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New full-sky studies of the distribution of ultra-high-energy cosmic-ray arrival directions

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Ground-based full-sky studies of the angular distribution of arrival directions of ultra-high-energy cosmic rays require combining data from different observatories, such as the Pierre Auger Observatory (Auger) and the Telescope Array (TA), because no single array can cover all declinations. A working group comprising members from the Auger and TA collaborations has been tasked with performing such studies for more than a decade and has found several indications of full-sky anisotropies. Here, we update the results for the large- and medium-scale anisotropy analyses using the latest data from TA, which include corrections for daily and yearly atmospheric effects in data for large-scale anisotropies and looser selection criteria in data for medium-scale anisotropies. We extend the latter one by considering two more galaxy catalogues, consisting of jetted or all AGNs. Finally we also introduce a new angular harmonic space analysis that allows us to measure both the auto-correlation and cross-correlation with all catalogues for all multipoles independently ($\ell_{\max} = 20$ in this work) and scanning the energy threshold.

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1. Introduction

The most energetic particles ever measured are ultra-high-energy cosmic rays (UHECRs), which are nuclei coming from space with energies above 1 EeV = 10^{18} eV. At such high energies, UHECRs interact with the cosmic microwave background (CMB) and the extragalactic background light (EBL) and quickly lose energy. This is why the sources of UHECRs must be nearby. Despite this, due to intervening magnetic fields, we do not expect the arrival direction of the particles to point back to the origin. As a result, direct association of an UHECR to its source is very challenging.

We look at large-scale anisotropies such as the dipole or quadrupole, where the effect of the magnetic fields is expected to be smaller [1]. To study larger scales, having full-sky coverage is extremely beneficial, since partial sky coverage could introduce strong degeneracies between the first few multipoles. We achieve this by combining data from the Pierre Auger Observatory (Auger) in Argentina and the Telescope Array (TA) in Utah, USA. Together they cover all declinations. Declinations $-15.7° < \delta < +44.8°$ are covered by both observatories, allowing us to cross-calibrate the data.

In this proceeding, we update the results of the large-scale and medium-scale anisotropy analyses that have been presented before [2, and refs. therein]. Additionally, we extend the medium-scale anisotropy analysis to two more galaxy catalogs previously used in Auger-only analyses [4], consisting of AGNs observed from the *Fermi*-LAT and *Swift*-BAT telescopes. Finally, we introduce a new angular harmonic-space analysis to search for anisotropies at large and medium scales at the highest energies.

2. The datasets

We use the latest datasets available, including events detected in Auger from 1 January 2004 to 31 December 2022 for Auger and in TA from 11 May 2008 to 10 May 2024. The Auger datasets are the same as in our previous work [2]: one with stricter cuts [3] for large-scale anisotropies, with an exposure of 123 000 $\mathrm{km^2\,sr\,yr}$, and one with looser cuts [4, but with a longer time period] for medium-scale anisotropies at the highest energies, whose exposure is 135 000 $\mathrm{km^2\,sr\,yr}$. As for TA, for large-scale anisotropies we use the same dataset as in our previous study [2], with strict cuts [5, but with a longer time period] and an effective exposure (accounting for energy resolution effects) of 19 500 $\mathrm{km^2\,sr\,yr}$, except that here for the first time we correct energy measurements for yearly and daily variations in the air density.[1] Additionally, for medium-scale anisotropies and the

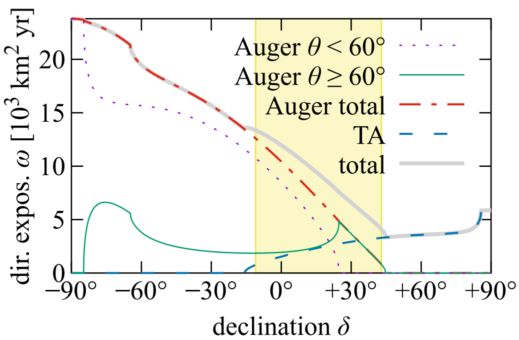

Figure 1: Directional exposures of the datasets we used for large-scale anisotropies (those for medium-scale anisotropies have the same shapes and slightly higher normalizations)

[1] Namely, $E_{\mathrm{corr}} = E_{\mathrm{raw}} \times \left(1 - 3.5\left(\frac{\rho}{1.042\,\mathrm{kg/m^3}} - 1\right)\right)^{-1/1.7}$, where ρ is the air density at the TA site obtained from the Global Data Assimilation System every three hours.

angular harmonic analyses, we use looser cuts [6, but with a longer time period] for events with $E_{TA} > 57\,\text{EeV}$, with 52 extra events and $5\,800\,\text{km}^2\,\text{sr}\,\text{yr}$ extra exposure compared to the strict-cut dataset. See Figure 1 for the exposure of the datasets as a function of declination.

