UHECR arrival directions in the latest data from the original Auger and TA surface detectors and nearby galaxies

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The distribution of ultra-high-energy cosmic-ray arrival directions appears to be nearly isotropic except for a dipole moment of order $6 \times (E/10 \, \text{EeV})$ per cent. Nonetheless, at the highest energies, as the number of possible candidate sources within the propagation horizon and the magnetic deflections both shrink, smaller-scale anisotropies might be expected to emerge. On the other hand, the flux suppression reduces the statistics available for searching for such anisotropies. In this work, we consider two different lists of candidate sources: a sample of nearby starburst galaxies and the 2MRS catalog tracing stellar mass within 250 Mpc.

We combine surface-detector data collected at the Pierre Auger Observatory until 2020 and the Telescope Array until 2019, and use them to test models in which UHECRs comprise an isotropic background and a foreground originating from the candidate sources and randomly deflected by magnetic fields. The free parameters of these models are the energy threshold, the signal fraction, and the search angular scale. We find a correlation between the arrival directions of $11.8\%^{+5.0\%}_{-3.1\%}$ of cosmic rays detected with $E \geq 38$ EeV by Auger or with $E \gtrsim 49$ EeV by TA and the position of nearby starburst galaxies on a $15.5°^{+5.3°}_{-3.2°}$ angular scale, with a 4.2σ post-trial significance, as well as a weaker correlation with the overall galaxy distribution.

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1. Introduction

Ultra-high-energy cosmic rays (UHECRs) are particles from outer space with energies greater than $1\,\text{EeV} = 10^{18}\,\text{EeV} \approx 0.16\,\text{J}$. They are electrically charged (protons and other atomic nuclei), so they are deflected by intergalactic and Galactic magnetic fields (typically by a few tens of degrees), meaning that, unlike with photons and other neutral messengers, the position of their sources cannot be directly reconstructed from their arrival directions.

Nowadays, arrays of particle detectors such as the Pierre Auger Observatory (Auger) [1] and the Telescope Array (TA) [2] cover areas of hundreds of square kilometers and detect thousands of events every year; nevertheless, over 60 years after the discovery of UHECRs, their origin remains unknown. Still, certain possibilities can be ruled out. The lack of anisotropies aligned with the Galactic plane excludes a sizable contribution of protons from within our Galaxy [3, 4], and mass estimates exclude a composition dominated by heavier nuclei [5, 6], hence most such particles must originate from outside our Galaxy. The lack of neutral particles such as neutrinos and gamma rays at these energies [7–10] excludes "top-down" mechanisms, e.g. the decay of super-heavy dark matter particles or topological defects, as a dominant origin (except possibly at $E \gtrsim 100\,\text{EeV}$). Therefore, UHECRs are widely believed to be ordinary matter accelerated to extreme energies by extragalactic astrophysical phenomena. Various possibilities that have been hypothesized [11, 12] include active galactic nuclei (AGNs), starburst galaxies (SBGs), gamma-ray bursts (GRBs) and tidal disruption events (TDEs).

A possible avenue to search for imprints of the distribution of UHECR sources in spite of magnetic deflections is to harness the huge statistics gathered by last-generation detector arrays to search for large-scale (dipolar and quadrupolar) anisotropies, which are the ones the least affected by a given amount of magnetic deflections. Another way is to focus on the highest-energy part of the UHECR spectrum, where magnetic deflections are expected to be smaller and the number of potential sources decreases, at the cost of the reduced statistics. A large-scale anisotropy has been reported in Auger data [13] whose statistical significance has now reached 6.6σ [14], but the lack of full-sky coverage impedes its interpretation in terms of dipole and quadrupole moments unless higher-order multipoles are assumed to vanish. Conversely, no medium- or small-scale anisotropy has been conclusively established so far, but a few indications have been reported (see the introduction of Ref. [15] for a review). In order to follow up on these indications using full-sky data, a working group has been established with members from both the Auger and TA collaborations. Our most recent results of searches for large-scale anisotropies are presented in Ref. [16], and those of searches for medium-scale anisotropies at the highest energies are presented here.

