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Update on the searches for anisotropies in UHECR arrival directions with the Pierre Auger Observatory and the Telescope Array

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The origin of ultra-high-energy cosmic rays (UHECRs), particles from outer space with energies $E \geq 1$ EeV, is still unknown, though the near-isotropy of their arrival direction distribution excludes a dominant Galactic contribution, and interactions with background photons prevent them from travelling cosmologically large distances. This suggests that their sources must be searched for in nearby galaxy groups and clusters. Deflections by intergalactic and Galactic magnetic fields are expected to hinder such searches but not preclude them altogether. So far, the only anisotropy detected with statistical significance $\geq 5\sigma$ is a modulation in right ascension in the data from the Pierre Auger Observatory at $E \geq 8$ EeV interpretable as a 7% dipole moment. Various hints for higher-energy, smaller-scale anisotropies have been reported. UHECR arrival direction data from both the Pierre Auger Observatory and the Telescope Array experiment have been searched for anisotropies by a working group with members from both collaborations; combining the two datasets requires a cross-calibration procedure due to the different systematic uncertainties on energy measurements but allows us to perform analyses that are less model-dependent than what can be done with partial sky coverage. We report a significant dipole pointing away from the Galactic Center and a $\sim 4.6\sigma$ anisotropy found when comparing the directions of UHECRs with a catalog of starburst galaxies.

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1. Introduction

The most energetic particles known in the universe are ultra-high-energy cosmic rays (UHECRs). These particles, nuclei that reach the Earth from yet unknown sources, have energies up to a few 10^{20} eV, i.e. hundreds of EeV. Being charged, they do not propagate in a straight line but are deflected by the magnetic fields they encounter in Galactic and intergalactic space. For this reason, their arrival directions are not expected to point directly to their sources.

UHECR are very rare: at the highest energies, only a few thousand have been detected in the last decades using detectors that cover areas of hundreds to thousands of square kilometers. The two largest detectors are the Pierre Auger Observatory (Auger) [1], located in Argentina, and Telescope Array (TA) [2], in the USA. The former has been in operation since 2004 and covers an area of ~ 3000 km^2. The latter covers ~ 700 km^2 and has been operating since 2008.

In this work, we update a joint effort between the TA and Auger collaborations, which has been been active for almost a decade (see [3, 9], and references therein). We use the two largest UHECR datasets available, together offering full-sky coverage, to study their arrival directions. Even if magnetic deflections hinder a direct association of a single cosmic ray with its source, a collective study could allow us to obtain information on the astrophysical objects that accelerated them.

2. The datasets

In this work, we use the most updated UHECR datasets available: from 1 January 2004 to 31 December 2022 for Auger and from 11 May 2008 to 10 May 2022 for TA. The field of view of TA covers the northern hemisphere down to a declination of $\delta = -15.7°$. The Auger dataset is divided into two different sets of events, reconstructed with different methods: the "vertical" events are those observed with zenith angles $\theta < 60°$, while "inclined" events are those with $60° \leq \theta \leq 80°$. In this way, the Auger field of view covers the whole southern hemisphere and part of the northern hemisphere up to $\delta = +44.8°$. The relative exposure of the two observatories as a function of declination is shown in figure 1. TA and Auger have different energy scales and for this reason we performed, with the same method used in [13], a cross-calibration of energies using events arriving in the part of the sky visible to both. The results of such a calibration are that

$$E_{\mathrm{Auger}} = E_0 \, e^{\alpha} \left(\frac{E_{\mathrm{TA}}}{E_0}\right)^{\beta}, \qquad E_{\mathrm{TA}} = E_0 \, e^{-\alpha/\beta} \left(\frac{E_{\mathrm{Auger}}}{E_0}\right)^{1/\beta}, \tag{1}$$

where $E_0 = 10$ EeV, $\alpha = -0.157$ and $\beta = 0.949$.

