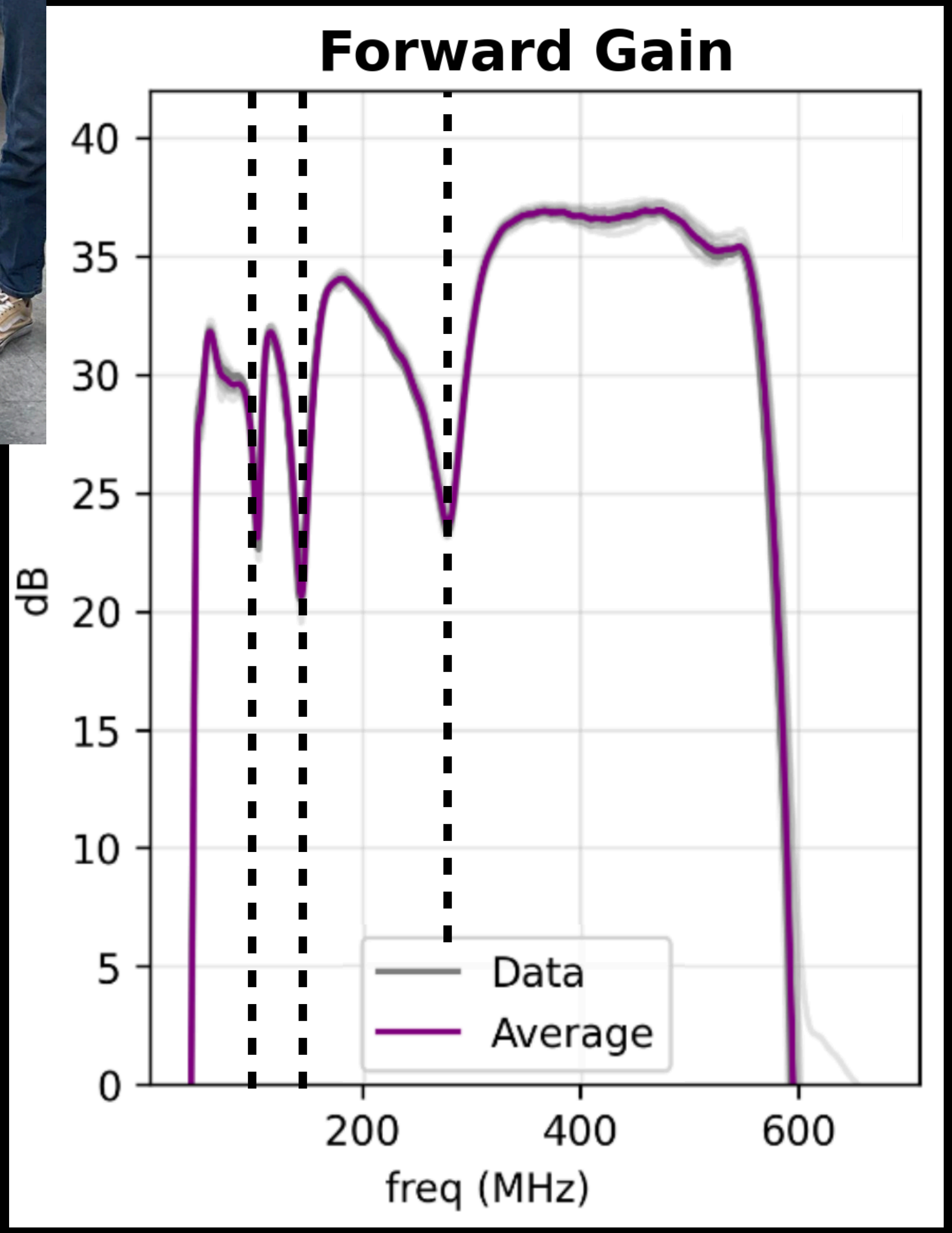


Compact quad-ridge horn antennas
Bandpass free from satellite contamination

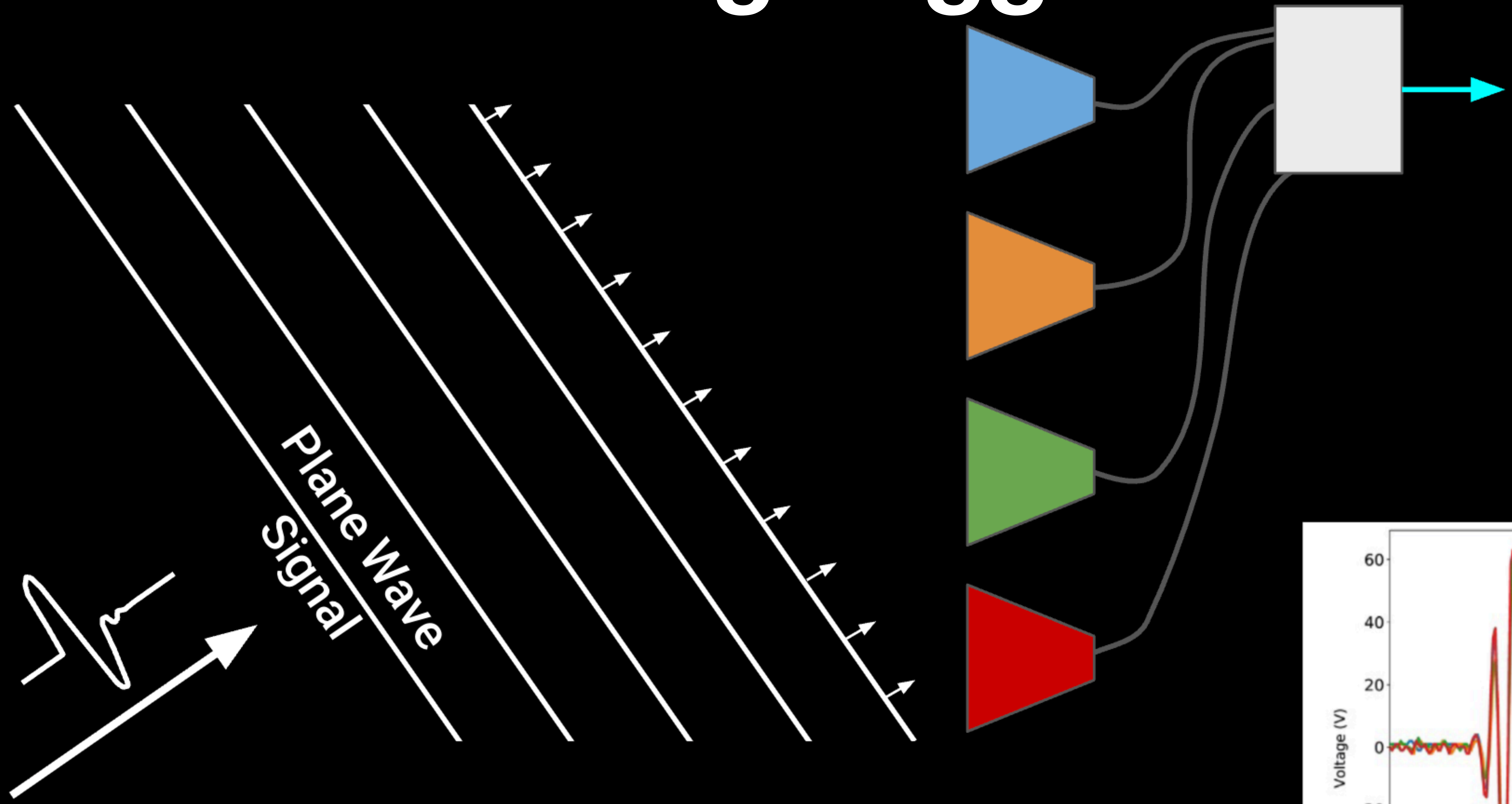


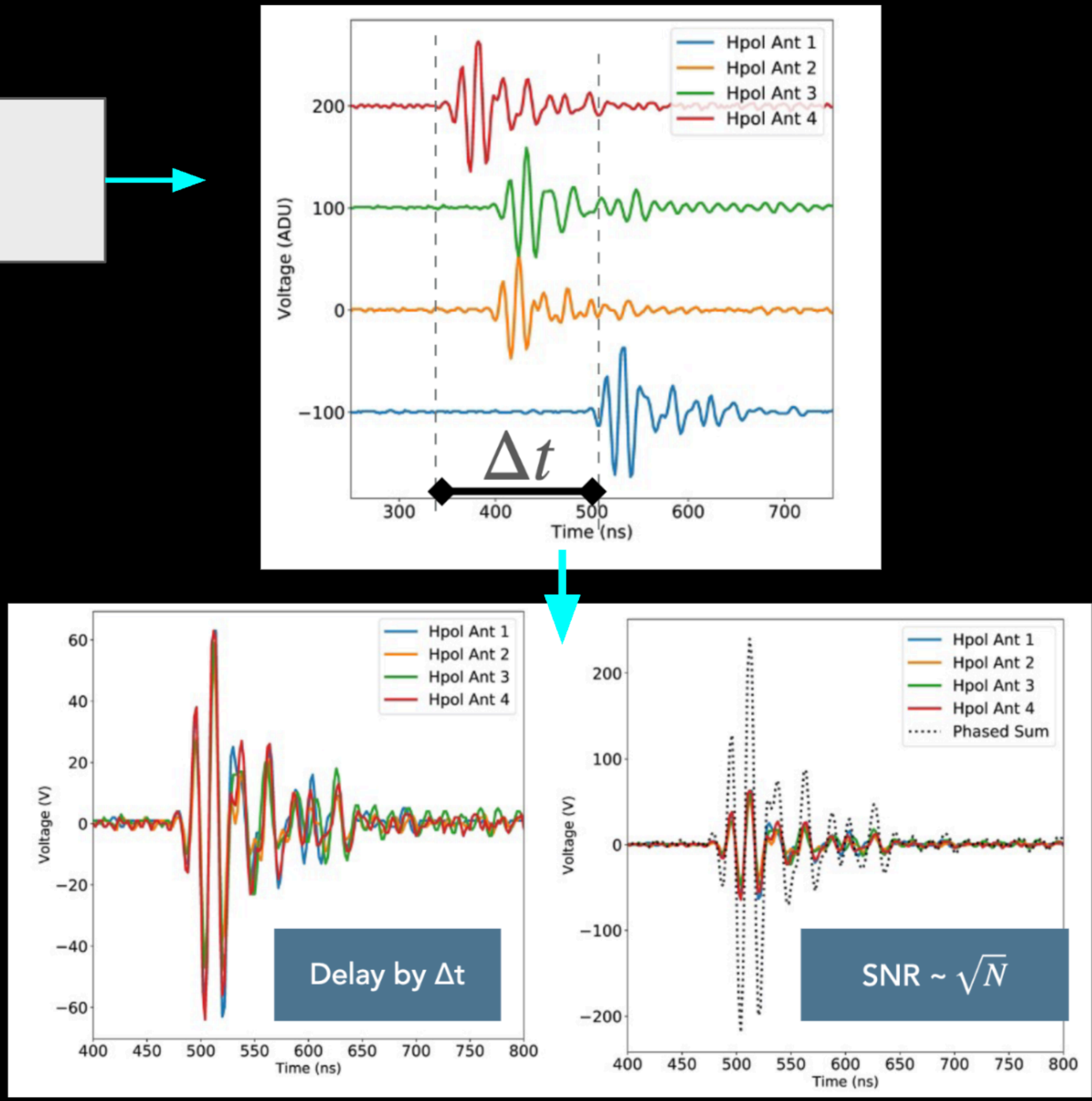


Fabric sinuous antennas
Bandpass more sensitive to where science signals peaks



Beamforming Trigger

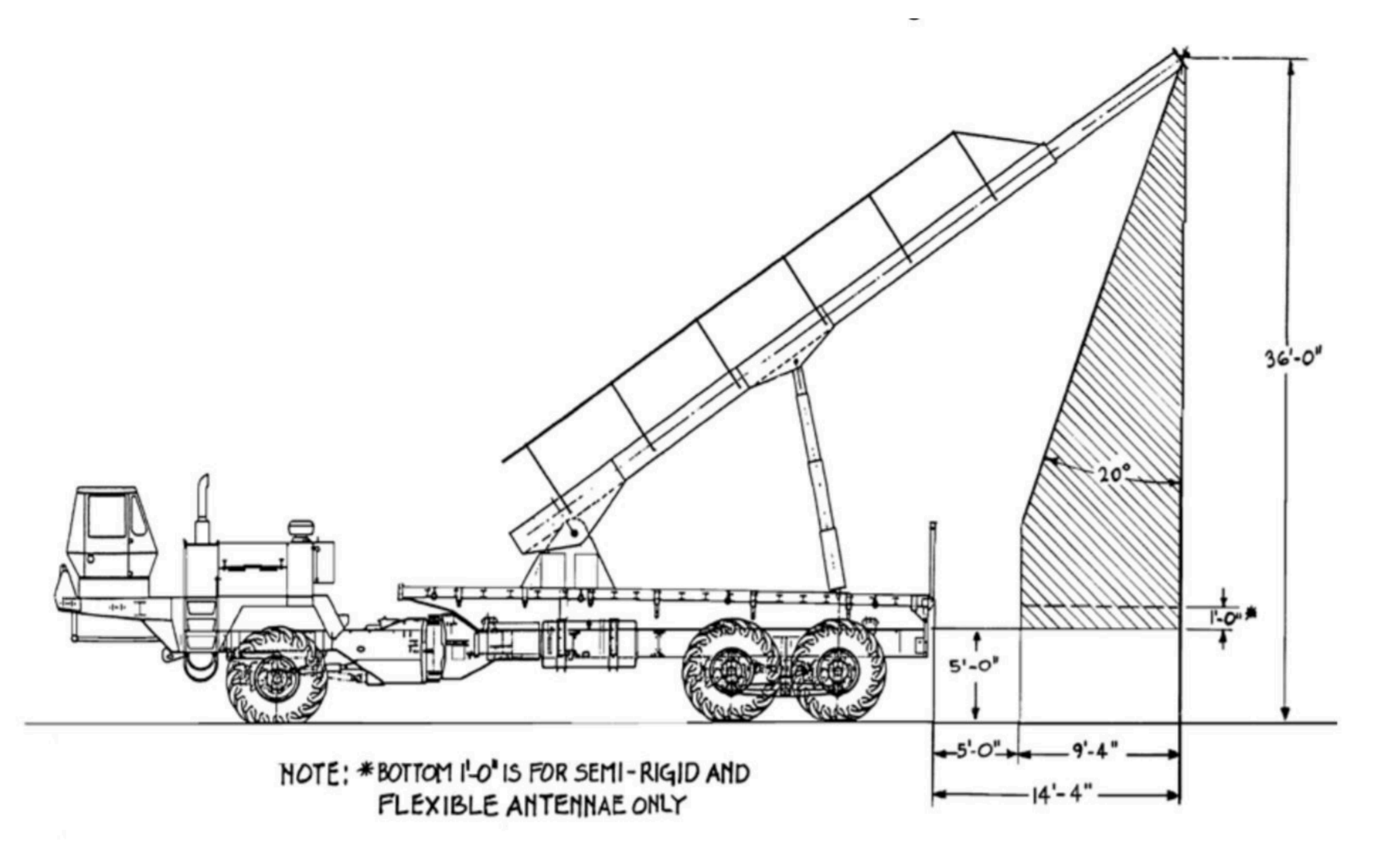




Credit: Zack Martin & BEACON Collaboration

- We expect neutrinos to come from all directions, so we need antennas situated to be sensitive to all directions

