Limiting the number density of ultra-high-energy cosmic ray sources

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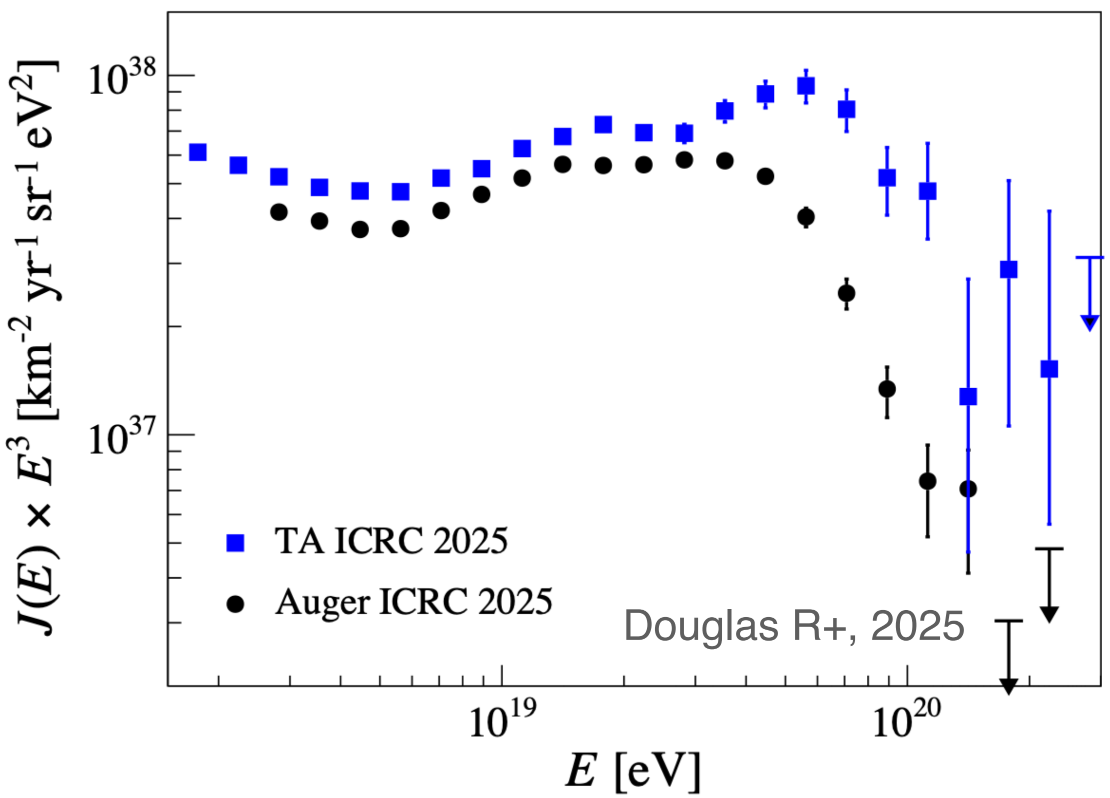
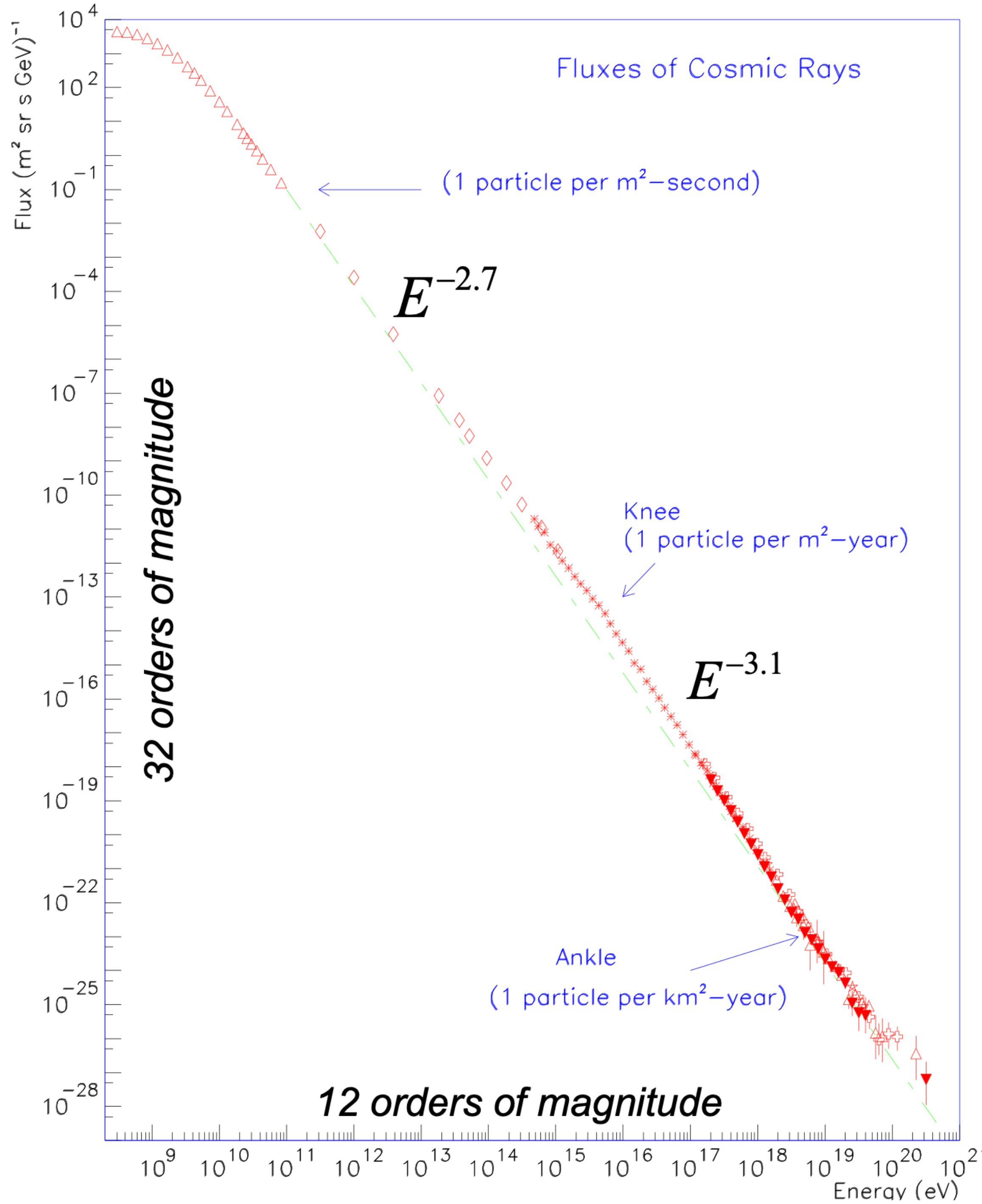
Ultra-high energy cosmic rays

- charged particles (protons and nuclei)
- energy range ≥ 10^{18} eV
- flux ~ 100 $\mathrm{km}^{-2}\mathrm{yr}^{-1}\mathrm{sr}^{-1}$
- steeply falling spectrum
- interactions with the cosmic microwave background (GZK effect)
- deflections by galactic magnetic fields