44,174 Auger and 6,014 TA events with energies $E^{\mathrm{TA}}_{\mathrm{Auger}} \geq {}^{10\ \mathrm{EeV}}_{8.55\ \mathrm{EeV}}$ are used in the large-scale studies discussed below. For the intermediate-scale analysis 2,936 Auger and 404 TA events with $E^{\mathrm{TA}}_{\mathrm{Auger}} \geq {}^{40.2\ \mathrm{EeV}}_{32\ \mathrm{EeV}}$ are used. The selection for the TA events is the same for the two cases, while in Auger a looser selection is used in the higher-energy data set, where events have larger footprint on the ground and a good reconstruction can be ensured even if part of the footprint is missing. This selection and reconstruction are the same as used in [4], where the data was also made public. The exposure for the former is 123,000 km^2 sr yr and 135,000 km^2 sr yr for the latter. For TA the effective exposure (taking into account the energy resolution) is 17,500 km^2 sr yr.[1]

[1] Auger exposures taking into account the energy resolutions are 125,000 km^2 sr yr and 137,000 km^2 sr yr, respectively

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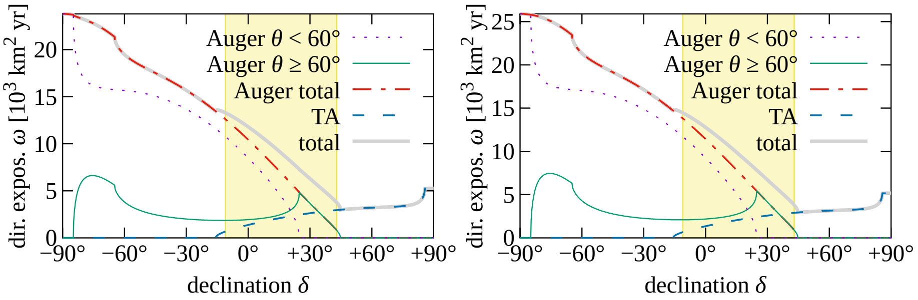

Figure 1: The exposure of the two observatories and their sum as a function of declination, using the selection criteria used for large (left) and intermediate (right) scales. The Auger exposure is divided in two components reflecting the two different reconstructions for the "vertical" and "inclined" events (see text for details). The yellow band is the common sky region used for the cross-calibration.

3. Large-scale studies

The full coverage of the sky enabled by the combination of the Auger and TA datasets allows us to perform large-scale studies with fewer assumptions than when using only one dataset. In particular, fitting the dipolar and quadrupolar components can be done with no assumption about higher-order multipoles.

We divide our dataset into three energy bins: $\frac{10\text{ EeV}}{8.55\text{ EeV}} \leq E^{\text{TA}}_{\text{Auger}} < \frac{19.4\text{ EeV}}{16\text{ EeV}}$, $\frac{19.4\text{ EeV}}{16\text{ EeV}} \leq E^{\text{TA}}_{\text{Auger}} < \frac{40.2\text{ EeV}}{32\text{ EeV}}$, and $E^{\text{TA}}_{\text{Auger}} \geq \frac{40.2\text{ EeV}}{32\text{ EeV}}$, plus a cumulative bin $E^{\text{TA}}_{\text{Auger}} \geq \frac{10\text{ EeV}}{8.55\text{ EeV}}$. We find a significant dipole in the lowest energy bin and in the cumulative bin,[2] while the quadrupole is not significant throughout the energy range. The dipole in the cumulative energy bin has a total amplitude of $|\mathbf{d}| = 6.51\% \pm 0.93\% \pm 0.65\%$ (the first uncertainty being statistical, the second due to the energy calibration), and is pointing towards $(\alpha, \delta) = (97.1^\circ \pm 9.4^\circ \pm 0.1^\circ, -35.7^\circ \pm 8.7^\circ \pm 7.8^\circ)$, which is 114° away from the Galactic Center and compatible with the position of the dipole measured with Auger-only data [5] and later found to be also compatible with TA data [6]. The observation of such dipole is a strong suggestion of an extra-galactic origin of UHECRs in this energy range. The evolution of the dipole direction with energy is shown in Galactic coordinates in figure 2. In all energy bins, the dipole points away from the Galactic center. In the figure, the results obtained with Auger only and reported in [7] are also shown, for reference. They are compatible with the exception of the highest energy bin, where a discrepancy between the two directions appears. This might be due to the presence in that energy bin of an overdensity in the northern hemisphere (see next paragraph) which might have driven the position towards higher declinations. It is however worth noting that, with the current statistics, we cannot claim the presence of a dipolar anisotropy in this highest energy bin. All the components of the dipole and quadrupole are reported in table 1 and shown in figure 3. A comparison of these results with expectations from different astrophysical models is provided in another contribution at this conference [8].

