Observation of cosmic ray anisotropy at the Pierre Auger Observatory and at the Telescope Array

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i) Large-scale anisotropies at the Auger Observatory
Control of the event rate

- Auger: Full efficiency of detection above 3 EeV
- But effective change of rate due to changes of atm. conditions

\[ E_{\text{grd}} = (1 + \eta(t))E \]
\[ I(E_{\text{grd}})dE_{\text{grd}} = I(E)dE = KE^{-\gamma}dE \]

Variations prop. to \( 1 + (\gamma - 1)\eta(t) \)
First harmonic in right ascension

- Control of the event rate and of the effective area vs time
- Control of the directional exposure in right ascension

Detection at >5σ (accounting for the null results in other energy ranges)
Interpretation in terms of a dipole

- Additional first harmonic analysis in local azimuth sensitive to the dipole component along the Earth axis
Extragalactic origin

- Dipole at the entrance of the Galaxy not ‘destroyed’ by the GMF (JF12 model here)

\[ Z \sim 1.7-5 \text{ at } 10 \text{ EeV} \]
\[ E/Z \sim 2-5 \text{ EeV} \]
Higher-order multipoles?

- Dipole moment following from extragalactic matter

- Higher order multipole signatures to constrain further models?

[Di Matteo & Tinyakov, arXiv:1706.02534]

➡ Measurement of high-order multipoles/angular power spectrum?
ii) Multipole analysis with partial-sky coverage
Beyond the dipole moment?

- Multipolar moment as seen through the coverage:

\[ b_{\ell m} = \int_{\Delta \Omega} d\Omega_n \tilde{\omega}(n, \Delta E) \Phi(n) Y_{\ell m}(n) \]

\[ = \sum_{\ell' \geq 0} \sum_{m' = -\ell'}^{\ell'} a_{\ell' m'} \int_{\Delta \Omega} d\Omega_n \tilde{\omega}(n, \Delta E) Y_{\ell' m'}(n) Y_{\ell m}(n). \]

- Recovering coefficients if \( \Phi(n) \) bounded to \( \ell_{\text{max}} \):

\[ \overline{a}_{\ell m} = \sum_{\ell' = 0}^{\ell_{\text{max}}} \sum_{m' = -\ell'}^{\ell'} [K_{\ell_{\text{max}}}^{-1}]_{\ell m}^{\ell' m'} b_{\ell' m'}. \]

▷ BUT exponential degradation of the resolution each time the bound is incremented by 1:
**Angular power spectrum—stationarity**

\[
[K]_{\ell\ell'}^{mm'} = \int_{4\pi} d\Omega Y_\ell^m(\Omega) \omega(\Omega) Y_{\ell'}^{m'}(\Omega). \quad \rightarrow \text{mixing matrix for the multipolar moments}
\]

\[
[M]_{\ell\ell'} = \frac{2\ell' + 1}{2} \int_{-1}^1 d(\cos \theta) P_\ell(\cos \theta) P_{\ell'}(\cos \theta) \mathcal{W}(\theta). \quad \rightarrow \text{mixing matrix for the power spectrum}
\]

**2pt function of the coverage:**

\[
\mathcal{W}(\theta) = \int \int \frac{d\Omega_1 d\Omega_2}{8\pi^2} W(\Omega_1) W(\Omega_2) \delta(\cos \theta - \cos \theta_{12}).
\]

**⇒ if** \( \langle \phi(n) \rangle = 0 \) and \( \langle \phi(n) \phi(n') \rangle = \xi(n.n') \), then it can be shown that

\[
\langle C_\ell^{\exp} \rangle = \sum_{\ell'} M_{\ell\ell'}^{-1} \langle \tilde{C}_{\ell'} \rangle = C_\ell + \frac{4\pi f_1^2}{N f_2}. \quad \rightarrow \text{"Poisson" noise term}
\]

estimated as in the case of full-sky coverage

\[
\langle C_{\ell'} \rangle = C_{\ell'} \quad \rightarrow \text{"true" power spectrum}
\]
Hypothesis: Stationarity

Under stationarity assumptions, no signal beyond the dipole moment.
iii) Multipole analysis with full-sky coverage
Meta-analysis of Auger and TA data

Auger+TA: full-sky coverage with full efficiency $>10$ EeV, but...