2. The datasets

In this work, we use the same data as in Ref. [16], namely those detected by the Pierre Auger Observatory from 2004 Jan 01 to 2020 Dec 31 and those detected by the Telescope Array from 2008 May 11 to 2019 May 10, but restricted to the highest-energy bin (above 32 EeV for Auger, above 40.8 EeV for TA), and using looser selection criteria for Auger events [17] resulting in 7% more events. The dataset comprises 2 625 Auger events and 315 TA events.
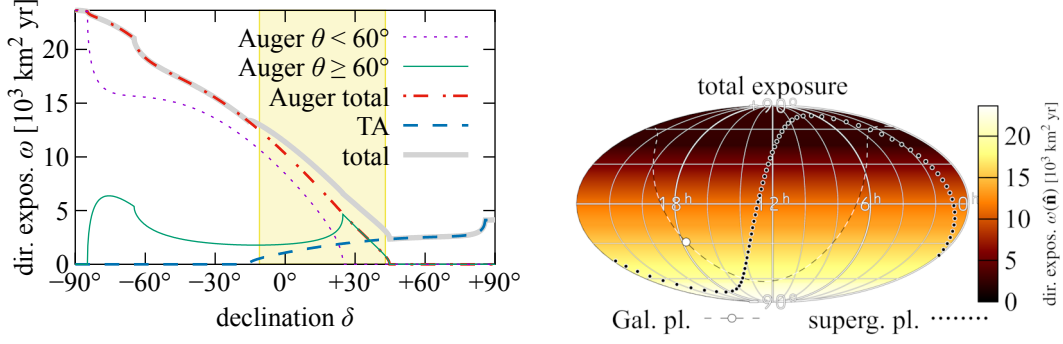
Figure 1: The directional exposure of the datasets we used. The yellow area in the left panel is the fiducial declination band used for the cross-calibration of energies [16].
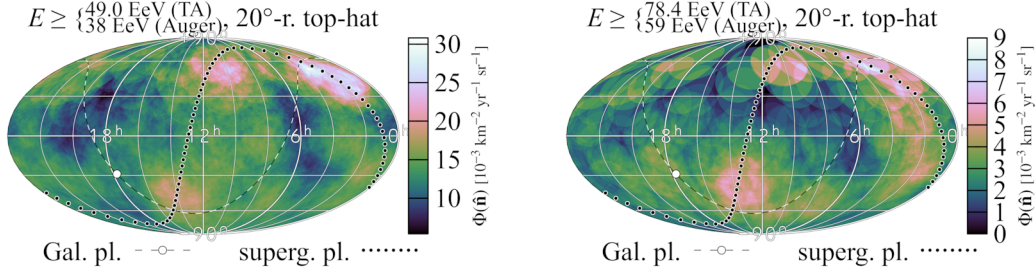

Figure 2: The flux distribution from our dataset above two selected energy thresholds, in equatorial coordinates

The geometrical exposure is $95\,700$ km^2 yr sr for Auger vertical events (zenith angles $\theta < 60°$) and $26\,300$ km^2 yr sr for Auger inclined events ($60° \leq \theta < 80°$). Taking into account the energy resolution effects, the effective exposure is $96\,600$ km^2 yr sr for Auger vertical events, $26\,600$ km^2 yr sr for Auger inclined events, and $13\,700$ km^2 yr sr for TA events. This represents a 33% increase from the last Auger–TA joint searches for medium-scale anisotropies [15]. The declination dependence of the directional exposure is computed in the approximation of 100% detector efficiency [18] and shown in Figure 1.

Following Ref. [16], we apply the conversion

$$E_{\text{TA}} \mapsto E_{\text{Auger}} = 8.57\,(E_{\text{TA}}/10\text{ EeV})^{0.937}\text{ EeV} \tag{1}$$

to TA event energies in order to correct them for the mismatch in the energy scales of the two experiments, which has been estimated by comparing their data in a common declination band in the intersection of their fields of view. The distribution of arrival directions of the events above two selected energy thresholds, averaged over $20°$-radius top-hat windows, is shown in Figure 2.

