20 years of Arrival Direction Studies at the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory is the largest detector for ultrahigh-energy astroparticles in the world. Located in Argentina, it observes cosmic rays from approximately 80% of the sky, including the Galactic Center. The Observatory is sensitive to cosmic rays at energies of approximately 10 PeV up to the highest energies, and significant discoveries in cosmic ray research were made with the collected data; for example, the discovery of a modulation in right ascension above 8 EeV with a current significance of $6.9\,\sigma$, suggesting an extragalactic origin of ultrahigh-energy cosmic rays. Furthermore, searches for localized and intermediate-scale excesses are ongoing. We present the latest results of searches for anisotropy in the Auger data, and we outline future prospects utilizing novel analysis methods and PhaseII of the Observatory.

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1 Introduction

While the age of multi-messenger astronomy has undoubtedly begun, the origin of ultrahigh-energy cosmic rays is *still* one of the great open questions in modern physics. Ultrahigh-energy cosmic rays are ionized nuclei with energies reaching beyond 100 EeV. To accelerate particles to such energies, extreme conditions must be met. Several types of celestial objects or events theoretically qualify as sources of ultrahigh-energy cosmic rays, but none match all the required limits that need to be imposed on their luminosity or the ability to confine particles long enough to accelerate them to the highest energies (for a comprehensive review, see e.g. [1]). Furthermore, no small-scale excesses of ultrahigh-energy cosmic rays have been identified, besides indications of anisotropy below the discovery level [2, 3]. However, there exist regions in the sky that could surpass the $5\,\sigma$ significance level very soon. We present an overview of the most important results of the arrival direction studies that have been conducted with data collected by the Pierre Auger Observatory within the last 20 years.

2 The Pierre Auger Observatory

The Pierre Auger Observatory is the largest detector for ultrahigh-energy cosmic rays in the world [4]. It spans an area of $3\,000\,\mathrm{km}^2$ and has thus – up to now – achieved an unmatched total exposure of over $135\,000\,\mathrm{km}^2\,\mathrm{sr\,yr}$. It was built to observe cosmic rays at $\approx$5 EeV and beyond at full efficiency and is located in the southern hemisphere near Malargüe, Argentina. Its field of view for cosmic rays covers the declinations $\delta \in [45, -90]$, and thus about 80% of the sky, including the center of the galaxy. The observatory employs a hybrid detector setup combining a fluorescence detector system, available in clear moonless nights, and a surface detector, which is operational almost 100% of the time. The two detector systems allow for a cross-calibration (and thus absolute calibration of the energy scale of the surface detector) and yield their own respective advantages; the fluorescence detector has direct access to mass-sensitive observables, while the surface detector is able to collect about 10 times more statistics due to its increased uptime and field of view with respect to the fluorescence detector. Cosmic rays recorded by the surface detector of the Pierre Auger Observatory can be reconstructed within a precision of $\approx 1^\circ$ in terms of their arrival direction in celestial coordinates, and within $\approx$15% in terms of their energy. The intention to built the observatory was to observe the arrival directions and the flux of highest energy cosmic rays, which at the time appeared inconsistent with expectations, and eventually to discover new physics. Over the years, remarkable progress was made using the Pierre Auger Observatory to study ultrahigh-energy cosmic rays. The spectrum of these cosmic rays was discovered to show yet unexplained features [5, 6], while the nuclear mass composition is mixed and is getting constantly heavier with increasing energy [7, 8]. At the same time, a large-scale dipole anisotropy discovered above 8 EeV implies that ultrahigh-energy cosmic rays are of extragalactic origin above these energies [9, 10].

For arrival direction studies, the surface detector data of the Pierre Auger Observatory is used. Well above 100 000 events have been recorded at full efficiency, with a steeply falling spectrum. The data set is composed of *vertical* events, with a zenith angle of $\theta \leq 60^\circ$ in local detector coordinates, and *inclined* events, with zenith angles between $60^\circ < \theta < 80^\circ$. Only the latter cover the sky at the declination $\delta \in [25^\circ, 45^\circ]$. The reconstruction procedure of the inclined and the vertical data are not identical, because the latter needs to take into account the effect of the geomagnetic field. The two data sets are merged and their respective exposure is taken into account accordingly.

