Arrival direction distribution of cosmic rays from 100 PeV to the highest energies detected at the Pierre Auger Observatory

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For the Pierre Auger Collaboration
~100 PeV and beyond

The ankle
- Origin
- Investigations

Near the cut-off region
- Origin
- Investigations
The Pierre Auger Observatory

- Designed to study UHECRs (E > 10^{18} eV)
- Located near Malargue, Argentina

*Hybrid detection of CRs*

- **Surface detector (3000 km²)**
  - 1660 water Cherenkov detectors, triangular grid, 1500 m spacing
  - 100% duty

- **Infill detectors (23.5 km²)**

- **Fluorescence detector (FD)**
  - 27 optical telescopes in 5 buildings
  - ~13% duty cycle
Anisotropy studies in PAO

UHECR anisotropies determined by:
- The (unknown) distribution of sources over the sky
- Deflections in cosmic magnetic fields (MF)
- Attenuation due to interaction with the radiation backgrounds

Different studies are undertaken in PAO:
- Large scale anisotropies
- Point source search
- Localized excesses search
- Neutron point source
- Photon point source
- ...

→ Complementary to energy spectrum & mass composition to understand CRs nature and origin

60 EeV proton deflection angles (Jannson, Farrar (2012))
Large-scale anisotropies
First harmonic analysis in R.A.

Harmonic expansion of the angular distribution in RA [APh 34 (2011) 628]

\[ \Phi(\alpha) = a_0 + \sum_{n>0} a_n^c \cos n\alpha + \sum_{n>0} a_n^s \sin n\alpha. \]

- Amplitude: \[ r = \sqrt{a^2 + b^2} \]
- Phase: \[ \phi = \arctan \left( \frac{b}{a} \right) \]

**Motivation:**

*If galactic at $10^{18}$ eV:* %-level modulation (depending on GMF, composition, distrib. of sources, ...)

*If extra-gal. at $10^{18}$ eV:* no structure except for a CMB-dipole ($\sim 0.6\%$)

No significant deviation from isotropy
Large-scale anisotropies
Spherical Harmonic Analysis

Angular distribution over the sphere \( \Phi(n) \) expanded in spherical harmonics [ApJs 203 (2012) 34]:

\[
\Phi(n) = \sum_{\ell \geq 0} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(n)
\]

\[
a_{\ell m} = \int_{4\pi} \Phi(n) Y_{\ell m}(n)
\]

- Non-zero \( \ell \) modes arise from variations of the flux on angular scales \( \sim 1/\ell \) rad
- With partial sky coverage, sensitivity depends on the mode assumed for the expansion (bounded to \( \ell < 3 \))

- Expected dipole amplitudes largely stand above the allowed limits for galactic protons
- The fraction of galactic protons should not exceed 10% of the CR composition
A Search for Point Sources of EeV Neutrons

Motivation:
- Neutrons travel on straight lines
- Produce EAS indistinguishable from EAS produced by protons.
- Mean travel distance for relativistic neutrons is $9.2 \times 10^3$ kpc
- Neutrons with $E > 1$ EeV ($> 2$ EeV) $\rightarrow$ GC (most of the Galaxy)

Method:
- Simulation dataset from scrambling of true arrival directions
- Median target radius is $1.36^\circ$ for 1-2 EeV, $1.02^\circ$ for 2-3 EeV, $0.69^\circ$ for $E > 3$ EeV, and $1.23^\circ$ for $E > 1$ EeV

Results [Astrophys. J. 760 (2012)]:

$\Rightarrow$ No obviously significant hot spots were identified
A Search for Point Sources of EeV Neutrons

No statistically significant excess of events

Celestial maps of the flux upper limit (particles) in Galactic coordinates. neutrons/(km² yr)

→ Upper limits are more stringent where the directional exposure is higher


The absence of any detectable neutron flux might suggest that the sources are extragalactic, or transient, or emitting in jets, or optically thin to escaping protons, or individually weak but densely distributed.
Challenging some Galactic scenarios on the origin of the ankle

