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Anisotropy studies of ultra-high-energy cosmic rays measured at the Pierre Auger Observatory

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Measurements of anisotropic arrival directions of ultra-high-energy cosmic rays provide important information for identifying their sources. On large scales, cosmic rays with energies above 8 EeV reveal a dipolar flux modulation in right ascension with a significance of 6.9σ, with the dipole direction pointing 113° away from the Galactic center. This observation is explained by extragalactic origins. Also, model-independent searches for small- and intermediate-scale overdensities have been performed in order to unveil astrophysically interesting regions. On these scales, no statistically significant features could be detected. However, intermediate-scale analyses comparing the measured arrival directions with potential source catalogs show indications for a coincidence of the measured arrival directions with catalogs of starburst galaxies and the Centaurus A region. In this contribution, an overview of the studies regarding anisotropies of the arrival directions of ultra-high-energy cosmic rays measured at the Pierre Auger Observatory on different angular scales is presented and the current results are discussed.

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1. Introduction

Extensive air showers in the Earth's atmosphere, induced by ultra-high-energy cosmic rays (UHECRs) with energies up to a few times 10^{20} eV, have been measured at the Pierre Auger Observatory [1] in Argentina since 2004. The data allows for an analysis of the arrival direction distribution, revealing information on their propagation and origin. Of the methods presented here, large-scale anisotropies can hint at general features of the source distribution. An immediate source association is challenged by the influence of magnetic fields, distorting the direct path of the charged particle proportional to their rigidity (energy divided by electric charge). Thus, the most energetic events are investigated in intermediate- and small-scale searches. The data sets used for the studies presented below include events measured at the Pierre Auger Observatory between January 2004 and December 2022 [2].

2. Large-scale anisotropy search

For the large-scale anisotropy search [3–5], as of the last update update [2] a data set containing about 50,000 events with energies above 8 EeV was analyzed. The left plot in Figure 1 shows the flux measured at the Pierre Auger Observatory in equatorial coordinates, smoothed with a 45° top-hat window. A harmonic analysis in right ascension reveals a dipolar modulation with a significance of 6.9σ. In the right plot in Figure 1, the normalized rates over right ascension are shown, where the modulation is visible. The analysis is extended to reconstruct the three-dimensional dipole which yields a dipole amplitude of $7.3^{+1.0}_{-0.8}\%$ with the direction pointing 113° away from the Galactic center, see Figure 1. These findings suggest extragalactic origin of UHECRs at these energies. When testing an additional quadrupolar component to the analysis, it was found to be not significant [2]. Furthermore, the energy-evolution of the dipole phase and amplitude is investigated, see Figure 2. Above a few EeV, the phase of the dipole shifts from close to the Galactic center to the opposite direction and the amplitude increases from below 1% to above 10% [2]. Above 4 EeV, the dipole amplitude rises with energy [2, 4]. A possible explanation is a larger relative contribution of nearby sources with rising energy due to increasing attenuation during propagation of further away sources and less diffusion by magnetic fields due to higher rigidities [4].

3. Intermediate- and small-scale anisotropies

To investigate smaller structures in the distribution of arrival directions of UHECRs, the energy threshold of the analysis is increased to 32 EeV to reduce the influence of magnetic field effects, resulting in approximately 2,700 events [2]. The following analyses have two parameters that are scanned to maximize a test statistic: the energy threshold E_{th}, between 32 EeV and 80 EeV in steps of 1 EeV as well as a search radius Ψ which is constrained between 1° and 30° [6, 7].

3.1 Overdensity search

The model-independent overdensity search reveals the most significant excess above E_{th} = 38 EeV for a search radius of 27° with 2.1σ post-trial significance [2]. The location of this excess is in the Centaurus region, pointing 2° from Centaurus A [2]. Figure 3 shows the corresponding

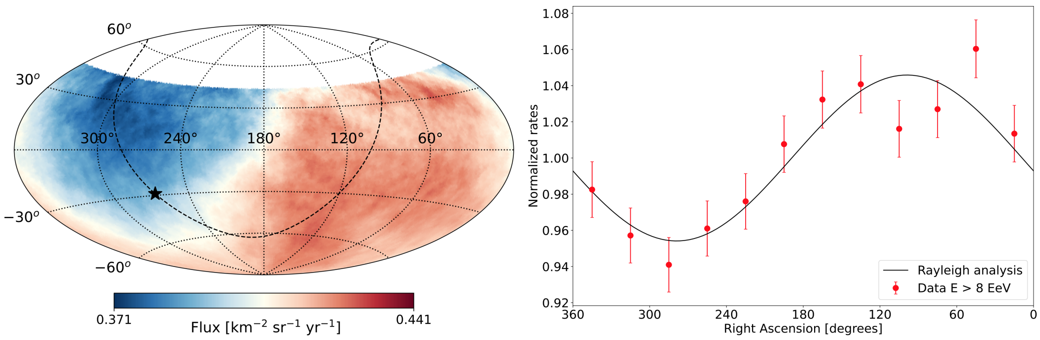

Figure 1: *Left*: Flux of UHECRs above 8 EeV measured at the Pierre Auger Observatory in equatorial coordinates. The solid line represents the Galactic plane and the black star shows the position of the Galactic center. From [2].
Right: Normalized rates over right ascension (red points) with the prediction by the Rayleigh analysis (solid line). From [2].