UHECR energy measurements are affected by sizeable systematic uncertainties (±14% for Auger and ±21% for TA). This must be carefully considered, as it may have a significant impact on the results, particularly on the dipole component. We use the events in the common declination band to cross-calibrate both datasets, as in [7].[2] This is done by fitting the spectrum model seen in Figure 2 and the parameters α and β in:

$$E_{\text{Auger}}/10\,\text{EeV} = e^{\alpha}(E_{\text{TA}}/10\,\text{EeV})^{\beta},$$
$$E_{\text{TA}}/10\,\text{EeV} = e^{-\alpha/\beta}(E_{\text{Auger}}/10\,\text{EeV})^{1/\beta}.$$

The values obtained are $\alpha = -0.150 \pm 0.011$ and $\beta = 0.962 \pm 0.016$, resulting in

$$E_{\text{TA}} = 10\,\text{EeV} \leftrightarrow E_{\text{Auger}} = 8.60\,\text{EeV}, \quad (E_1)$$
$$E_{\text{Auger}} = 16\,\text{EeV} \leftrightarrow E_{\text{TA}} = 19.1\,\text{EeV}, \quad (E_2)$$
$$E_{\text{Auger}} = 32\,\text{EeV} \leftrightarrow E_{\text{TA}} = 39.2\,\text{EeV}. \quad (E_3)$$

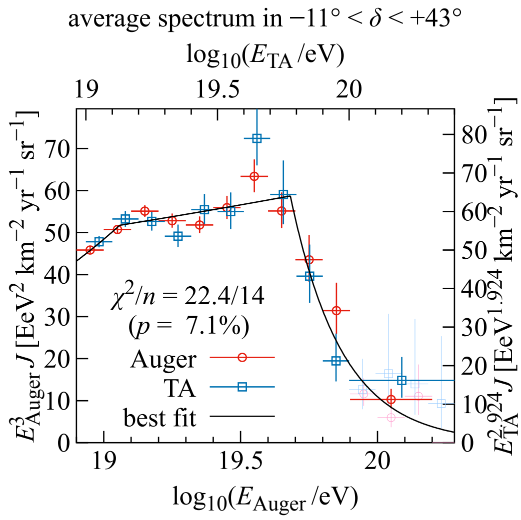

Figure 2: The spectrum fit to the two datasets in order to obtain a mapping between Auger and TA energy scales. The highest-energy bins of each dataset (denoted by thin pale lines) are combined into one larger bin (denoted by regular lines) to ensure the probability distribution can be approximated as log-normal.

In the dataset used for large-scale anisotropies, there are 43 600 Auger events with $E \geq E_1$, of which 13 027 with $E \geq E_2$ and 2 739 with $E \geq E_3$, and 6 611 TA events with $E \geq E_1$, of which 1 967 with $E \geq E_2$ and 484 with $E \geq E_3$. The flux distribution in this dataset in the three energy bins is shown in Figure 3.

As previously mentioned, for the intermediate scale anisotropies and the harmonic analyses we use the TA loose-cut data for $E_{TA} \geq 57\,\text{EeV}$. However, since this dataset does not have available atmospheric corrections, we use the energy calibration from [2], with $\alpha = -0.159$, $\beta = 0.954$, and $E_{\text{Auger}} = 32\,\text{EeV} \leftrightarrow E_{\text{TA}} = 40.0\,\text{EeV}$. We have 2 936 Auger events above 32 EeV and 513 TA events above 40.0 EeV (of which 285 TA strict-cut events with $40.0\,\text{EeV} \leq E_{\text{TA}} < 57\,\text{EeV}$ and 228 TA loose-cut events with $E_{\text{TA}} \geq 57\,\text{EeV}$).