3. The analysis

In this work, we present the result of a likelihood ratio test between flux models including a contribution from nearby galaxies and and the isotropic null hypothesis, similar to Refs. [17, 19, 20].

We define the test statistic

$$\text{TS}(\psi, f, E_{\min}) = 2 \ln \frac{L(\psi, f, E_{\min})}{L(\psi, 0, E_{\min})}, \quad L(\psi, f, E_{\min}) = \prod_{E_i \geq E_{\min}} \frac{\Phi(\hat{\mathbf{n}}_i; \psi, f)\omega(\hat{\mathbf{n}}_i)}{\int_{4\pi} \Phi(\hat{\mathbf{n}}; \psi, f)\omega(\hat{\mathbf{n}}) \, d\Omega}, \quad (2)$$

where $\omega(\hat{\mathbf{n}})$ is the combined directional exposure of the dataset, and the flux model is

$$\Phi(\hat{\mathbf{n}}; \psi, f) = f\Phi_{\text{signal}}(\hat{\mathbf{n}}; \psi) + (1 - f)\Phi_{\text{background}}, \quad (3)$$

where the contribution of each source is a von Mises–Fisher distribution:

$$\Phi_{\text{signal}}(\hat{\mathbf{n}}; \psi) = \frac{1}{\sum_j w_s} \sum_j w_s \frac{\psi^{-2}}{4\pi \sinh \psi^{-2}} \exp\left(\psi^{-2}\hat{\mathbf{n}}_s \cdot \hat{\mathbf{n}}\right); \qquad \Phi_{\text{background}} = \frac{1}{4\pi}, \quad (4)$$

where E_i and $\hat{\mathbf{n}}_i$ are the energy and arrival direction of the i-th event; w_s and $\hat{\mathbf{n}}_s$ are the weight and position of the s-th source candidate as defined in subsection 3.1; and ψ is the root-mean-square deflection per transverse dimension (i.e. the total r.m.s. deflection is $\sqrt{2} \times \psi$).[1] The von Mises–Fisher distribution is the analog of a Gaussian on a 2-sphere, centered on the position of each source. In reality, magnetic deflections include both regular and turbulent parts, but the directions of the former are not sufficiently well known to be used in a log-likelihood ratio test. In a future work, we plan to investigate using simulations how much realistic amounts of regular magnetic deflections can affect the result of an analysis which does not explicitly model them.

Since the null hypothesis (isotropy) is a special case of the model (obtained for $f = 0$) and for a fixed $E_{\min}$ the TS is a smooth function of ψ and f, according to Wilks' theorem [22] $\max_{\psi, f}$ TS is χ^2-distributed with two degrees of freedom.

The analysis is repeated using energy thresholds of 32 EeV, 33 EeV, . . . , 80 EeV on the Auger scale, corresponding to 40.8 EeV, 42.2 EeV, . . . , 108.6 EeV on the TA scale.

3.1 The galaxy catalogs

In this work, we use two different lists of candidate sources. The first is a list of 44 113 galaxies of all types at distances 1 Mpc $\leq D <$ 250 Mpc, based on the 2MASS catalog with distances from HyperLEDA, with weights assumed proportional to the near-infrared flux in the K-band (2.2 μm). The second is a list of 44 starburst galaxies at distances 1 Mpc $\leq D <$ 130 Mpc, taken from Ref. [23] except that we removed the SMC and LMC (which are dwarf irregular galaxies, not starburst galaxies, as evidenced by their infrared-to-radio flux ratio much lower than all other objects of the list), and added the Circinus galaxy with data from the Parkes telescope ($\alpha = 213.29°$, $\delta = -65.34°$, $D = 4.21$, $S_{1.4\,\text{GHz}} = 1.50$ Jy); these galaxies were assigned weights proportional to their radio flux at 1.4 GHz. More details about these selections are found in Ref. [17].