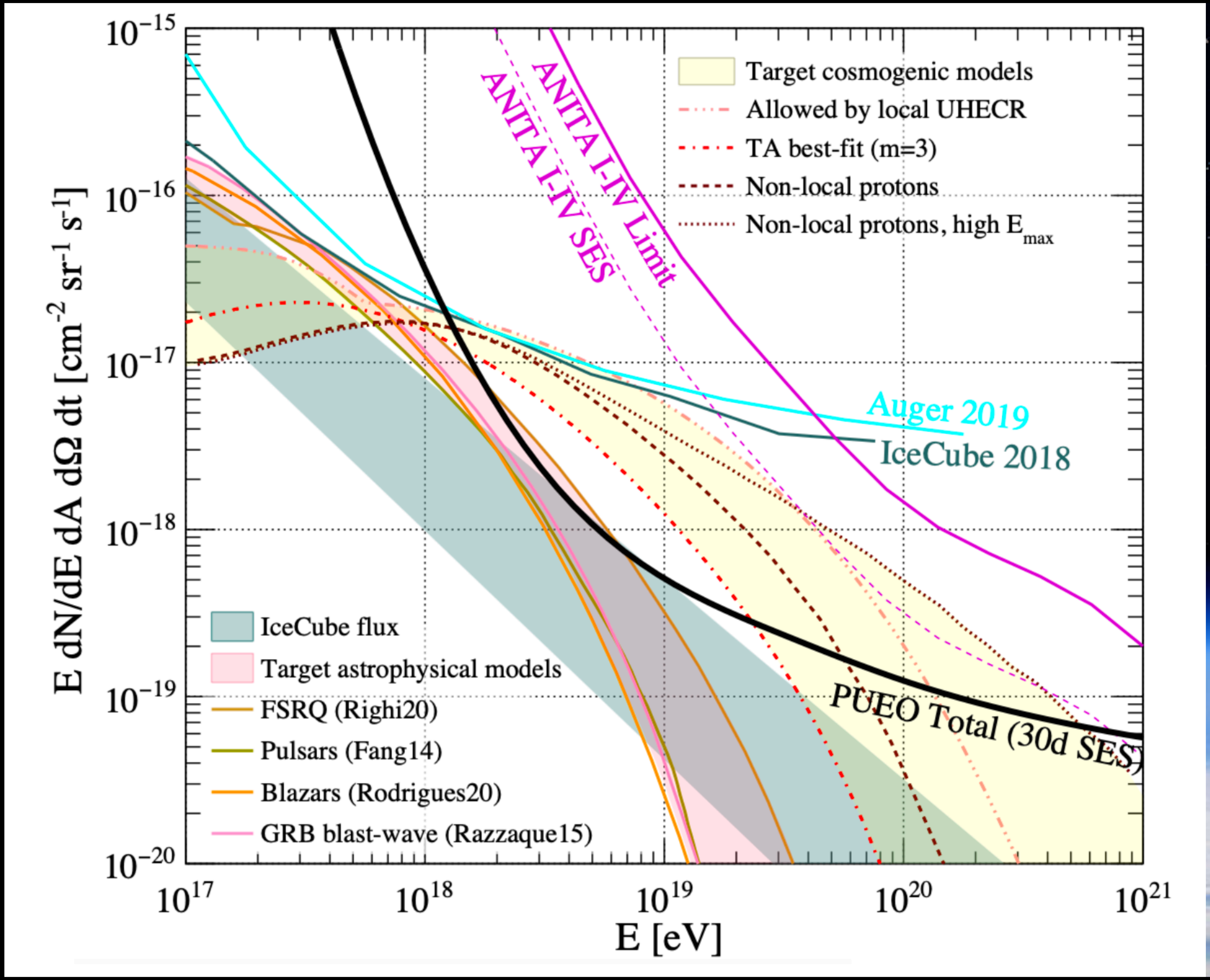
Designing PUEO Around Science Goals

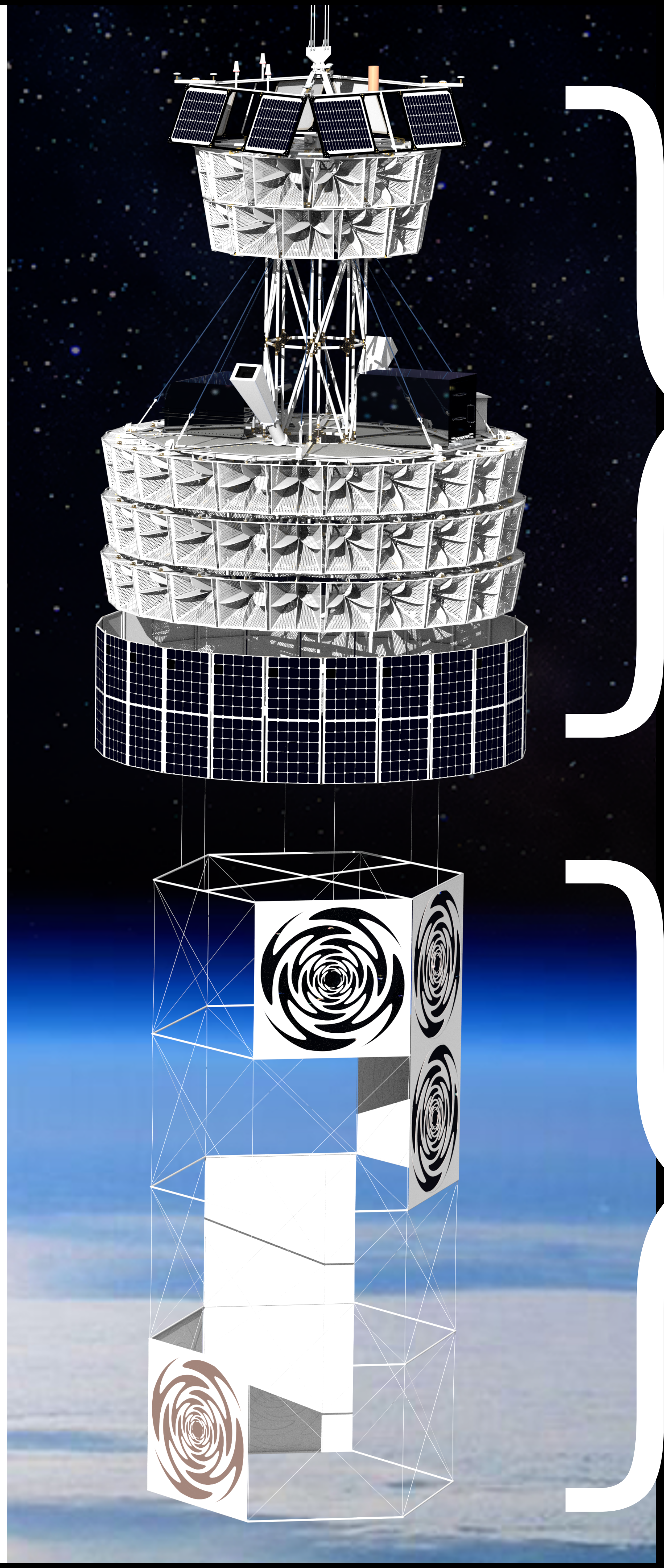


Structure is limited by what can be launched!

To fully leverage the beam forming trigger, we want to fully utilize the available launch volume + deploy additional antennas after launch

PUEO: Payload for Ultrahigh Energy Observations





"Main Instrument"

- 96 quad ridge horn antennas
- 192 receiving channels
- 300 - 1200MHz

"Low Frequency Instrument"

- 8 sinuous antennas
- 16 receiving channels
- 50 - 600 MHz
- Developed here at PSU!

Lessons On How to Design Experiments

- PUEO experiment is a very mature experimental design with over 2 decades of experience behind it
- Every iteration learned new lessons that were carried forward
- The payload design was motivated by the science. When you are designing an experiment, study the science and the signal you want to measure. Learn how to exploit as many aspects of it as possible!

What Might PUEO See?

Hillas Criterion (energy a particle needs to escape a source's magnetic field):

$$E \leq E_H = qBR$$

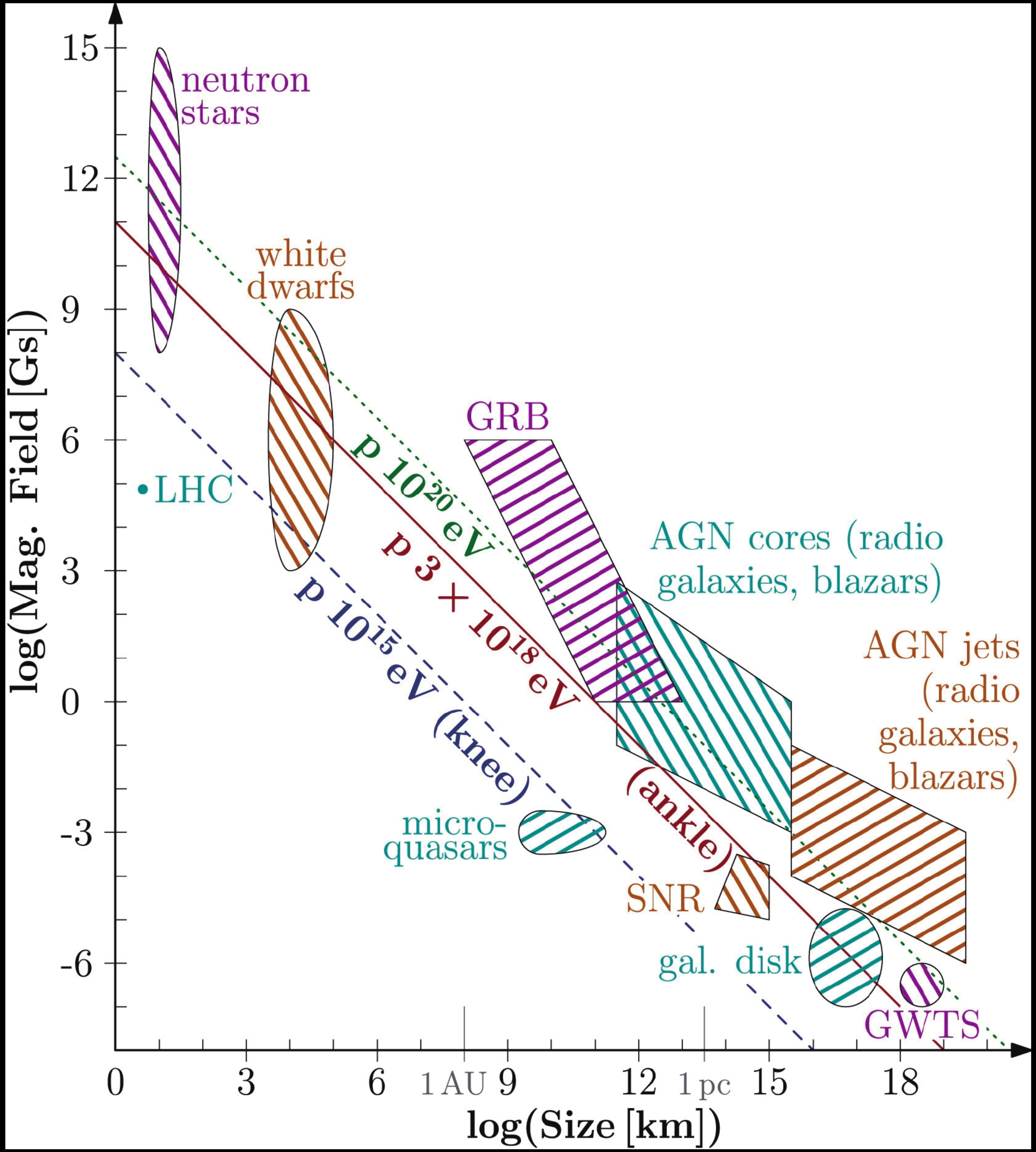
q: charge of CR

B: magnetic field of source

R: radius of source

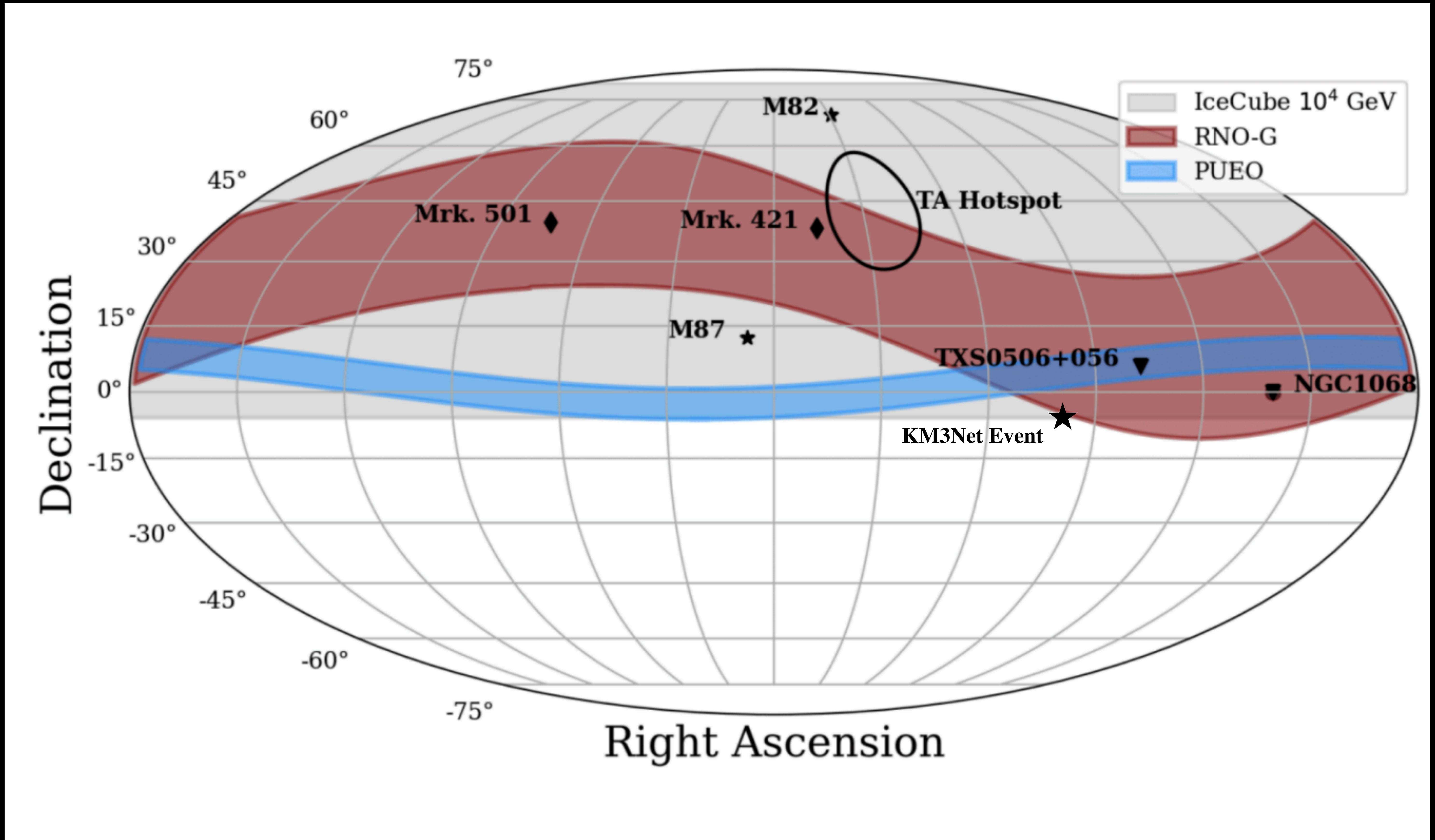
Neutrinos inherit ~0.05E_p, so UHE neutrinos probe interesting, obscure sources

A.M. Hillas, *The Origin of Ultra-High-Energy Cosmic Rays*



J.B. Tjas & L. Mertin, *Closing in on the origin of Galactic cosmic rays using multimessenger information*

Specific Interesting Sources



Blue band is *instantaneous field of view*

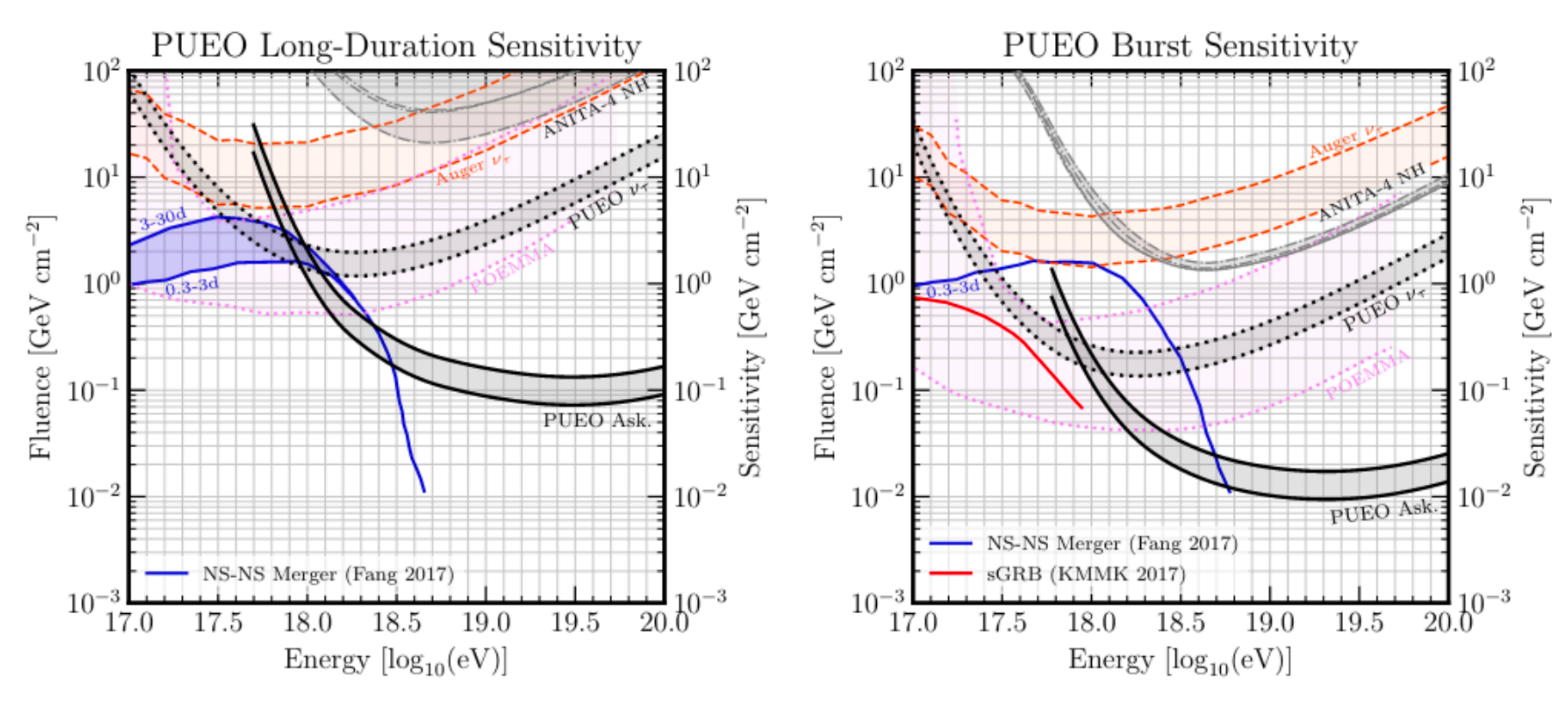
For PUEO's full flight, smear this band across all RAs