- Indications for the predominance of light components around $10^{18}$eV
- Hardening of light element energy spectrum at $\sim 10^{17}$eV

Challenging some Galactic scenarios on the origin of the ankle

- Iron nuclei should mark the highest energy particles detected before the transition to extragalactic CRs

- But ...
  - Mass composition studies show that the contribution of heavy elements, if any, should be subdominant around the ankle
  - Absence of anisotropies might hint to an already present extragalactic contribution (if Galactic, protons should be less than 10%)
  - Absence of neutron flux might suggest that the sources are extragalactic at these energies

- The ankle marking the transition between the end of Galactic cosmic rays and extragalactic ones is in clear tension with contemporary observational results.
- The Iron knee at $10^{17}$eV is most likely the feature making the end of the Galactic cosmic rays
Phase measurements of the first harmonic

- Hint to a smooth transition from a common phase of RA ~270° in the bins below 1EeV to Ra ~90° above 2EeV
- will be established with 99% confidence level if the ongoing prescribed test is successful

- interesting hints for large-scale anisotropies that will be important to further scrutinise with increased statistics

How to explain global low levels of anisotropy?
Phase measurements of the first harmonic

- Amplitudes seem too low to be naturally explained by a Galactic scenario.
- Isotropy down to a higher level is a robust expectation in this energy range for an extragalactic scenario.

Total flux $\Phi_{\text{tot}}(E,n)$ as the sum of a dominant isotropic component $\Phi_X(E)$ and of a subdominant anisotropic component $\Phi_{\text{Fe}}(E,n)$ of iron-nuclei elements:

$$\Phi_{\text{tot}}(E, n) = \Phi_X^0 E^{-\gamma_X} + \Phi_{\text{Fe}}^0 E^{-\gamma_{\text{Fe}}} \left(1 + r_{\text{Fe}}(E) d \cdot n\right)$$

Dominant isotropic Extragalctic protons
Subdominant anisotropic iron nuclei
Flux suppression at the highest energies
The GZK horizon for protons and nuclei

- A suppression of the flux above $4 \times 10^{19}$ eV is now confirmed
- Current data are insufficient to conclude whether the observed feature is due to:
  - energy loss during propagation
  - the fact that the astrophysical accelerators reach their limit
  - both source properties and propagation effects

Around 90% of the flux of protons with $E > 6 \times 10^{19}$ eV should come from distances smaller than 200 Mpc.
For highest energies, the GZK horizon «shrinks» should be easier to identify the sources.

[D. Harari et al. (2006)]
Searches for localized excesses of the UHECR flux

The Centaurus A excess

- Excess of the UHECR events with $E > 55$ EeV around the direction towards the Centaurus supercluster at a distance of about 60 Mpc
- Excess towards Centaurus A, a close AGN at a distance of about 3.5 Mpc

- The largest excess was found for a circular region of the angular size 18°
- Region includes 10 /60 events above 55 EeV (2.44 expected from isotropy)
- No excess at lower energies

[Pierre Auger Collaboration (2011)]
Search for point sources

- E > 55 EeV, Maximum distance in VCV catalog < 75 Mpc, maximum opening angle 3.1° fixed from independent data sets in exploratory scans
- Search for correlations in VCV catalog

Early part of the data there was a substantial deviation from isotropy, with the accumulation of events, the correlation strength has decreased to 33 ± 5% compared to 21% expected from isotropy.

[Pierre Auger Collaboration(2012)]
Conclusion

- No significant amplitudes at large scales – stringent upper limits obtained
- Interesting phase alignment indicative of anisotropies with small amplitudes
- No neutron source at energies > 10^{18} eV
- No correlation with local extragalactic matter at UHE

→ Extragalactic component could start to dominate the flux below the ankle
→ The absence of correlation with sources at UHE might be the consequence of the contribution of heavy elements increasing with energy

- Scientific goals with PAO Upgrade:
  - measure the composition-discriminated flux in the range from about 10^{18} eV up to the highest energies,
  - carry out composition-enhanced anisotropy searches based on event-by-event estimates of the primary mass