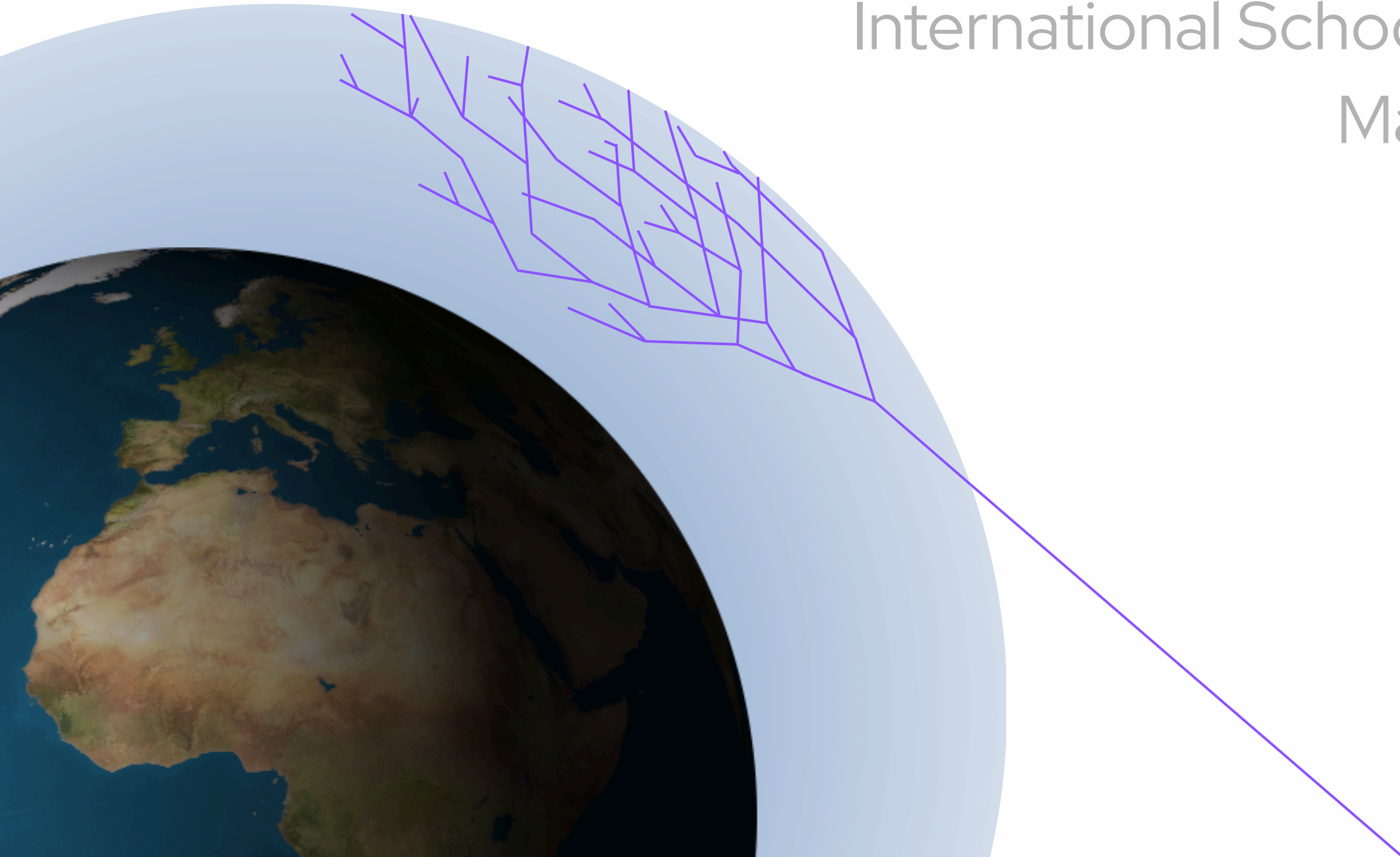


# COREAS AND ZHAIRES RADIO AIR-SHOWER SIMULATIONS FOR POEMMA BALLOON WITH RADIO (PBR)

International School of Cosmic Ray Astrophysics,  
Maurice M. Shapiro, 24th Course  
ISCRA 2026

Paula Gálvez Molina  
for the JEM-EUSO Collaboration

July 30<sup>th</sup> 2026





# PROBE OF EXTREME MULTI-MESSENGER ASTROPHYSICS



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Proposed NASA space-based mission

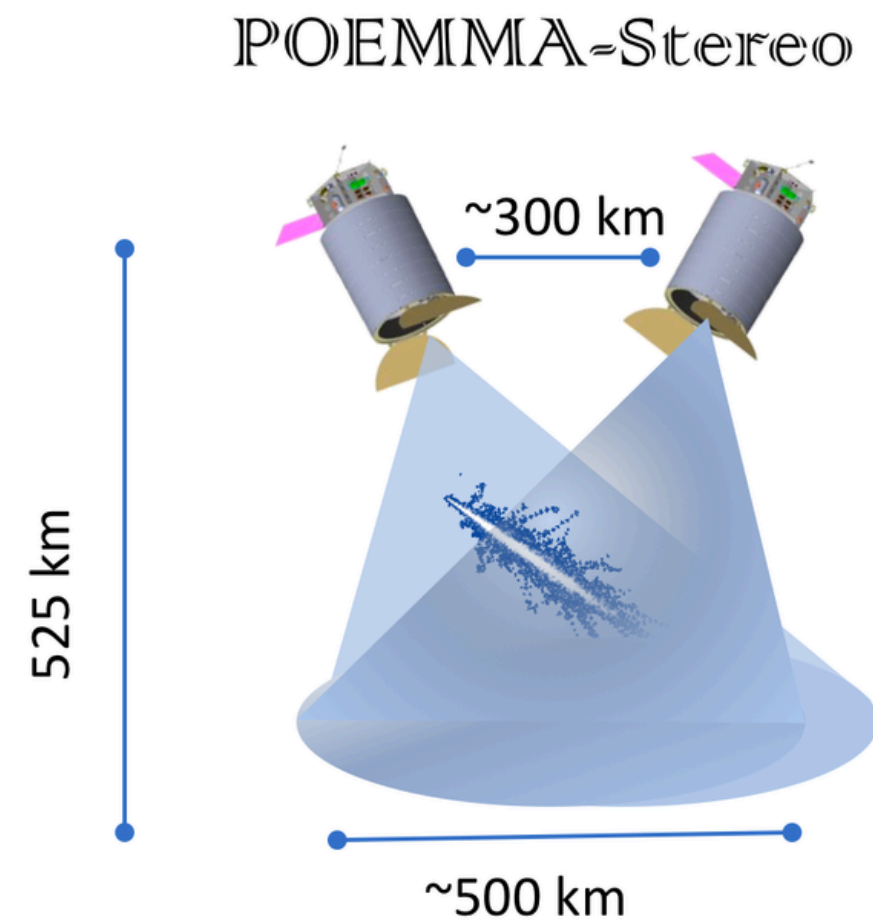
Flying 2 identical satellites at an altitude of 525 km



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Proposed NASA space-based mission

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10.1088/1475-7516/2021/06/007

Optimized for the fluorescence  
observation of EAS

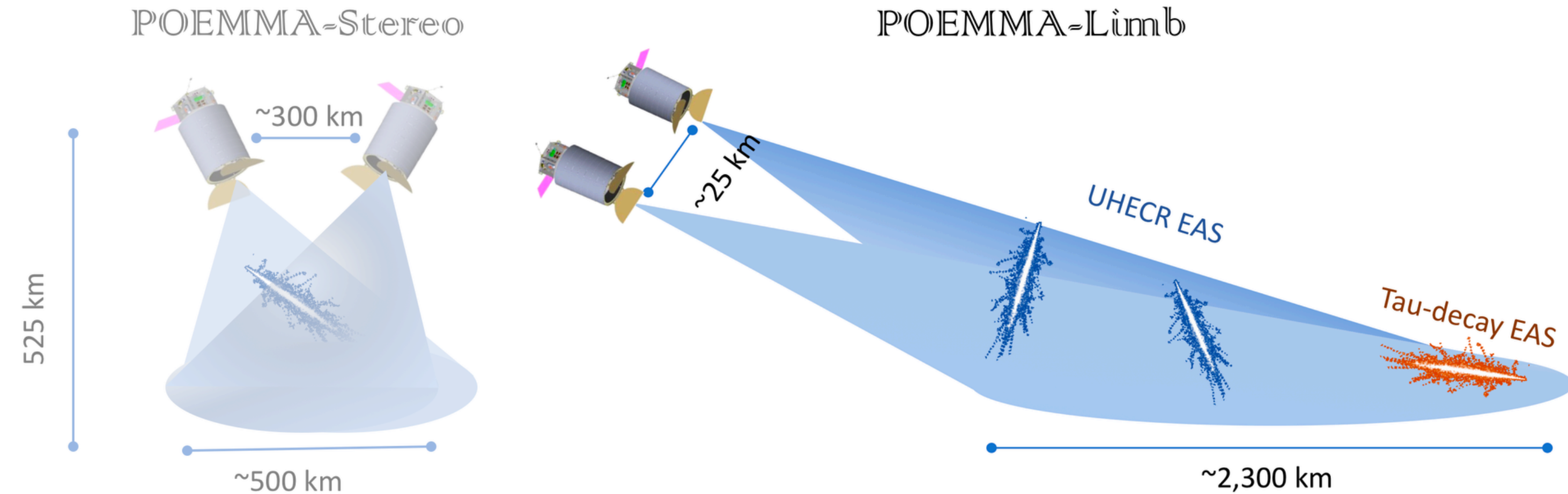




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Proposed NASA space-based mission

Flying 2 identical satellites at an altitude of 525 km



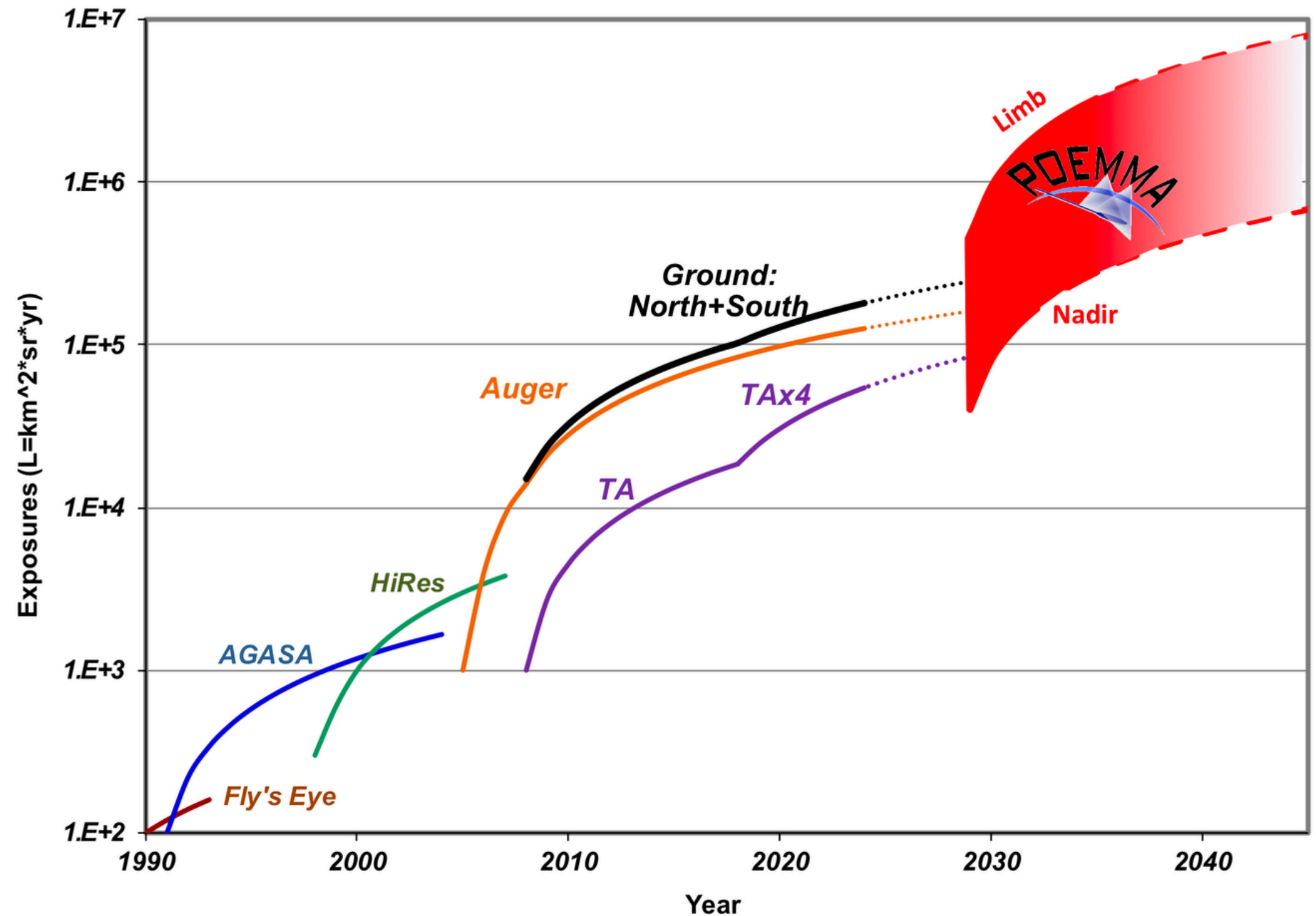
10.1088/1475-7516/2021/06/007

Optimized for the fluorescence  
observation of EAS

Optimized for observations from  
Target of Opportunities



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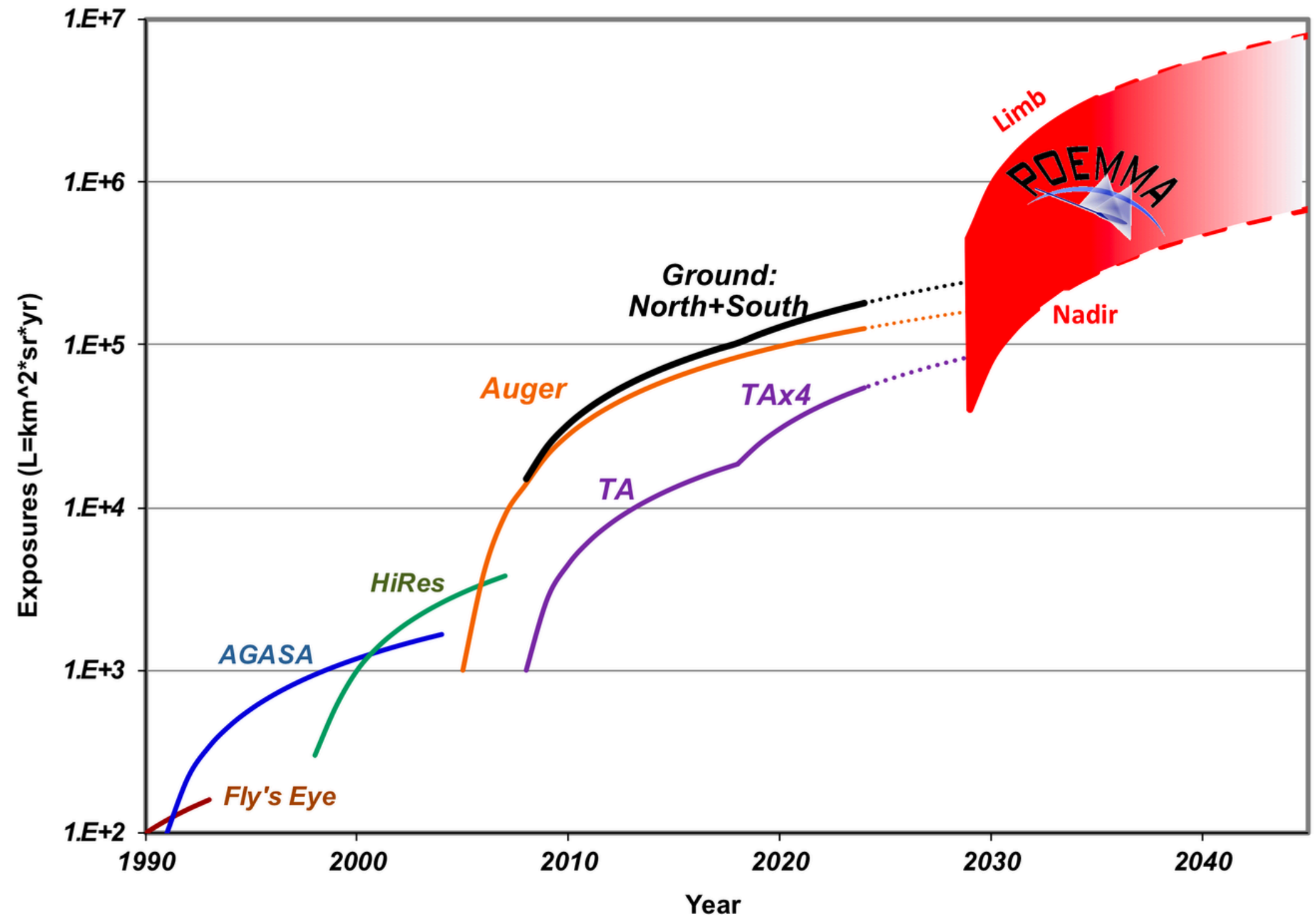


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- POEMMA's exposure from nadir (stereo) to limb observations surpasses that of ground-based detectors

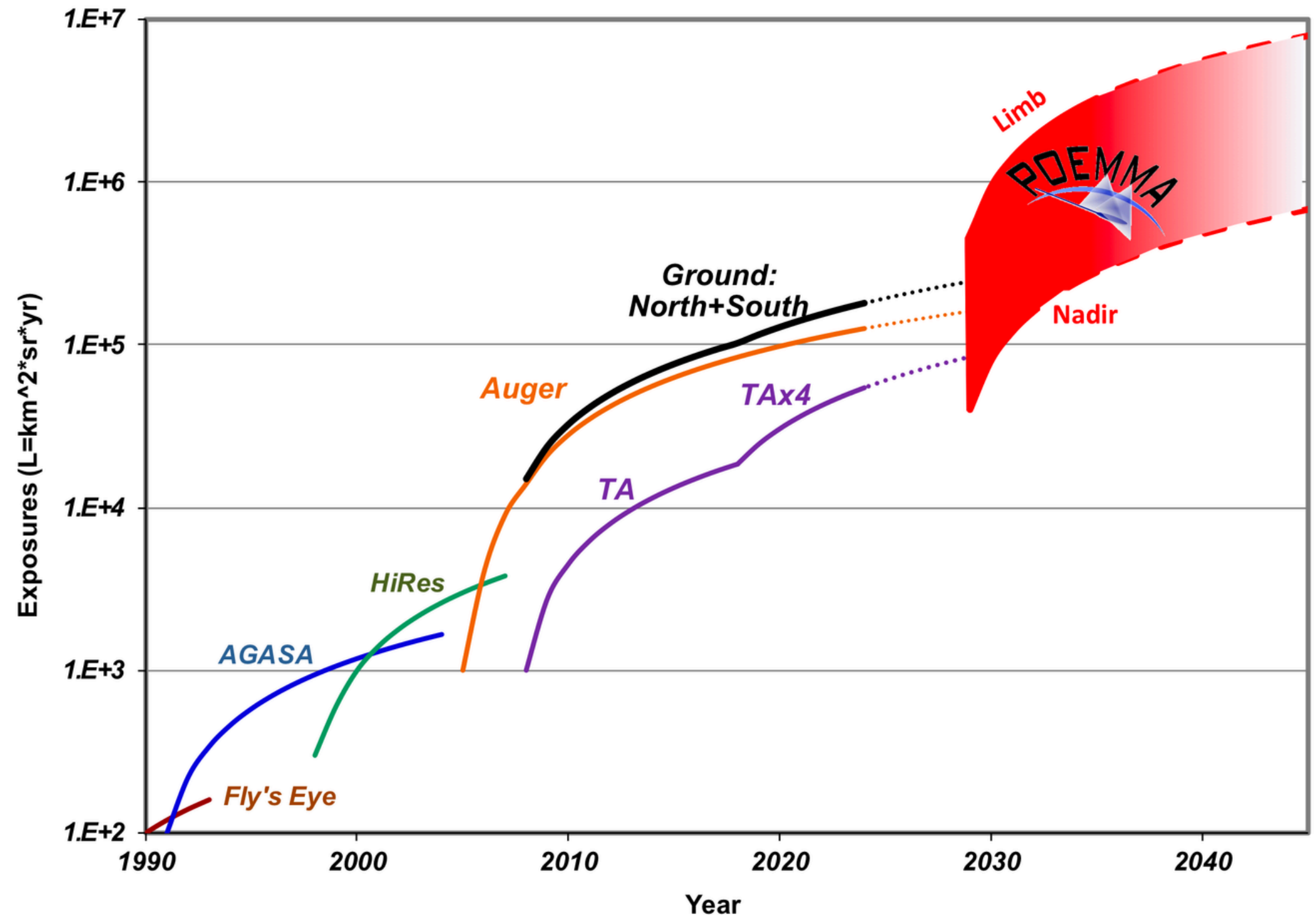


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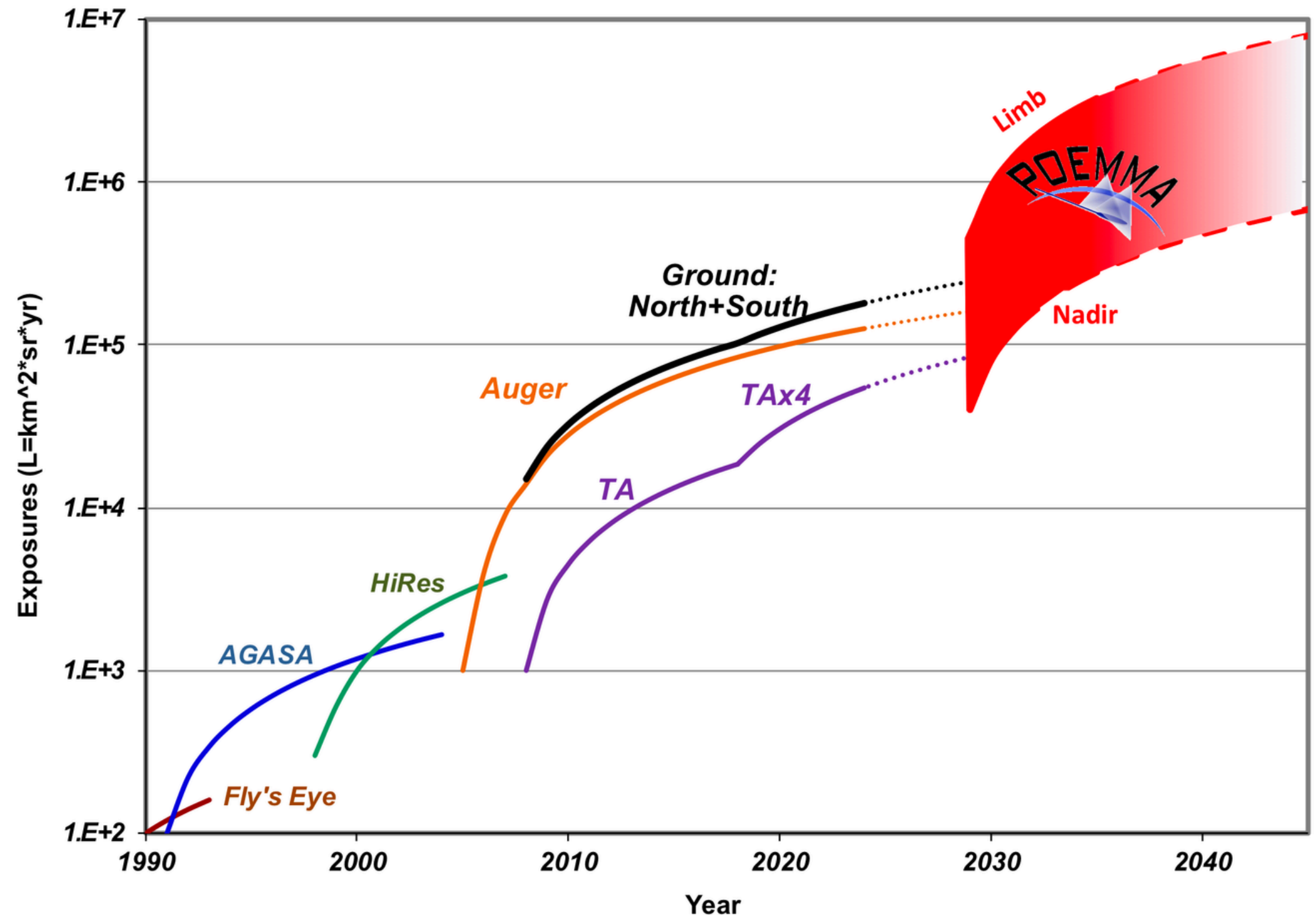
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- POEMMA's exposure from nadir (stereo) to limb observations surpasses that of ground-base detectors
- Near full-sky coverage
- The large exposure is expected to yield high statistics for UHECRs detection

