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Update on full-sky searches for large- and medium-scale anisotropies in the UHECR flux using the Pierre Auger Observatory and the Telescope Array

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The flux of ultra-high-energy cosmic rays (UHECRs) is remarkably uniform across all directions in the sky. The only anisotropy detected with a significance greater than 5σ is a large-scale dipolar modulation in right ascension for energies above 8 EeV. To enhance our sensitivity to potential anisotropies, which may be obscured by significant deflections by magnetic fields, two strategies can be employed: (1) focusing on large-scale anisotropies, such as the dipole and quadrupole moments across various energy intervals, which are anticipated to be more resilient to magnetic deflections; or (2) focusing on the highest energies, where the background from distant sources is more attenuated. The unique aspect of our research is achieving full-sky coverage by combining data for the Pierre Auger Observatory and the Telescope Array, which would not be possible with a single detector array. This comprehensive coverage enables the application of analysis techniques that would otherwise require specific assumptions with partial sky coverage. Accounting for potential systematic effects in energy reconstruction is crucial to avoid spurious north–south anisotropies; the overlapping sky region observed by both arrays allows us to address this in an entirely data-driven manner. In this contribution, we present the latest results using the largest UHECR dataset collected to date, with events detected until December 2022 at the Pierre Auger Observatory and until May 2024 at the Telescope Array. It is shown that the dipolar modulation is the only anisotropy that is significantly (4.6σ) identified in the angular power spectrum. The hypothesis of correlations with the starburst galaxies is supported at the significance of 4.4σ.

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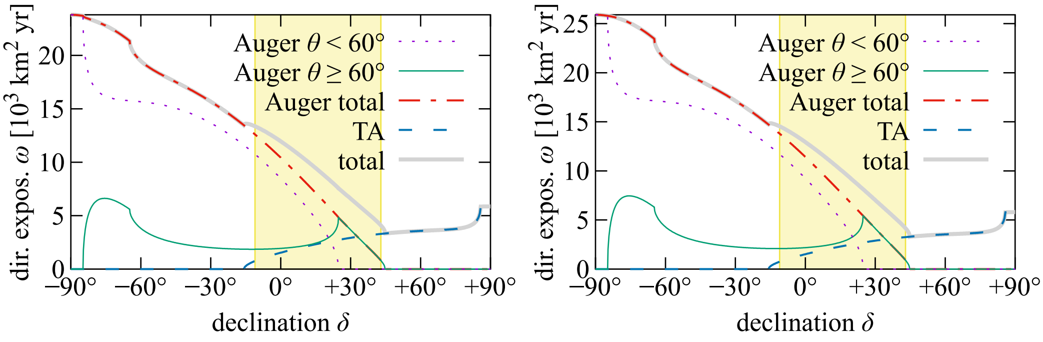

Figure 1: Directional exposures of the datasets we are using in searches for (left) large- and (right) medium-scale anisotropies

1. Introduction

The two largest cosmic-ray observatories currently in operation are the Pierre Auger Observatory (Auger) in Malargüe, Mendoza, Argentina, and the Telescope Array (TA) in Delta, Utah, USA. By combining data from both experiments, we obtain a dataset with full-sky coverage. In this work, we present the largest such dataset compiled to date and we present the results of a large-scale anisotropy analysis, studying the angular power spectrum, including the dipole and quadrupole moments, and a medium-scale one, searching for correlations with galaxy catalogs.

2. The datasets

The TA dataset we use in this work comprises events detected between 11 May 2008 and 10 May 2024 (16 years, two more than in our previous report [1]) and zenith angles $\theta < 55^\circ$, with an effective exposure of 19,500 km^2 sr yr. It includes 6,712 events with energies above $E_{\text{TA}} = 10$ EeV, of which 461 have energies exceeding $E_{\text{TA}} = 39.96$ EeV.