[2] The significance for the cumulative bin is 4.2σ ($p = 2.6 \times 10^{-5}$). It is lower than that reported by Auger because here we are testing for dipoles in any directions, including d_z, while in Auger-only analyses the significance is computed based on the search for a first-harmonic modulation along the equatorial plane.

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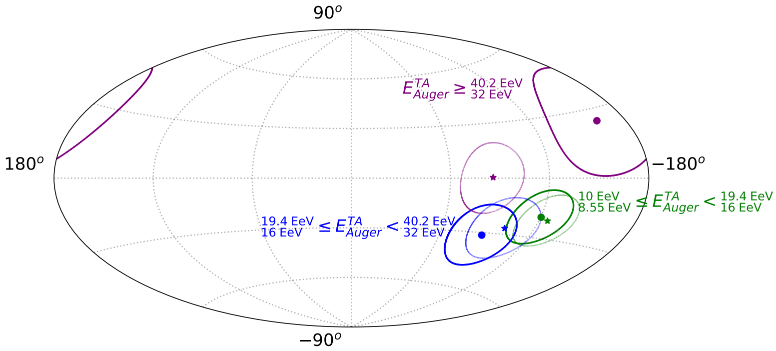

Figure 2: Direction of the reconstructed dipole in the considered energy bins in Galactic coordinates. The stars and fainter contours represent the corresponding Auger results presented in [7], obtained under the assumption that the moments higher than the dipole are null. Note that the lowest energy bin is 8–16 EeV in the Auger analysis, while here it is 8.55–16 EeV.

E_{Auger} [EeV] E_{TA} [EeV]	[8.55, 16) [10, 19.4)	[16, 32) [19.4, 40.2)	[32, +∞) [40.2, +∞)	[8.55, +∞) [10, +∞)
d_x [%]	−0.5 ± 1.0 ± 0.0	+0.3 ± 1.8 ± 0.0	−5.3 ± 3.5 ± 0.1	−0.7 ± 0.9 ± 0.0
d_y [%]	+5.3 ± 1.0 ± 0.0	+4.0 ± 1.8 ± 0.0	+9.3 ± 3.4 ± 0.0	+5.2 ± 0.9 ± 0.0
d_z [%]	−3.3 ± 1.2 ± 1.2	−7.7 ± 2.2 ± 1.3	+4.7 ± 4.3 ± 3.5	−3.8 ± 1.0 ± 1.1
$Q_{xx} - Q_{yy}$ [%]	−4.5 ± 4.4 ± 0.0	+12.7 ± 7.7 ± 0.0	+31.2 ± 14. ± 0.1	+1.7 ± 3.7 ± 0.0
Q_{xz} [%]	−2.1 ± 2.6 ± 0.0	+5.9 ± 4.6 ± 0.0	+4.6 ± 9.5 ± 0.1	+0.1 ± 2.2 ± 0.0
Q_{yz} [%]	−5.2 ± 2.6 ± 0.0	−6.9 ± 4.5 ± 0.1	+12.0 ± 8.9 ± 0.2	−4.5 ± 2.2 ± 0.0
Q_{zz} [%]	+0.5 ± 3.0 ± 1.5	+5.5 ± 5.3 ± 1.5	+25.2 ± 10. ± 4.3	+3.2 ± 2.5 ± 1.4
Q_{xy} [%]	+2.0 ± 2.2 ± 0.0	−1.6 ± 3.9 ± 0.0	+4.7 ± 7.5 ± 0.0	+1.3 ± 1.9 ± 0.0

Table 1: Dipolar and quadrupolar components. The first uncertainty is statistical, the second is due to the energy calibration.

