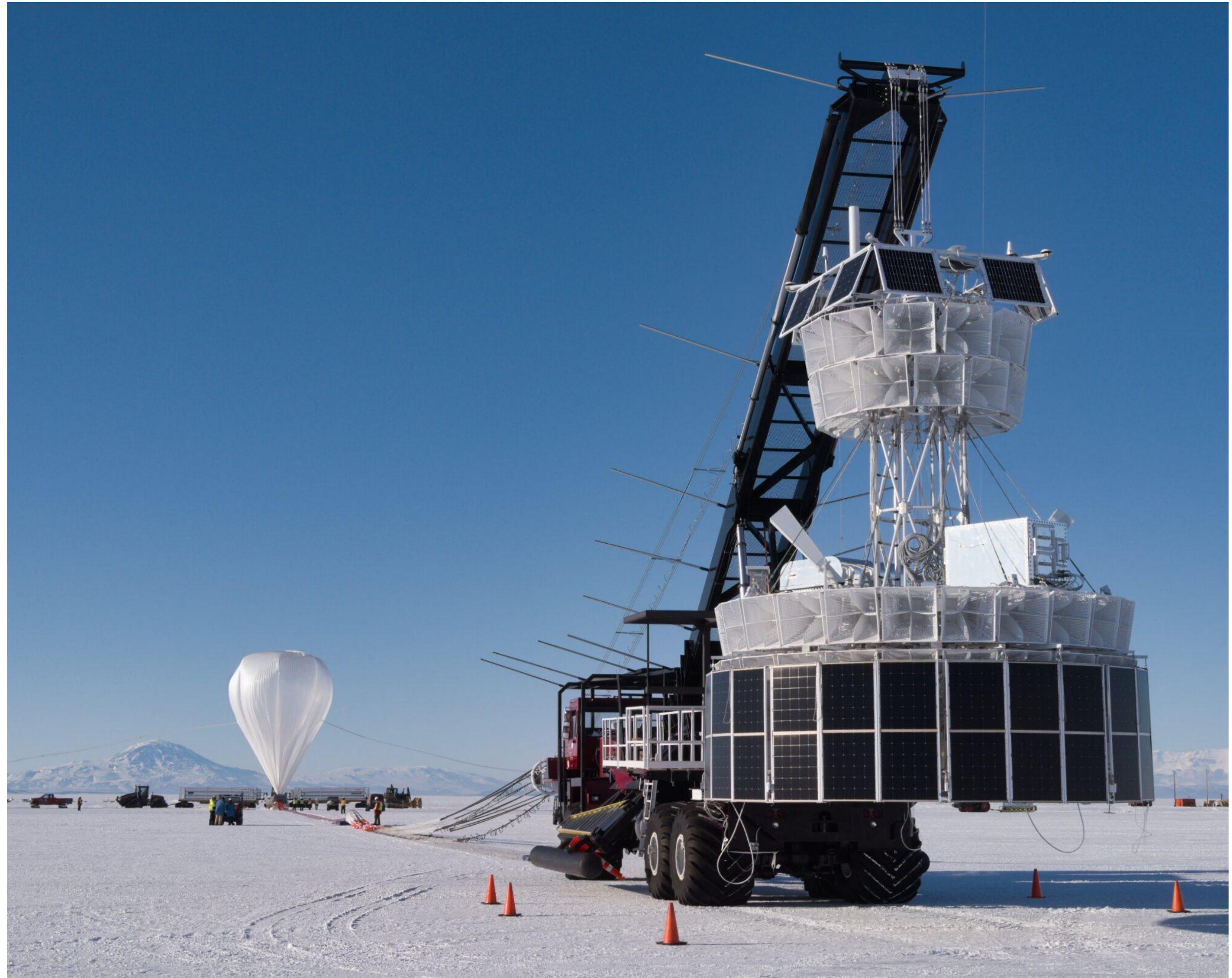
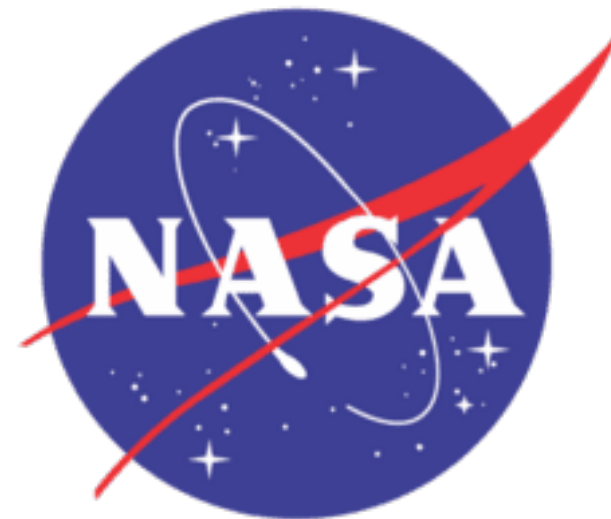


Tuning into Neutrinos

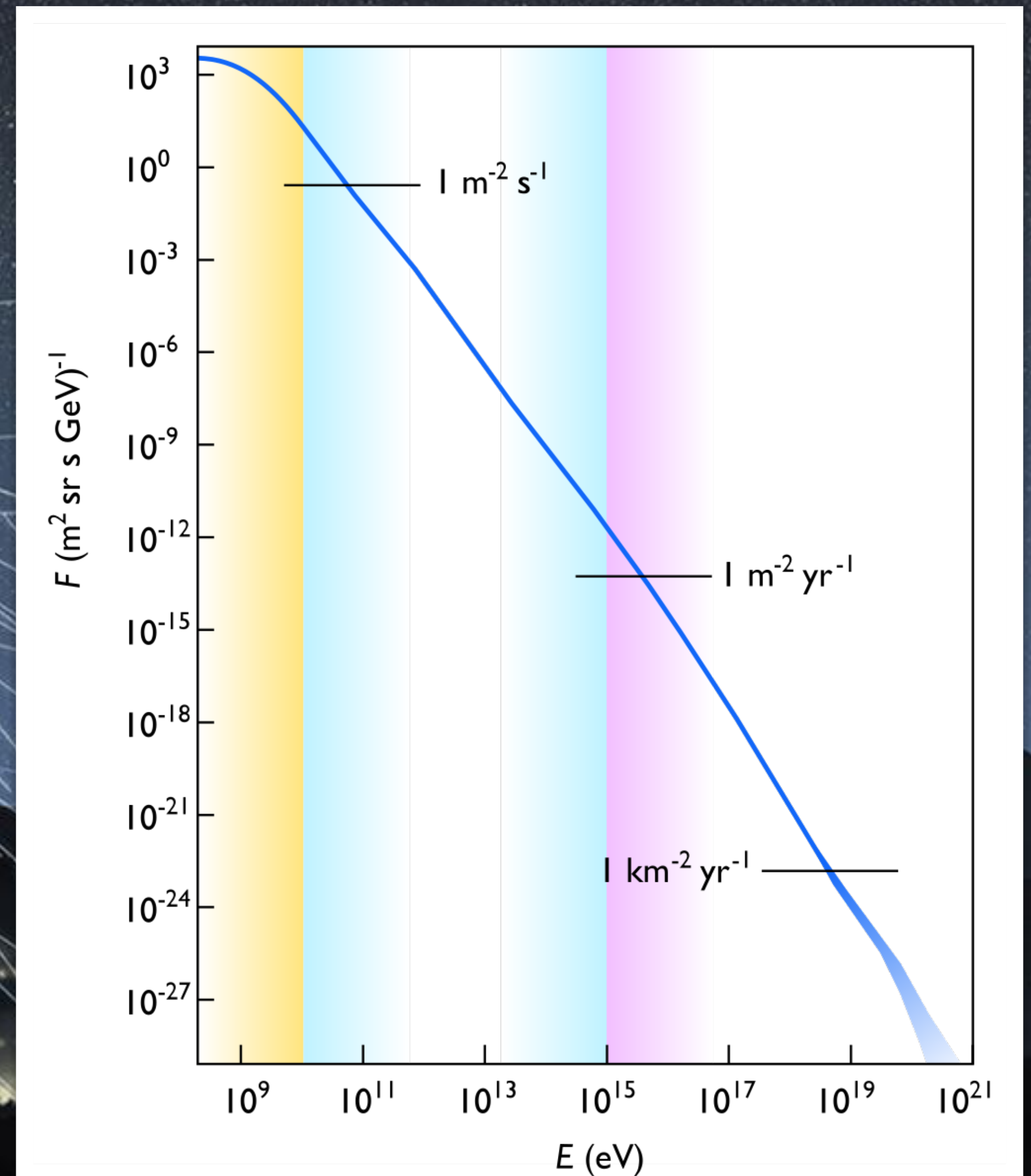
from a Balloon in Antarctica

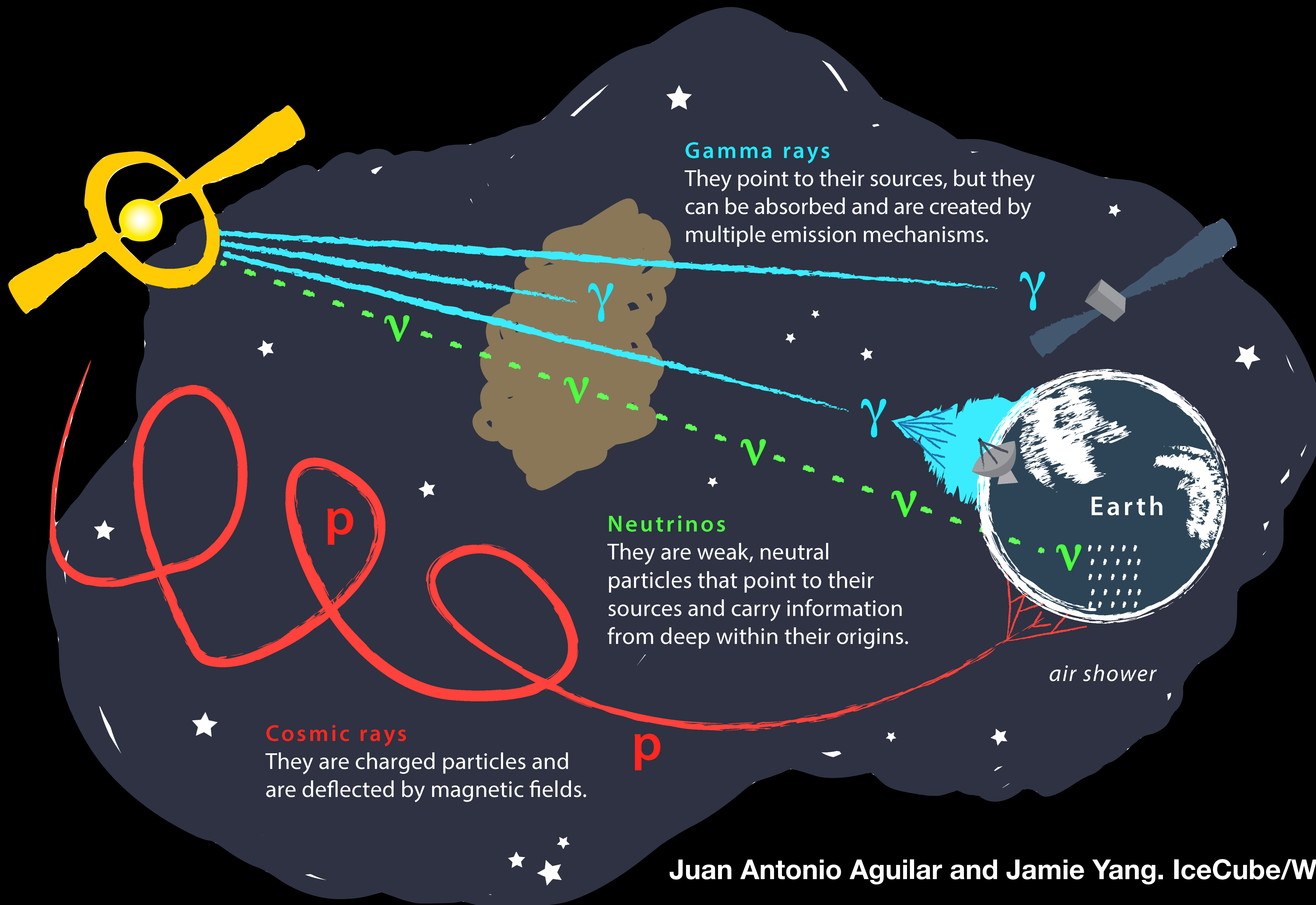


Stephanie Wissel, LPNHE Seminar, 15 June 2026

Cosmic Rays

- Energy density $\rho \sim 1 \text{ eV cm}^{-3}$ equivalent to cosmic microwave background radiation
- At highest energies (most energetic particle $3.2 \times 10^{20} \text{ eV}$) rare and of unknown origin





Gamma rays

They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos

They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays

They are charged particles and are deflected by magnetic fields.

Gamma rays

They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos

They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays

They are charged particles and are deflected by magnetic fields.

Earth

air shower

Redshift



$z = 0$

Note: v sources can be steady-state or transient



Redshift

$z = 0$

MeV γ

Discovered

TeV–PeV ν

“High-energy”

PeV p

Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

ν detection

HE ν

Redshift

$z = 0$

MeV γ

Discovered

TeV–PeV ν

“High-energy”

PeV p

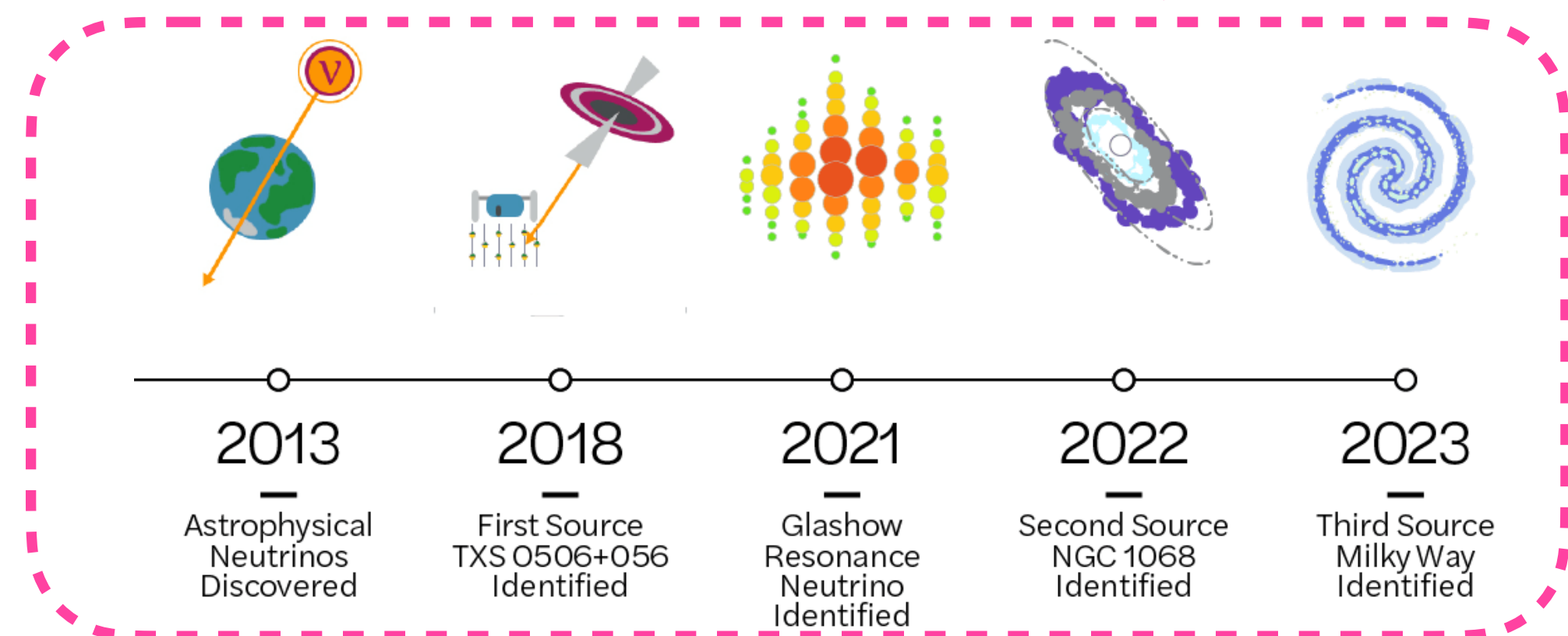
Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

ν detection

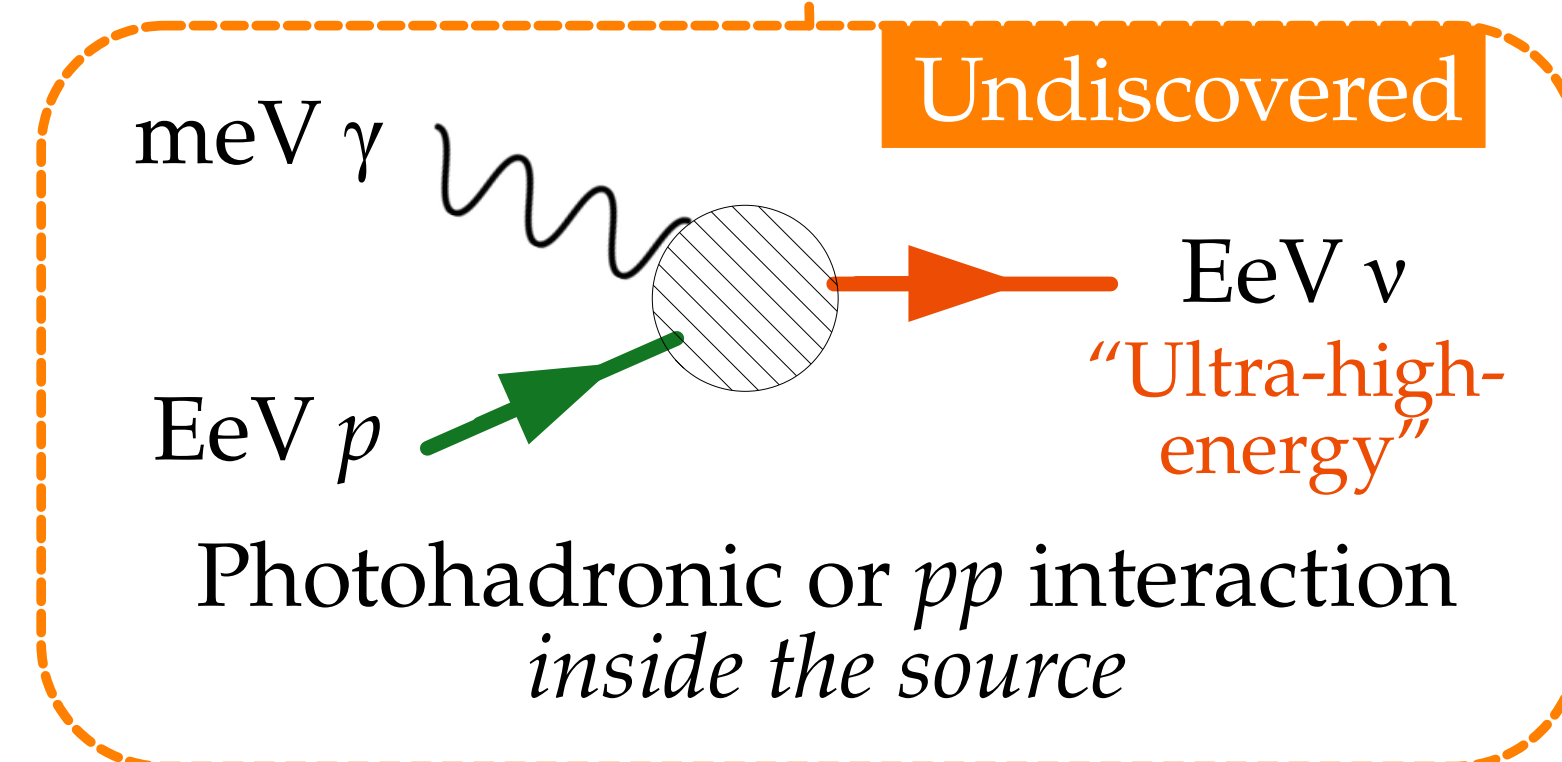
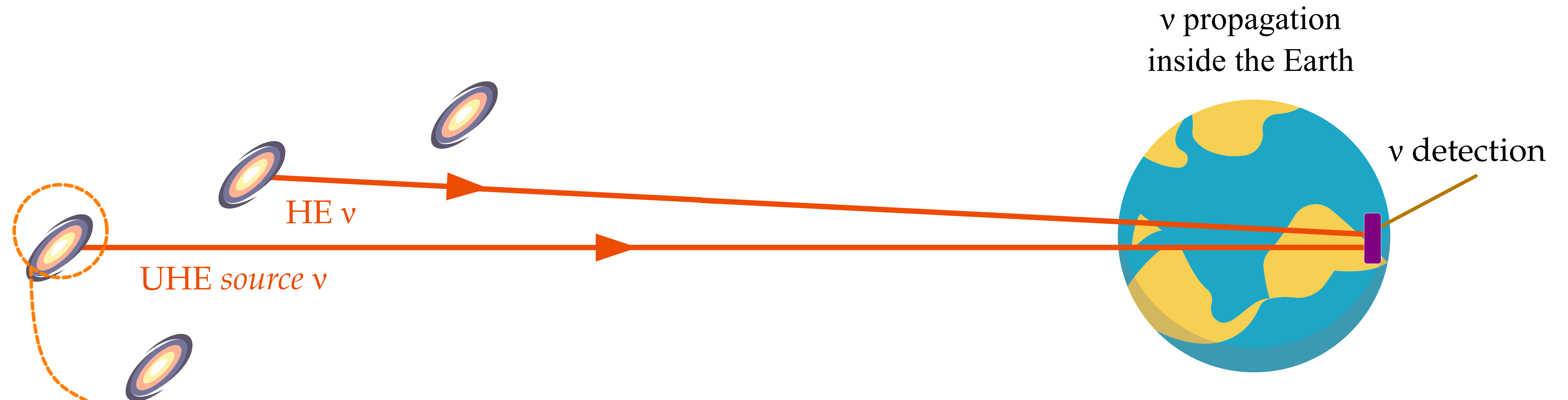
HE ν



Redshift

$z = 0$

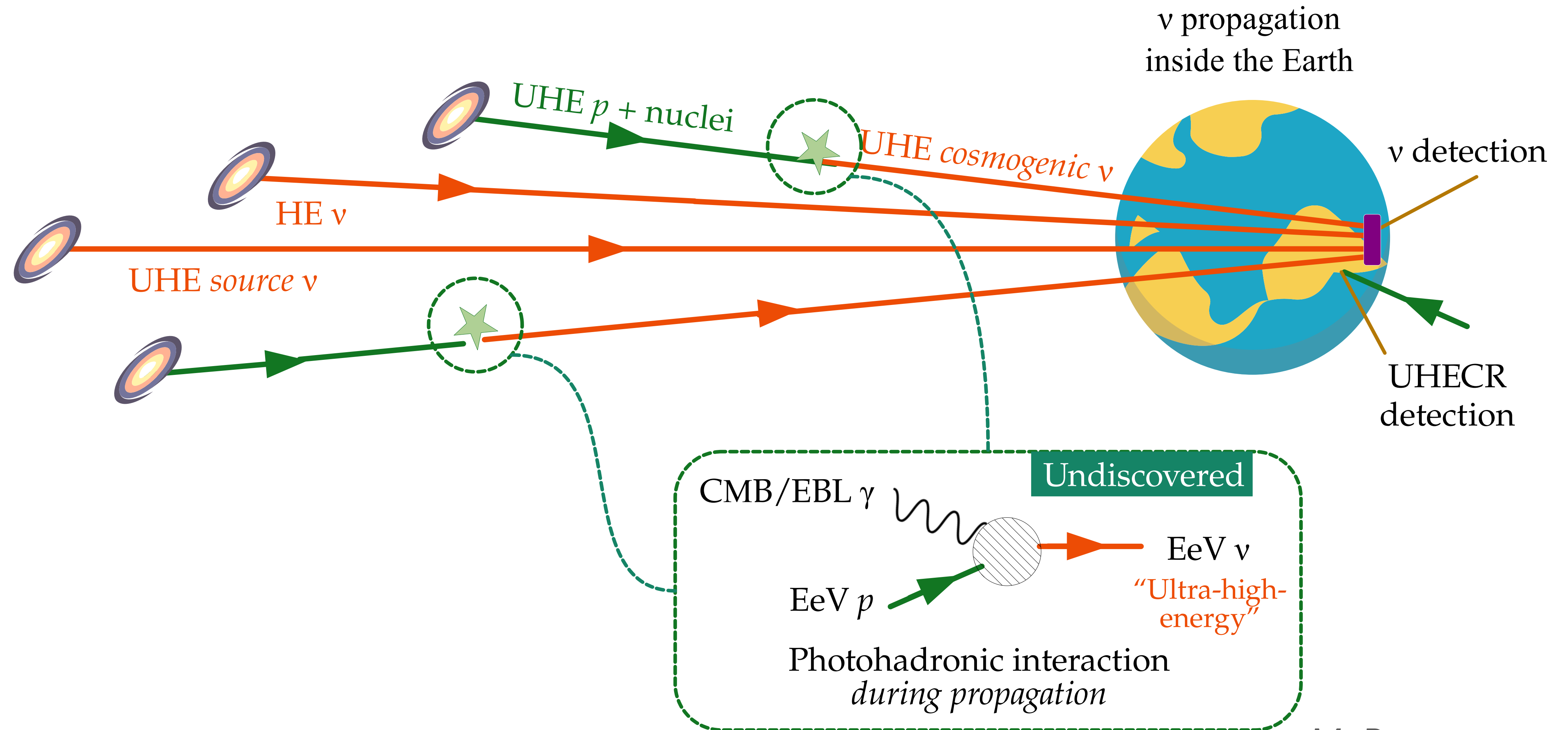
Note: ν sources can be steady-state or transient



Redshift

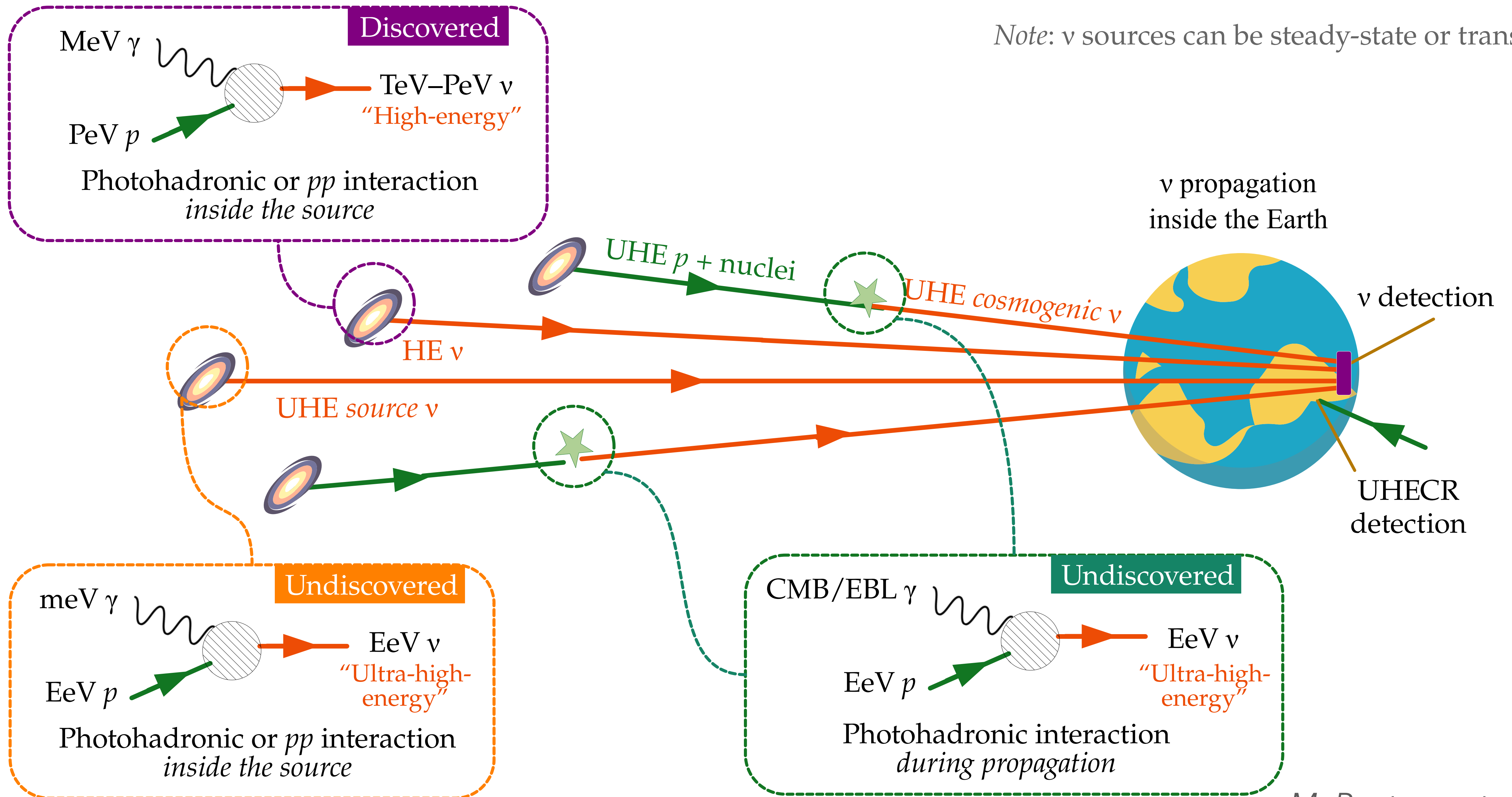
$z = 0$

Note: ν sources can be steady-state or transient



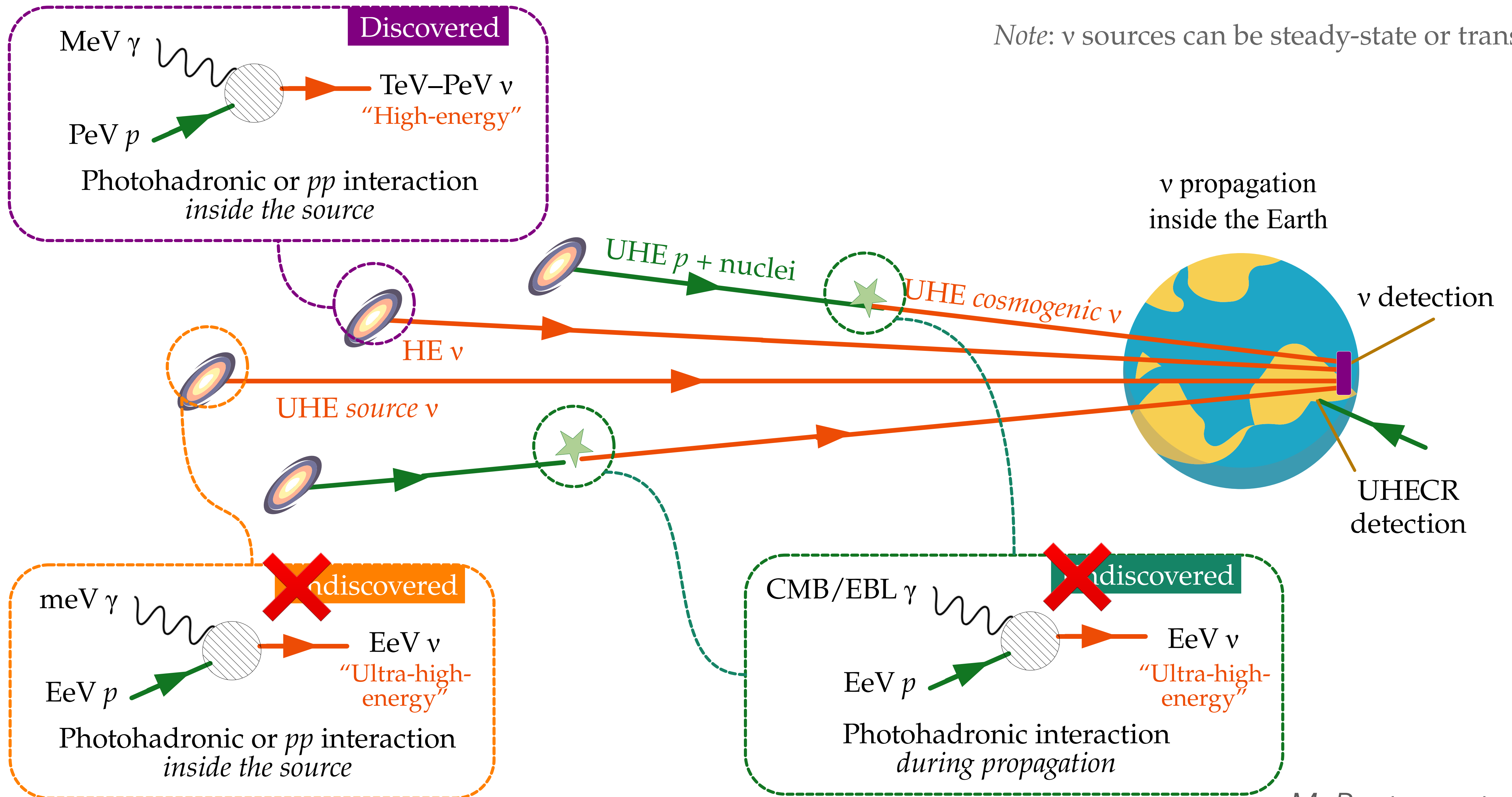
Redshift ← $z = 0$

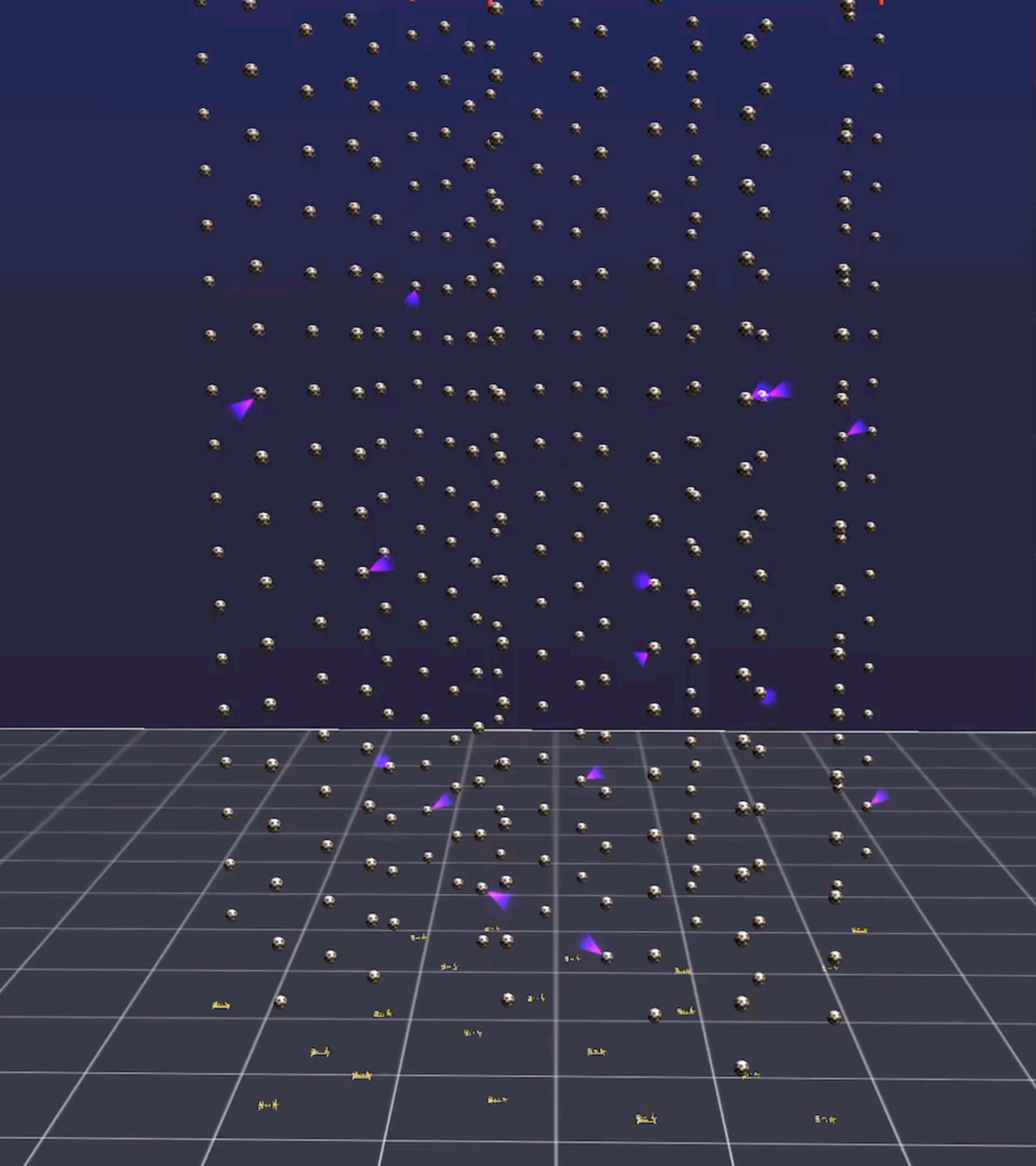
Note: ν sources can be steady-state or transient



Redshift ← $z = 0$

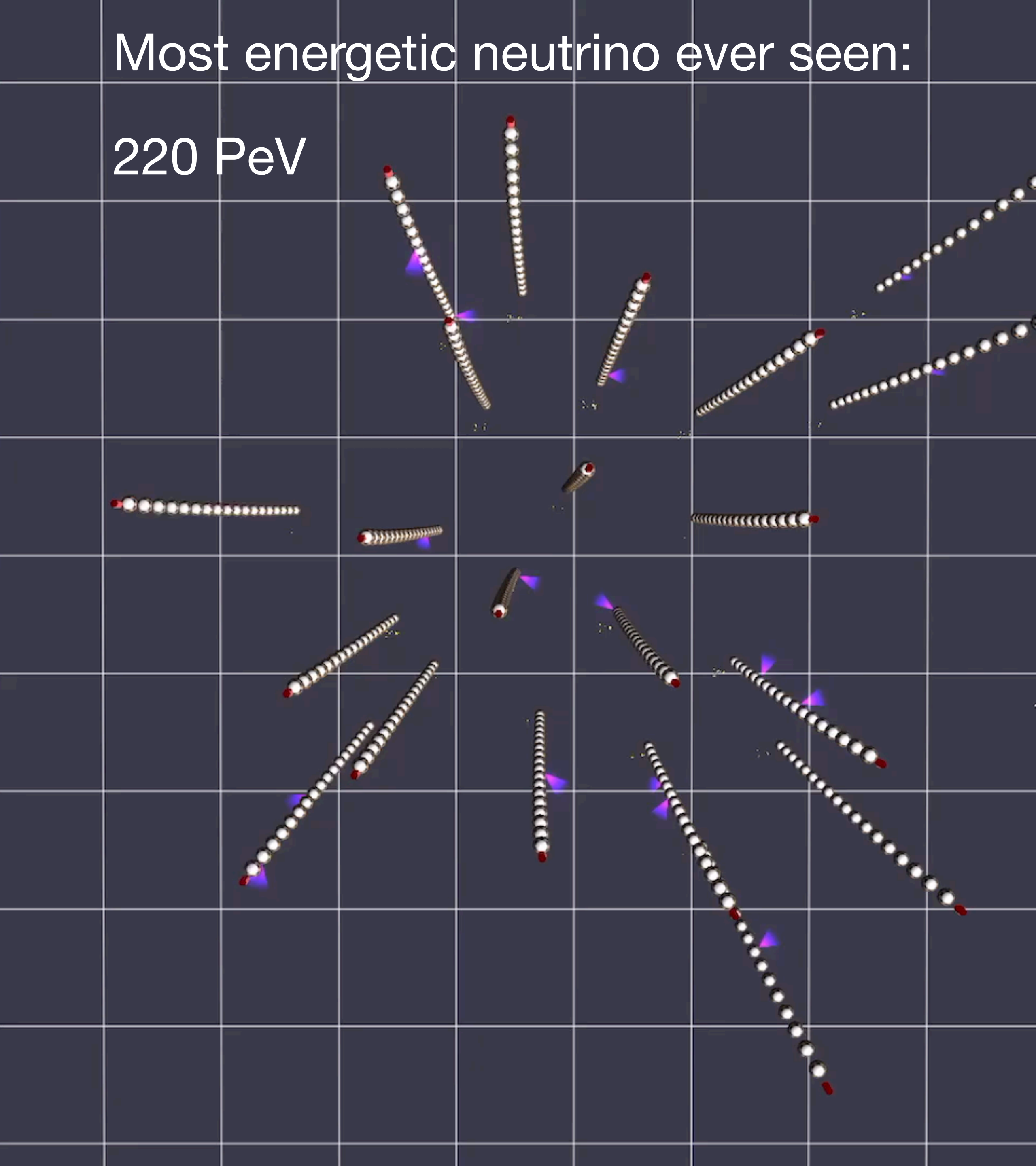
Note: ν sources can be steady-state or transient

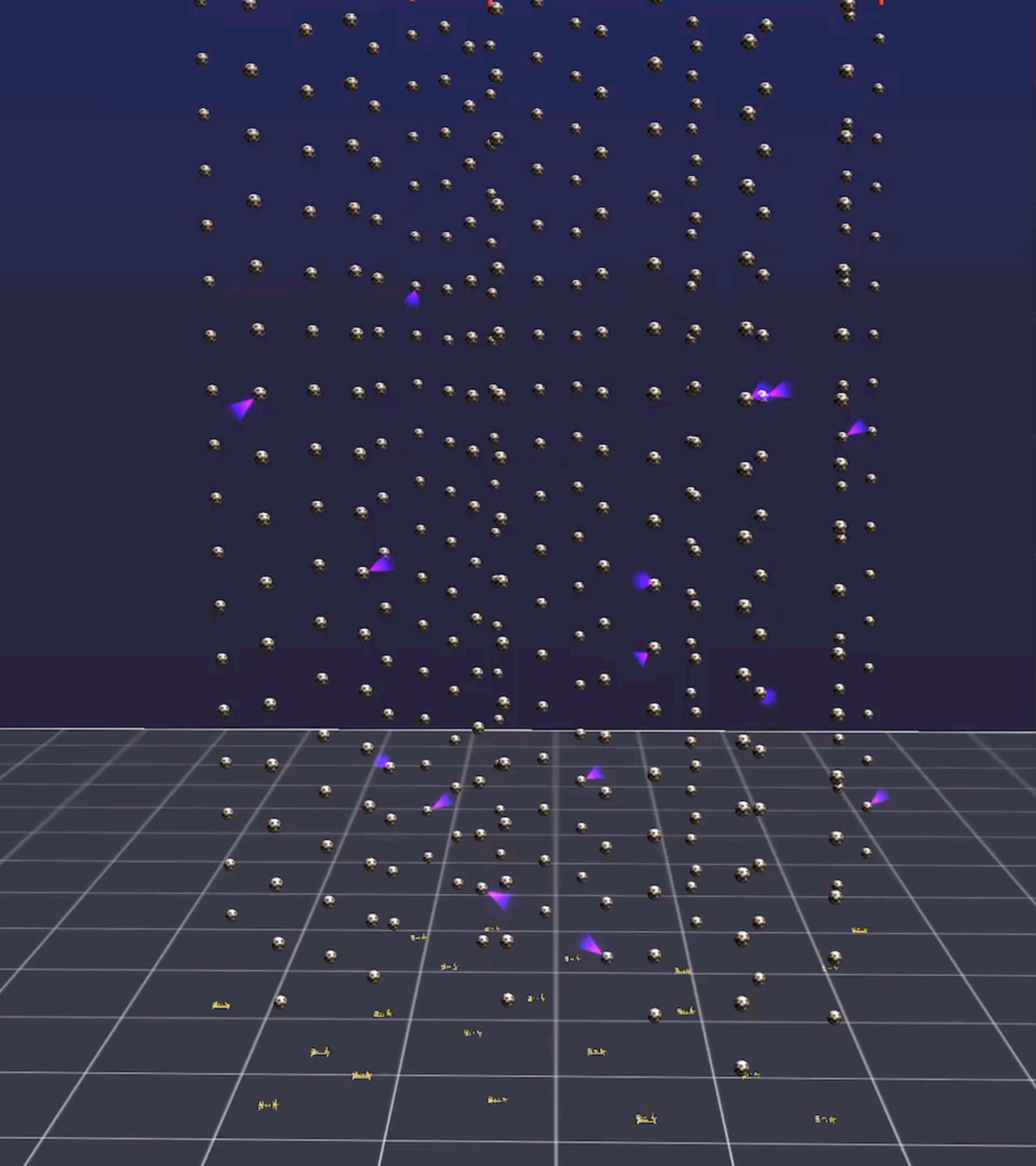




Most energetic neutrino ever seen:

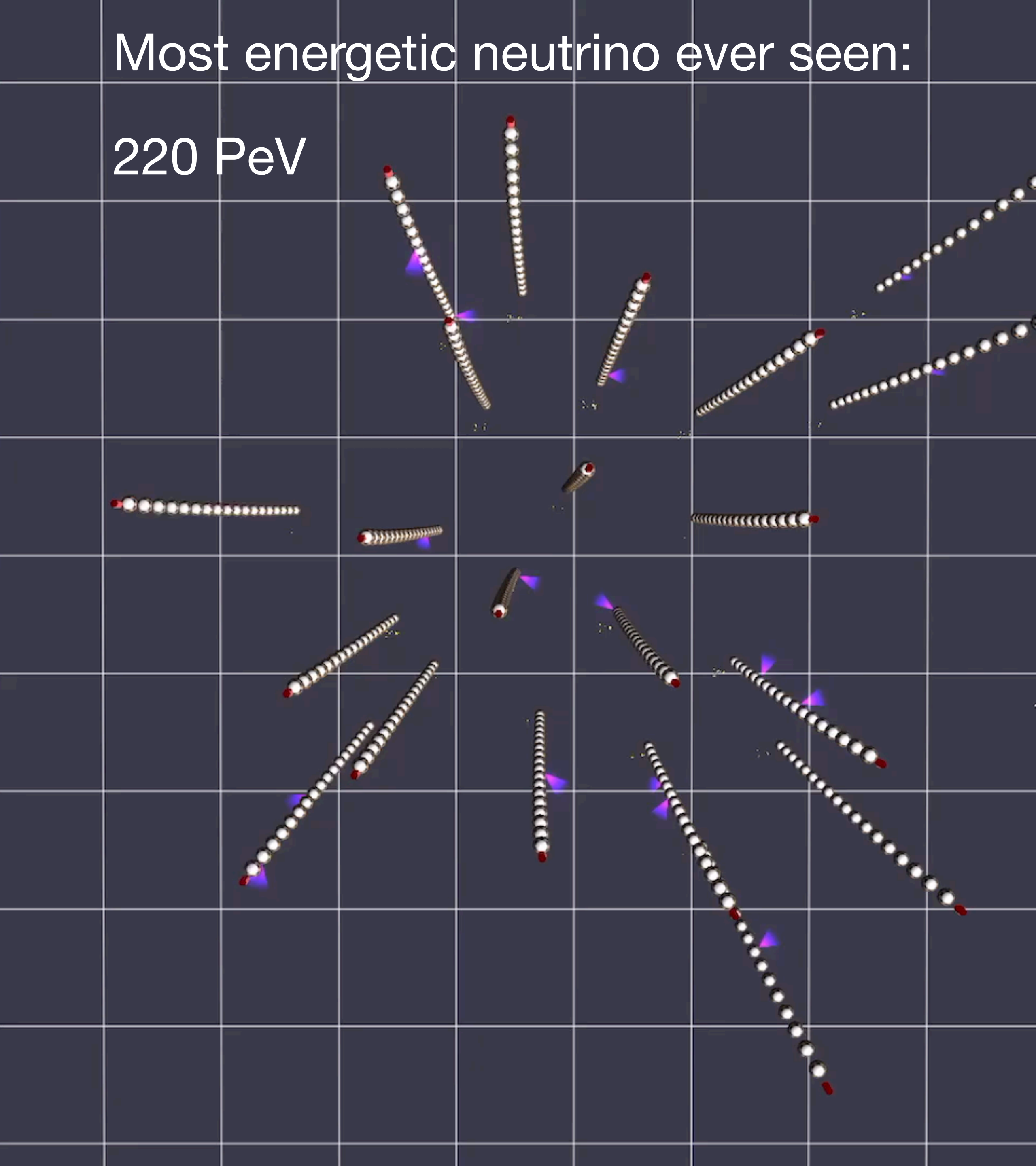
220 PeV





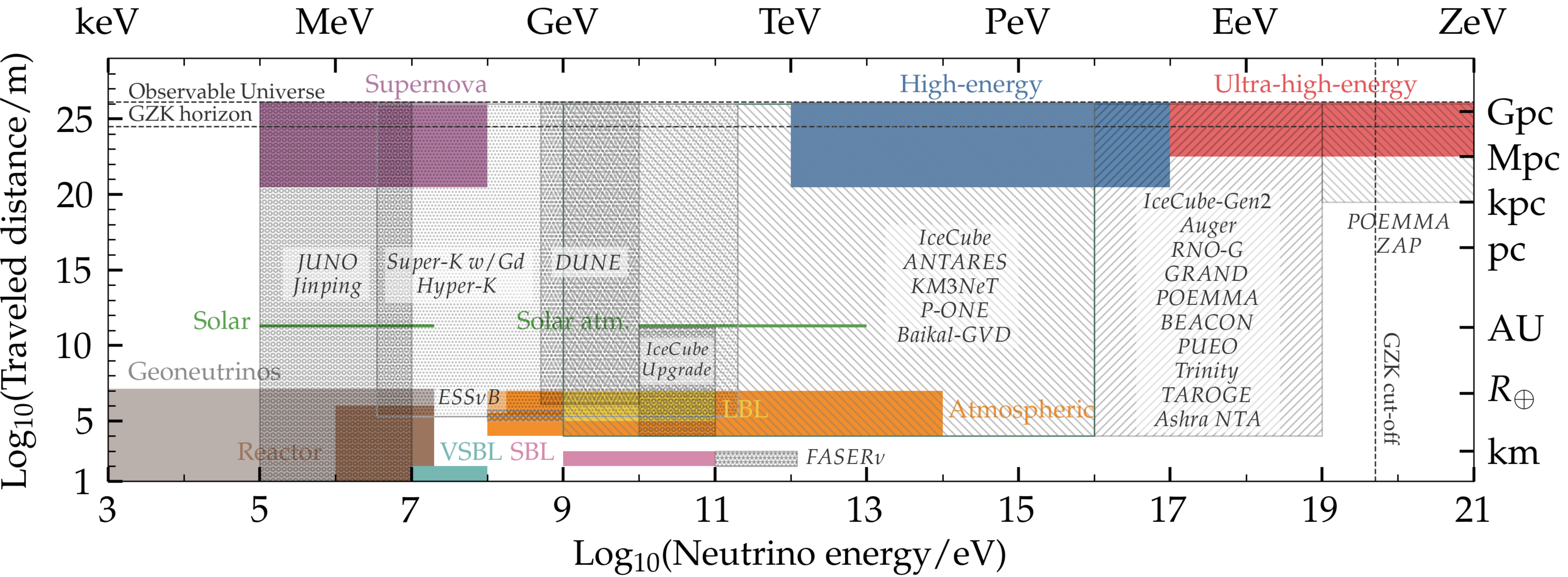
Most energetic neutrino ever seen:

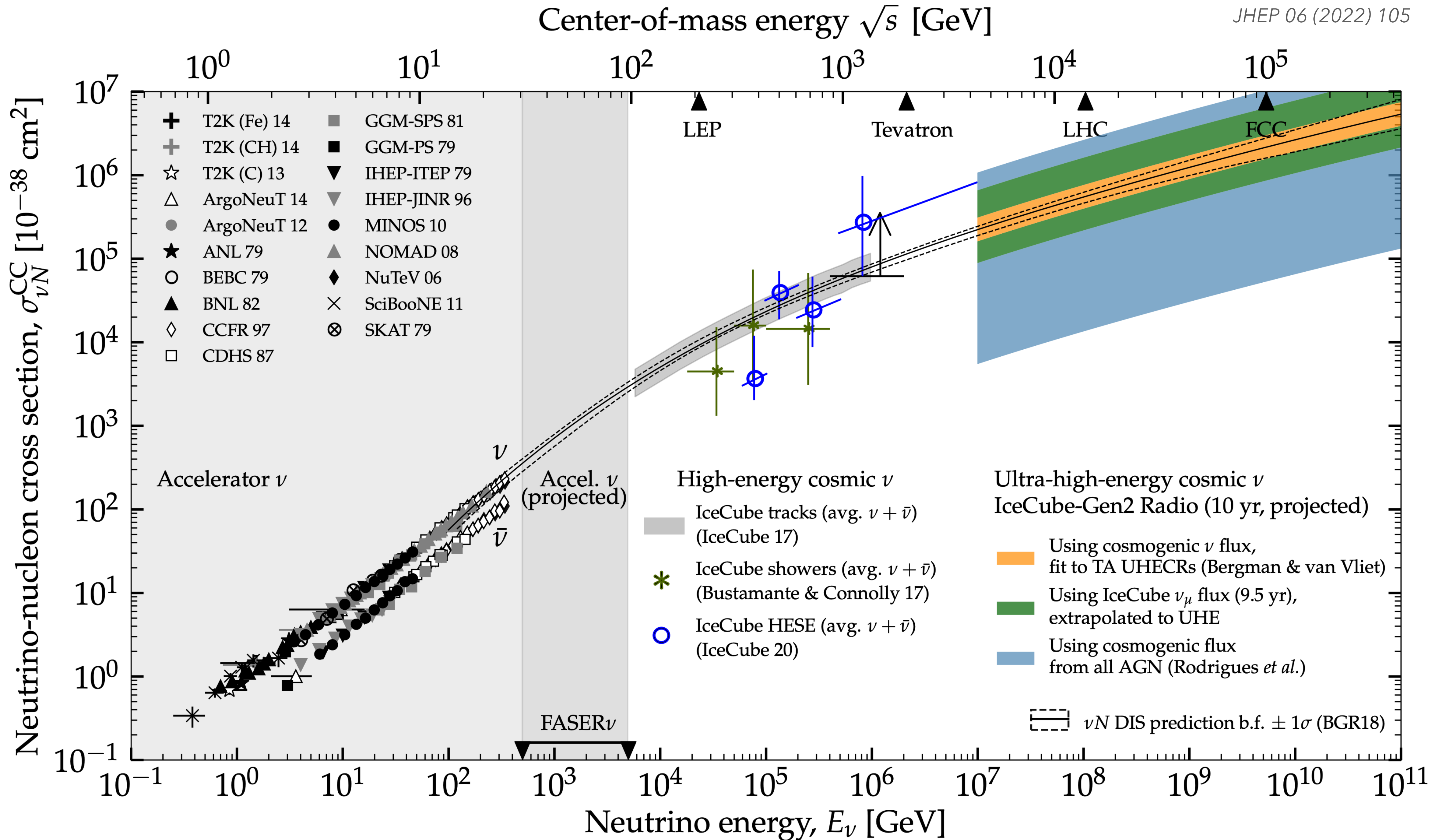
220 PeV



FUNDAMENTAL PHYSICS AT THE HIGHEST ENERGIES

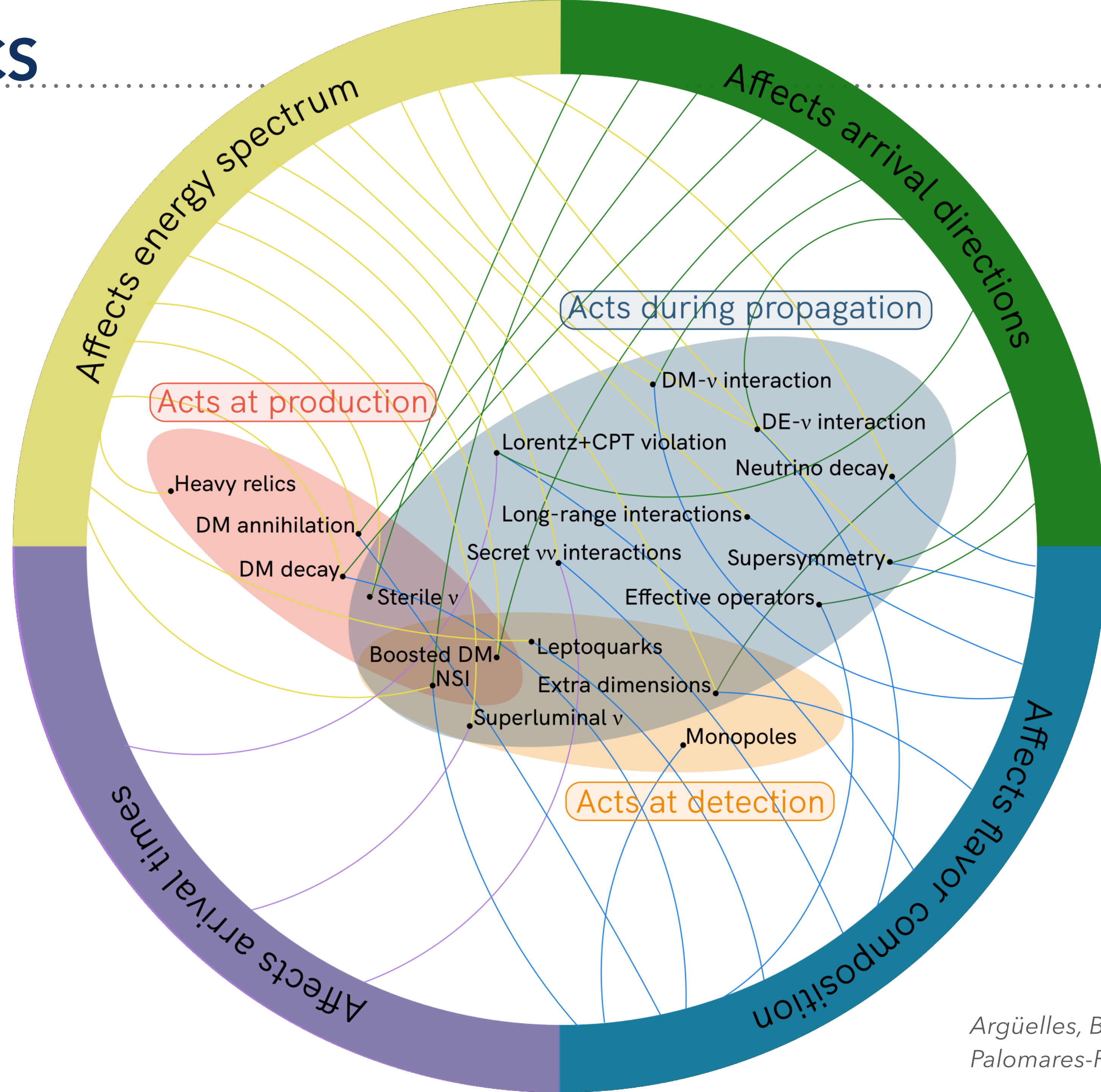
- Fundamental physics probe at the highest energy scales (TeV to ZeV)
- Longest baselines (~Gpc) allow even small effects to accumulate





NEW PHYSICS

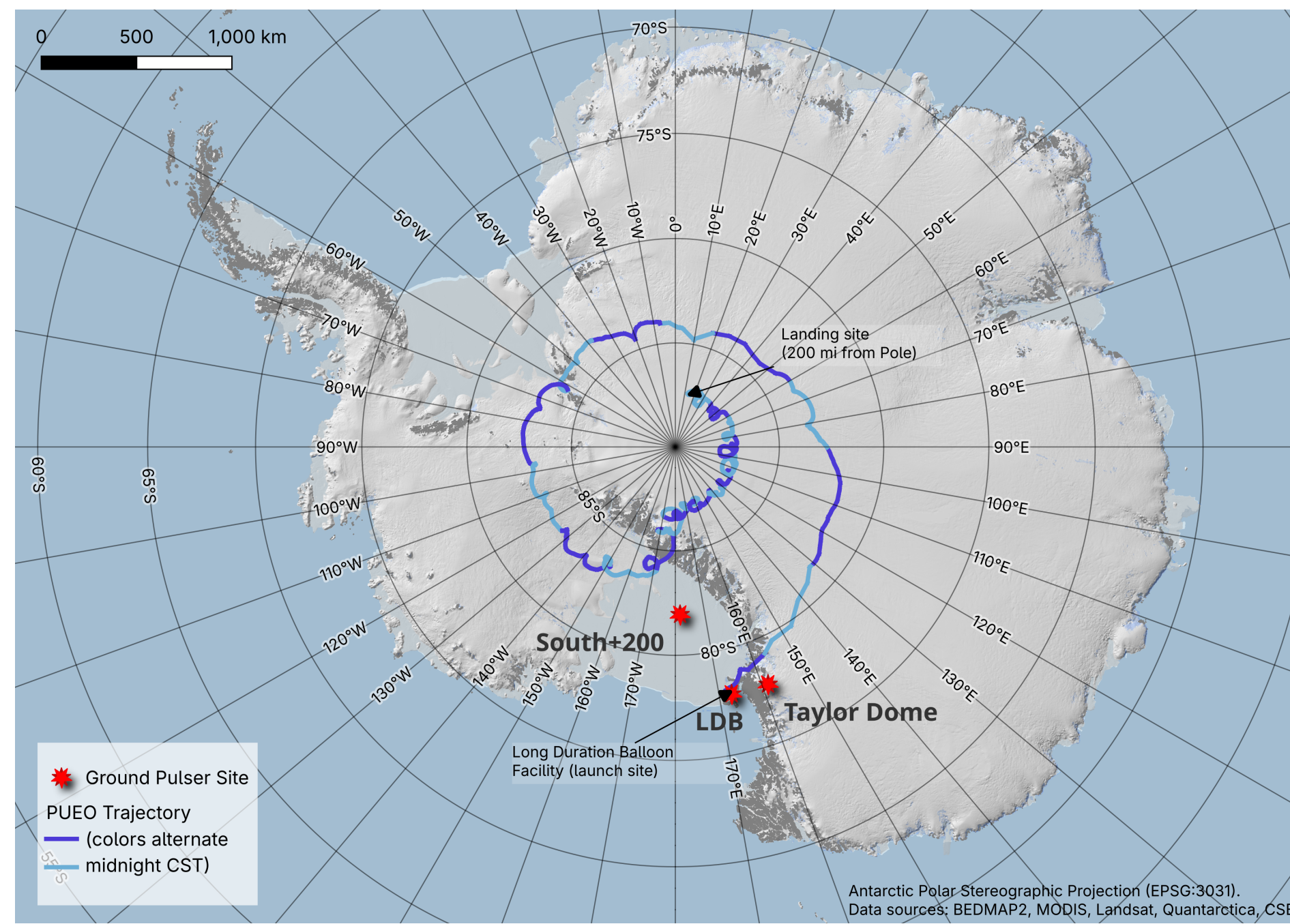
IMPACT ON NEUTRINOS



PUEO

and its flight

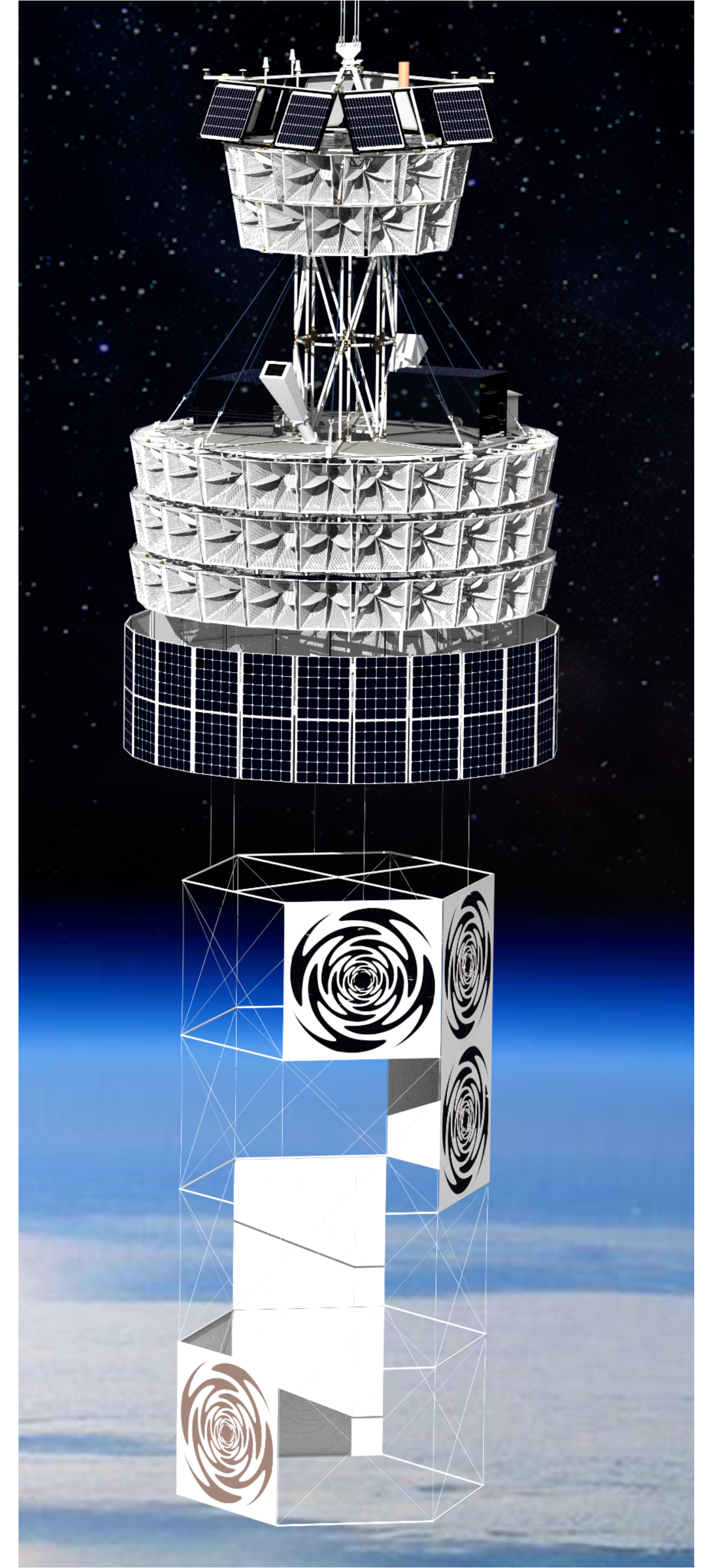
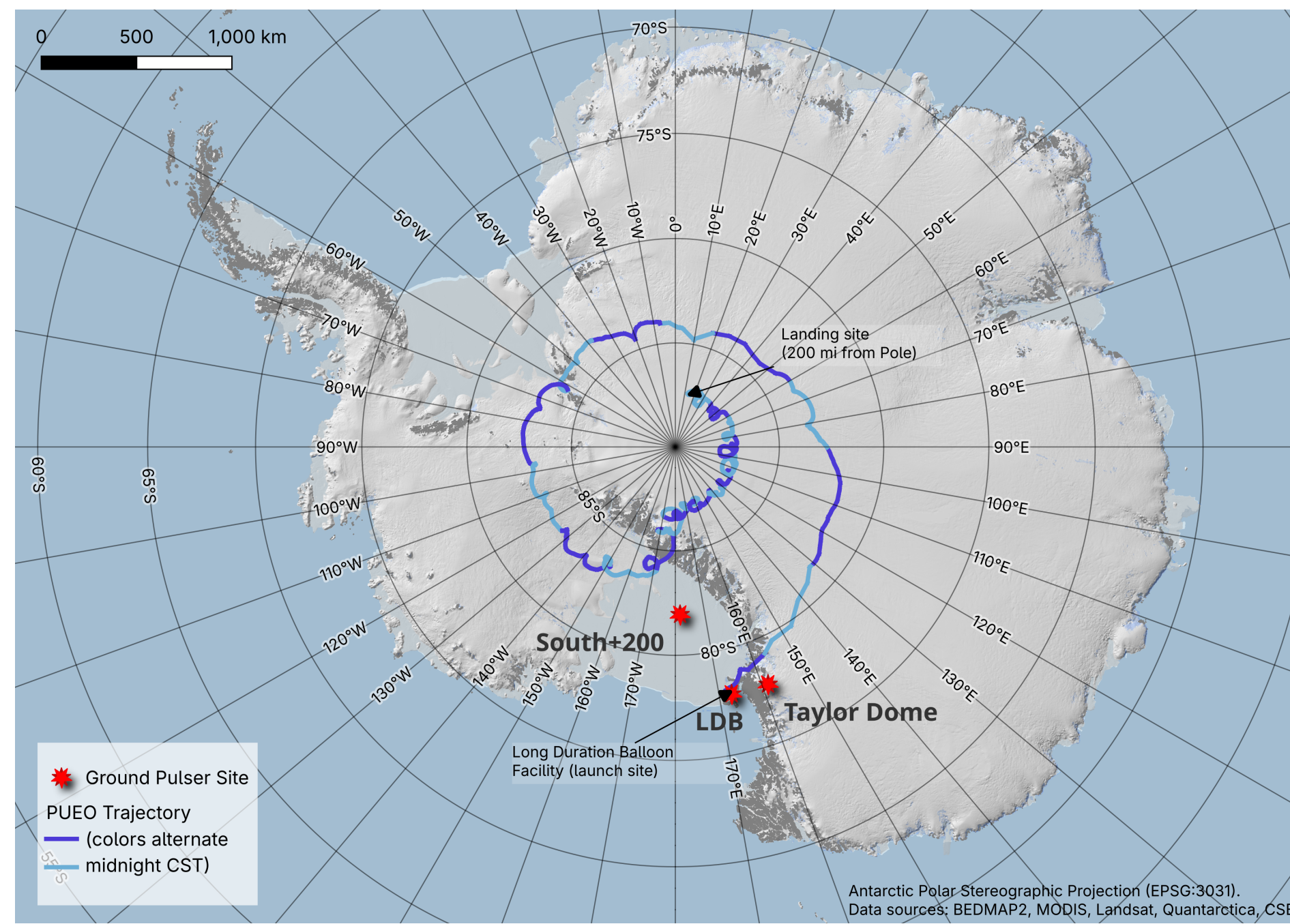
- Discovery mission – main science goal is to detect ultrahigh energy (UHE), >1 EeV, neutrinos
- Long duration balloon-borne payload, successor to ANITA I-IV – designed to detect neutrinos as they interact in Antarctic ice
- Launched from McMurdo on December 20, 2025 and flew for 23 days, 9 hours day flight



PUEO

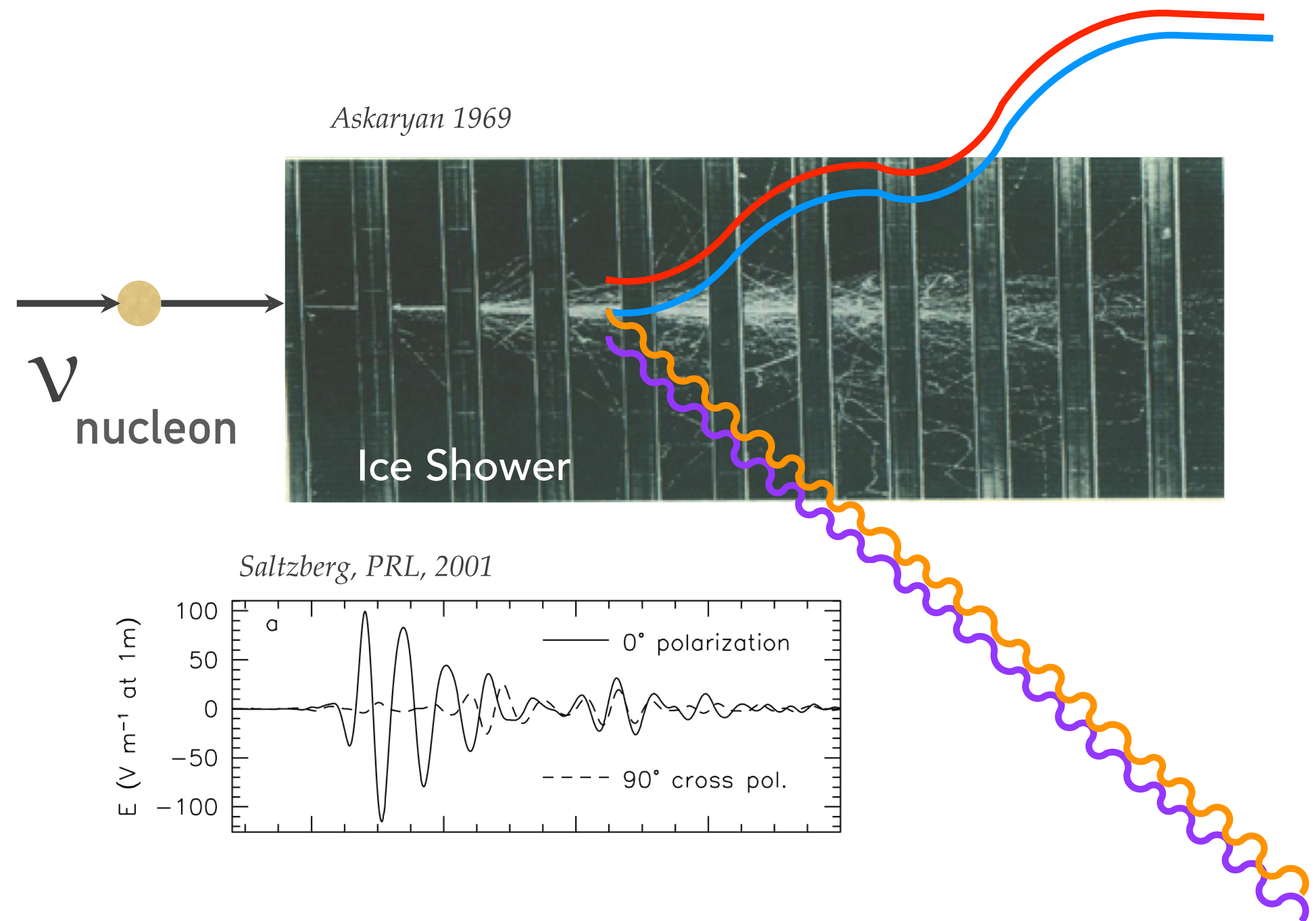
and its flight

- Discovery mission – main science goal is to detect ultrahigh energy (UHE), >1 EeV, neutrinos
- Long duration balloon-borne payload, successor to ANITA I-IV – designed to detect neutrinos as they interact in Antarctic ice
- Launched from McMurdo on December 20, 2025 and flew for 23 days, 9 hours day flight



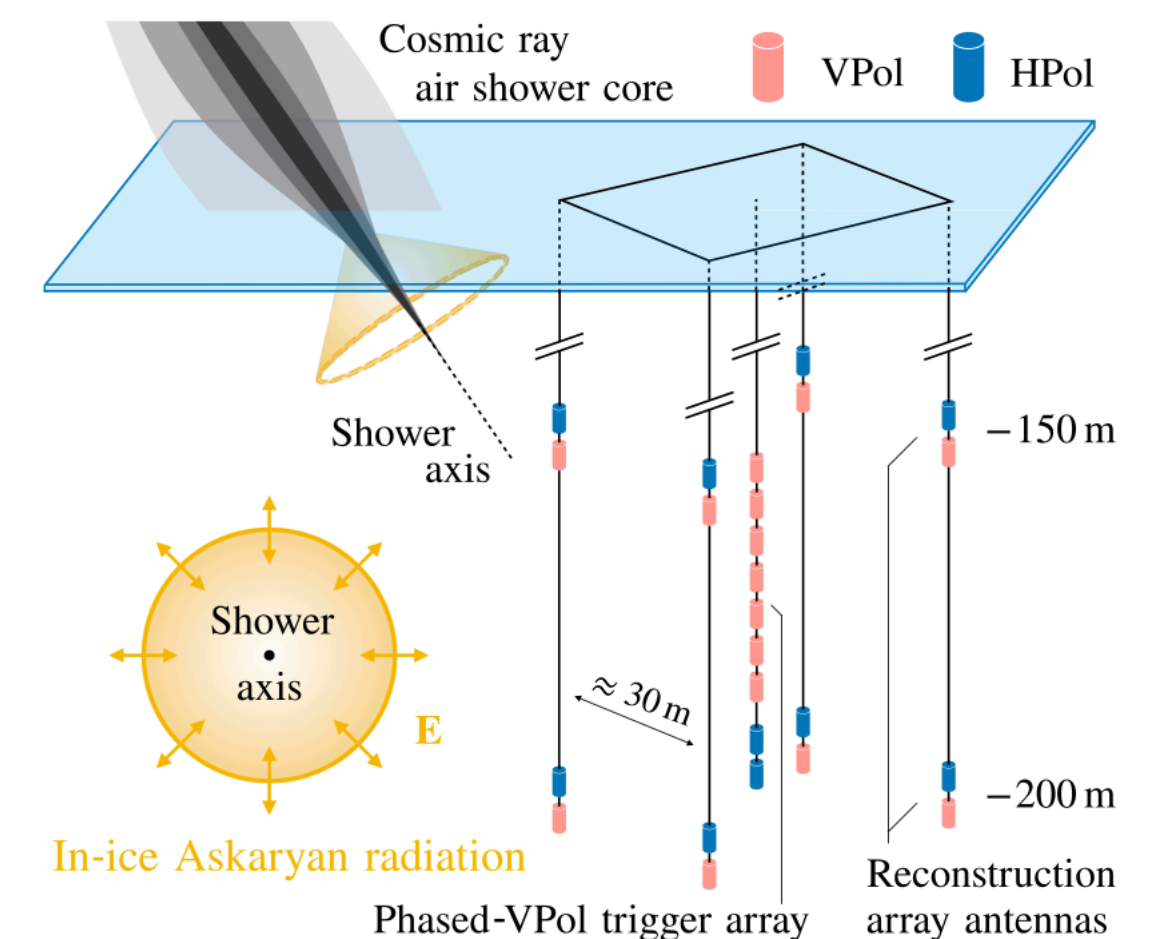
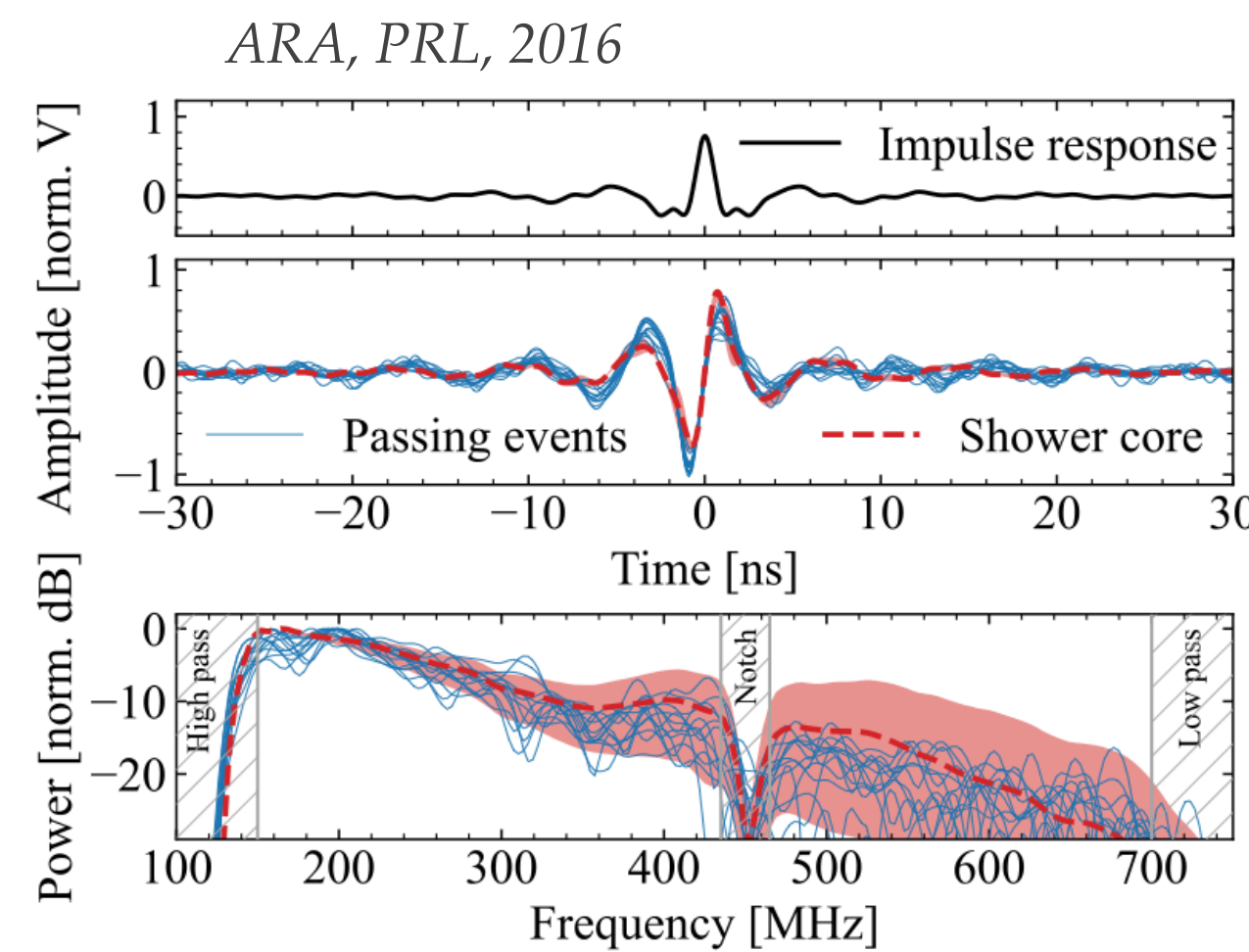
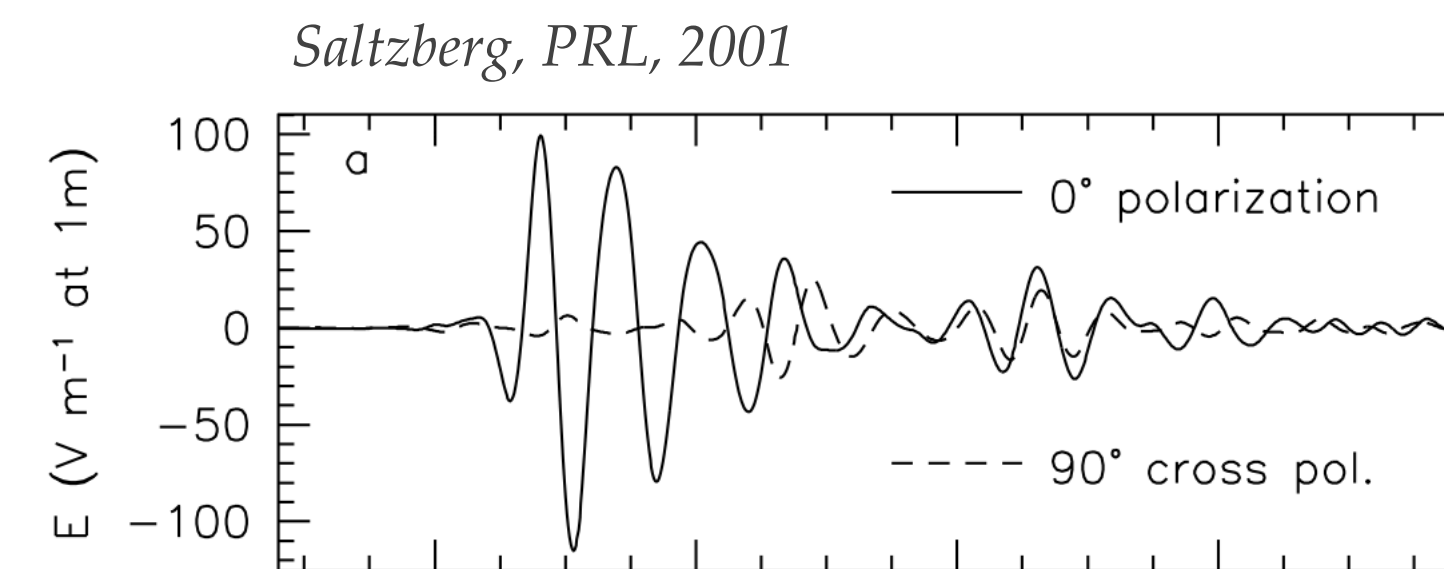
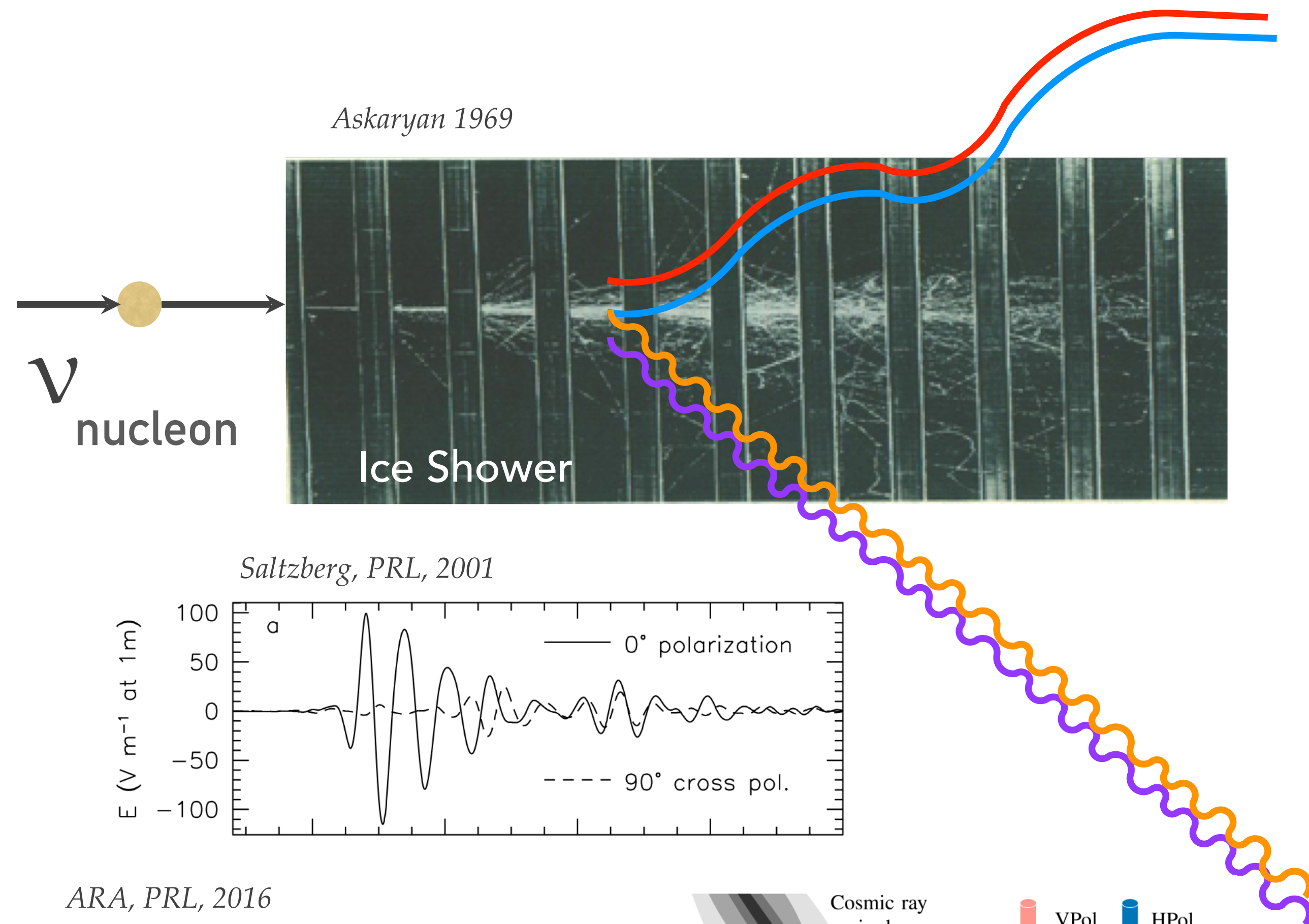
Radio Emission from Neutrino In-Ice Showers

- **Askaryan emission:** radiation from net negative charge excess in shower. Dominant for ***in-ice*** showers
- Boost due to coherence effects near the Cherenkov angle



Radio Emission from Neutrino In-Ice Showers

- **Askaryan emission:** radiation from net negative charge excess in shower. Dominant for ***in-ice*** showers
- Boost due to coherence effects near the Cherenkov angle



Balloon-Borne Radio Neutrino Detection Concept

Compact shower from neutrino interaction in ice

Askaryan Radiation: Coherent radio emission due to the charge excess

Effective area boosted by high-altitude flight



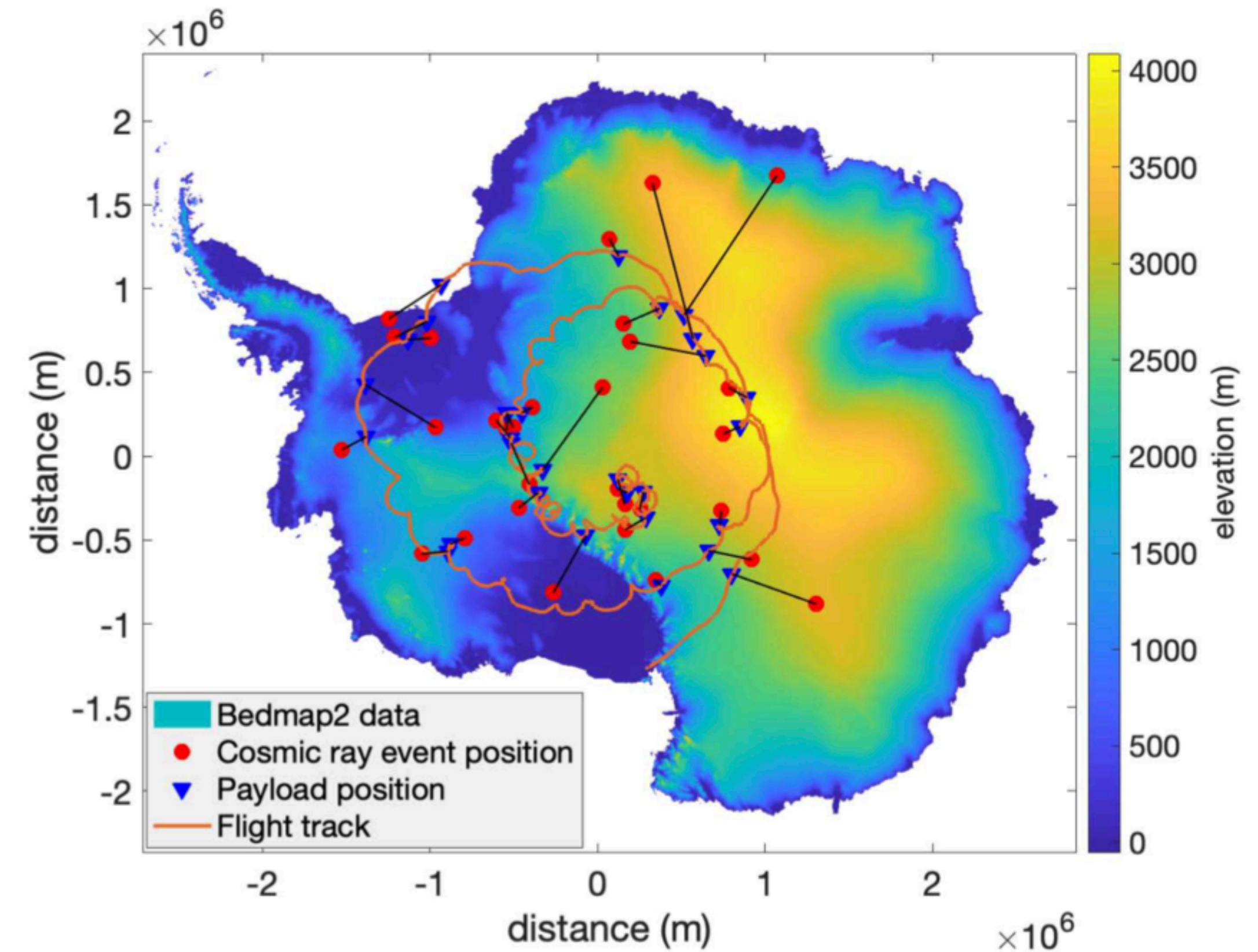
PUEO's design targets specifically the Askaryan neutrino channel

Builds on heritage of four flights of ANITA

Why Antarctica?

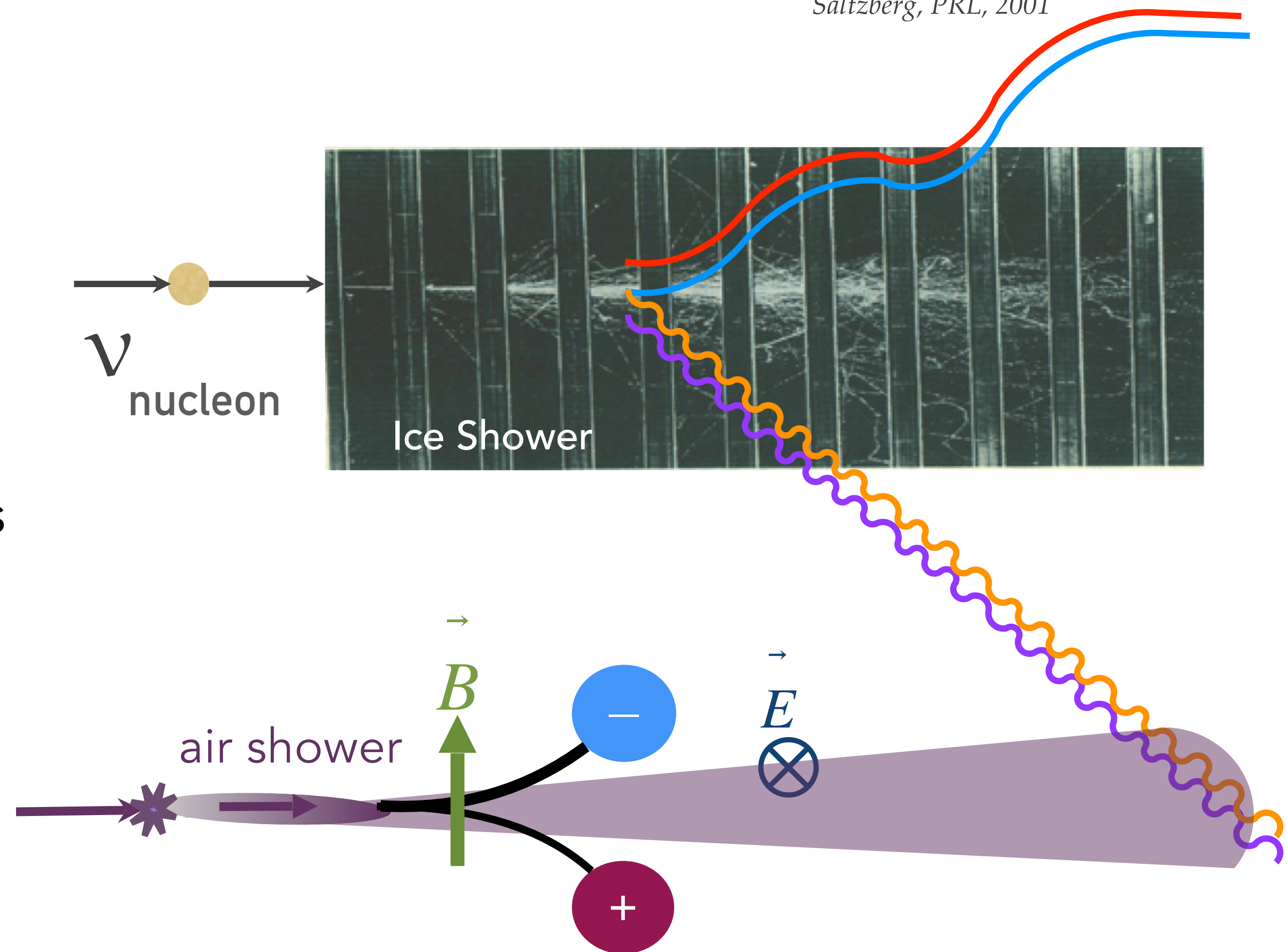
Favorable location because:

- Very cold ice has a long attenuation length
- Established ballooning infrastructure provided by NASA
- Circumpolar vortex keeps the balloon over the continent for weeks
- Large volume of ice – 3 km depth across much of the continent means $\mathcal{O}(10^6)$ km³ visible to a balloon through much of the flight



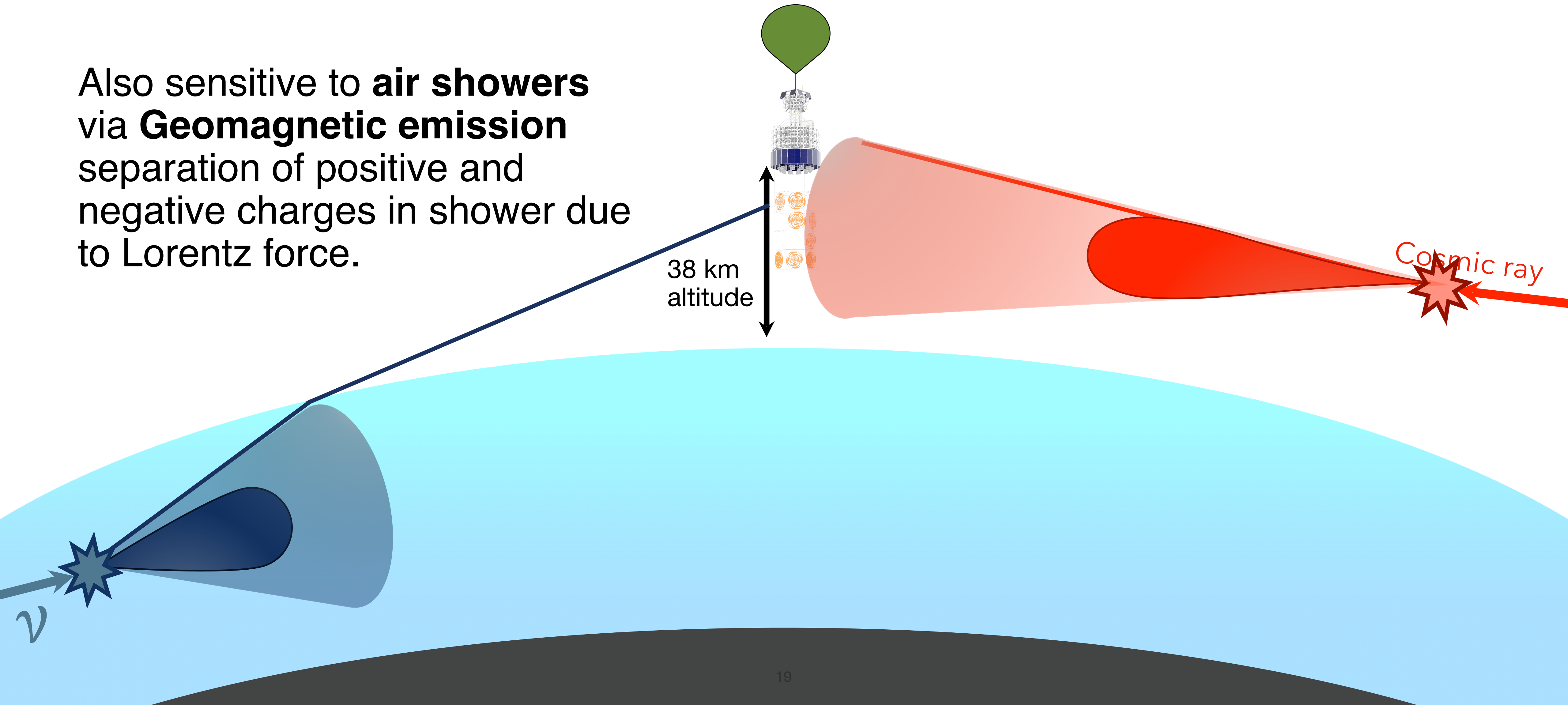
Radio Emission from Particle Showers

- **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

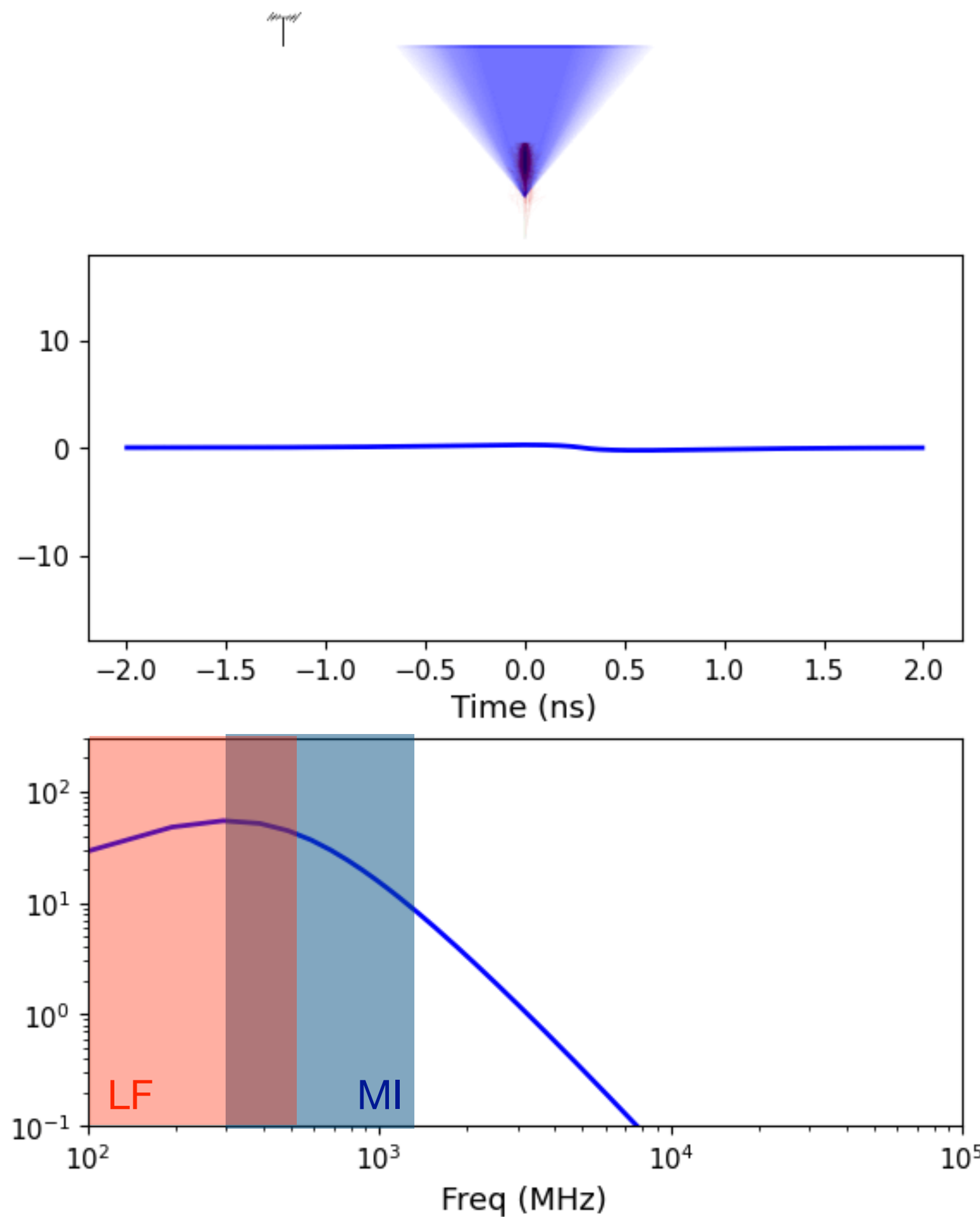
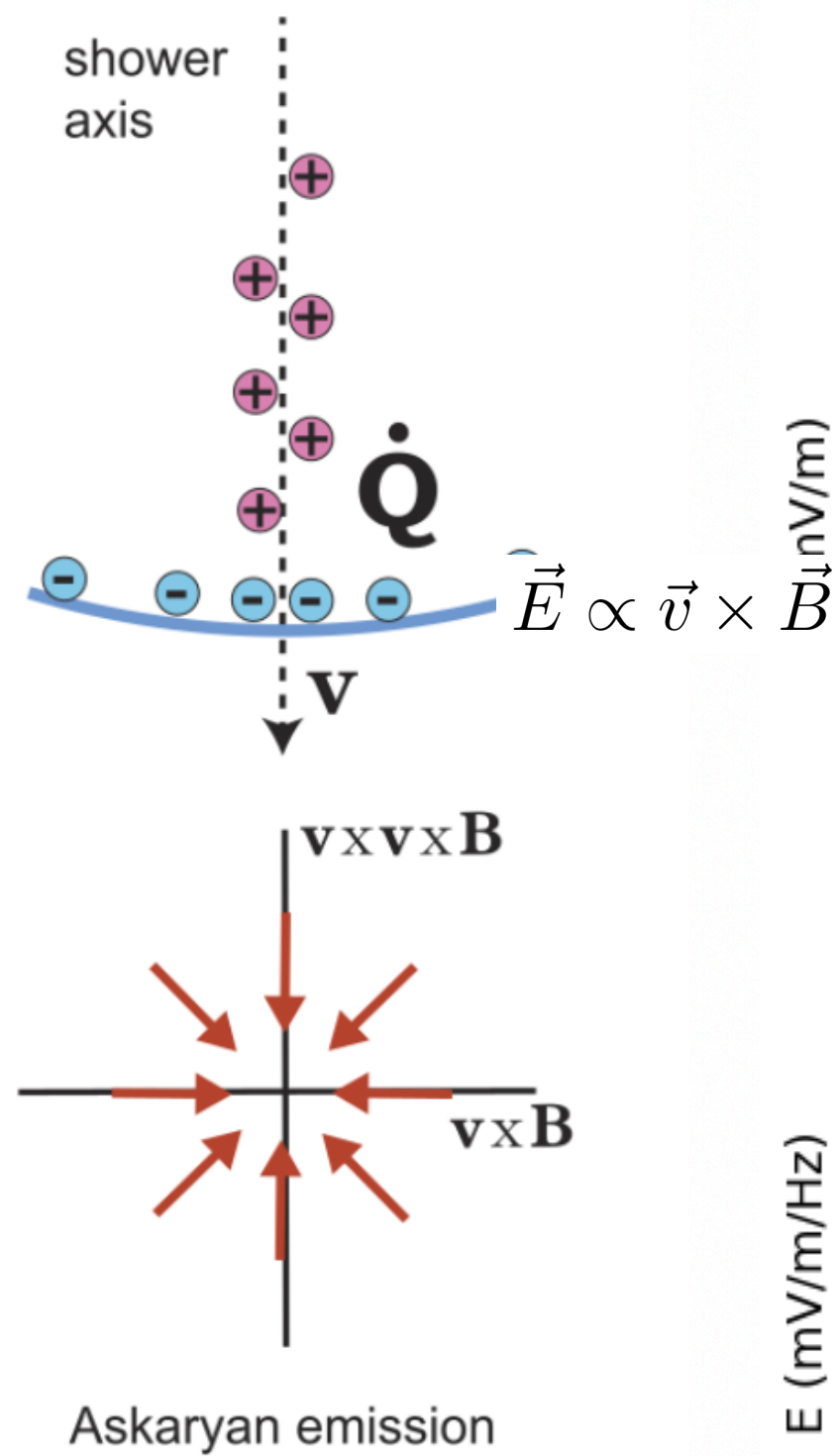


PUEO's Astroparticle Detection Channels

Also sensitive to **air showers** via **Geomagnetic emission** separation of positive and negative charges in shower due to Lorentz force.

