Searching for the sources of the most energetic cosmic rays #259

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1. Introduction and aims

The recent detection of the “Amaterasu particle” by the Telescope Array Collaboration, the second most energetic cosmic ray ever detected (2.44×10^{20} eV), has motivated investigations not only into its possible candidate sources (Abbasi et al., 2023; Unger & Farrar, 2024) but also into other highly energetic events. These particles are less deflected by cosmic magnetic fields due to their extremely high energy, which aids in backtracking them to their sources.

Therefore, the aim of this work is to analyze the events from the catalog of the 109 most energetic particles detected by the Pierre Auger Observatory (Abdul Halim et al., 2023) to search for their origin. Figure 1 displays the distribution of arrival directions of these particles along with their respective energies. One of the goals is to calculate the localization volumes from which these particles originate using the most up-to-date Galactic magnetic field models and to statistically correlate these volumes with known astrophysical objects from catalogs.

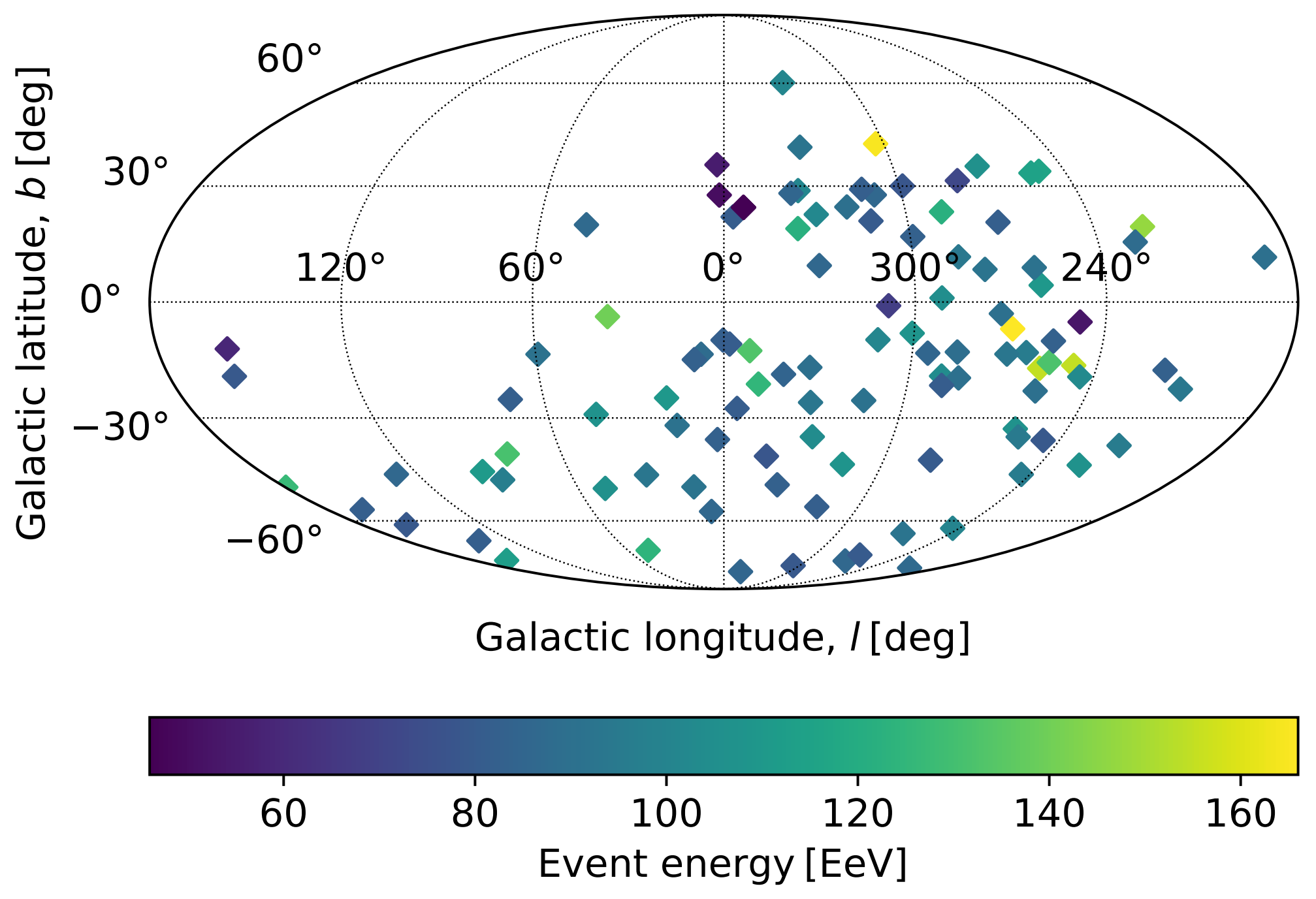

Figure 1: *Map of the most energetic events detected by the Pierre Auger Observatory in Galactic coordinates.*

2. Propagation distances

Ultra-high-energy cosmic rays undergo energy losses due to interactions with cosmic radiation fields. These interactions constrain the maximum distance from which the detected events could originate without experiencing significant energy loss that would make them not having such high energy.

We replicated the analysis conducted by Unger & Farrar (2024) for the Amaterasu particle (Abbasi et al., 2023) to determine the maximum distance for these most energetic events. In particular, we performed one-dimensional simulations of the propagation of ultra-high-energy cosmic rays using CRPropa 3 (Alves Batista et al., 2022) for several energies and propagation distances. For each propagation distance and energy of the particle on Earth, it was possible to compute the fraction in which the normalized number of cosmic rays is below 0.1 and consider this boundary as the maximum distance traveled. Taking into account uncertainties in the energy measurement, a maximum distance range from 10.00 to $53.94\ \mathrm{Mpc}$ was identified for the Amaterasu particle (Figure 2), and the same procedure was applied to the catalog of the most energetic particles detected by the Pierre Auger Observatory.

