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#### Abstract

Unveiling the sources of ultra-high-energy cosmic rays remains one of the main challenges of high-energy astrophysics. Measurements of anisotropies in their arrival directions are key to identifying their sources, yet magnetic deflections obscure direct associations. In this work, we reconstruct the sky regions of possible origin of the highest-energy cosmic-ray events detected by the Pierre Auger Observatory by tracing their trajectories through Galactic magnetic fields using up-to-date models, while fully accounting for energy and directional uncertainties. A mixed composition at injection is assumed to model the detected charge distributions of such events. Different classes of astrophysical sources are investigated and tested for a correlation with the inferred regions of origin of the events. By incorporating constraints on the maximum propagation distances, we also allow for a three-dimensional localization of the possible source regions. Our findings provide new constraints on the sources of the highest-energy cosmic particles and offer fresh insights into the role of Galactic magnetic fields in shaping the observed ultra-high-energy cosmic-ray sky.

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# Constraining the origin of the highest-energy cosmic-ray events detected by the Pierre Auger Observatory: a three-dimensional approach

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Unveiling the sources of ultra-high-energy cosmic rays remains one of the main challenges of high-energy astrophysics. Measurements of anisotropies in their arrival directions are key to identifying their sources, yet magnetic deflections obscure direct associations. In this work, we reconstruct the sky regions of possible origin of the highest-energy cosmic-ray events detected by the Pierre Auger Observatory by tracing their trajectories through Galactic magnetic fields using up-to-date models, while fully accounting for energy and directional uncertainties. A mixed composition at injection is assumed to model the detected charge distributions of such events. Different classes of astrophysical sources are investigated and tested for a correlation with the inferred regions of origin of the events. By incorporating constraints on the maximum propagation distances, we also allow for a three-dimensional localization of the possible source regions. Our findings provide new constraints on the sources of the highest-energy cosmic particles and offer fresh insights into the role of Galactic magnetic fields in shaping the observed ultra-high-energy cosmic-ray sky.

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## 1. Introduction

Ultra-high-energy cosmic rays (UHECRs) are the most energetic particles observed in nature, being defined as charged particles with energies exceeding  $10^{18}$  eV. Their origin remains uncertain, as they are deflected by extragalactic and Galactic magnetic fields (EGMFs and GMFs) during propagation. While intermediate-scale anisotropy measurements have provided hints of structure in their arrival directions, individual source association remains challenging. Significant progress in the search for UHECR sources has been made thanks to the data from the Pierre Auger Observatory, the world's largest area and exposure detector for UHECRs [1].

In this contribution, we present our work to constrain the potential origin of UHECRs with energies  $E \geq 100$  EeV. We reconstruct their possible sky regions of origin via Galactic backtracking, using up-to-date GMF models [2], and apply horizon constraints that limit the accessible source volume. This three-dimensional approach was first introduced in [3], followed by [4–6]. Several classes of astrophysical sources are tested for a spatial correlation with the reconstructed sky regions.

## 2. Data set and source catalogs

Our study is based on the 40 most energetic events recorded at the Pierre Auger Observatory during Phase I from Jan. 2004 to Dec. 2022. Of these, 36 were detected from 2004 to 2020 and were included in the catalog released in 2023 [7], whereas the other 4 were detected in 2021 and 2022. As reported in [7], the statistical uncertainty on the energy is of the order of  $\sim 8\%$ , while the systematic uncertainty is assumed to be  $\sim 14\%$ . At the highest energies, arrival directions are reconstructed with a precision better than  $\sim 0.4^\circ$ .

Different astrophysical source classes are investigated and tested for correlations with the reconstructed UHECR source regions. In particular, we consider six catalogs of sources:

1. 44 nearby galaxies with a high star formation rate, denoted as starburst galaxies (SBGs), based on the Lunardini catalog [8] and weighted by their radio fluxes – “starburst galaxies”;
2. 523 active galactic nuclei (AGNs), based on the Swift-BAT 105-month catalog [9] and weighted by their hard X-ray fluxes – “all AGNs”;
3. 26 jetted active galactic nuclei, based on the Fermi-LAT 3FHL catalog [10] and weighted by their  $\gamma$ -ray fluxes – “jetted AGNs”;
4. 44,113 galaxies of all types from the 2MASS catalog, based on the Two Micron All Sky Survey [11] and weighted by their near-infrared fluxes – “all galaxies”;
5. 575 radio galaxies from the van Velzen catalog [12] – “radio galaxies”;
6.  $\sim 400,000$  galaxies of all types from the Biteau catalog [13], based on 2MASS, HyperLEDA, and Local Volume data, and weighted by their stellar mass (weight 1) or star formation rate (weight 2) estimates – “all galaxies B”.