We performed a measure of the power spectrum of our data, in the same energy bins used before, up to $\ell = 20$. The results are shown in figure 4: the only significant point is again $\ell = 1$ in the first two energy bins and in the cumulative one (with a significance of 3.5σ, 3.2σ and 4.2σ, respectively). A small departure from isotropy is found also for $\ell = 10$ in the $E^{\text{TA}}_{\text{Auger}} \geq \frac{40.2 \text{ EeV}}{32 \text{ EeV}}$ energy bin, and for $\ell = 3$ in the cumulative bin, but their significance (2.8σ and 2.6σ level pre-trial, respectively) is within the expectations for random fluctuations.

4. Intermediate-scale studies

The search for anisotropies at smaller angular scales is performed at the highest energies, where the magnetic deflections are expected to be smaller. In our case we consider the energy bin $E^{\text{TA}}_{\text{Auger}} \geq \frac{40.2 \text{ EeV}}{32 \text{ EeV}}$ where we have a combined dataset of 3,340 events.

We use this data to search for anisotropy in a targeted likelihood analysis, using two different catalogs, the same used in [9] and [13]. The first one is a set of more than 44,000 galaxies based

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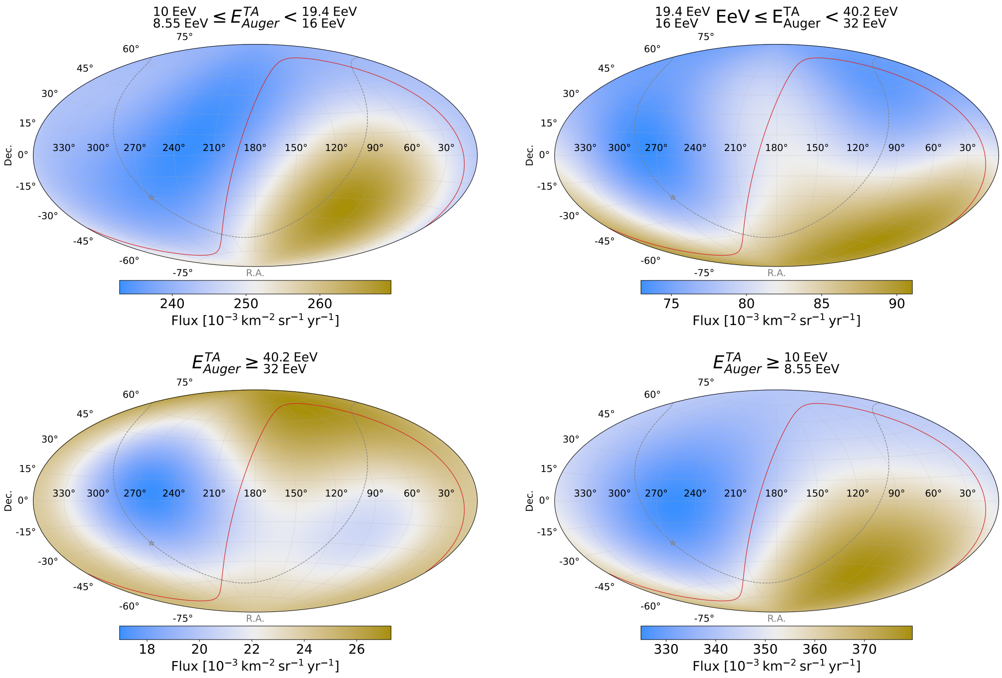

Figure 3: The best-fit dipole+quadrupole in the 4 energy bins considered in this work, in Equatorial coordinates. The grey line represents the Galactic Plane, with the star on it representing the Galactic Center, and the red line the Super Galactic Plane.

on the Two Micron All-Sky Survey (2MASS catalog, [11]), whose distances are extracted from the HyperLEDA database [12]. We assume in this case that the UHECR luminosity is proportional to stellar mass and we track it by using the K-band flux (2.16 µm). The second catalog is based on [10] and includes 44 starburst galaxies (SBGs). From the original selection, the two Magellanic Clouds were removed and the Circinus galaxy was included. For this catalog, we weight each source based on its emission in the 1.4 GHz band. For both catalogs we checked the distances from the HyperLEDA database, if available, taking into account peculiar motion and exploiting cosmic-distance-ladder estimates if available.

