# On the challenging problem to estimate the energy of the Ultra High Energy Cosmic Rays

*Valerio* Verzi[1,*]

[1]INFN, Sezione di Roma “Tor Vergata”, via della Ricerca Scientifica 1, Roma, Italy

**Abstract.**
Ultra High Energy Cosmic Rays (UHECRs) are rare nuclei that collide in the atmosphere with energy larger than $10^{18}$ eV. In this contribution we critically review the experimental techniques for estimating their energy, trying to address current limitations and potential improvements that can be developed in the coming years.

## 1 Introduction

One of the main problems in the study of UHECRs is the measurement of the energy of the primary particle. The main limitation of experiments using a surface detector array is the need to analyze the recorded signals through Monte Carlo (MC) simulations, because they rely on hadronic interaction models at energies higher than those explored by existing accelerators that, given the non-perturbative nature of QCD, are affected by large and unknown uncertainties.

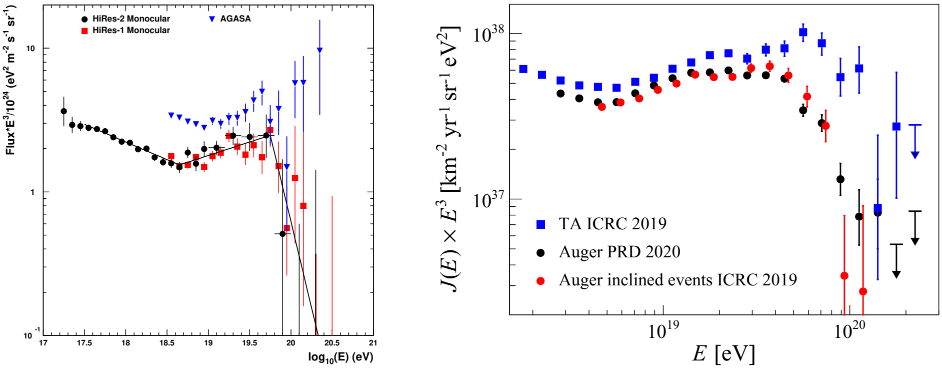

**Figure 1.** Left panel: energy spectrum measured by AGASA [1] and Hires [2]. Right panel: energy spectrum measured by TA [3] and Auger [4, 5].

This problem explains the large discrepancy between the energy spectrum measured in the early 2000s by the AGASA [1] and Hires [2] experiments shown in the left panel of Fig. 1. AGASA was an array of plastic scintillator detectors using simulations to obtain the shower energy, while Hires used the fluorescence detection technique which measures the longitudinal profile of the energy deposit providing a calorimetric estimate of the primary energy. The large discrepancy between the AGASA and Hires fluxes was due to a mismatch

---

[*] e-mail: valerio.verzi@gmail.com

in the energy scales of even more 30%[1]. The wrong energy estimation combined with the low statistics brought AGASA to claim that at the highest energies there was not the Greisen-Zatsepin-Kuz'min (GZK) suppression evoking the possibility to have new physics beyond the SM of the interactions. On the contrary the suppression was observed by Hires [2].

In order to encompass the problem of the energy determination, the modern UHECRs observatories are equipped with both a fluorescence detector (FD) and a giant surface detector (SD) that extends several orders in magnitude in comparison to previous experiments. With this hybrid system, the tiny flux of UHECRs are studied with the high efficiency of the SD and with a calorimetric energy scale provided by the FD, the latter being operative only during moonless and clear nights with a duty cycle of about 10%. The calibration of the SD signals againts the FD energies is done analysing the (hybrid) events detected simultaneously by the two detectors. The UHECR hybrid detectors nowadays operative are the Telescope Array (TA) [3] in Utah (U.S.) and the Pierre Auger Observatory [4] in Argentina. The energy spectra measured at the two observatories are shown in the right panel fig. 1. Given that for both detectors the energy scales are calorimetric one should expect a good agreement within the fluxes. This is certainly true below the suppression, but at the highest energies there is a significant difference. The Hires spectrum is in fairly good agreement with the Auger and TA ones, but does not help to accurately characterize the energy region of the suppression, given the limited statistics available with the fluorescence telescopes.

