

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

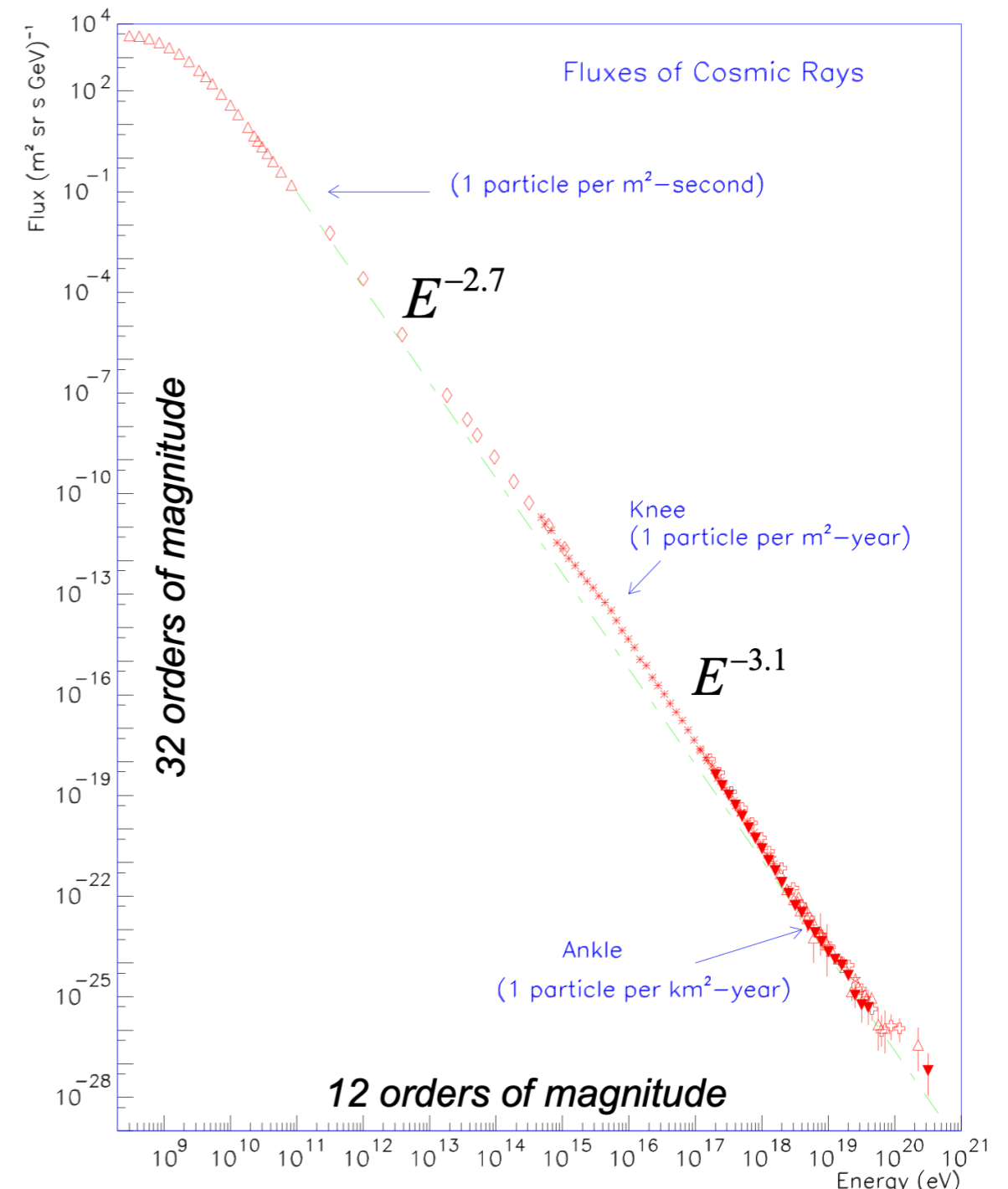
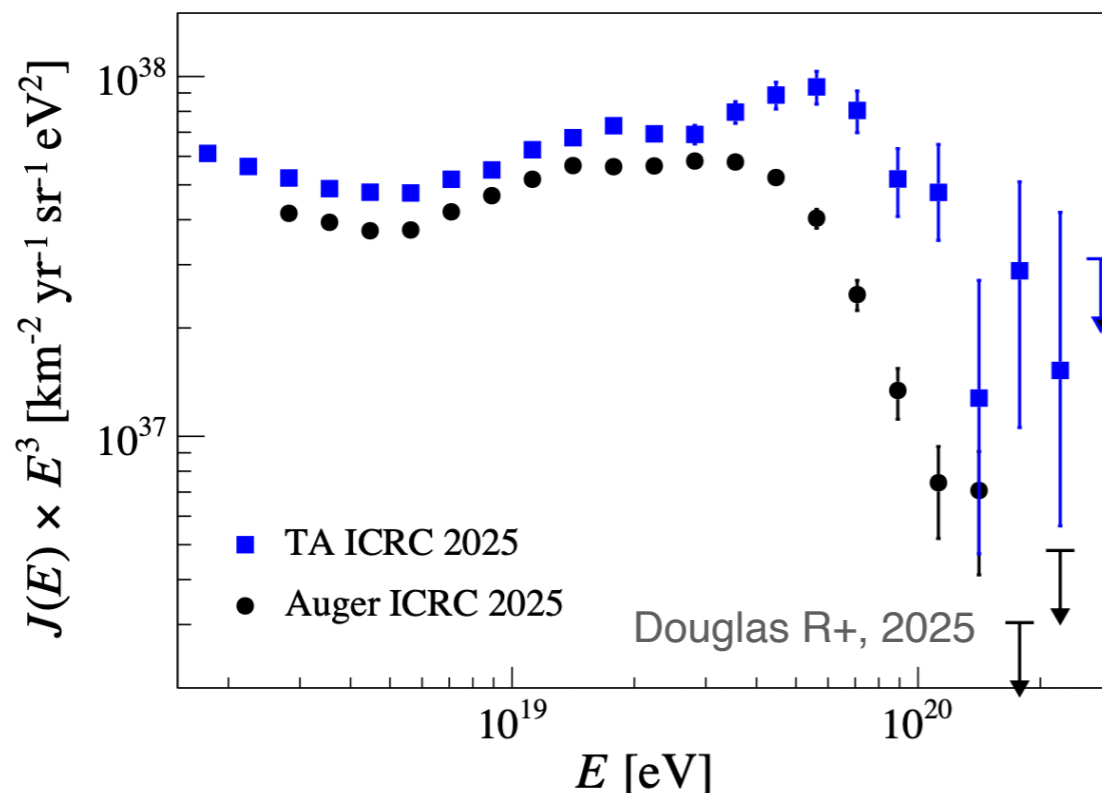
**speaker: Anastasia Pavlyuk**

**scientific supervisor: Mikhail Kuznetsov**

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# Ultra-high energy cosmic rays