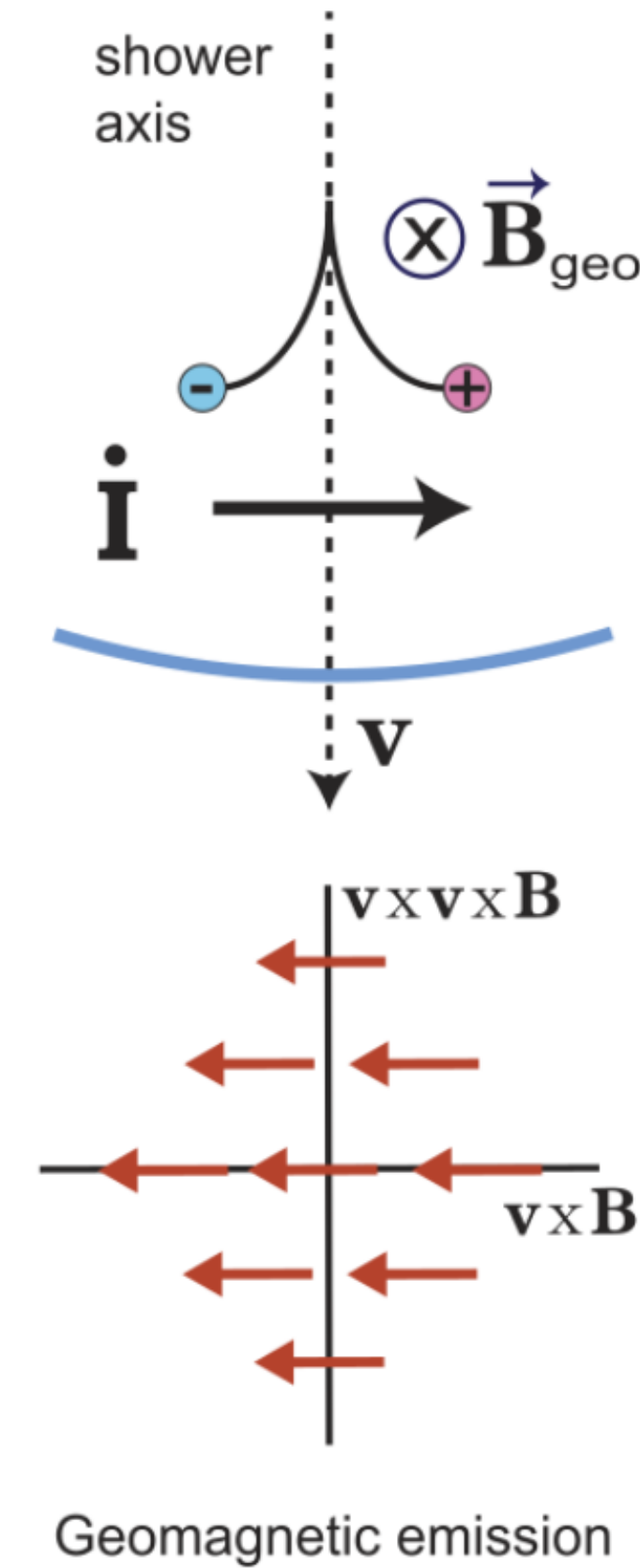
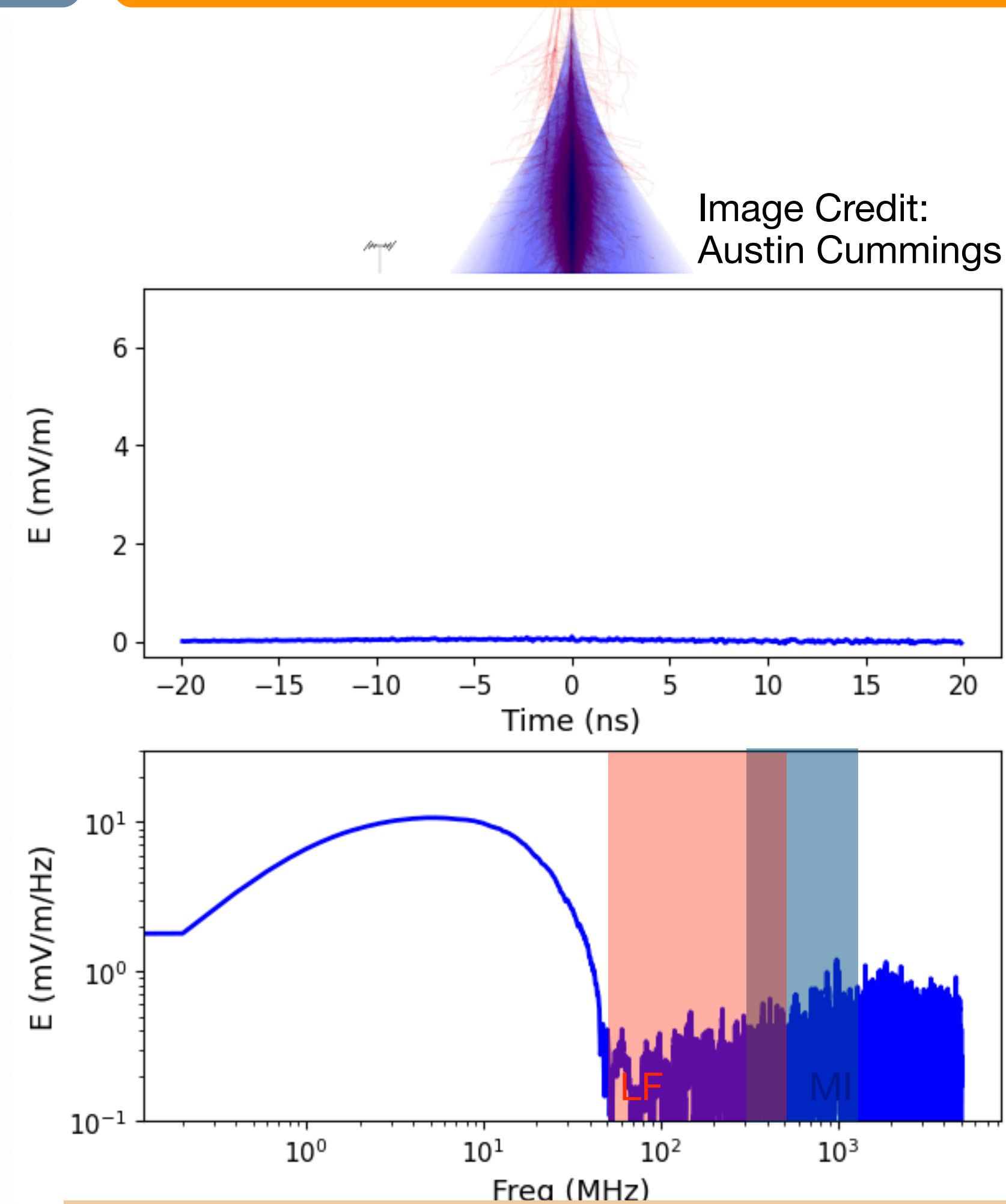


In-Ice Showers (Askaryan)



- Net 20% charge excess (e^+ annihilation & Bhabba)
- Radially Polarized
- Coherent up to scattering length in compact showers cutoff $\mathcal{O}(\text{cm}) \rightarrow \mathcal{O}(10\text{GHz})$ at Cherenkov angle (54° in ice)

Air Showers (Geomagnetic)

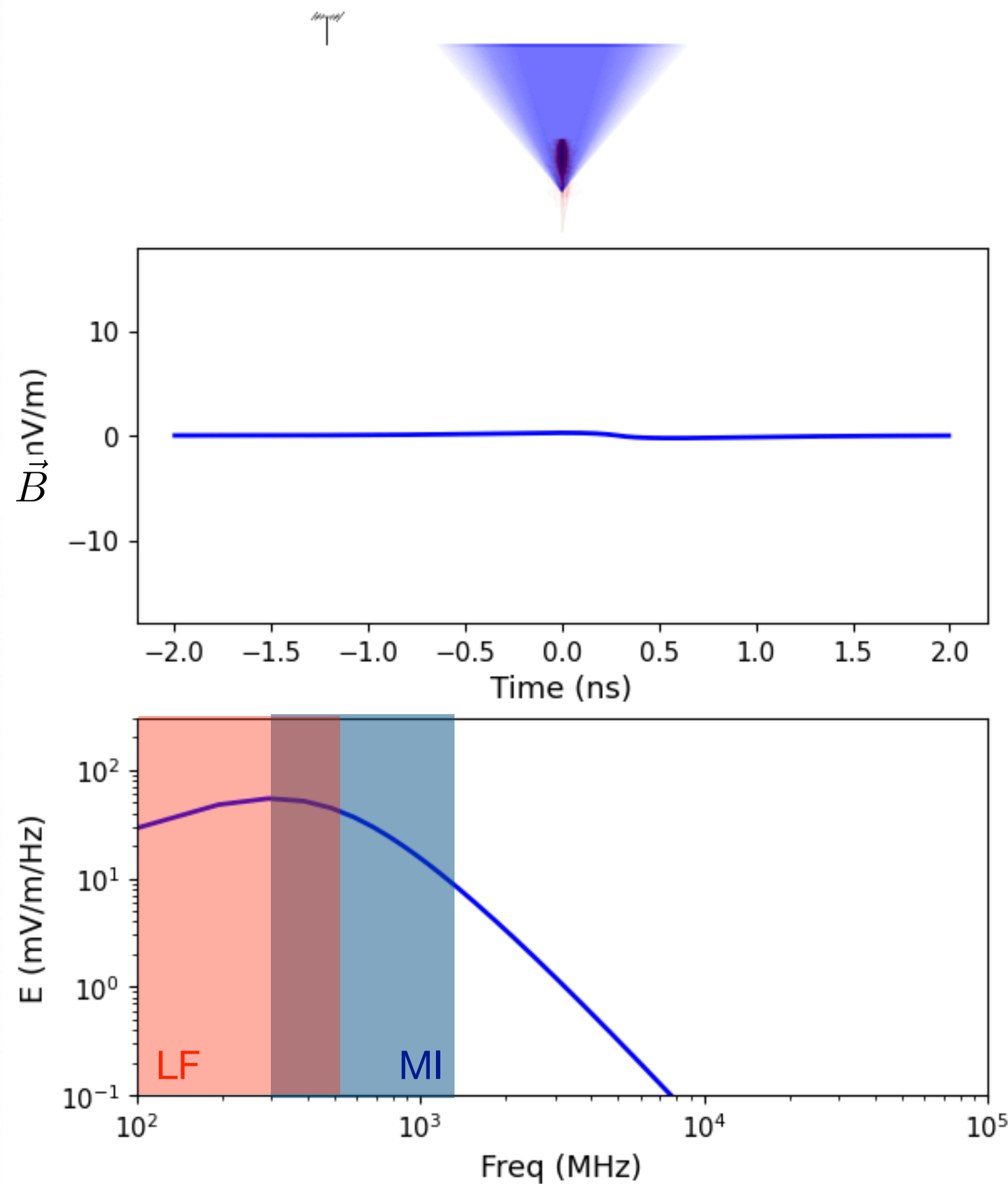
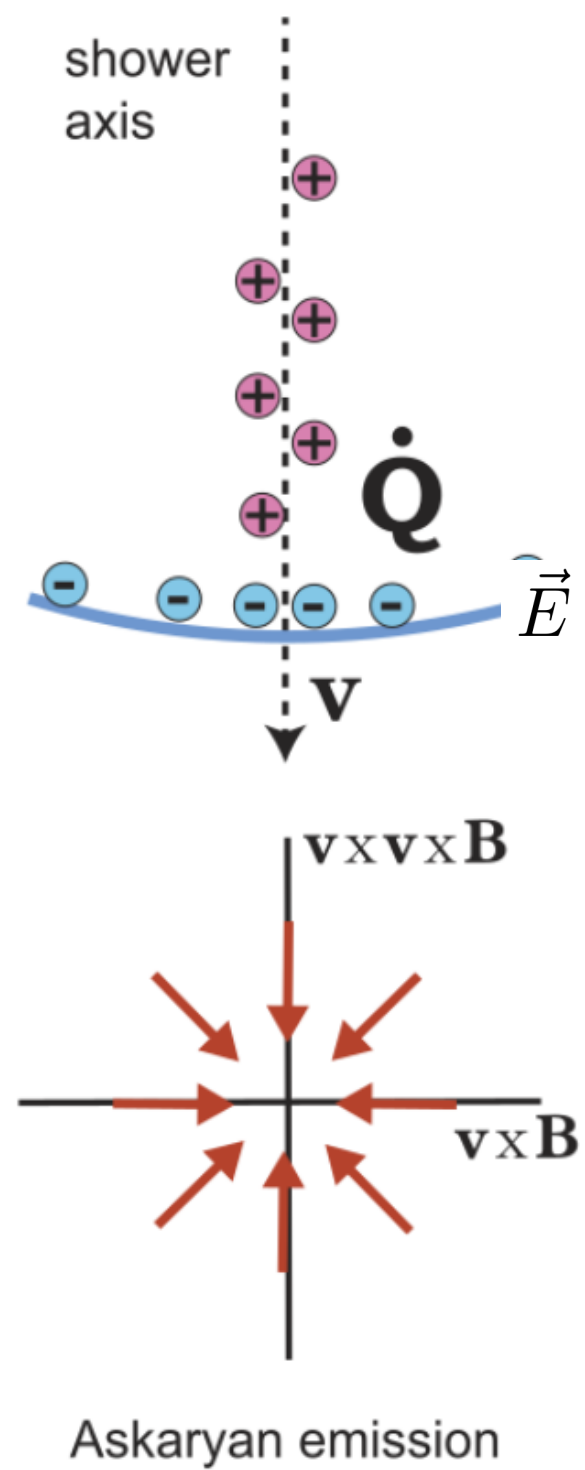


- Deflection of $e^\pm$ via Lorentz force produces time varying current
- Linear polarization, given by $\vec{E} \propto \vec{v} \times \vec{B}$
- Coherent up to $\mathcal{O}(1 \text{ GHz})$ at Cherenkov angle 1°



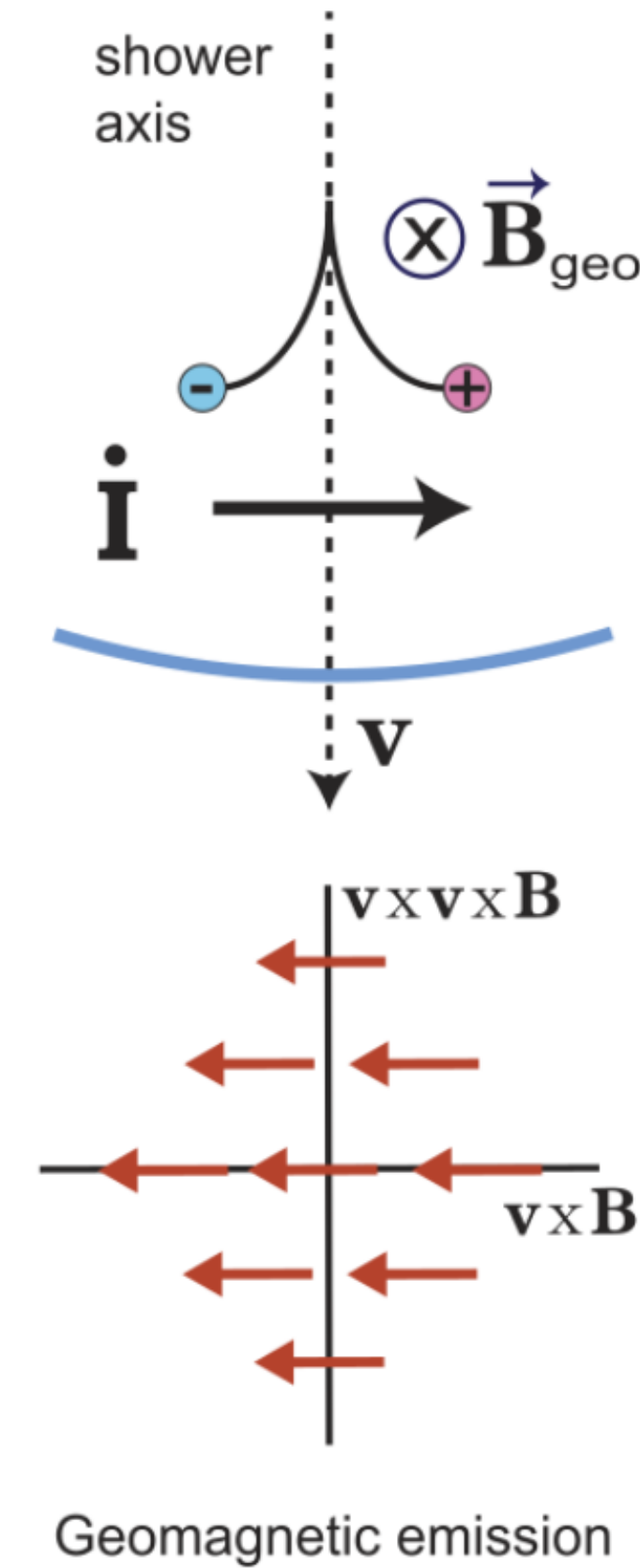
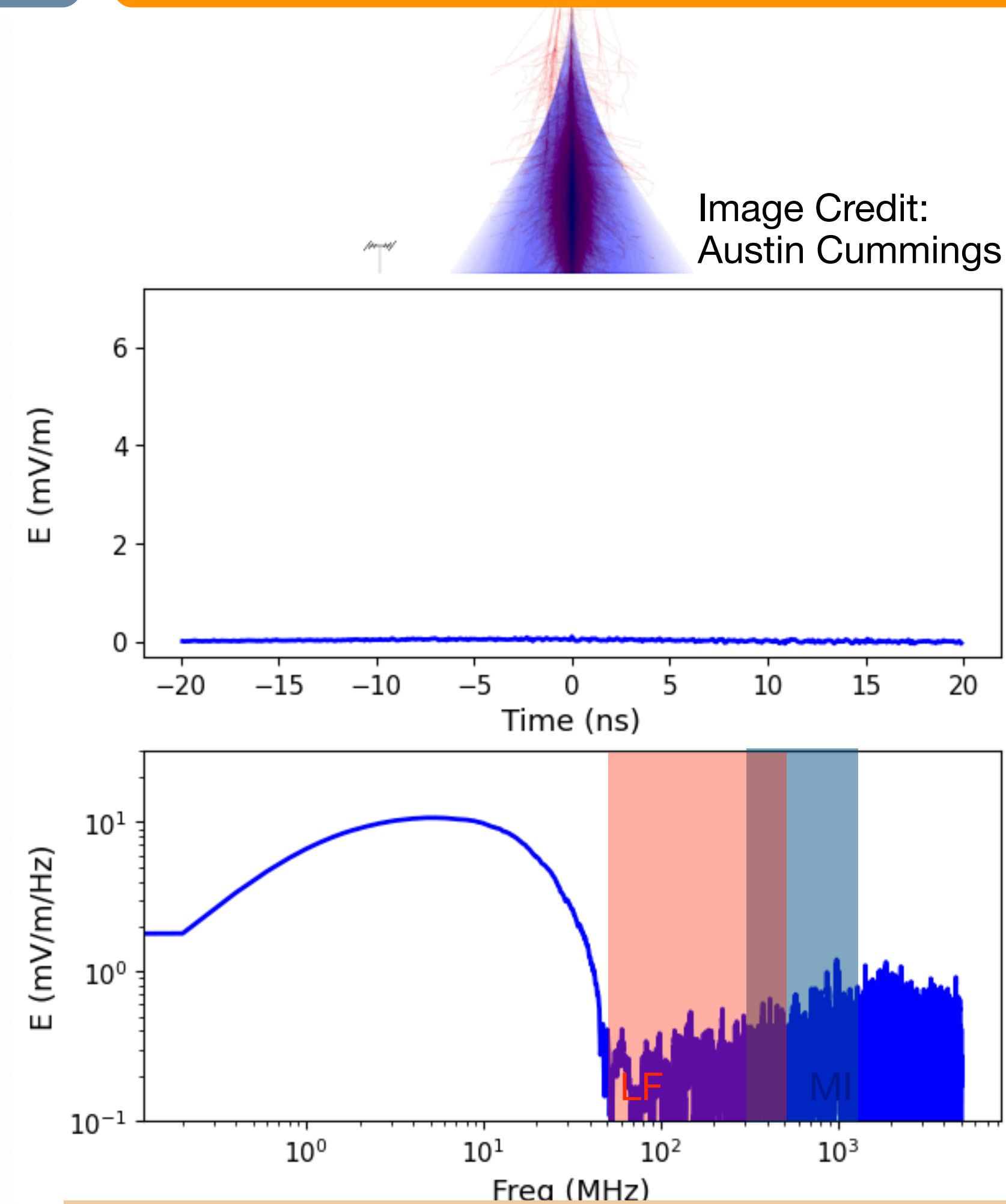
Austin Cummings

In-Ice Showers (Askaryan)



- Net 20% charge excess (e^+ annihilation & Bhabba)
- Radially Polarized
- Coherent up to scattering length in compact showers cutoff $\mathcal{O}(\text{cm}) \rightarrow \mathcal{O}(10\text{GHz})$ at Cherenkov angle (54° in ice)

Air Showers (Geomagnetic)

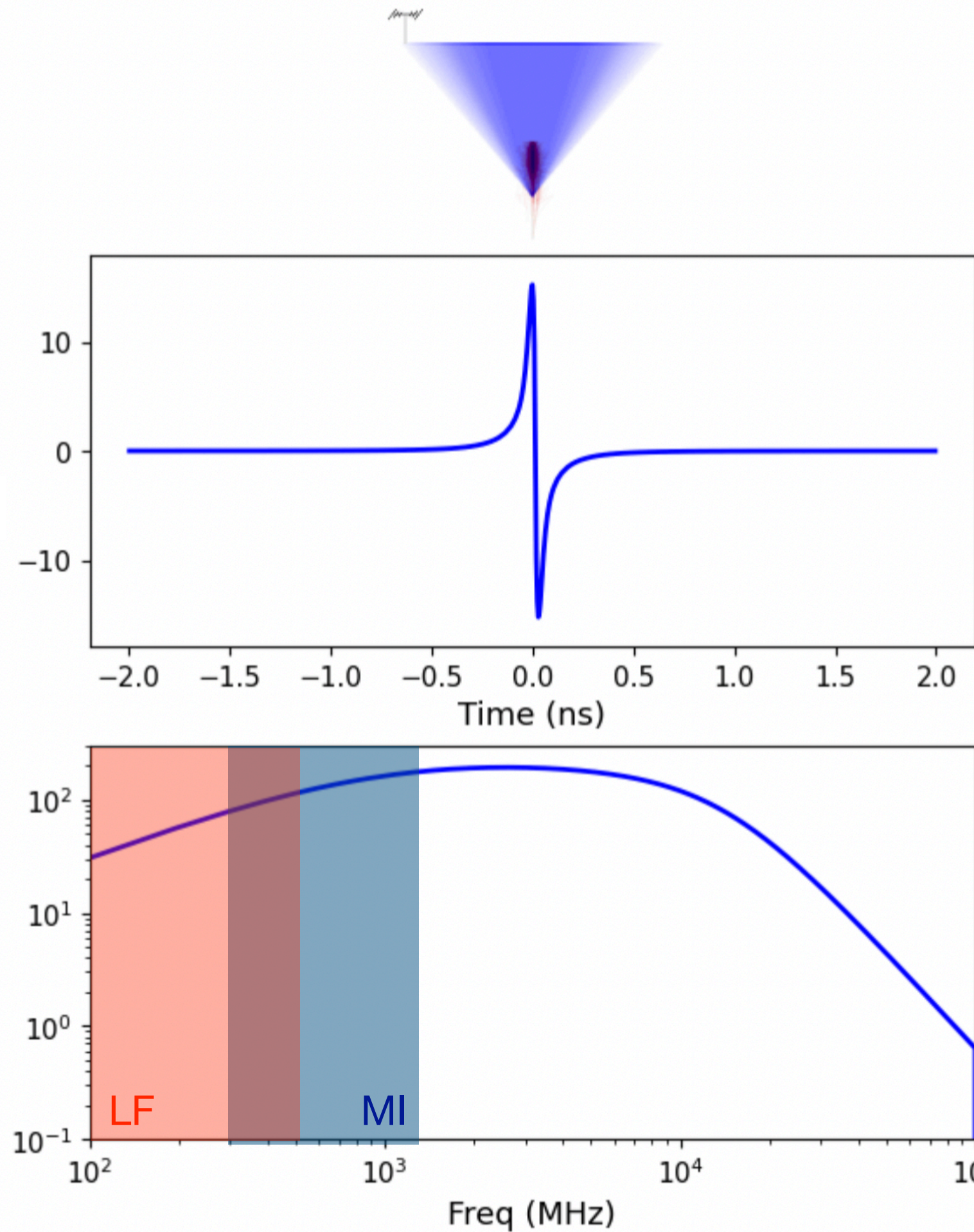
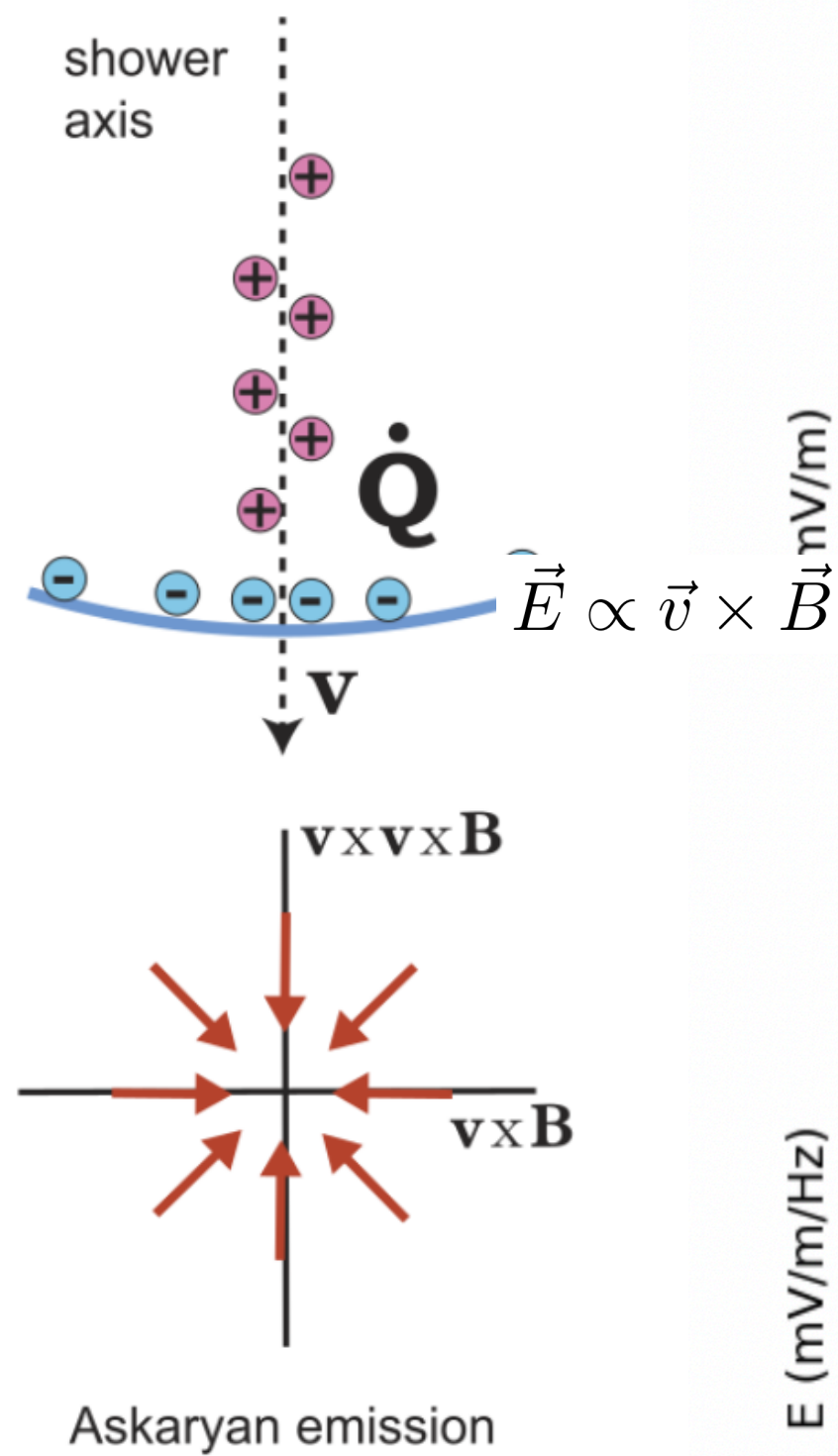


- Deflection of $e^\pm$ via Lorentz force produces time varying current
- Linear polarization, given by $\vec{E} \propto \vec{v} \times \vec{B}$
- Coherent up to $\mathcal{O}(1 \text{ GHz})$ at Cherenkov angle 1°



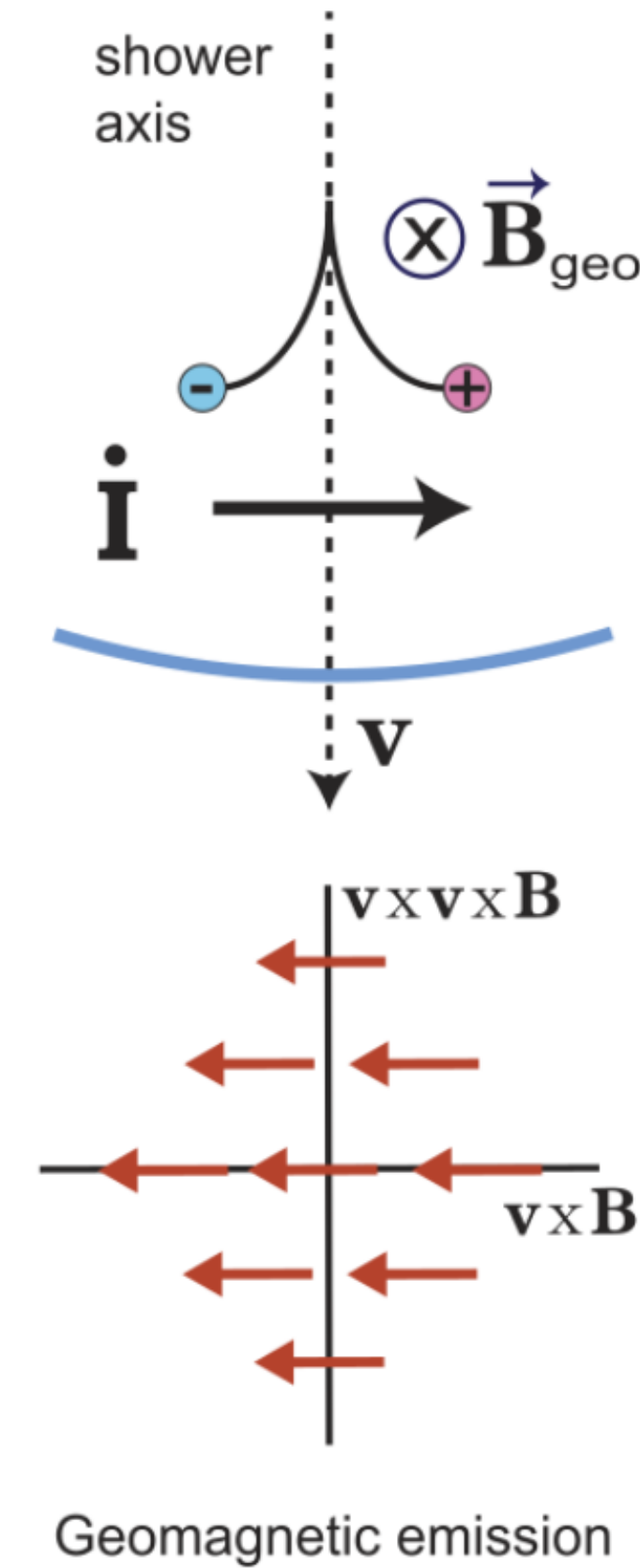
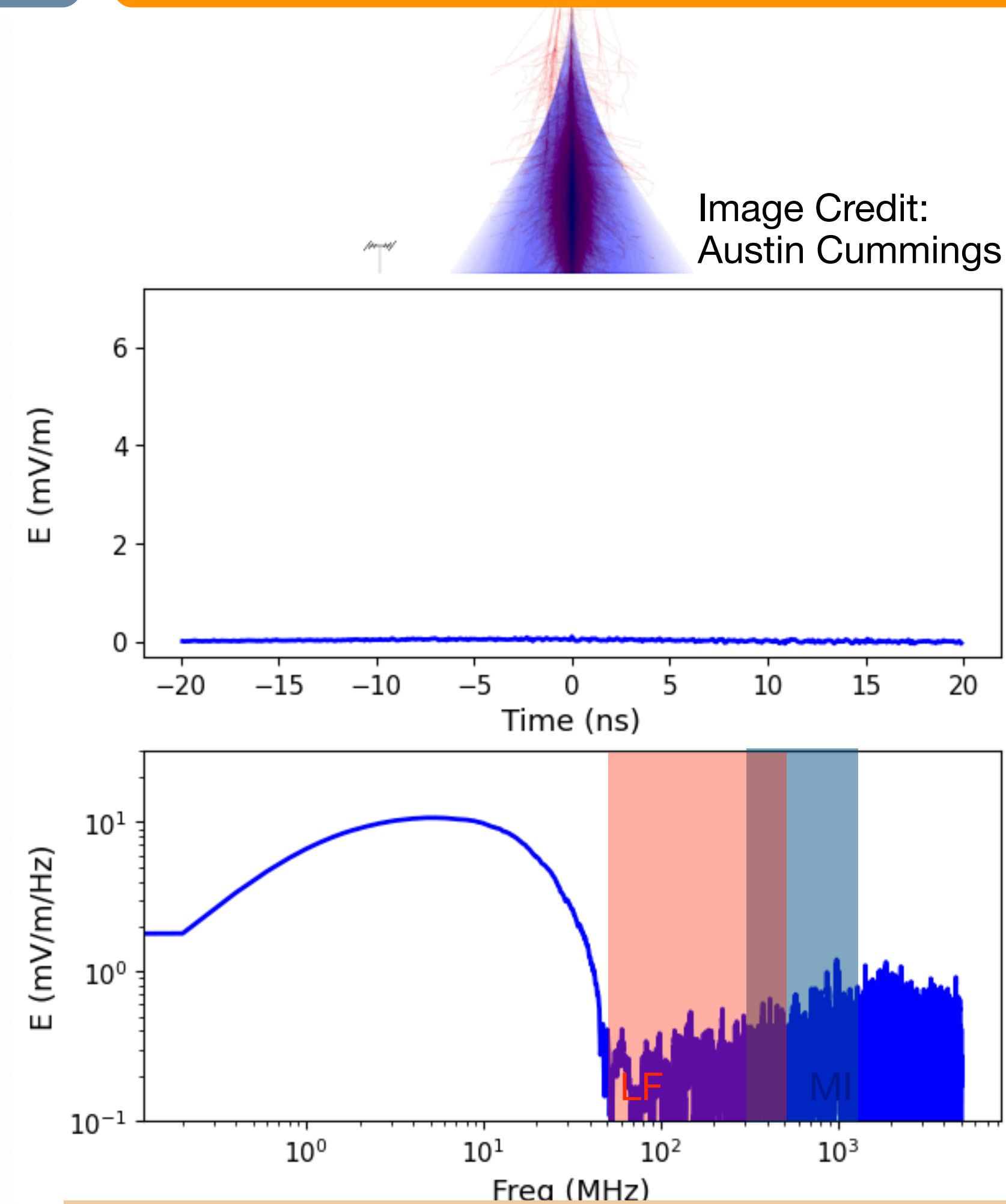
Austin Cummings

In-Ice Showers (Askaryan)



- Net 20% charge excess (e^+ annihilation & Bhabba)
- Radially Polarized
- Coherent up to scattering length in compact showers cutoff $\mathcal{O}(\text{cm}) \rightarrow \mathcal{O}(10\text{GHz})$ at Cherenkov angle (54° in ice)

Air Showers (Geomagnetic)

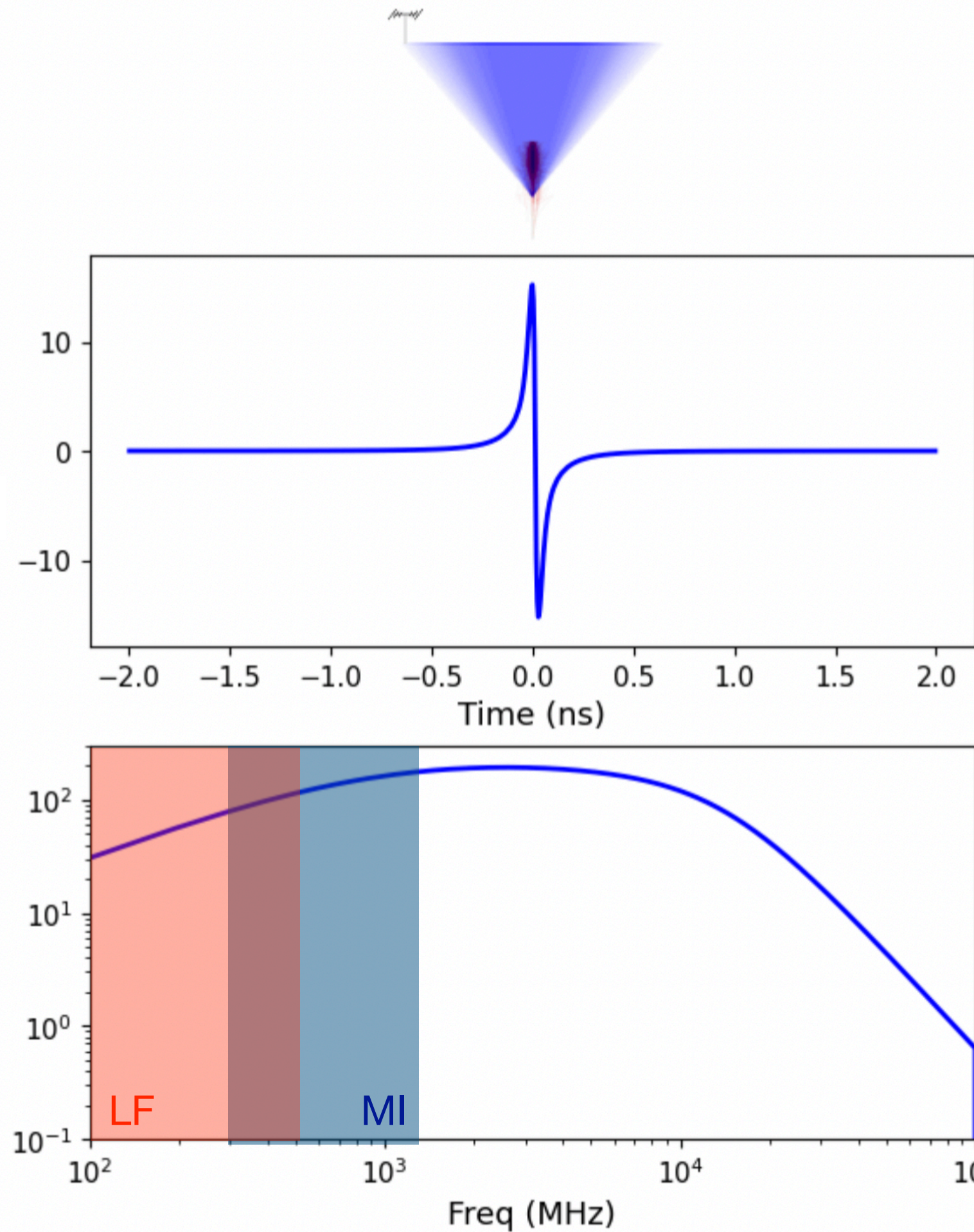
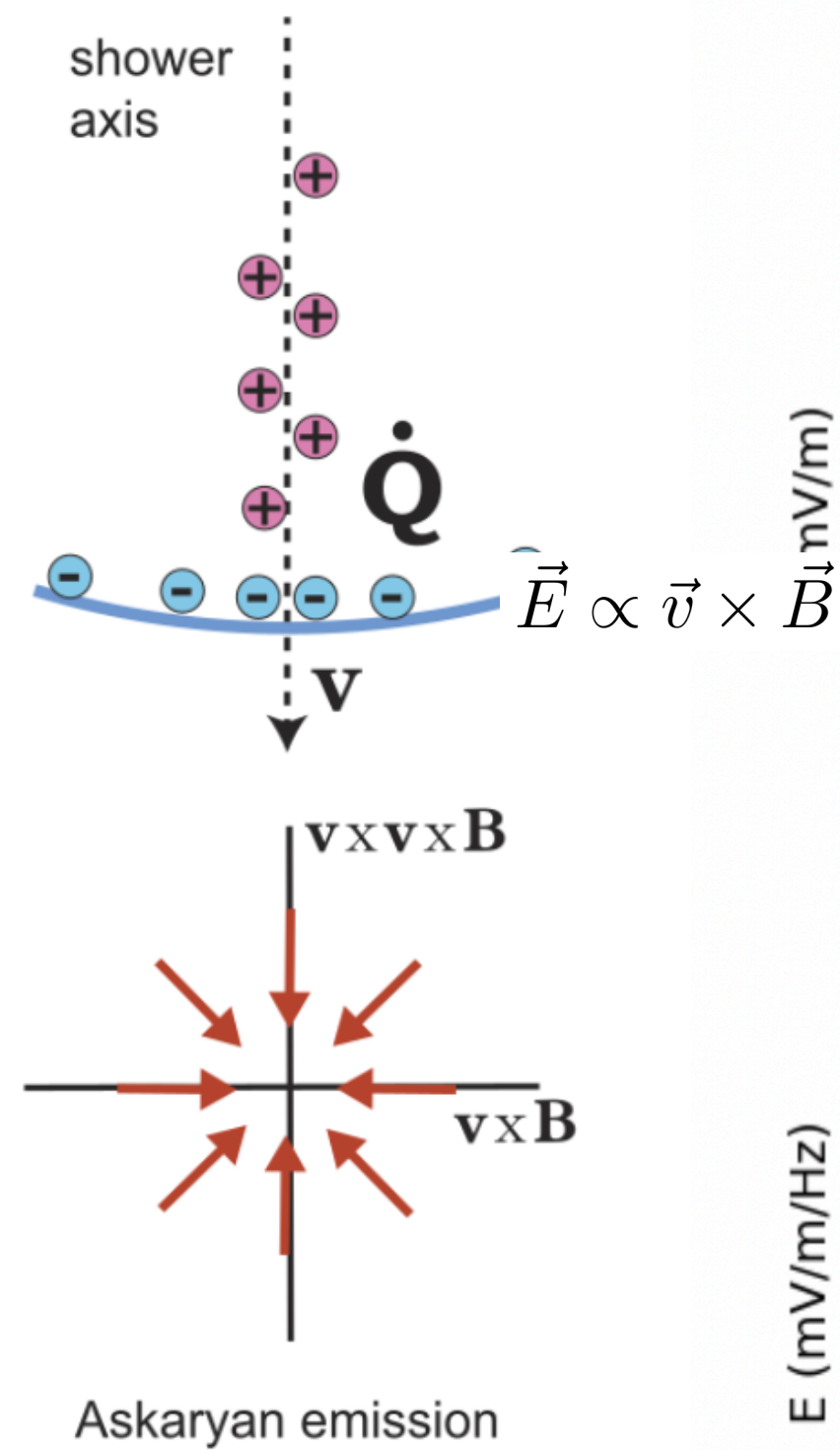


- Deflection of $e^\pm$ via Lorentz force produces time varying current
- Linear polarization, given by $\vec{E} \propto \vec{v} \times \vec{B}$
- Coherent up to $\mathcal{O}(1 \text{ GHz})$ at Cherenkov angle 1°



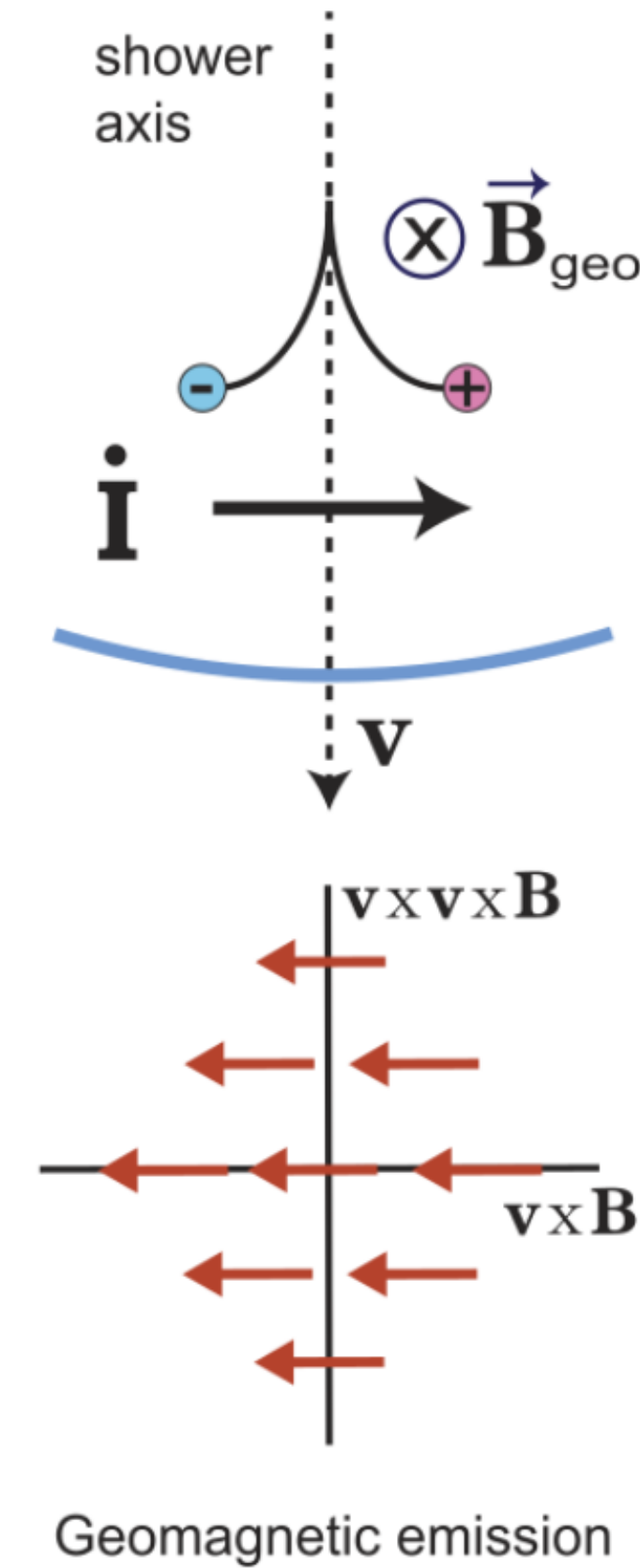
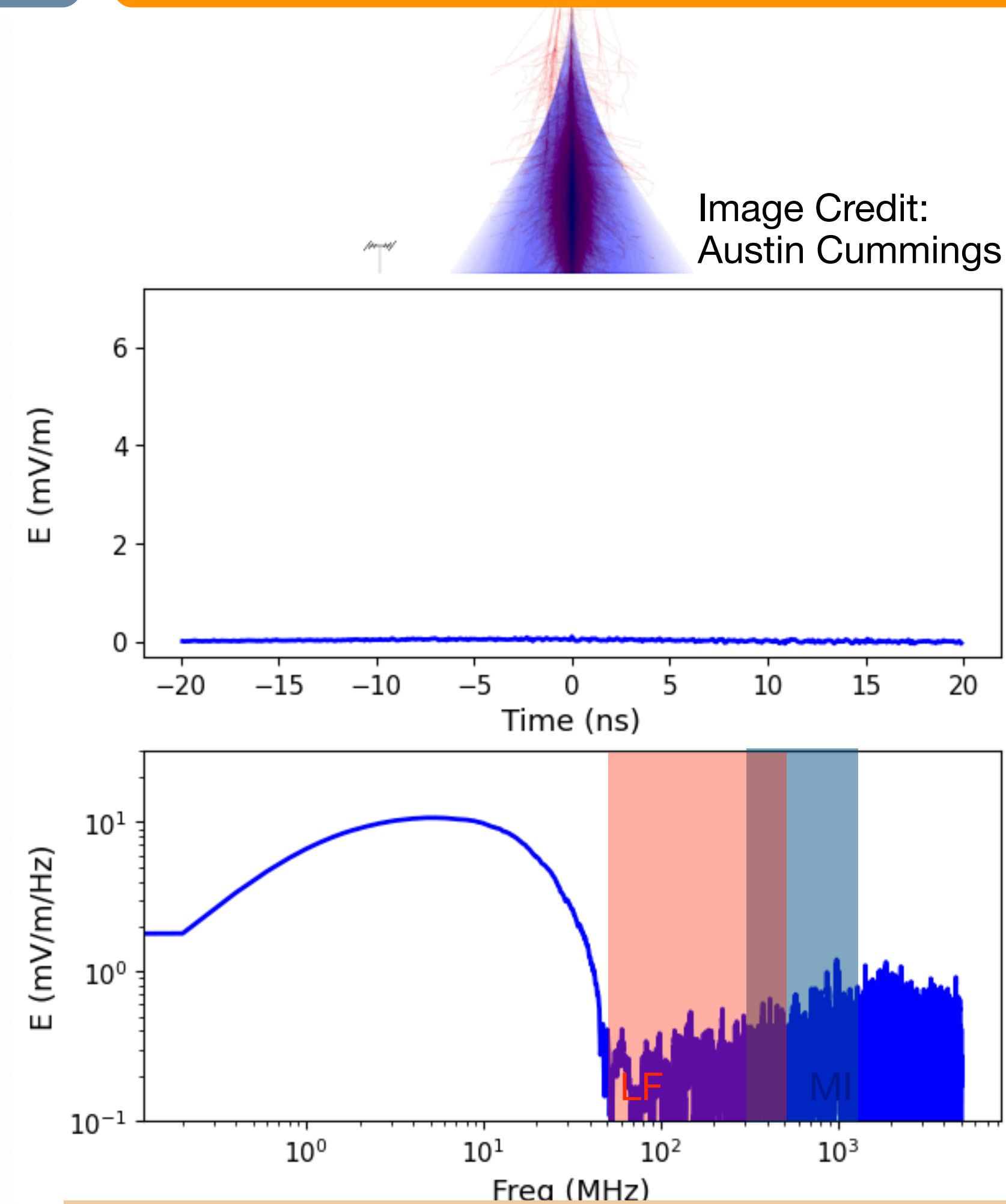
Austin Cummings

In-Ice Showers (Askaryan)



- Net 20% charge excess (e^+ annihilation & Bhabba)
- Radially Polarized
- Coherent up to scattering length in compact showers cutoff $\mathcal{O}(\text{cm}) \rightarrow \mathcal{O}(10\text{GHz})$ at Cherenkov angle (54° in ice)

Air Showers (Geomagnetic)

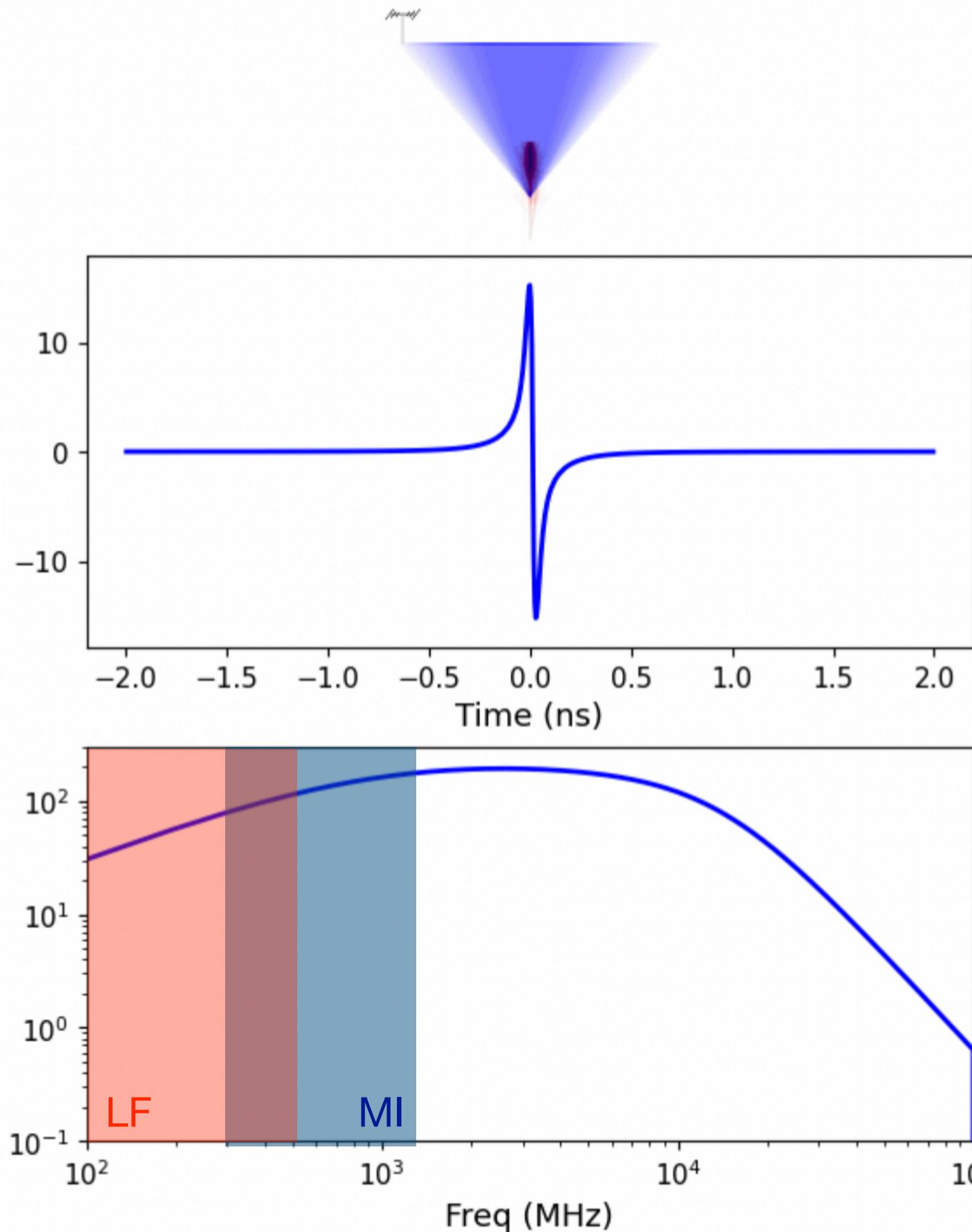
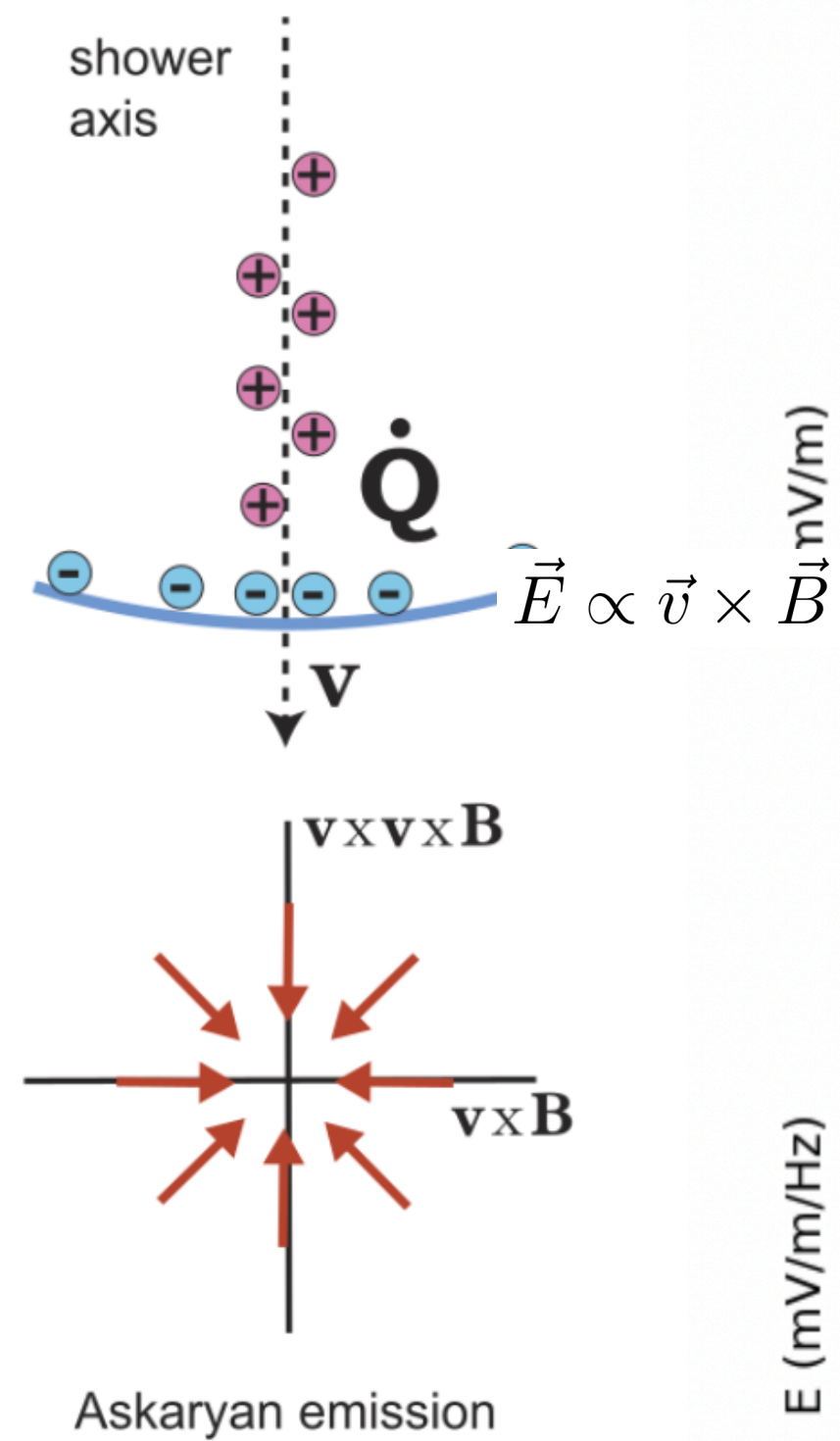


- Deflection of $e^\pm$ via Lorentz force produces time varying current
- Linear polarization, given by $\vec{E} \propto \vec{v} \times \vec{B}$
- Coherent up to $\mathcal{O}(1 \text{ GHz})$ at Cherenkov angle 1°



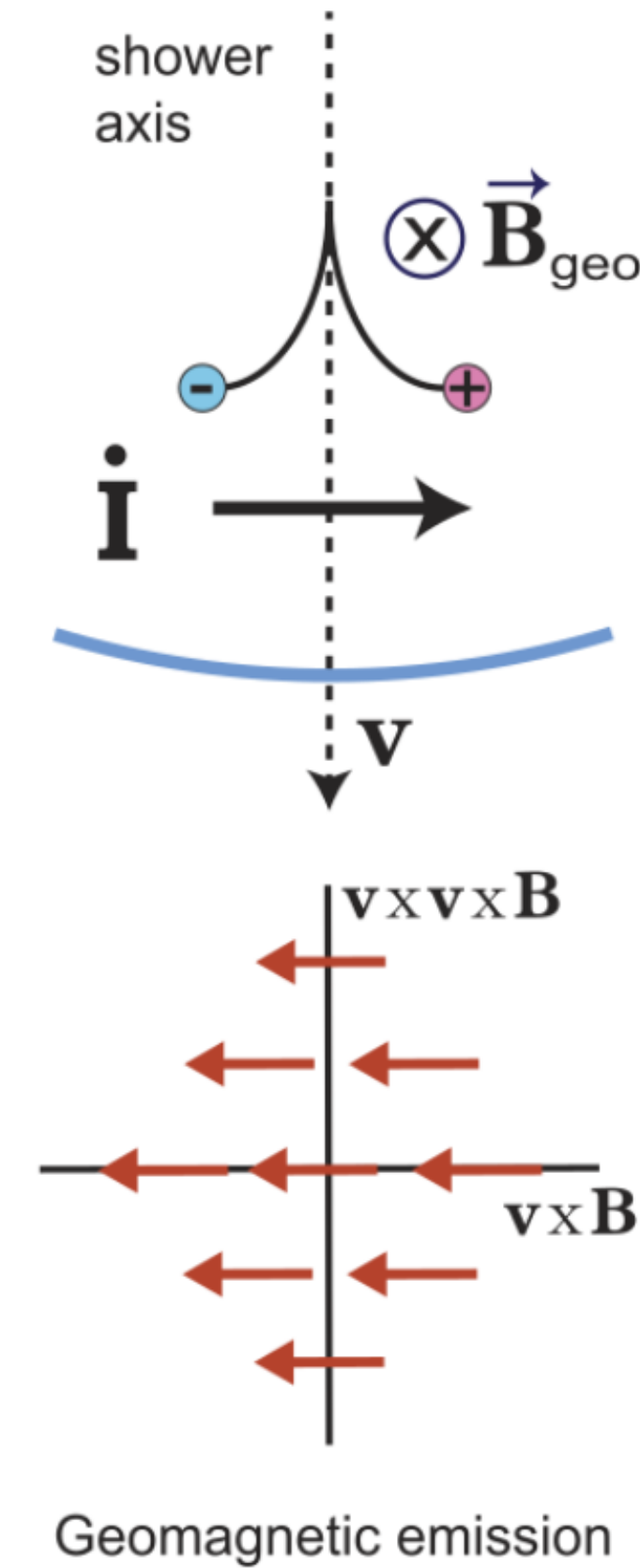
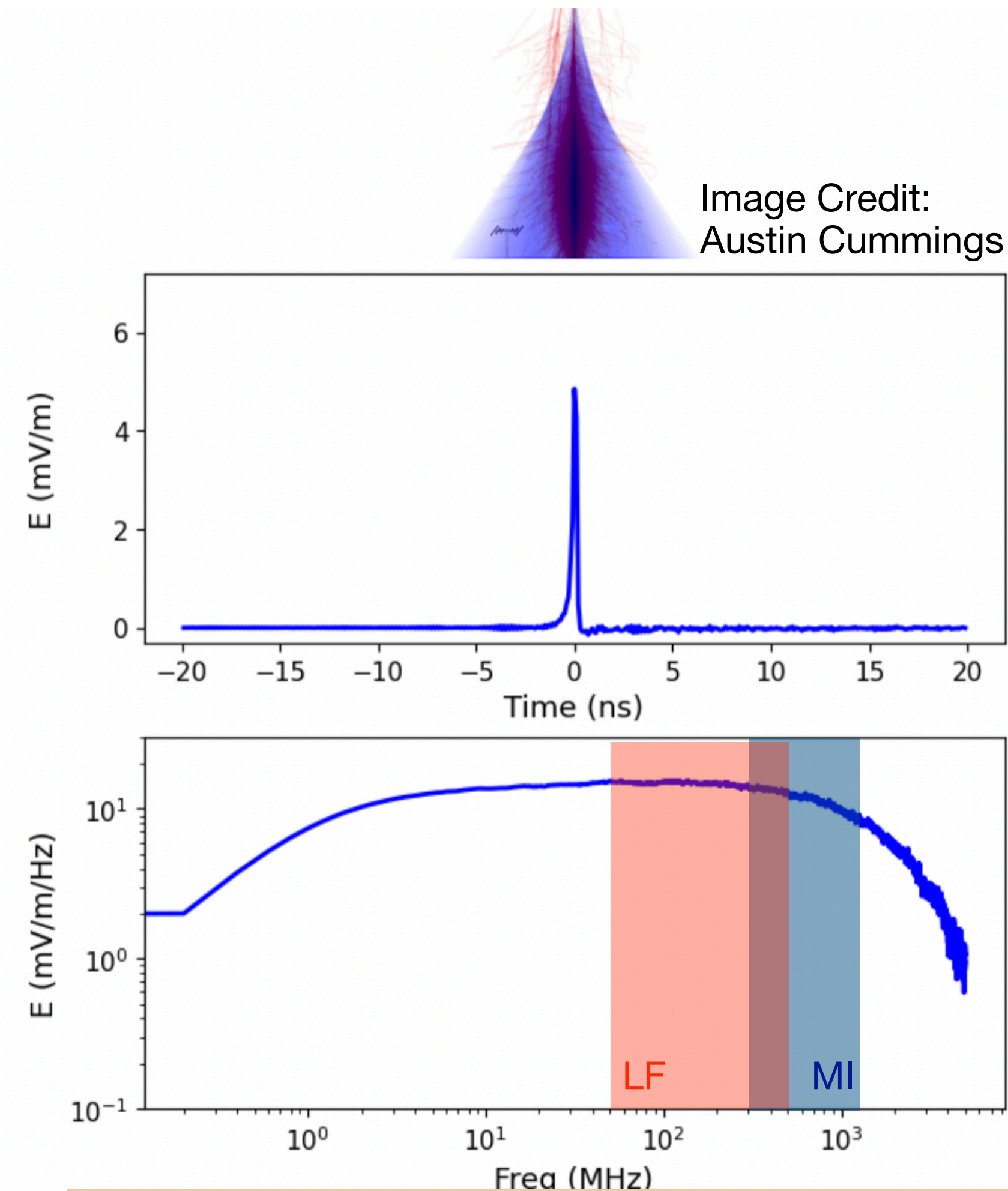
Austin Cummings

In-Ice Showers (Askaryan)



- Net 20% charge excess (e^+ annihilation & Bhabba)
- Radially Polarized
- Coherent up to scattering length in compact showers cutoff $\mathcal{O}(\text{cm}) \rightarrow \mathcal{O}(10\text{GHz})$ at Cherenkov angle (54° in ice)

Air Showers (Geomagnetic)



- Deflection of $e^\pm$ via Lorentz force produces time varying current
- Linear polarization, given by $\vec{E} \propto \vec{v} \times \vec{B}$
- Coherent up to $\mathcal{O}(1 \text{ GHz})$ at Cherenkov angle 1°



Austin Cummings

Polarization Signature

- Askaryan neutrinos are predominately **vertically polarized**, because PUEO picks up the top of the cone *N.B: Birefringence can modify the polarization angle*

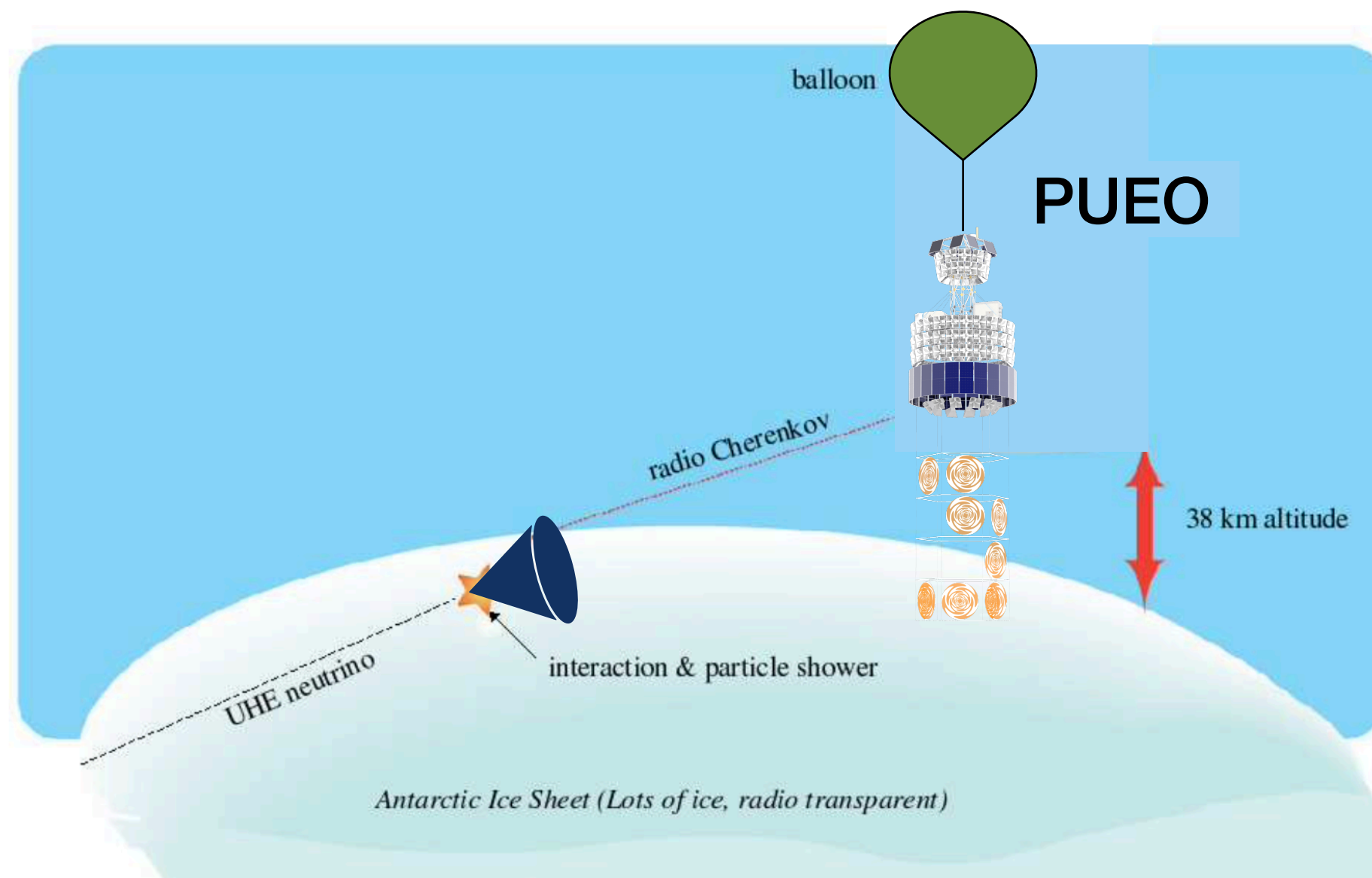
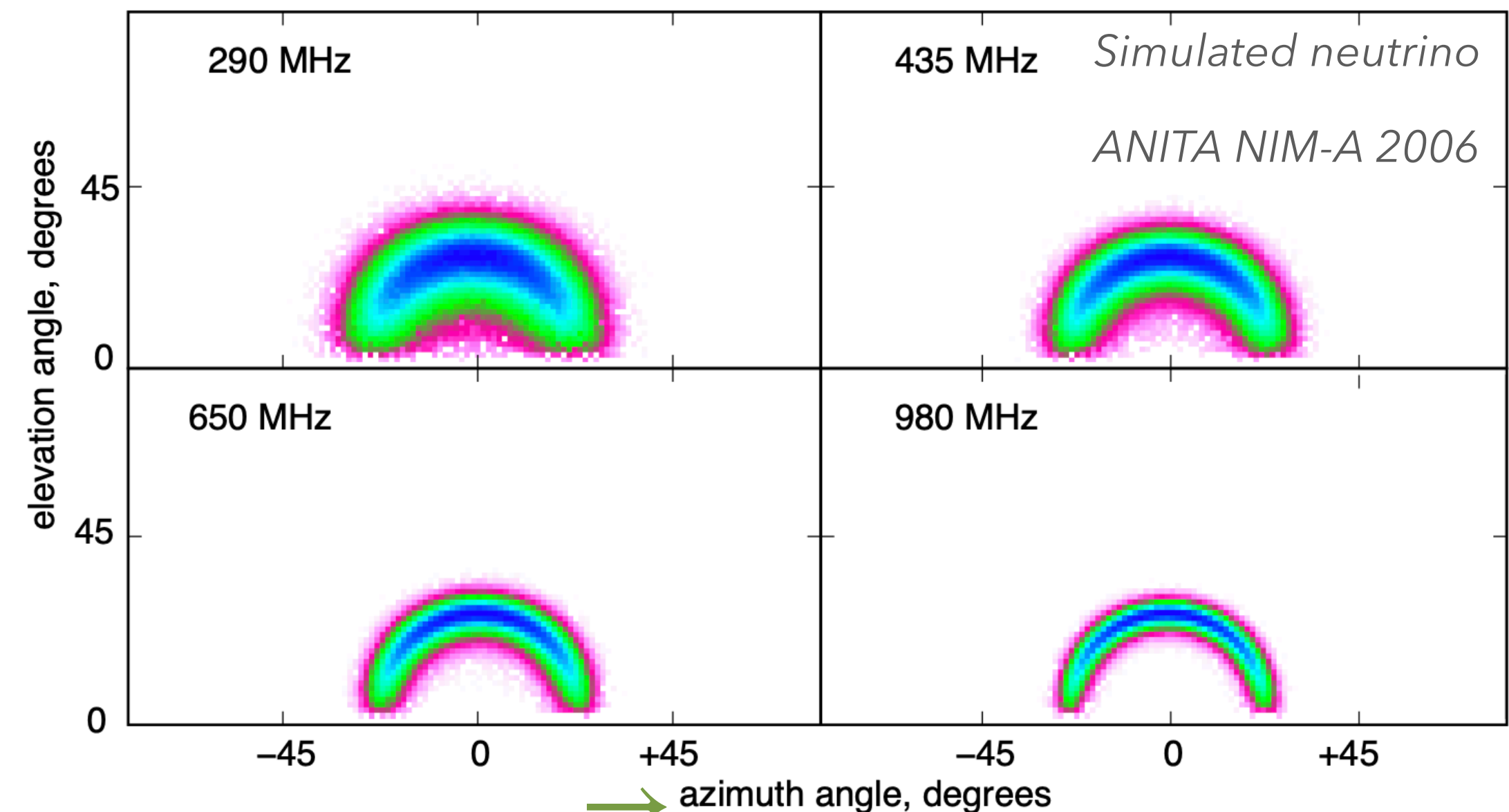
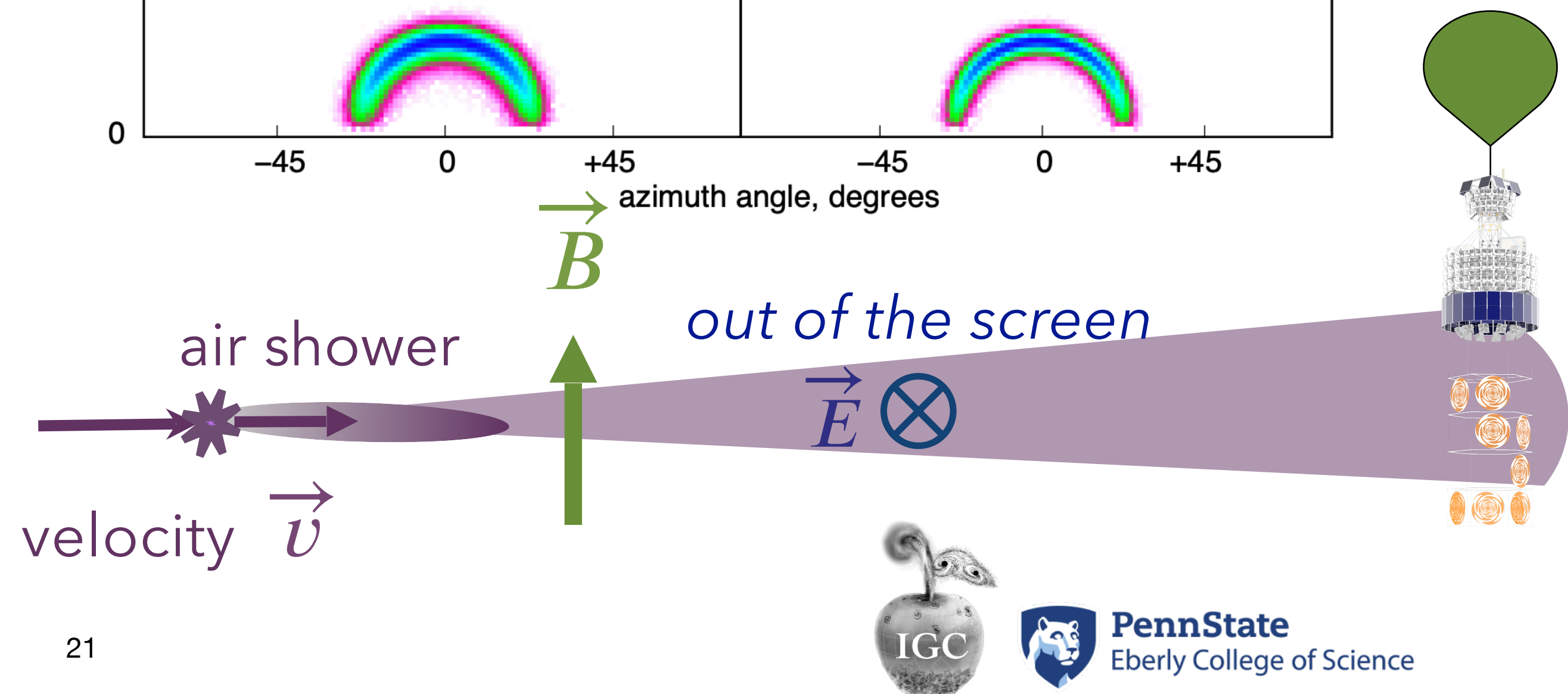


Image Credit: Stephen Hoover



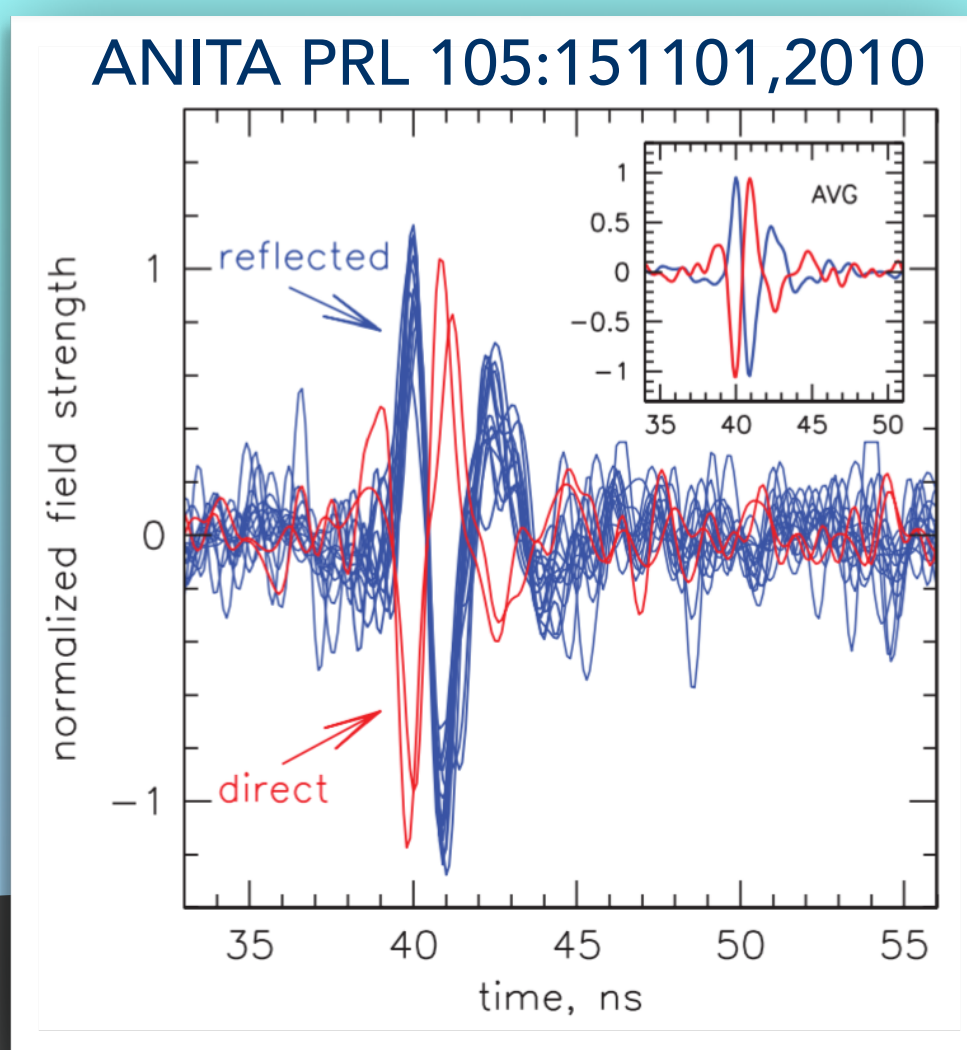
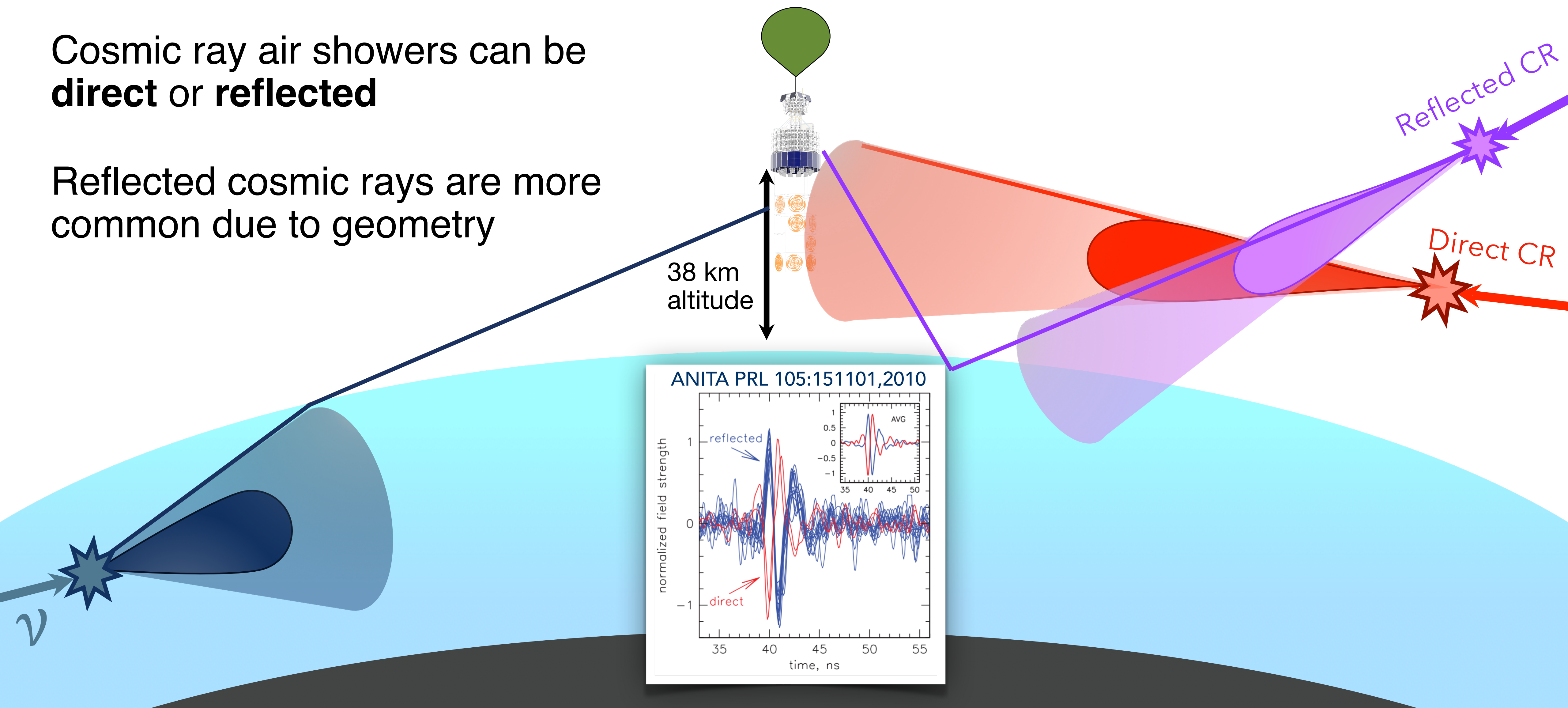
- Air showers are predominately **horizontally polarized**, because the Earth's magnetic field vertical at South Pole



PUEO's Astroparticle Detection Channels

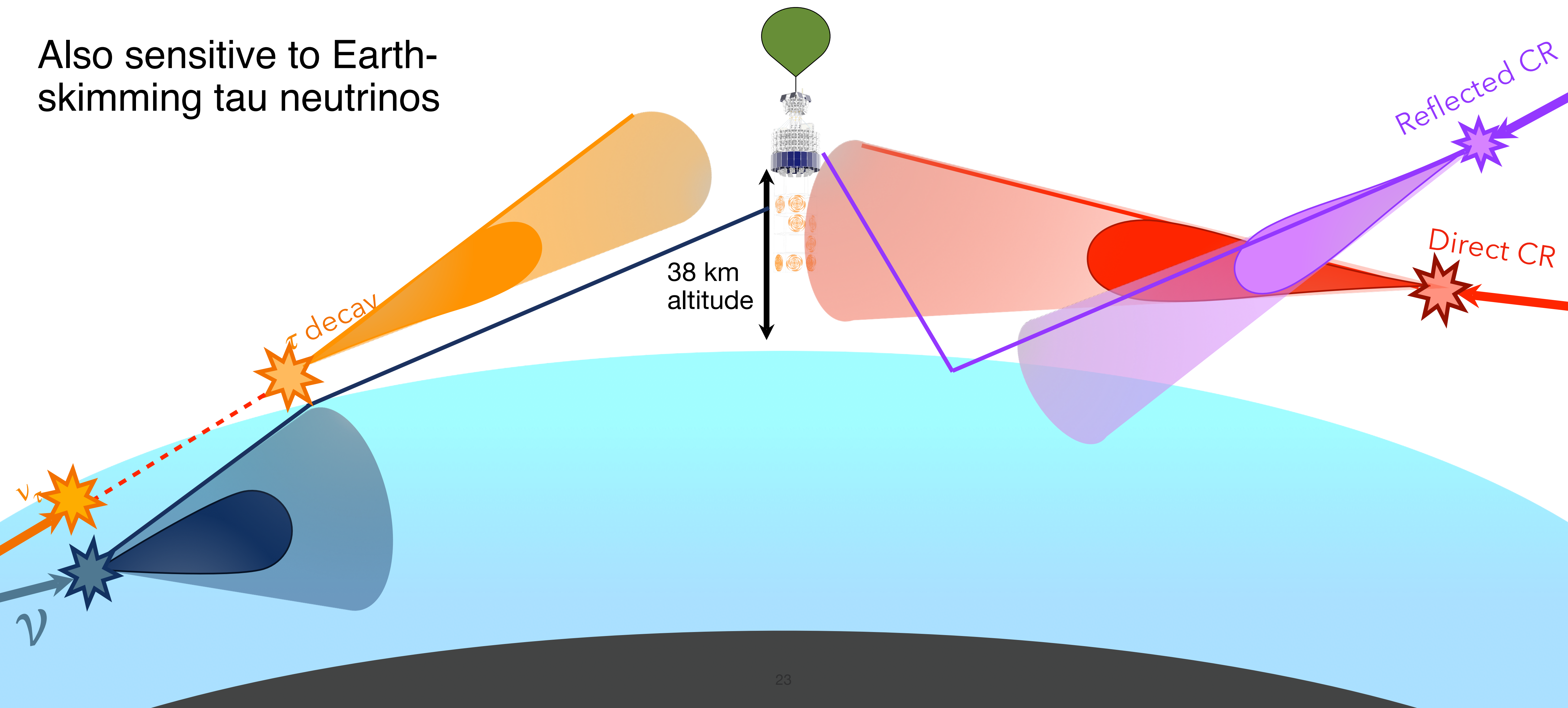
Cosmic ray air showers can be **direct** or **reflected**

Reflected cosmic rays are more common due to geometry



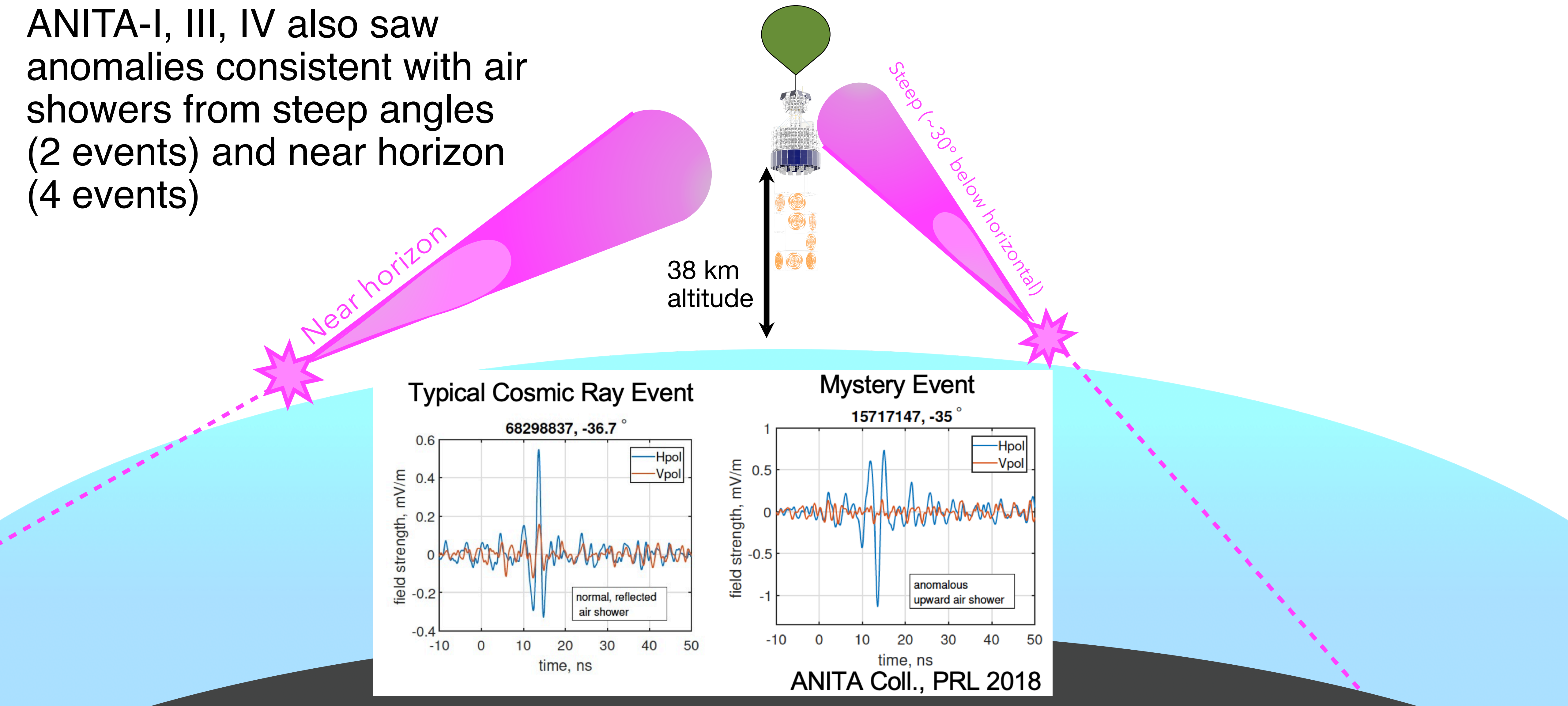
PUEO's Astroparticle Detection Channels

Also sensitive to Earth-skimming tau neutrinos

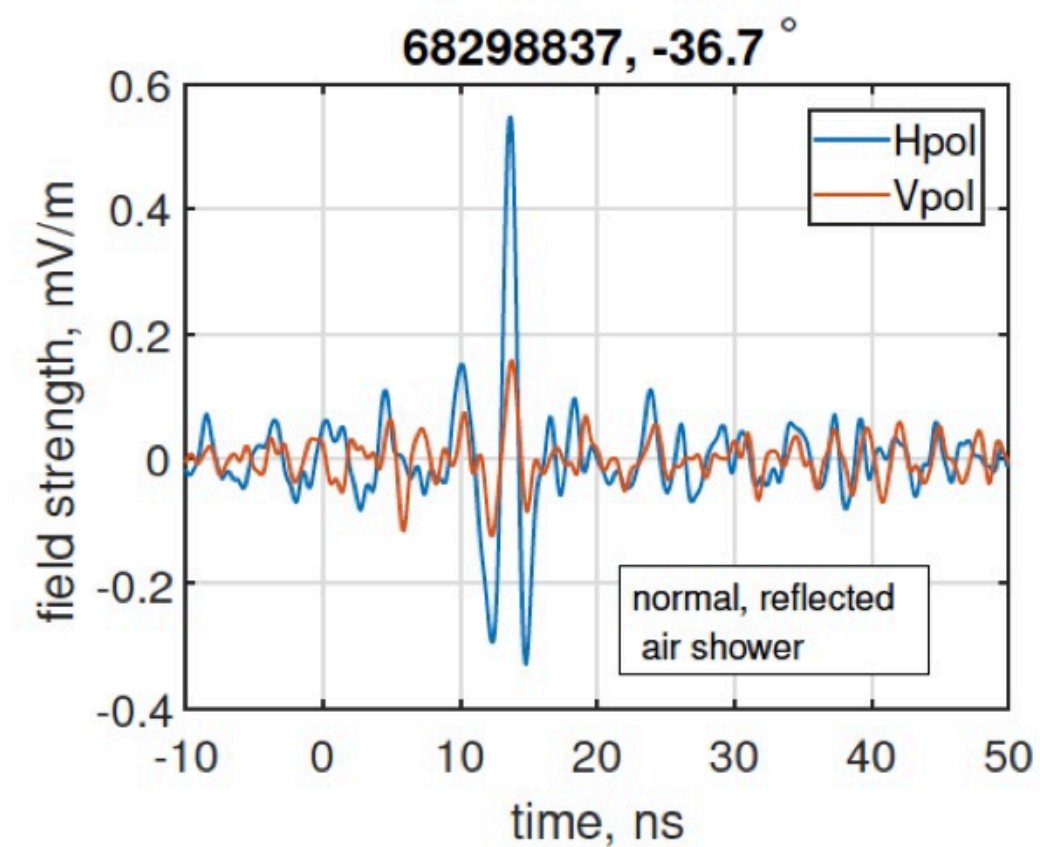


PUEO's Astroparticle Detection Channels

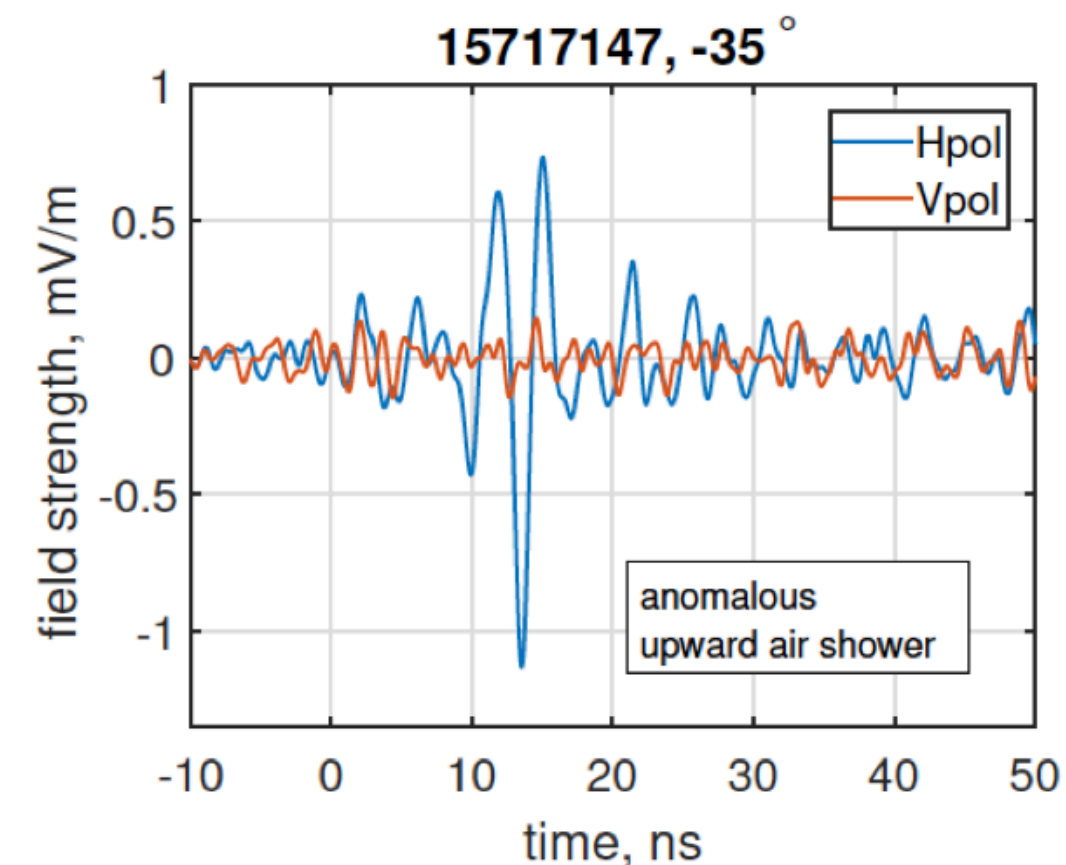
ANITA-I, III, IV also saw anomalies consistent with air showers from steep angles (2 events) and near horizon (4 events)



Typical Cosmic Ray Event



Mystery Event

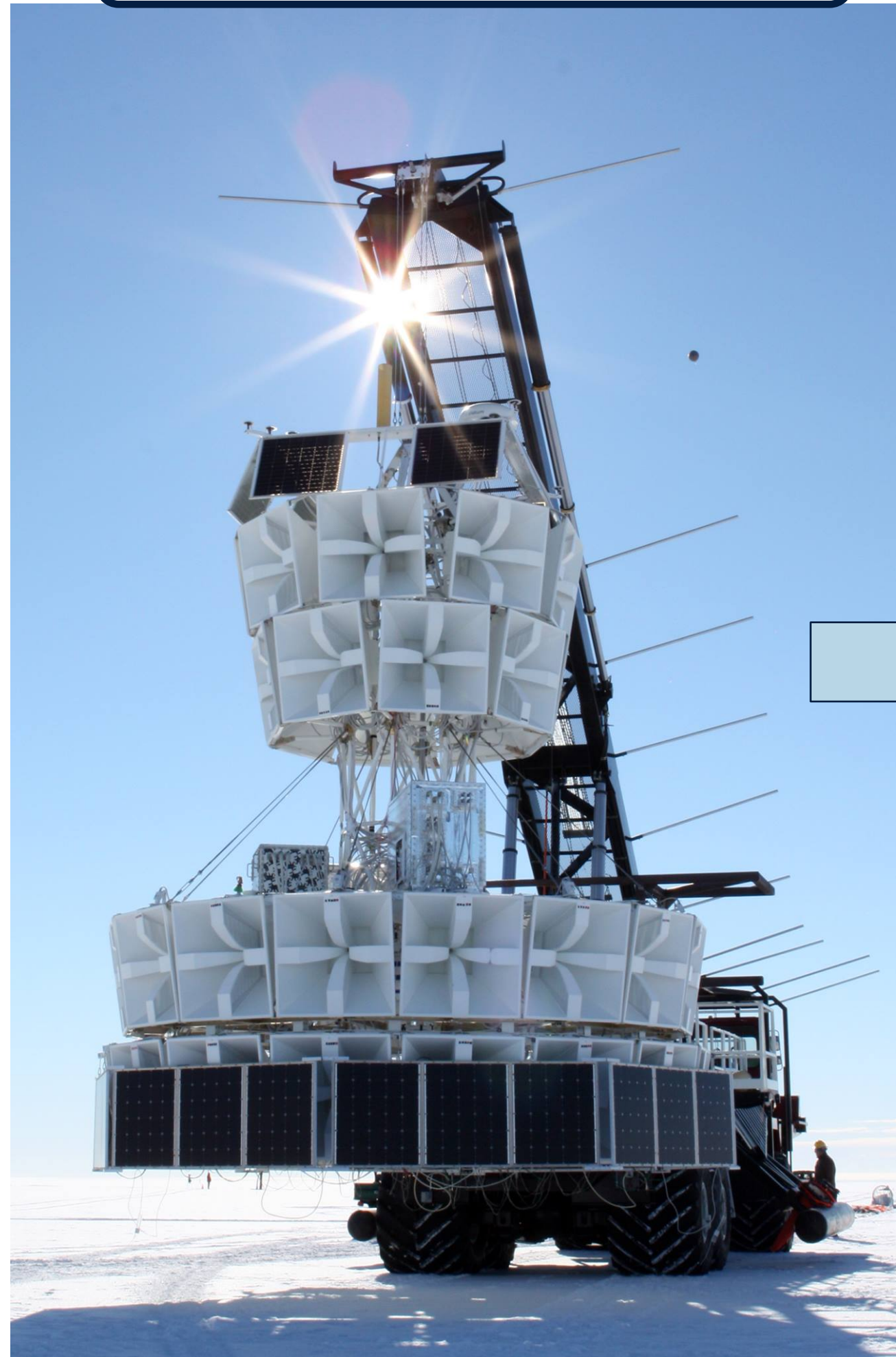


ANITA Coll., PRL 2018

What's the difference between ANITA and PUEO?

Improved Sensitivity

ANITA (2005-2016)



PUEO (2025)

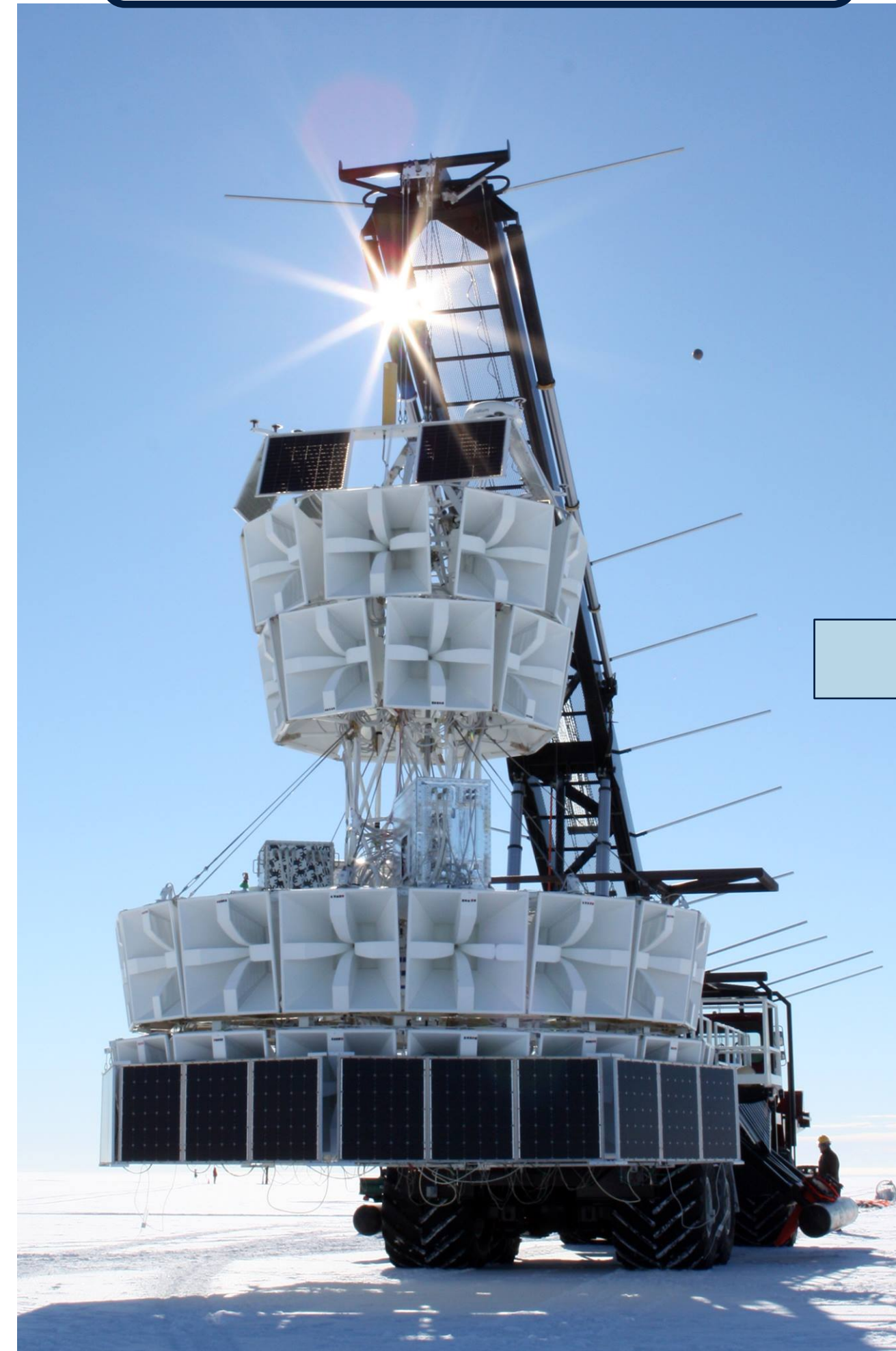


What's the difference between ANITA and PUEO?

Improved Sensitivity

- Same size, same altitude, similar flight duration

ANITA (2005-2016)



PUEO (2025)

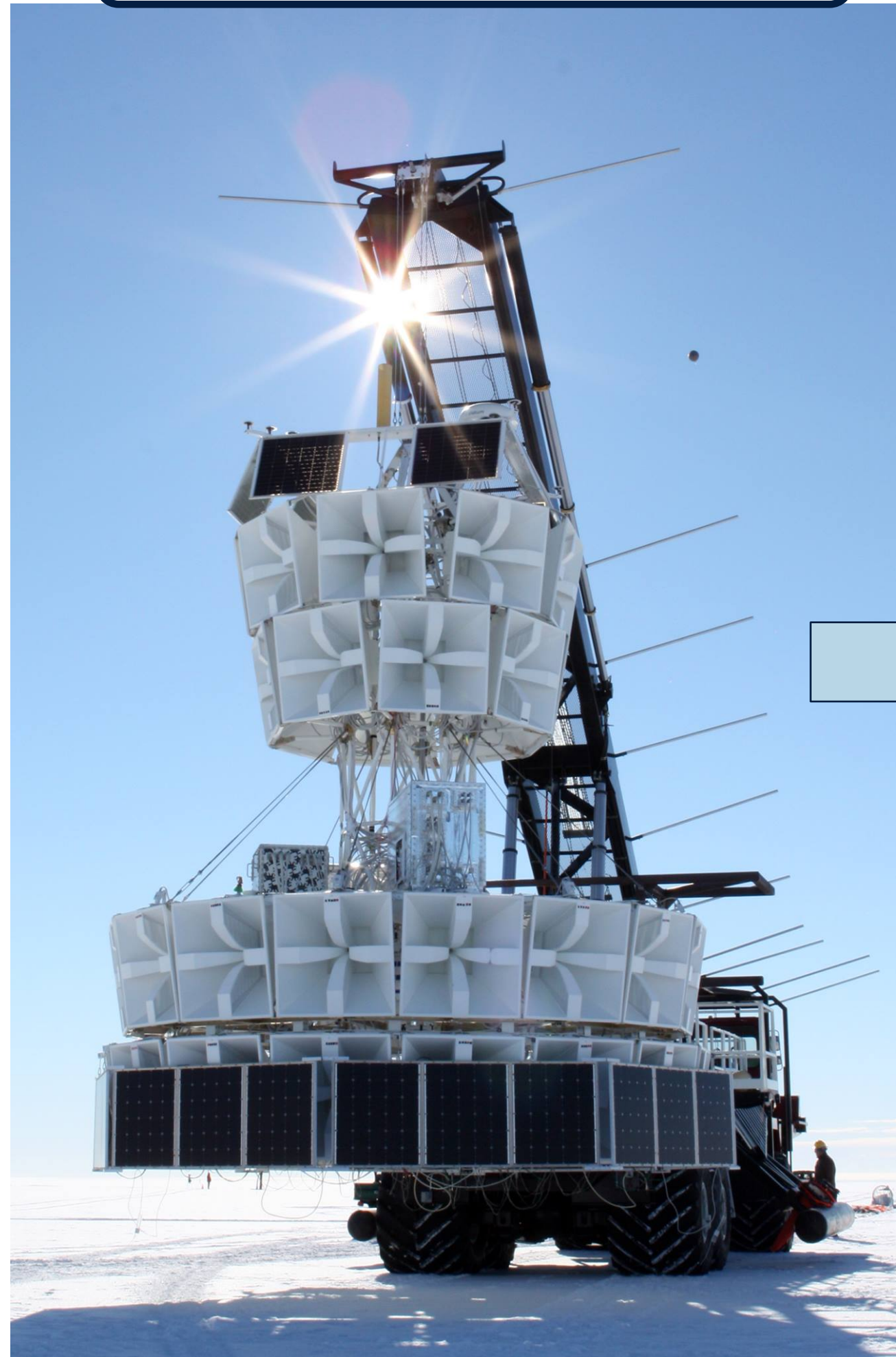


What's the difference between ANITA and PUEO?

Improved Sensitivity

- Same size, same altitude, similar flight duration
- **2x antennas** → narrower frequency range (300-1300 MHz vs 180-1300 MHz), **higher gain** *[MI Instrument]*

ANITA (2005-2016)



PUEO (2025)

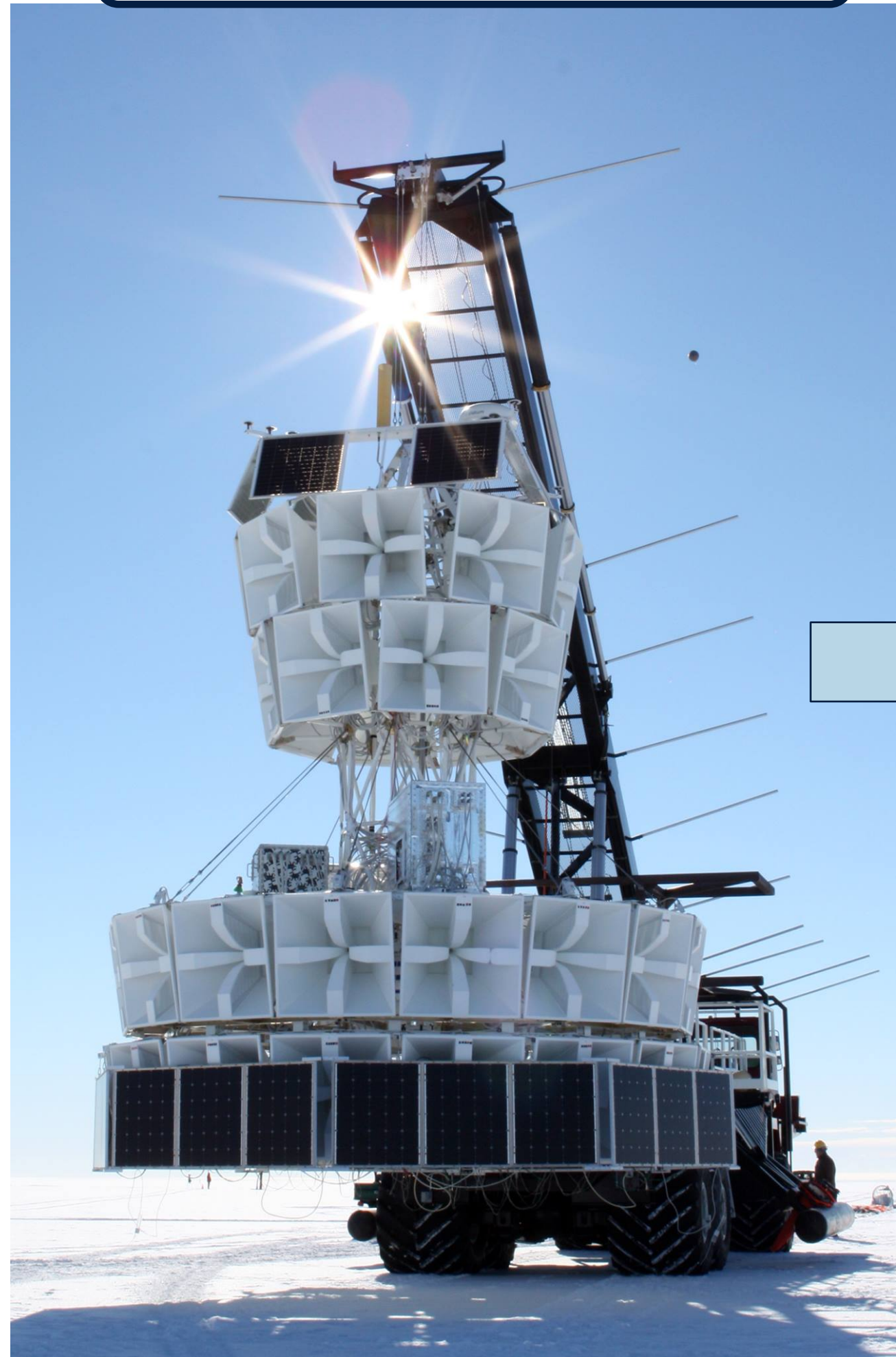


What's the difference between ANITA and PUEO?