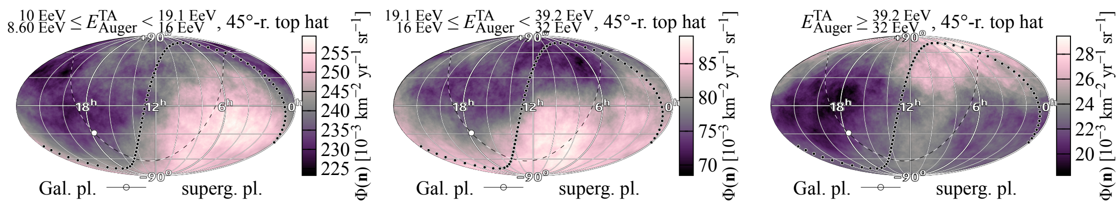

Figure 3: The flux distribution of the dataset we use for large-scale anisotropies (equatorial coordinates, Mollweide projection), smoothed by a 45°-radius top-hat window

[2]This cross-calibration is optimized for anisotropy studies and should not be used outside of the scope of this analysis.

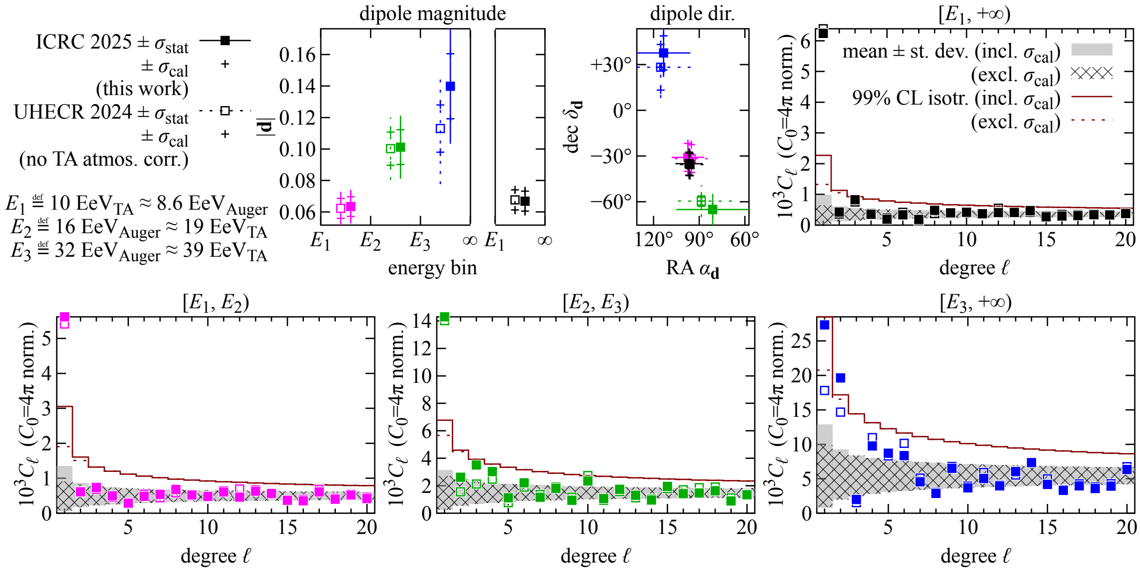

Figure 4: The first and second panels show how the magnitude and direction of the dipole have changed with the inclusion of TA atmospheric corrections; the next ones show how the harmonic space auto-correlation (also known as angular power spectrum) has changed in the different energy bins used.

3. Large-scale analysis

Given our data map of UHECRs, we can expand it in spherical harmonics as

$$M(\mathbf{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\mathbf{n}) \rightarrow a_{\ell m} = \int d\Omega\, Y_{\ell m}(\mathbf{n}) M(\mathbf{n}).$$

The $\ell = 1$ contribution can be expressed as a dipole vector $\boldsymbol{d} = \sqrt{3}(a_{11}, a_{1-1}, a_{10})$, its direction and magnitude shown in the first two plots of Figure 4. Since we have a full-sky dataset, we can directly measure $a_{\ell m} = \sum_{\text{evt}} Y_{\ell m}(\mathbf{n}_{\text{evt}})/\omega(\mathbf{n}_{\text{evt}})$, where ω is the total directional exposure of the combined dataset. We perform the analysis in three energy bins $[E_1, E_2)$, $[E_2, E_3)$, $[E_3, +\infty)$ as defined in the previous section plus a cumulative bin $[E_3, +\infty)$. The results are shown in Figure 4, and compared with our previous results [2] using the same time periods but without TA atmospheric corrections. The dipole and quadrupole in the highest energy bin have become stronger, but still not particularly significant, respectively at $p = 0.011$ (2.5σ) and $p = 0.0041$ (2.9σ) pre-trial. All results are otherwise similar to the previous ones.