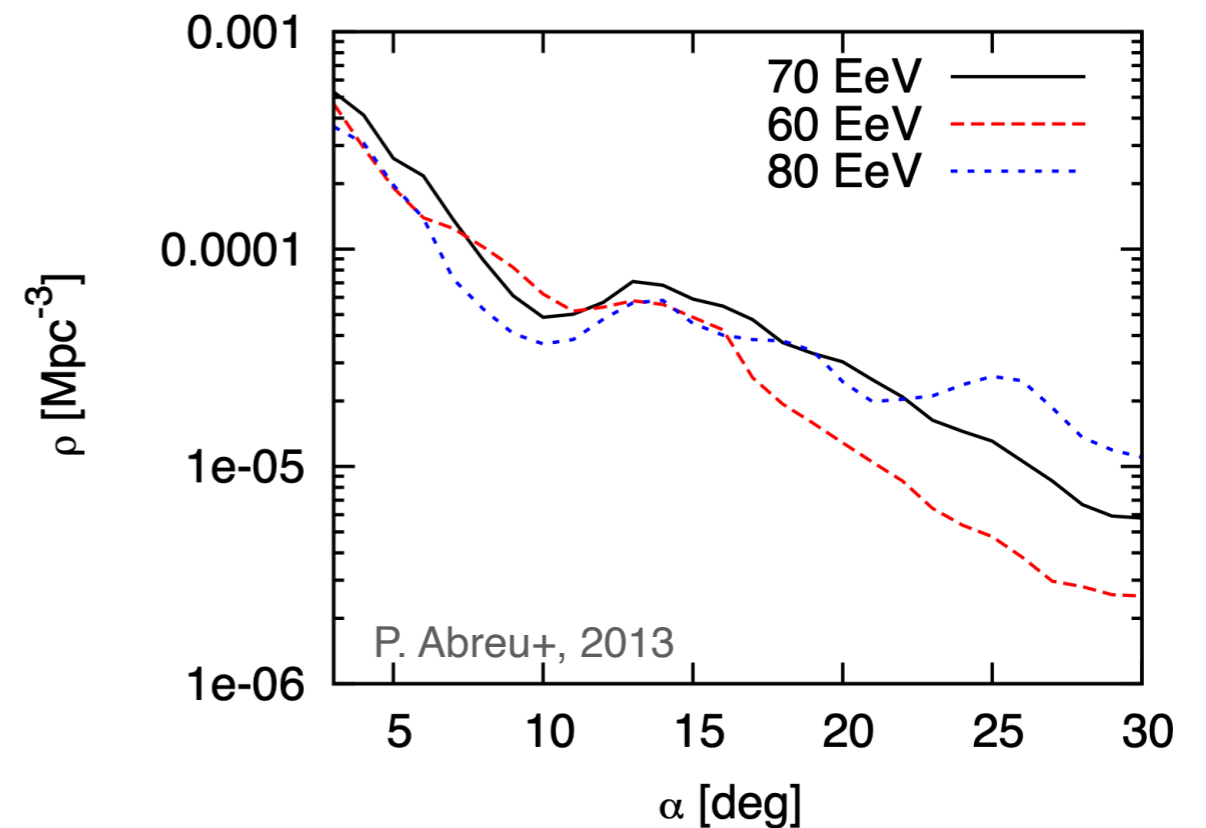
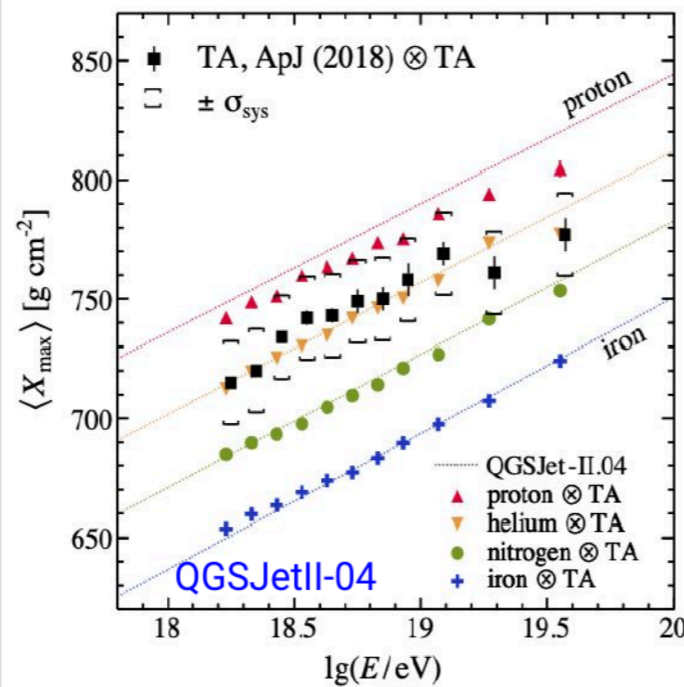
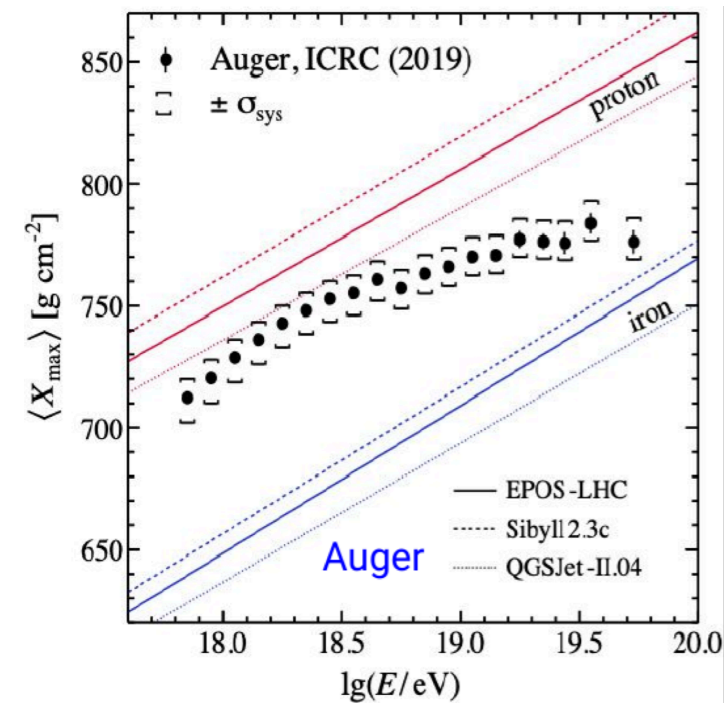
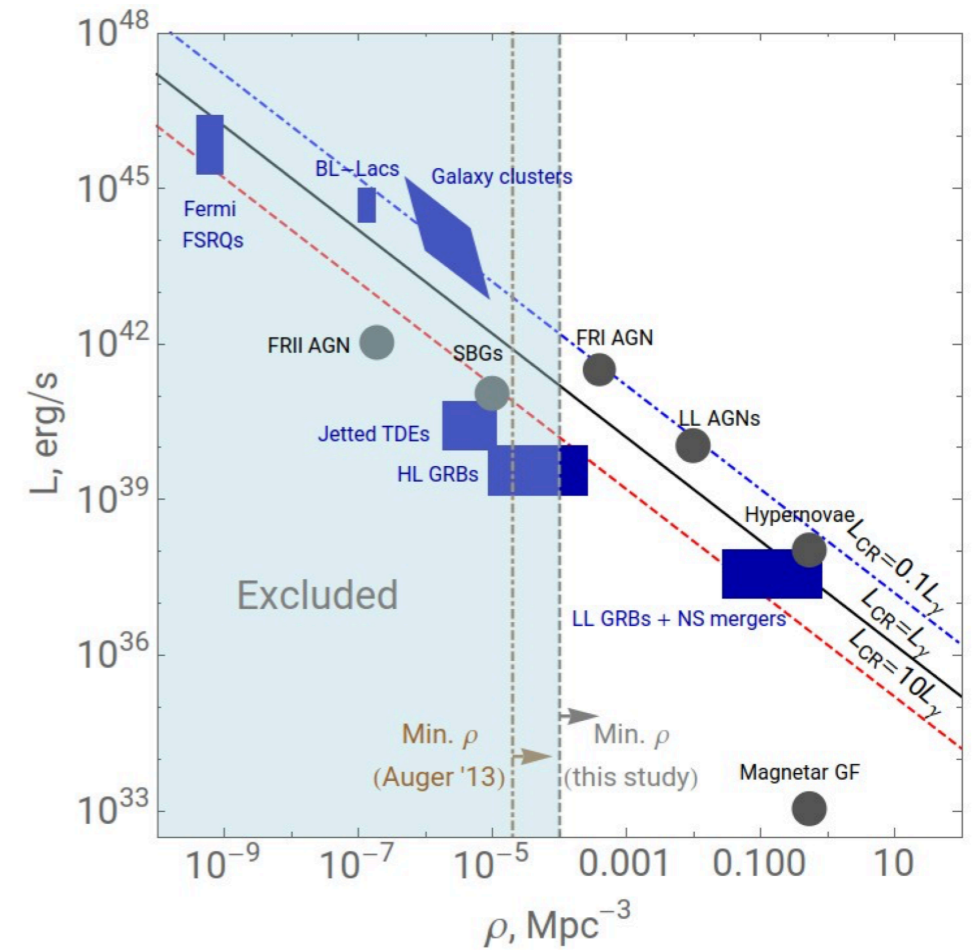
- charged particles (protons and nuclei)
- energy range  $\geq 10^{18}$  eV
- flux  $\sim 100 \text{ km}^{-2}\text{yr}^{-1}\text{sr}^{-1}$
- steeply falling spectrum
- interactions with the cosmic microwave background (GZK effect)
- deflections by galactic magnetic fields



