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# Latest results and future prospects of the pierre auger observatory

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**Abstract.** The Pierre Auger Observatory is the largest observatory for the detection of ultra high energy cosmic rays (UHECRs). It allows a detailed measurement of the energy spectrum, the mass composition and the arrival directions of the primary cosmic rays with energies above 100 PeV. The data collected with the Pierre Auger Observatory show a suppression of the cosmic ray flux at energies above 40 EeV but the nature of this suppression is still unclear; according to theoretical prediction it could be caused by the interaction of cosmic rays with the CMB or by energy limitations of the cosmic rays sources. Another puzzle concerns the specific origin of UHECRs. Some indications can be obtained from studying the distribution of their arrival directions. Recently a dipole anisotropy has been observed which indicates that UHECRs have an extragalactic origin. I will present the recent results of the Pierre Auger Observatory about the energy spectrum, the mass composition and the arrival directions of UHECRs. I will also discuss the future prospects of the Observatory.

## 1. Introduction

Since 2004, in the province of Mendoza in Argentina is operational the largest facility to detect cosmic rays built so far; namely the Pierre Auger Observatory [1]. It combines, in order to measure extensive air showers, a Surface Detector (SD) and a Fluorescence Detector (FD). The Surface Detector is composed by about 1600 water-Cherenkov detector stations deployed on a triangular grid with a spacing of 1500 m (SD-1500) covering a total area of about 3000 km<sup>2</sup>. This area is overlooked by 24 fluorescence telescopes in 4 FD buildings located on the boundary of the observatory.

In order to lower the energy threshold, 61 surface detector station were added covering 23.5 km<sup>2</sup> on a 750 m grid (SD-750) named *infill array*. To detect lower energy showers three additional fluorescence telescopes pointing at higher elevations are located near one of the FD sites (Coihueco); these three telescopes are named *HEAT*. In Fig.1 and Fig.2 are presented the layout of the Pierre Auger Observatory, showing the Water-Cherenkov Detectors (WCD, black dots) and the azimuthal field of views of the 27 fluorescence telescopes (blue and red lines), and a photograph of one of the upgraded WCD stations (see Section 5), with a FD site visible in the background.

The simultaneous detection of air showers by both the surface array and fluorescence telescopes was conceived to exploit the *hybrid* concept. The SD collects showers with a duty cycle of

§[http://www.auger.org/archive/authors\\_2019\\_05.html](http://www.auger.org/archive/authors_2019_05.html)



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$\approx 100\%$ , whereas the FD can operate only during clear moonless nights with a duty cycle of  $\approx 15\%$ . Only a small fraction of the SD showers are actually reconstructed by the FD.

The hybrid technique represents a breakthrough in the detection of UHECRs since it allows the system to have the same energy scale in the SD and the FD and to derive the energy spectra entirely data-driven and free of model-dependent assumptions in hadronic interactions at high energies.

I will summarize some recent results and the future prospects of the Pierre Auger Observatory. For more information about the Pierre Auger Observatory see [2], [3] and [4].

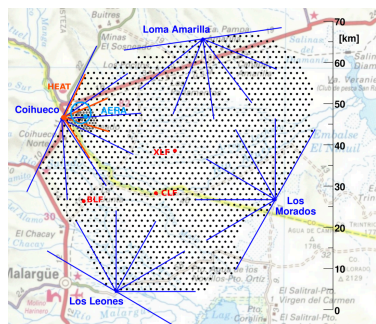


Figure 1: Layout of the Pierre Auger Observatory, showing the WCD (black dots) and the azimuthal field of views of the 24+3 FD (blue and red lines).



Figure 2: Photograph of one of the (upgraded) WCD stations, with a FD site visible in the background.

## 2. Energy spectrum

In order to measure the cosmic ray spectrum at the highest energy and with high precision, the Pierre Auger Collaboration exploited all data collected by the observatory, divided into four different samples. A first sample is obtained with the SD-1500 for showers with zenith angle  $\theta < 60^\circ$ . A second sample is obtained with the SD-750 infill array for showers with zenith angle  $\theta < 55^\circ$ . For more inclined showers with zenith angles ( $60^\circ < \theta < 80^\circ$ ) a different reconstruction procedure is needed. A fourth set of data is made of events observed by both SD and FD that are named hybrid events.