The dipole direction in the cumulative bin is 92° away from the Galactic Centre. A hint of a quadrupole along the supergalactic plane is found in the highest energy bin, motivating section 5.

4. Intermediate-scale analysis

This analysis must be performed at the highest energies, where the deflections due to magnetic fields are expected to be smaller. We perform targeted searches using four source catalogues [4]:

- 44 113 galaxies of all types, based on the 2MASS catalogue, weighted by their near-IR fluxes;

- 44 starburst galaxies, based on the Lunardini catalogue, weighted by their radio fluxes;
- 523 AGNs, based on the *Swift*-BAT catalogue, weighted by their X-ray fluxes; and
- 26 jetted AGNs, from the *Fermi*-LAT catalogue, weighted by their gamma-ray fluxes.

For more details about the data sources, selection criteria, and weights used for compiling these catalogues see [4]. All these catalogues include galaxies with distances $1\,\text{Mpc} \leq D < 250\,\text{Mpc}$, except the starburst galaxy one, which includes galaxies with distances $1\,\text{Mpc} \leq D < 130\,\text{Mpc}$.

We then define the test statistics

$$\text{TS}(\Theta, f, E_{\text{min}}) = 2\ln\left(\frac{\mathcal{L}(\Theta, f, E_{\text{min}})}{\mathcal{L}(\Theta, f=0, E_{\text{min}})}\right), \quad \mathcal{L}(\Theta, f, E_{\text{min}}) = \prod_{E_i > E_{\text{min}}} \frac{\Phi(\hat{\boldsymbol{n}}_i, \Theta, f)\omega(\hat{\boldsymbol{n}}_i, E_i)}{\int_{4\pi} d\Omega \Phi(\hat{\boldsymbol{n}}, \Theta, f)\omega(\hat{\boldsymbol{n}}, E_i)}.$$

Here, i refers to the i-th UHECR, while the weight $\omega(\hat{\boldsymbol{n}}, E)$ is the directional exposure, which (unlike in our previous studies [2, 4]) is also a function of the energy because a TA dataset with stricter cuts is used for $40\,\text{EeV} \leq E_{\text{TA}} < 57\,\text{EeV}$ but one with looser cuts, hence larger exposure, is used for $E_{\text{TA}} \geq 57\,\text{EeV}$; and $\Phi(\hat{\boldsymbol{n}}_i, \Theta, f)$ is defined as:

$$\Phi(\hat{\boldsymbol{n}}, \Theta, f) := f\Phi_{\text{signal}}(\hat{\boldsymbol{n}}, \Theta) + (1-f)\Phi_{\text{background}},$$

where the background contribution is isotropic and the signal contribution is a sum of von Mises–Fisher distributions for each source

$$\Phi_{\text{signal}}(\hat{\boldsymbol{n}}, \Theta) := \frac{1}{\sum_s a(D_s, E_{\text{min}}) w_s} \sum_s \frac{a(D_s, E_{\text{min}}) w_s \Theta^{-2}}{4\pi \sinh(\Theta^{-2})} e^{\Theta^{-2}\hat{\boldsymbol{n}}_s \cdot \hat{\boldsymbol{n}}}, \qquad \Phi_{\text{background}} := \frac{1}{4\pi},$$

where the index s runs over sources in the galaxy catalogue, w_s is the flux of the s-th source, and $a(D_s, E_{\text{min}})$ is the attenuation, computed as in [4] following the best fit to Auger data above the ankle energy [8] assuming the Epos LHC hadronic interaction model, with a mixed mass composition (67.3% He, 28.1% N and 4.6% Si at $E = 1\,\text{EeV}$) and a relatively hard spectrum ($\propto E^{-0.96}\exp(-R/10^{18.68}\,\text{V})$ where $R = E/Z$) at injection.