In this work, we neglect the energy losses undergone by cosmic rays, hence the distant objects are assigned a larger weight than if energy losses were taken into account. Given the distance distributions of the objects we are considering, the effect of energy losses on the results can be presumed to be relatively small in the case of galaxies of all types and negligible in the case of starburst galaxies, though the precise rates depend on the mass composition of UHECRs. Also, like in previous studies [17, 19, 20], we do not attempt to correct for the fact that the catalogs are

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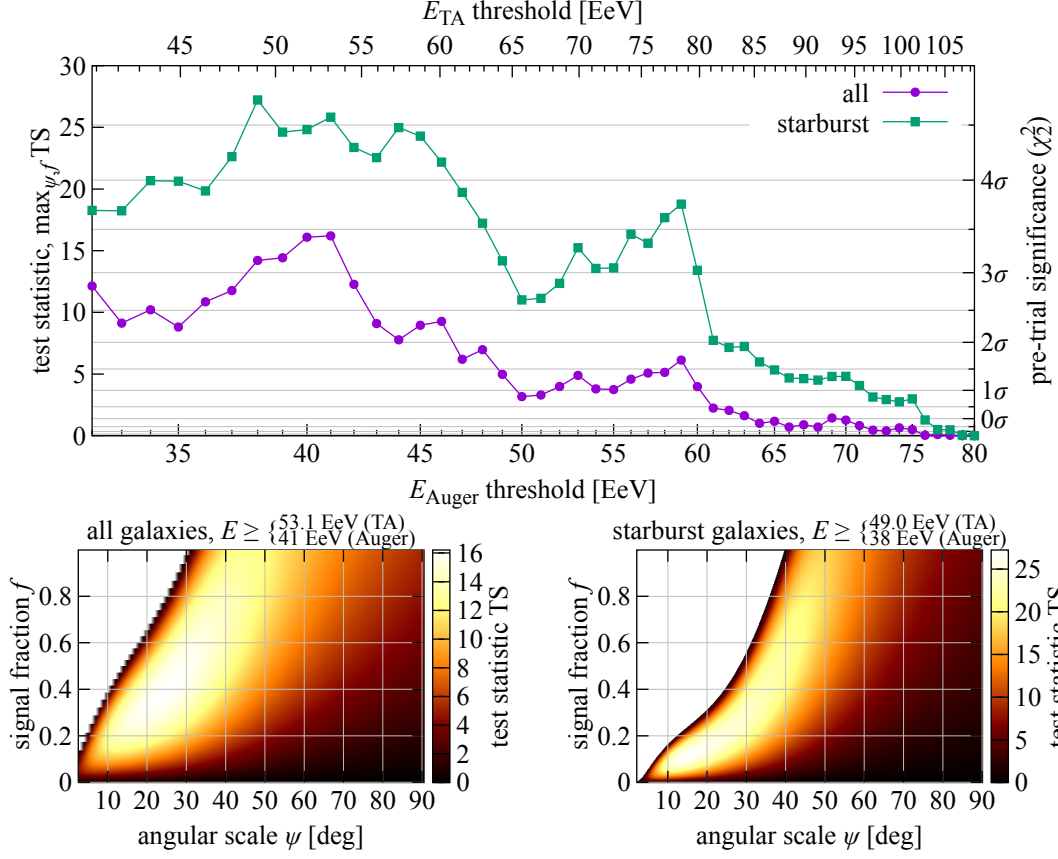[1]The equivalent top-hat radius is $\Psi = 1.59\psi$ [21].

Figure 3: The test statistic TS as a function of the energy threshold E_{min} (top) and of the angular scale ψ and signal fraction f (bottom). In the top panel, for each E_{min} the corresponding best ψ and f are used, whereas in each of the bottom panels the same E_{min} is used for all ψ and f. In the top panel, the significances on the right-hand side take into account the maximization over ψ and f but not over E_{min}. The white areas at small ψ in the bottom panels correspond to models with TS < 0, i.e. fitting the data worse than the isotropic null hypothesis.

limited in flux rather than in intrinsic luminosity, meaning that distant objects can be excluded even if otherwise-identical objects would be included if closer to us. An estimate of the size of the effects of this limitation on the results is left for future works.