3 Small- and Intermediate-Scale Anisotropy Searches

Searches for small-scale and intermediate-scale anisotropies in the sky are conducted at the highest energies, where cosmic rays are expected to be rigid enough to possibly maintain localized excesses after propagating through the extragalactic and galactic magnetic field. Ultrahigh-energy cosmic rays are extremely rare and arrival direction studies have to deal with low statistics[1], but the surface detector data of the Pierre Auger Observatory comprises an unmatched number events at the highest energies. At energies above 32 EeV extensive searches for small-scale excesses have been performed using the available $\sim$2600 ultrahigh-energy cosmic ray events [2]. Since the time of the cited publication, this number grew to $\sim$3000. Excesses are searched using a blind-search analysis, direct correlation with celestial structures, and a search for auto-correlation. In the blind-search analysis the sky is divided into equiareal bins of about $1\,\mathrm{deg}^2$. The significance of a possible excess in each bin is then evaluated by comparing the number of events above an energy E_{th} and within an angular distance ψ against the respective expectation from an isotropic sky. A scan for the most significant excess is performed using the ranges $E_{\mathrm{th}} \in [32\,\mathrm{EeV}, 80\,\mathrm{EeV}]$ in steps of 1 EeV, and $\psi \in [1^\circ, 30^\circ]$ in steps of 1°. The same analysis is performed not only for arbitrary point-like regions in the sky, but also for the galactic center, the galactic plane, and the supergalactic plane. A way to assess possible clustering of cosmic-ray arrival directions, is to count the overall number of event-multiplets whose arrival directions coincide within a radius of ψ (auto-correlation). All p-values obtained in this way are penalized for the number of trials performed by the scan in E_{th} and ψ.

While none of the aforementioned search strategies yield a significant excess, the region around the radio-active galaxy Centaurus A shows an intriguing excess of ultrahigh-energy cosmic rays. The most recent results [13] for the all-sky blind search and the search centered around Centaurus A are listed in Table 1. A skymap showing the results for the blind search for the individual pixels using the best-scan values for E_{th} and ψ is given in Fig. 1.

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[1] An earlier analysis of the Pierre Auger Observatory reporting active galactic nuclei as possible source of ultrahigh-energy cosmic rays turned out to be a fluctuation and was later updated after more data was collected and the signal strength decreased [11, 12].

Table 1: Results of the search for localized excesses.

strategy	E_{th}	ψ	$n_{\text{obs}}/n_{\text{exp}}$	local p-value	post-trial p-value
blind	38 EeV	27°	245/172	1.8×10^{-8}	0.02 (2.1 σ)
Centaurus A	38 EeV	27°	237/169	1.1×10^{-7}	3×10^{-5} (4.0 σ)

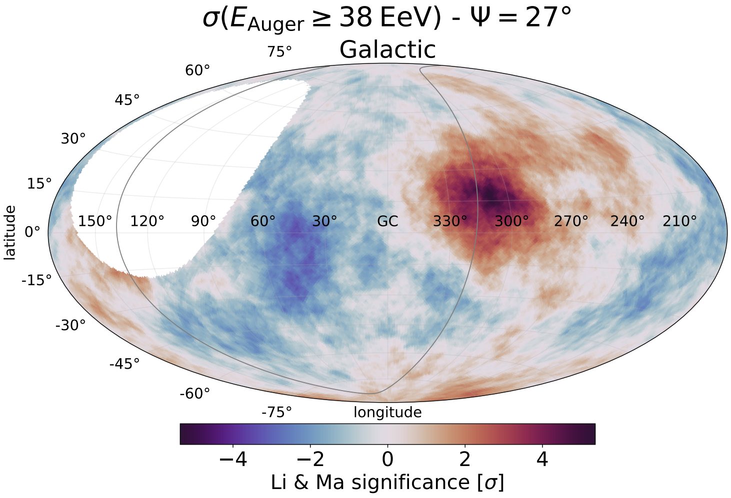

Figure 1: Results of the blind search analysis of the Pierre Auger data, shown in galactic coordinates [13]; the Galactic Center (GC) is located in the center of the coordinate system. The color scale indicates the local excess Li-Ma significance of the number of events above 38 EeV within a 27° radius for each pixel in units of σ. The white region in the top left is the part of the sky that is invisible to the observatory.