# Current problems

- Composition
- Sources

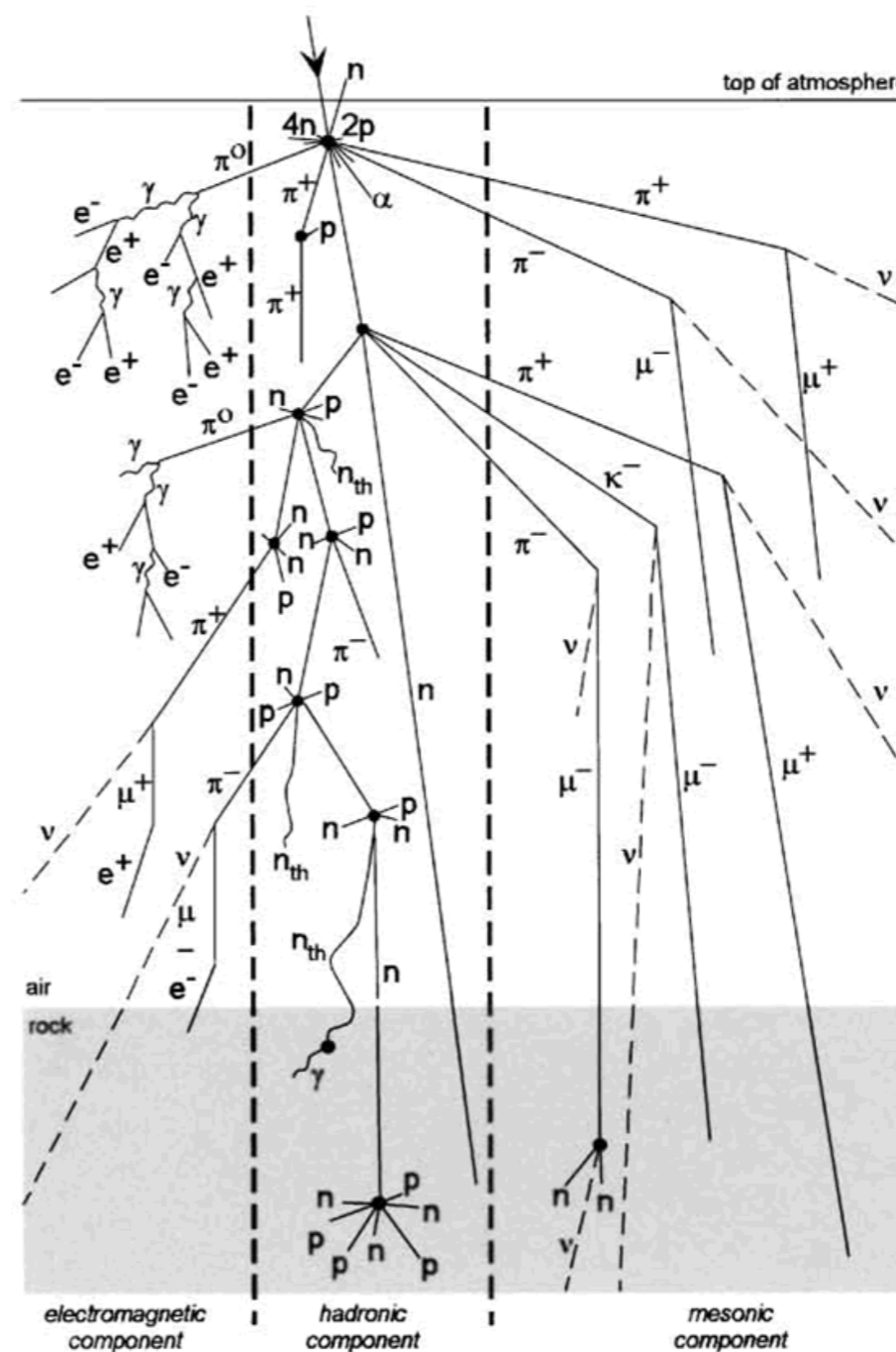
In this work we will consider the possibility of limiting the number density of UHECR sources.



# 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)

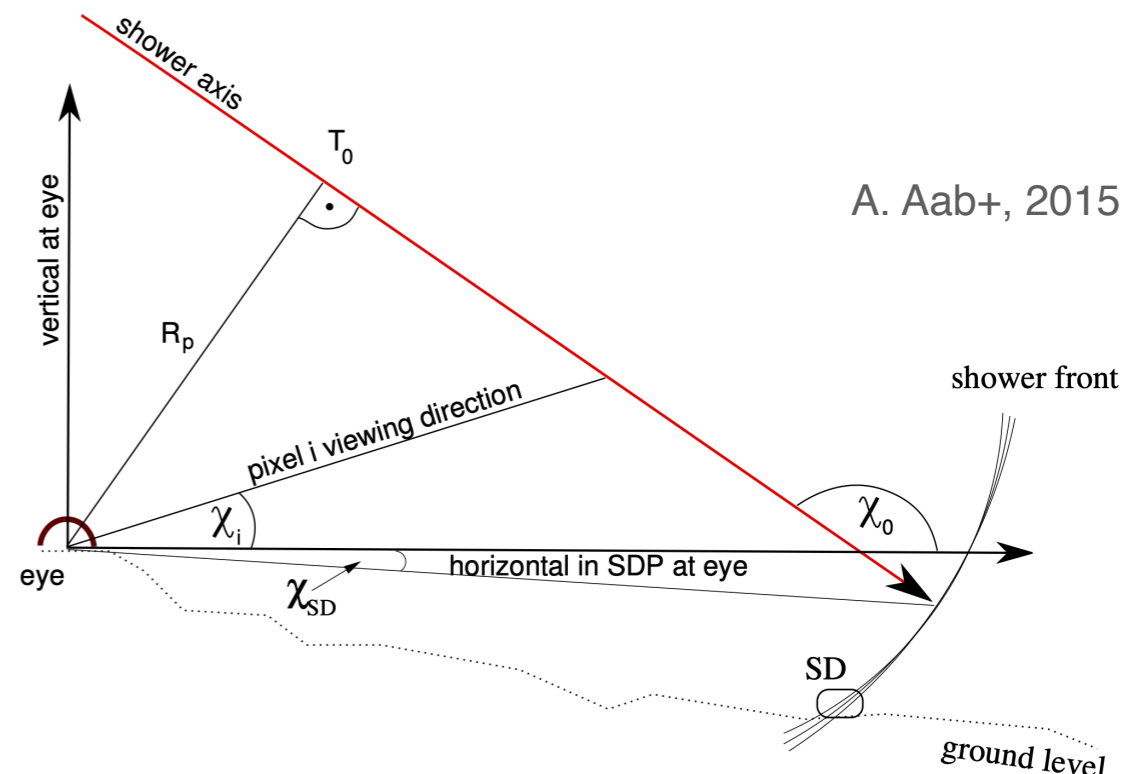
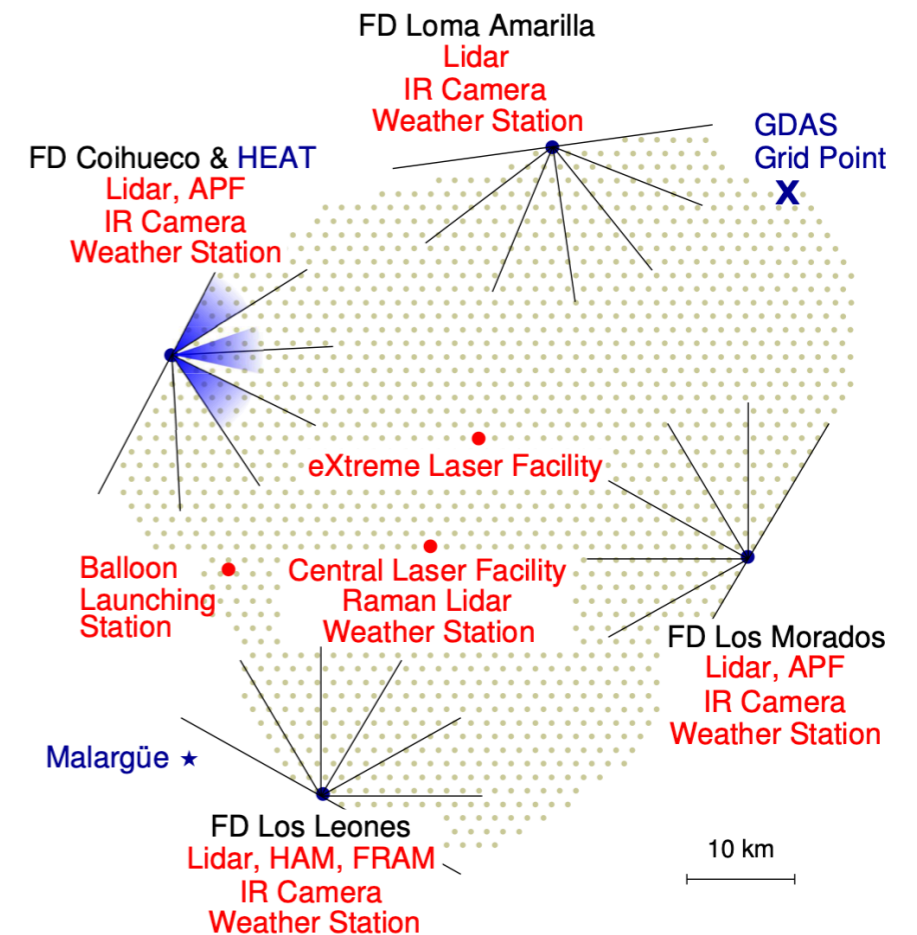
- calorimetric measurement of energy
- 4 sites
  - $E > 10^{18}$  eV
- HEAT
  - $E > 10^{17}$  eV