The Local Group galaxies ( $D < 1$  Mpc) are excluded from all catalogs. The first four catalogs are the same as those employed in [14].

## 3. Determination of the mass of the fragments at Earth

Deflections of charged particles in magnetic fields depend on their rigidity, therefore it is necessary to model the probability distributions of the detected charge of the events. To this aim,

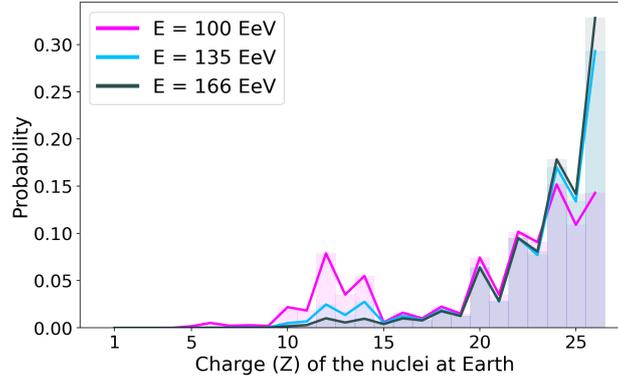
we perform simulations with CRPropa 3.2 [15]. According to the results of the combined fit of the energy spectrum and mass composition measured at the Pierre Auger Observatory [16], we assume a mixed composition at the source, an injection spectrum  $\propto E^{1.47}$  and a rigidity cutoff  $\mathcal{R}_{\max} = 10^{18.19}$  V. The events are generated uniformly in a distance range  $\in [1, 200]$  Mpc.

For each of the 40 events with  $E \geq 100$  EeV, we estimate their predicted mass composition at Earth by selecting simulated events whose energies match the observed ones, via a weight  $w(E, E_i)$  [4]. This is defined as:

$$w(E, E_i) = e^{-\frac{(E-E_i)^2}{2\sigma^2}} \quad (1)$$

and it is proportional to the Gaussian probability to reconstruct the observed energy  $E_i$  at Earth, given the simulated energy  $E$  and the statistical uncertainty  $\sigma \sim 8\%$ .

Fig. 1 illustrates the distributions of charges from  $Z = 1$  to  $Z = 26$  of the fragments at Earth with energies compatible with three events in the dataset. These events are detected with  $E_1 = 166$  EeV,  $E_2 = 135$  EeV and  $E_3 = 100$  EeV. At higher energies, the distribution is dominated by heavy elements, while going towards lower energies the CNO group contribution starts to be non-negligible.



**Figure 1:** Simulated charge distributions of fragments at Earth compatible with the detected energies of three events in the Auger dataset and assuming source composition as in [16].

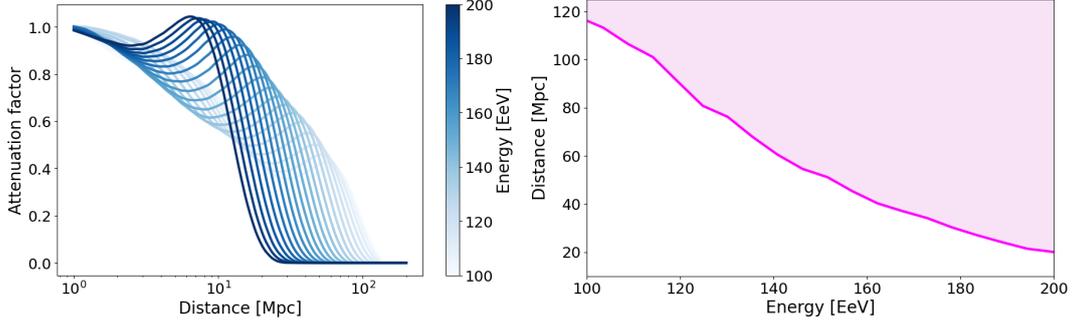
#### 4. Determination of the UHECR horizon

The three-dimensionality of our analysis is only possible if we take into account the UHECR horizon – the maximum distance within which the bulk of UHECRs with  $E \geq 100$  EeV can be produced. The calculation is carried out using the same simulation setup described in Sec. 3.