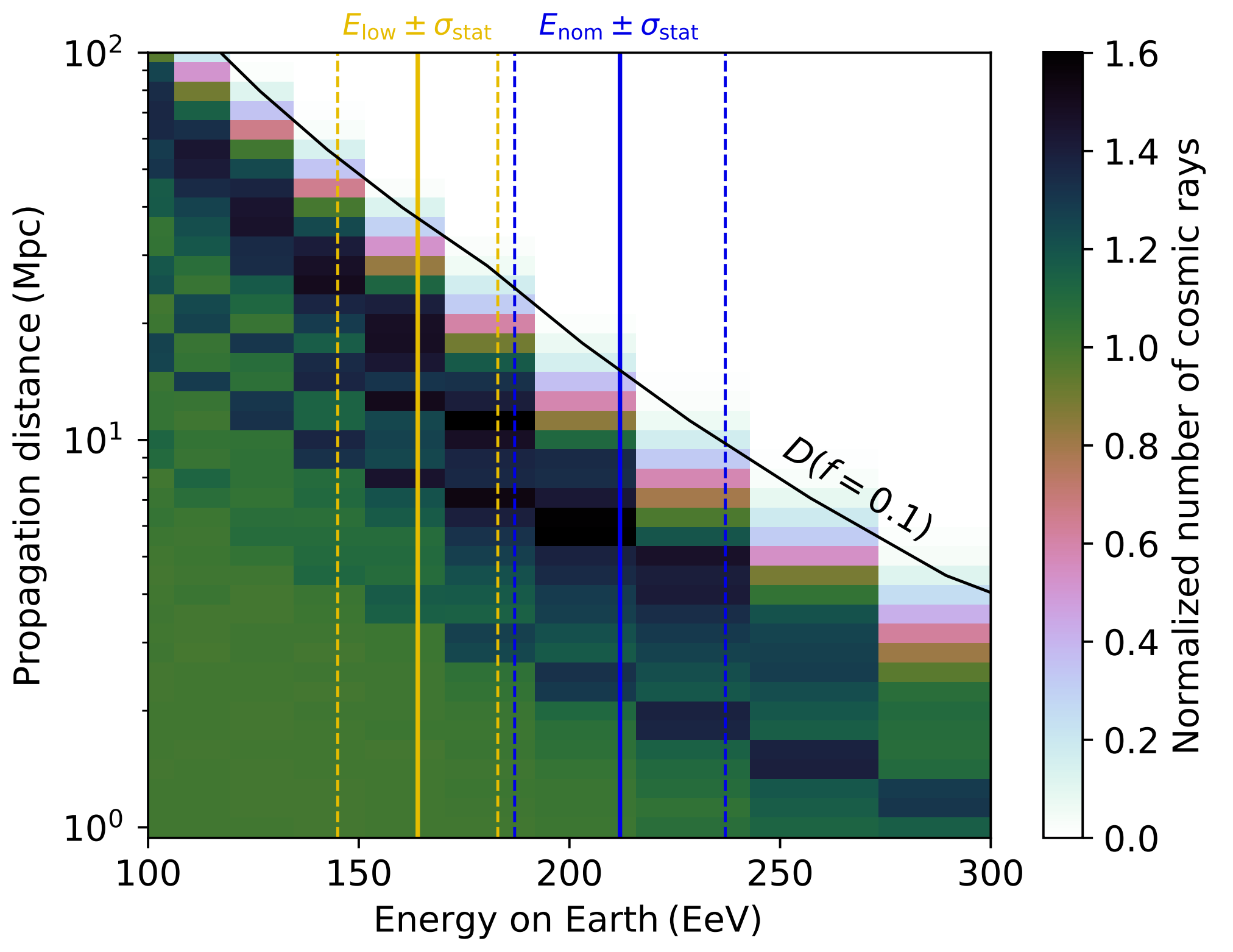

Figure 2: *Propagation distances of cosmic rays arriving on Earth compared to the nominal and low energies of the Amaterasu particle.*

3. Arrival directions

We replicated the analysis conducted by Romano (2024) to simulate the interaction between the most energetic particles detected by the Pierre Auger Observatory and the Galactic magnetic fields to obtain the direction of their sources (Figures 3 to 7). In particular, we used CRPropa 3 to backtrack the particles that reached Earth to the edge of our Galaxy by employing the Galactic magnetic field Jansson & Farrar (2012).

As expected, particles with higher atomic numbers are more deflected by magnetic fields, which means that heavier particles have fewer constraints on the region of the sky from which they originate.