## Surface detector array (SD)

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

## Data

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



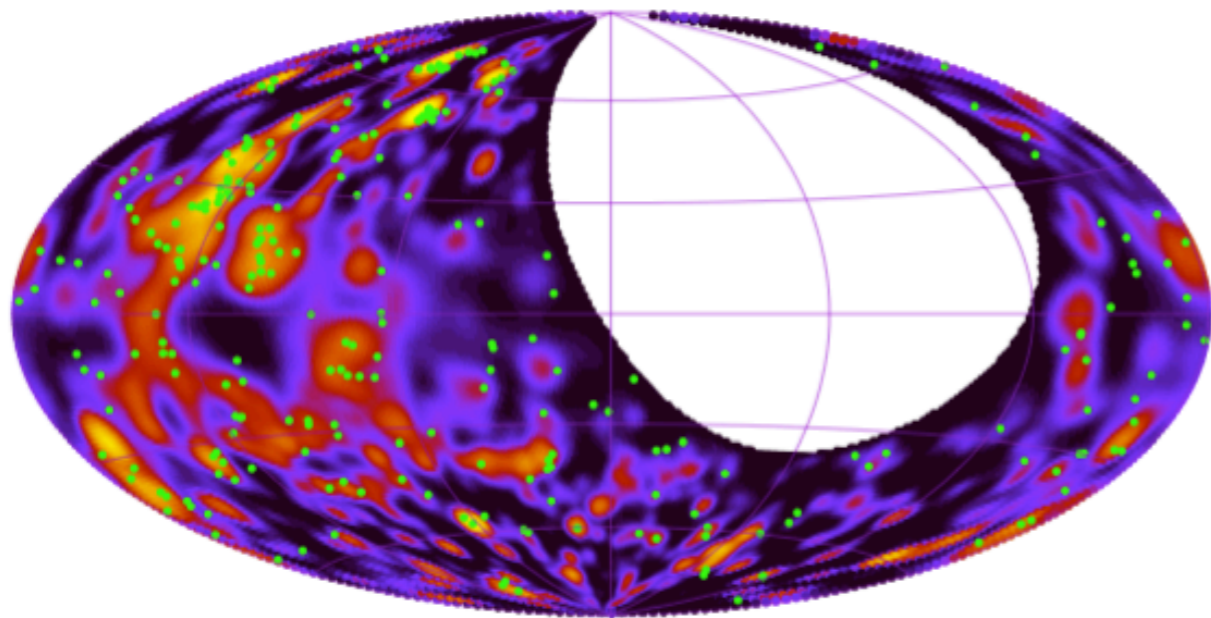
# Modeling

**100 catalogs are generated for each source density.**

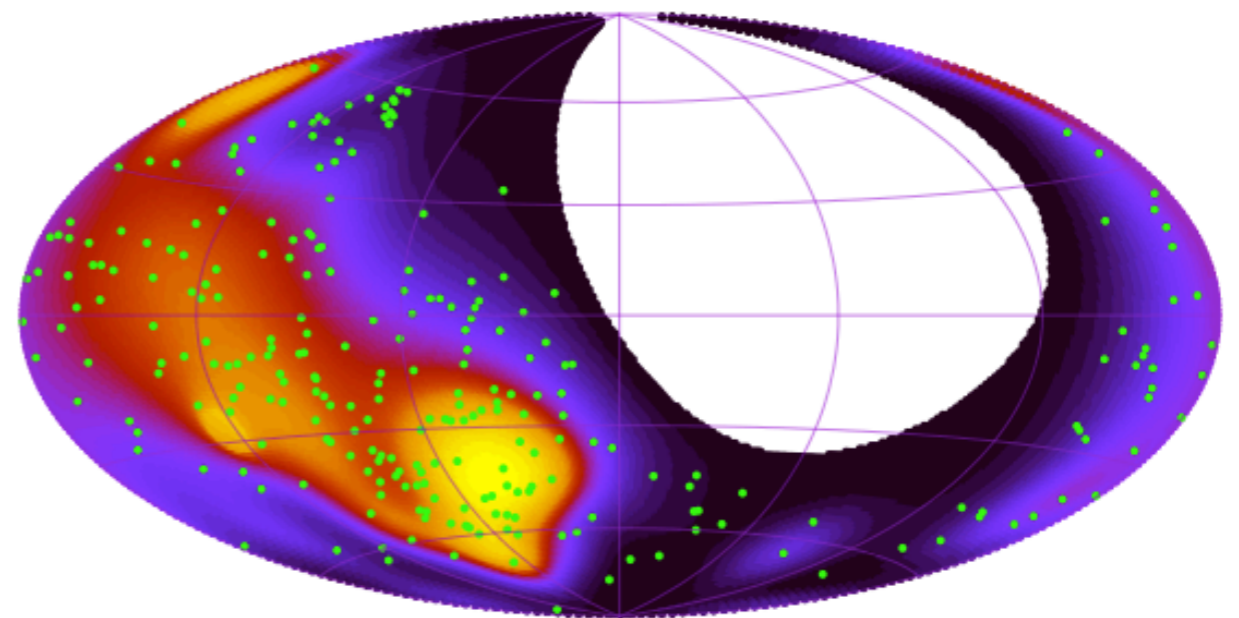
- Several objects are randomly selected from the initial catalog of space objects (corrected 2MRS catalog up to 250 Mpc) so that their number corresponds to the specified density.

**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  $\theta$ . It gives the flux map  $\Phi_k(\theta, n)$ .
- From the flow maps  $\Phi_k$ , a simulated 100 sets of UHECR events is generated that would be detected by an experiment on Earth.