Interesting sources:

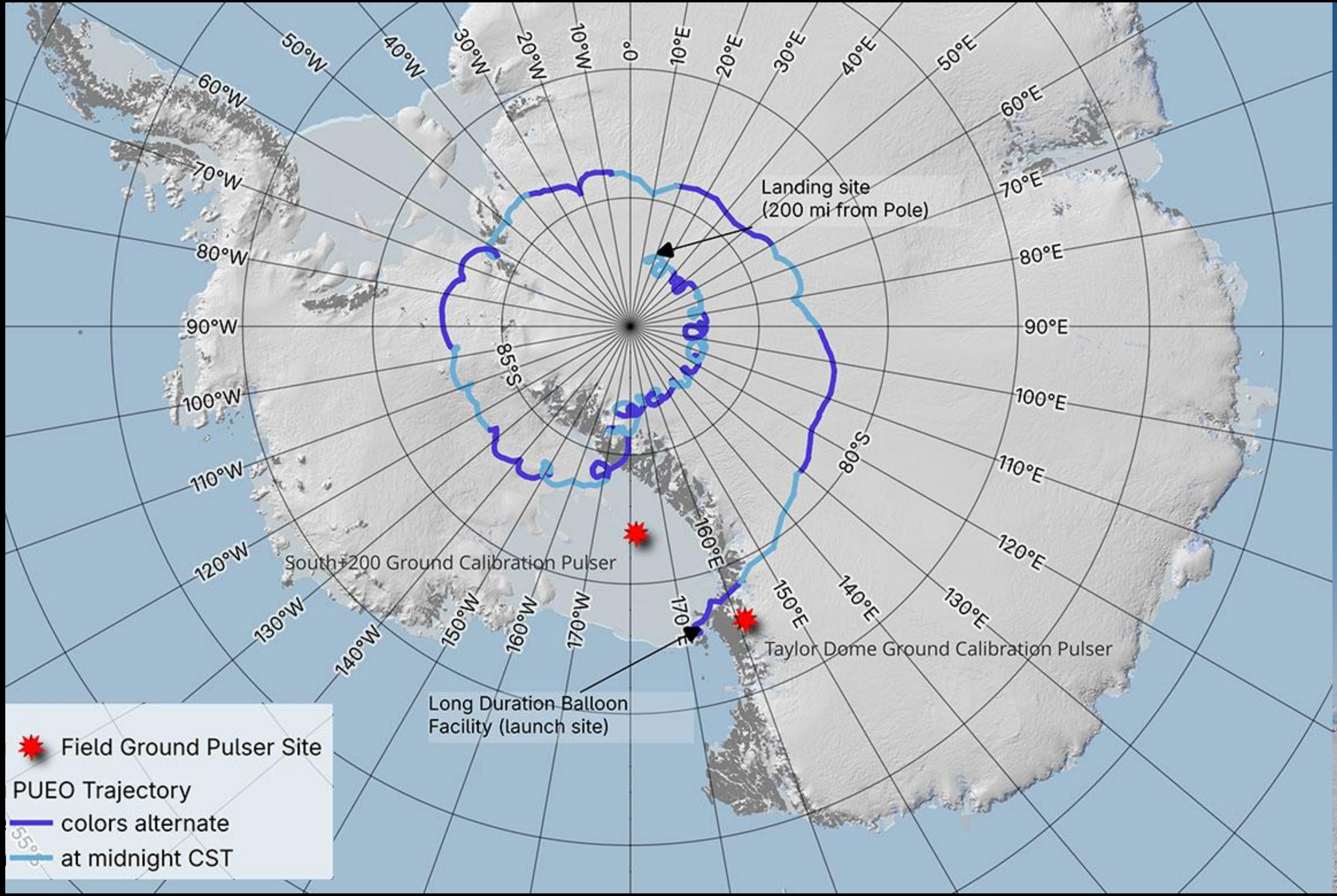
- TXS 0506+056
- NGC1068
- Perhaps M87

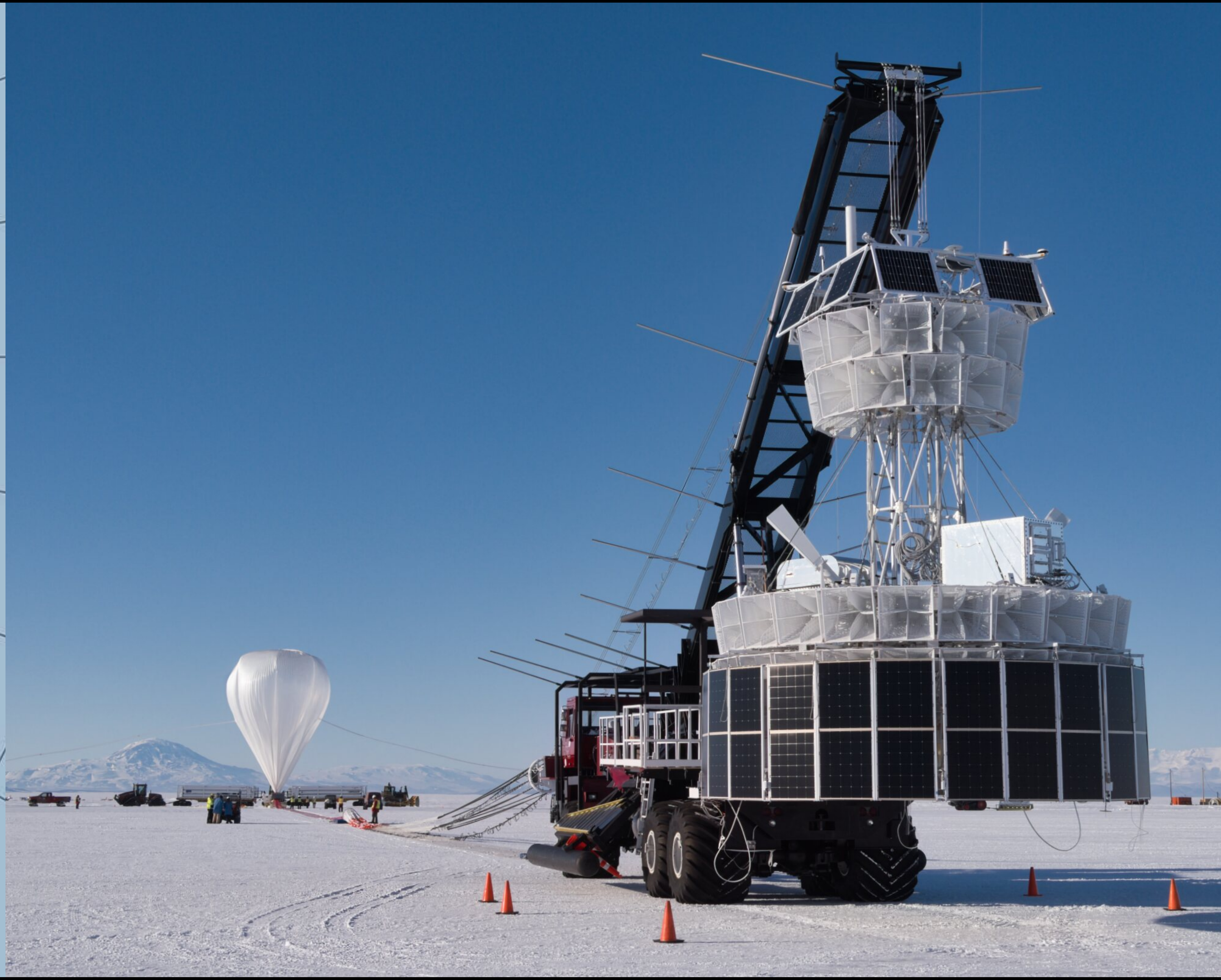
PUEO as a Transient Telescope

- Somewhat accidentally, PUEO is an excellent neutrino telescope for transients



PUEO's Flight

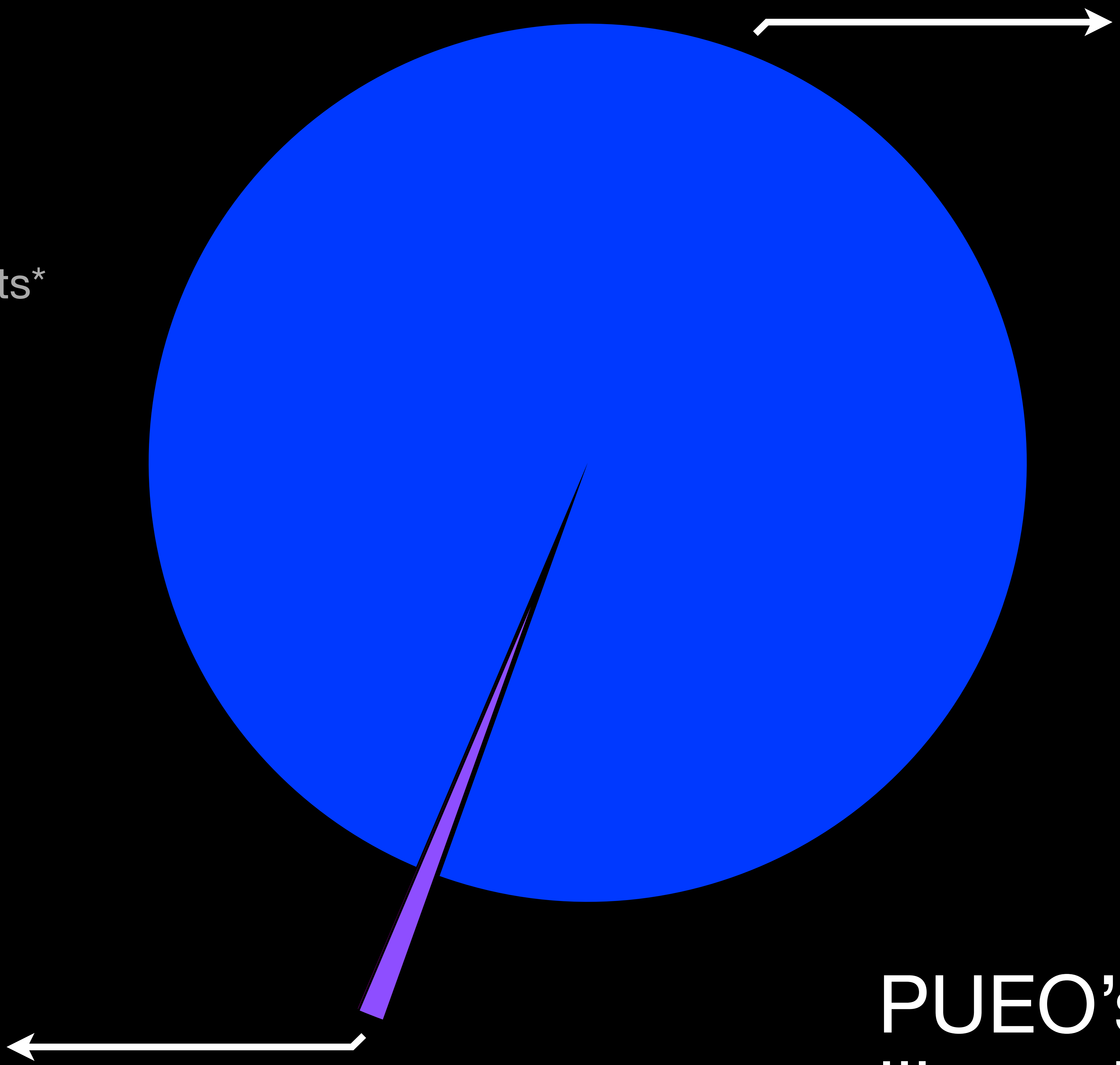




PUEO flew from December 20, 2025 - January 12, 2026 (NZDT) for a total of 23 days, 10 hours with ~55% livetime, and collected 55TB of data (>100 million events)

PUEO's Data

percentages based off of previous ANITA experiments



PUEO's dataset is dominated by non-signal like noise (thermal, CW) and signal-like noise from humans (anthropogenic)

How do we find neutrinos in all of that?

The Difficulty with Discovery Experiments

	IceCube's Astrophysical Diffuse Flux	CERN's Higgs Boson	Super-K's Proton Decay Limit
Signal Events	100 events / year	1 / s	0 events
Background Events	9.5×10^{10} events / year	1×10^{9} / s	2.9×10^{10} events
Signal / Background Fraction	1.1×10^{-9}	1×10^{-9}	0

IceCube Collaboration et al. PHYS. REV. D 110, 022001 (2024)

ATLAS Collaboration et al., Science 388, 1576 - 1582 (2012)

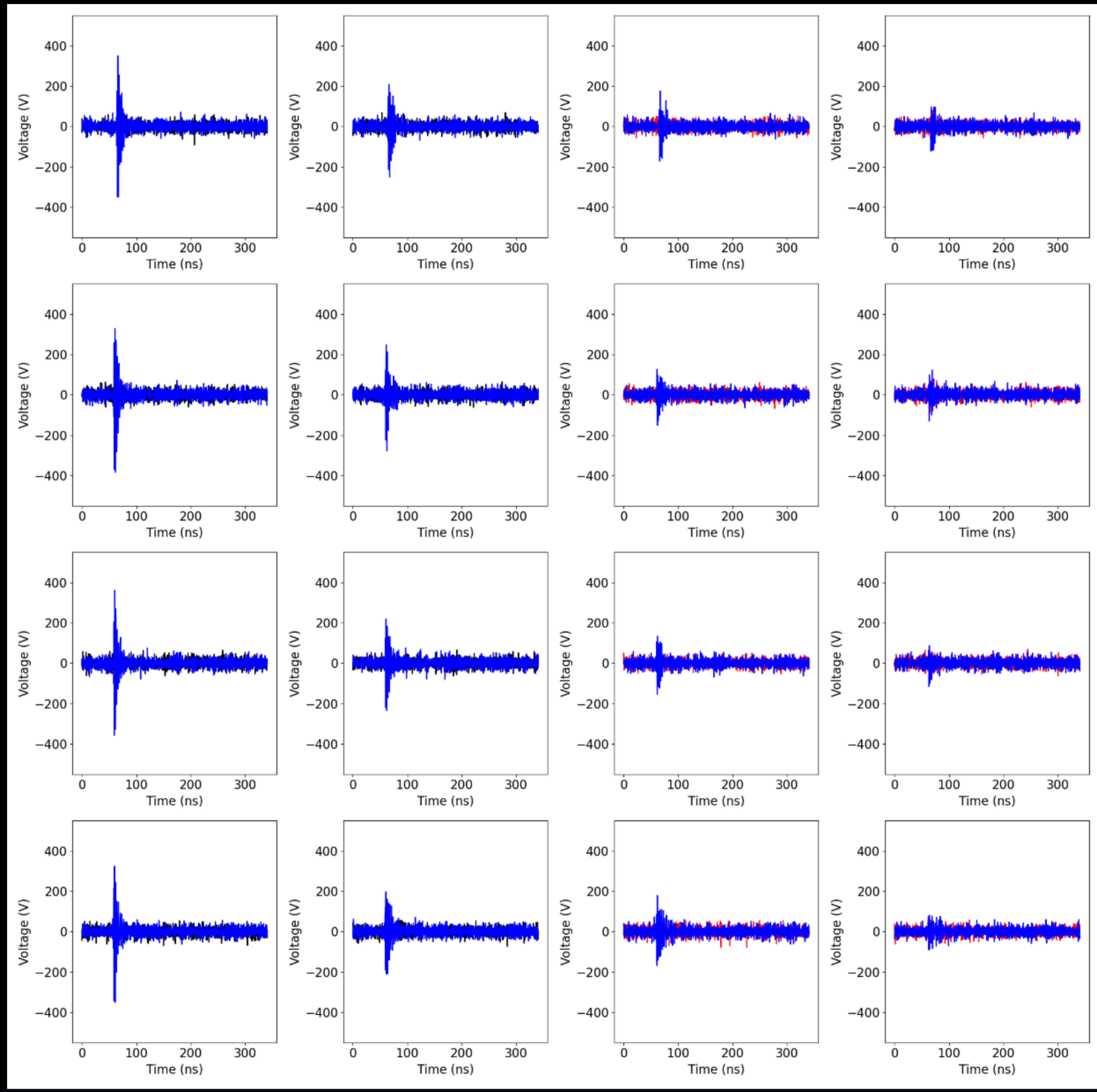
Super-K Collaboration et al. PHYS. REV. D 102, 112011 (2020)

A discovery analysis needs to be able to distinguish between 0 and *almost* 0!

