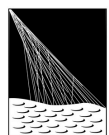




Observation of EarthCARE Laser Emissions with the Pierre Auger Observatory

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PIERRE
AUGER
OBSERVATORY

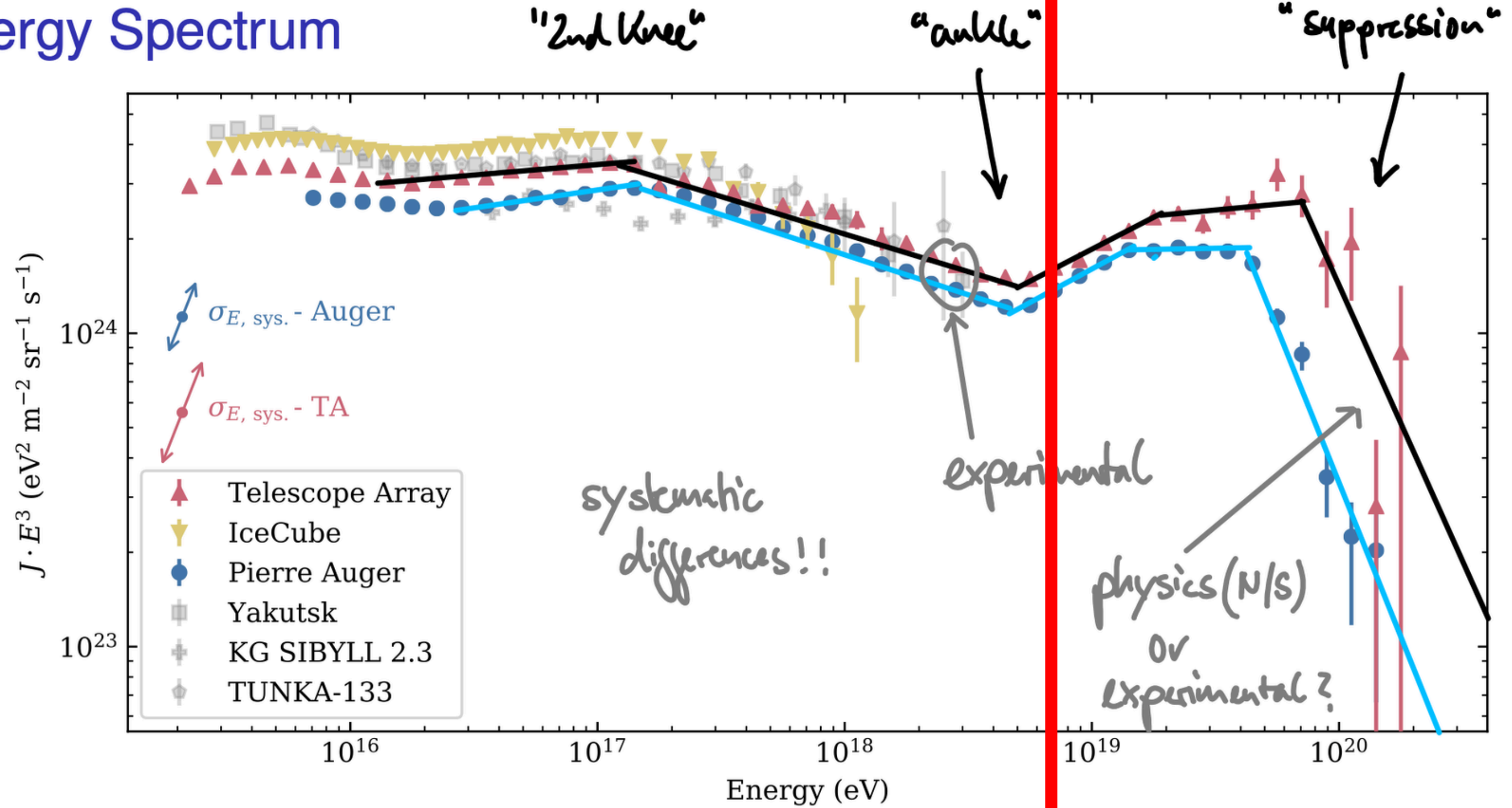


Karlsruher Institut für Technologie

thara.pineda@kit.edu

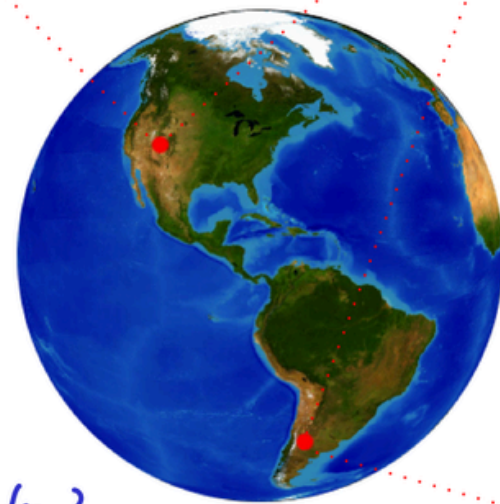
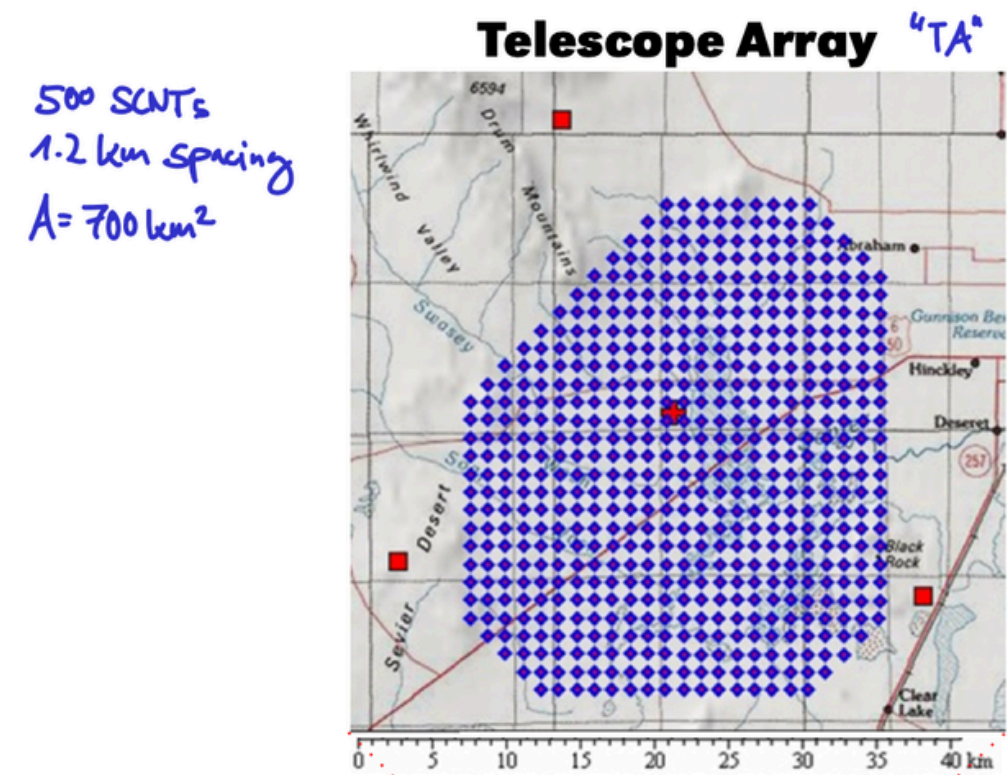
Credits: S. Saffi/wikimedia/ESA.

