Dipolar anisotropy of cosmic rays above 8 EeV

O. Taborda\textsuperscript{a} for The Pierre Auger Collaboration

\textsuperscript{a}Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET)

Bariloche, Argentina
INTRODUCTION

Origin and nature of CRs still open problems in Astrophysics

→ New insights from studies of Large Angular Scale Anisotropies

THE PIERRE AUGER OBSERVATORY

- SURFACE DETECTORS (lateral profile)
  - ~1600 water-Cherenkov stations at 1.5 km spacing
  - ~3000 km²

- FLUORESCENCE DETECTORS (longitudinal profile)
  - 27 telescopes at 4 buildings

35.2° S, 69.3° W
1400 m a. s. l.
THE DATASET

- Zenith angles $\theta < 80^\circ$ → covering 85% of the sky
- $E > 4\,\text{EeV}$ → full trigger efficiency (bins [4-8] EeV and $E \geq 8\,\text{EeV}$)
- Periods of unreliable data acquisition removed
- Trigger: previous LSA analyses considered events with 6 working stations around the hottest one (mandatory at lower energies)

We also include events with 5 active neighbors (exposure increased by 18.7%)

Larger period + relaxed trigger → 60% increase in exposure respect to ApJ2015

Total exposure: 76,800 km$^2$ sr yr
The Dataset

More than 99% of events with $E > 4$ EeV have more than 4 triggered detectors → reconstruction still reliable.

Reliability of reconstruction with relaxed trigger checked using artificial events with one detector removed from the ones passing the stricter trigger.

Changes below uncertainties:

$\Delta E/E$ (statistics) 16% ($E > 4$ EeV)

12% ($E > 10$ EeV)

$\Delta E/E$ (systematic) 14%

[V. Verzi in Proc. ICRC 2013]

Angular resolution $\sim 1^\circ$

[NIM A 798 (2015) 172]

→ relaxed selection is safe
THE DATASET – systematic effects corrected

- Energies corrected by atmospheric changes for $\theta < 60^\circ$
  - Air-density \rightarrow lateral distribution of EM component
  - Pressure \rightarrow longitudinal depth of observation

Induces modulations of $\pm 1.7\%$ in solar frequency

[Auger Coll. JINST 12 (2017) P02006]

Negligible effects at $60^\circ < \theta < 80^\circ$ (EM component suppressed)

[See A. Coleman poster – CRI164]

Geomagnetic field breaks circular symmetry of showers

[Auger Coll. JCAP 11 (2011) 022]

Effect accounted in energy estimation

azimuth spurious modulation ~0.7\%
Weighted harmonic analysis

\[ a^x = \frac{2}{N} \sum_{i=1}^{N} w_i \cos x_i , \quad b^x = \frac{2}{N} \sum_{i=1}^{N} w_i \sin x_i \]

\[ x = \alpha \text{ or } \phi \]

\[ N = \sum_{i=1}^{N} w_i \]

weights \rightarrow small variations in coverage and tilt of the array

\[ r^\alpha = \sqrt{(a^\alpha)^2 + (b^\alpha)^2} , \quad \phi^\alpha = \text{atan} \frac{b^\alpha}{a^\alpha} \]

Amplitude and phase of the first harmonic modulation

\( \alpha \): right ascension

\( \phi \): azimuth

HARMONIC ANALYSIS IN RIGHT ASCENSION

<table>
<thead>
<tr>
<th>$E$ [EeV]</th>
<th>$N$</th>
<th>$a^\alpha$</th>
<th>$b^\alpha$</th>
<th>$r^\alpha$</th>
<th>$\varphi^\alpha[^\circ]$</th>
<th>$P(\geq r^\alpha)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 8</td>
<td>81 701</td>
<td>0.001 ± 0.005</td>
<td>0.005 ± 0.005</td>
<td>$0.005^{+0.006}_{-0.002}$</td>
<td>80 ± 60</td>
<td>0.60</td>
</tr>
<tr>
<td>$\geq 8$</td>
<td>32 187</td>
<td>$-0.008 \pm 0.008$</td>
<td>0.046 ± 0.008</td>
<td>$0.047^{+0.008}_{-0.007}$</td>
<td>100 ± 10</td>
<td>$2.6 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

