Arrival directions of the highest-energy cosmic rays detected by the Pierre Auger Observatory

Ugo Giaccari\textsuperscript{1} for the Pierre Auger Collaboration\textsuperscript{2}

\textsuperscript{1}Instituto de Física – Universidade Federal Rio de Janeiro – Brazil

\textsuperscript{2}now at Centro Brasileiro Pesquisa Física Rio de Janeiro – Brazil

\textsuperscript{2}Av. San Martín Norte 304, 5613 Malargüe, Argentina

\textsuperscript{1}ICRC2017 - The Astroparticle Physics Conference

12-20 JULY, 2017

BEXCO, BUSAN, KOREA

**two largest departures from isotropy**
**both with post-trial probability ~1.4 × 10^{-2}**

---

**Around Centaurus A**  
energy threshold $E_{th} = 58$ EeV  
for an angular window $\psi = 15^\circ$

**Bright AGNs of the Swift-BAT catalog**  
$E_{th} = 58$ EeV, $\psi = 18^\circ$, for objects within 130 Mpc and brighter than $10^{44}$ erg/s

- ✔ Report an update of these two excesses with enlarged dataset
- ✔ Search for deviations from isotropy using two extra-galactic populations of gamma-ray sources
  - Star-forming galaxies and AGNs motivated by gamma-ray observations of Fermi-LAT
  - Weight individual sources in proportion to their fluxes
  - Same flux-weight analysis for the objects of the Swift-BAT catalog
The Dataset

Events detected by the Surface Detector of the Pierre Auger Observatory (*) from 1st Jan. 2004 to 30th April 2017 above 40 EeV, with ~90,000 km² sr yr

✓ zenith angle \( \theta \leq 60° \), 650 ("vertical") events
✓ zenith angle \( 60° \leq \theta \leq 80° \), 170 ("inclined") events

Same quality cuts used in ApJ 804 (2015),1

Vertical/Inclined exposure: 71,070/18,650 km² yr sr

820 events \( E > 40 \text{ EeV} \) ~30% increase in the statistic respect to previous results

(*) see F. Fenu’s talk

For each energy threshold in this analysis energy migration effects taken into account

Correct vertical and inclined exposures for unfolding factors as in spectrum studies (*)

E > 40 EeV: ~ 5/6% for vert./incl.
E > 80 EeV: ~ 8% for vert, ~20% for incl.
The Centaurus A region

✓ Compare the cumulative number of observed ($n_{\text{obs}}$) events with the expected on average from isotropic simulations ($n_{\text{exp}}$)

✓ Compute the cumulative binomial probability ($P$) to measure $n_{\text{obs}}$ given $<n_{\text{exp}}>$

✓ Scan in parameters: $E_{\text{th}}$ in [40; 80] EeV in steps of 1 EeV  
  $\Psi$ in [1°; 30°] in steps of 0.25° up to 5°, 1° for larger angles

Largest excess  
$E_{\text{th}} = 58$ EeV, $\Psi = 15°$  
$n_{\text{obs}} = 19$, $n_{\text{exp}} = 6.0$  
$P \sim 1.1 \times 10^{-5}$

Post-trial probability  
~ $1.1 \times 10^{-3}$

(fraction of isotropic simulations that have a smaller probability under the same scan)

Region of secondary minima above $\sim 40$ EeV
Cross-Correlation with bright AGNs (Swift-BAT)

✓ Count the cumulative number of pairs btw CRs and objects directions ($n_{obs}$)

✓ Excess probability provides by the fraction of isotropic simulations ($f_{min}$) with equal or greater number of pairs

✓ Scan in parameters: $E_{th}$ in [40; 80] EeV in steps of 1 EeV
  $\Psi$ in [1°; 30°] in steps of 0.25° up to 5°, 1° for larger angles

Largest excess

$E_{th} = 62$ EeV, $\Psi = 16°$

$n_{obs} = 57$, $n_{exp} = 26.4$

$f_{min} = 1 \times 10^{-7}$

Post-trial probability

$\sim 6.5 \times 10^{-4}$

after accounting for the scan in ($E$, $\Psi$, $D_{max}$, $L_{min}$)
Gamma-ray Sources