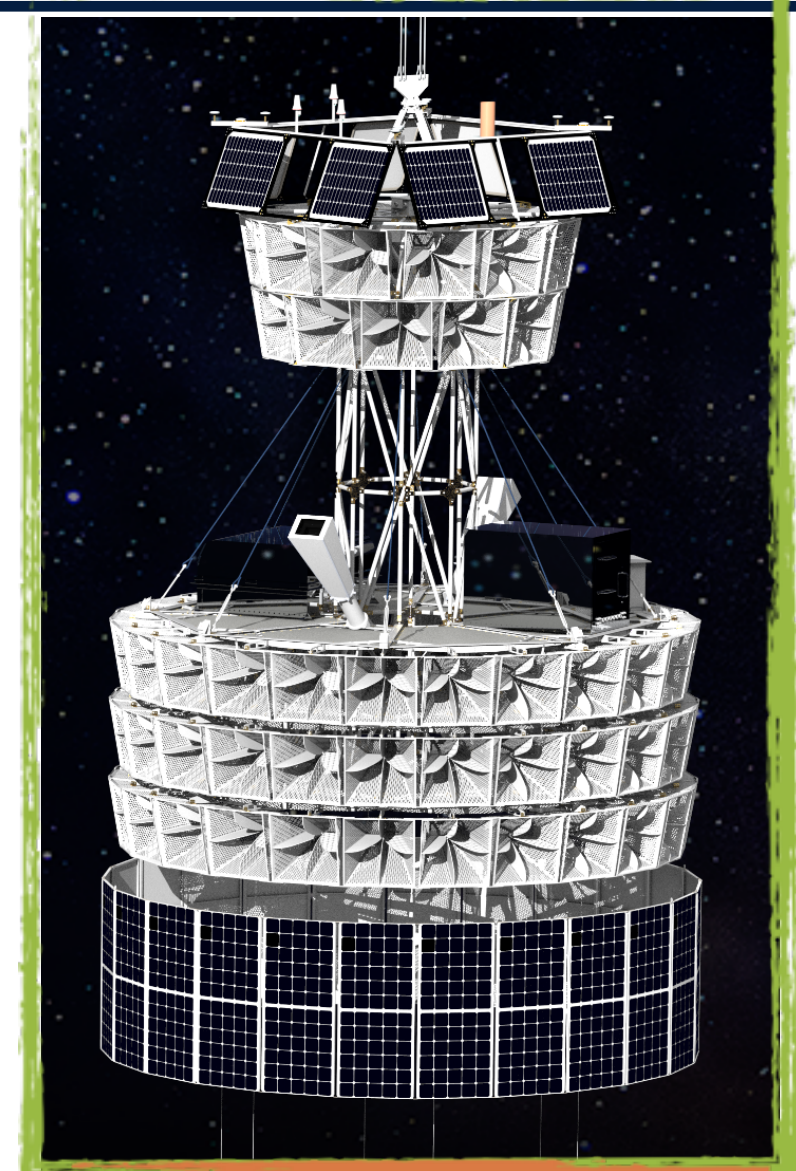
Improved Sensitivity

- Same size, same altitude, similar flight duration
- **2x antennas** → narrower frequency range (300-1300 MHz vs 180-1300 MHz), **higher gain** *[MI Instrument]*

ANITA (2005-2016)



PUEO (2025)

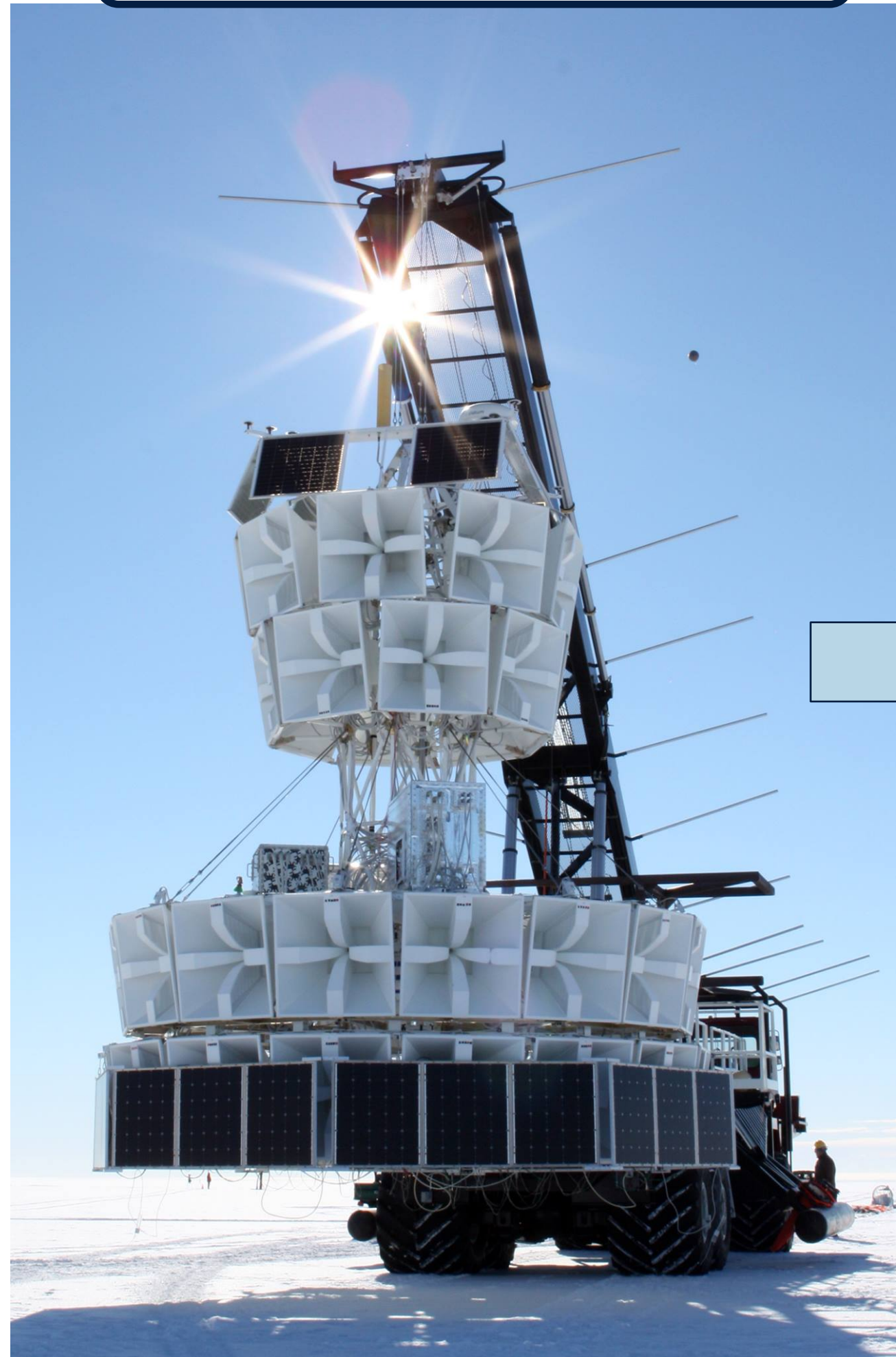


What's the difference between ANITA and PUEO?

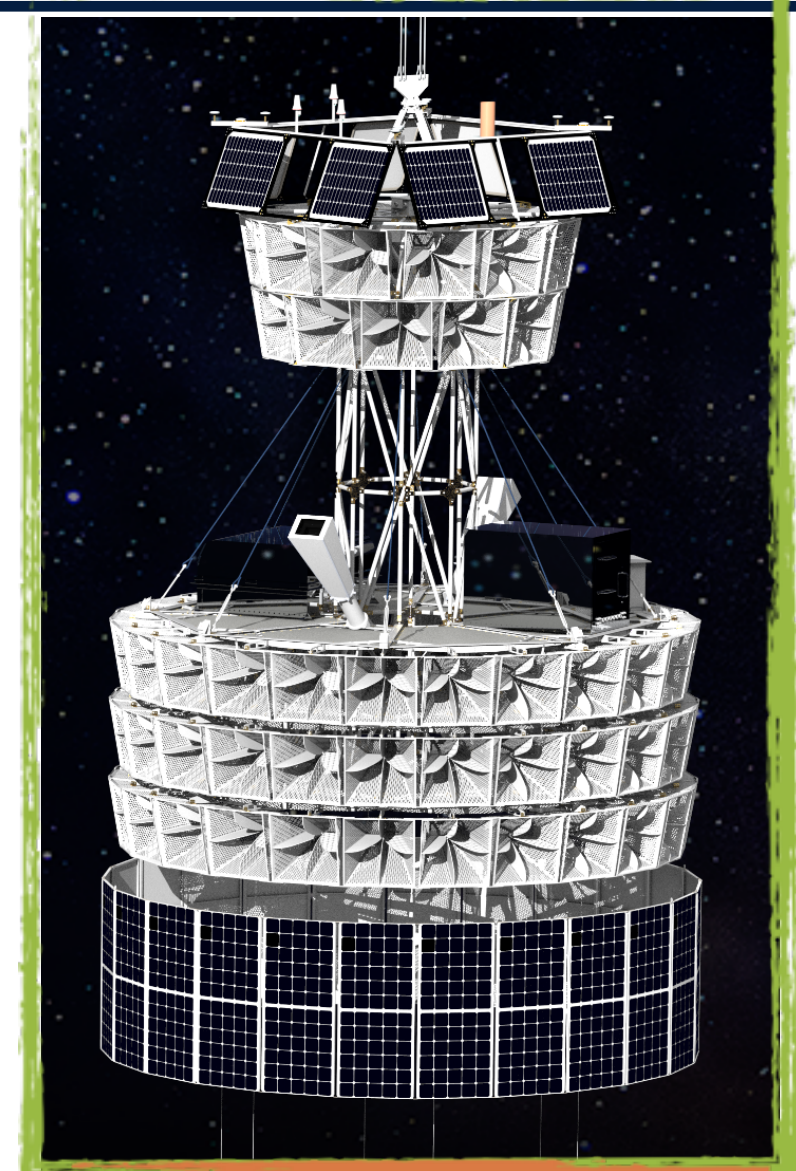
Improved Sensitivity

- Same size, same altitude, similar flight duration
- **2x antennas** → narrower frequency range (300-1300 MHz vs 180-1300 MHz), **higher gain** *[MI Instrument]*
- Deployable low frequency antenna array targeting air showers *[LF instrument]*

ANITA (2005-2016)



PUEO (2025)

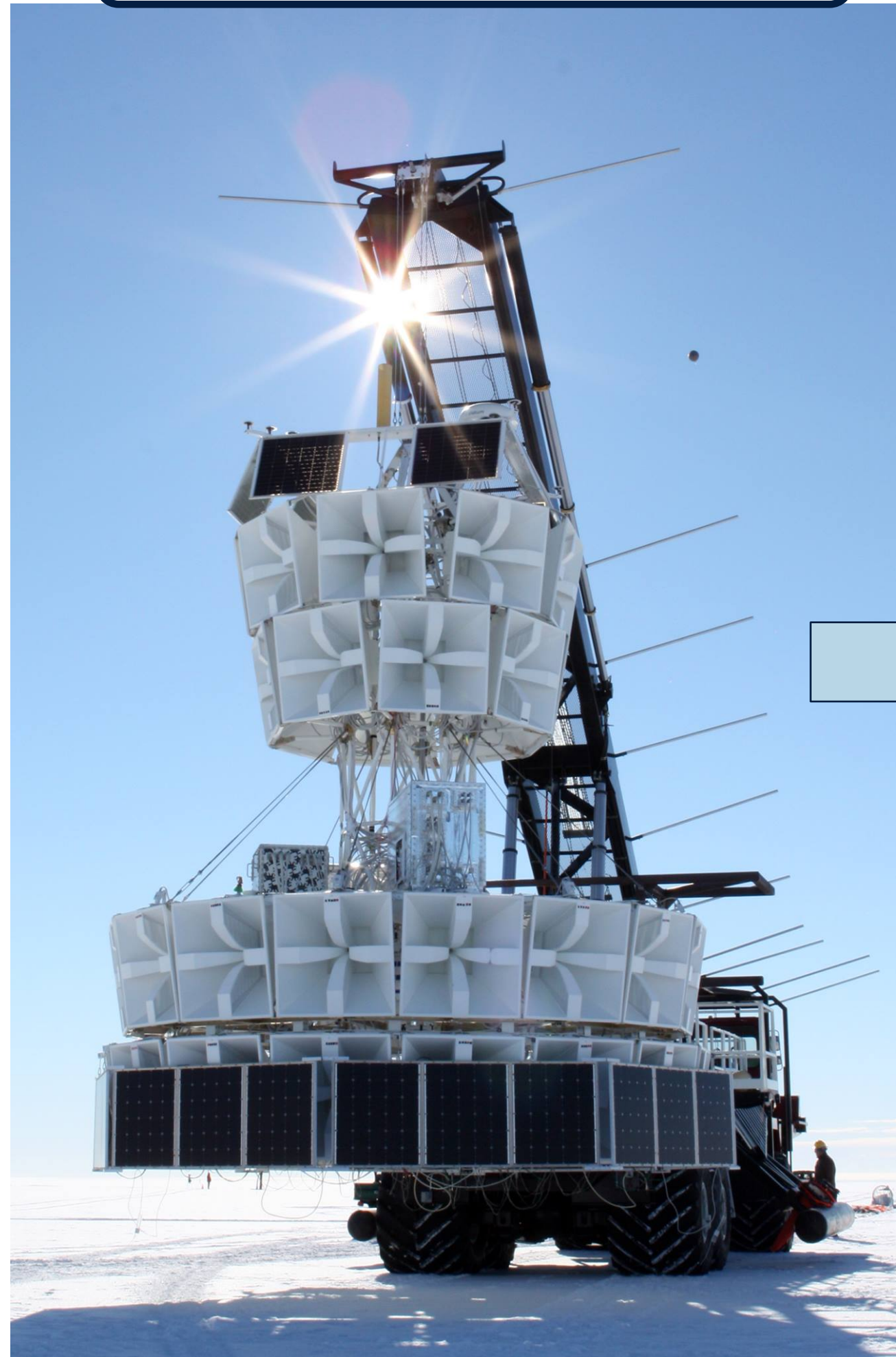


What's the difference between ANITA and PUEO?

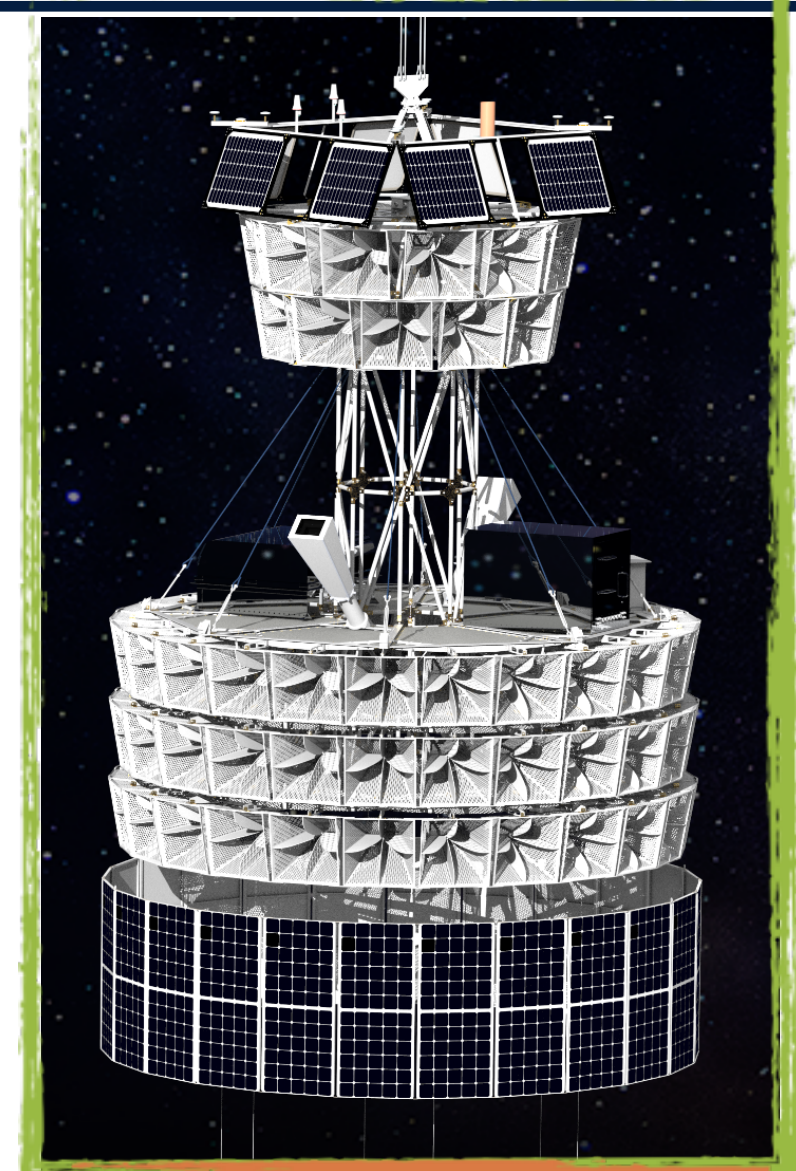
Improved Sensitivity

- Same size, same altitude, similar flight duration
- **2x antennas** → narrower frequency range (300-1300 MHz vs 180-1300 MHz), **higher gain** *[MI Instrument]*
- Deployable low frequency antenna array targeting air showers *[LF instrument]*

ANITA (2005-2016)



PUEO (2025)

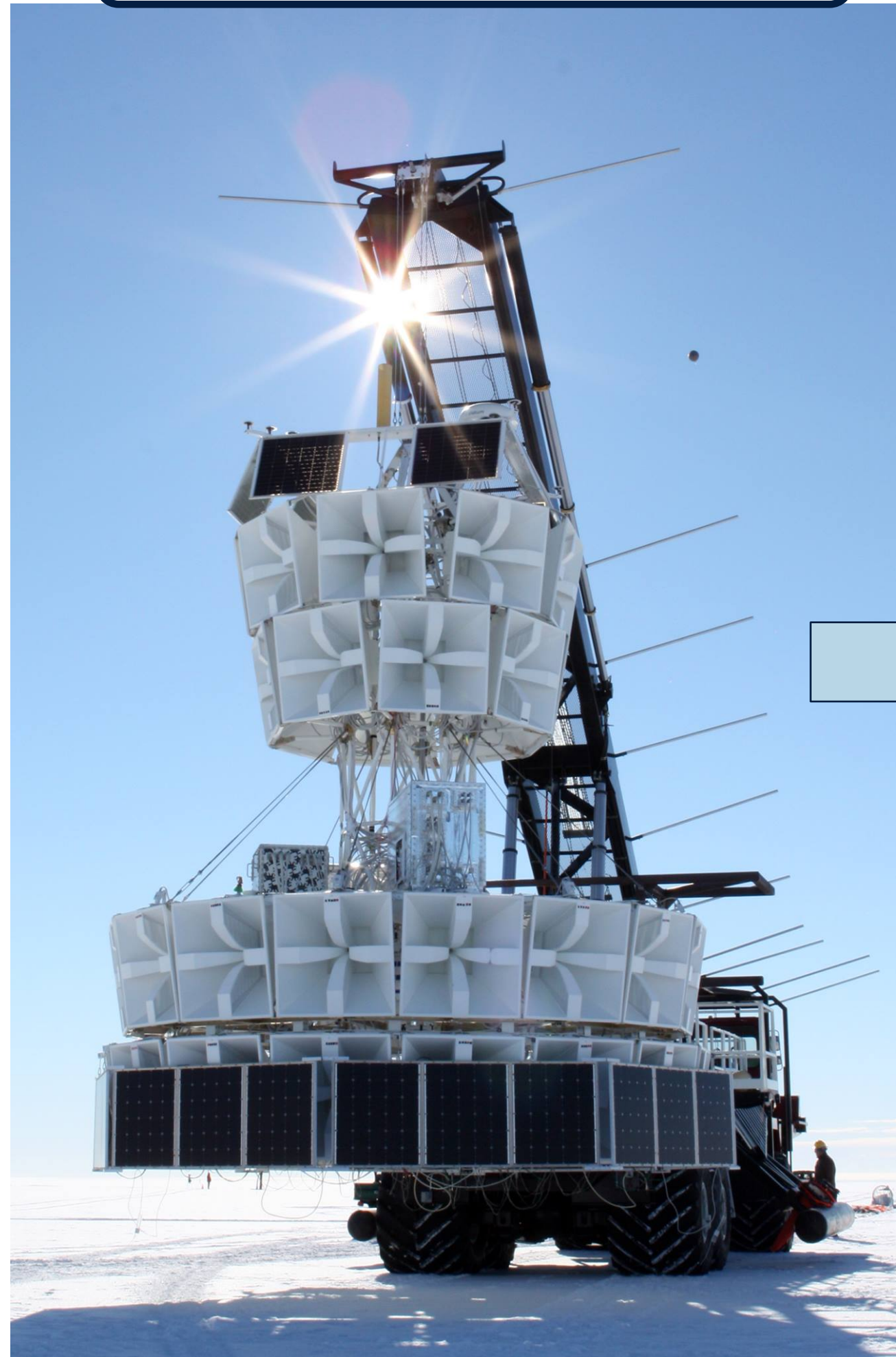


What's the difference between ANITA and PUEO?

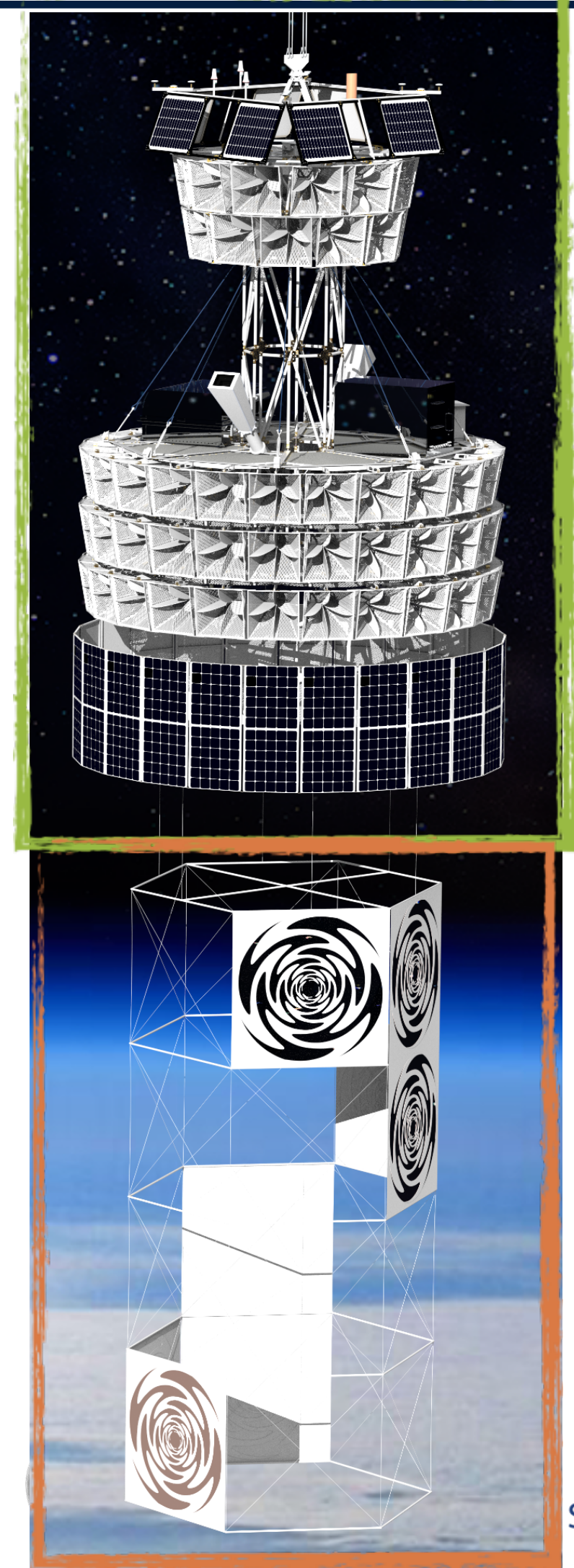
Improved Sensitivity

- Same size, same altitude, similar flight duration
- **2x antennas** → narrower frequency range (300-1300 MHz vs 180-1300 MHz), **higher gain** *[MI Instrument]*
- Deployable low frequency antenna array targeting air showers *[LF instrument]*
- **Beamforming**

ANITA (2005-2016)



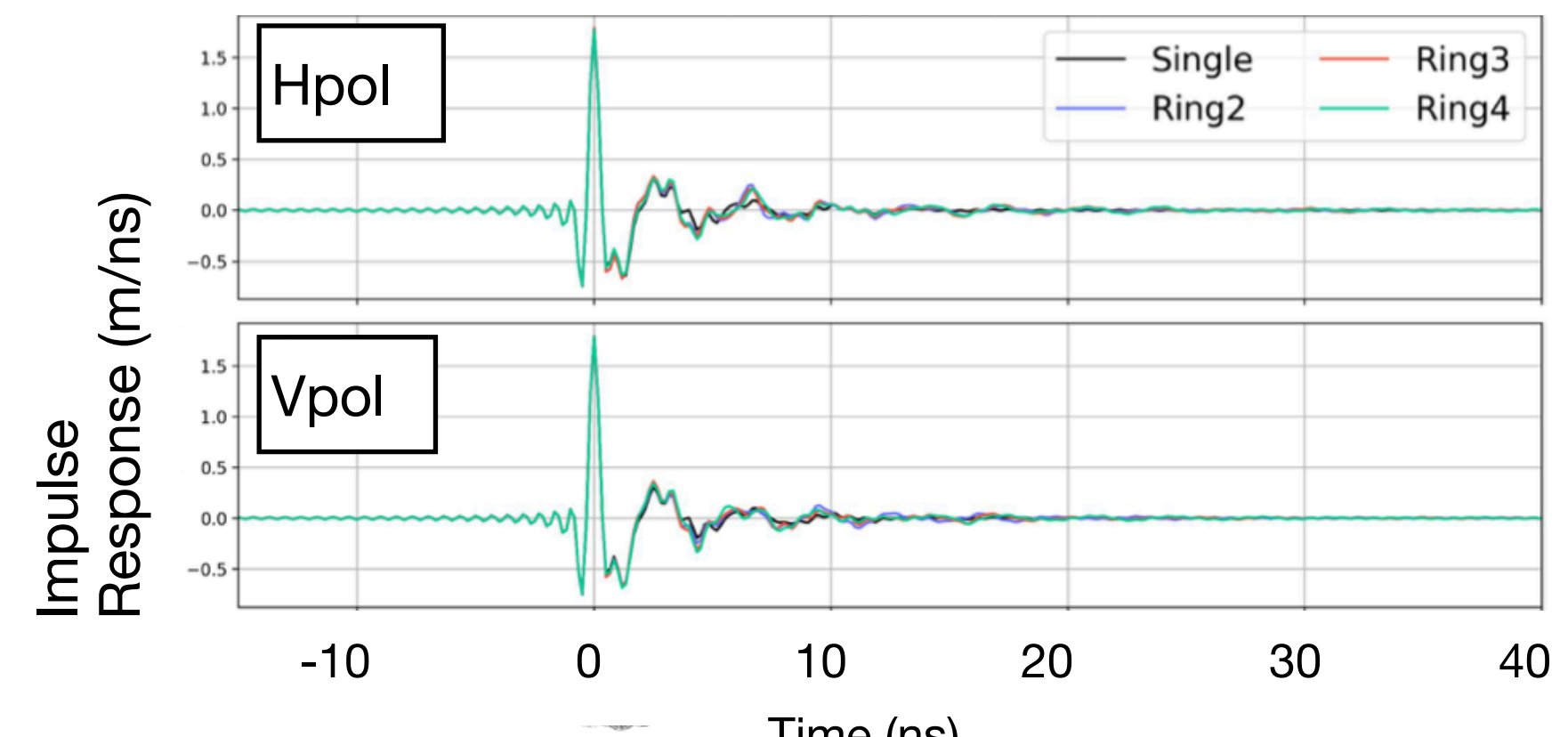
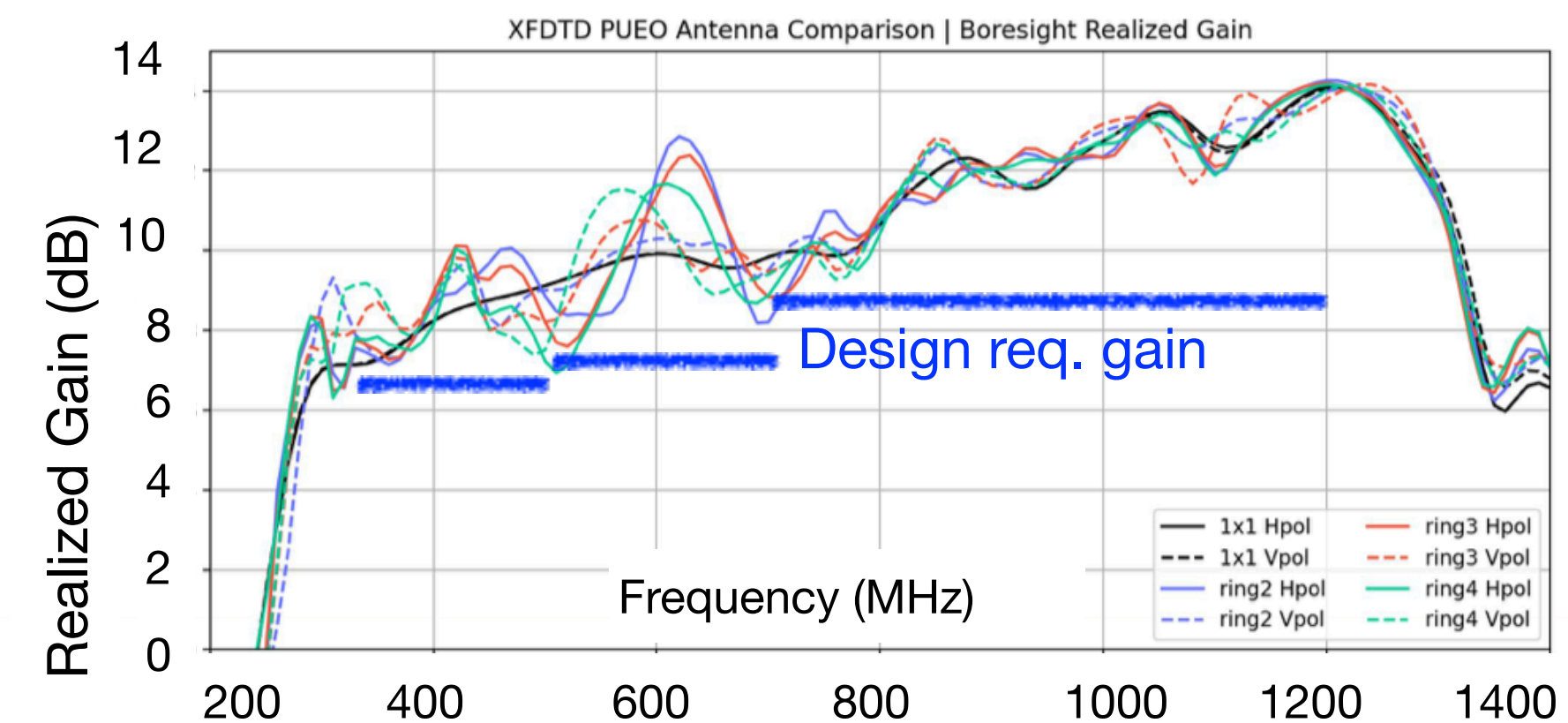
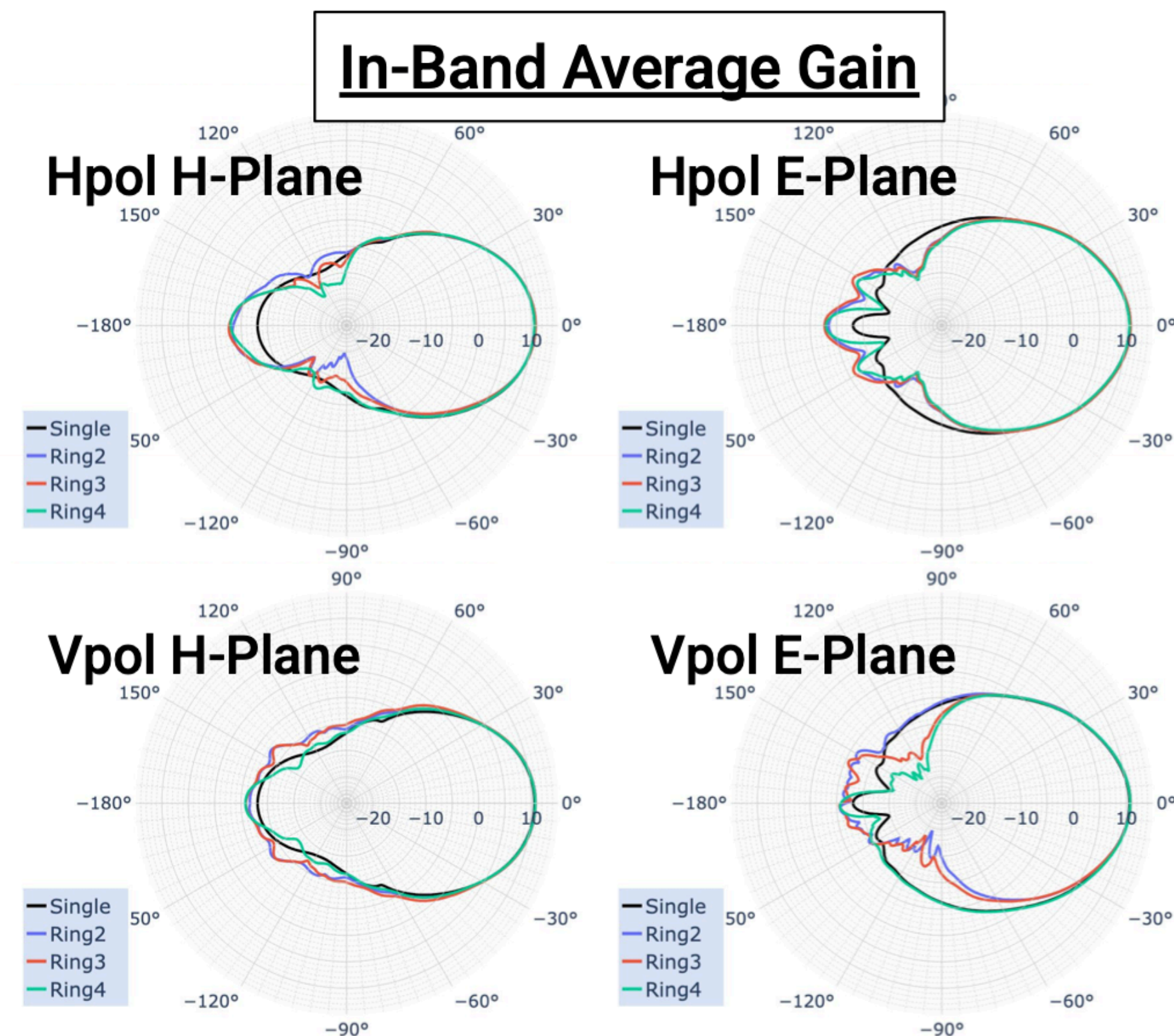
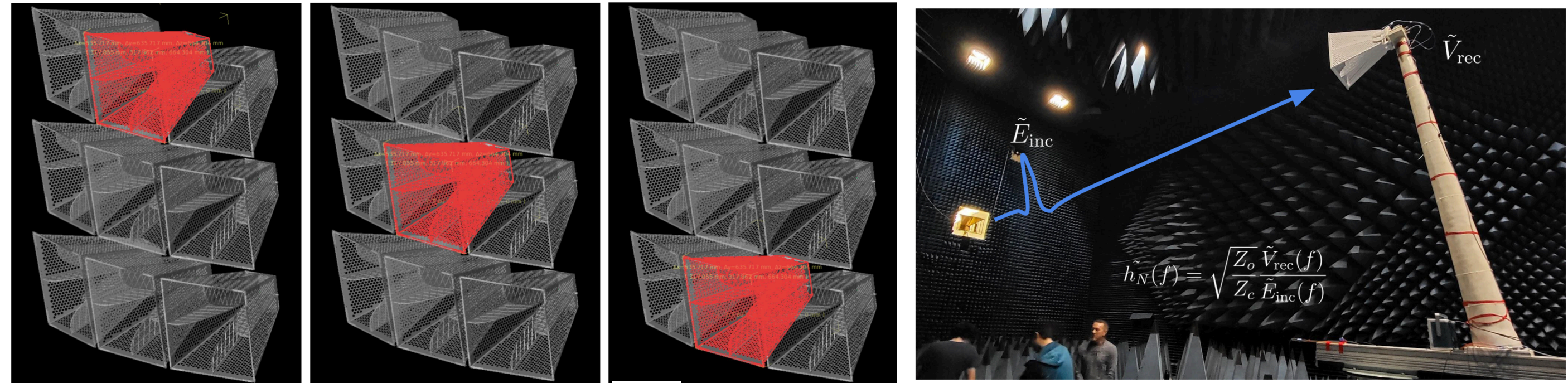
PUEO (2025)

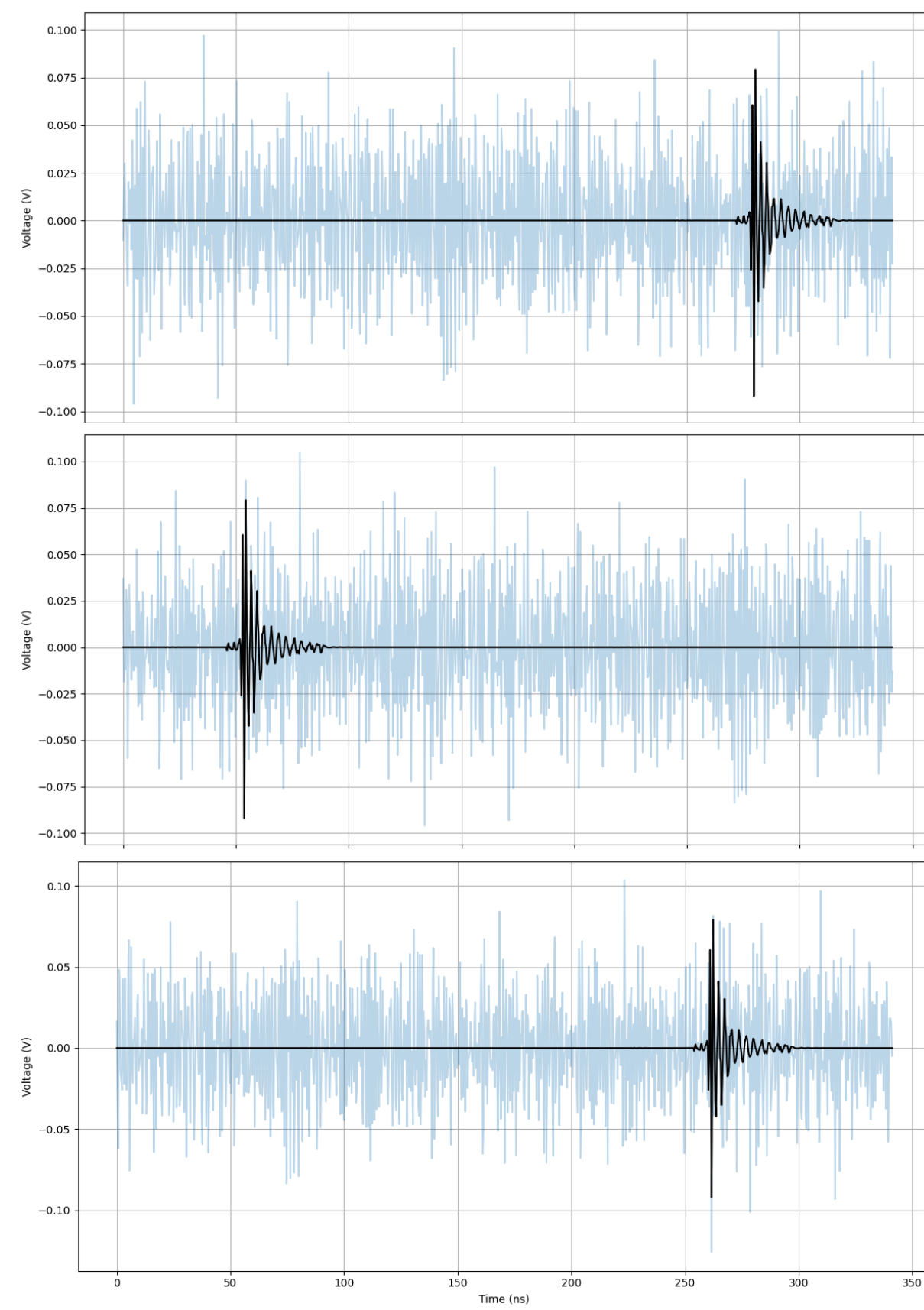


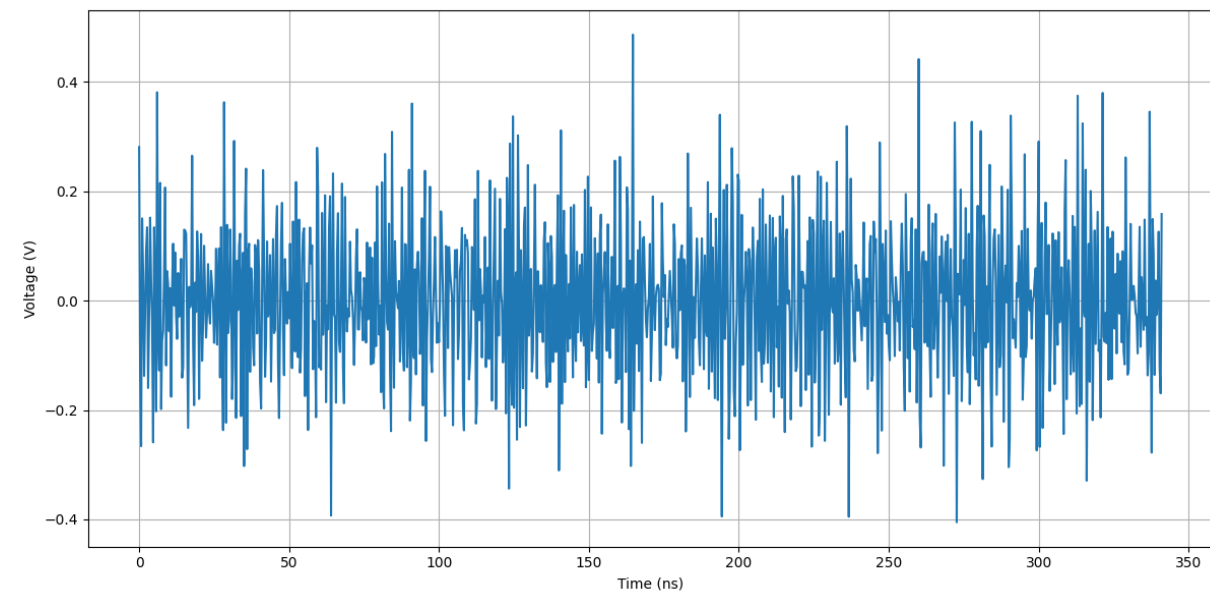
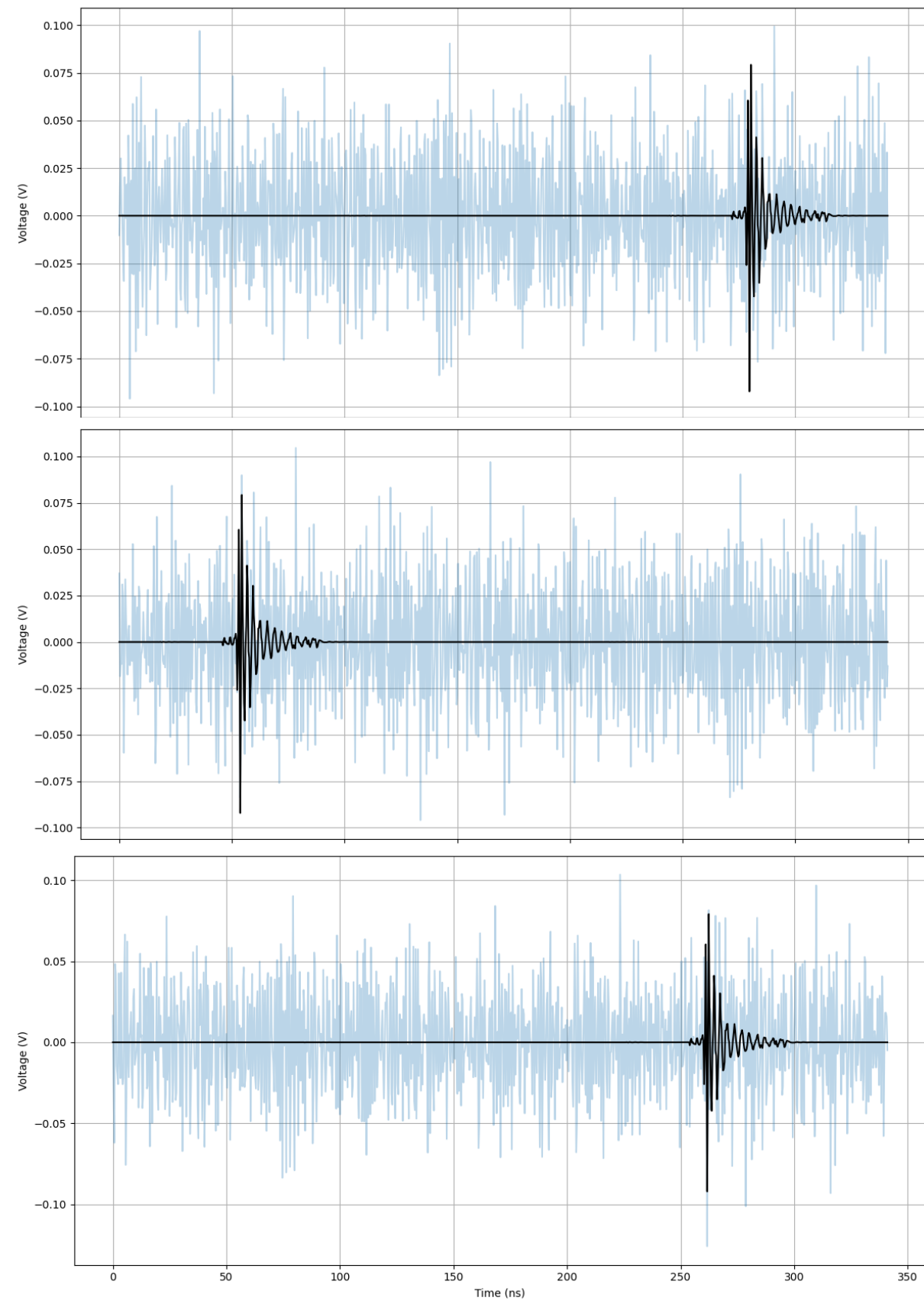
Antenna Performance

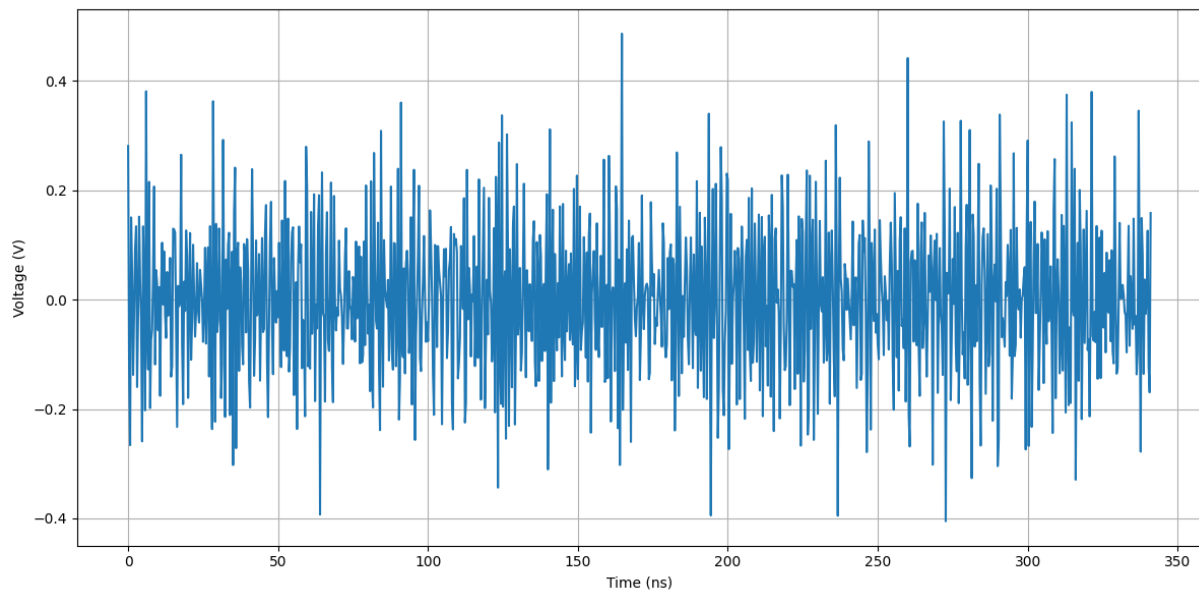
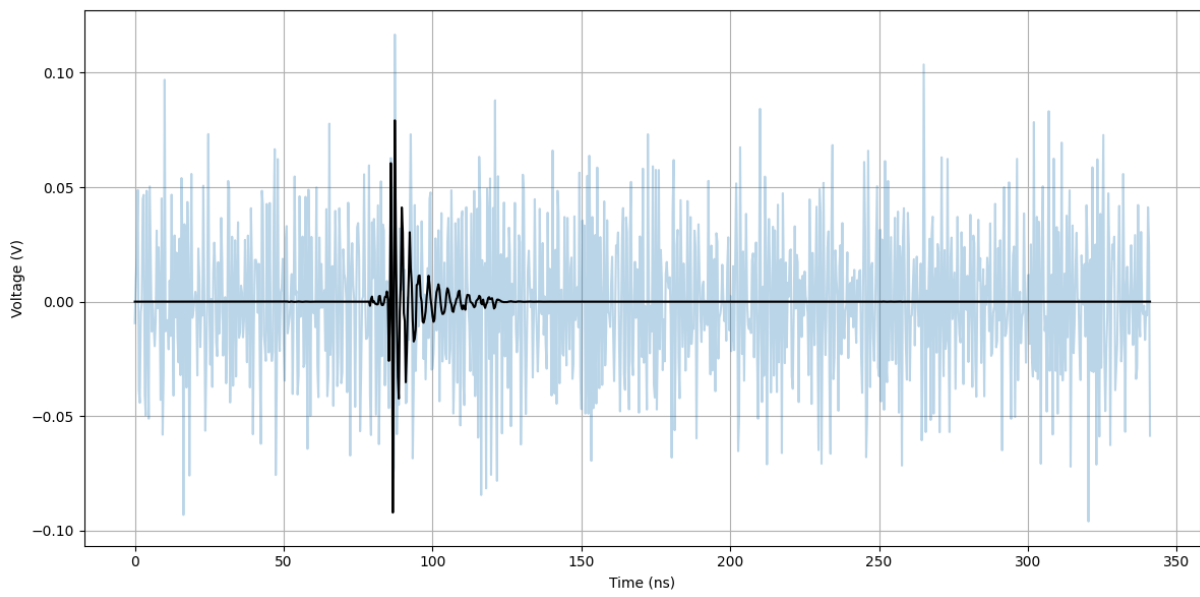
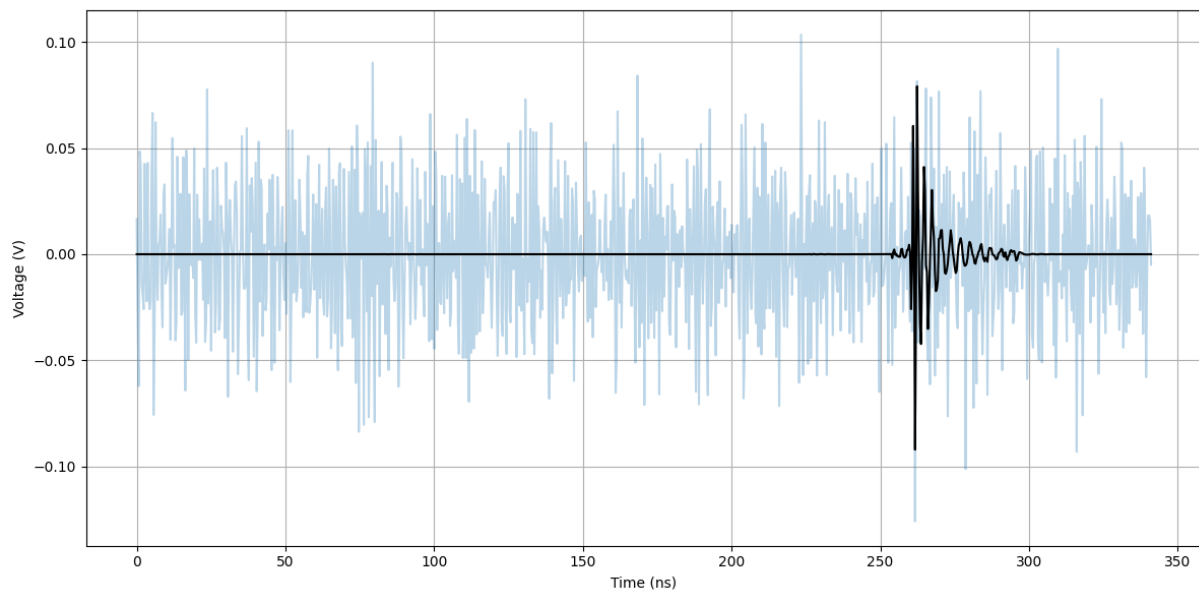
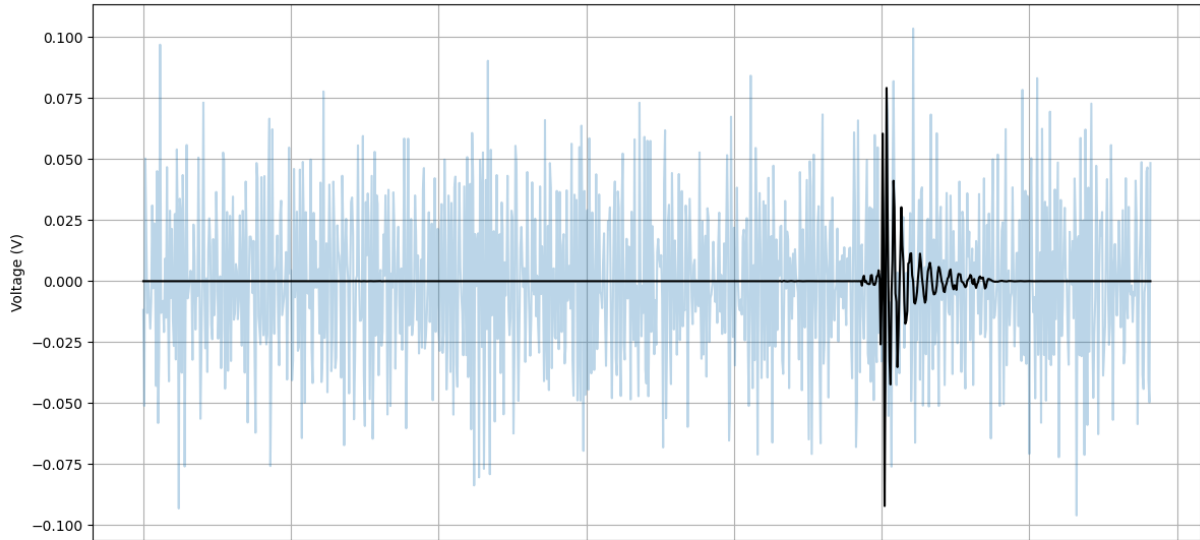
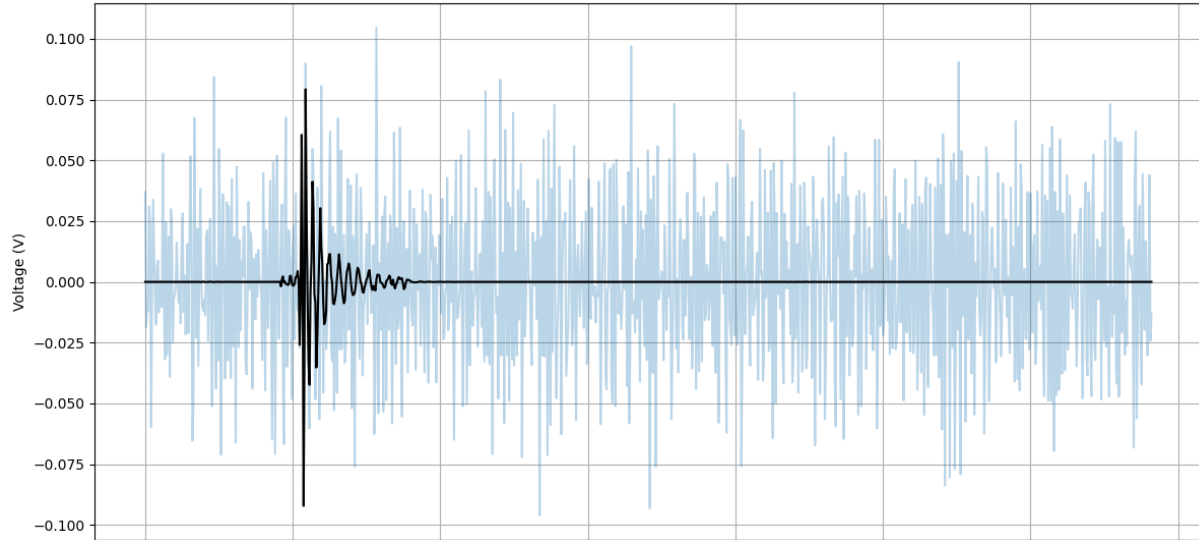
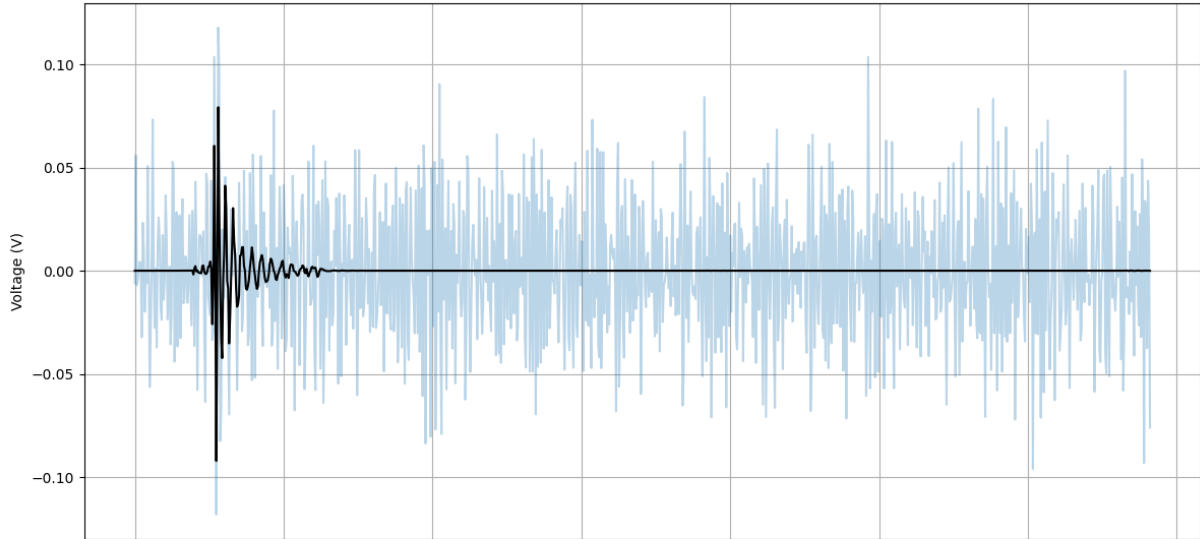
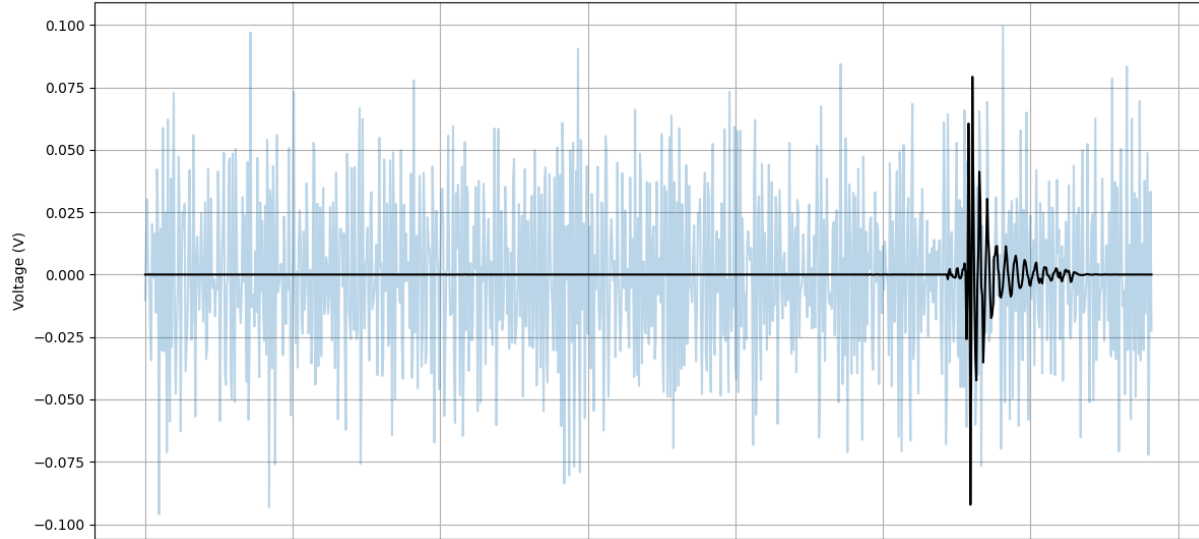
Main Instrument Antennas

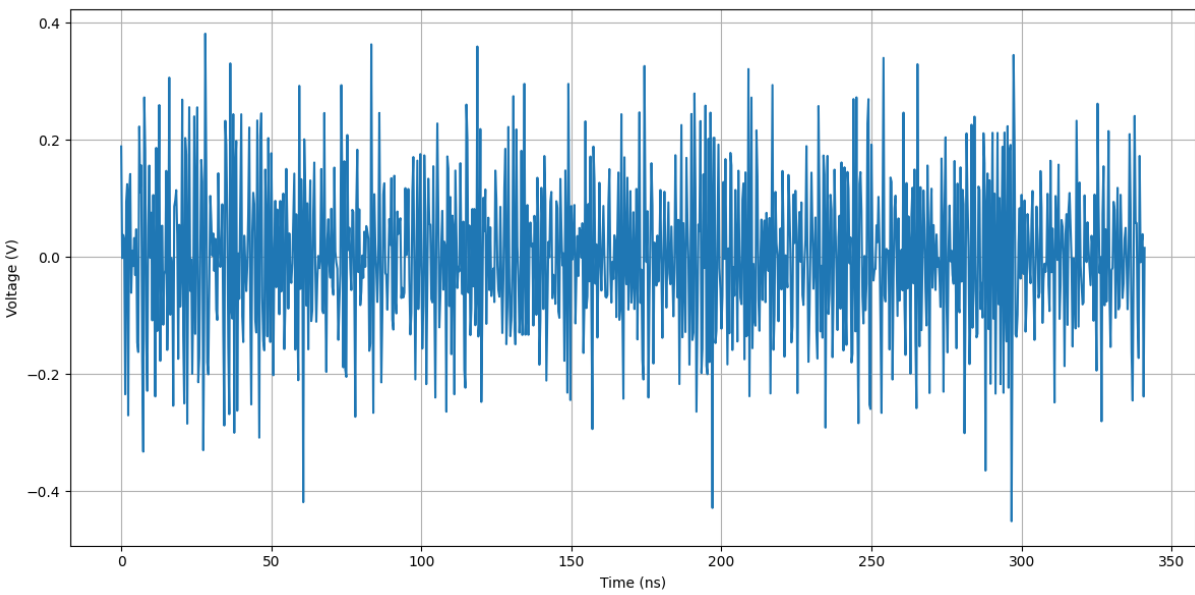
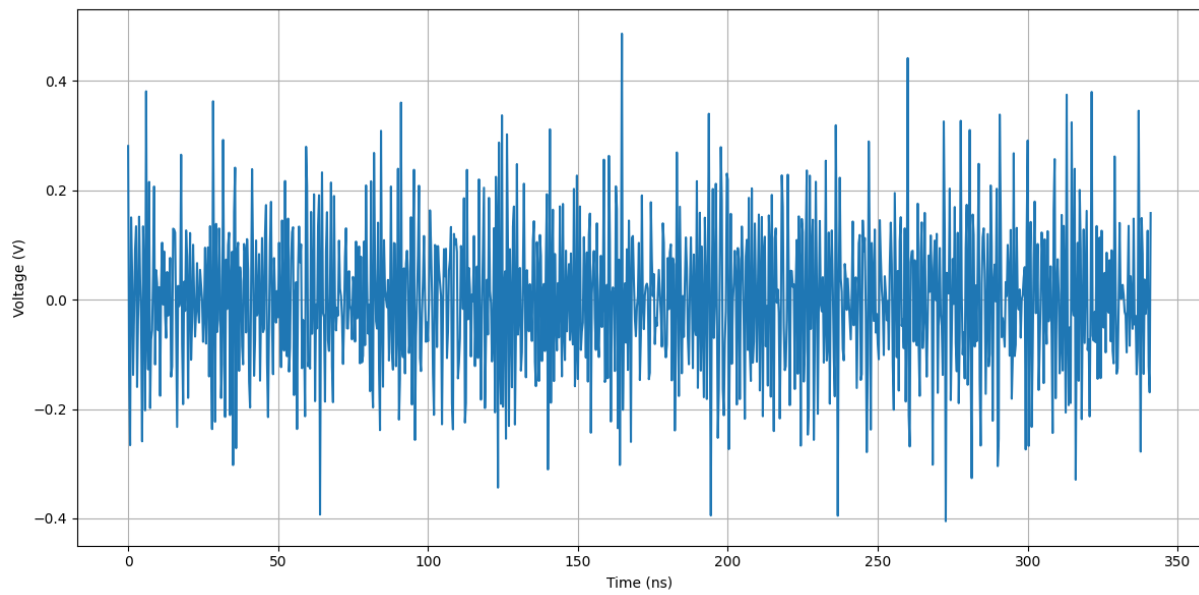
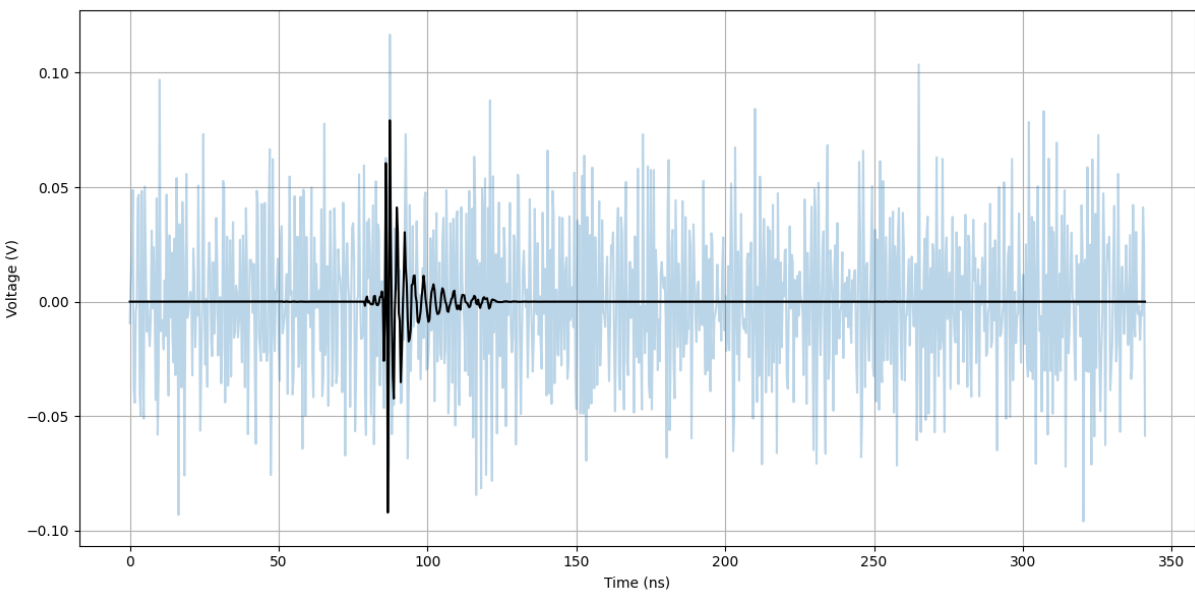
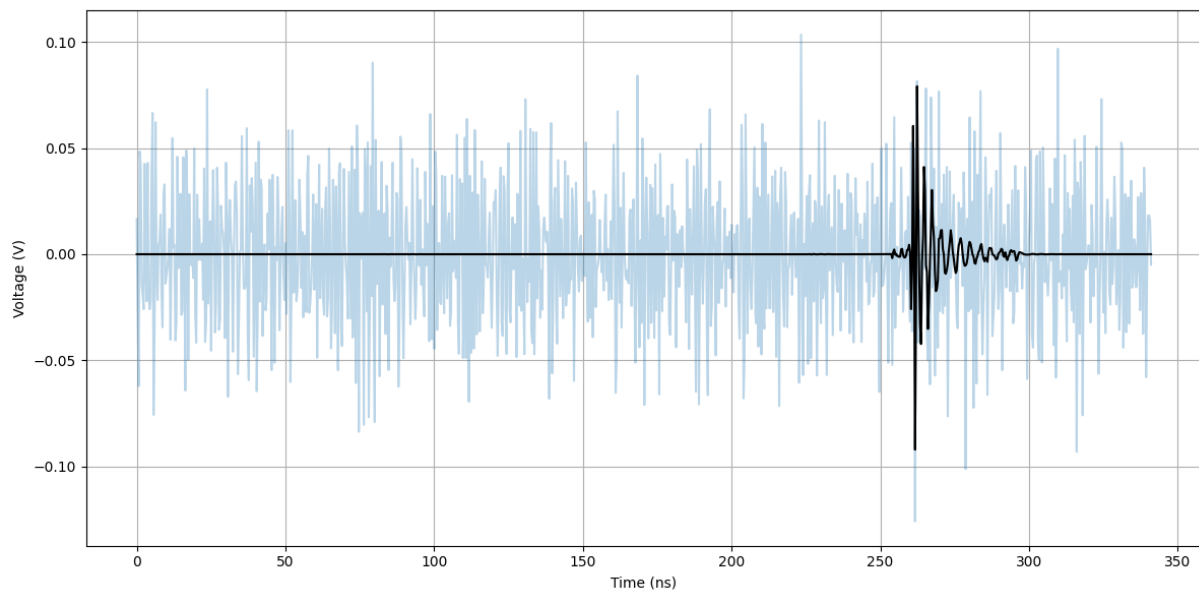
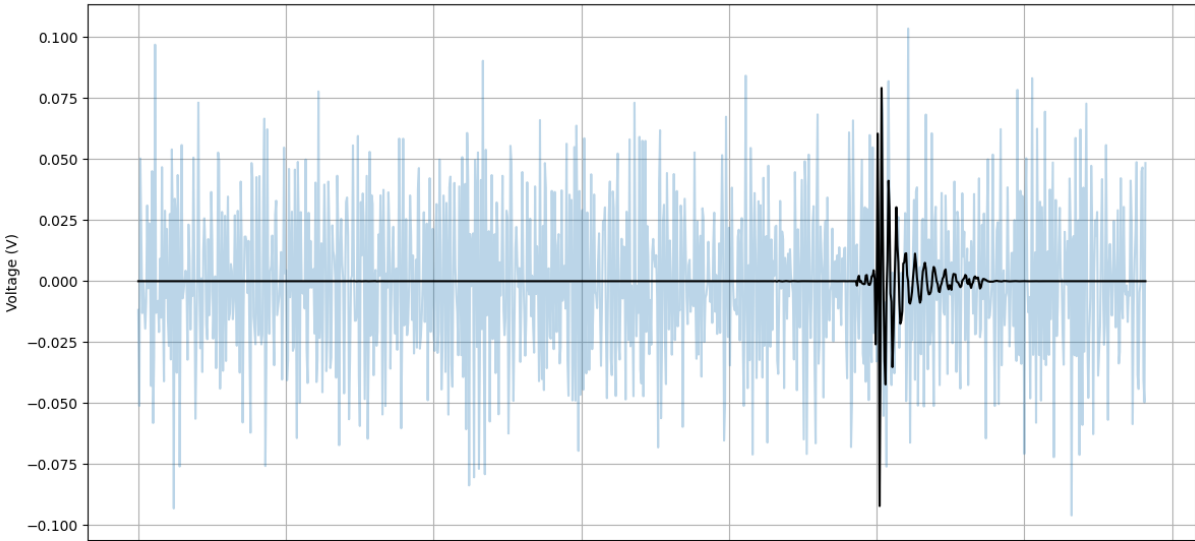
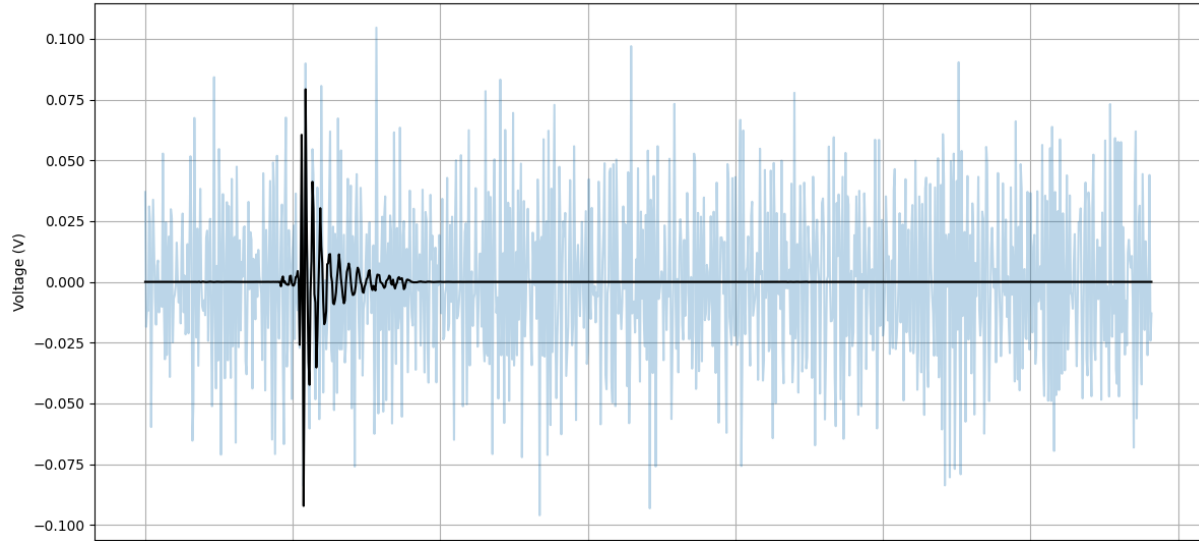
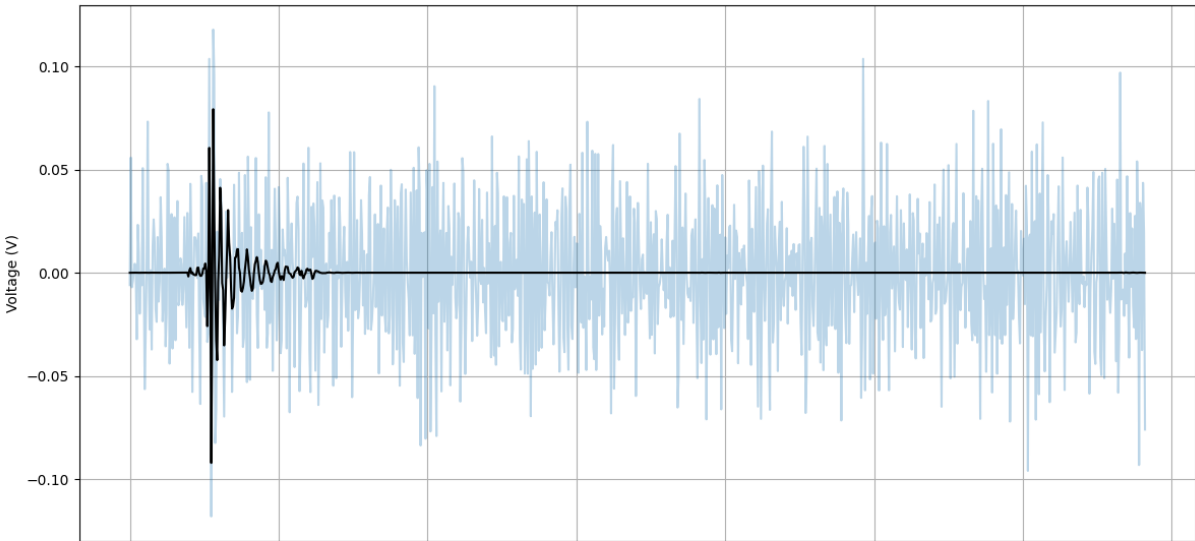
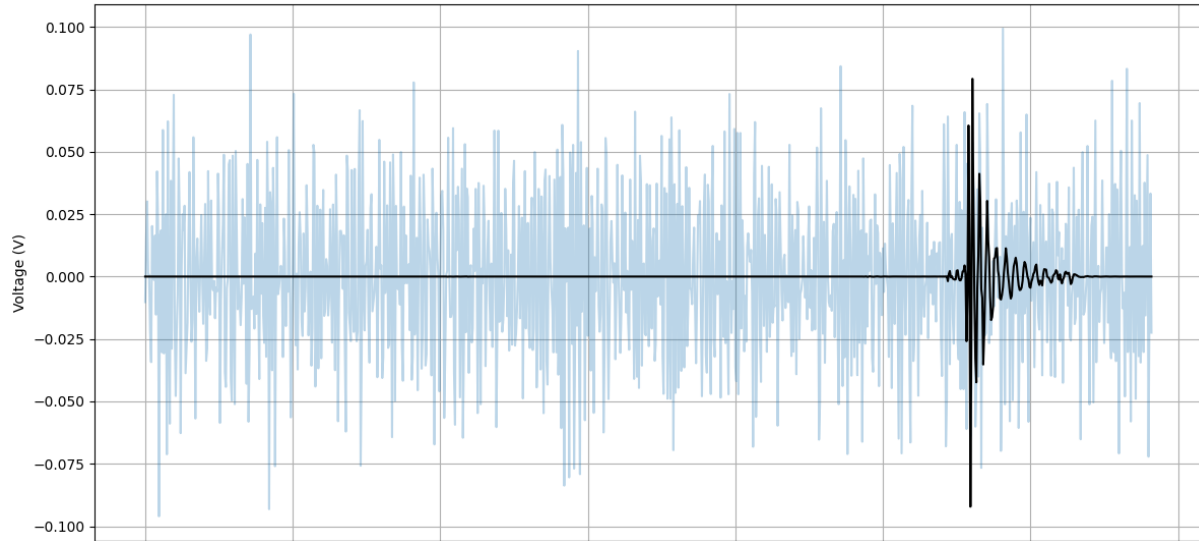
- Quad-ridged horn antennas 300-1200 MHz show improved gain (8-10 dBi) over ANITA horns

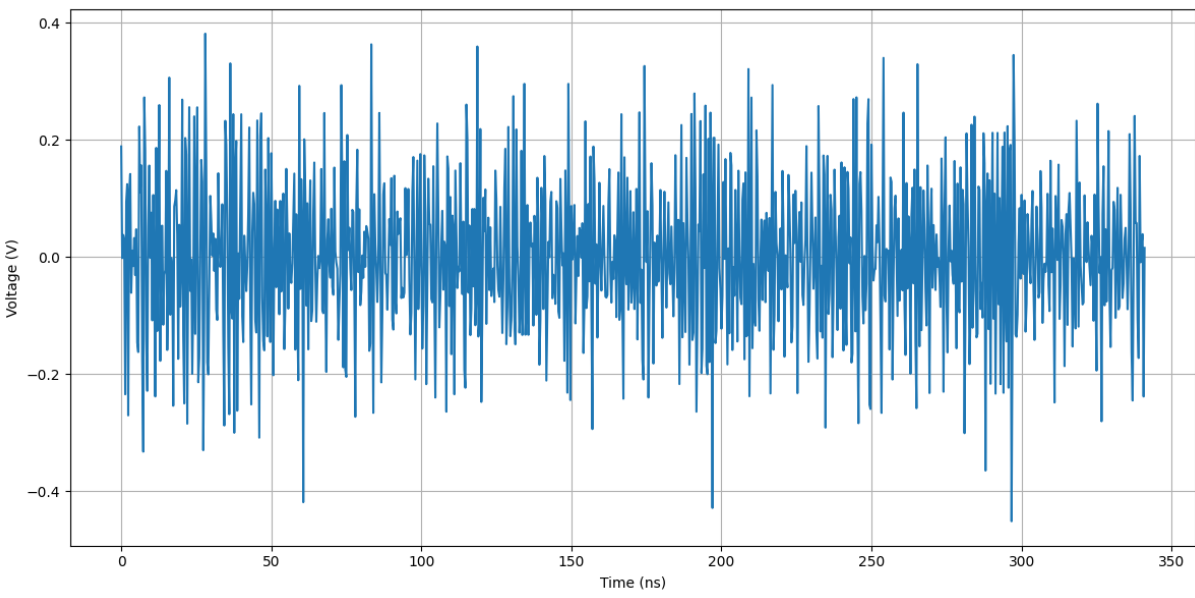
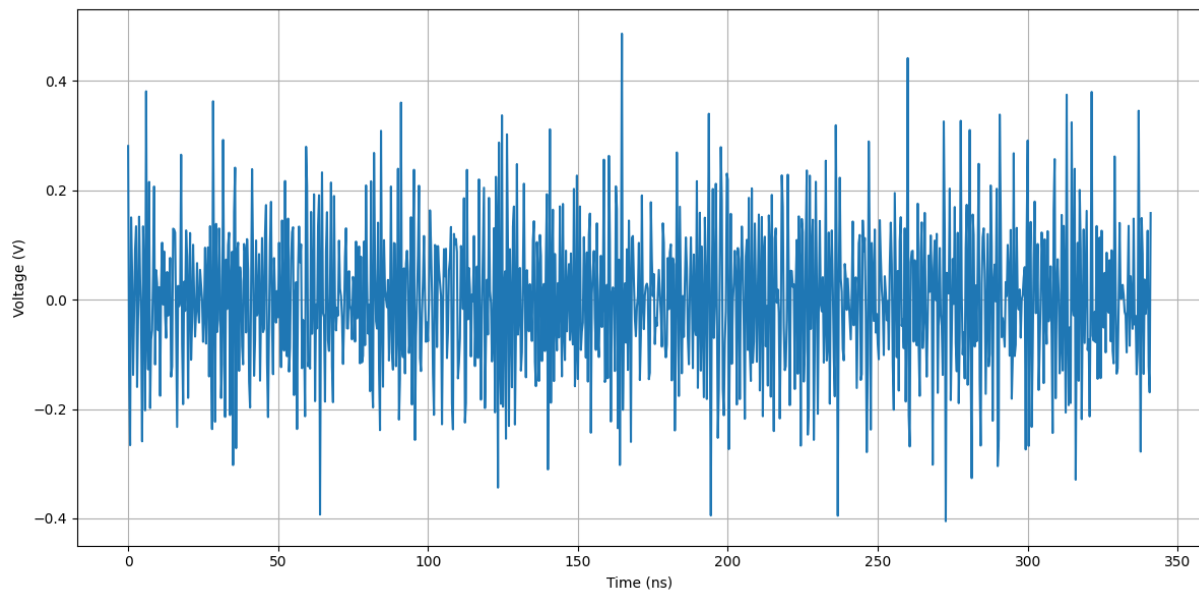
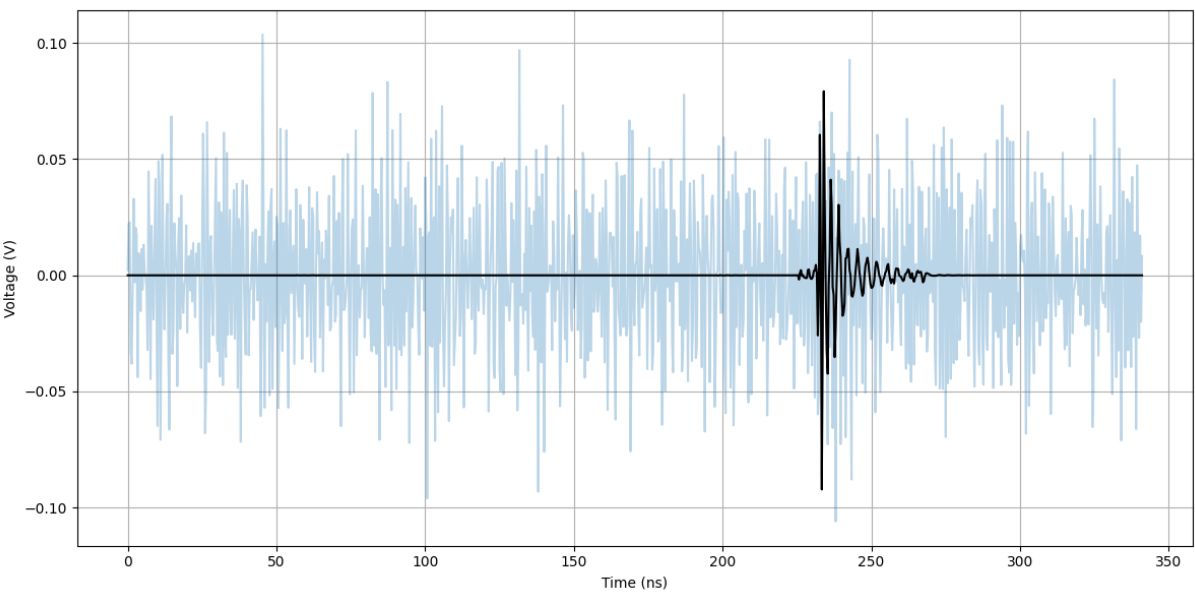
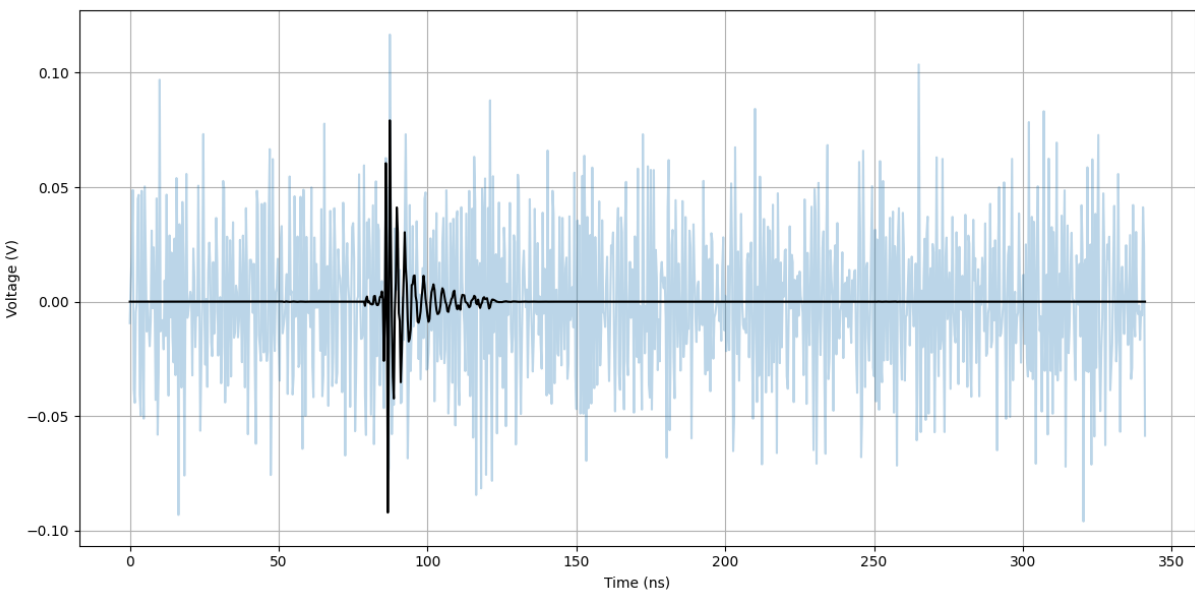
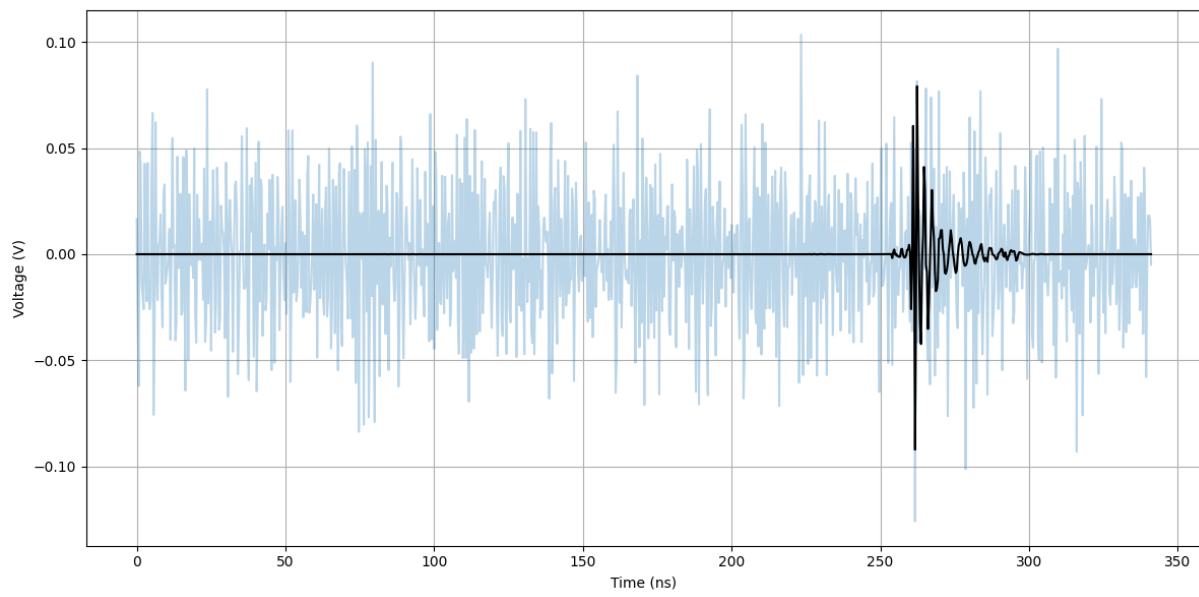
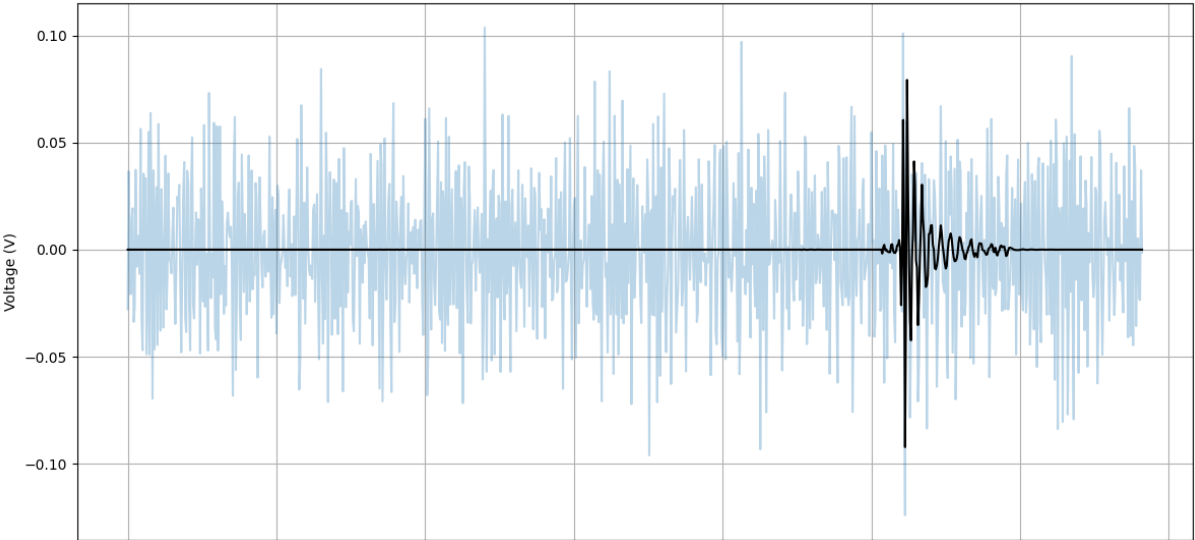
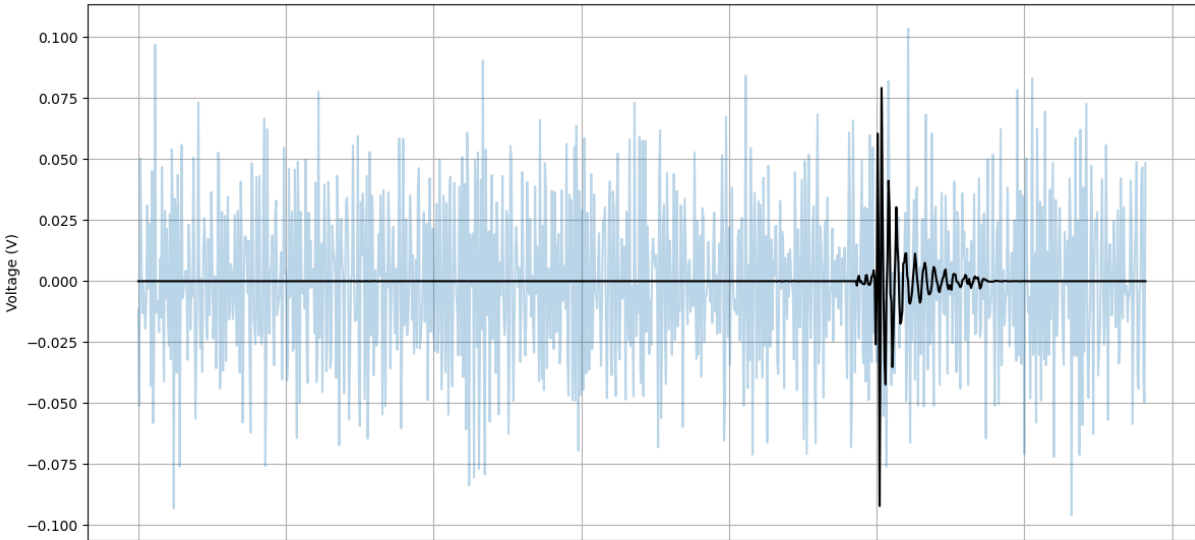
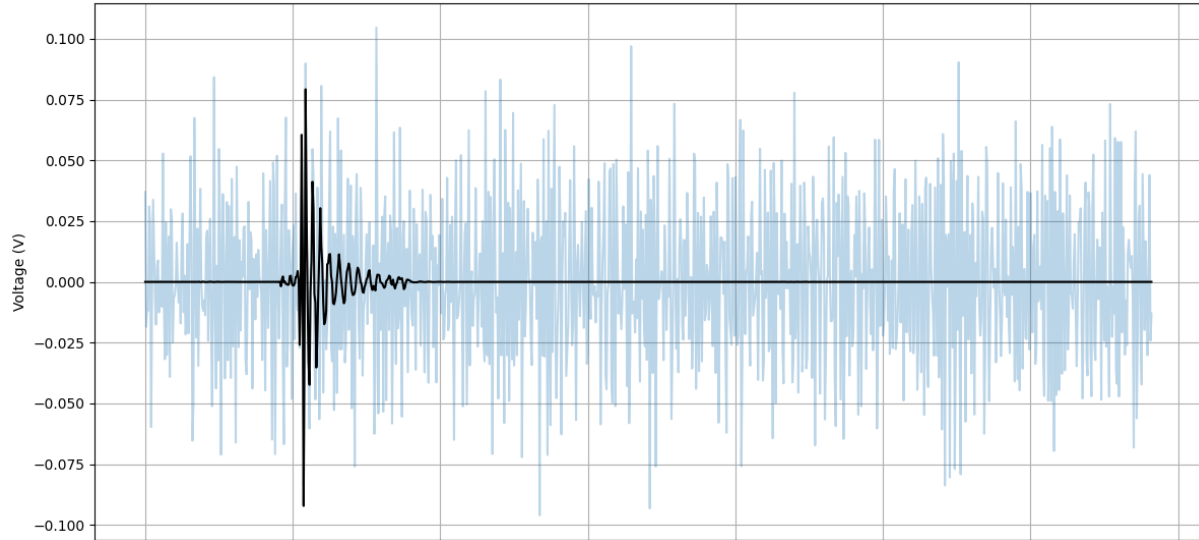
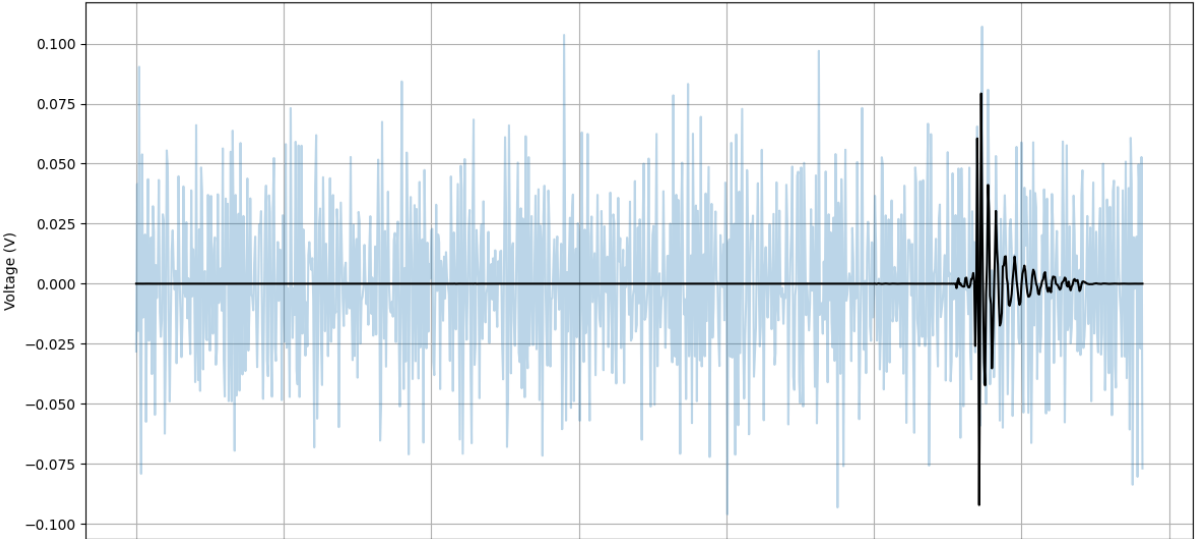
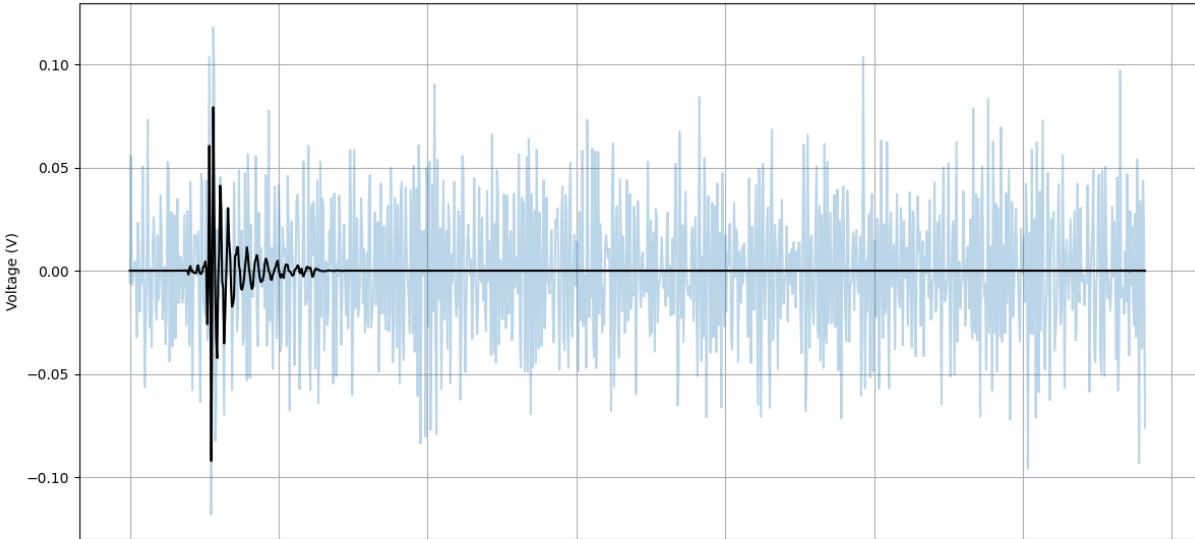
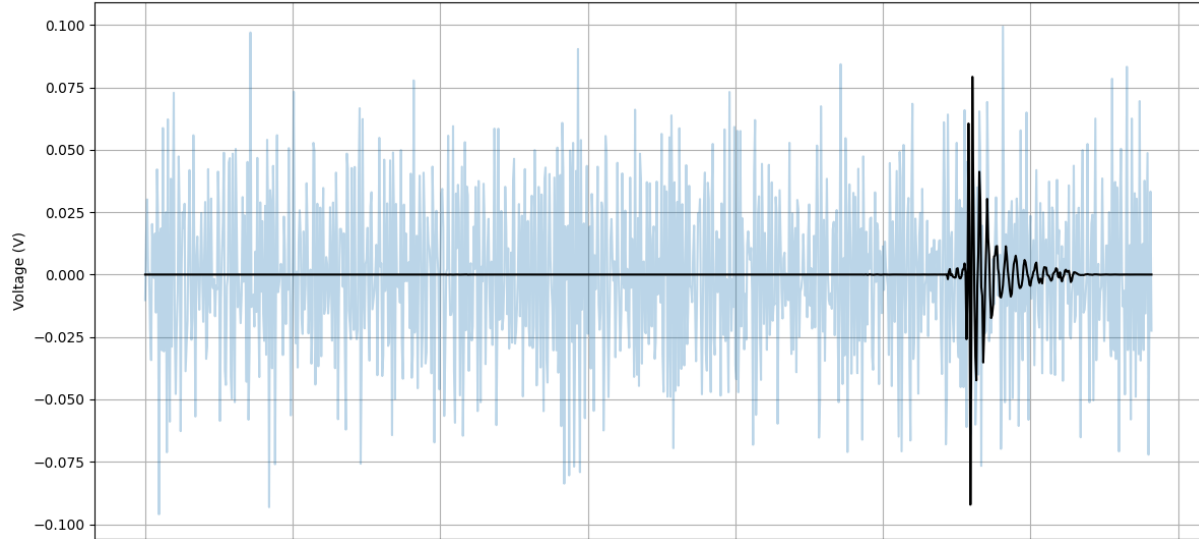
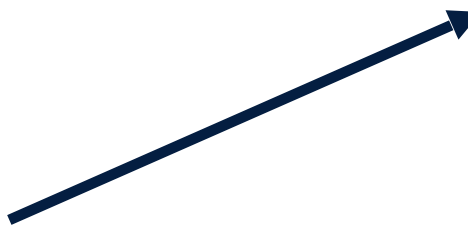