Uncertainty on energy scale
Auger: 14%
TA: 21%
Intensity in the common band

• Aim: guarantee the same intensity in the common field of view

• If anisotropies, possible distortions by the directional exposure functions

⇒ Remove distortions induced from different directional exposures in case of anisotropies:

\[
J_{1/\omega}(E) = \frac{1}{\Delta\Omega\Delta E} \sum_{i=1}^{N} \frac{1}{\omega(\delta_i)}
\]

⇒ Tune the energy scale to get \(J_{\text{Auger}}(>E) = J_{\text{TA}}(>E)\) in the common f.o.v.
Performances

\[ \sigma_{\ell m}^2 \approx \frac{4\pi f_1 N}{\Omega_0^2} \int d\Omega \left( \frac{\mu_r(n)}{\mu_r^2(n)} \right)_p Y_{\ell m}^2(n) + \frac{N^2}{\Omega_0^2} \int d\Omega d\Omega' \left[ \left( \frac{\mu_r(n)\mu_r(n')}{\mu_r(n)\mu_r(n')} \right)_p - 1 \right] Y_{\ell m}(n) Y_{\ell m}(n'). \]

Degradation of resolution w.r.t. a perfect detector with full-sky coverage

Poisson

Combination of experiments

\[ \sigma_{10}/\sigma_{10}^0 \]

Moment

- 15 -
Figure 4: Angular power spectrum.

To visualise the indication of the dipole, an average flux smoothed out at an angular scale of 60° per solid angle unit can be derived using the joint data set in the following way:

\[
\frac{\bar{w}(n_0)}{dN(n_0)} = \frac{1}{R_Q} \frac{dN}{dn} Z_Q \frac{dN}{dn_0} f(n, n_0) \ , \quad (11)
\]

with \(f\) the top-hat filter function at the angular scale \(Q\). This average flux is displayed using the Mollweide projection in fig. 3, in \(\text{km}^2\text{yr}^{-1}\text{sr}^{-1}\) units. This map is drawn in equatorial coordinates.

To exhibit the dipole structure, the angular window is chosen to be \(Q = 60°\). The directions of the reconstructed dipole is shown as the blue cross.

The angular power spectrum \(C_`\) is a coordinate-independent quantity, defined as the average \(|a`m|^2\) as a function of \(`\):

\[
C_` = \frac{1}{2} \hat{A}_m = `|a`m|^2\ . \quad (12)
\]

In the same way as the multipole coefficients, any significant anisotropy of the angular distribution over scales near \(1/`\) radians would be captured in a non-zero power in the mode \(`\). Although the exhaustive information of the distribution of arrival directions is encoded in the full set of multipole coefficients, the characterisation of any important overall property of the anisotropy is hard to handle in a summary plot from this set of coefficients. Conversely, the angular power spectrum does provide such a summary plot. In addition, it is possible that for some fixed mode numbers \(`\), all individual \(a`m\) coefficients do not stand above the background noise but meanwhile do so once summed quadratically.

From the set of estimated coefficients \(\bar{a}`m\), the measured power spectrum is shown in fig. 4. The gray band stands for the RMS of power around the mean values expected from an isotropic distribution.
Dipole/Quadrupole moments

\[ \Phi(n) = \frac{\Phi_0}{4\pi} \left( 1 + r d \cdot n + \lambda_+(q_+ \cdot n)^2 + \lambda_0(q_0 \cdot n)^2 + \lambda_-(q_- \cdot n)^2 + \cdots \right) \]

Dipole amplitude

\[ r = (6.5 \pm 1.5)\%, \quad P = 5 \times 10^{-3} \]

Quadrupole amplitudes within fluctuations
Angular power spectrum

Power Spectrum

99% CL isotropy

Moment

-10^{-4} - 10^{-3} - 10^{-2}

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
iv) The highest energies
Magnetic deflections

At UHE, CRs may be rigid enough to point back to their sources within a few degrees

+ Reduced horizon

⇒ Possibility to identify nearby sources?

[Jansson & Farrar 2012]

[Harari et al., 1999]

[Unger & Farrar 2017]
Searches for hot spots

- Scan on energy threshold $E$ and circular window radius $\Psi$ to compute the obs/exp number of events
- $4.3 \sigma$ for $E>54$ EeV and $\Psi=12^\circ$
- Post-trial p-value: 69%

- 134 events $>57$ EeV, 34 within the $25^\circ$ window (13.5 exp.)
- Post-trial significance: $P\sim1.0 \times 10^{-3}$ (3.0$\sigma$)
Selection of *non-thermal* sources

**Selected from the 2FHL catalog** (*Fermi*-LAT, >50 GeV), within 250 Mpc

[Ackermann *et al.*, 2016]

(lepptonic processes preferred)

**Selected from *Fermi*-LAT search list** (HCN survey) within 250 Mpc, with radio flux>0.3 Jy

[Gao & Salomon, 2005]

(hadronic processes preferred)

**Assumption:** UHECR flux $\propto$ non-thermal photon flux

$\Rightarrow$ Reasonable for UHECRs and gamma rays originating from the same population of sources producing CRs at a similar rate from low energies to the highest ones, CRs which then undergo energy losses in calorimetric environments
Best fit and residual maps (through Auger f.o.v.)