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



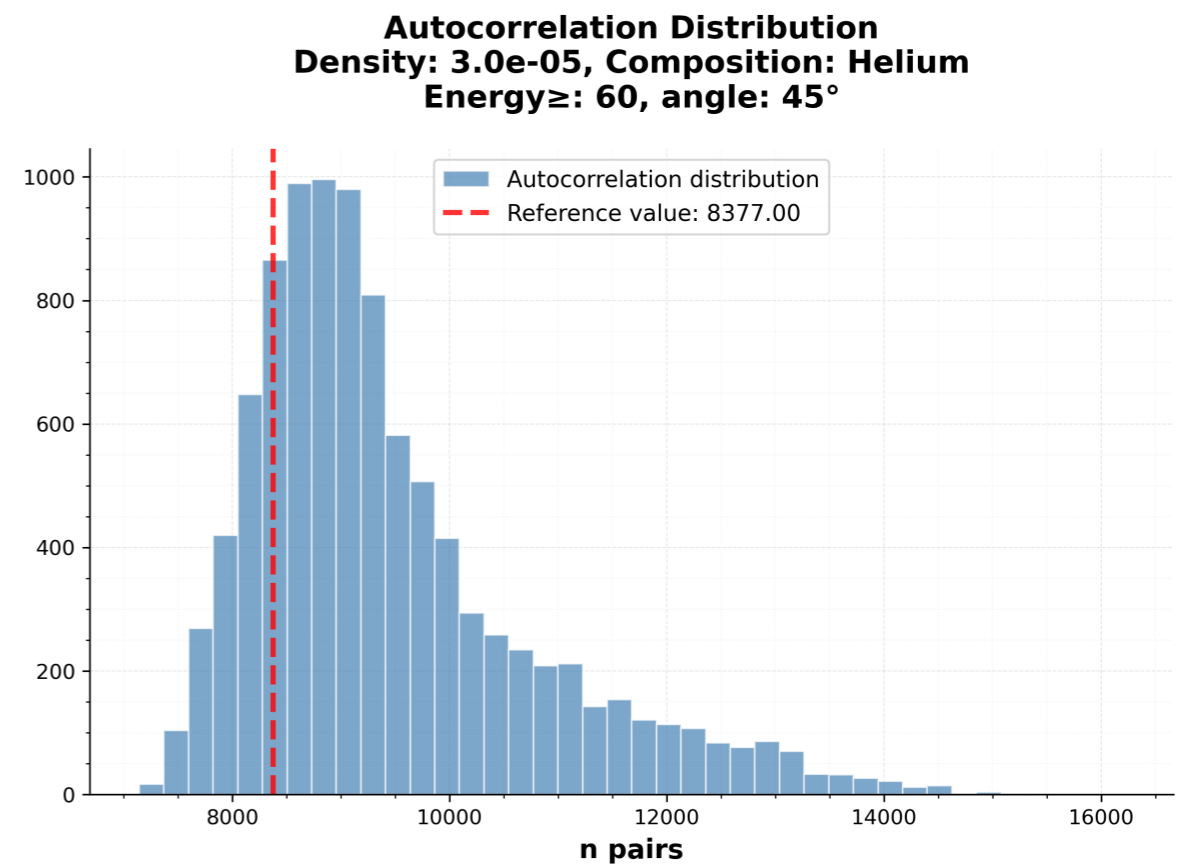
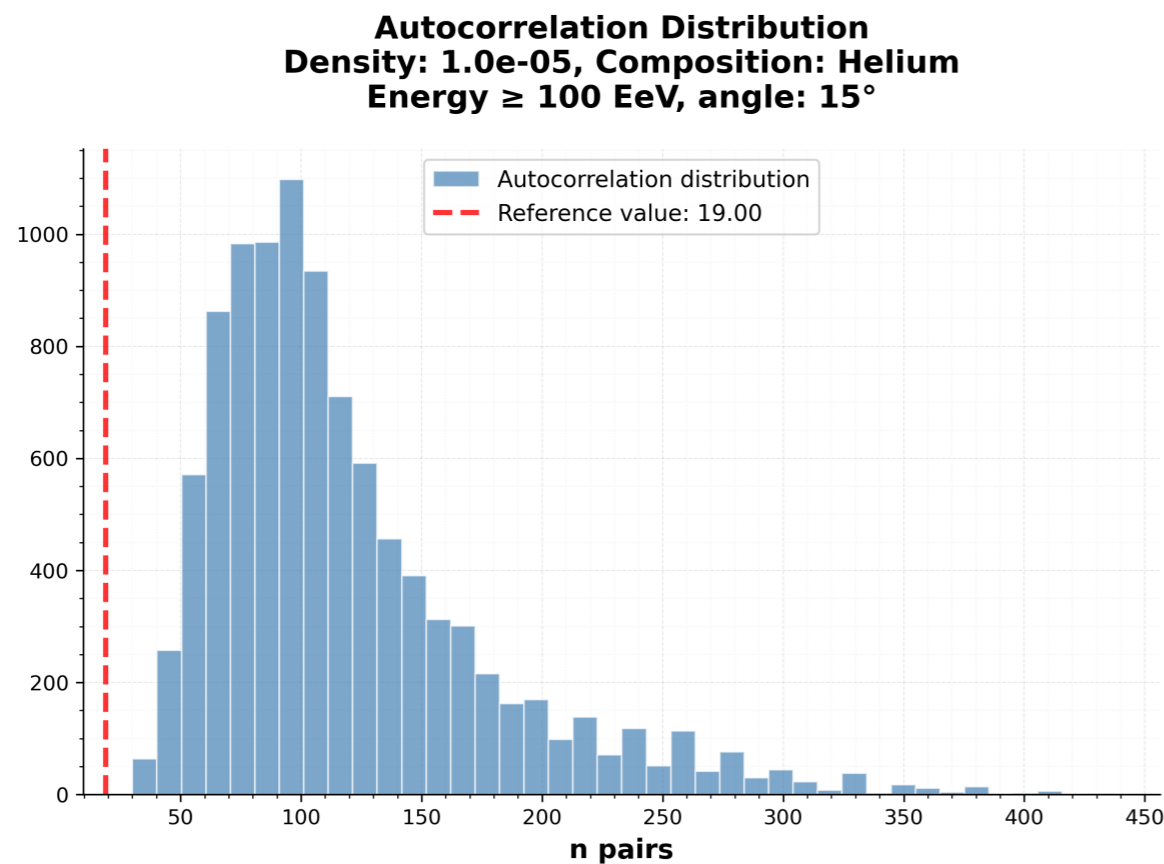
Density:  $6 \cdot 10^{-5} \text{ Mpc}^{-3}$   
Composition: silicon  
Energy  $\geq 60 \text{ EeV}$

# Statistical method

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

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

where  $\Theta$  is the step function, and  $\alpha_{ij}$  is the angular distance between events  $i$  and  $j$  of  $N$  cosmic rays.

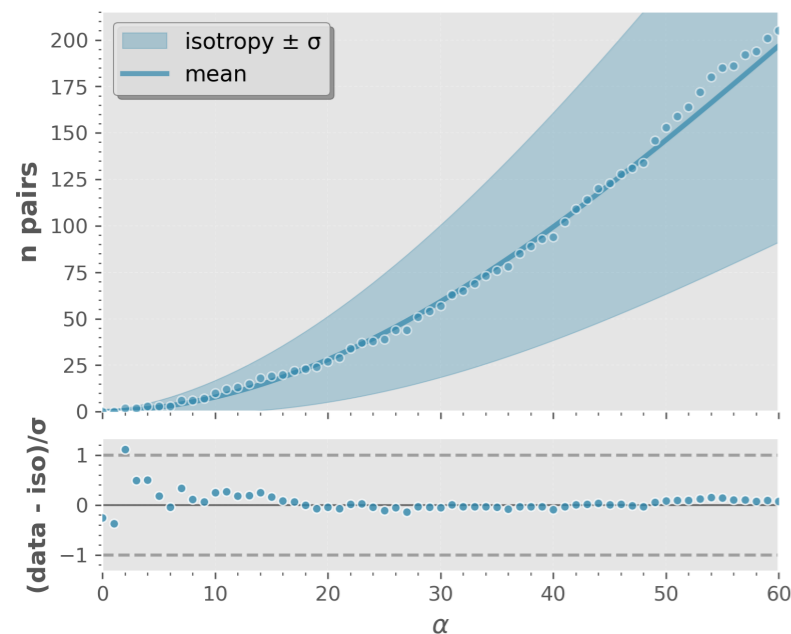


Autocorrelation is calculated for simulated event sets. This distribution is compared with the value from the data. The compatibility criterion at the level is: the proportion of values smaller than the reference value is at least 5%.