Energy Spectrum

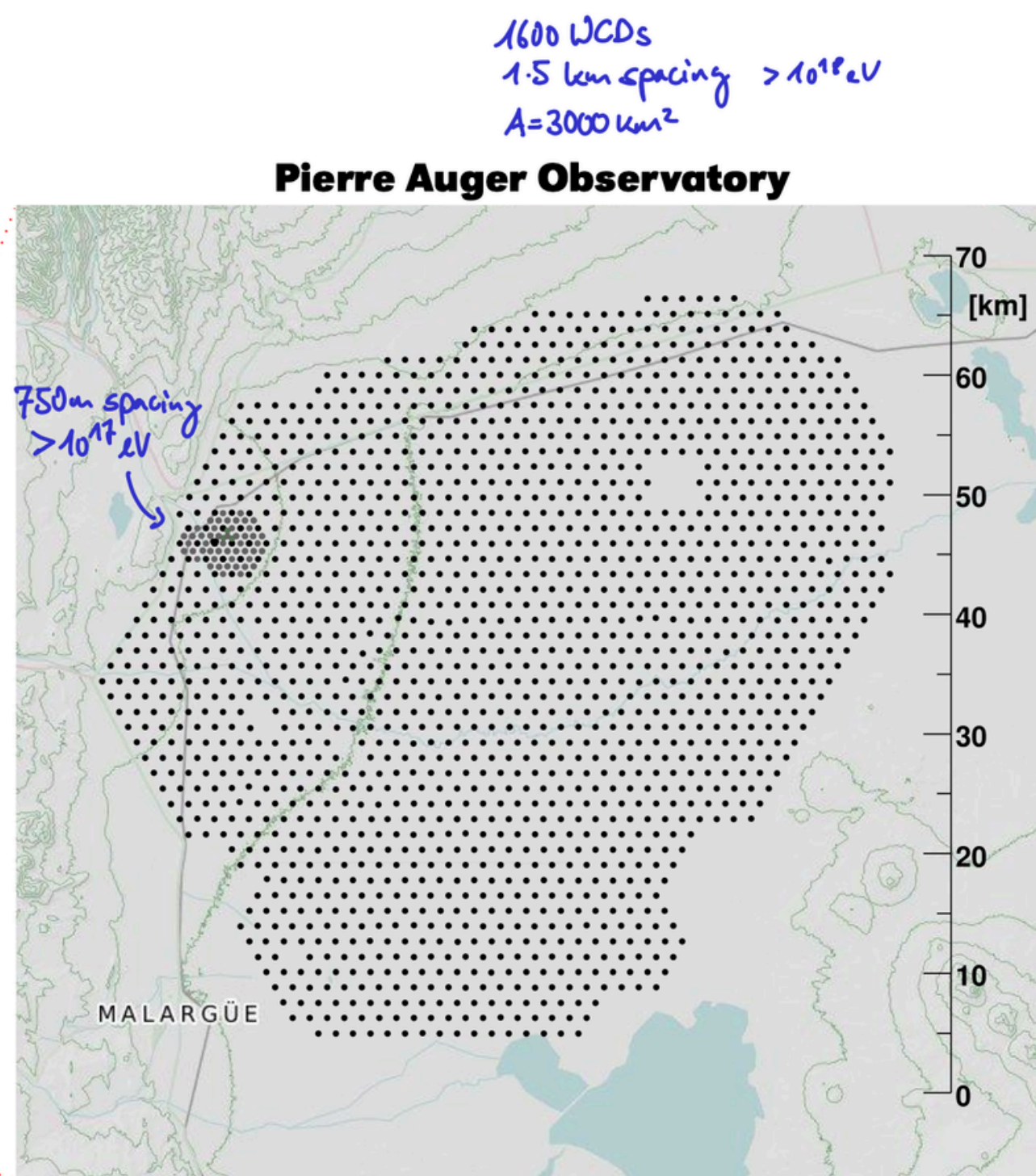


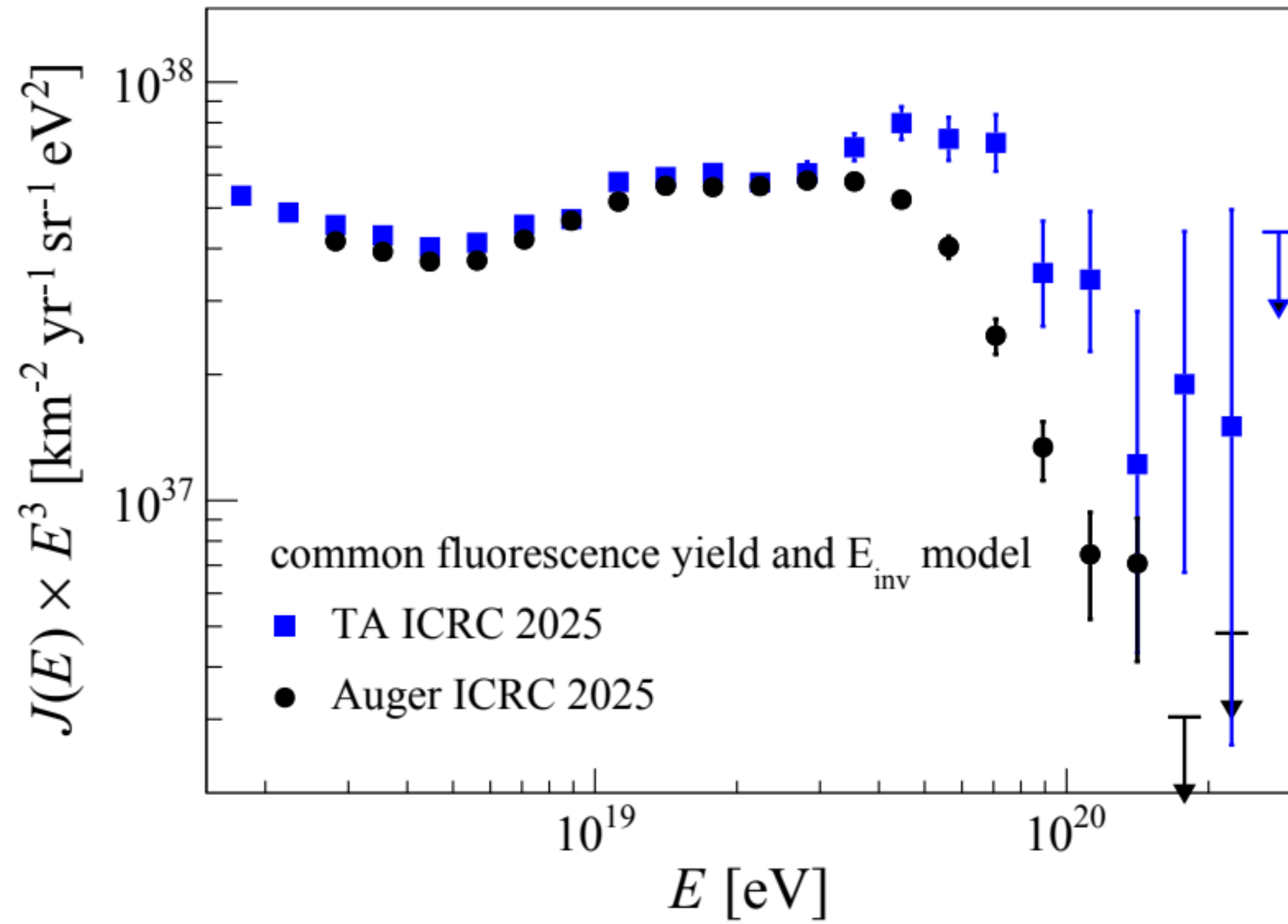
arXiv:2205.0584

From Michael Unger lecture



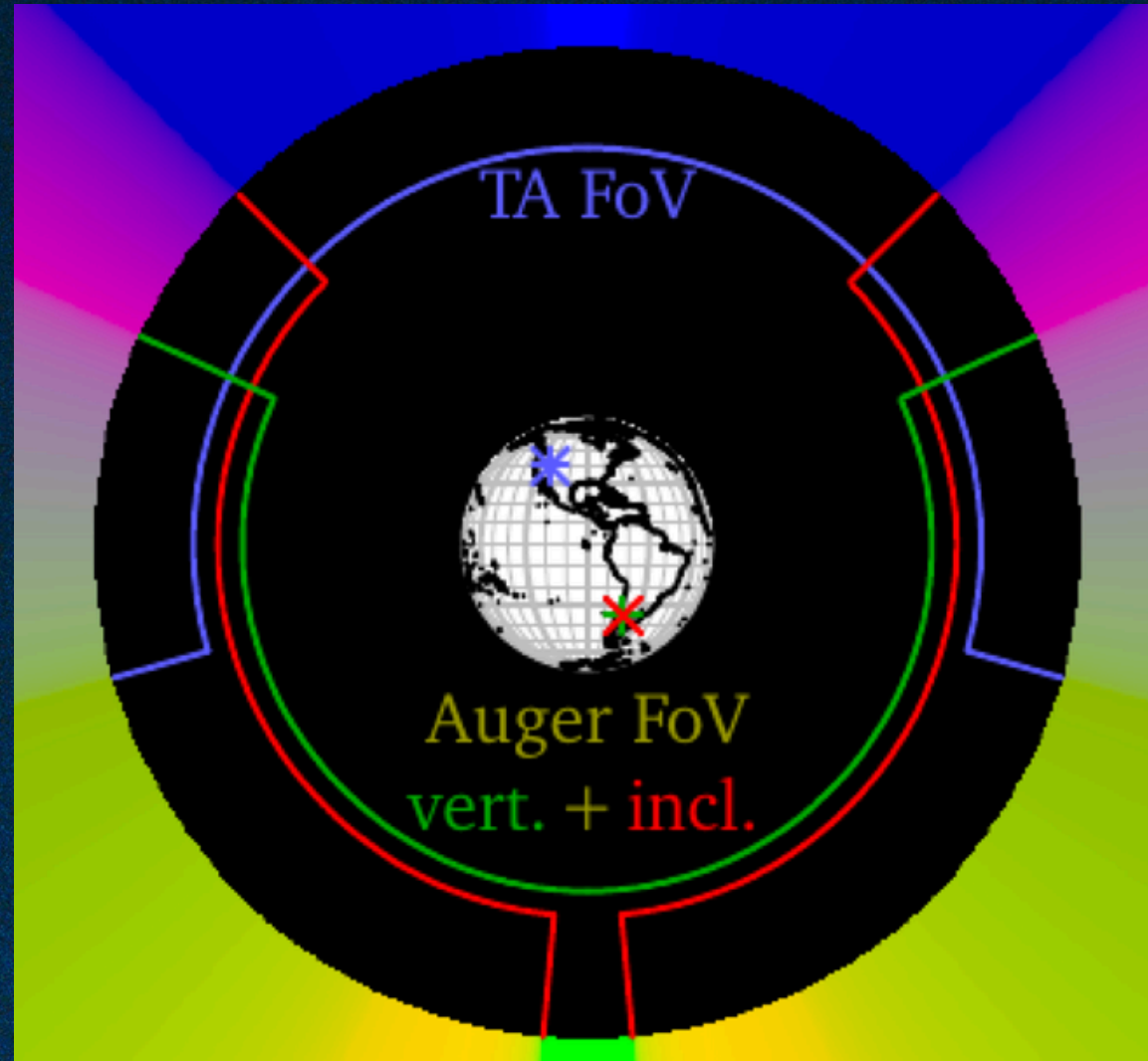
both at $X_{\text{ground}} \approx 850 \text{ g/cm}^2$





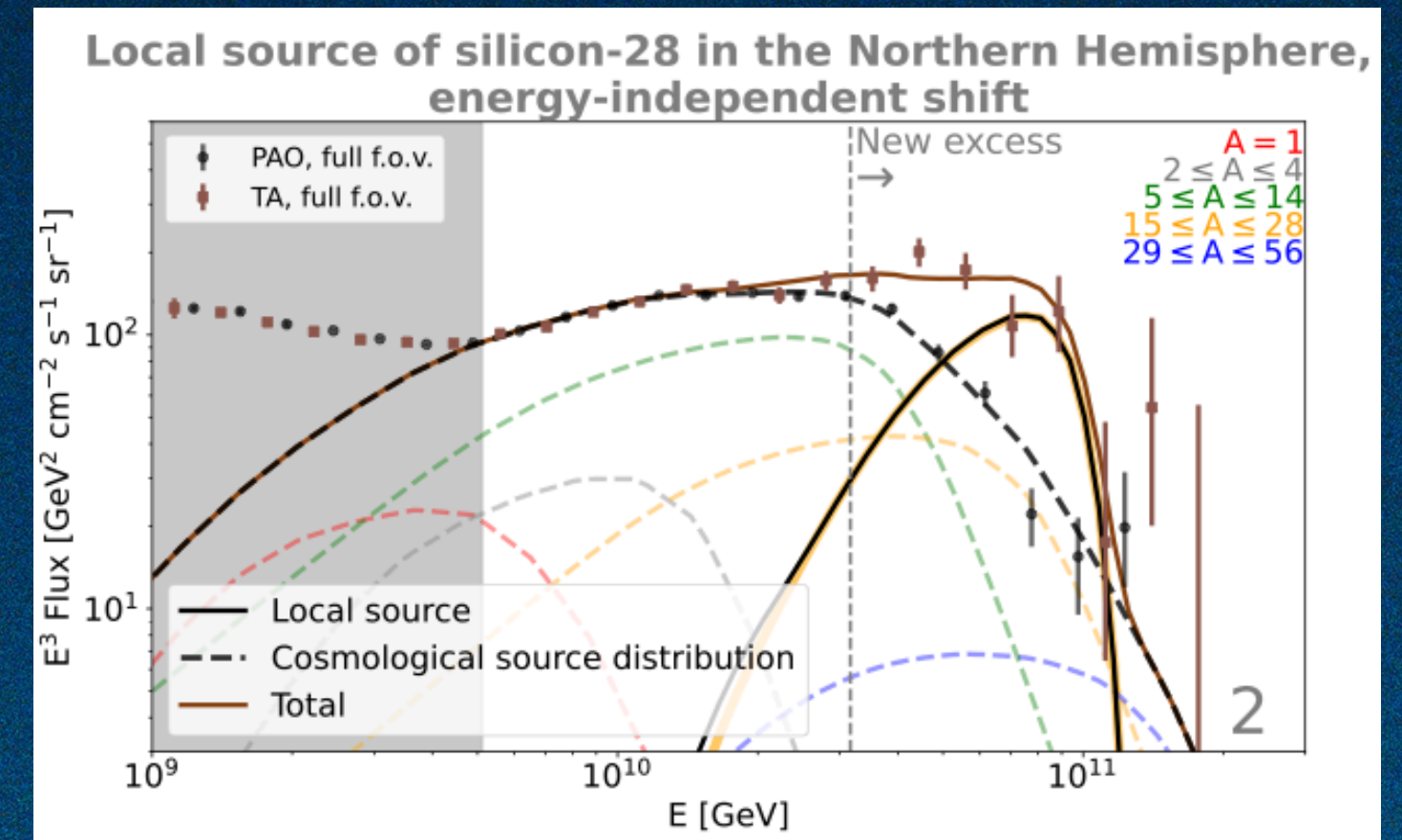
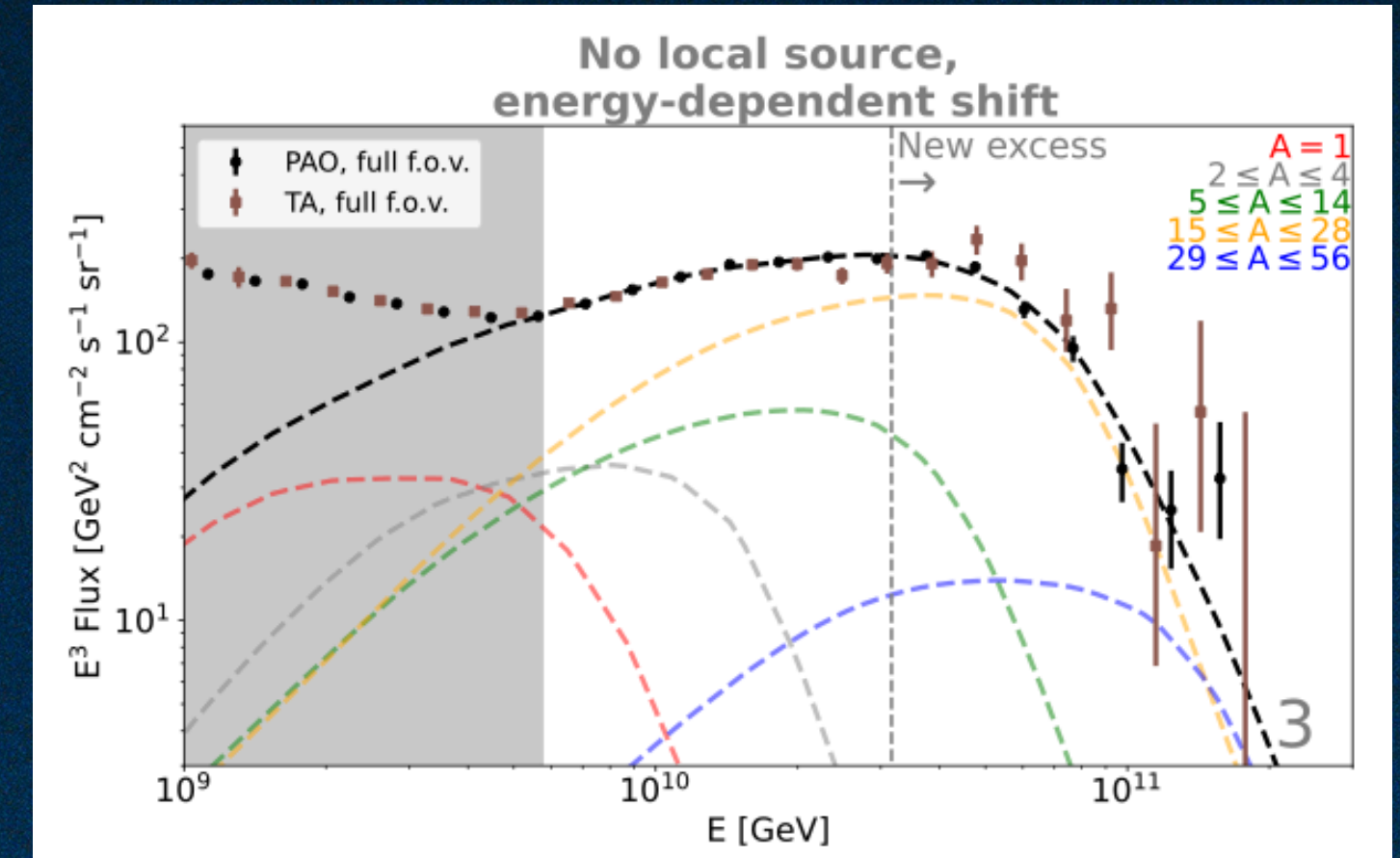
D.R.Bergman (TA&Auger Coll.) ICRC25 arXiv:2509.05530.

Source in the northern sky?



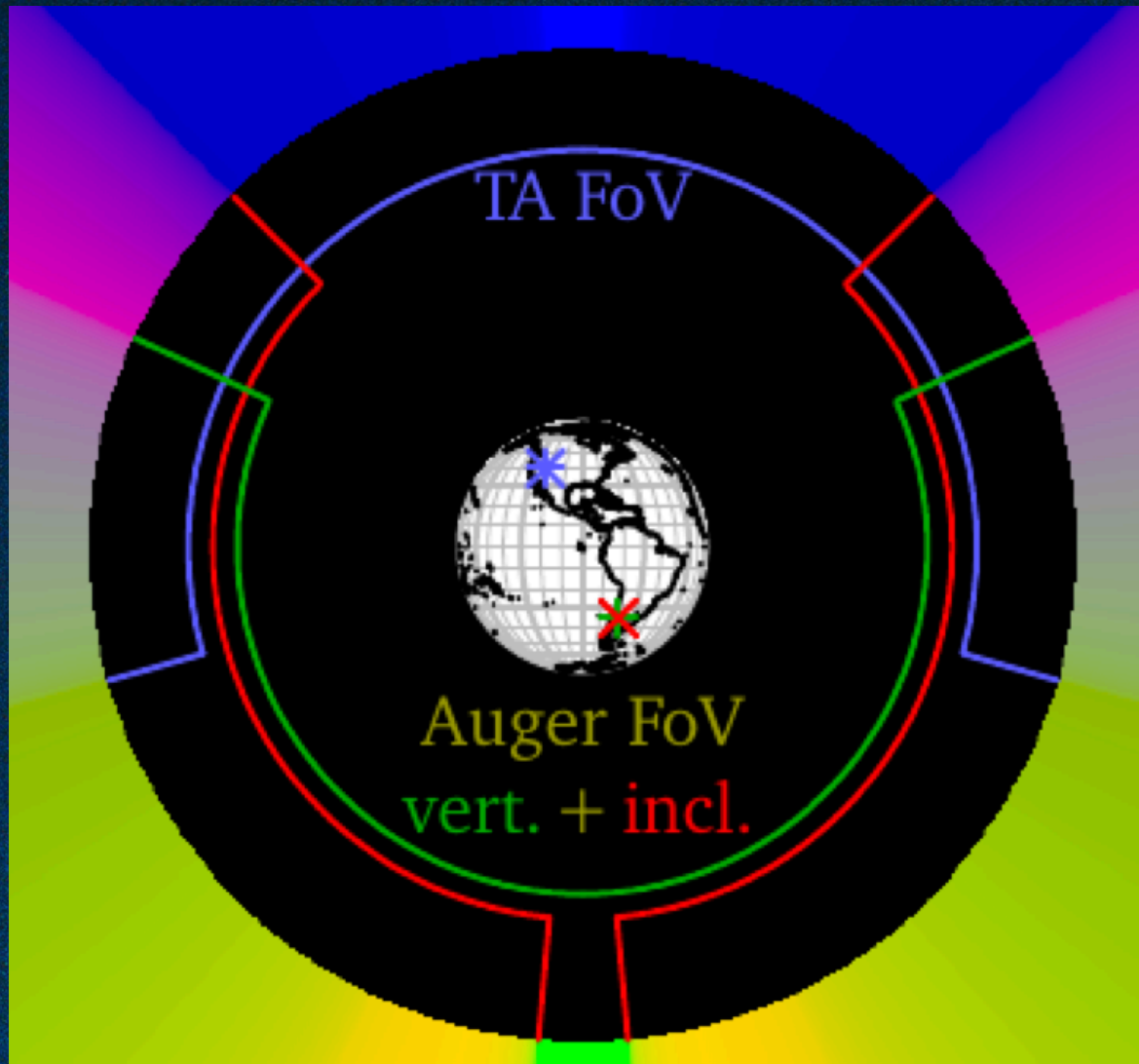
U.A. Galvez (TA & Auger Coll.) ICRC25 arXiv:2507.10441

