Snowmass2021 - Letter of Interest

Probing the highest energy frontier with UHECRs

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: The existence of protons and nuclei with kinetic energies at the joule scale – up to 10^{20} eV, known as ultra-high-energy cosmic rays (UHECRs), is one of the most intriguing unsolved problems in modern astrophysics. Clarifying their origin would lead to understanding the most energetic and violent phenomena in the Universe. Precise measurement of their energy spectrum is of special importance: its absolute scale and shape are related to the distribution of the sources, to the production and acceleration mechanisms in non-thermal regions of high-energy phenomena, and to the propagation from the sources to the Earth. Moreover, the energy range above a few 10^{20} eV remains unexplored, due to the limited exposure of the current experiments. Investigating this region will allow new physics to be explored, such as the possibility of Planck scale Lorentz invariance violation (LIV). In this Letter of Interest, we summarize the experimental progress in the last decades, the present status, and prospects and proposals for future studies.

The physics case

Soon after the discovery of the cosmic microwave background (CMB) radiation, Greisen, and Zatsepin and Kuzmin independently, predicted that the cosmic-ray spectrum should be strongly suppressed at far distances from their sources somewhere below 10^{20} eV due to energy loss processes with CMB photons [1,2]. The so-called GZK suppression was not experimentally confirmed for more than fifty years due to the extremely low flux of UHECRs: about one particle per year per 100 square kilometers. The Pierre Auger Observatory (Auger) [3] and Telescope Array (TA) [4,5] are the largest CR observatories ever built and cover areas of 3 000 km^2 and 700 km^2 respectively. The two observatories are based on the so-called hybrid approach, where the bulk of the events is obtained with an array of detectors deployed on the ground and the energy scale is determined calorimetrically with a sub-sample of events also detected with fluorescence telescopes. In this way, the spectrum reconstruction is almost model independent and avoids relying on hadronic model extrapolations at these extreme energies. The measurements of the energy spectrum are based on the combination of different techniques [6–16] and span over a large range in energy, from $10^{15.5}$ eV up to above 10^{20} eV. They are illustrated in Fig. 1 in the common energy range of both experiments [17,18], and agree within systematic uncertainties ($\pm 14\%$ for Auger [19] and $\pm 21\%$ for TA [20] for the absolute energy scale).

The spectra can be superposed if an energy-independent shift of $+5.2\%$ and -5.2% is applied to Auger and TA data respectively. A possible tension however remains above 5×10^{19} eV, where an additional 10% per decade is needed above 10^{19} eV to bring the spectra in agreement [21]. The energy spectrum can be described by a sequence of power laws with spectral indexes changing from $\gamma \approx 2.9$ to ≈ 3.3 (at $\approx 10^{17}$ eV) and to ≈ 2.6 (at $\approx 5 \times 10^{18}$ eV). An additional steepening has been recently measured at the Auger observatory at $\approx 10^{19}$ eV [7], while a flux suppression (where γ increases to ≈ 5) has been observed beyond any doubt by both collaborations above $\approx 5 \times 10^{19}$ eV. The spectral features and the flux scale are tracers of the processes happening at the sources and during propagation. They are important complementary information to the mass composition and arrival direction of cosmic rays needed to shed light on the origin of UHECRs. The distribution of UHECR arrival directions is almost uniform, with a small, but significant, dipole component [22,23] observed by Auger, and an event clustering [24] observed by TA. Neither of them are correlated with Galactic objects or the Galactic plane, strongly suggesting an extragalactic origin of UHECR. In line with this interpretation, evidence for anisotropy at the intermediate scale correlated with the direction of local extragalactic sources has been also reported by Auger and TA [25–28]. As for the mass composition, the Auger and TA measurements of $X_{\max}$, the main mass-sensitive observable of cosmic ray showers in the atmosphere, are found to be in very good agreement to within their uncertainties when corrected for detector effects [29–33]. The composition measured by the two experiments [34] shows that a light composition is present around $\sim 10^{18}$ eV. The Auger measurement [35,36] shows that the mass becomes progressively heavier towards higher energies, while the TA experiment [37,38] is currently collecting enough