The analysis is performed via a maximum likelihood test, comparing the observed distribution of events with the probability map expected from the specific source model. The probability maps are obtained modeling the contribution of each source in the catalog with a von Mises–Fisher distribution with an angular width Θ. This angle is the first free parameter of the analysis, taking into account the unknown deflection of UHECR in magnetic fields. The contribution of each object is weighted based on its relative flux in the band chosen for each catalog, as mentioned before. An isotropic map, also taking into account the directional exposures of the two observatories, is then added to the probability map to take into account the possibility that a fraction of events is practically isotropized due to large magnetic deflections and/or because they come from faint sources not included in the considered catalogs. The relative weight of the anisotropic map, or signal fraction, f is the second free parameter of the analysis. The likelihood function $\mathcal{L}$ is then the product over all the events of the probability map defined this way. The test statistics (TS) is

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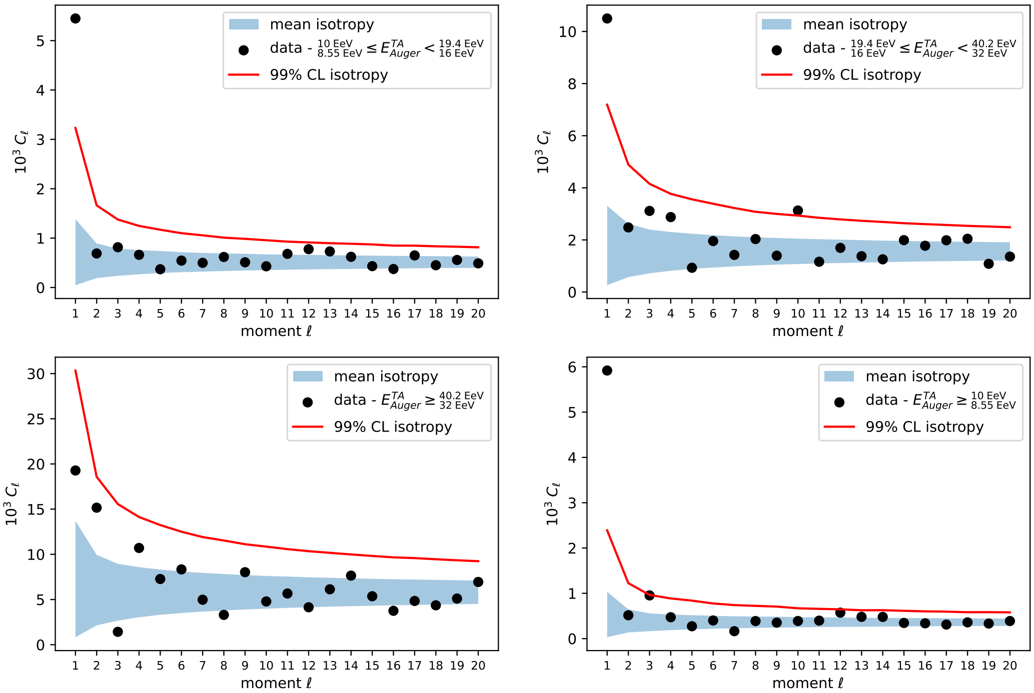

Figure 4: Angular power spectrum of the large scale distribution of UHECRs, in the four energy bins used in this work. The blue band is the average expectation from isotropy with a 1σ dispersion. The red line delimits the expectation band from an isotropic distribution of UHECRs at 99% CL.

defined taking as null hypothesis an isotropic distribution of UHECR:

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

The analysis has been performed cutting the dataset with different energy thresholds $\frac{40.2\ \text{EeV}}{32\ \text{EeV}} \leq E^{\text{TA}}_{\text{Auger}} \leq \frac{105.5\ \text{EeV}}{80\ \text{EeV}}$ in steps of 1 EeV on the Auger energy scale. The results are shown in figure 5, where the best TS found for each energy threshold is plotted. The best value is found for the SBG catalog for $E^{\text{TA}}_{\text{Auger}} \geq \frac{48.2\ \text{EeV}}{38\ \text{EeV}}$. The best fit parameters are $\Theta = (15.4^{+5.2}_{-3.0})^\circ$ (equivalent to $\Psi = 24.5^\circ$ for a top-hat), $f = (11.7^{+4.7}_{-2.9})\%$ and the TS = 30.5. The post-trial significance for this TS value, taking into account the energy scan, is 4.6σ (1-sided, $p = 1.7 \times 10^{-6}$). For the 2MRS catalog, the best TS = 14.7 is found at the same energy threshold, with parameters $\Theta = (19^{+15}_{-7})^\circ$, $f = (25^{+24}_{-10})\%$ with a penalized significance of 2.8σ ($p = 2.8 \times 10^{-3}$).

With respect to the previous update of this analysis [9], which used the same dataset from TA but 2 years less data from Auger, the significance has slightly decreased for the SBG catalog (it was 4.7σ post-trial, $p = 1.1 \times 10^{-6}$) and unchanged for the all-galaxies catalog.

5. Conclusions

We have updated the search for anisotropy in the arrival directions of the most energetic cosmic rays observed. In large-scale studies, we observe only one significant feature, a dipole in the lower

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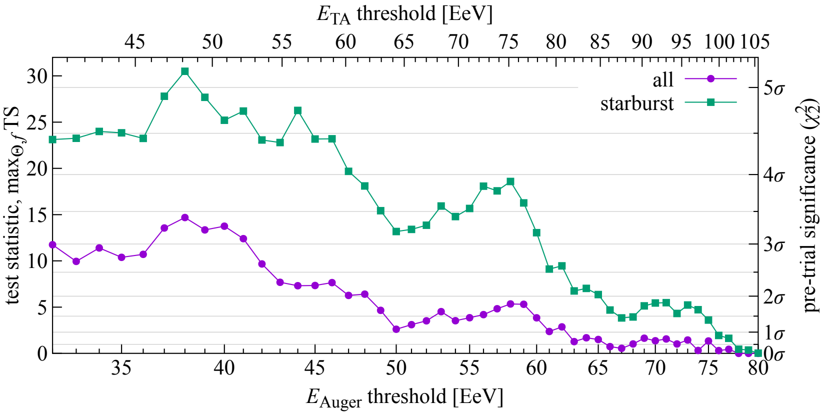

Figure 5: The best TS found as a function of energy threshold for the SBG (green squares) and 2MRS (purple circles) catalogs.

energy bin, while higher multipoles are compatible with expectations from an isotropic distribution of UHECRs. The amplitude and direction of the significant dipole, pointing away from the Galactic Center, are compatible with those reported by Auger alone.

In the intermediate-scale studies, we confirm the findings reported in previous work [9]. In particular, a departure from isotropy with a significance of 4.6σ is observed when comparing the arrival directions of UHECRs with the positions of starburst galaxies. We observed a slight decrease in the significance, compared with [9], but the result is consistent with the expected fluctuations around a linear growth with the number of events. In the map of the flux and Li-Ma significance of UHECR on the sky, shown in figure 6 in both galactic and equatorial coordinates, we show the main "warm spots" in the southern hemisphere (in the direction of the Centaurus constellation) and in the northern hemisphere (two spots, one in the direction of the Perseus-Pisces region, and the other roughly in the direction of the Ursa Major region). We note that the high significance of the SBG sample is driven by the presence of two of the most prominent galaxies of the catalog (NGC4945 and M83) in the Centaurus region and a third, M82, in the Ursa Major constellation. For possible astrophysical interpretations of such results, which takes into account the effects of coherent deflections in magnetic fields, please refer to the other joint contribution at this conference [8].