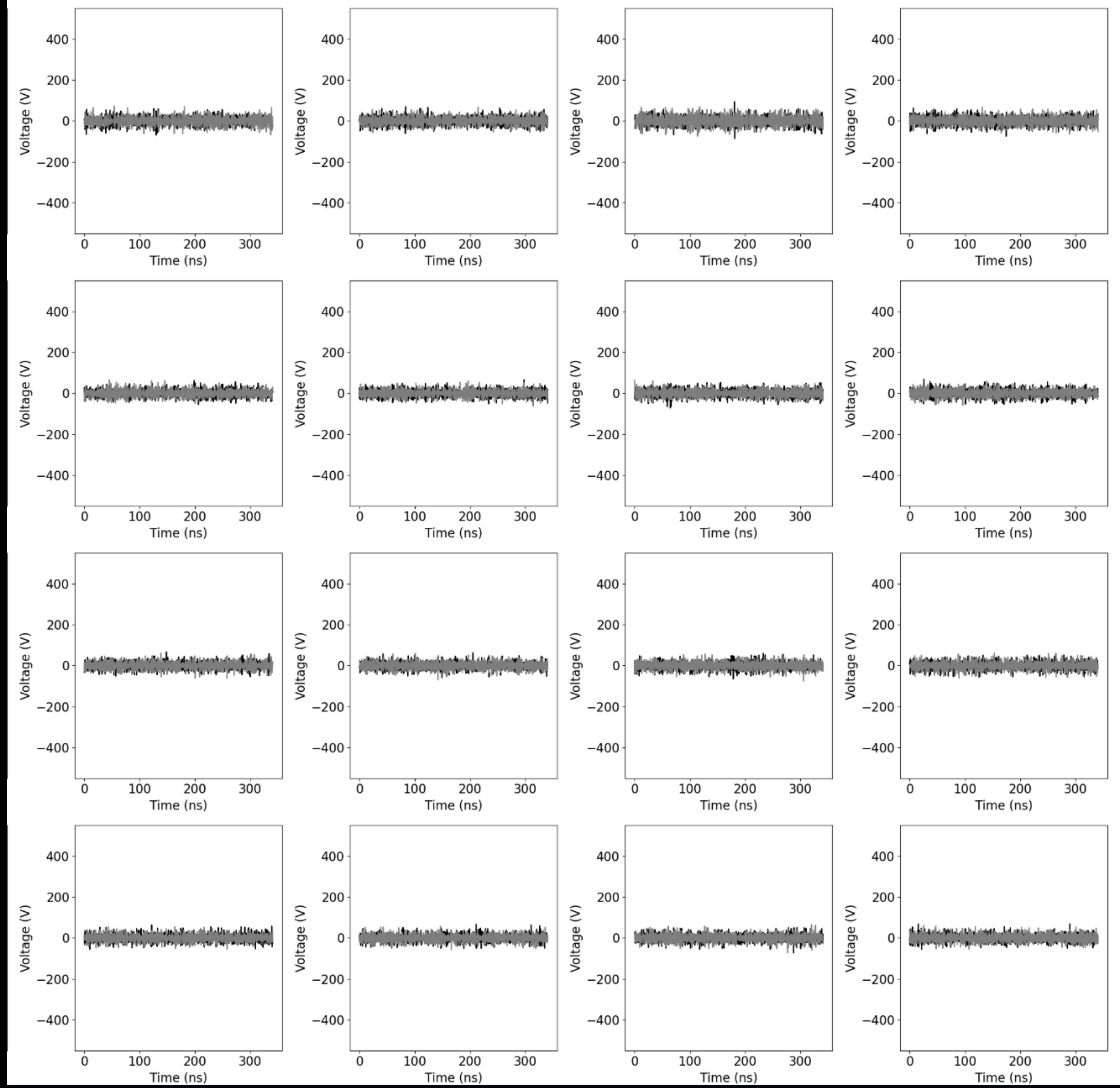
Pulling Neutrinos Out (hopefully)

Name of the game is to leverage known features of Askaryan Emission from neutrino interactions to separate background vs noise!

<u>Signal-like Event (Calibration Pulse)</u>



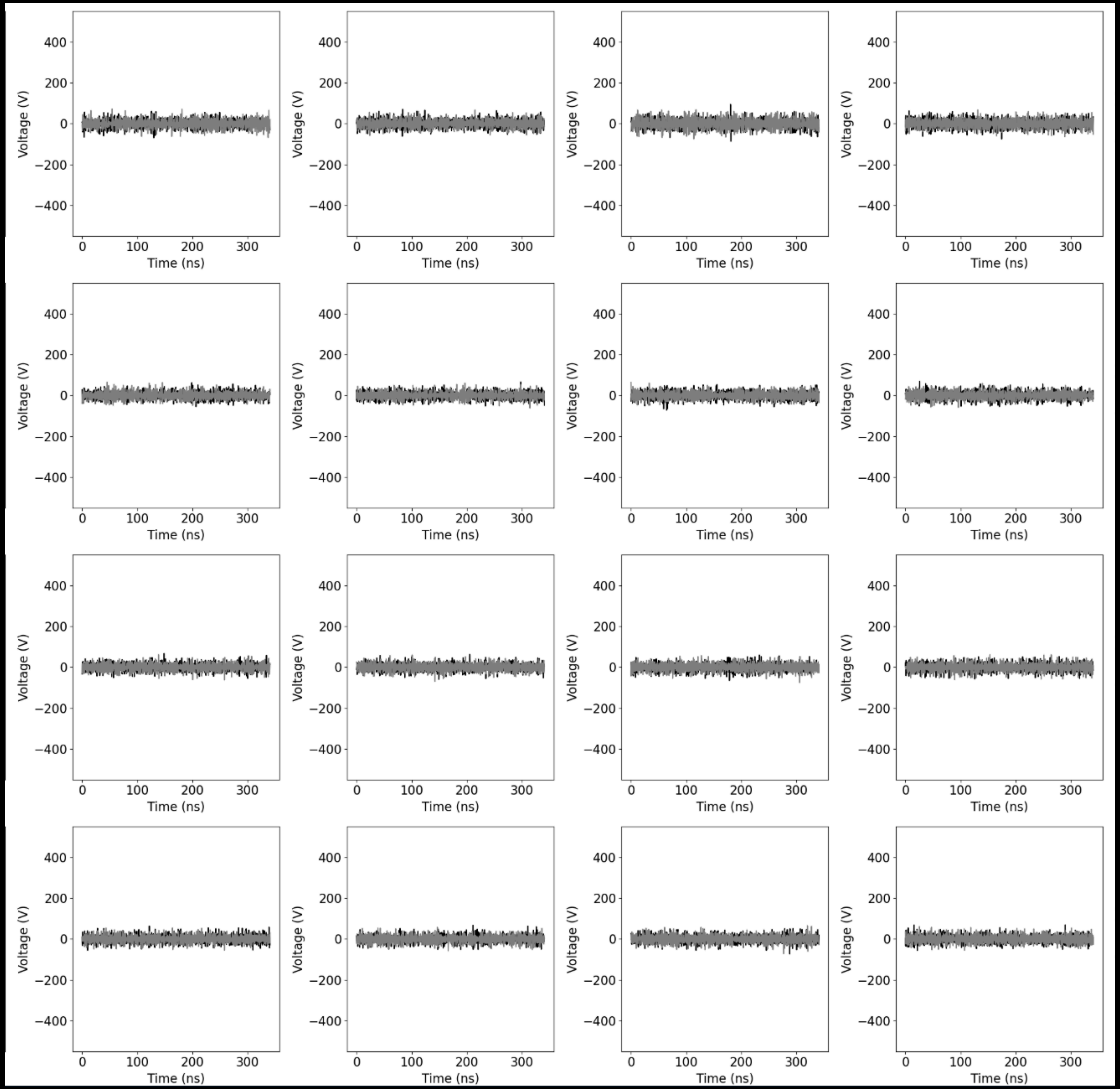
<u>Background-like Event (Thermal)</u>



Back to the Basics

Thermal noise will not be impulsive, and will be largely uncorrelated between antennas looking at the same ice

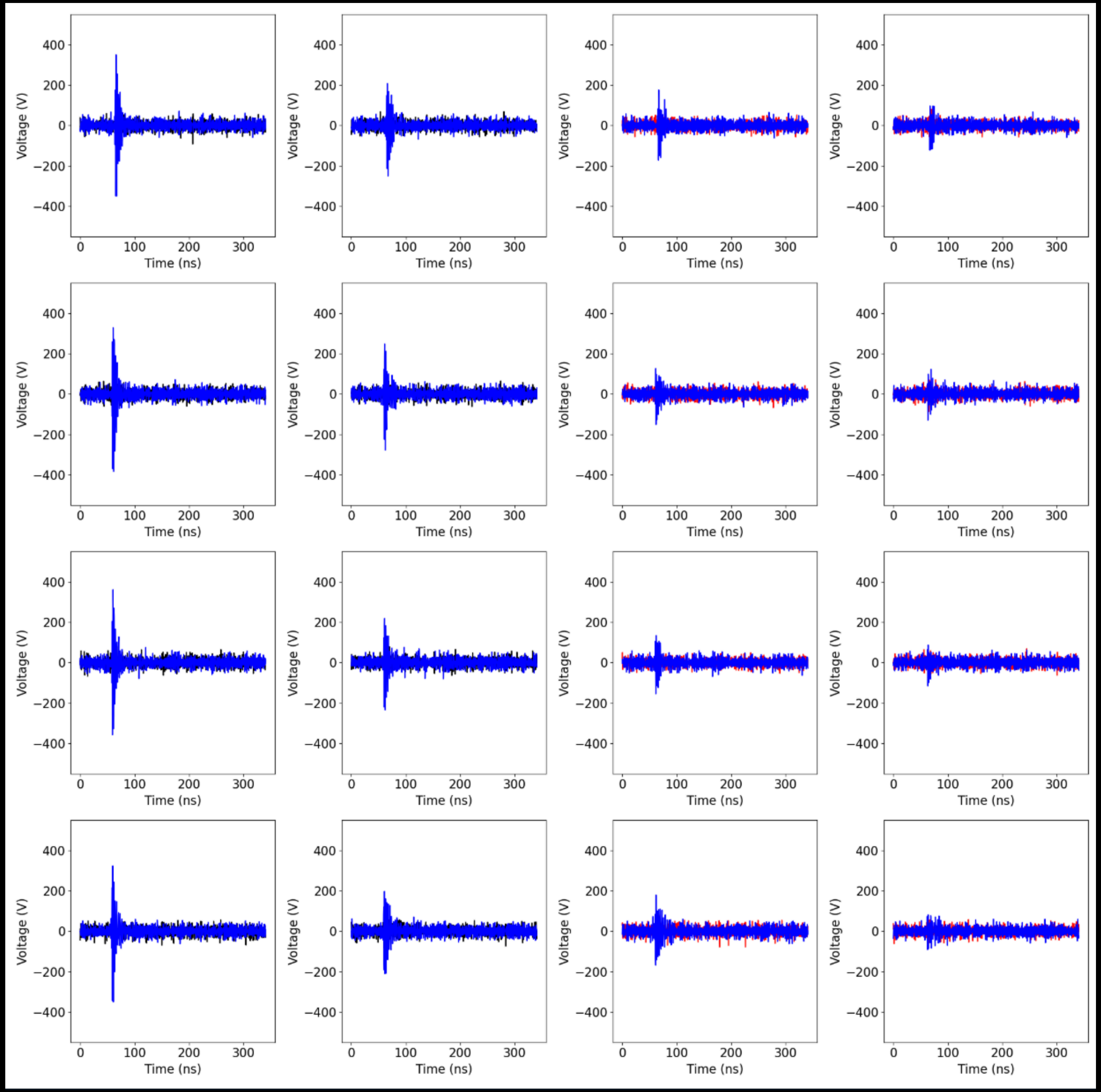
It will arise isotropically in ice and air



Back to the Basics

Neutrinos will be impulsive and have similar pk2pk values for antennas looking at the same ice

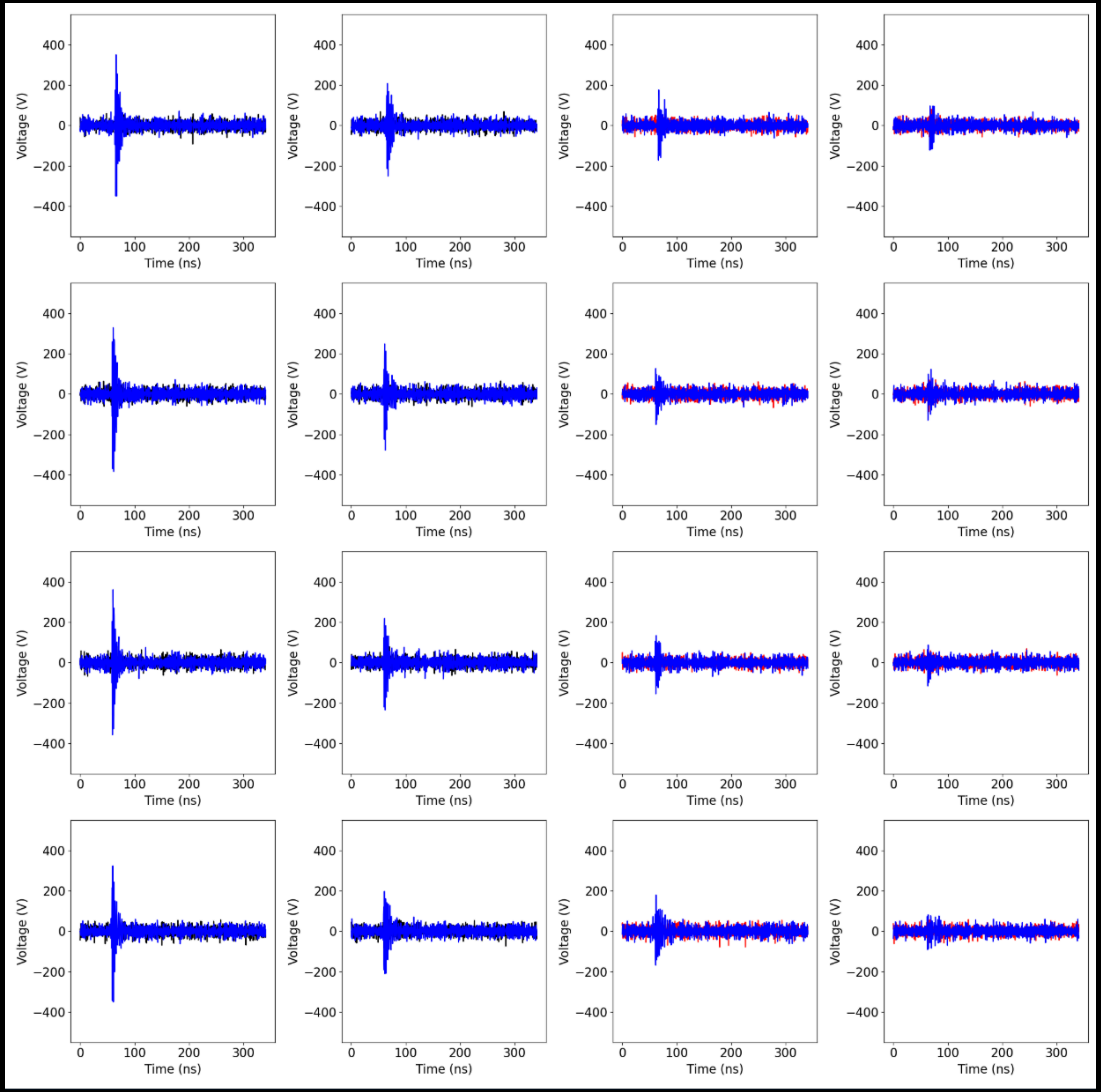
They will arise isotropically from the ice itself