Pavlo Plotko et al. (2023) simulated different systematics and local source models in the northern sky. **They found that energy-dependent systematics and a local source in the northern sky explained the data equally well.**

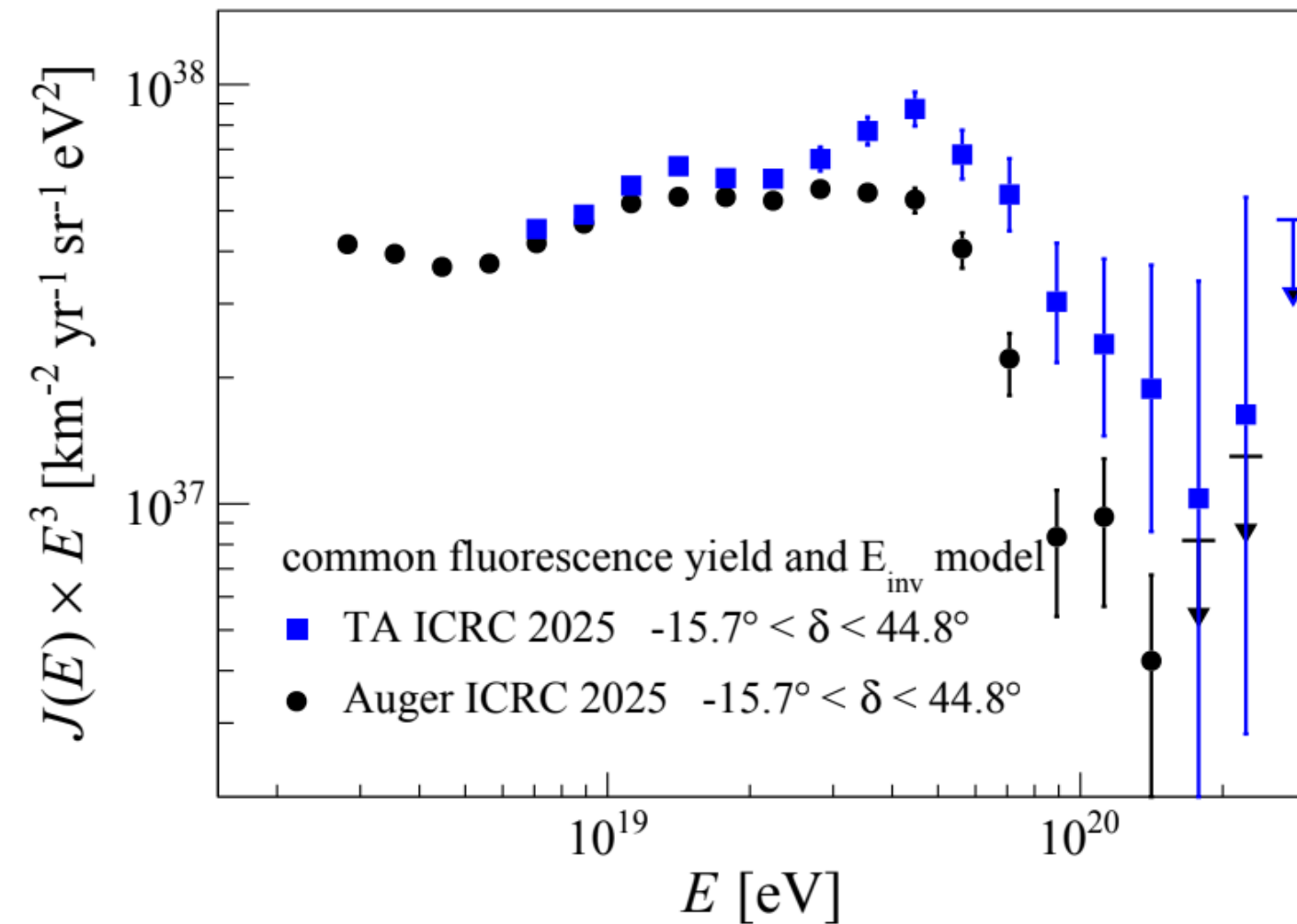


Even within the common declination band...

Different spectra measured!



U.A. Galvez (TA & Auger Coll.) ICRC25 arXiv:2507.10441.

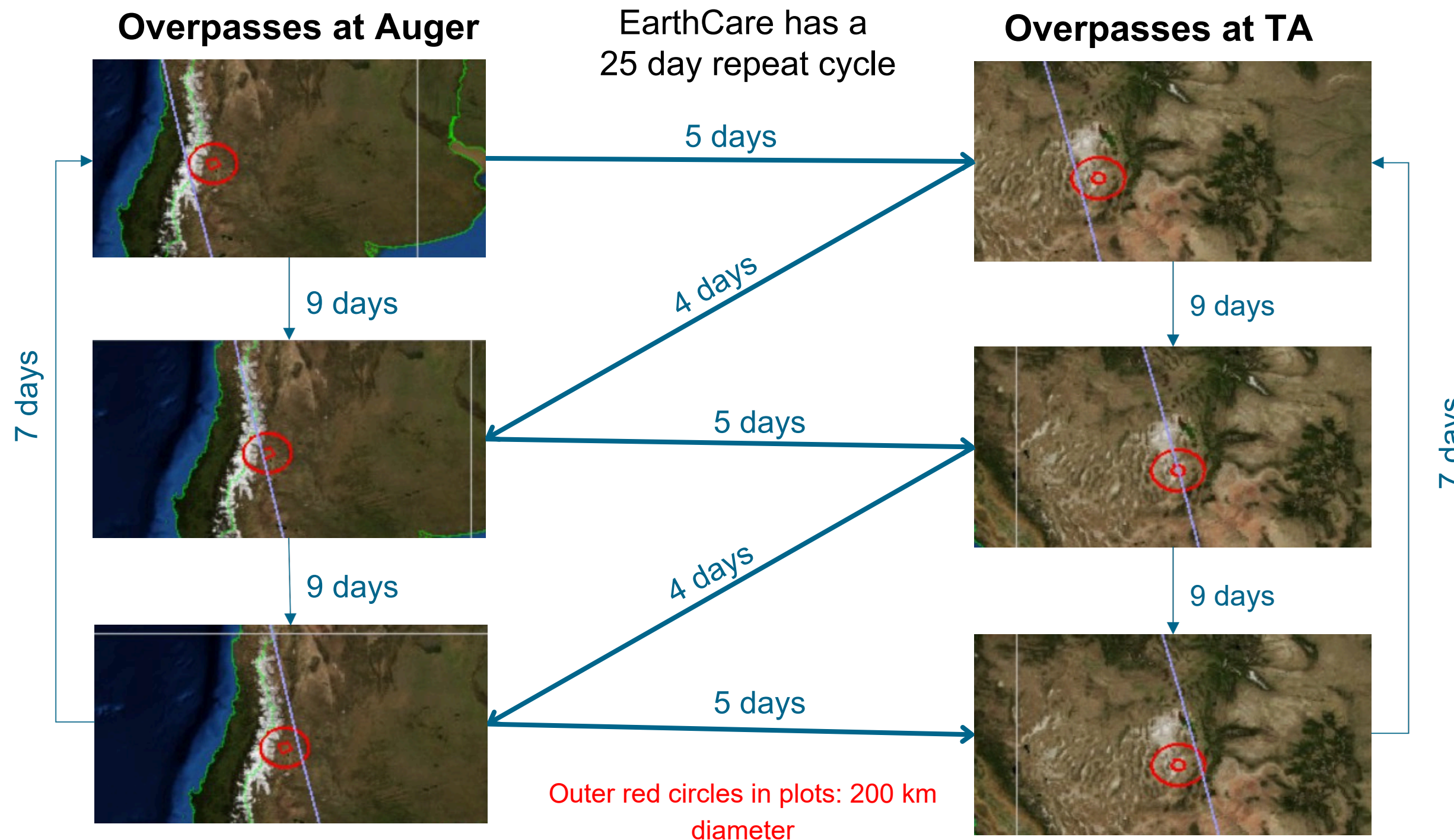


D.R.Bergman (TA&Auger Coll.) ICRC25 arXiv:2509.05530.

Source in the northern sky or systematics?
We need a reference light!

EarthCARE can help!

**Same calibrated laser observed by both sites →
Compare reconstructed energy.**



Launch: 28 May 2024.

Switch-on: July 2024

Expected lifetime: 10 years.

Energy: 38 mJ

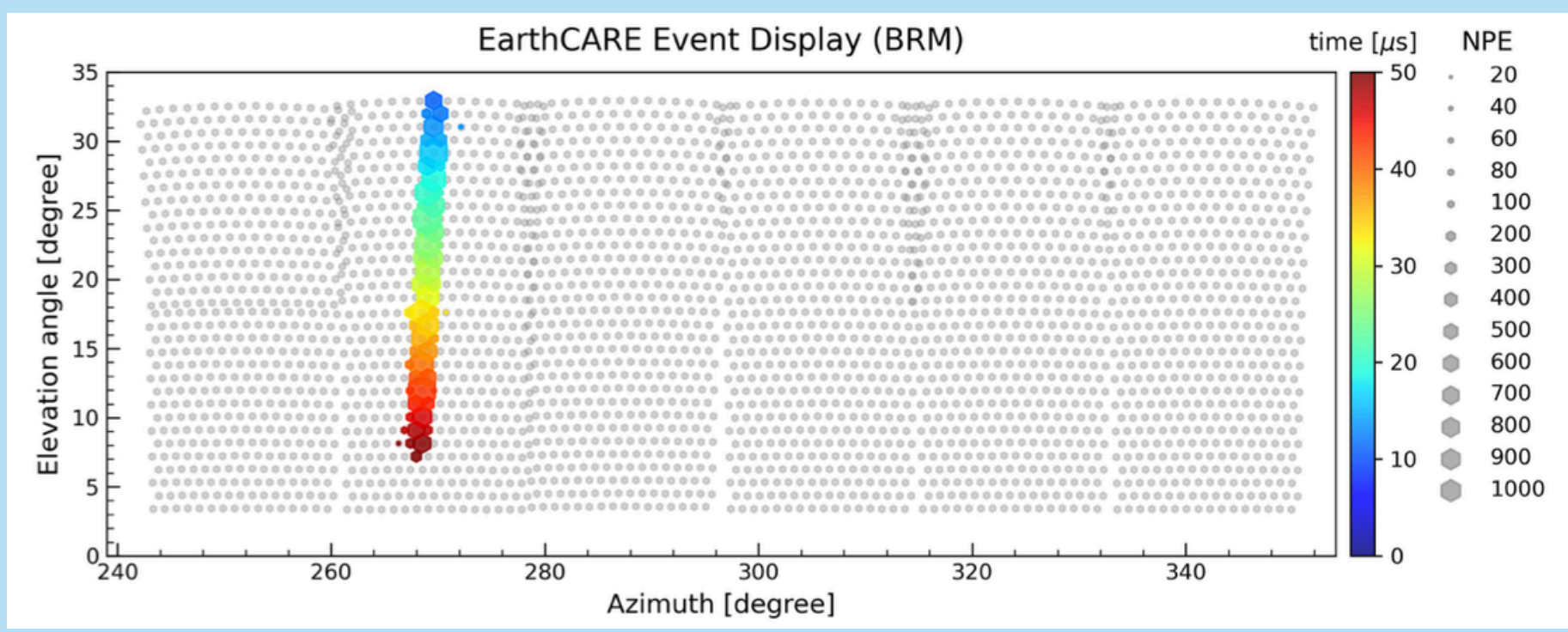
Frequency: 51 Hz

Wavelength: 354.8 nm

Krisch/Reitebuch DLR.

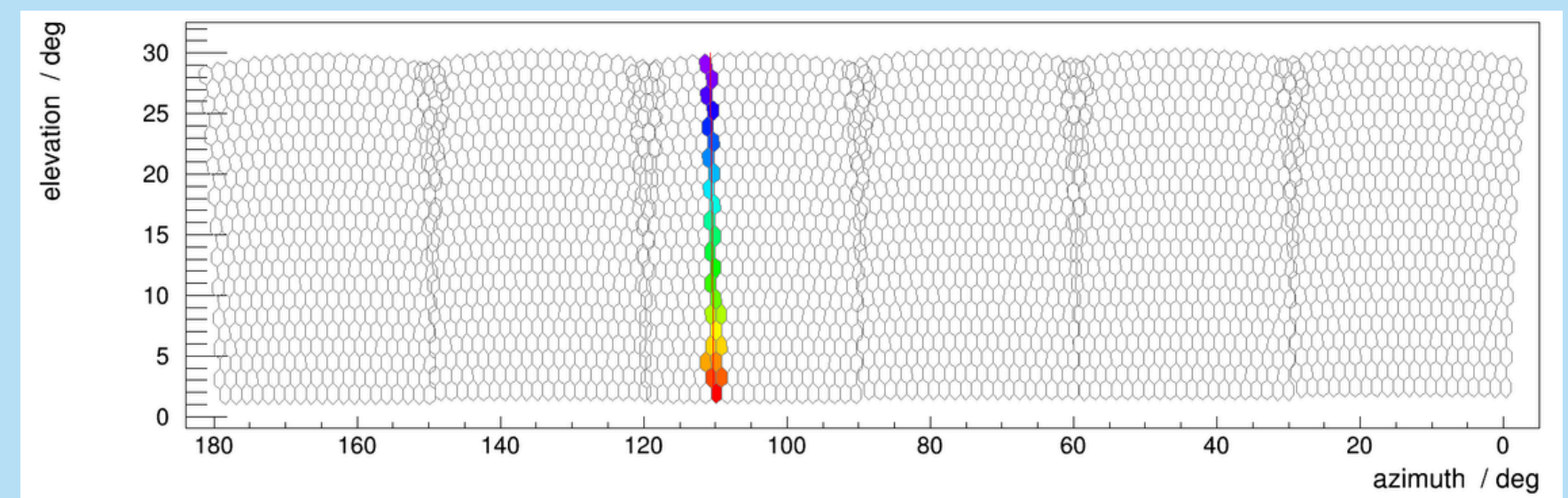
Compare energy reconstruction with the Telescope Array

Telescope Array Project



Teramoto, Masaki. Poster at EarthCARE Science and Validation Workshop 2025.