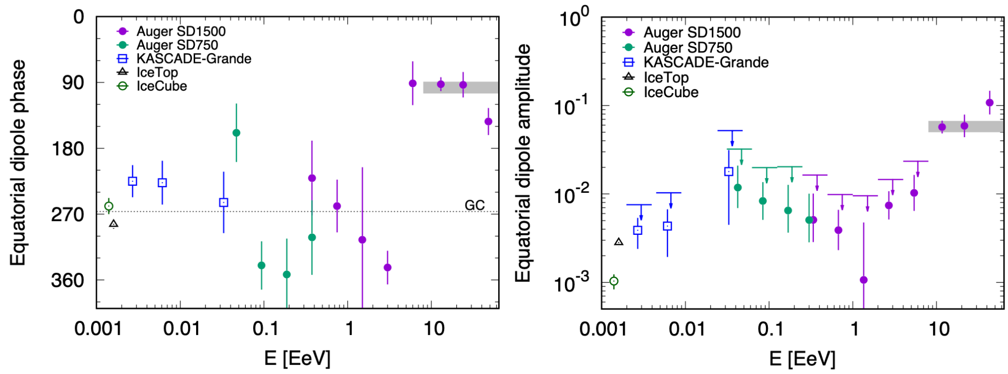

Figure 2: Energy-evolution of the dipole phase *(left)* and dipole amplitude *(right)* measured at the Pierre Auger Observatory given by filled circles. For the amplitude, the 99% confidence upper limits are given in bins with p-values larger than 1%. Results from different experiments are denoted by other markers. From [2].

flux- and significance maps. When constraining the search to the direction of Centaurus A as potential source region [7], the significance is maximized for the same parameters with a post-trial significance of 4σ [2].

3.2 Catalog-based searches

Furthermore, catalog-based searches have been conducted [2, 8]. Here, the measured flux is compared to models containing a catalog contribution in addition to an isotropic distribution. In a simple approach, weight factors are assigned to every extragalactic source candidate representing the prediction for the expected flux, which is assumed to be proportional to electromagnetic emission and includes distant-dependent attenuation factors. The four sets of tested source candidates are based on the near-infrared emission of galaxies (*"all galaxies"*), the radio emission from starburst galaxies (*"SBGs"*), X-rays from active galactic nuclei (*"all AGNs"*) as well as γ-rays from jetted AGNs (*"jetted AGNs"*) [2, 8]. Additionally to the aforementioned free parameters, namely the

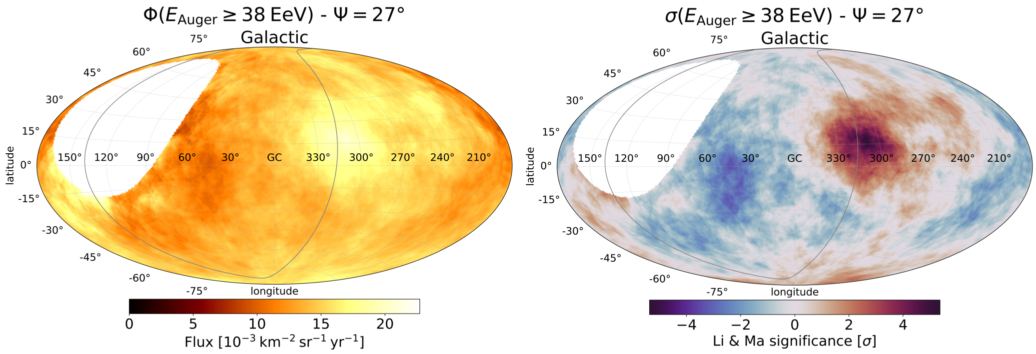

Figure 3: Flux- *(left)* and significance *(right)* maps for the best-fit values, energy threshold and search radius, of the overdensity search in Galactic coordinates. The grey line shows the supergalactic plane. From [2].

energy threshold and search radius, the fraction of the catalog contribution is optimized. The resulting post-trial significances all lie between 3.2σ and 3.8σ [2]. It can be noted that the best-fit energy threshold is the same for all tested catalogs (E_{th} = 38 EeV) and the angular scale is very similar ($\Psi \approx 24°$) [2]. However, the post-trial significances do not allow a distinct preference, although the significance for the SBGs is nominally highest. This is can be attributed to the fact that the overdensity of the Centaurus region is captured by all models, whereas the SBG model adds the subtle overdensity at the Galactic South Pole (NGC253) present in the data, compare to Fig. 3.

3.3 Combination with additional observables

To investigate this correlation further, in [9] a more detailed astrophysical model was used, including more precise propagation effects and a rigidity-dependent magnetic field blurring. A fit to the energy spectrum, maximum shower depth distributions, and energy-dependent arrival directions was applied to distinguish between the γ-AGN catalog and the SBG catalog. The results are based on data up to 2020 and show that a UHECR-flux proportional to γ-rays in the AGN catalog is disfavored [9, 10]. The SBG model on the other hand is favored with 4.5σ over a homogeneous model. Again, the main contribution to the significance can be attributed to the Centaurus region [9]. This study also illustrates the benefit of combining as many observables as possible.

4. Conclusion

The data of the Pierre Auger Observatory reveals a dipolar flux modulation in right ascension with a significance of 6.9σ. The direction of the dipole is pointing away from the Galactic center, suggesting extragalactic origin of UHECRs at these energies. Additionally, an increase of the amplitude with energy is observed. On smaller scales, the data shows a 4σ excess in the direction of the Centaurus region. Regarding further catalog-based searches, no clear distinction between the tested catalogs can be made. Including information on the energy spectrum and mass composition, results in a favoring of a SBG model over the γ-AGN model. In the near future, event-by-event mass estimates using deep-learning techniques [11] and the AugerPrime upgrade [12] will allow for an improved investigation with more information on the rigidities of the particles.

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