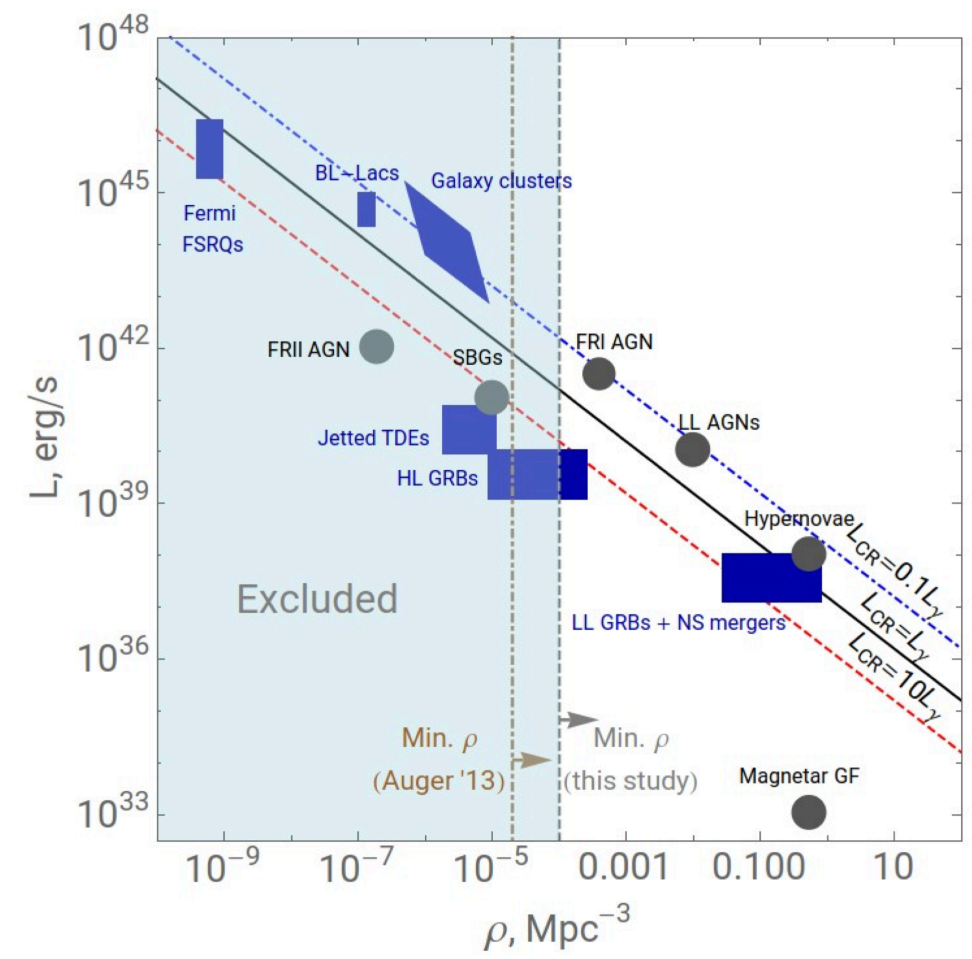


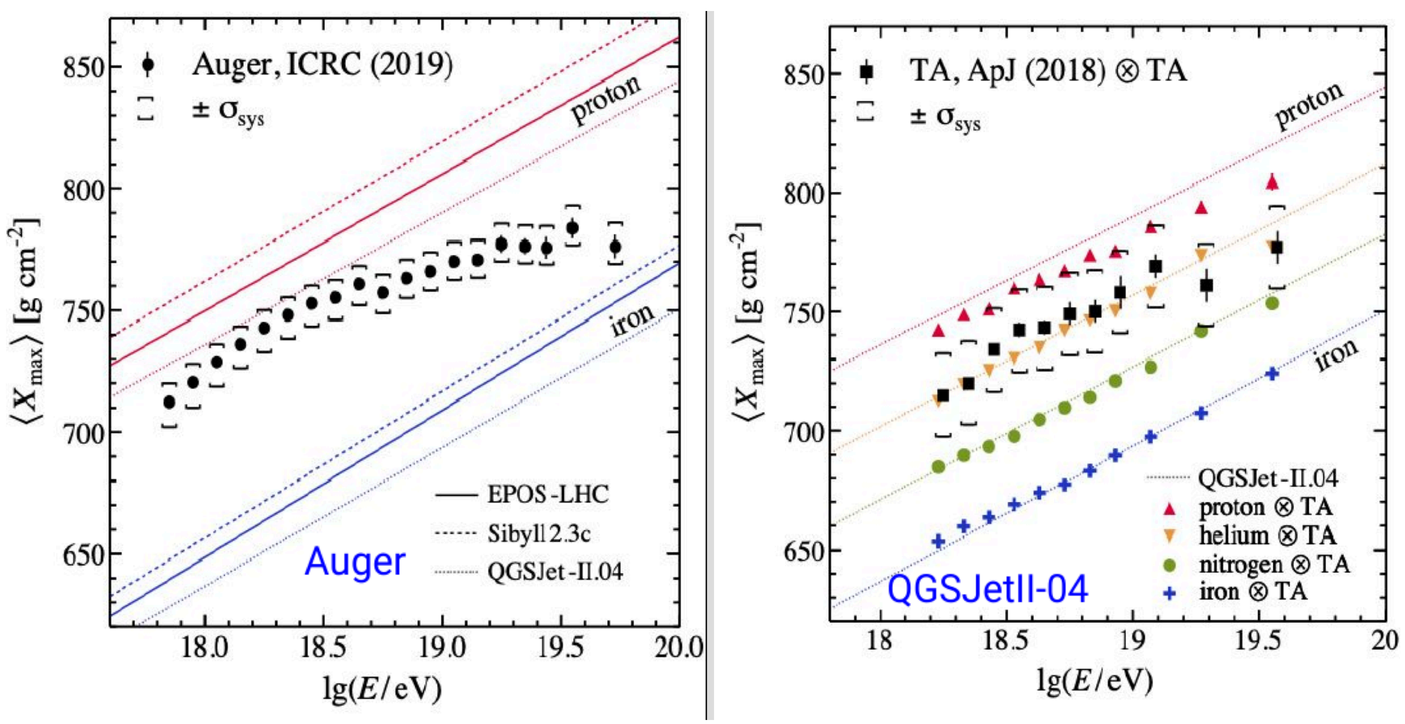


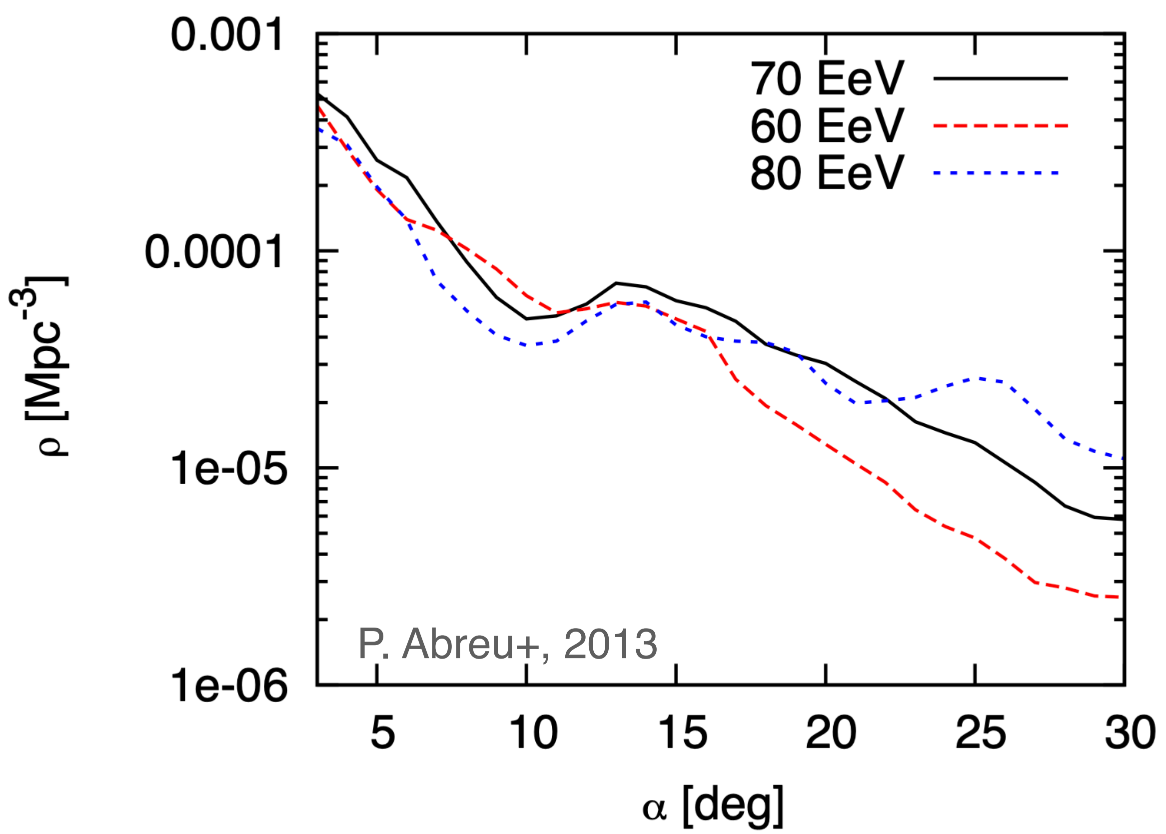
Current problems

- Composition
- Sources

In this work we will consider the possibility of limiting the number density of UHECR sources.



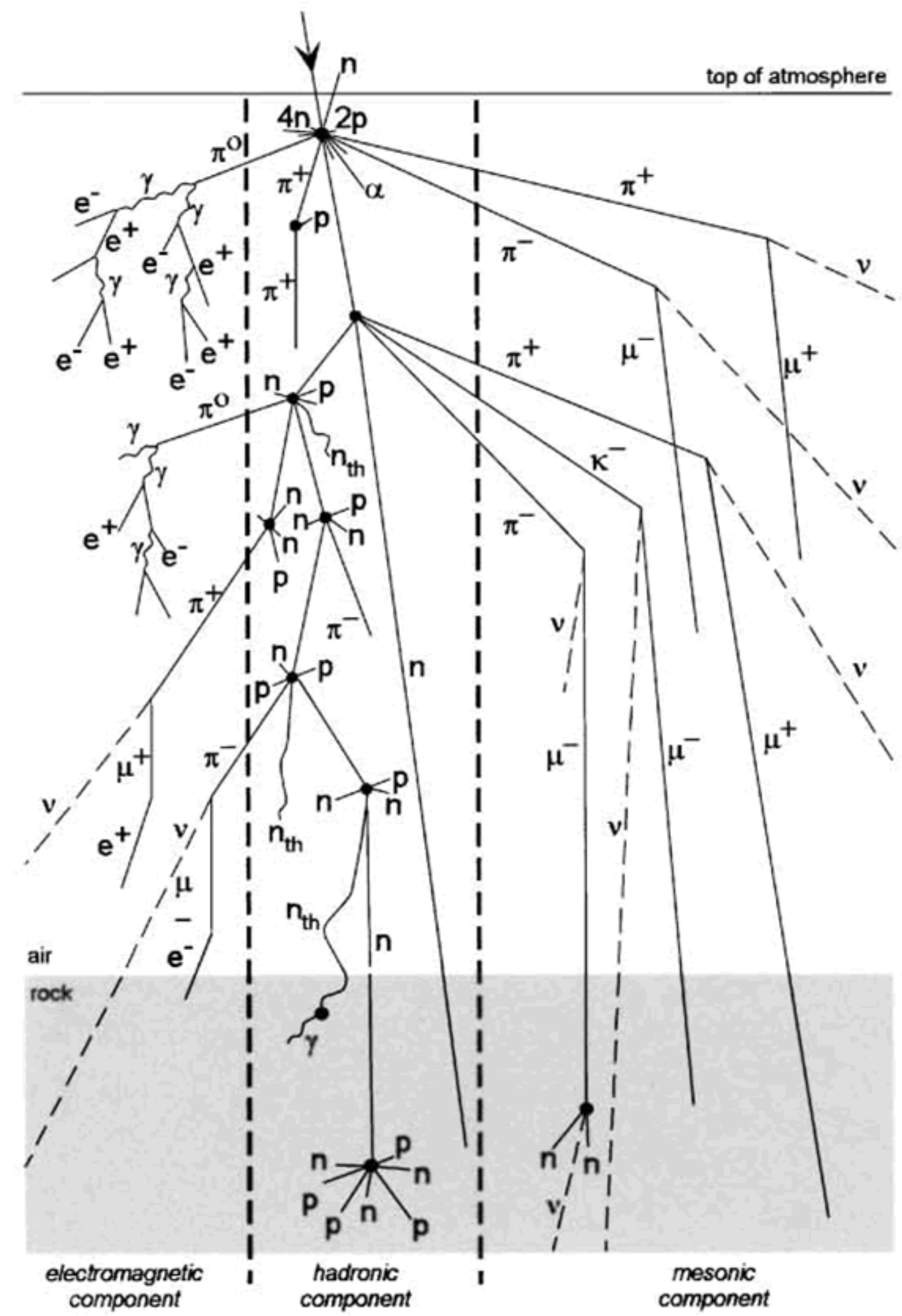




Observation of UHECR

A cosmic ray collides with an atomic nucleus in the upper atmosphere (at an altitude of ~10 km).

- The collision generates numerous secondary particles.
- Streams of these particles continue to collide with air nuclei, generating a cascade of billions of particles that reach the surface—a extensive air shower.



Pierre Auger Observatory

is located in western Argentina, operation since 2008.