## 2 Energy estimation of UHECRs at the Pierre Auger Observatory and the Telescope Array

The differences in energy spectrum measurements by Auger and TA have been the subject of a detailed study by a Working Group (WG) composed of members of the two collaborations [5, 6]. The offset in the spectrum normalization below $10^{19}$ eV (see fig. 1) can be interpreted as a mismatch in the energy scales of 9%. This 9% energy shift is reduced to a few % if the two collaborations reconstructed the fluorescence events using the same models for the fluorescence yield and the invisible energy correction. Since this offset is well understood, it is subtracted from the measured spectra in order to better understand the differences in the flux at the highest energies. The resulting energy spectra are shown in the left panel of fig. 2. The measurements are performed in a declination band accessible to both detectors to ensure

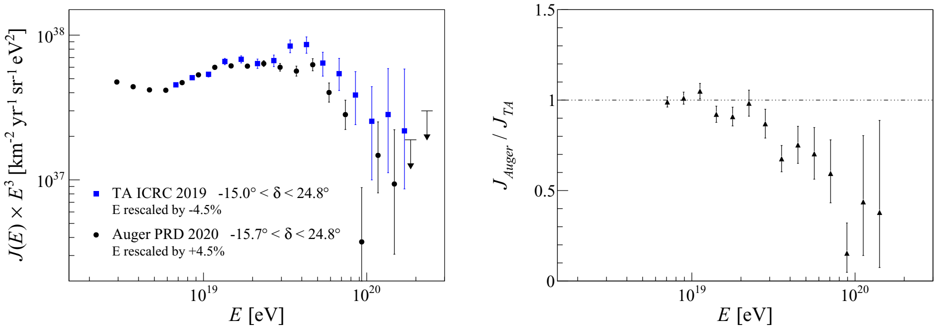

**Figure 2.** Left panel: energy spectrum measured by TA and Auger in the declination band accessible by both observatories after a rescaling of the energy by an overall 9% factor [5]. Right panel: ratio of the Auger to TA spectra shown in the left panel.

---

[1] The relation between the uncertainty in energy and the one in the flux $J$ is $\Delta J/J \approx (\gamma - 1)\, \Delta E/E$, where $\gamma$ is the spectral index.

that the observed differences are not due to astrophysical effects and therefore their origin is of instrumental only. As we can see, at the highest energies the TA data points are all above the Auger ones. This is better evident in the figure of the right panel, where the ratio of the two spectra is shown. The difference in flux corresponds to an energy dependent energy shift of 20%/decade above $10^{19}$ eV.

The discrepancy in the energy scale of 20%/decade is not understood since it goes beyond the systematic uncertainties cited by the two experiments [5]. The difficulty arises from the fact that the uncertainties associated with the FD energy scale (14% for Auger and 21% for TA) are almost independent of the energy. Therefore, it is natural to investigate possible biases arising from the reconstruction of the SD energy estimator that cannot be corrected by the calibration with respect to the FD energies.

The techniques used for the SD energy reconstruction adopted by the two collaborations are quite different as they are optimized for their detector, water cherenkov for Auger and scintillator for TA. The most relevant difference is in the calibration technique. The relationship between the SD energy estimator ($S$) and the energy ($E$) is generally well described by a power-law relationship $E = AS^B$, where the parameter $B$ is typically close to 1. In Auger, $S$ is derived in a fully data-driven way and both the parameters A and B are fitted to the hybrid data. In TA $S$ is the energy reconstructed using MC simulations and only the parameter $A$ is fitted, being $B$ fixed to 1.

The main difficulty in addressing the systematics in the SD energy at the highest energies is obviously the lack of hybrid statistics. A check of potential biases provided by Auger comes from the comparison of the spectra measured with the events with zenith angles below and above 60°. The two data sets are affected by different systematics as they are independent and require completely different reconstruction algorithms. As we can see in fig. 1, the two spectra show only minor differences, well below of what is needed to explain the discrepancy with TA. For TA $B$ is fixed to 1 and therefore the extrapolation to the highest energies relies on the MC used to reconstruct the energy. As explained in [7], the MC energy can vary up to 15% depending on the hadronic interaction model and the primary mass, with a value for light nuclei that is larger than the one for heavier ones. Since the TA energy is derived by assuming protons at all energies and considering that the mass composition becomes heavier at higher energies [8], one should expect a positive bias in the TA energy estimation that goes in the direction to explain the discrepancy with Auger.