For each distance, we define the attenuation factor as the ratio of particles detected at Earth to particles injected in the same energy interval, similarly to [4, 17, 18]. In particular, the attenuation factor for an event of energy  $E_i$  and a source of distance  $d$ , is:

$$a(E_i, d) \propto \sum_{A=1}^{56} \int dE w(E, E_i) T_A(E, d), \quad (2)$$

where  $T_A(E, d)$  is the differential spectrum at Earth of particles with mass number  $A$  injected from sources at distance  $d$  and  $w(E, E_i)$  is the weight defined in Eq. (1). The attenuation factor is summed over all nuclear species that can be possibly detected at Earth.



**Figure 2:** **Left panel:** Attenuation factor  $a(E_i, d)$ , as a function of the distance, for several energies (color scale). **Right panel:** Horizon distance  $D_{0.1}(E_i)$  obtained from the condition  $a(E_i, d) = 0.1$ . Both panels adopt the combined-fit source model described in Sec. 3.

In the left panel of Fig. 2, the attenuation factor is shown as a function of the distance, for several representative energies. In particular,  $a(E_i, d) = 1$  means no attenuation, and  $a(E_i, d) = 0$  means complete attenuation. In the right panel, the corresponding distance  $D_{0.1}(E_i)$ , defined by the condition  $a(E_i, d) = 0.1$ , is displayed. We assume this value as the maximum distance that a cosmic ray of energy  $E_i$  is allowed to travel, hence the horizon.

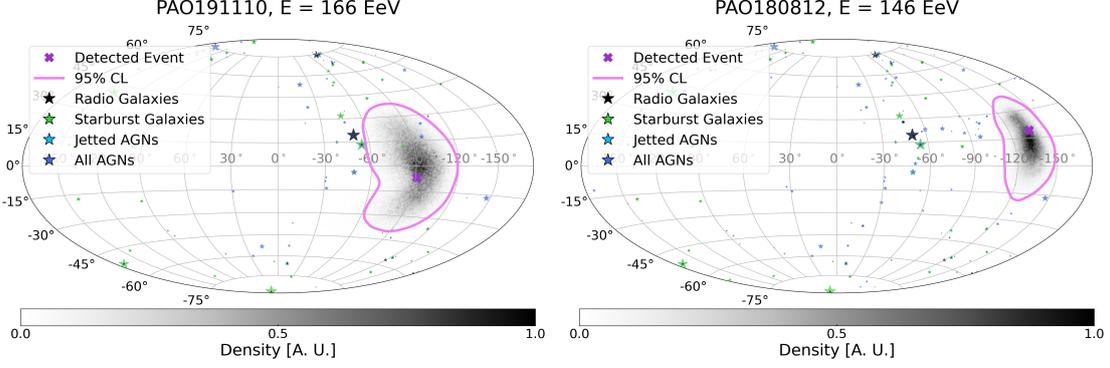
## 5. Galactic backtracking

The sky regions of possible origin of the 40 UHECR events detected by the Pierre Auger Observatory are reconstructed through Galactic backtracking using CRPropa 3.2. This approach consists in simulating the propagation of a particle of same rigidity but opposite charge, starting from the Earth and propagating it backward through the Galactic magnetic field. As a result, the backward-propagated antiparticle traces a trajectory equivalent to the forward path of the original cosmic ray. The trajectory is followed until the particle exits the Galaxy, which is modeled as a sphere of 20 kpc radius. The final direction of the particle at this boundary is taken as the best estimate of the source direction when extragalactic magnetic fields are neglected. In our analysis, the UF23 ensemble of eight coherent model variations [2] is used to model the regular field and the JF12 model with corrections by the Planck Collaboration [19] to model the turbulent field. Extragalactic magnetic field deflections are neglected.

To account for statistical uncertainties in the detected energy and arrival direction of the particle, the randomness of the turbulent component of the Galactic magnetic field, and the possible particle masses, the backtracking procedure is repeated 20,000 times. In each iteration, the energy of the particle is drawn from a Gaussian distribution centered on the nominal value, with a standard deviation of 8%. Its Galactic longitude and latitude are also sampled from a Gaussian distribution centered on the nominal arrival direction, with a standard deviation of  $0.5^\circ$ . The charge is determined from the probability density functions described in Sec. 3 (see, e.g., Fig. 1). The turbulent magnetic field is generated for each iteration with a different seed extracted from a uniform distribution.