Fluorescence detector (FD)

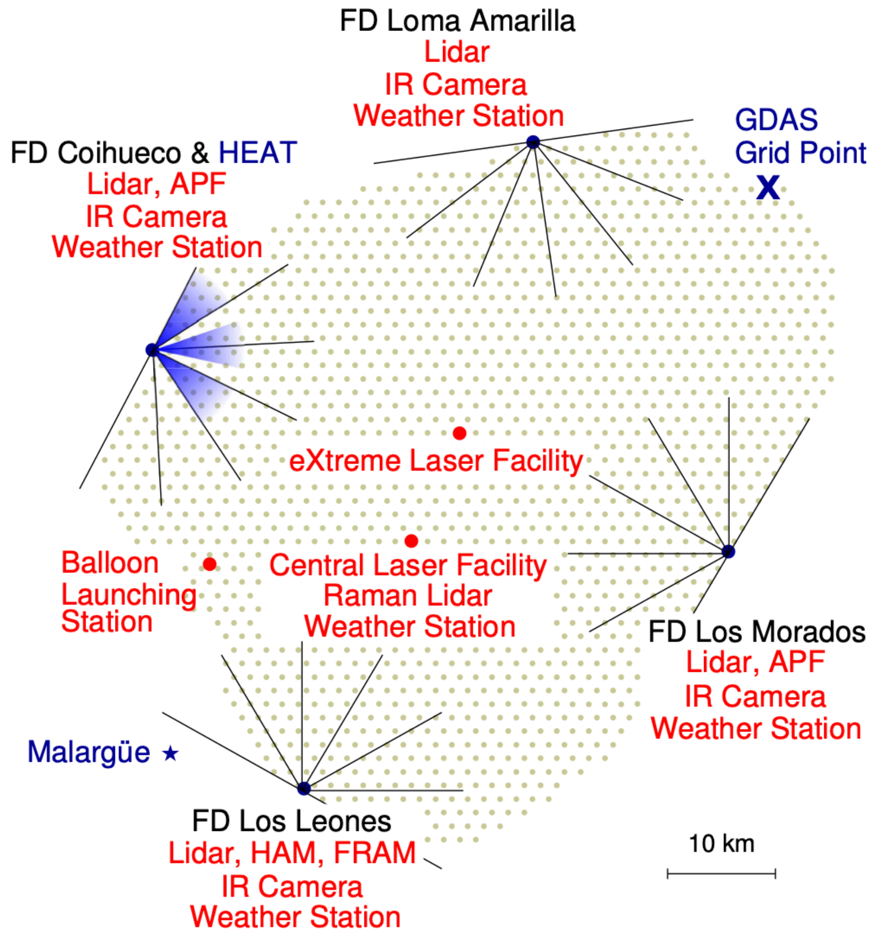
- calorimetric measurement of energy
- 4 sites
  - E>10^{18} eV
- HEAT
  - E>10^{17} eV

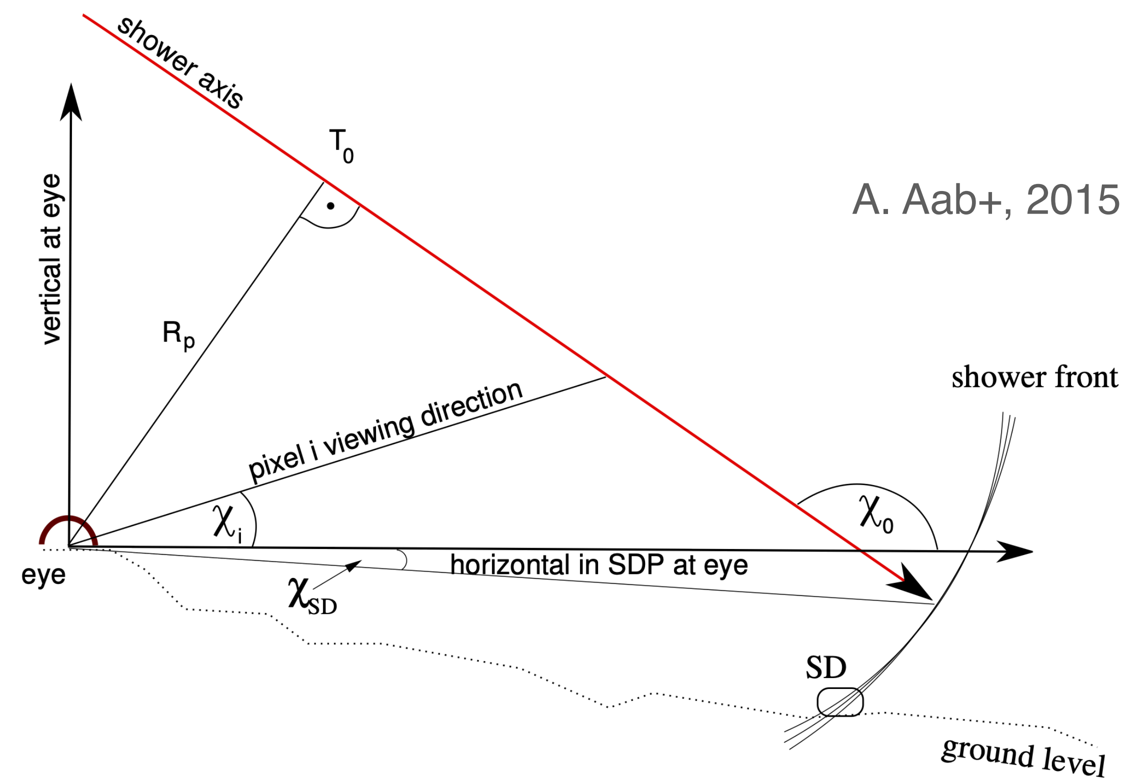
Surface detector array (SD)

- Water Cherenkov Tanks (WCD)
- Grid of 1500 m
- 3000 km^2
- 1660 stations
  - Threshold: $10^{18.5}$ eV

Data

Open Auger data (time, direction, energies): 2040 events with θ < 60° and 595 with θ > 60° above 32 EeV (P. Abreu+, 2022). The reconstruction procedure is described in Pierre Auger Collaboration (Aab, A.+, 2020).





A. Aab+, 2015

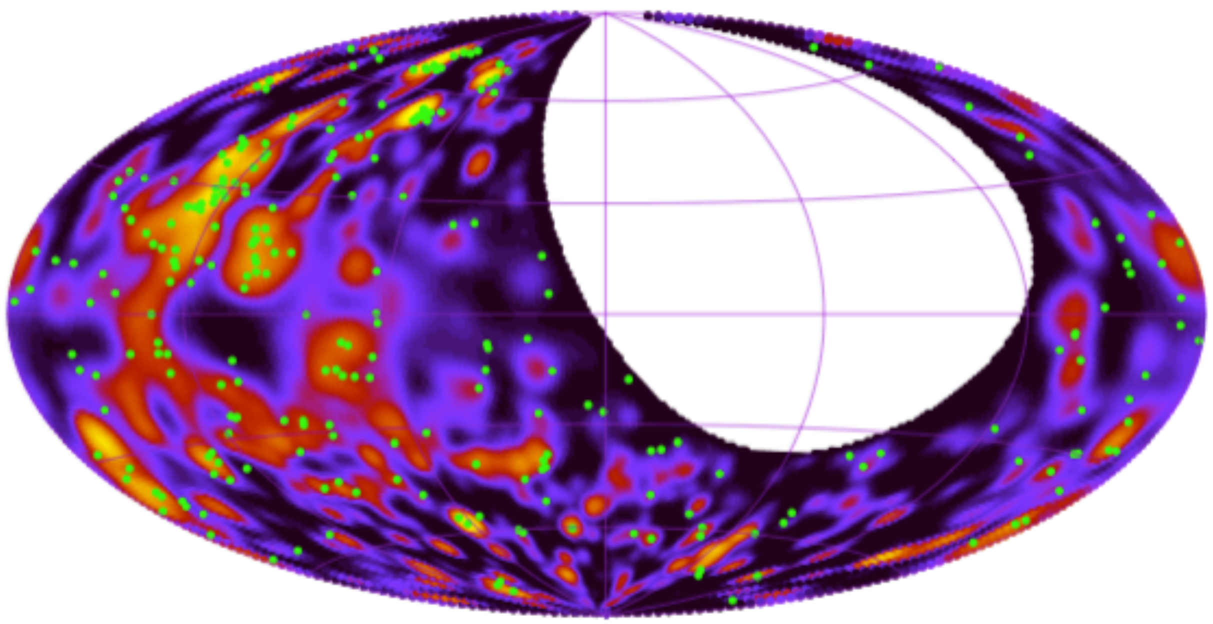
Modeling

100 catalogs are generated for each source density.