The analysis is repeated for increasing energy thresholds, $E_{\text{Auger}} = 32\,\text{EeV}, 33\,\text{EeV}, \ldots, 80\,\text{EeV}$. The results are presented in Figure 5. The details of the maximum TS for each galaxy catalogue are shown in Table 1. To allow a direct comparison to our previous results [2] where the TA loose-cut data were not used, in the case of the all-galaxy and starburst galaxy catalogues we also shown results obtained neglecting the attenuation.

5. Angular Harmonic Space Analysis

For this analysis we combine the Harmonic Auto-Correlation as calculated in section 3 with the energy scanning from section 4. We also perform the same analysis with Harmonic Cross-Correlation of the UHECR map and the galaxy catalogues introduced in the previous section (including the attenuations). The Cross-Correlation is a valuable tool as it inherently involves more information than the Auto-Correlation, making it more likely to break possible degeneracies. Furthermore, for the Cross-Correlation the statistical and systematic noises do not correlate, resulting in a clearer signal. In the case in which the number of sources in the catalogue is much bigger than

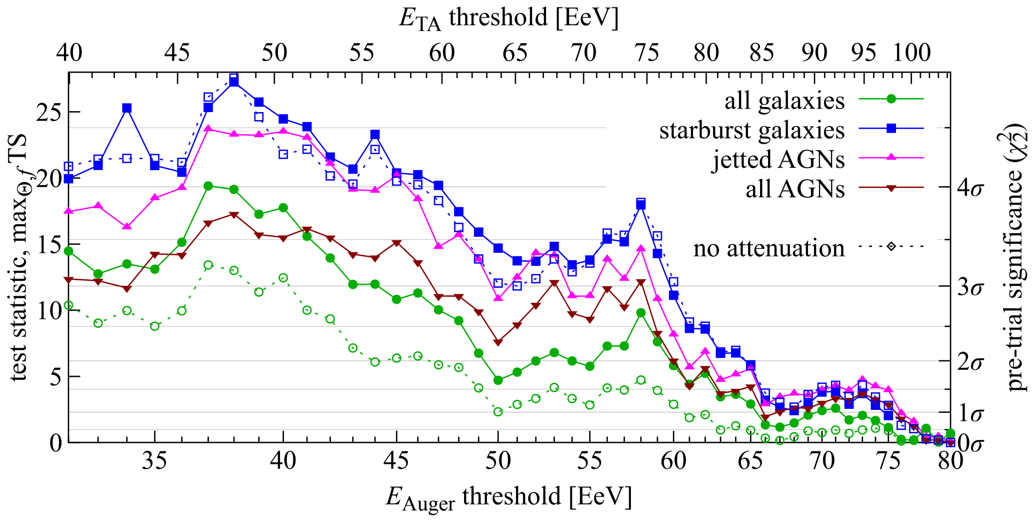

Figure 5: Significances of the correlations with galaxy catalogues as a function of the energy threshold.

	$E_{\min}$	TS	$f/\%$	$\Theta/°$	post-trial
All galaxies	$37\,\text{EeV}_{\text{Auger}} \approx 47\,\text{EeV}_{\text{TA}}$	19.3	$13.1^{+4.7}_{-3.6}$	$15.5^{+6.1}_{-3.6}$	3.4σ
Starburst galaxies	$38\,\text{EeV}_{\text{Auger}} \approx 48\,\text{EeV}_{\text{TA}}$	27.3	$10.6^{+56.6}_{-3.2}$	$17.6^{+26.6}_{-4.1}$	4.2σ
All AGNs	$38\,\text{EeV}_{\text{Auger}} \approx 48\,\text{EeV}_{\text{TA}}$	17.6	$4.8^{+1.6}_{-1.4}$	$15.4^{+3.5}_{-2.8}$	3.3σ
Jetted AGNs	$37\,\text{EeV}_{\text{Auger}} \approx 47\,\text{EeV}_{\text{TA}}$	22.9	$8.8^{-2.6}_{-2.3}$	$17.4^{+3.4}_{-2.8}$	3.8σ
All gal. (no atten.)	$37\,\text{EeV}_{\text{Auger}} \approx 47\,\text{EeV}_{\text{TA}}$	13.5	$33.6^{+26.3}_{-19.4}$	$29.2^{+12.9}_{-17.5}$	2.8σ
Starburst gal. (no atten.)	$38\,\text{EeV}_{\text{Auger}} \approx 48\,\text{EeV}_{\text{TA}}$	27.3	$10.6^{+4.0}_{-2.7}$	$15.0^{+4.8}_{-2.9}$	4.2σ