In Fig. 3, the sky regions of origin inferred employing this method are shown for two events with energies above 100 EeV. The maps result from the combination of the eight GMF model variations of the UF23 ensemble. The gray scale represents the pixel density, namely  $\rho = \sum_{j=1}^8 \rho_j$ ,

where the index  $j$  runs over the models and  $\rho$  is normalized to the maximum. All the 40 events are studied using this approach. Their localization uncertainties vary from  $\sim 3\%$  to  $\sim 33\%$  of  $4\pi$ , depending on the latitudes and energies of the events.



**Figure 3:** The combination of 20,000 backtracking iterations for the eight model variations is shown in a *healpy* map with  $n_{\text{side}} = 64$ , in Galactic coordinates, for candidate host galaxies for the two events PAO191110 (**left panel**) and PAO180812 (**right panel**). The violet line represents the 95% confidence level (CL) that identifies the inferred region of origin of the event. Only the sources that satisfy the maximum distance criterion of Sec. 4 are shown in the maps.

## 6. Correlation with astrophysical sources

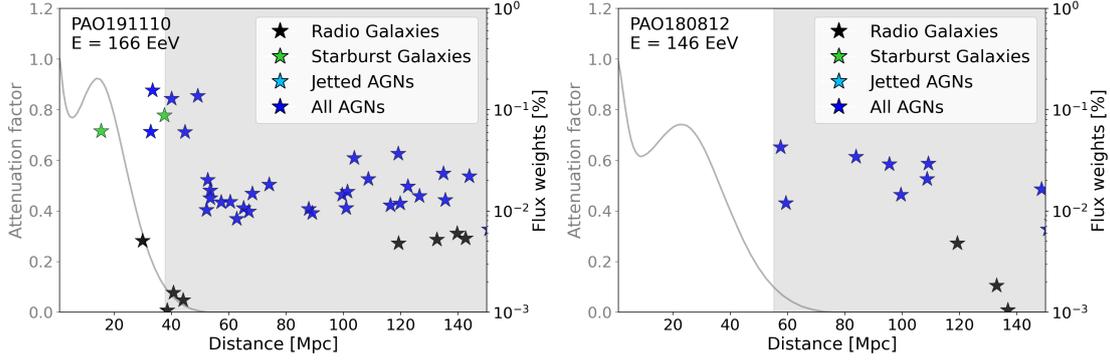
In this Section, we investigate possible correlations between the inferred regions of localization of the 40 events above 100 EeV detected at the Pierre Auger Observatory and several classes of astrophysical sources.

**Single-event analysis** We inferred the possible regions of origin of the 40 events using the method discussed in Sec. 5, as shown in Fig. 3. Sources compatible within the inferred regions were selected taking into account the horizon estimation discussed in Sec. 4. In Fig. 4, summary plots for two events are shown. Here, the indication of the exclusion region due to the horizon is only used for illustrative purposes, as the exact determination has a level of arbitrariness.

For nearly all the 40 UHECR events, potential astrophysical sources, such as active galactic nuclei, starburst galaxies, and radio galaxies, are found within the identified volume. The only exception is the case of PAO180812, for which no such candidates were identified, except for those in the “all galaxies” and “all galaxies B” catalogs. However, these galaxies tend to have relatively low fluxes, making them weak candidate sources.

An important consideration is the  $\sim 14\%$  systematic uncertainty in the energy scale. To account for this, we repeated the analysis also for the cases  $E = E_{\text{nom}} \pm 14\%$ . Under a  $-14\%$  shift, the PAO180812 event is compatible with two marginal ( $\lesssim 5\%$  relative flux weights) AGNs traced by their X-ray emission.

Analyzing individual high-energy events does not provide enough statistical evidence to establish a definitive correlation with any specific class of astrophysical sources. A statistical analysis is needed to provide quantitative constraints. However, the case of the PAO180812 event remains interesting. Setting aside systematic effects and under the assumption of the GMF models we are



**Figure 4:** Candidate host galaxies for the two events PAO191110 (**left panel**) and PAO180812 (**right panel**). Only galaxies whose positions fall inside the 95% CL region (Sec. 5) are shown; marker colors distinguish the source catalogs. *Left ordinate* (solid grey curve): attenuation factor  $a(E, d)$  from Sec. 4. The shaded gray band marks distances where  $a < 0.1$  and are therefore excluded by our horizon criterion. *Right ordinate* (colored symbols): relative flux weight of each galaxy, normalized to the maximum flux in the sample.

considering, it could potentially be interpreted as the effect of a non-negligible influence of the EGMF [20], which was not included in our study, or as a transient, or perhaps as a contribution from ultra-heavy elements beyond iron [21].

