The most energetic messengers of the Universe

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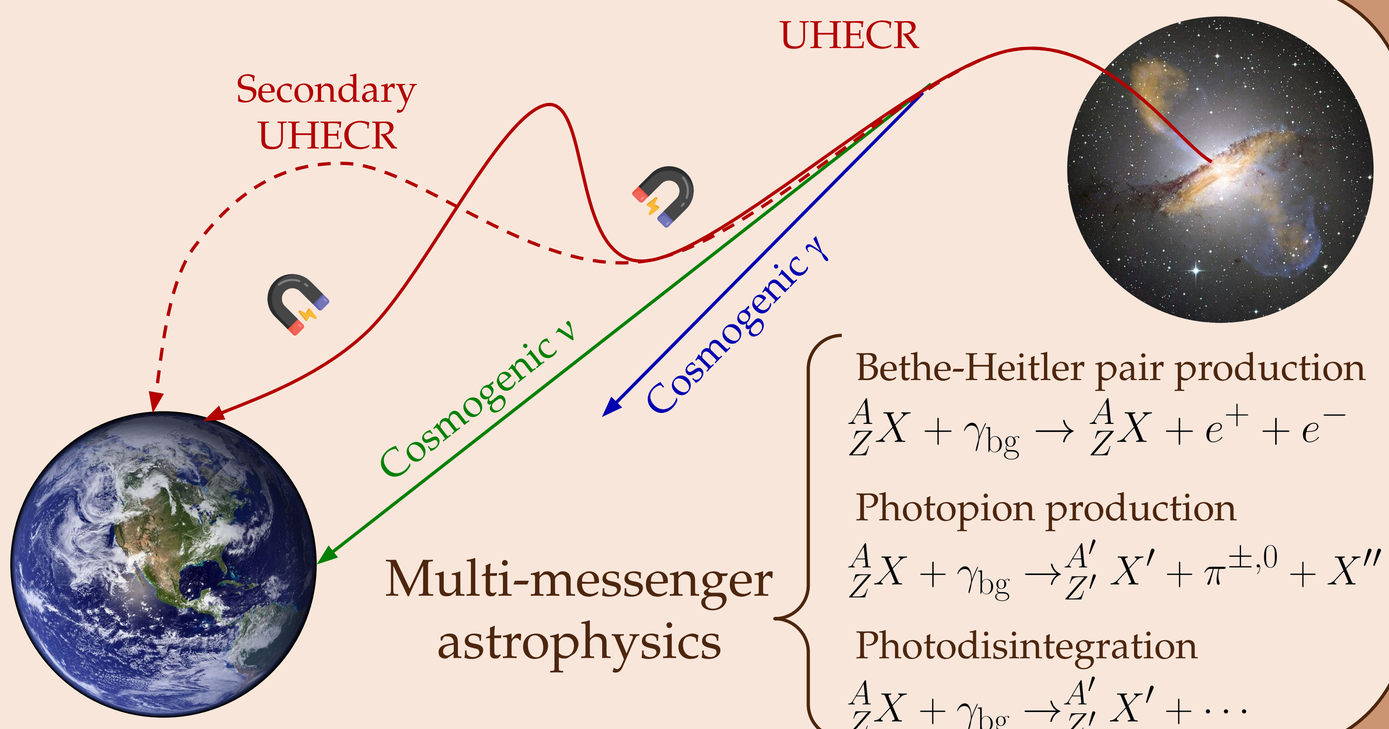
Ultra-high energy cosmic rays (**UHECRs**):

- ➔ Protons and heavier nuclei of extraterrestrial origin that have energy above 10^{18} eV;
- ➔ Unknown origin:
  - ◆ Low flux (~1 km per year per km^2);
  - ◆ Deflection by poorly understood cosmic magnetic fields;
  - ◆ Altered energy spectrum and mass composition during propagation.