Table 1: Best fit of the medium-scale analysis for each of the galaxy catalogues considered. We show both the optimal parameters and the TS that was achieved, as well as the corresponding one-tailed post-trial significance. The reasons for the increase in the upper uncertainties on f and Θ when including the attenuation in the starburst galaxy catalogue are under investigation.

the number of cosmic rays (like is the case for the all-galaxy catalogue), the shot noise is greatly reduced, for more details see [10].

Both the Harmonic Auto-Correlation of the UHECRs and their Cross-Correlation with the different galaxy catalogues can be obtained for any multipole following section 3 and using

$$C_l^{\text{CR CR}} := \frac{1}{2\ell+1}\sum_{m=-\ell}^{+\ell} a_{lm}^{\text{CR}} a_{lm}^{*\text{CR}}; \qquad C_l^{\text{CR Cat}} := \frac{1}{2\ell+1}\sum_{m=-\ell}^{+\ell} a_{lm}^{\text{CR}} a_{lm}^{*\text{Cat}}.$$

For the Cross-Correlation, the map used includes the attenuation discussed in section 4. Then, using isotropic simulations, we can obtain the pre-trial significance of each multipole (we consider $\ell_{\max} = 20$ in this work). To reduce computational time, it is assumed that isotropic

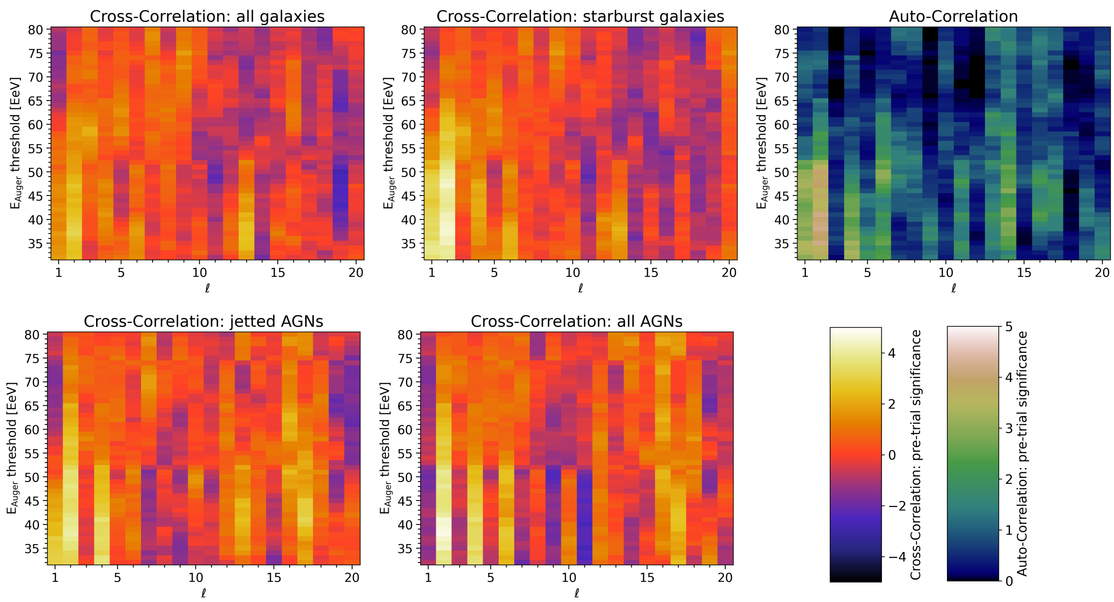

Figure 6: Pre-trial significances for each multipole order and energy threshold of the Auto-Correlation and the Cross-Correlation with all galaxies, starburst galaxies, jetted AGNs and all AGNs.