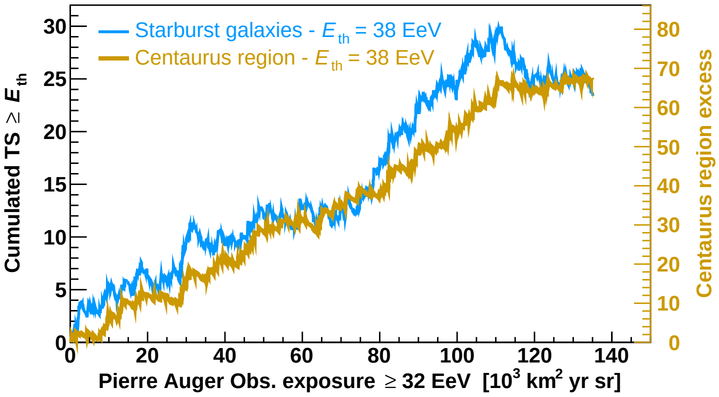

Figure 2: Signal evolution of the test statistics (TS) of the starburst model as well as the Centaurus region excess over integrated exposure [13].

Table 2: Results for the reconstructed dipole in arrival directions of the data of the Pierre Auger Observatory in different energy bins.

E in EeV	n_{events}	$d_\perp$	d_z	d	(R.A., δ)	p-value $\perp$
$4-8$	118 835	$0.010^{+0.006}_{-0.004}$	-0.014 ± 0.008	$0.017^{+0.008}_{-0.005}$	$(91^\circ\pm30^\circ,\ -53^{\circ}{}^{+21^\circ}_{-19^\circ})$	0.15
$8-16$	36 683	$0.057^{+0.010}_{-0.009}$	-0.030 ± 0.014	$0.065^{+0.012}_{-0.009}$	$(92^\circ\pm10^\circ,\ -28^{\circ}{}^{+11^\circ}_{-12^\circ})$	1.2×10^{-8}
$16-32$	10 288	$0.059^{+0.020}_{-0.015}$	-0.07 ± 0.03	$0.094^{+0.026}_{-0.019}$	$(93^\circ\pm18^\circ,\ -51^{\circ}{}^{+13^\circ}_{-13^\circ})$	4.5×10^{-3}
≥32	2 739	$0.11^{+0.04}_{-0.03}$	-0.13 ± 0.05	$0.17^{+0.05}_{-0.04}$	$(143^\circ\pm19^\circ,\ -51^{\circ}{}^{+14^\circ}_{-13^\circ})$	8.4×10^{-3}
≥8	49 710	$0.058^{+0.009}_{-0.008}$	-0.045 ± 0.012	$0.073^{+0.010}_{-0.008}$	$(97^\circ\pm8^\circ,\ -37^{\circ}{}^{+9^\circ}_{-9^\circ})$	7.4×10^{-12}

While the Centaurus region remains the most interesting region in the data, a search for localized excesses around starburst-galaxies indicates almost the same significance. This was examined using an unbinned-likelihood analysis, where events are weighted according to their vicinity to cataloged locations of known extragalactic source candidates[2] [2, 14]. It is tested whether the data in each direction $\mathbf{u}$ can be described by the sum of an isotropic contribution $n_0(\mathbf{u})$ and an anisotropic contribution, so that the total number of events $n_{\text{tot}}(\mathbf{u})$ is given by

$$n_{\text{tot}}(\mathbf{u}) = (1-\alpha)\, n_0(\mathbf{u}) + \alpha\, \frac{\sum\limits_i s_i(\mathbf{u},\Theta)}{\sum\limits_{i,j} s_i(\mathbf{u}_j,\Theta)}, \tag{1}$$

where s_i is the von-Mises-Fisher distribution centered around the position of galaxy i with a smearing angle Θ, and j is the summation index for all sky pixels. The threshold energy E_{th} and the smearing angle Θ are free parameters of the likelihood analysis. The resulting best-fit values are obtained for $E_{\text{th}} = 38\,\text{EeV}$ and are given by $\Theta = 16^\circ{}^{+8^\circ}_{-4^\circ}$ and $\alpha = 9\%^{+7\%}_{-4\%}$. The post-trial p-value is given by 6.6×10^{-5}. The results are of course strongly driven by the excess in the Centaurus region (hosting the starburst galaxy NGC4945), however also the mild excess at the galactic south pole (close to starburst galaxy NGC253) that can be seen in Fig. 1 is expected from the starburst model.