Pierre Auger Observatory



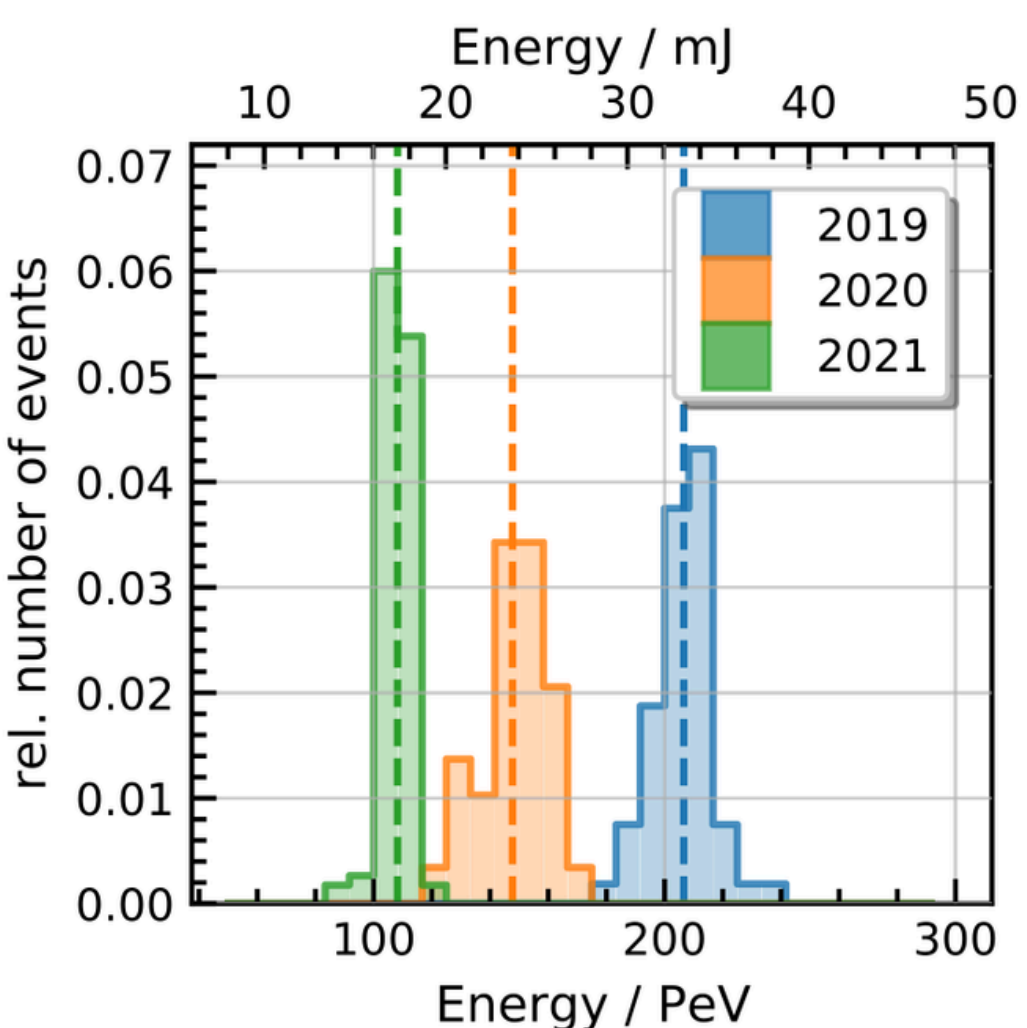
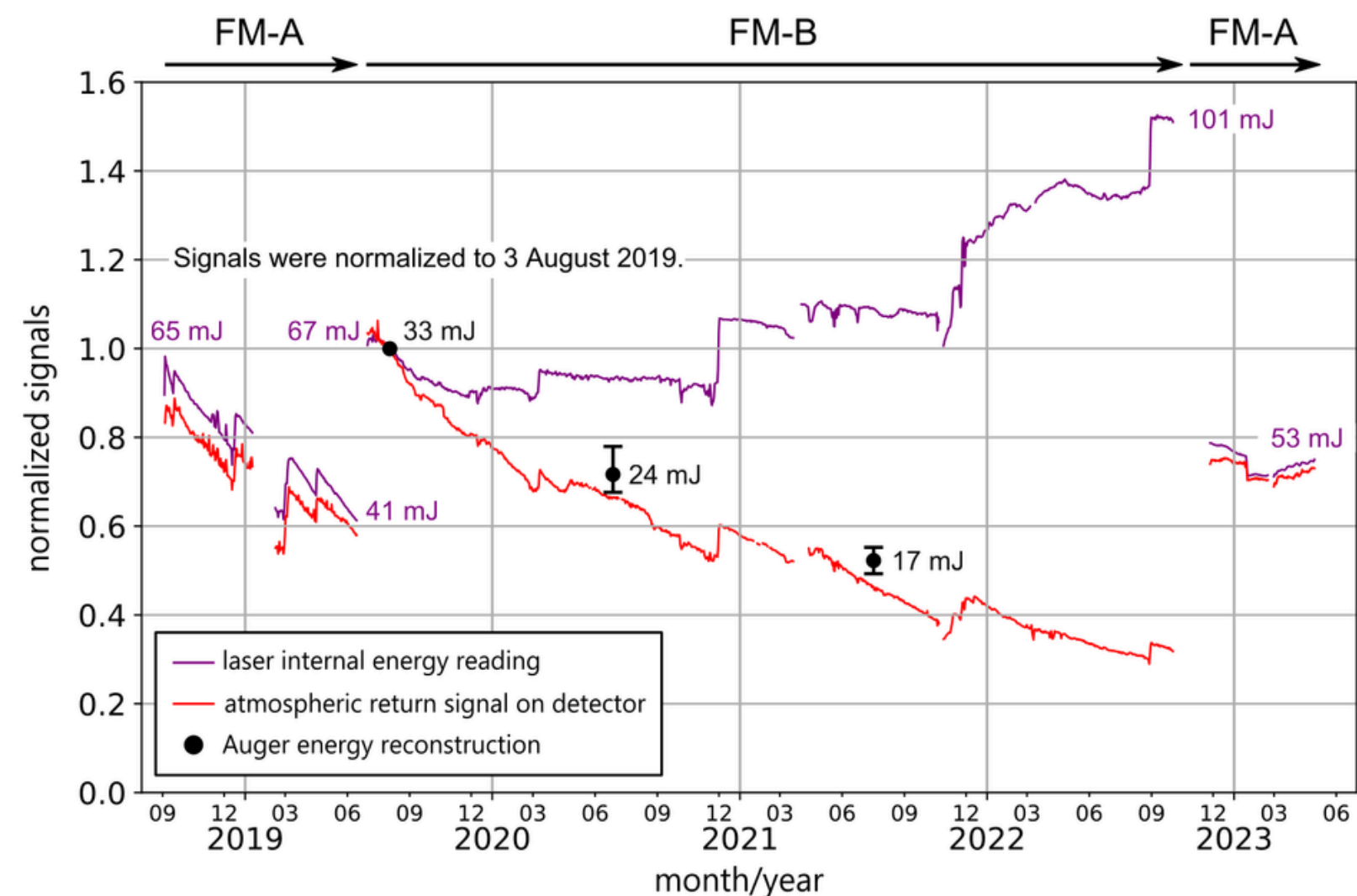
EarthCARE Event Display (Loma Amarilla).

Seen by VERITAS and CTAO as well!

Validate EarthCARE's laser properties

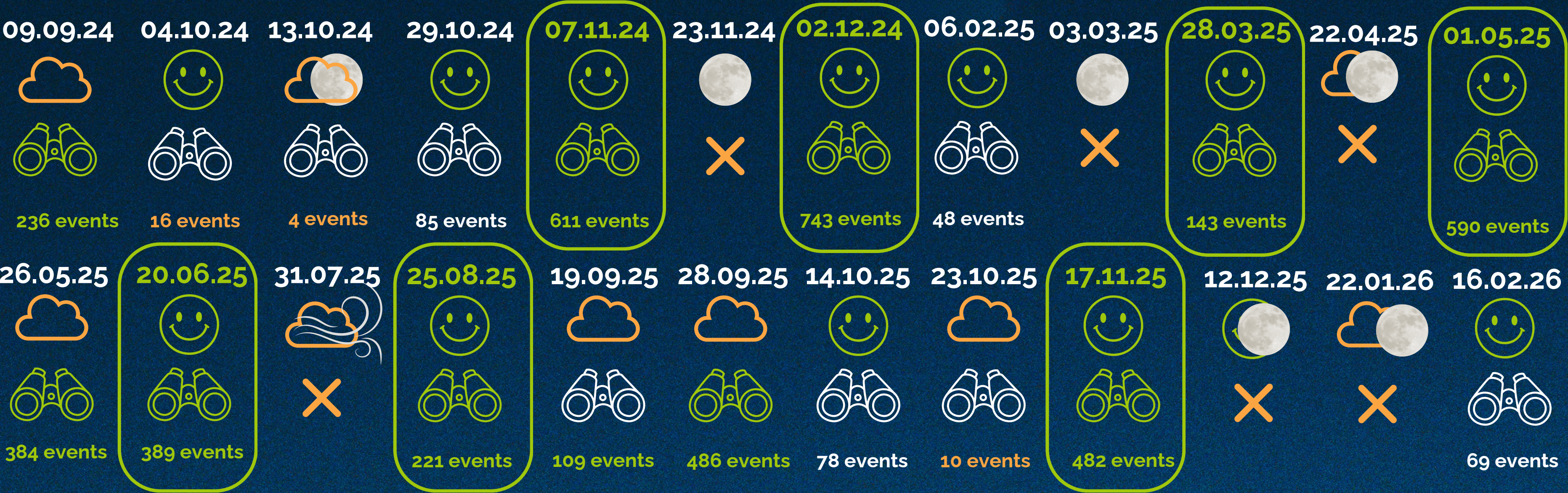
Example: Previous studies with Aeolus Lidar

Auger Coll., et al. Optica, vol. 11, no. 2, 2023, pp. 263–63.



Results:

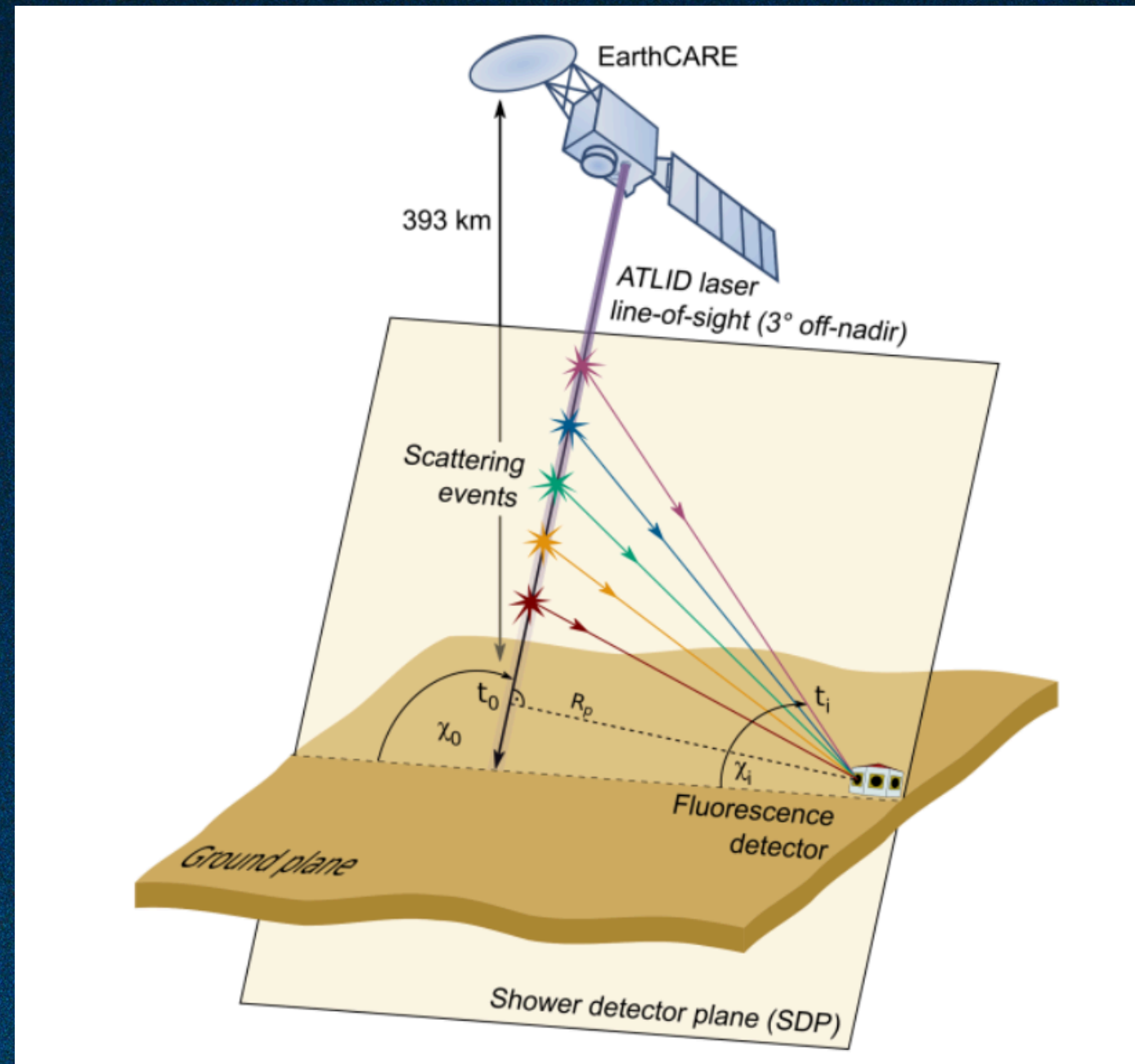
18 EarthCARE overpasses detected from September 2024 to February 2026.



Preliminary

Event Reconstruction

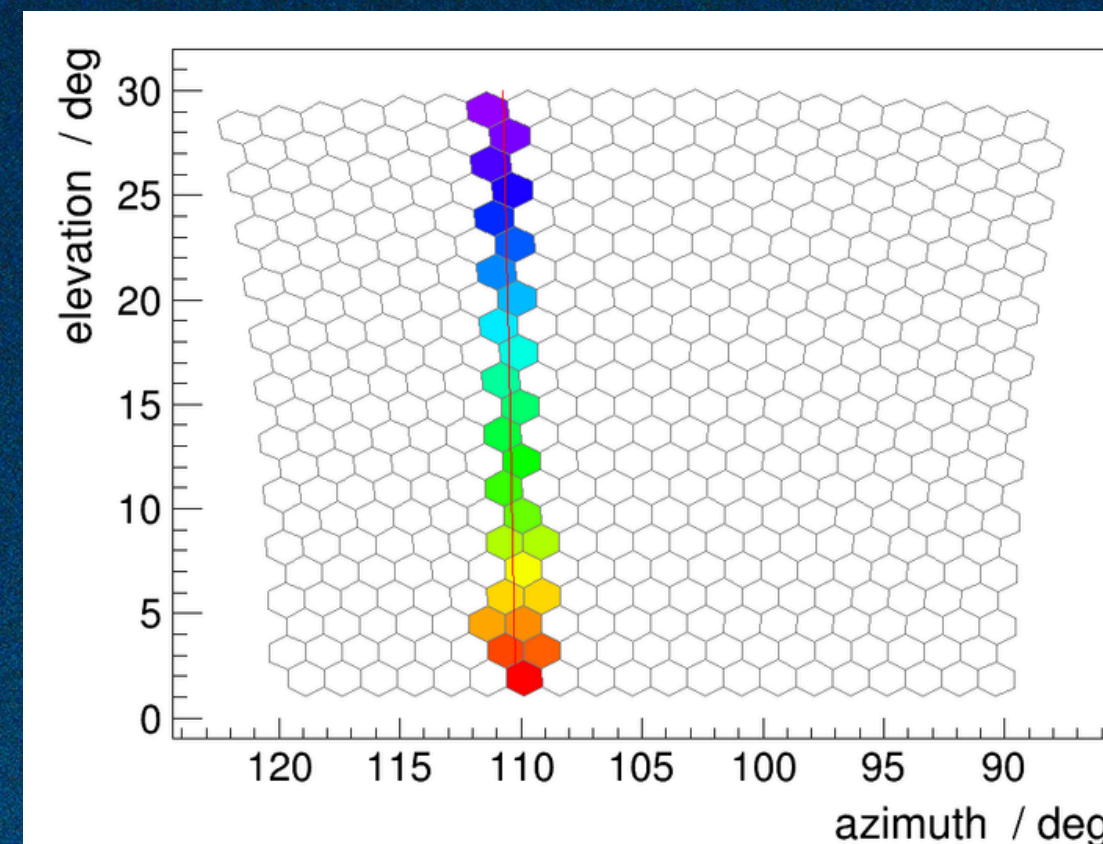
Geometric reconstruction + energy reconstruction



Oliver Lux (DLR).

