Overview

Energy spectrum and mass composition of cosmic rays from Phase I data measured using the Pierre Auger Observatory

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Abstract

The Pierre Auger Observatory concluded its first phase of data taking after seventeen years of operation. The dataset collected by its surface and fluorescence detectors (FD and SD) provides us with the most precise estimates of the energy spectrum and mass composition of ultra-high energy cosmic rays yet available. We present measurements of the depth of shower maximum, the main quantity used to derive species of primary particles, determined either from the direct observation of longitudinal profiles of showers by the FD, or indirectly through the analysis of signals in the SD stations. The energy spectrum of primaries is also determined from both FD and SD measurements, where the former exhibits lower systematic uncertainty in the energy determination while the latter exploits unprecedentedly large exposure. The data for primaries with energy below 1 EeV are also available thanks to the high-elevation telescopes of FD and the denser array of SD, making measurements possible down to 6 PeV and 60 PeV, respectively.

Conclusions

In its Phase I, the Pierre Auger Observatory successfully measured, using several techniques, basic characteristics of UHECRs, namely their energy spectrum and the mass composition. The energy spectrum clearly exhibits features colloquially named the *low-energy ankle*, the 2^{nd} *knee*, the *ankle*, the *instep* and a steep suppression above 47 EeV. The mass composition seems to evolve according to Peters' cycle, being dominated by protons around 1 EeV, followed by helium nuclei around 10 EeV and the CNO group at about 50 EeV and above. Nevertheless, this inference heavily depends on predictions of high-energy interaction models and will be precised with our knowledge of these interactions.

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Energy spectrum

Energy spectrum

- At the Pierre Auger Observatory, the spectrum is estimated using **six different methods** shown in Figs. 1 and 3.

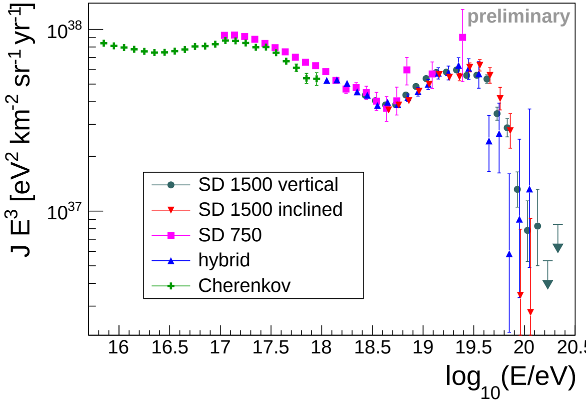

Figure 1: Energy spectrum of cosmic rays from FD (hybrid, Cherenkov) and SD data.

- **Individual estimates are combined**, taking into account residual systematic differences between spectra.

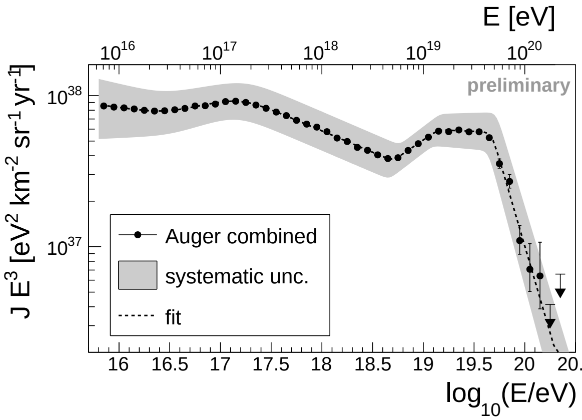

Figure 2: Combined spectrum. Common systematic uncertainty is driven by 14% uncertainty in the energy scale.

- Using the function in Eq. (1), the combined spectrum can be described by following fit values or **features**.

$$J(E) = J_0 \left(\frac{E}{10^{16}\ \text{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}, \qquad j = i+1, \tag{1}$$

normalization	$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}$ km^{-2}sr^{-1}yr^{-1}eV^{-1}	
		$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
low-energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV	$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
2^{nd} *knee*	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV	$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV	$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
instep	$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV	$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
suppression	$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV	$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

Table 1: Parameters of the best fit of Eq. (1) to the combined spectrum. The first uncertainty is statistical and the second one systematic. Transition width parameters were fixed to $\omega_{01} = \omega_{12} = 0.25$ and $\omega_{23} = \omega_{34} = \omega_{45} = 0.05$.

- Presence of the 2^{nd} *knee* at $(2.30 \pm 0.50_{\text{stat.}} \pm 0.35_{\text{syst.}}) \times 10^{17}$ eV was confirmed by the SD 433 m measurement.

