Large Scale Anisotropy in the Arrival Directions of Cosmic Rays Measured by the Pierre Auger Observatory

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The Pierre Auger Observatory

3000 km² surface array (1660 detectors)
1.5 km triangular grid
27 fluorescence telescopes
• Data-driven energy calib. using hybrid events
• Different SD estimators are correlated to the quasi-calorimetric energy measured by the FD
• Here, we should use two samples, depending on the zenith angle of the events:
  • Vertical: $0^\circ < \theta < 60^\circ$ ($S_{38} \times E_{FD}$)
  • Inclined: $60^\circ < \theta < 80^\circ$ ($N_{19} \times E_{FD}$)

• Inclined sample provides about ~30% of extra sky coverage
• This extra coverage is very important to many of the analyses to be discussed here
Dipole above $8 \text{ EeV} (8 \times 10^{18} \text{ eV})$ - dataset

• Period: 01-01-2004 to 08-31-2016
• Additional sky coverage (~30%) provided by inclined events ($60^\circ < \theta < 80^\circ$)
• Enhanced statistics (~19%) with the use of relaxed (but high quality) triggers
• Two major systematic effects understood and corrected:
  • Weather (temperature and pressure) induced modulations
  • Distortions on ground level muon density by the geomagnetic field
• Total integrated exposure of 76,800 km$^2$ sr year
Analysis of first harmonic modulation in RA and azimuth

\[ a_\alpha = \frac{2}{N} \sum_{i=1}^{N} w_i \cos \alpha_i \]

\[ b_\alpha = \frac{2}{N} \sum_{i=1}^{N} w_i \sin \alpha_i \]

Amplitude and phase of modulation

\[ r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2} \]

\[ \tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha} \]

\[ P(r_\alpha) = \exp \left( -\frac{N r_\alpha^2}{4} \right) \]

- 5.6 \( \sigma \) pre-trial signal
- 5.2 \( \sigma \) post-trial (penalized for scan in 2 energy bins)
Components parallel and perpendicular to the Earth rotation axis:

\[ d_z \approx \frac{b_\varphi}{\cos \ell_{\text{obs}} \langle \sin \theta \rangle} \quad d_\perp \approx \frac{r_\alpha}{\langle \cos \delta \rangle} \]

Right ascension and declination:

\[ \alpha_d = \varphi_\alpha \quad \tan \delta_d = \frac{d_z}{d_\perp} \]

<table>
<thead>
<tr>
<th>Energy (EeV)</th>
<th>Dipole component (d_z)</th>
<th>Dipole component (d_\perp)</th>
<th>Dipole amplitude (d)</th>
<th>Dipole declination (\delta_d (^\circ))</th>
<th>Dipole ascension (\alpha_d (^\circ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 to 8</td>
<td>(-0.024 \pm 0.009)</td>
<td>(0.006^{+0.007}_{0.003})</td>
<td>(0.025^{+0.010}_{0.007})</td>
<td>(-75^{+17}_{-8})</td>
<td>(80 \pm 60)</td>
</tr>
<tr>
<td>(\geq 8)</td>
<td>(-0.026 \pm 0.015)</td>
<td>(0.060^{+0.011}_{0.010})</td>
<td>(0.065^{+0.013}_{0.009})</td>
<td>(-24^{+12}_{-13})</td>
<td>(100 \pm 10)</td>
</tr>
</tbody>
</table>

- Reconstruction assumes the dipole is the dominant component of the anisotropy
- Analysis of the power spectrum gives support to this hypothesis
Time evolution of the signal

- Steady drop of the chance probability as data is accumulated
• Broad 45° top-hat beam applied
• Dipole maximum is about 125° away from the galactic center
Final sky maps: EQU, GAL and SGAL coordinates
Is it consistent with local matter distribution and mag. fields?

2MASS Redshift Survey (2MRS)

- 91% of sky coverage
- 97.6% of completeness
- ~ 43k galaxies
- $K_s \leq 11.75$ mag
- $D < 300$ Mpc

3 components: spiral disk + toroidal at halo + poloidal

Rotation measures

Synchrotron emission (WMAP)

Is it consistent with local matter distribution and mag. fields?

- Two rigidities shown: $E/Z = 2, 5$ EeV representing the typical Z values (1.7-5) inferred from $X_{\text{max}}$ at 10 EeV
- Typically, up to 5-20% (around 10 EeV) dipole amplitudes can be obtained from local inhomogeneities and deflection in magnetic fields depending on CR composition
AugerPrime

- **SSD (Surface Scintillator Detector)**
  for improved measurement of electromagnetic to muon abundance

- **UMD (Underground Muon Detector)**
  for direct counting of muons

- **SDEU (SD Electronics Upgrade)**
  faster sampling of the PMT signals (40 MHz to 120 MHz),
  better timing accuracy (new GPS) and larger dynamic range

- **Enhanced FD duty cycle**
  15% to 25% increase in the FD operation time
  by operating with lower PMT gain
Summary

• Observation of a dipolar large scale pattern at more than 5σ level above 8 EeV
• Direction of the dipole (~125° away from GC) is better explained if the bulk of these UHECRs are extragalactic in origin
• No statistically significant sign of anisotropy seen so far at lower energies (around and below the ankle)
• The upgrade of the Auger detectors (AugerPrime) is in progress and should boost anisotropy studies by providing samples classified according to mass composition variables