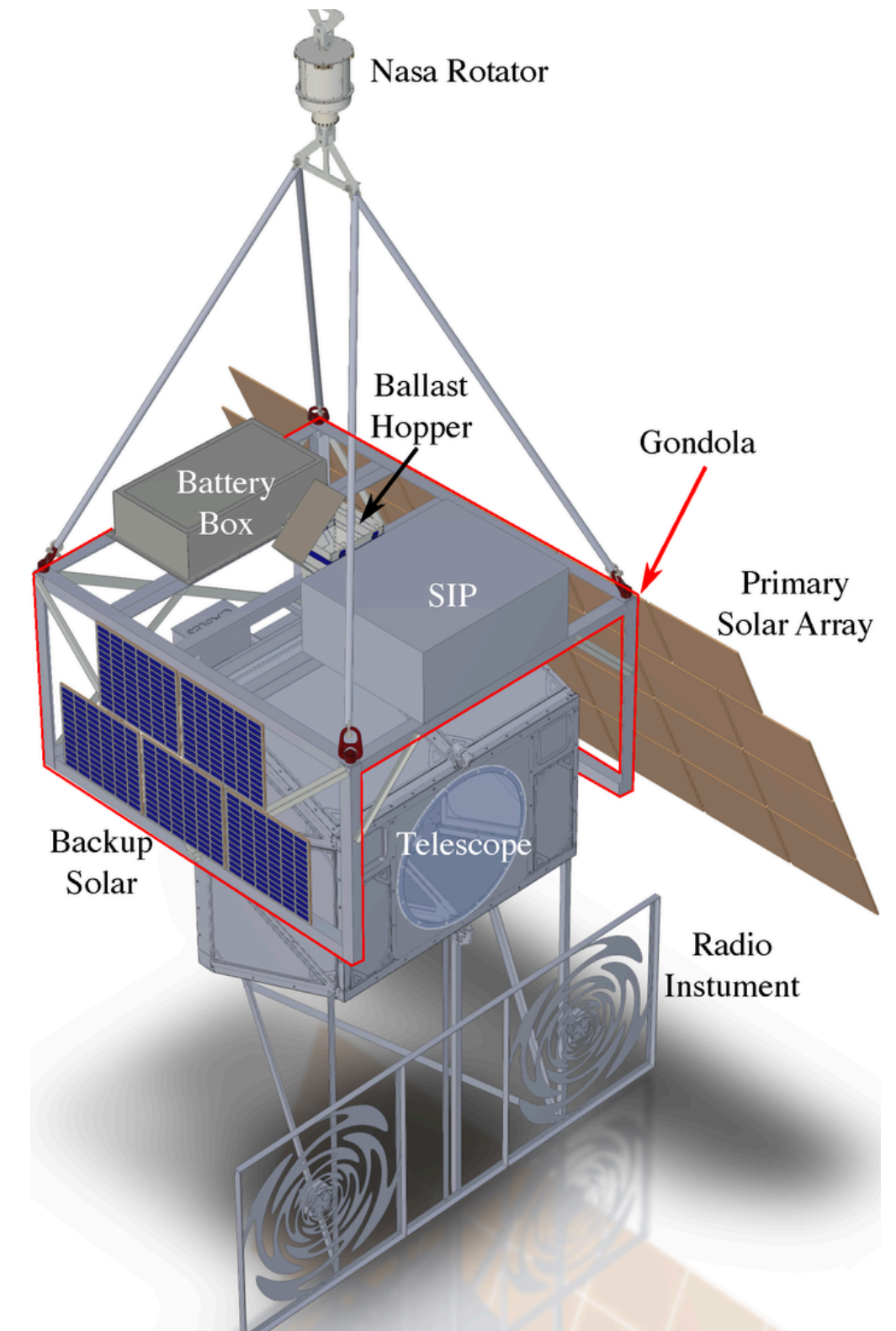


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# POEMMA BALLOON WITH RADIO

- Pathfinder experiment for POEMMA



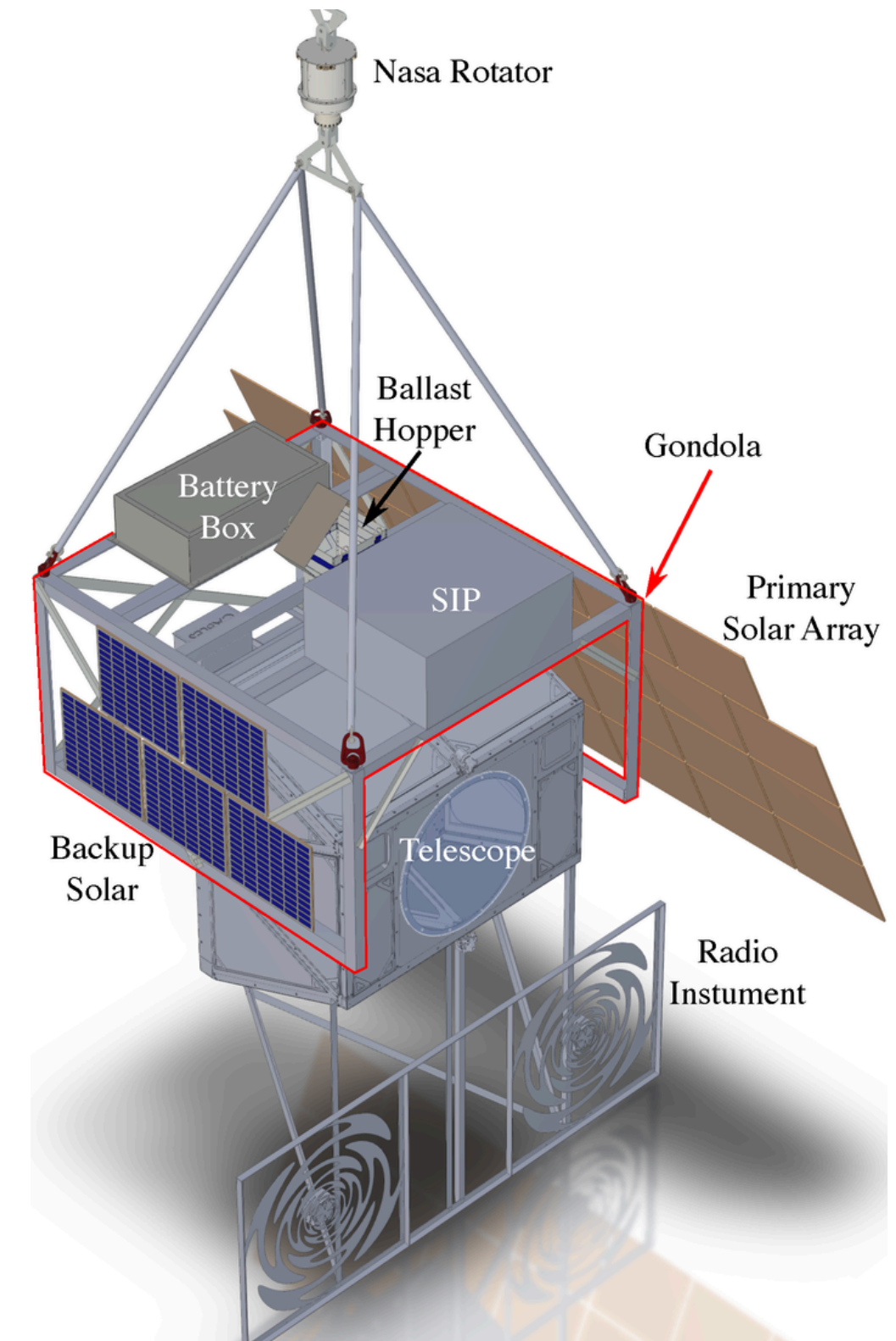
PoS(ICRC2025)249





# POEMMA BALLOON WITH RADIO

- Pathfinder experiment for POEMMA
- **Payload** scheduled to fly in early 2028 with an expected duration of more than 20 days at 33 km a.s.l. from Wanaka, New Zealand

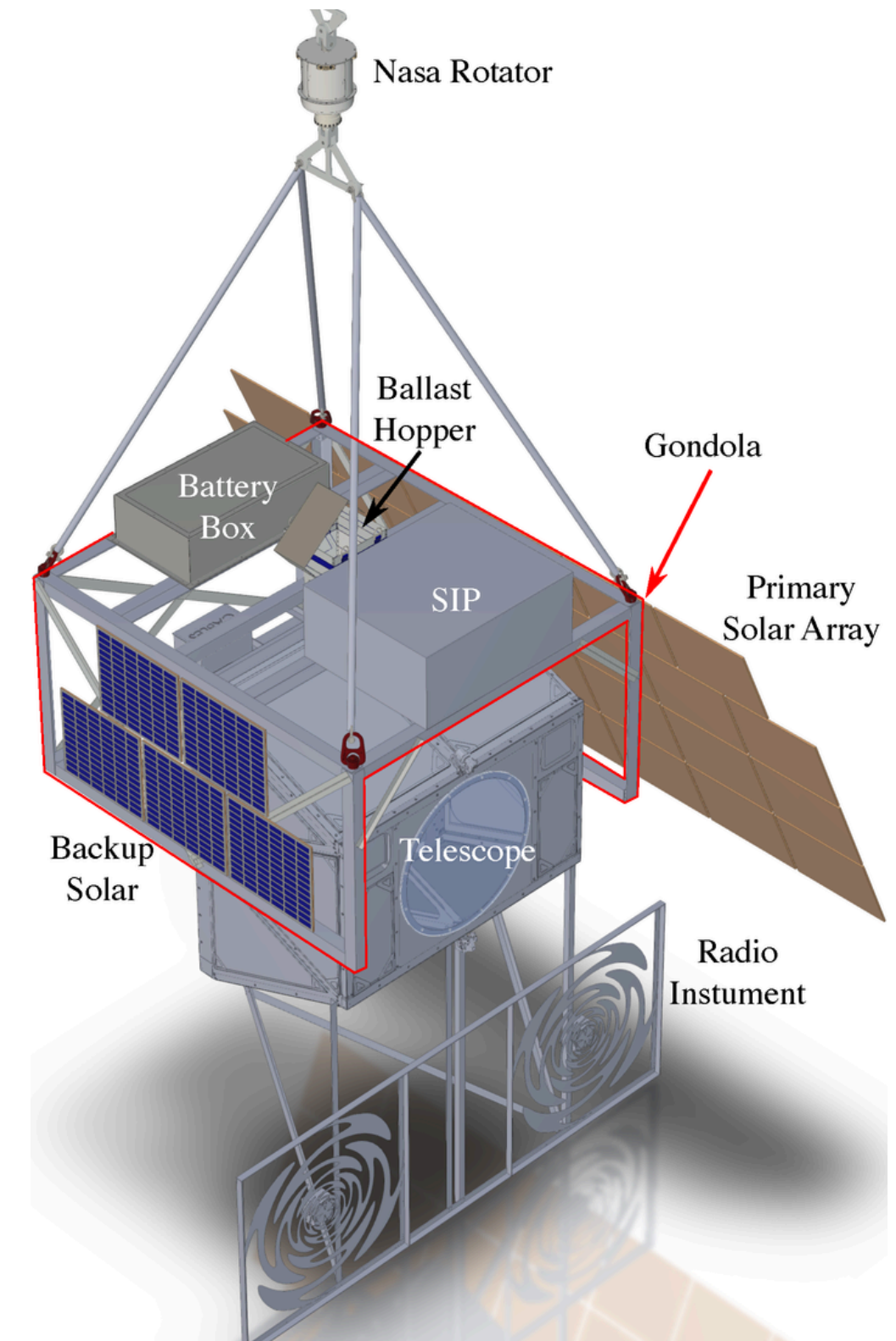


PoS(ICRC2025)249



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  1. Observation of Ultra High Energy Cosmic Rays from *above*
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  3. Neutrino search from *Targets of Opportunity*

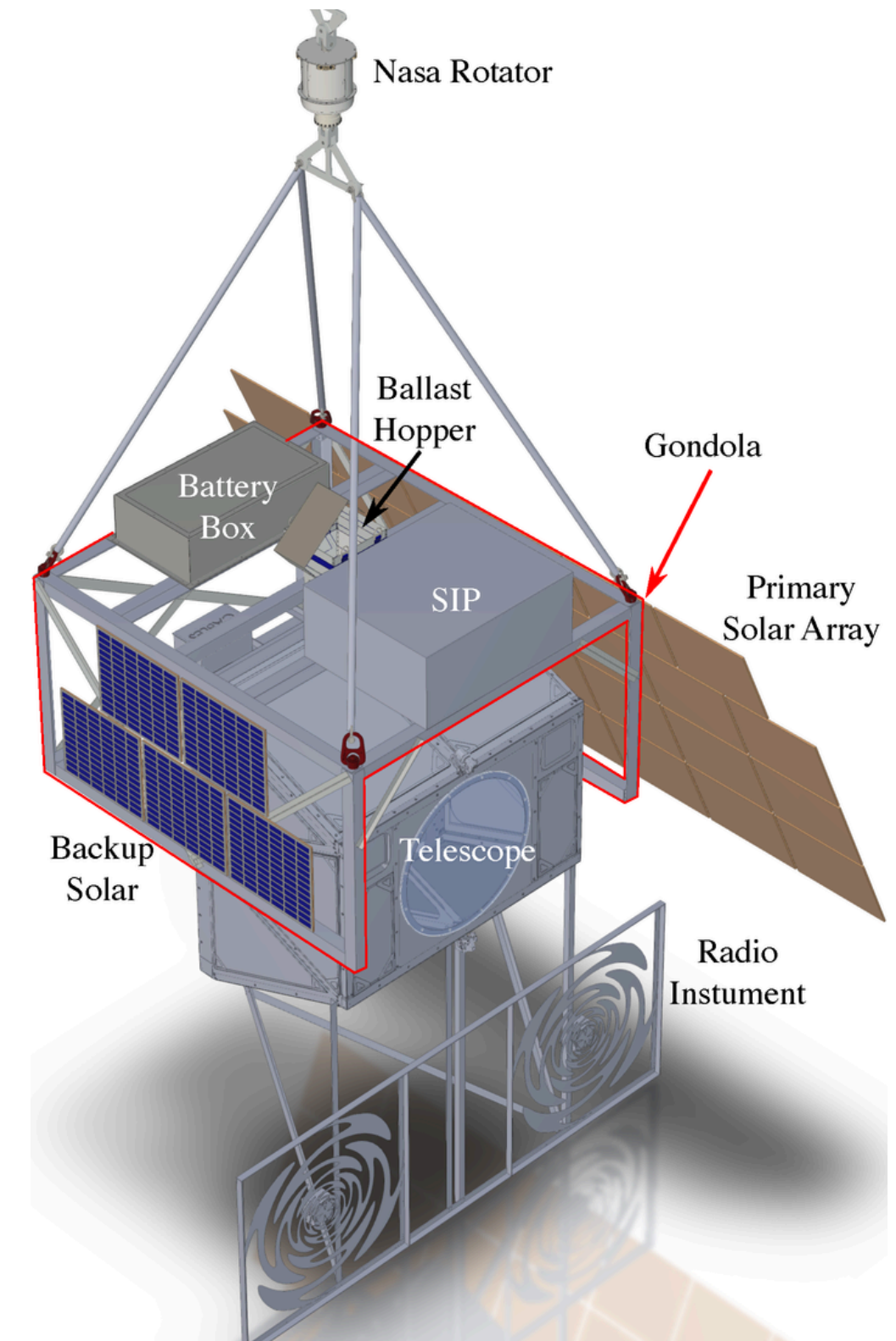


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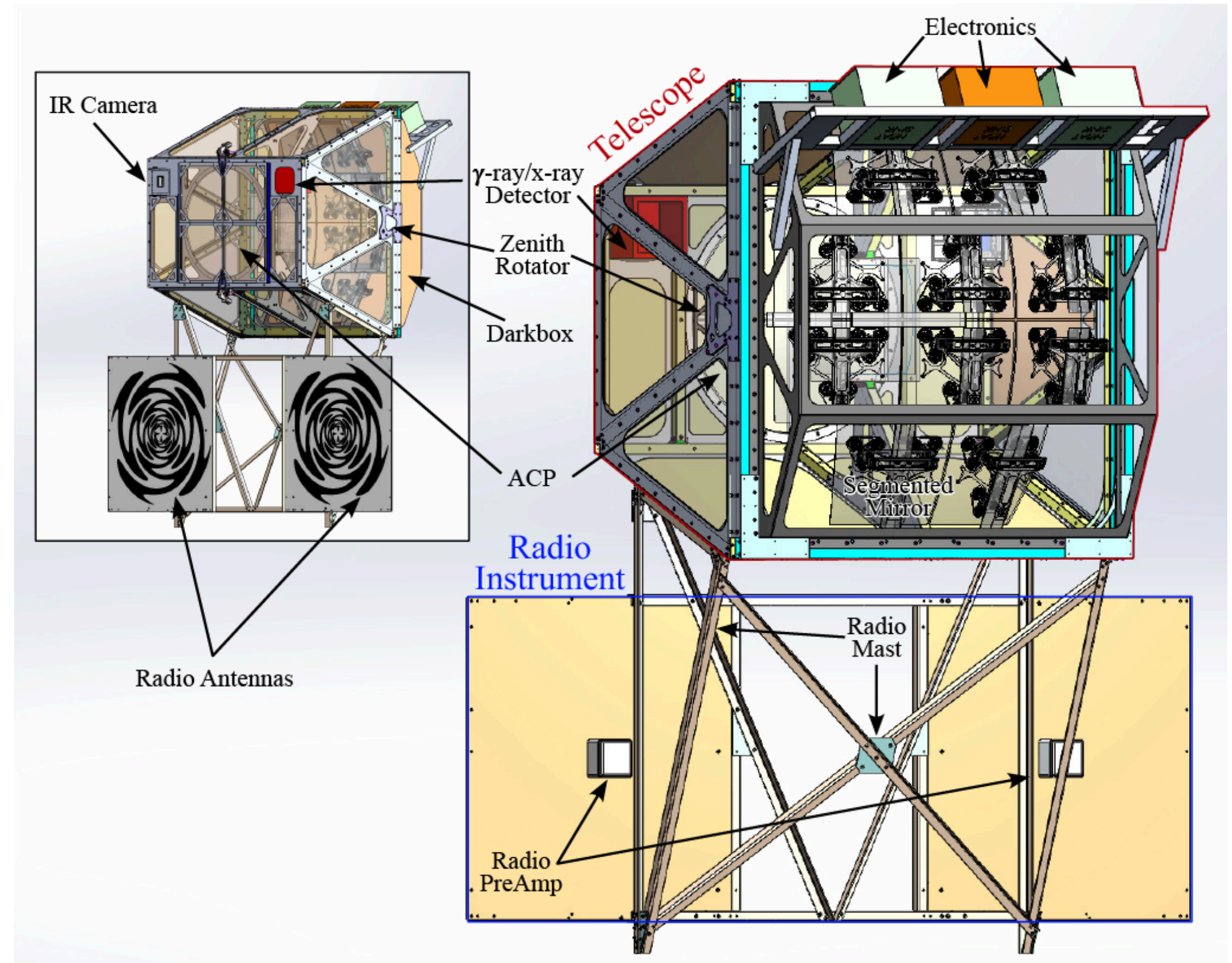


PoS(ICRC2025)249



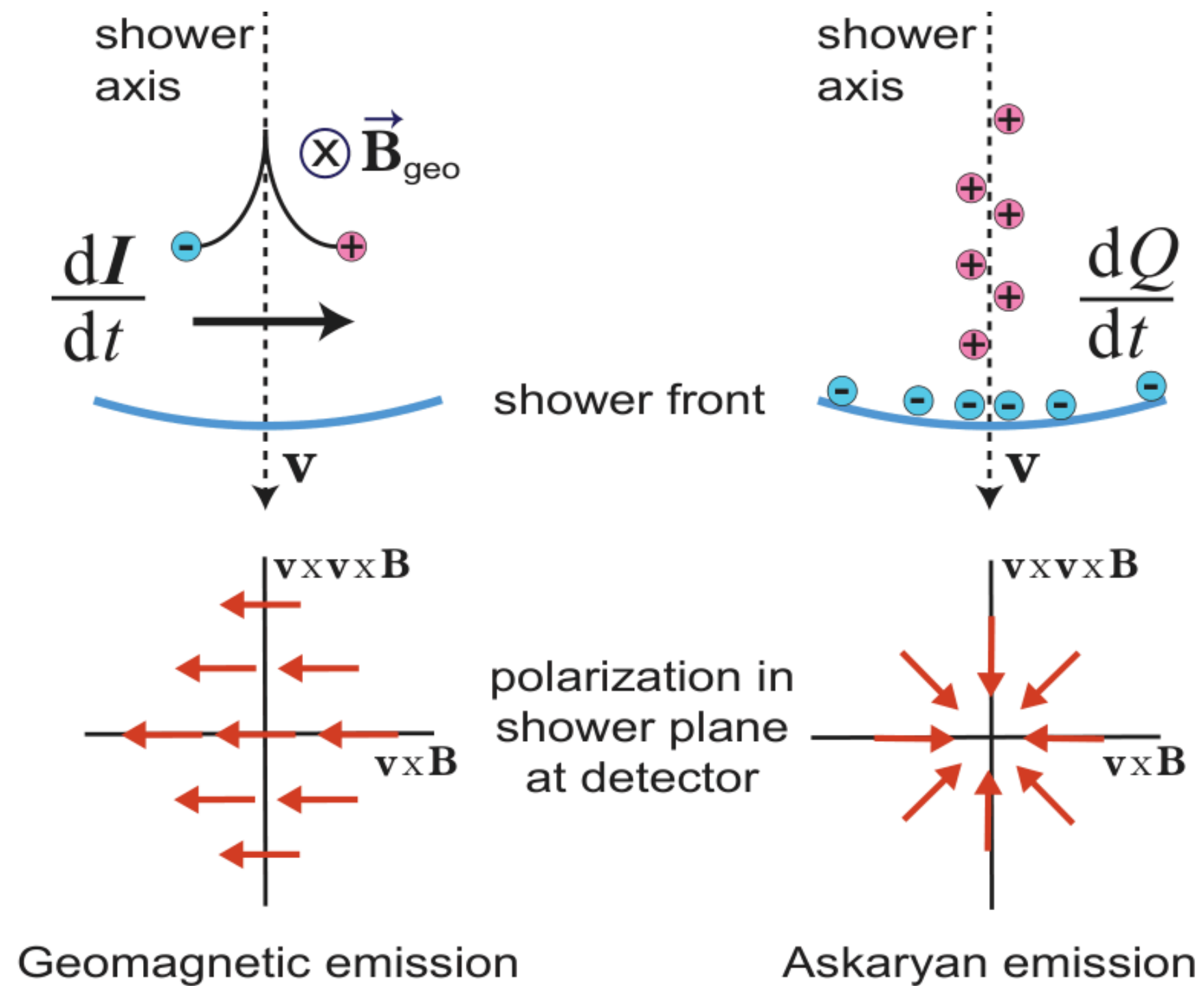
Consists of four main instruments:

- Fluorescence Camera
- Cherenkov Camera
- $\gamma$ /X-ray detector
- **Radio Instrument**



arXiv:2601.19997

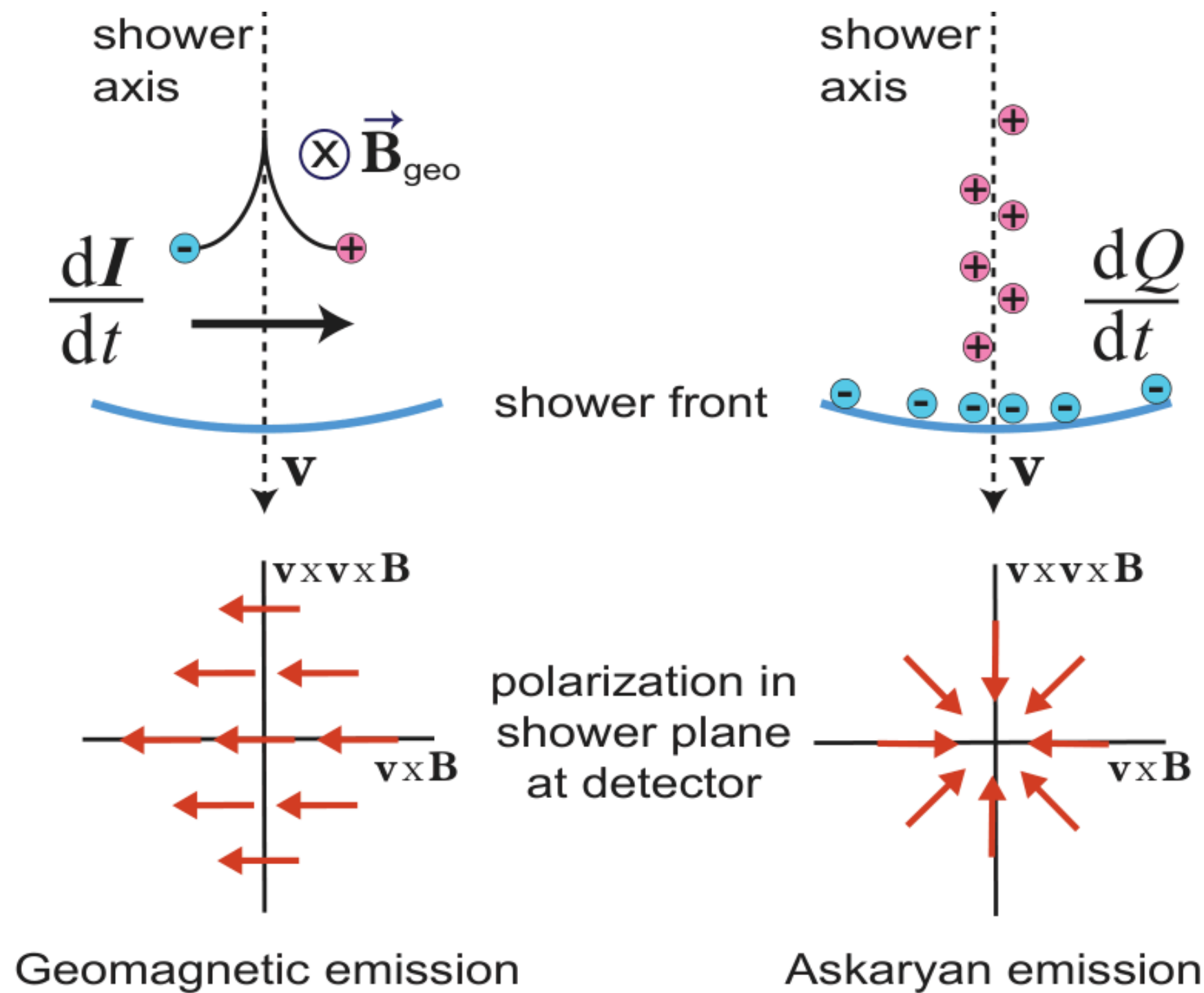
## RADIO EMISSION MECHANISMS



F.G. Schröder, 2016



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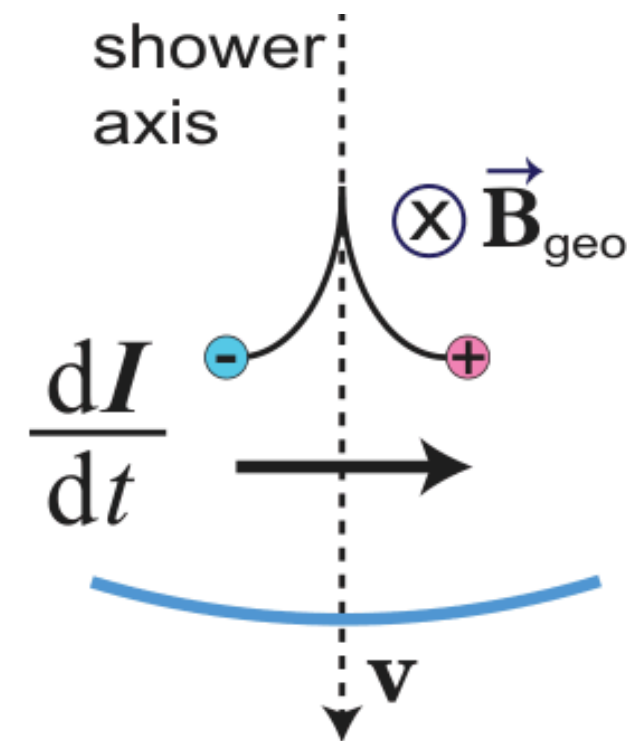


More about this during Jörg Hörandel's course!

F.G. Schröder, 2016

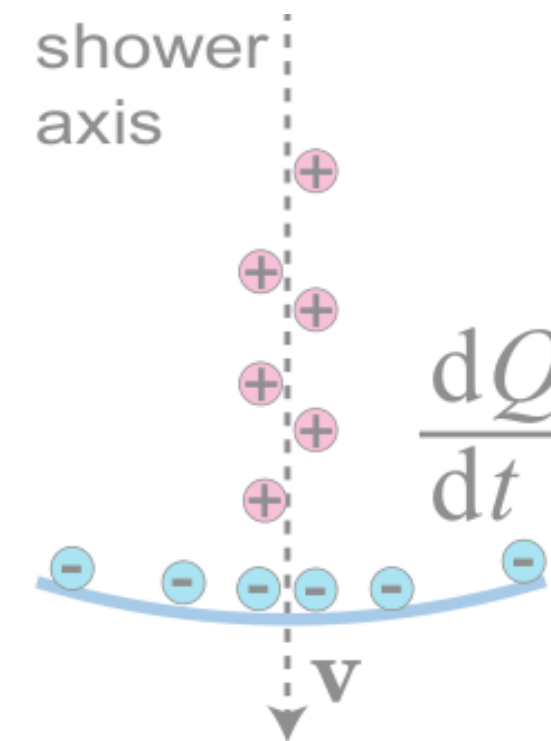
## RADIO EMISSION MECHANISMS

Responsible for over 90% of radio emission in air for inclined downgoing showers



Geomagnetic emission

shower front



Askaryan emission

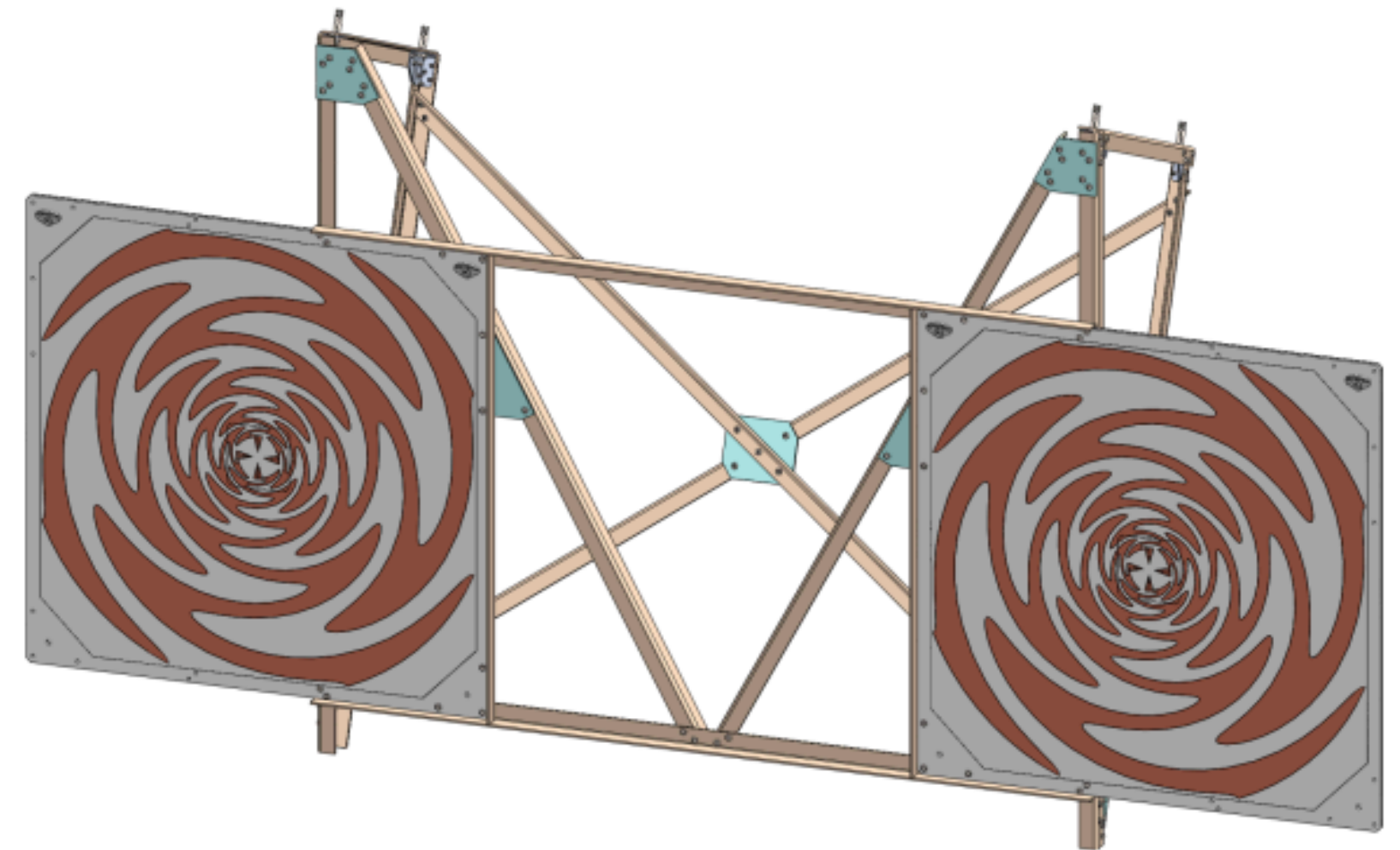
polarization in shower plane at detector

F.G. Schröder, 2016

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# RADIO INSTRUMENT OF PBR

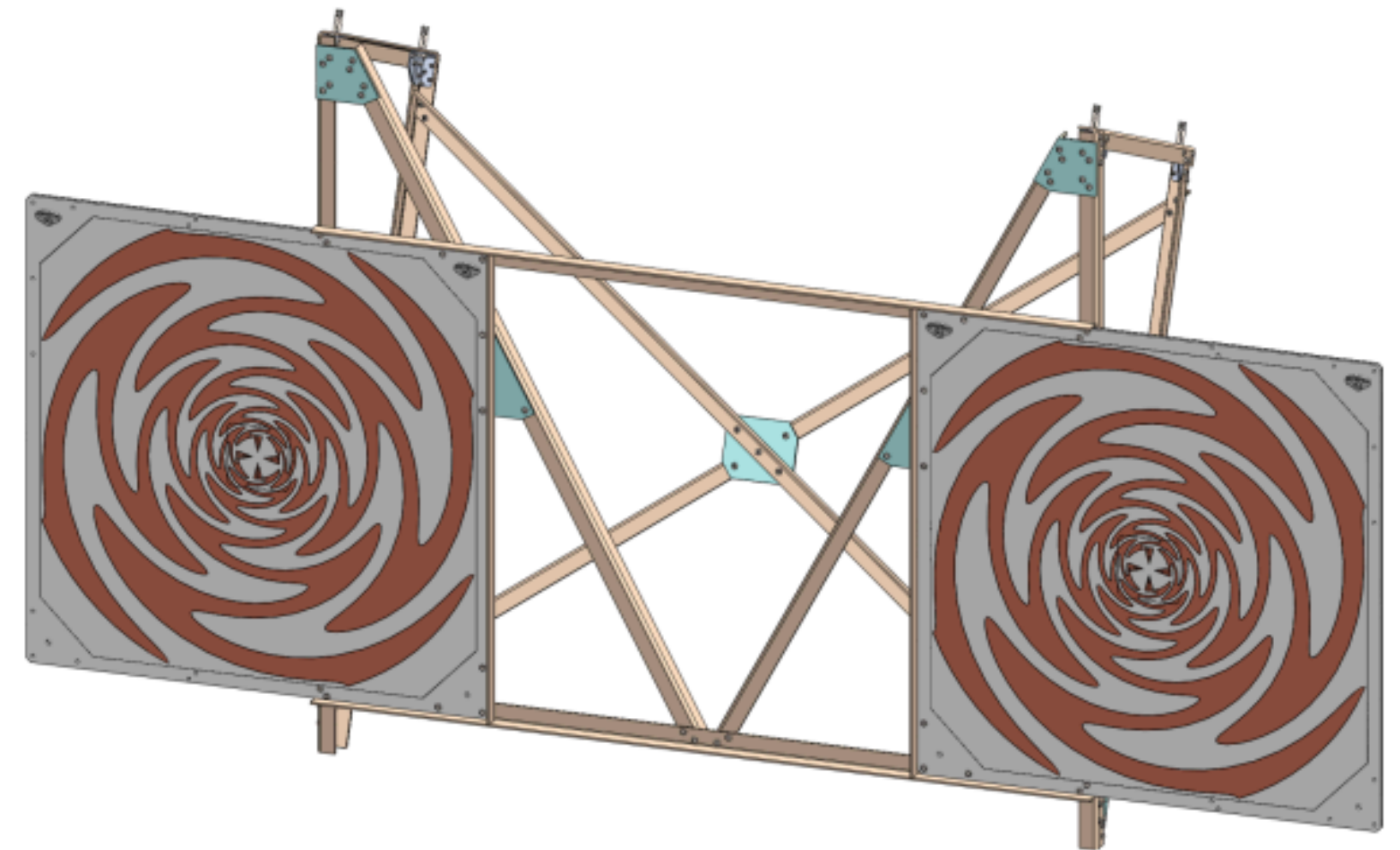
- Two radio receivers, each featuring dual-polarized sinuous antennas



[doi.org/10.48550/arXiv.2601.19997](https://doi.org/10.48550/arXiv.2601.19997)

## RADIO INSTRUMENT OF PBR

- Two radio receivers, each featuring dual-polarized sinuous antennas
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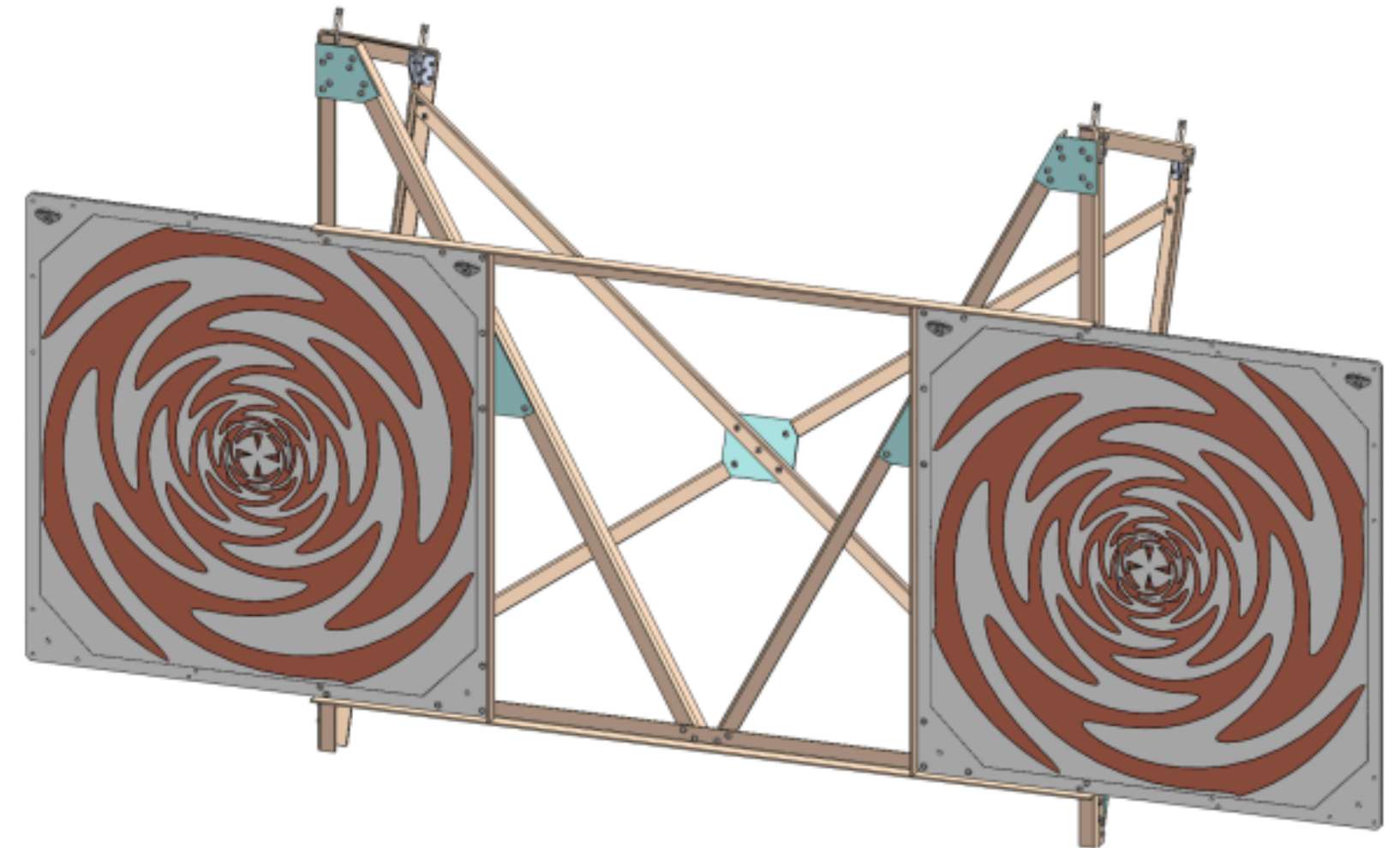
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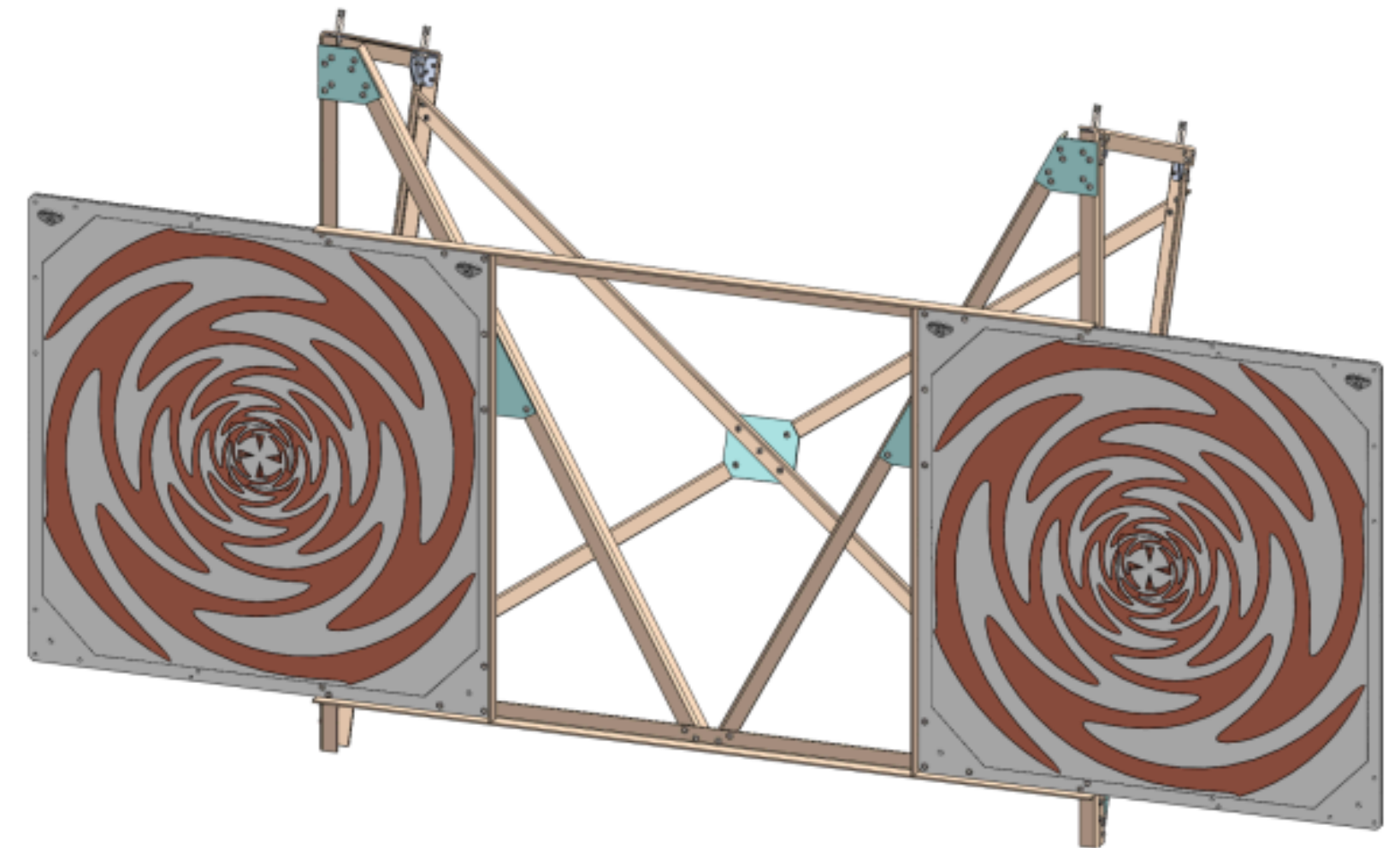