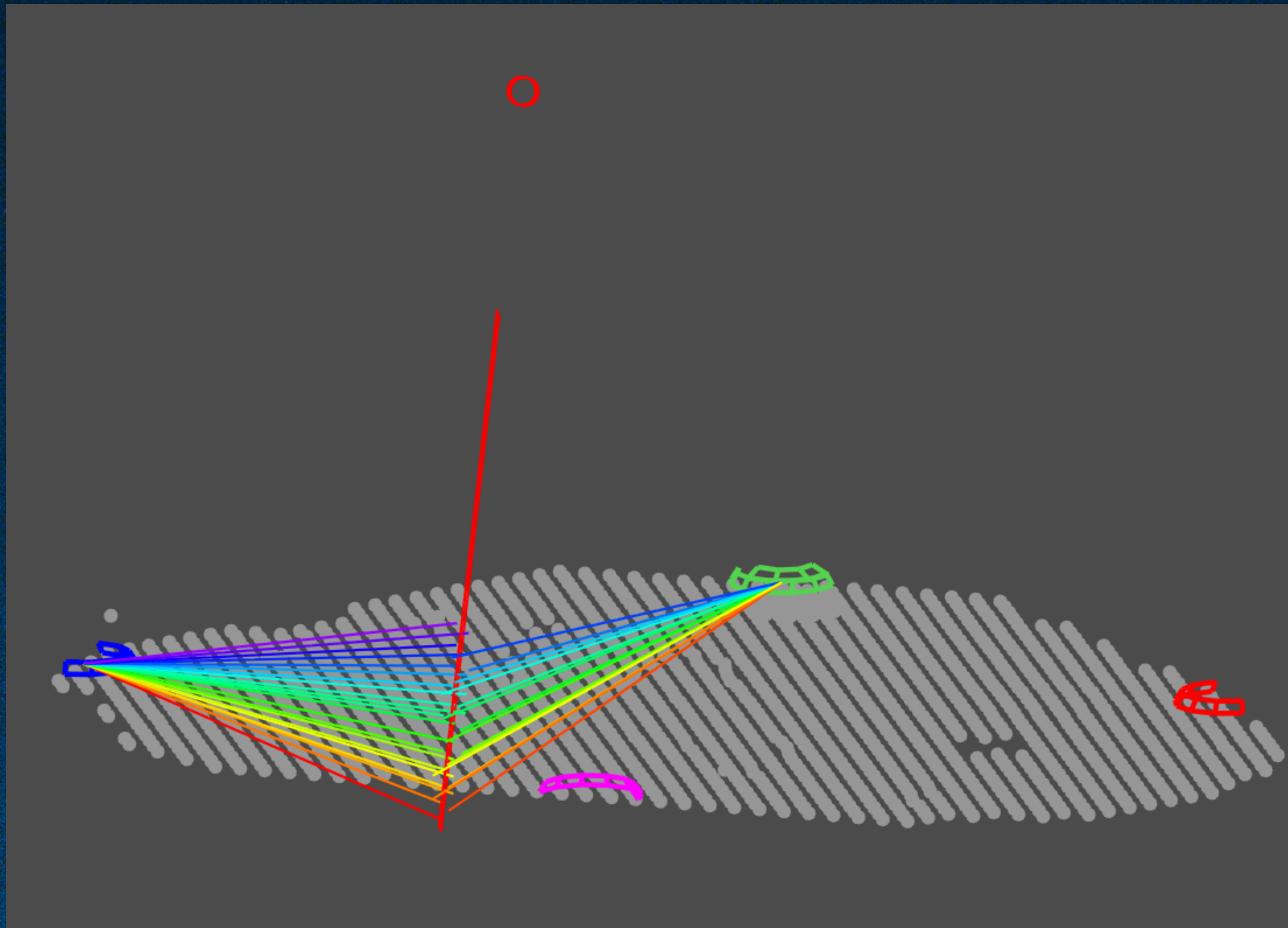
We fit the zenith and azimuth angles and the ground position.

Reconstruction improves when the zenith and azimuth are fixed to nominal values.



Event Reconstruction

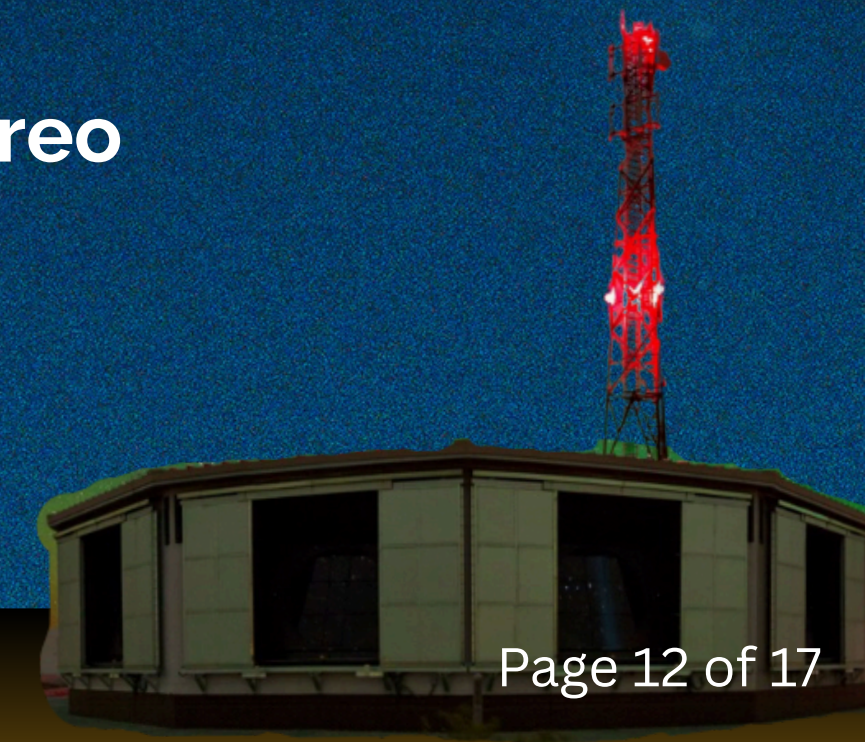
Geometric reconstruction of stereo events + energy reconstruction



We have a much better constraint geometry with stereo events.

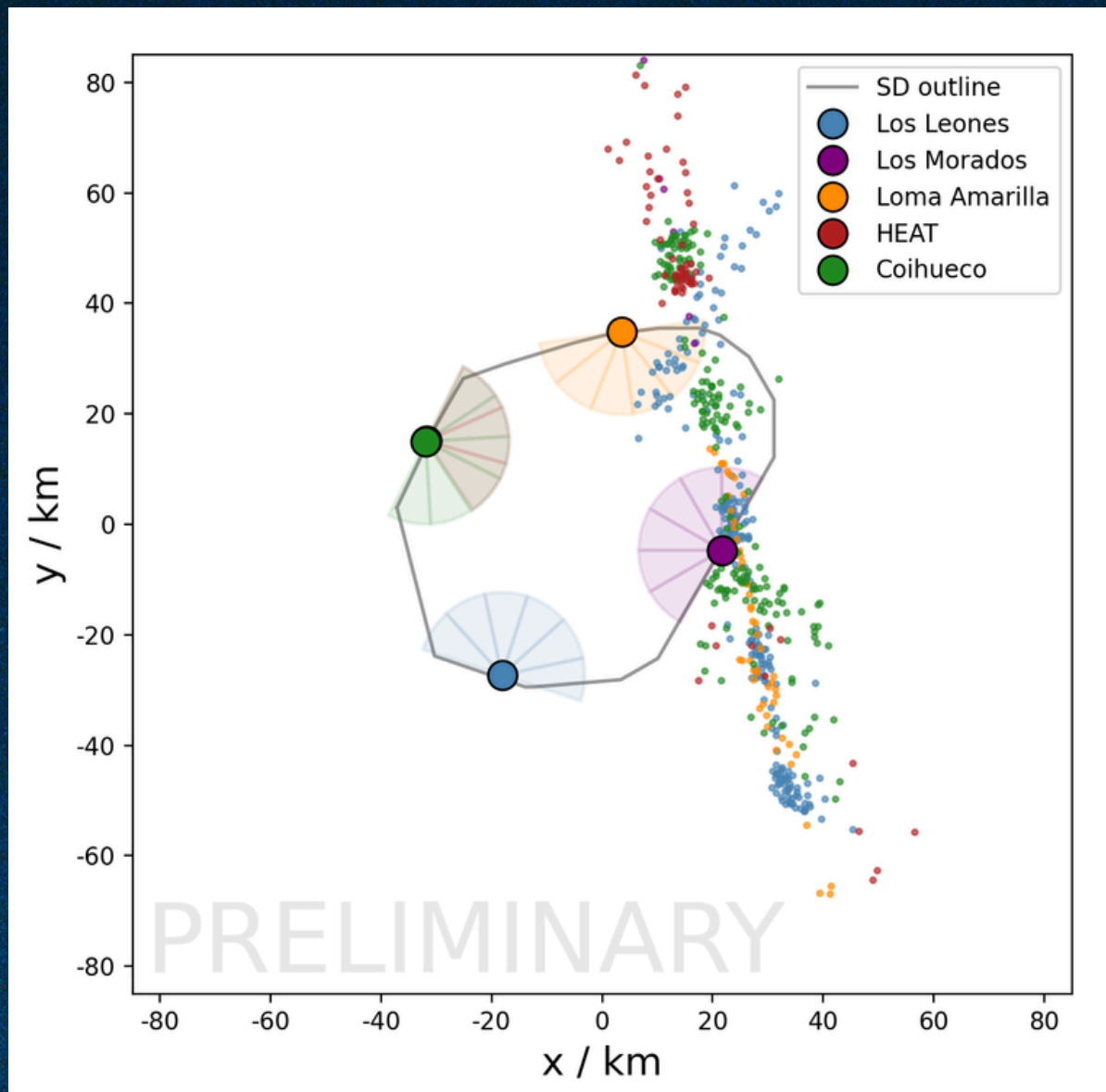
We find the zenith and azimuth values from the stereo reconstruction.

So far we have 567 stereo events.