**Likelihood analysis** The Galactic magnetic field maps the position of a source ( $\hat{N}_{\text{src}}$ ) to the arrival direction of an event ( $\hat{n}_{\text{evt}}$ ). Assuming a GMF model and a rigidity  $\mathcal{R} = E/Z$ , backtracking allows us to compute the inverse mapping  $\hat{n}_{\text{evt}} \rightarrow \hat{N}_{\text{src}}$  in one shot, whereas the direct mapping is much less trivial to determine. The probability  $p(\hat{N}_{\text{src}} | \hat{n}_{\text{evt}})$  can be estimated by backtracking  $\hat{n}_{\text{evt}}$  over many realizations of the random field, detected energy, arrival direction, and particle charge, assuming a fixed model variation. This probability can in turn be used to approximate the inverse quantity,  $p(\hat{n}_{\text{evt}} | \hat{N}_{\text{src}})$ .

Given a model, a source, and an event, the likelihood  $\mathcal{L}_{\text{src,evt,model}}$  can be computed via a kernel density estimate (KDE) of the pixel density  $\rho_j$  obtained as described in Sec. 5. The KDE is smooth, therefore to each pixel (or source position) we can now assign a probability value. For a source catalog, event, and model, the likelihood can then be expressed as:

$$\mathcal{L}_{\text{cat,evt,model}} = \sum_{\text{src}} w_{\text{src}} \mathcal{L}_{\text{src,evt,model}}, \quad (3)$$

where  $w_{\text{src}}$  is a weight assigned to each source, computed as the product of its flux by the attenuation factor  $a(E_i, d)$ , defined in Eq. (2) and evaluated in the energy  $E_i$  of the event and the distance  $d$  of the source. This is normalized such that  $\sum_{\text{src}} w_{\text{src}} = 1$ . This weight is fundamental for our analysis, since it allows the three-dimensionality of our constraints. Additionally, for radio galaxies, the minimum power required for the acceleration is taken into account, as in [22]. Moreover, an isotropic fraction can be added to the equation:

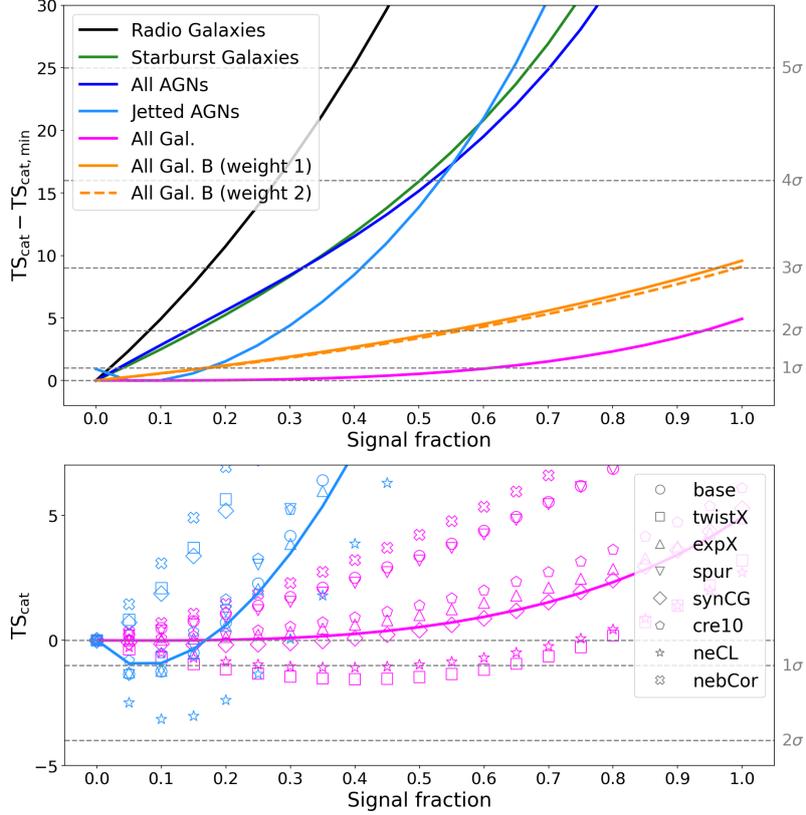
$$\mathcal{L}_{\text{cat,evt,model}} = (1 - f_{\text{iso}}) \mathcal{L}_{\text{cat,evt,model}} + f_{\text{iso}}, \quad (4)$$