Multi-messenger astrophysics

Bethe-Heitler pair production

$${}^{A}_{Z}X + \gamma_{\rm bg} \rightarrow {}^{A}_{Z}X + e^{+} + e^{-}$$

Photopion production

$${}^{A}_{Z}X + \gamma_{\rm bg} \rightarrow {}^{A'}_{Z'}X' + \pi^{\pm,0} + X''$$

Photodisintegration

$${}^{A}_{Z}X + \gamma_{\rm bg} \rightarrow {}^{A'}_{Z'}X' + \cdots$$

Pierre Auger Observatory

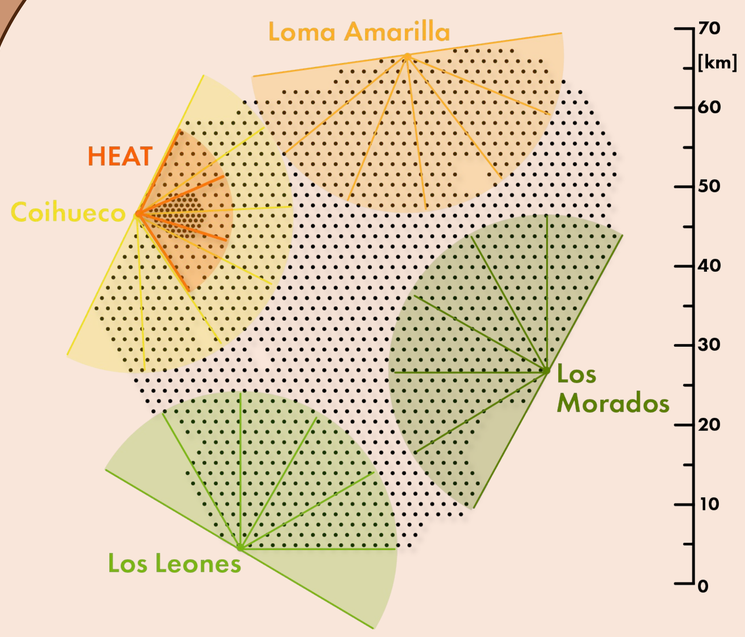


Figure 2. Schematic representation of the Pierre Auger Observatory.

Telescope Array

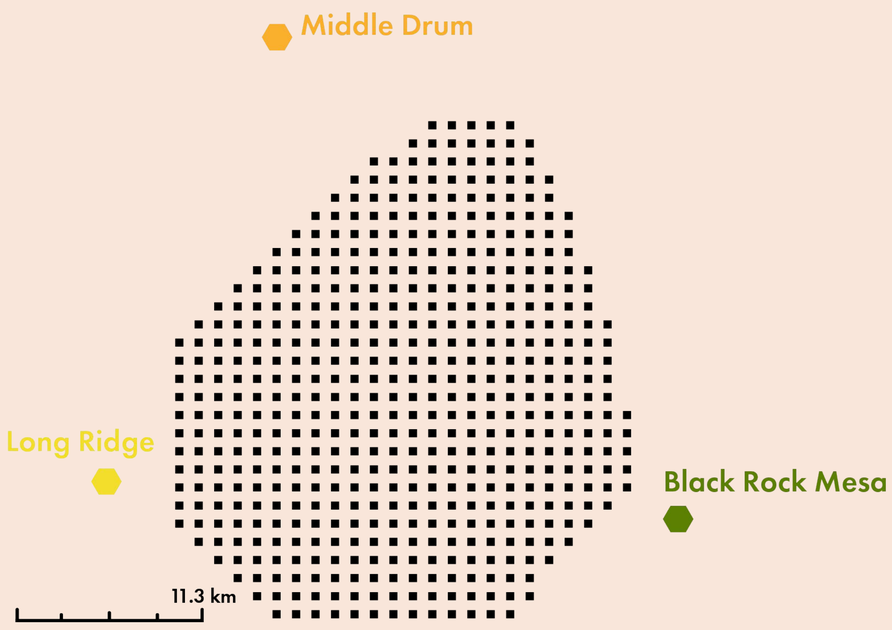


Figure 3. Schematic representation of the Telescope Array.

