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Study of the origins of ultra high energy cosmic rays

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The Pierre Auger Observatory is the largest cosmic-ray observatory to date. It has been built in order to study the most energetic particles in the universe, commonly known as Ultra High Energy Cosmic Rays (UHECR). With a surface of 3,000 km^2(30 times Paris), the observatory detects cosmic rays from $10^{17.5}$ to $10^{20.5}$ eV. The energy, the shower depth $\mathrm{X}_{\mathrm{max}}$ (which is linked to the mass), and the arrival direction are reconstructed. In 2017, the observatory observed a large-scale anisotropy at $\mathrm{E} \geq 8 \times 10^{18}$ eV, described as a dipole with 5.2σ confidence level, pointingto right ascension $\alpha_{\mathrm{d}} = 100 \pm 10$ and declination $\delta_{\mathrm{d}} = -24^{+12}_{-13}$.
This direction gives strong evidence for an extra galactic origin of UHECRs. Moreover, in 2018, the collaboration published an indication of intermediate-scale anisotropy at $\mathrm{E} \geq 39 \times 10^{18}$ eV with a 4.0σ significance level. The intermediate-scale anisotropy is found comparing the UHECR sky map with the flux pattern of extragalactic gamma-ray sources (especially Starburst galaxies & Active Galactic Nuclei).
To interpret the data, an astrophysical model has been compared to UHECR spectrum and shower depth data, through a method called the Combined Fit. Nuclei are injected according to a production rate and following a distribution of sources. The nuclei propagate through space interacting with the cosmic microwave and infrared backgrounds.
The Combined Fit then enables to determine the relative importance of propagation and acceleration in shaping the UHECR composition and spectrum.
Starting from the Combined Fit and from arrival directions, I will present how we can include the anisotropies in the Combined Fit to have a model that describes the three main observables: Xmax, spectrum, arrival directions. Such an astrophysical model could constrain the sources in an unprecedented way and could be a key in understanding them.

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