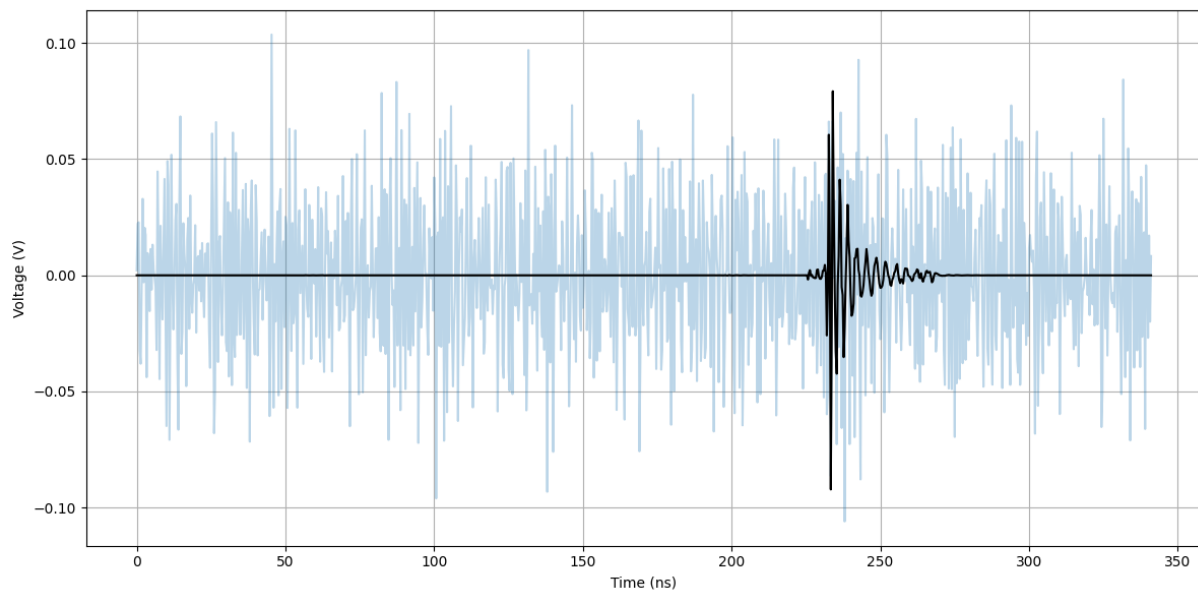
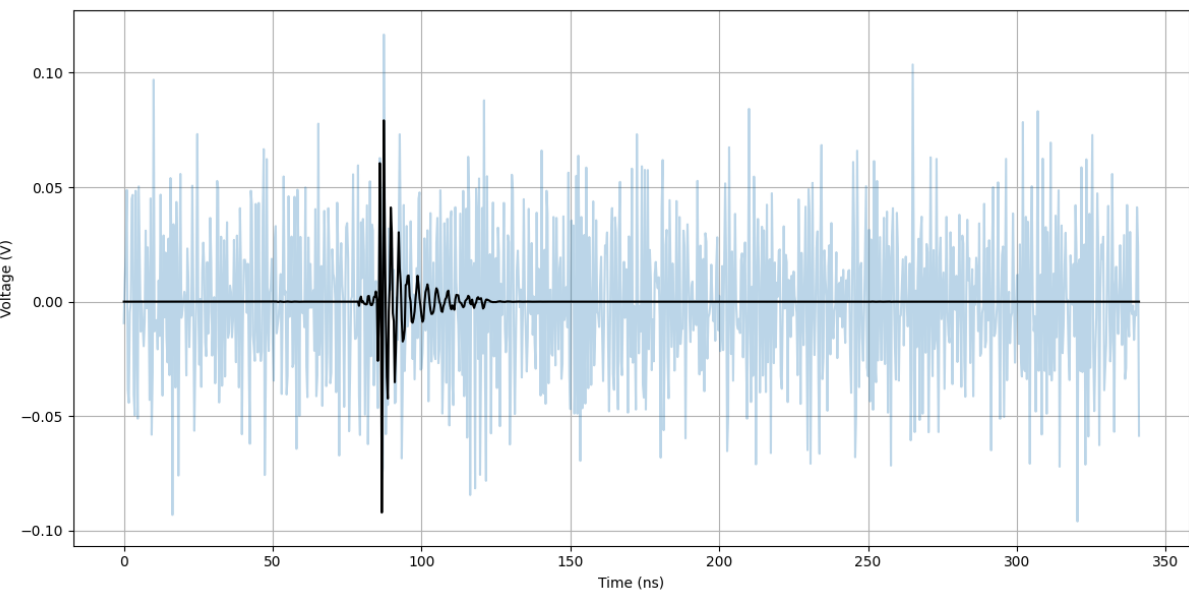
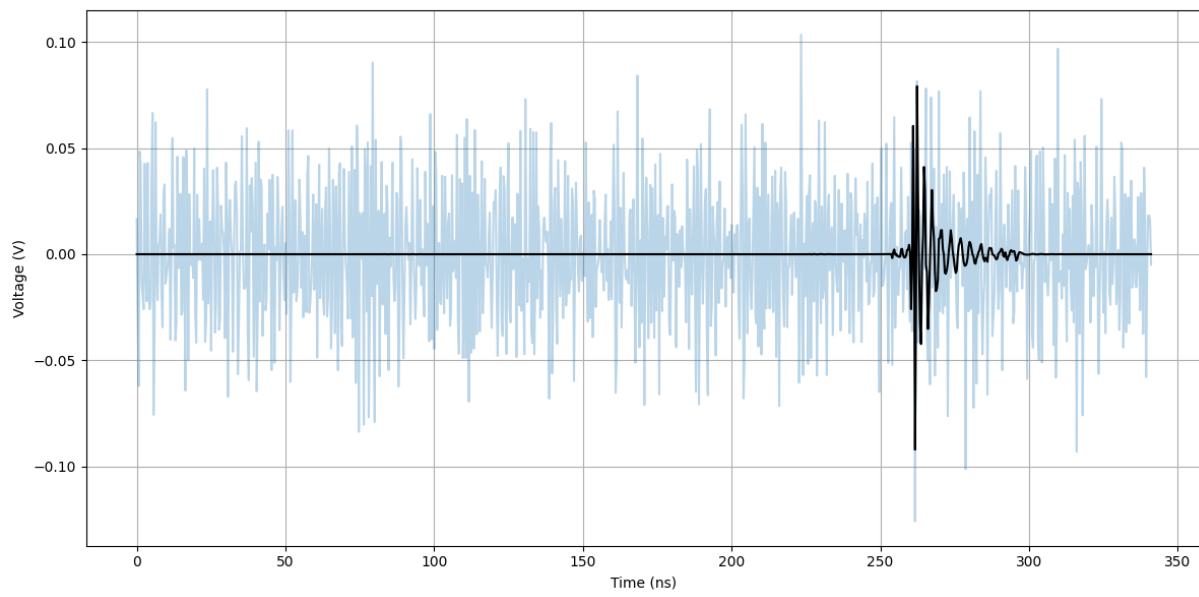
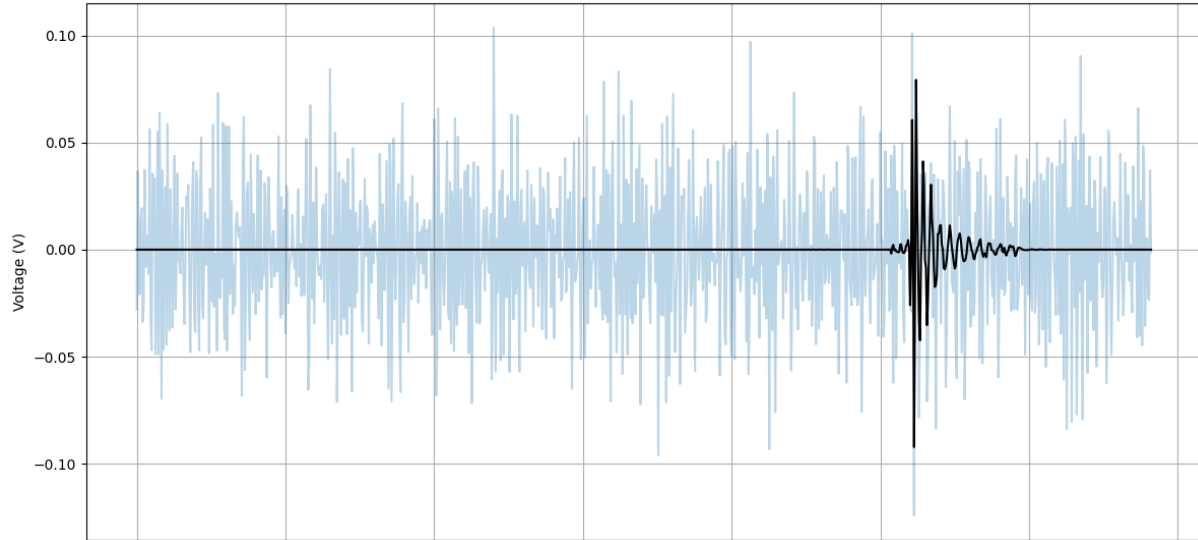
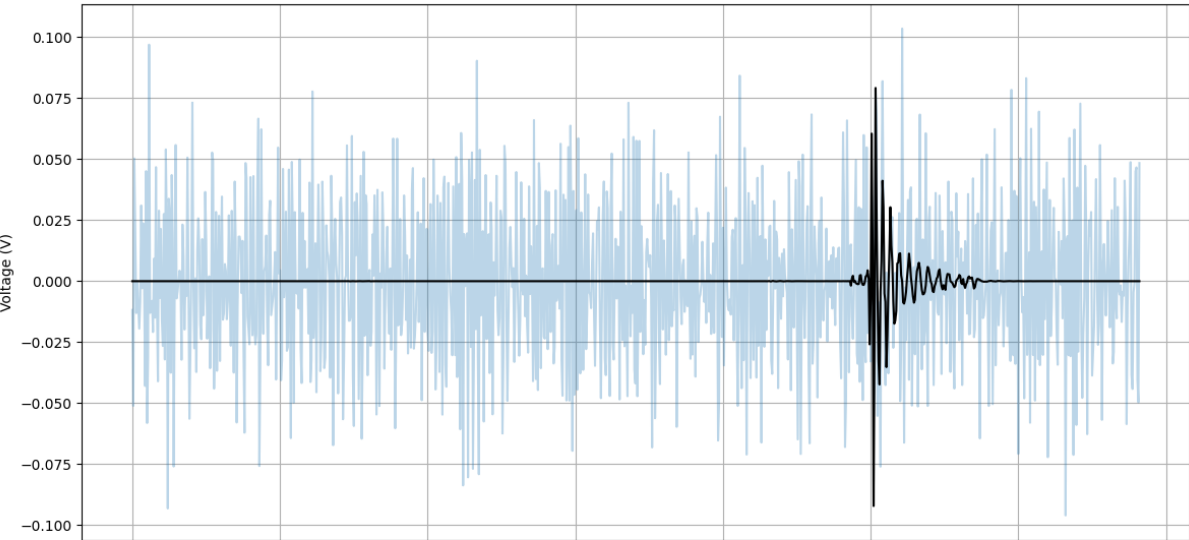
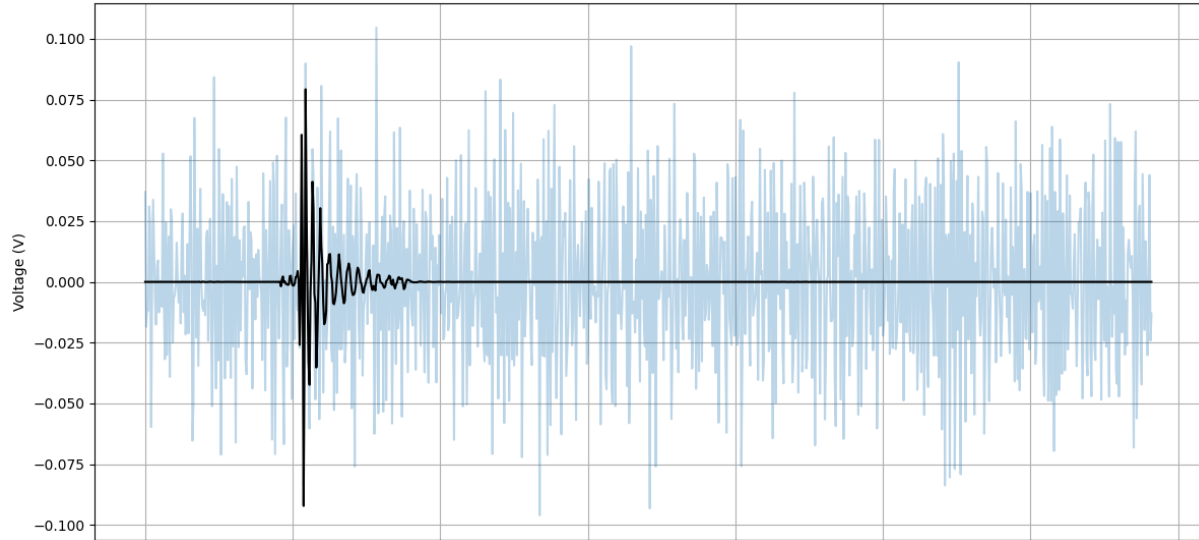
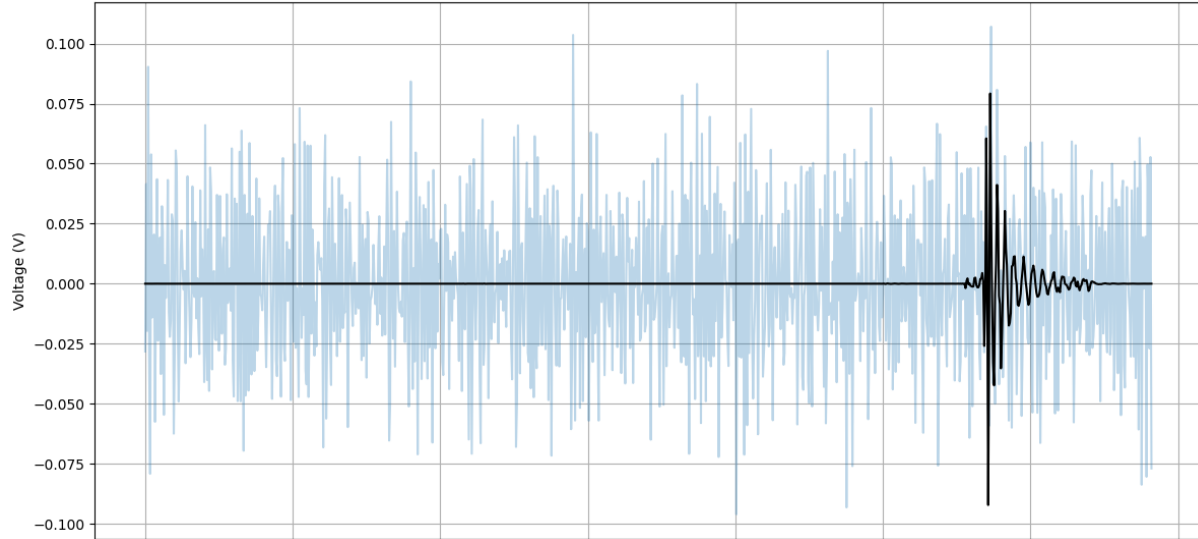
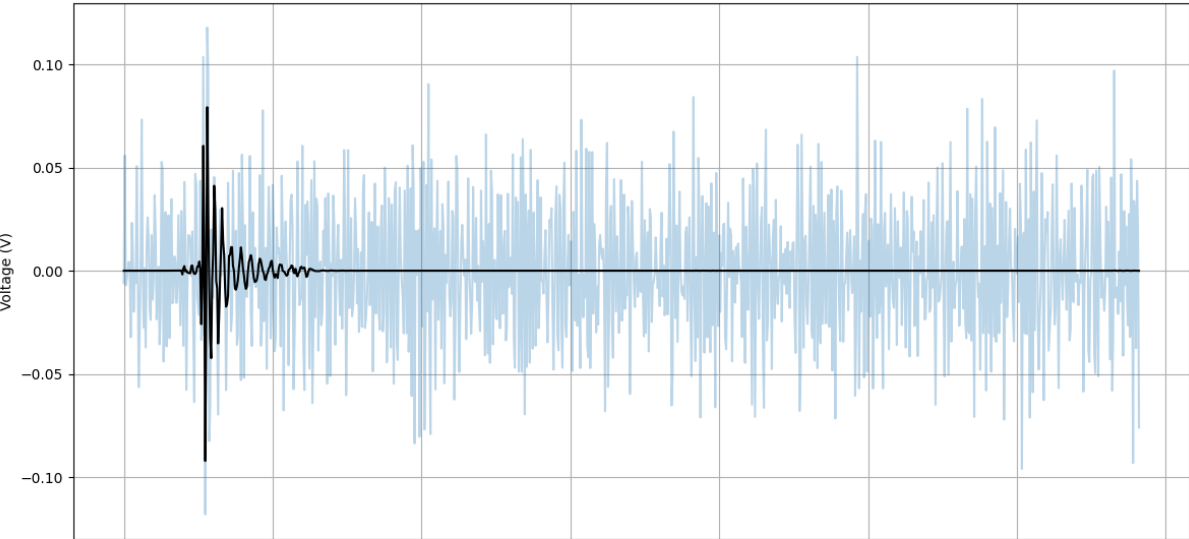
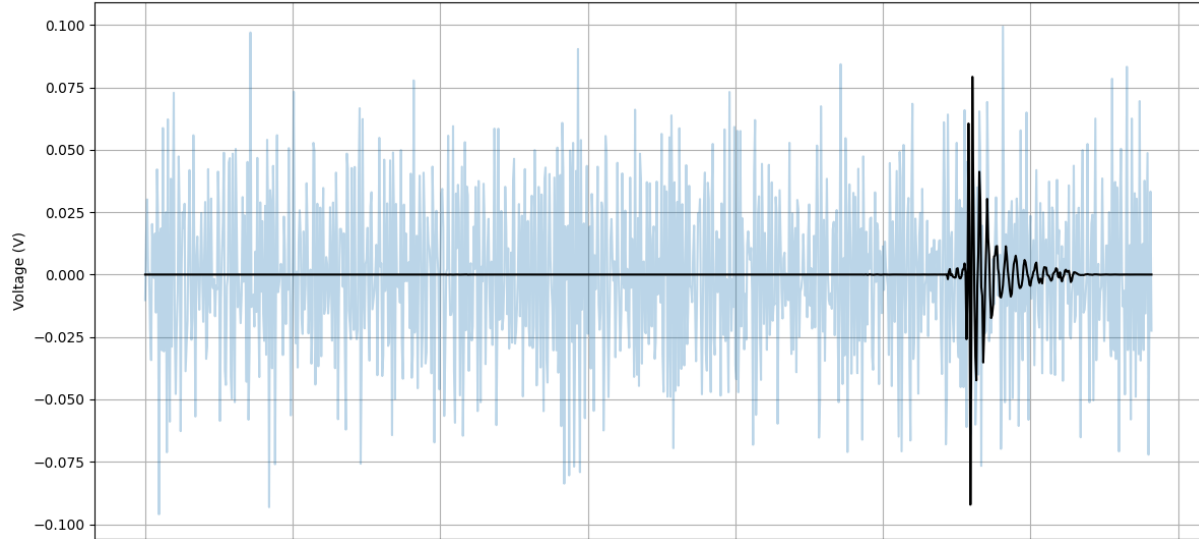
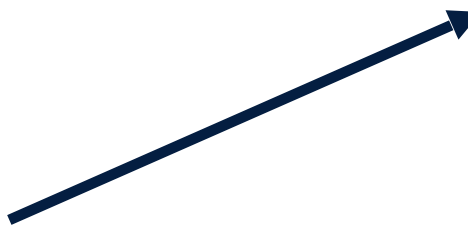








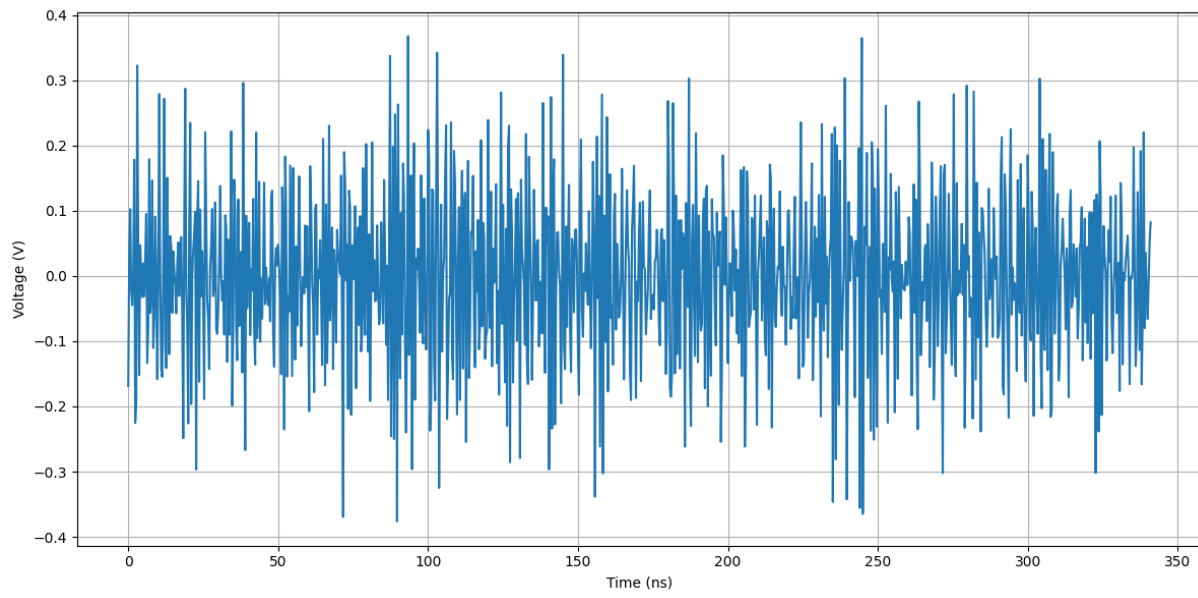
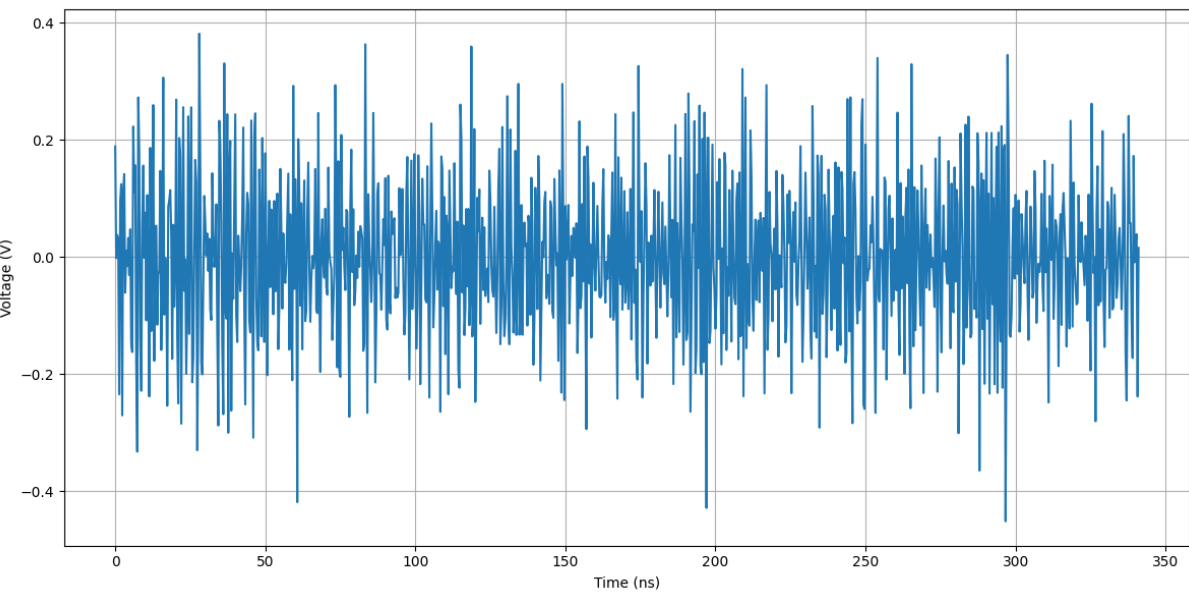
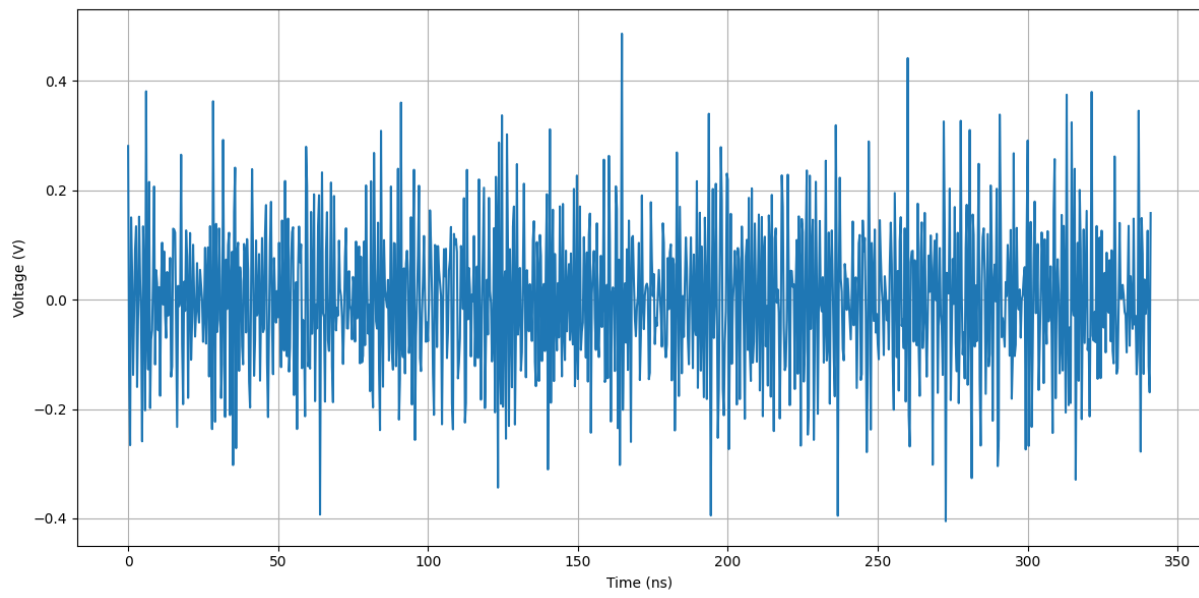


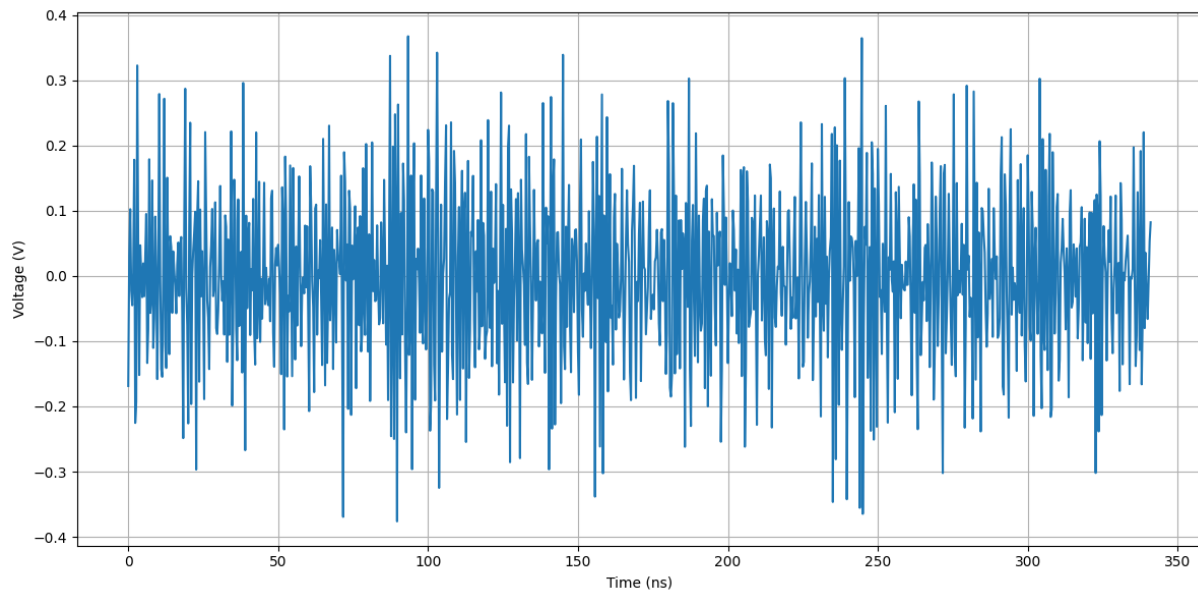
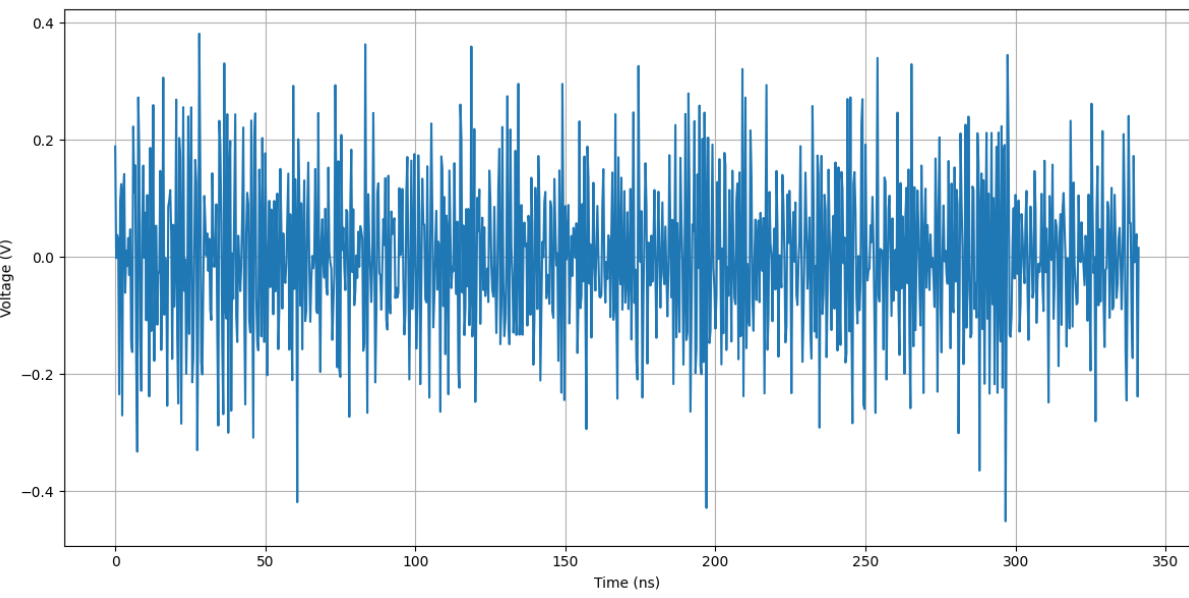
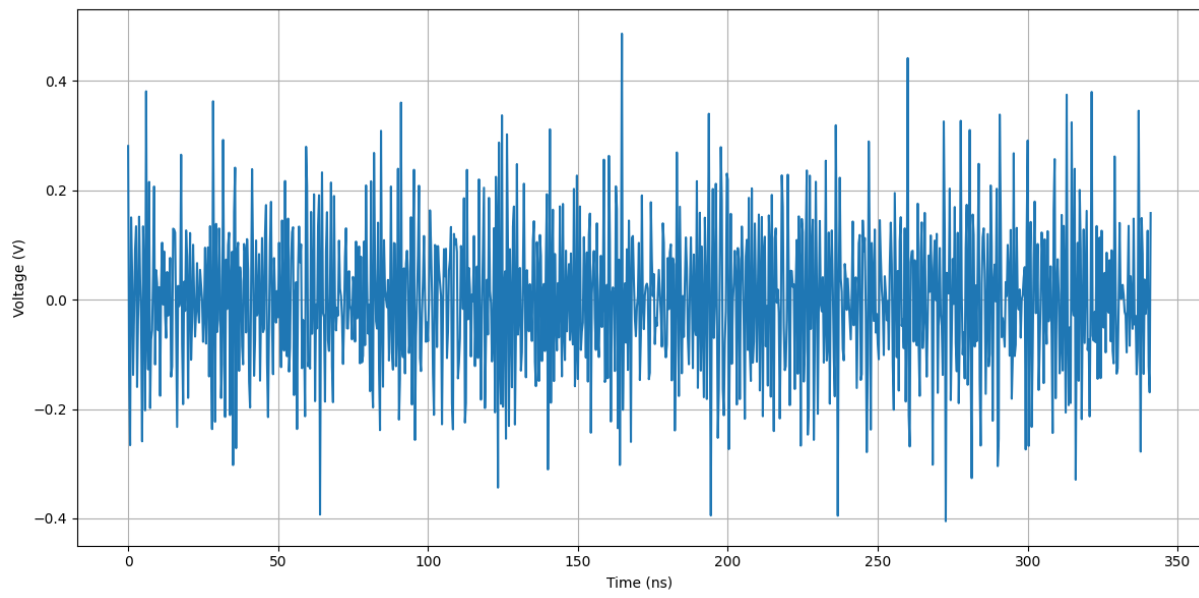
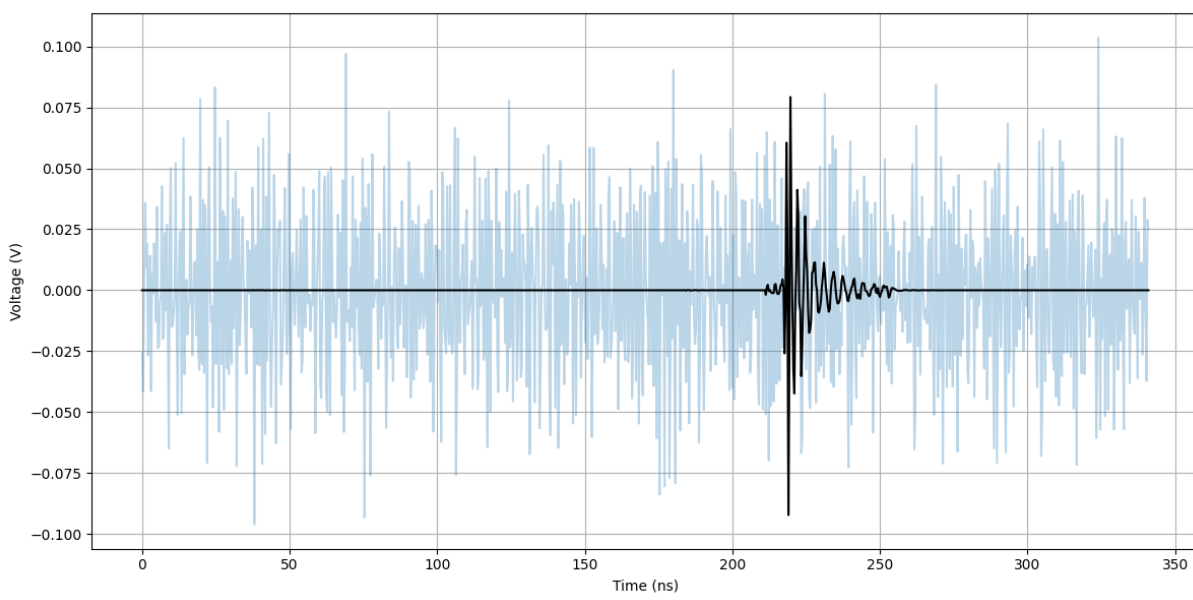
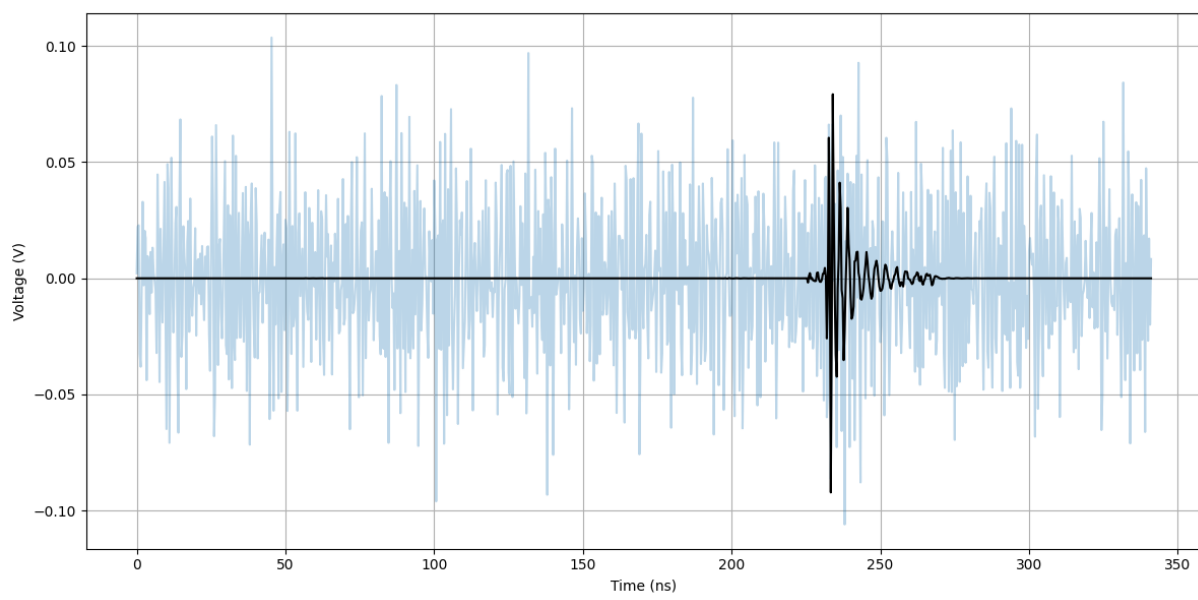
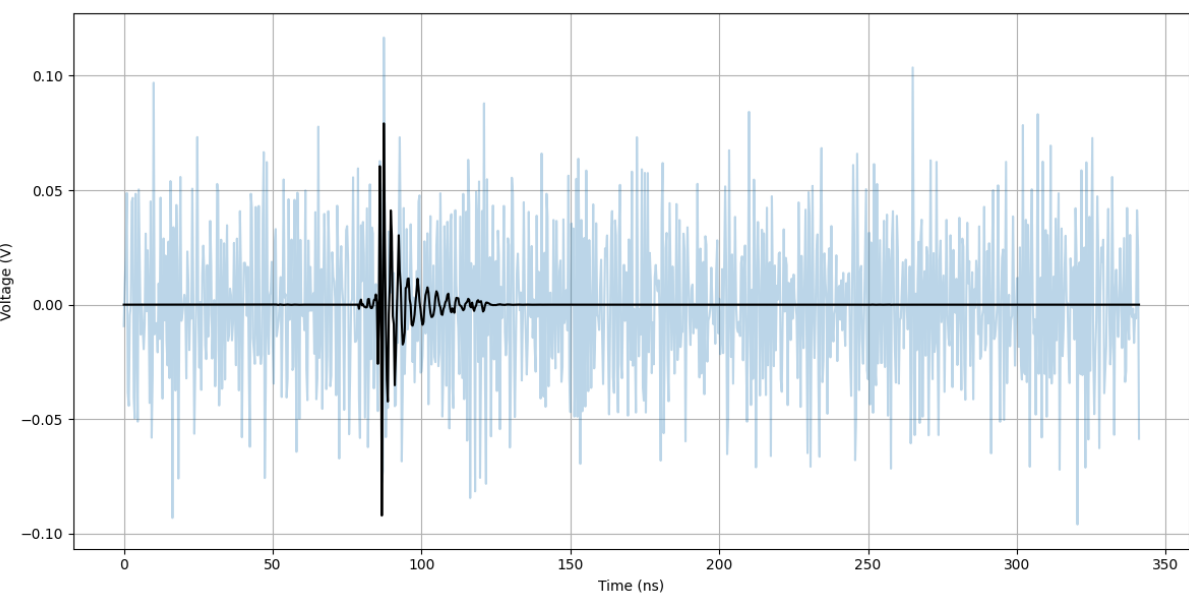
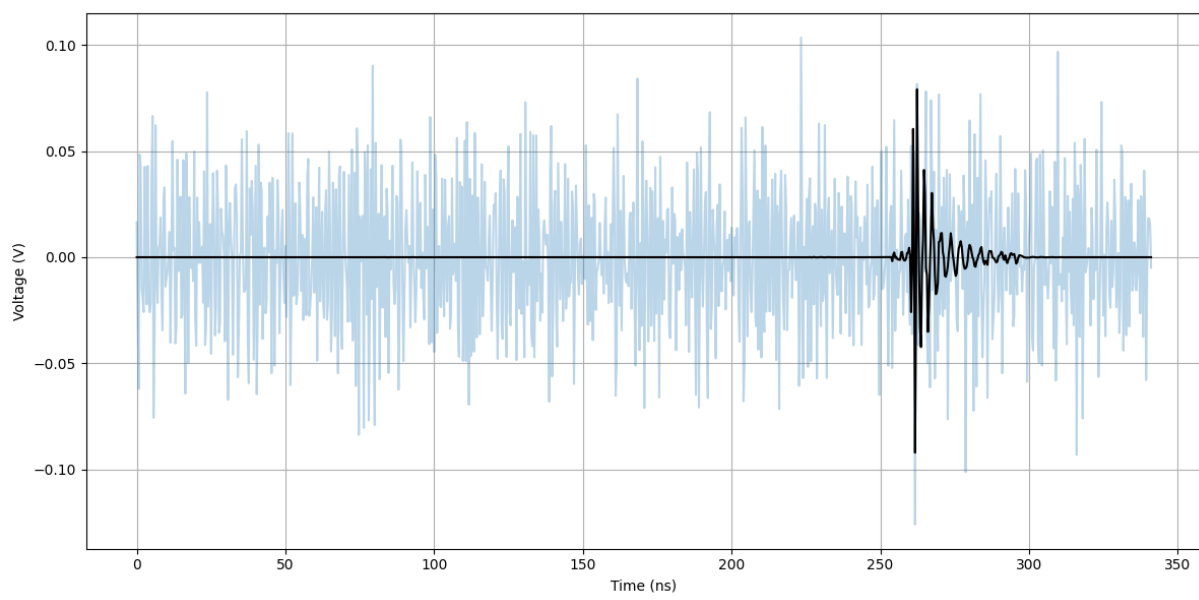
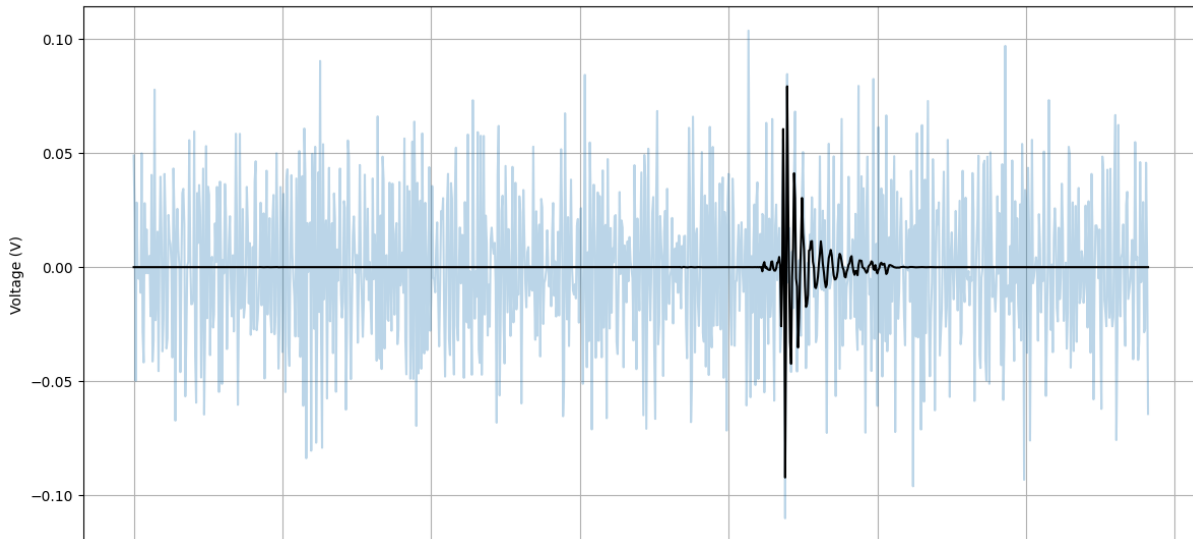
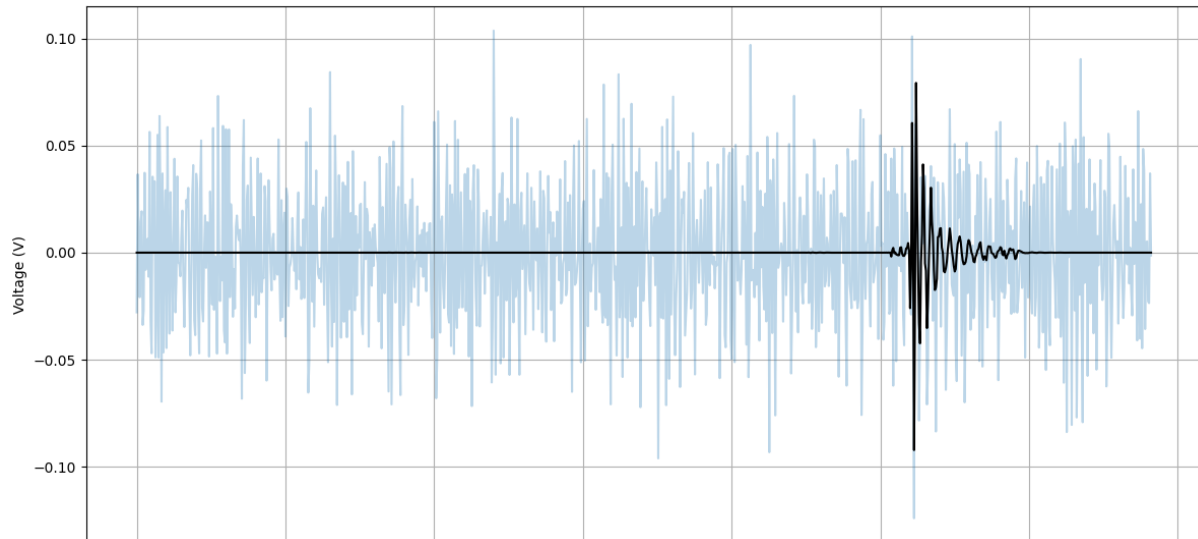
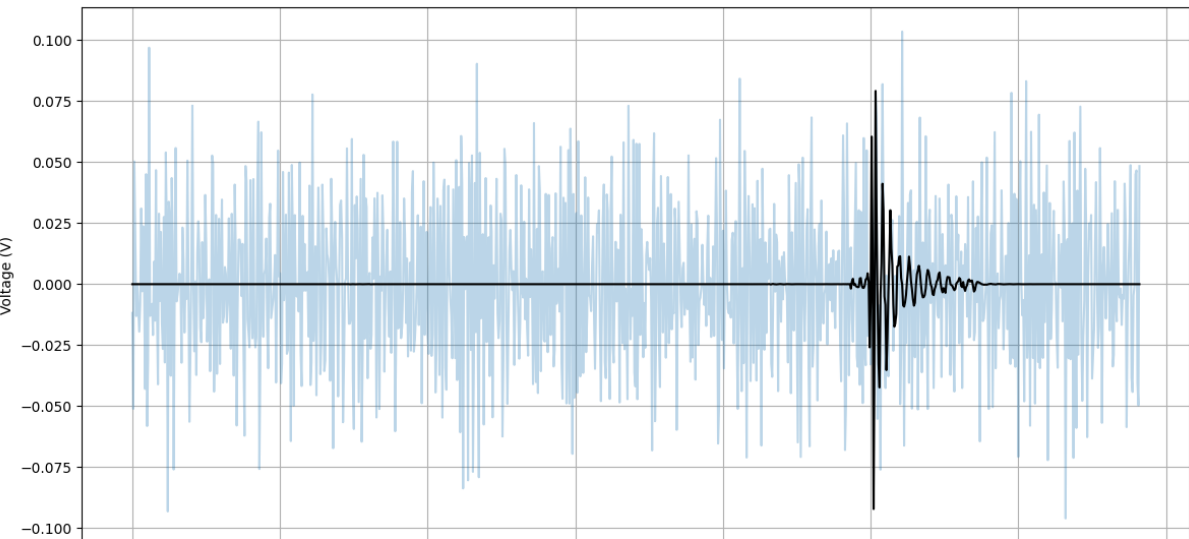
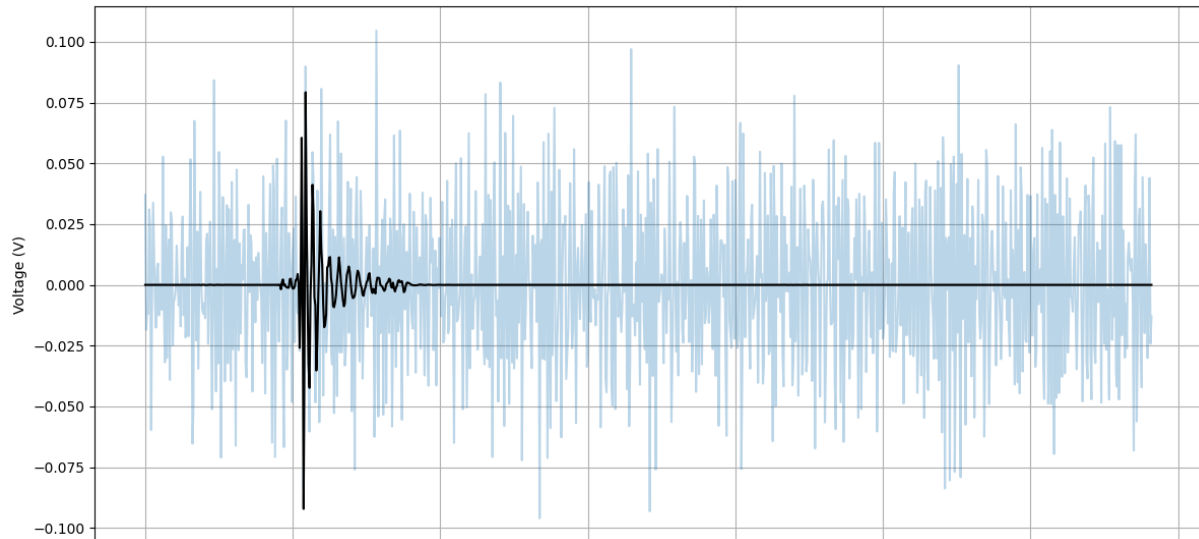
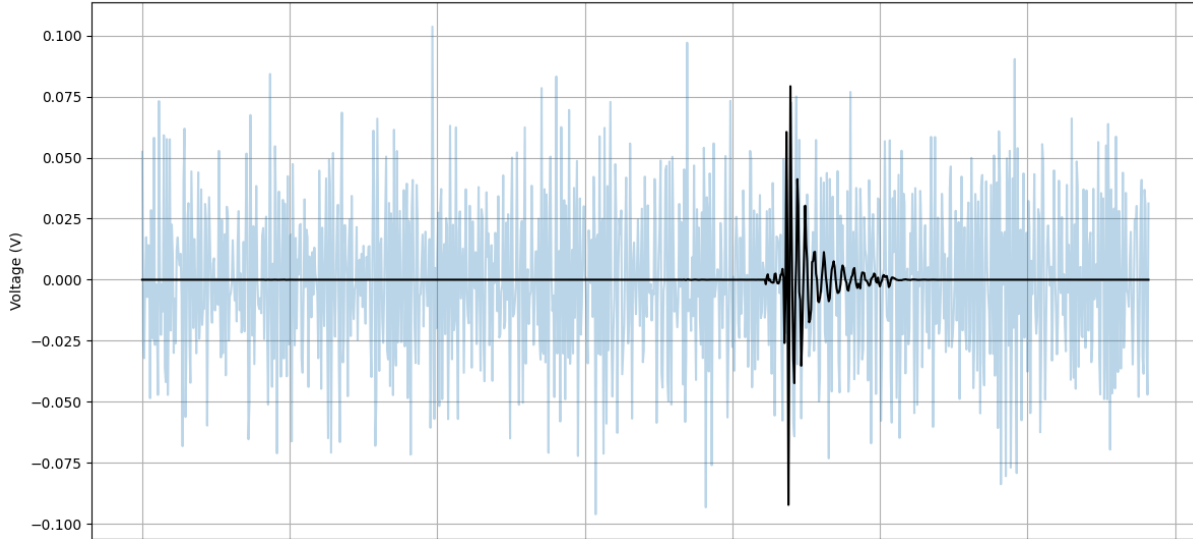
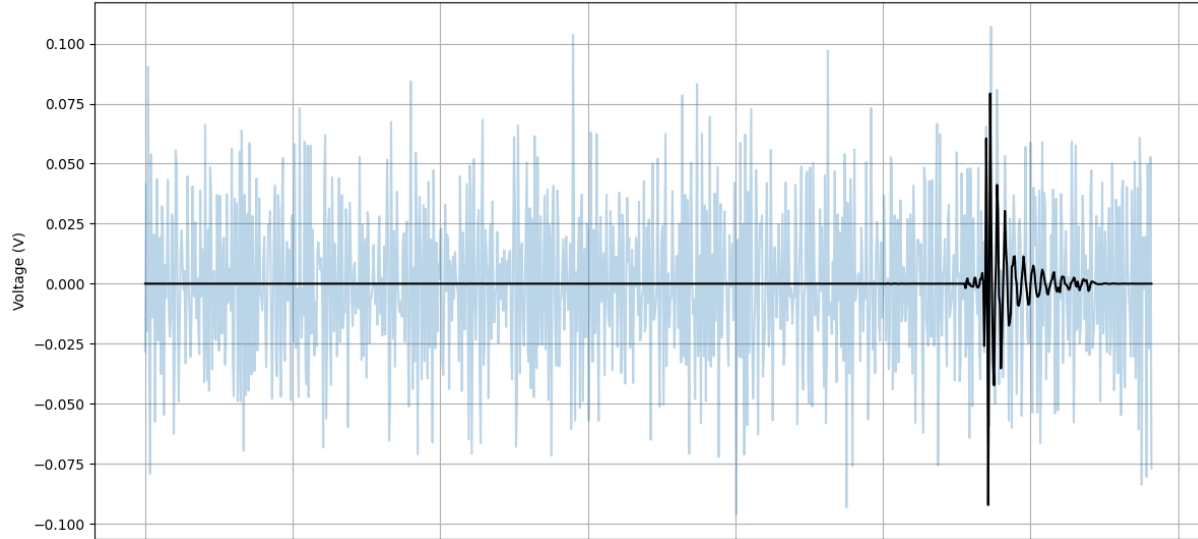
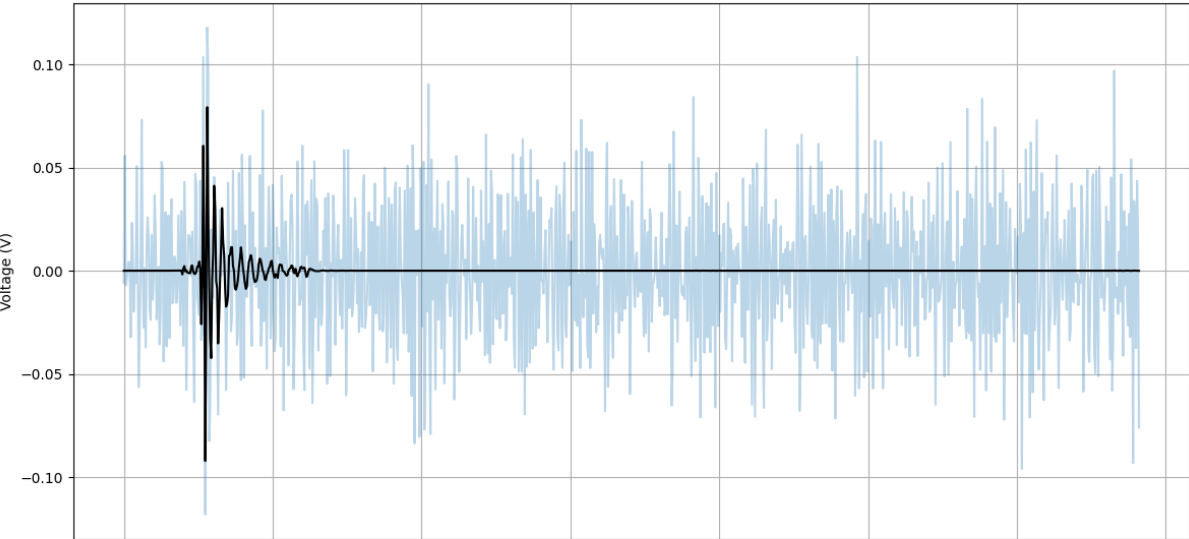
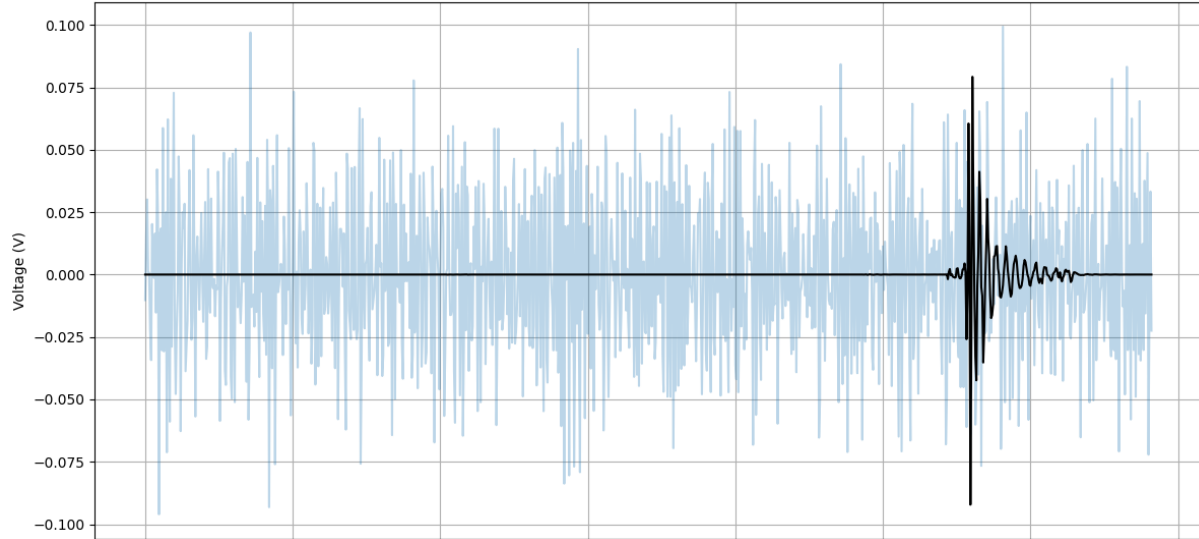
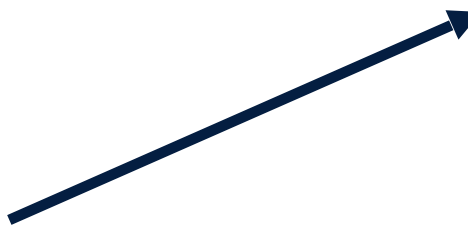


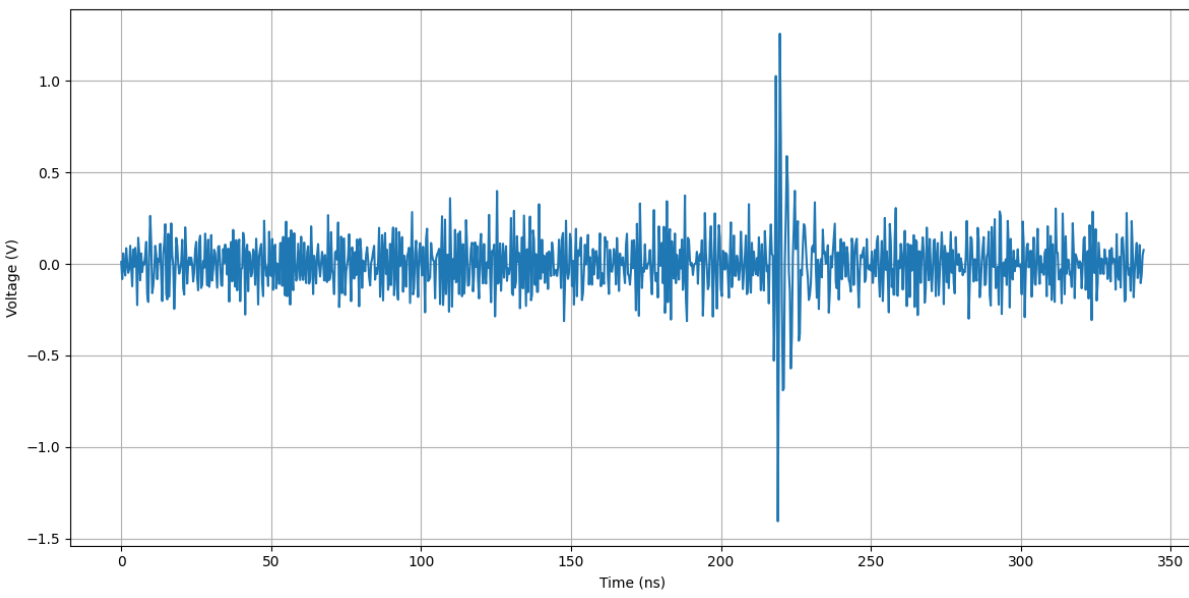
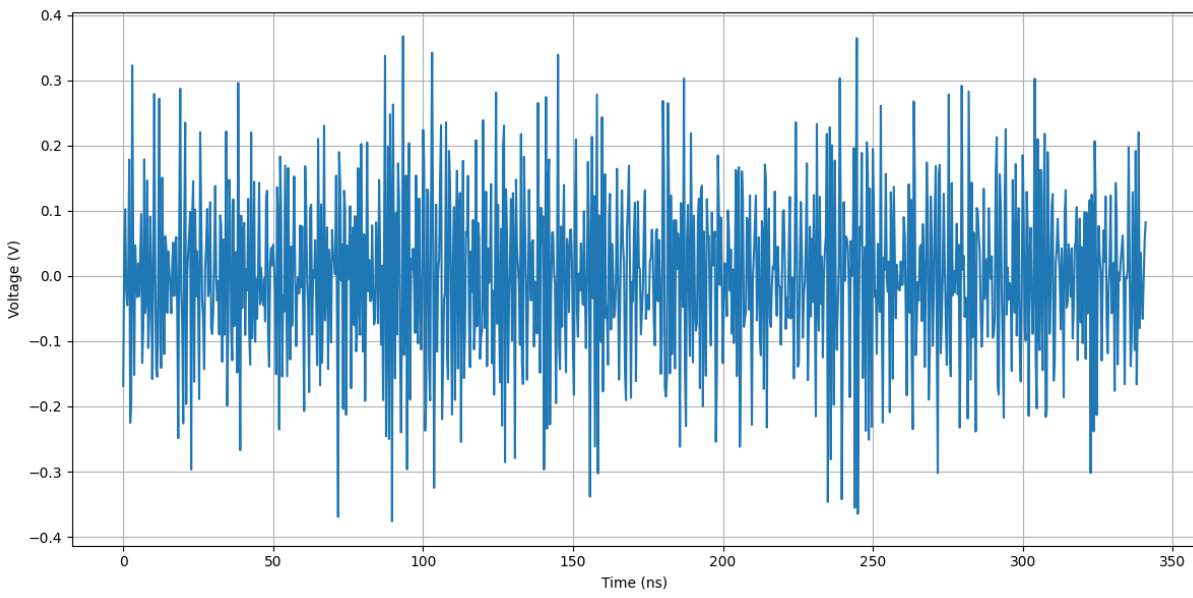
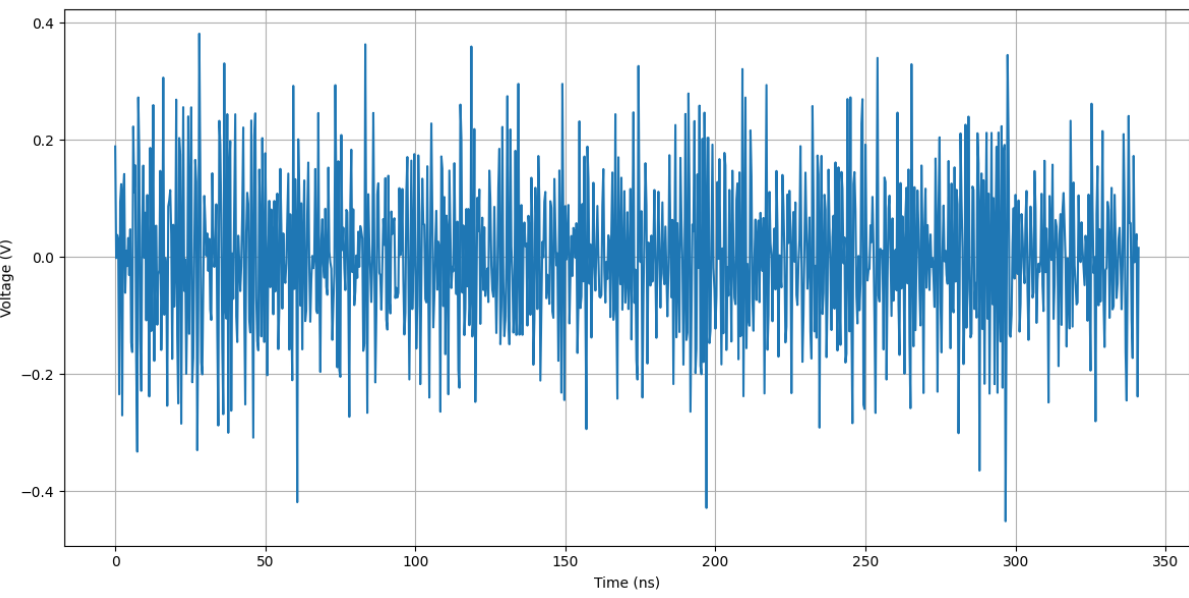
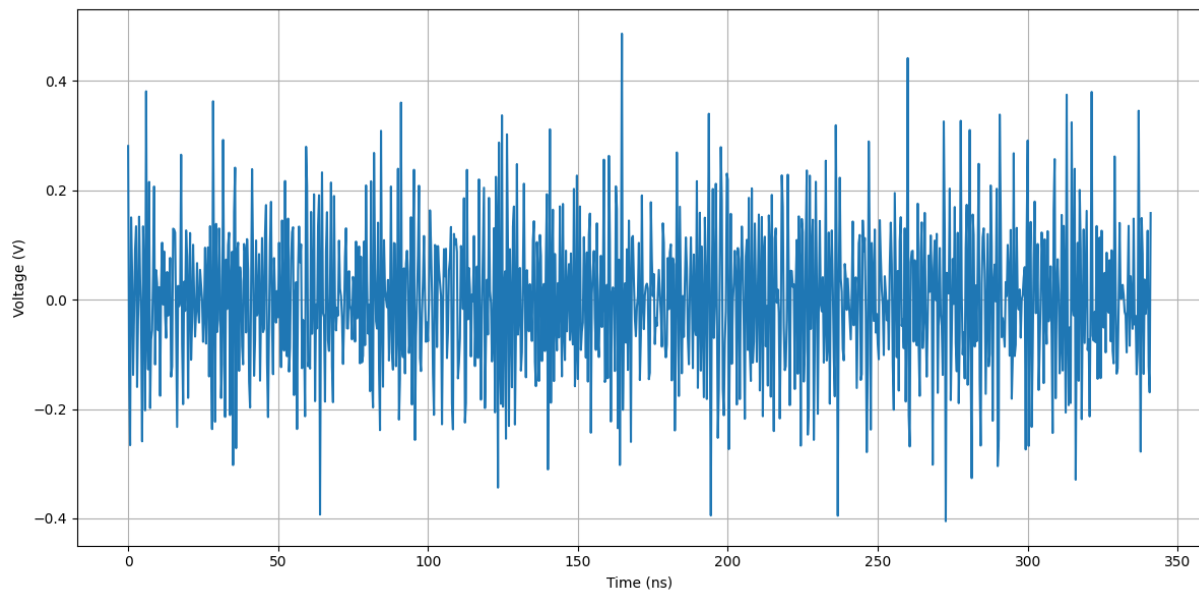
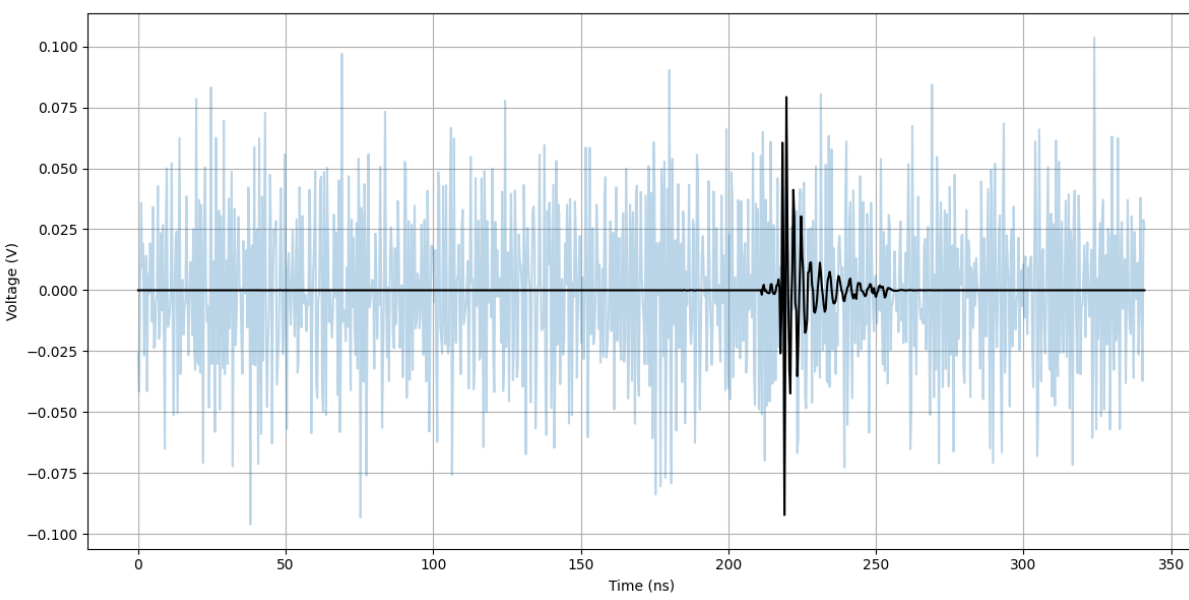
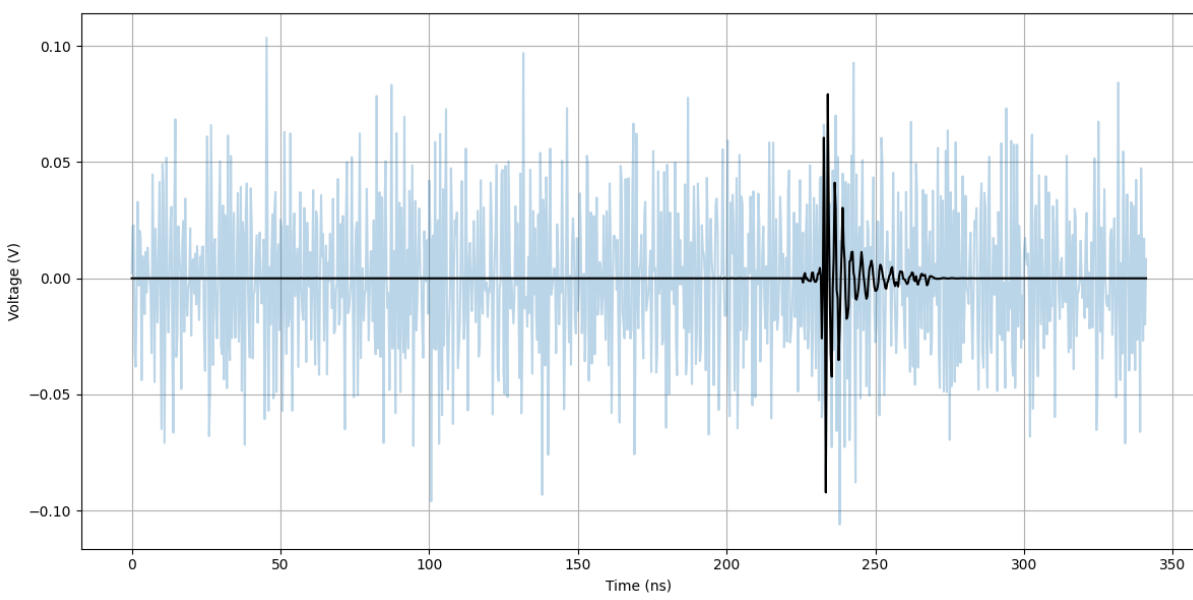
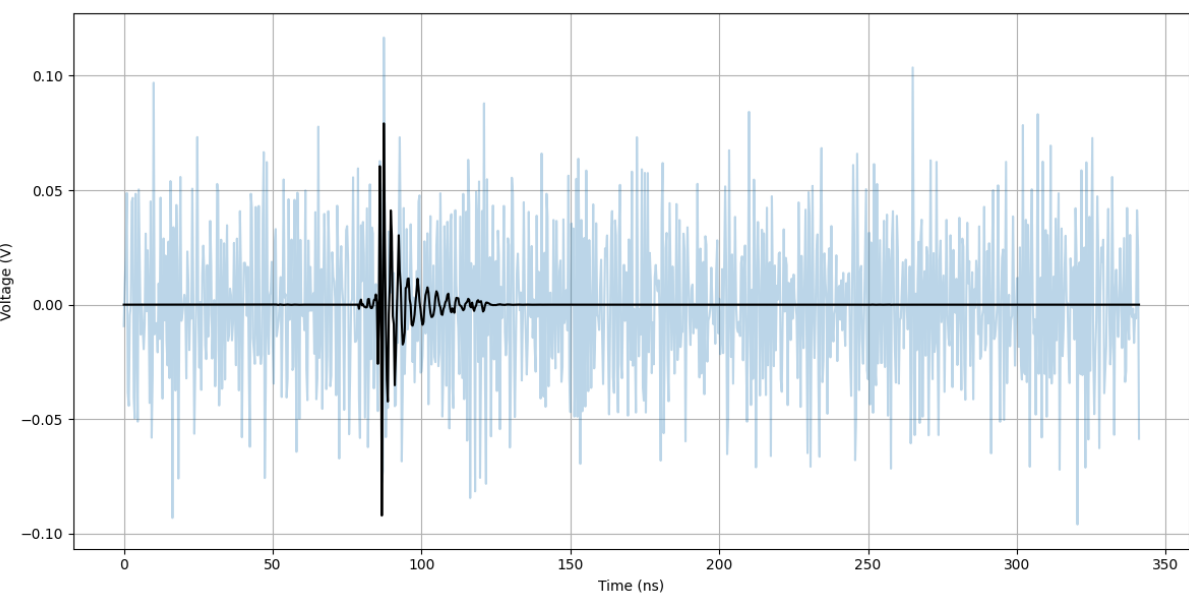
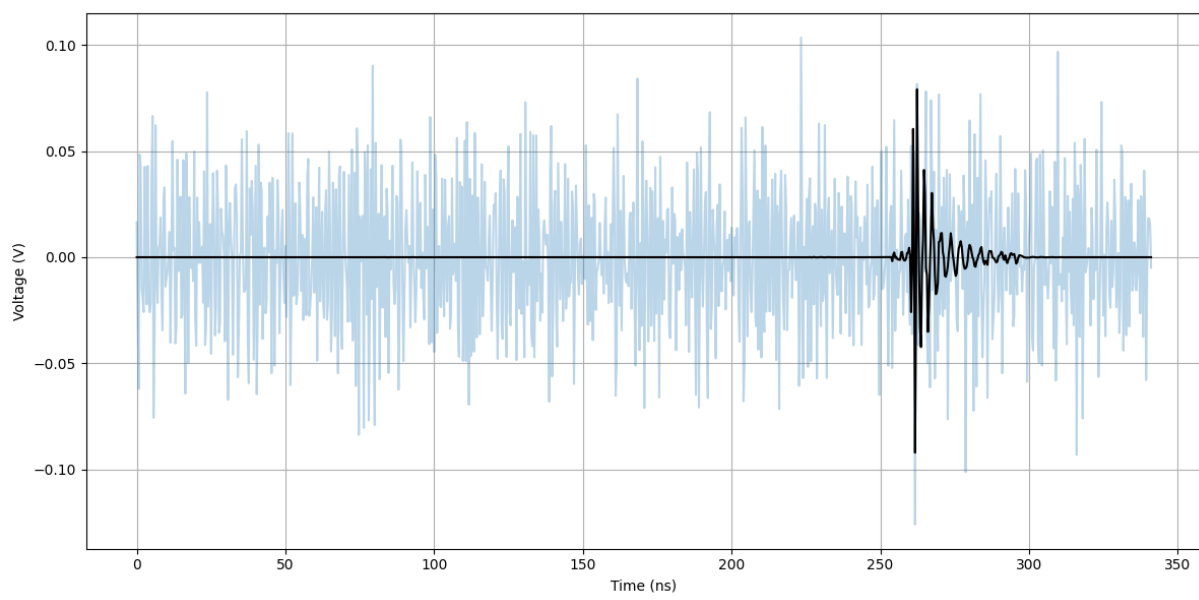
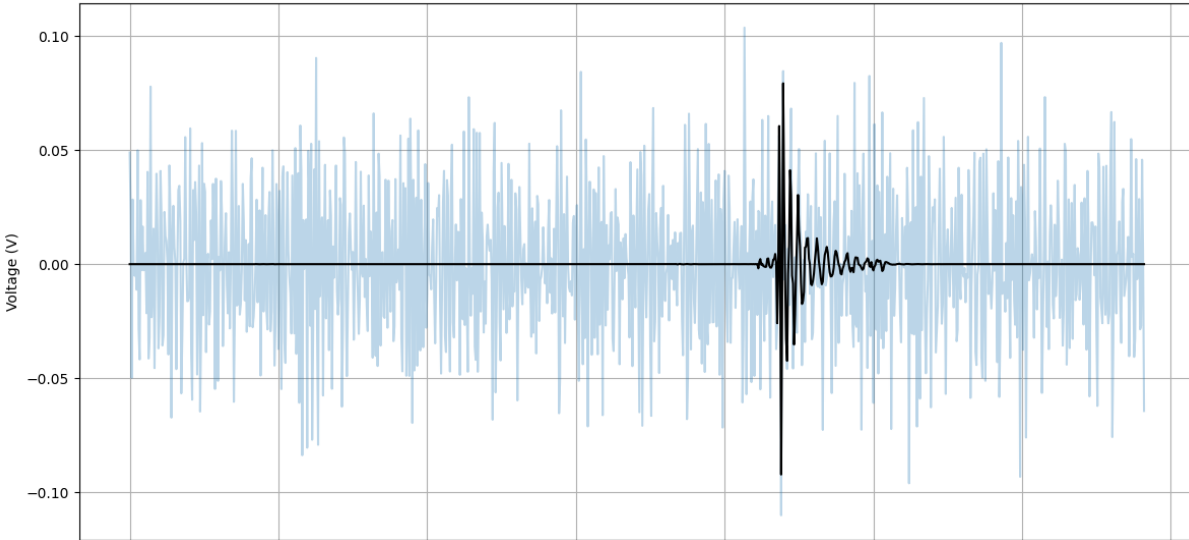
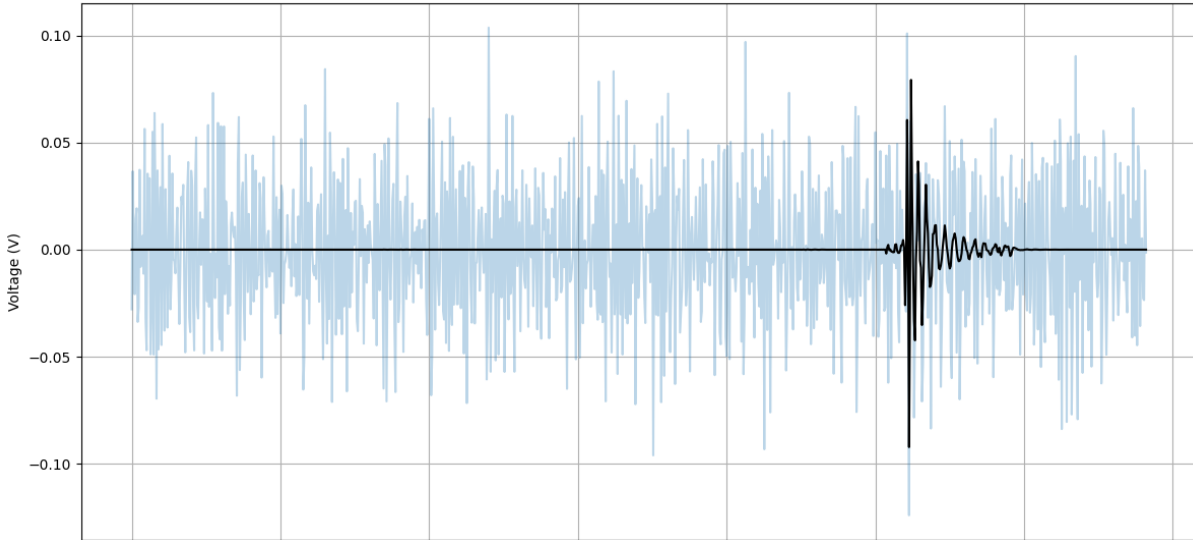
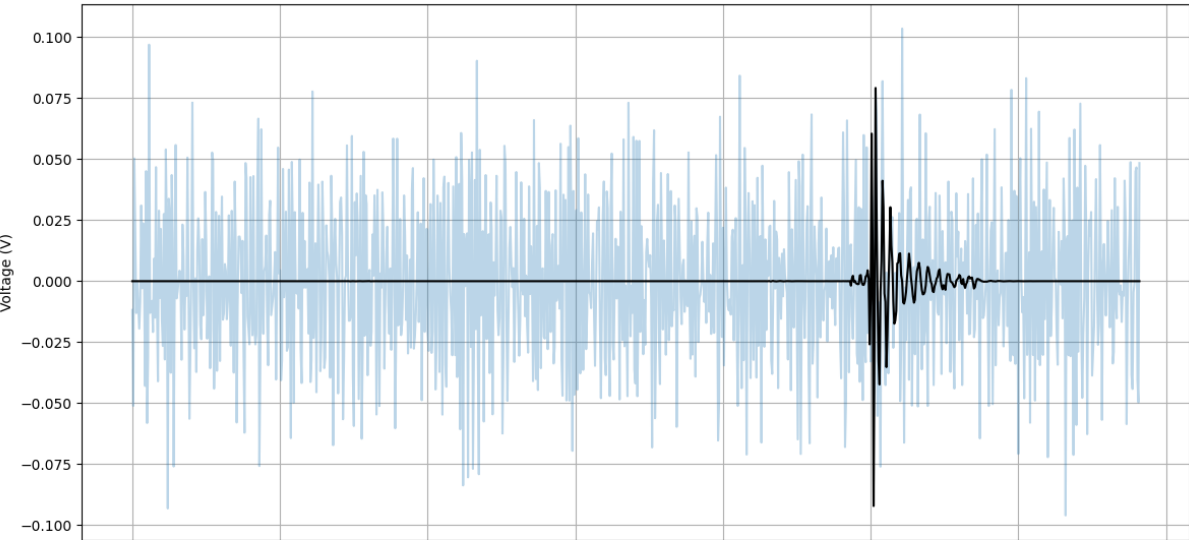
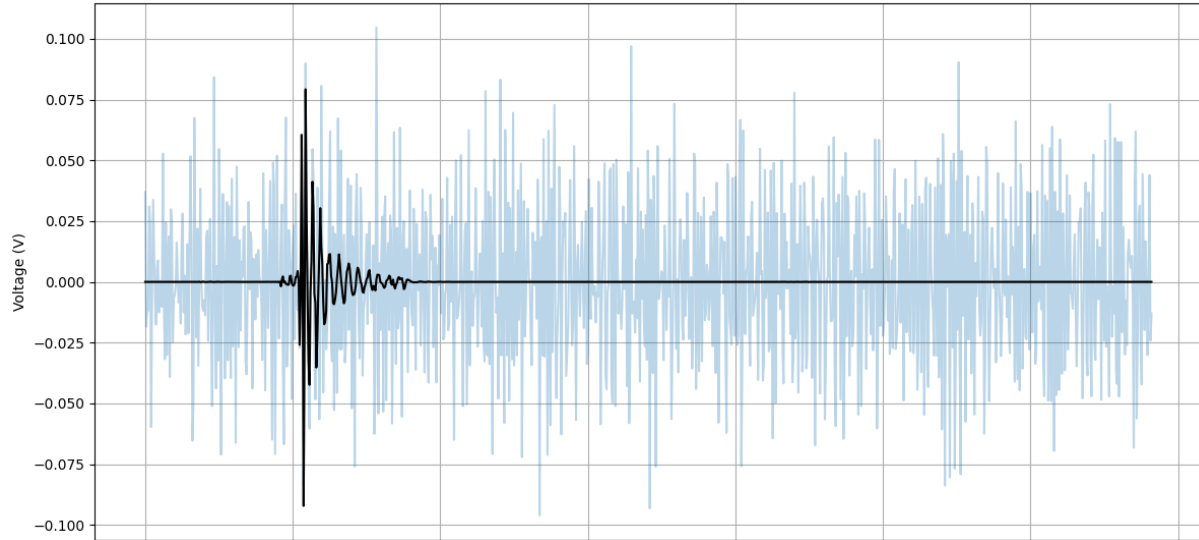
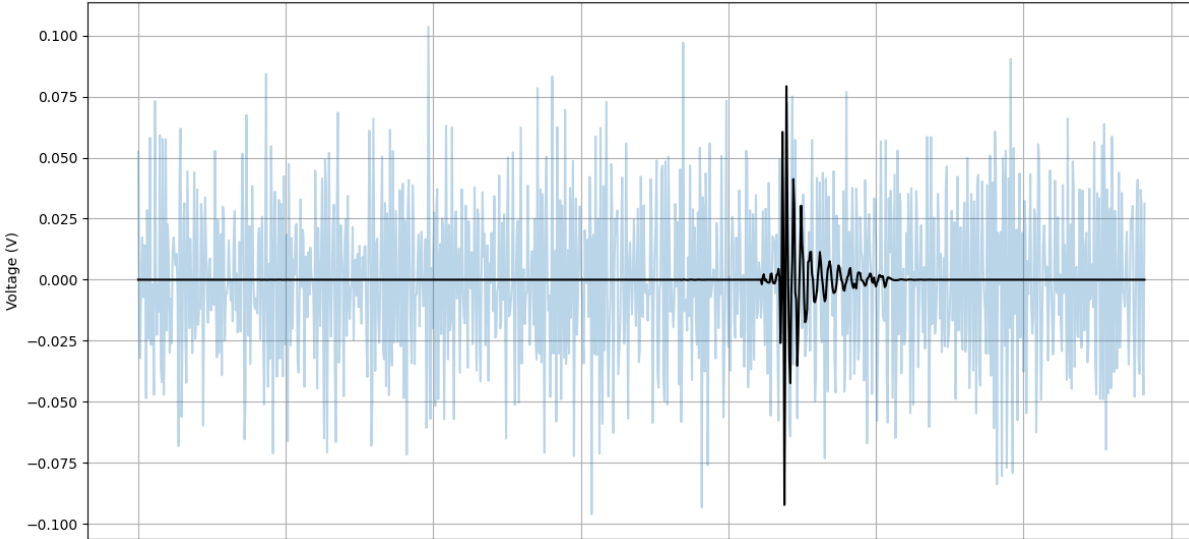
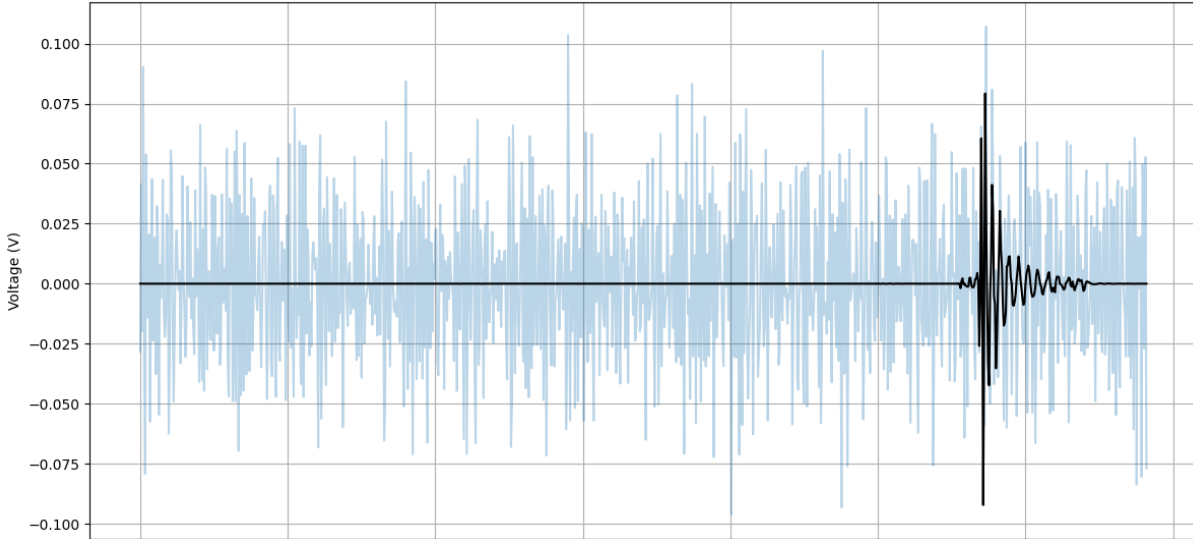
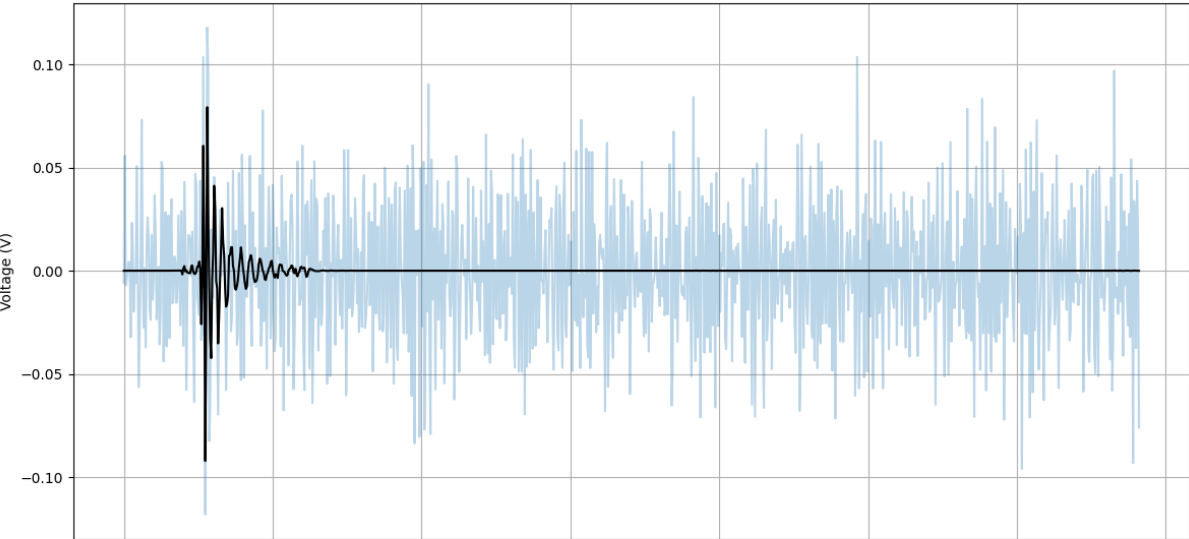
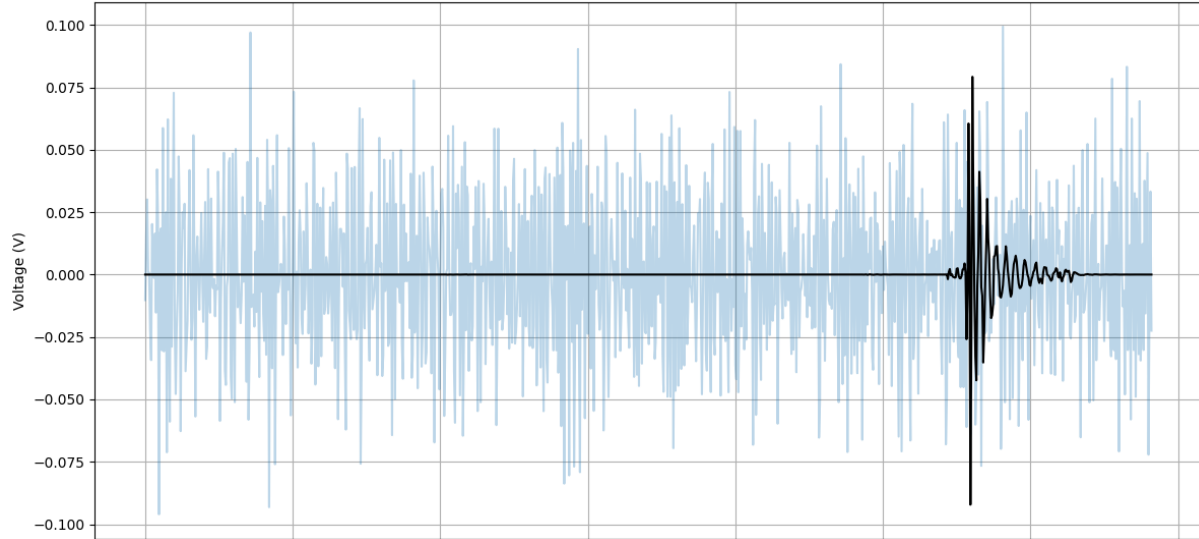
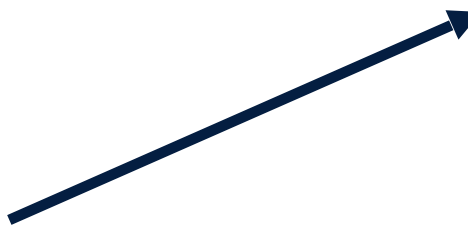
■ ■ ■

■ ■ ■

■ ■ ■

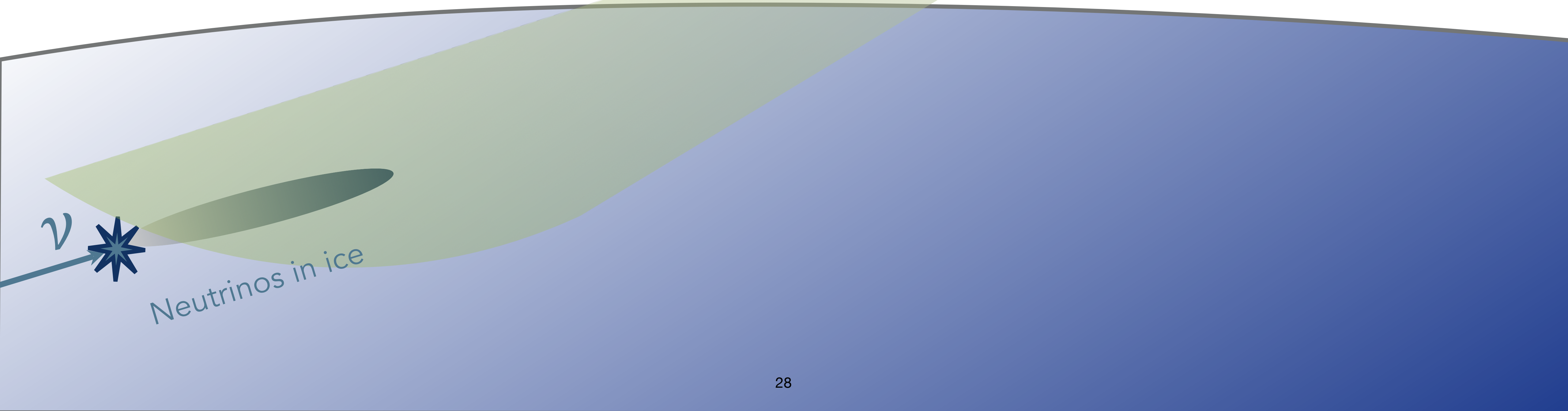
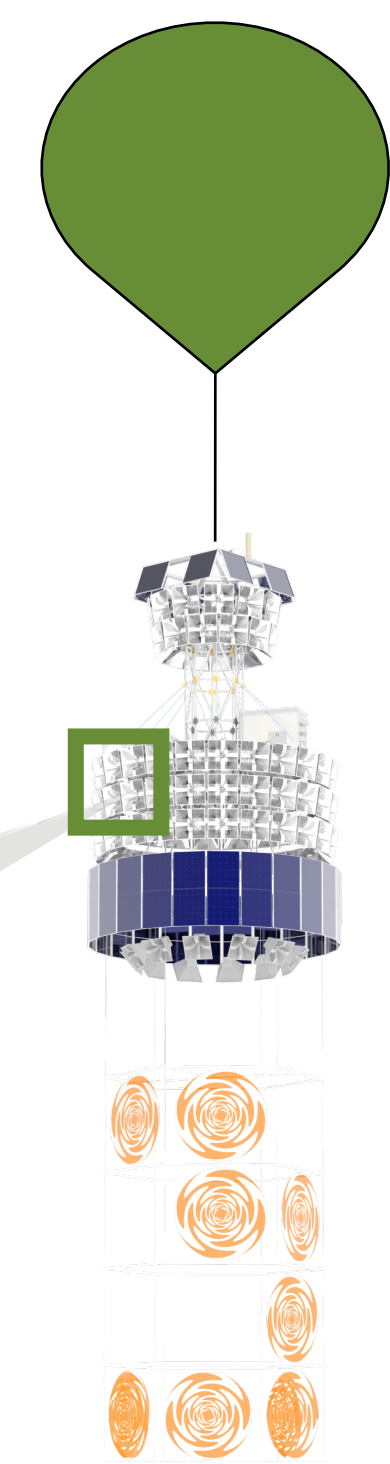






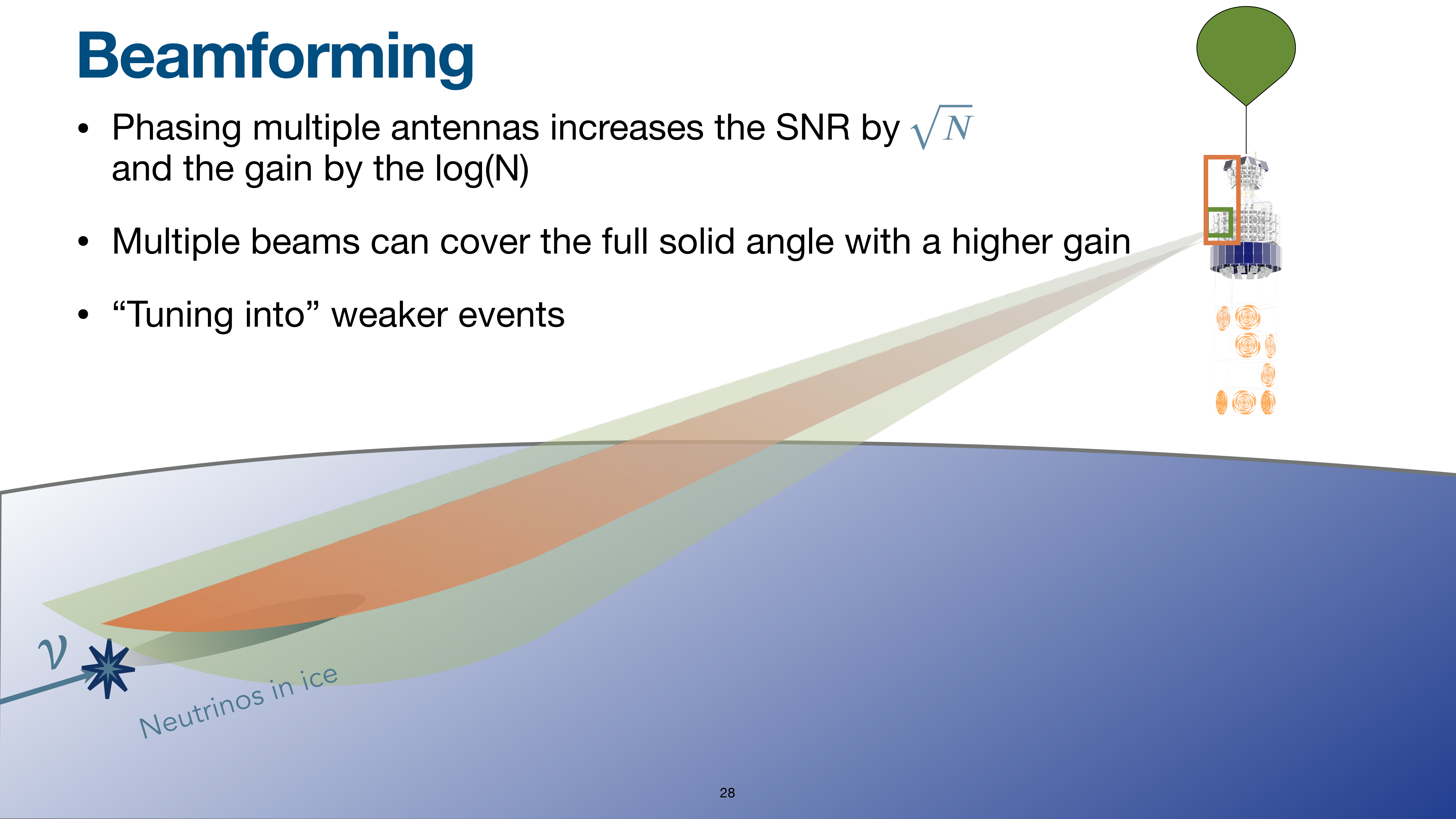
Beamforming

- 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



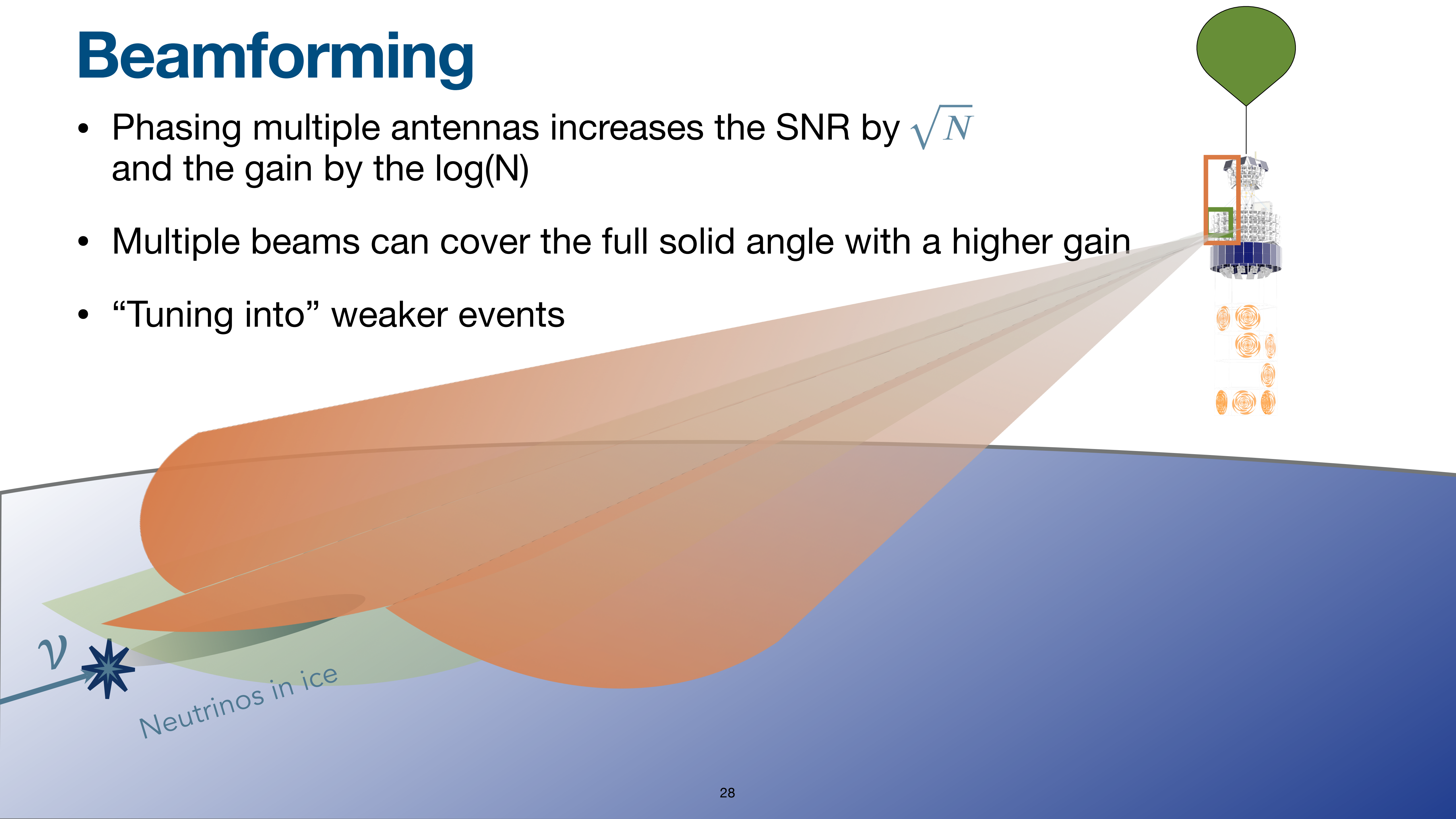
Beamforming

- 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



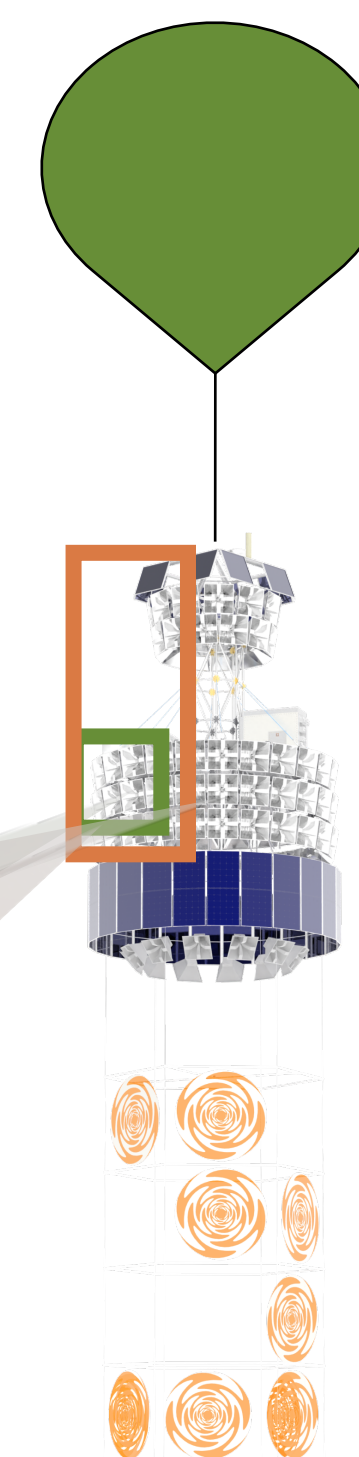
Beamforming

- 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

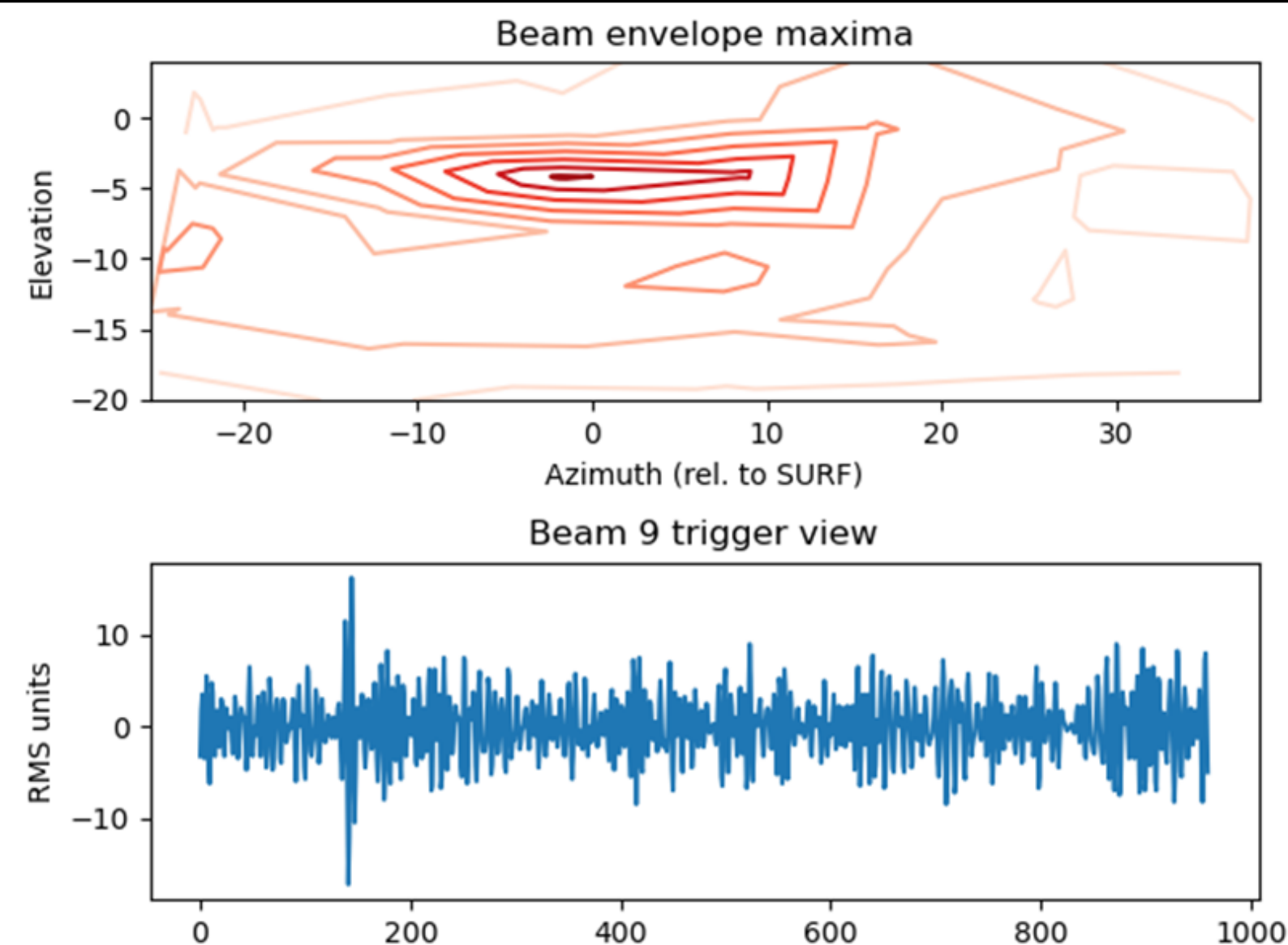
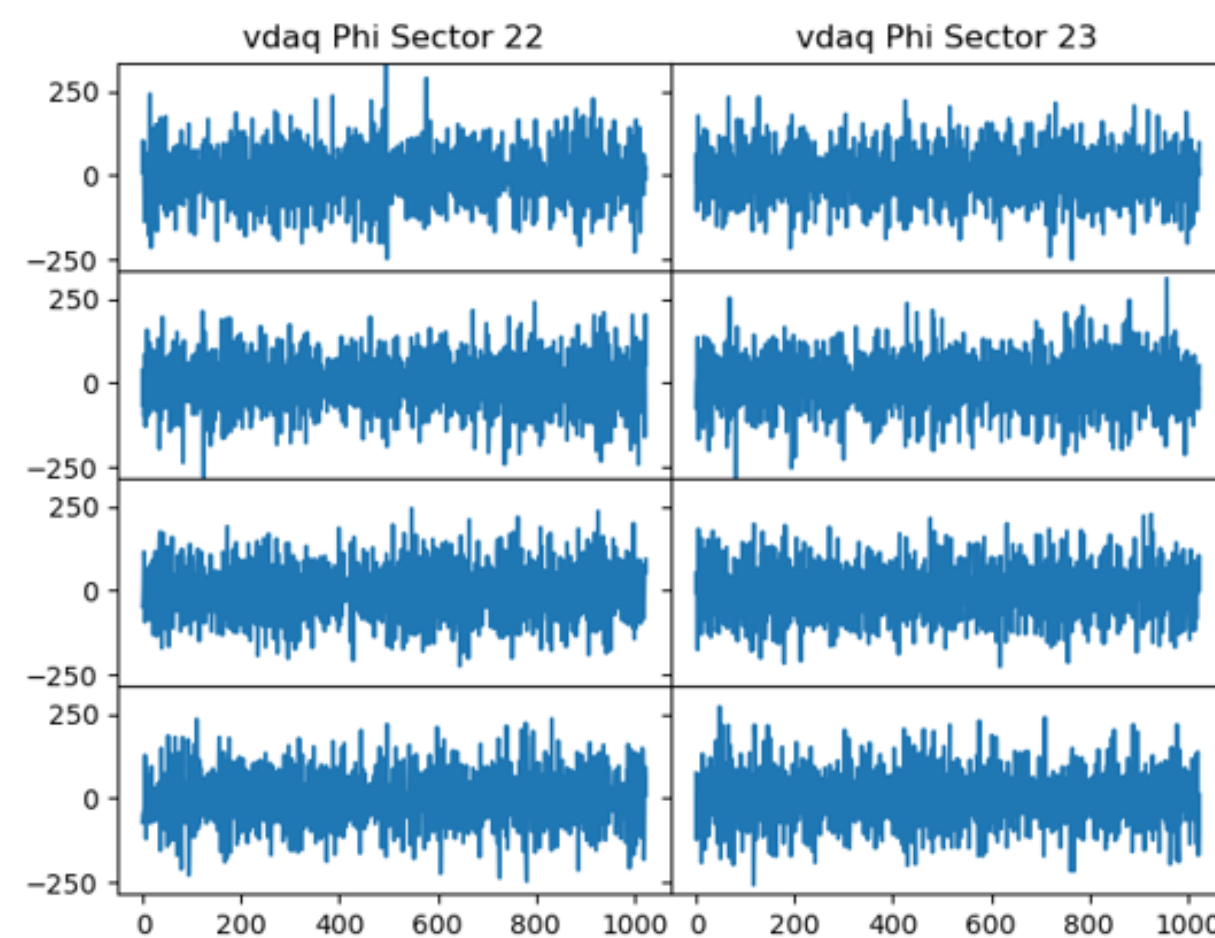