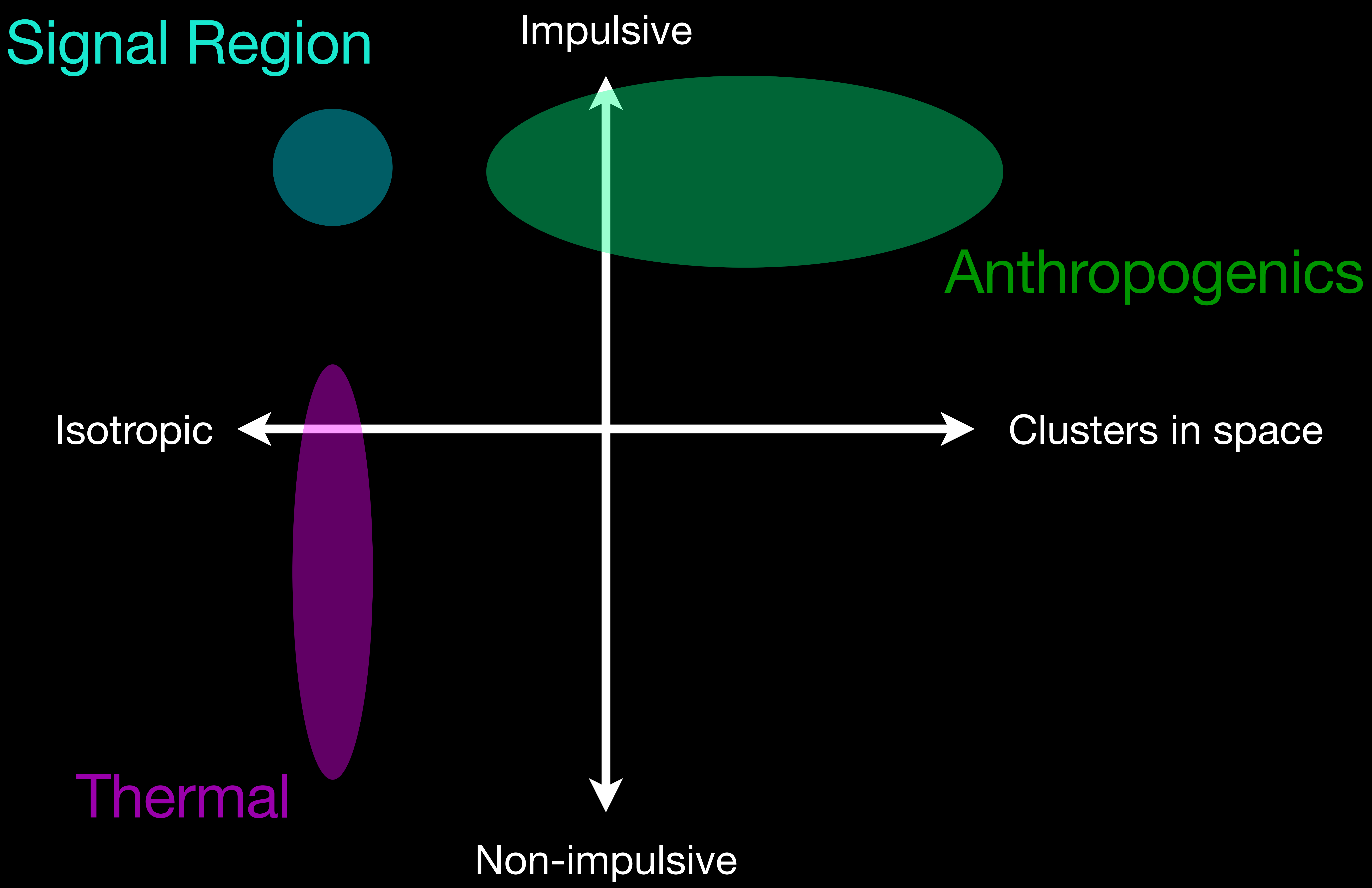
Back to the Basics

Anthropogenics will be impulsive and have similar pk2pk values for antennas looking at the same ice

They will typically cluster with other events from the same spots of the ice

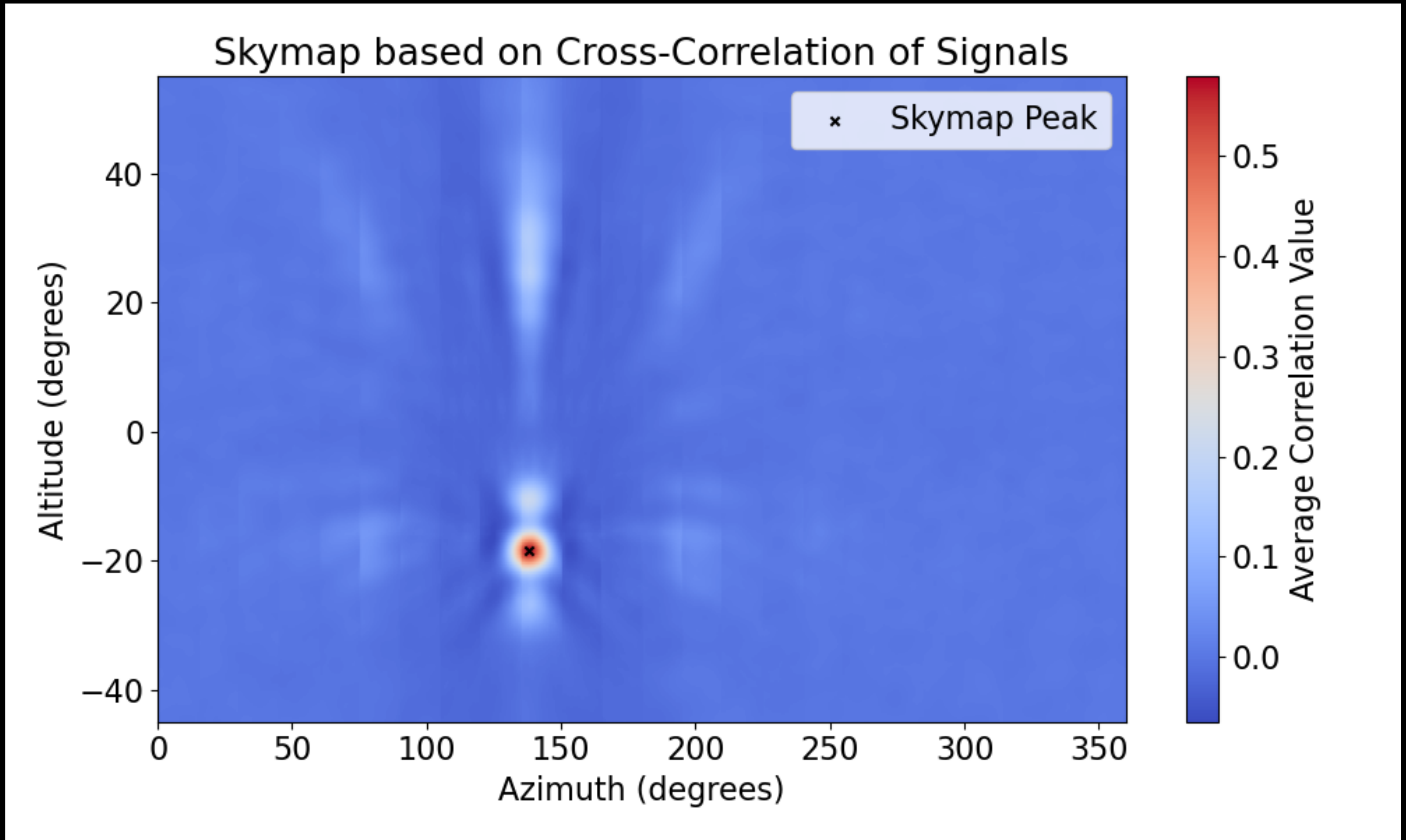


Slicing Phase Space: One Example



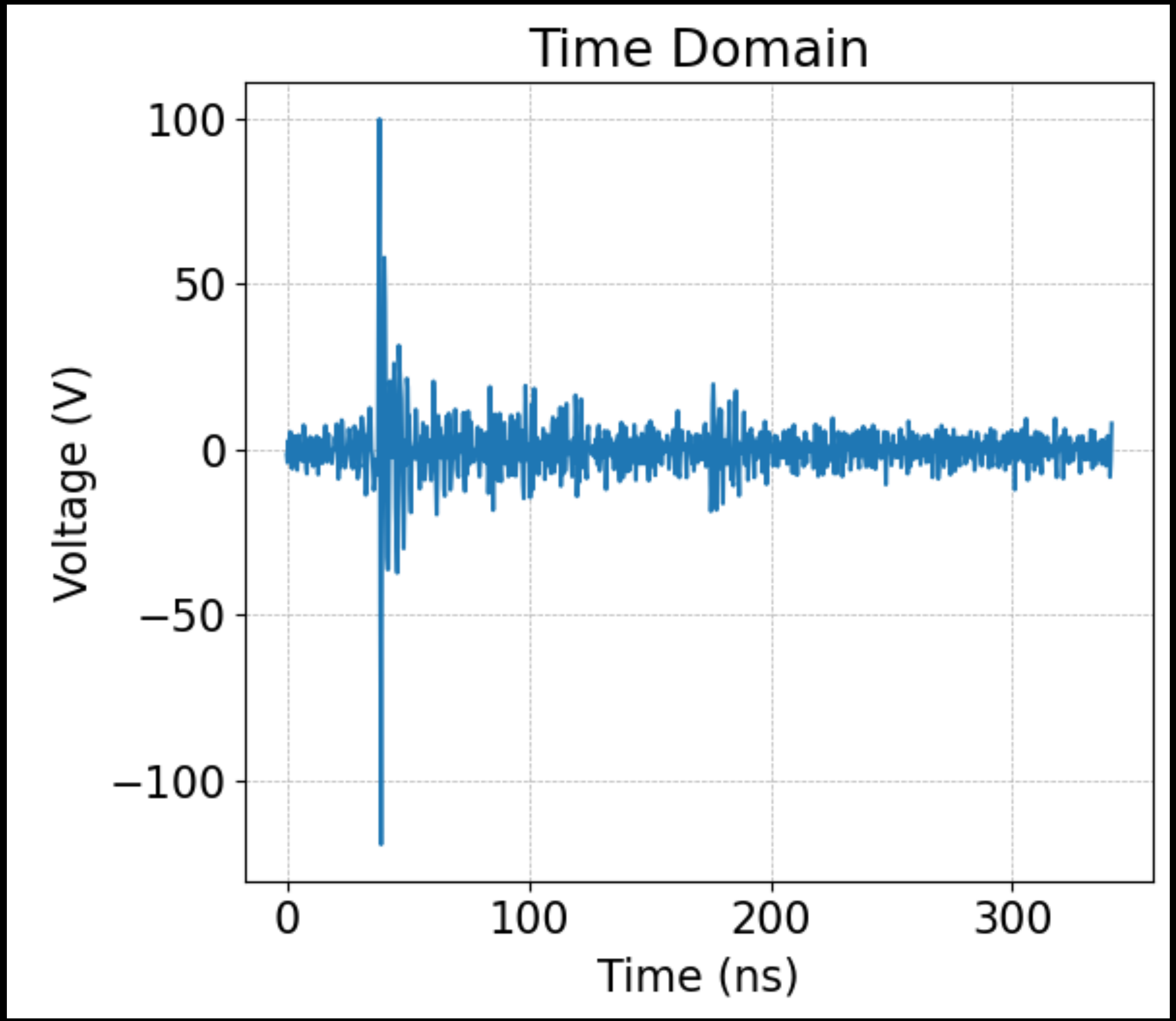
What Tools Do We Have?

Interferometric Maps



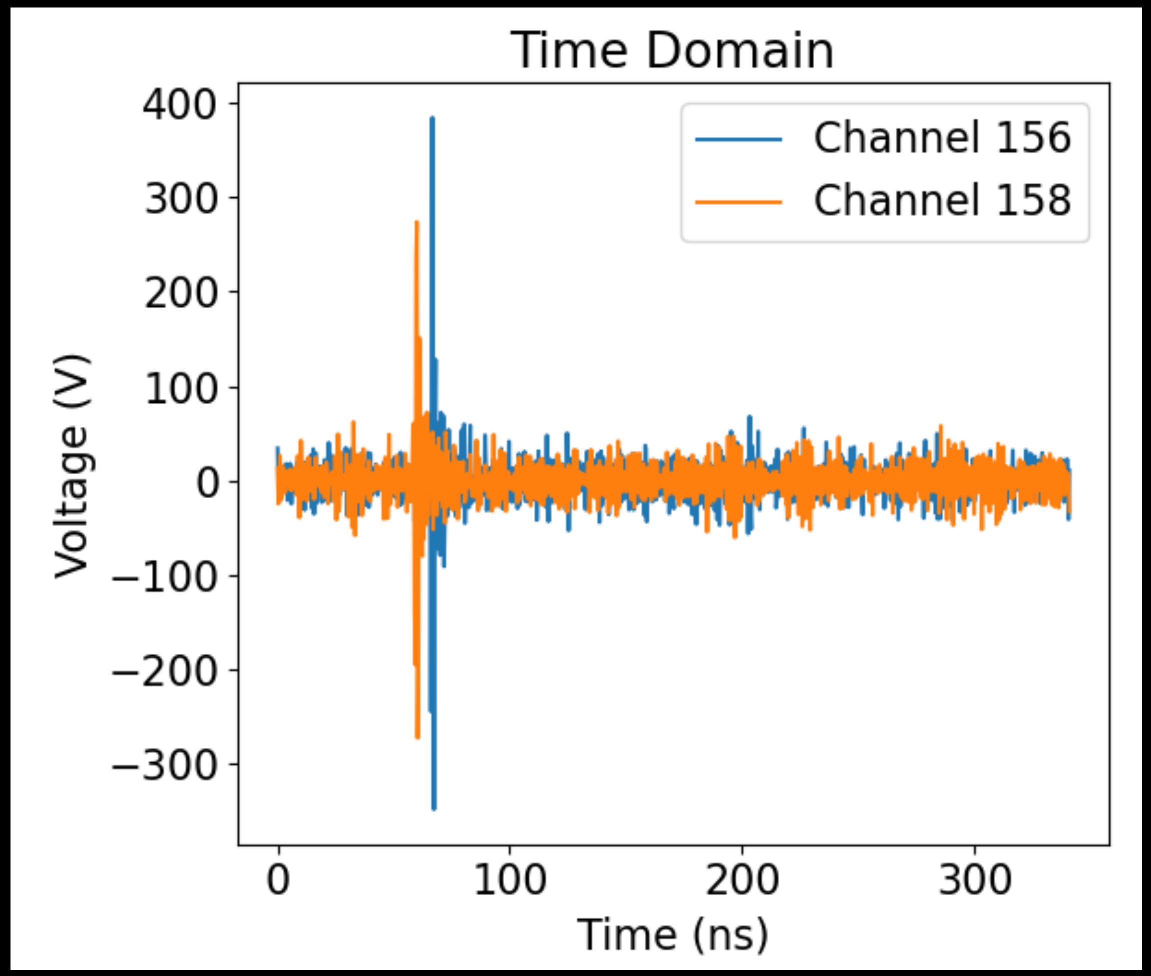
Helps us determine the source location of the event

Coherent Sums



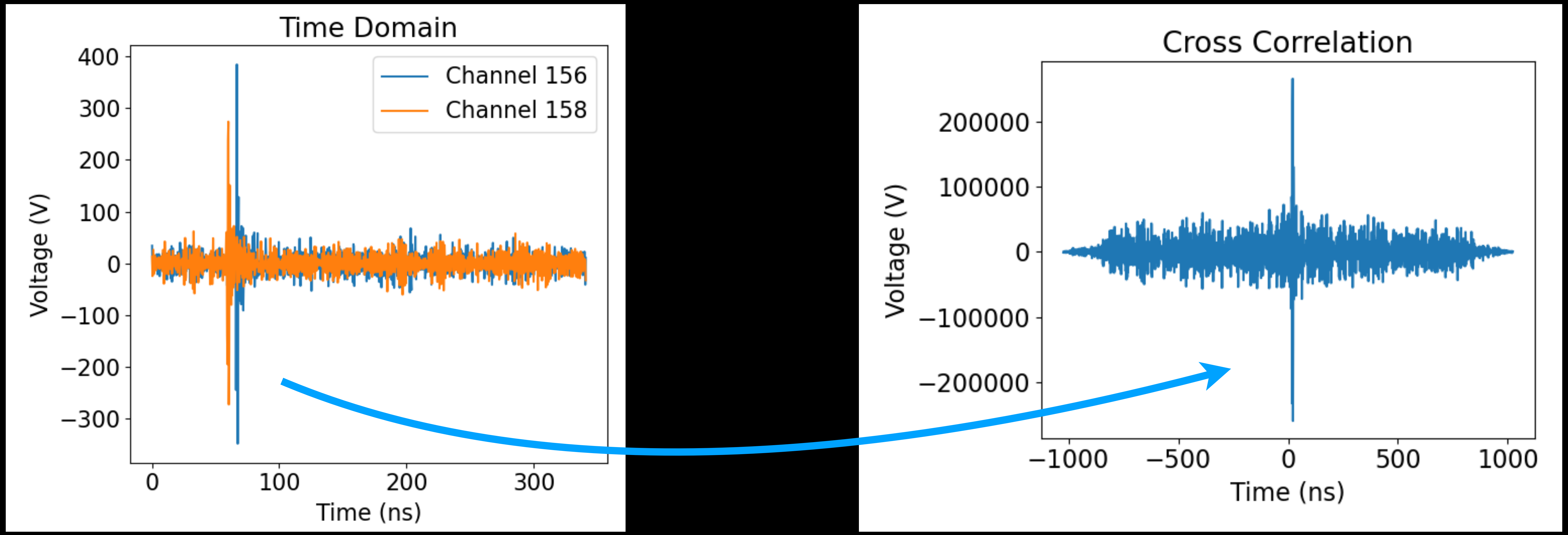
Helps us measure impulsivity and coherence of events

