Anisotropy of High Energy Cosmic-Rays

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In collaboration with Eli Waxmann
arxiv:0801.4516, JCAP05(2008)006
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Isotropy of $E > 10$ EeV Cosmic Rays - Motivation

- What are the sources?

$$L_{tot} > 5 \times 10^{44} \frac{\text{erg}}{s} \left( \frac{E_p}{100 \ \text{EeV}} \right)^2 \frac{\Gamma^2}{\beta}$$

(1 EeV = 10$^{18}$ eV)

⇒ only GRB sources and AGNs are possible, have different correlation to galaxy density.
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- New Auger Observatory - 3000 km$^2$: many events.

- Our work:

What is the best statistics to extract the correlation between UHCRs and LLS (Large scale structures)?
GZK suppression

\[ p\gamma \rightarrow \pi n \Rightarrow d_{GZK}(E \sim 60 \text{ EeV}) \sim 200 \text{ Mpc} \ll 4 \text{ Gpc} \]
Cosmic ray intensity

IRAS catalog → Integrated galaxy density till $d = 75$ Mpc
How to measure correlation?

- Most of the literature: Two-point angular correlation:

\[ W(D) = \sum_{i}^{N} \sum_{j<i}^{\theta} \Theta(D - D_{ij}) \]

Angular power spectrum:

\[ C_{\ell} = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} a_{\ell m}^2. \]
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- Here: Cross Correlation (i - bin no. of 6° × 6°)
  \[ X_{C,UB} = \sum_{\{i\}} \frac{(N_i - N_{i,ISO})(N_{i,UB} - N_{i,ISO})}{N_{i,ISO}} \]

To compare: \[ X_Y(\ell) = \sum_\ell \frac{(C_\ell - C_{iso,\ell})^2}{\sigma_\ell^2}, \sigma_\ell^2 - the variance. \]
Results: cross correlation is better

\[ P(I/UB) \equiv \text{probability for ruling out isotropy assuming unbiased}. \]

For simulated events with Auger exposure and \( s_0 = 10^{-4}/\text{Mpc}^3 \) at 95\% CL:

\[
\begin{array}{c|ccc}
E > 40 \text{ EeV} & 100 \text{ events} & P(I/UB) & P(I/B) & P(UB/B) \\
\hline
X_C(UB) & \text{23\%} & \text{79\%} & \text{42\%} \\
X_W(\{D\} = \{0 : 10 : 40\}) & \text{7\%} & \text{12\%} & \text{10\%} \\
X_C(\{\ell\} = 2) & \text{6\%} & \text{8\%} & \text{7\%} \\
\end{array}
\]
**Results: cross correlation is better**

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For simulated events with Auger exposure and \( \bar{s}_0 = 10^{-4}/\text{Mpc}^3 \) at 95% CL:

<table>
<thead>
<tr>
<th>( E &gt; 40 \text{ EeV} ) 100 events</th>
<th>( X_C(UB) )</th>
<th>P(I/UB)</th>
<th>P(I/B)</th>
<th>P(UB/B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

One should take the cutoff at \( E > 40 \text{ EeV} \) for isotropy analysis:

<table>
<thead>
<tr>
<th>( X_{C, UB} ) 300 events</th>
<th>( E &gt; 20 \text{ EeV} ) (1205 events)</th>
<th>P(I/UB)</th>
<th>P(I/B)</th>
<th>P(UB/B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( E &gt; 40 \text{ EeV} ) 300 events</td>
<td>39%</td>
<td>94%</td>
<td>52%</td>
</tr>
<tr>
<td></td>
<td>( E &gt; 60 \text{ EeV} ) (94 events)</td>
<td>31%</td>
<td>87%</td>
<td>42%</td>
</tr>
<tr>
<td></td>
<td>( E &gt; 80 \text{ EeV} ) (31 events)</td>
<td>22%</td>
<td>63%</td>
<td>24%</td>
</tr>
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</table>
Analyzing Auger’s signal

Auger (Science, Nov07): “inconsistency with Isotropy based on correlation with AGNs at 99% CL”.

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Veron-Cetty and Vernon paper:

This catalogue should not be used for any statistical analysis as it is not complete in any sense, except that it is, we hope, a complete survey of the literature.