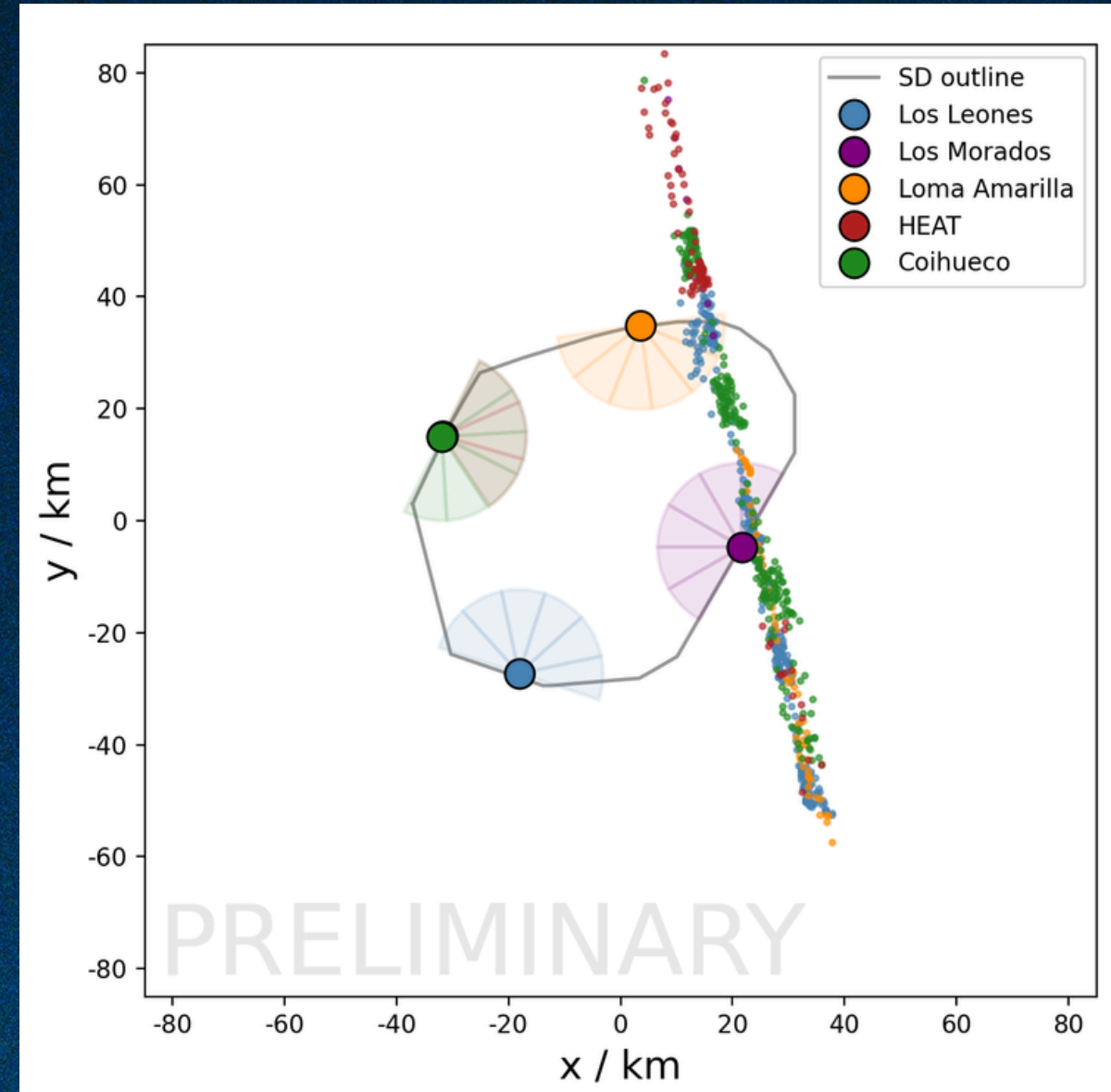


Results: Reconstructed Impact Point

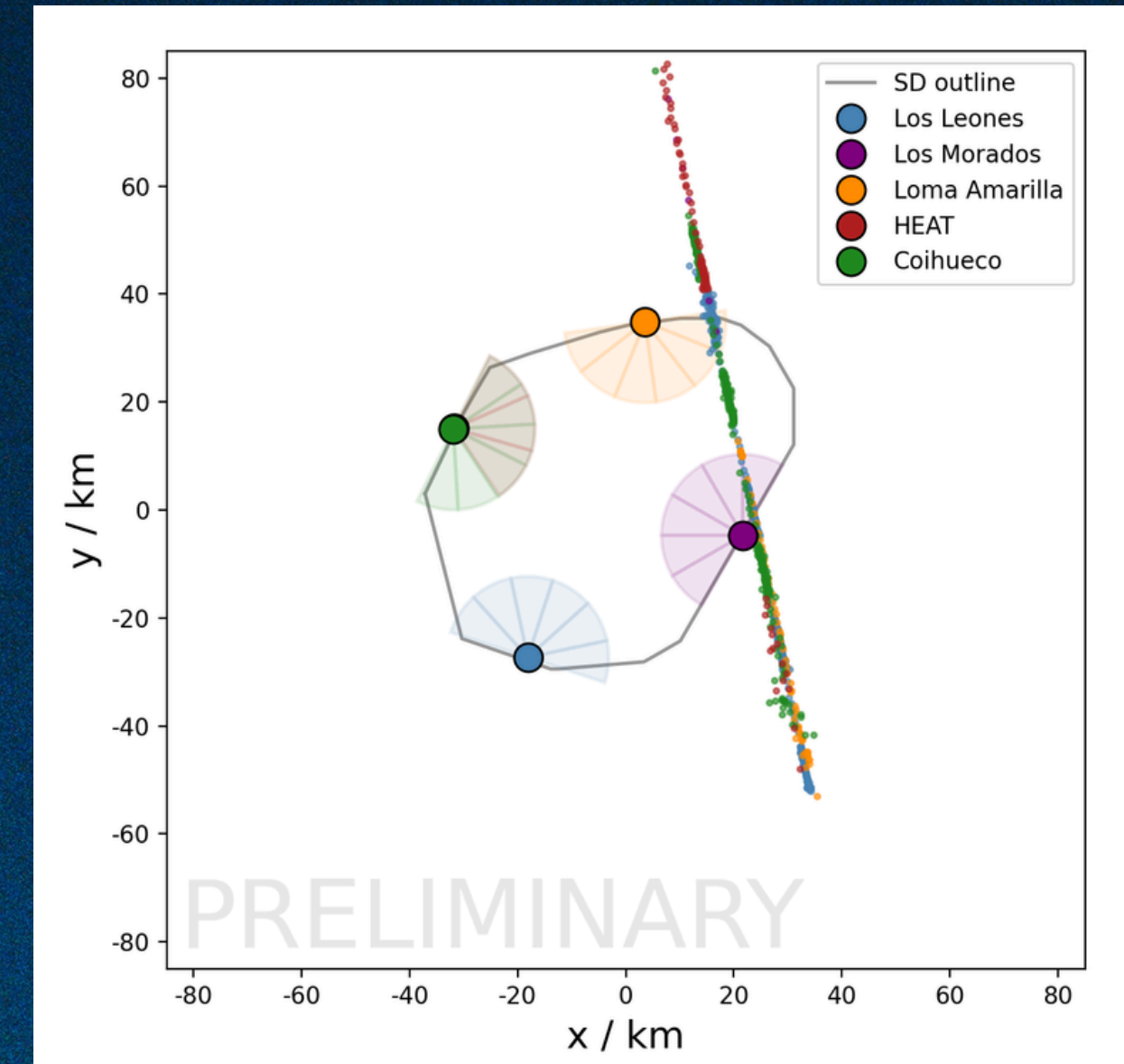
Overpass from 02 December 2024, seen by all of the FD.



No angular constraint



Zenith fixed

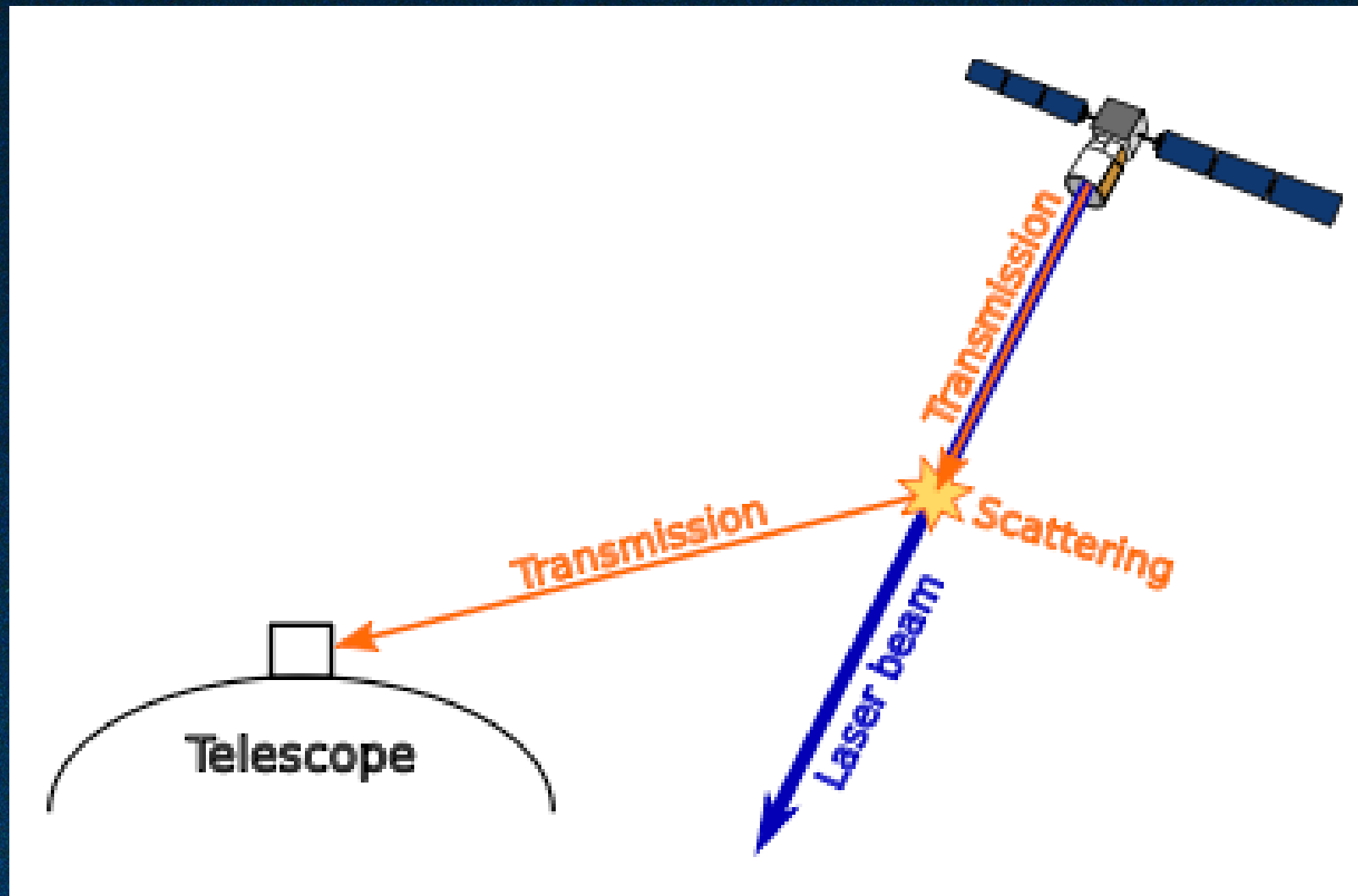


Zenith and azimuth fixed

Preliminary

Event Reconstruction

Geometric reconstruction + **energy reconstruction**



Auger Coll., et al. Optica, vol. 11, no. 2, 2023, pp. 263–63.

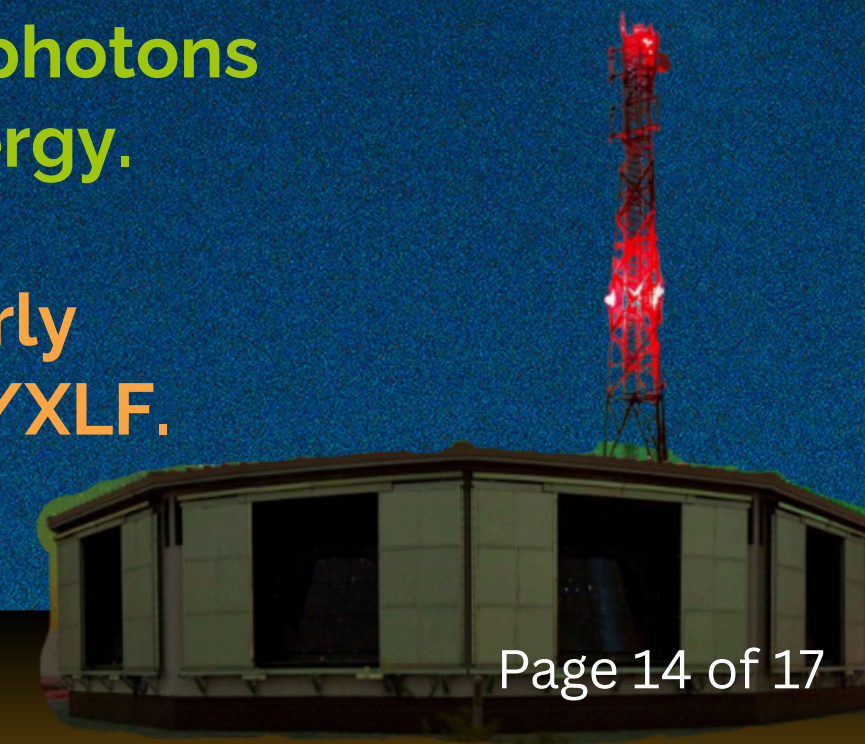
$$N_{\gamma,i} = E \cdot c_{\text{atm},i} \cdot \frac{\lambda}{hc}$$

$$c_{\text{atm}} = T_{1,\text{R}} \cdot T_{1,\text{M}} \cdot T_{2,\text{R}} \cdot T_{2,\text{M}} \cdot (S_{\text{R}} + S_{\text{M}}) \cdot \varepsilon .$$

Atmospheric effects of Rayleigh and Mie scattering + the wavelength dependent efficiency of the telescope.

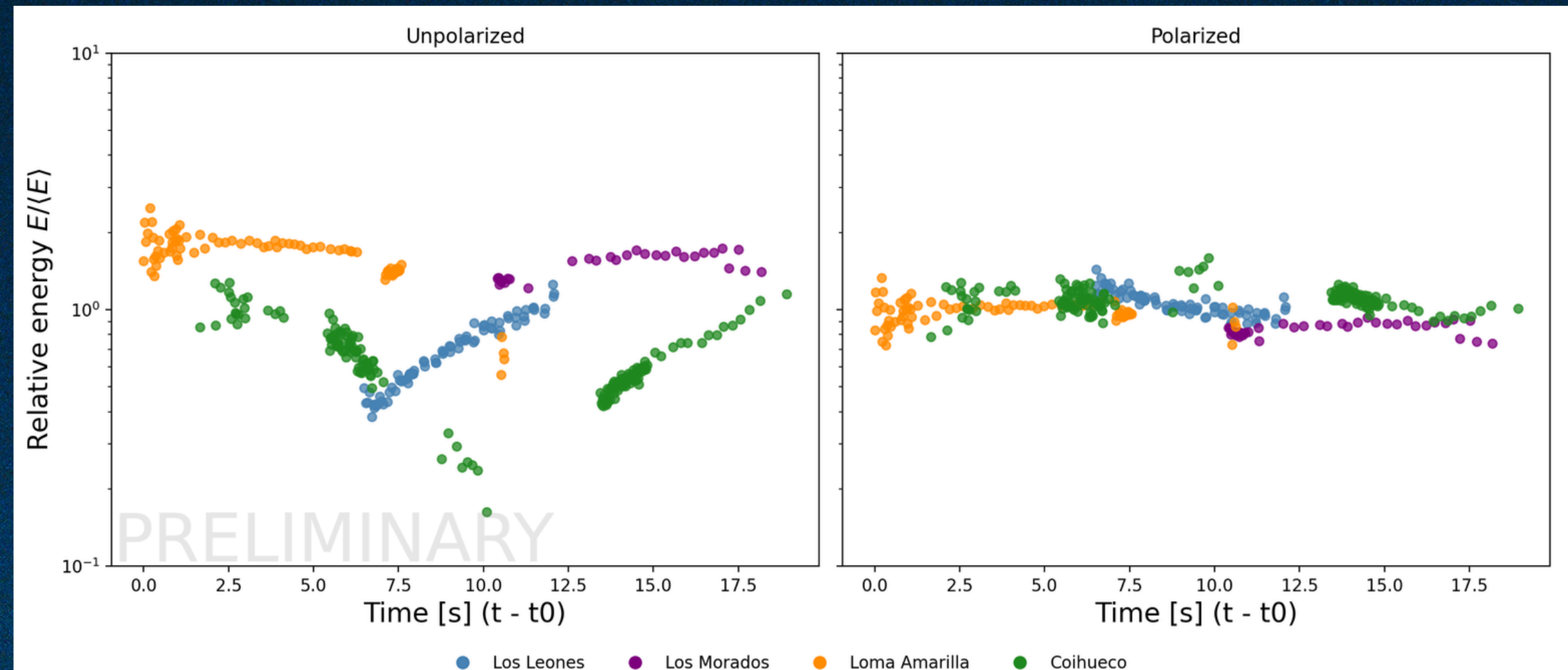
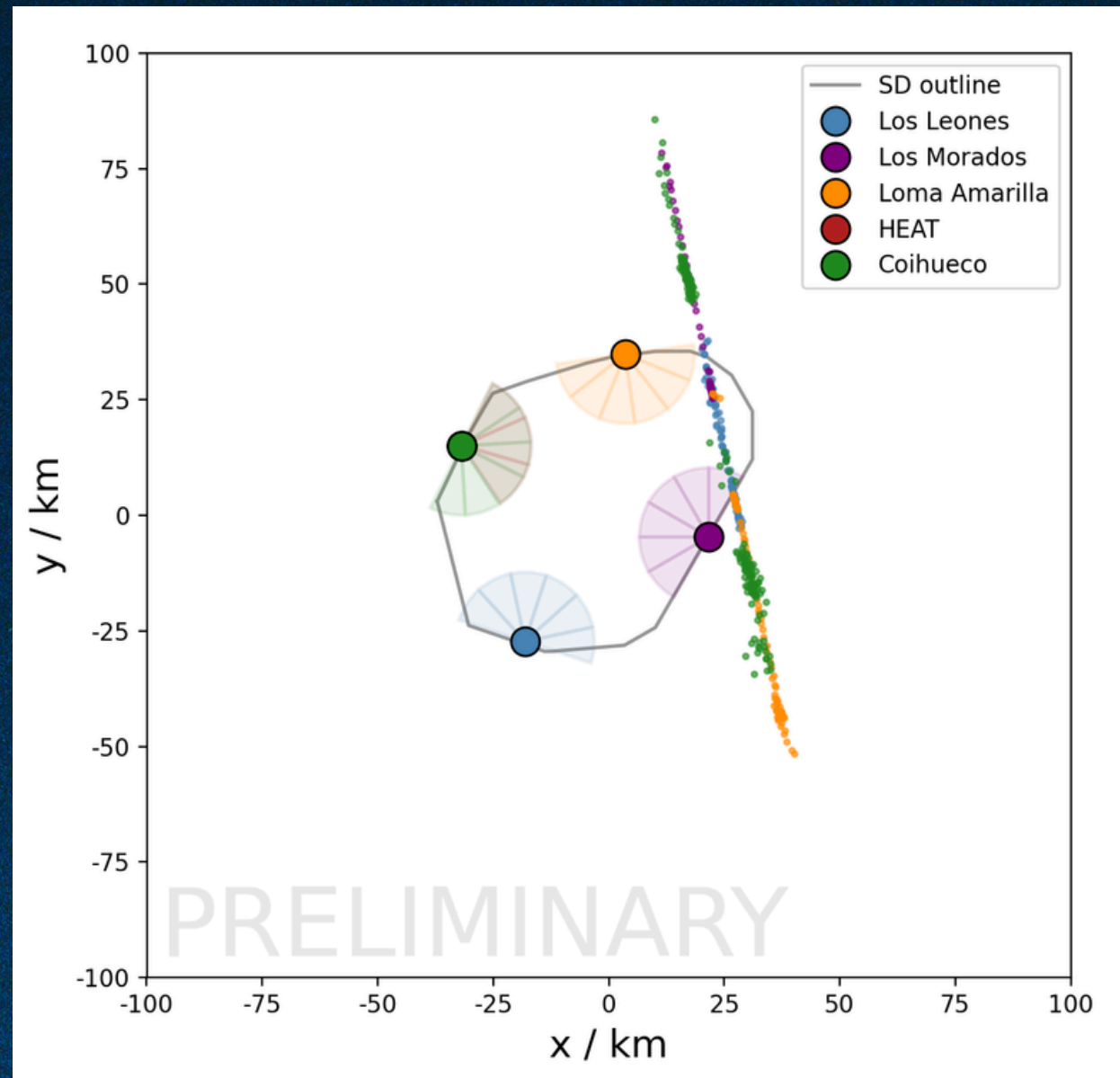
We perform a likelihood fit where we compare the measured number of photons to the expected value for a test energy.