the isotropic likelihood being  $\mathcal{L}_{\text{iso}} = 1$  due to our choice of normalization. Finally, assuming statistical independence among the observed events, the total likelihood for the model is given

by the product over all events, and can be evaluated in logarithmic form for convenience, as  $\ln \mathcal{L}_{\text{cat,model}} = \sum_{\text{evt}} \ln \mathcal{L}_{\text{cat,evt,model}}$ . The total likelihood can then be converted into a test statistic (TS), as:

$$\text{TS}_{\text{cat,model}} = -2 \ln \mathcal{L}_{\text{cat,model}}. \quad (5)$$

The signal fraction ( $1 - f_{\text{iso}}$ ) is scanned from 0 to 1 in steps of 0.05. By construction, the pure isotropic case corresponds to  $\text{TS} = 0$ . The significance at which a given signal fraction is disfavored with respect to the best-fit one (minimum TS,  $\text{TS}_{\text{min}}$ ) is given by  $\sqrt{\text{TS} - \text{TS}_{\text{min}}}$ . In particular, for the catalogs where the minimum TS is 0 at  $f_{\text{iso}} = 1$ ,  $\sqrt{\text{TS}}$  is the significance at which a given signal fraction is disfavored with respect to isotropy. The results of this analysis are presented in Fig. 5.



**Figure 5:** The test statistic (TS, see Eq. 5) is shown as a function of the signal fraction ( $1 - f_{\text{iso}}$ ) for different source classes. The marginal TS over the different GMF models ( $\exp(-\text{TS}_{\text{marg}}/2) = \frac{1}{8} \sum_{i=1}^8 \exp(-\text{TS}_i/2)$ ) is computed for each catalog. **Top panel:** The quantity  $\text{TS} - \text{TS}_{\text{min}}$ , marginalized over GMF models, is shown as a solid line for each catalog. **Bottom panel:** The marginal TS is shown as a solid line, while the TS values for individual GMF models are represented with different marker styles. A limited number of catalogs are displayed to better appreciate the cases where the TS is negative and the model is preferred over isotropy.

Starburst and radio galaxies, and active galactic nuclei can be excluded as dominant contributors to the observed cosmic-ray flux above 100 EeV at the  $5\sigma$  level. In particular, we exclude signal fractions greater than 40%, 65%, 67% and 70% for radio galaxies, jetted AGNs traced by their  $\gamma$ -ray emission, starburst galaxies, and AGNs traced by their X-ray emission, respectively. The “jetted AGNs” catalog provides a better description of the data than the isotropic case, when small

signal fractions are considered, while the “all galaxies” catalog does only in a few specific GMF configurations, at intermediate signal fractions. The most significant scenario consists in a 10% signal fraction of jetted AGN sources in the neCL GMF model.

## 7. Conclusions

In this work, we reconstructed the possible sky regions of origin of the highest-energy cosmic rays detected by the Pierre Auger Observatory during Phase I through Galactic backtracking, including constraints on the maximum propagation distance. Two complementary approaches were presented: a single-event analysis and a likelihood-based framework.

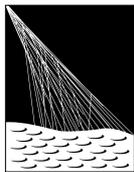
From the single-event analysis, we find that every event but one has at least one plausible astrophysical counterpart within the 95% CL localization region. The sole exception is PA0180812, which exhibits no clear counterpart among known source classes – but does so when the 14% systematic energy shift is accounted for.

The likelihood analysis indicates that, within the set of assumptions and the approach adopted here, most tested source catalogs can be excluded as dominant contributors to the ultra-high-energy cosmic ray flux above 100 EeV. This may suggest that more than one type of source populations should contribute, or that more common galaxies could also play a role. Also, the EGMF might significantly deflect the UHECRs before they arrive to our Galaxy, or a contribution from ultra-heavy nuclei could also be relevant.

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