The Auger datasets are the same as in our previous report [1], comprising events detected between 2004 and 2022 inclusive (19 years). The dataset we use in searches for large-scale anisotropies has a geometrical exposure of 123,000 km^2 sr yr, and includes 44,309 events with energies above $E_{\text{Auger}} = 8.529$ EeV. In searches for medium-scale anisotropies we use a dataset with more relaxed selection criteria, with a geometrical exposure of 135,000 km^2 sr yr and 2,936 events with energies above $E_{\text{Auger}} = 32$ EeV.

The directional exposures of these datasets as a function of declinations are shown in Figure 1. See ref. [1] and references therein for more details about the datasets.

3. The energy scale cross-calibration

The systematic uncertainty in the absolute energy calibration is ±14% for Auger and ±21% for TA. We use the procedure we introduced in ref. [2] to correct for possible systematic errors affecting the two observatories differently: namely, we require that the binned energy spectrum in the common declination band $-11^\circ < \delta < +43^\circ$ agrees in both observatories after a mapping

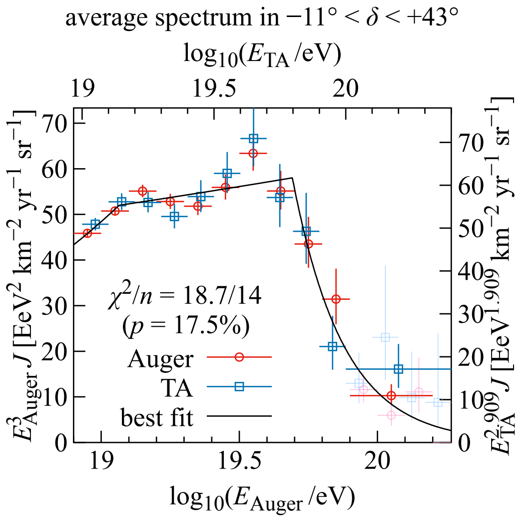

Figure 2: Combined fit using the two data samples adopted to obtain a mapping between Auger and TA energy scales. The highest-energy bins of each dataset (denoted by thin pale lines) are combined into one larger bin (denoted by regular lines) to ensure the probability distribution can be approximated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

between the two energy scales of the form

$$\frac{E_{\text{Auger}}}{10\ \text{EeV}} = a\left(\frac{E_{\text{TA}}}{10\ \text{EeV}}\right)^{b}.$$

We simultaneously fit the parameters a and b and a spectrum model to both Auger and TA data, as shown in Figure 2. We obtain $\ln a = -0.159 \pm 0.011$ and $b = 0.954 \pm 0.015$. The significance of the non-linearity of this conversion, $\frac{1-b}{\sigma_b}$, is 2.9σ, down from 3.1σ in our previous report [1]. We use these values to convert the energy thresholds used in this work as

$$\begin{aligned} E_1 &= 8.529\ \text{EeV}_{\text{Auger}} = 10\ \text{EeV}_{\text{TA}}; \\ E_2 &= 16\ \text{EeV}_{\text{Auger}} = 19.33\ \text{EeV}_{\text{TA}}; \\ E_3 &= 32\ \text{EeV}_{\text{Auger}} = 39.96\ \text{EeV}_{\text{TA}}. \end{aligned} \quad (1)$$

4. Large-scale anisotropies

As charged particles, UHECRs undergo deflections in Galactic and extragalactic magnetic fields. It has been proposed that the dipole and quadrupole anisotropy are relatively robust against the magnetic field model [3]. The dipole modulation in right ascension for $E \geq 8$ EeV was first discovered by the Pierre Auger Collaboration in 2017 [4] and has now reached 6.8σ significance [5]. Quadrupole anisotropy is considered an important signature of the UHECR origin models, but it has not been detected so far. We computed the angular power spectrum of our dataset in three energy bins and in the whole energy range. The results are shown in Figure 3. The most significant multipole moments are listed in Table 1; all other local p-values are greater than 10^{-2}.[1]

[1] The significance of the $\ell = 3$ moment in the whole energy range, which in our previous report [1] was $p = 1.0 \times 10^{-3}$ (3.3σ), has now weakened to $p = 3.1 \times 10^{-2}$ (2.2σ).