Energy spectrum
Distribution of arrival directions
Mass composition $(X_{\rm max} \leftrightarrow \ln A)$

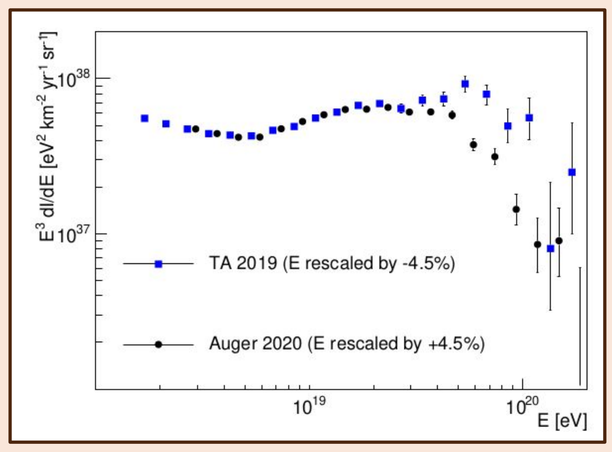


Figure 4. Energy spectra measured by the Pierre Auger Observatory and by the Telescope Array scaled by energy cubed.

Large-scale anisotropies

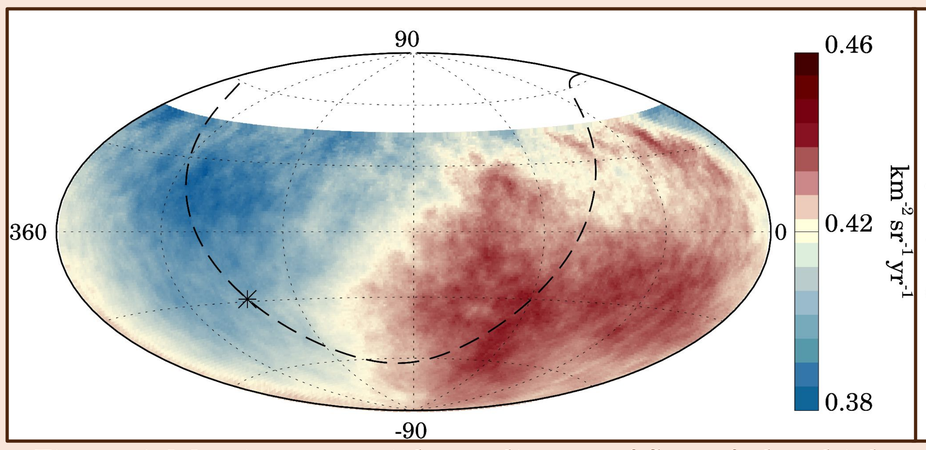
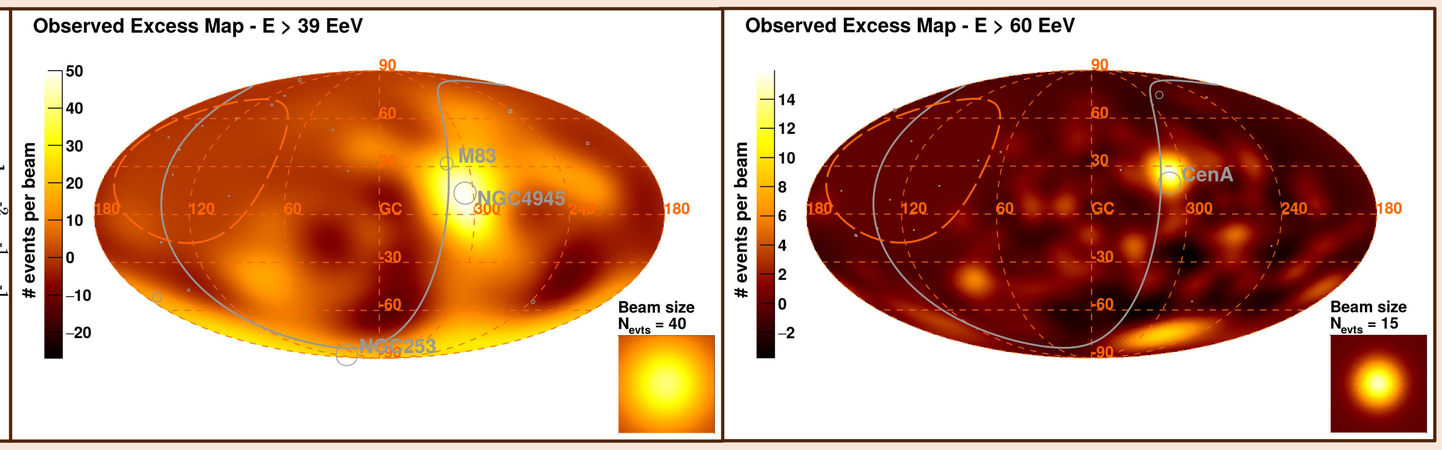