Interferometric Maps



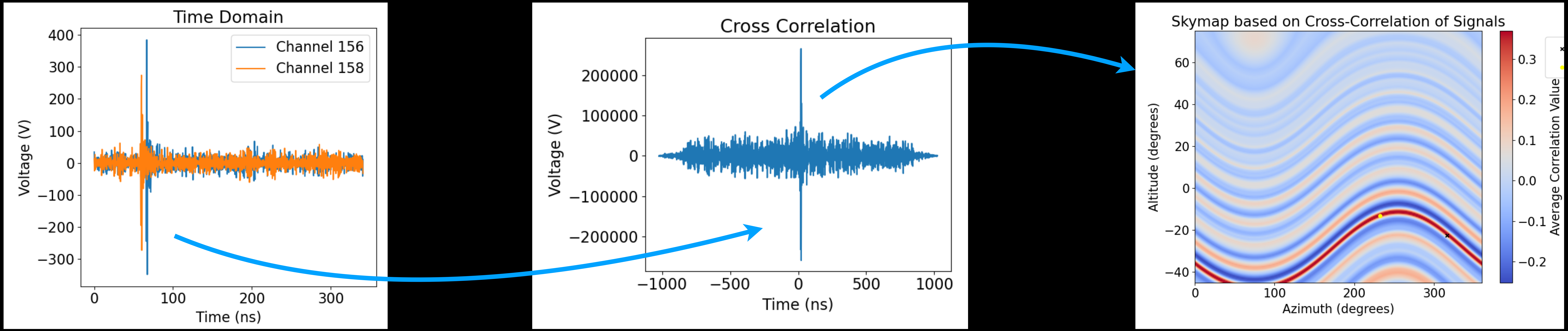
Nearby antennas will see similar signals, with some time delay based on source location of signal

Interferometric Maps



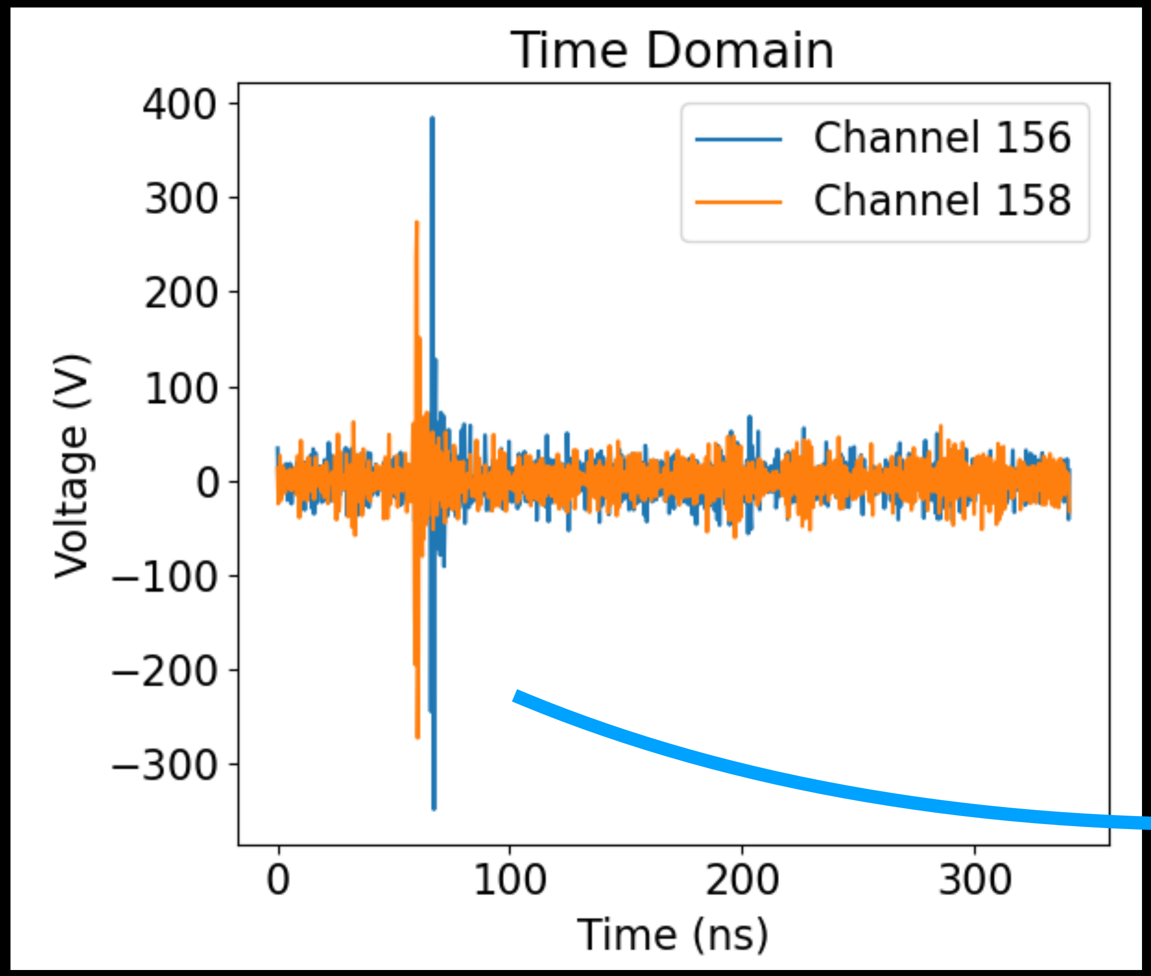
Cross correlating nearby antennas will pick out time delays where similar features appear

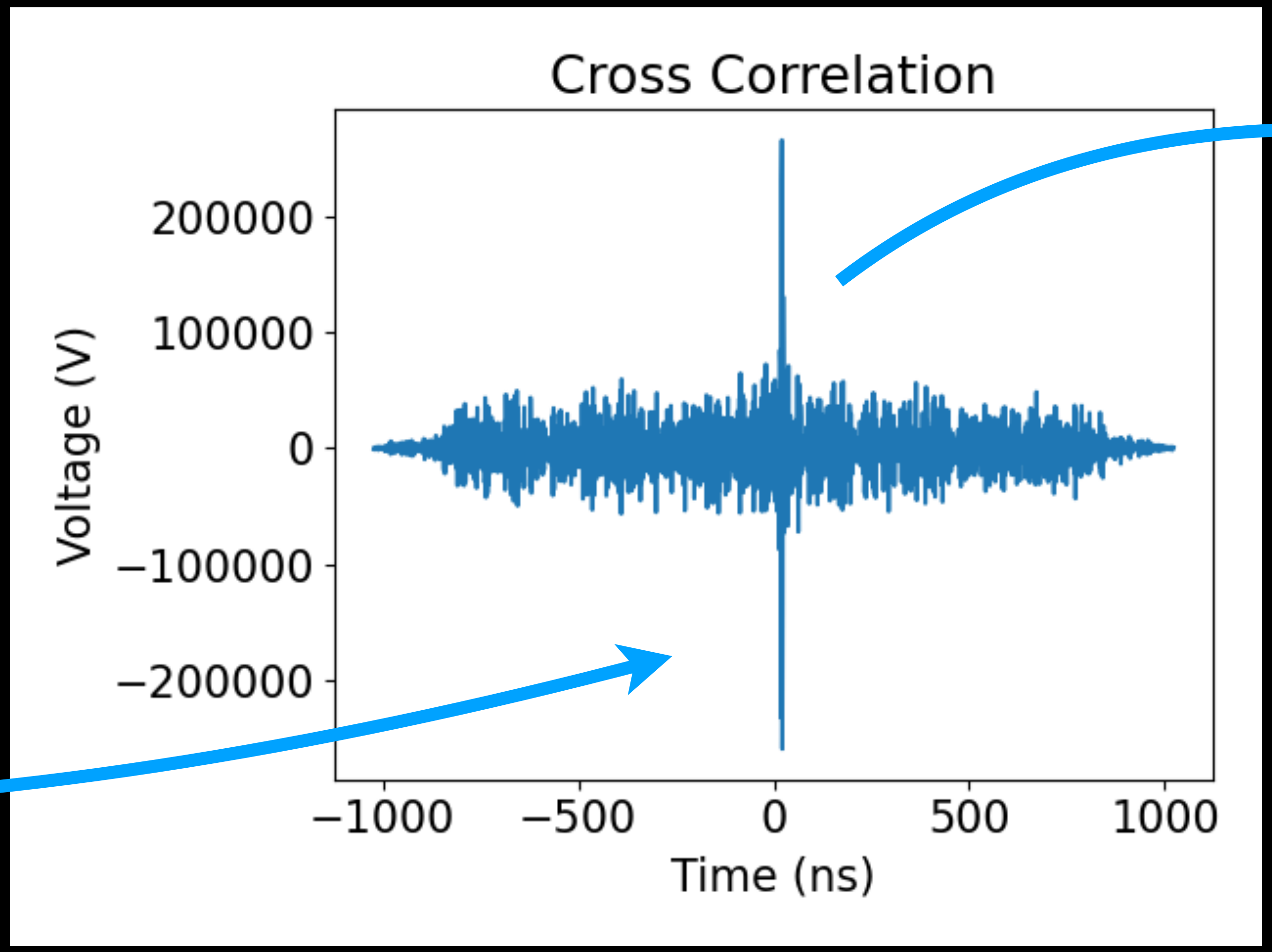
Interferometric Maps

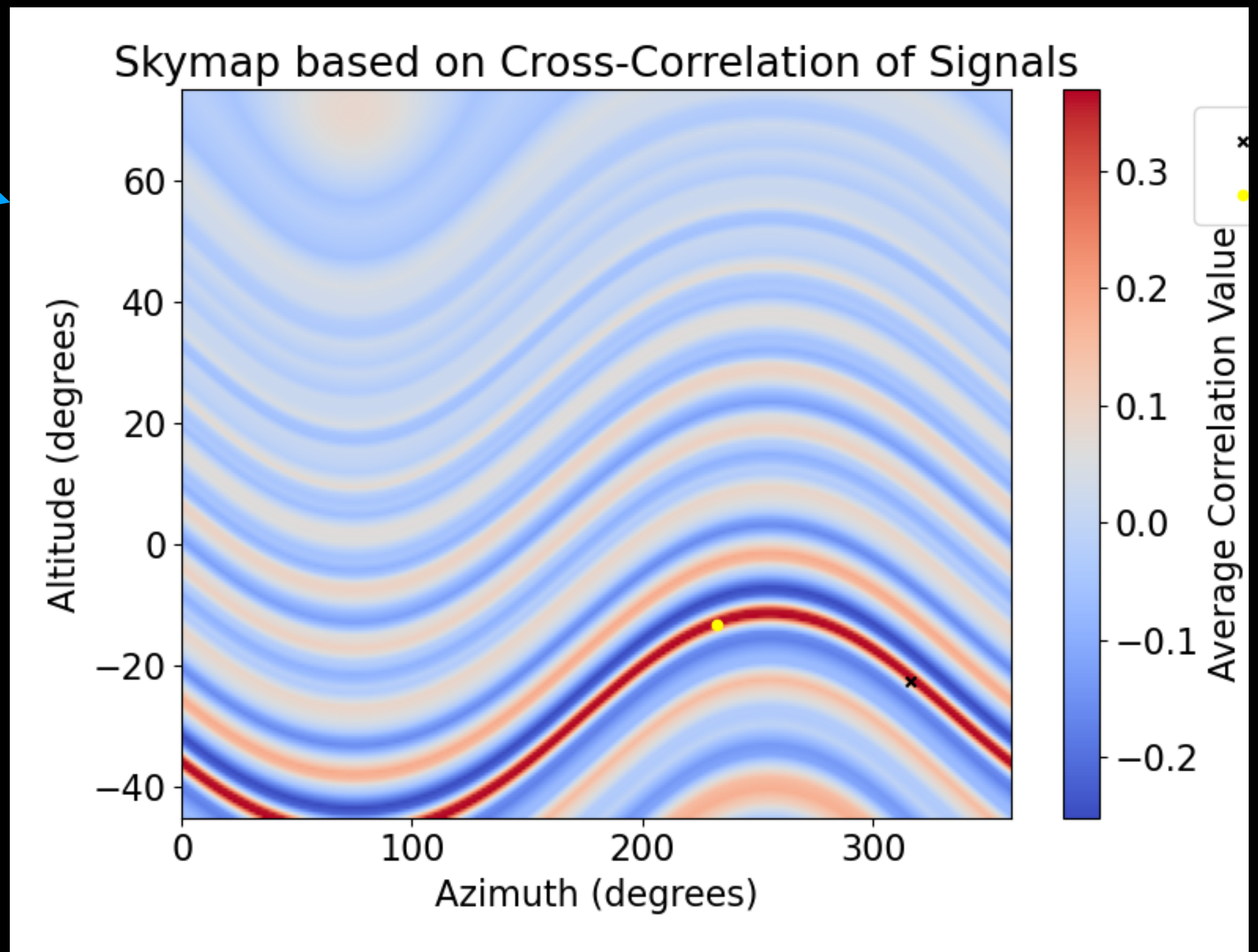


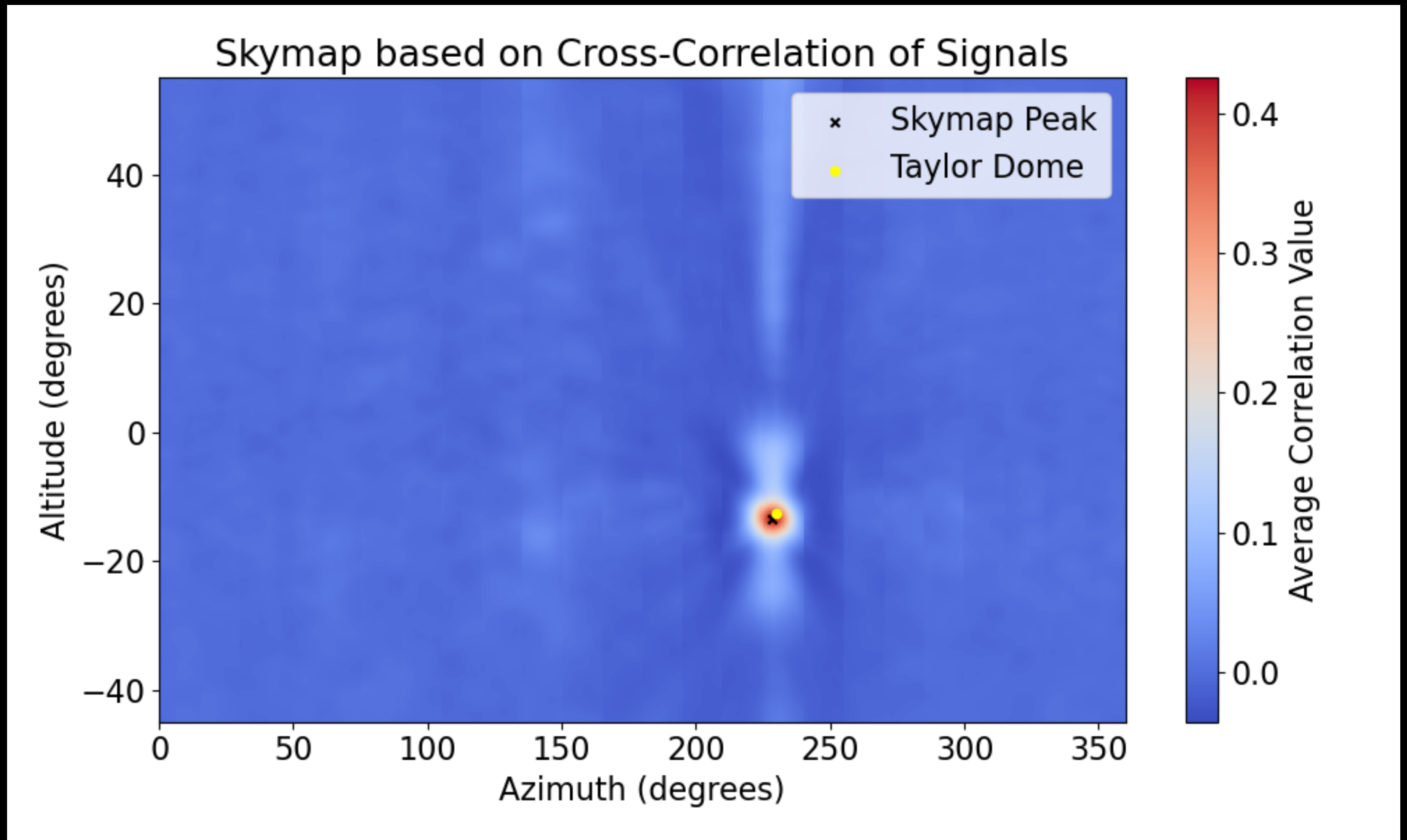
Sampling this cross correlation at time delays consistent with different source locations builds a map