Beamforming

- 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

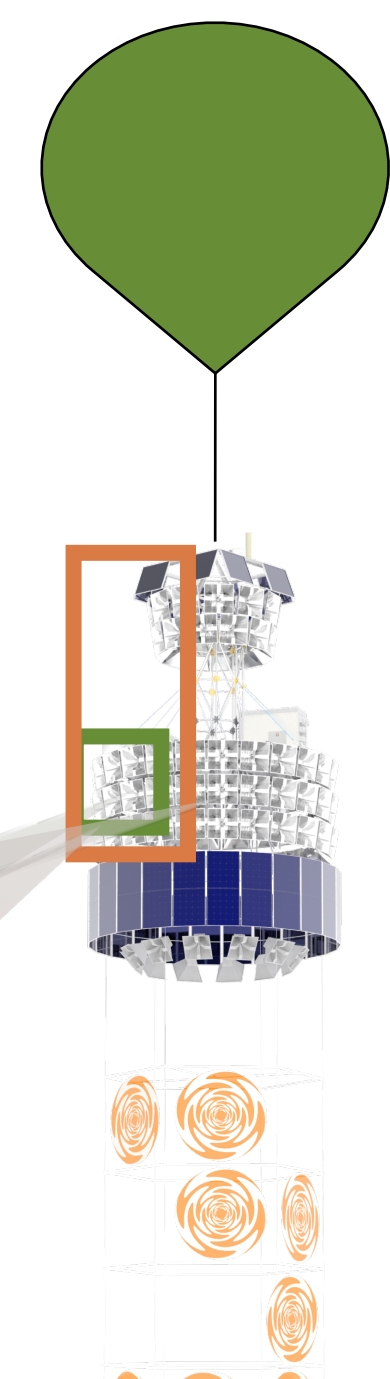


Signal at antenna

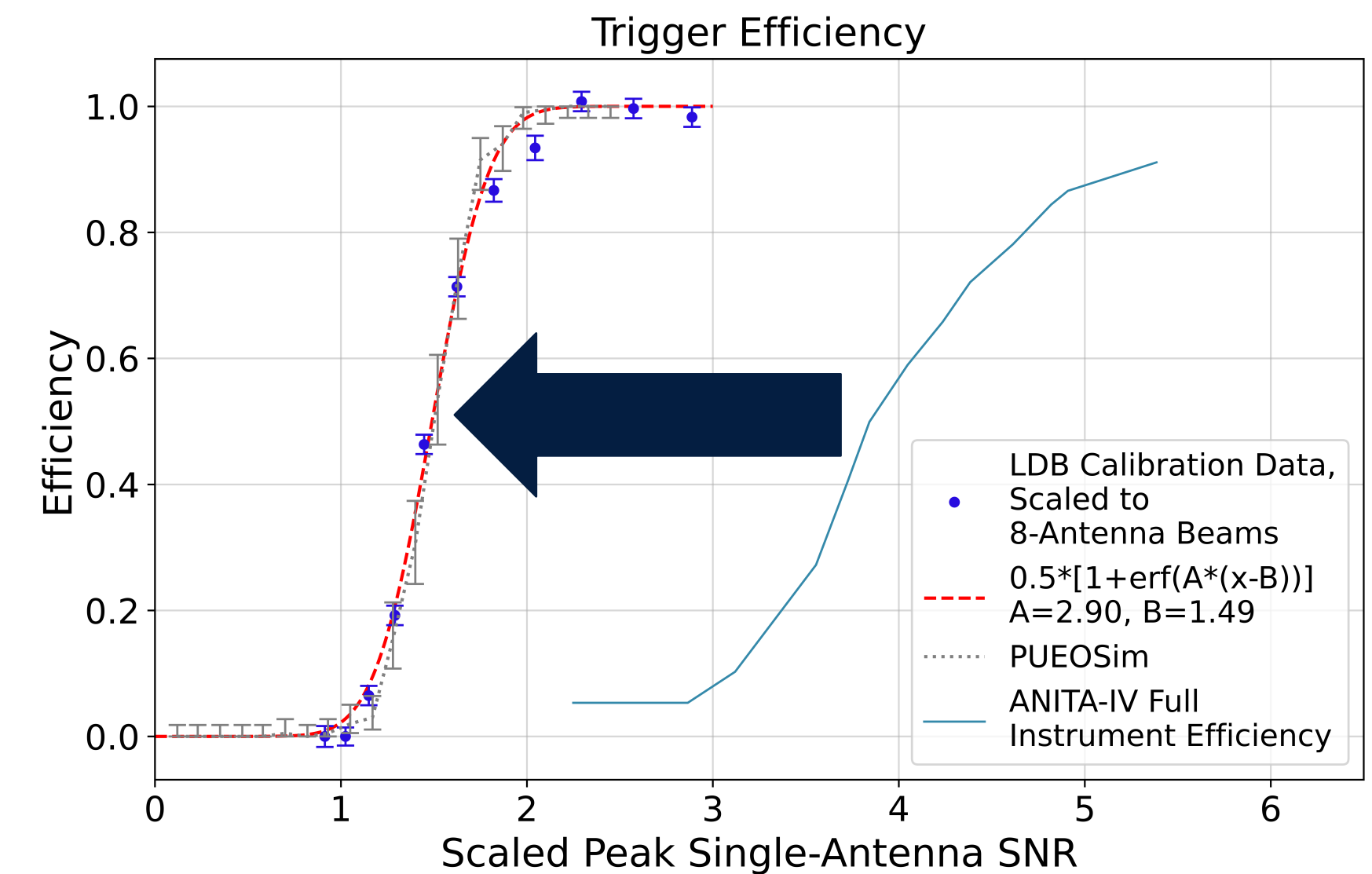
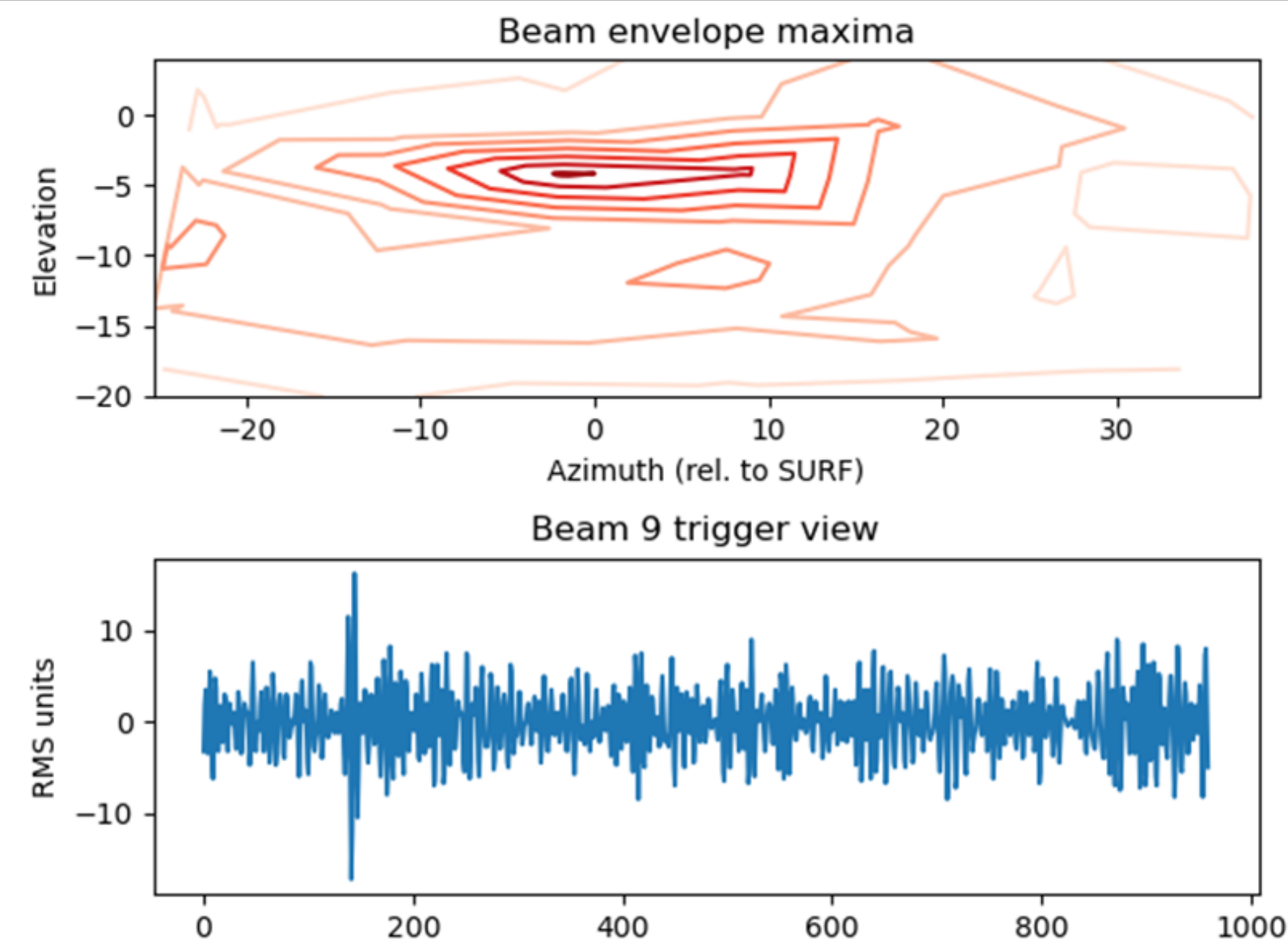
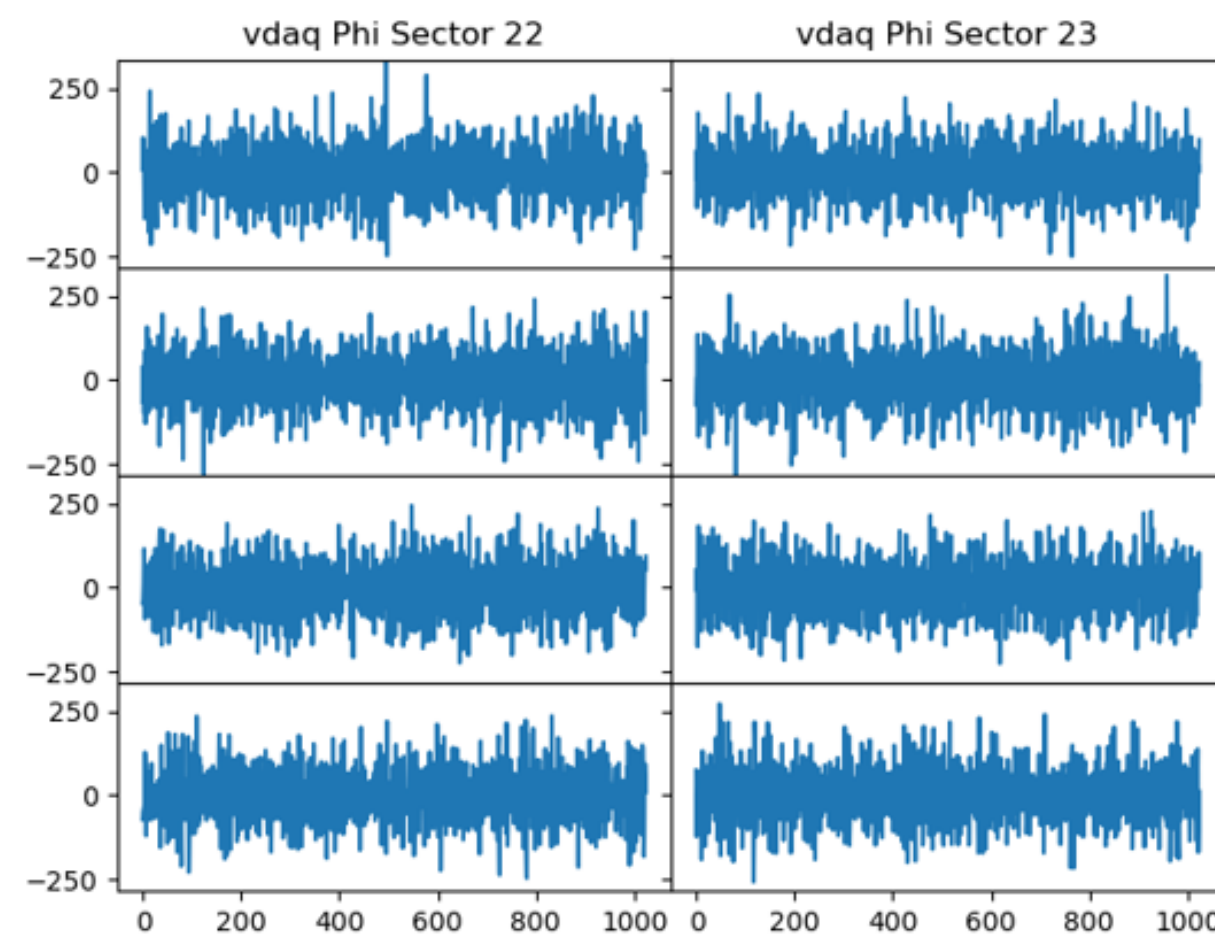


Beamforming

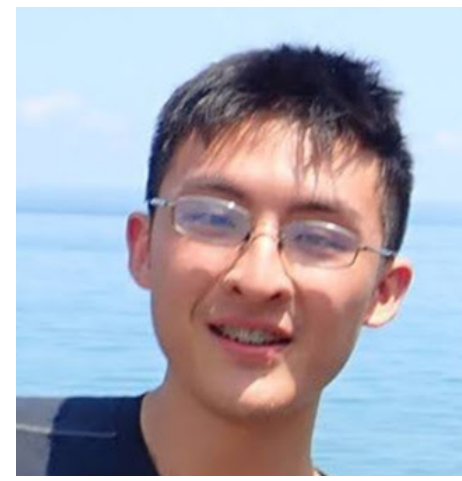
- Phasing multiple antennas increases the SNR by $\sqrt{N}$ and the gain by the $\log(N)$
- Multiple beams can cover the full solid angle with a higher gain
- “Tuning into” weaker events



Signal at antenna

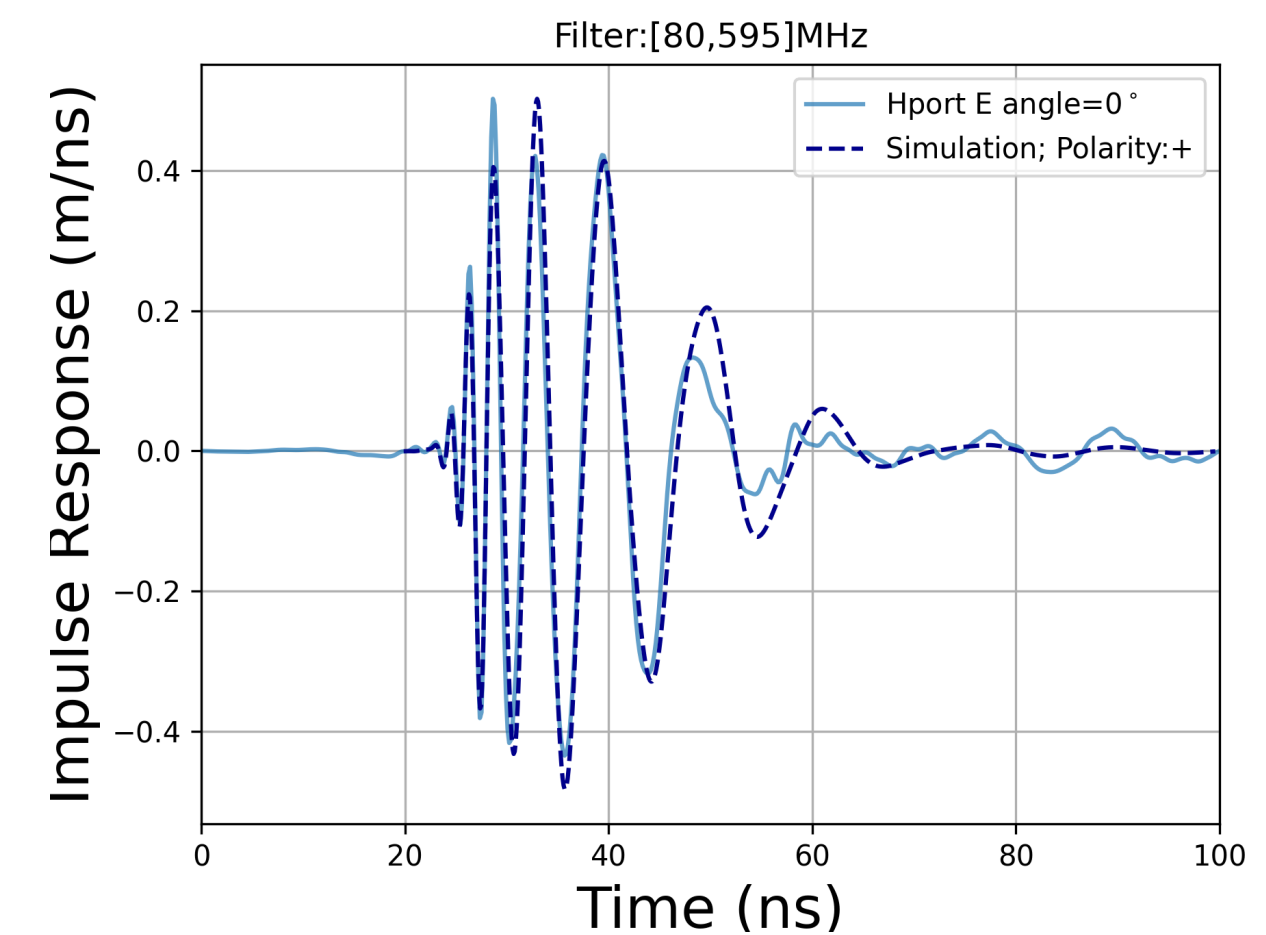
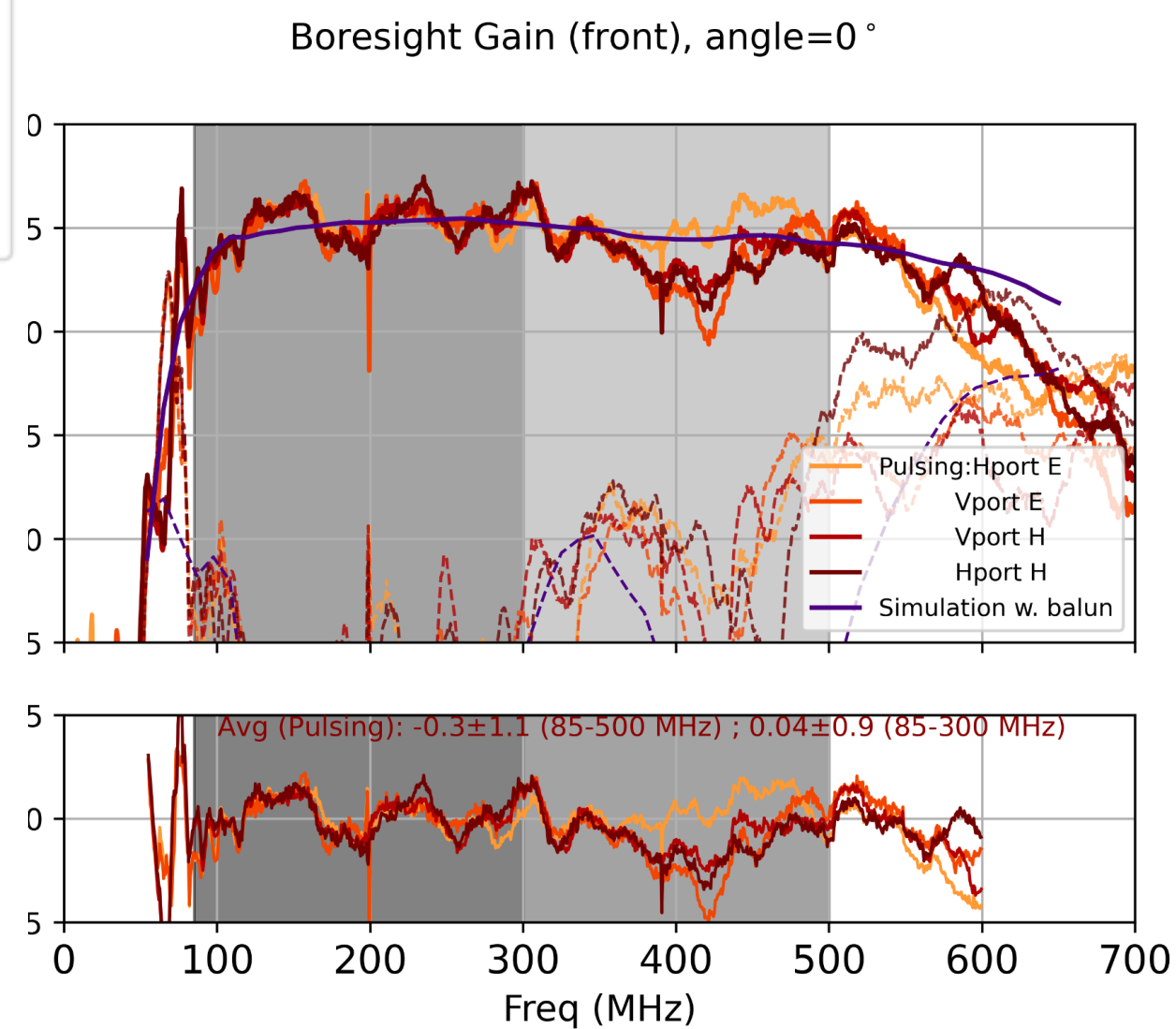
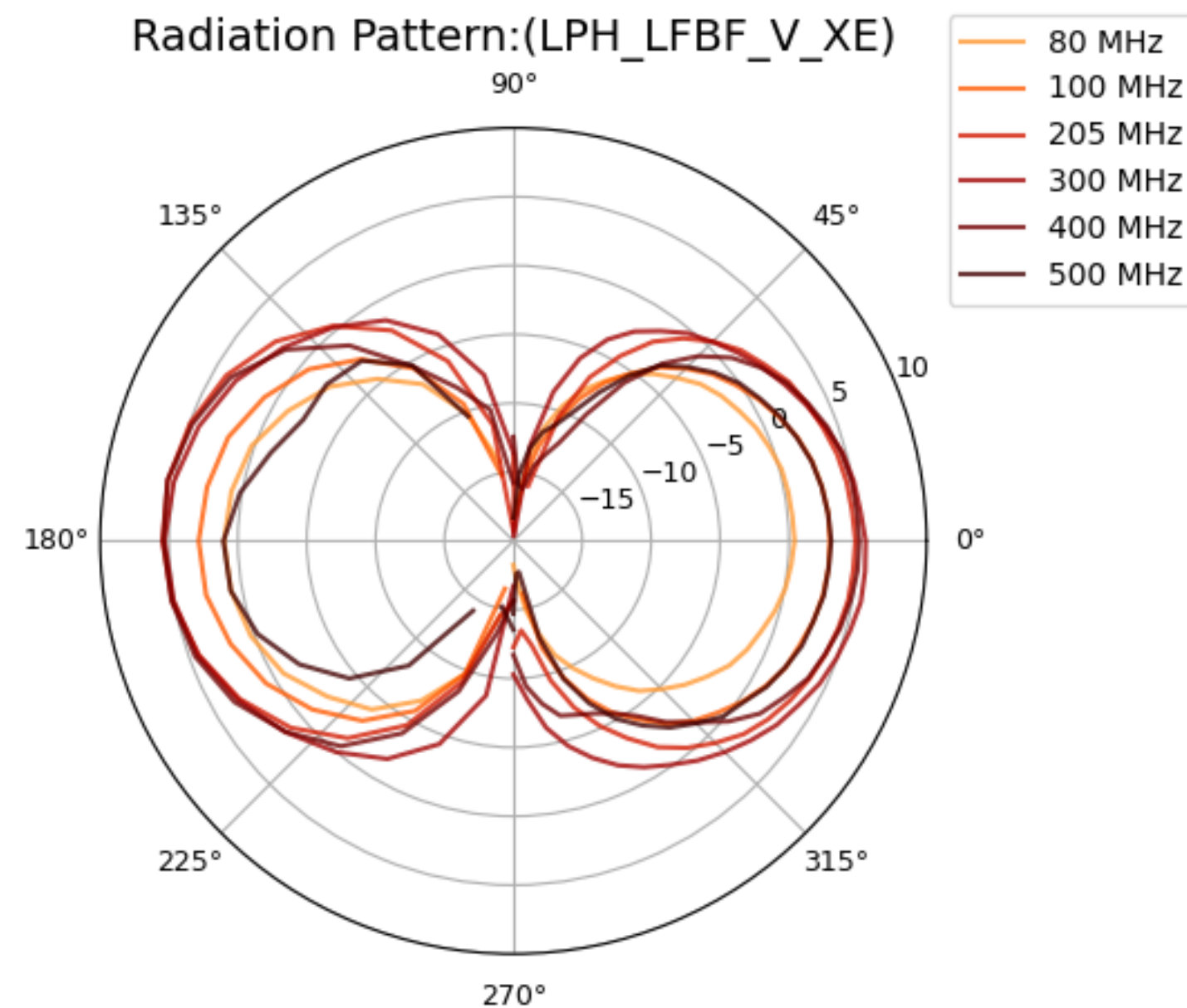
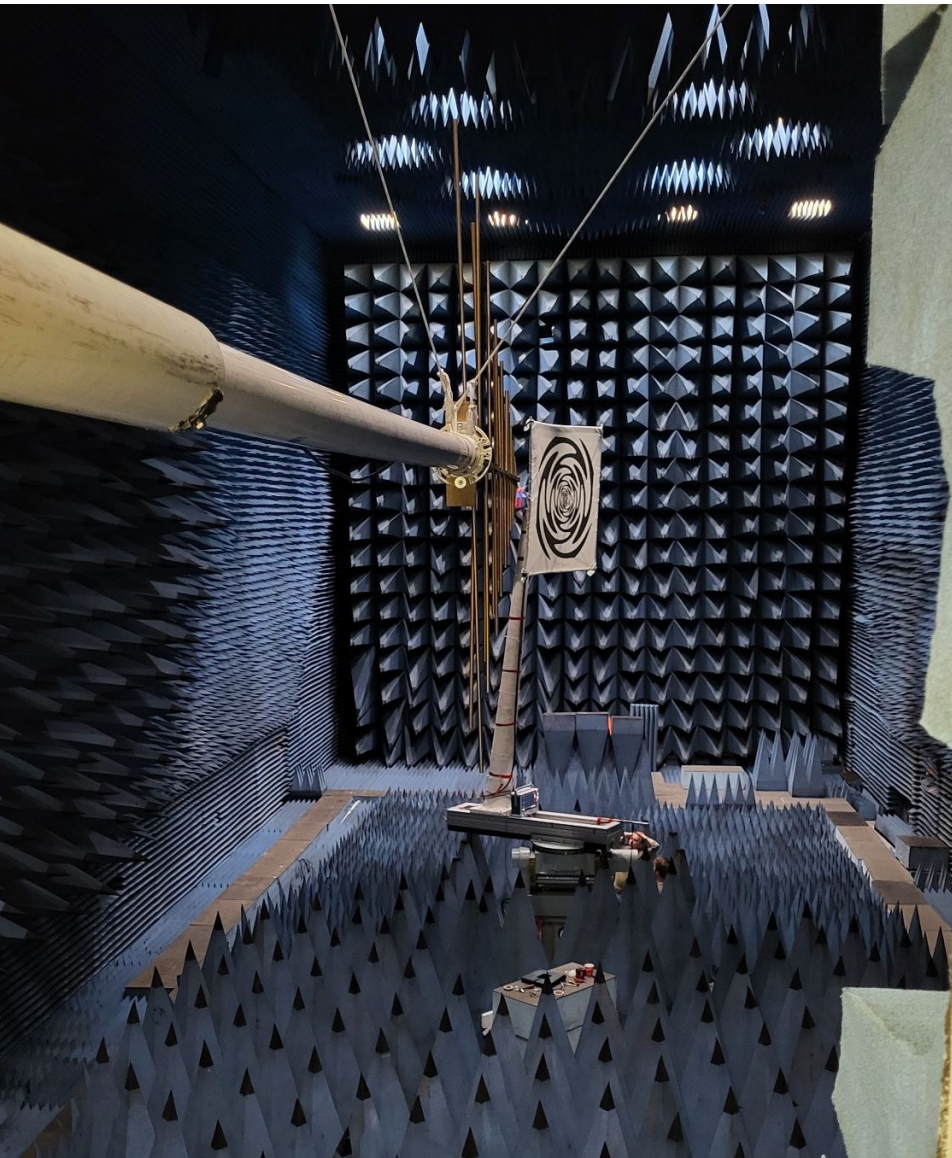


LF Antenna Performance



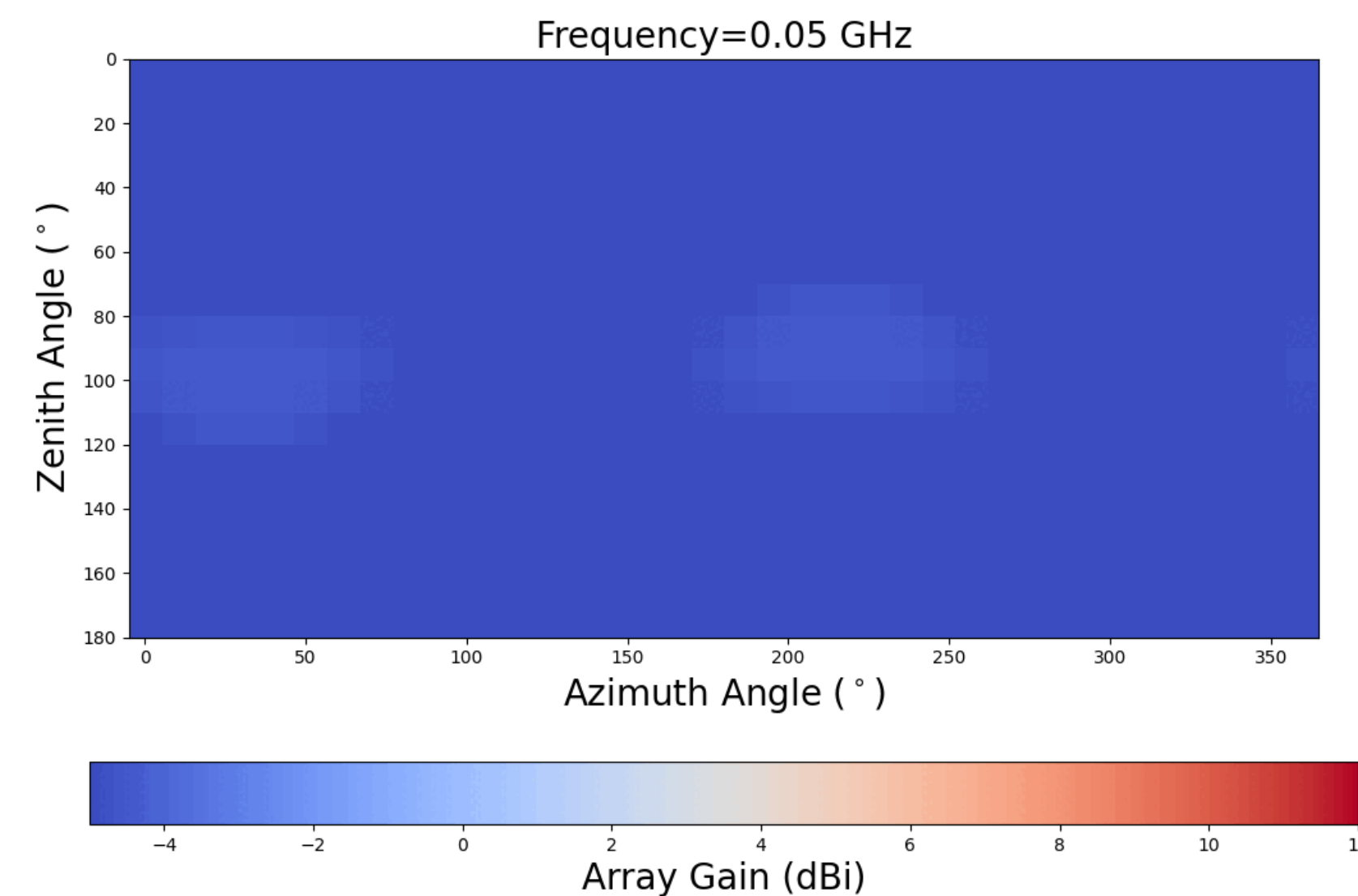
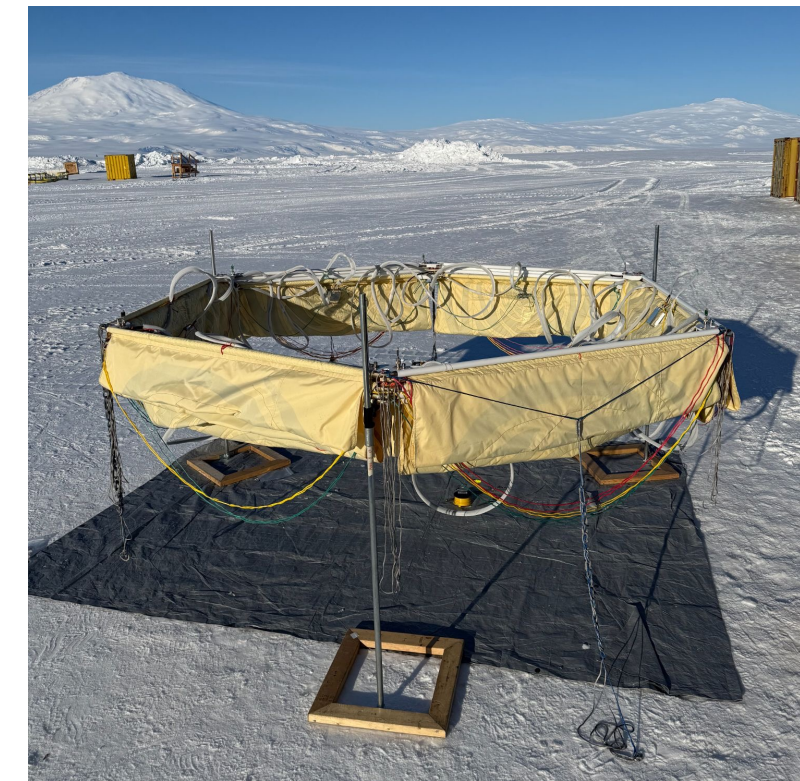
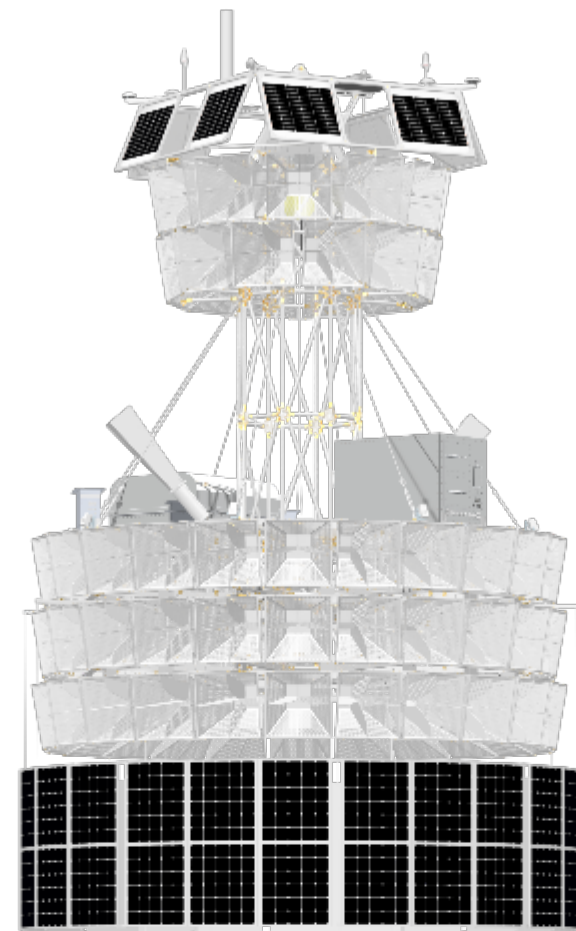
Yuchieh Ku

- Dual polarized, log periodic sinuous antennas: 50-500 MHz, 4-6 dBi
- Nearly uniform front & back lobes: 6 dBi



LF Array

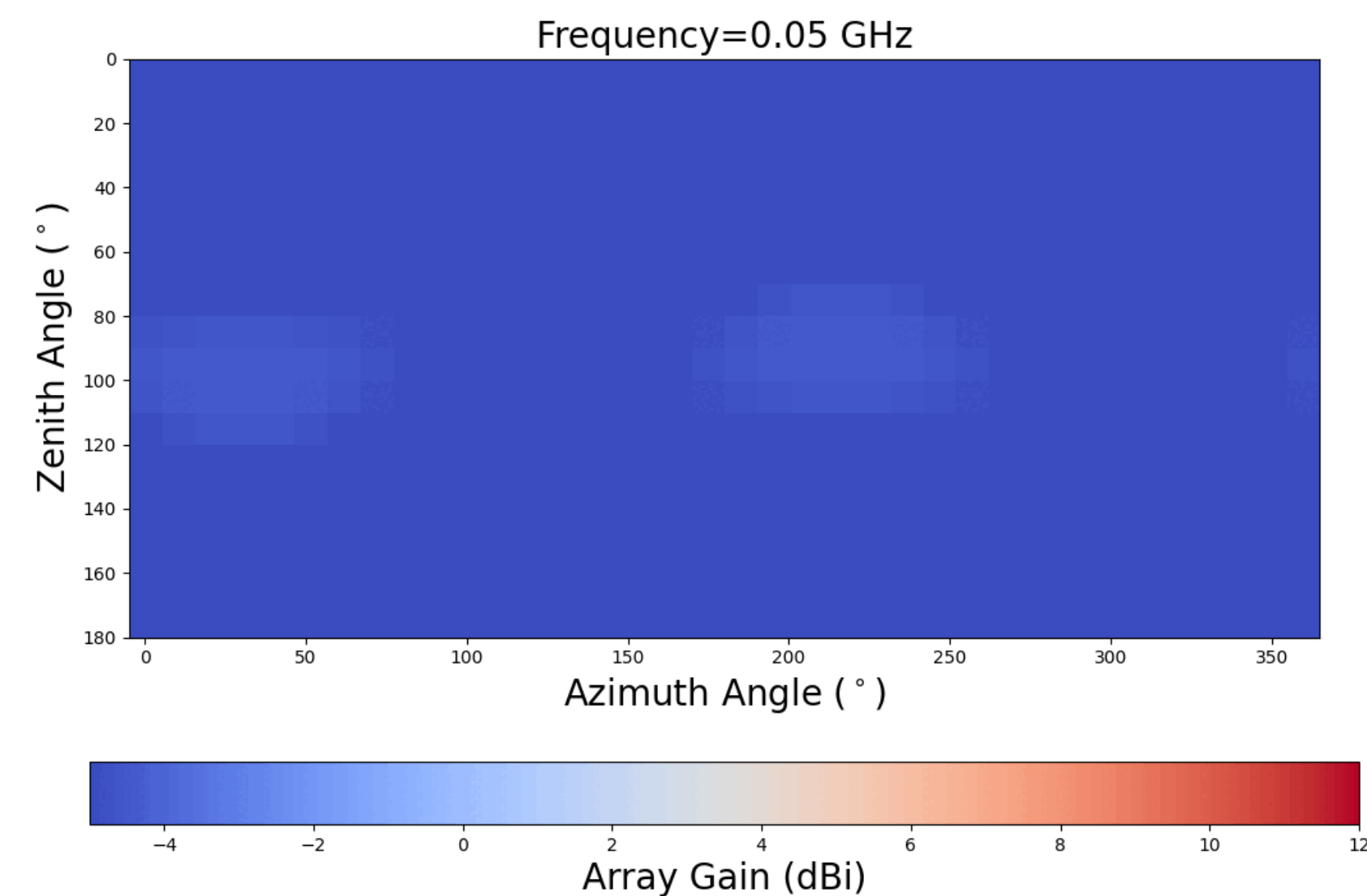
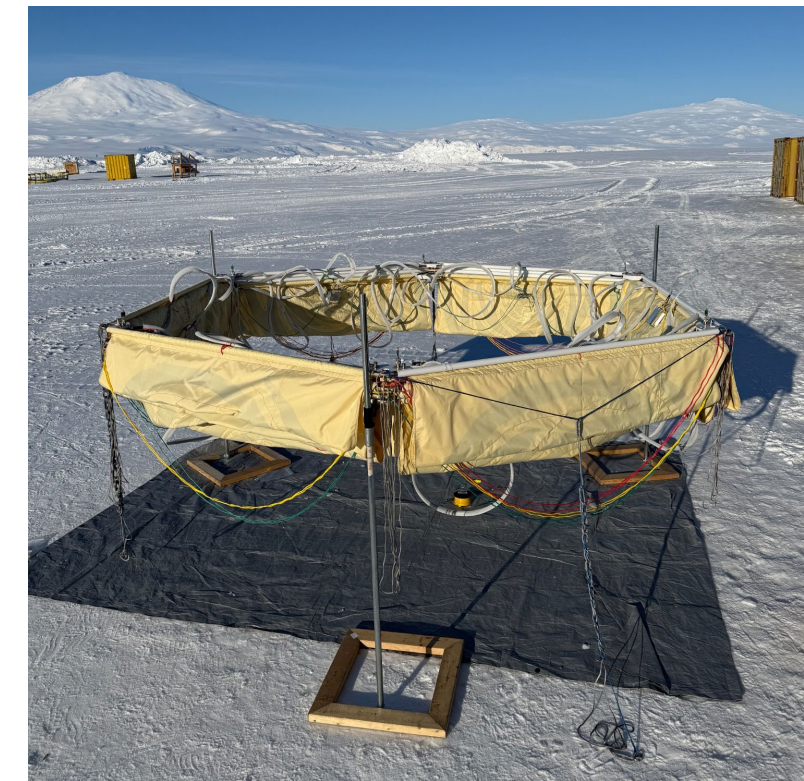
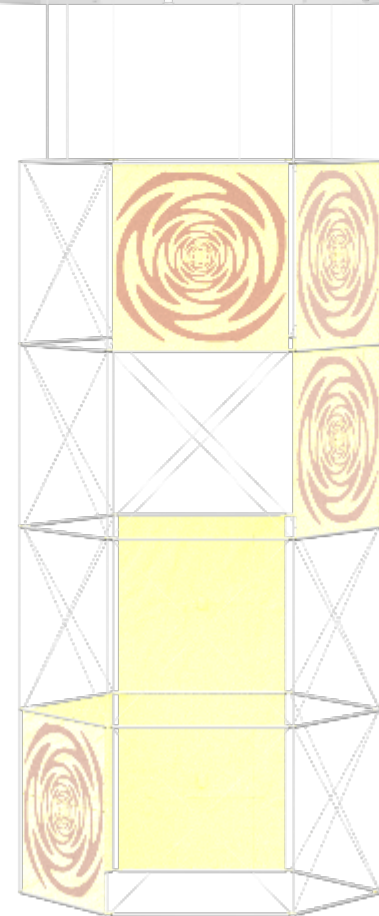
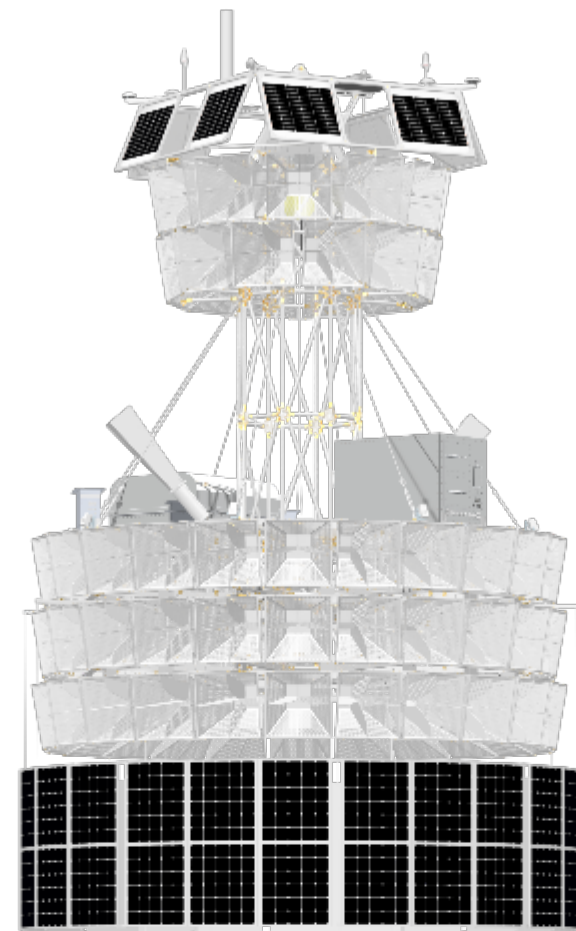
- Deployable antennas sewn into fabric to stow under payload
- 8 antennas on a hexagon, arranged to make full use of the back-lobes



PennState
Eberly College of Science

LF Array

- Deployable antennas sewn into fabric to stow under payload
- 8 antennas on a hexagon, arranged to make full use of the back-lobes



Integration and Testing

Pre-Flight

Chicago



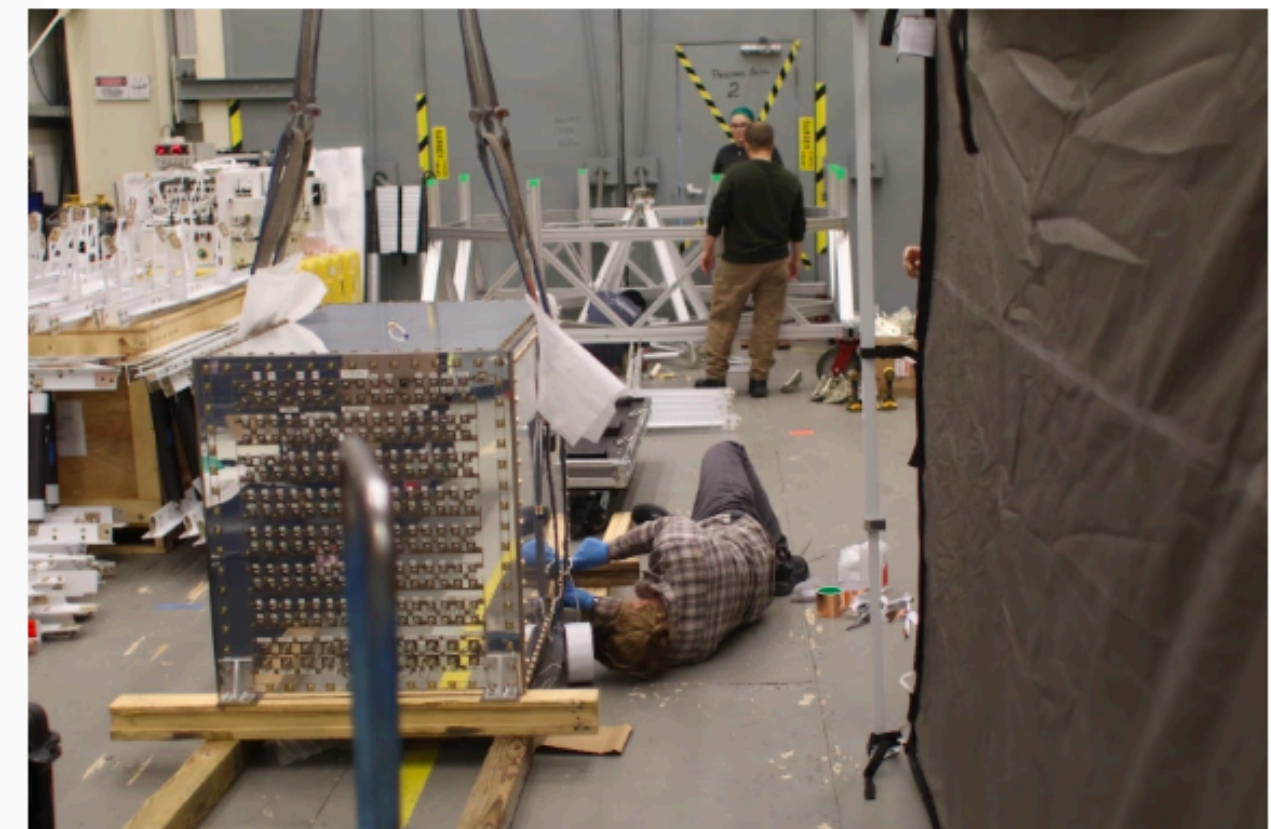
Gondola assembly

CSBF: Palestine, Tx



Thermal vac &
telemetry compatibility

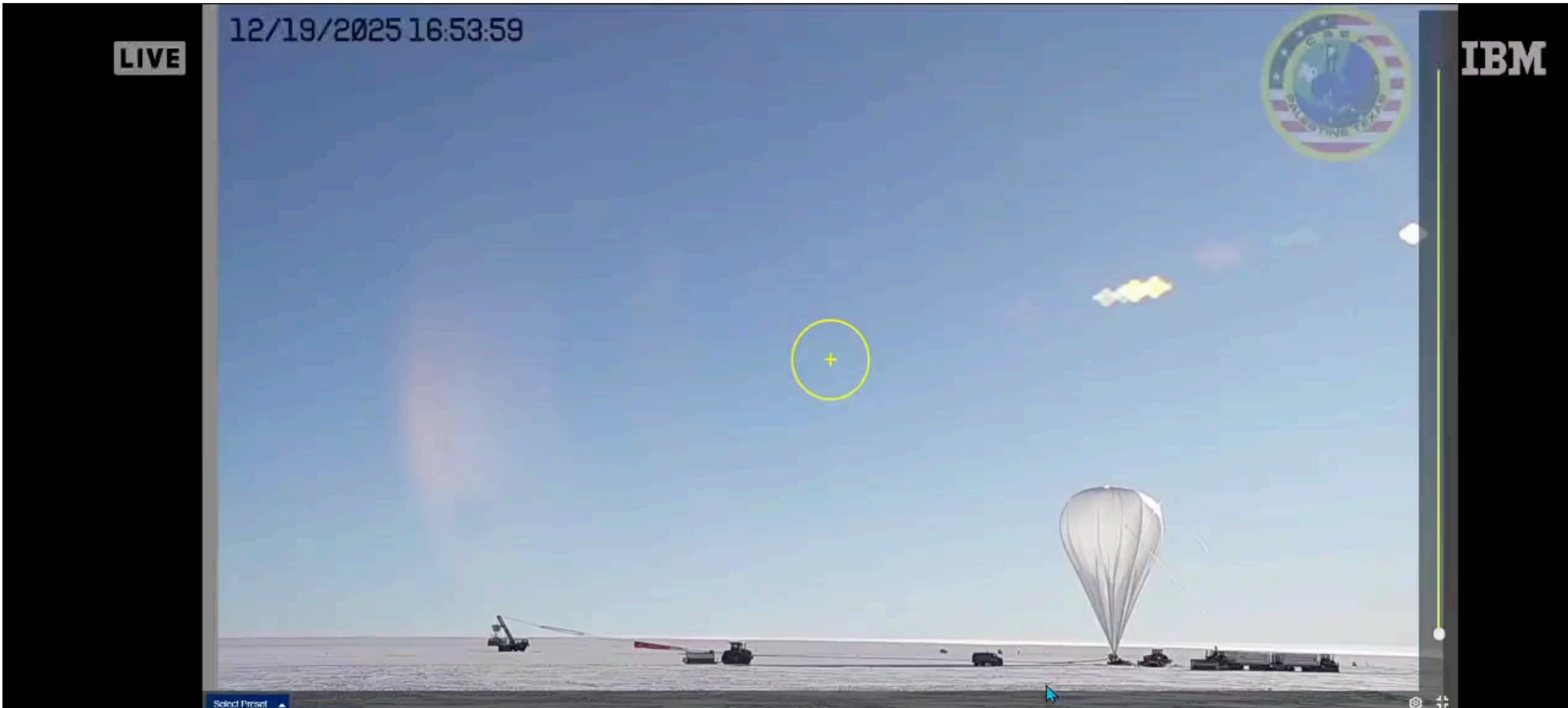
LDB, McMurdo, Antarctica



Final firmware & DAQ burn in

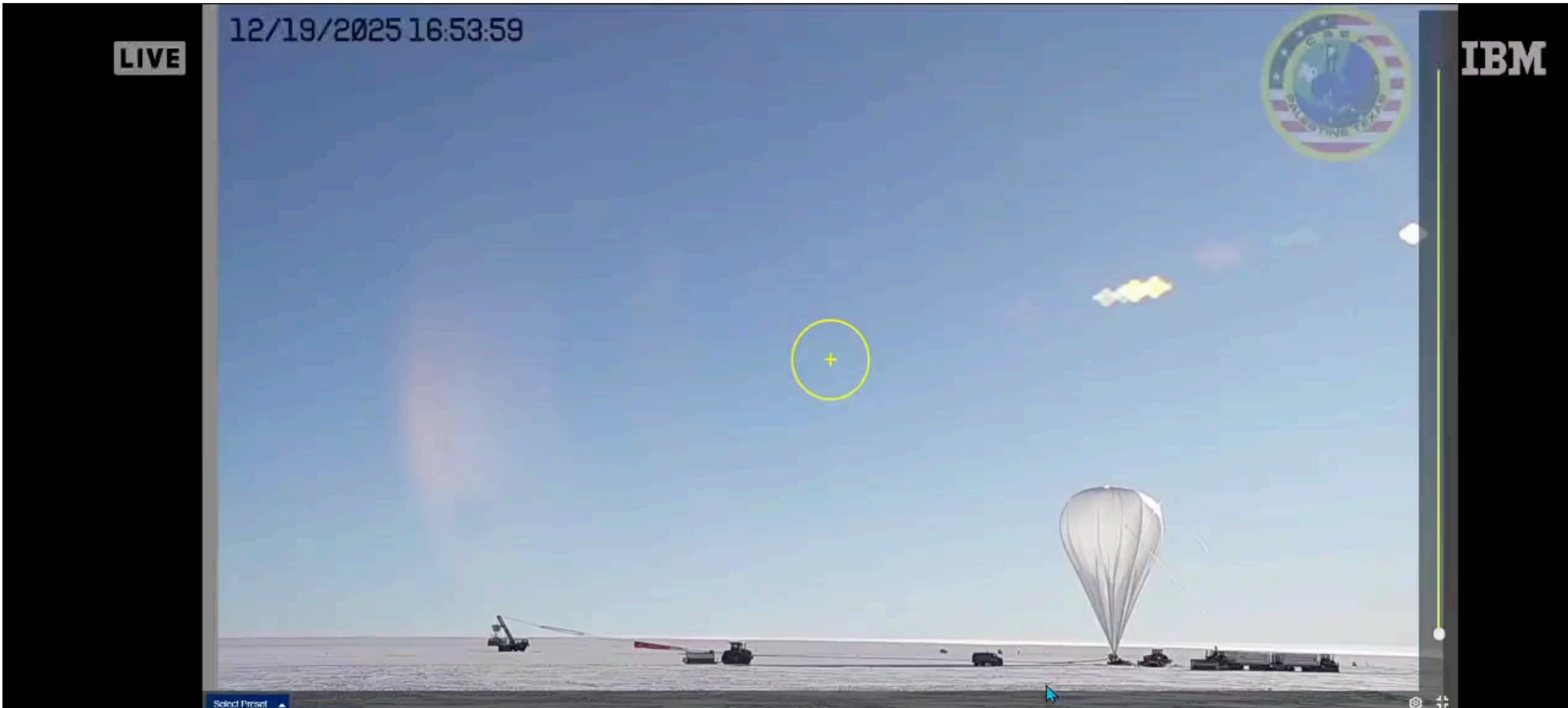
A Successful Launch!

*Video sped up by 5x



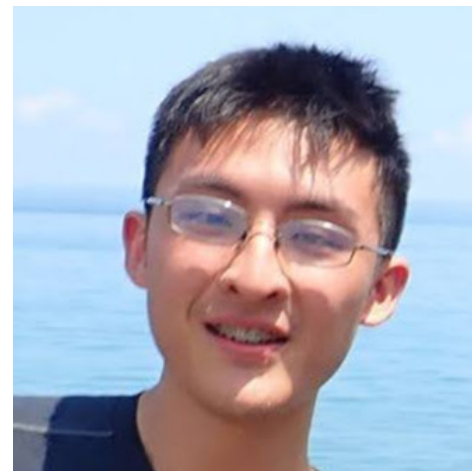
A Successful Launch!

*Video sped up by 5x



LF Array Deployment

- Gravity release from a dual-actuator system
- Rigorous testing to ensure 100% success rate (one shot!)



Yuchieh Ku

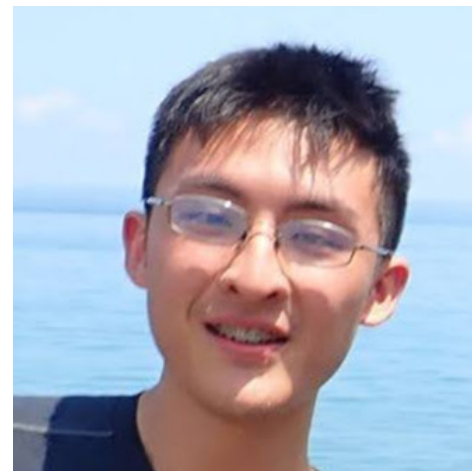


Austin Cummings



LF Array Deployment

- Gravity release from a dual-actuator system
- Rigorous testing to ensure 100% success rate (one shot!)



Yuchieh Ku

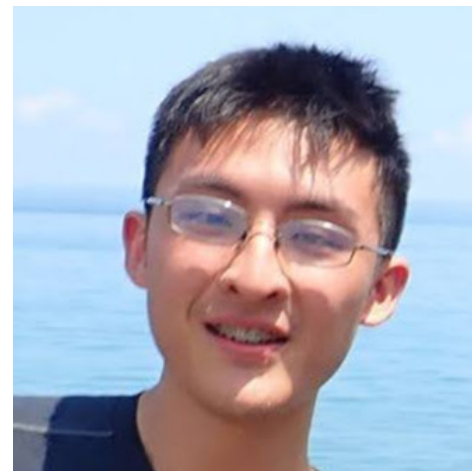


Austin Cummings



LF Array Deployment

- Gravity release from a dual-actuator system
- Rigorous testing to ensure 100% success rate (one shot!)



Yuchieh Ku

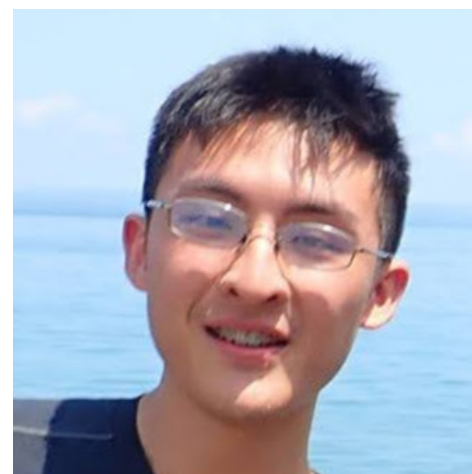
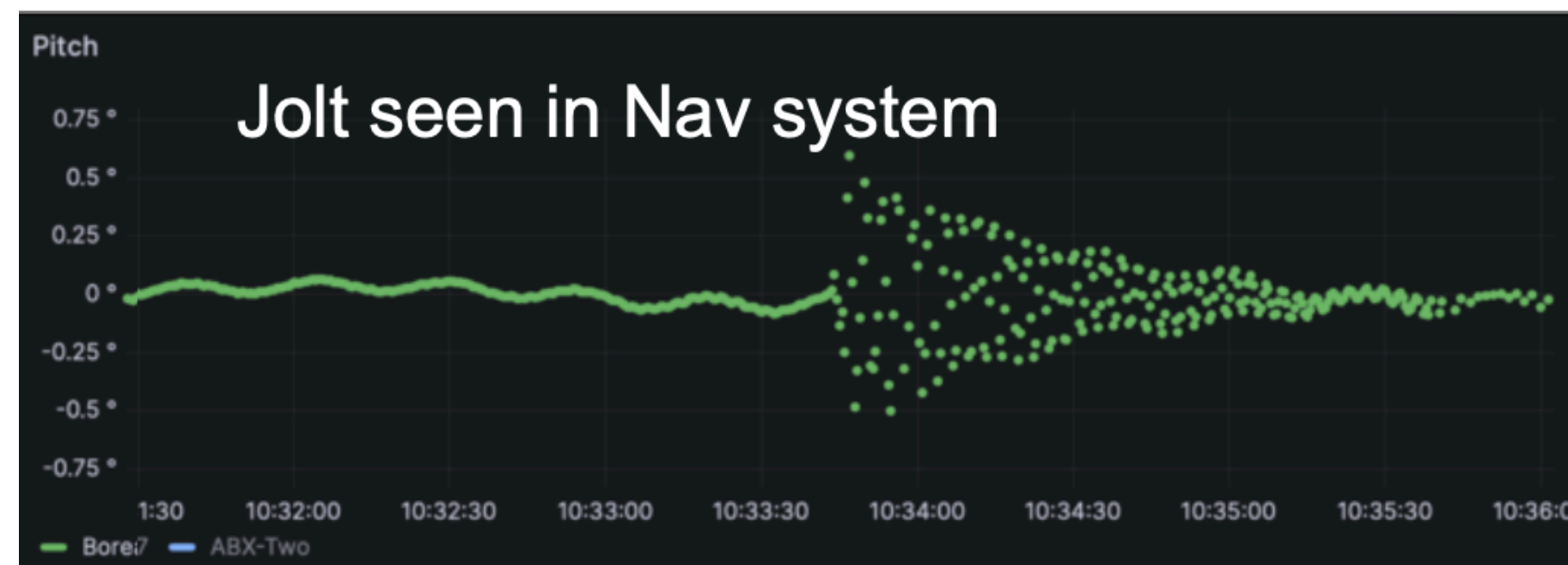


Austin Cummings



LF Array Deployment

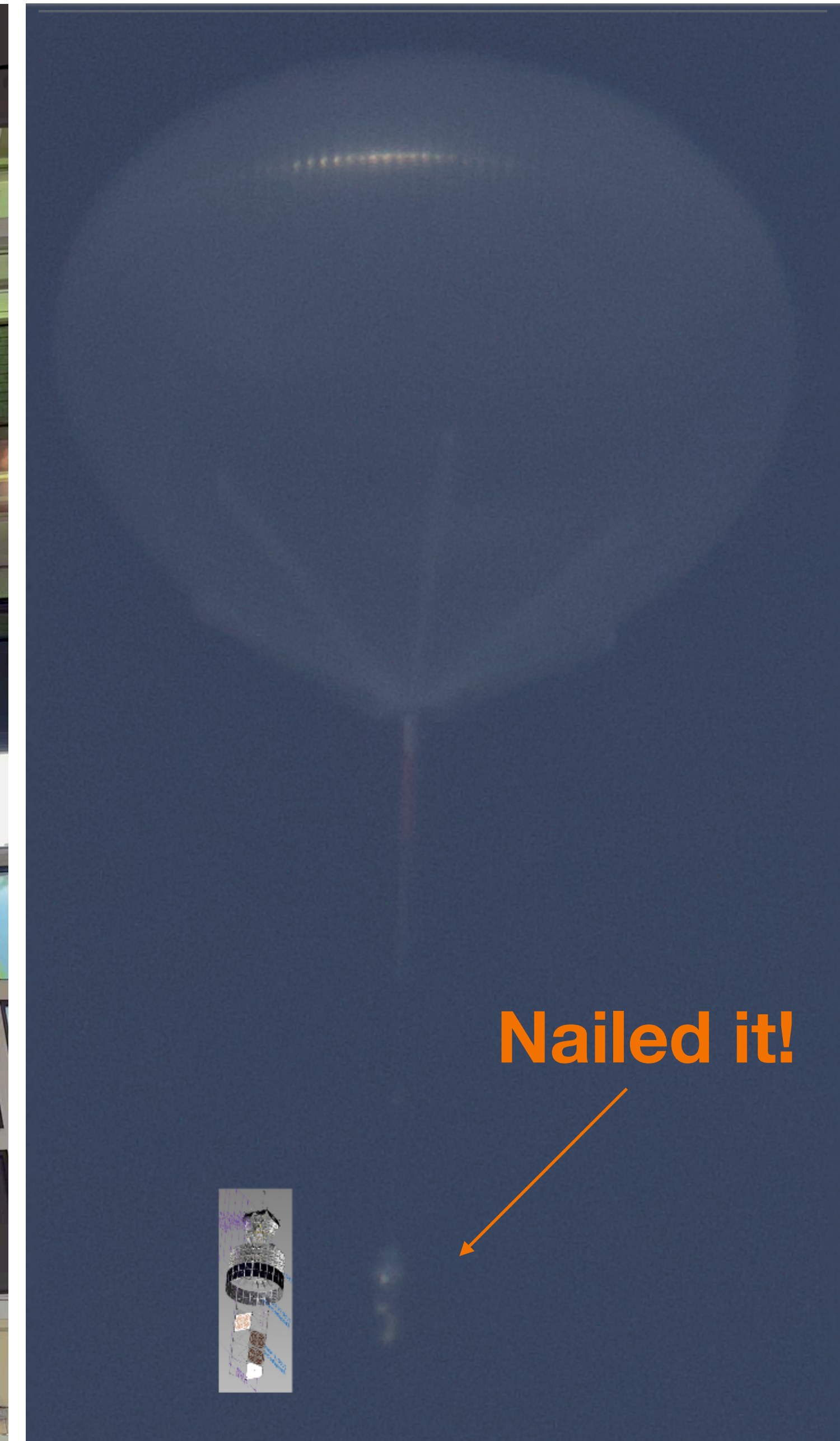
- Gravity release from a dual-actuator system
- Rigorous testing to ensure 100% success rate (one shot!)



Yuchieh Ku



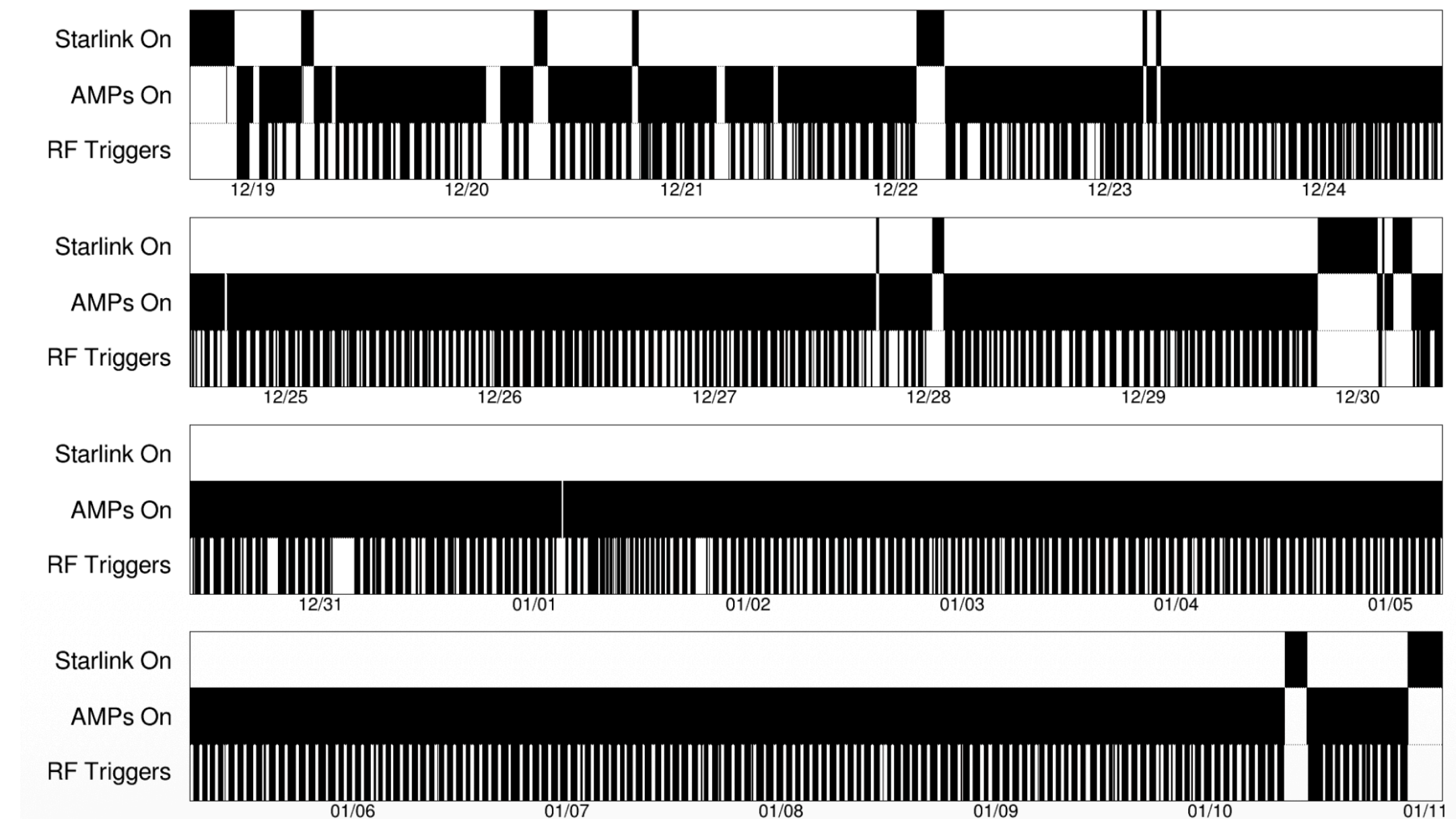
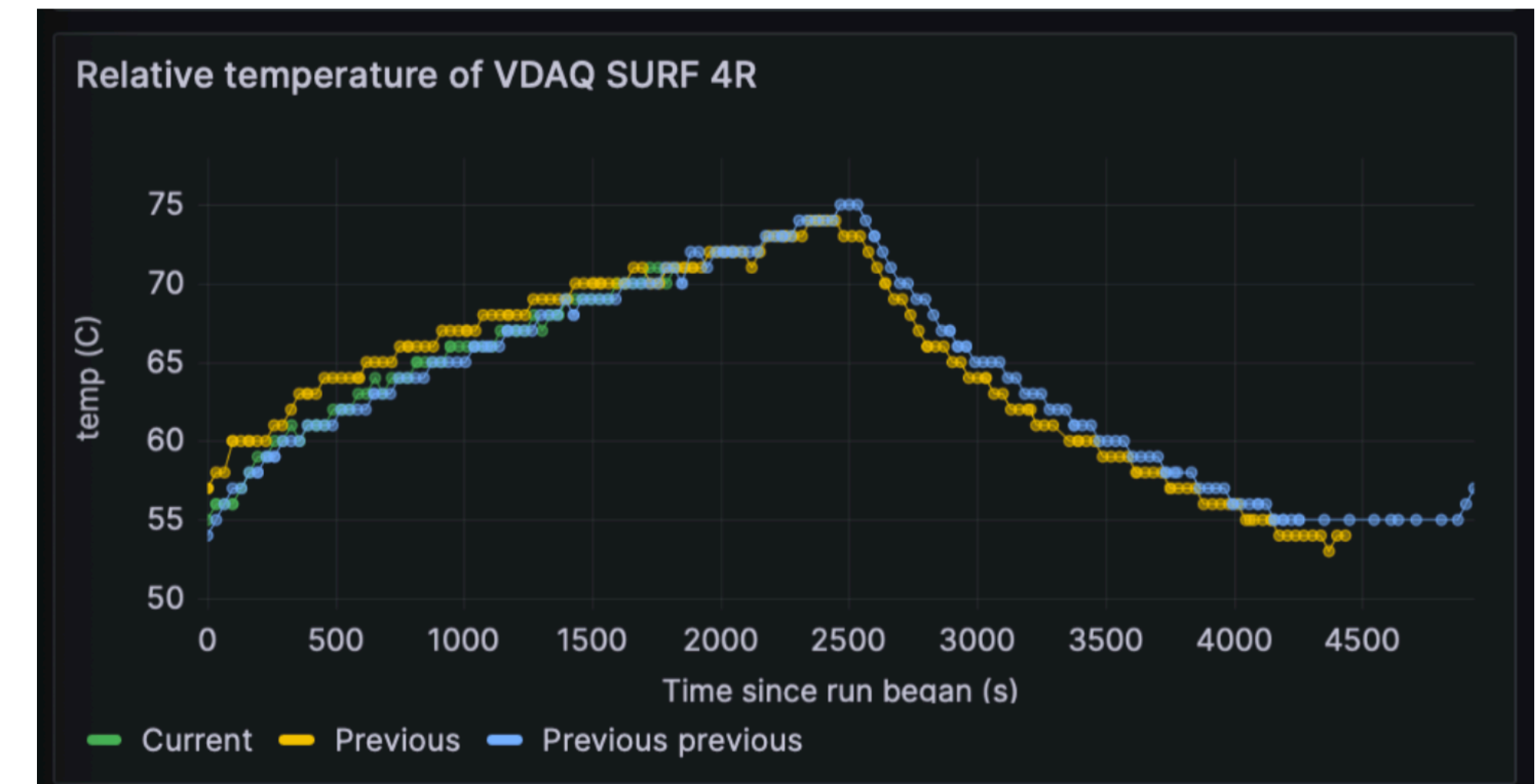
Austin Cummings



Nailed it!

Flight Operations

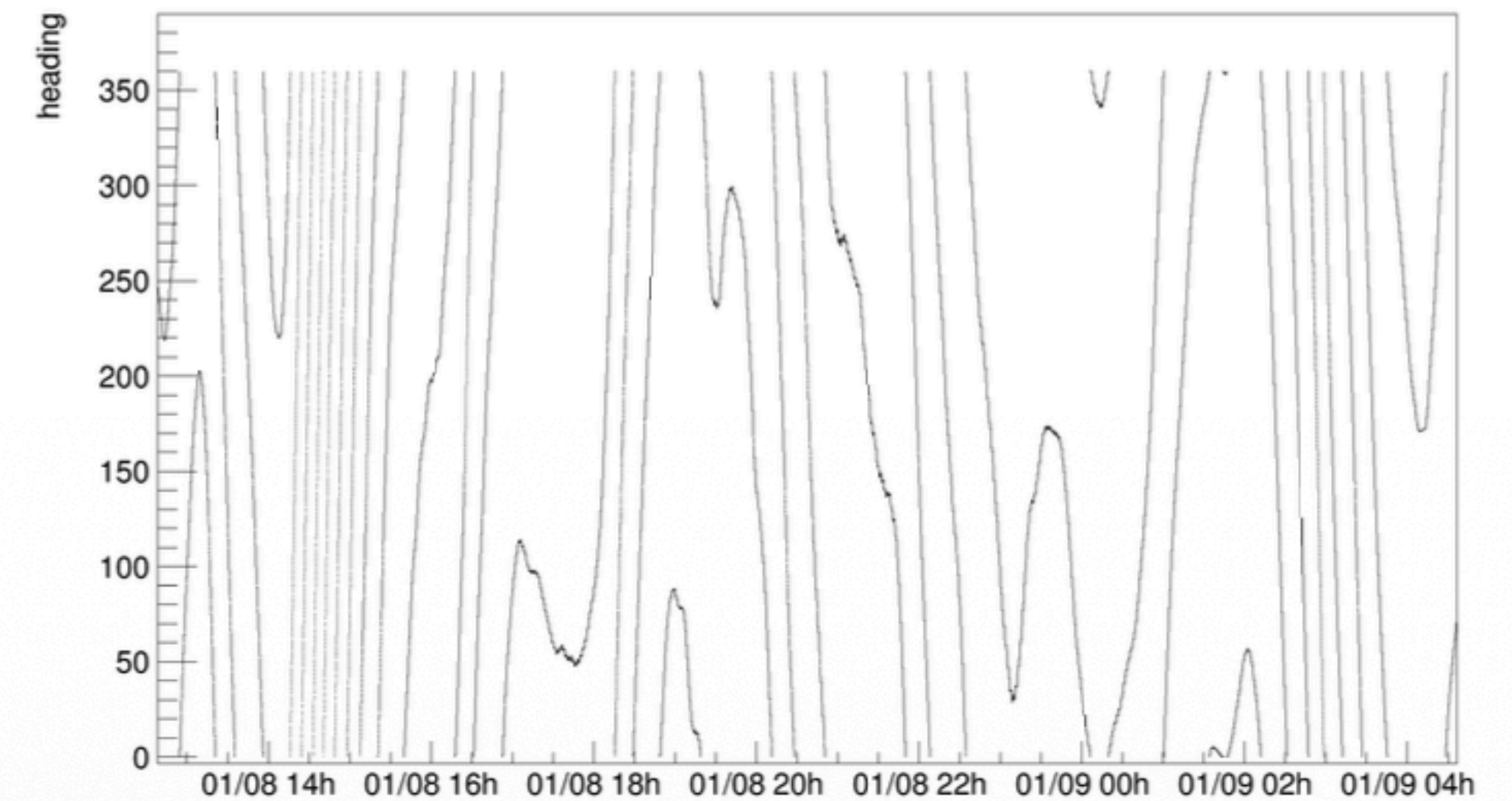
- **Telemetry:** Telemetry via 10 Mbps LOS when near McMurdo, otherwise TDRSS (6 kbps) when available or Iridium (< 1 kbps). Starling occasionally but noisy and power hungry (200 W)
- **Thermal:**
 - Pre-flight tests suggested that the thermal model was off by a few Watts
 - Firmware revisions: removed LF trigger, dropped in-flight notching
 - Radiator plate not cooling sufficiently & dependent on balloon rotation
 - Continuous babysitting and power cycling to prevent overheating → 53% duty cycle



Navigation

Redundancy is key

- Navigation system gives first guess at location, heading, pitch, and roll
- Several redundant systems: Differential GNSS (ABX-2), two IMU's (Boreas and CPT7), two star cameras, magnetometer and sun sensors
- Brownouts led to failures for star trackers, CPT7, Boreas re-calibration
- ABX-2, sun sensors + magnetometer are usable for the whole flight, and

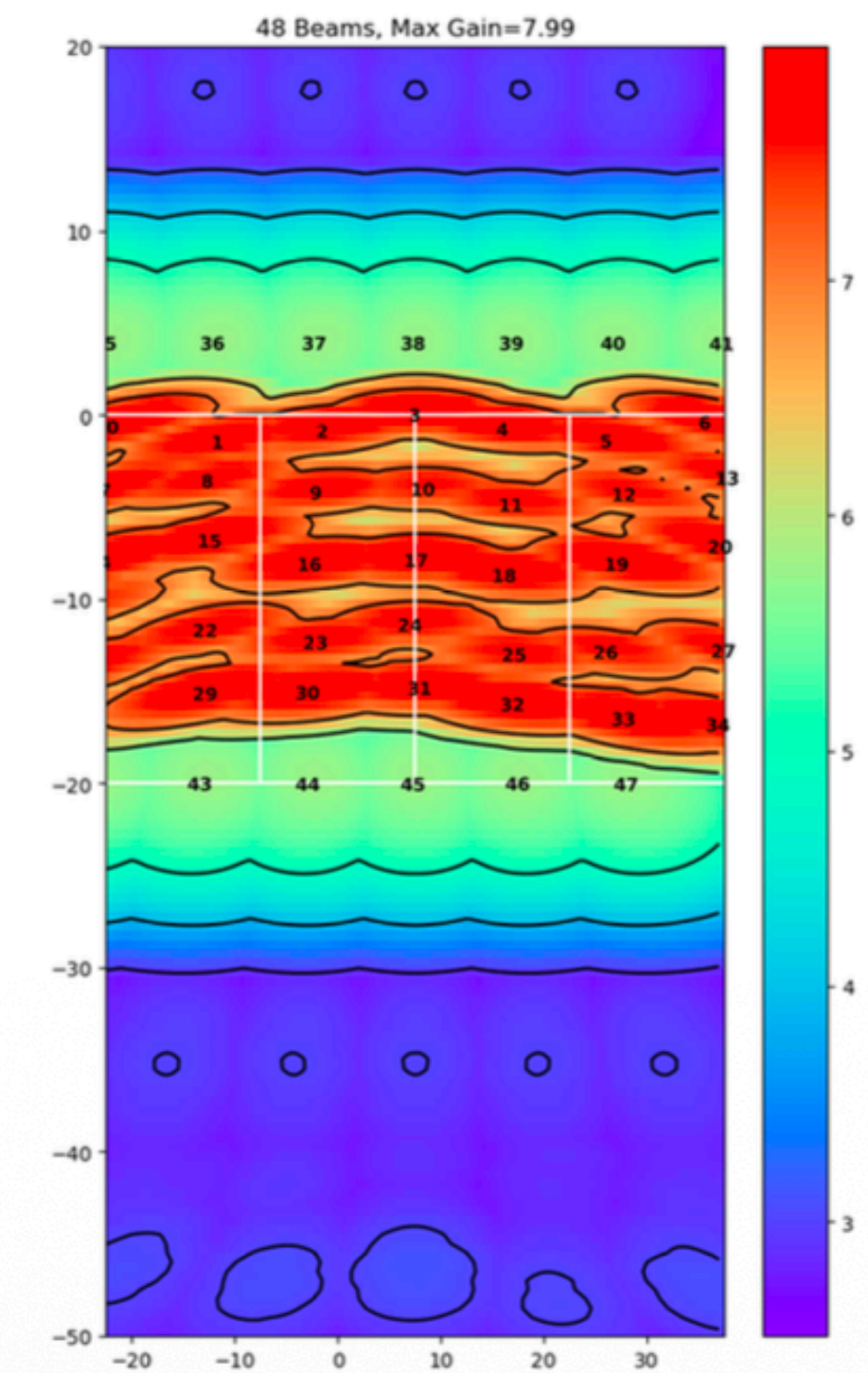
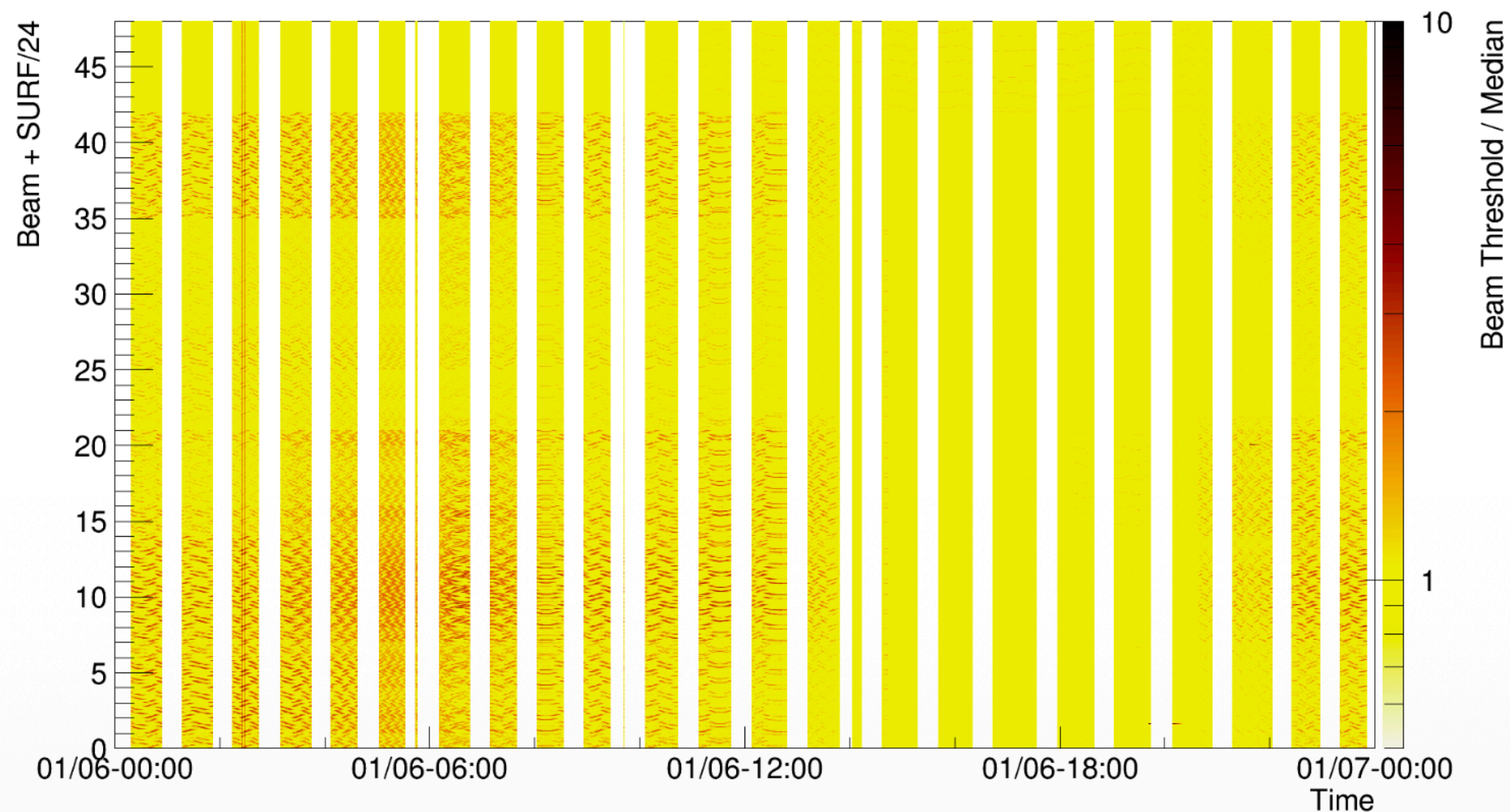


ABX-2 heading

Dynamic Thresholds

Tuning to Rate of 100 Hz

- Phased array trigger (L1 Trigger)
 - power over threshold in beam
 - 1152 beams: 48 beams per RF-SoC (24)
- Two dynamic adjustments:
 - Thresholds in each beam
 - Automatic Gain Control on FPGA

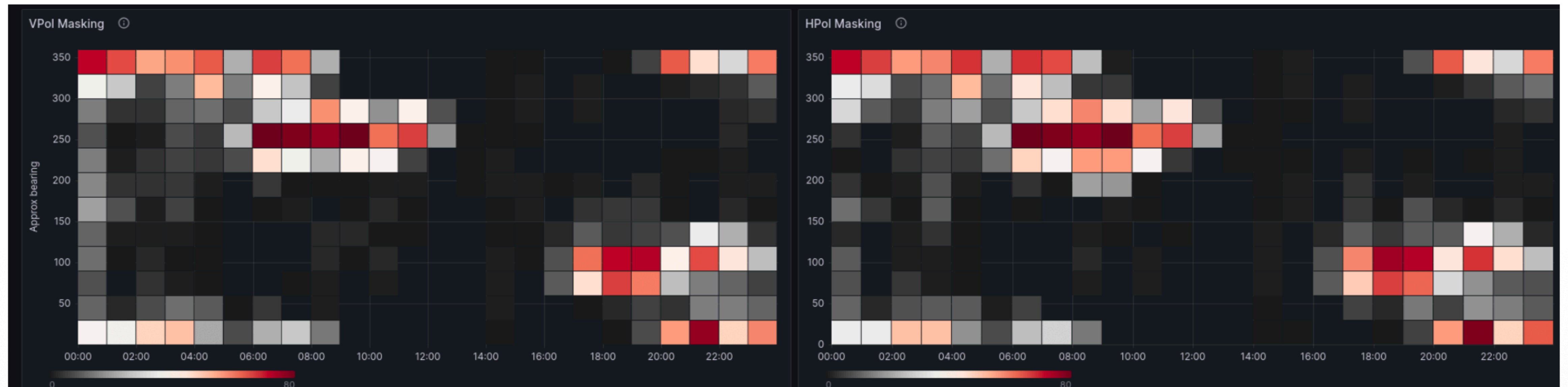


Beam Map

Dynamic Directional Masking

Reject Persistent MUOS Satellites

- L2 trigger is coincident L1 in approximately same direction from neighboring phi-sector pairs.
- Azimuthal masking applied if L2 rate exceeds 30 Hz.
- Away from Pole, always masking MUOS satellite directions, which were blasting at 360-380 MHz, but near Pole, MUOS sets so we have periods where all azimuths sensitive.



January 9th, near Pole.

What Goes Up...

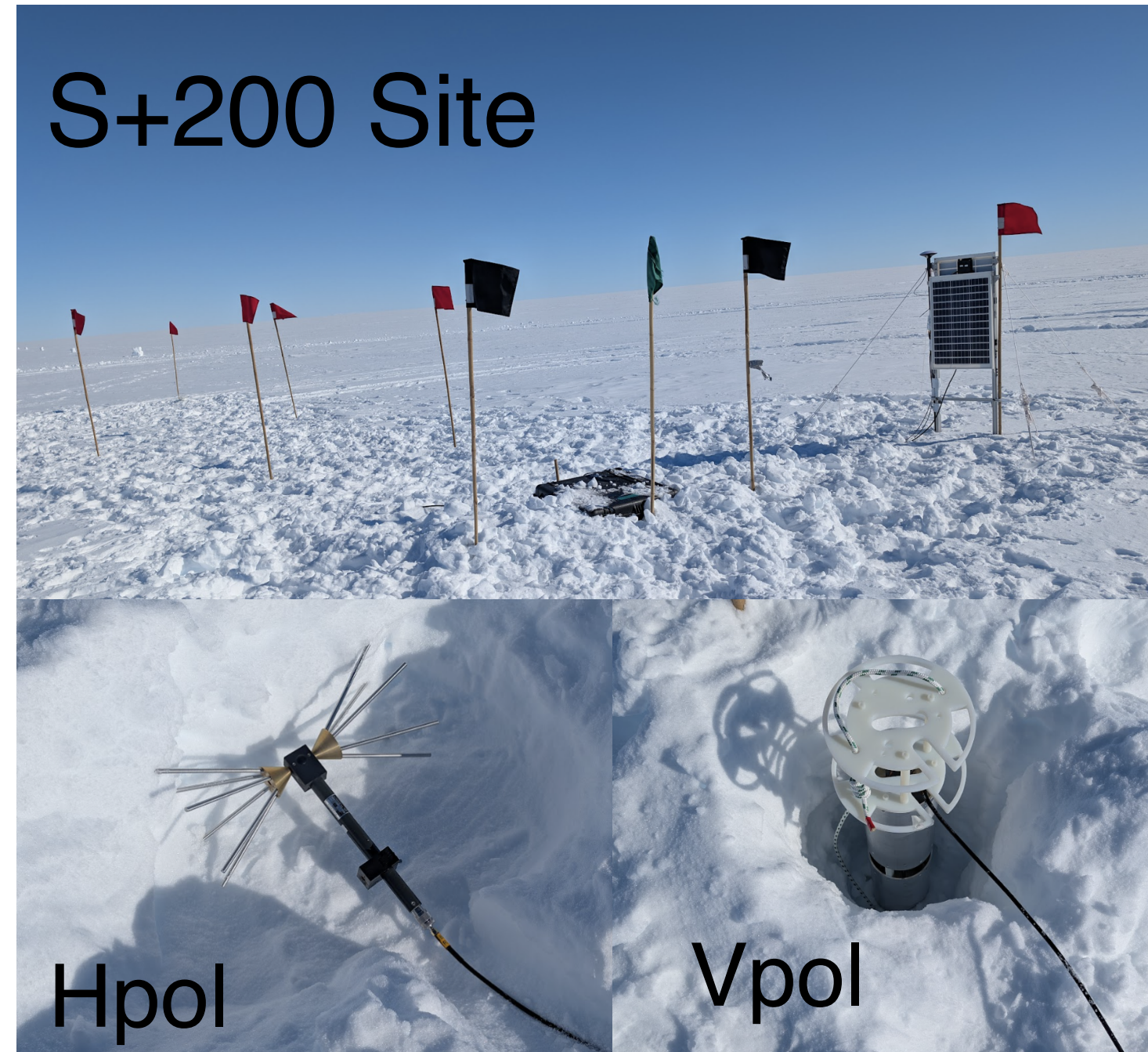
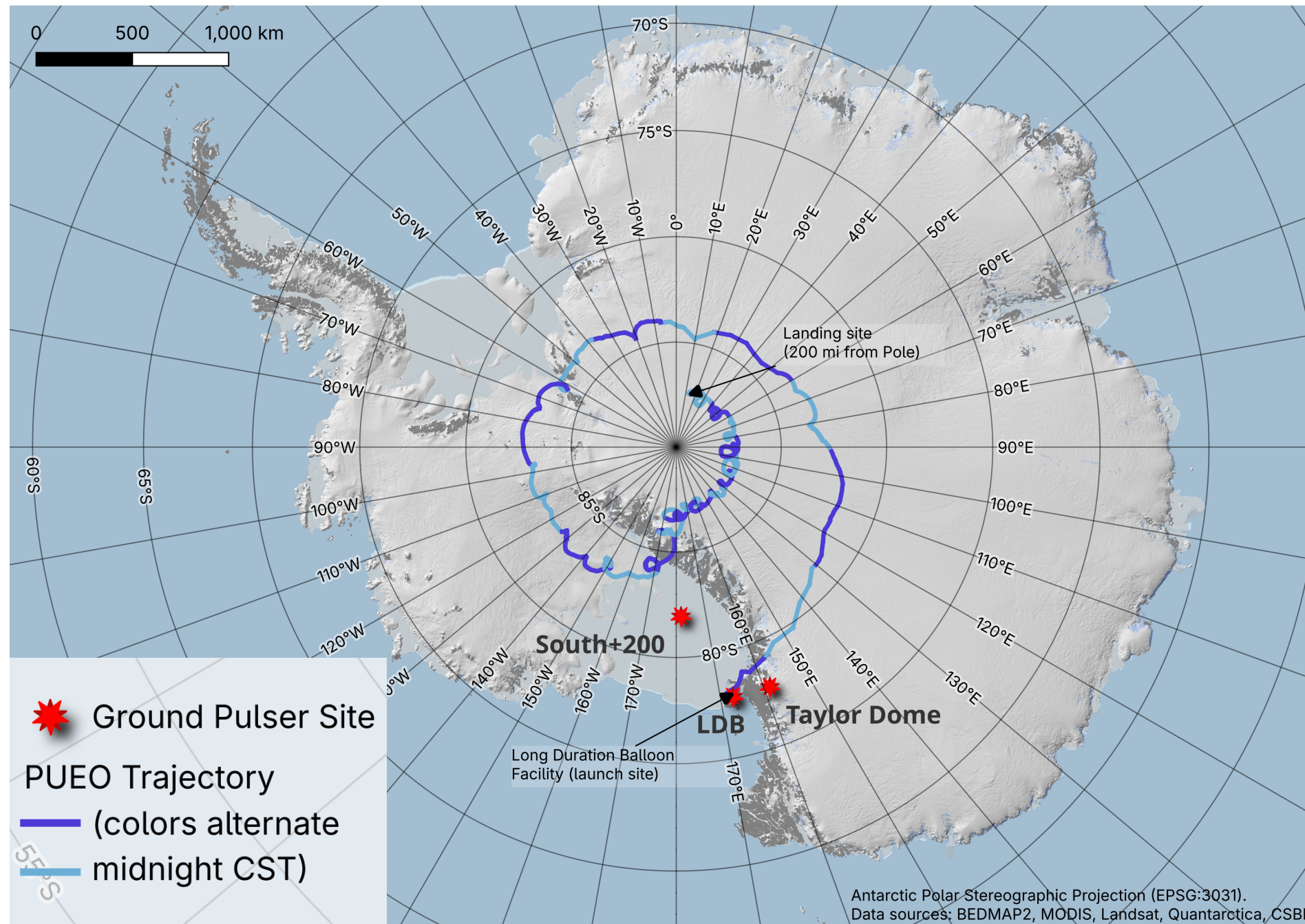
- Terminated near South Pole to ensure access with Arctic Trucks
- Full recovery within 1 day of landing
- Data and cargo back in the US and analysis underway



Ground Calibration



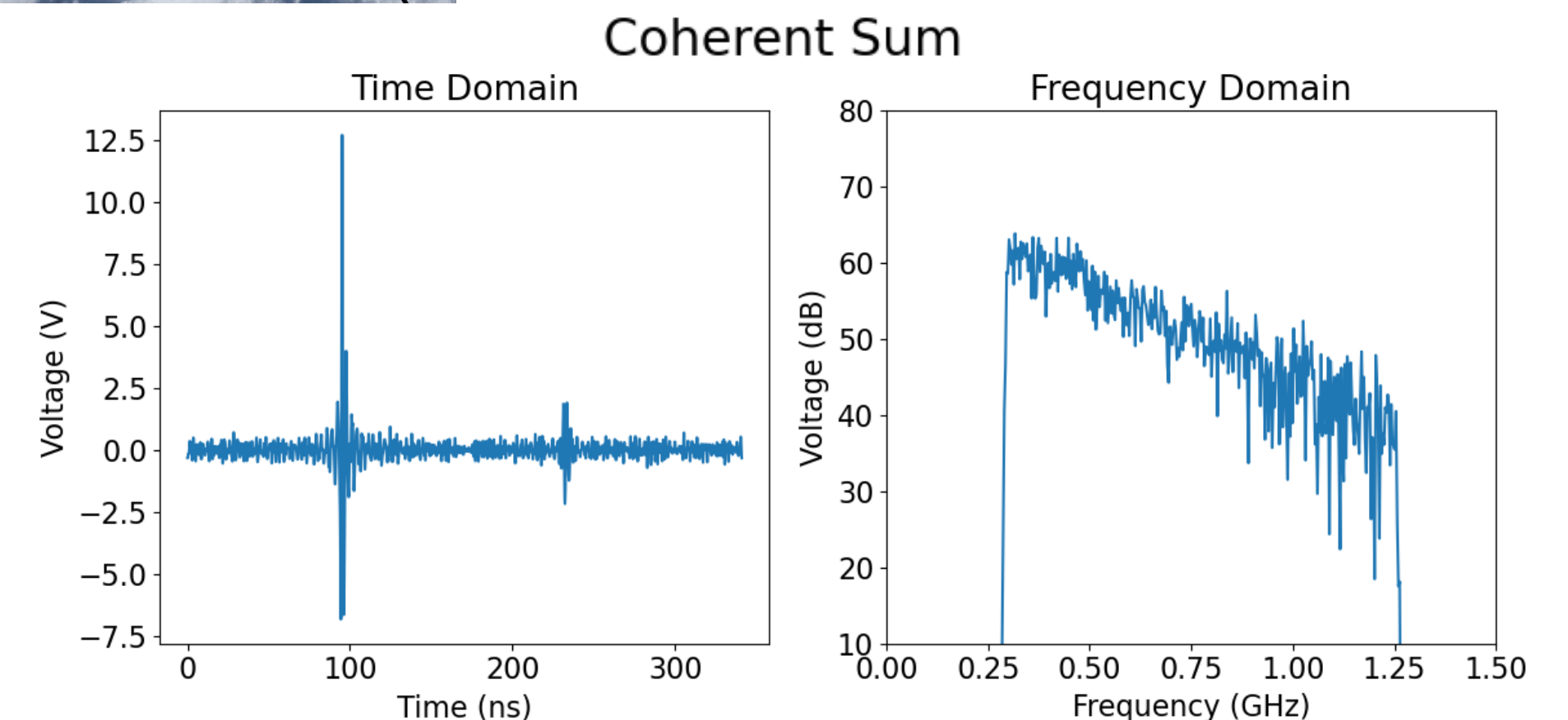
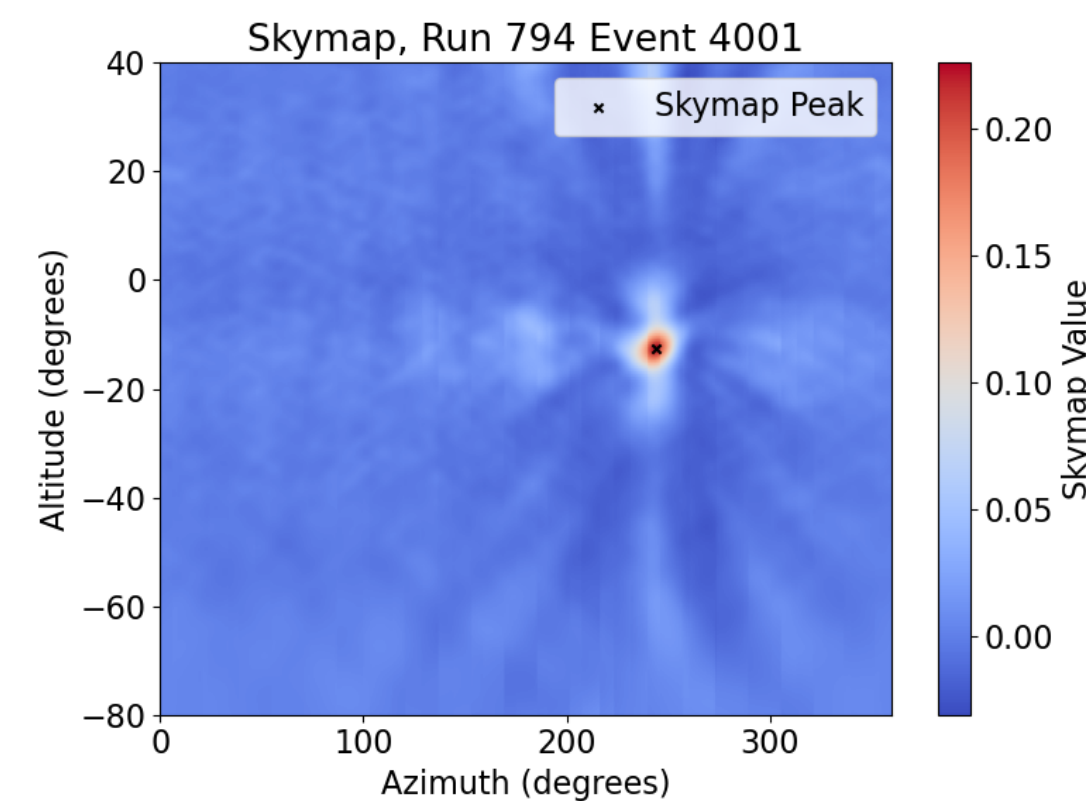
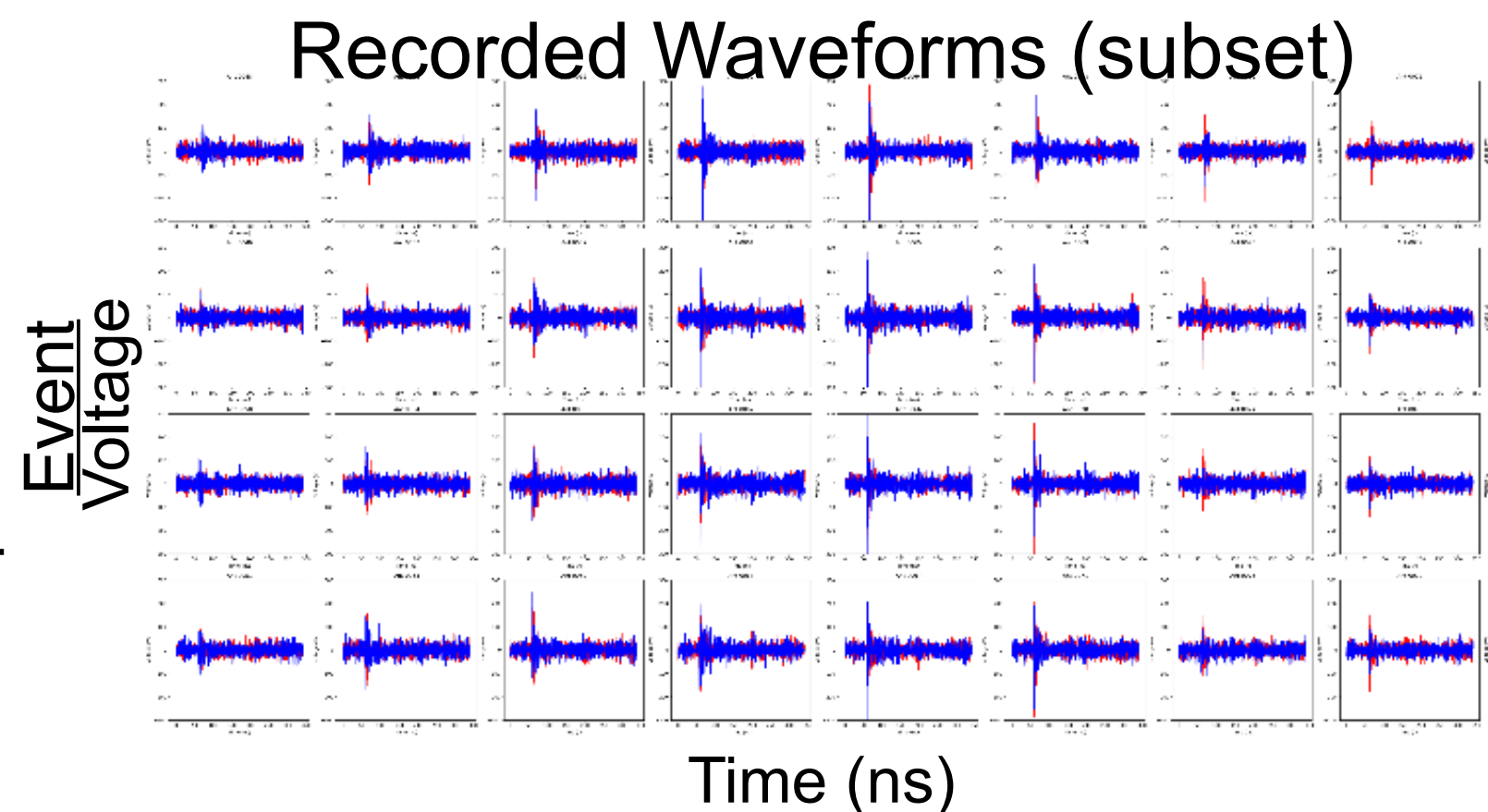
Julien Alfaro



3 ground stations with high voltage pulsers were set up near McMurdo for in flight calibration.

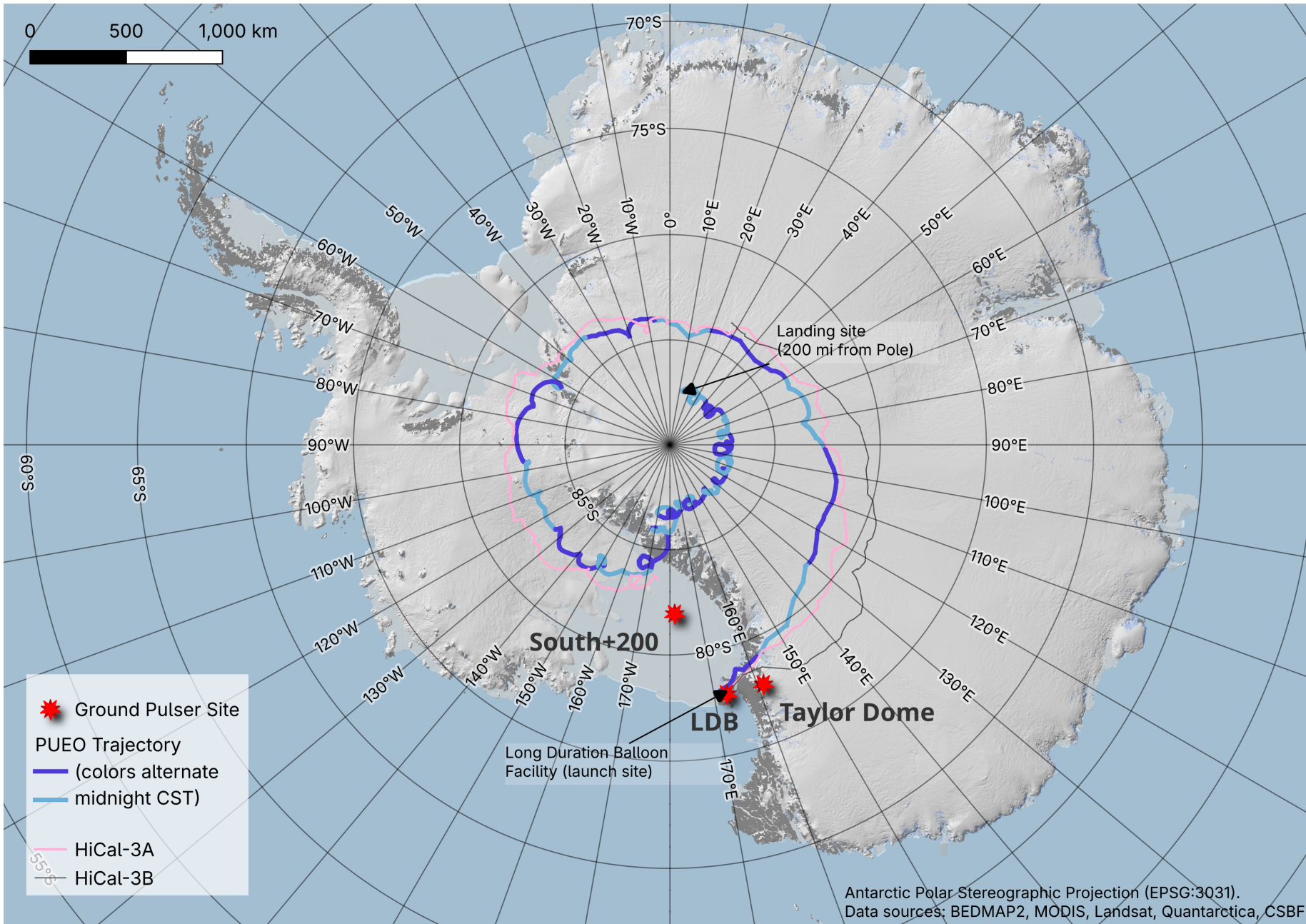
Pulses were seen from all 3 locations!