4. Results

Using the list of starburst galaxies, we find a maximum test statistic of TS = 27.2 with an energy threshold of E_{min} = 38 EeV on the Auger scale (49 EeV on the TA scale), an angular scale $\psi = 15.5°^{+5.3°}_{-3.2°}$,[2] and a signal fraction $f = 11.8\%^{+5.0\%}_{-3.1\%}$. Using the list of all types of galaxies galaxies, we find a maximum TS = 16.2 with E_{min} = 41 EeV on the Auger scale (53 EeV on the TA scale), $\psi = 24°^{+13°}_{-8°}$,[3] and $f = 38\%^{+28\%}_{-14\%}$. The TS as a function of the parameters for the two catalogs is shown in Figure 3. The best-fit flux models are shown in Figure 4. Using both catalogs, there

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[2]Equivalent top-hat radius: $\Psi = 24.6°^{+8.4°}_{-5.1°}$.

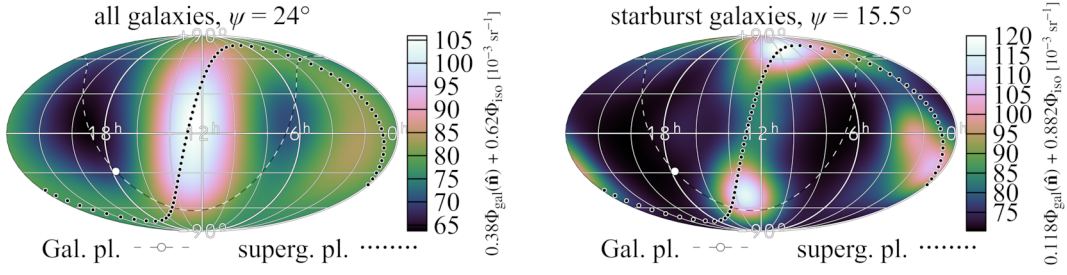[3]Equivalent top-hat radius: $\Psi = 38°^{+21°}_{-13°}$.

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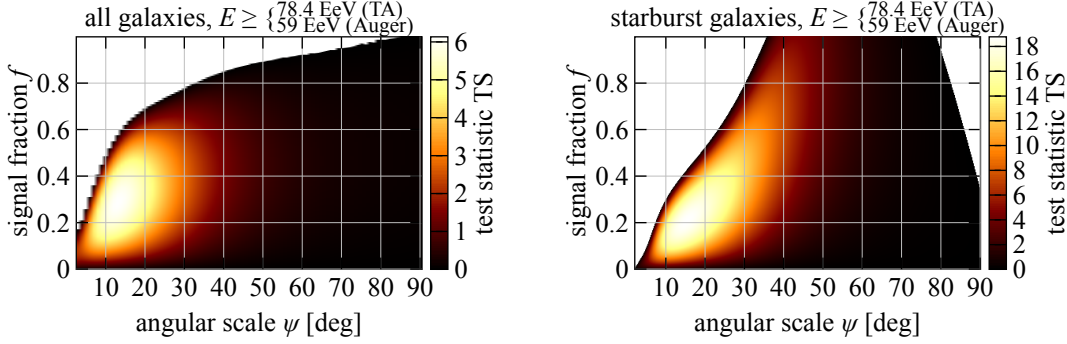**Figure 4:** The best-fit flux models for the two catalogs we used

Figure 5: Same as in Figure 3 bottom, but with a higher energy threshold

also is a local maximum at $E_{min} = 59$ EeV on the Auger scale (78 EeV on the TA scale); the TS as a function of ψ and f at this threshold is shown in Figure 5.

According to Wilks' theorem [22], when accounting for the scan over ψ and f (but not E_{min}) these test statistics correspond to local statistical significances of 4.7σ and 3.4σ respectively. Wilks' theorem is not applicable to E_{min} because the likelihood is not a smooth function of it, so we computed the post-trial significances accounting for all three free parameters using simulations in each of which the number and energies of events are the same as in the real data, but the arrival directions are randomly generated according to the combined directional exposure of the two arrays. The resulting distribution of test statistics is shown in Figure 6. We find that for the starburst galaxy model TS = 27.2 corresponds to a 4.2σ post-trial significance, and for the all-galaxy model TS = 16.2 corresponds to a 2.9σ post-trial significance.