Rayleigh scattering model for linearly polarized light unlike Aeolus and C/XLF.



Results: Energy reconstruction

Overpass from 20 June 2025, seen by all FD, very good agreement.

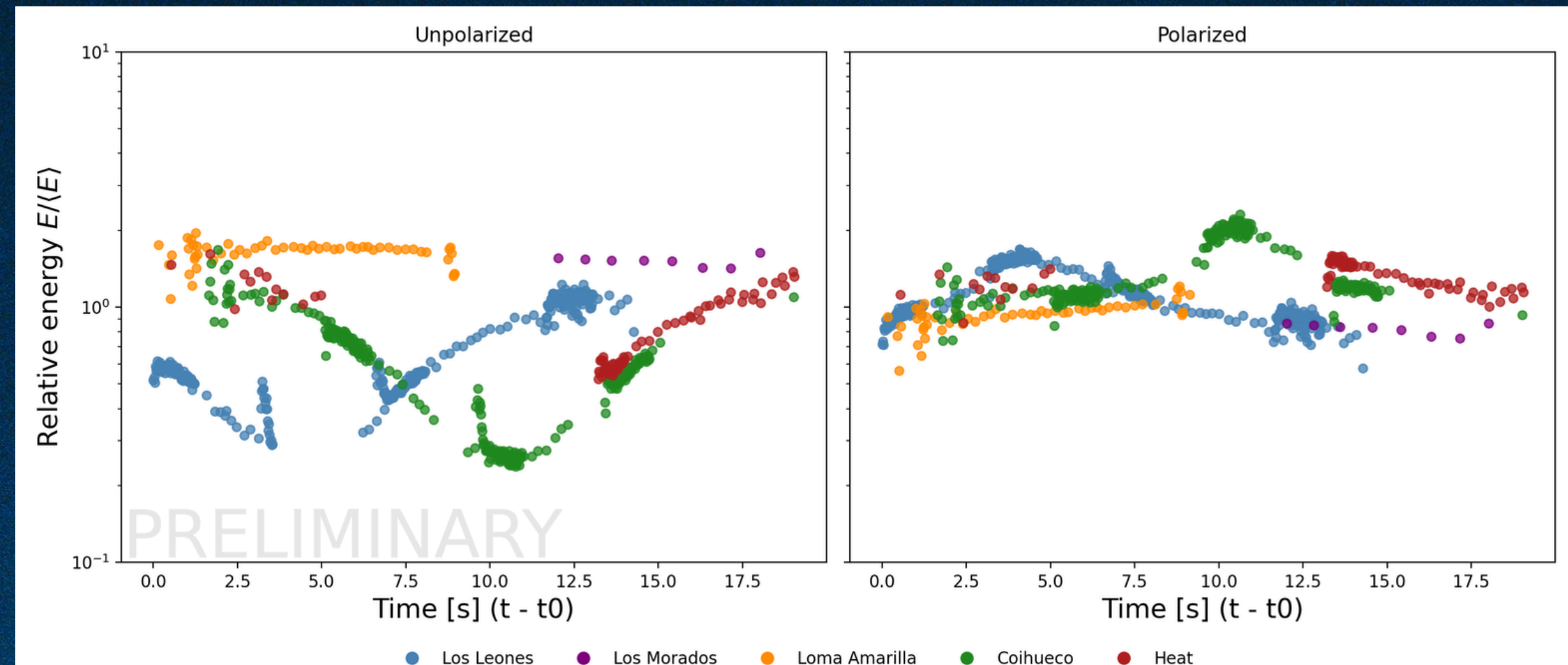
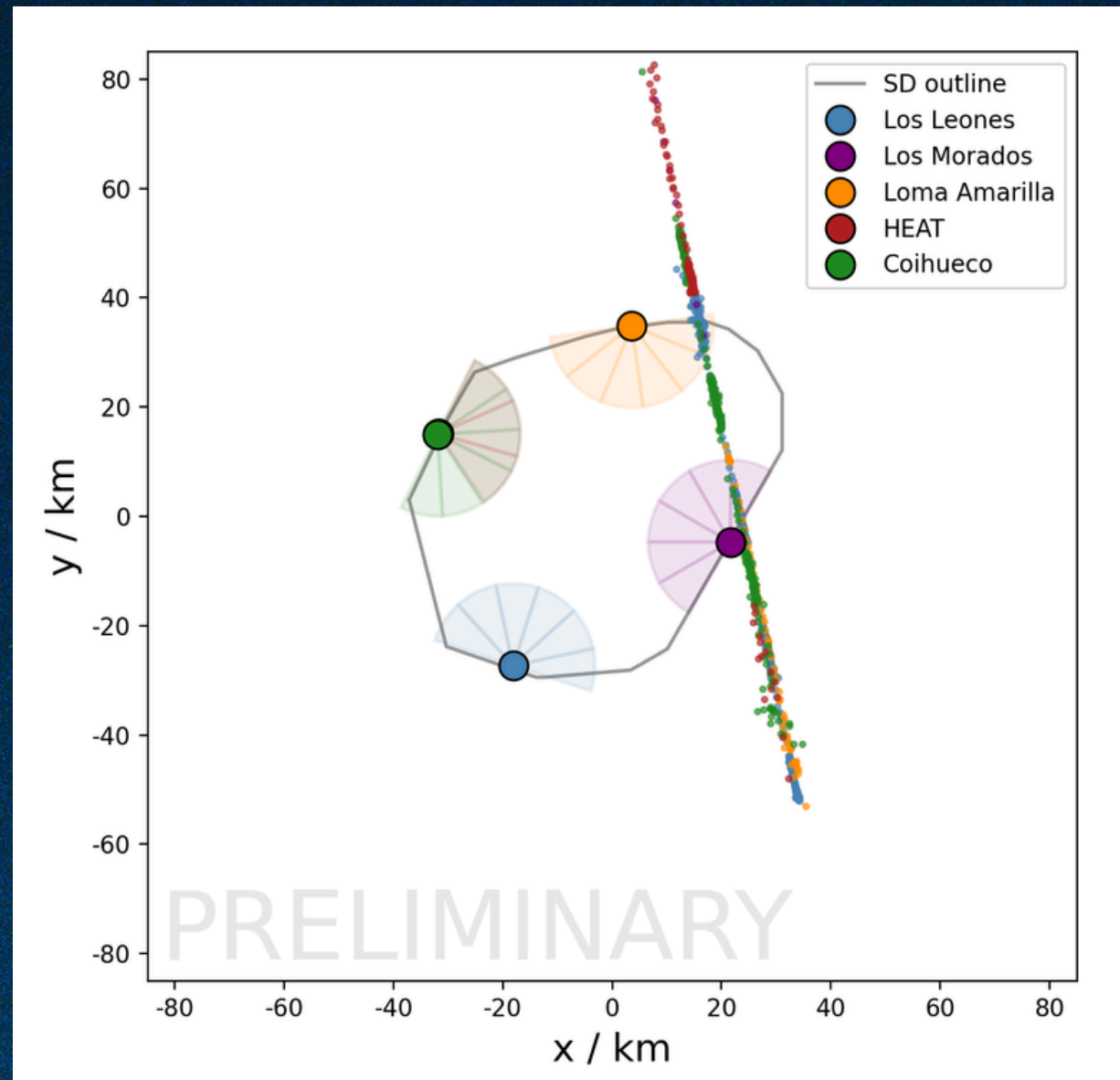


Reported laser energy ~ 38 mJ

Very preliminary (using average aerosol density and 2023 calibration constants).

Results: Energy reconstruction

Overpass from 02 Dec 2024, seen by all FD, possible impact of aerosols?



Reported laser energy ~ 38 mJ

Very preliminary (using average aerosol density and 2023 calibration constants).

Summary

- **EarthCARE provides a reference light source for cross-calibration with the Telescope Array and validation of aerosol measurements.**
- Since September 2024, we have detected 18 EarthCARE overpasses and reconstructed their trajectories. 7 good comparison candidates.
- First energy-reconstruction results are promising.

Outlook

- Refine the geometry and energy reconstruction.
- Use events for atmospheric studies.
- Cross-calibration with Telescope Array and with ESA/JAXA.



The agreement on lower energies needs to be scrutinized

Auger systematics

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	3.6%
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	3.4% ÷ 6.2%
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	9.9%
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	6.5% ÷ 5.6%
Invisible energy	3% ÷ 1.5%
Statistical error of the SD calib. fit	0.7% ÷ 1.8%
Stability of the energy scale	5%
TOTAL	14%

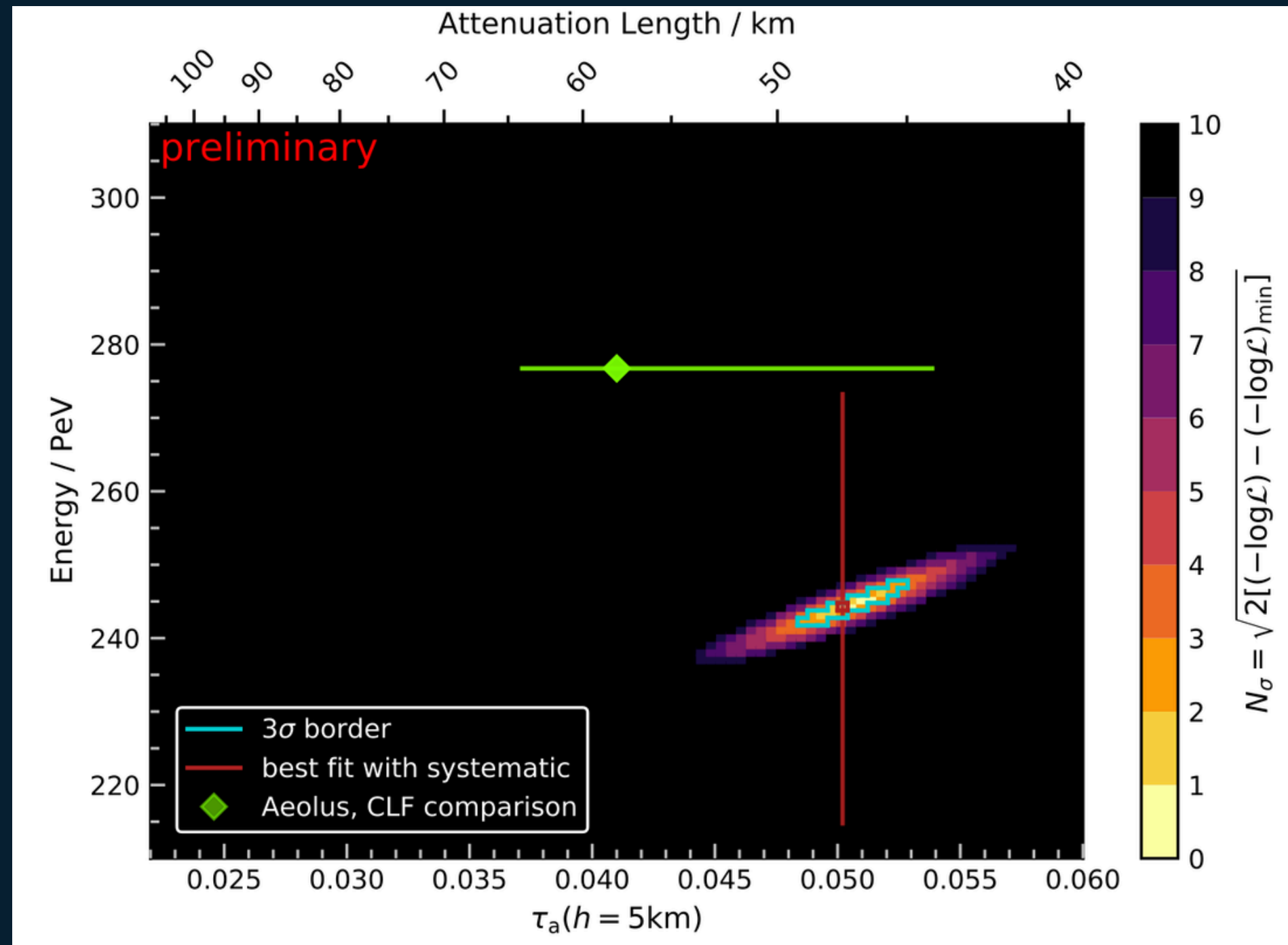
TA systematics

Item	Error (%)	Contributions
Detector sensitivity	10	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11	model (10%), humidity (4%), atmosphere (3%)
Reconstruction	10	model (9%)
		missing energy (5%)
Sum in quadrature	21	

Why do we have this agreement at lower energies if other systematics are not considered?