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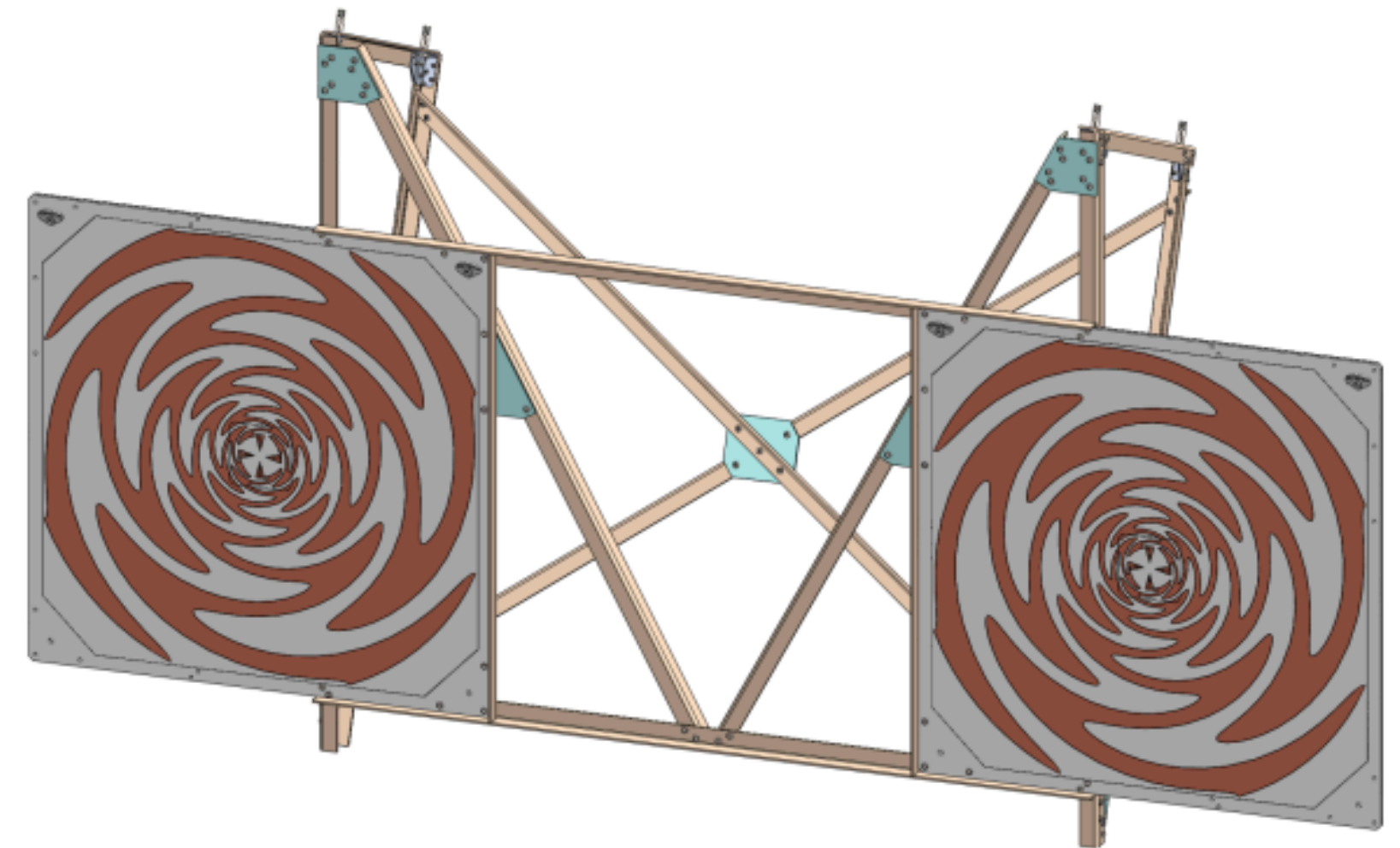


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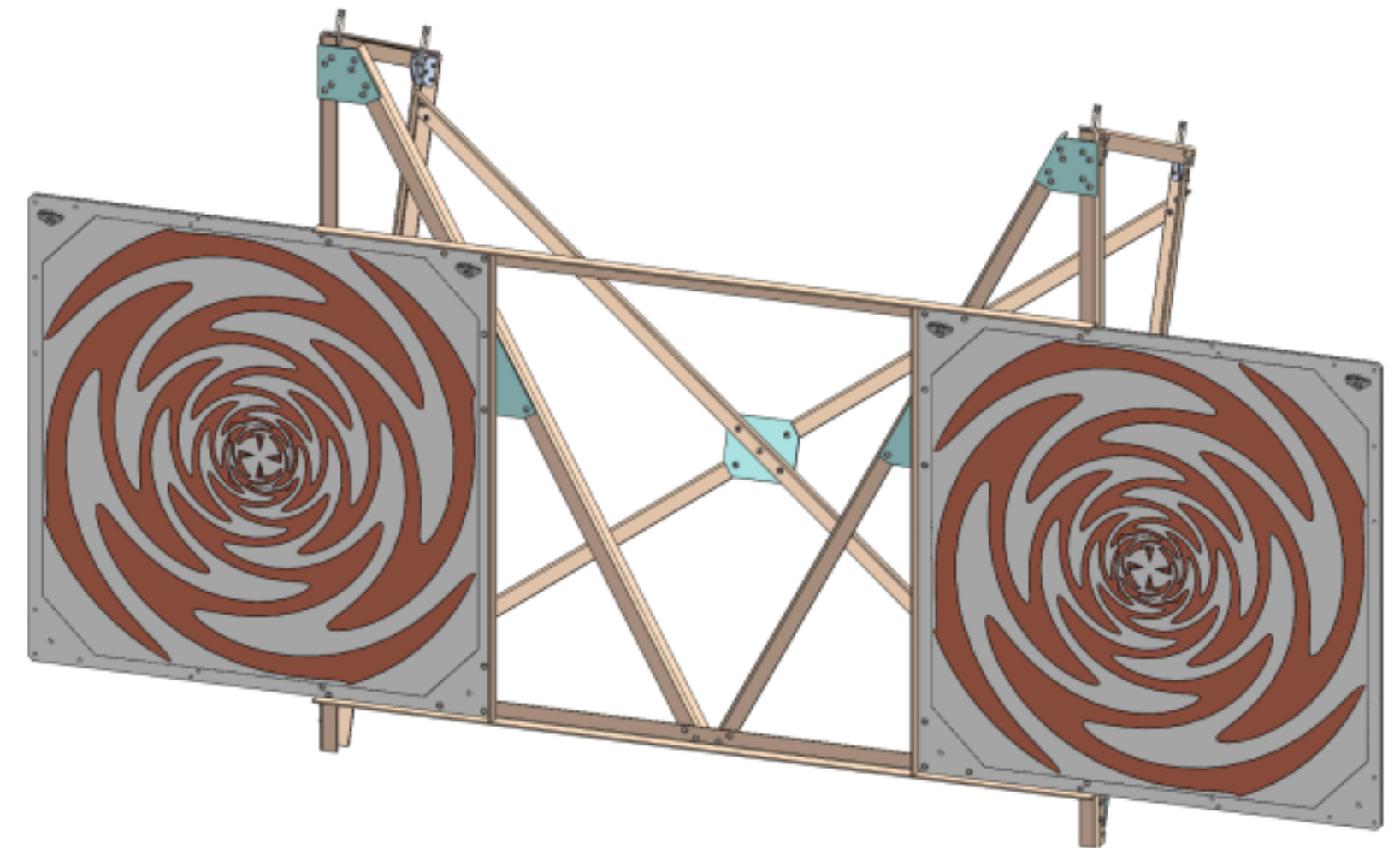
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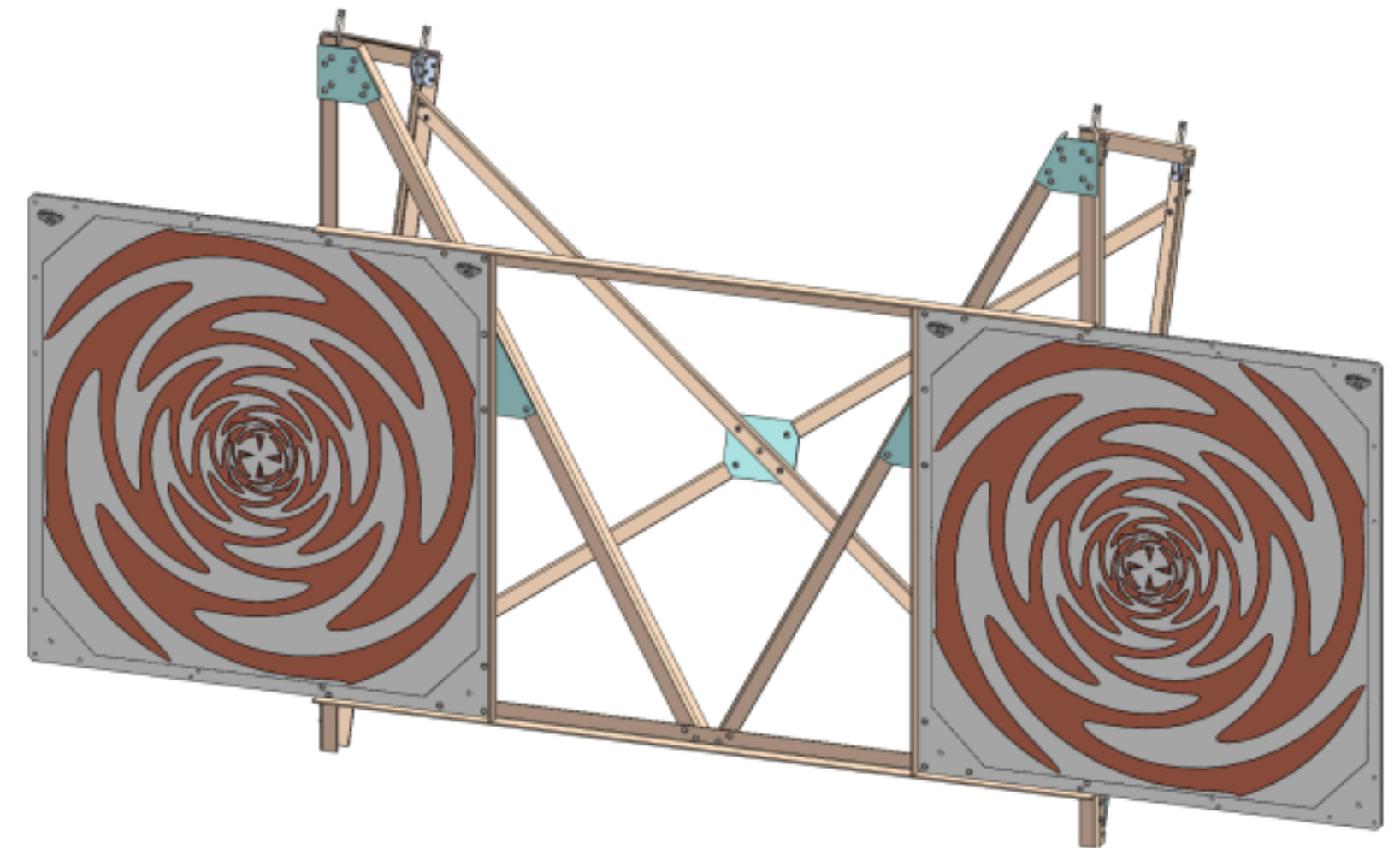
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- Sensitive to showers  $\sim 10^{17}$  eV

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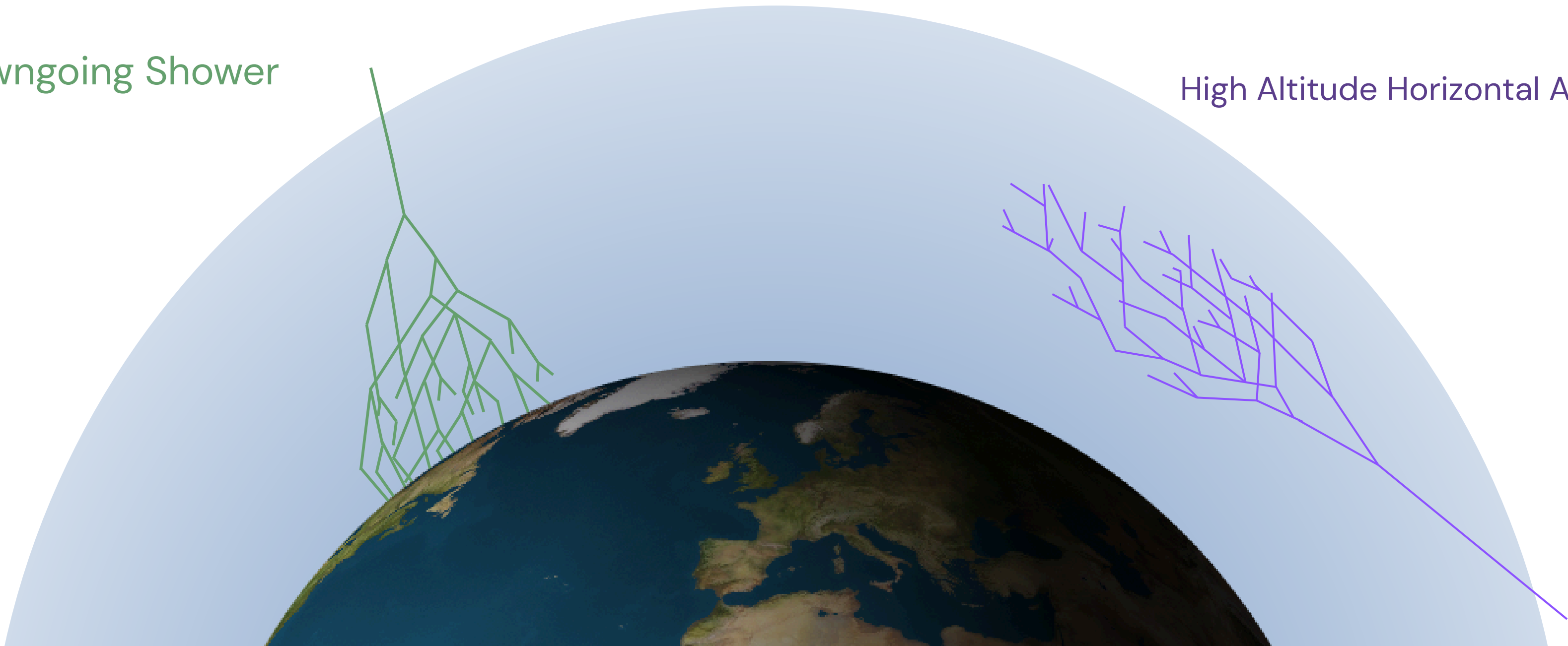


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## RECALL PBR'S SECOND MAIN SCIENCE GOAL: OBSERVATION AND STUDY OF **HAHAS**

Downgoing Shower



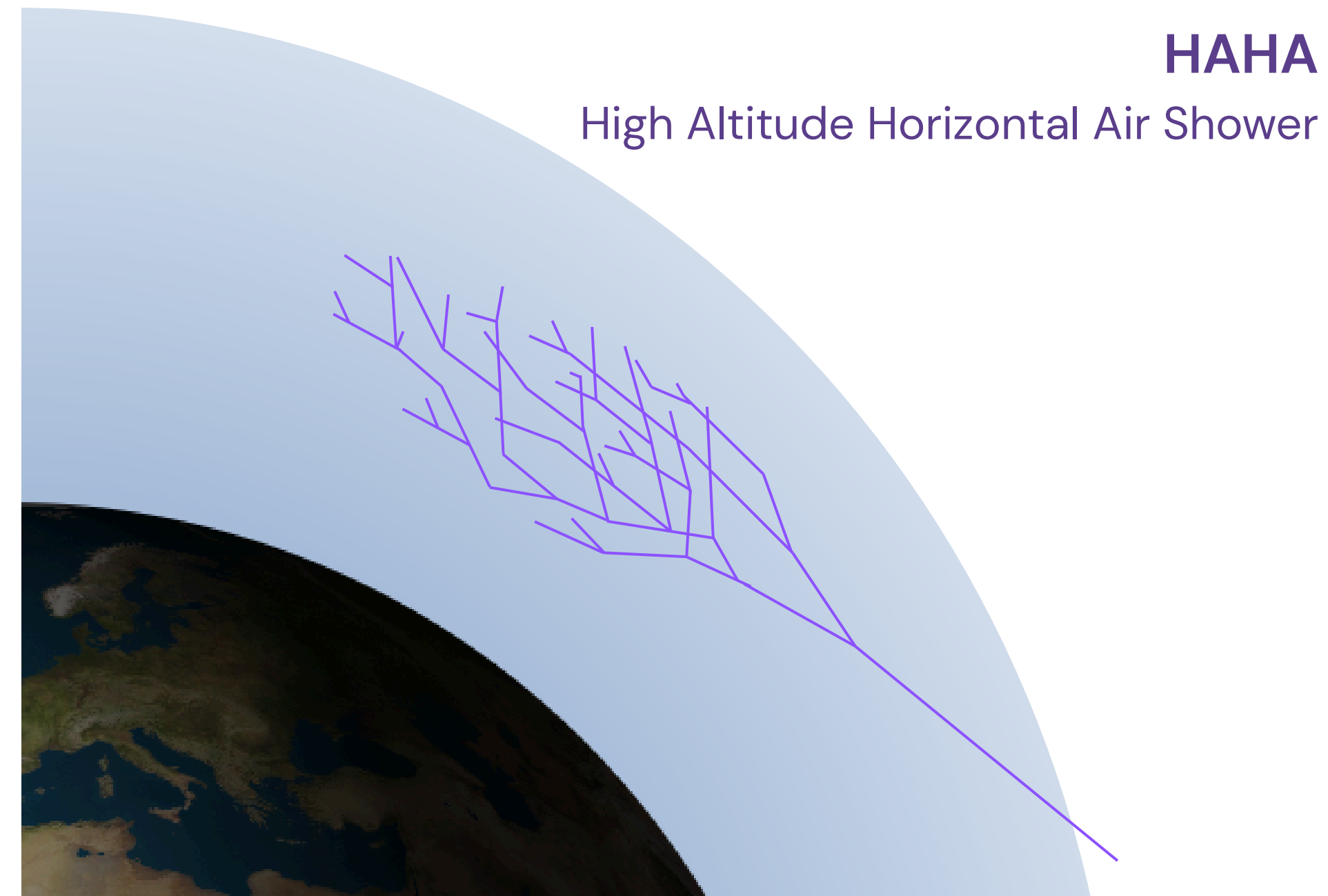
**HAAHA**

High Altitude Horizontal Air Shower



## CHARACTERISTICS

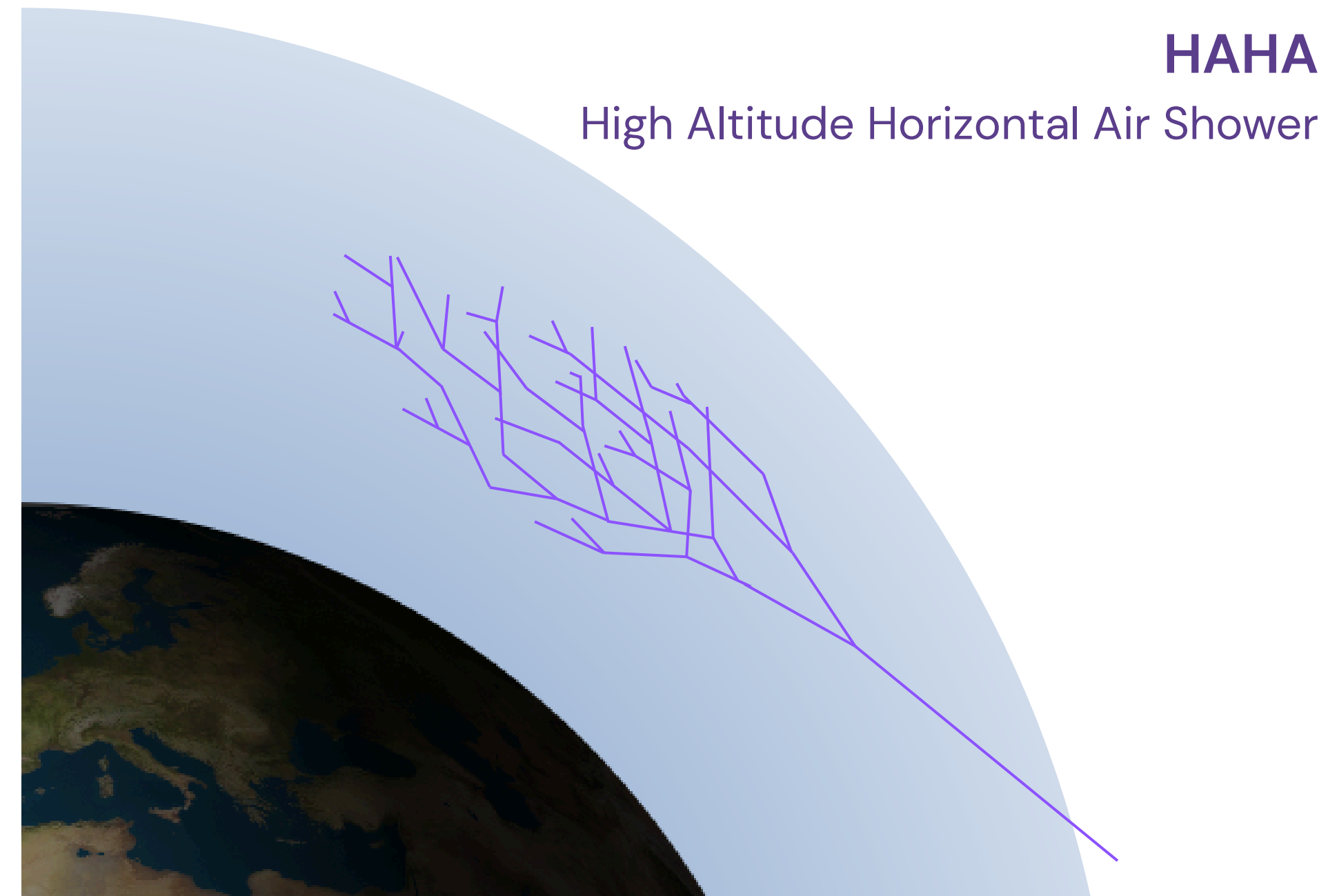
- Entire development in atmosphere
  - AKA Earth-skimming, Atmosphere-skimming showers