To derive the spectra, the applied analysis method is entirely data-driven. For the SD data sample, we convert the measured shower sizes to a size estimator that is independent of zenith angle by using the method of constant intensities cuts (CIC). Attenuation-corrected shower sizes are used as energy estimates after calibrating them with the calorimetric energy available for hybrid events.

Combining all spectra with a maximum likelihood method we obtain a spectrum which extends over more than three energy decades as depicted in Fig.3. The overall systematic uncertainty of the energy scale is 14% [2].

Fig.3 presents some characteristic features; the inflection point around  $10^{17}$  eV is known as second knee, while the dip at about  $6 \cdot 10^{18}$  eV is usually referred to as the ankle. Moving higher in energy, the spectrum become flatter and undergoes a strong suppression above an energy of  $5 \cdot 10^{19}$  eV. The energy at which the integral spectrum drops by a factor of two in comparison to a power law expectation is  $E_{1/2} = (14 \pm 4) \cdot 10^{18}$  eV.

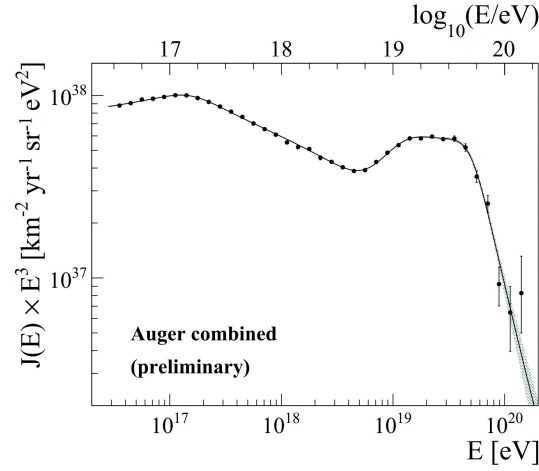


Figure 3: Combined energy spectrum obtained from different measurements. [2]

### 3. Mass composition

With the FD, measuring the depth of the maximum in the energy deposit of shower particles ( $X_{\max}$ ), it is possible to address the mass composition.

The sensitivity of  $X_{\max}$  to mass composition relies on the fact that showers from heavier nuclei develop higher in the atmosphere and their profiles fluctuate less, while showers from lighter nuclei develop deeper in the atmosphere and their profiles fluctuate more.

In Fig.4 are reported the  $X_{\max}$  and  $\sigma(X_{\max})$  measurements for hybrid showers with energies larger than  $10^{17.8}$  eV [3]. Up to a certain energy the mass composition is getting lighter and then becomes heavier above.

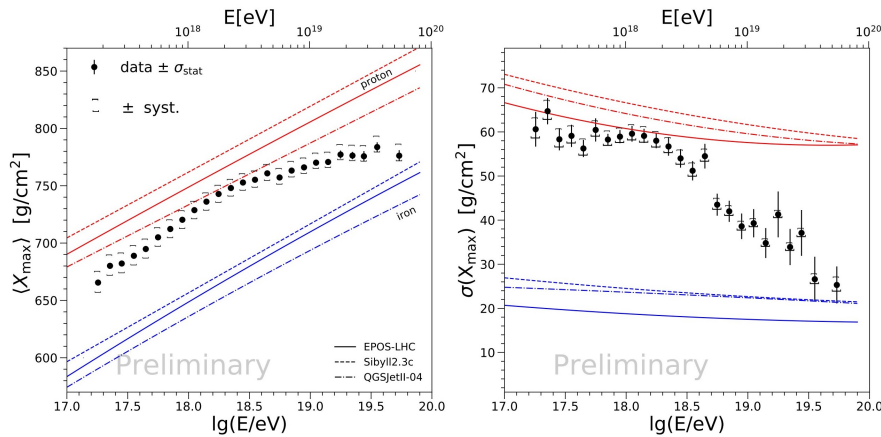


Figure 4: On the left the mean of the  $X_{\max}$  distribution and on the right the  $\sigma(X_{\max})$  distribution measured by Auger, as a function of energy. Air-shower simulations for protons and iron primaries are also reported. [3]