## 3 Outlook and future perspectives

Understanding the discrepancy in the energy estimations of TA and Auger is extremely important because, only combining the data collected by the two observatories, it is possible to study the UHECRs with a full coverage of the celestial sphere. A cross-calibration of the energy scales has been done requiring that the fluxes in energy are the same [9], however the procedure is clearly not optimal as the systematic uncertainties are not understood. Furthermore the cross-calibration becomes too uncertain at the very high energies making it extremely difficult to combine the data for analyses similar to the one reported in [7].

A promising perspective to better understand the cross-calibration is provided by the recent upgrade of the observatories. With AugerPrime [8] the SD array has been equipped with scintillator detectors similar to the TA one and this will allow a more straightforward comparison of the energy reconstruction techniques. The upgrade of TA, dubbed TAx4 [10], consists in increasing the size of the array by a factor 4 and this will allow to increase the exposure and the precision of the measurement of the spectrum at the highest energies.

Another interesting perspective is provided by the new emerging radio detection technique [11]. AugerPrime foresees the installation of a radio detector in each SD stations.

The advantage of this new technique is that the emission of the electric field by the charged particles of the shower is a classical electrodynamics process which makes the MC based reconstruction of the shower energy largely independent on the hadronic interaction models. With AugerPrime, for the showers inclined at large zenith angles for which the array of radio detectors becomes fully efficient, it will be possible to check the energy estimation at the very high energies where the FD statistics is very low.

An important perspective is also the comparison of the energy scales provided by the fluorescence telescopes and the radio detector. The two techniques are completely independent with different systematic uncertainties. The radio signals are not affected by the aerosols in the atmosphere that are a source of a not negligible uncertainty in the FD energy estimation. The advantage of the FD is that the fluorescence yield is precisely measured in lab [6] and, given the nature of the emission process, the reconstruction of the showers is rather straightforward and can be done in a fully data-driven way. Instead, the correct interpretation of the radio signals requires a calculation of the electric field emitted by all charged particles of the showers and this is done with complex MC simulations that have not been checked with measurements performed in lab. It is expected that the uncertainty in the radio energy scale will be of a comparable amount of the FD one and this will give the opportunity to combine the information of both detectors to improve the energy estimation.

Another important item will be the improvement of the absolute calibration of the FD telescopes that is known with an uncertainty of 10% and gives the largest contribution to the total uncertainty in the energy scale. Auger is developing a new calibration system [12] and noteworthy is the successful cross-check of the calibration of the telescopes done by TA using a linac accelerator installed at their site [6]. It will be important also to scrutinize the excellent agreement between the Auger and TA spectra below $10^{19}$ eV to better understand its implications in the understanding of the FD energy estimation. A new interesting perspective for the comparison of Auger and TA energy scales is through the detection of lasers that will be fired accross the two observatories from the Aeolus satellite [13].

We conclude this paper underlying the importance of all these studies to improve the understanding of the muon number excess [14], and more in general all the UHECR physics.

## References

[1] M. Takeda et al., Astropart. Phys. **19**, 447 (2003).
[2] R. U. Abbasi et al., Phys. Rev. Lett. **100**, 101101 (2008).
[3] Telescope Array Collaboration, Astrophys. J. **768**, L1 (2013).
[4] Pierre Auger Collaboration, Phys. Rev. D **102**, 062005 (2020).
[5] D. R. Bergman et al., (Telescope Array and Pierre Auger Collaborations), EPJ Web Conf. **283**, 03002 (2023).
[6] V. Verzi, D. Ivanov, and Y. Tsunesada, Prog. Theor. Exp. Phys. **2017**, 12A103 (2017).
[7] Telescope Array Collaboration, Science **382**, 903 (2023).
[8] A. Castellina (Pierre Auger Collaboration), EPJ Web Conf. **210**, 06002 (2019).
[9] A. di Matteo et al., (Telescope Array and Pierre Auger Collaborations), EPJ Web Conf. **283**, 02003 (2023).
[10] J. Kim (Telescope Array Collaboration), Proc. Sci. **ICRC2023**, 337 (2023).
[11] T. Heuge, Phys. Rep. **620**, 1 (2016).
[12] C. Schäfer (Pierre Auger Collaboration), Proc. Sci. **ICRC2023**, 305 (2023).
[13] Pierre Auger Collaboration, O. Lux et al., Optica **11**, 263 (2024).
[14] Pierre Auger Collaboration, Phys. Rev. Lett. **117**, 192001 (2016).