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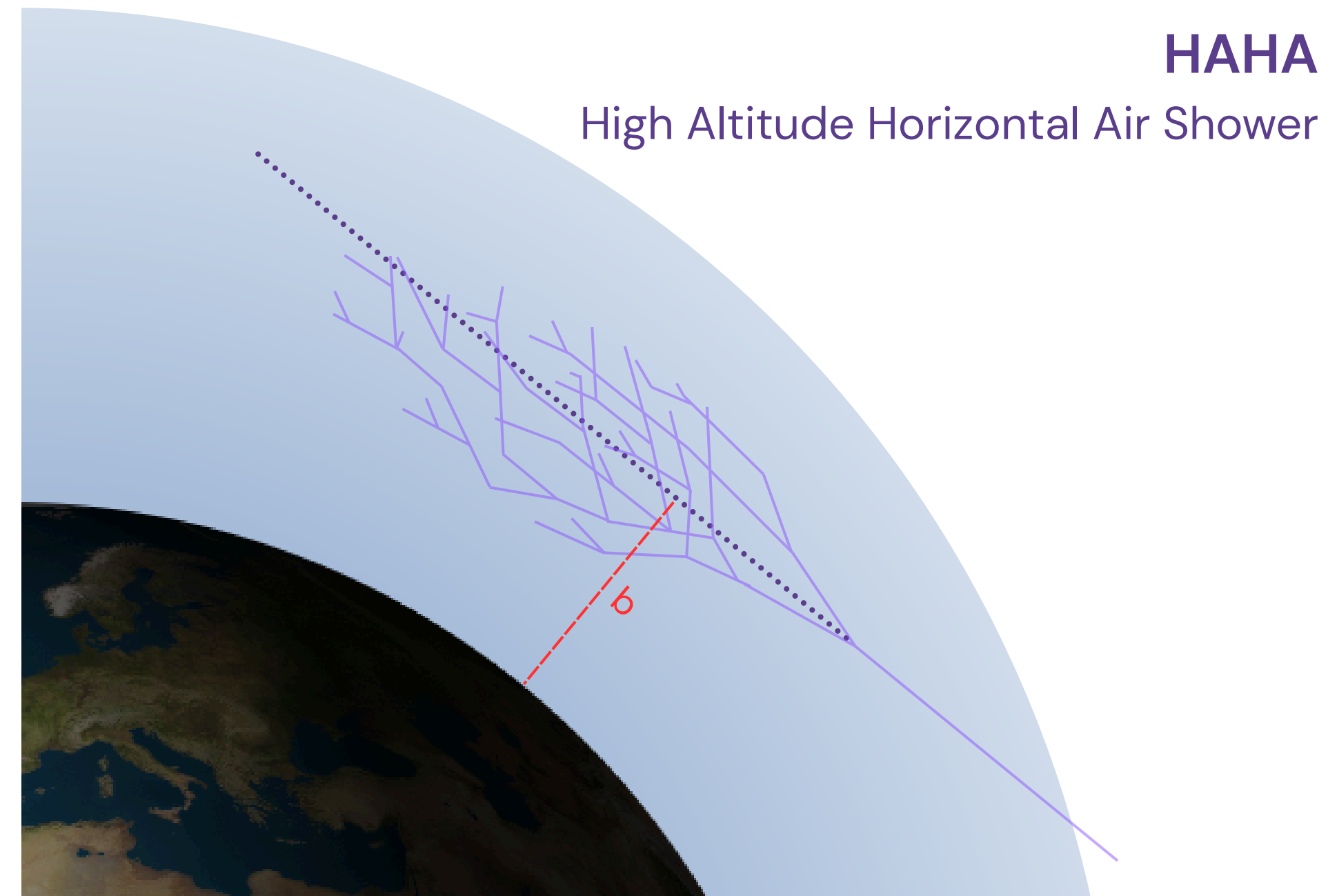






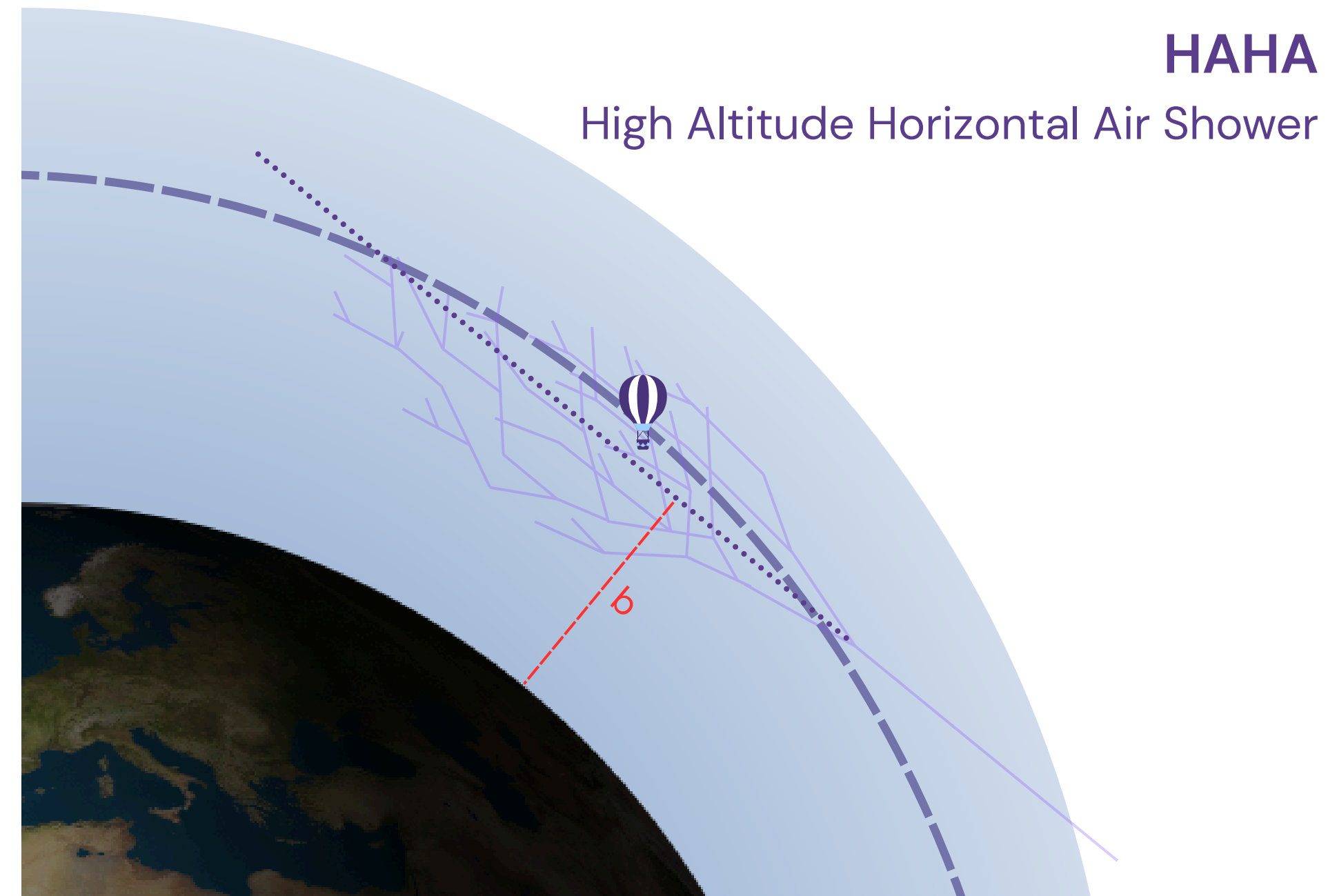
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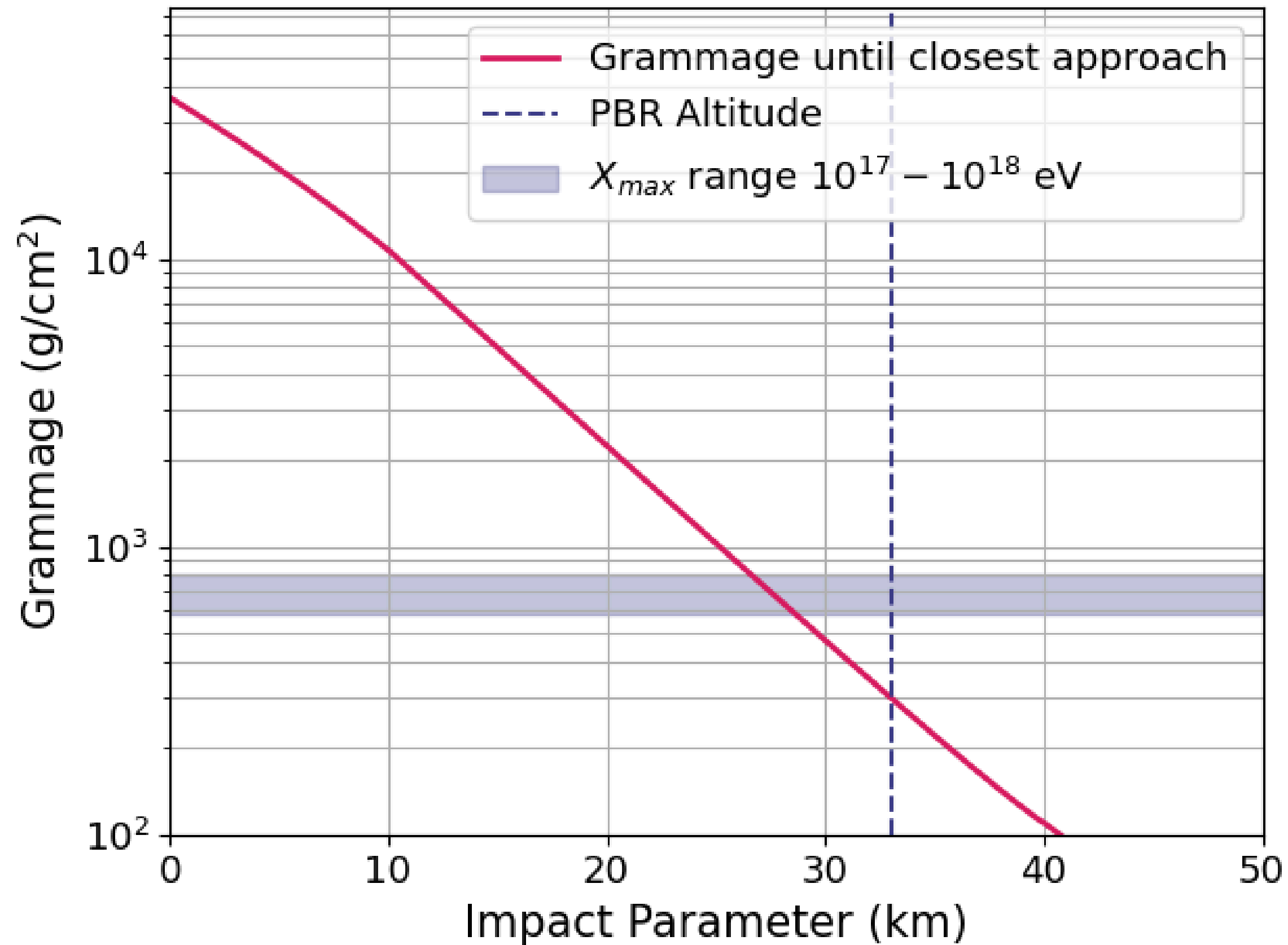
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  - AKA Earth-skimming, Atmosphere-skimming showers
- Described by:
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- For low impact parameters, HAHAs can fully develop to shower maximum







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ISCRA 2026 ◦ July 30<sup>th</sup>, 2026 ◦ Paula Gálvez Molina ◦ paulagm@udel.edu



## GOAL

Get a baseline expectation of radio emission from HAHAs for PBR using AIRES and CORSIKA





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### FIRST PHASE

Characterize difference between ZHAireS and CoREAS for familiar geometries: **downgoing showers**

### SECOND PHASE PLAN

Characterize difference between RASPASS and CoREAS for **HAHAs**



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Run multiple showers with same parameters\*

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\*(same energy, primary, magnetic field, antenna placement, vary zenith bin)



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**ZHAireS-RASPASS (Aires Special Primary for Atmospheric Skimming Showers)**  
Standalone version of ZHAireS that accommodates simulations of HAHAs

\*(same energy, primary, magnetic field, antenna placement, vary zenith bin)



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Run multiple showers with same parameters



Select showers with similar development



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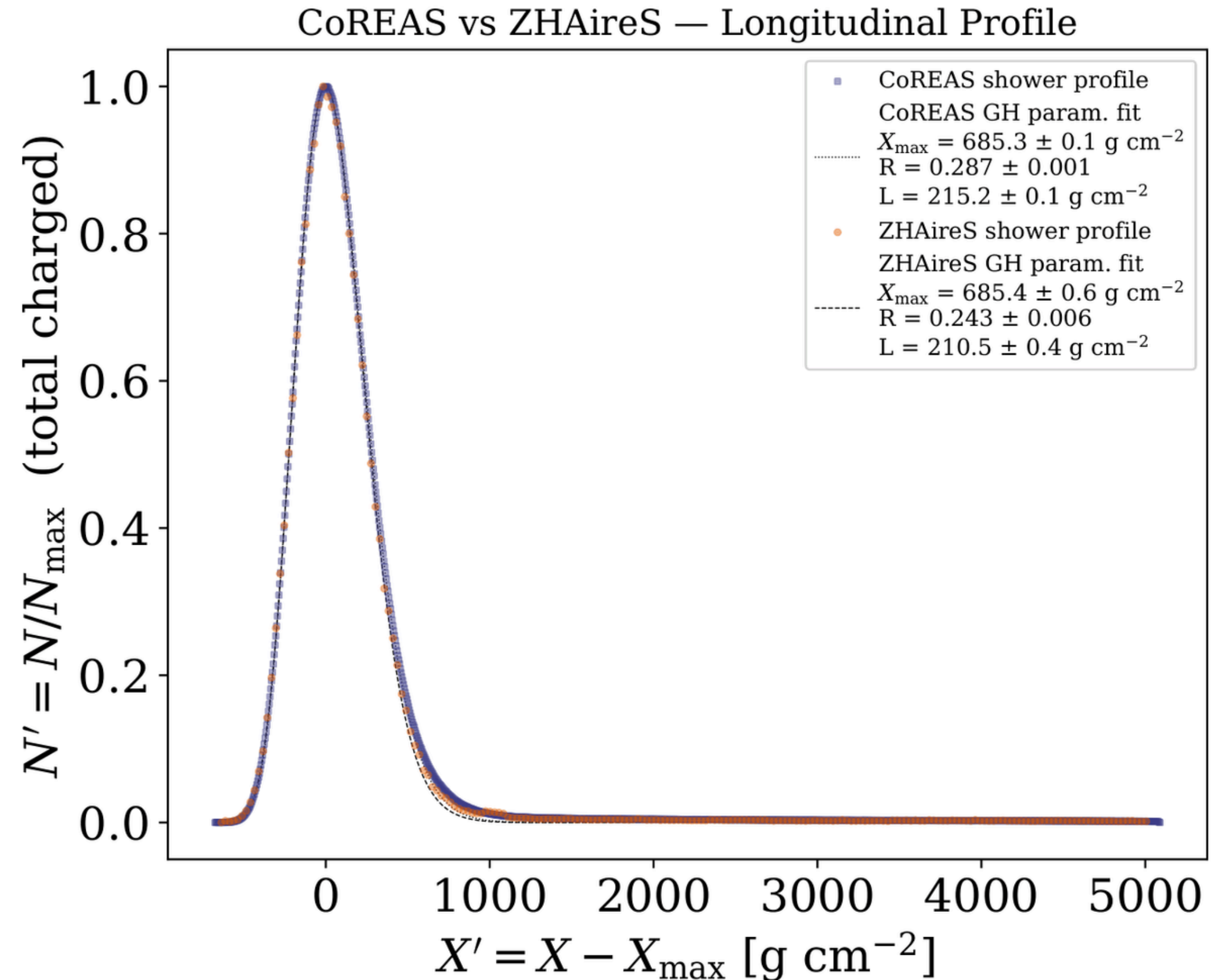
## FIRST PHASE

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Primary Particle: Proton

Zenith: 80°

Primary energy:  $10^{17}$  eV





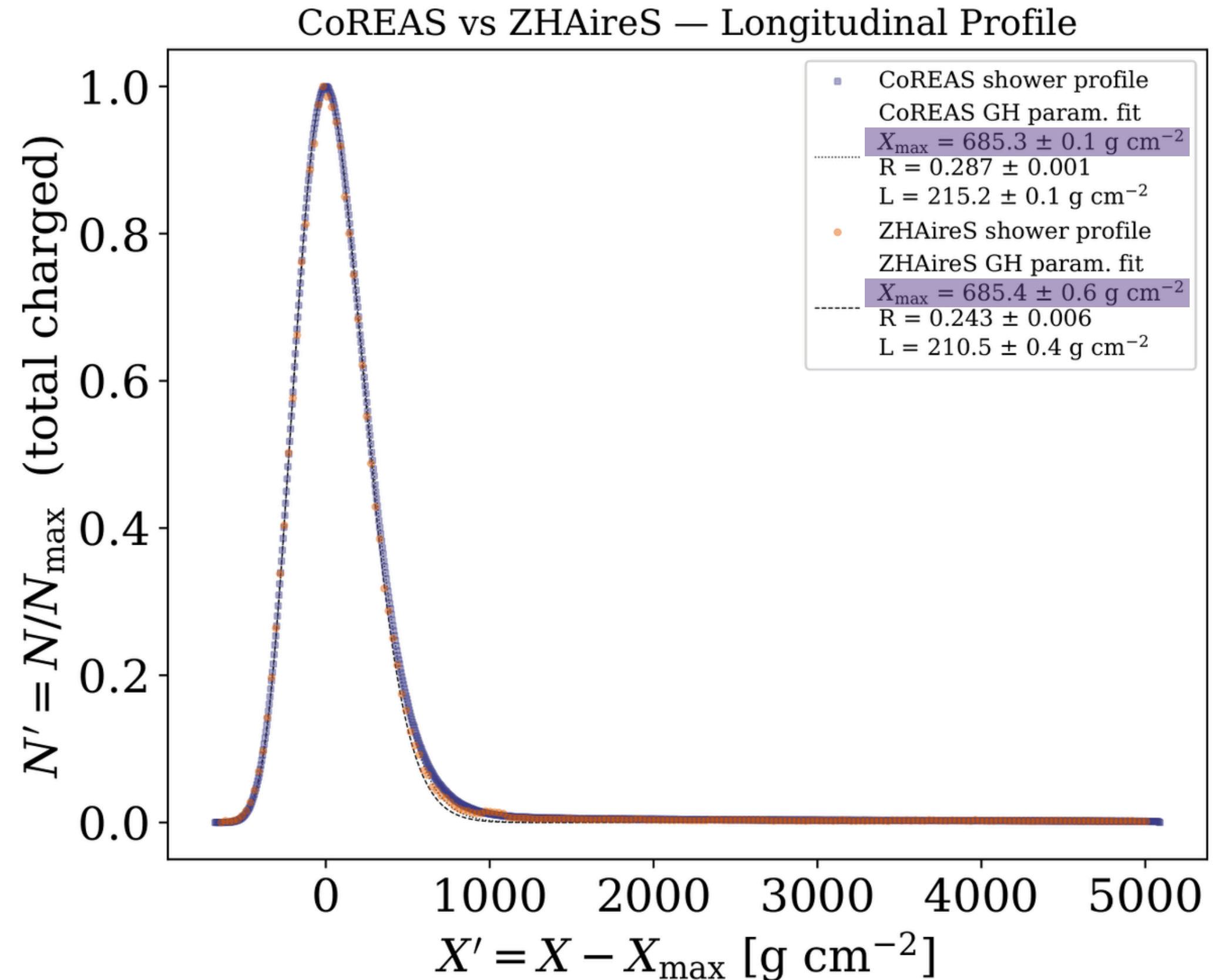
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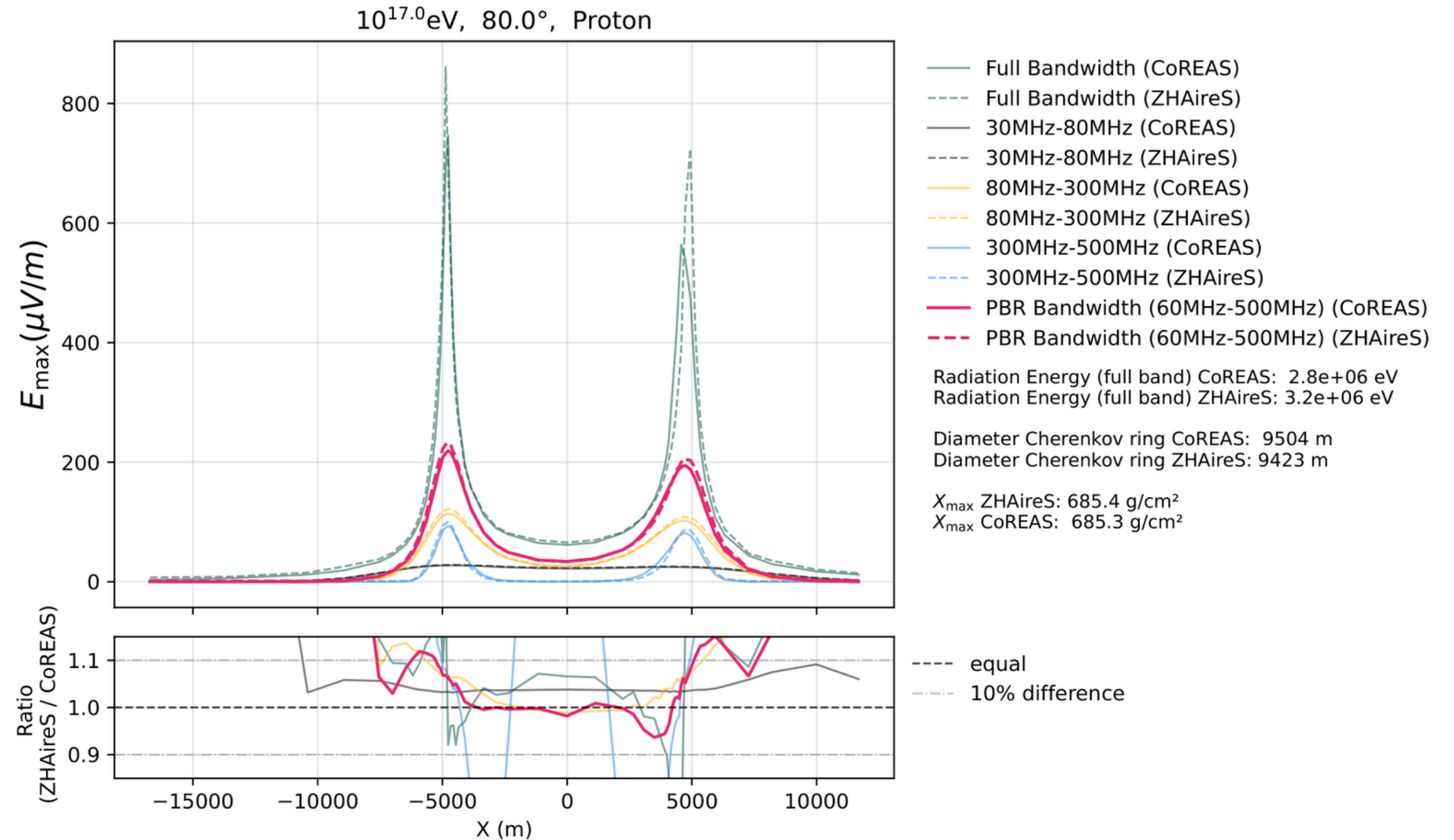
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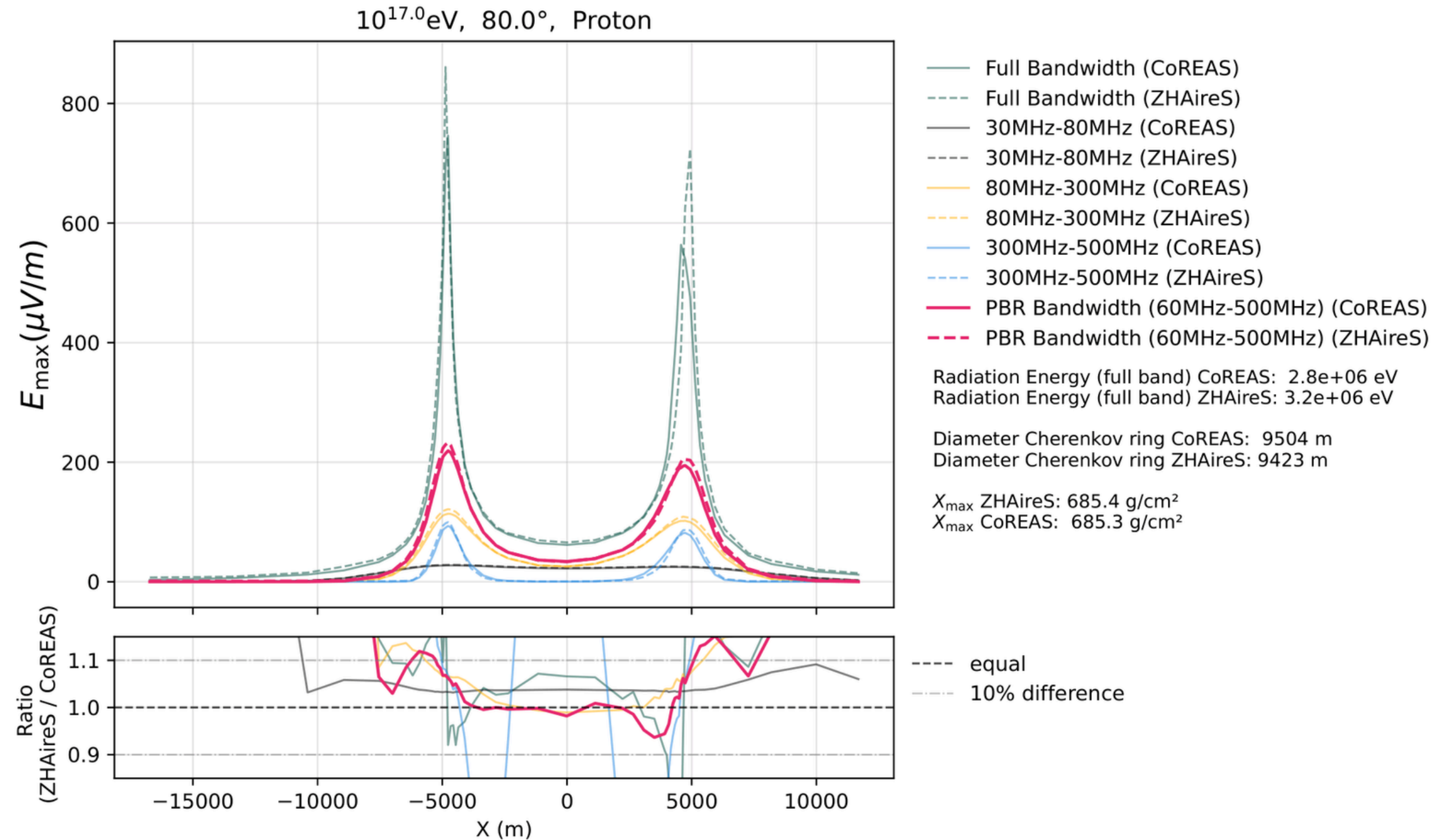