The value of the elongation rate, obtained fitting the variation of  $\langle X_{\max} \rangle$  per decade of energy, is  $77 \pm 2(stat)$  g cm<sup>-2</sup>/decade below  $E_0 = 10^{18.32 \pm 0.03}$  eV, and becomes  $26 \pm 2(stat)$  g cm<sup>-2</sup>/decade above this energy [4]. In the case of a constant mass composition, simulations

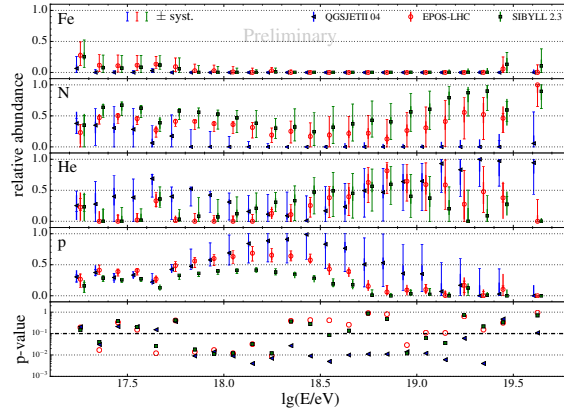


Figure 5: Results from a fit of the  $X_{\max}$  distributions with a superposition of H, He, N and Fe induced air showers.

predict a value of the elongation rate that is about  $60 \text{ g cm}^{-2}/\text{decade}$  for the total energy range. Also the evolution of  $\sigma(X_{\max})$  shows a trend of a changing mass composition from light to intermediate-heavy; see Fig.4 (right side of figure).

The  $X_{\max}$  measurements and distributions allow a possible interpretation of mass composition by studying the energy evolution of the first two moments of  $\ln A$  [6, 8] and of the fractions of four mass groups (H, He, N, Fe) from the fit of the  $X_{\max}$  distributions [8, 9]. Fig.5 shows the results from a fit of the  $X_{\max}$  distributions with a superposition of H, He, N and Fe induced air showers. The bottom panel indicates the goodness of the fits ( $p$ -values).

The composition at high energies is dominated by different elemental groups, starting from protons below the *ankle* and going through helium to nitrogen with increasing energy. Due to the small values of the  $X_{\max}$  dispersion this evolution occurs with limited mass mixing. The interpretation of these data depends upon the hadronic interaction models.

#### 4. Anisotropy studies

Different anisotropy studies have been performed by the Auger Collaboration, among them the observation of a large-scale anisotropy in the arrival directions of cosmic rays for energy larger than  $8 \cdot 10^{18} \text{ eV}$  [10].

The Auger Collaboration analysed the amplitude of the first harmonic in right ascension by dividing the directional data in two energy bins; from  $4 \text{ EeV} < E < 8 \text{ EeV}$  and  $E \geq 8 \text{ EeV}$  for a total exposure of  $76,800 \text{ km}^2 \text{ sr yr}$ .

The right ascension anisotropy found in the first energy bin has an amplitude  $0.5^{+0.6}_{-0.2}\%$  while for energy  $E \geq 8 \text{ EeV}$  the amplitude is  $4.7^{+0.8}_{-0.7}\%$ . The events from  $4 \text{ EeV} < E < 8 \text{ EeV}$  follow an arrival distribution which is consistent with isotropy while for  $E \geq 8 \text{ EeV}$  a significant anisotropy was found, with a  $p$ -value of  $2.6 \cdot 10^{-8}$  under the isotropic null hypothesis.

The high energy 3D dipole, obtained combining the first-harmonic analysis in right ascension with a similar one in the azimuthal angle, has a direction in galactic coordinates  $(l, b) = (233^\circ, -13^\circ)$ , which correspond to about  $125^\circ$  away from the Galactic Centre, indicating that these UHECR have an extragalactic origin.