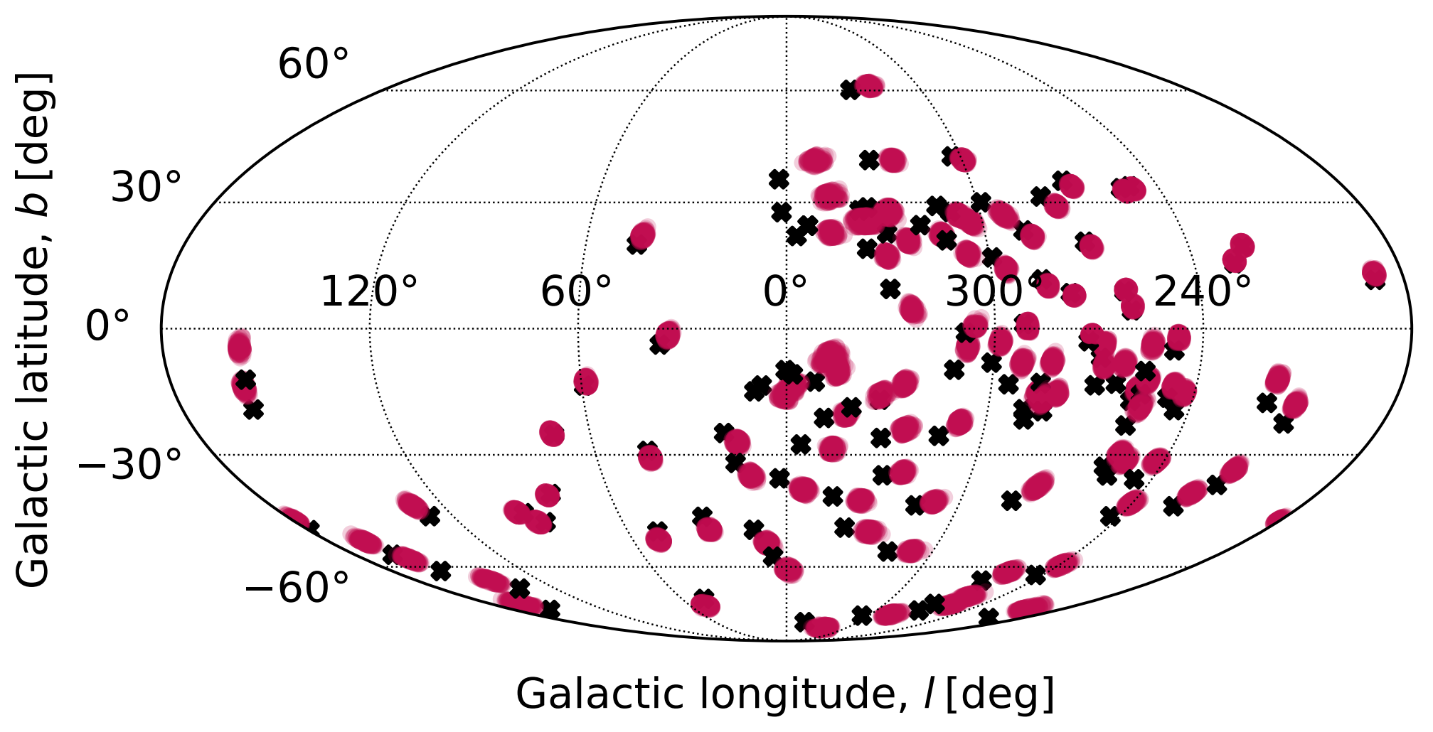

Figure 3: *Positions of the most energetic events detected by the Pierre Auger Observatory after simulating backtracking in the Galactic magnetic field for proton nuclei as primaries.*