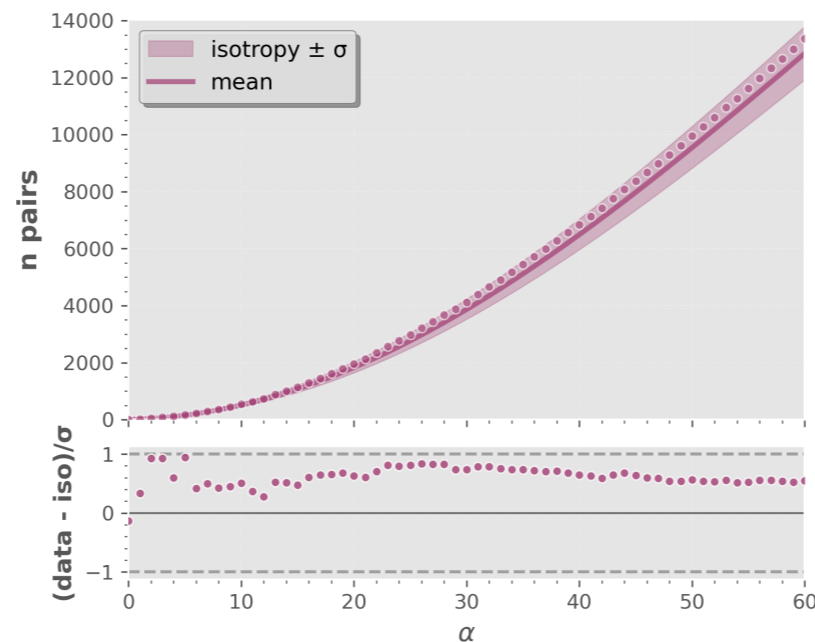
# Results

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

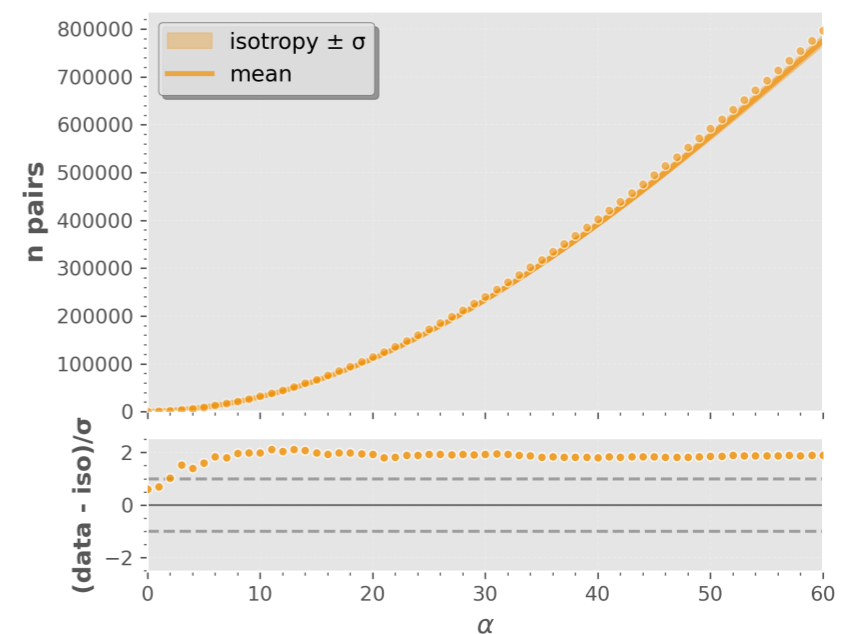
Autocorrelation function for energies  $\geq 100$  EeV



Autocorrelation function for energies  $\geq 60$  EeV