Active Galactic Nuclei

- Selected from 2FHL Catalog (Fermi-LAT, 360 sources):
  \[ \phi(> 50 \text{ GeV}) \] ---> proxy for UHECR flux
- Selection of the 17 objects within 250 Mpc
- Majority blazars of BL-Lac type and radio-galaxies of FR-I type

Star-forming or Starburst Galaxies

Use of Fermi-LAT search list for star-formation objects (Ackermann+ 2012)

- 63 objects within 250 Mpc, only 4 detected in gamma rays:
  correlated \[ \phi(> 1.4 \text{ GHz}) \] ---> proxy for UHECR flux
- Selection of brightest objects (flux completeness) with \[ \phi(> 1.4 \text{ GHz}) > 0.3 \text{ Jy} \]
- 23 objects, size similar to the gamma-ray AGN sample

Assumption UHECRs flux proportional to non thermal photon flux
Maximum likelihood technique

Build probability maps of CRs arrival directions

- Weight objects by their relative flux in the corresponding electromagnetic wavelength
- Fisher-Von Mises (∼2D Gaussian) smearing centered on astrophysical objects
- Isotropic fraction (diffuse flux)
- Account for directional exposure and normalize to the total number of events

Test statistic (TS) likelihood ratio

\[ TS = 2 \log \left[ \frac{L(\Psi, f_{ani})}{L(f_{ani} = 0)} \right] \]

Wilk’s Theorem: TS distributed according a \( \chi^2 \) with two degrees of freedom (good agreement with isotropic simulations)

Scan in energy threshold [20; 80] EeV in steps of 1 EeV

Maximum deviation from isotropy found at ∼40 EeV for one model

lowering minimum energy to 20EeV
4396 (“vertical”) events
1118 (“inclined”) events
Test Statistic vs. Energy

Mass composition model following JCAP 04 (2017) 38 for accounting CRs propagation

Homogeneous distribution of sources
EPOS-LHC, \( \gamma = 1 \)
\[ \log_{10}(R_{\text{cut}}/V) = 18.68 \]
\( f_{\text{H}}(\%) = 0, f_{\text{He}}(\%) = 67.3, f_{\text{N}}(\%) = 28.1 \)
\( f_{\text{Si}}(\%) = 4.6, f_{\text{Fe}}(\%) = 0 \)

**attenuation:** negligible impact on nearby objects (starburst)
more impact on distant objects (AGNs)

Other scenarios also tested

**Starburst Galaxies**
TS = 24.9, \( E_{\text{th}} = 39 \text{ EeV} \)

\( \gamma \)-ray detected AGNs
TS = 15.2, \( E_{\text{th}} = 60 \text{ EeV} \)

**Swift-BAT AGNs**
TS = 19.9, \( E_{\text{th}} = 60 \text{ EeV} \)
Best-fit parameters

Starburst Galaxies
\( f_{\text{ani}} = 10\% \), \( \Psi = 13^\circ \)
\( TS = 24.9 \) → \( p\)-value \( 3.8 \times 10^{-6} \)
Post-trial probability
\( 4 \times 10^{-5} \) ( \( \sim 3.9 \sigma \) )

\( \gamma \)-ray detected AGNs
\( f_{\text{ani}} = 7\% \), \( \Psi = 7^\circ \)
\( TS = 15.2 \) → \( p\)-value \( 5.1 \times 10^{-4} \)
Post-trial probability
\( 3 \times 10^{-3} \) ( \( \sim 2.7 \sigma \) )

preliminary
Maps for the best-fit parameters

Observed Excess Map - $E > 39$ EeV

**E > 39 EeV**

$\Psi = 10^\circ$

Model Excess Map - Starburst galaxies - $E > 39$ EeV

NGC 4945

$M 83$

3.7 Mpc

Model Excess Map - Active galactic nuclei - $E > 60$ EeV

CenA

$\sim 4$ Mpc

NGC 253

2.5 Mpc

NGC 1068

16.7 Mpc

Residual Map - Starburst galaxies - $E > 39$ EeV

Residual Map - Active galactic nuclei - $E > 60$ EeV

Galactic coordinate
Conclusion

Update of the previously unlikely findings
Centaurus A, brightest Swift AGNs

✓ Significance of the association increased in both cases at \(\sim 3.\sigma(\*)\) level with three additional years of data

examine CRs arrival direction in relation to gamma-ray sources

✓ We have measured a \(\sim 3.9\sigma\) (\*) deviation from isotropy at an intermediate angular scale.