4.1 Effect of the uncertainty in the energy cross calibration

As explained in Ref. [16], the statistical uncertainty in the cross calibration of energies can be treated as a $\pm 6.4\%$ uncertainty on the ratio between "effective" exposures, but we find that such an uncertainty has a negligible effect on the current study: if we increase the TA exposure by $\pm 6.4\%$, the maximum TS changes by ∓ 0.4 and ± 0.1, for the starburst galaxy model and the all-galaxy model respectively, with changes in ψ and f of less than $1°$ and 1% respectively. The reason for this is that neither hemisphere dominates the anisotropic component of either model, so the fit to the data cannot be substantially improved or worsened just by rescaling the flux in one or the other hemisphere.
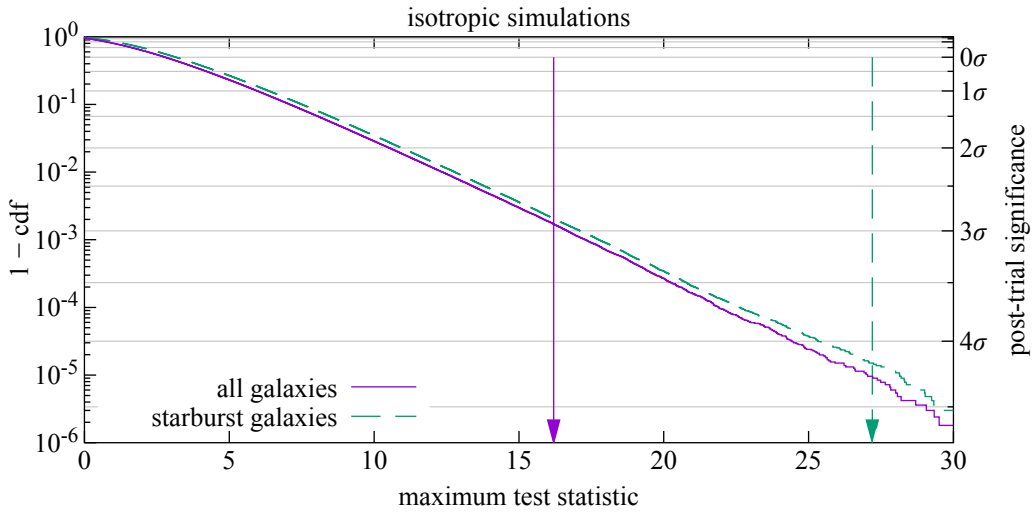
Figure 6: The distribution of TS among isotropic simulations

5. Conclusion

Our combined dataset hints at an association between the arrival directions of around 12% of cosmic rays detected with $E \geq 38$ EeV by Auger or with $E \gtrsim 49$ EeV by TA and the position of nearby starburst galaxies on an angular scale of around 16°, with a stronger significance than the Auger-only data [17] but still short of the discovery level, as well as a weaker association with the overall galaxy distribution. The astrophysical interpretation of this association is complicated by our incomplete knowledge about intergalactic and Galactic magnetic fields and the UHECR mass composition. Therefore we leave the possible interpretations of these results for future studies.

In the coming years, the upgraded arrays AugerPrime [24] and TA×4 [25] will gather more exposure, allowing us to probe flux models with more statistical sensitivity. It will be interesting to see if the new data will be able to confirm or dispute this finding. Furthermore, improved mass estimation from new analysis techniques (such as ones involving machine learning [26, 27]) and from the new detectors of Auger [24] will allow us to select high-rigidity event samples, which are expected to undergo smaller magnetic deflections.

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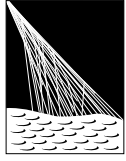
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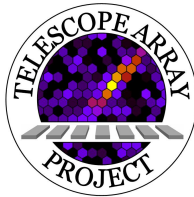
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