Perform atmospheric studies

Example: Previous studies with Aeolus Lidar

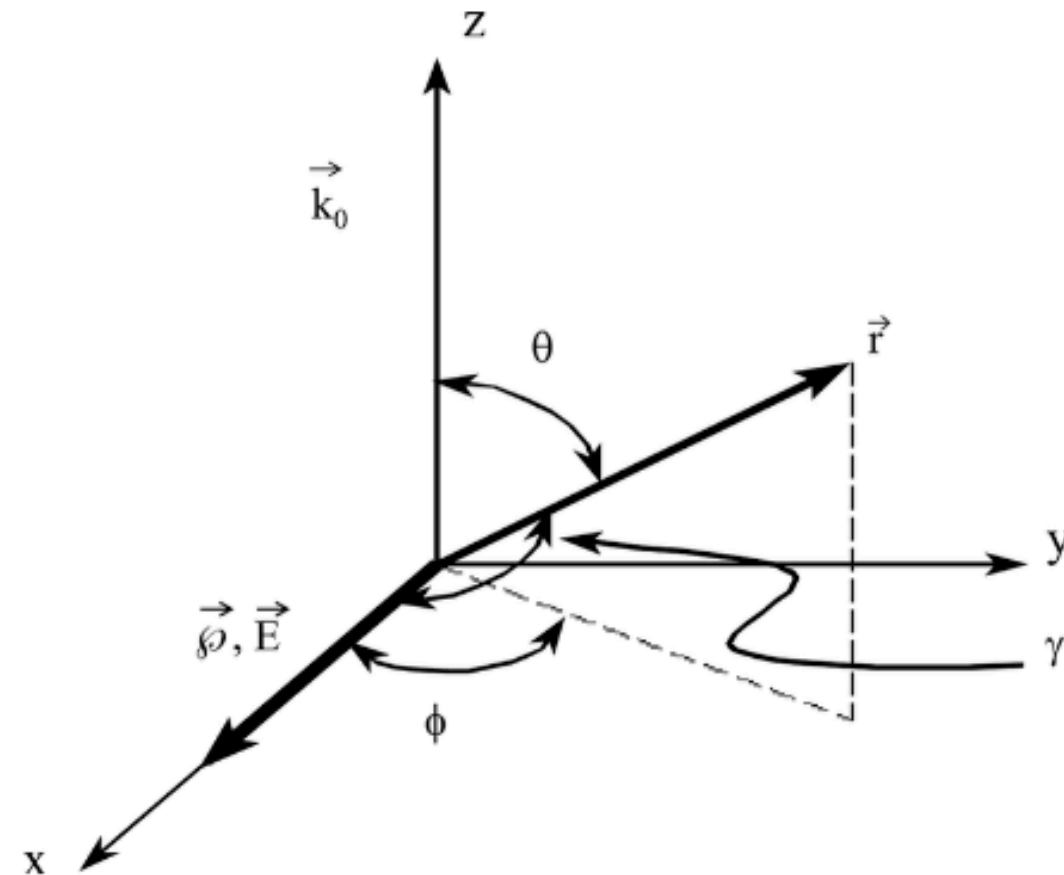


A. Puyleart (Auger Coll.) PoS ICRC2021 (2021), 235.

**Standard Auger aerosol
measurement:
side-scattering from vertical
laser shots, central/extreme
laser facilities
(C/XLF)**

Event Reconstruction

Rayleigh scattering model for linearly polarized light unlike Aeolus and C/XLF.

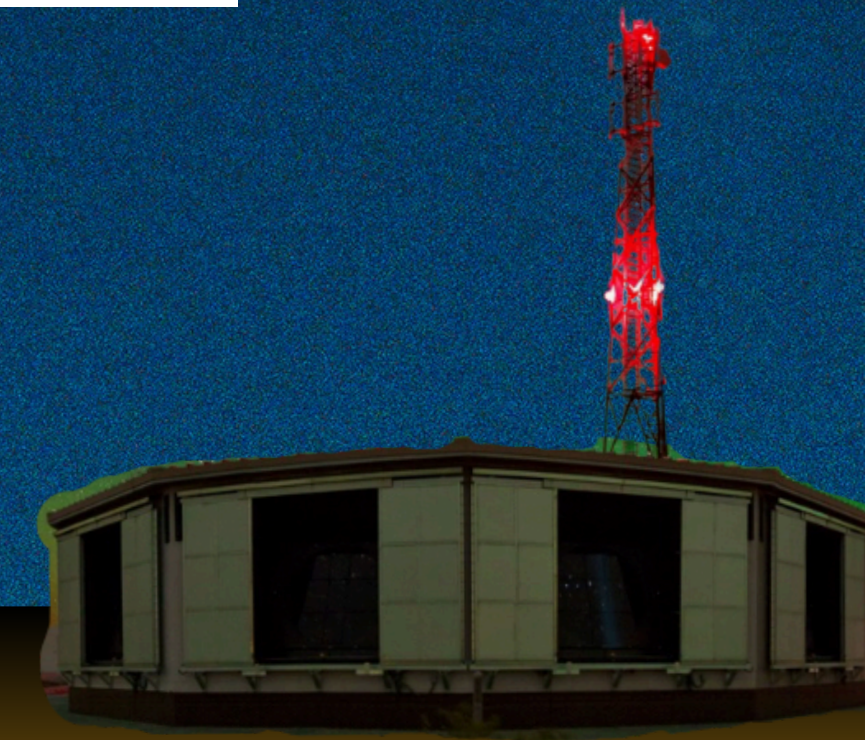


What changes is the **phase function** which describes the angular distribution of the Rayleigh scattered light.

$$\sin^2 \gamma = 1 - \sin^2 \theta \cos^2 \phi.$$

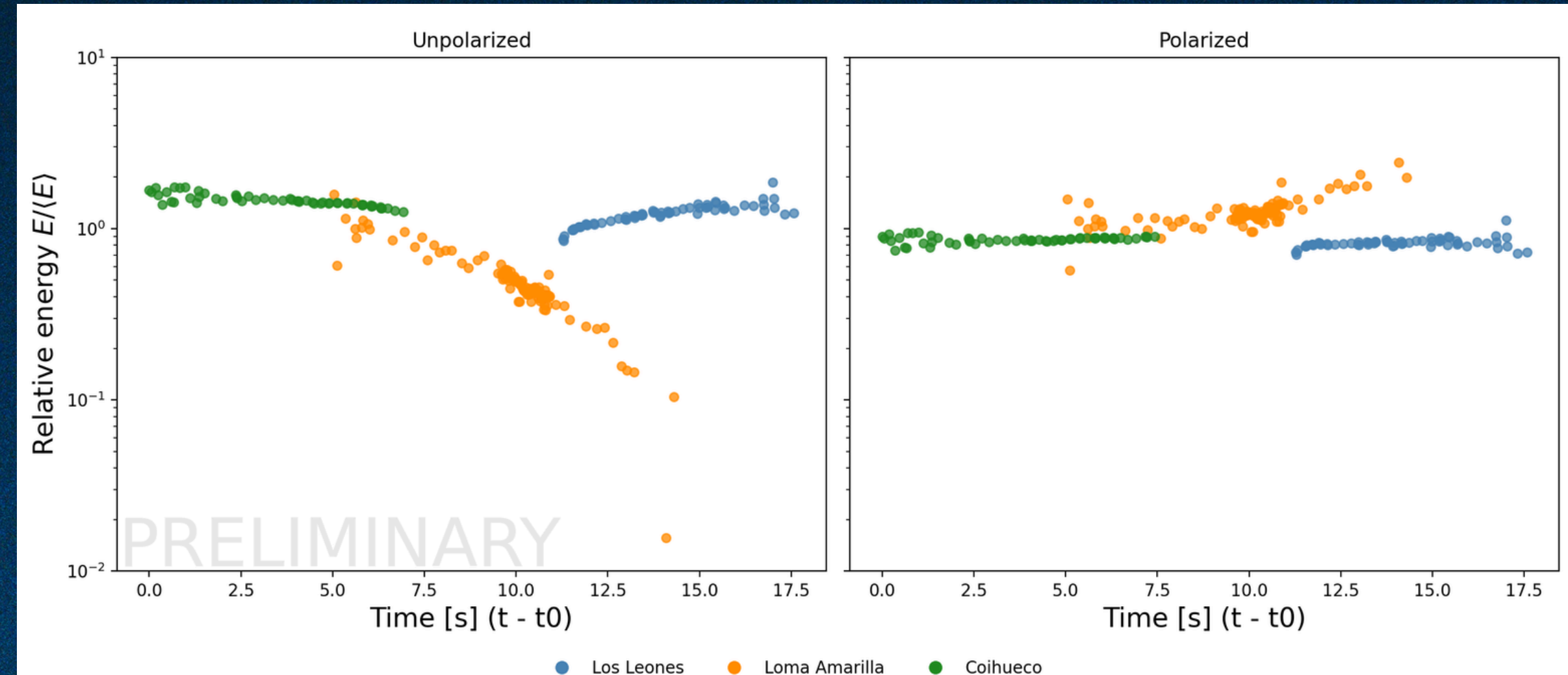
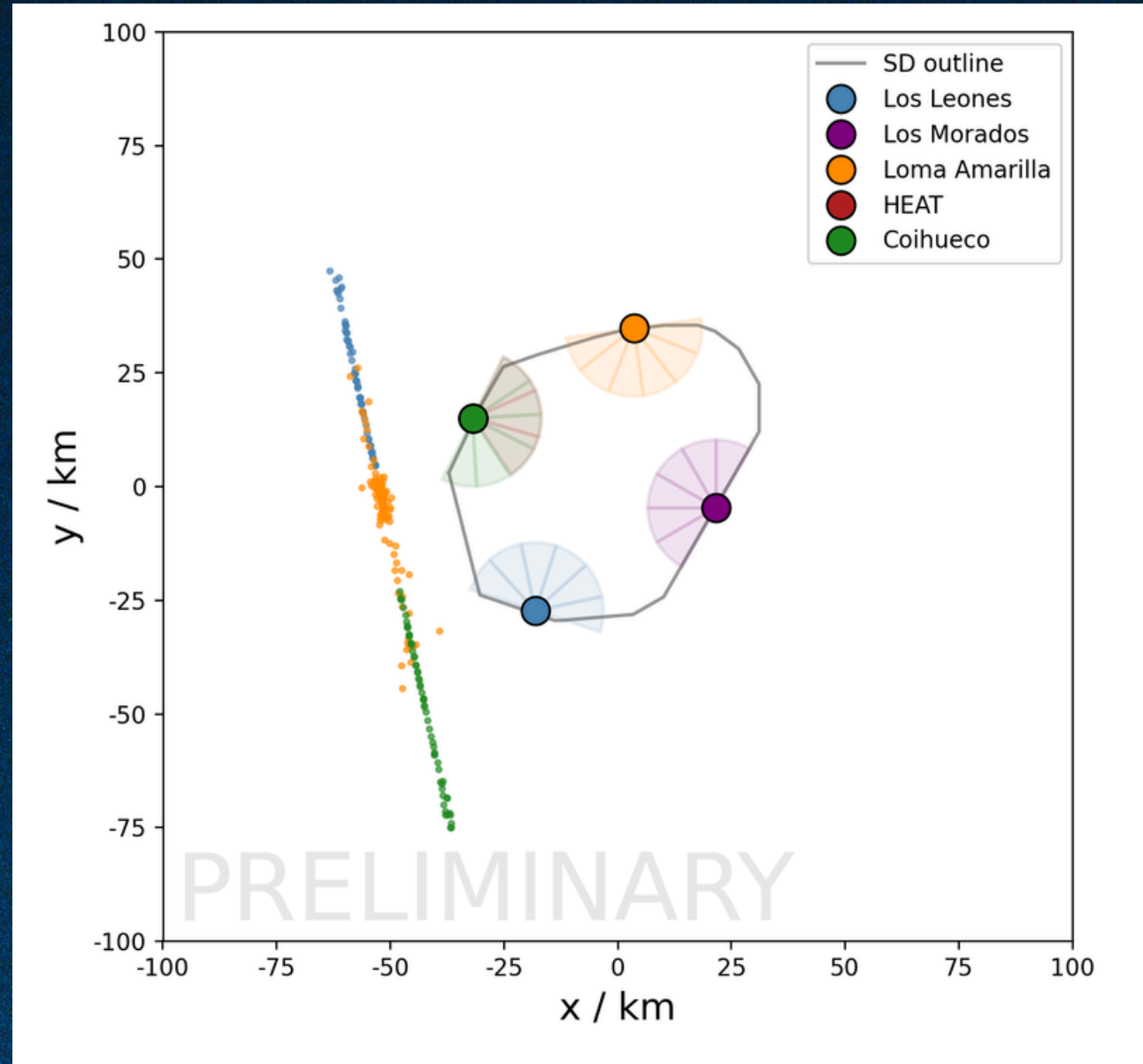
Figure 3.7. Coordinates for light propagation in the z -direction, with an induced dipole along the direction of the electric field (in the x - y plane).

Brecha, Robert J, and J. Michael O'Hare. Optical Radiation and Matter. 2021.



Results: Energy reconstruction

Overpass from 25 August 2025, example of a good western overpass.



Reported laser energy ~ 38 mJ

Very preliminary (using average aerosol density and 2023 calibration constants).

340 4.3.1 Atmospheric Model Description

341 The atmospheric aerosol model adopted in this analysis is based on the assumption that the aerosol
342 distribution in the atmosphere is horizontally uniform. The aerosol attenuation is described by
343 two parameters, the *aerosol horizontal attenuation length* L_{aer} and the *aerosol scale height* H_{aer} .
344 The former describes the light attenuation due to aerosols at ground level, the latter accounts for
345 its dependence on the height. With this parameterization, the expression of the aerosol extinction
346 $\alpha_{\text{aer}}(h)$ and the vertical aerosol optical depth $\tau_{\text{aer}}(h)$ are given by

$$\alpha_{\text{aer}}(h) = \frac{1}{L_{\text{aer}}} \left[\exp \left(-\frac{h}{H_{\text{aer}}} \right) \right], \quad (4.4)$$

347

$$\tau_{\text{aer}}(h_2 - h_1) = \int_{h_1}^{h_2} \alpha_{\text{aer}}(h) dh = -\frac{H_{\text{aer}}}{L_{\text{aer}}} \left[\exp \left(-\frac{h_2}{H_{\text{aer}}} \right) - \exp \left(-\frac{h_1}{H_{\text{aer}}} \right) \right]. \quad (4.5)$$

348 Using Eq. 2.5, the aerosol transmission factor along the path s can be written as

$$T_{\text{aer}}(s) = \exp \left(\frac{H_{\text{aer}}}{L_{\text{aer}} \sin \varphi_2} \left[\exp \left(-\frac{h_2}{H_{\text{aer}}} \right) - \exp \left(-\frac{h_1}{H_{\text{aer}}} \right) \right] \right), \quad (4.6)$$

Auger Coll., et al. JINST 8 (2013), P04009

The **vertical aerosol optical depth** (VAOD) characterizes the amount of light that is lost due to aerosol scattering on a vertical path up to a reference height. By setting the scale height to a fixed value based on the yearly average, the VAOD and the laser energy are used as free parameters in a likelihood fit.