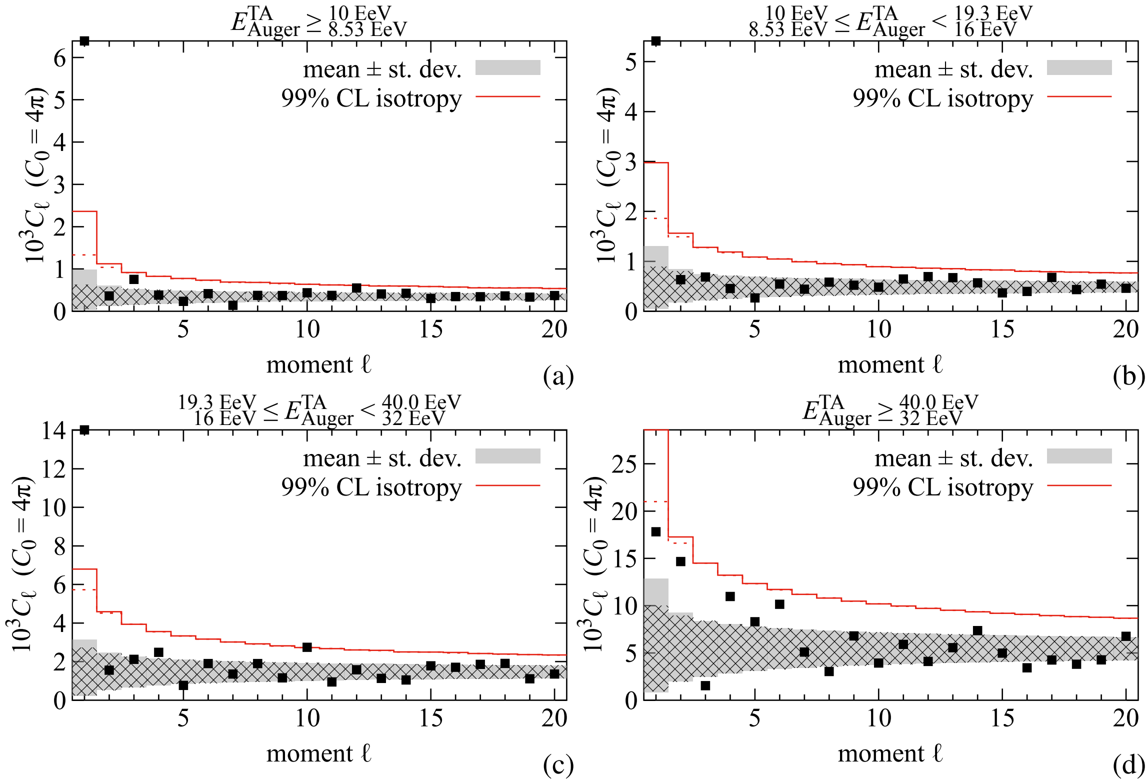

Figure 3: The angular power spectrum of our dataset in the whole energy range (a) and in the three energy bins (1) $E_1 \leq E < E_2$ (b), $E_2 \leq E < E_3$ (c), and $E \geq E_3$ (d). The solid gray band and solid red line show isotropic predictions accounting for the statistical uncertainty in the Auger–TA energy calibration, whereas the hatched region and dashed red line show predictions neglecting it.

Table 1: The most significant multipole moments in our dataset. All p-values and significances are local.

		this work		ICRC 2023 [1]	
energy bin	ℓ	p	signif.	p	signif.
$[E_1, +\infty)$	1	3.9×10^{-6}	4.6σ	2.6×10^{-5}	4.2σ
$[E_1, E_2)$	1	3.3×10^{-4}	3.6σ	5.0×10^{-4}	3.5σ
$[E_2, E_3)$	1	7.8×10^{-5}	4.0σ	1.2×10^{-3}	3.2σ
	10	9.6×10^{-3}	2.6σ	5.0×10^{-3}	2.8σ

The dipole has become more significant compared to our previous report [1], but still no other multipole moment stands out.