The evolution of the signal for both the excess in the Centaurus region as well as for the coincidence with starburst galaxy locations is depicted in Fig. 2. Both show a stable growth in signal over time on average; at the current rate of data taking, a discovery – should the signal persist – is expected within only a few years at an integrated exposure of approximately $165\,000\,\text{km}^2\,\text{yr}\,\text{sr}$ and an excess of about 85 events in the Centaurus region, or a test statistic at approximately 33 for the starburst model.

4 Large-Scale Anisotropy

Searches for large-scale anisotropy can be conducted at lower energies, where particles suffer from considerable deflection by the (extra-)galactic magnetic field. Given the rotation of the Earth, the exposure of the observatory is flat[3] in right-ascension, R.A.; this means that a modulation of the event rate in R.A. indicates a signal of anisotropy with relatively little systematic uncertainty. The amplitude of such modulations translates to the perpendicular (equatorial East-West, $\perp$) dipole amplitude in celestial coordinates. At the same time, the azimuthal angle of the arrival direction of a cosmic ray in local coordinates of the observatory is sensitive to the parallel (equatorial North-South, z) amplitude of a dipole anisotropy. Results from several experiments show a non-zero perpendicular dipole amplitude, $d_\perp$, with the phase of the modulation pointing towards the Galactic Center, indicating the galaxy could be the main origin of cosmic rays up to energies of $E \simeq 1\,\text{EeV}$. Above $4\,\text{EeV}$, the direction of the cosmic ray dipole shifts away from the Galactic Center by more than 100°, which is strong evidence for the extragalactic origin of ultrahigh-energy cosmic rays.

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[2] In the same manner as the search for coincidence arrival directions with nearby starburst galaxy locations, catalog-based searches were performed for active galactic nuclei observed in hard X-rays from the Swift-BAT catalog, jetted active galactic nuclei from Fermi 3FHL, and all nearby galaxies of the 2MASS all-sky survey.

[3] Second-order effects such as the uptime of the observatory that propagates into the exposure are taken into account.

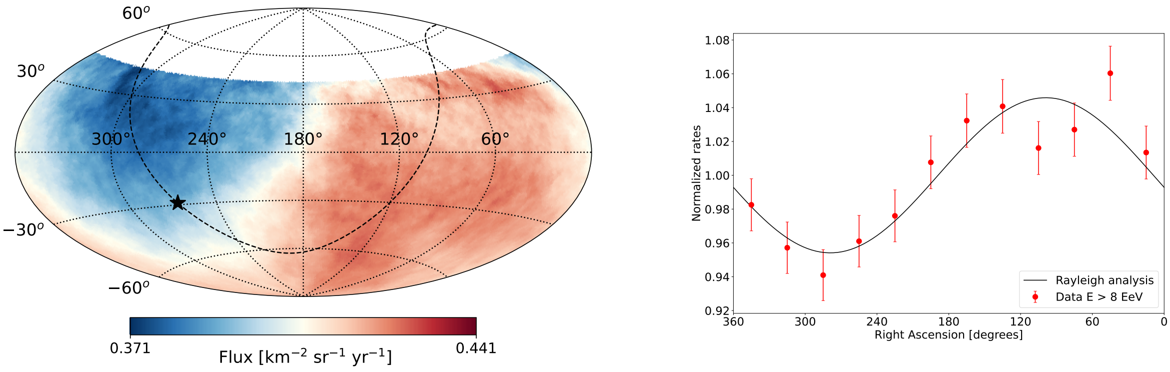

Figure 3: **Left:** Map of the arrival direction data of the Pierre Auger Observatory above a primary energy of 8 EeV, using a 45°-top-hat smoothing, showing a large-scale dipole anisotropy; the arrival directions are depicted in equatorial coordinates, with the Galactic Center marked as a black star. **Right:** Modulation of the event rate as a function of R.A., the red markers show the average rate alongside the respective statistical uncertainty, the black line depicts the sinusoidal modulation derived from a Rayleigh analysis.