Maps for the best-fit parameters

- Observed Excess Map - $E > 39$ EeV
  - $\Psi = 10^\circ$

- Observed Excess Map - $E > 60$ EeV
  - $\Psi = 7^\circ$

Preliminary

- 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
  - ~ 4 Mpc

- Residual Map - Starburst galaxies - $E > 39$ EeV
  - NGC 253
  - 2.5 Mpc

- Residual Map - Active galactic nuclei - $E > 60$ EeV
  - NGC 1068
  - 16.7 Mpc

Galactic coordinate
Best fit parameters

- \( f_{\text{ani}} = 10\%, \Psi = 13^\circ \)
  \[ \frac{\text{TS}}{\text{TS} = 24.9} \quad p\text{-value} \quad 3.8 \times 10^{-6} \]

- \( f_{\text{ani}} = 7\%, \Psi = 7^\circ \)
  \[ \frac{\text{TS}}{\text{TS} = 15.2} \quad p\text{-value} \quad 5.1 \times 10^{-4} \]

- \( 3.6 \times 10^{-5} \) (\( \sim 4 \sigma \))

- @ 10–100 GeV, energy release of CRs per \( \log(\text{energy}) \) = \( 10^{47} \) erg per solar mass of star formation in both the Milky Way and SBGs, where the SFR differs by order of magnitude

- for \( z < 2 \), SBGs responsible for \( \approx 15\% \) of the total SFR

\( \therefore \) Proportionality between UHECR production rate and SFR?
Auger+TA?

Energy-dependent systematic…

First attempt [UHECR2016]
Summary and perspectives

- Ultimate goal: full-sky survey of UHECR patterns in the sky
- Large scale studies $>\sim 10$ EeV (beyond the dipole)
- Over-densities/correlations with xGal matter at UHE

$E_{TA} > 10$ EeV / $E_{Auger} > 8.5$ EeV

Equatorial Coordinates - 60° smoothing

$E_{TA} > 57$ EeV / $E_{Auger} > 42$ EeV, 20°-radius window

$\Phi(n, > E)$ [km$^{-2}$ yr$^{-1}$ sr$^{-1}$]


A. Di Matteo, UHECR2016
Extragalactic gamma-ray background

dominated by 2 types of sources:

- UHECR source candidates:
  requirement on power
  - >1 EeV, energy production rate close to $10^{45}$ erg Mpc$^{-3}$ yr$^{-1}$
  - Both local SBGs & γAGNs match this requirement

- γAGNs: For a jet with a relativistic bulk motion, UHECRs emitted isotropically in the bulk frame would appear to be coming out in the jet direction in our cosmic reference frame.

- SBGs: high gamma-ray luminosity thought to be due to intense starburst episodes possibly triggered by galaxy mergers; could harbor with an increased rate cataclysmic events associated with the deaths of short-lived, massive stars, such as gamma-ray bursts, hypernovae, and magnetars.

[Dermer & Razzaque 2010]
Catalog of star-forming galaxies

GeV—TeV observations

- **TeV**: M 82 (0.9% Crab), NGC 253 (0.2% Crab), NGC 4945 ⊗, NGC 1068 (<5%), M 83 (<2%)

- **GeV**: M 82, NGC 253, NGC 4945, NGC 1068 firmly detected. GeV/FIR/radio correlation
  
  - Flux at 1.4 GHz used as a *proxy* for the UHECR flux

**Selected catalog**

- Cut @ 0.3 Jy to maximize the completeness
- Cut that matches a ~200 Mpc GZK horizon: take the most luminous source in the sample, place it as far away as you can to detect it above 0.3 Jy → 173 Mpc
- 23 brightest (/63) — ~80% of total flux
Stationarity? example #1
This yields the power spectrum expansion of the field we intended to. We only have access to what is called the pseudo-power spectrum of the window field, where we have expanded the window field on the measurement of the angular spectrum. Turning now to the correlation between two multipole estimates, it is easy to show that

\[ \tilde{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |\tilde{a}_{\ell m}|^2 \]

and we define them as convolution kernel which mixes the modes of the angular spectrum relative exposure in the direction of the true exposure becomes full sky but non-uniform. This has an immediate effect in the determination as we cannot compute the coefficients.

\[ \langle \tilde{C}_\ell \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |\tilde{a}_{\ell m}|^2 \]

Clearly, on convolution kernel which mixes the modes of the angular spectrum we want to measure is the same as the one found in the framework of the CMB.
Stationarity? example #2

\[ \tilde{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{m=\ell} |\tilde{a}_{\ell m}|^2 \]
Stationarity? example #2

\[ \tilde{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}|^2 \]
Stationarity: example #2

\[ \langle \tilde{C}^\ell \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |\tilde{a}_m|^2 \]

\[ \tilde{C}^\ell \]

\[ \sum \]

\[ \tilde{a}_m \]

\[ \rangle \]

\[ \langle \]

\[ \sum \]

\[ \tilde{C}^\ell \]

\[ \tilde{a}_m \]

\[ \rangle \]

\[ \sum \]

\[ \tilde{a}_m \]