Sample GroundCal



HiCal Calibration

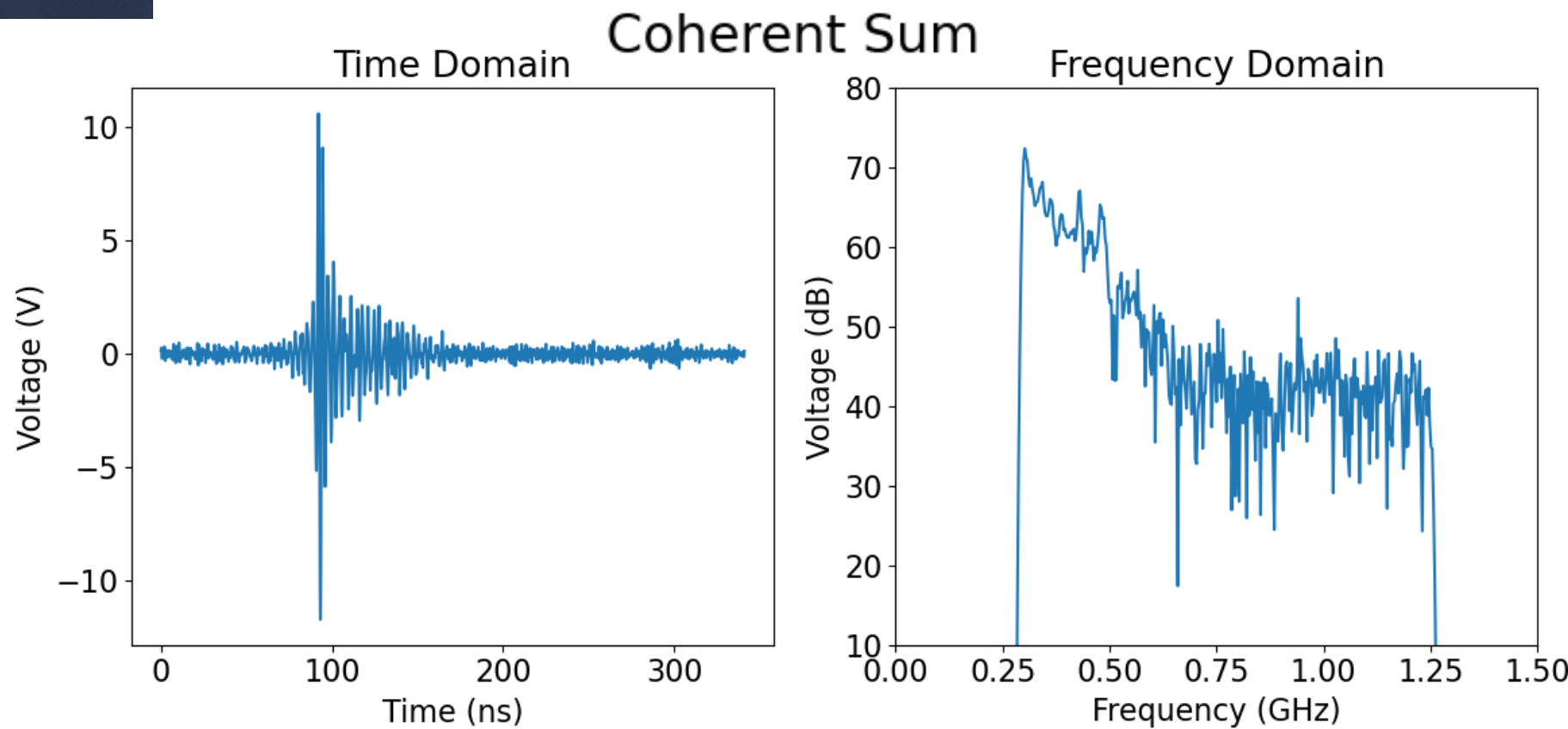
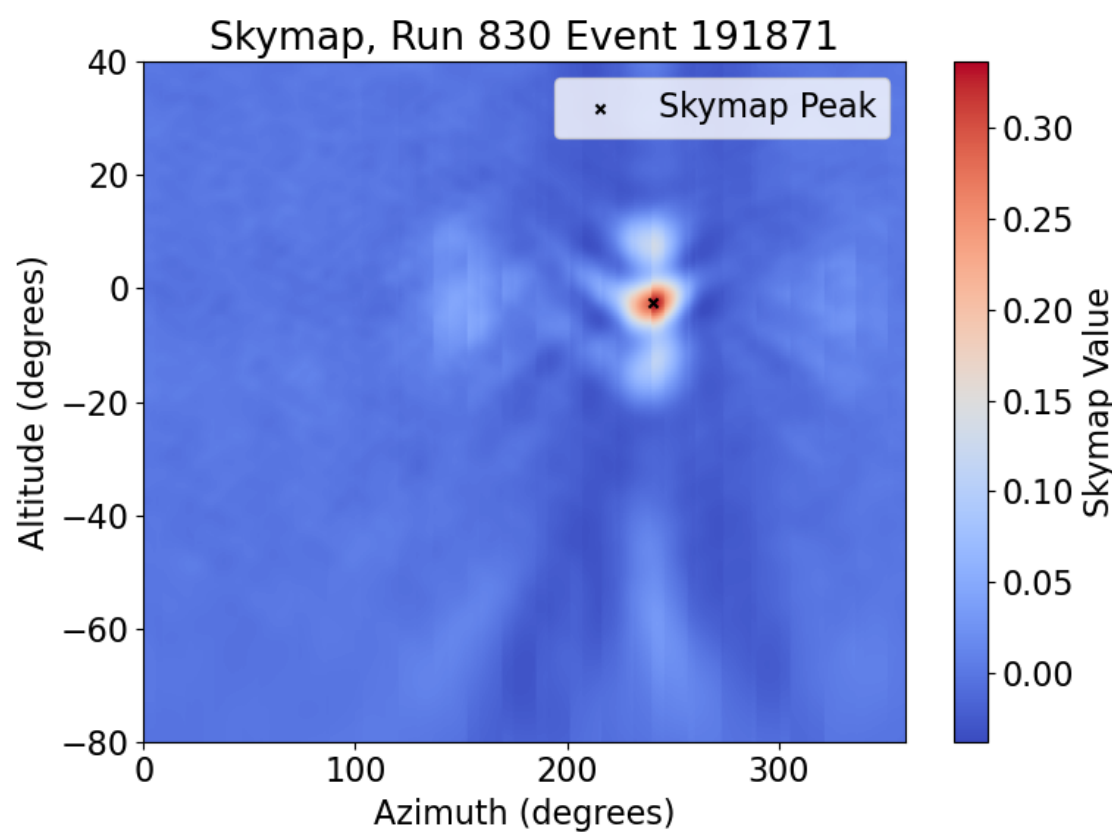
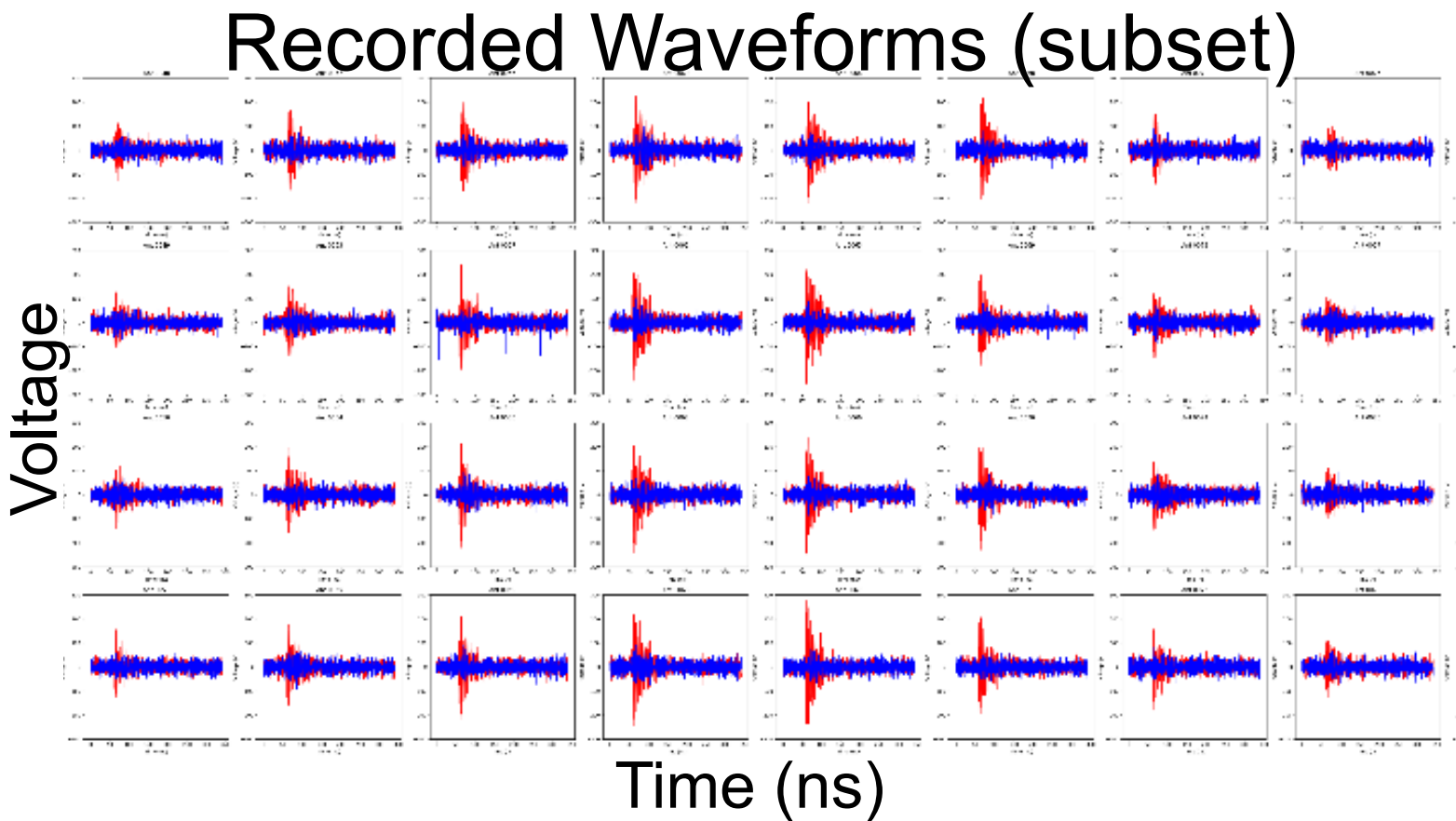
See K. Couberly's talk



Two balloon-borne calibration pulser payloads (HiCal) were launched a day after PUEO.

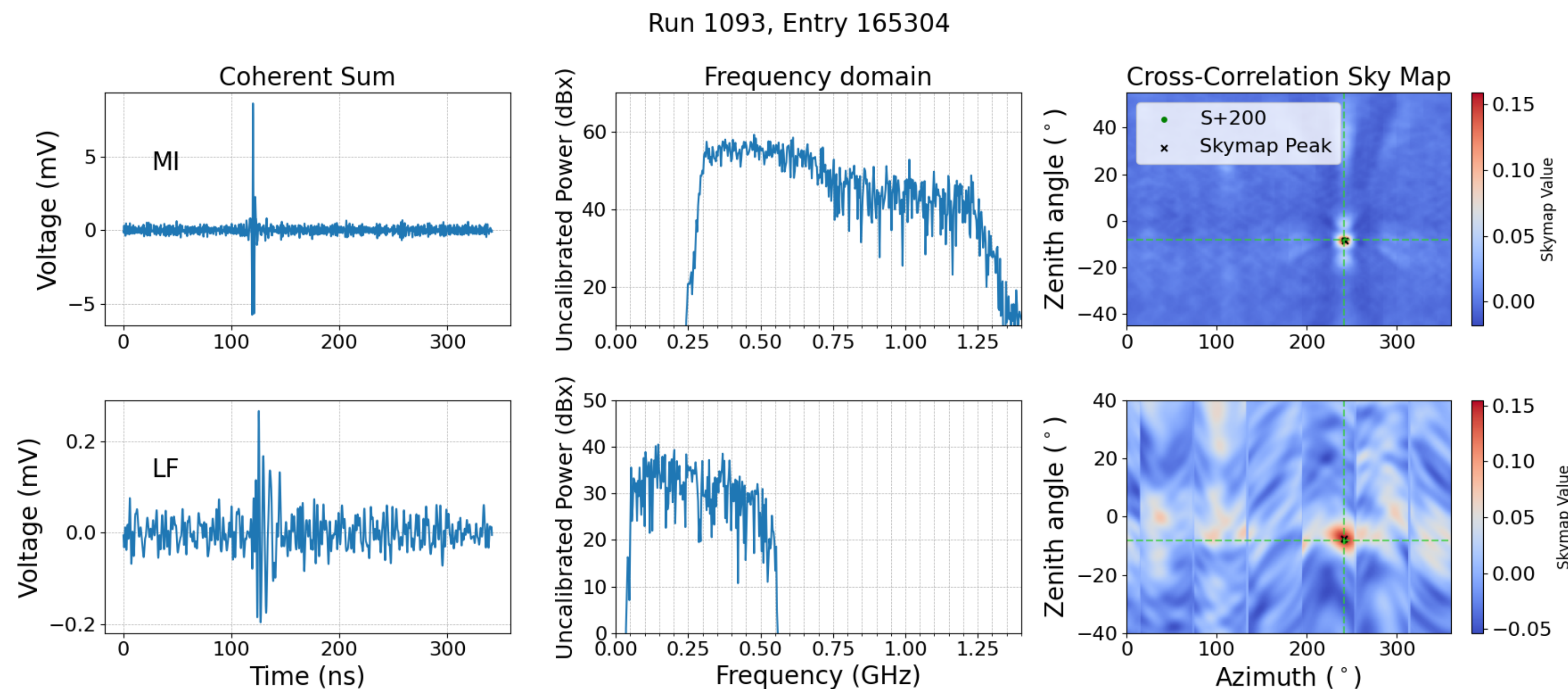
Bright pulses in both polarizations recorded from HiCals!

Sample HiCal Event



Event Reconstruction

- **Pointing reconstruction:** cross-correlation is done between pairs of antennas on the payload to create an interferometric map
- **Polarity and polarization reconstruction** needed for (1) separation of neutrino and air shower signals and (2) classification of air shower events
- **Rejection of backgrounds:**
 - Thermal noise does not strongly point anywhere
 - Anthropogenics (e.g. bases, camps) point back to the same location, cluster in space and time
 - Air shower leakage based on event polarization and polarity
 - Comparison of MI and LF provide independent measures of event parameters



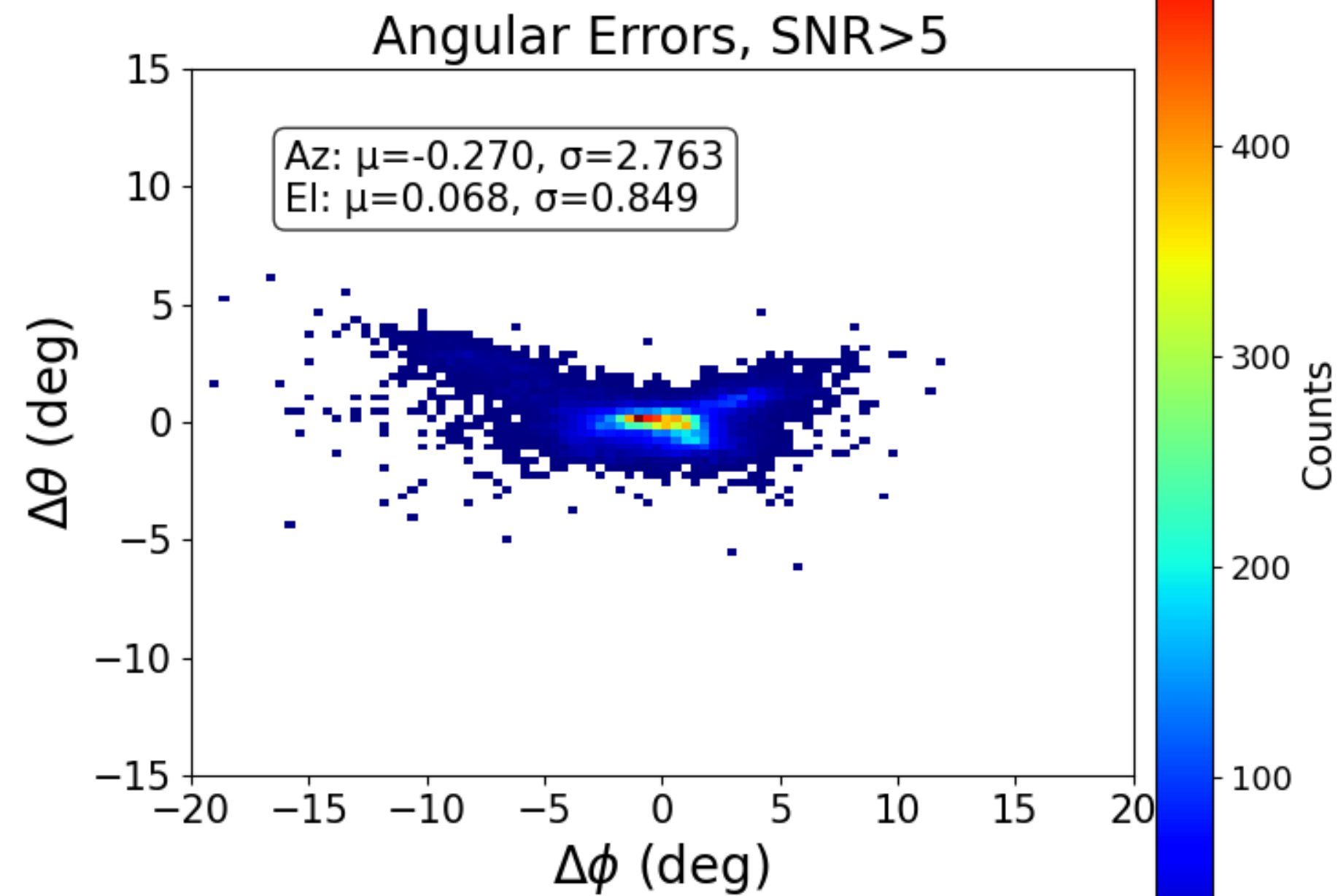
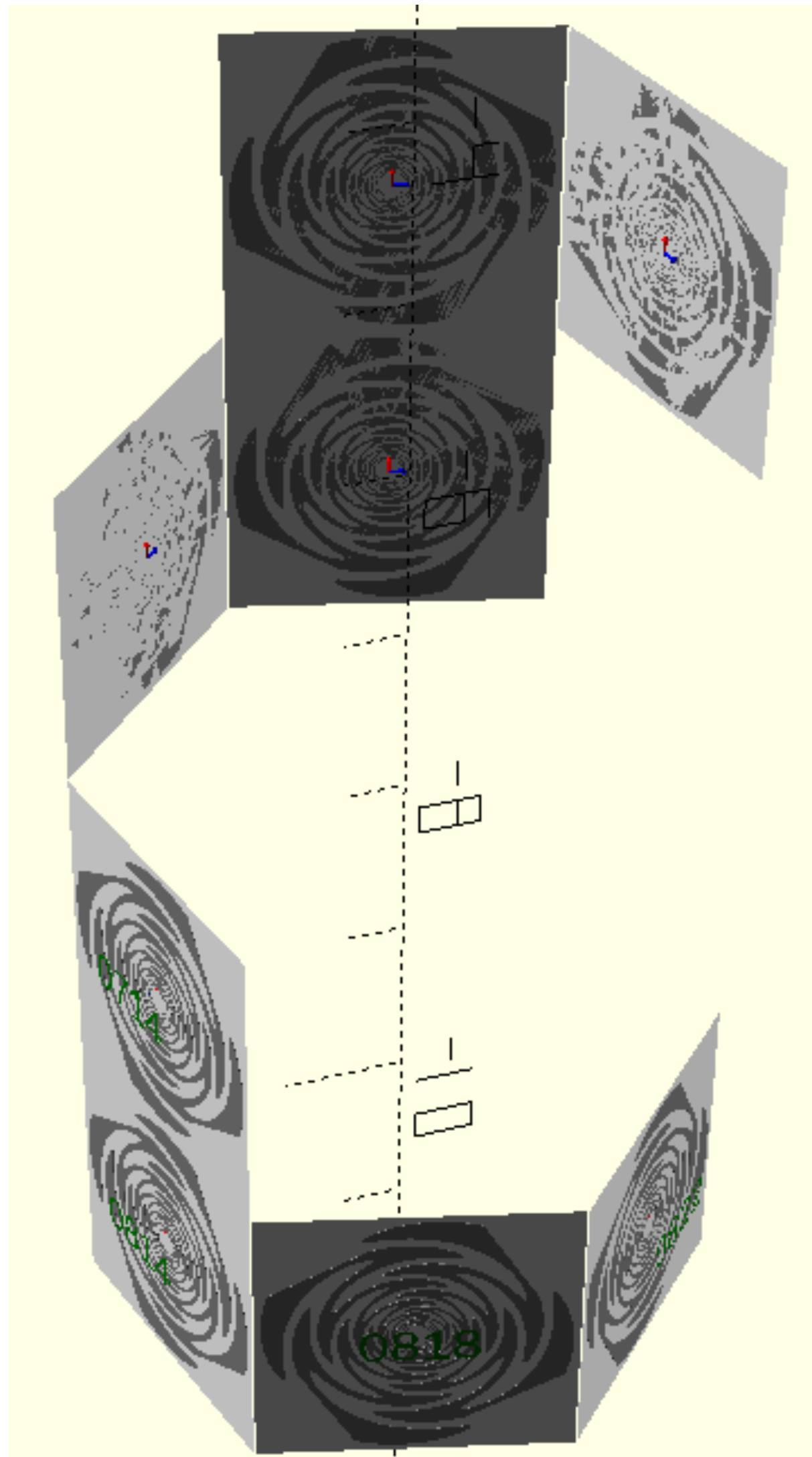
*Event points back to ground cal station in both MI and LF
Angular analysis suggests 0.1°-scale pointing on RF direction.*

LF Calibration



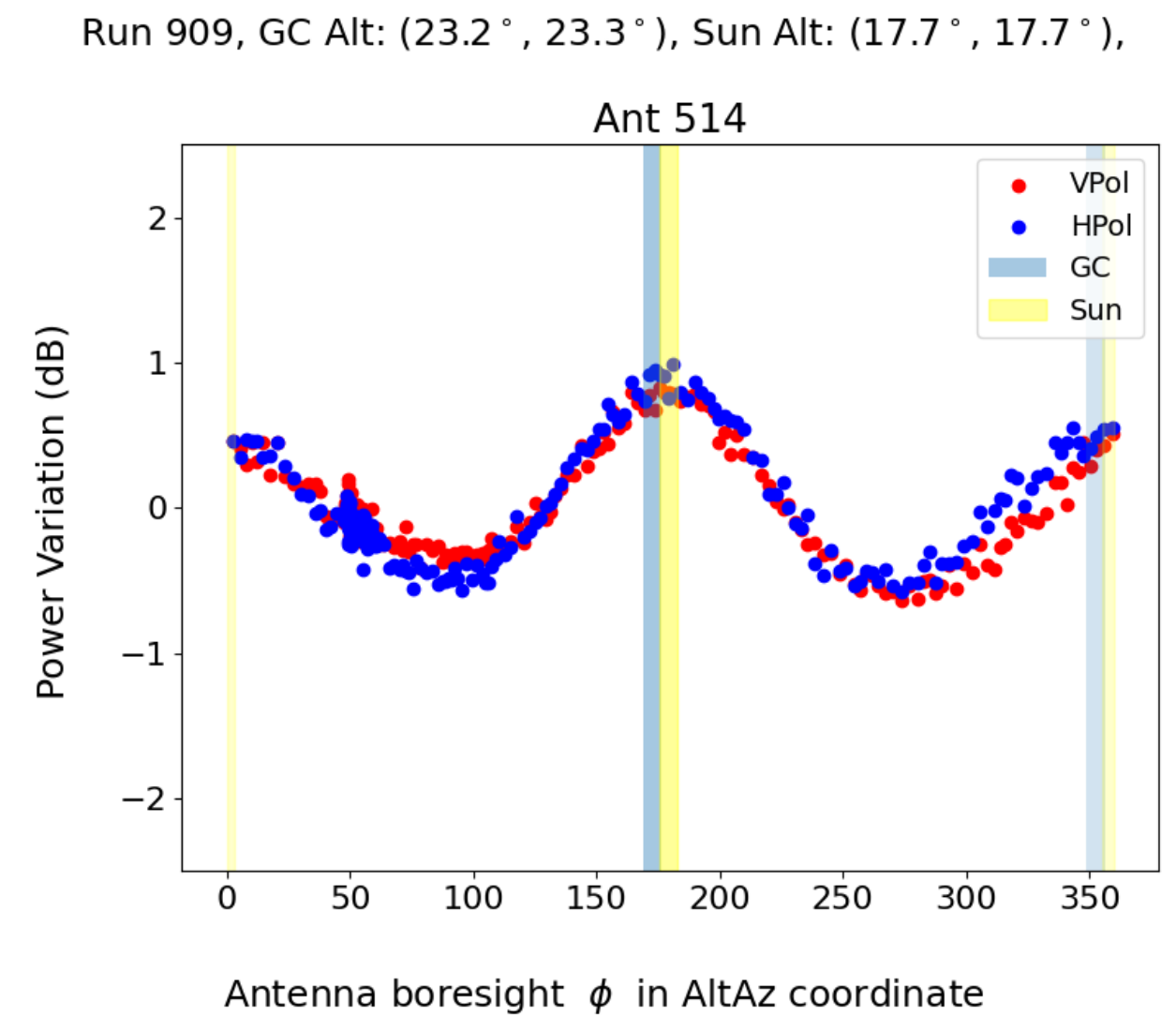
Yuchieh Ku

Calibrated Positions with Ground Cal



Resolution: 0.8° in elevation
 2.8° in azimuth

Galactic Noise



- Galactic noise provides absolute power reference
- 1-2 dB higher than nearby sun during quiet periods



PennState
Eberly College of Science

Solar Bursts

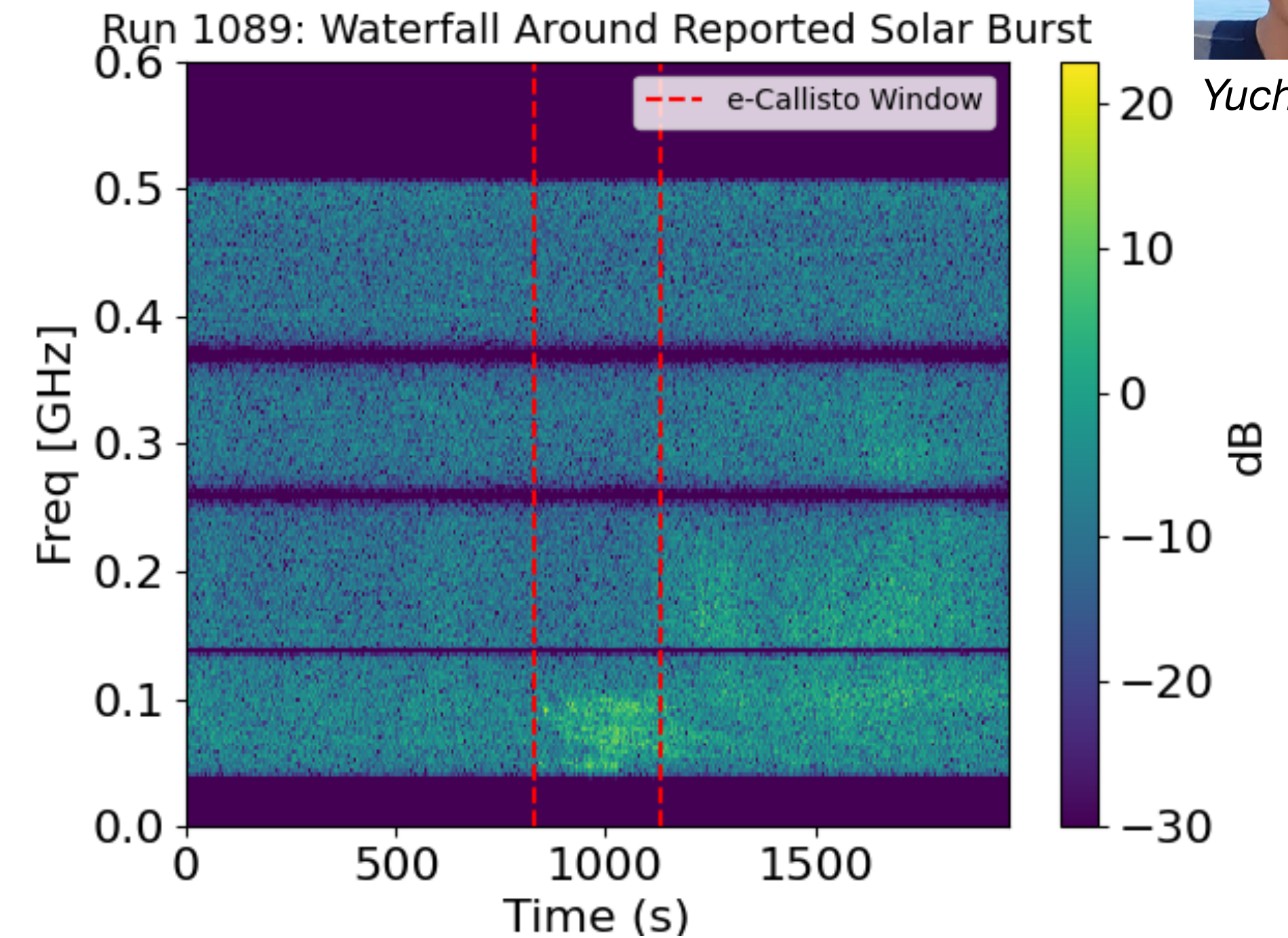
Visible at Low Frequencies

- e-Callisto International Network reported ~130 solar radio bursts coincident with PUEO's flight.
- $\mathcal{O}(10,000)$ unbiased LF events are associated with solar bursts and reconstruct back to sun location

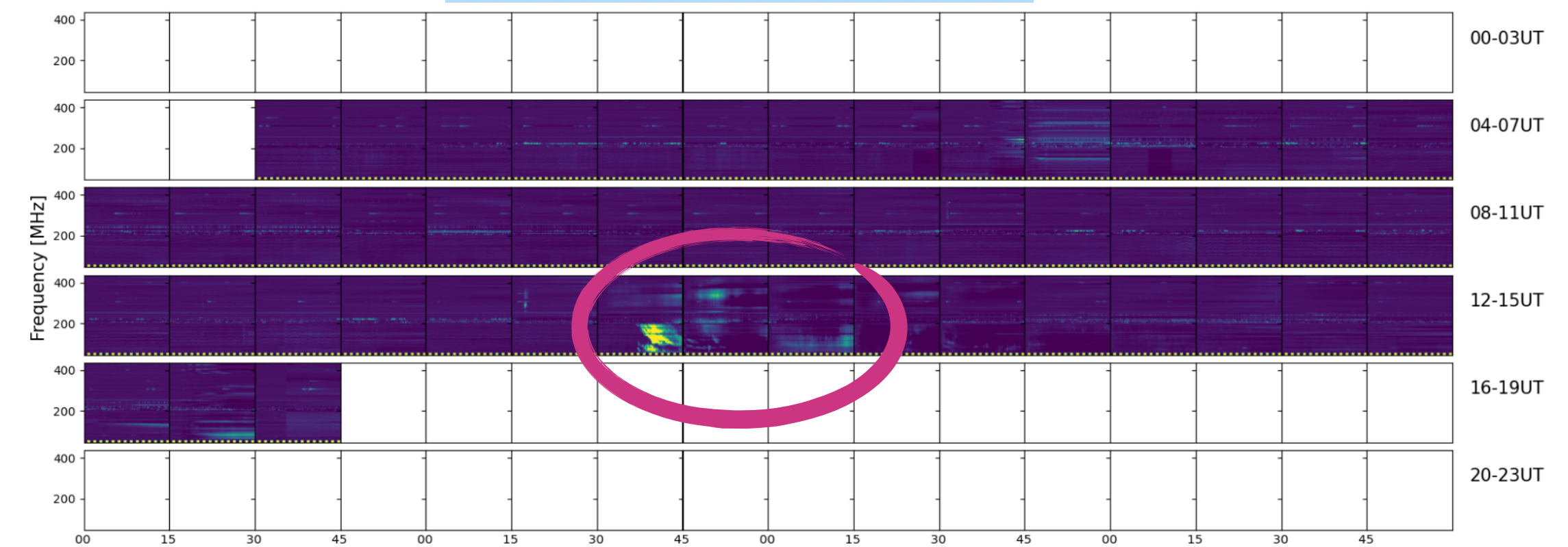
LF Spectrogram



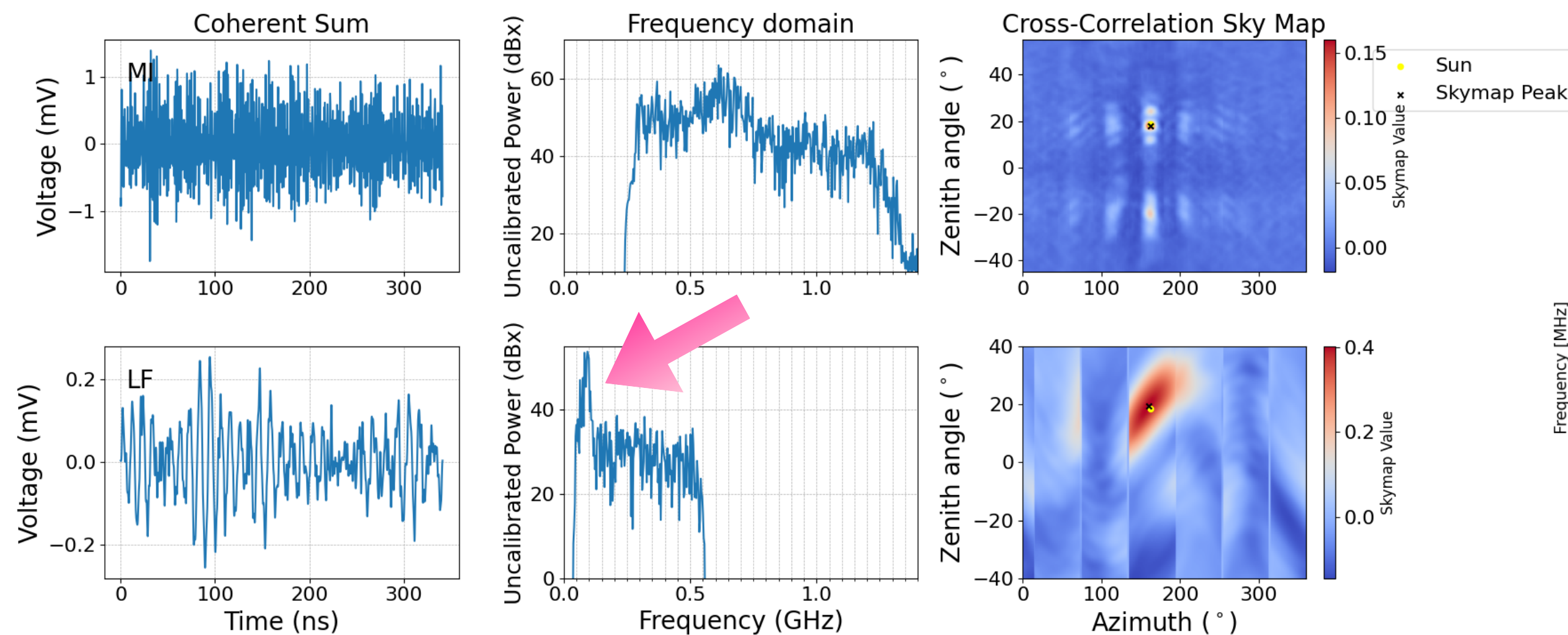
Yuchieh Ku



HUMAIN observatory

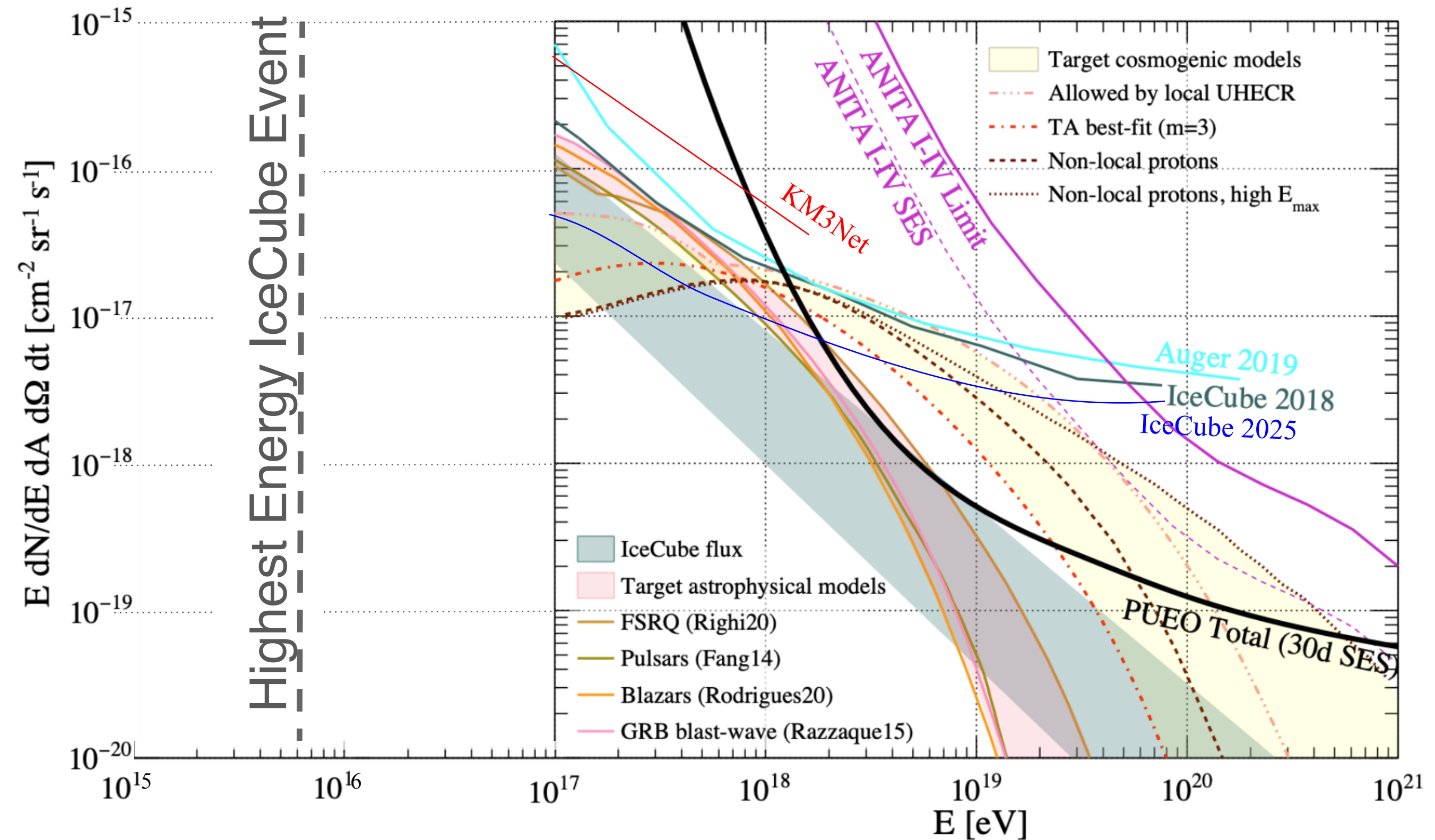


Run 1089, Entry 113895 (Soft Trg, solar burst)



Science Opportunities

- Sensitive to the flux of neutrinos at the end of the neutrino spectrum
- Addresses questions about the nature of cosmic ray accelerators of the highest energy particles >EeV neutrinos
- Analyses underway:
 - Diffuse neutrino search
 - Point source searches
 - Air shower searches

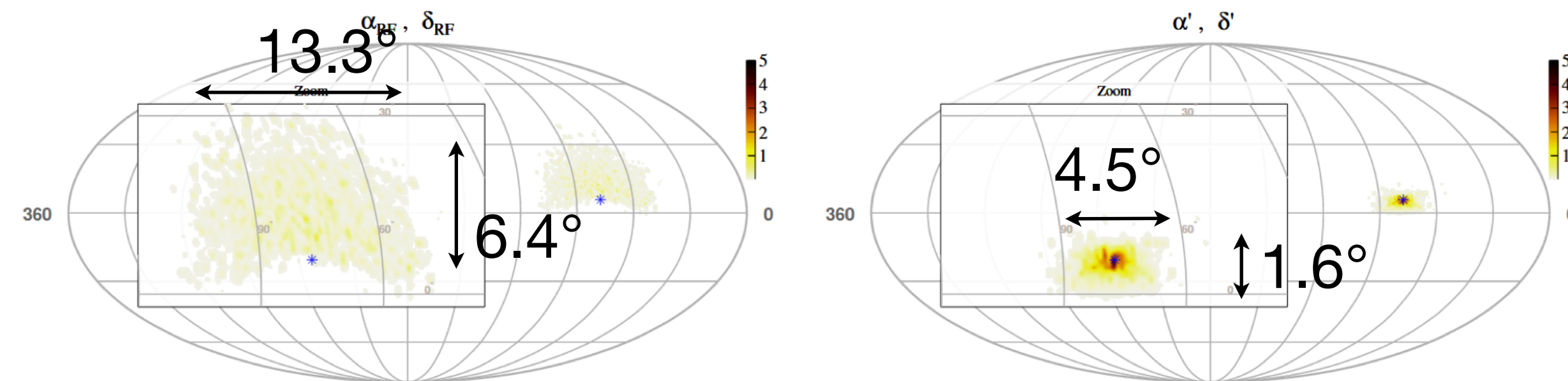


IceCube Collaboration. "Search for extremely-high-energy neutrinos and first constraints on the ultrahigh-energy cosmic-ray proton fraction with IceCube."
 The KM3NeT Collaboration "Observation of an ultra-high-energy cosmic neutrino with KM3NeT"

Point Source Searches

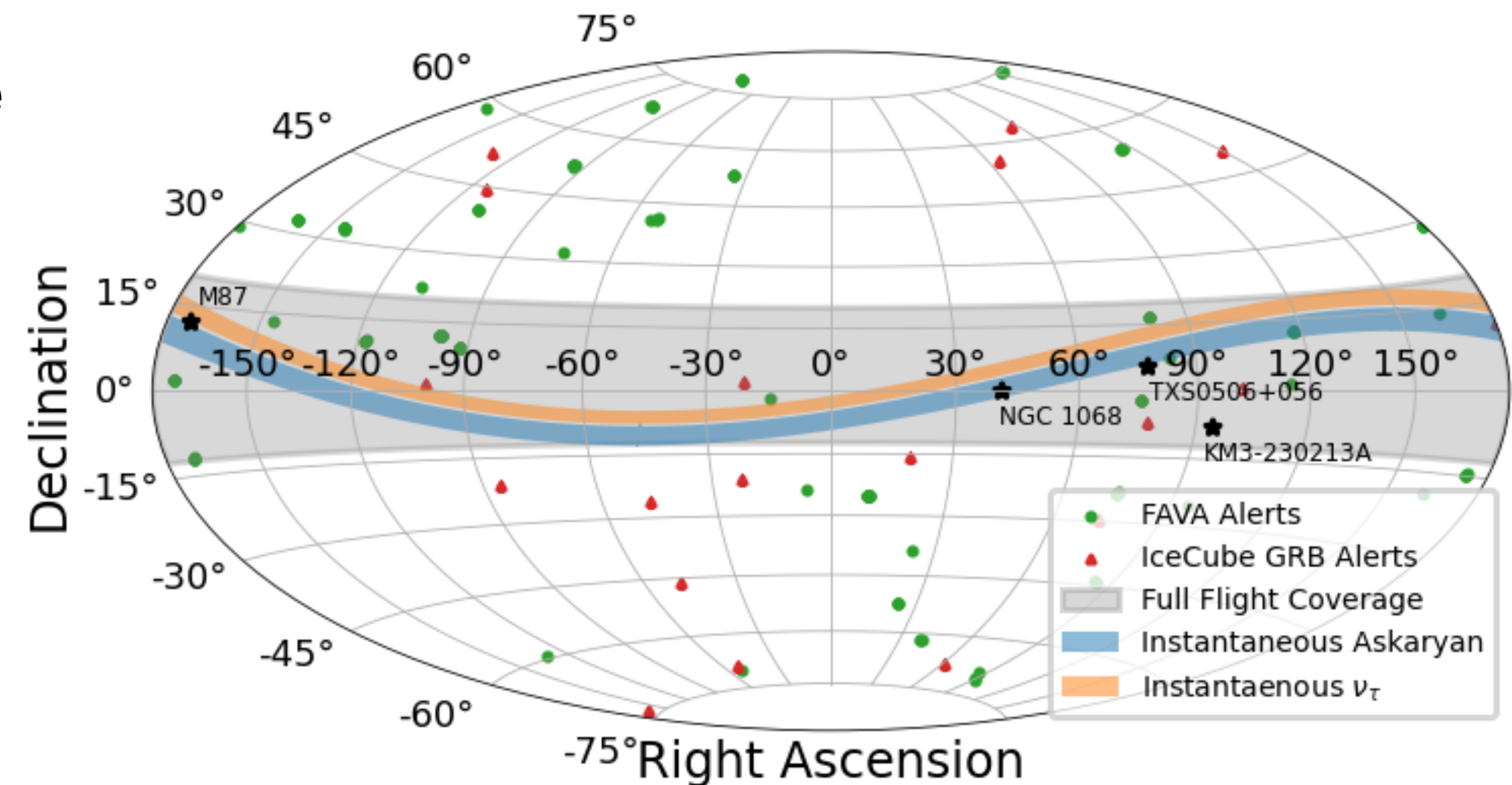
- Point source search can reduce backgrounds and lower thresholds in the direction of the sources [expect
- Catalog of Fermi Fermi All-Sky Variable Analysis events, IceCube GRBWeb, AGN, KM3NeT 220 PeV event, IceCube sources, optical transients being compiled
- Considering transients up to 100 days prior to the flight and searching across the entire flight
- No reported BNS mergers during flight [LVK not operating]

Arrival Direction Reconstruction (ANITA)



Mapping the RF direction of neutrinos from a source creates a banana shape, while reconstructing the neutrino trajectory constrains it to a smaller area. Figure: ANITA-III Source Search.

Point Sources in FoV during Flight



Air Shower Searches

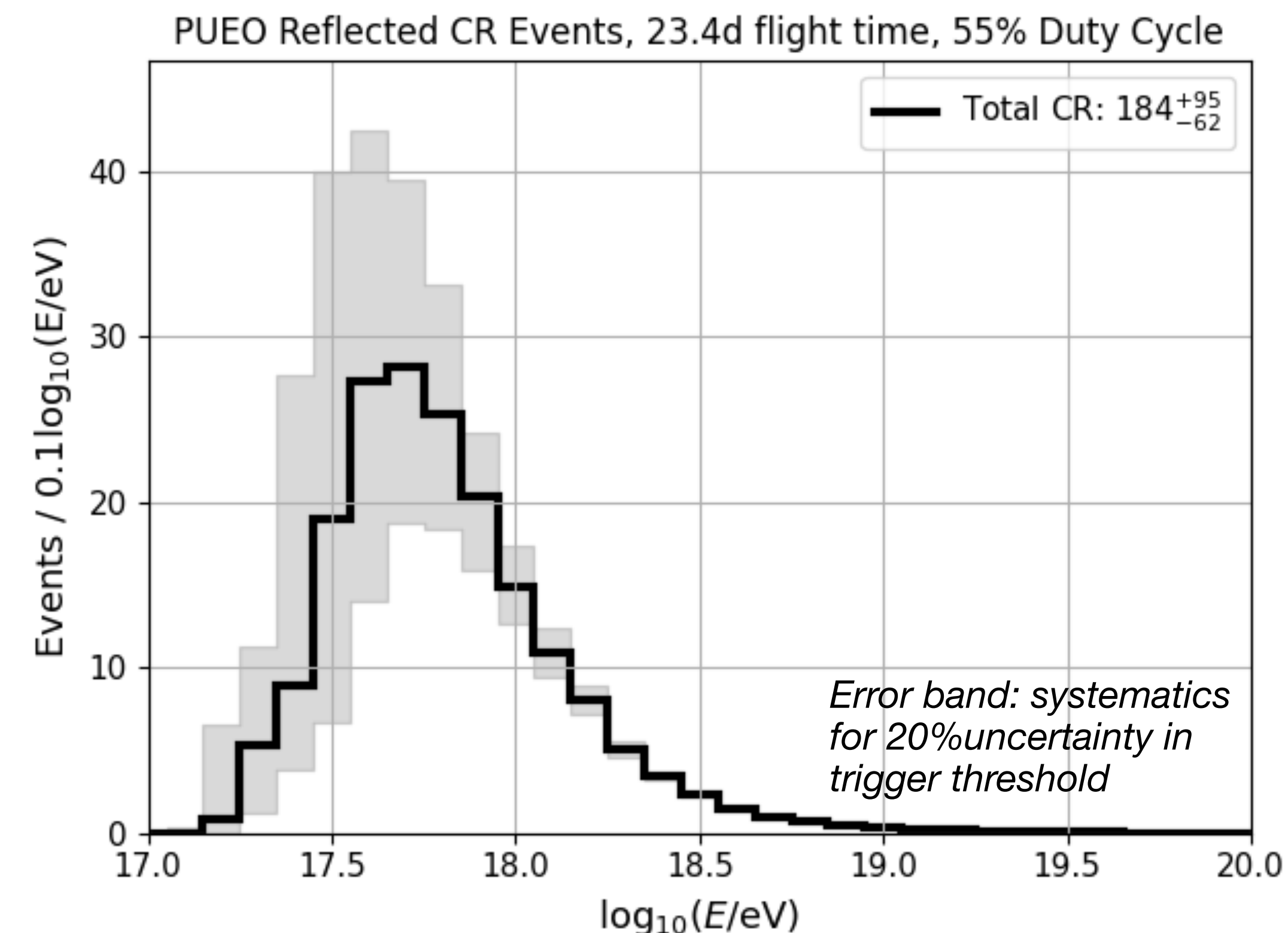
Reflected, Direct/Stratospheric, ν_τ



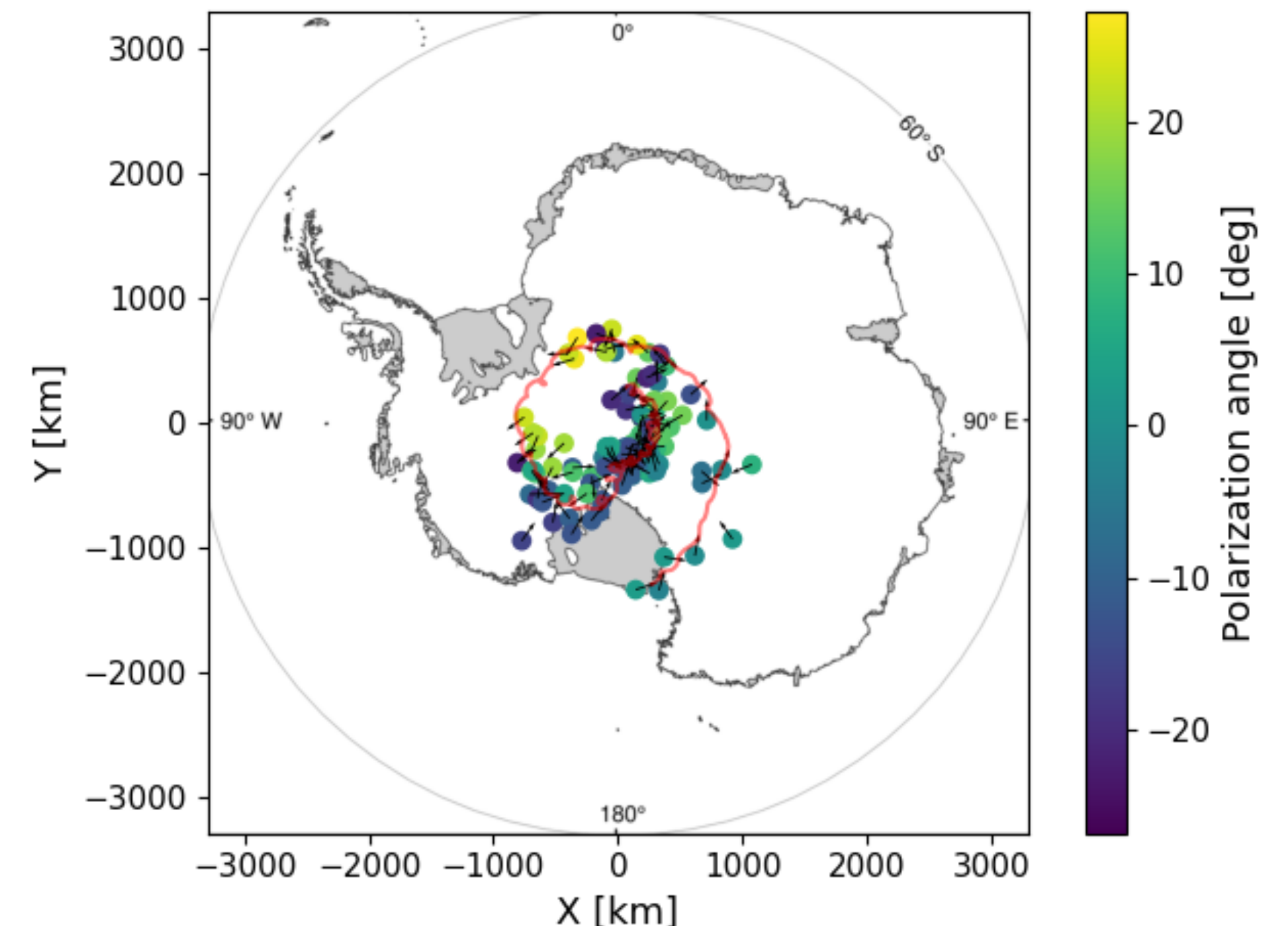
Austin Cummings

- PUEO expects to detect ~200 cosmic ray events during its flight
- Multiple observations with the MI and LF of the spectra, polarization, polarity to classify into reflected, direct, Earth-skimming tau neutrinos

Expected reflected CR air showers



Modeled triggered reflected CR Sims Polarization angle



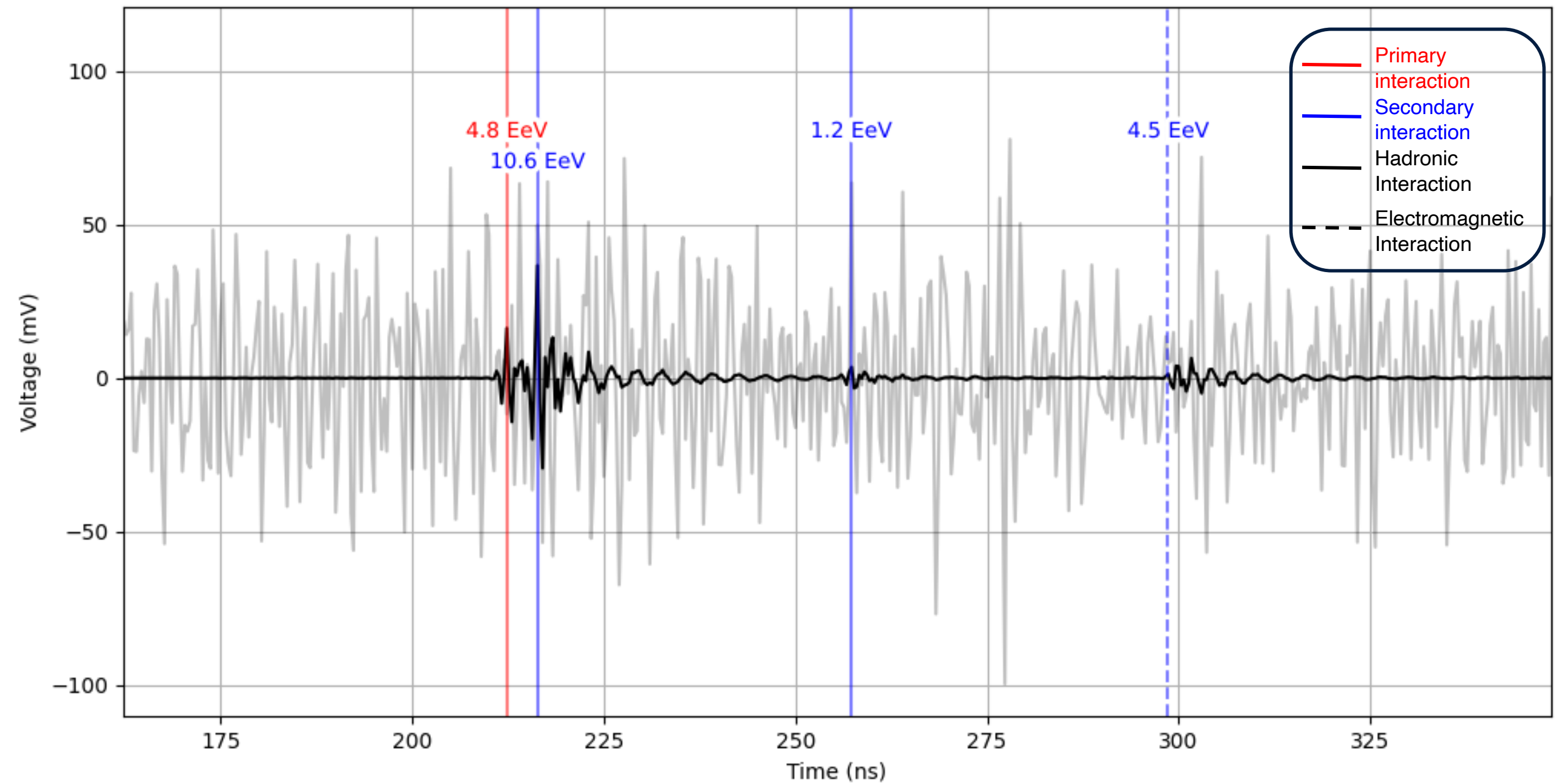
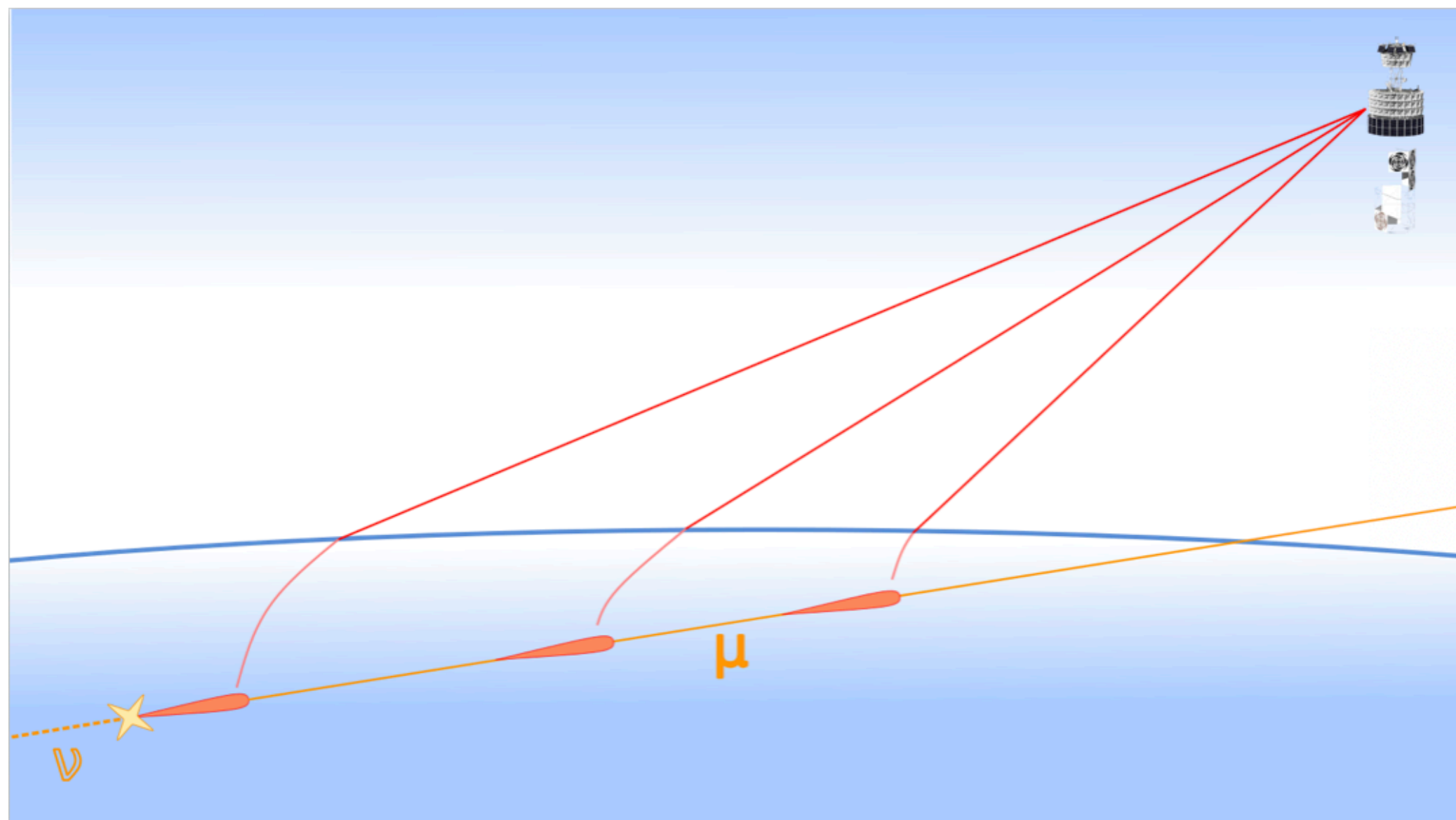
Flavor Physics with PUEO

ν_μ, ν_τ Secondary showers

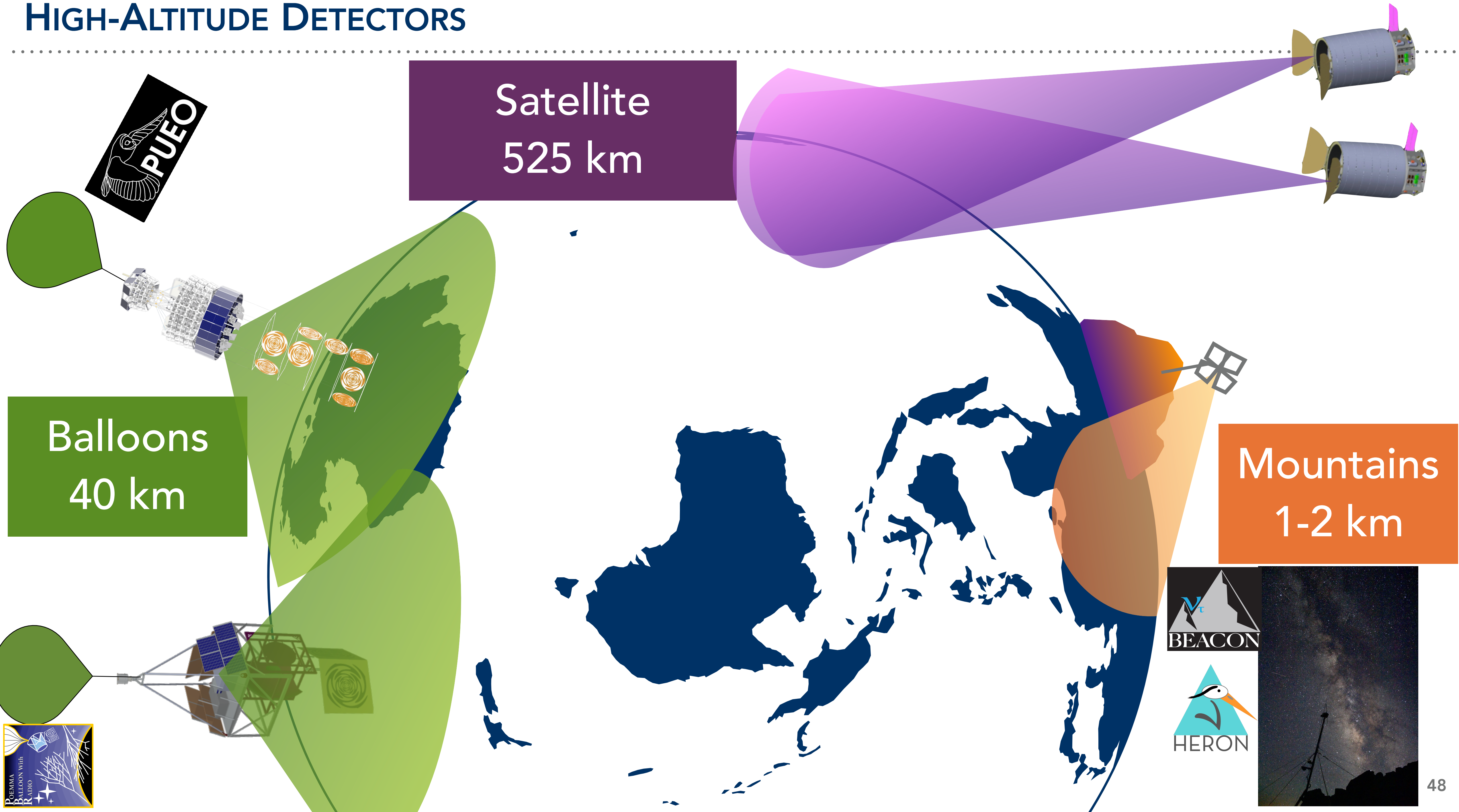


Christoph Welling Austin Cummings

Multiple showers may be observable *in the same window* with PUEO



HIGH-ALTITUDE DETECTORS



NEUTRINO FLAVOR

Learn about the Sources from Flavor Ratios

- At the sources, we expect only ν_e and/or ν_μ

$$p + \gamma \rightarrow \pi^+ + n \begin{cases} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \end{cases}$$

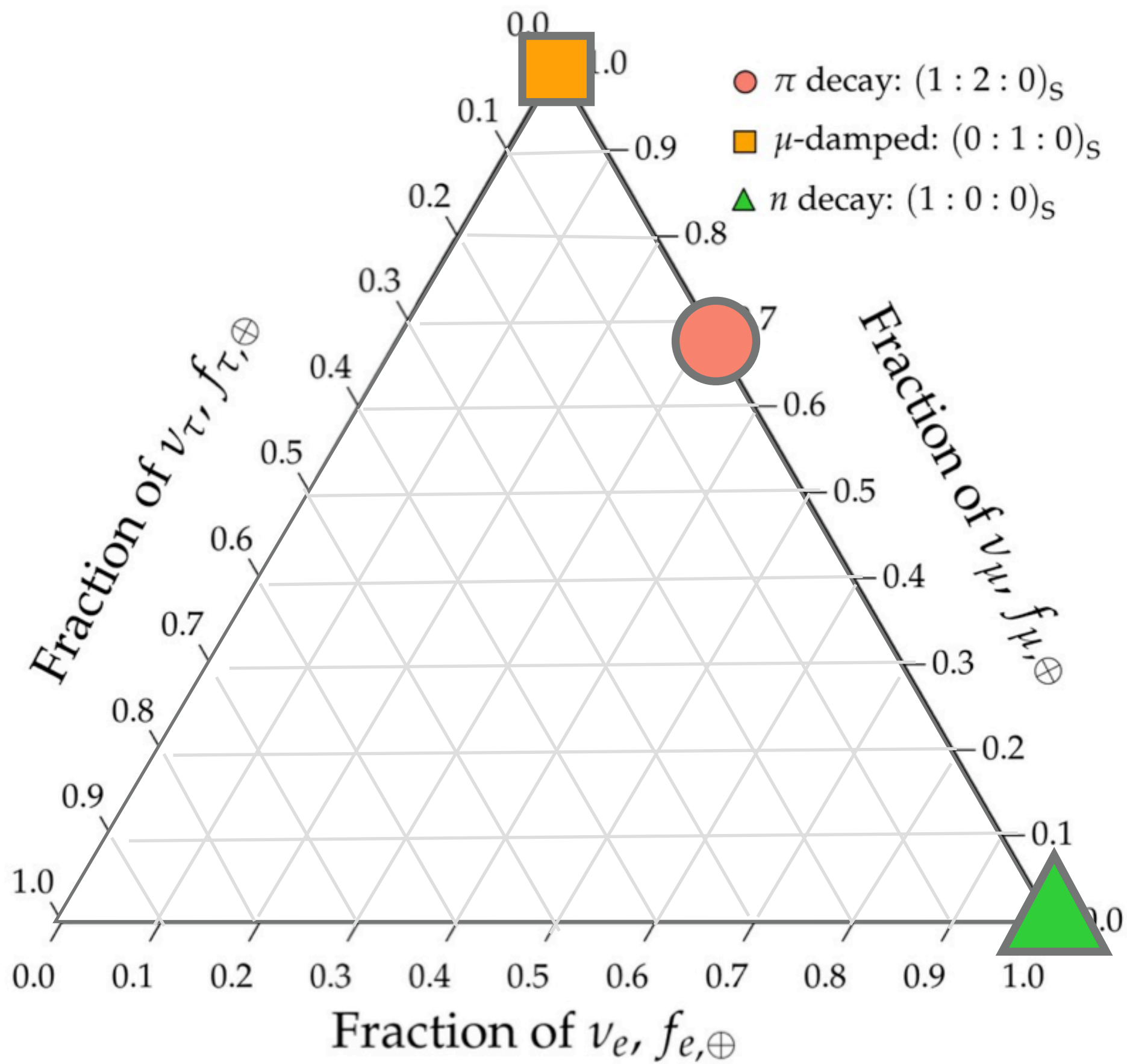
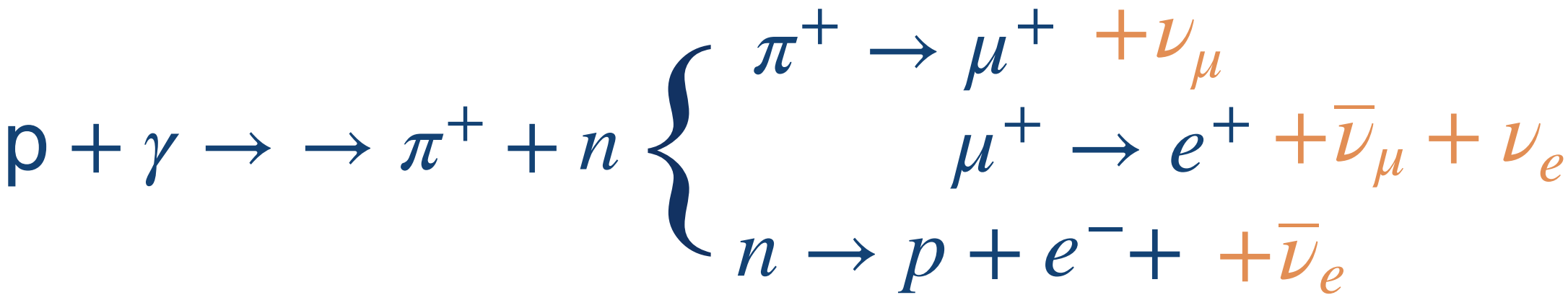
NEUTRINO FLAVOR

**Deviations from standard flavor ratios expected from Beyond-Standard-Model scenarios*

e.g. Song, et al JCAP 2021

Learn about the Sources from Flavor Ratios

➤ At the sources, we expect only ν_e and/or ν_μ



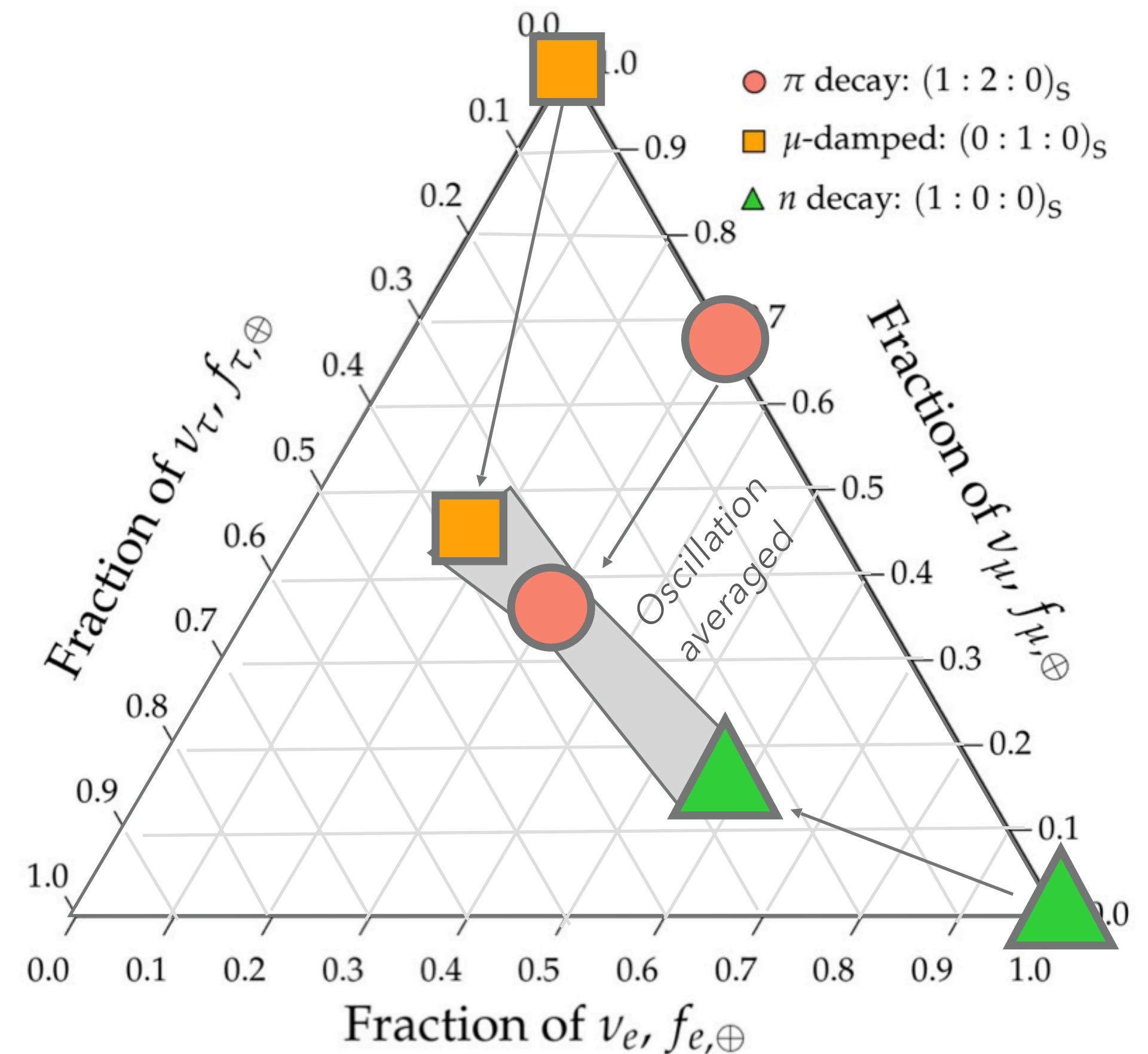
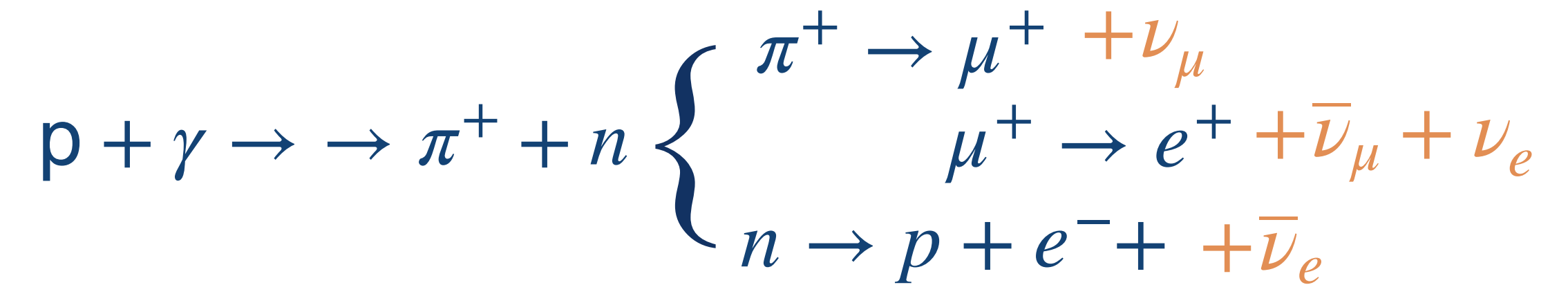
NEUTRINO FLAVOR

*Deviations from standard flavor ratios expected from Beyond-Standard-Model scenarios

e.g. Song, et al JCAP 2021

Learn about the Sources from Flavor Ratios

- At the sources, we expect only ν_e and/or ν_μ
- Even Flavor ratios $1 \nu_e : 1 \nu_\mu : 1 \nu_\tau^*$ expected due to flavor oscillations over Gpc length scales



NEUTRINO FLAVOR

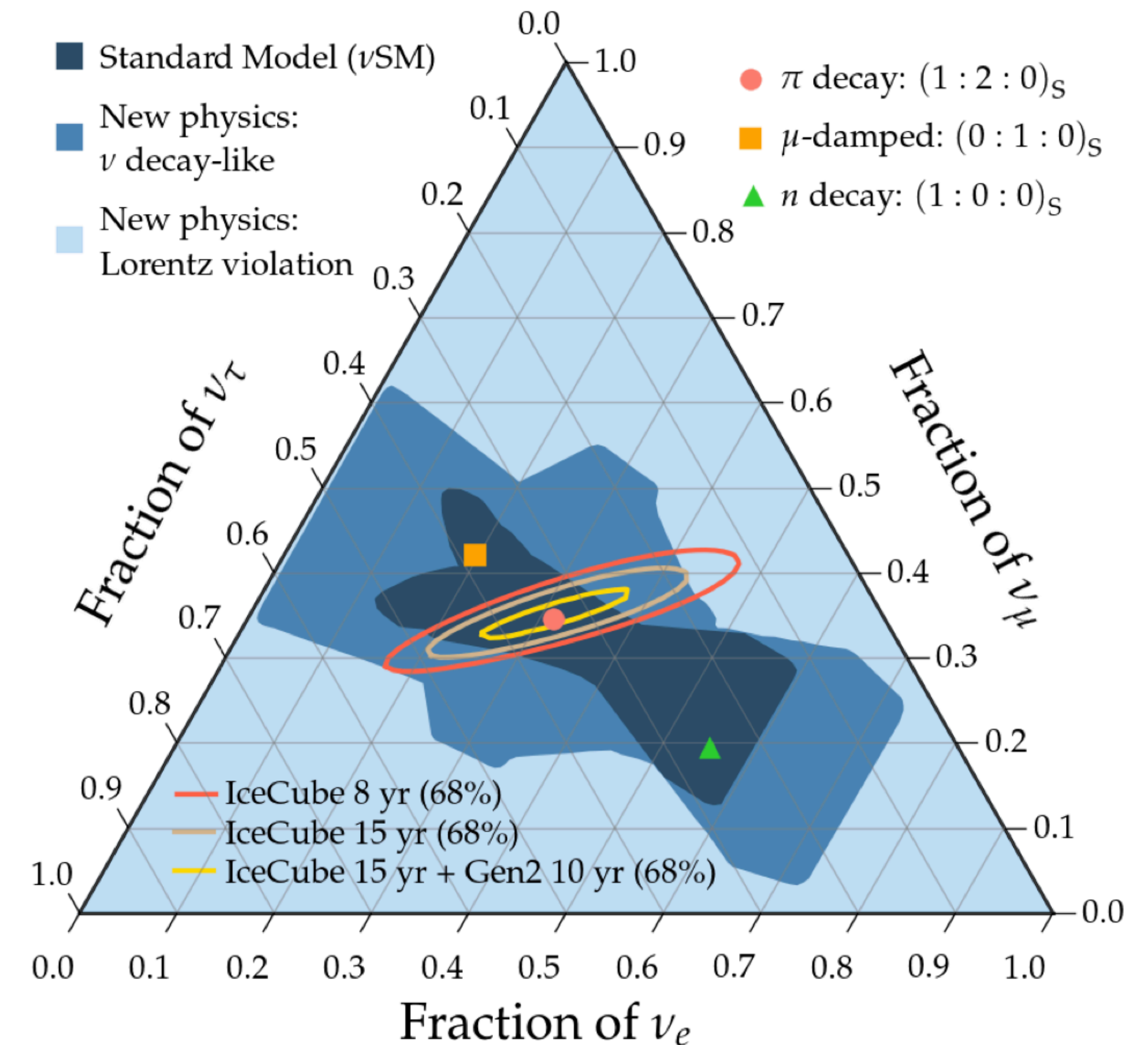
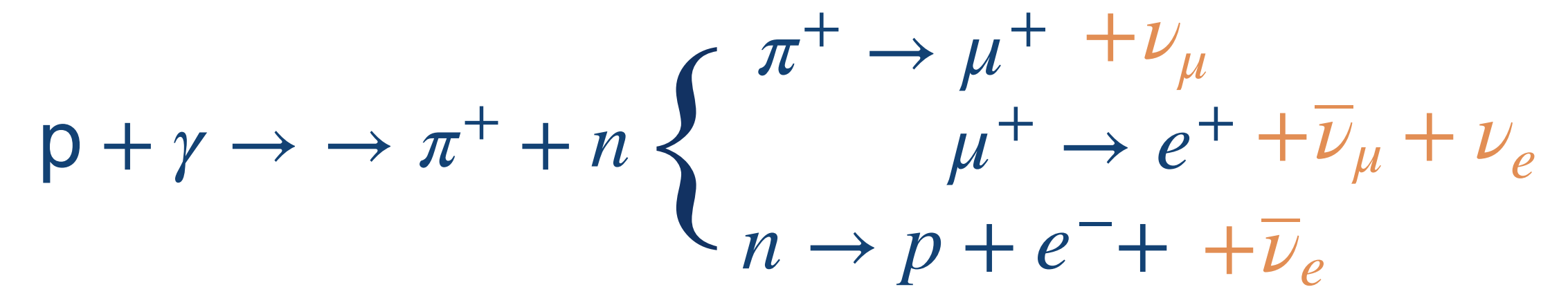
Learn about the Sources from Flavor Ratios

- At the sources, we expect only ν_e and/or ν_μ
- Even Flavor ratios $1 \nu_e : 1 \nu_\mu : 1 \nu_\tau^*$

expected due to flavor oscillations over Gpc length scales

**Deviations from standard flavor ratios expected from Beyond-Standard-Model scenarios*

e.g. Song, et al JCAP 2021



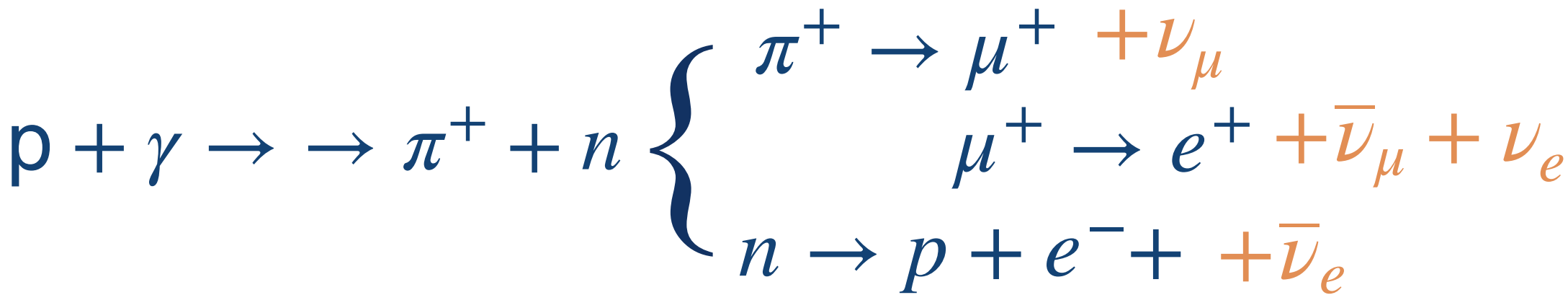
NEUTRINO FLAVOR

*Deviations from standard flavor ratios expected from Beyond-Standard-Model scenarios

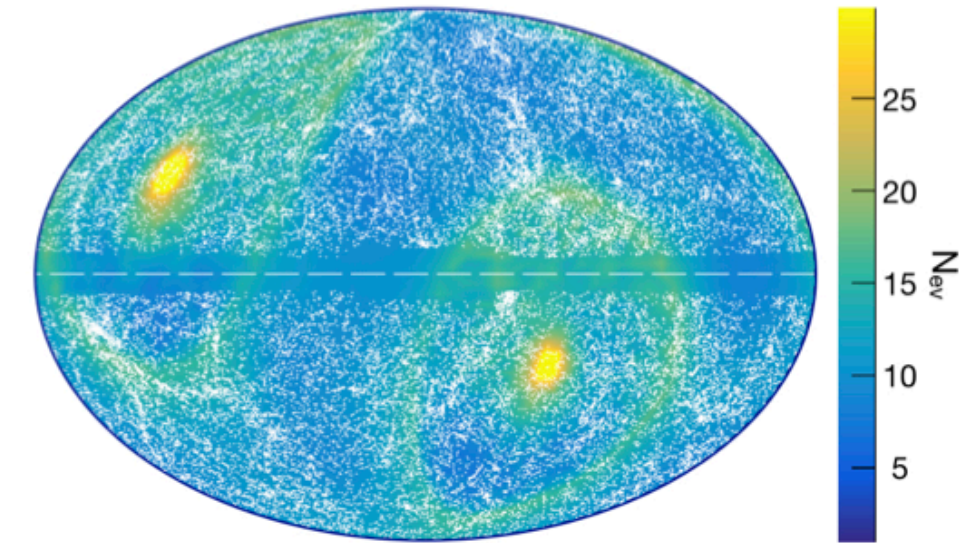
e.g. Song, et al JCAP 2021

Learn about the Sources from Flavor Ratios

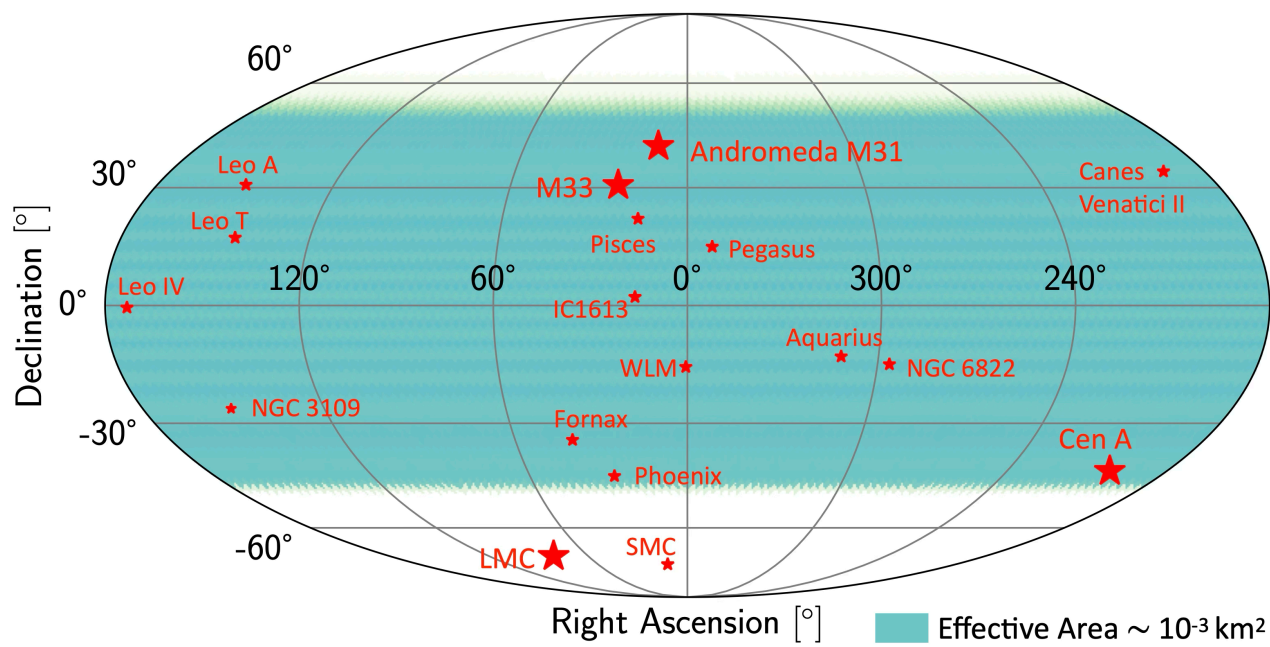
- At the sources, we expect only ν_e and/or ν_μ
- Even Flavor ratios $1 \nu_e : 1 \nu_\mu : 1 \nu_\tau$ *
expected due to flavor oscillations over Gpc length scales



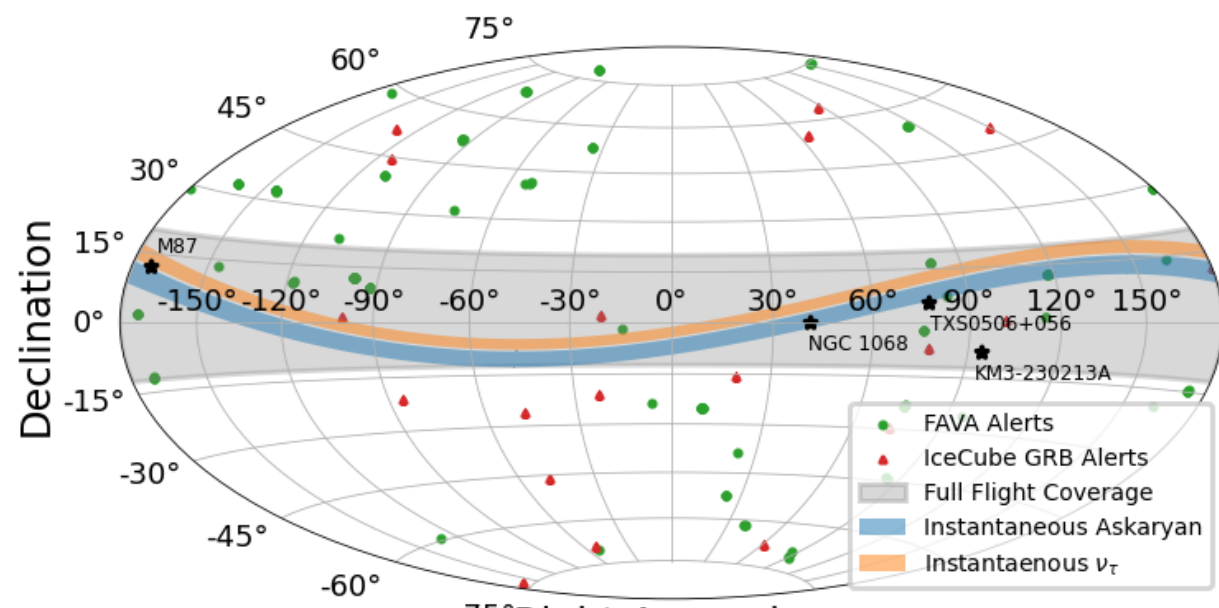
Complementary Sky Views



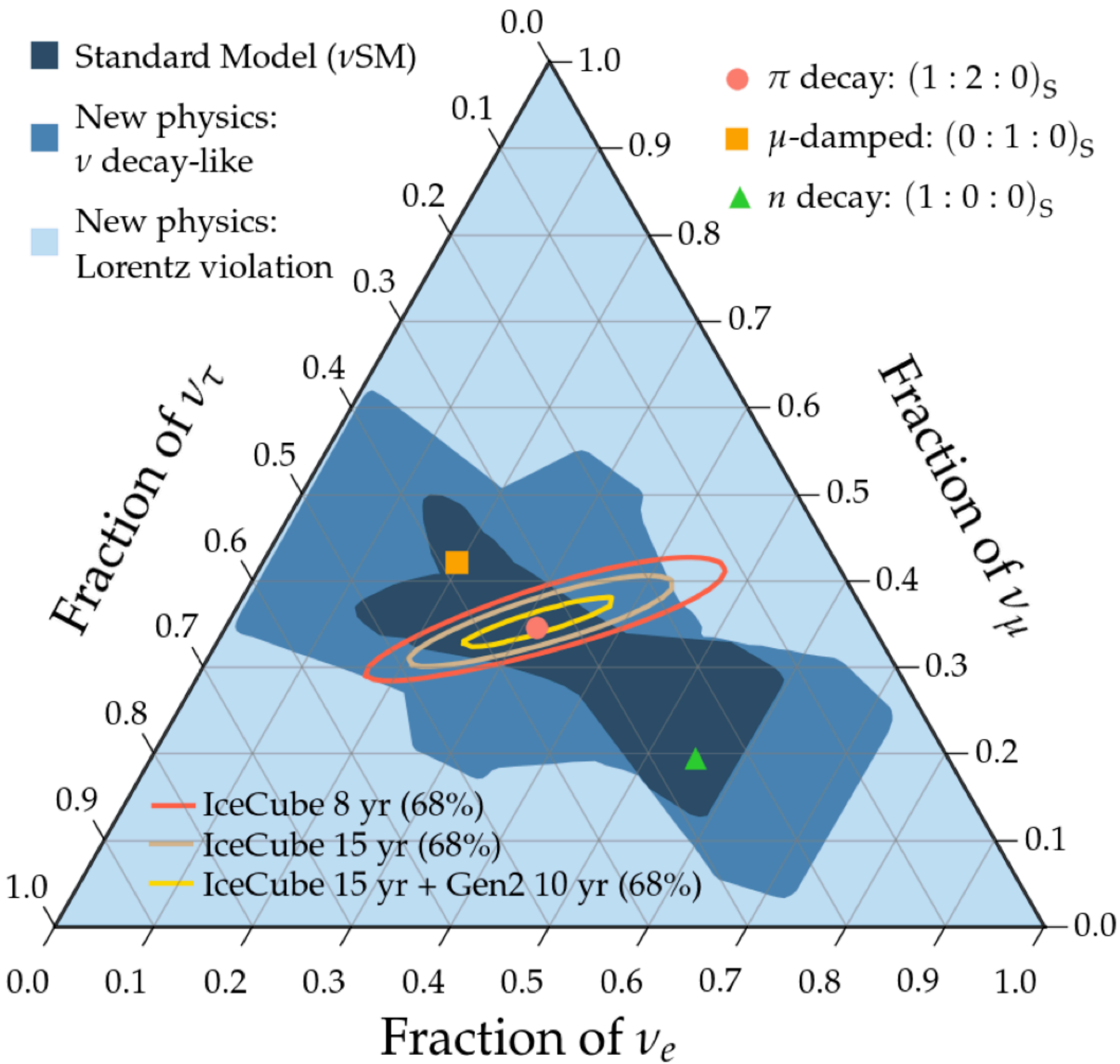
POEMMA ToO for BNS mergers at 5 Mpc, galactic coordinates



HERON FOV



PUEO FOV



Hybrid Elevated Radio Observatory for Neutrinos (HERON)



European Research Council
Established by the European Commission



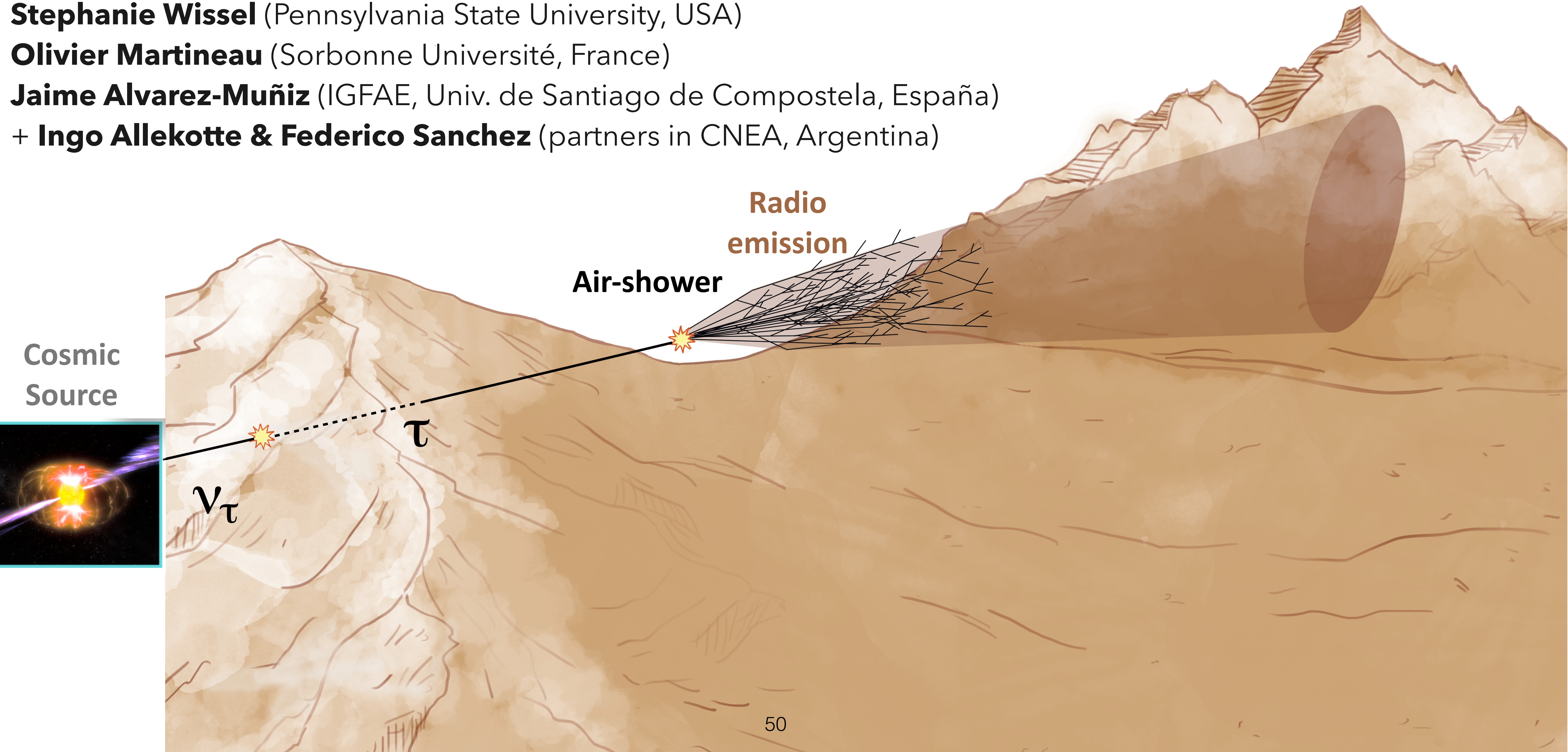
Kumiko Kotera (IAP, CNRS, France)

Stephanie Wissel (Pennsylvania State University, USA)

Olivier Martineau (Sorbonne Université, France)

Jaime Alvarez-Muñiz (IGFAE, Univ. de Santiago de Compostela, España)

+ **Ingo Allekotte & Federico Sanchez** (partners in CNEA, Argentina)



Hybrid: phased antenna arrays + standalone antennas

Elevated: altitude & large extension enable broad viewing area for ν_τ interactions

Radio Observatory: $\approx 100\%$ duty cycle, cost-efficient, robust, scalable

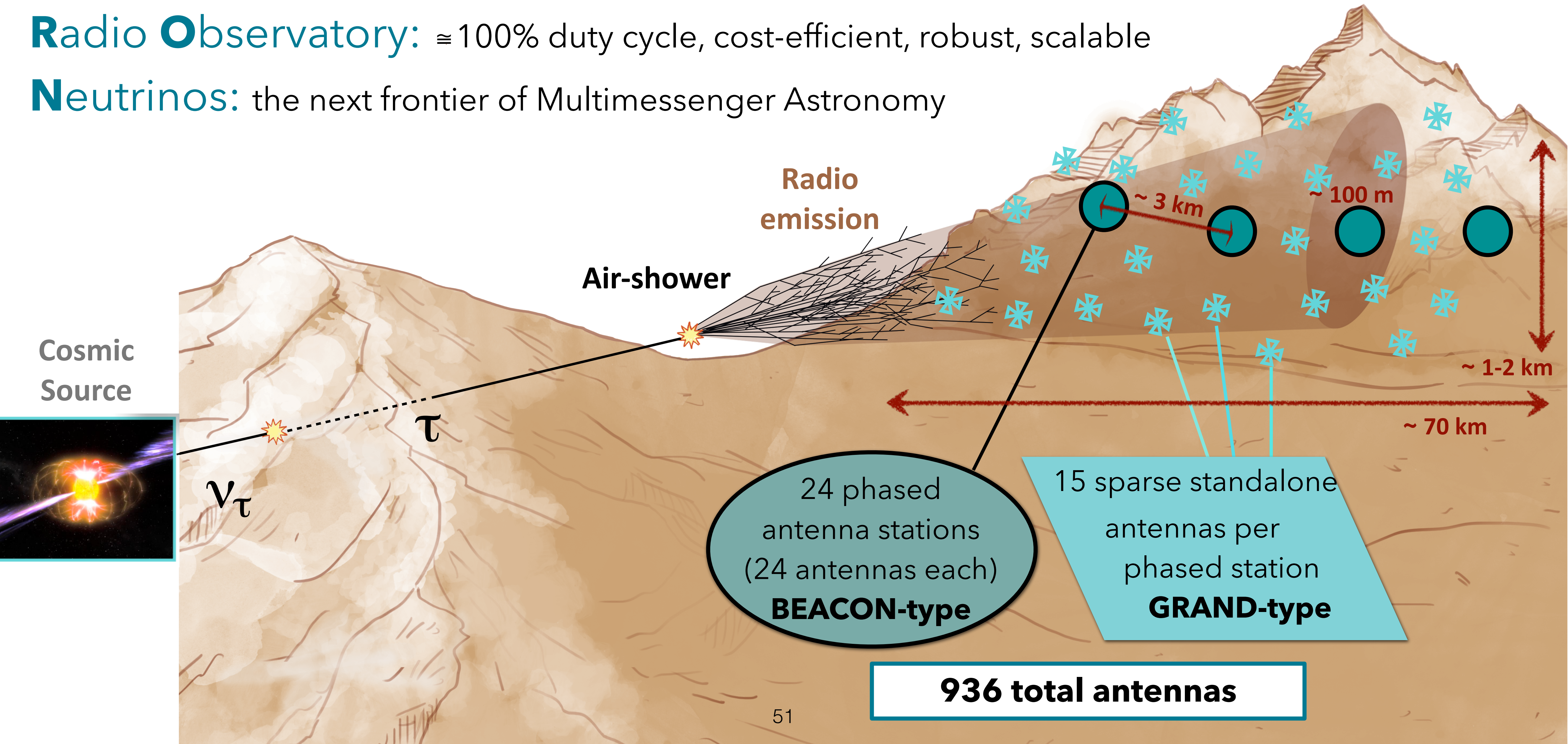
Neutrinos: the next frontier of Multimessenger Astronomy