The amplitudes and directions of the dipole ($\ell = 1$) moments for different energy ranges are shown in Figure 4 and the amplitudes of the dipole and quadrupole ($\ell = 2$) moments are shown in Table 2 and as a map in Figure 5. We note that the contribution of the quadrupole is most noticeable in the highest energy range, although its significance still does not reach 99% CL. On the other hand, the dipole is significant in all energy ranges except the highest.

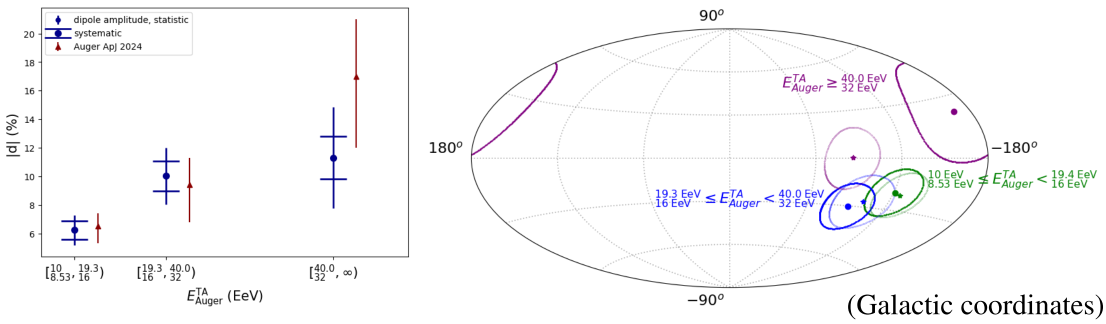

Figure 4: The amplitude (left) and direction (right) of the dipole moment in our data as a function of energy. In the right panel stars and pale ellipses denote Auger-only [5] results.

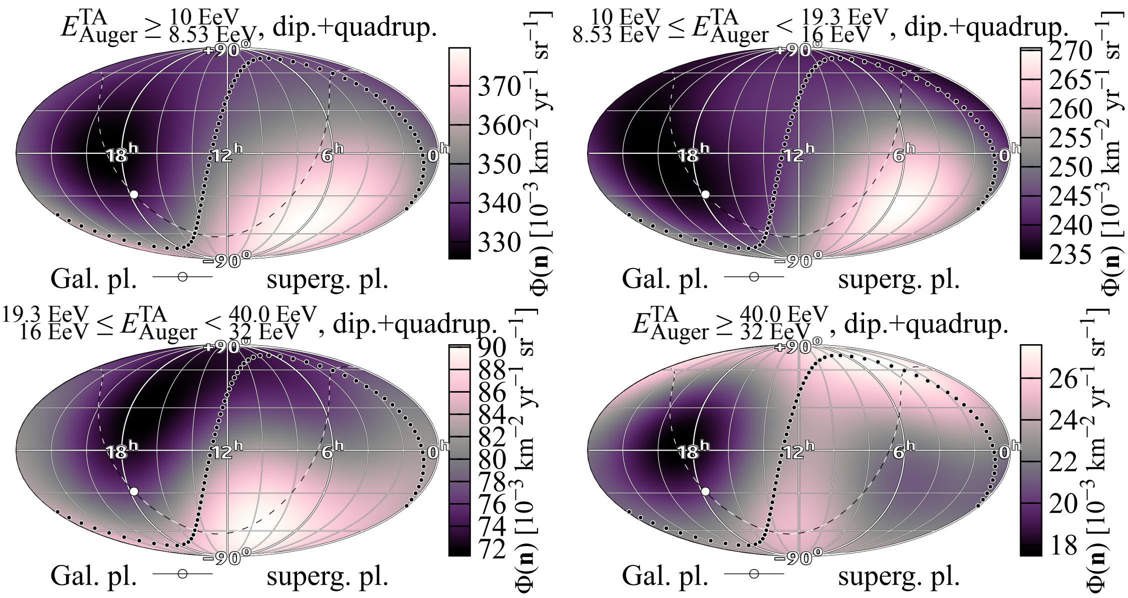

Figure 5: Maps showing the multipolar expansion of the UHECR flux (in equatorial coordinates) up to $\ell = 2$ (dipole and quadrupole) in our data in the whole energy range and the three energy bins (1)