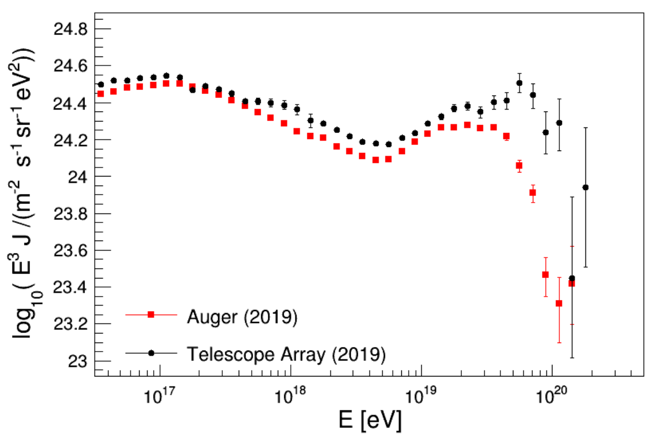

Figure 1: The energy spectra measured by the Pierre Auger [17] and Telescope Array [18] collaborations. Only statistical uncertainties are shown.

exposure to allow, in the near future, disentangling a heavy from a pure proton component. Both experiments currently lack the required statistics to determine the mass composition in the flux suppression region.

The path to new discoveries

Origin of the flux suppression. The interpretation of the UHECR flux suppression above 5×10^{19} eV is still open. It is unclear if the dominant cause for the steepening is related to the maximum acceleration energy at the sources, to the energy loss processes during propagation, or to a combination of both effects[39,40]. Upgrades of the Pierre Auger Observatory[41] and of the Telescope Array[42] endeavor to answer this question. The Telescope Array will increase its exposure by a factor 4, while the Auger Prime upgrade will improve the sensitivity to composition of its surface detector by adding scintillators and radio antennas to the water Cherenkov detectors. High statistics combined with mass-composition information will be fundamental to test the origin of the suppression.

Energy spectra for different regions of the sky. Another challenge in UHECR studies is to determine the energy spectrum in different regions of the sky. Attempts in this direction have been made by both Auger and TA, by dividing their respective field-of-view in different declination bands. No significant differences were observed so far[6,7], though an indication for a higher cutoff energy in the north polar cap $+24.8^\circ < \delta < +90.0^\circ$ than in the equatorial band $-16.0^\circ < \delta < +24.8^\circ$ has been reported in TA data[18]. A possible change of the energy spectrum in the different regions of the sky could be further investigated by combining the results of the two experiments. However, this study remains limited by the 10% difference in the absolute energy scales. A joint working group is working to understand these differences[21,43–46]. A complementary joint effort aims to deploy seven independently-operated Auger stations, placed on the typical Auger hexagonal grid, at the TA site[47–50]. This will help cross-calibrate the two experiments by measuring the same air showers with the two different surface detector types.

The energy spectrum for different mass groups. The combination of flux and primary composition measurements will allow mass-enhanced anisotropy studies to be performed, so as to increase the chance of source identification, providing hence strong constraints on the production mechanisms[7]. Due to propagation effects, measuring a significant proton component at the highest energies would hint to the presence of a local UHECR source. Moreover, measuring the energy spectra for different mass groups in the flux suppression region has a direct implication on multi-messenger studies and on predictions for the cosmogenic neutrino flux.

Beyond 10^{20} eV. A new hardening in the flux suppression of the energy spectrum could indicate the presence of a local source capable of accelerating particles at these energies[51] and would provide new insights on the understanding of the mechanisms responsible for the acceleration of the highest-energy CRs[52]. A "recovery" of the spectrum above 10^{20} eV has been predicted[53] in the context of Lorentz invariance (LI) violation. Measurements in this region will possibly test the frontier of particle acceleration in the Universe, and new physics as well. Some quantum gravity theories suggest that, at very high energies related to the Planck scale, LI might be weakly broken[54] or just modified preserving the space-time isotropy and homogeneity[55,56]. Observation of cosmic rays at such extreme energies together with their mass identification will be of primary interest in probing the space-time structure[57] and investigating different scenarios[58–63].

In the future, next-generation experiments will need to gain at least an order of magnitude in exposure to probe the UHECR spectrum beyond the flux suppression. New giant ground arrays will use a variety of detection techniques, including radio[64], fluorescence[65], surface detectors[66] or a combination of them, while space-based, wide field-of-view observatories will use the fluorescence technique to detect UHECR extensive air showers developing in the Earth's atmosphere[67–69].

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