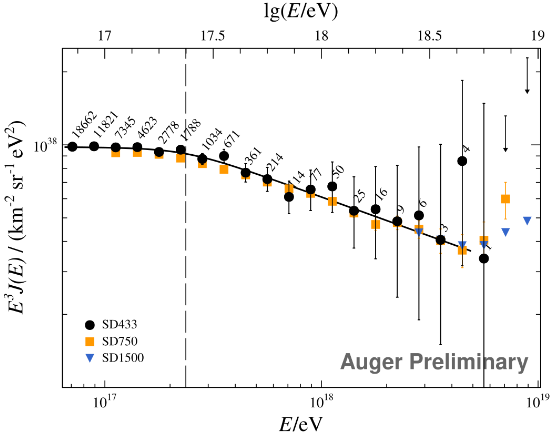

Figure 3: The 2^{nd} *knee* measured using the SD 433 m array.

- **References:**

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Mass composition

Mass composition

- In Phase I of the Observatory measurements, we mostly rely on **the depth of shower maximum, $X_{\max}$**.

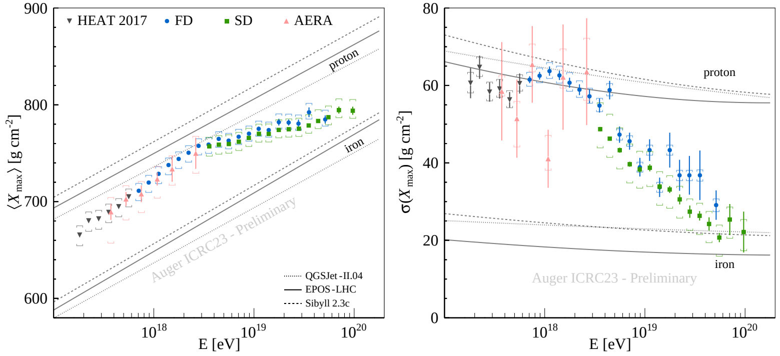

Figure 4: Average and standard dev. of $X_{\max}$ from FD (FD, HEAT 2017), SD deep learning, and radio (AERA) data.

- Using particular high-energy interaction model, the **$X_{\max}$ moments can be translated to $\ln A$ moments**.

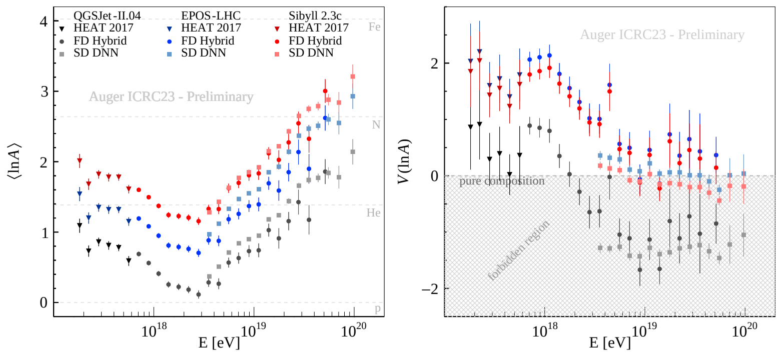

Figure 5: First two central moments of $\ln A$ calculated using contemporary models of hadronic interactions.

- **Fractions of primary mass groups** are derived by fitting model predictions to full $X_{\max}$ distributions in energy bins.

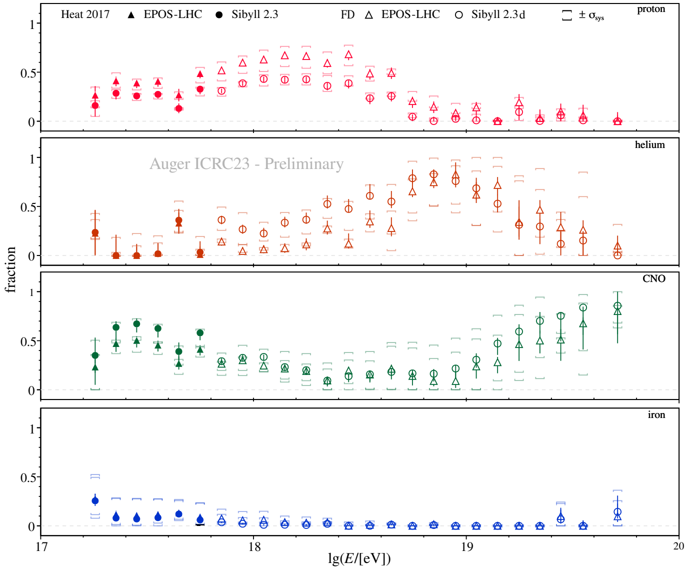

Figure 6: Primary fractions derived from the FD-measured $X_{\max}$ distributions.

- The interpretation of $X_{\max}$ in terms of the mass number is heavily influenced by our (lack of) knowledge of hadronic interactions at ultra-high energies.
- **An unphysical region of negative $\ln A$ variances** is shown by gray band in Fig. 5. Data-points in this region stress the incompatibility between measured data and predictions of models of hadronic interactions.
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