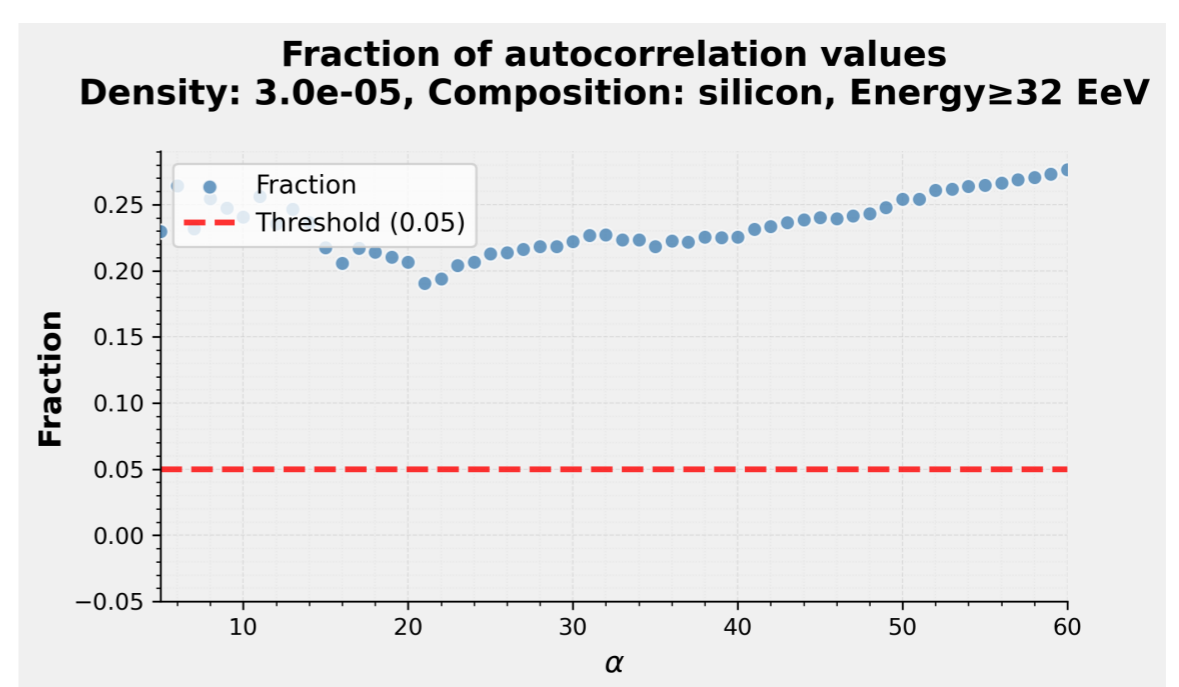
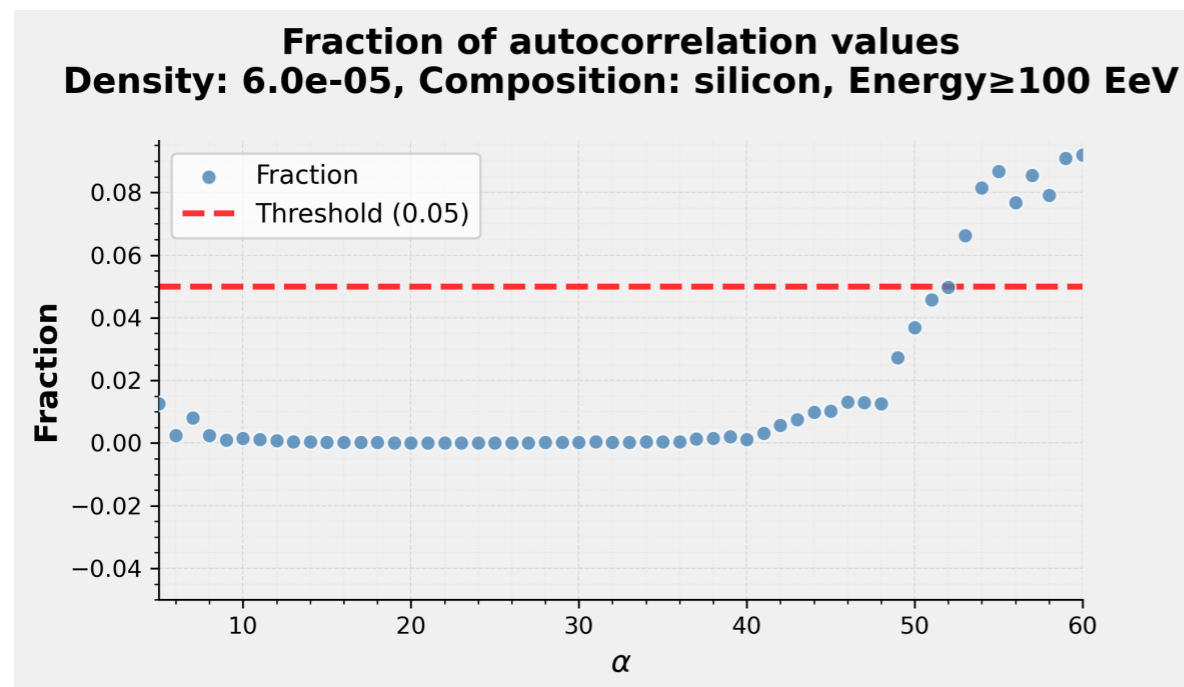
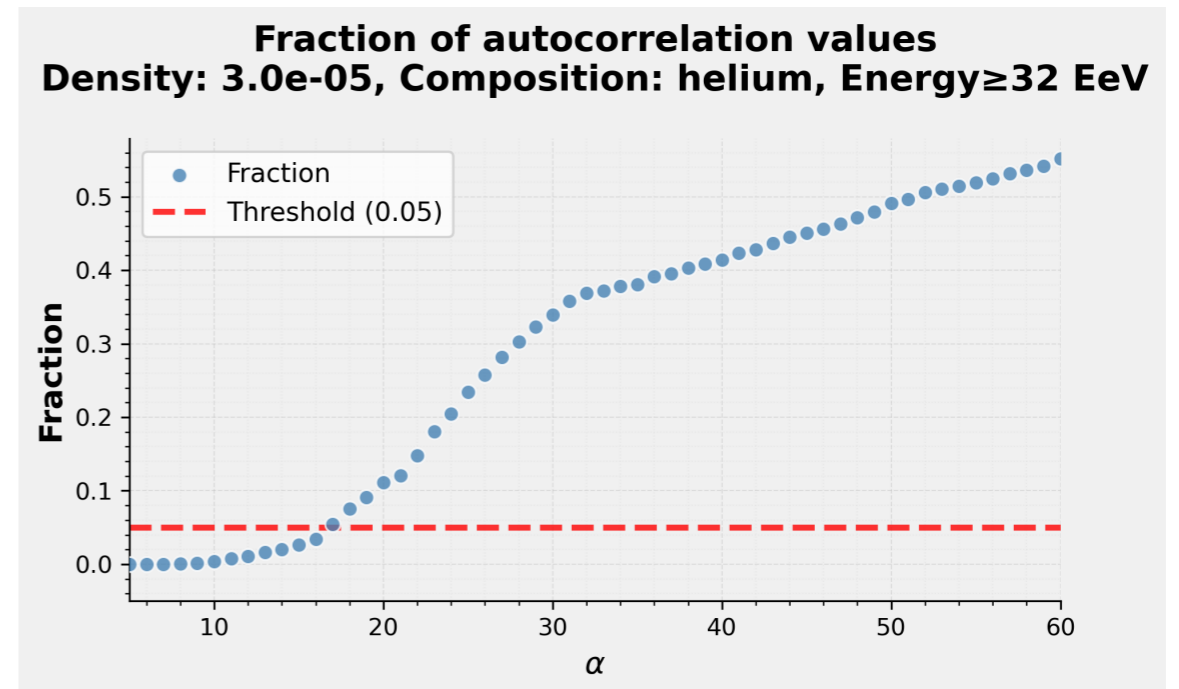
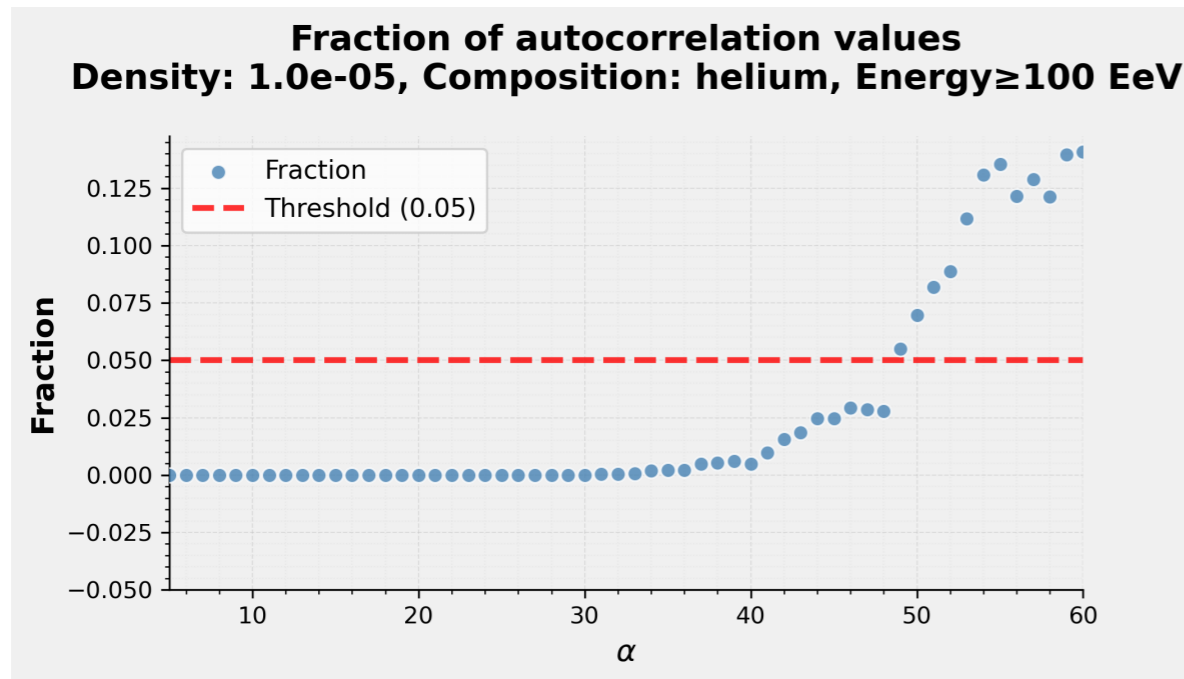
Autocorrelation function for energies  $\geq 32$  EeV