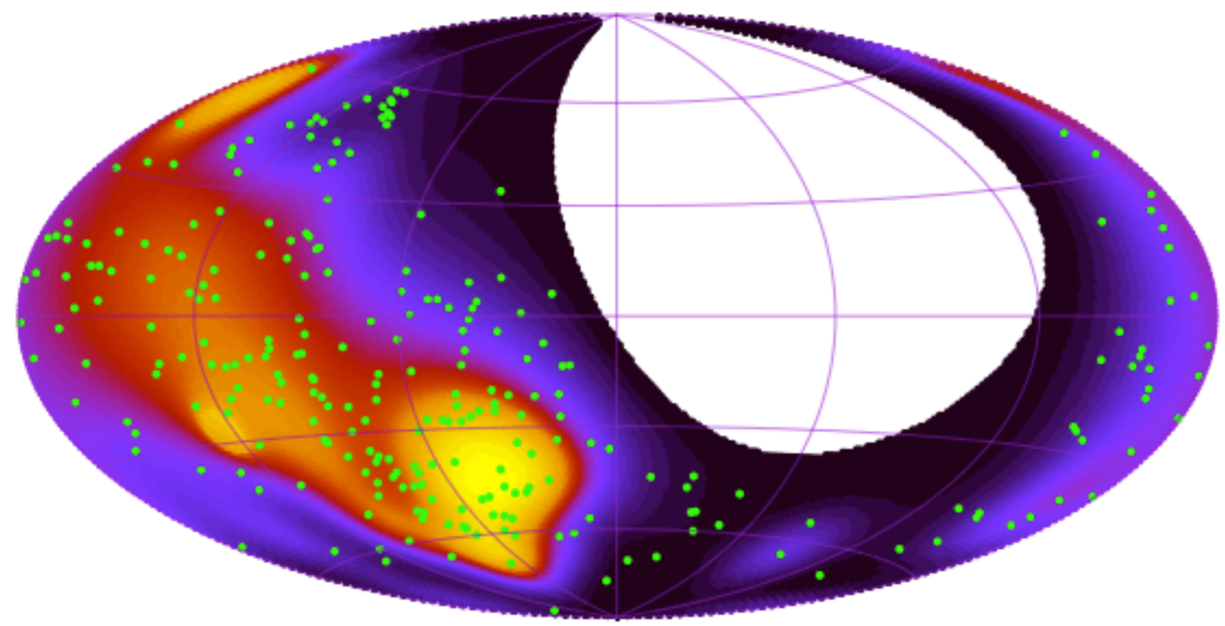
- Several objects are randomly selected from the initial catalog of space objects (corrected 2MRS catalog up to 250 Mpc) so that their number corresponds to the specified density.

Next, modeling is performed based on each catalog:

- The flux in the energy bin k is calculated with the attenuation and smeared with the Gaussian function of the width θ. It gives the flux map $\Phi_k(\theta, n)$.
- From the flow maps Φ_k, a simulated 100 sets of UHECR events is generated that would be detected by an experiment on Earth.



Density: $6 \cdot 10^{-5}$ Mpc^{-3}
Composition: helium
Energy ≥ 60 EeV



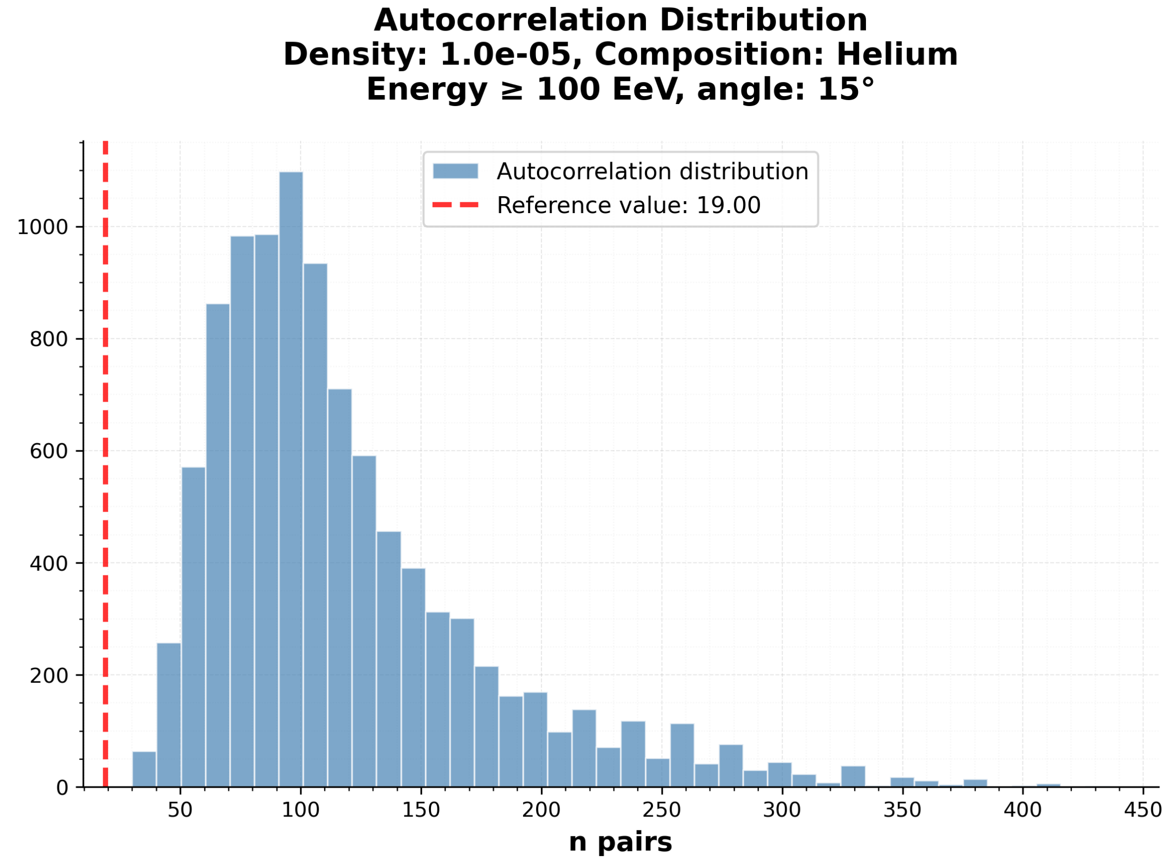
Density: $6 \cdot 10^{-5}$ Mpc^{-3}
Composition: silicon
Energy ≥ 60 EeV