**Table 1:** Results of the first harmonic analysis in right ascension.

[4 – 8] EeV: compatible with isotropy → $r^\alpha < 0.012$ @ 95% CL

E > 8 EeV: significant modulation @ 5.6σ → $p$-value ~20 times smaller than the 5σ discovery limit\(^1\)

Previous LSA results for $E \geq 8$ EeV:

\[ r^\alpha = 0.046 \pm 0.013 \quad p\text{-value } 0.001 \]
\[ \varphi^\alpha = 86^\circ \pm 16^\circ \quad N = 12292 \]
\[ r^\alpha = 0.044 \pm 0.010 \quad p\text{-value } 6.4 \times 10^{-5} \]
\[ \varphi^\alpha = 95^\circ \pm 13^\circ \quad N = 19797 \]

\(\Theta < 60 \text{ up to 2012} \quad [\text{I. Sidelnik ICRC 2013}]\)

\(\Theta < 80 \text{ up to 2013} \quad [\text{ApJ 802 (2015) 111}]\)

\(^1\)penalizing for the six energy bins explored in APP2011 → significance above 5.2σ
Compatible with dipolar distribution

First Harmonic
($\chi^2$/dof = 10.5/10)
FLUX MAP ABOVE 8 EeV

Equatorial coordinates

Galactic center
RECONSTRUCTION OF THE DIPOLE

- Right ascension distribution sensitive to equatorial dipole component

- Azimuth distribution sensitive to N-S dipole

| $E$ [EeV] | $N$    | $b^\phi$          | $P(\geq |b^\phi|)$ |
|-----------|--------|-------------------|-------------------|
| 4 - 8     | 81 701 | $-0.013 \pm 0.005$| 0.009             |
| $\geq$ 8  | 32 187 | $-0.014 \pm 0.008$| 0.08              |

**Table 2:** Harmonic analysis in azimuth.

$\langle \cos \delta \rangle = 0.78$

$\langle \sin \theta \rangle = 0.65$

\[ d_\perp \approx \frac{r^\alpha}{\langle \cos \delta \rangle}, \]
\[ d_z \approx \frac{b^\phi}{\cos \ell_{\text{obs}} \langle \sin \theta \rangle}, \]
\[ \alpha_d = \varphi^\alpha, \]
\[ \delta_d = \arctan \left( \frac{d_z}{d_\perp} \right), \]

$E > 8$ EeV

Dipole 6.5% amplitude

$(\alpha_d, \delta_d) = (100^\circ, -24^\circ)$

<table>
<thead>
<tr>
<th>$E$ [EeV]</th>
<th>$d_z$ [%]</th>
<th>$d_\perp$ [%]</th>
<th>$d$ [%]</th>
<th>$\delta_d$ [$^\circ$]</th>
<th>$\alpha_d$ [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 8</td>
<td>$-2.4 \pm 0.9$</td>
<td>$0.6^{+0.7}_{-0.3}$</td>
<td>$2.5^{+1.0}_{-0.7}$</td>
<td>$-75^{+17}_{-8}$</td>
<td>$80 \pm 60$</td>
</tr>
<tr>
<td>$\geq$ 8</td>
<td>$-2.6 \pm 1.5$</td>
<td>$6.0^{+1.1}_{-1.0}$</td>
<td>$6.5^{+1.3}_{-0.9}$</td>
<td>$-24^{+12}_{-13}$</td>
<td>$100 \pm 10$</td>
</tr>
</tbody>
</table>

**Table 3:** Dipole components and direction in Equatorial coordinates.
DISCUSSION

Flux map above 8 EeV- Galactic coordinates

Dipole's equatorial plane

observed dipole: (l, b) = (233°, -13°)

dipole direction ~ 125° from GC  disfavors galactic origin
DISCUSSION

Large-scale anisotropy can arise from:

- Inhomogeneous large-scale distribution of sources
- Diffusion in extragalactic magnetic fields from dominant nearby sources