Table 2: The dipole and quadrupole coefficients of our dataset in the whole energy range and the three energy bins (1). The first uncertainty in each value is statistical, the second is due to the uncertainty in the Auger–TA energy scale cross calibration.

	all	$E_1 \le E < E_2$	$E_2 \le E < E_3$	$E \ge E_3$
d_x [%]	$-0.6 \pm 0.9 \pm 0.0$	$-0.5 \pm 1.0 \pm 0.0$	$+0.1 \pm 1.8 \pm 0.0$	$-4.3 \pm 3.4 \pm 0.1$
d_y [%]	$+5.5 \pm 0.8 \pm 0.0$	$+5.3 \pm 1.0 \pm 0.0$	$+5.1 \pm 1.8 \pm 0.0$	$+9.0 \pm 3.3 \pm 0.0$
d_z [%]	$-3.9 \pm 1.0 \pm 1.1$	$-3.3 \pm 1.2 \pm 1.2$	$-8.6 \pm 2.1 \pm 1.2$	$+5.3 \pm 4.1 \pm 3.3$
$Q_{xx} - Q_{yy}$ [%]	$+1.9 \pm 3.7 \pm 0.0$	$-3.8 \pm 4.4 \pm 0.0$	$+12.7 \pm 7.6 \pm 0.0$	$+26.8 \pm 14. \pm 0.1$
Q_{xz} [%]	$+0.6 \pm 2.1 \pm 0.0$	$-1.9 \pm 2.5 \pm 0.0$	$+5.8 \pm 4.4 \pm 0.0$	$+9.4 \pm 9.2 \pm 0.0$
Q_{yz} [%]	$-3.7 \pm 2.1 \pm 0.0$	$-5.3 \pm 2.6 \pm 0.0$	$-3.1 \pm 4.4 \pm 0.0$	$+11.5 \pm 8.6 \pm 0.2$
Q_{zz} [%]	$+2.7 \pm 2.4 \pm 1.3$	$+0.6 \pm 2.9 \pm 1.4$	$+3.0 \pm 5.1 \pm 1.4$	$+24.7 \pm 9.7 \pm 4.0$
Q_{xy} [%]	$+1.1 \pm 1.8 \pm 0.0$	$+1.6 \pm 2.2 \pm 0.0$	$-1.6 \pm 3.8 \pm 0.0$	$+4.1 \pm 7.3 \pm 0.1$

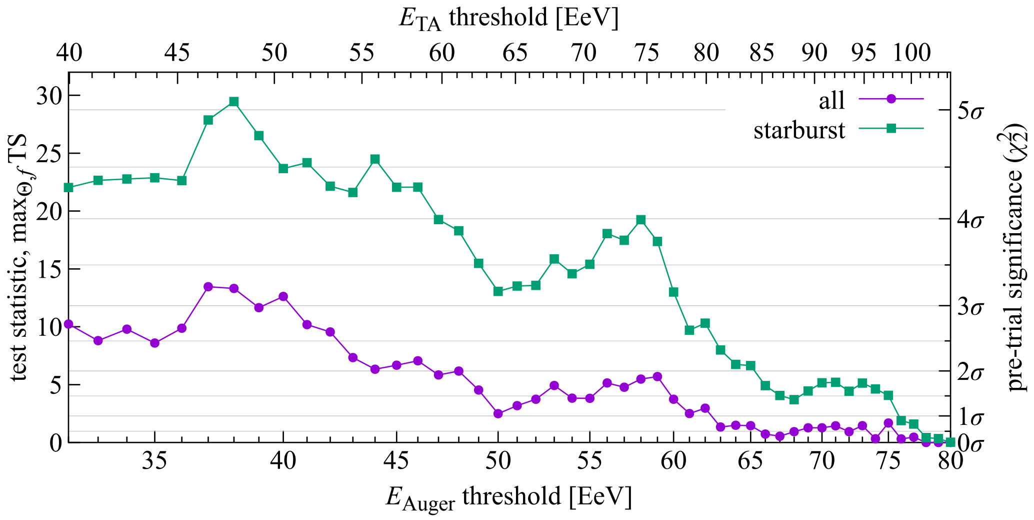

Figure 6: Significances of the correlations with galaxy catalogs as a function of the energy threshold