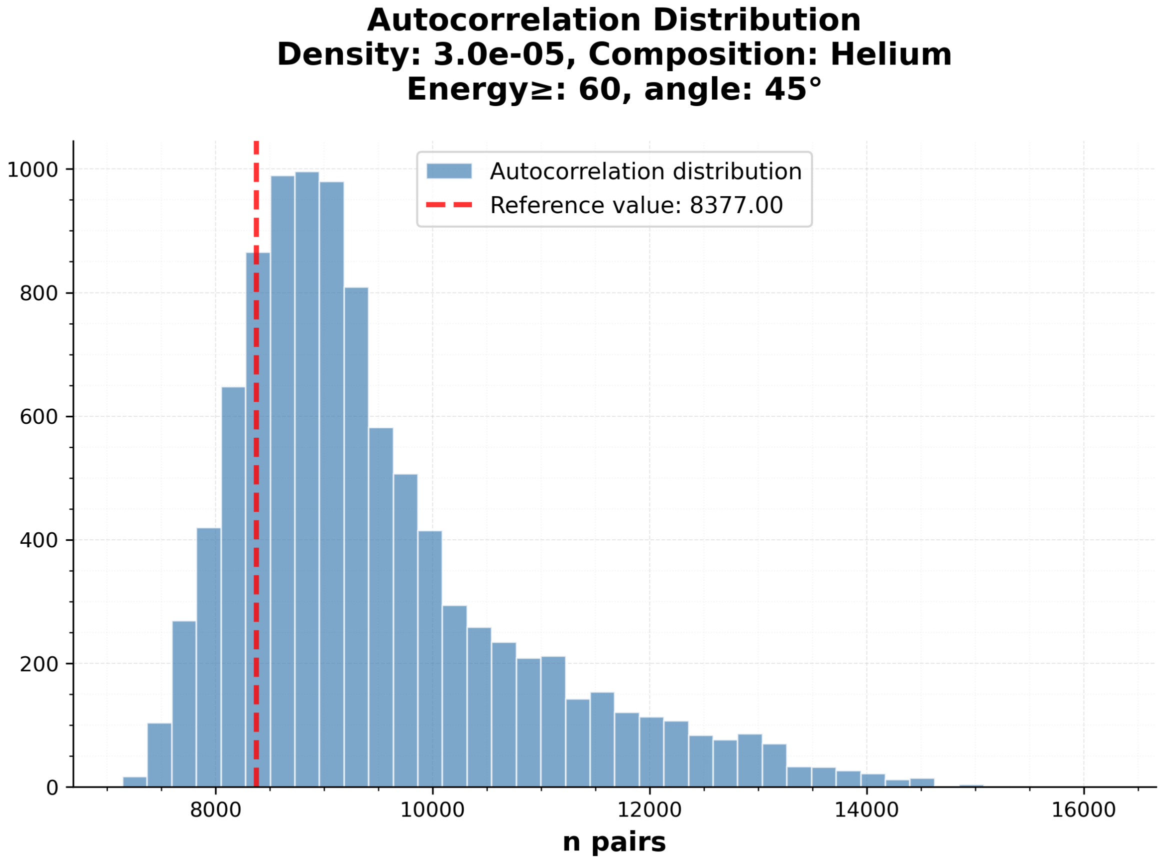
Statistical method

A standard tool for the study of clustering in astronomical arrival directions is the two-point angular correlation function, n(α), which gives the number of pairs separated by an angle smaller than α:

$$\mathrm{n}(\alpha) = \sum_{i=2}^{N} \sum_{j=1}^{i-1} \Theta(\alpha - \alpha_{ij}),$$

where Θ is the step function, and α_{ij} is the angular distance between events i and j of N cosmic rays.

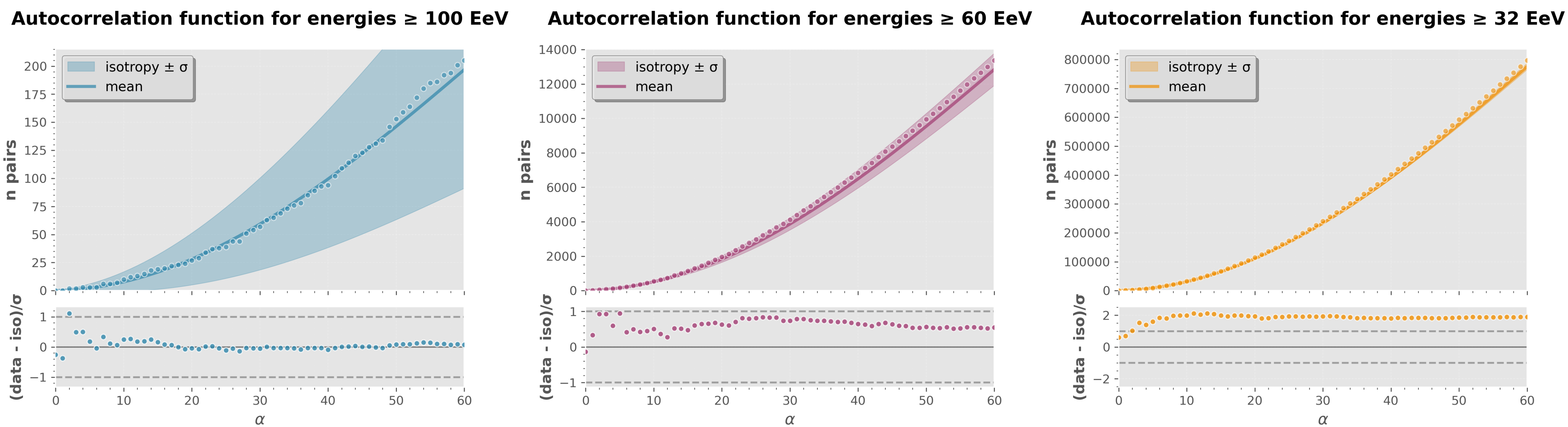




Autocorrelation is calculated for simulated event sets. This distribution is compared with the value from the data. The compatibility criterion at the level is: the proportion of values smaller than the reference value is at least 5%.

Results

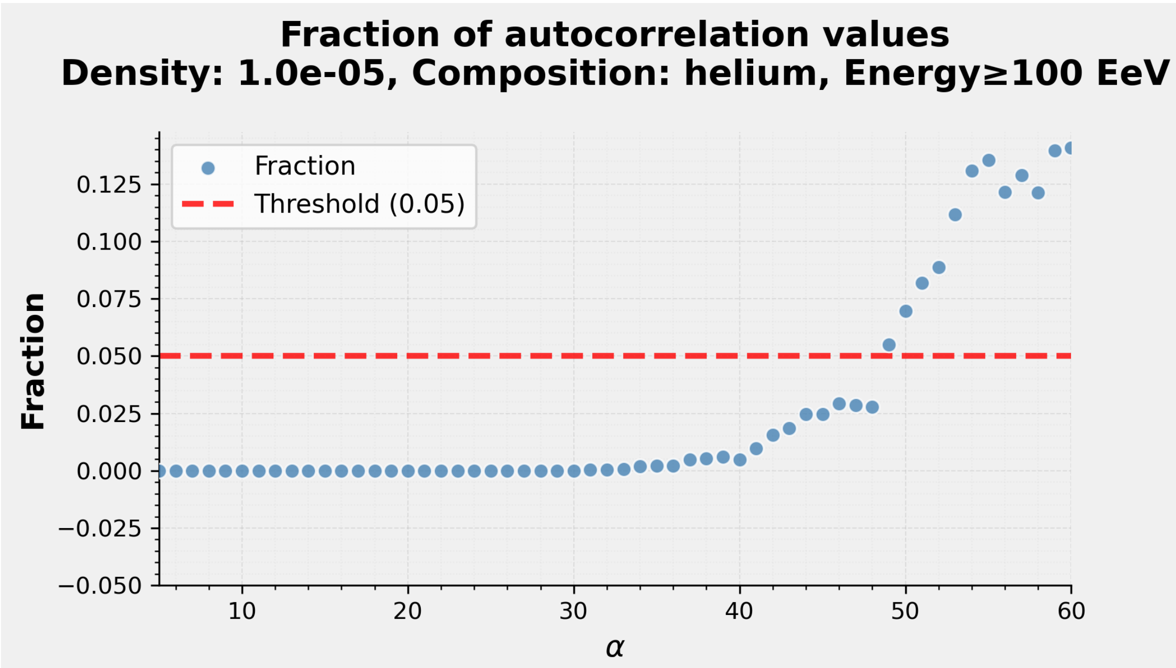
Data from the Pierre Auger Observatory collected between 2004 and 2020 with a zenith angle less than 60° were analyzed. Energy thresholds: 32 EeV (2040 particles), 60 EeV (263) and 100 EeV (33).