Typical dipole amplitudes \( \sim 5\%-20\% \) at \( 10 \text{ EeV} \), depending on source distribution and CR composition

2MASS Redshift Survey
DISCUSSION

The flux-weighted dipole from IR galaxy distribution in 2MRS points to \((l,b)=(251^{\circ},38^{\circ}) \rightarrow \sim 55^{\circ}\) from observed

[Auger Coll. PRD 90 (2014) 122006]

Accounting GMF deflections


\(Z \sim 1.7 - 5\) at 10 EeV \(\rightarrow\) \(E/Z \sim 2 - 5\) EeV

[Auger Coll. PRD 90 (2014) 122006]

Improves agreement observation \(\leftrightarrow\) 2MRS
SUMMARY

- First measurement with more than $5\sigma$ significance of an anisotropy in the arrival directions of UHECRs has been reported.
- It corresponds to a large-scale dipolar modulation for $E > 8\text{ EeV}$.
- Indicative of an extragalactic origin.
BACKUP
\[ w_i = \left[ \Delta N_{\text{cell}}(\alpha_0^i) (1 + 0.003 \tan \theta_i \cos (\phi_i - \phi_0)) \right]^{-1} \]

Right Ascension of the zenith

\[ \Delta N_{\text{cell}}(\alpha^0) = \frac{N_{\text{cell}}(\alpha^0)}{\langle N_{\text{cell}} \rangle} \]

\[ N_{\text{cell}}(\alpha^0) = \sum_j n_{\text{cell}}(\alpha^0 + jT_{\text{sid}}) \]

\[ \langle N_{\text{cell}} \rangle = T_{\text{sid}}^{-1} \int_0^{T_{\text{sid}}} d\alpha^0 N_{\text{cell}}(\alpha^0) \]

Total number of active cells and its relative variations.
p-value vs exposure

The graph shows the probability as a function of exposure for different trigger conditions:
- Tight Triggers
- Relaxed Triggers
- All Triggers

Key points:
- 5σ
- 5.5σ
NORMALIZED RATE vs AZIMUTH

E > 8 EeV

First Harmonic
($\chi^2$/dof = 10.7/11)

$b^\Phi = -0.014 \pm 0.008$
RECONSTRUCTION RELIABILITY OF RELAXED TRIGGER

\[ \langle \Delta E / E \rangle = 0.2 \% \]
\[ \sigma (\Delta E / E) = 5 \% \]

\[ \langle \Delta \hat{u} \rangle = 0.3^\circ \]
\[ \sigma (\Delta \hat{u}) = 0.4^\circ \]

\[ \langle \Delta E / E \rangle = 0.3 \% \]
\[ \sigma (\Delta E / E) = 8 \% \]

\[ \langle \Delta \hat{u} \rangle = 0.4^\circ \]
\[ \sigma (\Delta \hat{u}) = 0.7^\circ \]
DIRECTIONAL EXPOSURE

\[ \omega(\delta) \text{ [km}^2 \text{ yr]} \]

\[ \theta < 60 \]

\[ 60 < \theta < 80 \]

\[ \theta < 80 \]

\[ \delta [^\circ] \]
DIPOLE AMPLITUDE: mixed composition scenario

\[ E_{\text{max}} = Z \times 6 \text{ EeV}, \gamma = 2 \]

\[(f_{p}, f_{\text{He}}, f_{C}, f_{\text{Si}}, f_{\text{Fe}}) = (0.19, 0.19, 0.4, 0.19, 0.03)\]

homogeneous distribution of sources

few % dipole amplitude at 10 EeV can easily arise

Extragalactic turbulent magnetic field

\[ B_{\text{rms}} = 1 \text{ nG} \]

\[ L_{c} = 1 \text{ Mpc} \]

\[ \rho = 10^{-4} \text{ Mpc}^{-3} \]

\[ \rho = 10^{-5} \text{ Mpc}^{-3} \]

\[ \rho = 10^{-4} \text{ Mpc}^{-3} \]
CONSTRAINS ON DIPOLE AMPLITUDES