HiRes: 24%.

Correlation with LSS? Unclear.
Analyzing Auger’s signal

Auger (Science, Nov07): “inconsistency with Isotropy based on correlation with AGNs at 99% CL”.

Our cross correlation with LSS:

▶ Isotropy ruled out at 98% CL.

▶ Consistent with source density following LSS.
Conclusions

1. Cross-correlation statistics is more sensitive to the expected anisotropy signature than power spectrum and two point correlation function.

2. In order to distinguish between the different bias models, $\Delta E/E_{abs}$ should be reduced (currently $\simeq 25\%$).

3. The angular distribution reported by Auger is:
   - inconsistent with Isotropy at 98% CL.
   - consistent with LSS with slight preference to a biased distribution.
The GZK Suppression

Differential Flux function in ΛCDM.
The Model

- The generation spectrum of cosmic rays above $10^{19}$ eV:
  \[ \frac{d\dot{N}}{d\epsilon} = \Phi_0 \epsilon^{-\alpha} \quad \text{with} \quad \alpha \approx 2, \]
  with energy production rate of $\Phi_0 = 0.8 \times 10^{44} \text{erg Mpc}^{-3} \text{yr}^{-1}$.

- Proton sources trace large-scale galaxy distribution.

- The number density of CR sources is Poisson distributed.

- The protons lose energy due to interactions with CMB photons, produce $e^+e^-$ and $\pi$’s ($\Rightarrow \nu$’s).
The Model parameters

- $\bar{s}(z)$ - the average comoving number density of CR sources at redshift $z$:

$$s(z) = \bar{s}_0 (1 + z)^{m+3}$$

where $\bar{s}_0 = 10^{-2} - 10^{-4} \, \text{Mpc}^3$, $m = 0 - 3$.

- $b(\delta \rho)$ - a (bias) function of the local galaxy overdensity $\delta = \frac{\delta \rho}{\bar{\rho}}$:
  1. Isotropic model: $b[\delta] = 1$
  2. Unbiased model: $b[\delta] = 1 + \delta$
  3. Biased model

$$b[\delta] = \begin{cases} 
1 + \delta & \delta > \delta_{\text{min}} \\
0 & \delta < \delta_{\text{min}}
\end{cases}$$
All distributions are Poisson distributions

1. The mean number density of CR sources in $dV$ at $z$

$$\bar{S} = \bar{s}(z)b(\delta \rho)dV$$

2. The mean number of detected CR events produced by source at redshift $z$ is

$$\bar{N}(> E, z) = \frac{dn}{dtdA} AT = \frac{\dot{n}_0[E_0(E, Z)]}{\bar{s}_0} \frac{(1 + z)AT}{4\pi d_L(z)^2}$$

- $A$ and $T$ are the detector area and observation time,
- $\dot{n}_0(E)$ is the CR production rate above energy $E$ per unit volume,
- $d_L(z)$ is the luminosity distance.

3. $\Rightarrow$ The mean number of observed CR events per steradian

$$\bar{N}_0(E, \hat{\Omega}) = \int drr^2 \bar{N}(E, z)s(z)b[\delta \rho(z, \hat{\Omega})]$$
Auger: correlation to AGNs?  

27 events with $E > 57$ EeV

<table>
<thead>
<tr>
<th>$X_{C, UB}(E &gt; 57 \text{ EeV})$</th>
<th>P(I)</th>
<th>P(UB)</th>
<th>P(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9%</td>
<td>3.8%</td>
<td>20.4%</td>
<td></td>
</tr>
<tr>
<td>$X_{C, UB}(E &gt; 68 \text{ EeV})$</td>
<td>1.5%</td>
<td>5.7%</td>
<td>27.6%</td>
</tr>
</tbody>
</table>
Sensitivity to parameters

Figure: Dashed: (a) $\alpha = -2.2$; (b) $\tilde{s} \propto (1 + z)^0$; (c) $\tilde{s}_0 = 10^{-2} \text{Mpc}^{-3}$; (d) 30 EeV (50 EeV) systematic energy uncertainty (actual energy 40 EeV).