Search for magnetically-induced signatures in the arrival directions of Ultra-High Energy Cosmic Rays measured by the Pierre Auger Observatory

Marcus Wirtz for the Pierre Auger Collaboration

ICRC 2019, Madison – July 27, 2019
Outline

1) Description of methods
   A) Multiplet search – correlation between energy and deflection
   B) Thrust ratio – measure of elongation of a pattern

2) Target selection – starburst galaxies & active galactic nuclei

3) Benchmark simulation

4) Sensitivity of the methods

5) Pierre Auger Observatory / data set

6) Application on data
   A) Targeted search   B) Blind search

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Multiplet search

- Relation between arrival direction $\vec{\Theta}$, source direction $\vec{\Theta}_s$ and magnetic field $\vec{B}$:

$$\vec{\Theta} = \vec{\Theta}_s + \frac{\vec{D}(\vec{\Theta}_s)}{E} \quad \text{with} \quad \vec{D}(\vec{\Theta}_s) = Ze \int_0^L d\vec{l} \times \vec{B}(\vec{l})$$

- In suitable coordinate system (sketch):

$$u \approx u_s + \frac{D(\vec{\Theta}_s)}{E}$$

- Find set of cosmic rays that fulfill:
  - Correlation coefficient $C(u, 1/E) > 0.9$
  - Transverse spread $\max(|w_i - \langle w \rangle|) < 1.5^\circ$
Thrust ratio

- Principal component analysis in region of interest (ROI), radius: 0.3 rad

\[ T_k = \max_{\vec{n}_k} \left( \frac{\sum_i |\omega_i^{-1} \vec{p}_i \cdot \vec{n}_k|}{\sum_i |\omega_i^{-1} \vec{p}_i|} \right) \]

strength of collimation along axis \( \vec{n}_k \)

- Successively maximize \( T_k : T_1 \geq T_2 \geq T_3 \)

- Ratio \( T_2/T_3 \) is a measure of the elongation of a pattern

**Isotropy:** \( T_2/T_3 \approx 1 \)

**Overdensity:** \( T_2/T_3 \approx 1 \)

**Elongated:** \( T_2/T_3 > 1 \)
**Target selection**

- Probe catalogs of starburst galaxies (SBGs) and active galactic nuclei (AGNs)
- Selection is based on attenuation of helium at 40 EeV and given distance:

**AGN**: Cen A, M87, Fornax A  
**SBG**: NGC 253, NGC 4945, Circinus, M83, NGC 4631, NGC 1808, NGC 1068

**Attenuation for AGN candidates**

**Attenuation for SBG candidates**
Benchmark simulations – Galactic magnetic field

- Test sensitivity of methods with simulation of arrival directions
- Upper and lower estimate of turbulence, two different models of GMF

**GMF-A**
- Model of Jansson & Farrar (2012), including striated / turbulent fields
- Coherence length = 60 pc

**GMF-B**
- Large uncertainty on turbulence (Planck)
- No striated component / Kolmogorov field down-scaled amplitude to value of 1/3
Benchmark simulations – Arrivals from CenA

Scenarios

$E_{\text{min}} = 40$ EeV
$N_{\text{CR}} = 900$

Composition:
He: $[40, 200]$ EeV

$E_{\text{min}} = 20$ EeV
$N_{\text{CR}} = 6000$

Composition:
p: $[20, 40]$ EeV
He: $[40, 80]$ EeV

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Expected sensitivity – Multiplet search

- Only applicable on 40 EeV energy cut
- Above 9 injected signal cosmic rays per source to obtain 3 sigma significance (1% signal fraction)
- Depends on source direction
- Sensitivity benefits from weaker turbulent field (GMF-B)

Above 1% signal fraction to obtain 3 sigma
Expected sensitivity – Thrust ratio

- Thrust ratio works better at lower energy threshold, $E > 20$ EeV (at 40 EeV worse than multiplets)
- Signal fraction above 0.7% for 3 sigma confidence level
- Similar performance for GMF-A and GMF-B models (robustness)

Above 0.7% signal fraction to obtain 3 sigma
Data set

- Data taken at the Pierre Auger Observatory between 1 January 2004 and 31 August 2018
- **Surface detector:** 1660 water-Cherenkov stations
- **Fluorescence detector:** 27 telescopes at four different sites
- Events with reconstructed zenith angle below 80°