The large-scale dipole anisotropy above 8 EeV that was reported in 2017 by the Pierre Auger Observatory [9, 10] has since even increased in significance, currently it is at the $6.9\,\sigma$ level. The energy bin at 8 EeV – 16 EeV is now above discovery level on its own, with a significance of $5.7\,\sigma$. Updated numbers for the reconstructed dipole direction and amplitude are given in Table 2. The data of the Pierre Auger Observatory above 8 EeV of primary energy, visualized using a 45° top-hat smoothing is shown in Fig. 3 in Equatorial coordinates, alongside the modulation in R.A.

5 Mass-Composition (enhanced) Anisotropy and PhaseII

The Pierre Auger Observatory confirmed that the mass composition of ultrahigh-energy cosmic rays is mixed and is becoming heavier with increasing primary energy [7, 8]. The absolute average of the nuclear mass as well as the exact composition, are, however, subject to research and debate. Furthermore, the mass composition at the highest energies is not directly accessible, because of the lack of statistics in fluorescence detector data. Nevertheless, it is tempting to try and disentangle possibly high-rigidity cosmic rays from a less rigid component to conduct arrival direction studies with only those particles that are less deflected by the (extra-)galactic magnetic field, or search for compositionally distinguishable regions in the sky.

At intermediate energies ($E \simeq 8\,\text{EeV}$) the number of events recorded by the fluorescence detectors is sufficient to perform a statistical analysis on the observable sky. In recent years, an indication of a possible mass-composition emerged [15]. Ultrahigh-energy cosmic rays whose arrival directions point towards the Galactic Plane could have a heavier nuclear mass on average than others. Recent changes in the reconstruction algorithm, however, seem to have eliminated a systematic effect that was exaggerating the signal strength and its growth rate over time was reduced [16]. At this point the precise cause of this effect is under investigation; if the anisotropy is real, at the current rate of signal growth, the $5\,\sigma$ confidence level would be expected to be reached in 2035.

Recent developments in the reconstruction of the surface detector data, such as machine-learning techniques [17] and likelihood fits using advanced shower models [18], will make it possible to estimate the nuclear mass of ultrahigh-energy cosmic rays also in the surface detector data set of the Pierre Auger Observatory. Rather than examining the average mass composition in regions of the sky, a possible way to enhance signals of anisotropy (or to suppress an isotropic background component) is to select and deselect events based on a nuclear mass-sensitive proxy observable and then repeat the aforementioned analyses. In this respect there is ongoing research within the Pierre Auger Collaboration. Furthermore, the recently completed upgrade of the Pierre Auger Observatory, which inaugurated *PhaseII* of the observatory, called AugerPrime [19], will allow for an even more precise estimation of nuclear mass-sensitive observables in the surface detector data. Thus, using a rigidity-enriched data set, anisotropies in the arrival directions of ultrahigh-energy cosmic rays could soon be detected within the PhaseII data of the Pierre Auger Observatory.

Furthermore, while the Pierre Auger Observatory is mainly designed as a cosmic ray detector, it is also capable of detecting ultrahigh-energy photons and neutrinos. In this case, point sources could be identified almost immediately, given sufficient statistics. However, while searches for photons and neutrinos are ongoing, up to now no such particles were confirmed to be detected [20, 21].

6 Summary

We present a brief overview of the last 20 years of arrival direction studies at the Pierre Auger Observatory as well as the most significant results. While the origin of ultrahigh-energy cosmic rays is still unknown, tremendous progress has been made in narrowing the corridor of possible hypotheses. There is strong evidence that ultrahigh-energy cosmic rays are of extragalactic origin, provided by a large dipole anisotropy above 8 EeV pointing away from the Galactic Center.

At the same time, an excess of events around Centaurus A is observed at the $4.0\,\sigma$ significance level. The excess in the Centaurus region also contributes to an excess of events coinciding with the locations of nearby starburst galaxies, which is, however, less significant at the moment ($3.8\,\sigma$). These (and further) scenarios may be either confirmed or ruled out as a dominant source of ultrahigh-energy cosmic rays by the Pierre Auger Observatory within the next few years, either by the accumulation of more (and improved) data over time, or by employing novel analysis techniques.

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