5. Medium-scale anisotropies

We use a different type of analysis for searching for medium-scale anisotropies, namely a likelihood analysis. We define a test statistic with two free parameters,

$$\mathrm{TS}(\Theta, f) = 2 \ln \frac{\mathcal{L}(\Theta, f)}{\mathcal{L}(f = 0)},$$

where Θ is an angular scale (inverse square root of the concentration parameter of a von Mises–Fisher distribution) and f is the fraction of correlating events ($f = 0$ denoting pure isotropy). The likelihood analysis is performed with two catalogs of galaxies:

- all types of galaxies at 1 Mpc $\leq D <$ 250 Mpc based on the 2MASS redshift survey (2MRS, [6]): over 44,000 galaxies, weighted based on their K-band flux (2.16 µm);
- starburst galaxies (SBG) at 1 Mpc $\leq D <$ 130 Mpc, based on ref. [7] but with the SMC and LMC removed and Circinus added from the Parkes telescope: 44 galaxies, weighted based on flux in the 1.4 GHz band.

The resulting test statistics as a function of the energy threshold are shown in Figure 6. The best-fit parameters are shown and compared to our previous results [1] in Table 3. The energy threshold at which the correlations reach their maximum has remained virtually unchanged compared to the ICRC 2023 results. At the same time, the angular scale Θ remained at about 15° for the starburst catalog and increased from 19° to 26° for all galaxies catalog. The statistical significance of both correlations has decreased slightly compared to the ICRC 2023 results.

The resulting sky map smoothed on a $\Theta = 15°$ angular scale is shown in Figure 7.

6. Conclusions and outlook

We presented updated results of the large and medium-scale anisotropy analyses, using 16 years of TA data and 19 years of Auger data. The dipolar modulation is the only anisotropy that is

Table 3: Best-fit parameters and significances in searches for correlations with galaxy catalogs

all galaxies, 1 Mpc ≤ D < 250 Mpc (2MRS catalog)						
dataset	$E^{\min}_{\text{Auger}}$	$E^{\min}_{\text{TA}}$	Θ	f	TS	post-trial
this work	37 EeV	46.5 EeV	26°	30%	13.5	2.6σ
ICRC 2023 [1]	38 EeV	48.2 EeV	19°	25%	14.7	2.8σ
starburst galaxies, 1 Mpc ≤ D < 130 Mpc (Lunardini+ '19 catalog)						
dataset	$E^{\min}_{\text{Auger}}$	$E^{\min}_{\text{TA}}$	Θ	f	TS	post-trial
this work	38 EeV	47.8 EeV	15.0°	11.1%	29.5	4.4σ
ICRC 2023 [1]	38 EeV	48.2 EeV	15.4°	11.7%	30.5	4.6σ

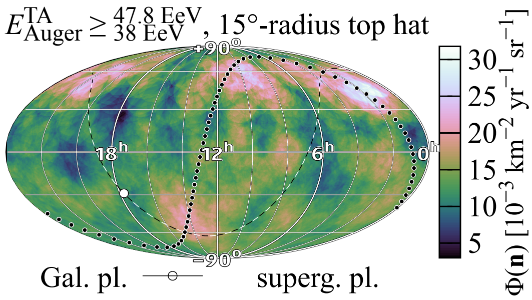

Figure 7: Medium-scale sky map (equatorial coordinates)

significantly (4.6σ) identified in the angular power spectrum. The hypothesis of correlations with the starburst galaxies is supported at the significance of 4.4σ. The upcoming data of AugerPrime and TA×4 will be crucial for the determination of the origin of UHECRs.

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