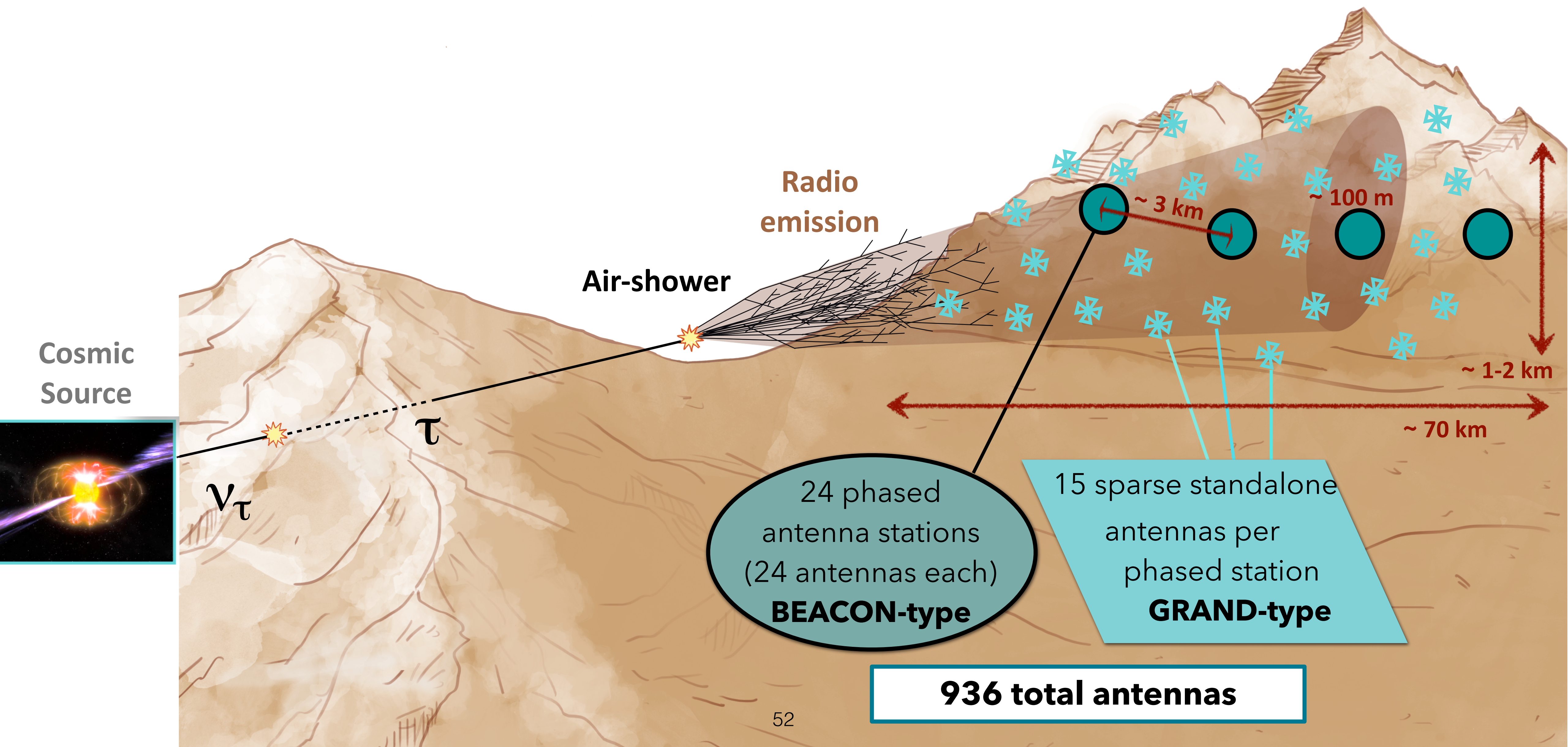


European Research Council
Established by the European Commission

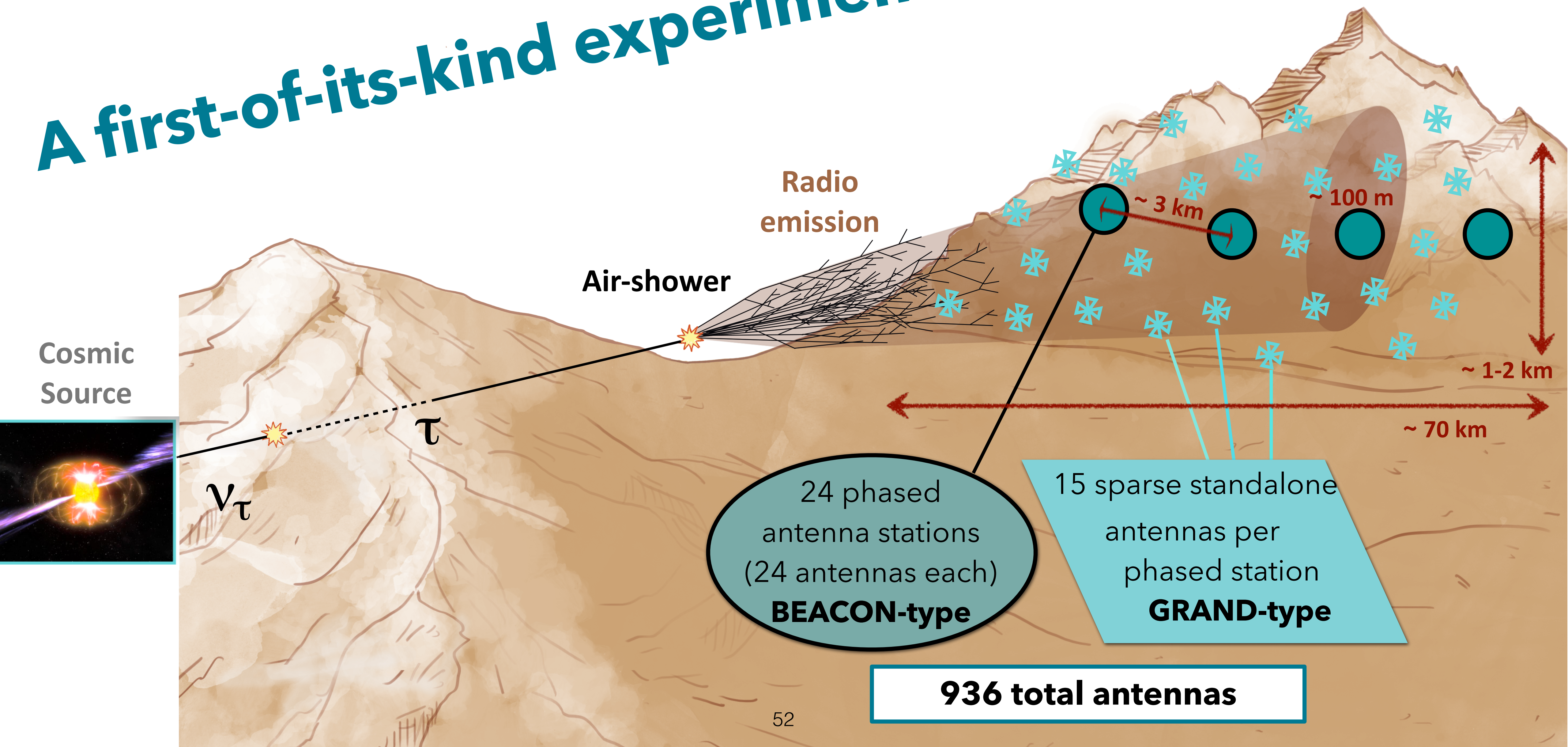


HERON

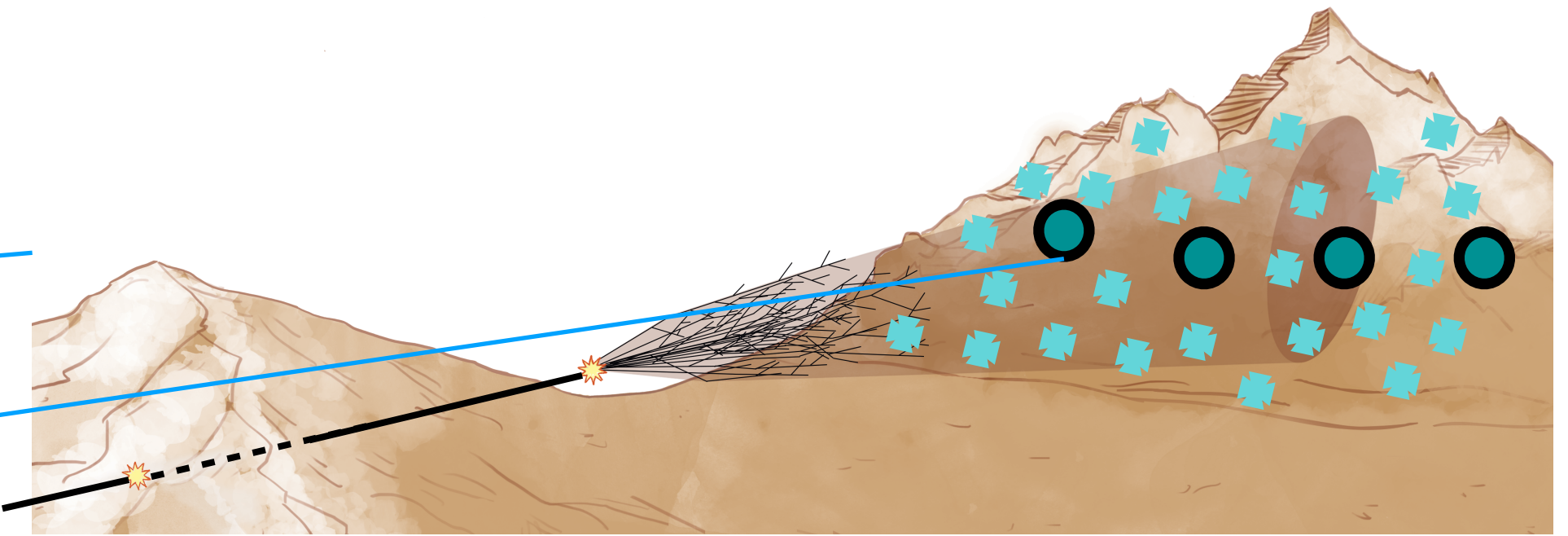
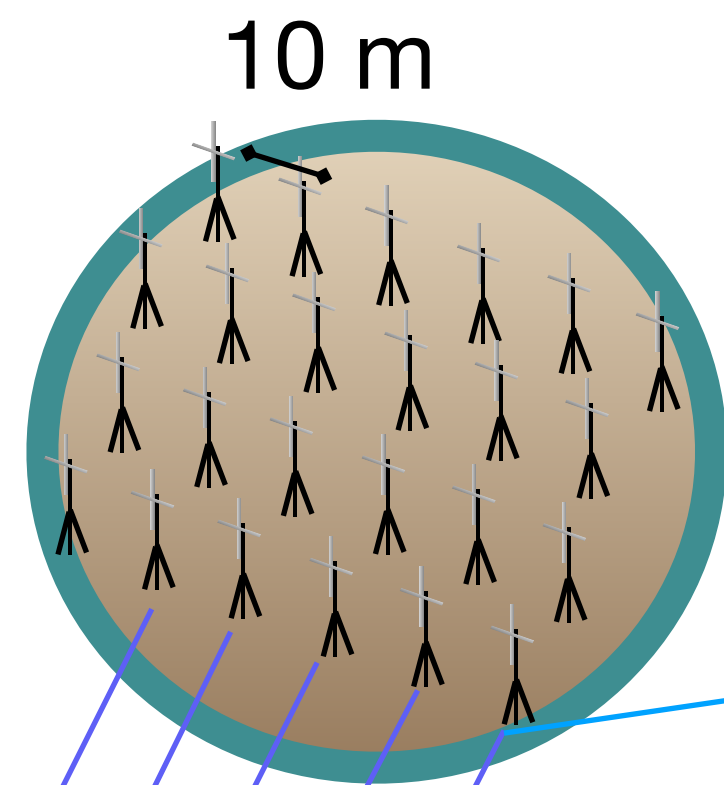




A first-of-its-kind experimental concept



HERON Phased Array Trigger



Beamforming for trigger & reconstruction of transient radio signals

On phased arrays:

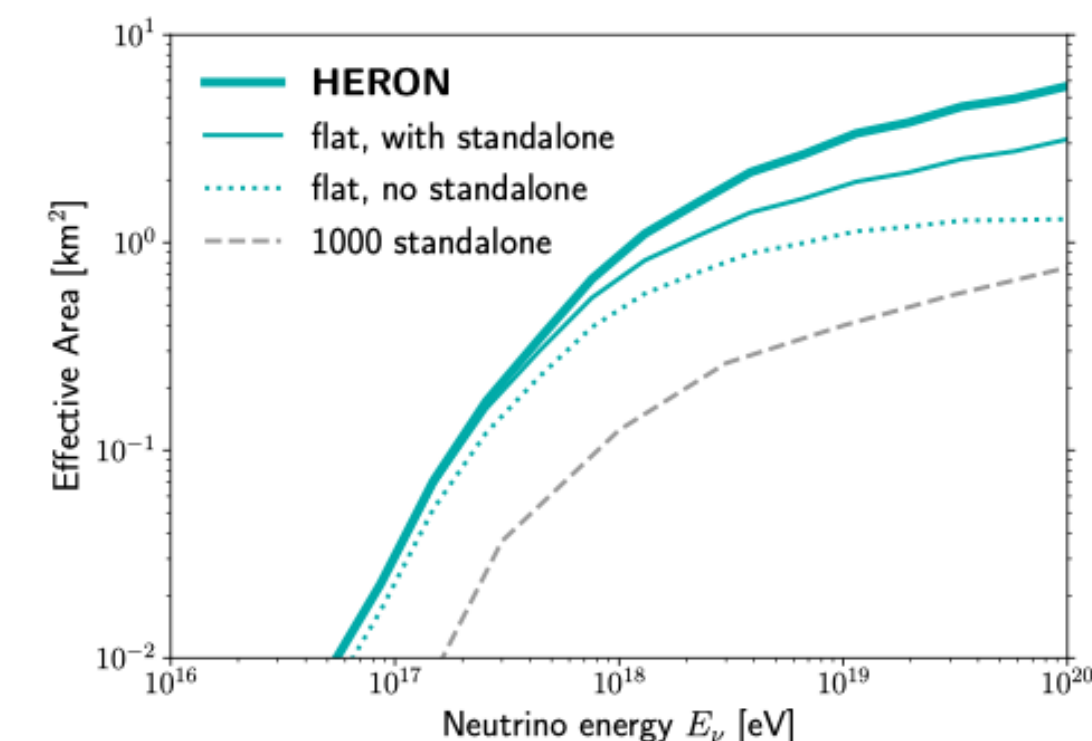
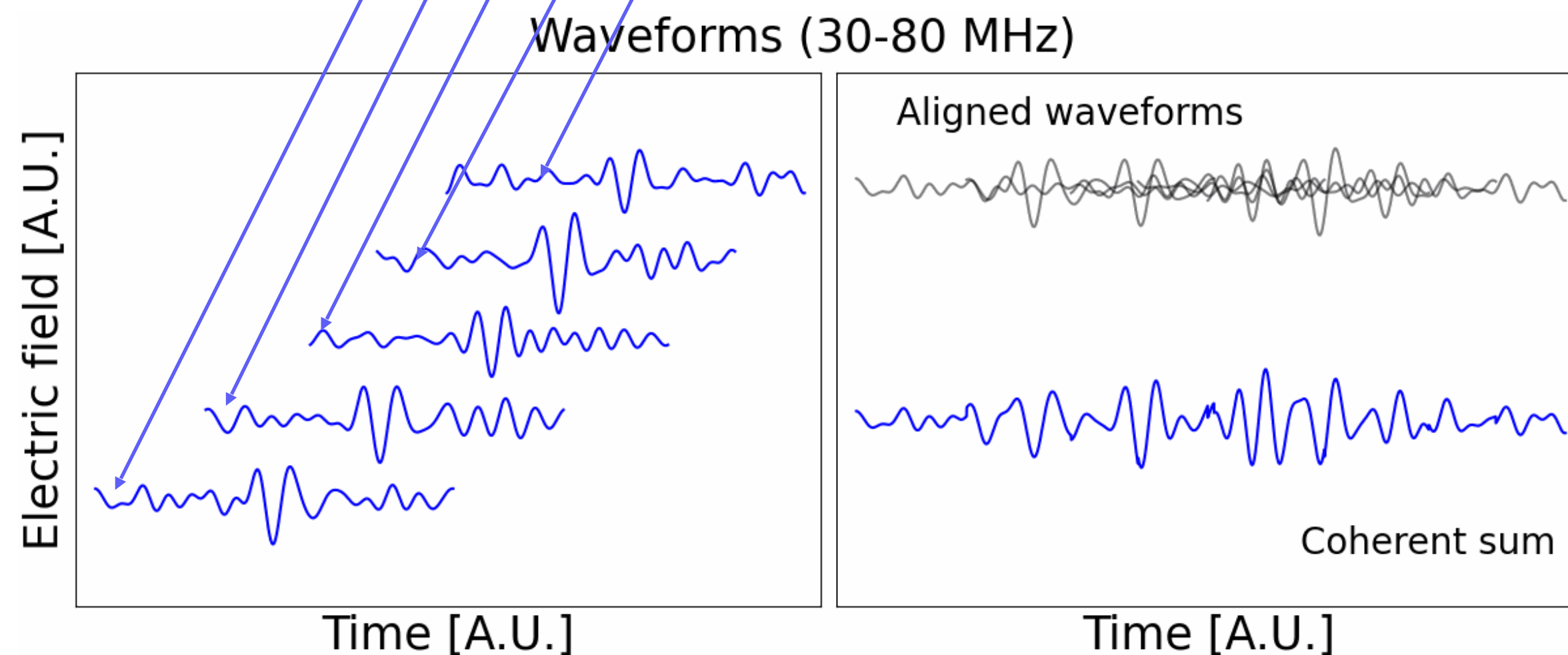
for trigger along beams

signal to noise $\sim \sqrt{N}$ ($N = 24$ antennas)

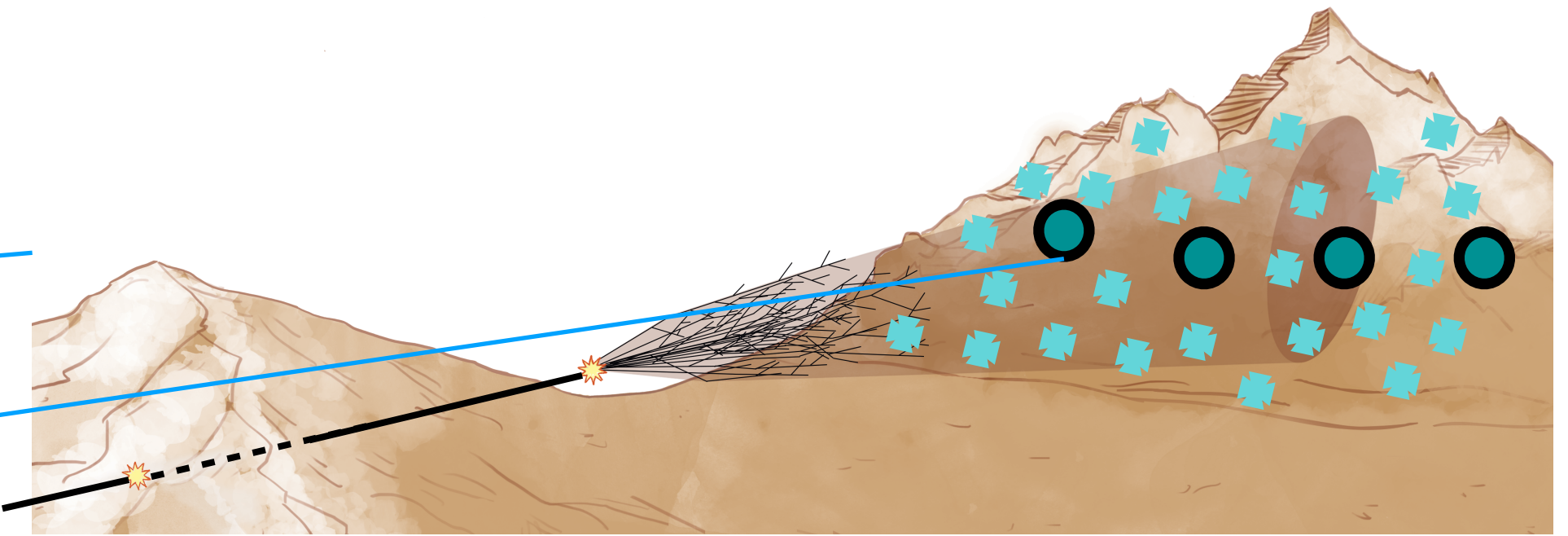
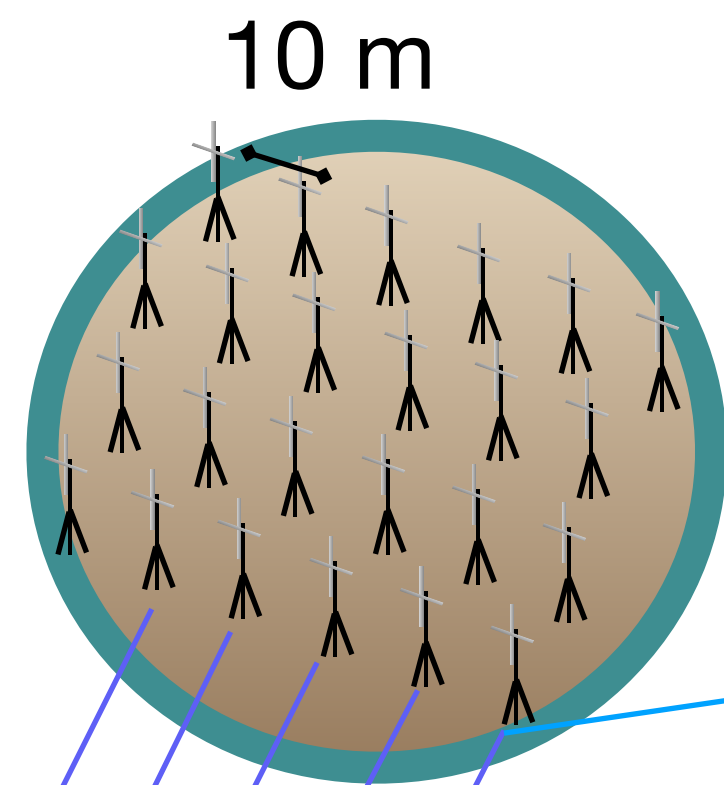
*improved threshold & effective area **x 20***

SW et al JCAP 2025

KK, JA, OM, SW, et al ICRC 2025



HERON Phased Array Trigger



Beamforming for trigger & reconstruction of transient radio signals

On phased arrays:

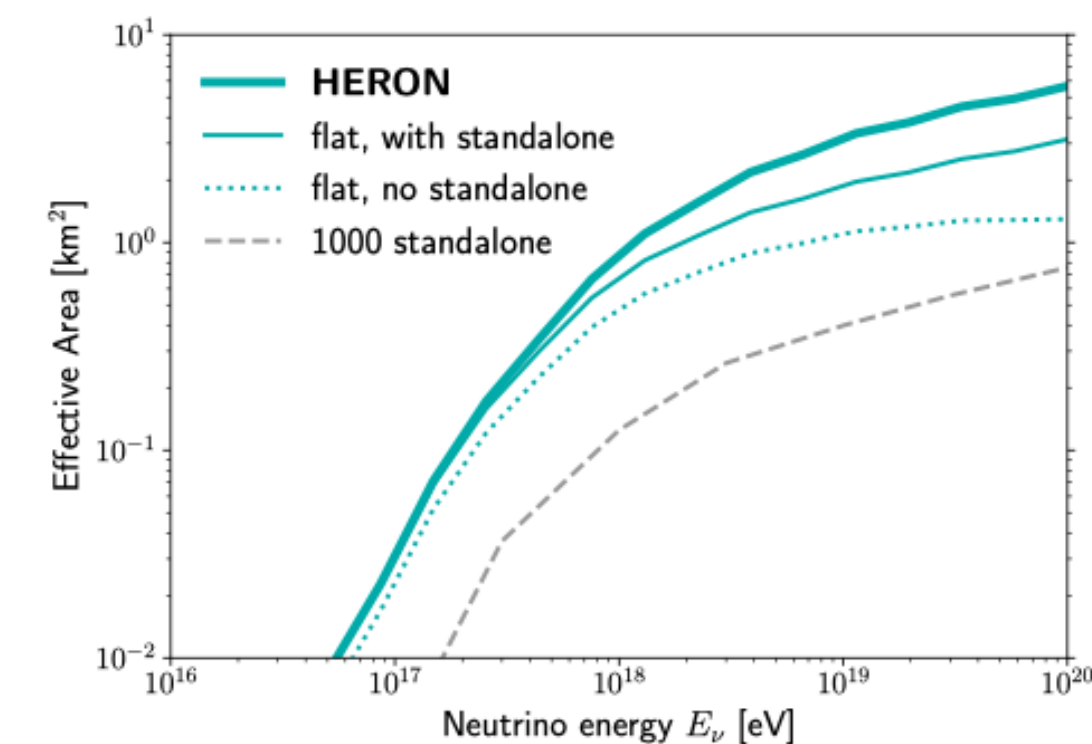
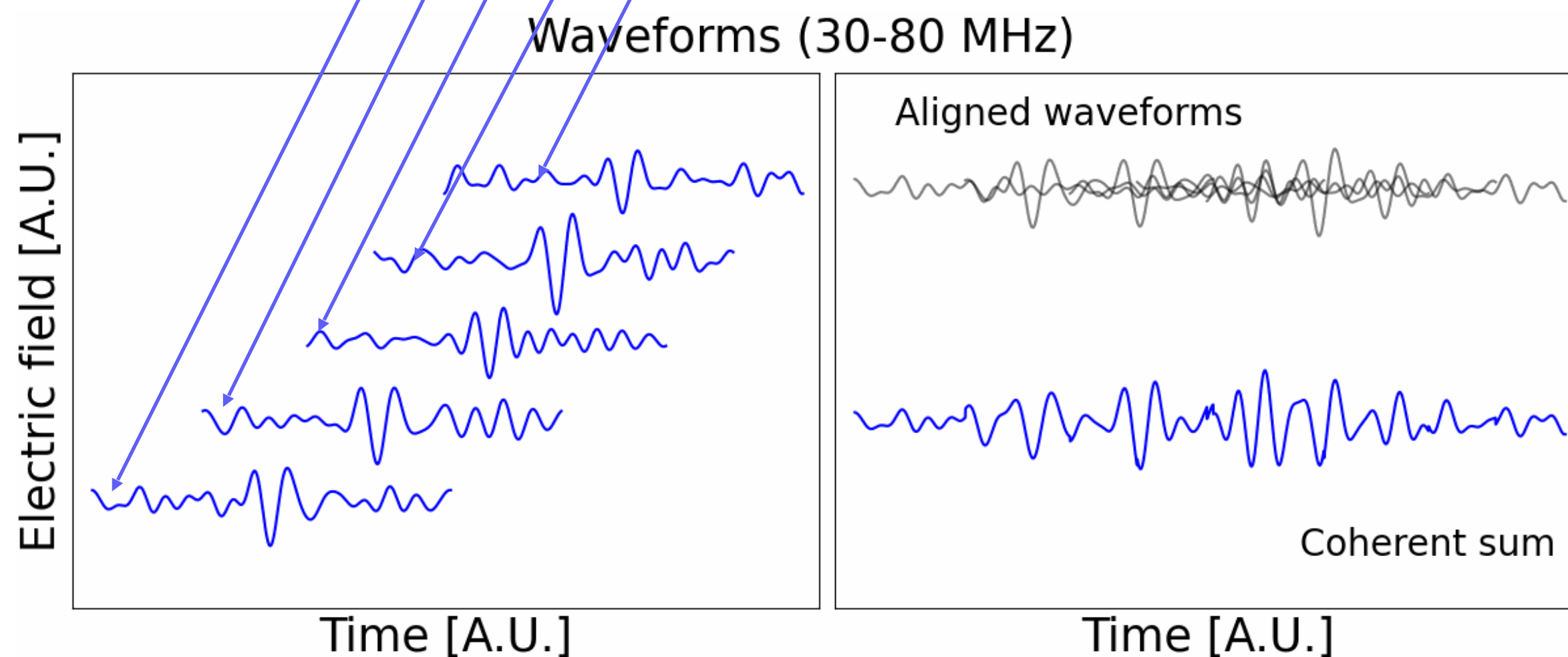
for trigger along beams

SW et al JCAP 2025

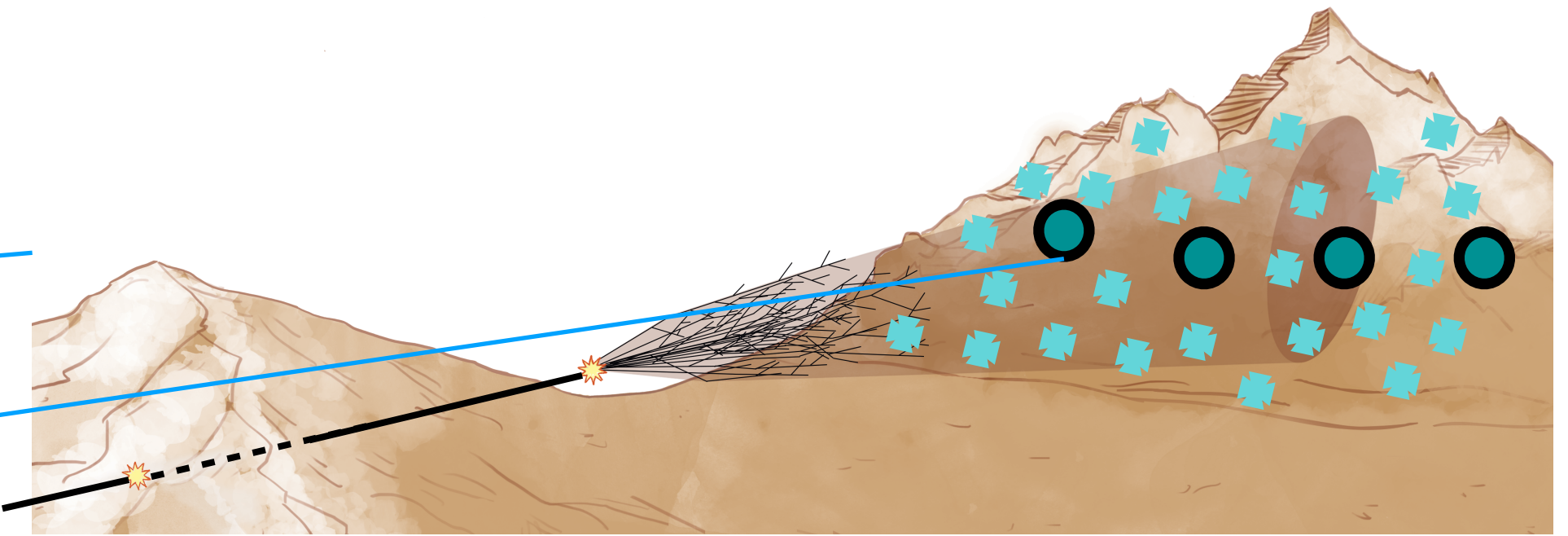
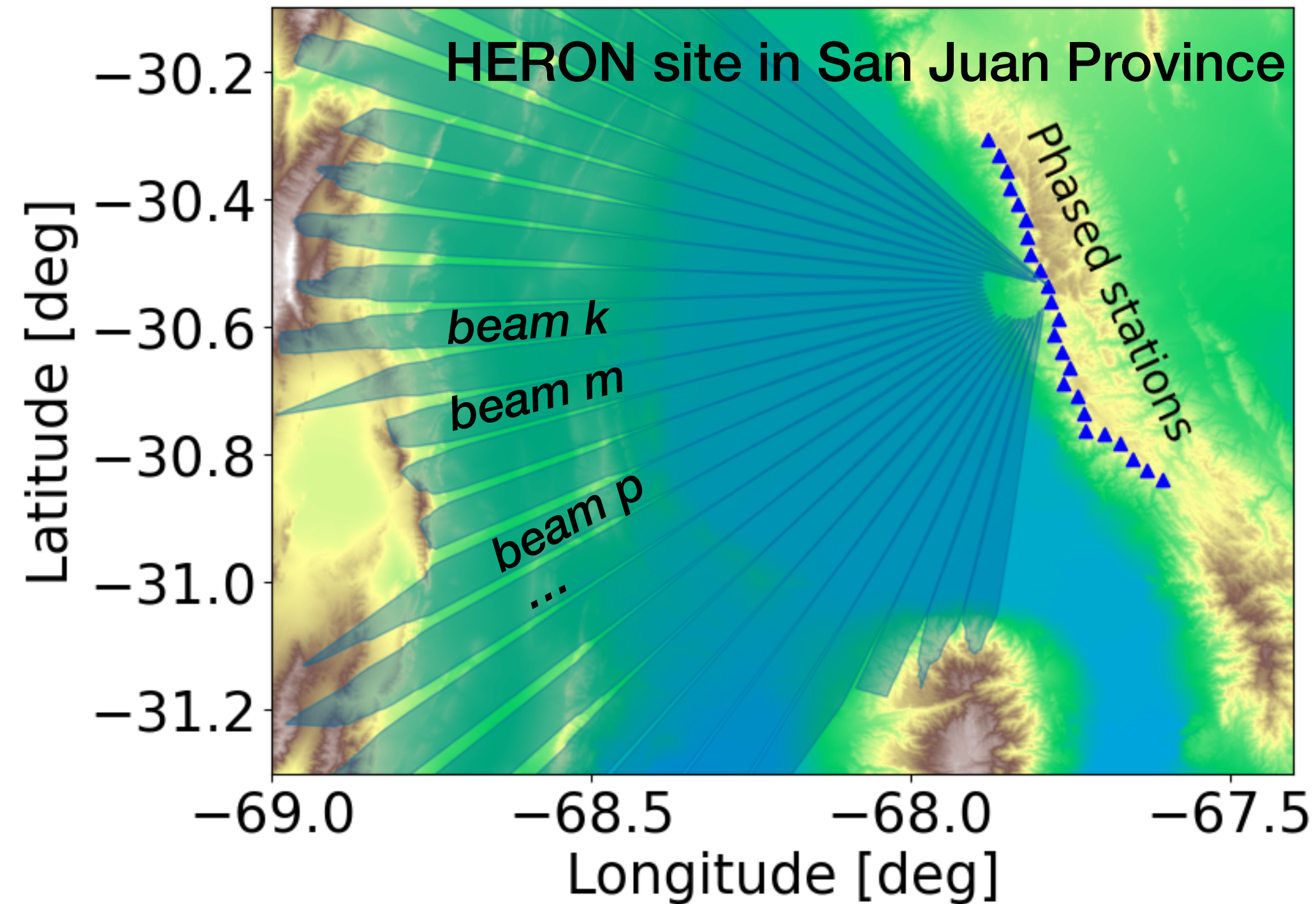
KK, JA, OM, SW, et al ICRC 2025

signal to noise $\sim \sqrt{N}$ ($N = 24$ antennas)

*improved threshold & effective area **x 20***



HERON Phased Array Trigger



Beamforming for trigger & reconstruction of transient radio signals

On phased arrays:

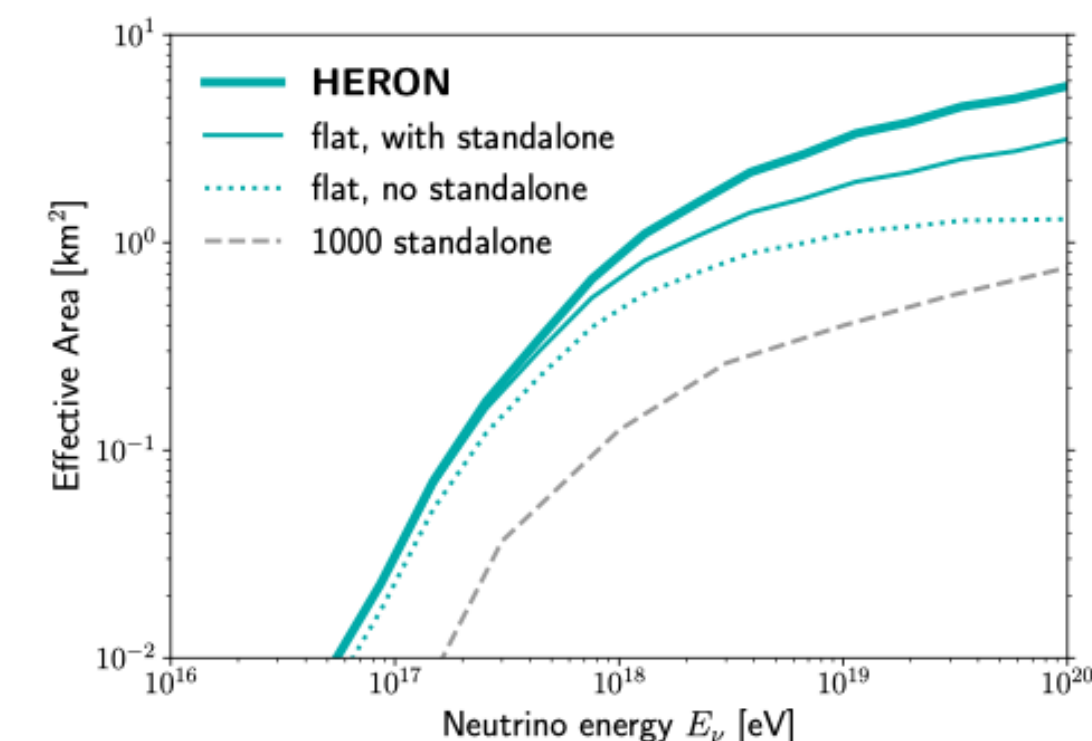
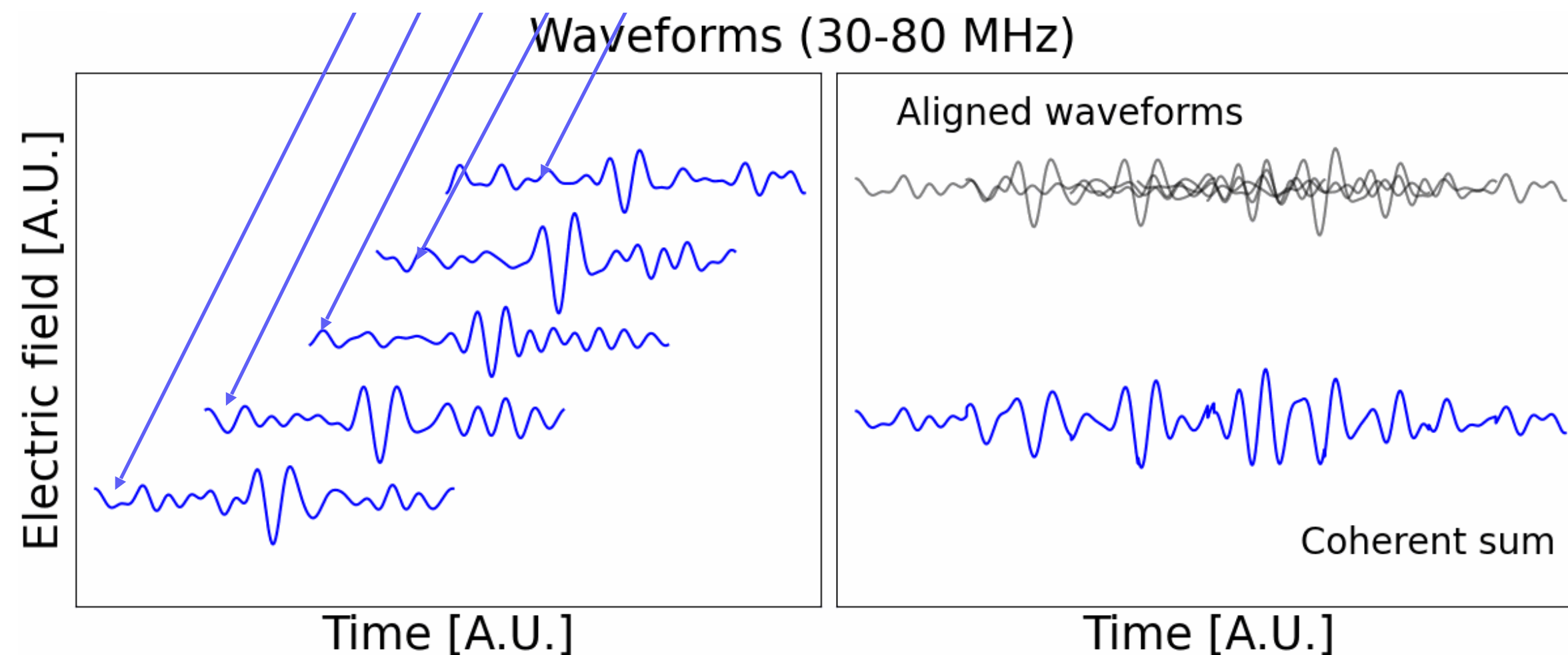
for trigger along beams

signal to noise $\sim \sqrt{N}$ ($N = 24$ antennas)

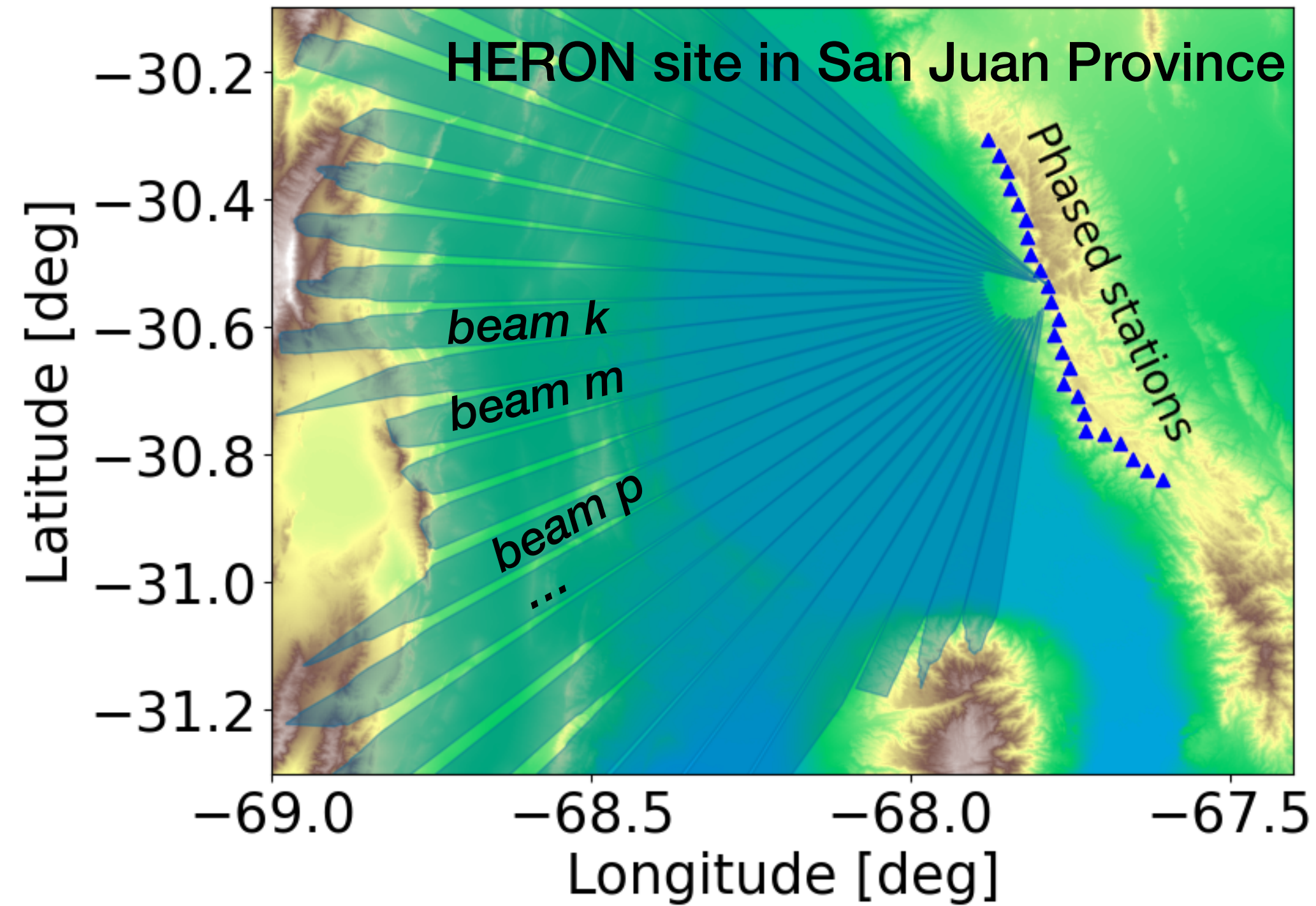
improved threshold & effective area **x 20**

SW et al JCAP 2025

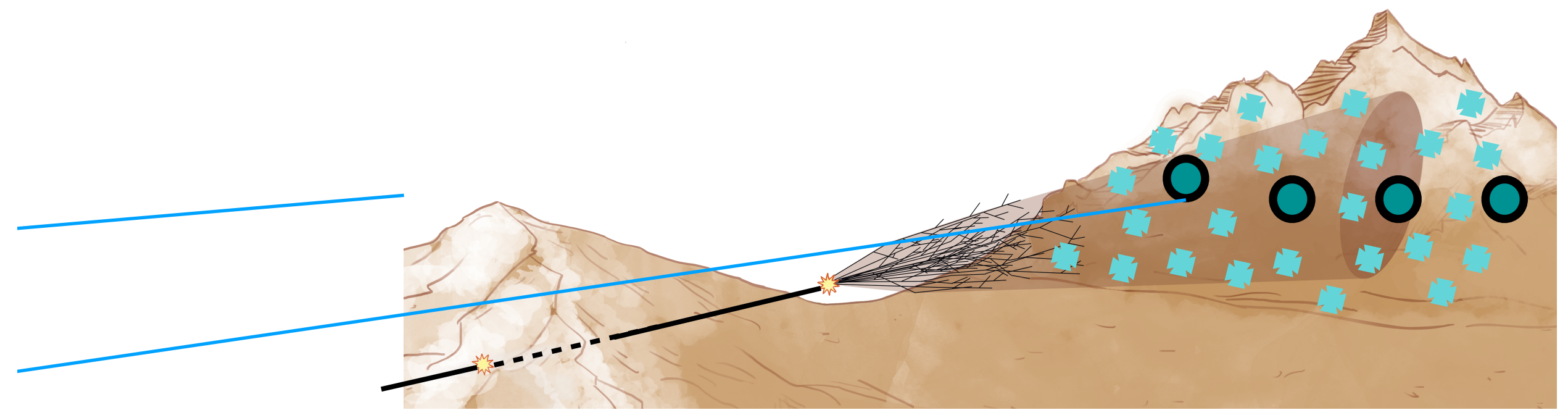
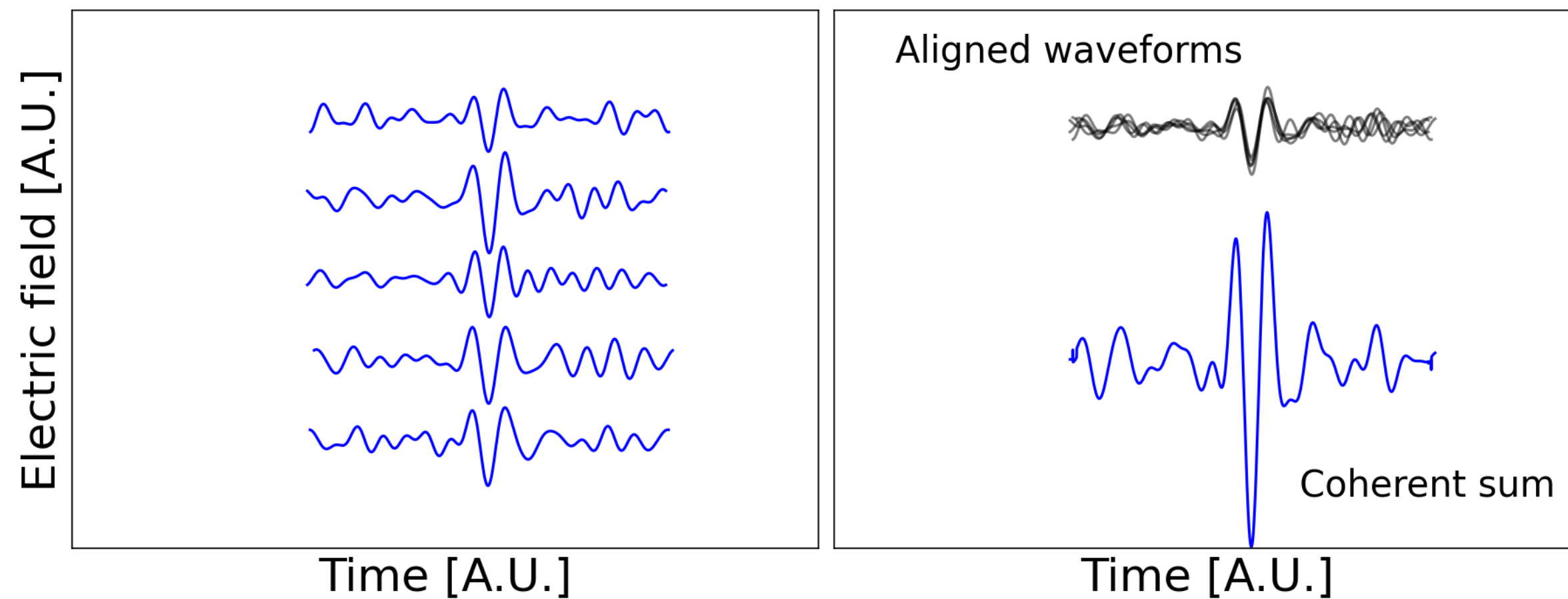
KK, JA, OM, SW, et al ICRC 2025



HERON Phased Array Trigger



Waveforms (30-80 MHz)



Beamforming for trigger & reconstruction of transient radio signals

On phased arrays:

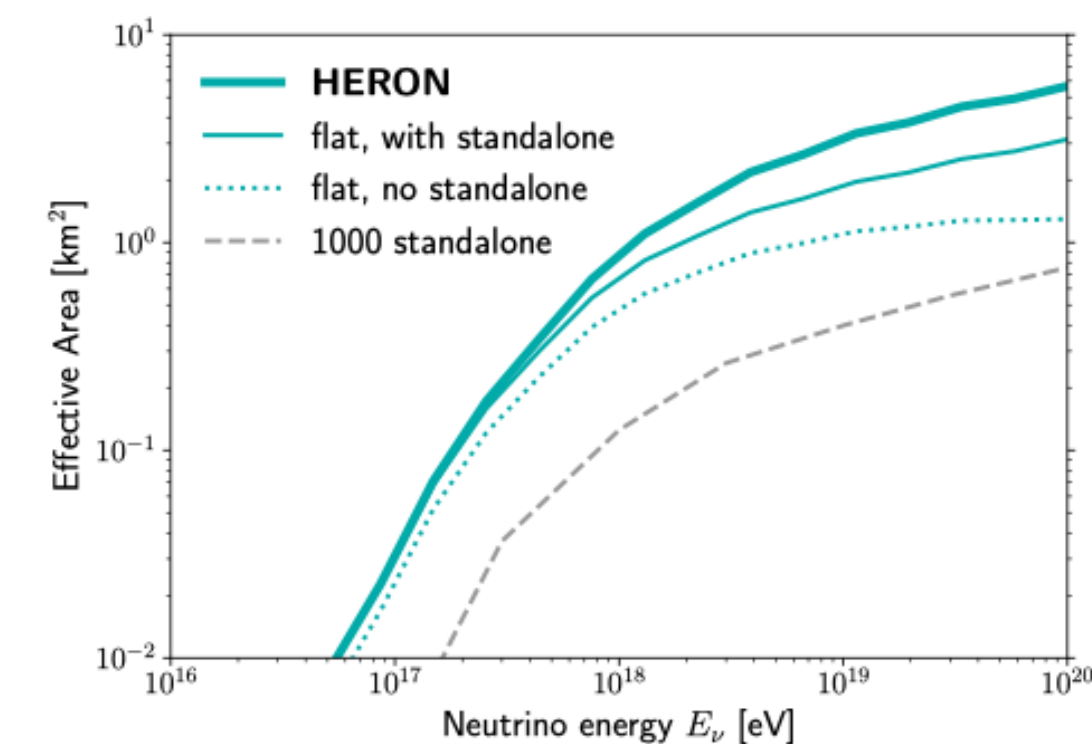
for trigger along beams

signal to noise $\sim \sqrt{N}$ (N = 24 antennas)

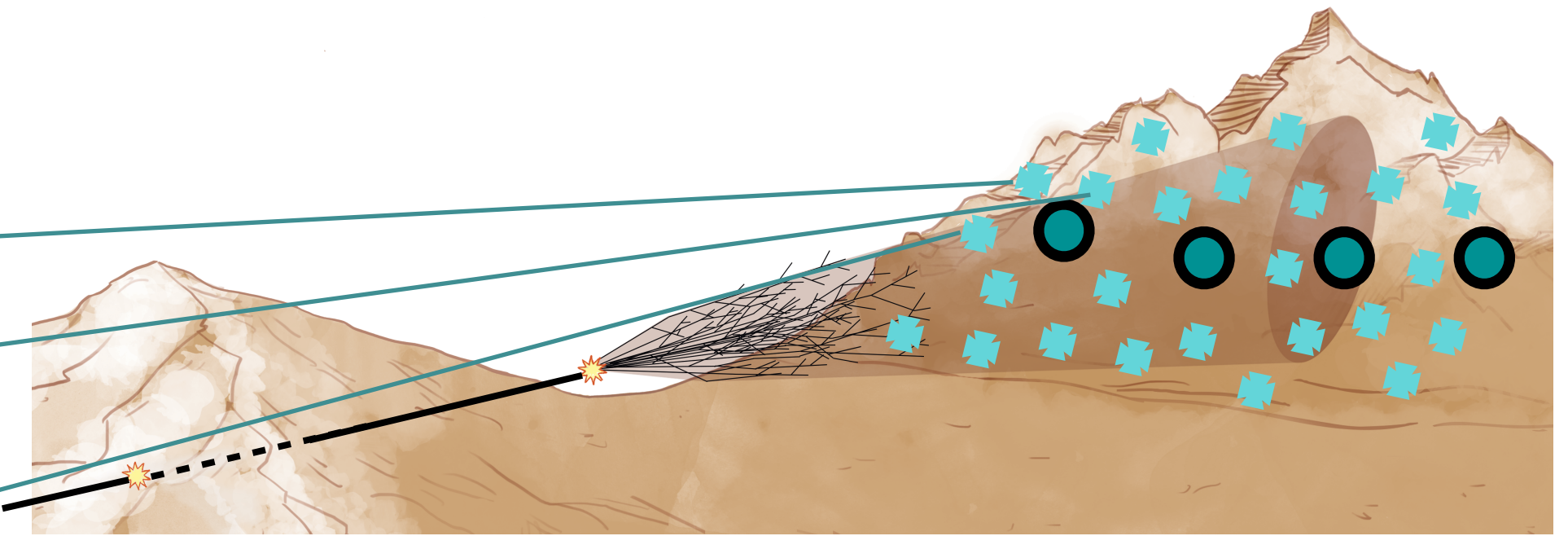
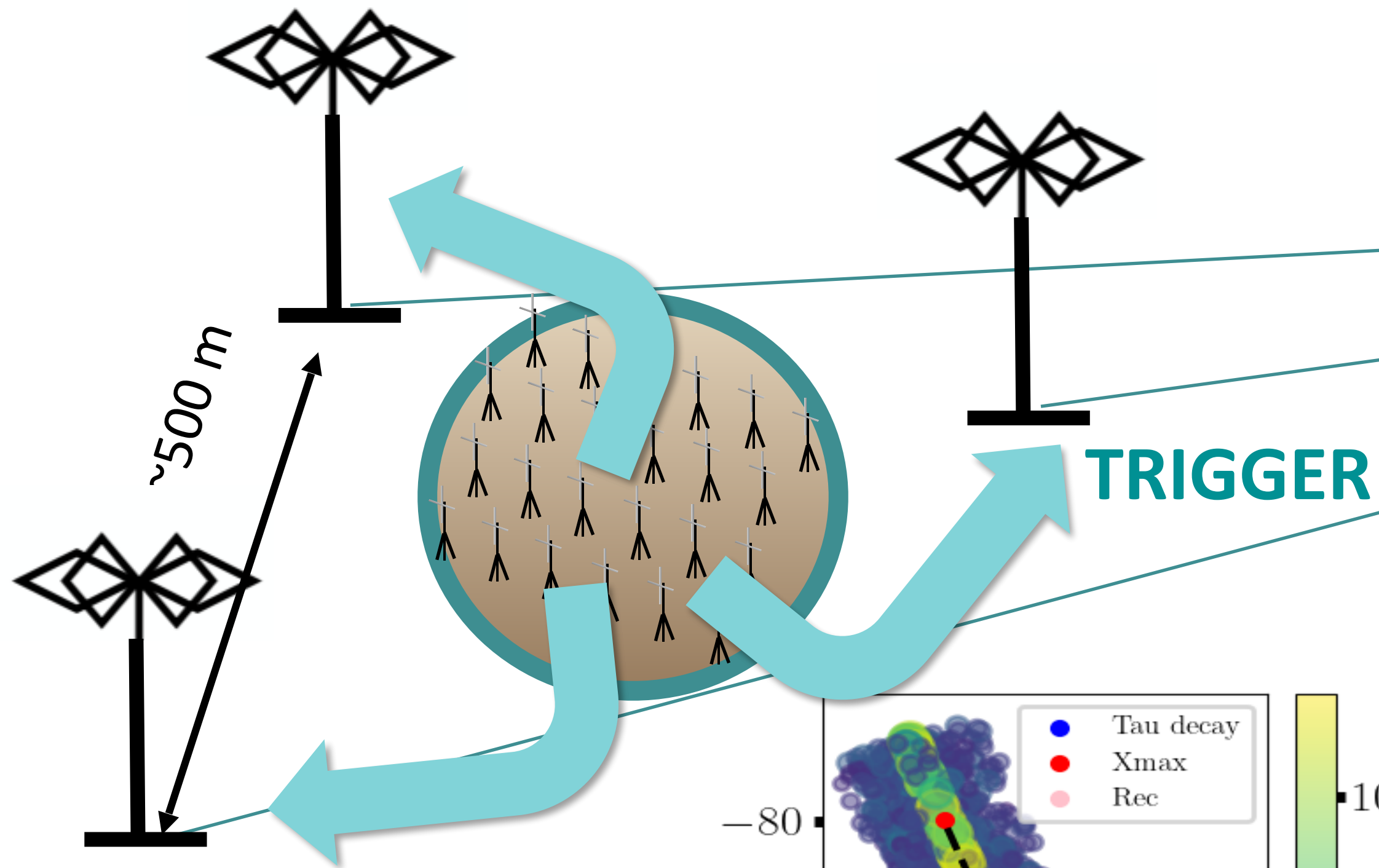
improved threshold & effective area **x 20**

SW et al JCAP 2025

KK, JA, OM, SW, et al ICRC 2025



HERON: Reconstruction



Beamforming for trigger & reconstruction of transient radio signals

On phased arrays:

for trigger along beams

signal to noise $\sim \sqrt{N}$ ($N = 24$ antennas)

improved threshold & effective area $\times 20$

SW, JA, JCAP 2025
KK, JA, OM, SW, ICRC 2025

On standalone antennas (offline):

→ 3D-map of the air shower

- *excellent background rejection*

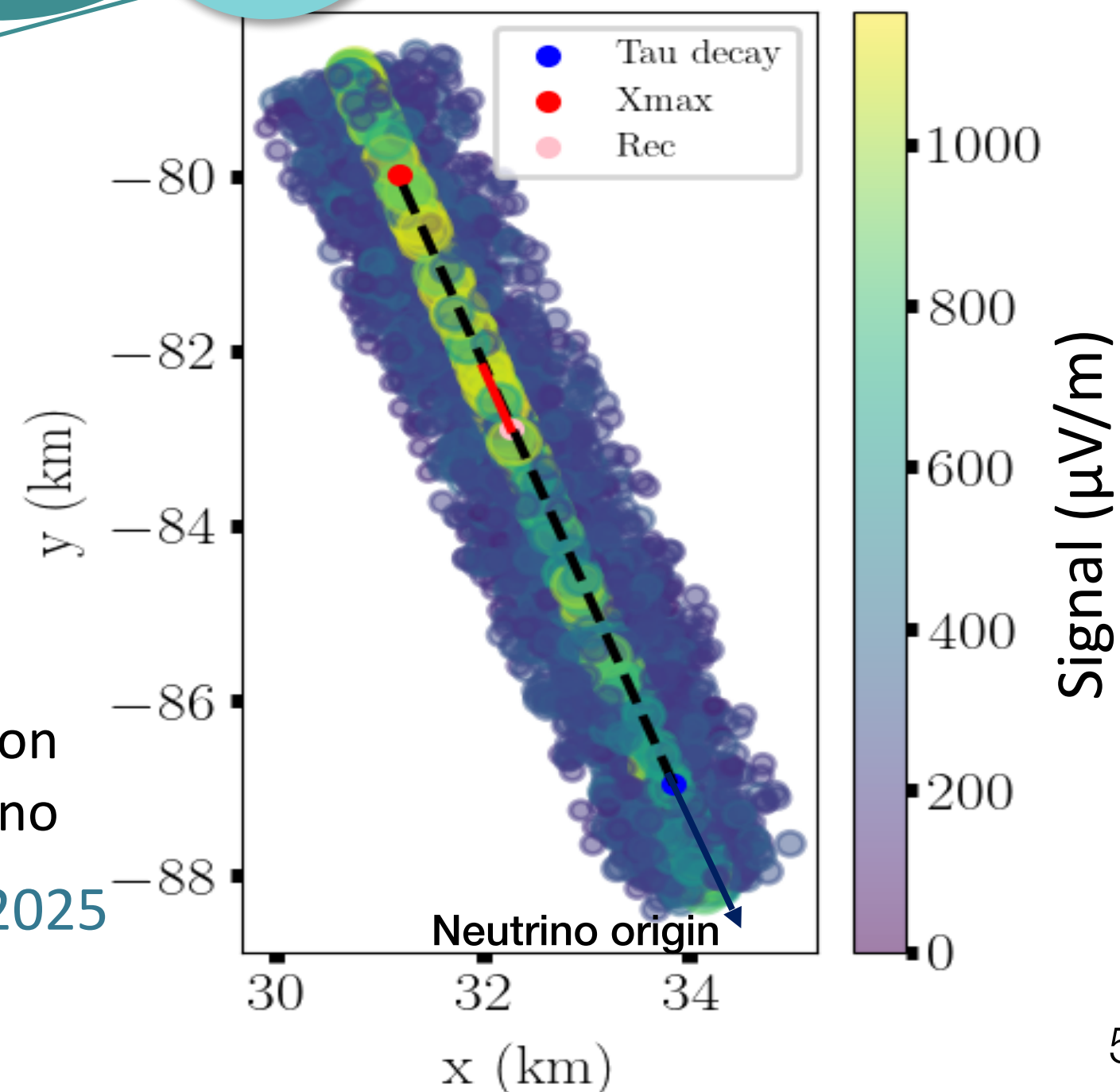
- *excellent direction reconstruction ($\sigma < 0.4^\circ$)*

→ **Neutrino astronomy**

Falcke et al., Nature 2005
Schoorlemmer et al.,
(incl JA), 2023, 2025

HERON simulation
for a $\sim 10^{18}$ eV neutrino

KK, JA, OM, SW, et al ICRC 2025

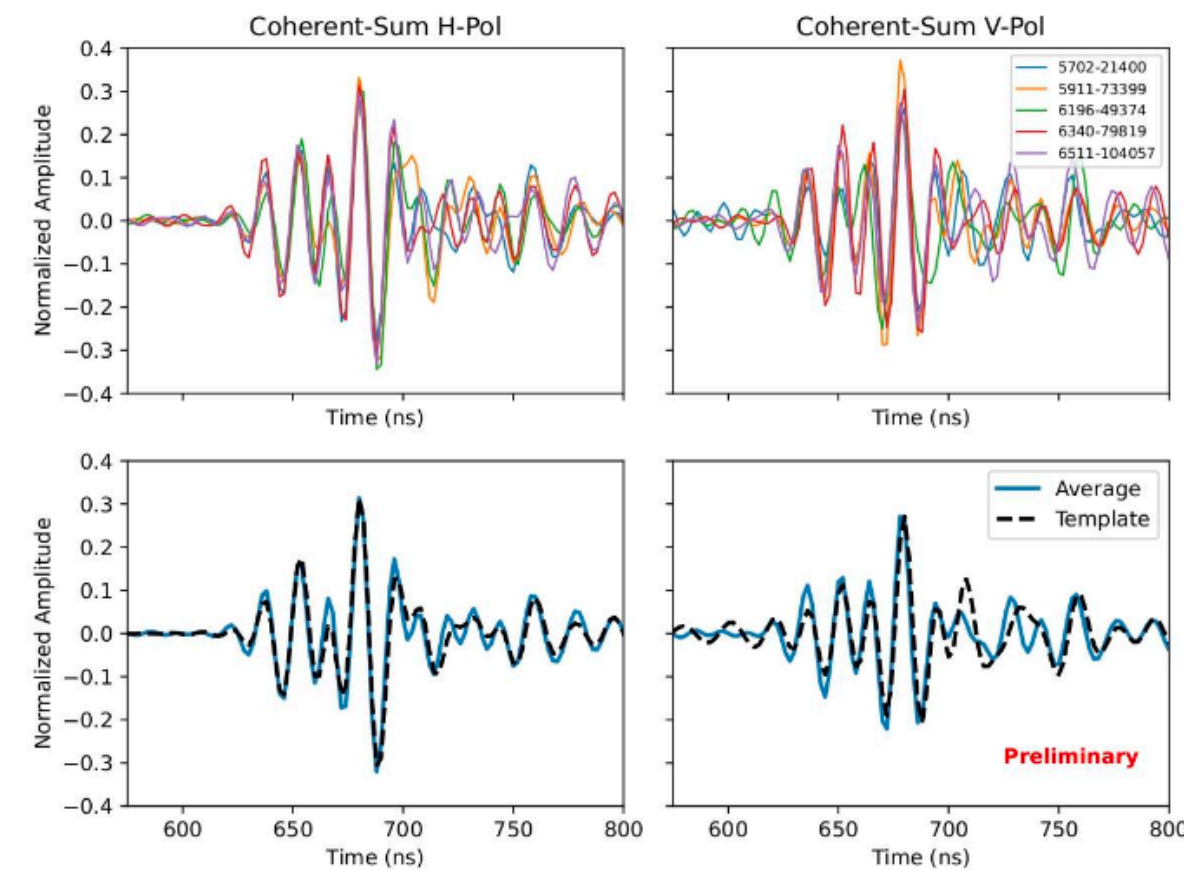


HERON is informed by BEACON and GRAND

BEACON: Elevated phased arrays

Sensitivity at 10^{18} eV with minimal instrumentation

◆ BEACON Prototype



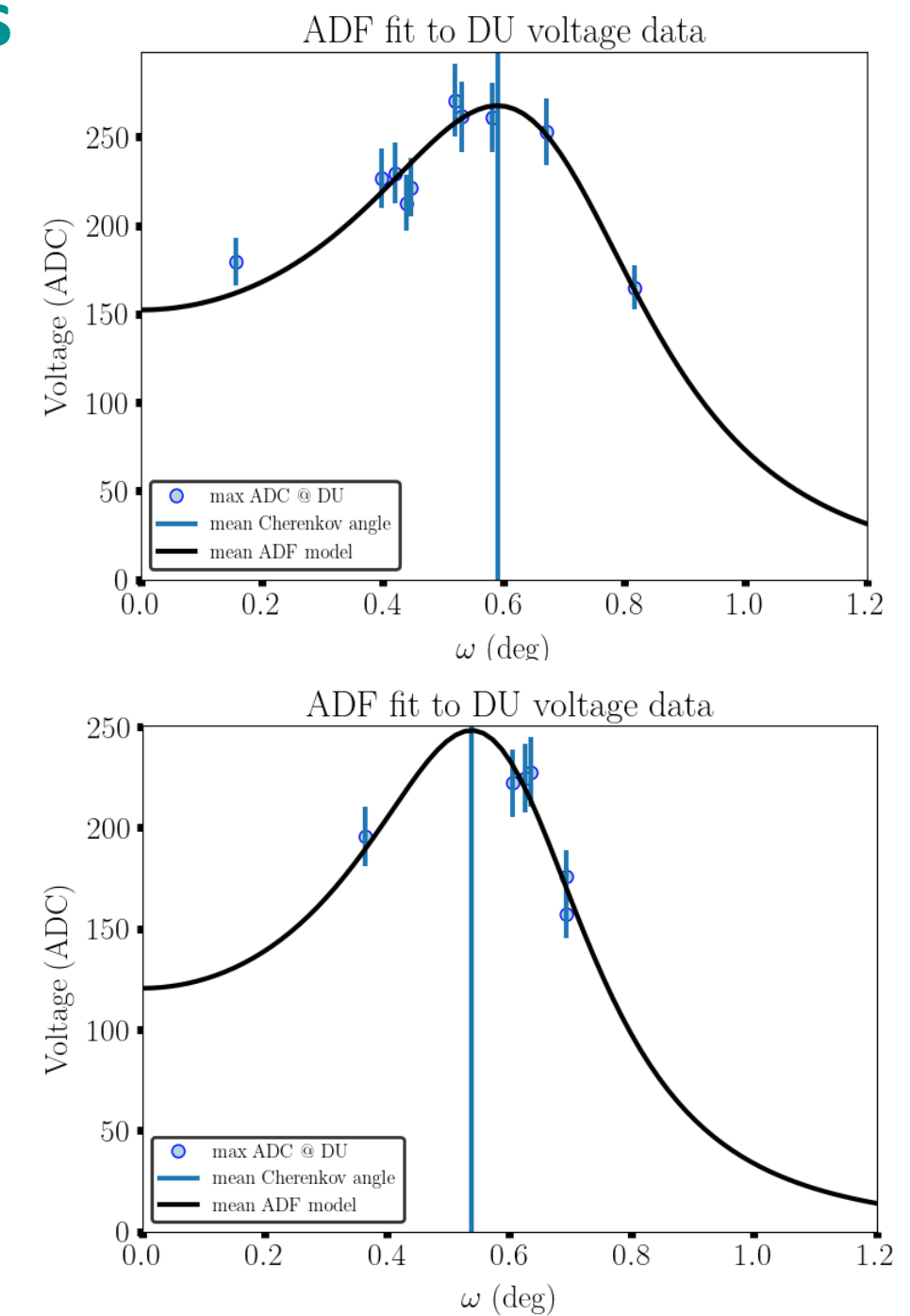
Zeolla for the BEACON collab ICRC2025

◆ 1 radio-only; 10 coincident radio + scintillator events

GRAND: Autonomous standalone antennas

Large area, precision pointing

◆ GP300: 41 cosmic ray candidates



ICRC2025 :
- GRAND collab
- de Mello for the GRAND collab

◆ GRAND@Auger: 1 coincident candidate GRAND+Auger

Mountaintop Phased Array Sensitivity

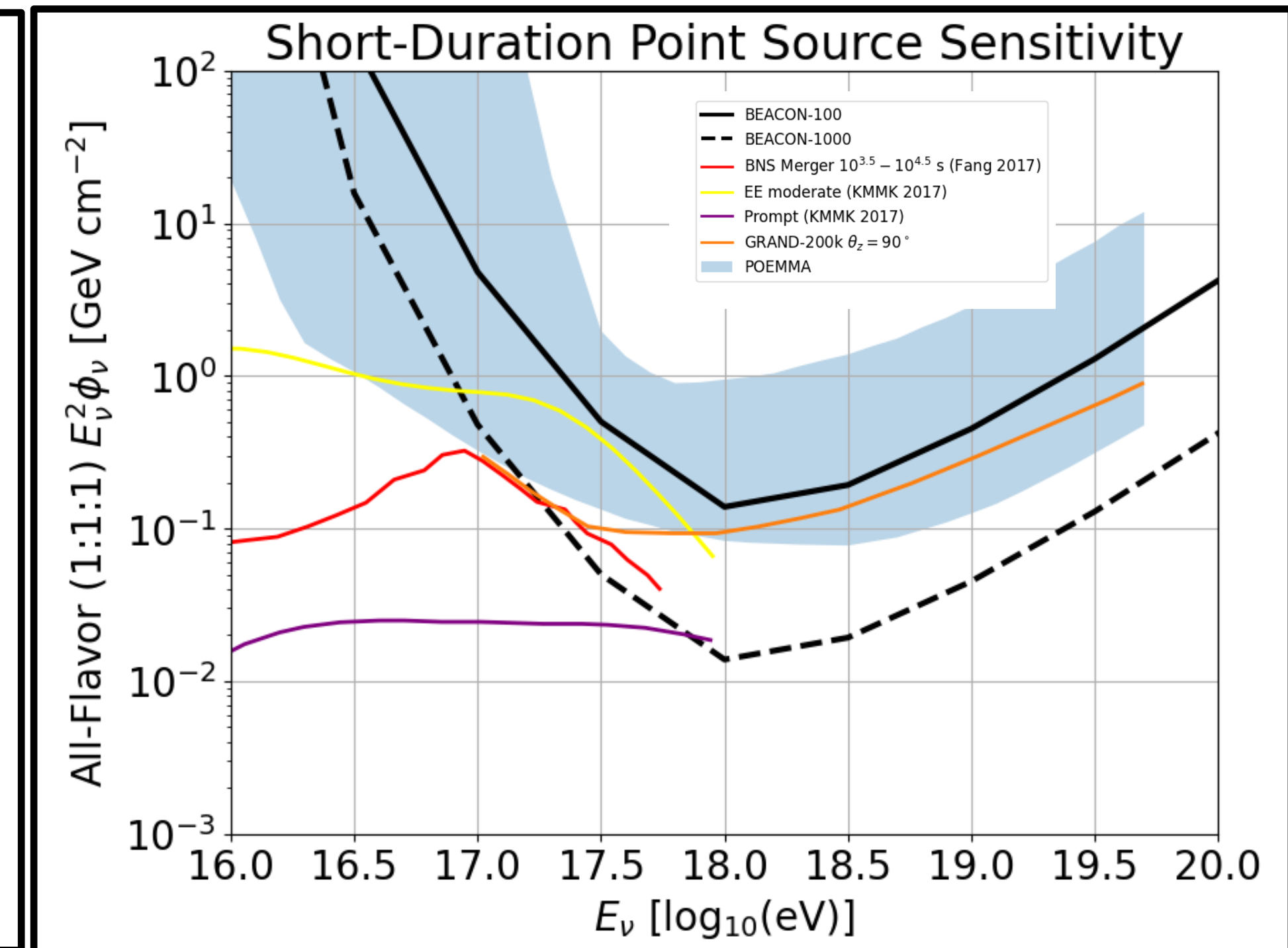
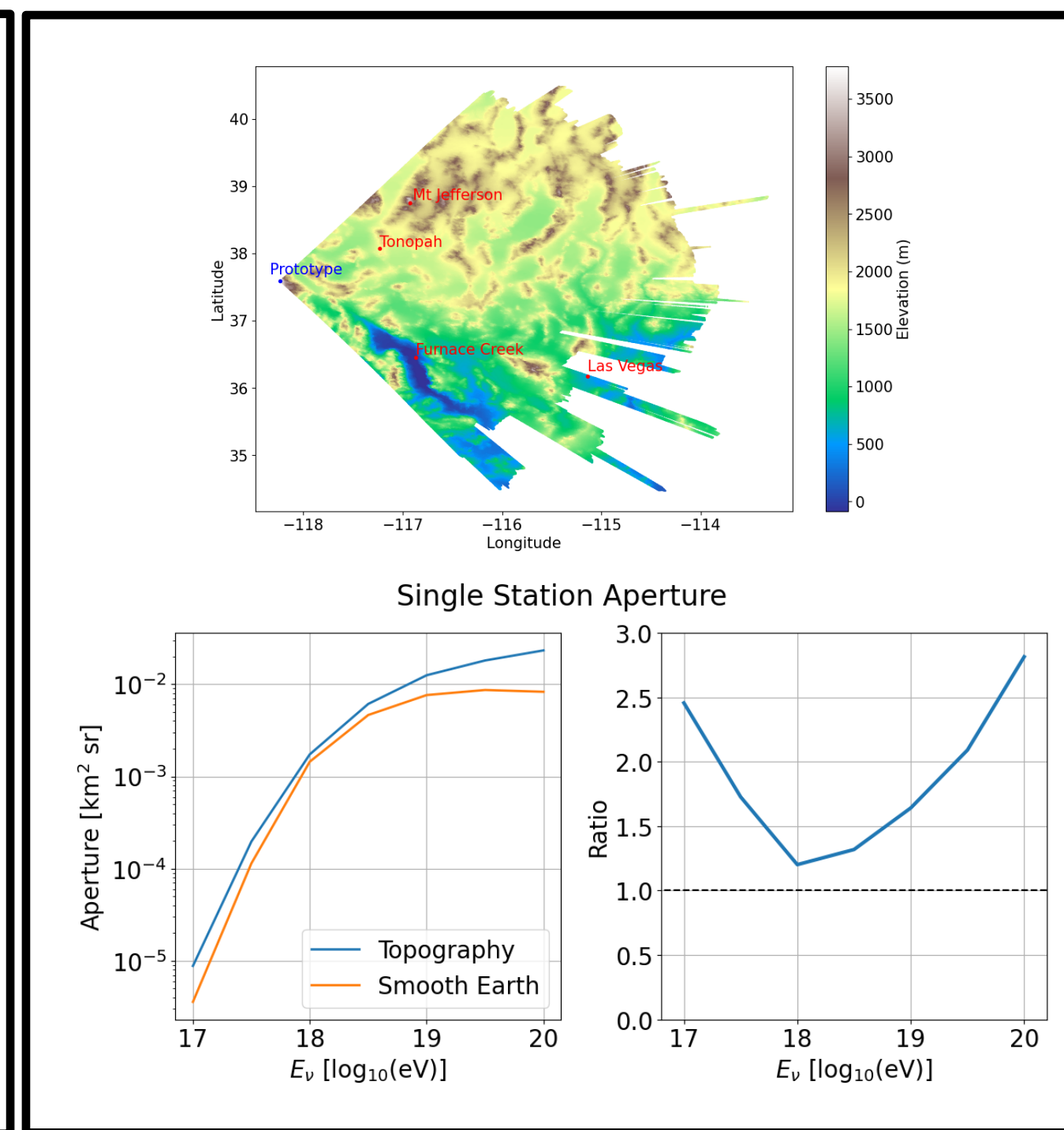
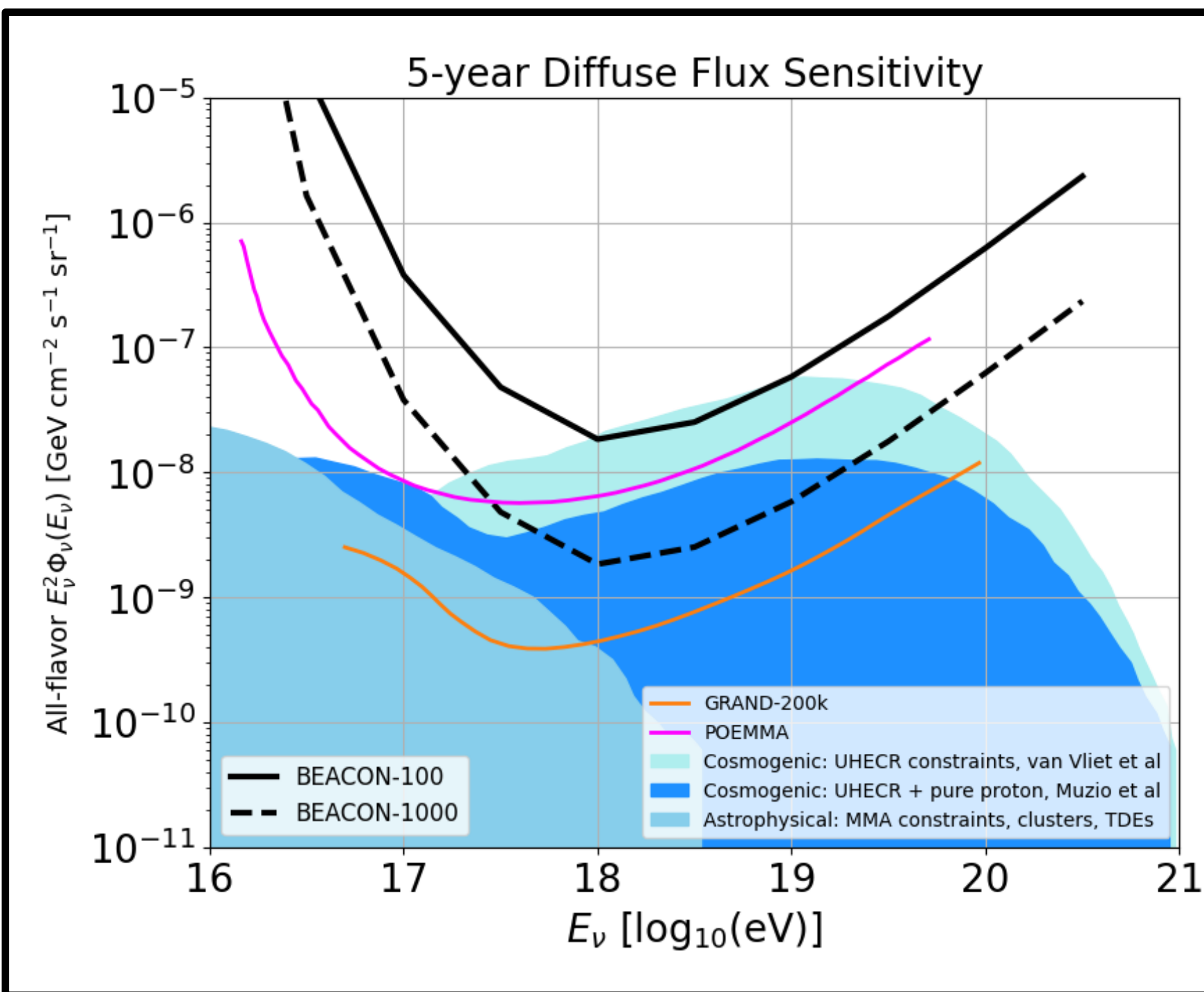


Andrew Zeolla

Efficient detector for EeV scale tau neutrinos

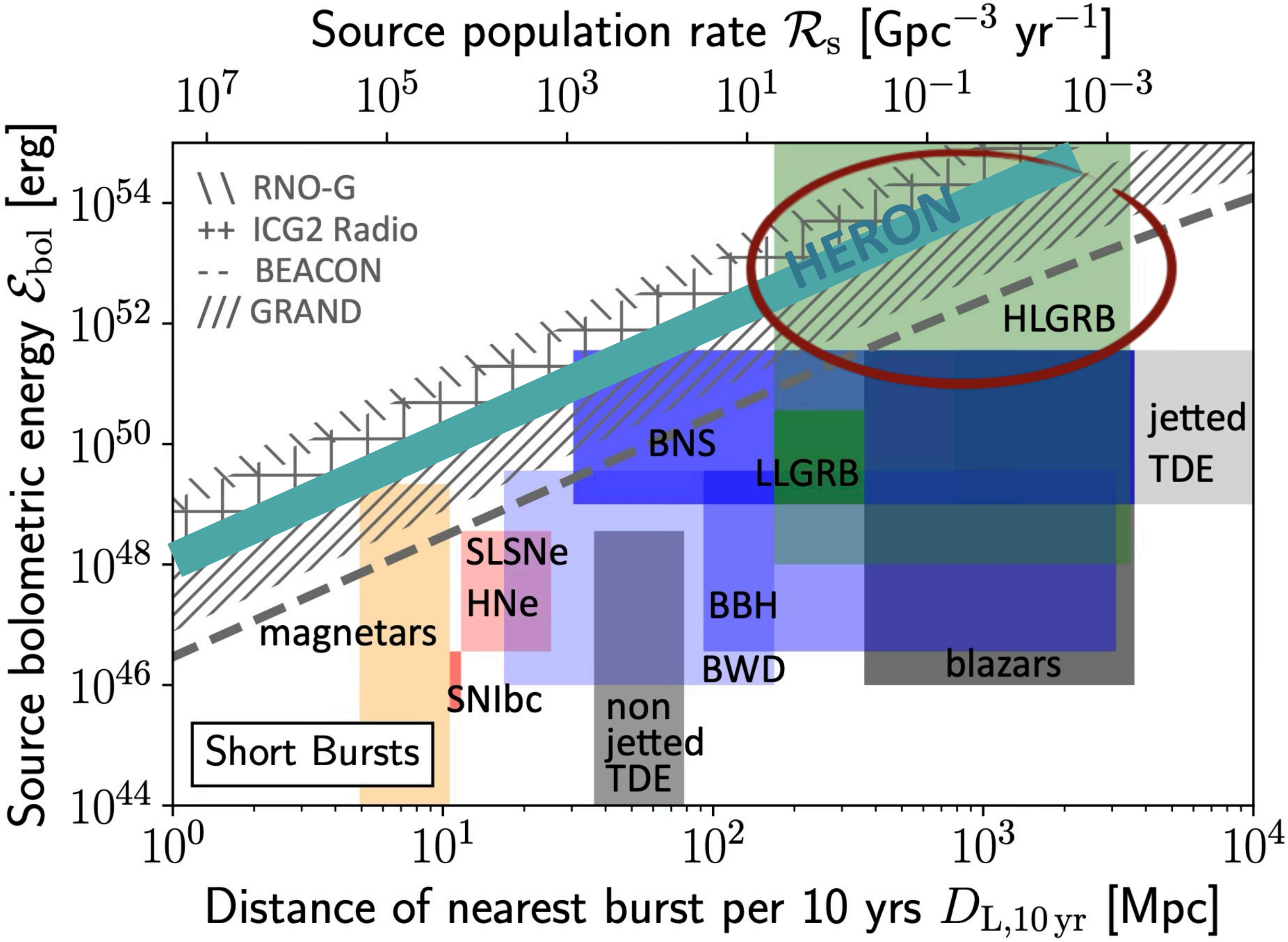
Topography can increase aperture (at prototype site)

Deep effective area for short duration transients



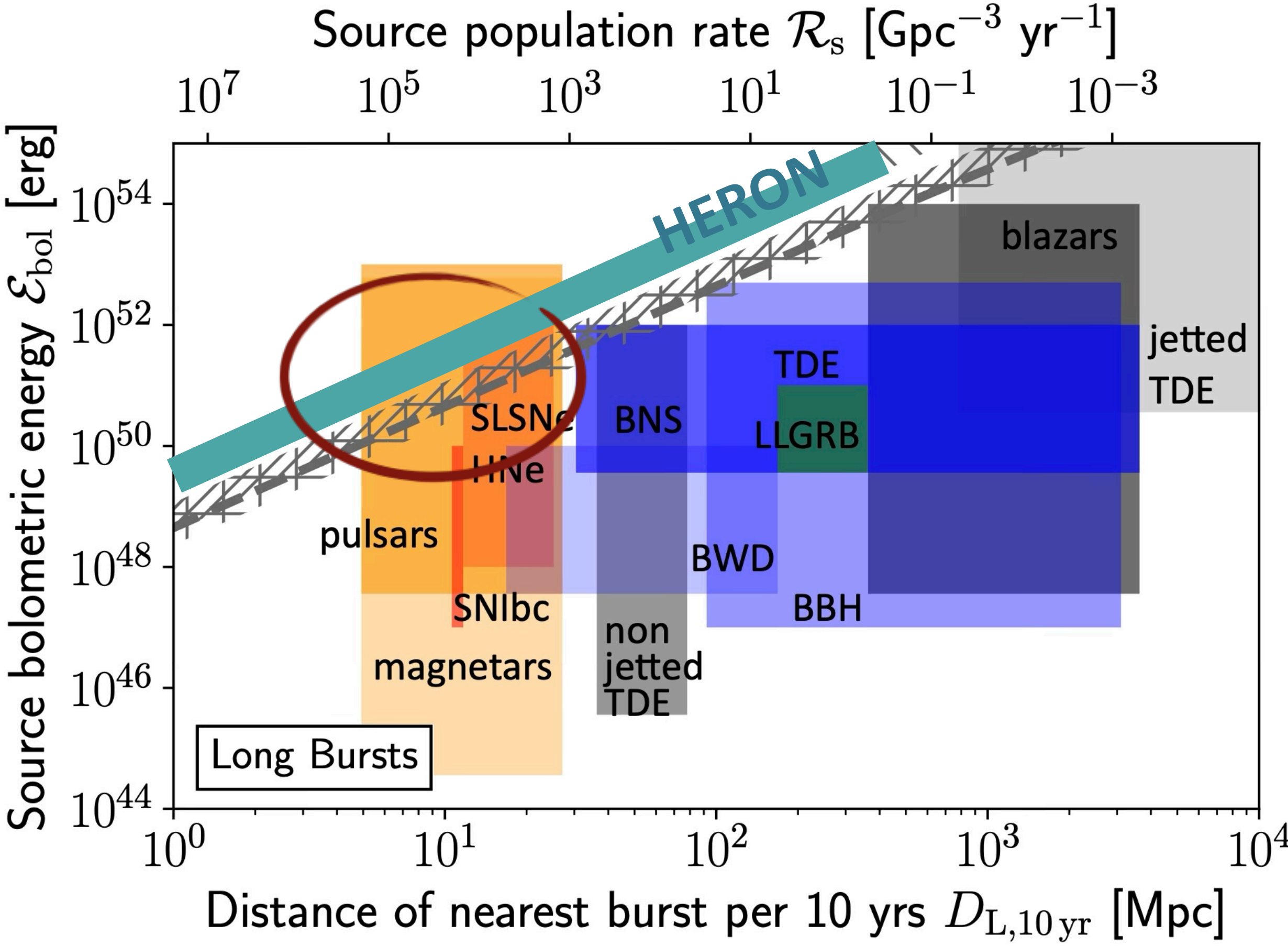
HERON is optimized for bursts

Kotera, Mukhopadhyay, Murase, Alves
Batista, Fox, Martineau, SW, Zeolla, 2025.



Short bursts: in the instantaneous field of view (FoV) of the instrument (within ~ 30 min - 1 day)

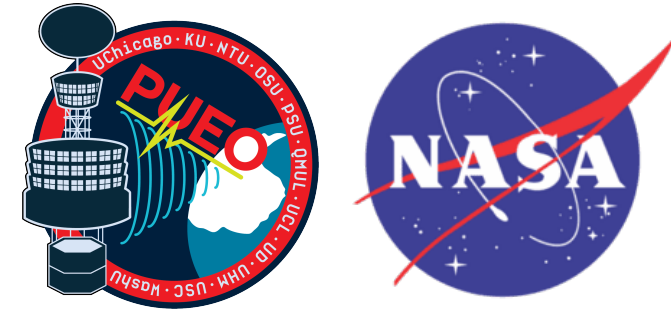
Detectable: Bright rare (distant) sources



Long bursts: any longer transients

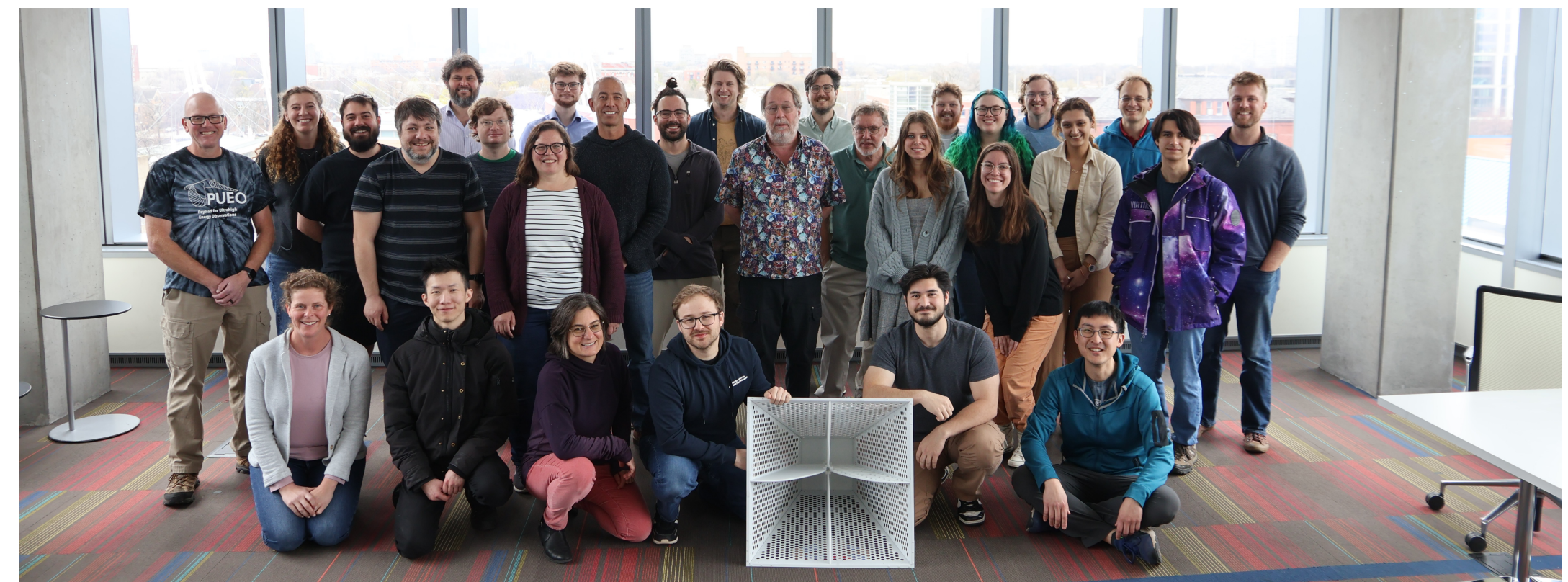
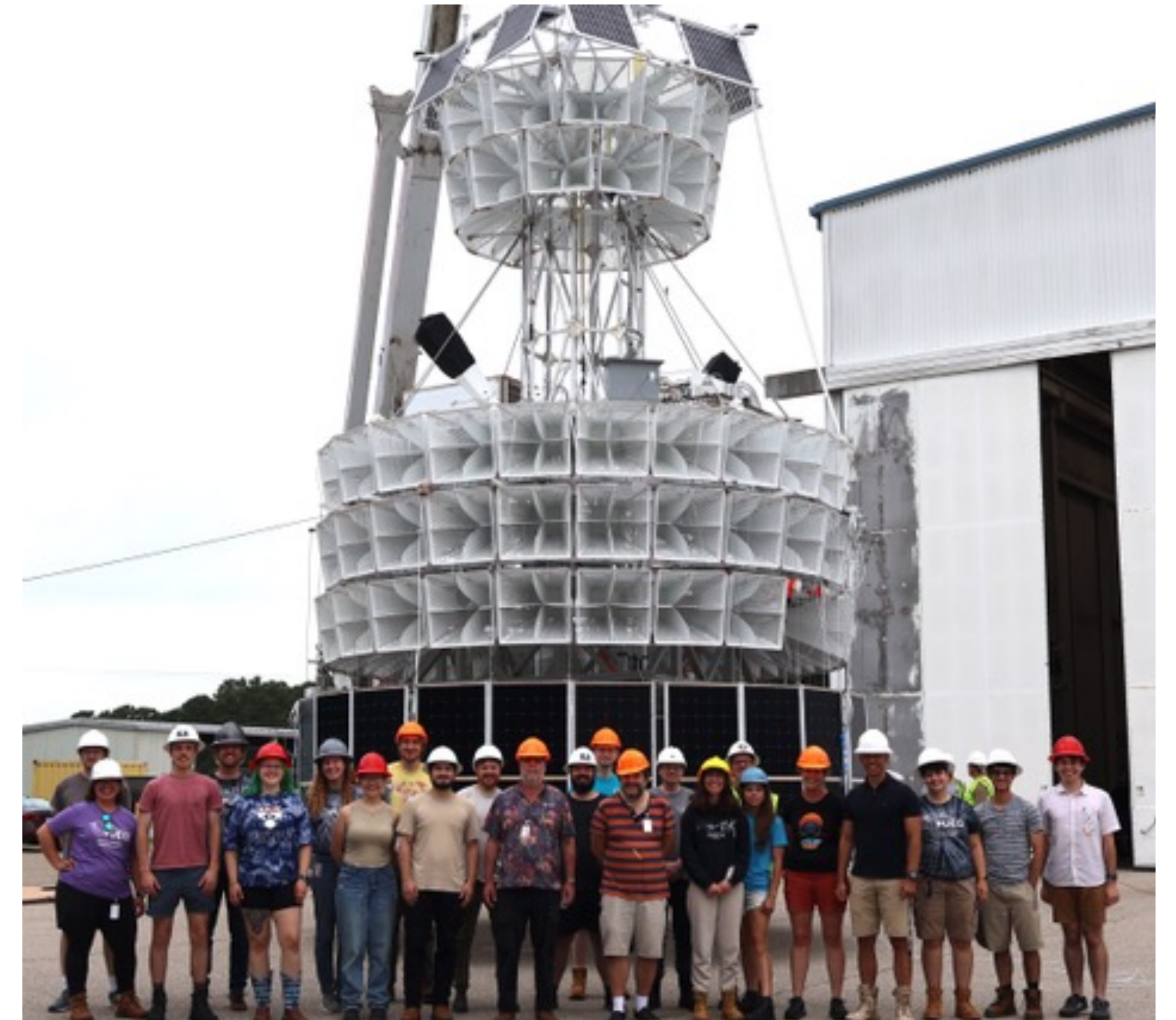
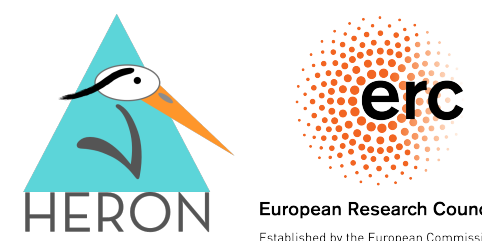
Detectable: Local Group & nearby galaxies

Conclusions



Stay tuned for upcoming results!

- PUEO aims observe or constrain the flux of neutrinos at the **very end of the neutrino spectrum** ($E > 10^{18}$ eV) with deep effective area
- **PUEO flight on Dec 2025 to Jan 2026.**
 - Some issues led to reduced lifetime
 - **Enhanced instrument sensitive** to weaker events than ever before. Important to fully reconstruct & characterize spectrum, polarity, polarization
 - **LF Instrument targets air showers**; already seeing solar radio bursts and galactic noise
- **We are just beginning to explore the UHE neutrino sky**
 - Targeting beyond the PeV scale
 - HERON will be the premier experiment for (tau) neutrino **sources**



Bonus Slides



EXPLANATIONS?

EXPLANATIONS?

- Isotropic ν_τ hypothesis disfavored by the Standard Model and existing limits

ARW, SAW, ANITA, et al PRD 2019

EXPLANATIONS?

➤ Isotropic ν_τ hypothesis disfavored by the Standard Model and existing limits

ARW, SAW, ANITA, et al PRD 2019

➤ Transient ν_τ in tension with other experiments

IceCube ApJ 2020

Prechelt, SAW, Romero-Wolf, ANITA PRD 2022

EXPLANATIONS?

- Isotropic ν_τ hypothesis disfavored by the Standard Model and existing limits

ARW, SAW, ANITA, et al PRD 2019

- Transient ν_τ in tension with other experiments

IceCube ApJ 2020

Prechelt, SAW, Romero-Wolf, ANITA PRD 2022

Other Possibilities?

- Air Shower with some other polarity non- or double inversion?

- Transition Radiation?

Motloch, et al PRD 95 4 2017
de Vries & Prohira PRL 091102 2019

- Sub-surface reflections, mirages?

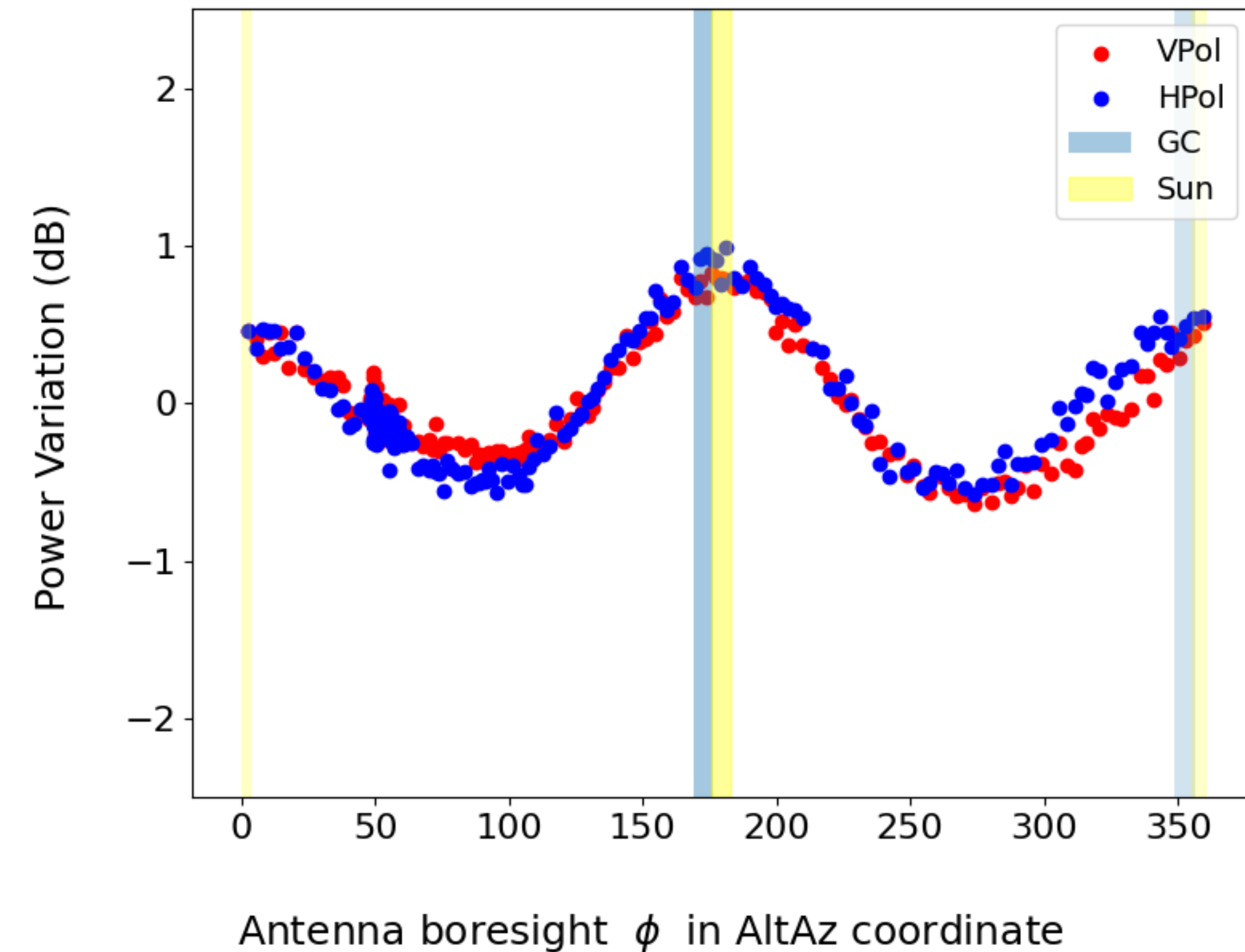
Shoemaker et al Annal. Glac. 2020
ANITA arXiv:2009.13010

- Beyond the standard model (sterile neutrinos, dark matter decay, supersymmetry, axions...)

arXiv:1802.01611, arXiv:1803.11554, arXiv:1804.05362,
arXiv:1805.07342, arXiv:1807.08892, arXiv:1809.09615,
arXiv:1810.08479, arXiv: 1812.00919, arXiv:1812.01520
arXiv:1905.10372, arXiv:1907.06308, arXiv:2003.08738
2003.02846, arXiv:2006.03325, 2004.09464, 2002.12910,

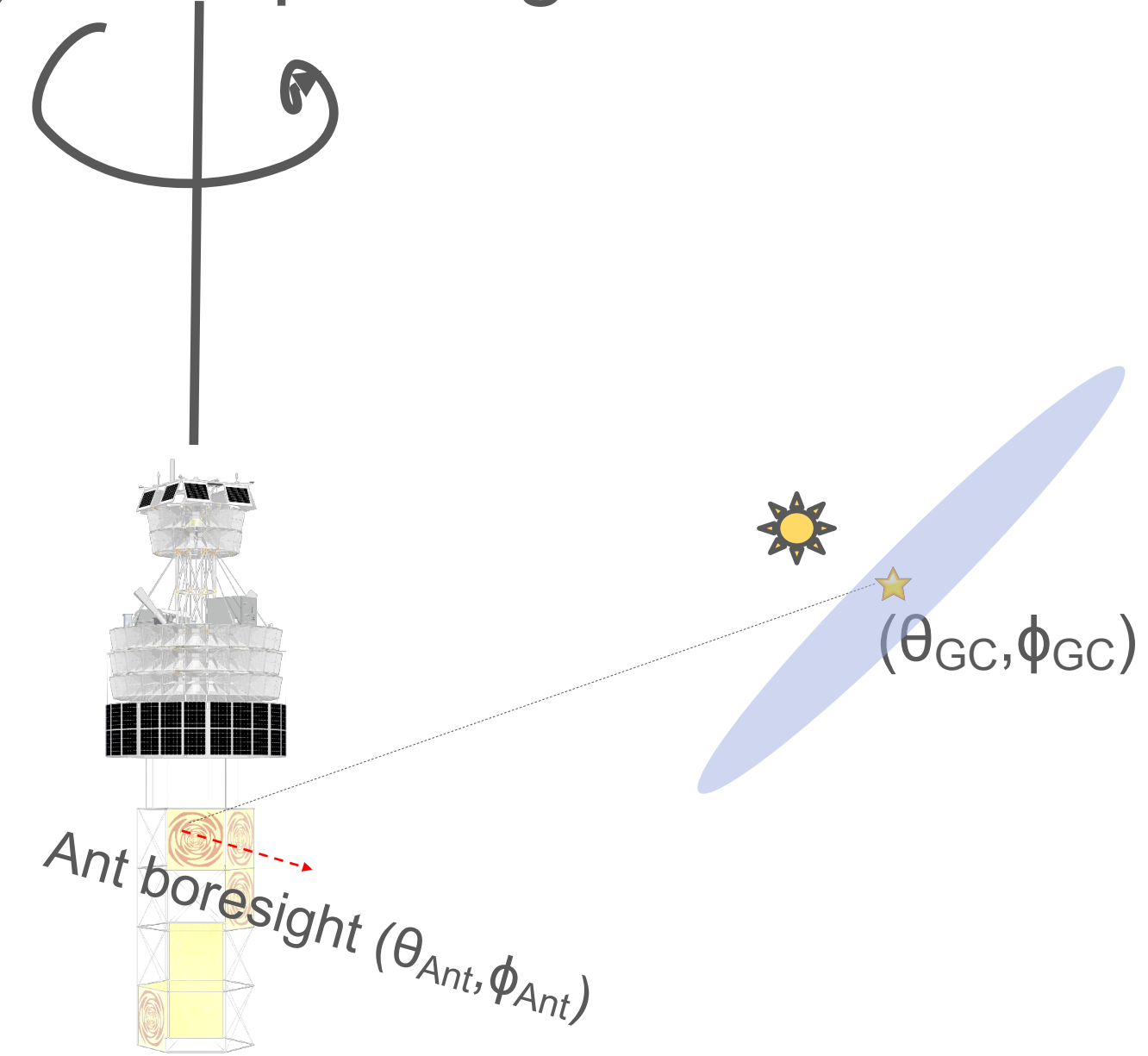
Run 909, GC Alt: (23.2 ° , 23.3 °), Sun Alt: (17.7 ° , 17.7 °),

Ant 514

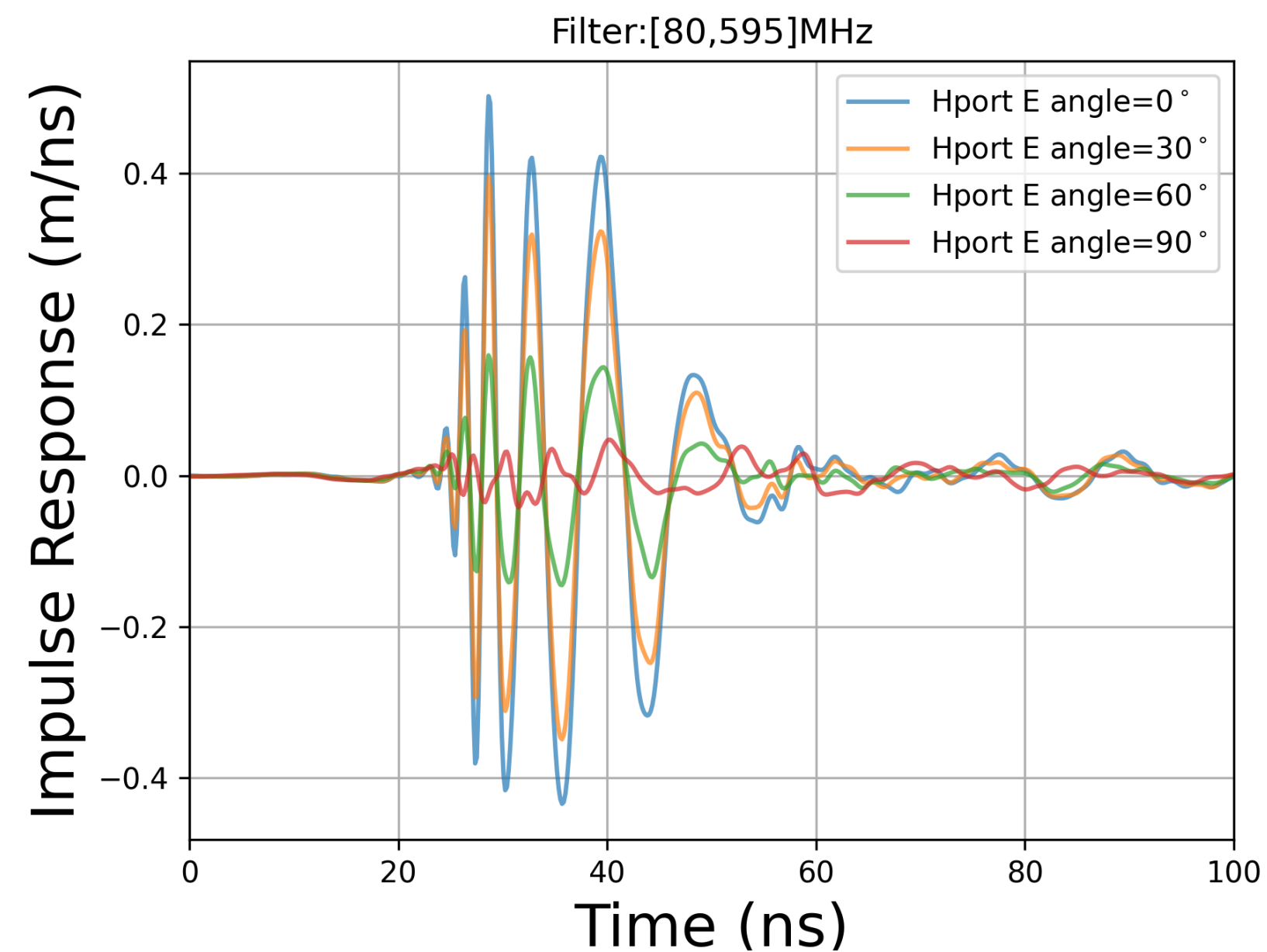
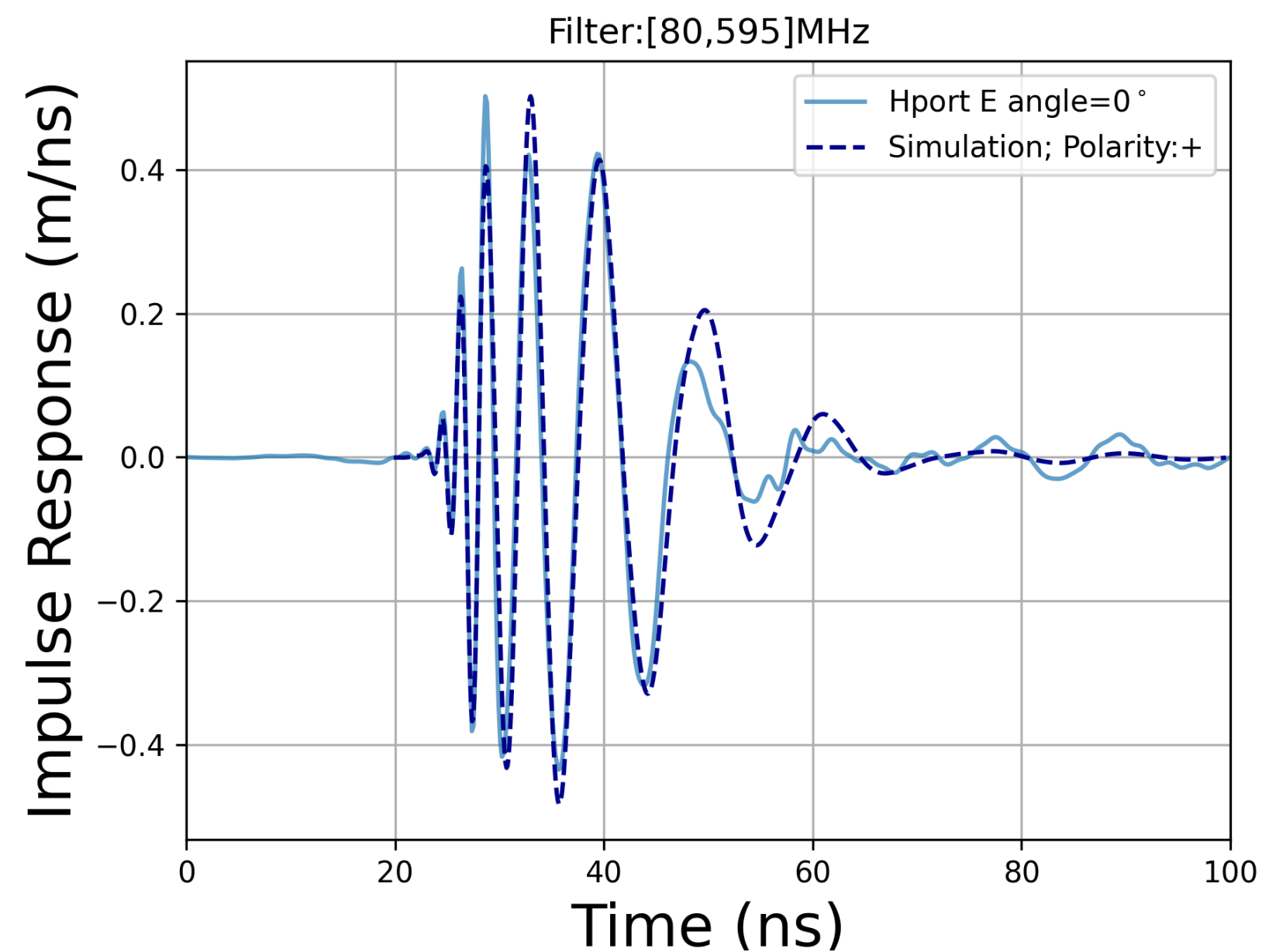


*Band pass to 50-300 MHz

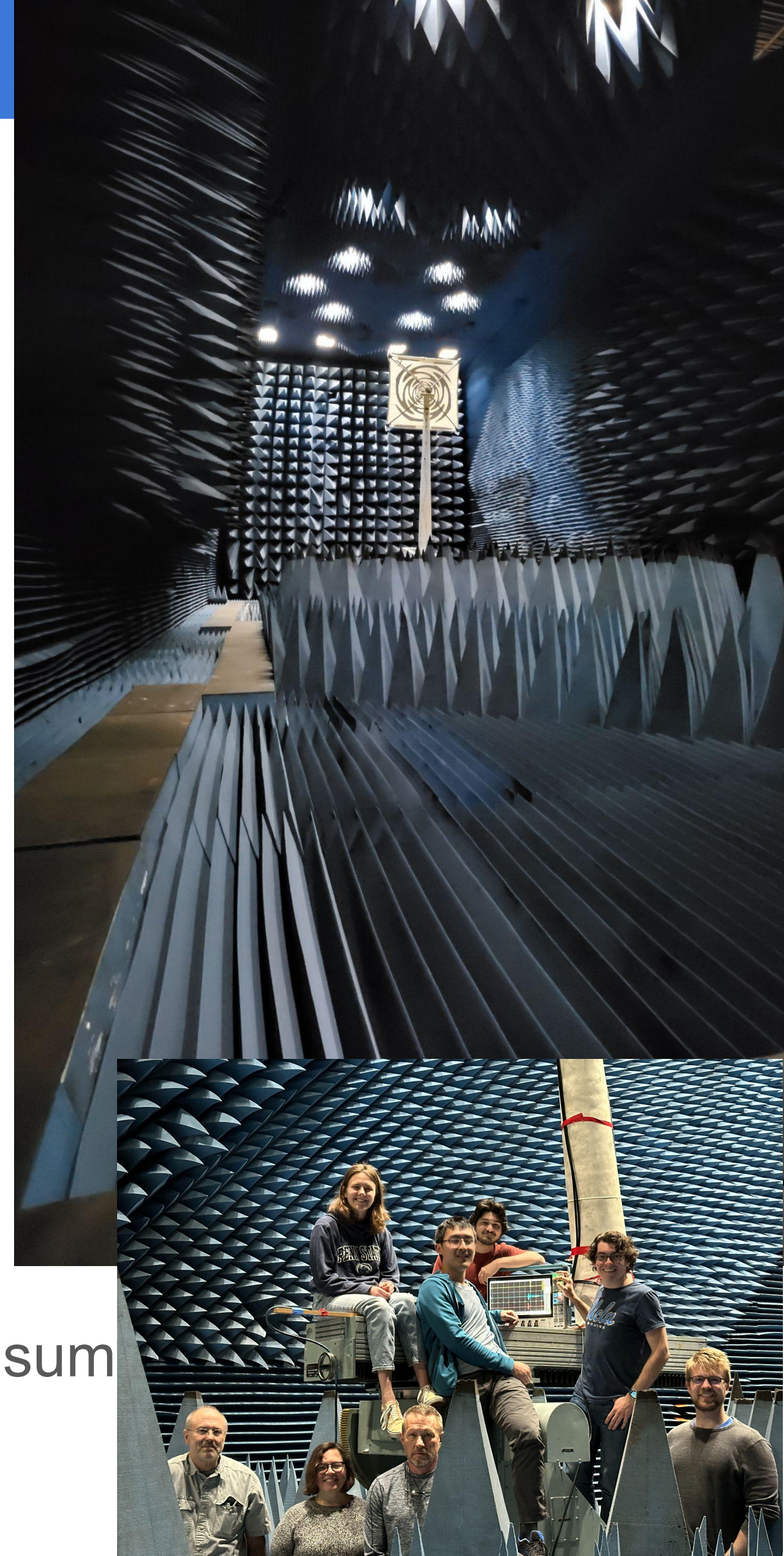
Payload spinning

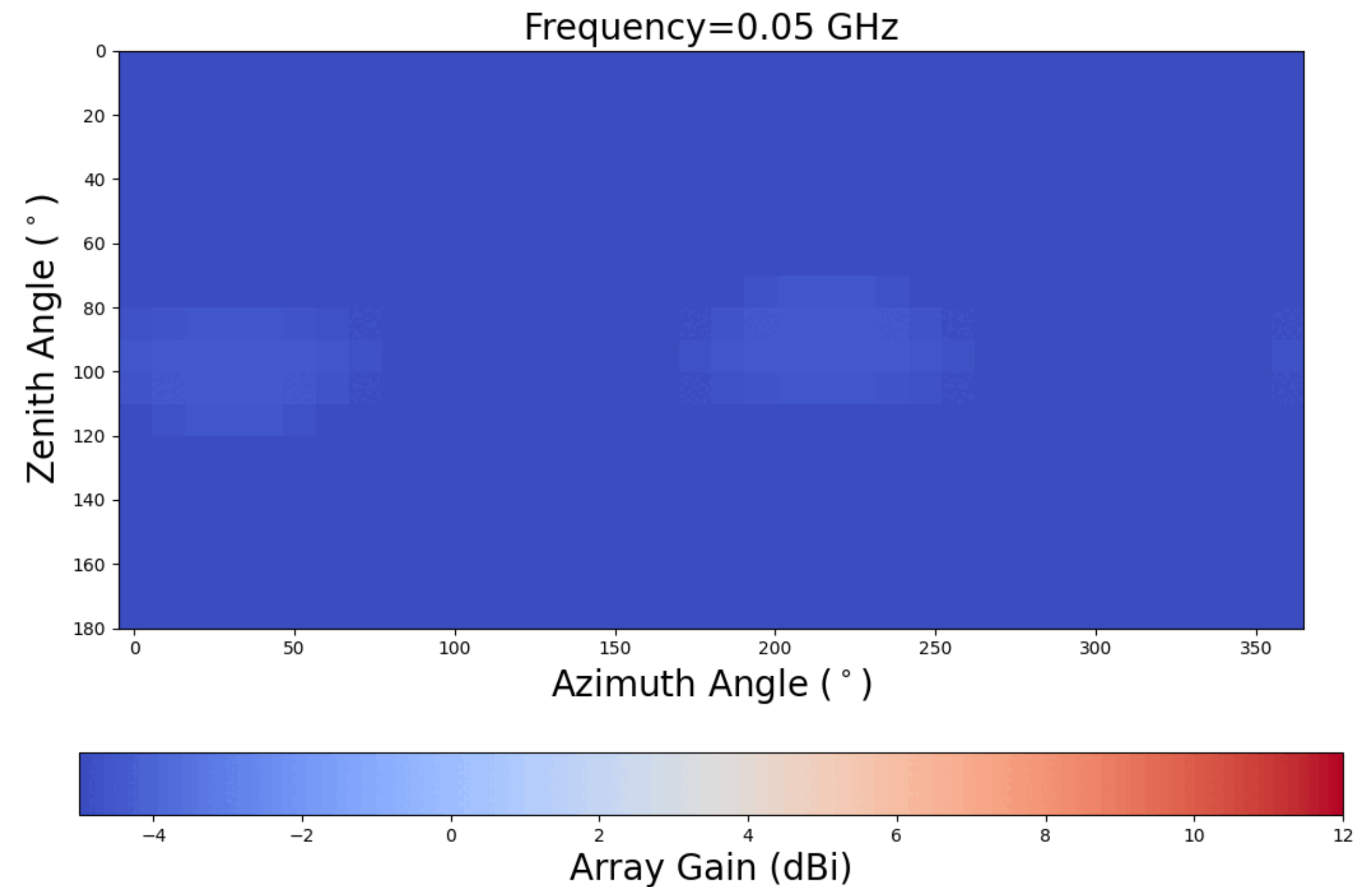
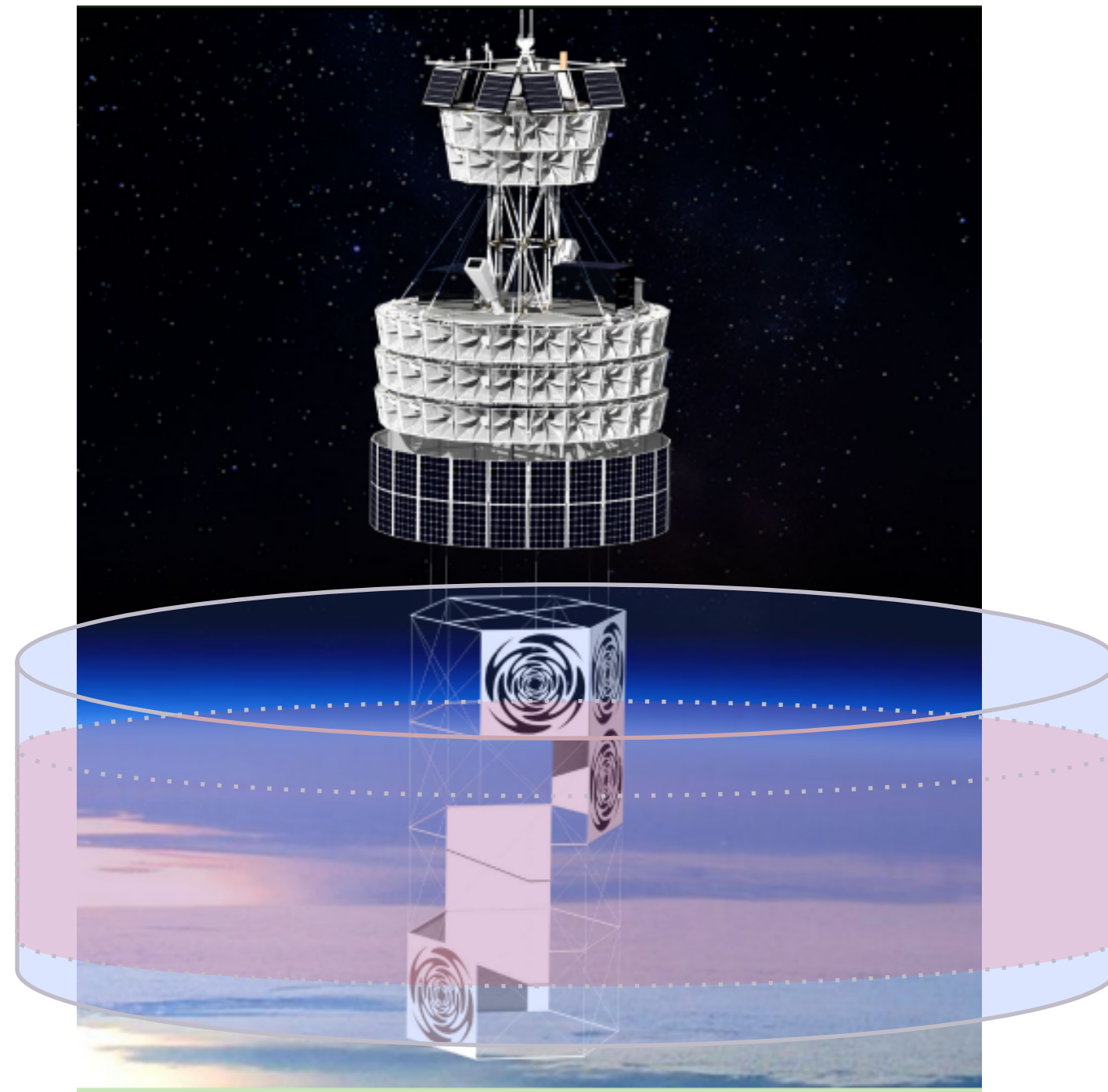


- Noise power is correlated with antenna orientation relative to the Galactic center (GC).
- During the flight, the Sun remained within $\sim 10^\circ$ of the Galactic Center, making the two contributions difficult to separate. However, during the quiet sun periods (no solar burst) galactic emission is expected to be 1-2 orders of magnitude brighter.
- Galactic noise provides a stable reference and will be used to calibrate the LF instrument.