Interferometric Maps



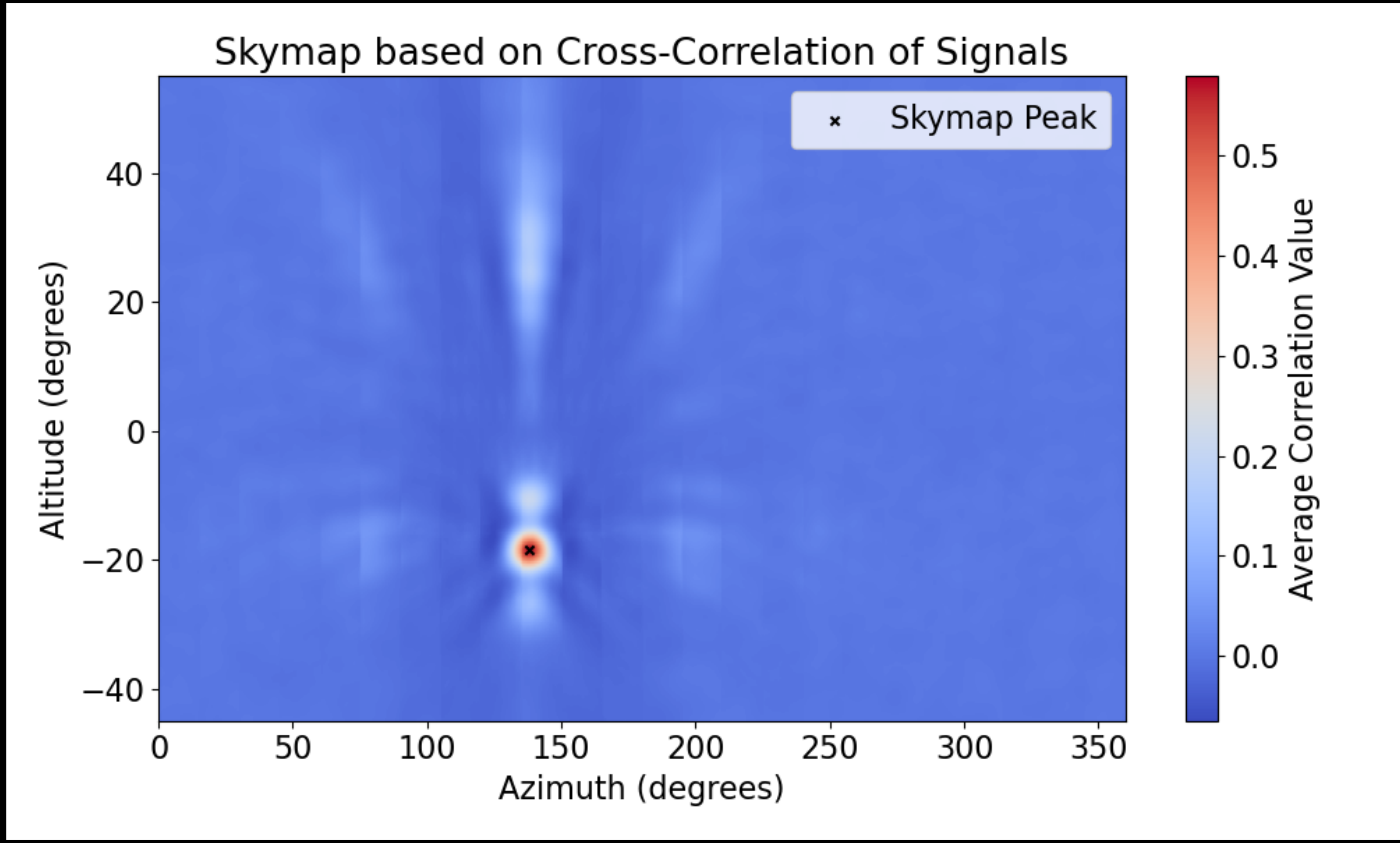


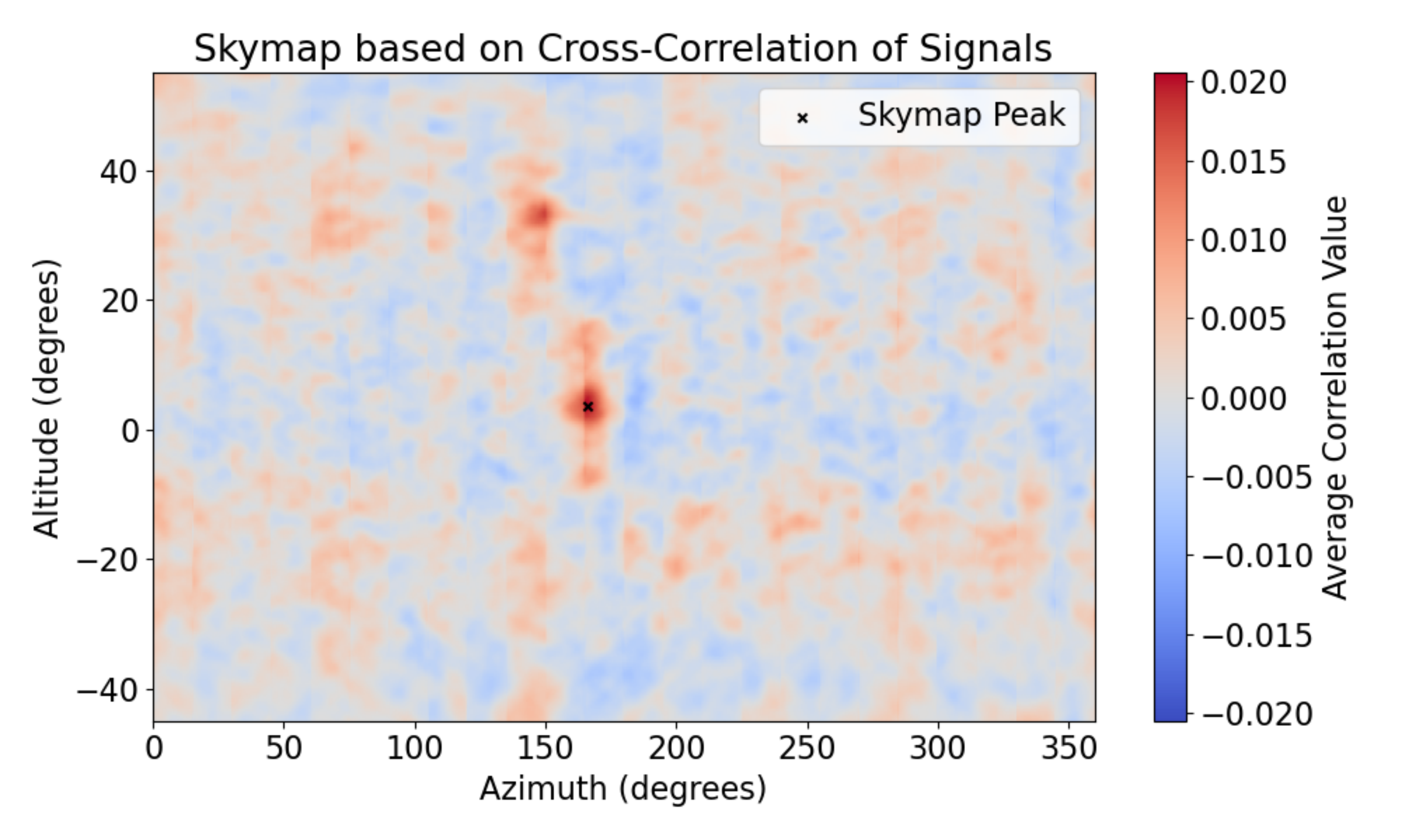




Summing together these maps for all antenna pairs gives you an interferometric map, or skymap!

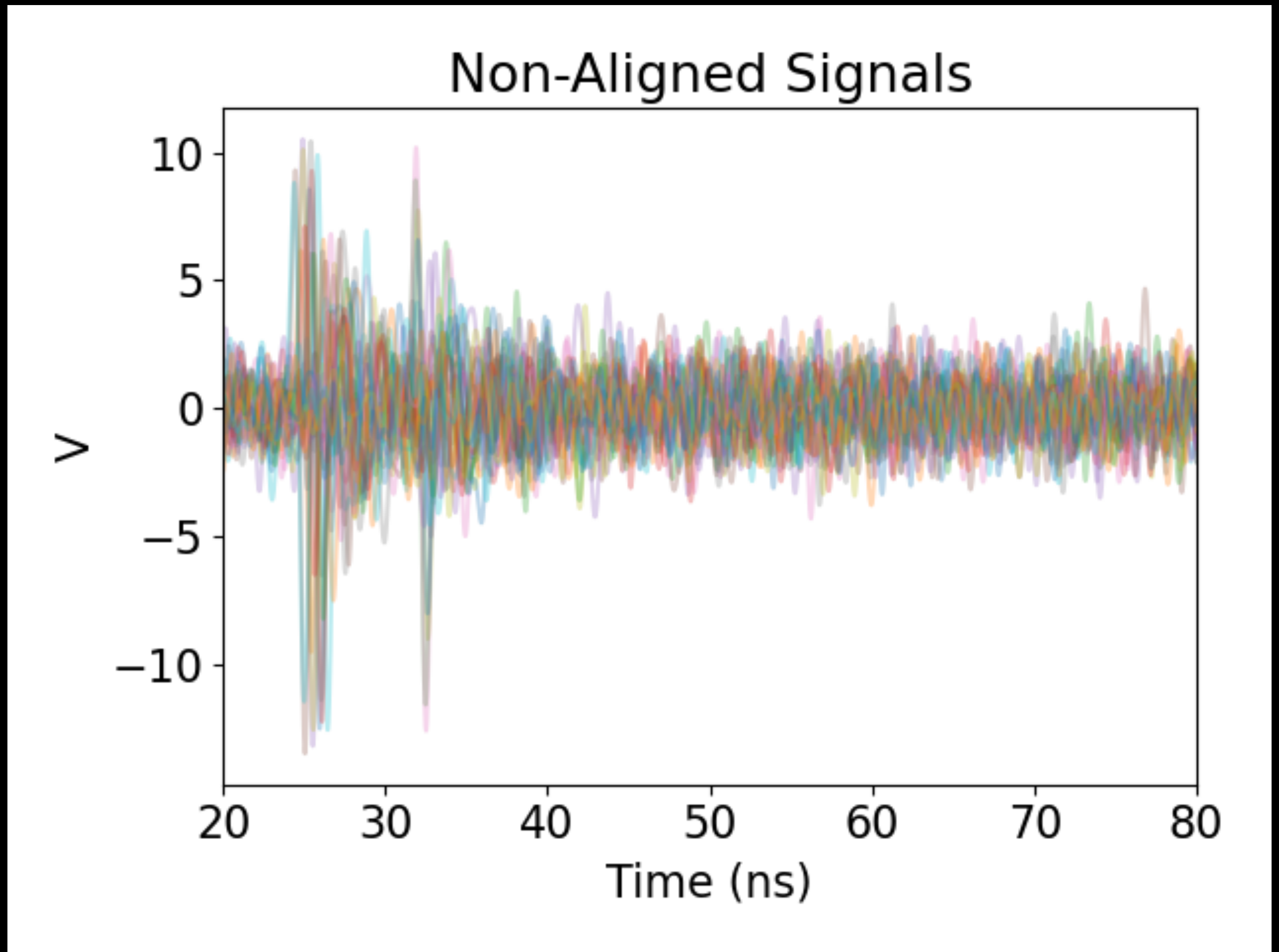
Interferometric Maps





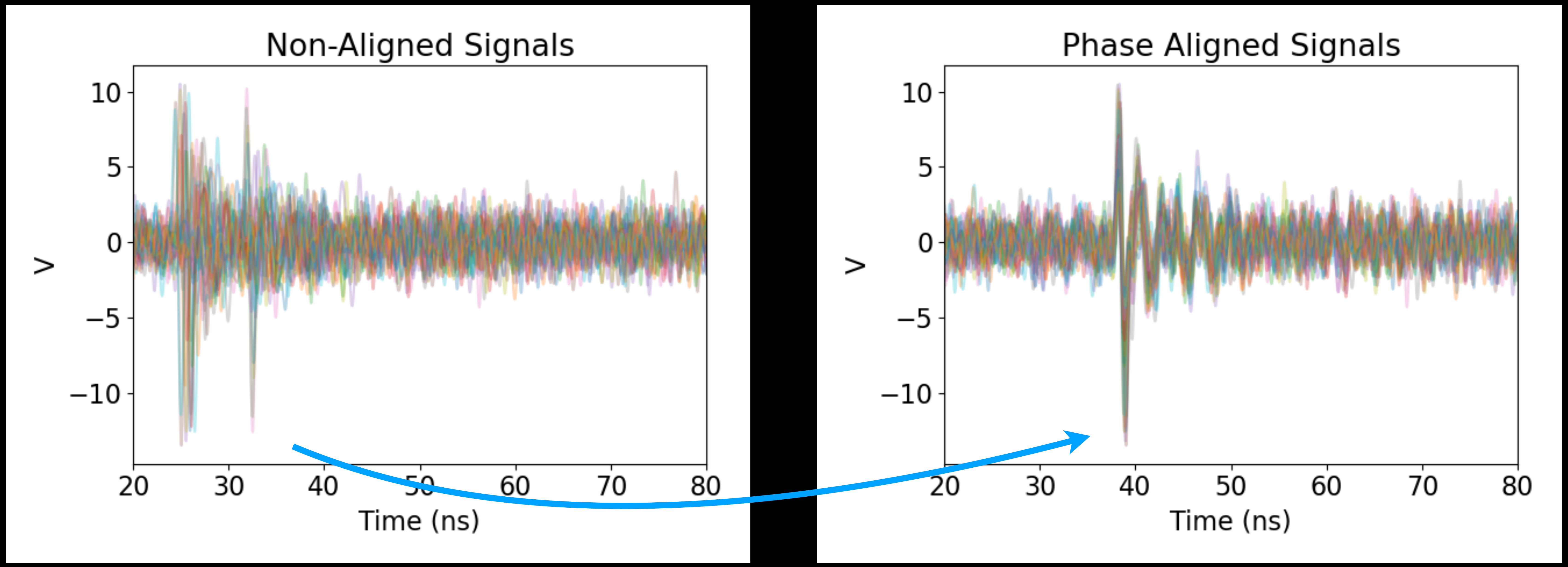
The resolution of these maps are heavily tied to the SNR of the signal — lower SNR events will produce more noise-dominated maps

Coherent Summing



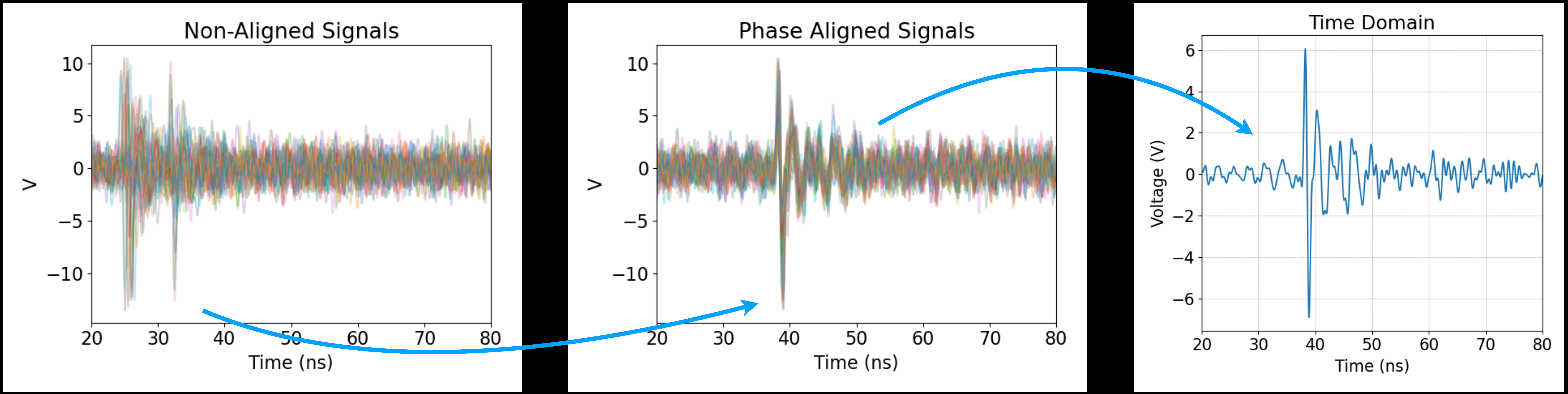
Antennas pointing towards the best skymap direction can see similar signals, delayed in time