The level of significance for this dipole is more than a  $5.2\sigma$  with an amplitude of  $6.5^{+1.3}_{-0.9}\%$ . Fig.6 shows the sky map in galactic coordinates with the cosmic-ray flux for  $E \geq 8 \text{ EeV}$  smoothed with a  $45^\circ$  top-hat function. The cross indicates the measured dipole direction while the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution

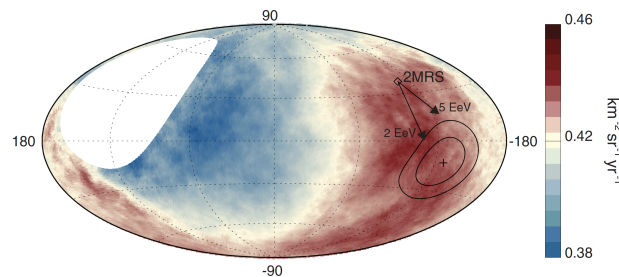


Figure 6: Sky map in galactic coordinates with the cosmic-ray flux for  $E \geq 8$  EeV. See text.

is also indicated and the arrows show the deflections expected for a particular model of the galactic magnetic field on particles with  $E/Z = 5$  or 2 EeV.

Because of the relative motion of cosmic rays with respect to the rest frame of background radiation some large scale anisotropy is expected but the expected amplitude for that effect is below a percent level.

## 5. AugerPrime

A lot of progress in the understanding of the nature and the origin of UHECRs have been made in these last decades, but more accurate and extended information about the mass composition of the primaries is required. This applies particularly for energies above 40 EeV where the intrinsic duty cycle of the FD and the scarce accuracy of the composition sensitive methods based on the SD data do not allow one to build a consistent picture. To improve the mass composition in the whole energy range the Pierre Auger Observatory is currently in an upgrading phase [11]. The AugerPrime foresees equipping each SD with a top scintillator layer in order to sample shower particles by both scintillators and Water-Cherenkov Detector (WCD) which have different responses to the muonic and electromagnetic components. Combining the two measurements it will enable disentangling these two components providing an estimate of both, mass and energy of the shower, on an event-by-event basis. The two detectors will be read out by a new faster and more accurate electronic sampling at 120 MHz. Also, AugerPrime will have an extra small photomultiplier installed in each tank in order to extend the dynamic range to more than 32 times the largest signals currently measured. AugerPrime will provide data with a duty cycle of almost 100%.

Other improvements of the Pierre Auger Observatory are the muon detector AMIGA [12] buried underground in the infill array and the increasing of the current FD duty cycle by  $\sim 50\%$ , extending the operational mode to periods with a higher night sky background. The deployment of the Surface Scintillator Detector (SSD) is expected to be finished in 2020.

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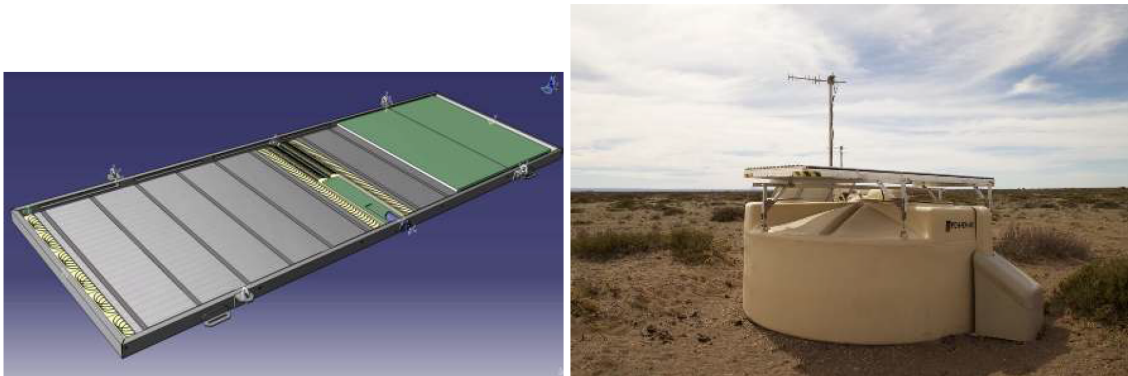


Figure 7: On the left the layout of the SSD. On the right one station of the AugerPrime composed by a WCD and a SSD

[12] A. Aab *et al.*, (2016) JINST **11** no.02, P02012.