Auger is currently undergoing an upgrade, called AugerPrime, which is expected to be completed by the end of 2023. For this work, only data coming from the non-upgraded part of the array (so-called "phase one") are used. In future work, the Auger Collaboration will make use of the upgraded detector, with a better insight on the mass of the UHECRs. This will allow the removal of those events with the largest expected magnetic deflections, potentially leading to a boost of significance beyond that expected on the basis of statistics.

TA is also undergoing an upgrade (TA×4) which will increase its area by a factor of four, making it similar to the Auger area. This will help gathering more data in the northern hemisphere and better understanding of the significance of the two excesses reported so far.

The continuous operation of the two observatories, with their complementary sky coverage,

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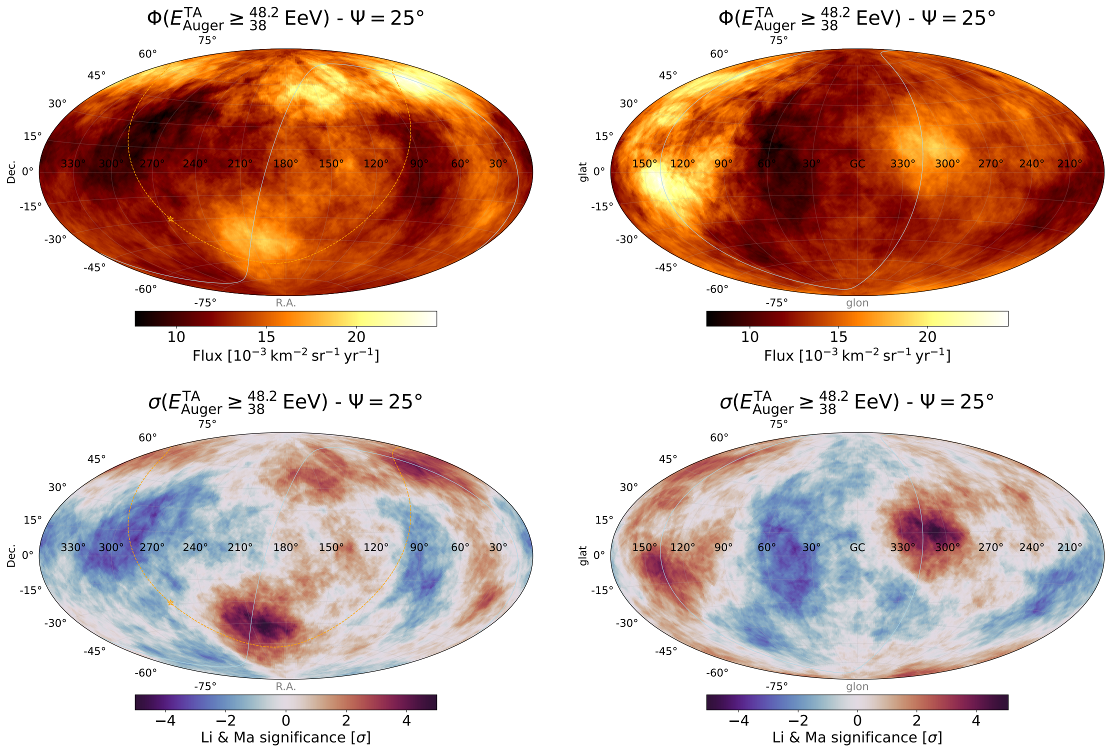

Figure 6: Flux map (top row) and Li-Ma significance map (bottom row) at energies $E^{\mathrm{TA}}_{\mathrm{Auger}} \geq \frac{48.2\ \mathrm{EeV}}{38\ \mathrm{EeV}}$ with a top-hat smoothing radius $\Psi = 25^{\circ}$ in Equatorial (left) and Galactic (right) coordinates. The supergalactic plane is shown as a grey line. In the left plot, the orange line represents the Galactic plane and the star the Galactic center.

is crucial to reach definite results on the analysis of the arrival directions of UHECR. Moreover, the cooperation between the two collaborations, now nearly a decade old, will be a key factor in reaching this result in a faster and more definitely way.

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The Telescope Array Collaboration

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