Coherent Summing



Using the best skymap direction, signals are delayed in time to align their phases

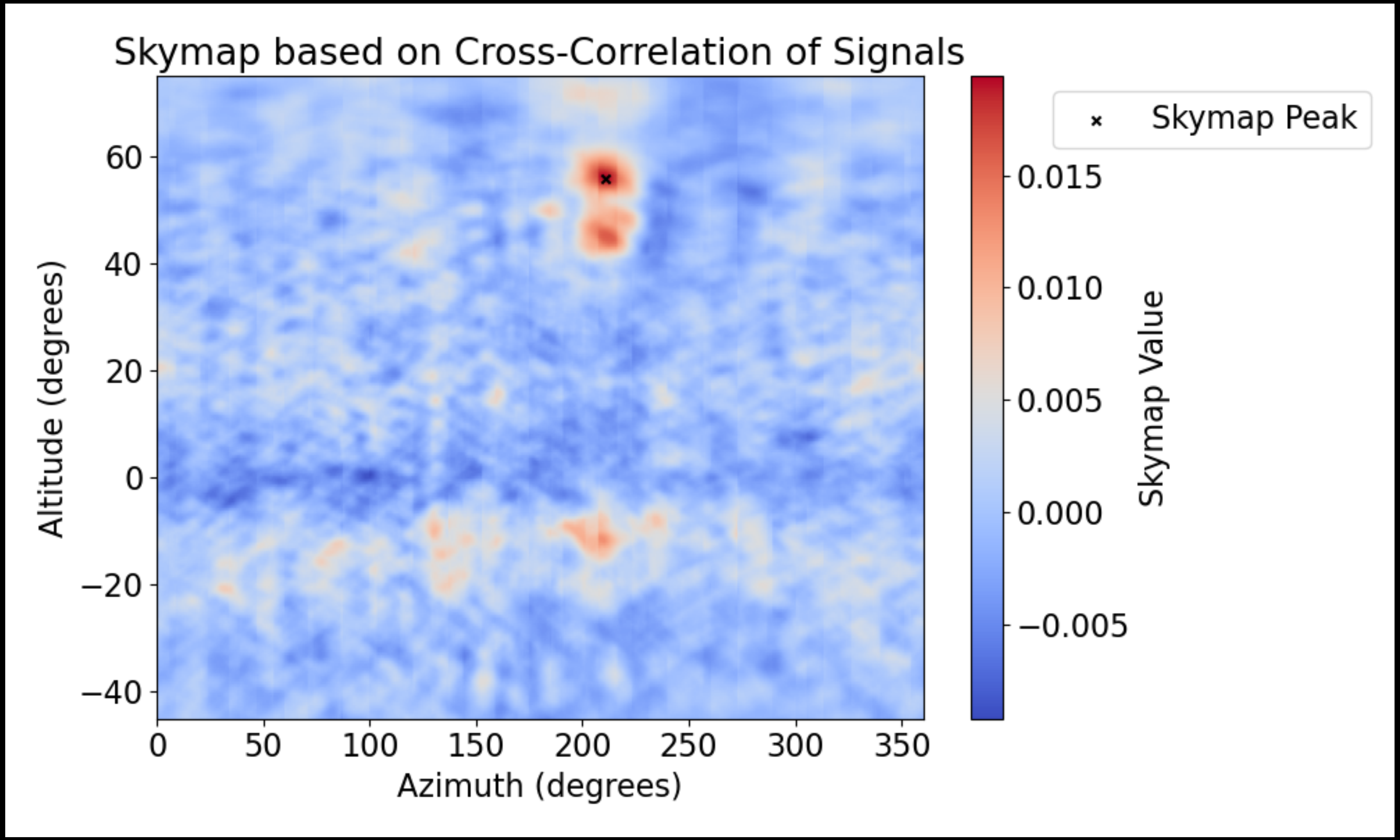
Coherent Summing



Signals are then summed after being phase aligned. The final SNR gets boosted by $\sim \sqrt{N}$

Weaknesses

Coherent sum relies on good pointing — what if an event mis-reconstructs for some reason?

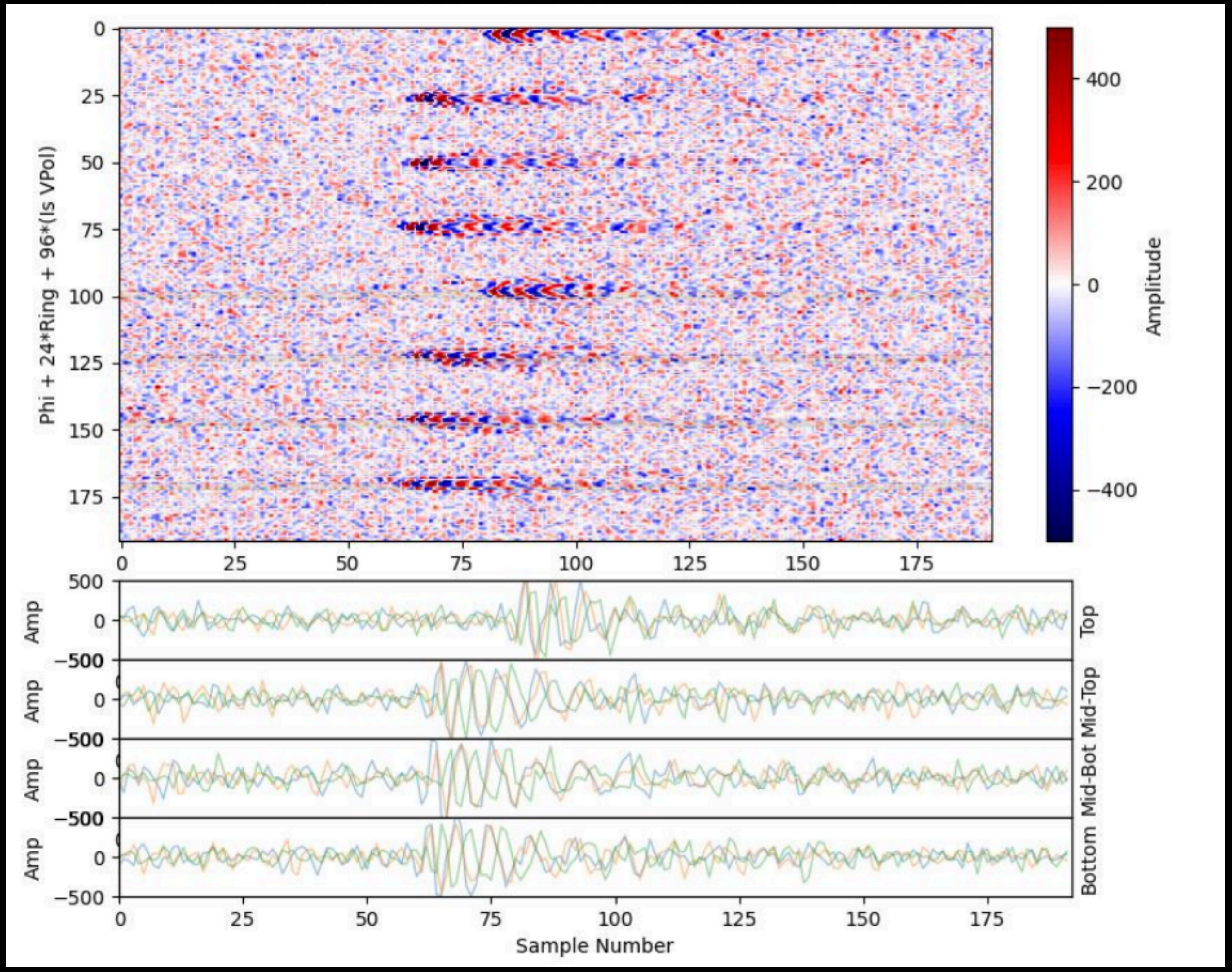


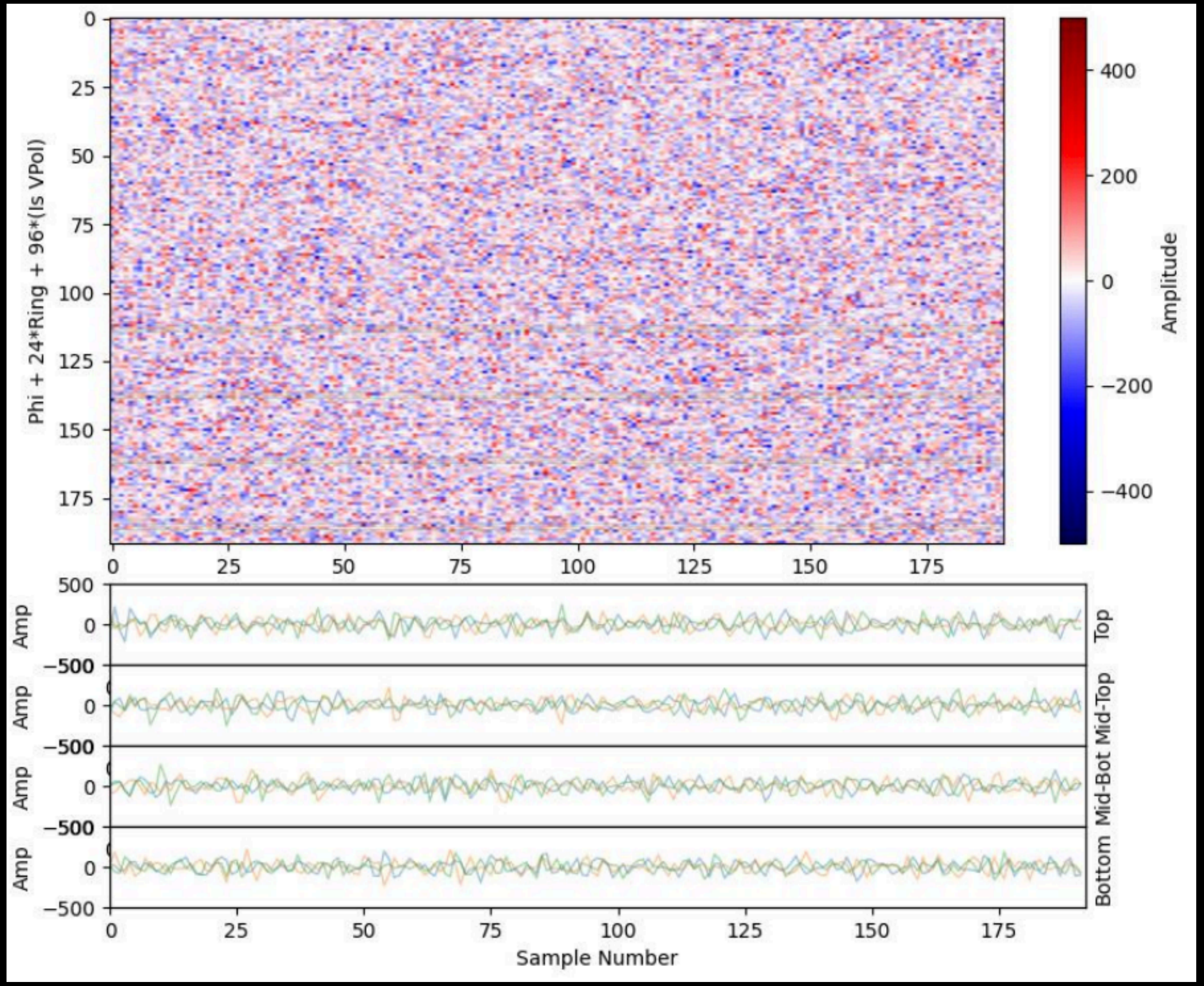
Skymaps are expensive to make! Its most naive implementation scales like N_{ant}^2

Areas for Improvement

In the era of big-data, Machine Learning can be a huge boon

- Can you train a CNN to identify the differences in these two images and pull out interesting science information?



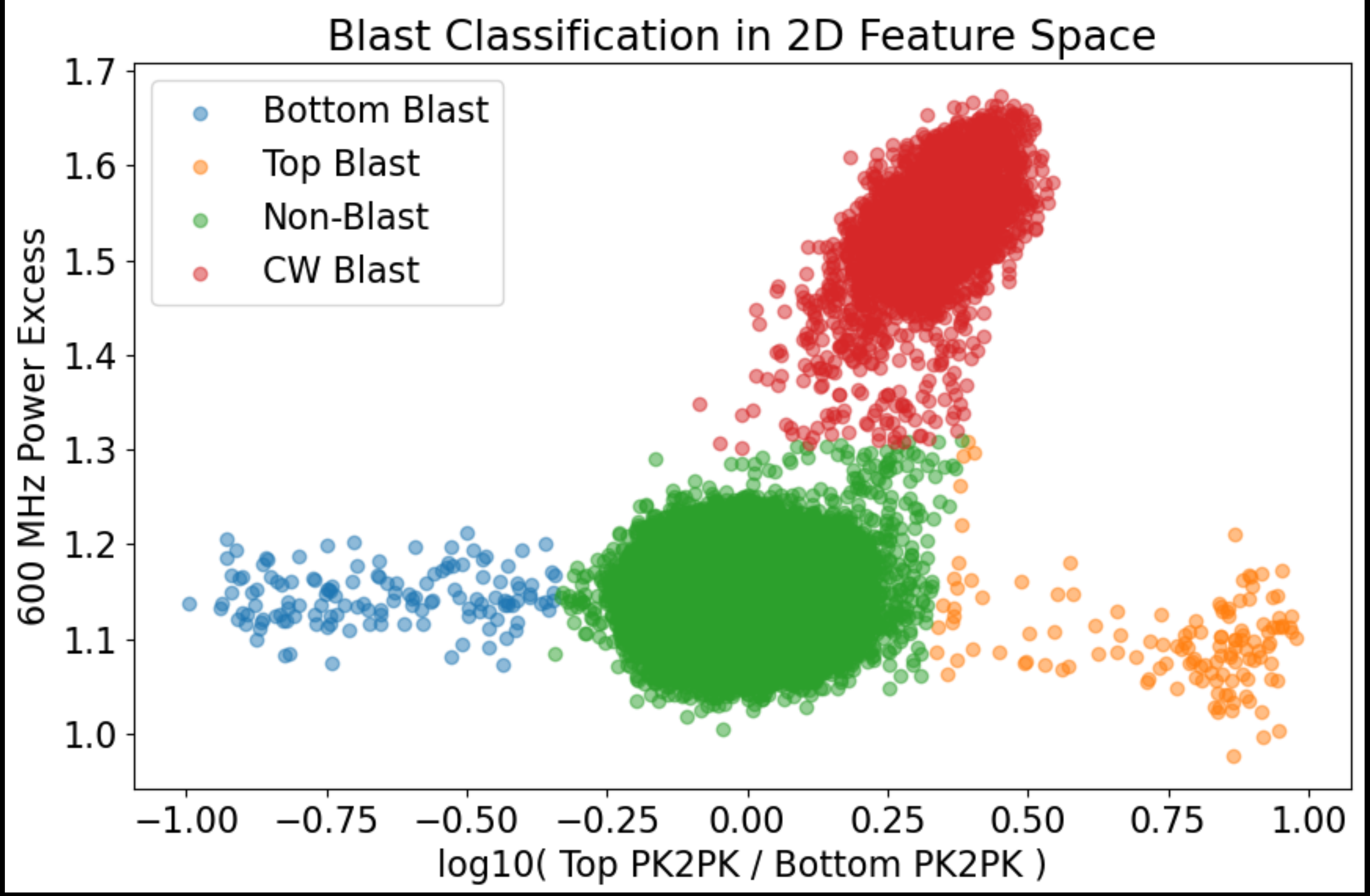


Credit: Ryan Nichol

Areas for Improvement

In the era of big-data, Machine Learning can be a huge boon

- Can you train a SVM to separate out event classes using reduced science products?



Food for Thought

How much should you trust simulations in a discovery experiment?

- If we've never seen a signal before, how confident can we be that we understand all the effects on a signal?

How much should you trust Machine Learning in a discovery experiment?

- If something has never been seen before, how do you confidently train something to find it? Or to not exclude it?

What place does Machine Learning have in experimental design?

- In what cases can it be used at the trigger level? Real time adaptive filtering? Feature extraction?
- Can you use it to quickly explore phase spaces of possible designs?