Figure 4. Map in equatorial coordinates of flux of ultra-high energy cosmic rays with energies above 8 EeV measured by the Pierre Auger Observatory.

Small-scale anisotropies → Correlations with AGNs and SBGs



Figures 5 and 6. Maps in galactic coordinates of flux of ultra-high energy cosmic rays with energies above 39 and 60 EeV measured by the Pierre Auger Observatory.

The need of local sources

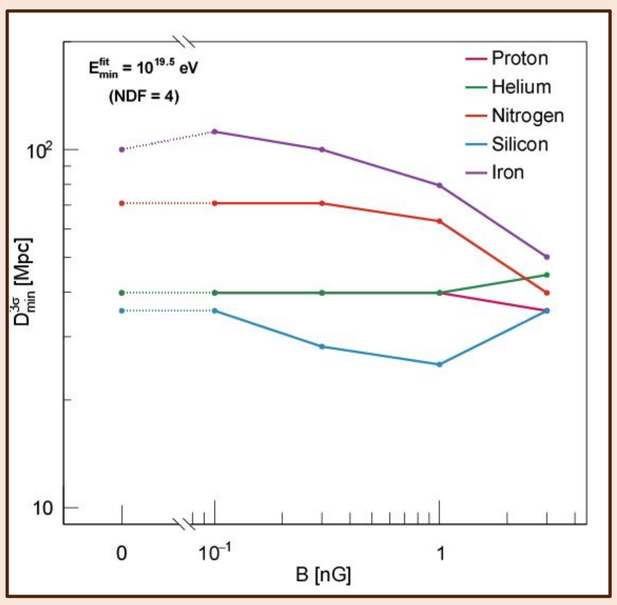


Figure 7. The evolution of the restrained distance to the nearest source in relation to the field strengt. Lang et al. (2020)

Development of phenomenological models for acceleration sources and extragalactic environments.

Due to the effects of ultra-high-energy cosmic ray propagation, there must be at least one nearby source (D < 100 Mpc) to explain the measurements obtained by the observatories.

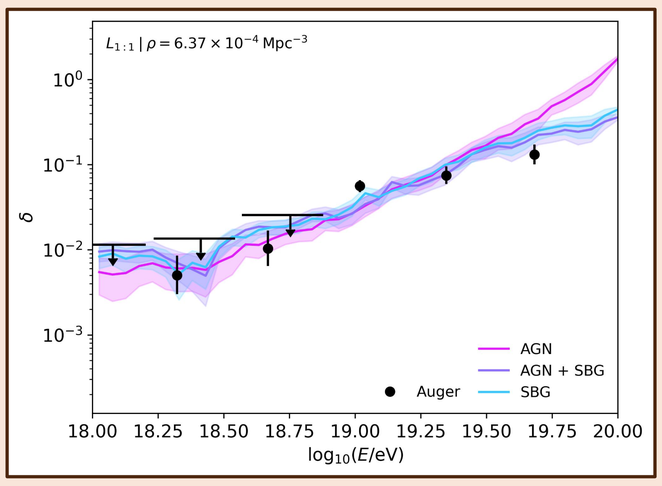


Figure 8. Amplitude of the dipole as a function of the energy for an equal emission of primaries regardless of the astrophysical source.