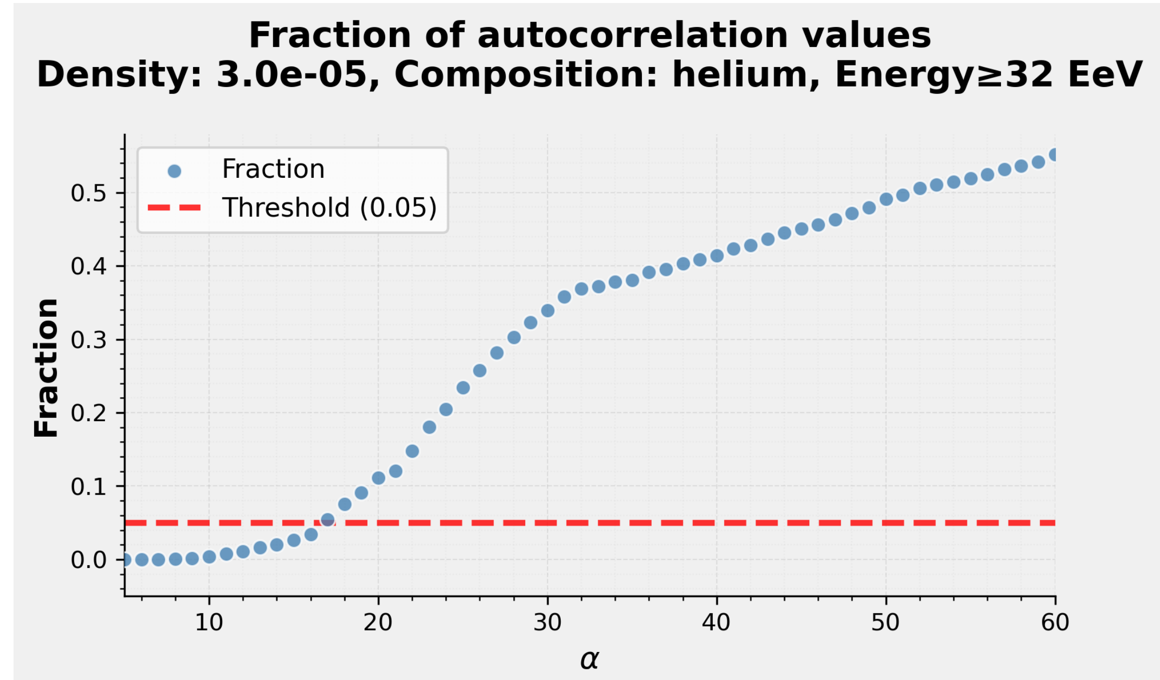


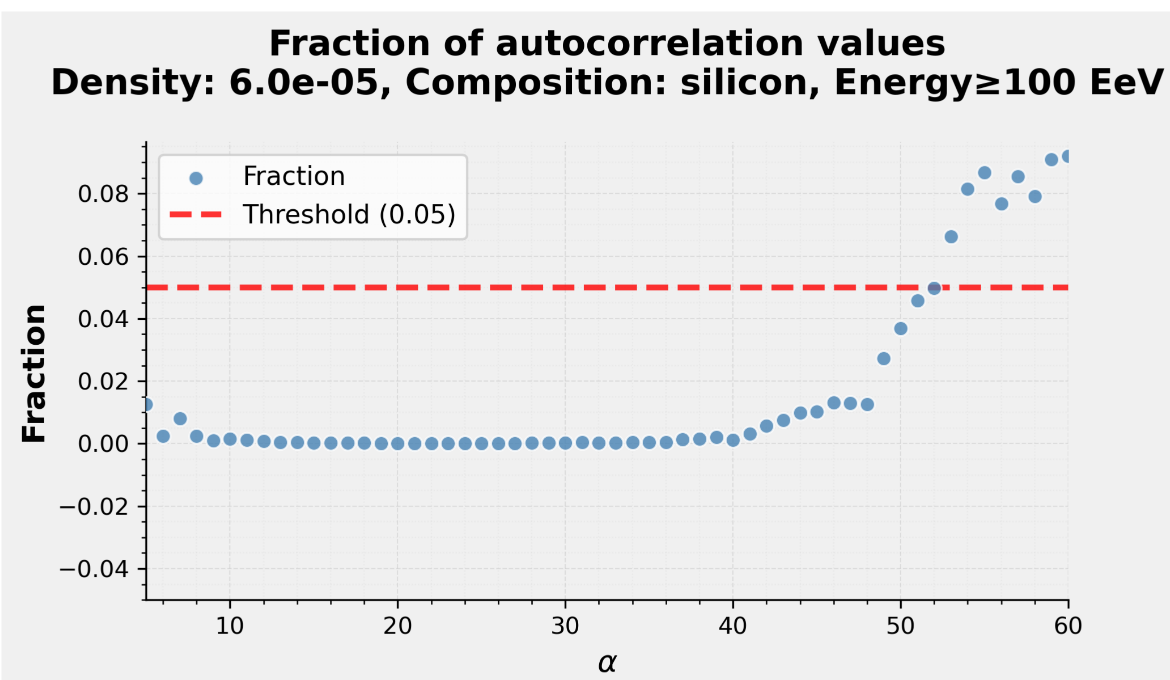
Data with energies ≥60 and ≥100 EeV are in good agreement (at the 1 standard deviation level) with the results of purely isotropic modeling. This is consistent with the results obtained in earlier studies (P. Abreu et al, arXiv:1305.1576v1).
This is not the case for the energy threshold of 32 EeV.