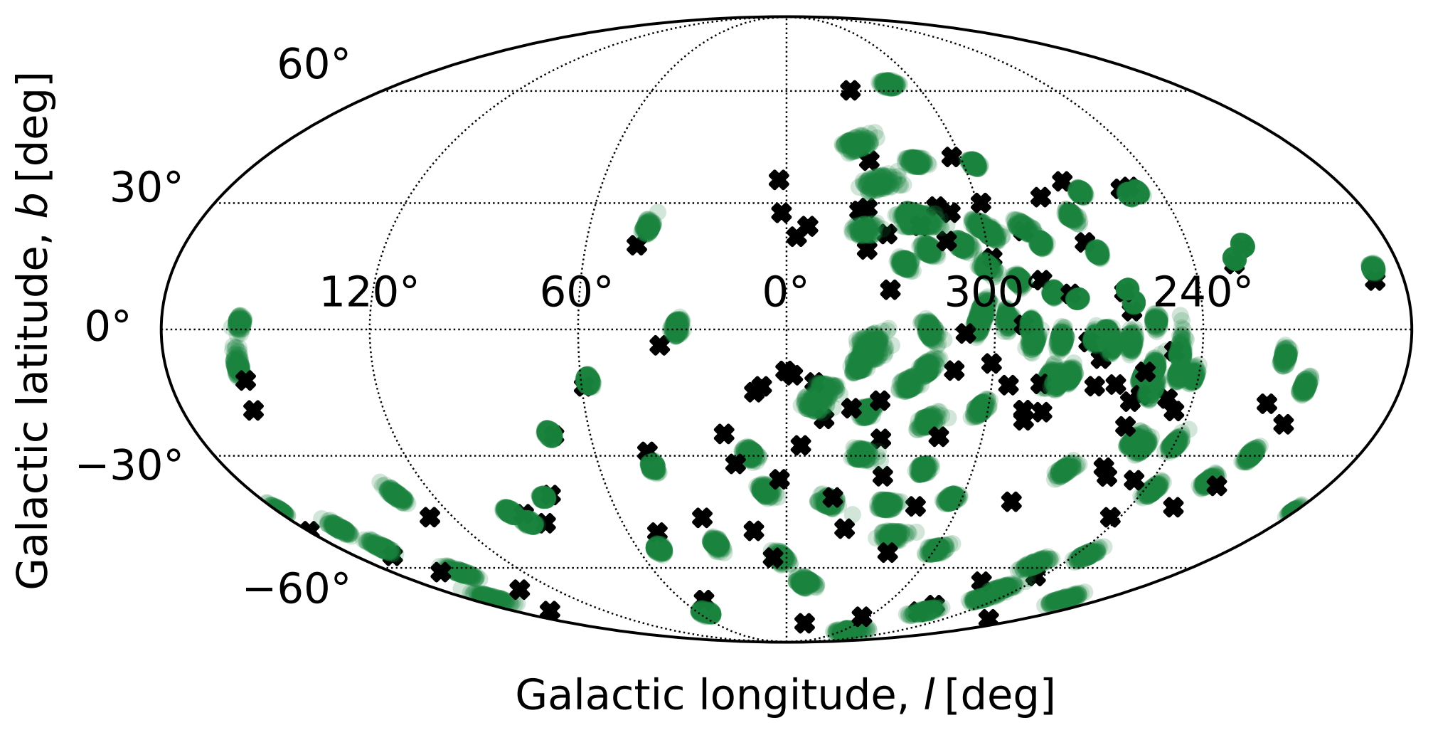

Figure 4: *Same as Figure 3, but for helium nuclei.*

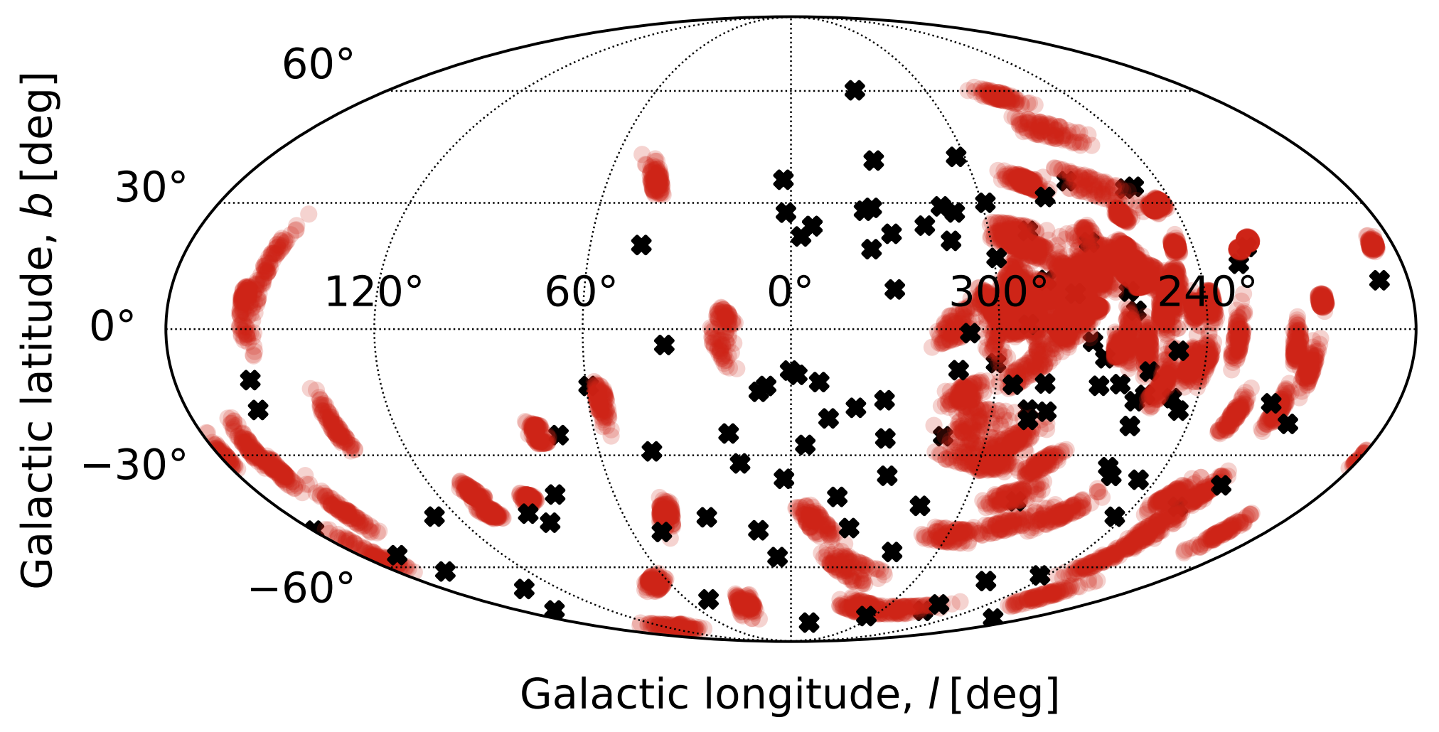

Figure 5: *Same as Figure 3, but for nitrogen nuclei.*

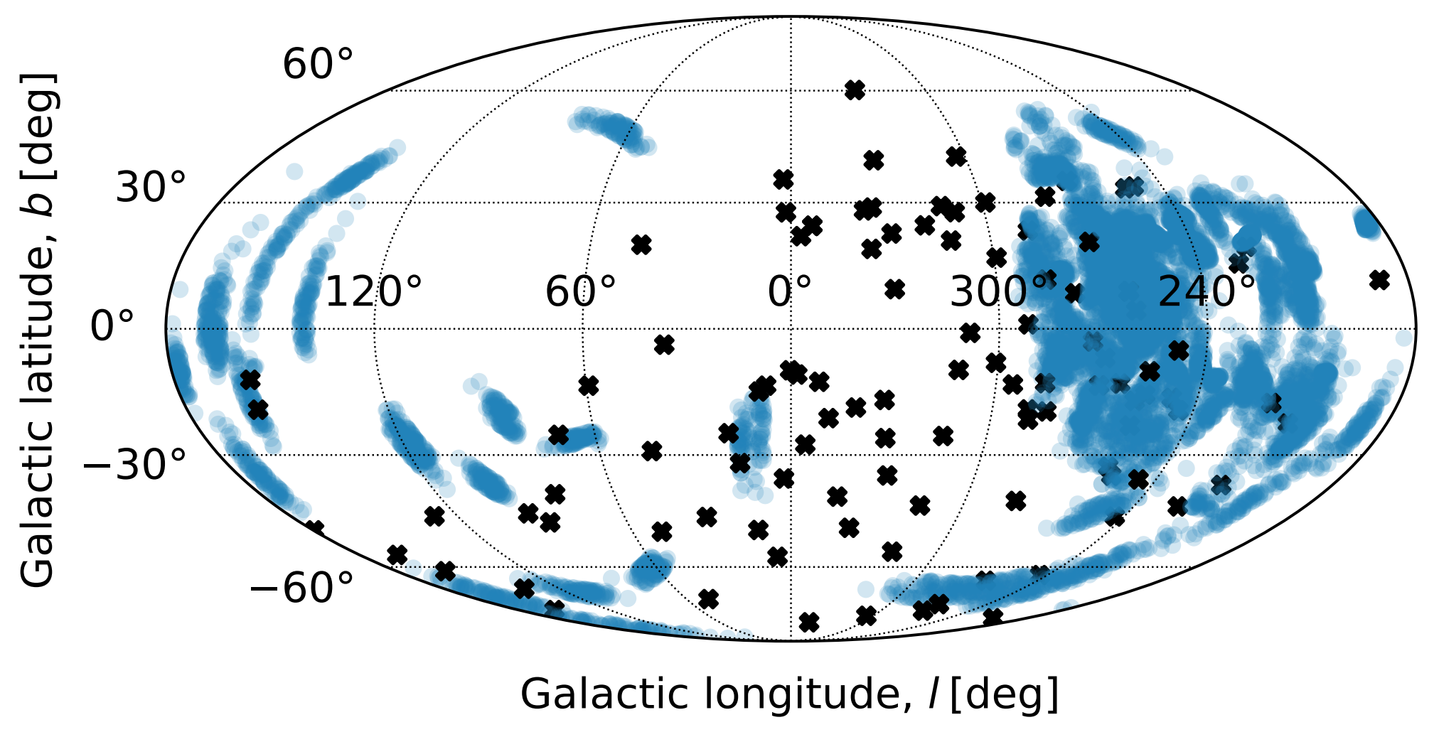

Figure 6: *Same as Figure 3, but for silicon nuclei.*

