UHECRs and the Pierre Auger Observatory

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Ultra-High Energy Cosmic Rays

Contemporary questions:

- Gal/XGal transition?
- Origin of the ankle?
- Origin of the UHE steepening?
- Composition at UHE?
- Sources?

NB: From neutrinos/photons upper limits, the bulk of UHECRs are accelerated particles in astrophysical objects.
1/ The Pierre Auger Observatory

Hybrid detector:

- Surface detector array (SD):
  - SD-1500:
    - 1660 spaced by 1.5 km
    - ~ 3000 km²
  - SD-750:
    - 49 spaced by 750 m
    - ~ 24 km²

- Fluorescence detector (FD):
  - 27 fluorescence telescopes in 5 buildings
The Pierre Auger Observatory - Surface Detectors

- Footprint of the shower at ground = lateral sampling
- 100% duty cycle
- Arrival direction + size of the shower
The Pierre Auger Observatory - Fluorescence Detectors

- longitudinal sampling
- calorimetric energy measurement
- $X_{\text{max}}$ measurement
- 13% duty cycle
2/ Tracking the Origin of UHECRs

Energy Spectrum at UHE

Two features: ankle and flux suppression at UHE
The GZK Paradigm

- Rapid reduction of the horizon $\implies$ Flux suppression at UHE
- Anisotropy of extragalactic local matter + small magnetic deflection for $10^{20}$ eV protons $\implies$ possibility of UHECR astronomy
Sky Maps at UHE

- Scan on energy threshold $E$ and circular window radius $\Psi$ to compute the obs/exp number of events
- $4.3 \sigma$ for $E>54$ EeV and $\Psi=12^\circ$
- Post-trial p-value: 69%

- Cross-correlation with catalogs of extragalactic matter:

<table>
<thead>
<tr>
<th>Objects</th>
<th>$E_{th}$ [EeV]</th>
<th>$\Psi$ [$^\circ$]</th>
<th>$D$ [Mpc]</th>
<th>$f_{min}$</th>
<th>$\mathcal{P}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MRS Galaxies</td>
<td>52</td>
<td>9</td>
<td>90</td>
<td>$1.5 \times 10^{-3}$</td>
<td>24%</td>
</tr>
<tr>
<td>Swift AGNs</td>
<td>58</td>
<td>1</td>
<td>80</td>
<td>$6 \times 10^{-5}$</td>
<td>6%</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>72</td>
<td>4.75</td>
<td>90</td>
<td>$2 \times 10^{-4}$</td>
<td>8%</td>
</tr>
</tbody>
</table>

- No significant indication of anisotropy
From $X_{\text{max}}$ to the Mass

![Graph showing fitted fraction and quality for the scenario of a complex mixture of protons, helium nuclei, nitrogen nuclei, and iron nuclei. The upper panels show the species fractions and the lower panel shows the p-values.](image-url)
Energy Loss vs Max. Acceleration Energy

✦ The \( \text{Xmax} \) measurements suggest a scenario with a rigidity-dependent maximum acceleration energy at the sources.

⇒ Fit \( > 10^{18.7} \text{ eV} \) both the energy spectrum and the \( \text{Xmax} \) measurements following a simple astrophysical scenario:

• Identical sources homogeneously distributed in a comoving volume

• Injection consisting only of \( ^1\text{H}, ^4\text{He}, ^{14}\text{N}, ^{56}\text{Fe} \) (approximately equally spaced in \( \ln A \))

• Power-law spectrum at the sources with rigidity-dependent broken exponential cutoff:

\[
\frac{dN_{\text{inj,i}}}{dE} = \begin{cases} 
J_0 \rho_i \left( \frac{E}{E_0} \right)^{-\gamma}, & E/Z_i < R_{\text{cut}} \\
J_0 \rho_i \left( \frac{E}{E_0} \right)^{-\gamma} \exp \left( 1 - \frac{E}{Z_i R_{\text{cut}}} \right), & E/Z_i > R_{\text{cut}}
\end{cases}
\]

⇒ 6 free parameters: \( (J_0, \gamma, R_{\text{cut}}, p_H, p_{\text{He}}, p_N); p_{\text{Fe}} = 1 - p_H - p_{\text{He}} - p_N \)
Energy Loss vs Max. Acceleration Energy

- Hard, meal-rich injection, low cutoff ($R_{\text{cut}} < 10^{18.7}$ V)!
- Mainly due to narrow $X_{\text{max}}$ distributions (little mixing of different masses at the same energy)
- NB: Relies on extrapolations of the mass at UHE
Full-Sky Map > 10 EeV (with Telescope Array)

Equatorial Coordinates - 60° smoothing

- Interesting dipole effect to monitor
- No strong destruction of a dipole pattern by the GMF
- Dipole direction related to the anisotropy contrast of the local sources
3/ The Ankle - End of Galactic CRs?

- Rigidity-dependent scenario for GCRs
- « Knees » = maximum acceleration energies
- Extragalactic protons entering progressively
The Ankle - End of Galactic CRs?

In addition to (extragalactic) protons, EeV CRs are from the CNO group, not Fe!

Gal/xGal scenario:

Observed scenario:
Origin of the Ankle?

direction/amplitude of the dipole in right ascension:

Phase roughly in the direction of the Galactic center

• CNO elements as the high-energy tail of the bulk of GCRs: breakdown of the rigidity-dependent paradigm?
• CNO: additional component?
4/ Particle Interactions - Muon Content of EAS

- Deficit of muons in simulations, between 30% and 80%
- Systematic uncertainty inherited from energy scale

- Constraints on hadronic interaction models (inelasticity, multiplicity)

Currently, tension between muon and e.m. contents of EAS in simulations
Proton-Air Cross-Section

- Tail of $X_{\text{max}}$ distribution sensitive to p-air cross-section

$$\frac{dN}{dX_{\text{max}}} \propto \exp\left(-\frac{X_{\text{max}}}{\Lambda_{\eta}}\right)$$

- Measurement of $\Lambda_{\eta}$ around 1 EeV, where a significant proton fraction is seen

- Choose $\eta = 0.2$ to achieve $\sigma(\text{stat}) \approx \sigma(\text{syst})$

- Extended Glauber conversion with inelastic screening + propagation of modeling uncertainties:

- **Lower energy point**
  - $76.95 \pm 5.4(\text{stat}) + 5.2/ -7.2(\text{syst}) \pm 7(\text{glauber})$
  - at $\sqrt{s_{pp}} = 38.7 \pm 2.5$ TeV

- **Higher energy point**
  - $85.62 \pm 5(\text{stat}) + 5.5/ -7.4(\text{syst}) \pm 7.1(\text{glauber})$
  - at $\sqrt{s_{pp}} = 55.5 \pm 3.6$ TeV
Summary

• Quest of UHECR origin more difficult than expected 10 years ago
  • Unexpected scenario for UHECR production
  • Unexpected scenario at EeV energies: ankle origin?

• Hadronic interaction models can benefit from muon content measurements

• Need for composition measurements at UHE: Upgrade of the Observatory designed to provide complementary measurements allowing better constraints on the muon content of EAS
  • Need for (much) larger exposure keeping similar resolutions...