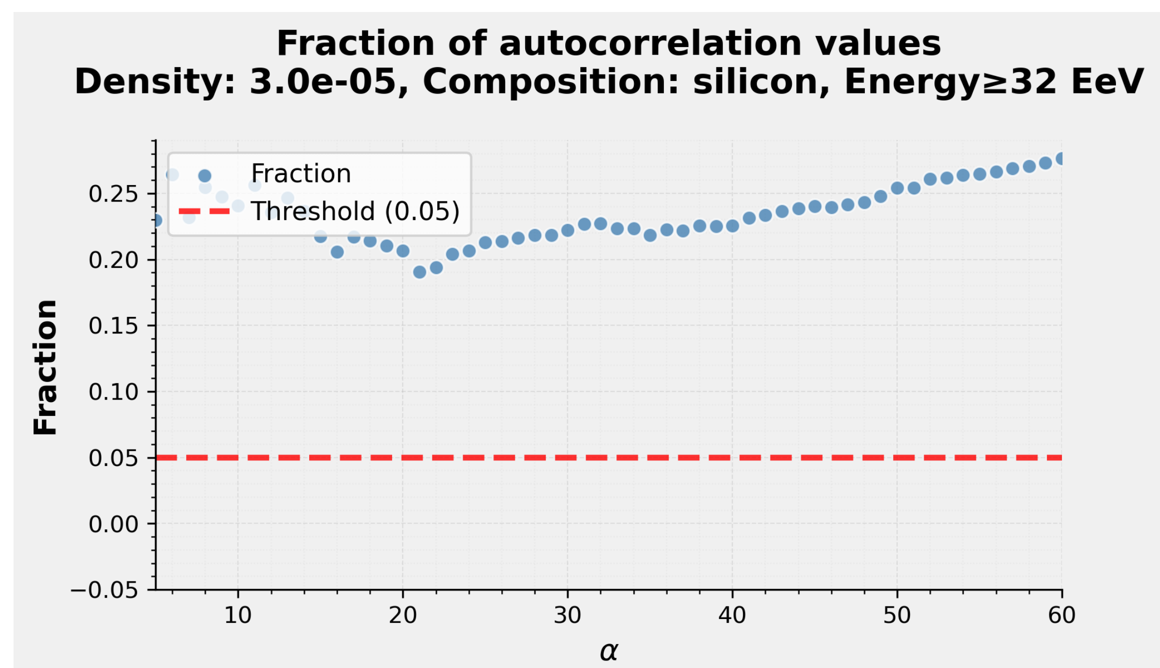
Results

Examples of proportions of fraction of event set more isotropic than data.





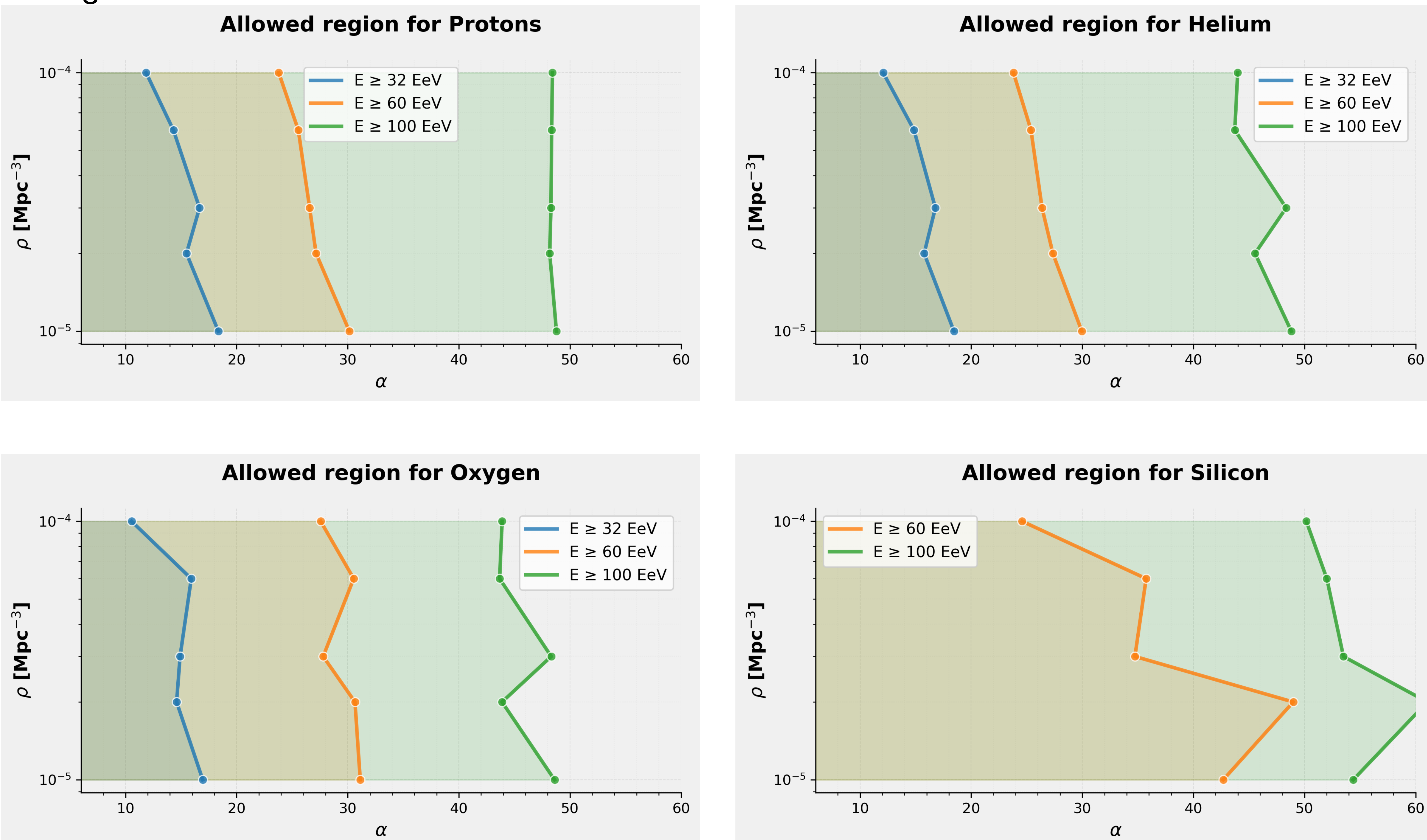




If for some values of the α parameter the proportion <5%, we consider the density to be excluded.

Results

95% CL allowed region (unshaded area) for the density of sources as a function of the angular scale.



Conclusions

- For all compositions and energies (except silicon with energies above 32 EeV), the modeling results are more anisotropic than the data for any source density;

- While numbers of density have not been ruled out, compositions have been ruled out, which is also in good agreement with earlier studies (R.U. Abbasi et al, arXiv:2406.19287v2);

- These preliminary results suggest the need to consider additional effects in simulation: extragalactic magnetic field and refinement of the model of propagation of nuclei. They can have a significant impact on the final picture.

Plans

- Repeat the analysis for other galactic field models;

- Investigate the influence of extragalactic magnetic fields;

- Apply other statistical methods (using test statistics, Landy-Szalay autocorrelation estimator);

- Repeat the analysis for the Telescope Array experiment.

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Backup: modeling

100 catalogs are generated for each source density.

- Several objects are randomly selected from the initial catalog of space objects (corrected 2MRS catalog up to 250 Mpc) so that their number corresponds to the specified density.
- This is done to ensure accurate application of the statistical method.

Next, modeling is performed based on each catalog:

- Sources in LSS (corrected 2MRS catalog up to 250 Mpc);
- Properly attenuated injected primaries (p-He-O-Si), secondaries for He & O are included (SimProp 2.4);
- Fix best fit injection spectrum separately for each primary (di Matteo & Tinyakov 2018) No EGMF deflections;
- GMF deflections: backtracking for regular component;
- Non-uniform gaussian smearing for random component (Pshirkov et al. 2013);
- Sets are generated according to these maps with a spectrum adjusted to the observed one.