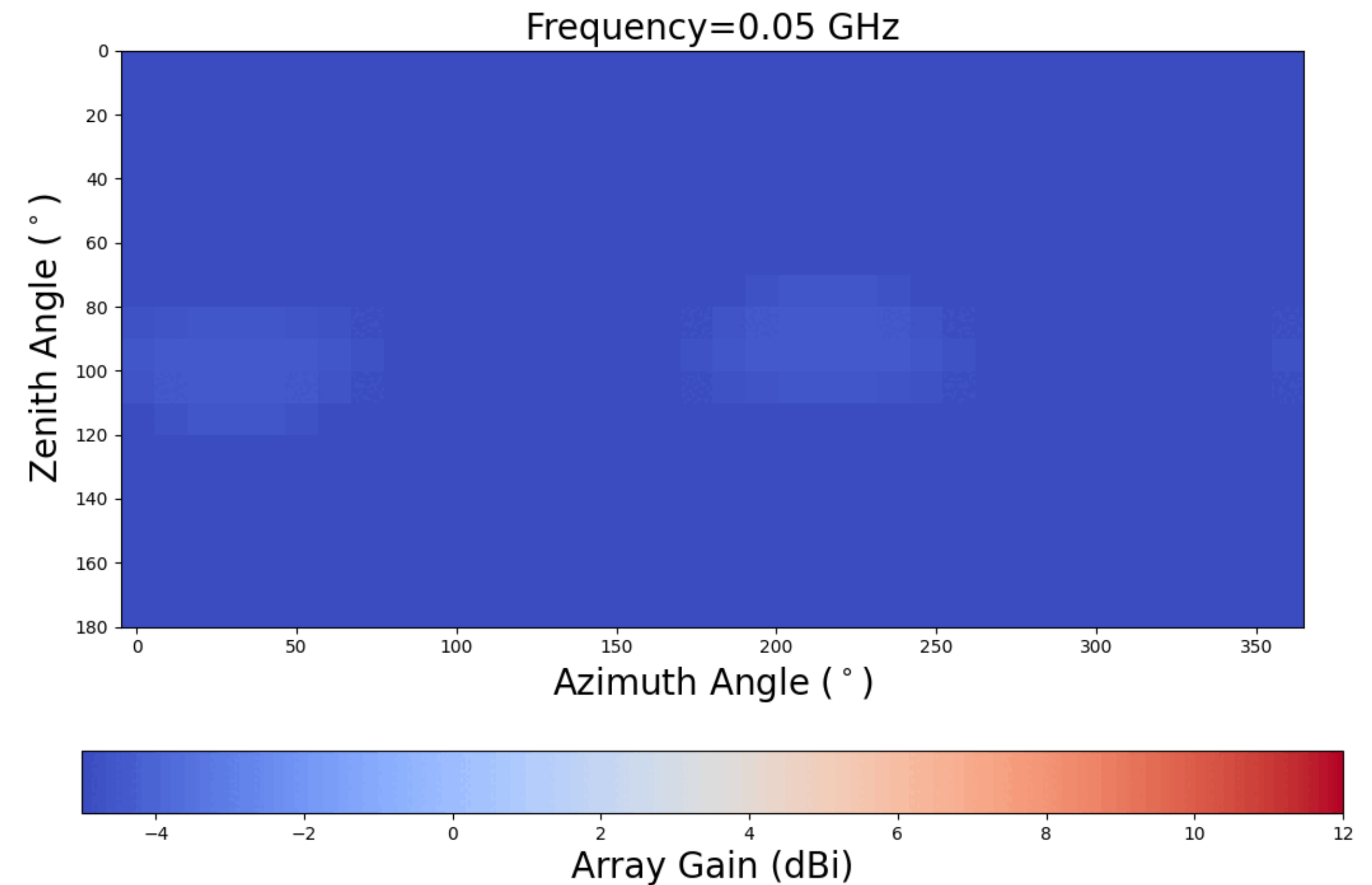
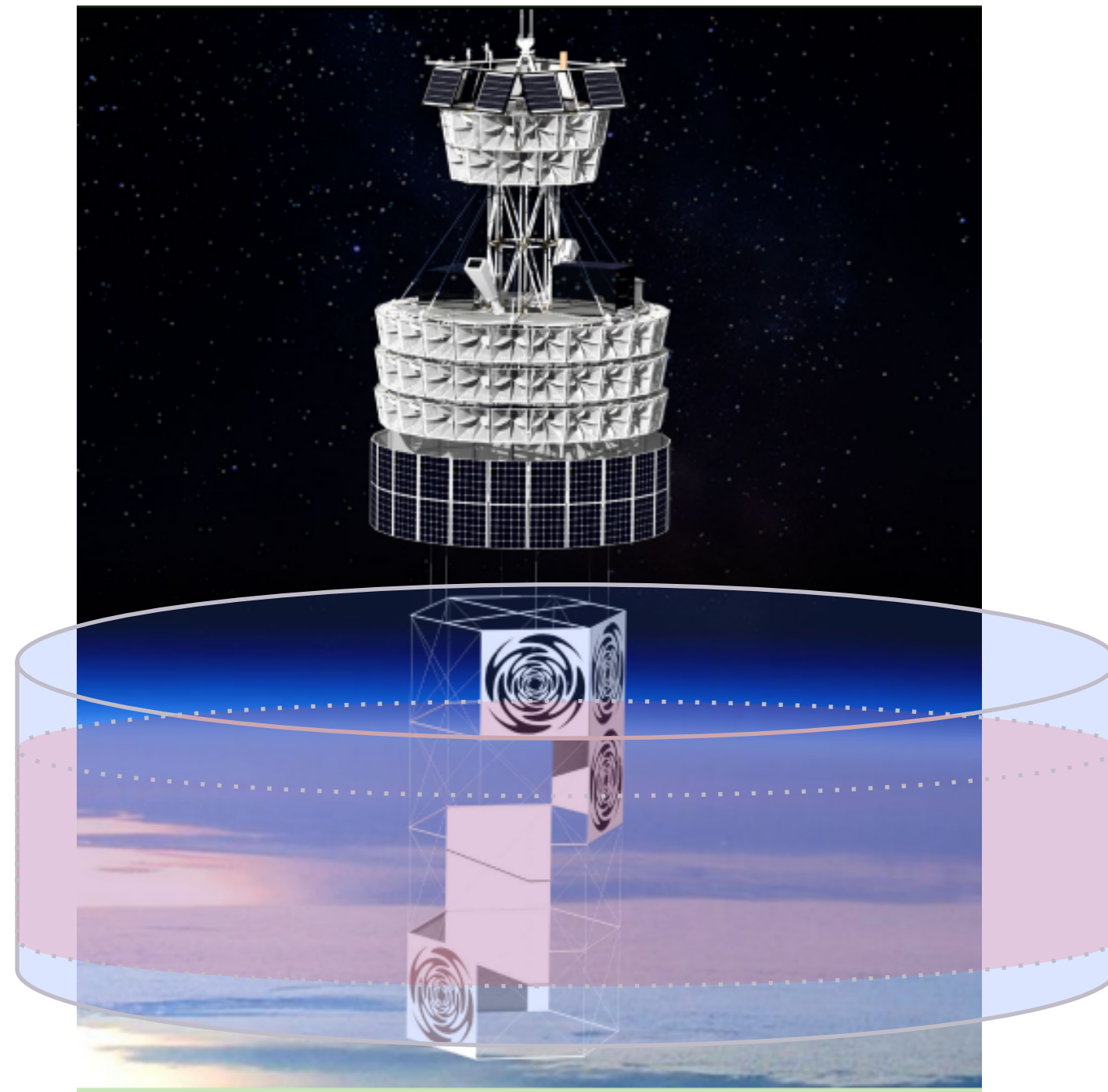


- Impulse response measurements match well with simulations.
- Angular responses have consistent phase response, making the coherent sum over antenna pointing at different directions feasible.



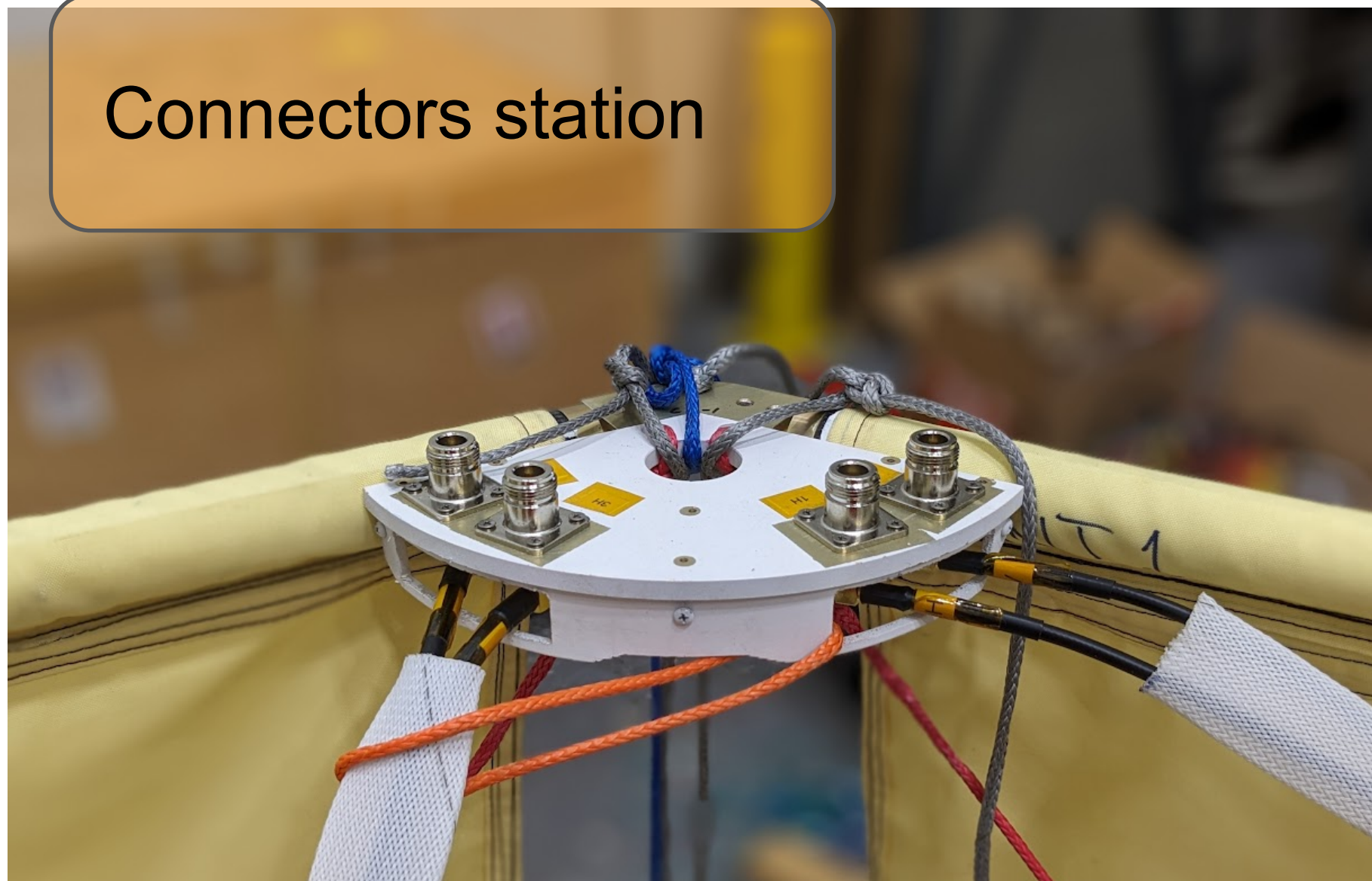


- 4 layers of hexagon ring provide vertical and horizontal baselines for interferometry.
- Keep antennas from blocking each other.
- Sub-deg angular resolution with $\text{SNR} > 5$

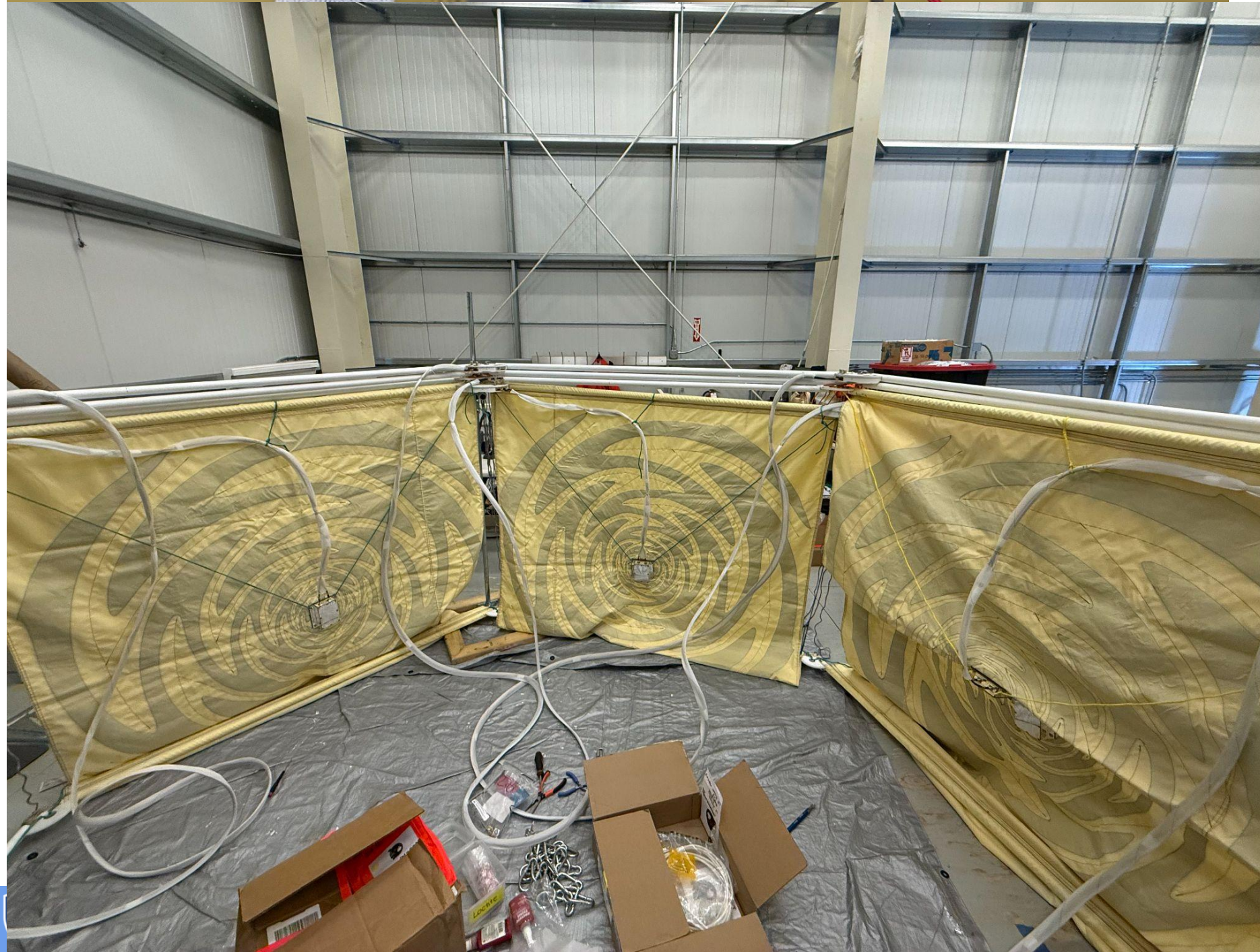
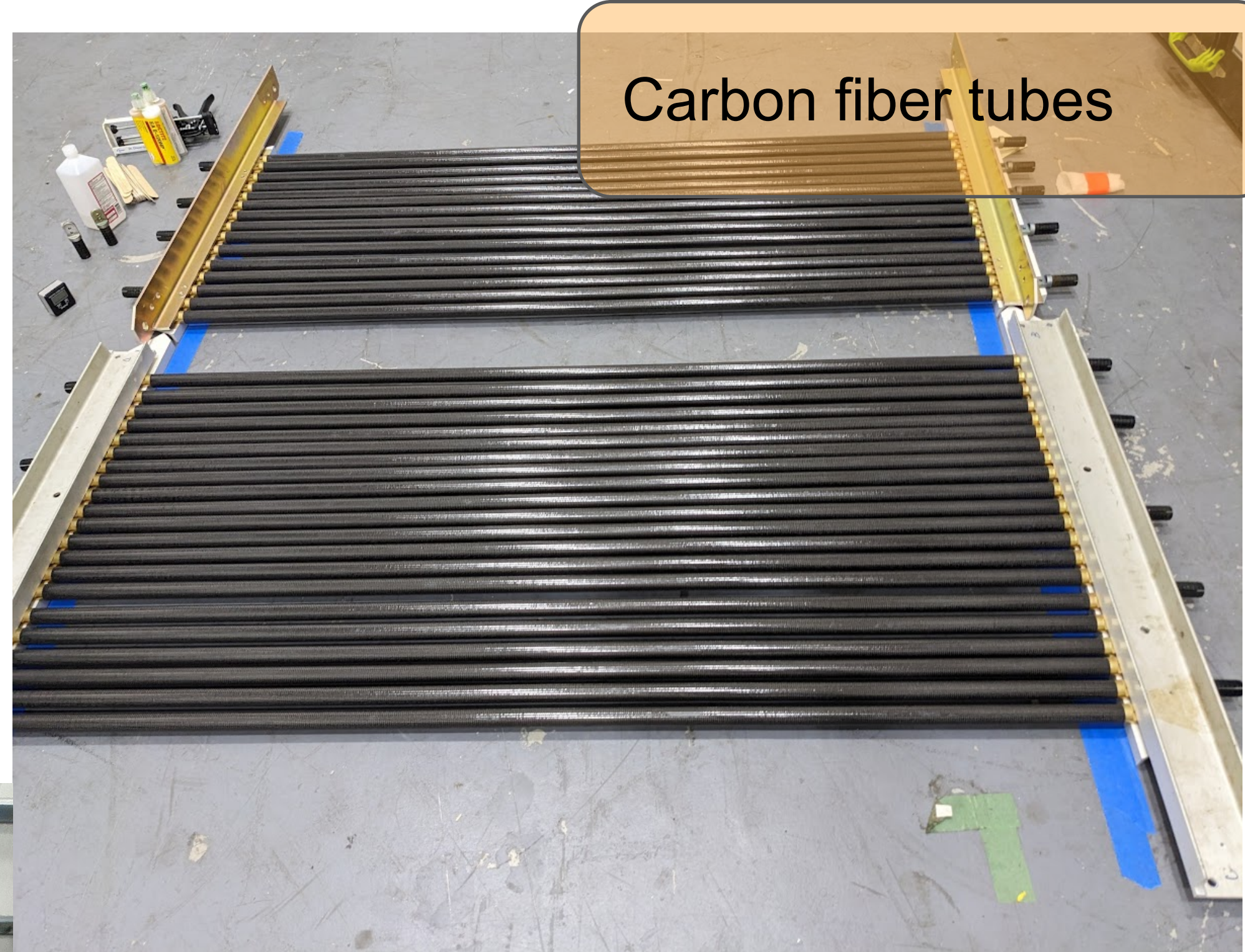


- 4 layers of hexagon ring provide vertical and horizontal baselines for interferometry.
- Keep antennas from blocking each other.
- Sub-deg angular resolution with SNR>5

Connectors station



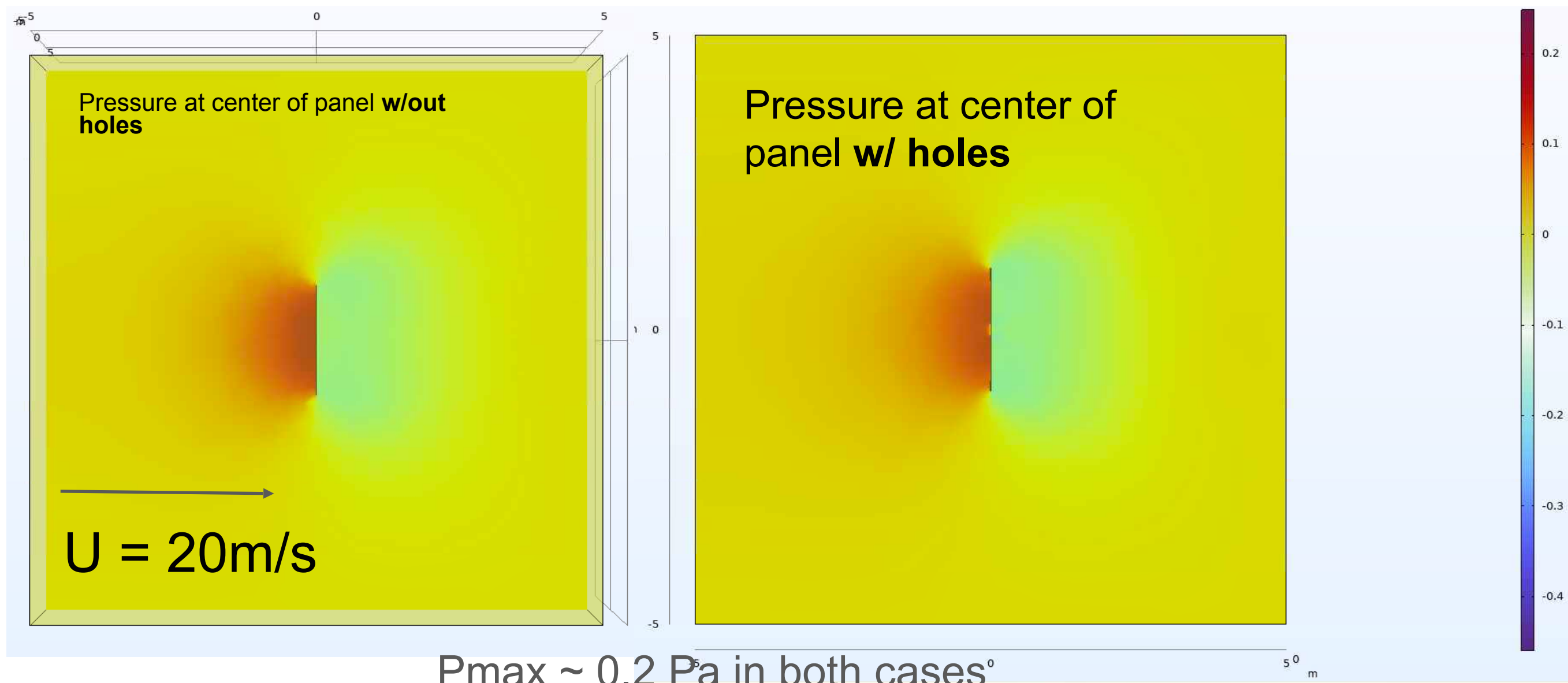
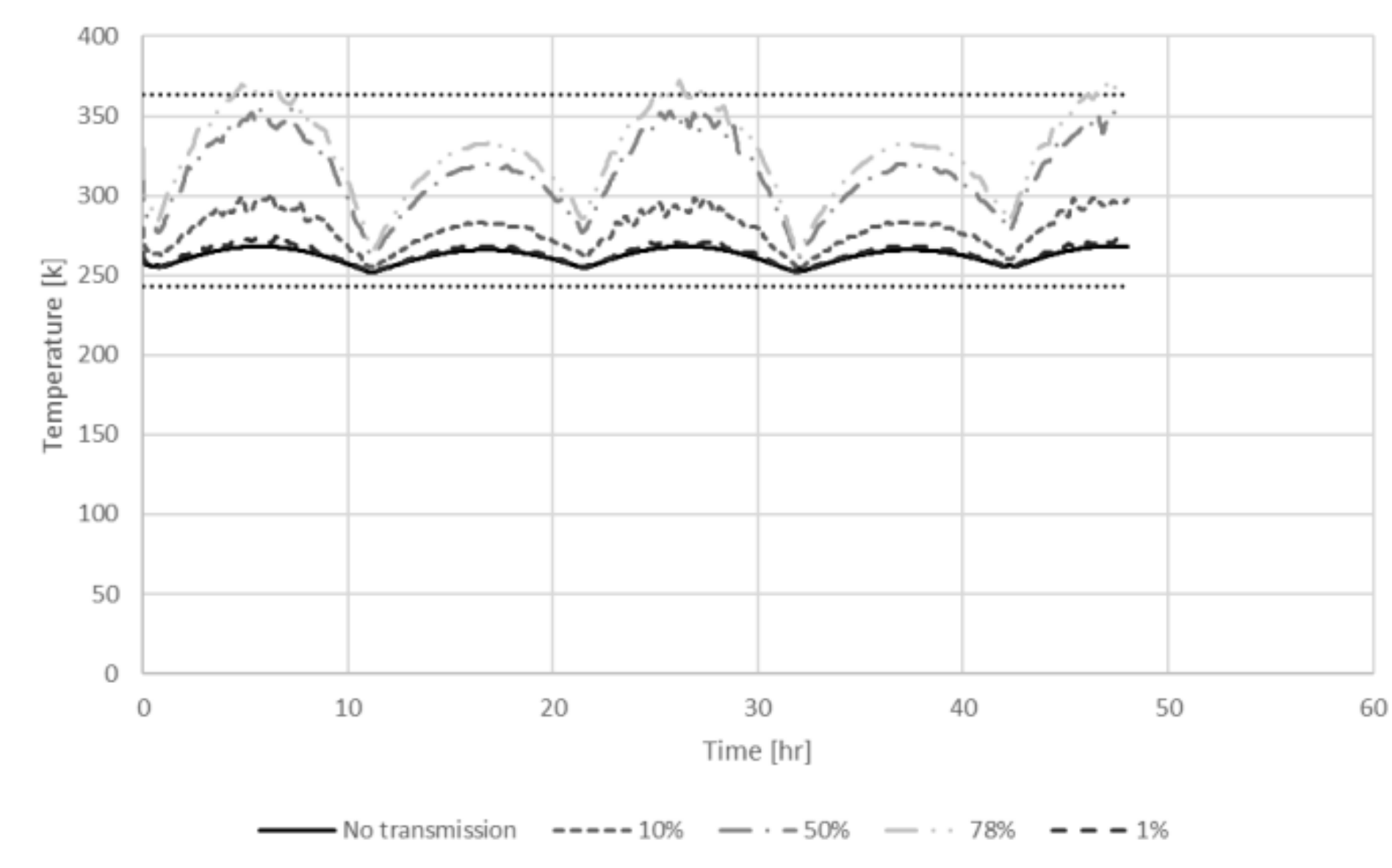
Carbon fiber tubes



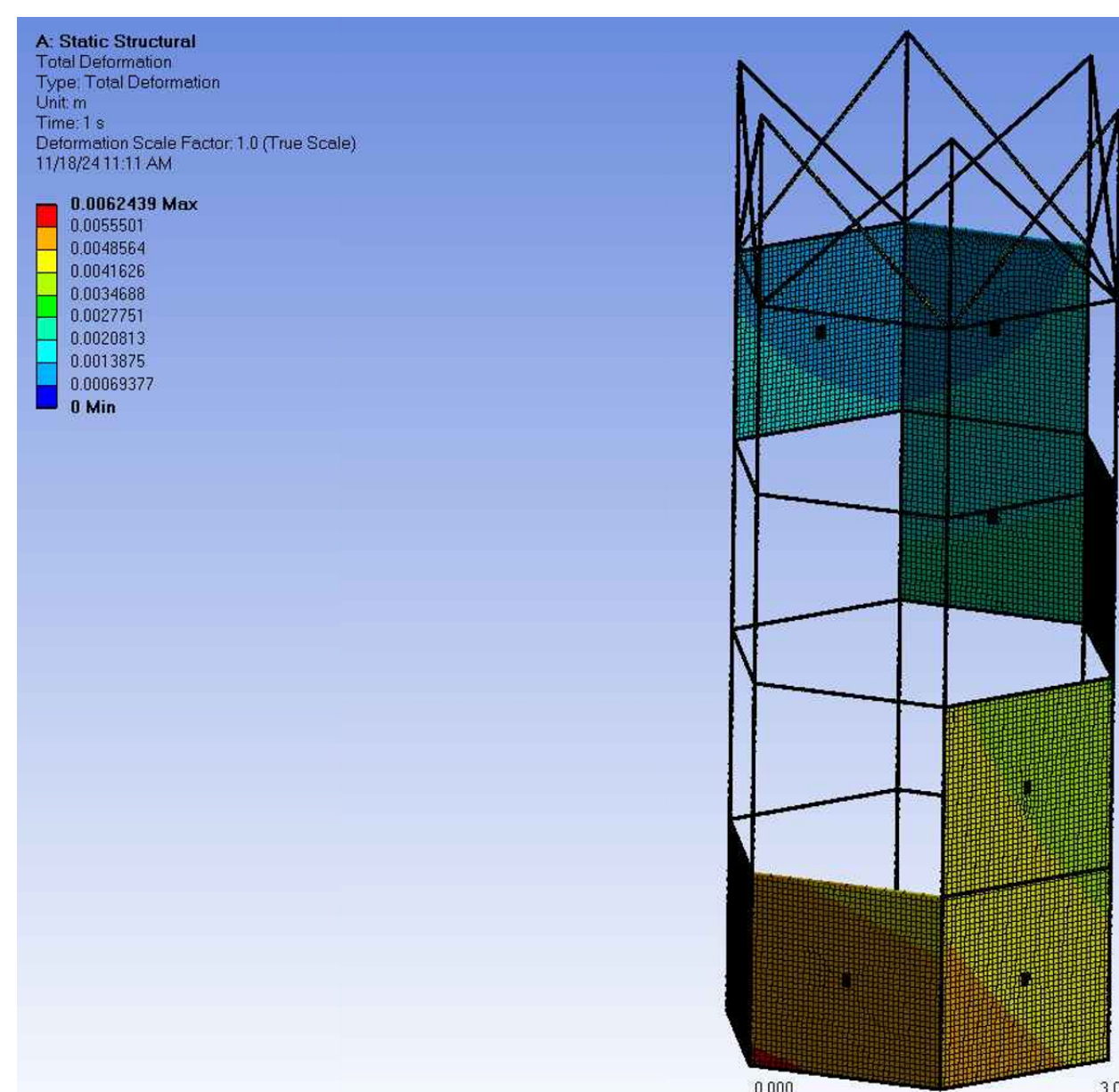
24 ft tall, 12 ft wide
100 lbs in total

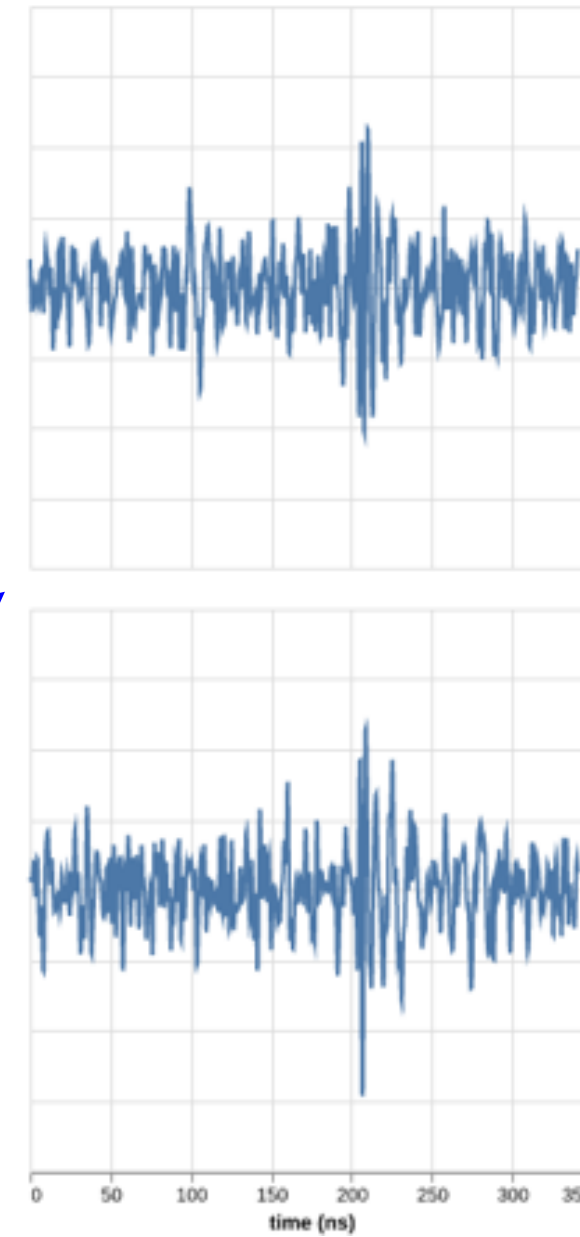
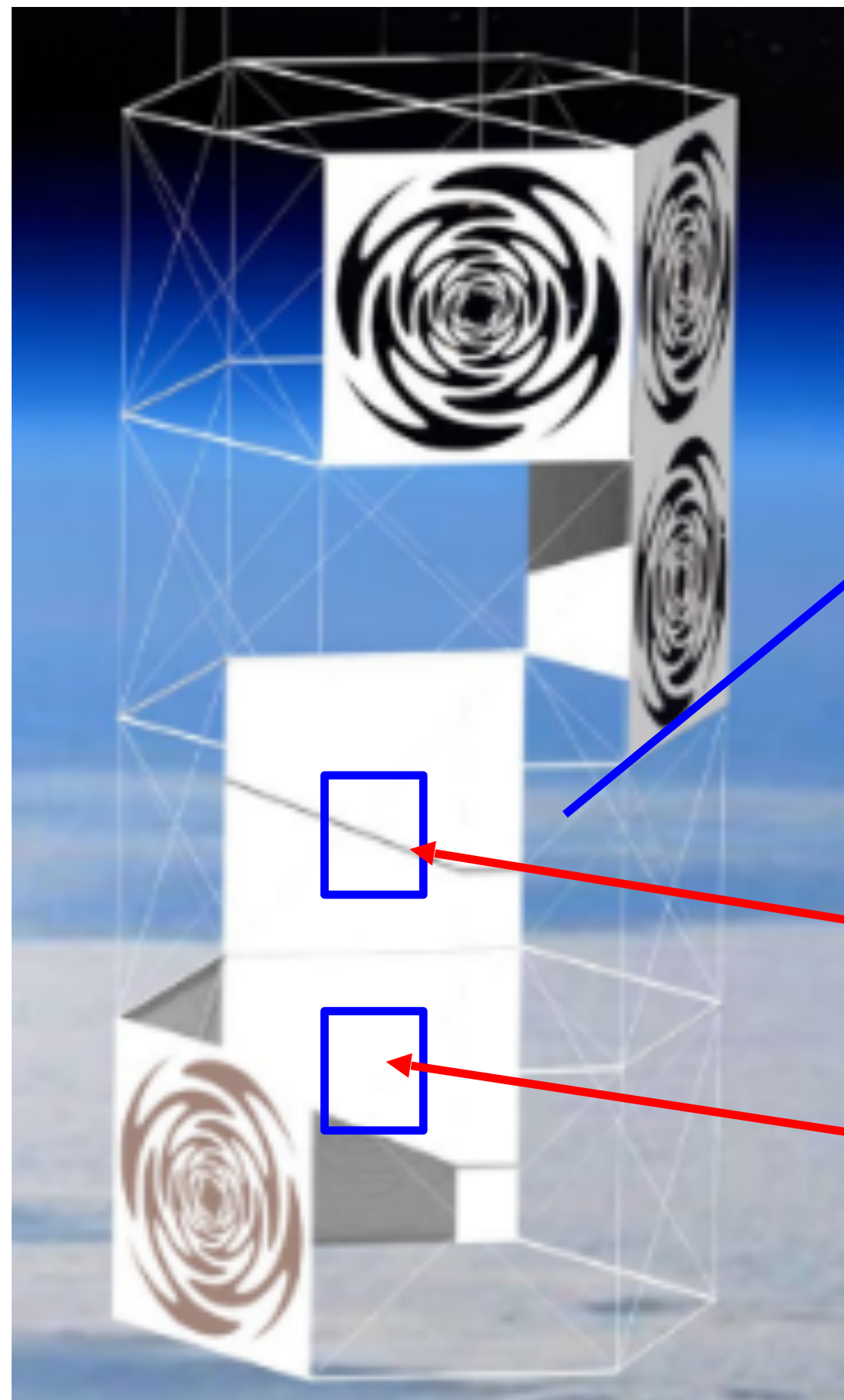


- Thermal study suggests that a >0.1 mm polyester heat shield is necessary.
- Wind study suggests that maximum deflection ~6 mm



Pmax ~ 0.2 Pa in both cases°





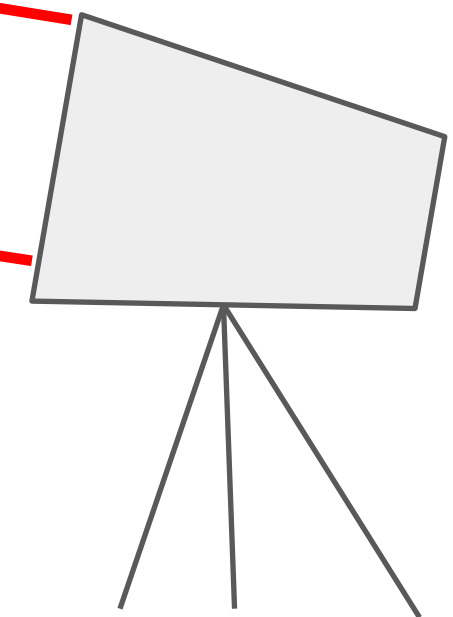
Measurement path:

$\Delta t_{\text{measure}}$ through correlate the measured waveforms

Geometry path: $\Delta t_{\text{expect}} (\Delta \rho, \Delta z, \Delta \phi, \Delta \text{Cabledelay})$
through known pulser loc, payload loc, and assumed **antenna position**.

$$\Delta T = \Delta t_{\text{measure}} - \Delta t_{\text{expect}} (\Delta r, \Delta z, \Delta \phi, \Delta \text{Cabledelay})$$

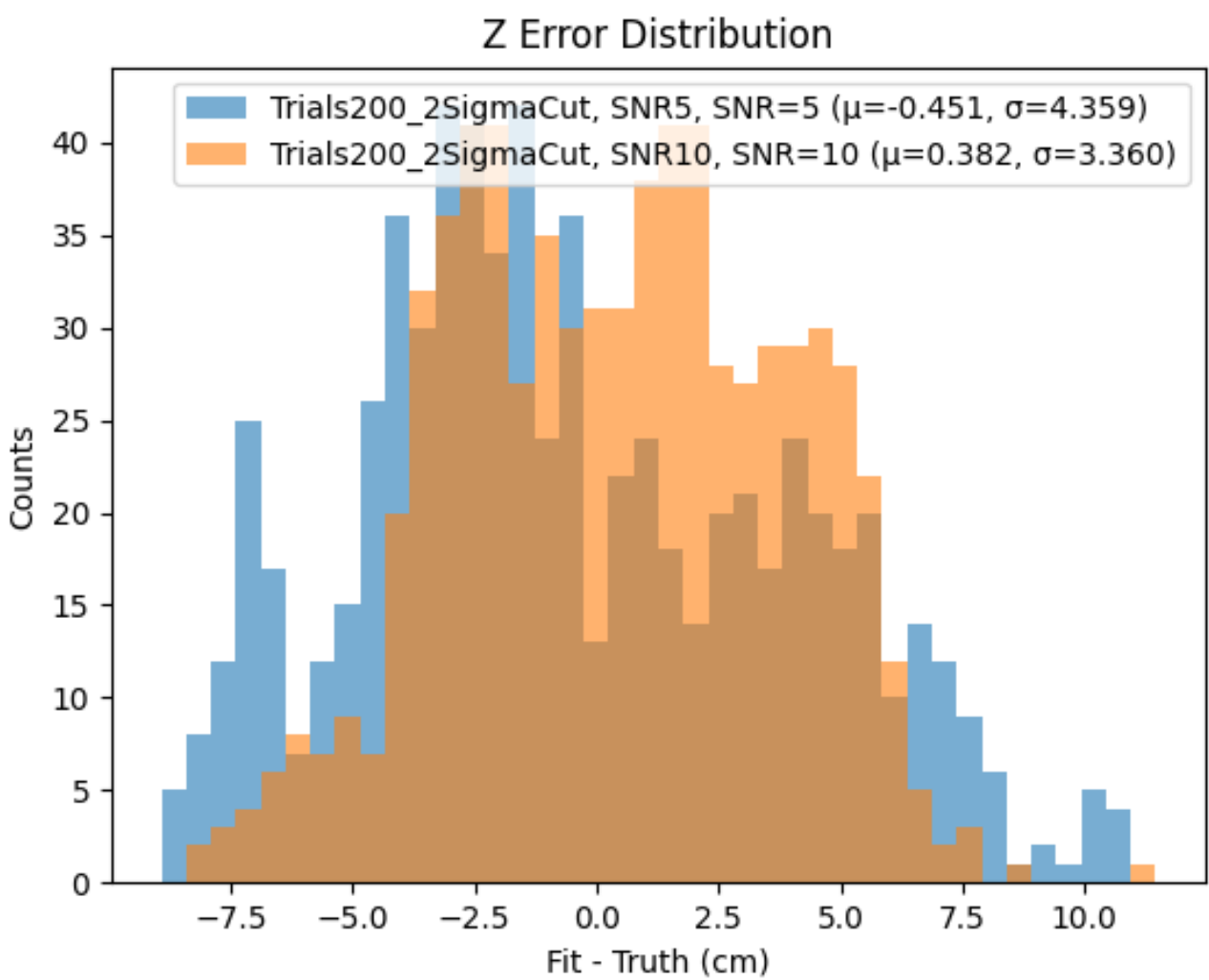
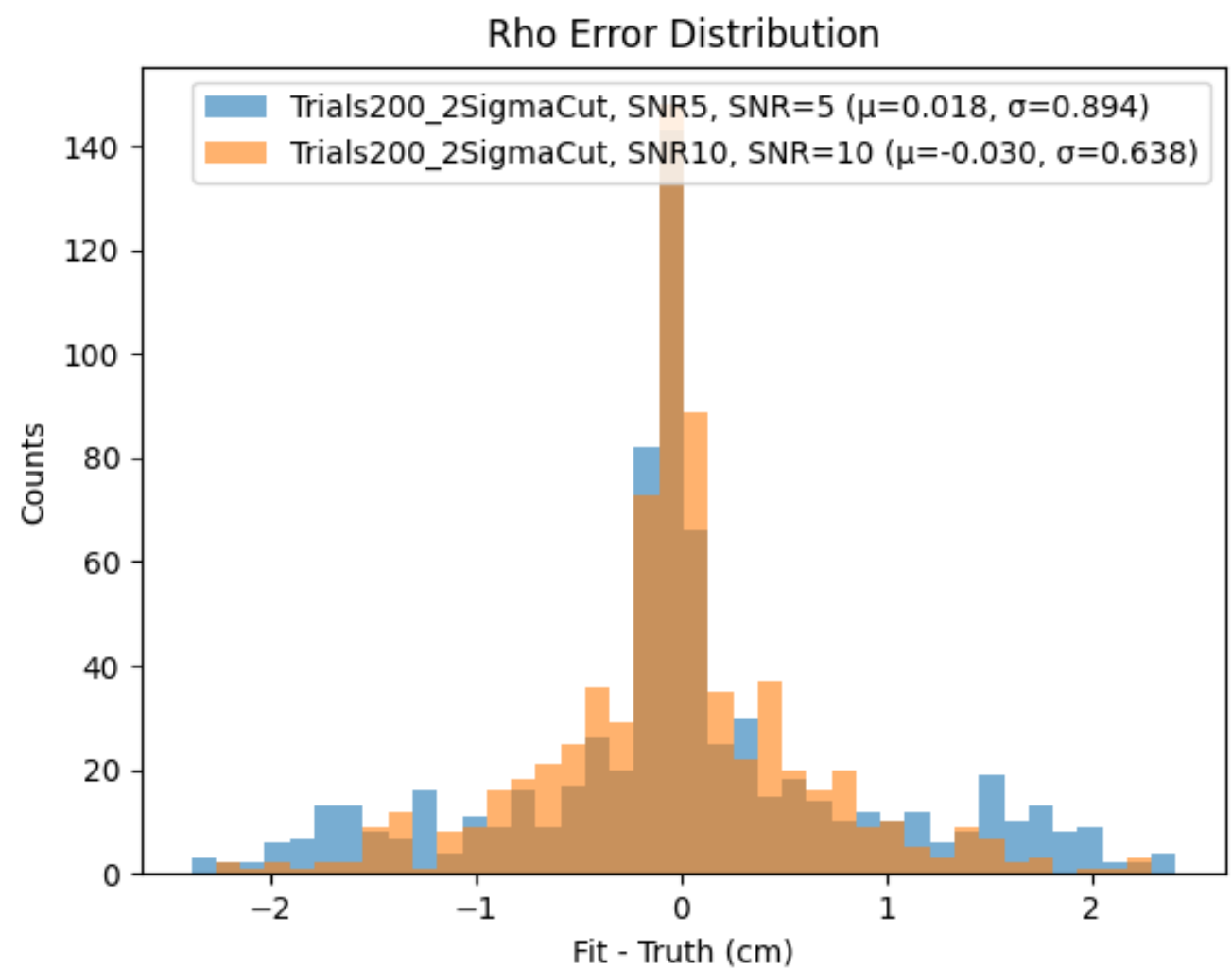
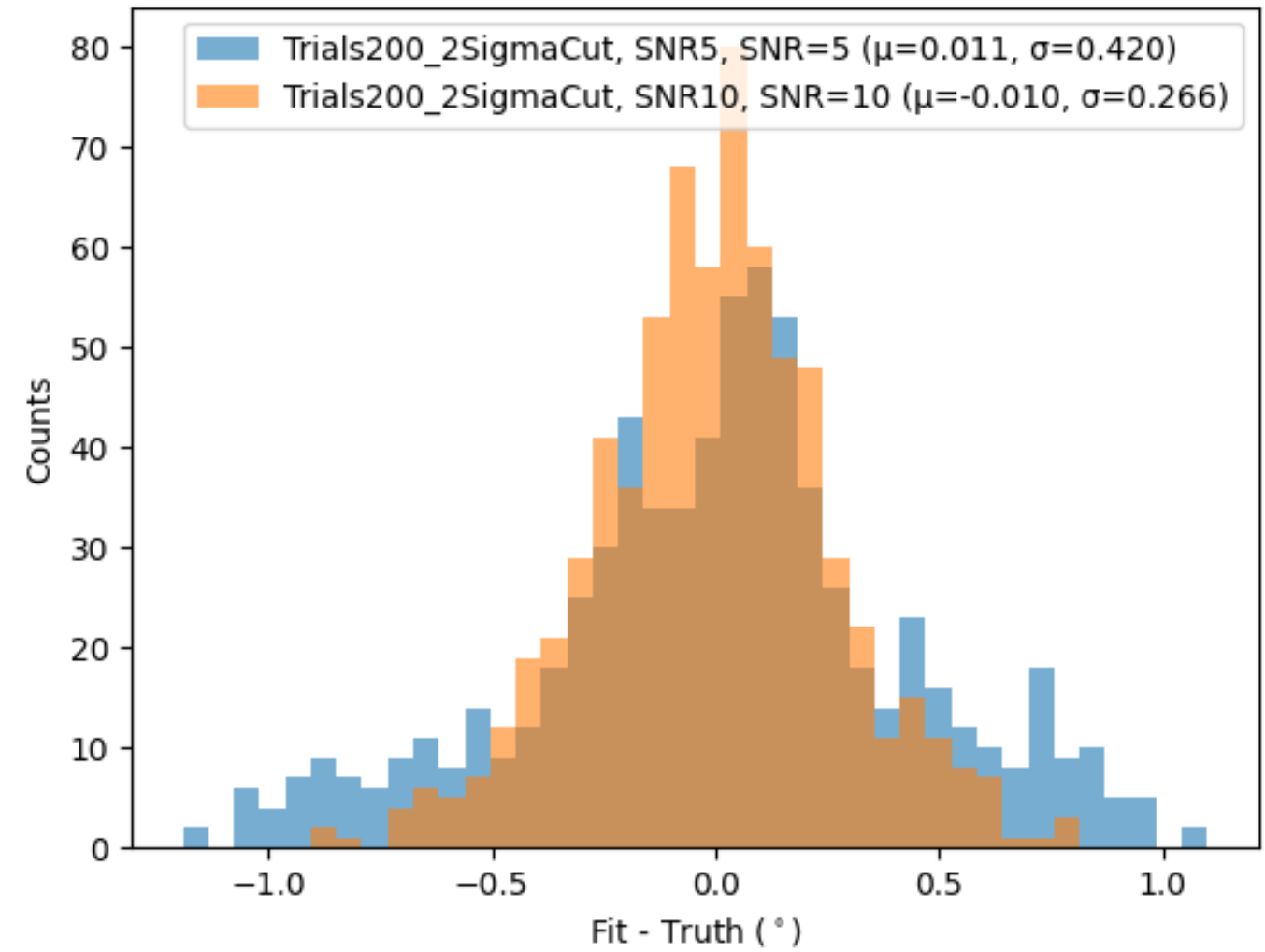
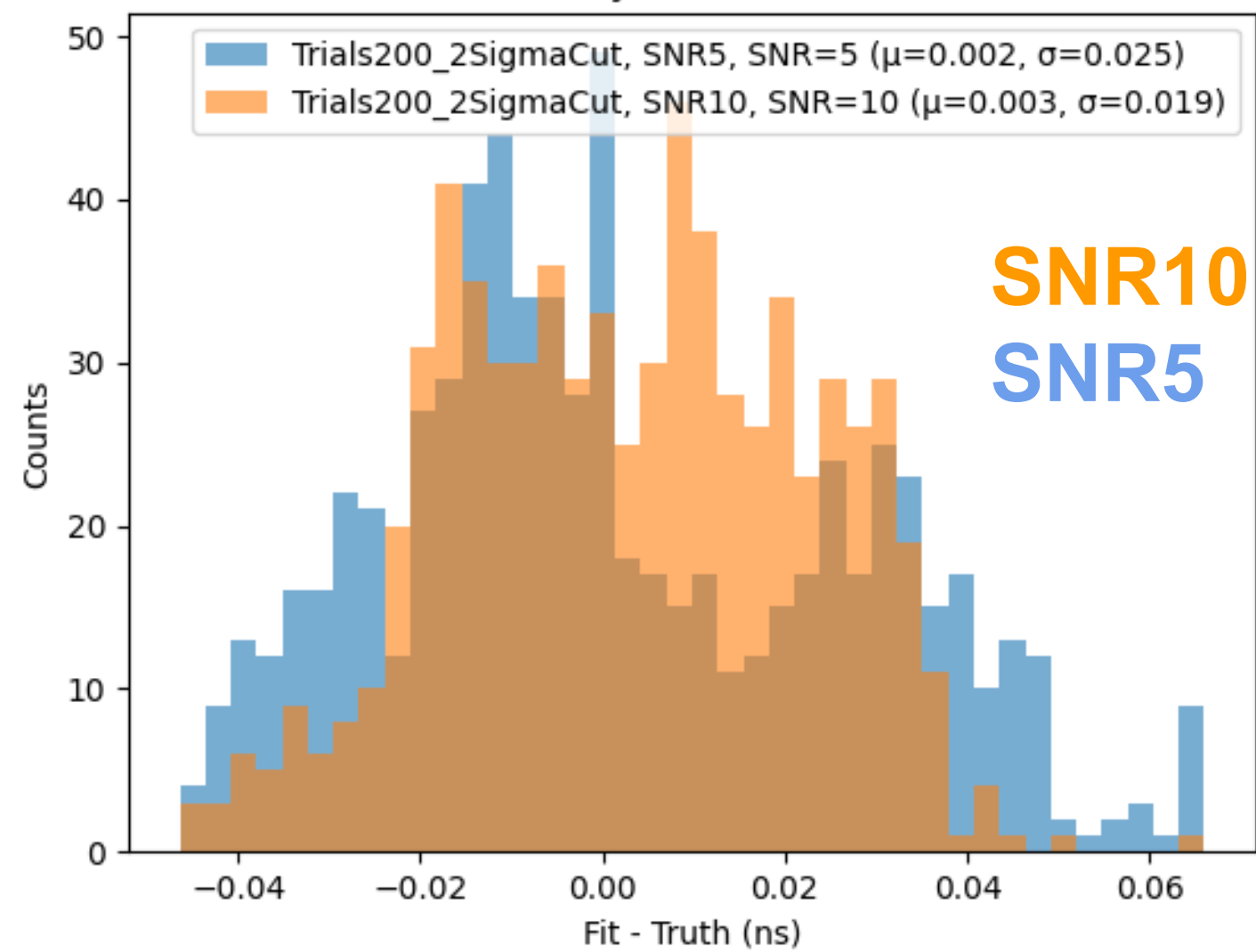
$$\text{Minimize } f(\Delta \text{CableDelay}, \Delta r, \Delta z, \Delta \phi) = \sum_j^{\text{AntennaPairs}} (\Delta T)^2$$



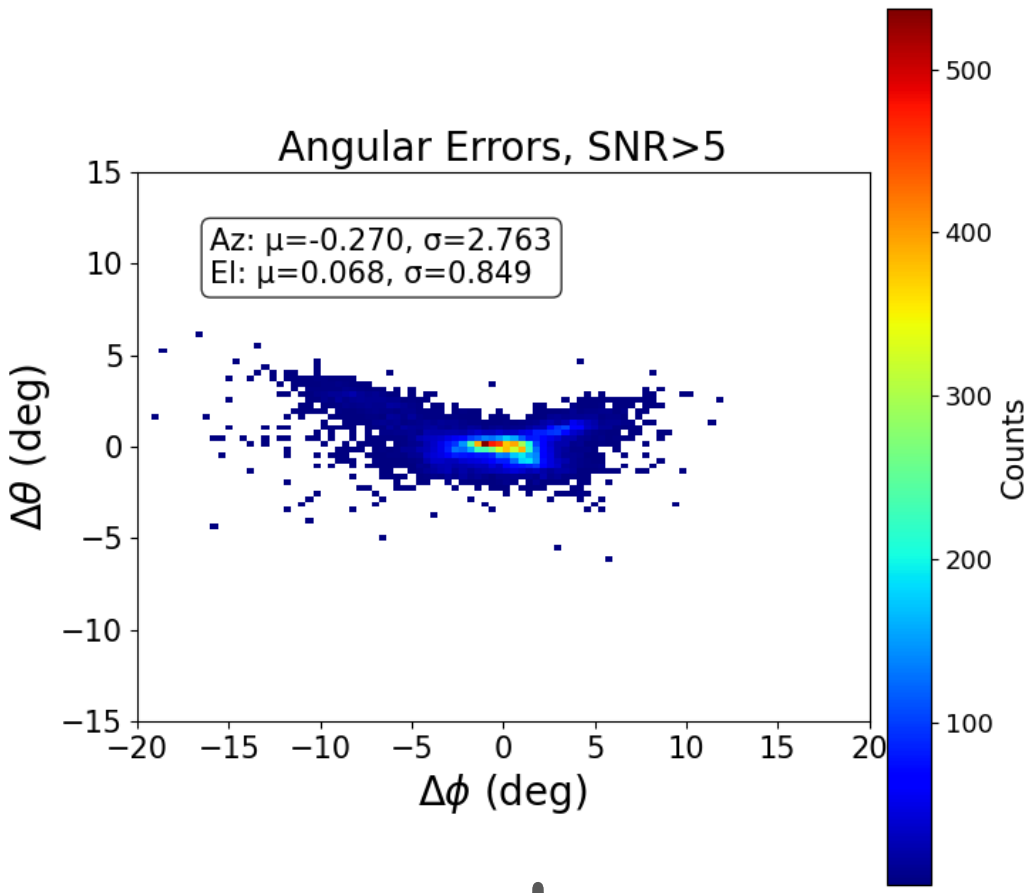
CableDelay~0.03ns
z ~ 4.5cm

$\rho \sim 0.9\text{cm}$

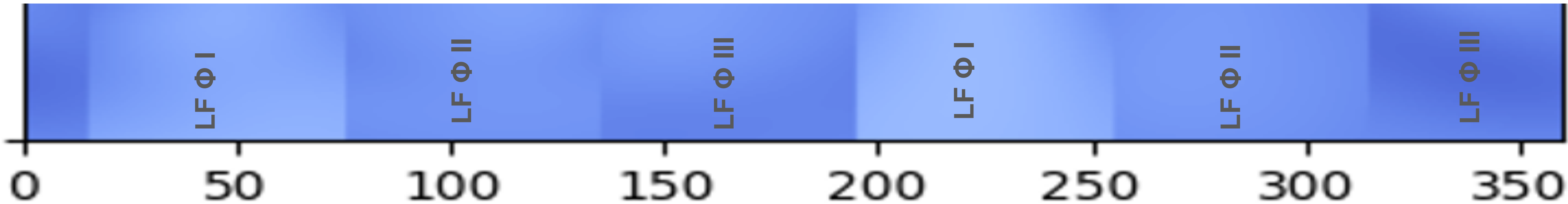
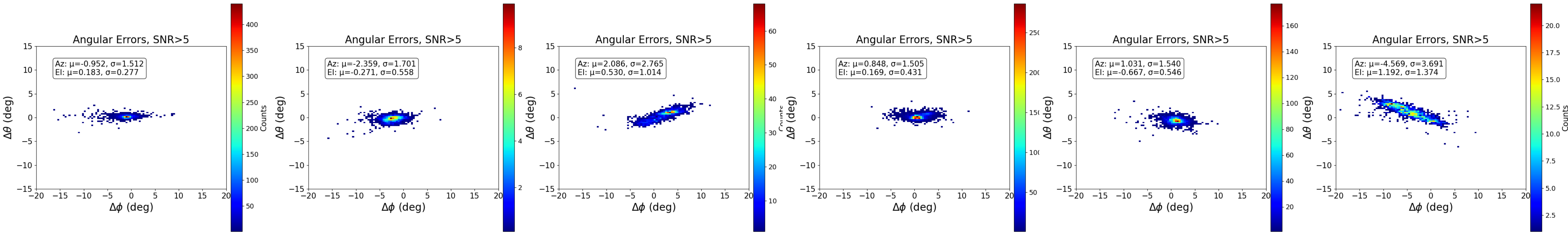
$\phi \sim 0.4 \text{ deg}$



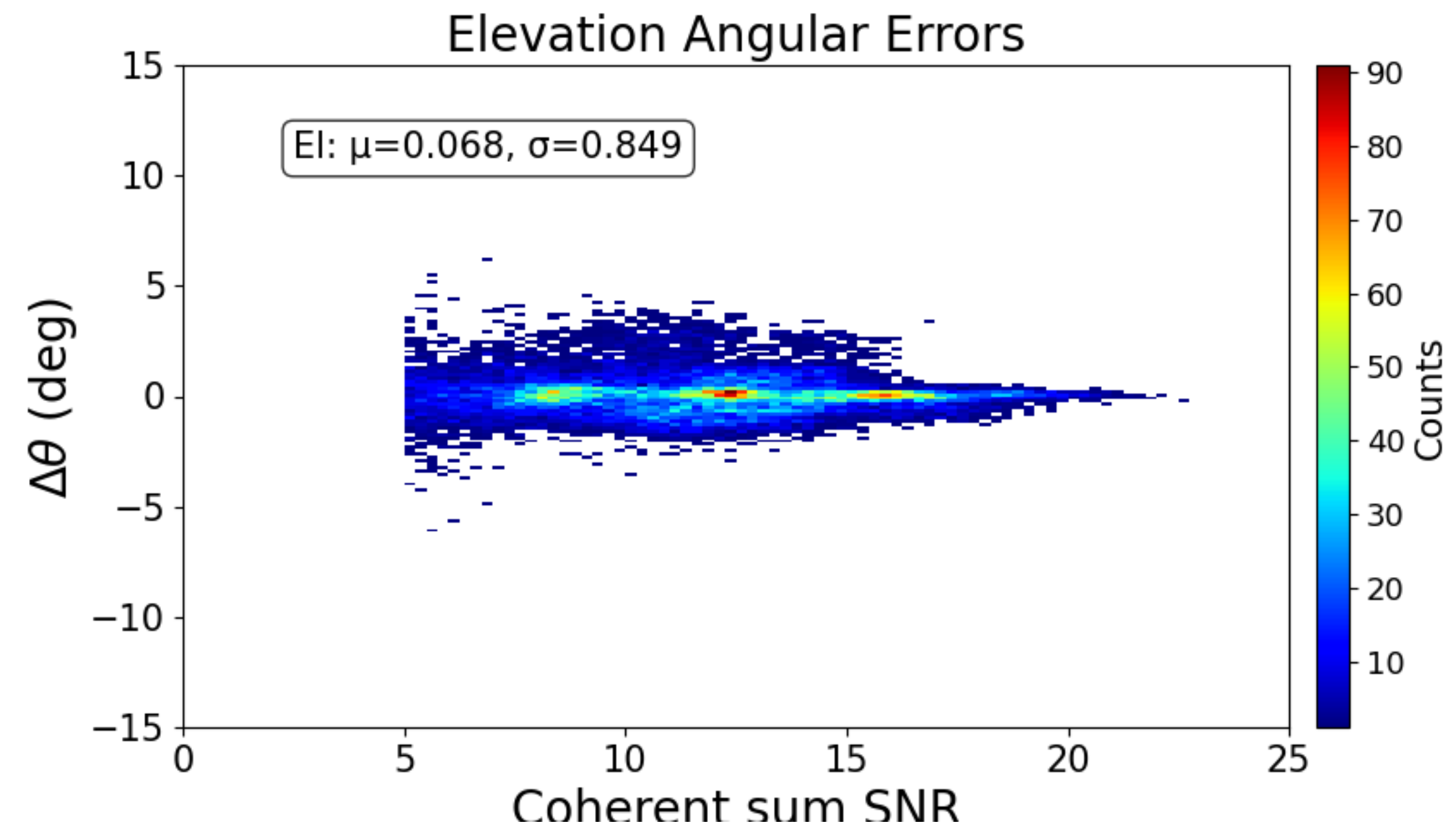
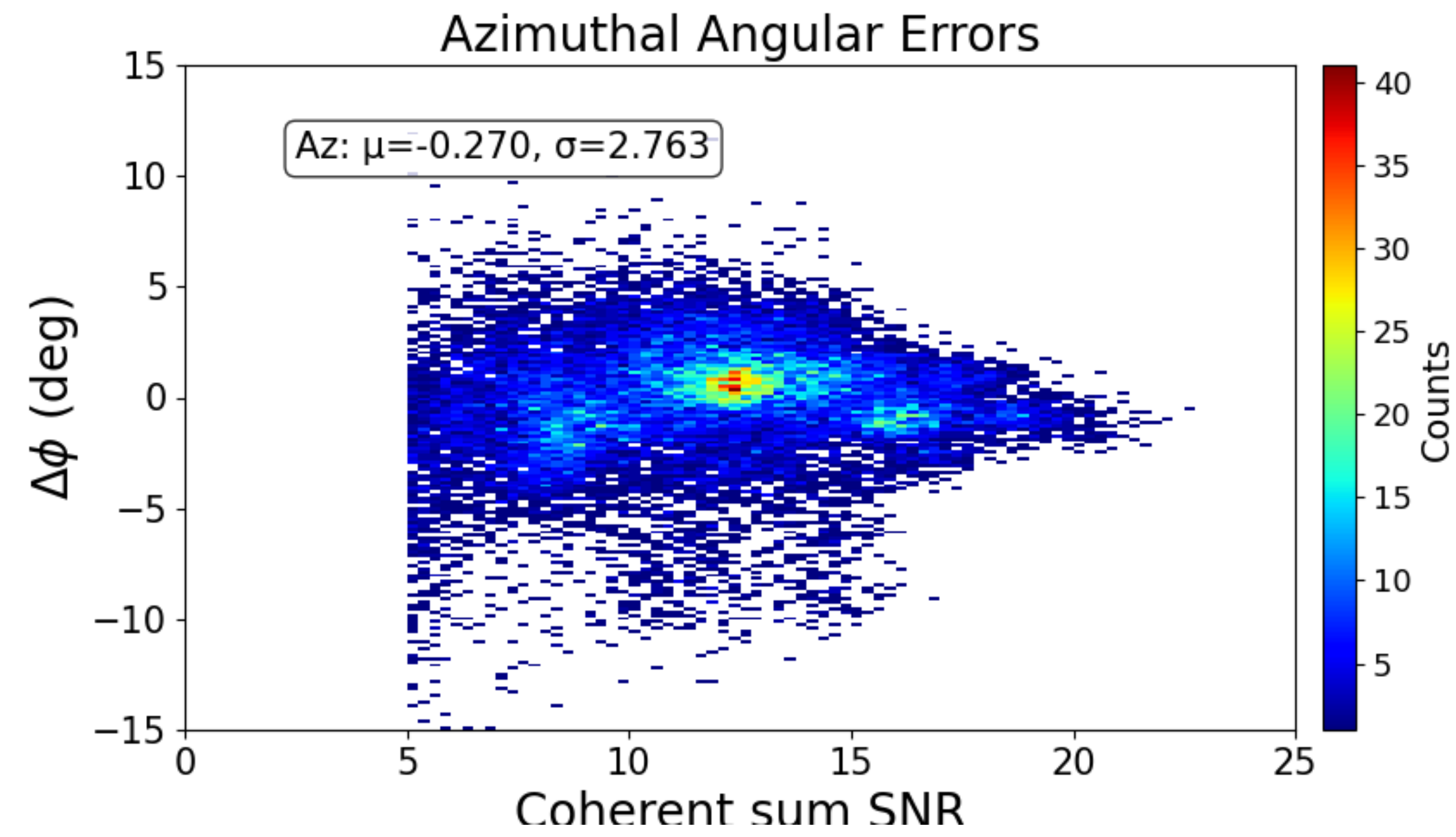
In each LF phi sector

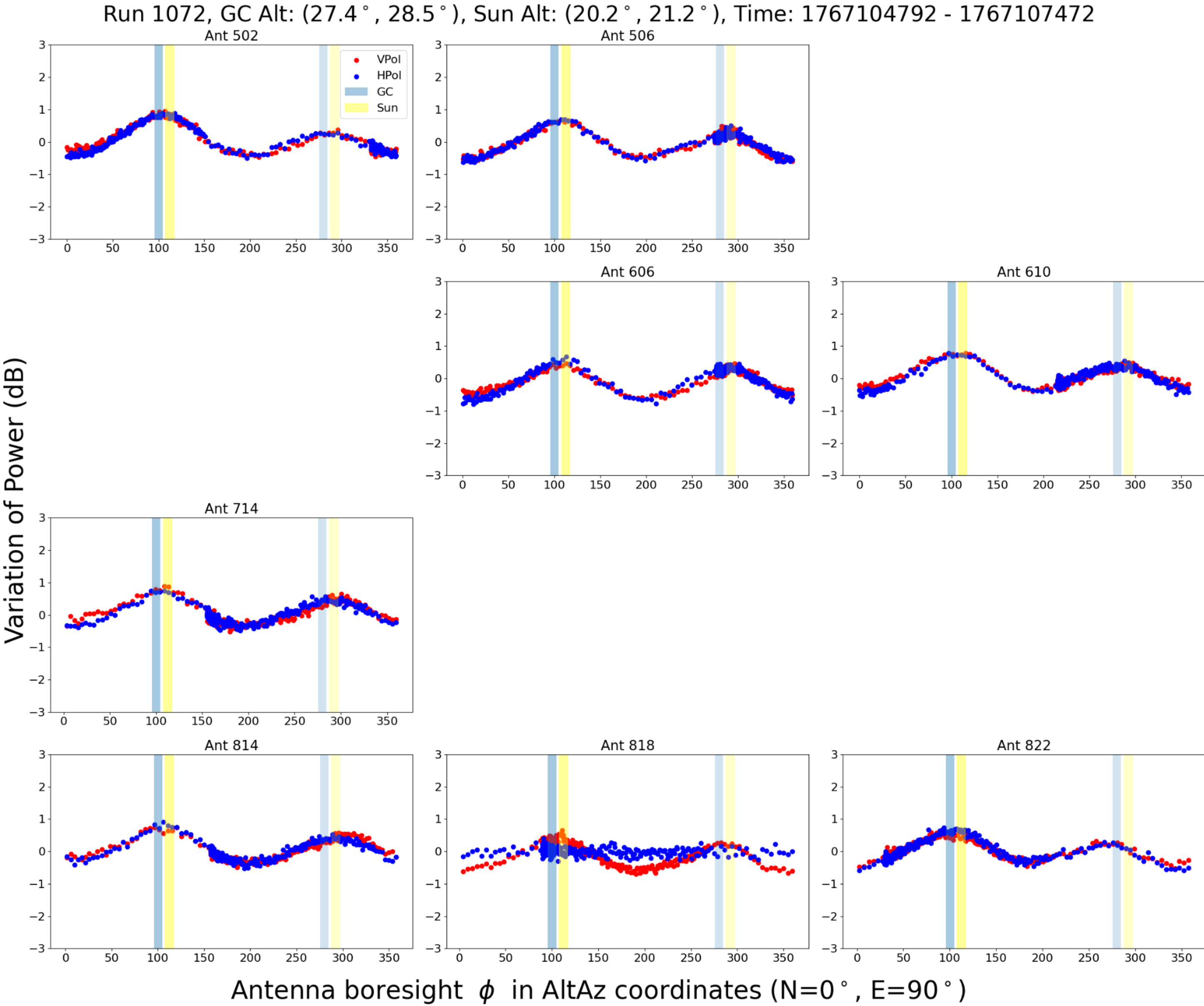


To investigate:
Azimuthal (ϕ) has an opposite-signed
offset at ϕ and $\phi+180$ deg

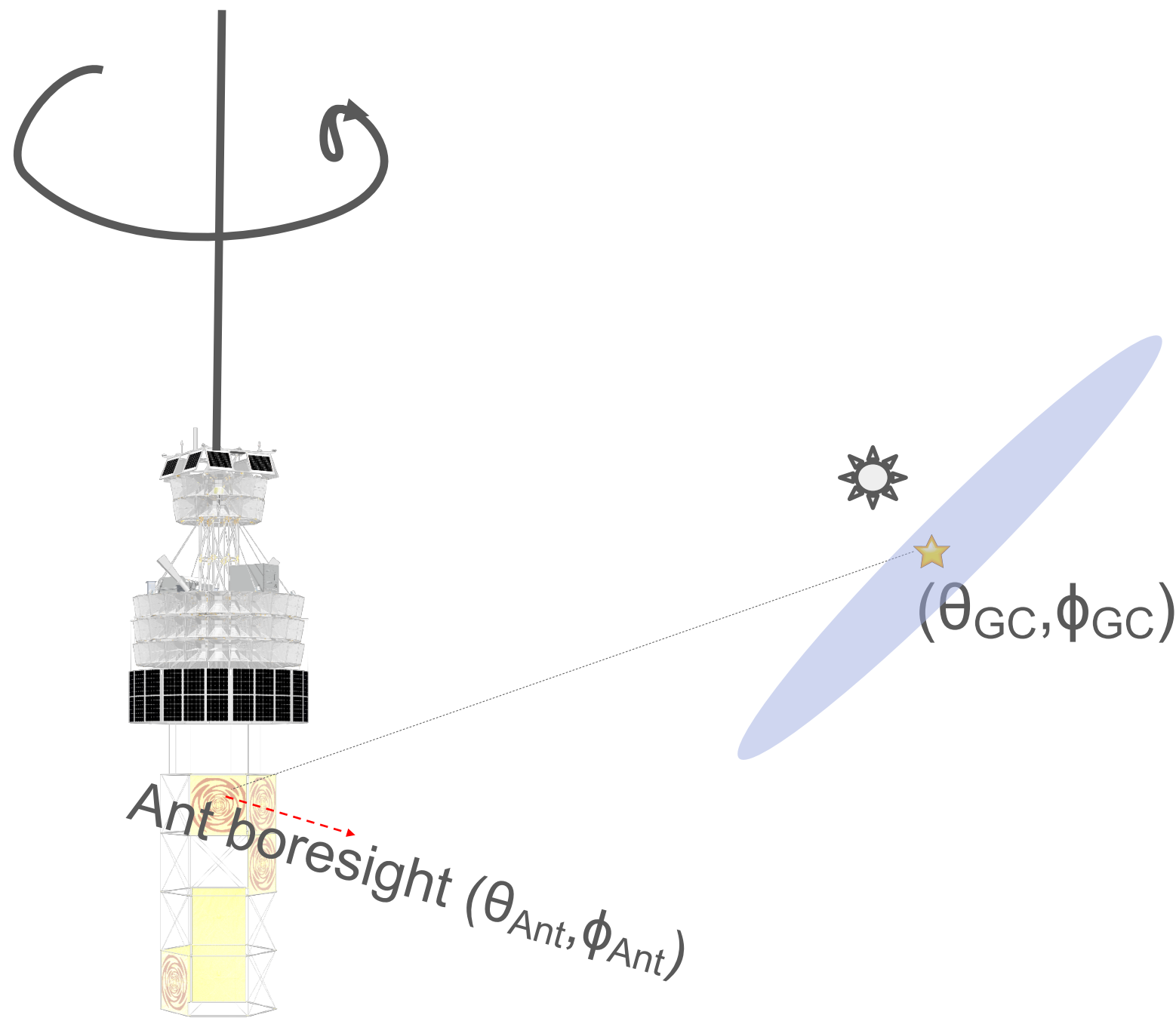


Azimuth in payload coordinate (deg)





Payload spinning

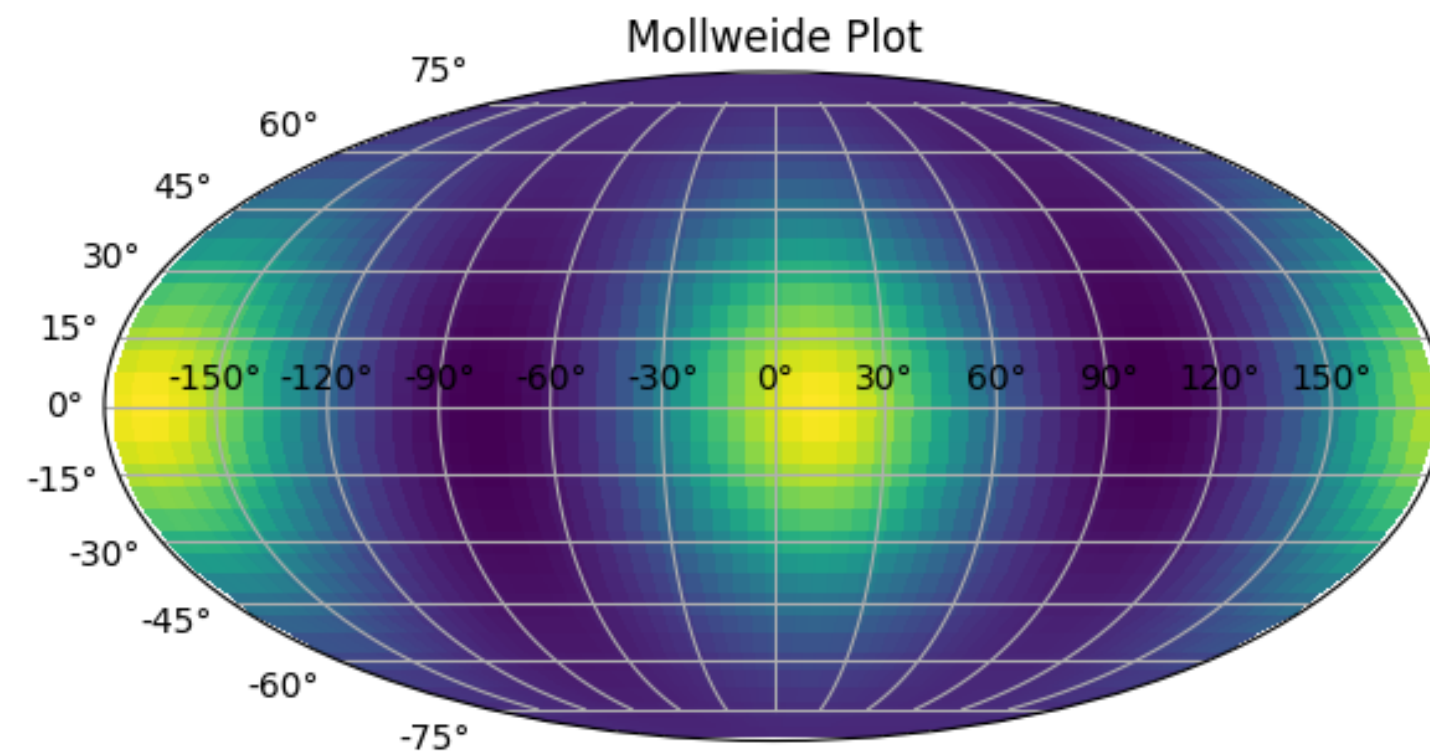


- Noise power strongly depends on the antennas orientation relative to the GC
- Sun is always close (~10 deg) to the GC during the flight, so it's hard to decouple the effects. However, during the quiet sun periods (no solar burst) galaxy is expected to be 1-2 orders of magnitude brighter.

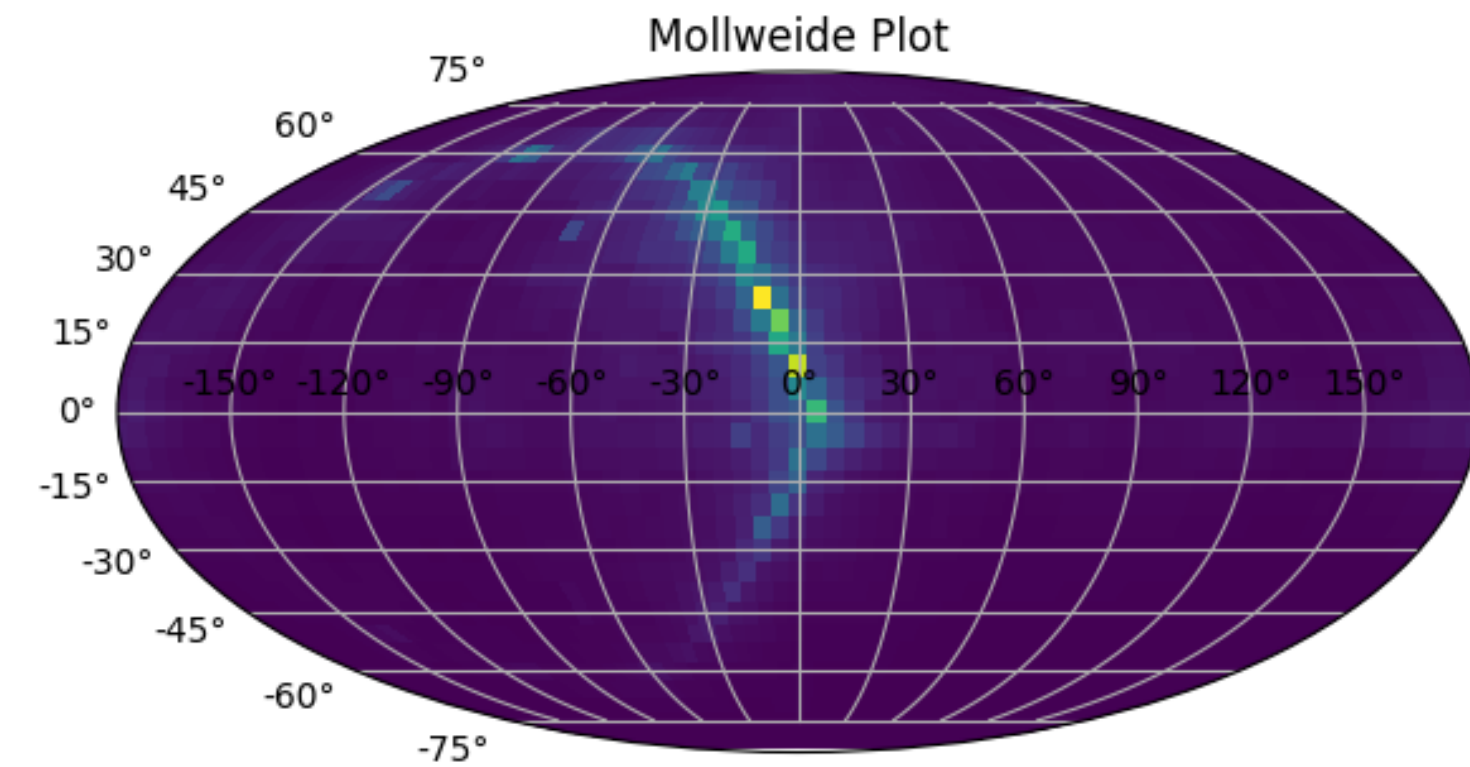
100 MHz

Antenna model

Haslam sky model



X



Antenna Temperature

$$T_A = \frac{1}{4\pi} \int G(\theta, \phi) T_b(\theta, \phi) d\Omega.$$

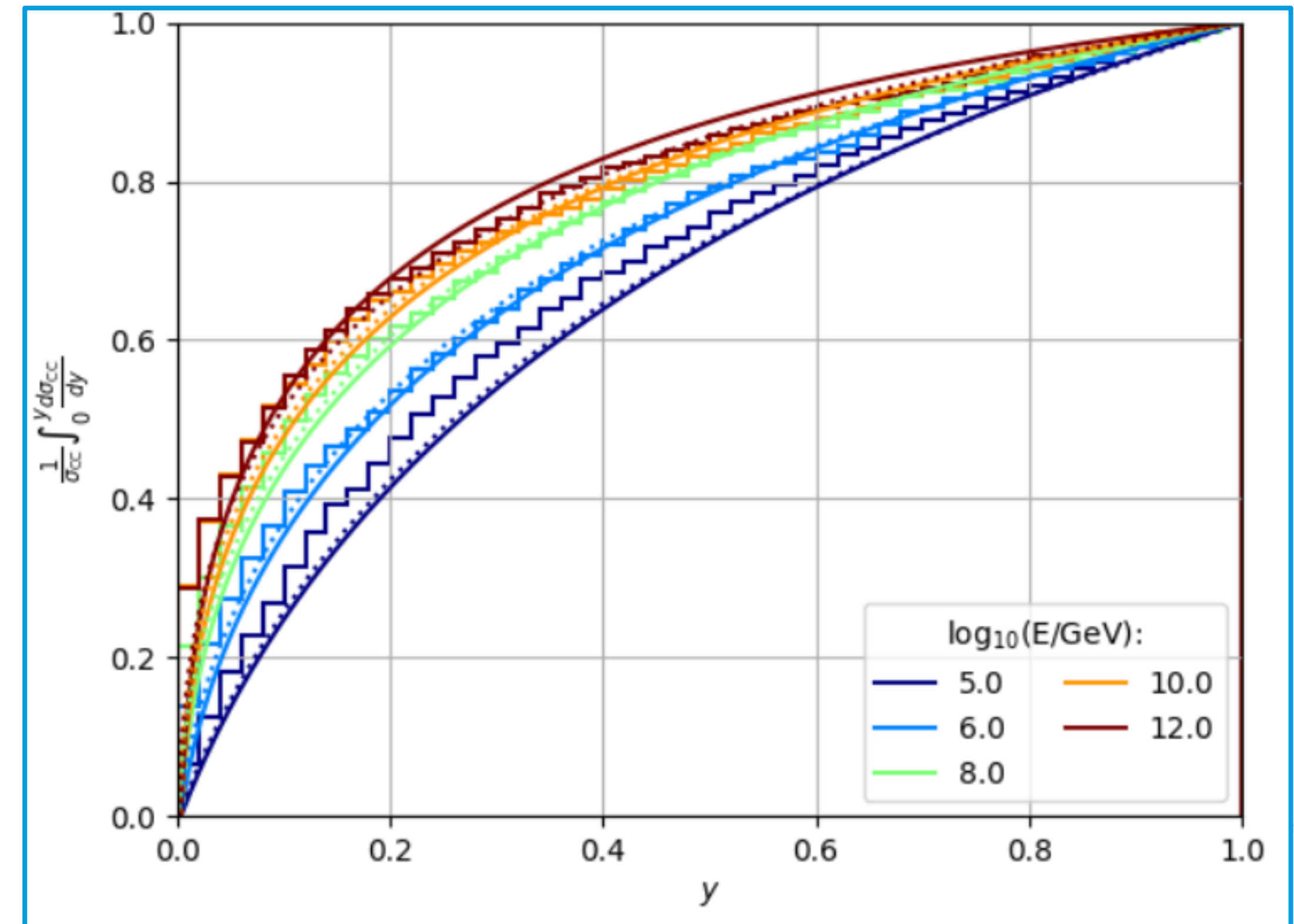
“Power at antennas’ feed”

$$P_{sky\ model}(t, \nu) = k_B T_A(t, \nu) \Delta B$$

$$P_{measured}(t, \nu) G_{RF\ chain}^{-1}(\nu) = P_{sky\ model}(t, \nu) C_0^2(\nu) + N_{tot}(\nu)$$

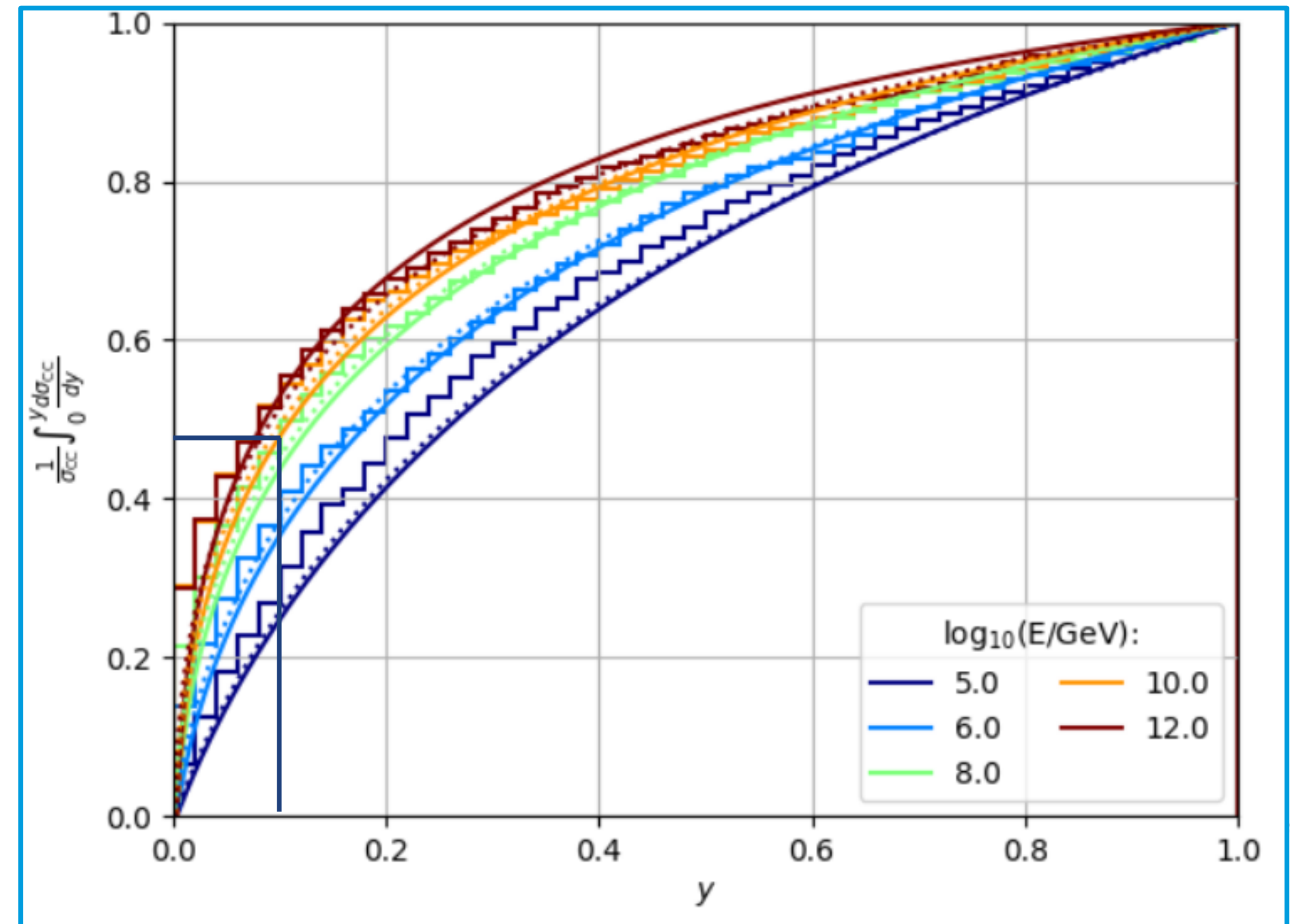
UHE Lepton Interactions

- Lepton keeps most of its energy



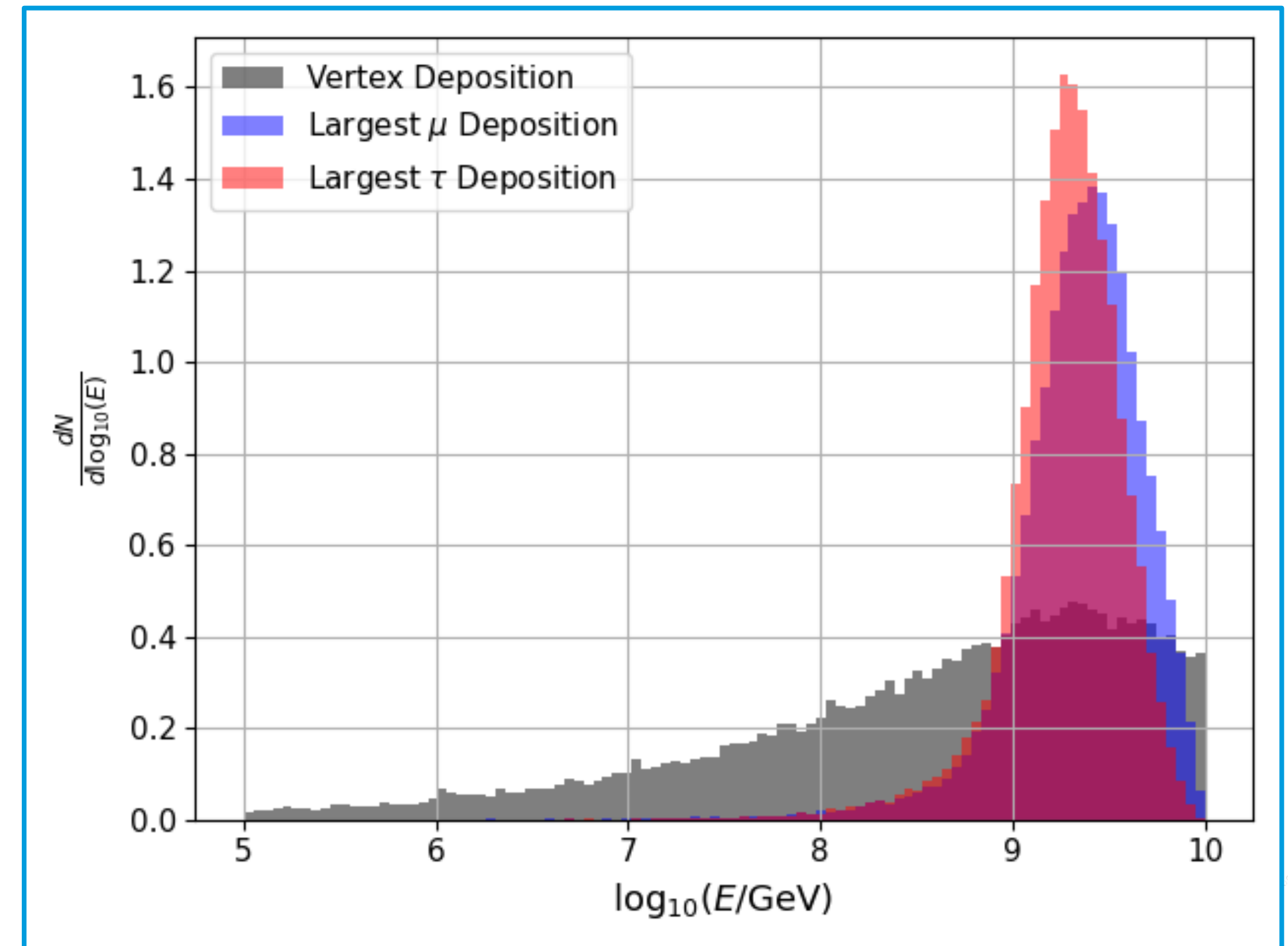
UHE Lepton Interactions

- Lepton keeps most of its energy
- At 10EeV: ~50% of events have >90% of energy in lepton



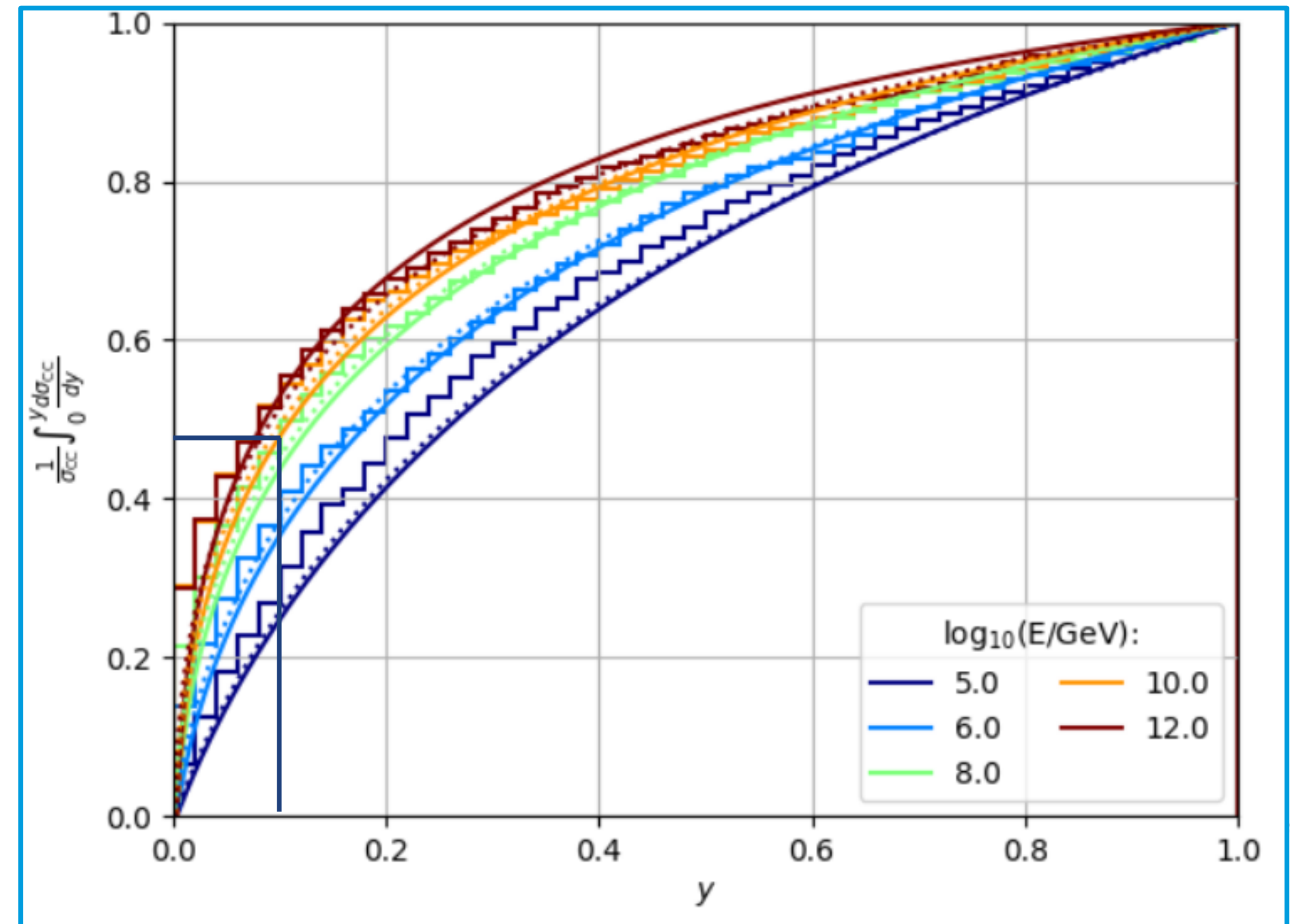
UHE Lepton Interactions

- Lepton actually produces higher-energy showers



UHE Lepton Interactions

- Lepton keeps most of its energy
- At 10EeV: ~50% of events have >90% of energy in lepton



UHE Lepton Interactions

- Lepton actually produces higher-energy showers