(*) not \textit{a priori} explorations, the significance do not account for the previous searches made within the Auger Collaboration and those made by others

✓ It can be attributed to charged cosmic rays coming preferentially from the directions of starburst galaxies in our vicinity of the Universe.

✓ We cannot exclude contributions from sources having same flux and angular distributions as the starburst galaxies
Extra-slides
The Data Sets

Events detected by the Surface Detector of the Pierre Auger Observatory from 1st Jan. 2004 to 30th April 2017 above 40 EeV

✓ zenith angle $\theta \leq 60^\circ$ ("vertical") events

- largest signal detector surrounded at least by 4 detectors
- core inside triangle of contiguous detectors (isosceles and/or equilateral)

full efficiency $> 3$ EeV

✓ zenith angle $60^\circ \leq \theta \leq 80^\circ$ ("inclined") events

- at least 5 detectors surround the one closest the shower core

full efficiency $> 4$ EeV

Above 10 EeV

✓ Angular resolution better than 0.9°
✓ Statistical uncertainty on energy estimation better than 12%
✓ Systematic in absolute energy scale ~ 14%
E \geq 58\ EeV, \ r = 15^\circ
f_{\text{min}} = 2 \times 10^{-4}
\text{n}_{\text{obs}} = 14
\text{n}_{\text{exp}} = 4.5
\text{post-trial probability} \sim 1.4\%

- Complete for $\Phi > 1.34 \times 10^{-11}$ erg/s/cm$^2$ in the band (14-195 keV)
- ~ 300 AGNs above the cut in flux within 200 Mpc
- Majority of Seyfert I&II spiral galaxies

$E_{\text{th}}$ in [40; 80] EeV in steps of 1 EeV
$\Psi$ in [1°; 30°] in steps of 0.25°/1°
$L_{\text{min}}$ in $[10^{42}; 10^{44}]$ erg/s, in steps of log(L) = 0.33
$D_{\text{max}}$ in [10; 190] Mpc, in steps of 20 Mpc

$E \geq 58$ EeV, $r = 18°$
$n_{\text{obs}} = 62$
$n_{\text{exp}} = 32.8$
pre-trial probability = $2 \times 10^{-6}$
post--trial probability = $1.3 \times 10^{-2}$
Zenith distribution

Dotted line: expected $\sin \theta \cos \theta$ distribution from isotropy
<table>
<thead>
<tr>
<th>reference model</th>
<th>main minimum</th>
<th>2nd minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(SPG — EPOS-LHC)</td>
<td>best fit</td>
<td>average</td>
</tr>
<tr>
<td>$\mathcal{L}_0 \ [10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}]$</td>
<td>4.99</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.96$^{+0.08}_{-0.13}$</td>
<td>0.93±0.12</td>
</tr>
<tr>
<td>$\log_{10}(R_{\text{cut}}/V)$</td>
<td>18.68$^{+0.02}_{-0.04}$</td>
<td>18.66±0.04</td>
</tr>
<tr>
<td>$f_{\text{H}}(%)$</td>
<td>0.0</td>
<td>12.5$^{+19.4}_{-12.5}$</td>
</tr>
<tr>
<td>$f_{\text{He}}(%)$</td>
<td>67.3</td>
<td>58.6$^{+12.6}_{-13.5}$</td>
</tr>
<tr>
<td>$f_{\text{N}}(%)$</td>
<td>28.1</td>
<td>24.6$^{+8.9}_{-9.1}$</td>
</tr>
<tr>
<td>$f_{\text{Si}}(%)$</td>
<td>4.6</td>
<td>4.2$^{+1.3}_{-1.3}$</td>
</tr>
<tr>
<td>$f_{\text{Fe}}(%)$</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>$D/n$</td>
<td>174.4/119</td>
<td></td>
</tr>
<tr>
<td>$D (J), D (X_{\text{max}})$</td>
<td>13.3, 161.1</td>
<td></td>
</tr>
<tr>
<td>$p$</td>
<td>0.026</td>
<td></td>
</tr>
</tbody>
</table>

* from $E_{\text{min}} = 10^{15}$ eV.