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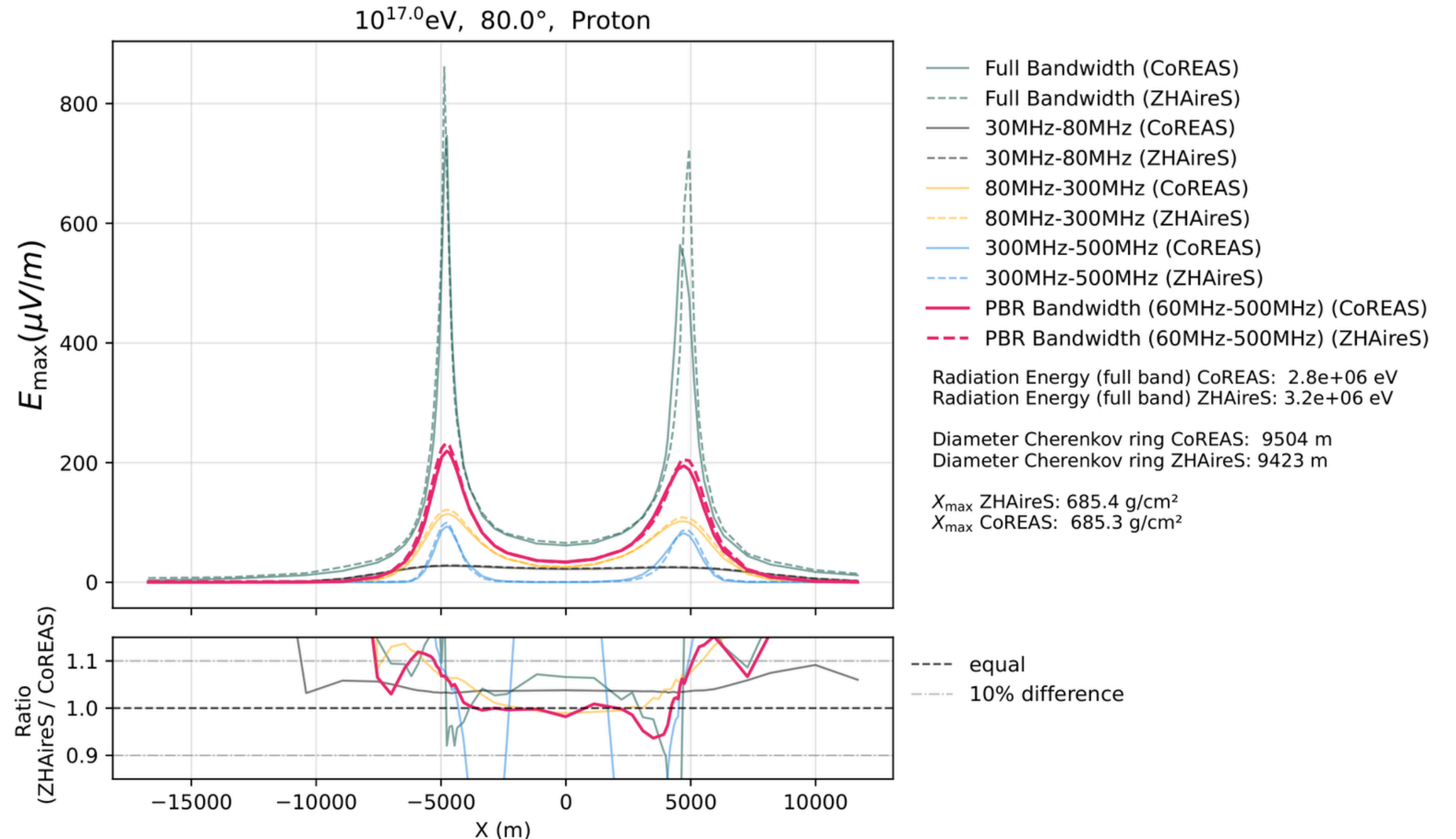
## FIRST PHASE

### Compare across bands of interest

- Overall simulations have similar results
- Agreement below 10% difference at Cherenkov ring of PBR Band (pink)
  - Not unexpected, as it has been reported<sup>1</sup> that radio emission adds incoherently at higher frequencies

<sup>1</sup>Cruz Sanchez, et. al., 2025

Proton shower, zenith: 80°, primary energy:  $10^{17}$  eV







## CONCLUSIONS & NEXT STEPS

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## THANK YOU, QUESTIONS?

This work is supported by NASA award 80NSSC24K1780.



## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support by NASA award 80NSSC22K1488 and 80NSSC24K1780, by the French space agency CNES and the Italian Space agency ASI. The work is supported by OP JAC financed by ESIF and the MEYS CZ.02.01.01/00/22\_008/0004596. We gratefully acknowledge the collaboration and expert advice provided by the PUEO collaboration. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231. We acknowledge the NASA Balloon Program Office and the Columbia Scientific Balloon Facility. We also acknowledge the invaluable contributions of the administrative and technical staffs at our home institutions.



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# SUPPORTING SLIDES



## FIRST PHASE

Run multiple showers with same parameters

12 groups of ~10 simulations per code (CoREAS, ZHAireS)

- Energy:  $10^{17}$  eV
- Azimuth:  $0^\circ$
- Primary: proton or iron
- Magnetic field: 50 nT downwards
- Zenith:  $0^\circ$ –  $85^\circ$  (increasing by  $\sim 10^\circ$  per group)
- ~224 antennas placed in multiples of the Cherenkov angle at  $X_{\max}$





## More info about PBR and its RI



A month-long SPB flight will provide about **9,000 HAHA events**, enabling a measurement of the cosmic-ray spectrum and the discrimination of the cosmic ray composition at energies around 0.5 PeV and above.



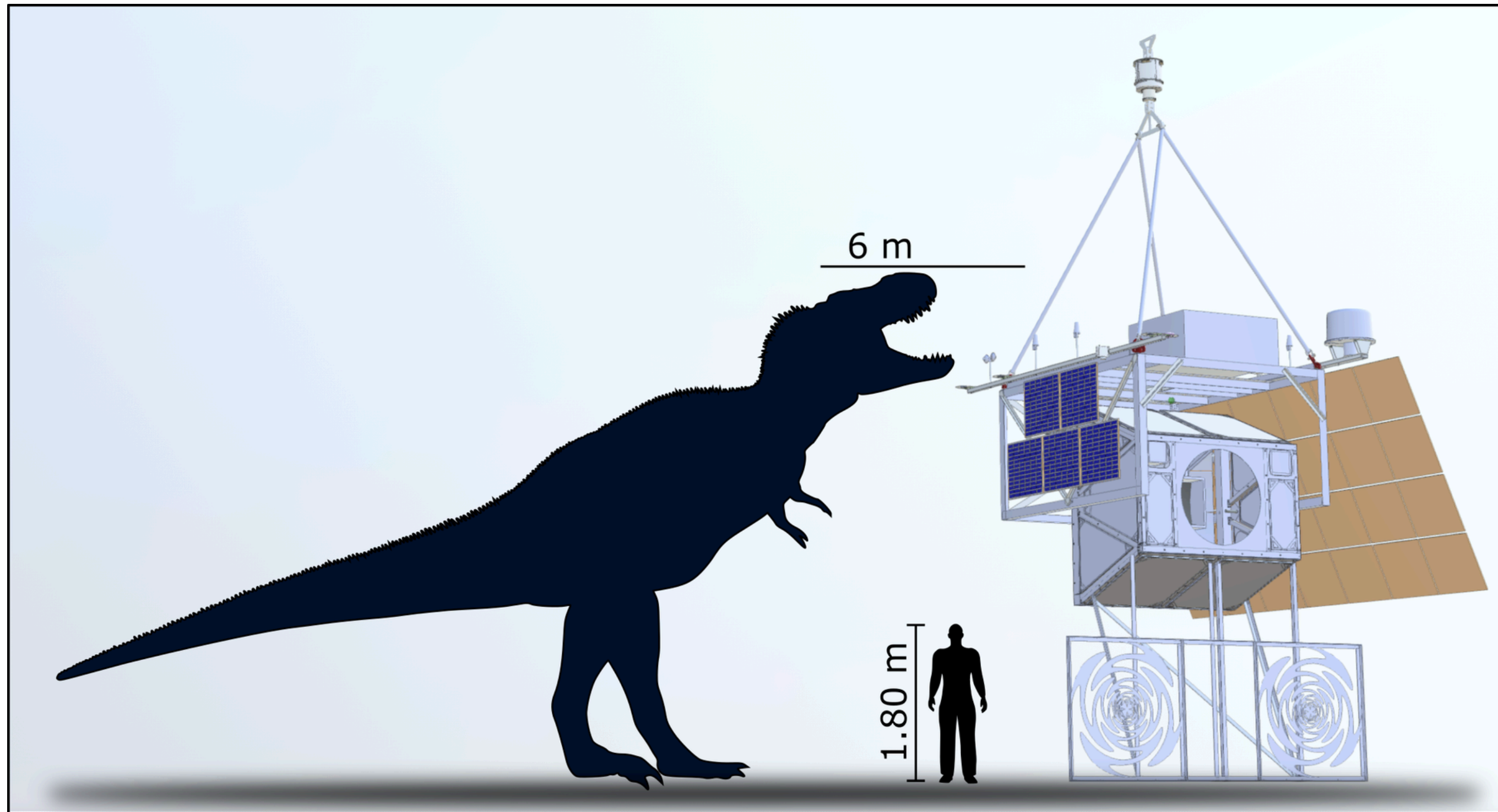
**The buffer** between the CC trigger and the RadioDAQ board **will not exceed ~130 ns** and data output will be no larger than ~20 kB per event.



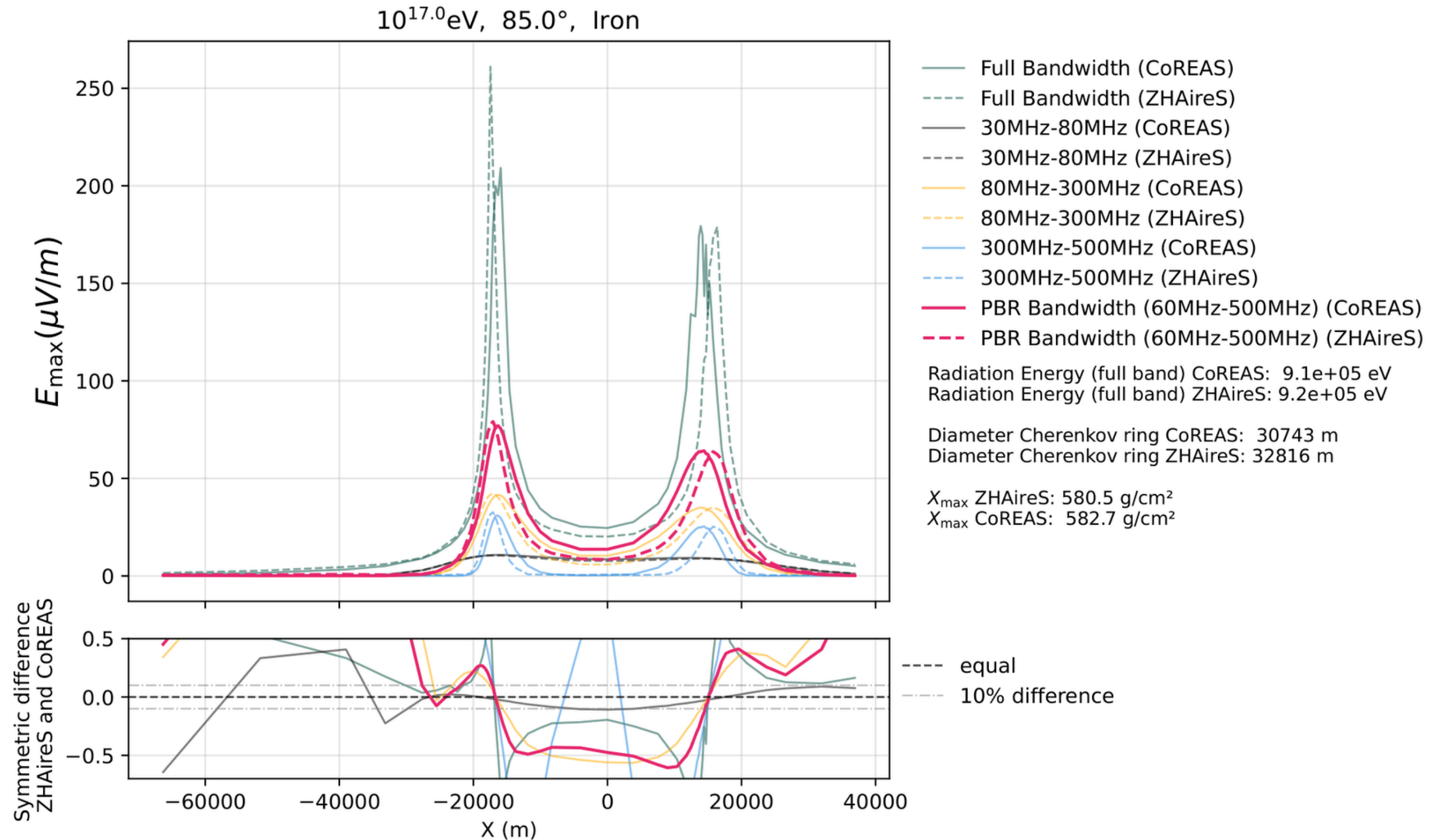
A flight of **14 days would allow to** get enough data to **achieve the science goals of PBR.**



# PBR SCALE



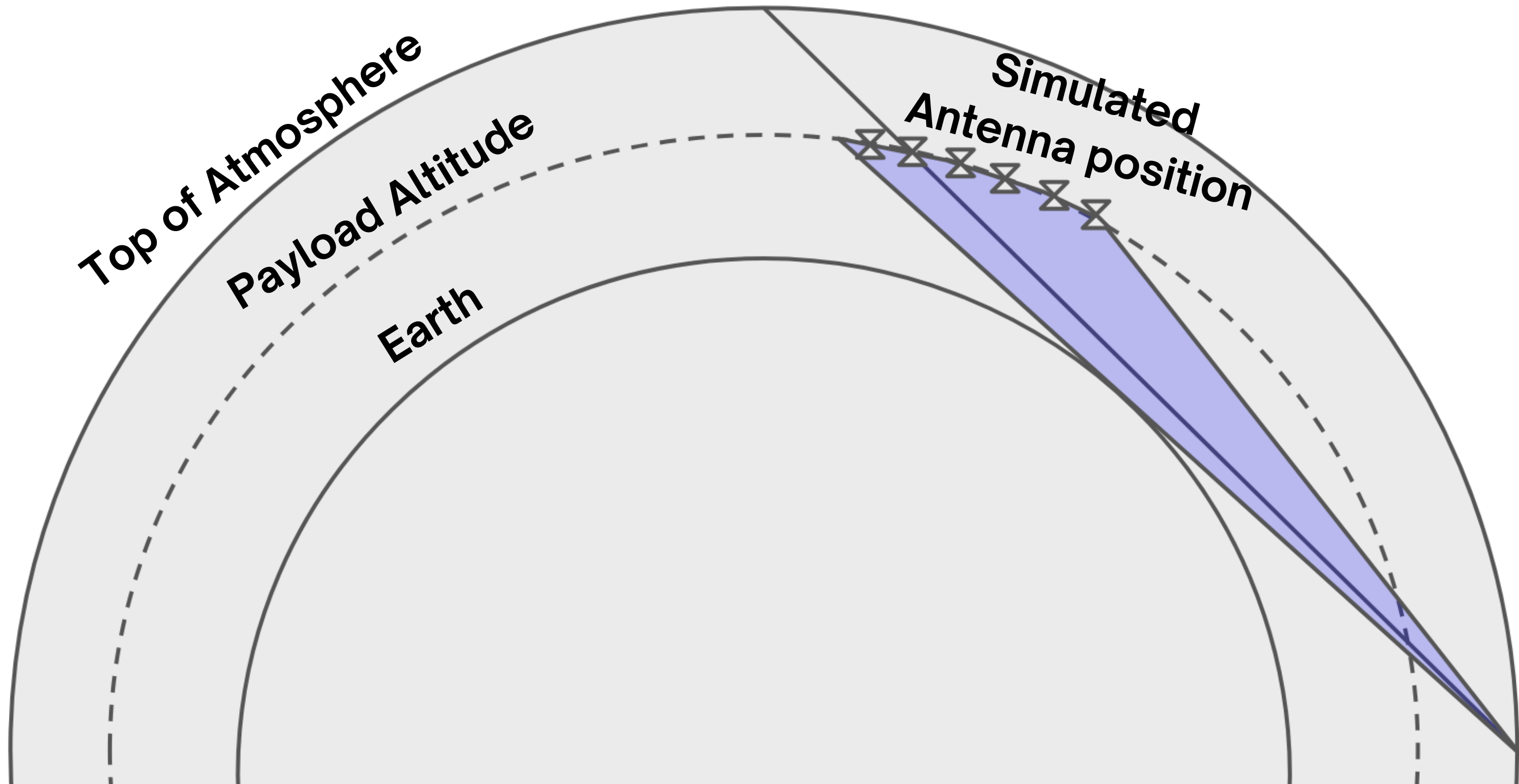
Iron shower, zenith: 85°, primary energy:  $10^{17}$  eV