Cross-Correlations follow a Gaussian distribution, while the Auto-Correlations follow [9]:

$$f(\bar{C}_\ell^{\mathrm{CR\,CR}}|C_\ell^{\mathrm{CR\,CR}}) \propto C_\ell^{\mathrm{CR\,CR}} \left(\frac{\bar{C}_\ell^{\mathrm{CR\,CR}}}{C_\ell^{\mathrm{CR\,CR}}}\right)^{\frac{2\ell+1}{2}-1} \exp\left(-\frac{(2\ell+1)\bar{C}_\ell^{\mathrm{CR\,CR}}}{2}C_\ell^{\mathrm{CR\,CR}}\right),$$

where $\bar{C}_\ell^{\mathrm{CR\,CR}}$ is expected value for isotropy, given by the average of all simulations. We can then calculate the p-value of a data point $C_{\ell,\mathrm{Data}}^{\mathrm{CR\,CR}}$ as

$$p\text{-value} = 1 - \frac{\int_0^{C_{\ell,\mathrm{Data}}^{\mathrm{CR\,CR}}} dC_\ell^{\mathrm{CR\,CR}}\, f(\bar{C}_\ell^{\mathrm{CR\,CR}}|C_\ell^{\mathrm{CR\,CR}})}{\int_0^{\infty} dC_\ell^{\mathrm{CR\,CR}}\, f(\bar{C}_\ell^{\mathrm{CR\,CR}}|C_\ell^{\mathrm{CR\,CR}})},$$

and equivalently for the cross-correlation, for which the function f would be a Gaussian with mean and standard deviation calculated directly from the isotropic simulations. Then the analysis is repeated for increasing energy thresholds as in section 4. For the Cross-Correlations we use the same galaxy catalogues as in section 4.

The results are shown in Figure 6. From this figure we see that the quadrupole is the most statistically significant multipole in all cases. We then find the energy threshold at which the quadrupole is the most significant in each plot of Figure 6 and obtain a corresponding post-trial significance. For this we follow the most conservative approach, by taking into account the scan in energy and the measurements of different mutipoles up to $\ell = 20$. The results for this analysis are then presented in Table 2.

6. Conclusions

We have presented an update to our previous analyses and introduced a new one. For the analysis on large angular scales, we have incorporated new atmospheric corrections to the energy

	ℓ	$E_{\min}$	pre-trial	post-trial
Auto-Correlation	2	$41\,\mathrm{EeV}_{\mathrm{Auger}} \approx 51.8\,\mathrm{EeV}_{\mathrm{TA}}$	4.2σ	2.1σ
All galaxies	2	$37\,\mathrm{EeV}_{\mathrm{Auger}} \approx 46.5\,\mathrm{EeV}_{\mathrm{TA}}$	3.2σ	—
Starburst galaxies	2	$38\,\mathrm{EeV}_{\mathrm{Auger}} \approx 47.8\,\mathrm{EeV}_{\mathrm{TA}}$	4.5σ	2.7σ
All AGNs	2	$38\,\mathrm{EeV}_{\mathrm{Auger}} \approx 47.8\,\mathrm{EeV}_{\mathrm{TA}}$	4.7σ	3.0σ
Jetted AGNs	2	$38\,\mathrm{EeV}_{\mathrm{Auger}} \approx 47.8\,\mathrm{EeV}_{\mathrm{TA}}$	4.1σ	2.0σ

Table 2: We show the ℓ and $E_{\min}$ at which the maximum significance is obtained for the Auto-Correlation and for the Cross-Correlation with each galaxy catalogue. We present the pre-trial maximum obtained and the post-trial result calculated from it.

of the TA data. Most of our results remain similar, except for those at the highest energies, where the dipole and quadrupole have become more significant (but within the statistical uncertainties).

For our intermediate-scale analysis, we have introduced new data from the TA side, using a dataset with looser cuts at the highest energies. For the first time in full-sky analyses, we have also taken into account the energy losses of UHECRs. Furthermore, we have extended the analysis to include two more source catalogues. The correlation with starburst galaxies remains the most significant, at 4.2σ post-trial, even after the inclusion of attenuations, which primarily enhanced the correlation with the all-galaxy catalogue.

Finally, we have studied the harmonic autocorrelation and cross-correlation methods. Our results show that, given an appropriate source catalogue, the cross-correlation can yield a clearer signal than the harmonic auto-correlation. As a next step, we plan to investigate how to combine auto- and cross-correlations, or how to merge different multipoles to enhance statistical significance. In the future, the method introduced here could serve as a robust tool for source matching, less sensitive to the specific characteristics of the Galactic magnetic field.

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