Data with energies  $\geq 60$  and  $\geq 100$  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

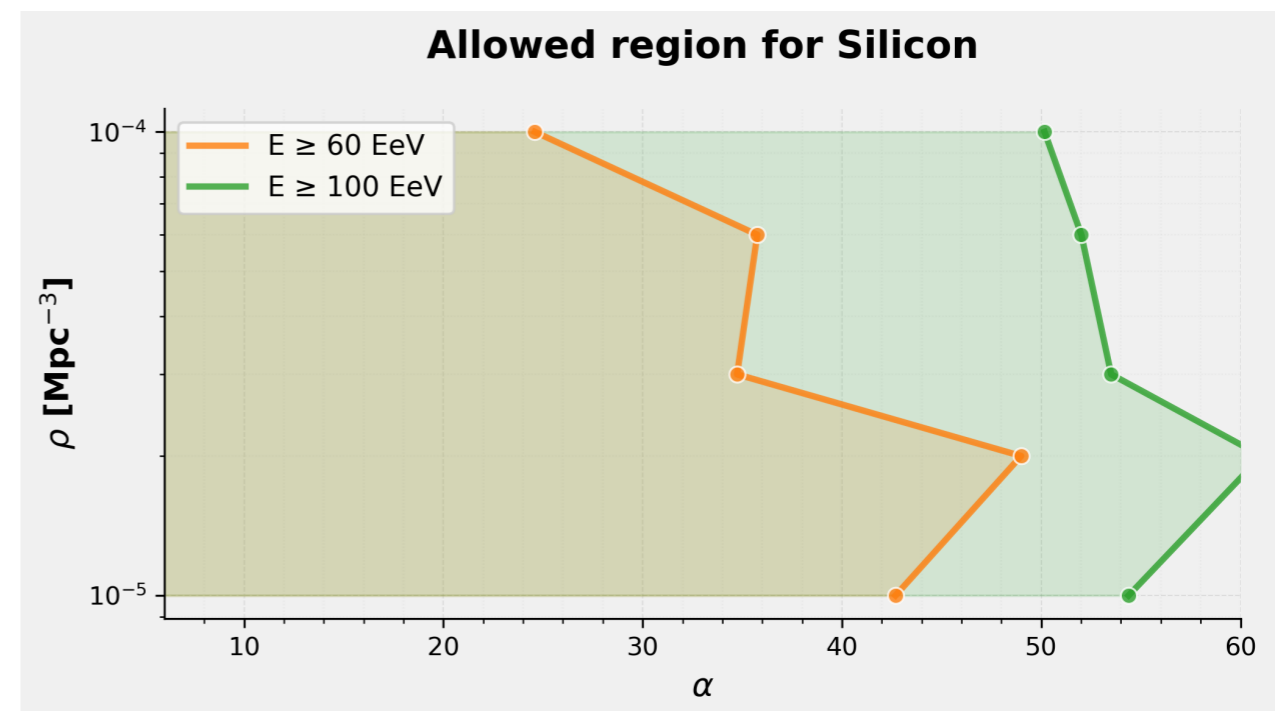
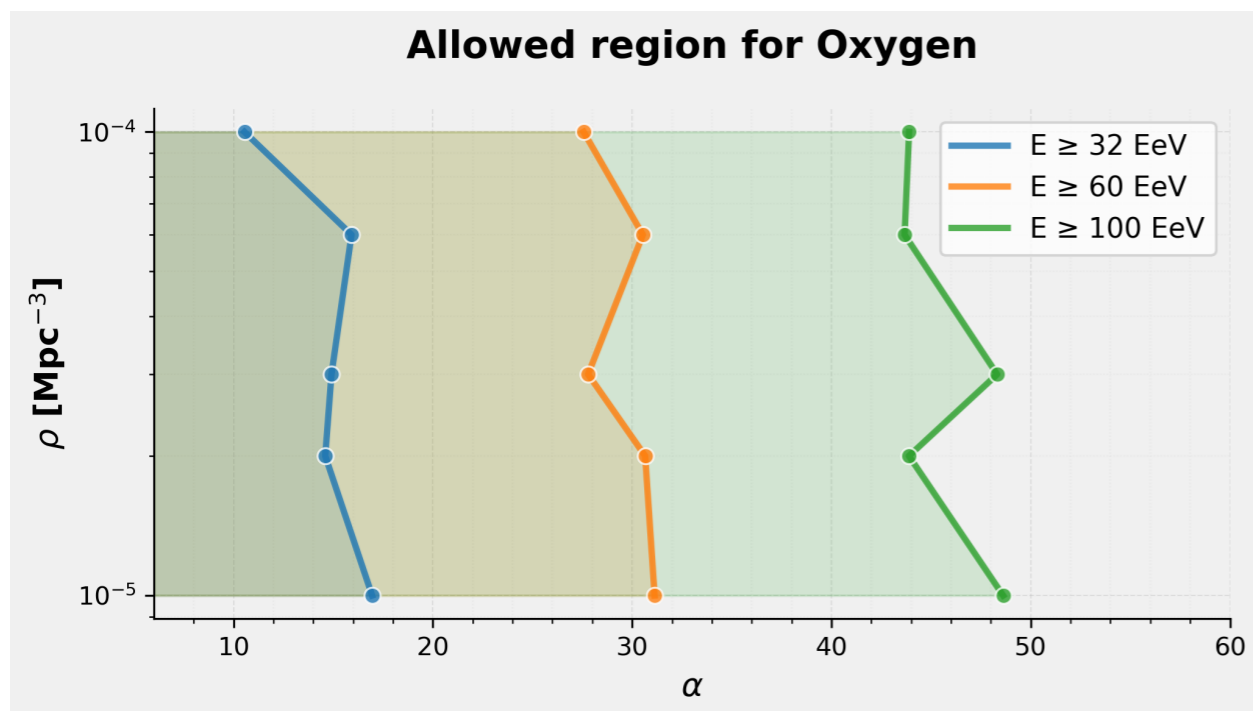
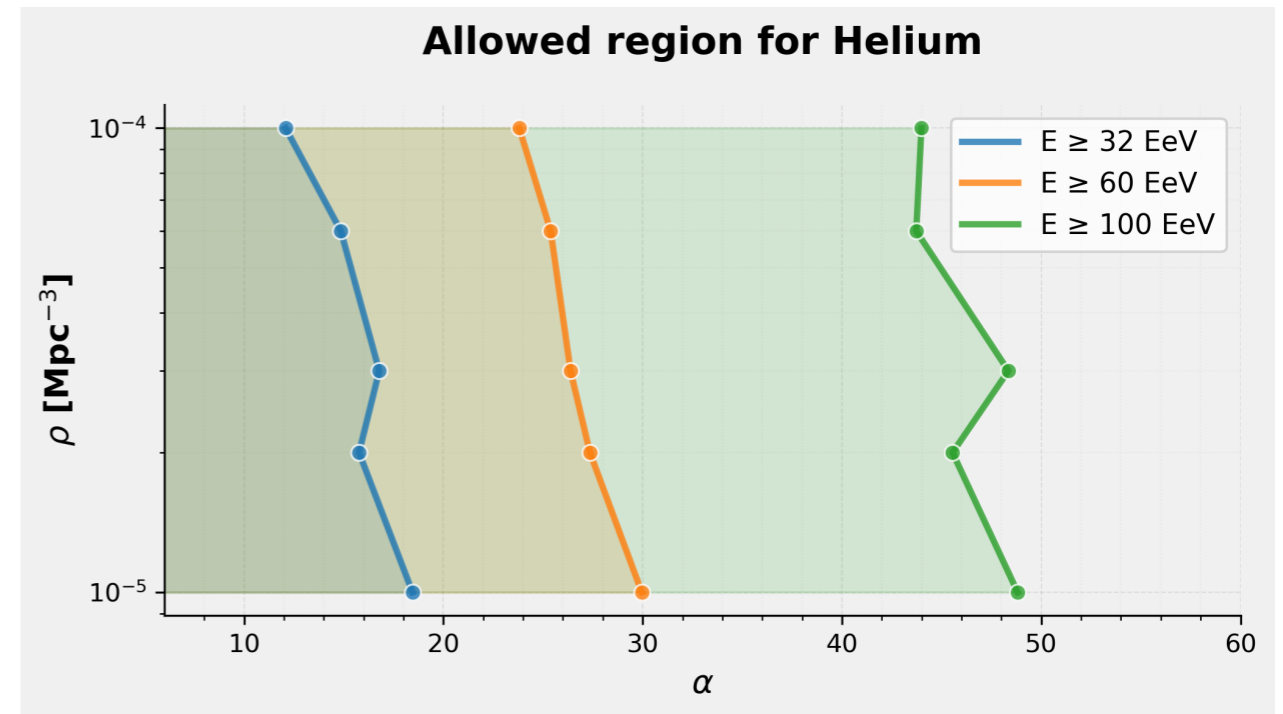
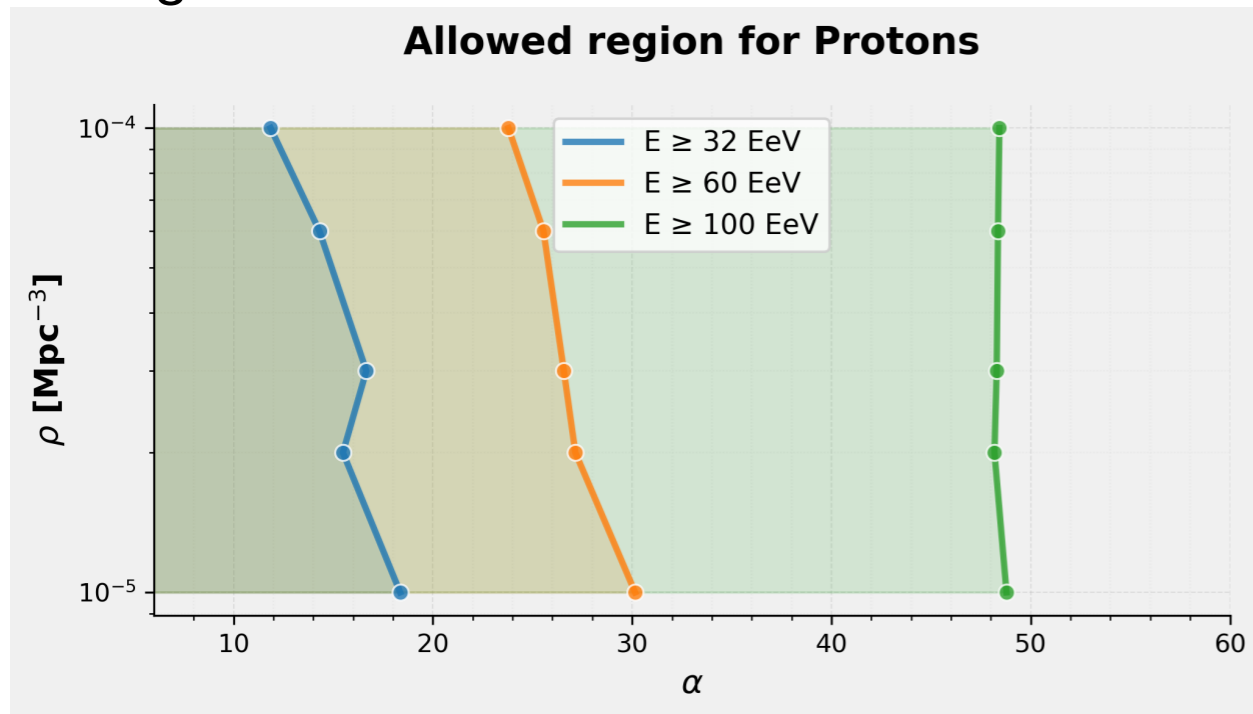
Examples of proportions of fraction of event set more isotropic than data.



If for some values of the  $\alpha$  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.

# 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.