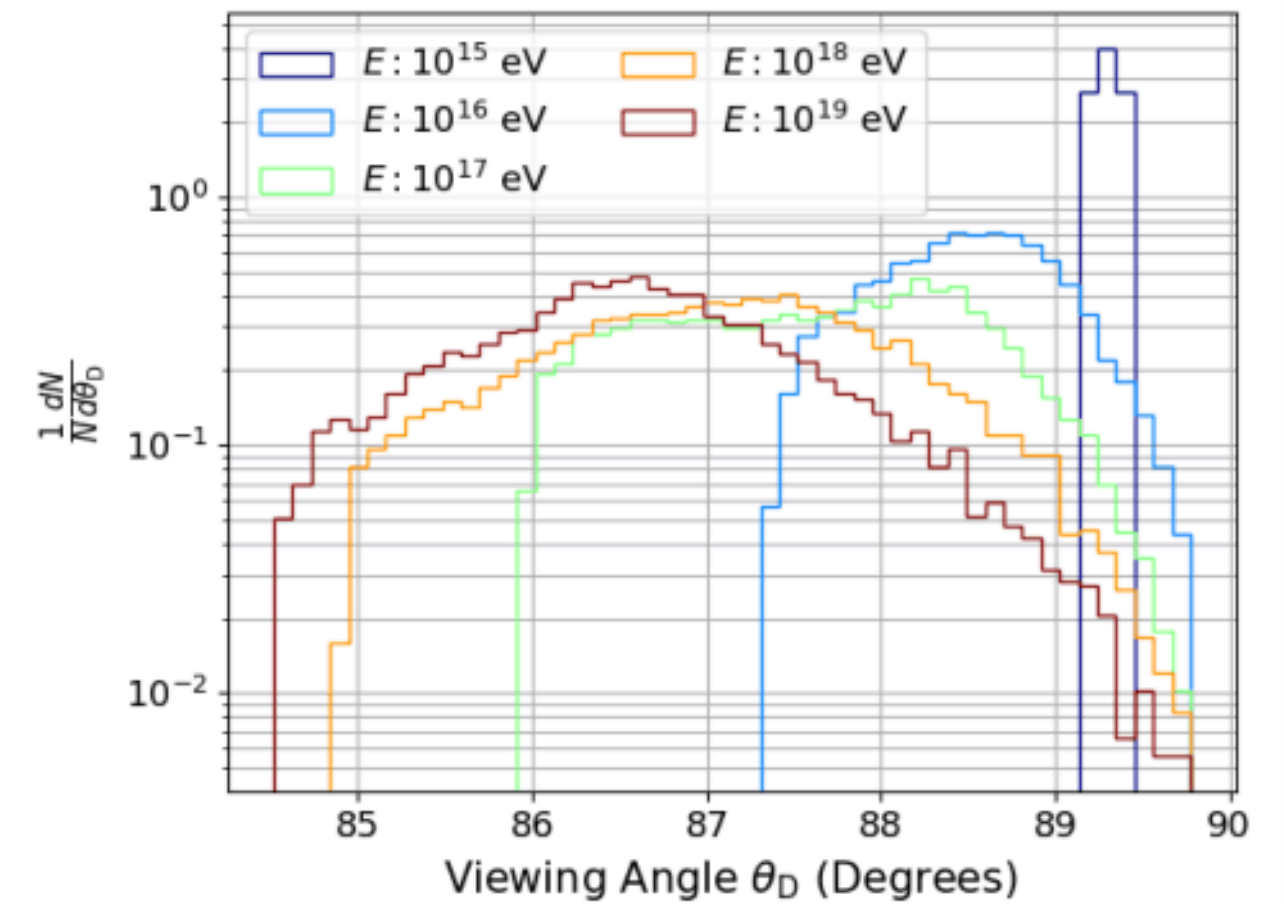
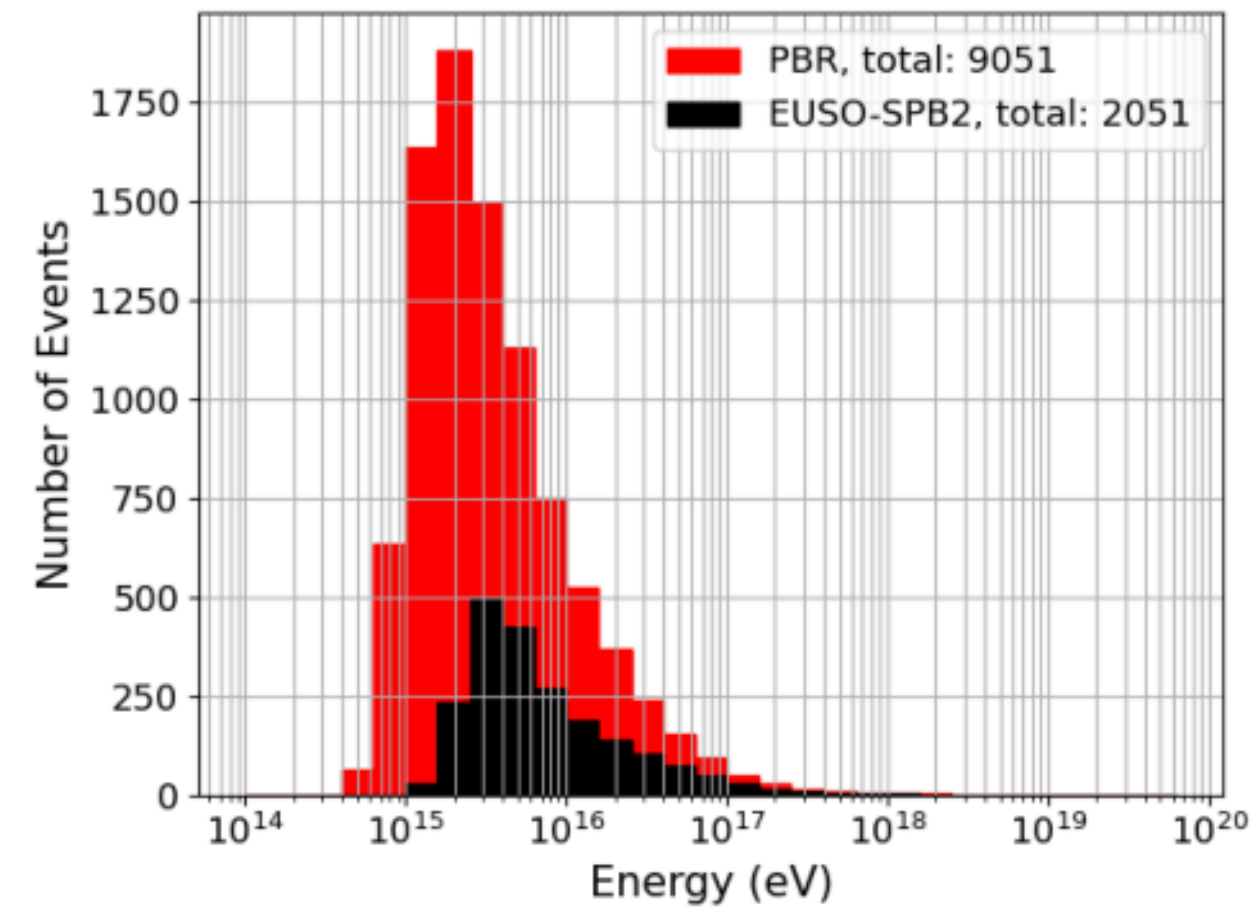
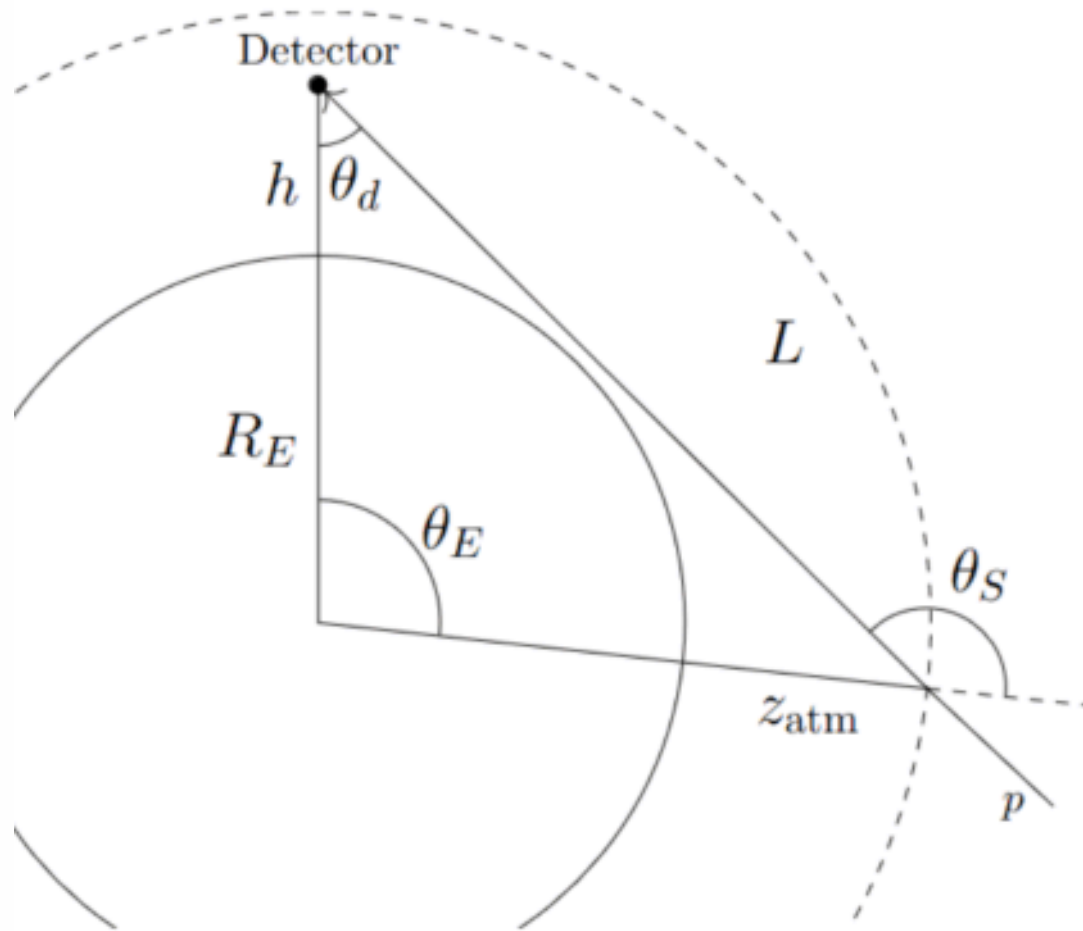






# Antenna positioning



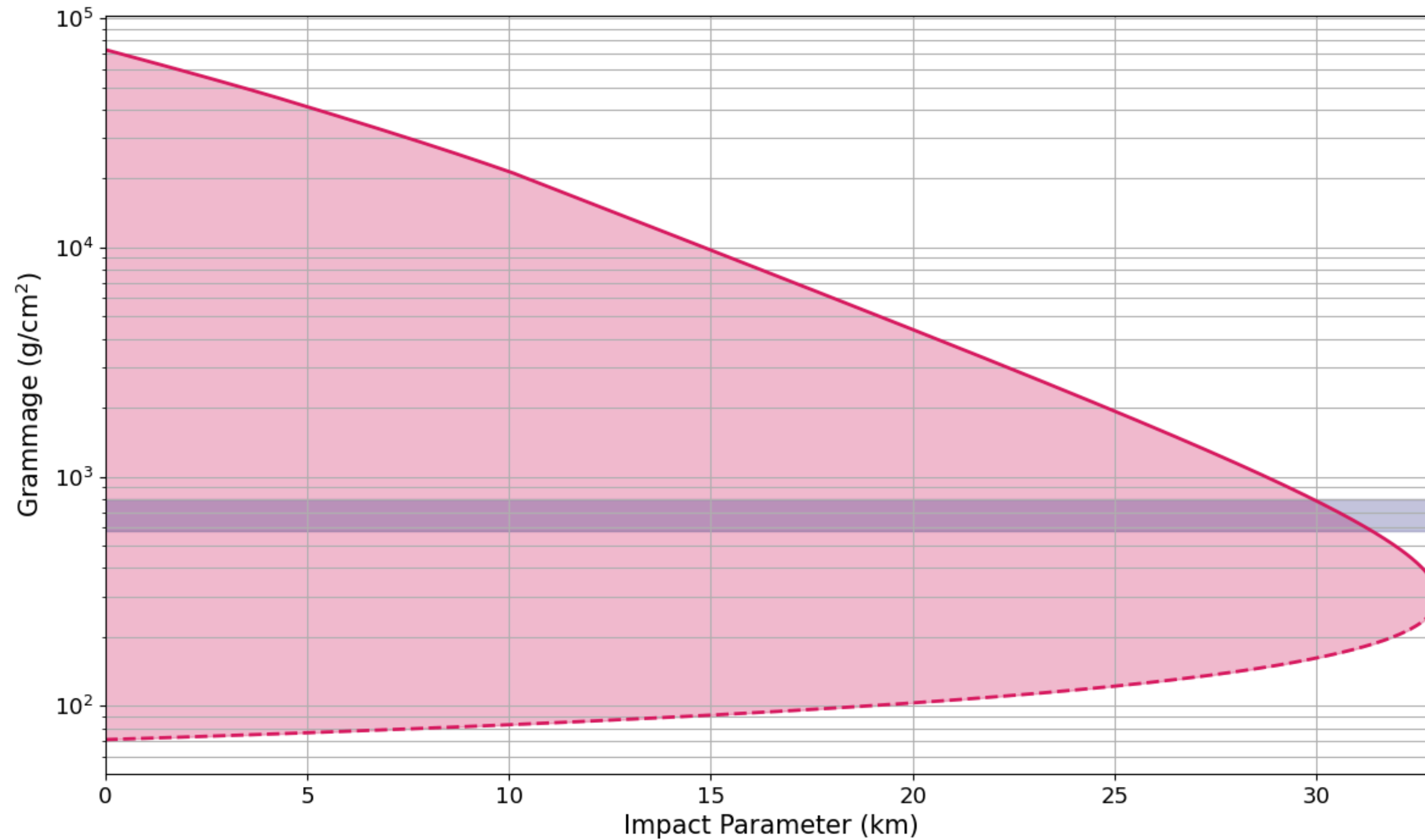






# COREAS AND ZHAIRIS RADIO AIR-SHOWER SIMULATIONS FOR POEMMA BALLOON WITH RADIO (PBR)

ISCRA 2026 ◦ July 30<sup>th</sup>, 2026 ◦ Paula Gálvez Molina ◦ paulagm@udel.edu



— Grammage until PBR altitude (second intersection)

- - - Grammage until PBR altitude (first intersection)

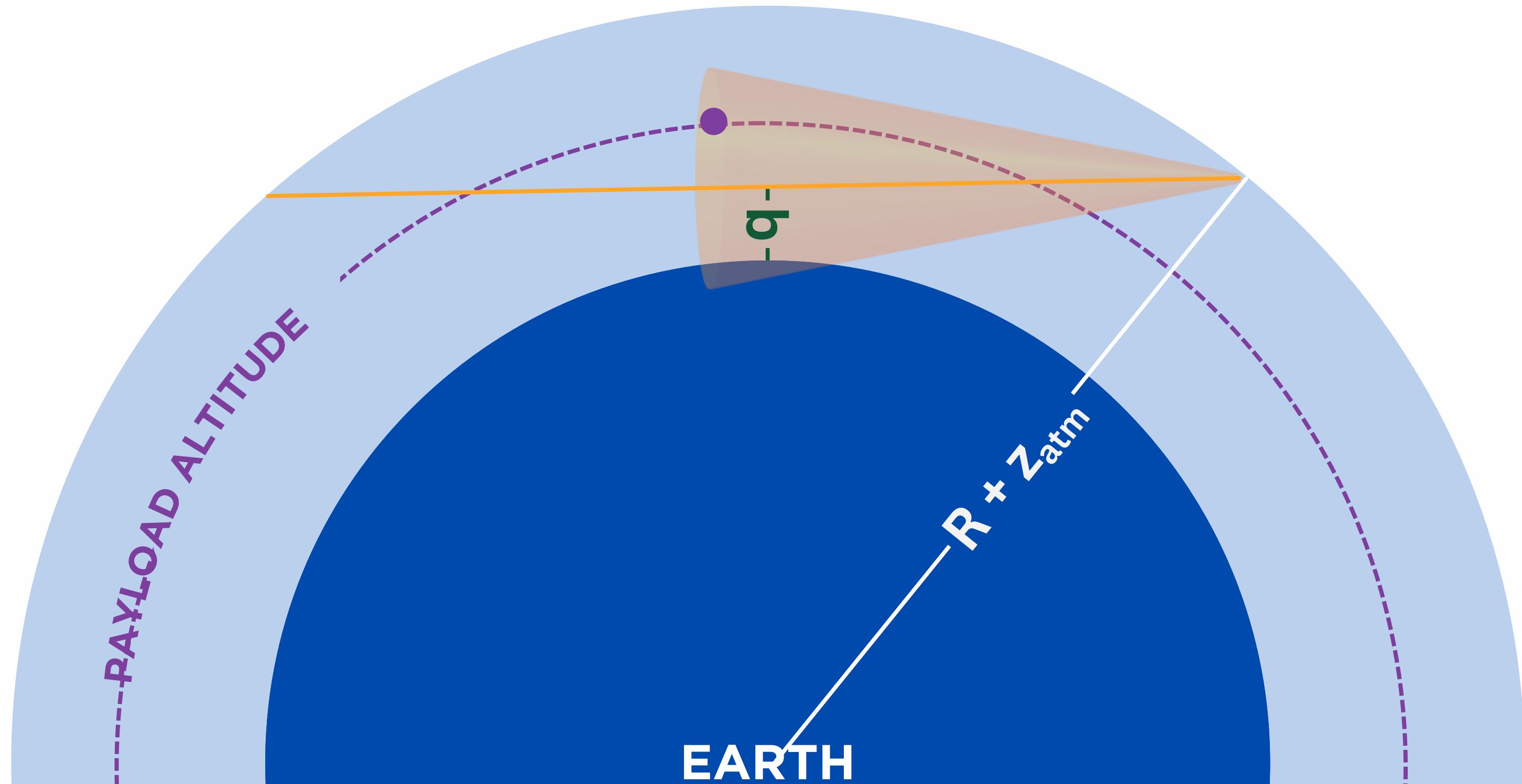
■  $X_{max}$  range  $10^{17} - 10^{18}$  eV



# COREAS AND ZHAIRC RADIO AIR-SHOWER SIMULATIONS FOR POEMMA BALLOON WITH RADIO (PBR)

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**\*not to scale**





## FIRST PHASE

| Primary | $\theta$<br>(°) | $X_{\max}^{\text{ZH}}$<br>(g cm <sup>-2</sup> ) | $X_{\max}^{\text{CO}}$<br>(g cm <sup>-2</sup> ) | $\Delta X_{\max}$<br>(g cm <sup>-2</sup> ) | $d_{\text{Ch}}^{\text{ZH}}$<br>(m) | $d_{\text{Ch}}^{\text{CO}}$<br>(m) | $\Delta d_{\text{Ch}}$<br>(m) | $E_{\text{rad}}^{\text{ZH}}$<br>(MeV) | $E_{\text{rad}}^{\text{CO}}$<br>(MeV) | $\Delta E_{\text{rad}}^{\text{sym}}$<br>(%) |
|---------|-----------------|-------------------------------------------------|-------------------------------------------------|--------------------------------------------|------------------------------------|------------------------------------|-------------------------------|---------------------------------------|---------------------------------------|---------------------------------------------|
| Proton  | 0               | 638.8                                           | 640.9                                           | -2.1                                       | 128                                | 159                                | -30                           | 0.0                                   | 0.0                                   | N/A                                         |
| Proton  | 11              | 666.9                                           | 667.1                                           | -0.2                                       | 123                                | 140                                | -17                           | 0.5                                   | 0.1                                   | 140.7                                       |
| Proton  | 20              | 744.7                                           | 745.3                                           | -0.6                                       | 44                                 | 138                                | -95                           | 0.7                                   | 0.2                                   | 101.6                                       |
| Proton  | 30              | 669.5                                           | 670.6                                           | -1.2                                       | 237                                | 228                                | 9                             | 0.9                                   | 0.5                                   | 59.3                                        |
| Proton  | 40              | 692.6                                           | 691.4                                           | 1.2                                        | 310                                | 351                                | -41                           | 1.2                                   | 0.8                                   | 41.5                                        |
| Proton  | 60              | 750.5                                           | 750.7                                           | -0.2                                       | 976                                | 1037                               | -61                           | 2.3                                   | 2.9                                   | -21.5                                       |
| Proton  | 70              | 696.6                                           | 694.0                                           | 2.6                                        | 2347                               | 2519                               | -172                          | 3.4                                   | 2.9                                   | 14.2                                        |
| Iron    | 70              | 626.0                                           | 631.1                                           | -5.1                                       | 2372                               | 2519                               | -147                          | 2.0                                   | 2.2                                   | -7.8                                        |
| Proton  | 75              | 659.5                                           | 659.8                                           | -0.3                                       | 4319                               | 4404                               | -84                           | 4.5                                   | 3.1                                   | 37.7                                        |
| Proton  | 80              | 685.4                                           | 685.3                                           | 0.1                                        | 9423                               | 9504                               | -81                           | 3.2                                   | 2.8                                   | 13.2                                        |
| Proton  | 85              | 697.1                                           | 700.7                                           | -3.6                                       | 33 461                             | 31 651                             | 1810                          | 2.1                                   | 2.1                                   | -0.7                                        |
| Iron    | 85              | 580.5                                           | 582.7                                           | -2.2                                       | 32 816                             | 30 743                             | 2072                          | 0.9                                   | 0.9                                   | 1.2                                         |