**Energy cuts**
- $E > 20\,\text{EeV}$: 6568 events
- $E > 40\,\text{EeV}$: 1119 events

Pierre Auger Observatory, Mendoza, Argentina
Targeted search

<table>
<thead>
<tr>
<th>Target</th>
<th>Multiplet (40 EeV)</th>
<th>Thrust-ratio (20 EeV)</th>
<th>Thrust-ratio (40 EeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cen A</td>
<td>$1.2 \times 10^{-2}$</td>
<td>0.75</td>
<td>0.42</td>
</tr>
<tr>
<td>M87</td>
<td>0.61</td>
<td>0.44</td>
<td>0.85</td>
</tr>
<tr>
<td>Fornax A</td>
<td>0.96</td>
<td>0.21</td>
<td>$1.9 \times 10^{-2}$</td>
</tr>
<tr>
<td>NGC 253</td>
<td>0.54</td>
<td>0.98</td>
<td>0.88</td>
</tr>
<tr>
<td>NGC 4945</td>
<td>0.25</td>
<td>$2.9 \times 10^{-2}$</td>
<td>$3.7 \times 10^{-2}$</td>
</tr>
<tr>
<td>Circinus</td>
<td>0.99</td>
<td>0.82</td>
<td>0.58</td>
</tr>
<tr>
<td>M83</td>
<td>0.20</td>
<td>0.14</td>
<td>0.54</td>
</tr>
<tr>
<td>NGC 4631</td>
<td>—</td>
<td>0.59</td>
<td>0.85</td>
</tr>
<tr>
<td>NGC 1808</td>
<td>0.61</td>
<td>0.63</td>
<td>0.77</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>0.75</td>
<td>$6.0 \times 10^{-2}$</td>
<td>0.29</td>
</tr>
</tbody>
</table>

- There is no significant pattern found in the arrival directions for the multiplet search and the thrust ratio
- Multiplet search: lowest p-value is 1.2% in the Cen A region
- Thrust-ratio: lowest p-value is 2% in the Fornax A region

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### Blind search – Multiplets

Multiplet search also applied in an all-sky scan above 40 EeV

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Number of multiplets</th>
<th>Deflection power</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1</td>
<td>(8.0 ± 1.3) deg 100 EV</td>
<td>0.114</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>(12 ± 2) deg 100 EV</td>
<td>0.191</td>
</tr>
</tbody>
</table>

None of the found multiplets is significant

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Summary

• Searched for source signatures with two methods in data of the Pierre Auger Observatory above 20 EeV (6568 events) and 40 EeV (1119 events)

• **Multiplet search**: correlation of deflection and inverse energy

• **Thrust ratio**: measure for elongation, constructed by principal component analysis

• Applied on: – **targeted search** (AGN and SBG candidates), both methods – **all-sky search** above 40 EeV, multiplet search

• **No significant pattern** has been found in data; lowest isotropic chance probabilities were found with 1% (2%) with the multiplet (thrust) search

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Backup
Multiplet method: GMF-A vs GMF-B
Multiplet method: study of hyperparameters

Scenario 1 (single composition helium)

- No strong dependency on variations in hyperparameters
- $W < 1.5$, $C > 0.9$, works well for most sources

Source ID: 0=CenA, 1=M87, 2=FornaxA, 3=NGC253, 4=NGC4945, 5=Circinus, 6=M83, 7=NGC1808, 8=NGC1068, 9=NGC4631
Thrust ratio on GMF-A vs. GMF-B

A) JF12 + stri + turb ($B_{rms}=1$)

B) JF12 + turb ($B_{rms}=1/3$)

Less turbulence, performance gets a bit better
However, effect not very big (thrust observable robust)
ROI size scan for Thrust – JF12 Full, $B_{RMS}=1$

**Scenario 1**
(helium)

**Scenario 2**
(proton / helium)
For ROI radius $r = 0.3$ rad

There is no clear best choice as it depends on the deflection power

Depends on direction in sky (and GMF model)

Overall $r=0.3$ rad seems to be OK
Target selection

- **3FHL**: The Third Catalog of HardFermi-LAT Sources (Fermi-Lat Collaboration)
- Distances up to 250 Mpc
- 33 sources before selection
- Cen A, M87, Fornax A

- Merged sample from (Ackermann 2012) and (Becker 2009) + Circinus
- Distances up to 250 Mpc
- 32 sources before selection
- NGC 253, NGC 4945, Circinus, M83, NGC 4631, NGC 1808, NGC 1068

**Attenuation for AGN candidates**

- Plot showing relative flux vs. distance in Mpc.

**Attenuation for SBG candidates**

- Plot showing relative flux vs. distance in Mpc.