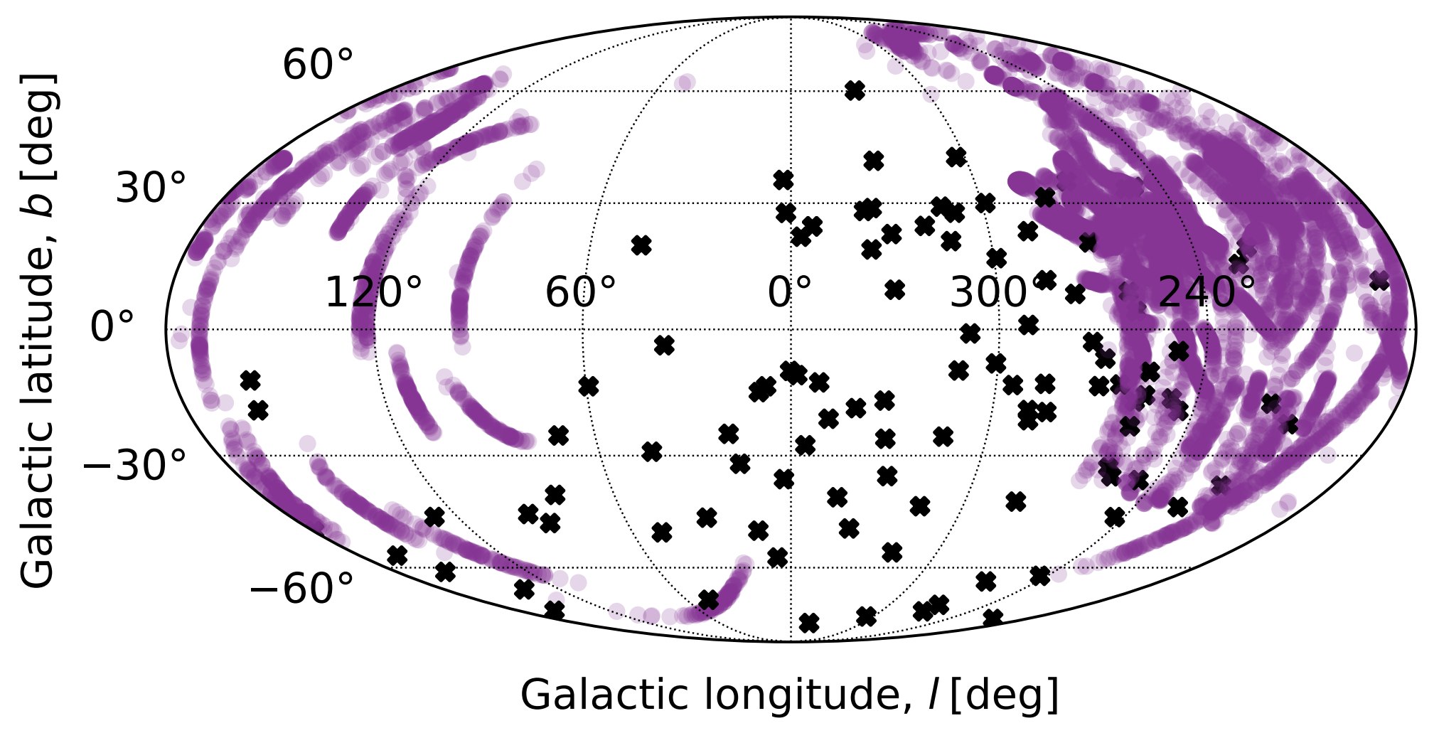

Figure 7: *Same as Figure 3, but for iron nuclei.*

4. Conclusions and next steps

- We are searching for the sources of the 109 most energetic events detected by the Pierre Auger Observatory.
- Until now, we have reproduced main results from the works Unger & Farrar (2024) and Romano (2024) to compute the maximum distance of the sources and the backtracked position of the particles.
- We are currently working on implementing the most up-to-date Galactic magnetic field models (Unger & Farrar, 2023) into the simulations to evaluate their relative uncertainties.
- A future step is to correlate the volume region of the origin of these particles with catalogs of astrophysical objects.

References

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