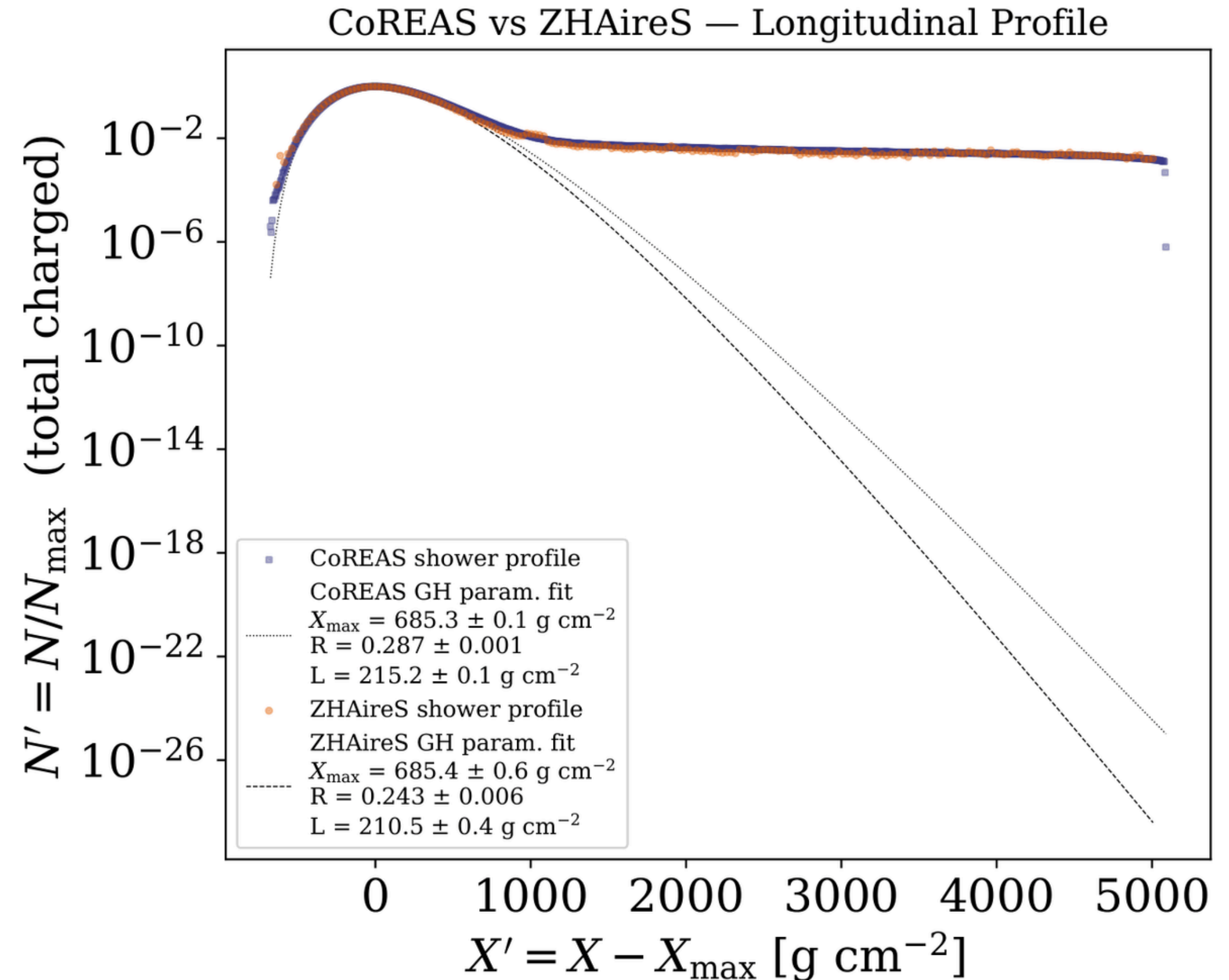
## FIRST PHASE

Select showers with similar  $X_{\max}$

Primary Particle: Proton

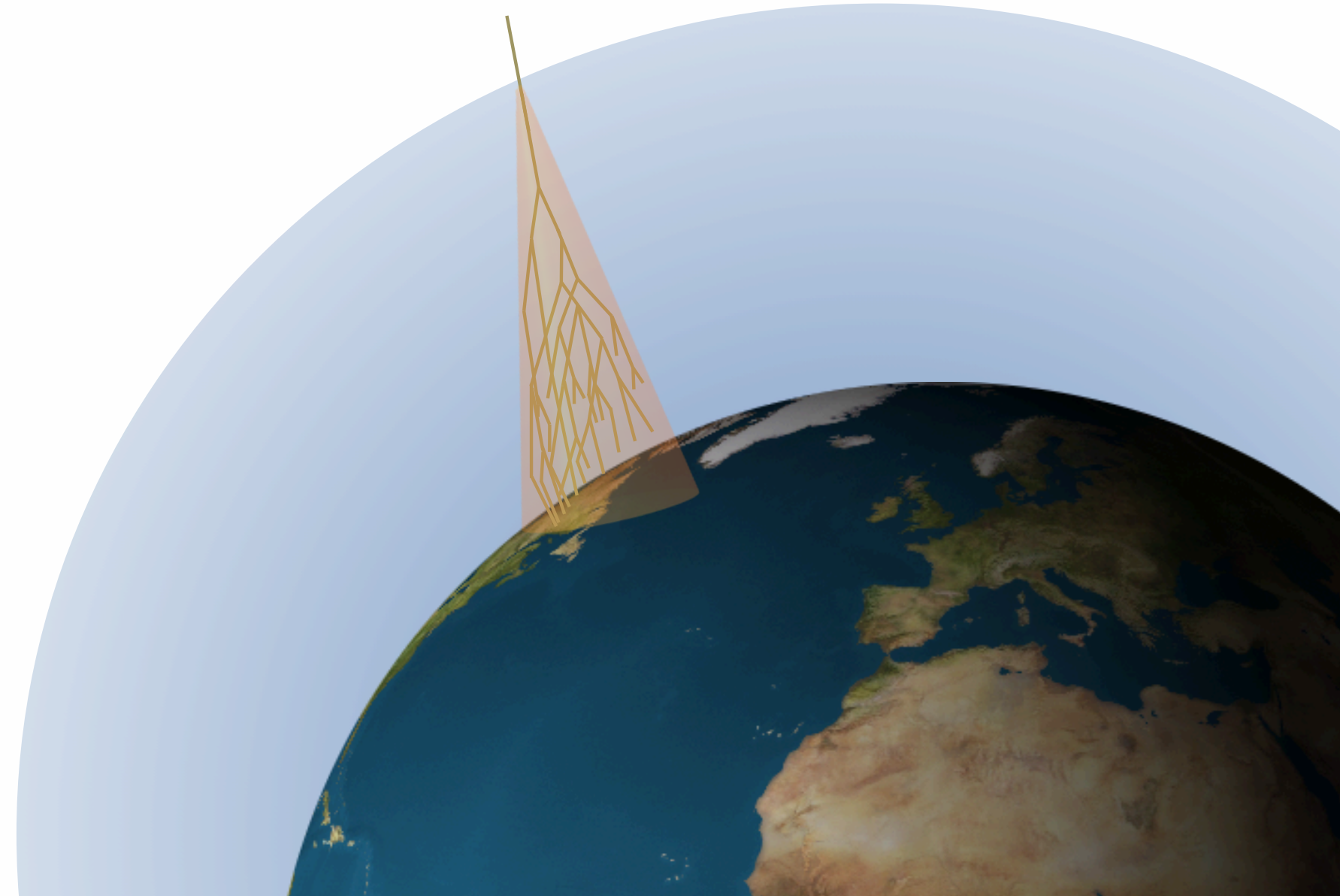
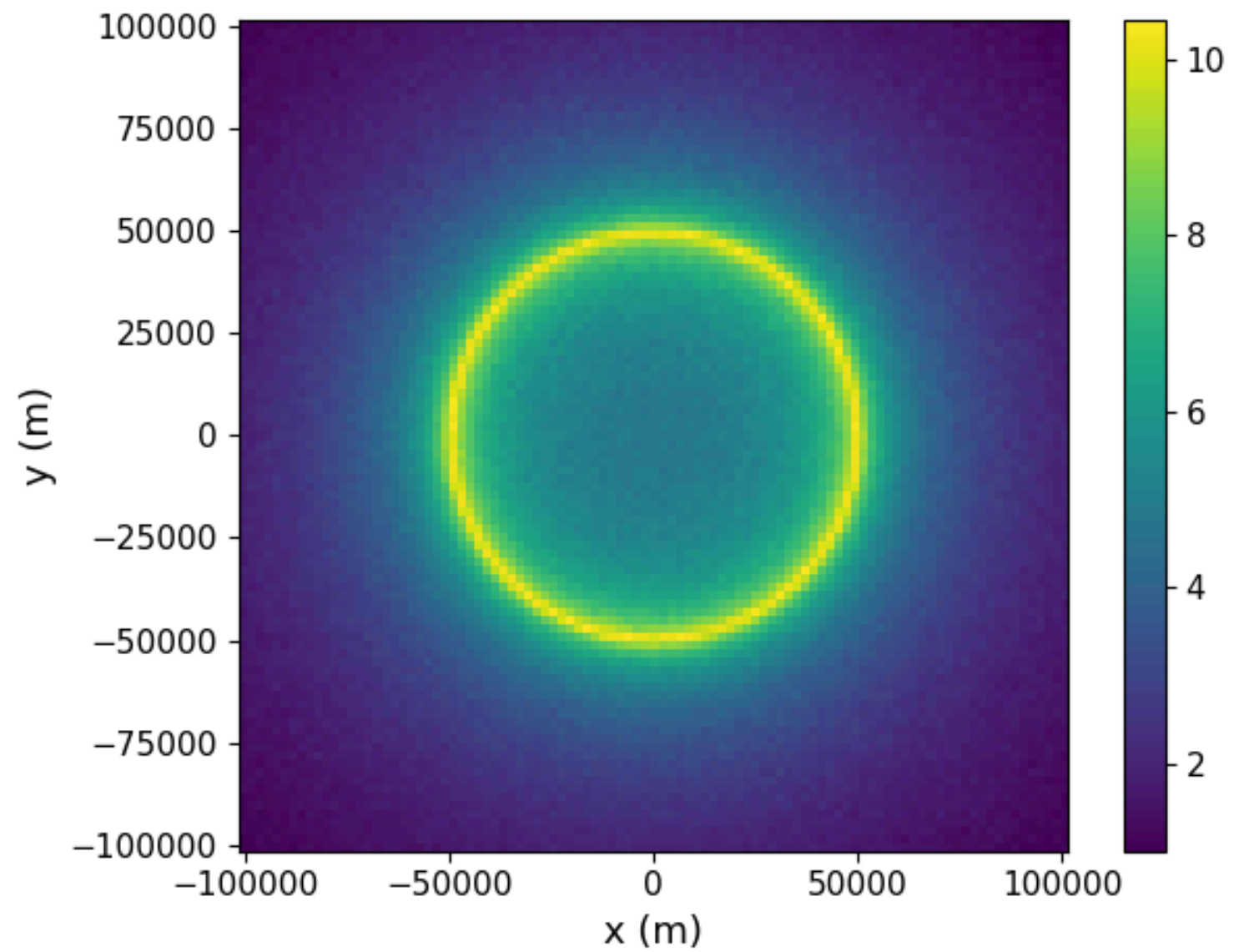
Zenith:  $80^\circ$

Primary energy:  $10^{17}$  eV





# Cherenkov ring

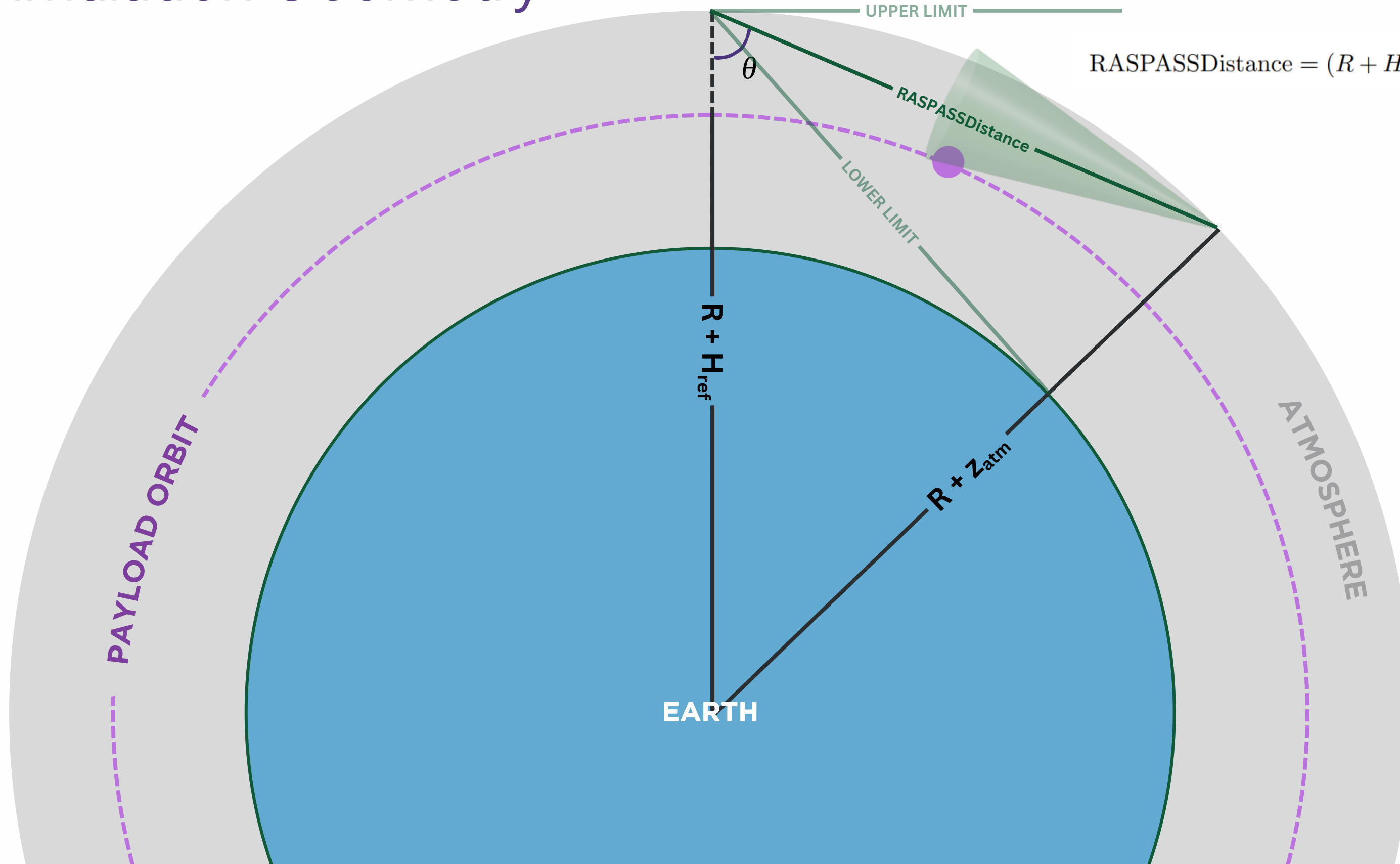




# Simulation Geometry

$$\theta = \sin^{-1}\left(\frac{R + b}{R + H_{\text{ref}}}\right)$$

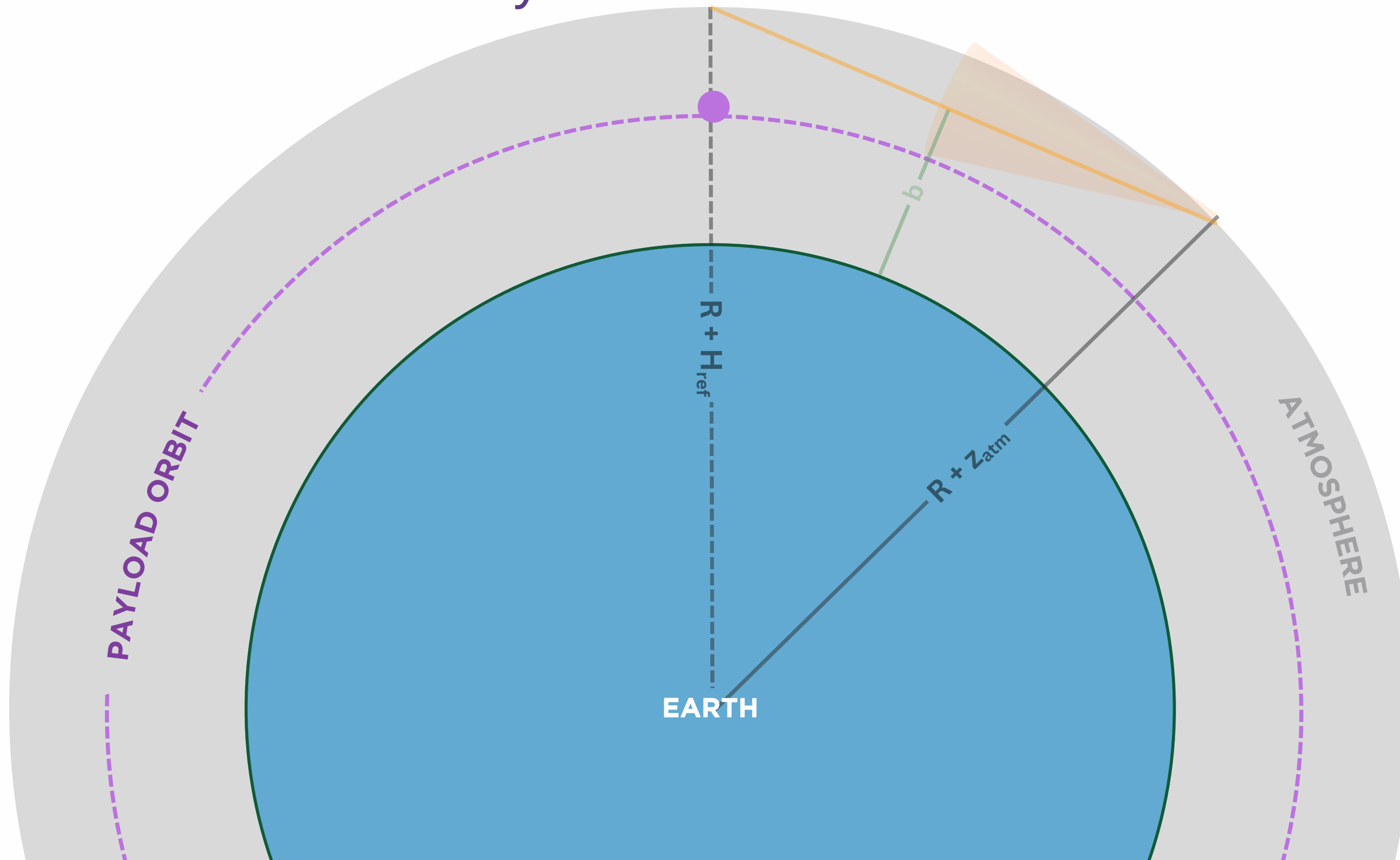
$$\text{RASPASDistance} = (R + H_{\text{ref}})\cos\theta + \sqrt{(R + z_{\text{atm}})^2 - (R + H_{\text{ref}})^2\sin^2\theta}$$



\*not to scale



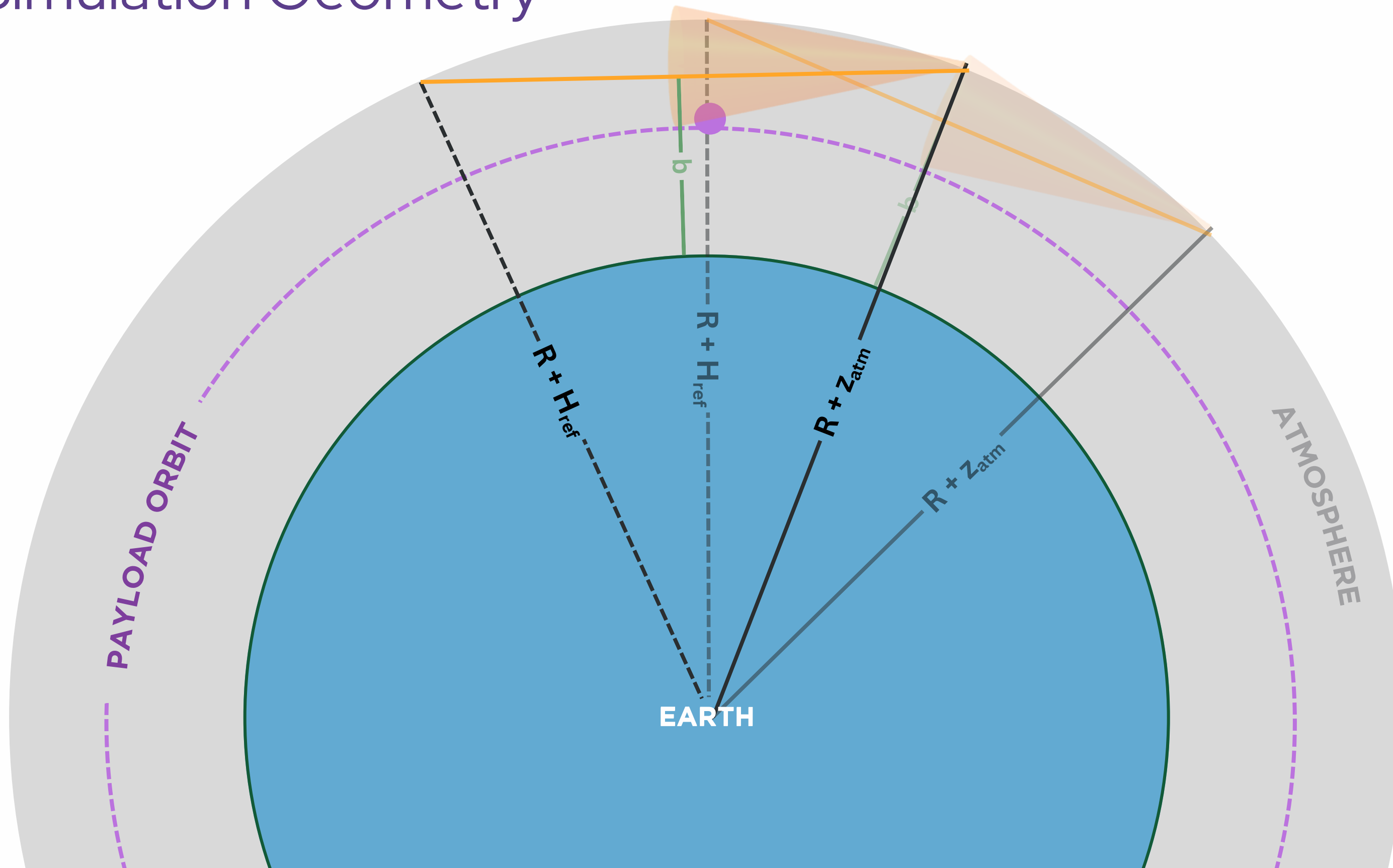
# Simulation Geometry



\*not to scale



# Simulation Geometry

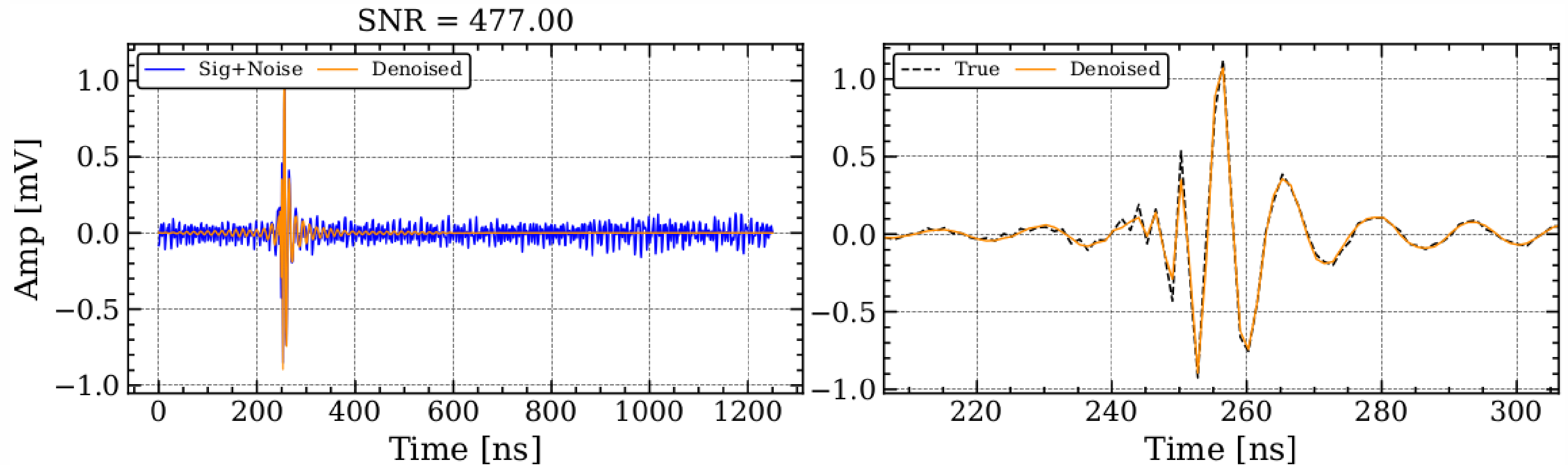


\*not to scale



# Denoiser

Using data from the prototype station at the IceCube Neutrino Observatory





# POEMMA Extra Info

10.1088/1475-7516/2021/06/007

- “POEMMA-Stereo performance can be summarized as follows: energy resolution:  $\leq 18\%$  above 50 EeV; angular resolution:  $< 1.5^\circ$  above 40 EeV; and Xmax resolution of  $< 40 \text{ g/cm}^2$  above 40 EeV.”
- “All of these improve as UHECR energy increases.”

| Observation Modes      | Telescope Separation | Pointing                                                                         | Science Goals (section)                                                                           |
|------------------------|----------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| POEMMA-Stereo (mode-2) | ~300 km              | down close to Nadir; overlapping atmospheric volumes                             | UHECR fluorescence (2.2, 2.3)<br>precision stereo reconstruction<br>UHECR lower energies 10s EeVs |
| POEMMA-Limb (mode-3)   | ~25 km               | towards the Limb; azimuth follows ToO target<br>overlapping volume at Limb       | Neutrino Cherenkov (2.4, 2.5, 2.6)<br>ToO-stereo                                                  |
|                        |                      | towards the Limb; overlapping volume nearby<br>non-overlapping at Limb           | UHECR fluorescence (2.2, 2.3)<br>stereo reconstruction 10s EeV<br>monocular for 100s EeVs         |
|                        | ~300 km              | fast slew towards the Limb from POEMMA-Stereo mode<br>azimuth follows ToO target | Neutrino Cherenkov (2.4, 2.5, 2.6)<br>ToO-dual                                                    |

**Figure 32.** POEMMA primary observation modes for UHECR science (§2.2 and §2.3) and cosmic neutrino science (§2.4, §2.5, and §2.6). Atmospheric science (§2.7) and observations of Meteors and nuclearites (§2.8) can be done in all modes.