Study of the arrival directions of ultra-high-energy cosmic rays detected by the Pierre Auger Observatory

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Anisotropy analysis with the Pierre Auger instrument. The key measurements, resolutions, stability

Analysis of arrival directions distribution:
- Anisotropy (via the VCV catalogue)
- Correlation with other distributions of extra-galactic matter
- Auto-correlation and largest excess
- Large scale patterns

Conclusions
Anisotropy analysis with the Pierre Auger instrument: key measurements
The Pierre Auger Observatory

Surface Detector (SD): 1600 water Cherenkov tanks, 100% duty cycle

Fluorescence Detector (FD): 4 x 6 telescopes, 10% duty cycle

12 t of purified water

Hybrid Detector
Two lines of analysis pursued in
Auger on CR arrival directions

At ≈ 50 EeV: “Small scale” studies

- The distance from which a source can contribute to the flux @ earth is limited (“GZK-Horizon”)
- Processes that produce UHECR require special conditions: few astrophysical objects are candidate
- Inhomogeneities in their spatial distribution may imprint anisotropy
- Comparison of UHECR arrival directions with astronomical objects is a tool for source identification

At EeV: “Large Scale” studies

- Study of the evolution of anisotropy vs energy to possibly identify the transition from galactic to extra-galactic component
- If CRs below the ankle galactic: sidereal modulations observable due to escape from the galaxy (% level, depending on GMF)
- If CRs below the ankle extra-galactic: sidereal modulations observable due to cosmological Compton-Getting effect

arXiv:1009.1855

Paper in preparation
Two lines of analysis pursued in Auger on CR arrival directions

<table>
<thead>
<tr>
<th>Key Measurements:</th>
<th>Arrival Direction</th>
<th>Energy</th>
<th>Exposure</th>
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<tbody>
<tr>
<td>Arrival direction</td>
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### At ≈ 50 EeV: “Small scale” studies
- The distance from which a source can contribute to the flux @ earth is limited (“GZK-Horizon”)  
- Processes that produce UHECR require special conditions: few astrophysical objects are candidate  
- Inhomogeneities in their spatial distribution may imprint anisotropy  
- Comparison of UHECR directions with astronomical objects is a tool for source identification

### At EeV: “Large Scale” studies
- Study of the evolution of anisotropy vs energy to possibly identify the transition from galactic to extra-galactic component  
- If CRs below the ankle galactic: sidereal modulations observable due to escape from the galaxy (0% level)  
- If CRs below the ankle extra-galactic: sidereal modulations observable due to cosmological Compton-Getting effect
Arrival direction

CR arrival direction from the times of flight of the EAS front among the detectors

Angular resolution: radius around the true direction that would contain 68% of the reconstructed showers

Estimated on event-by-event basis

Verified with hybrid events (2 independent geometrical reconstructions)

$E > 10^{19}$ eV: > 6 tanks: < 1°

N.B. Angular resolution over 6 years of data: stable within 0.1°
Energy

Particle lateral distribution

$S(1000)$ [signal at 1000 m] is the Auger energy estimator

$E \propto \text{area under the curve}$

Calorimetric measurement
Hybrid Events are used to calibrate the SD energy estimator, $S(1000)$ [converted to the median zenith angle, $S38$] with the FD calorimetric energy.

Statistical uncertainty: 
$\approx 20\%$ at the lowest energies 
$\approx 10\%$ at the highest ones

Systematic uncertainty $\approx 22\%$

N.B. Energy resolution over 6 years of data: stable within 5\%
Exposure: Trigger efficiency

SD trigger = Coincidence of at least 3 detectors

Full efficiency above 3 EeV
Purely geometrical acceptance
**Exposure: Stability**

Array growth and dead-Times: may modulate the exposure

Exposure modulation in six FULL years of data: \(\%\) level (and yet, we can correct by it!)
Arrival directions:

UHECR anisotropy
(via the VCV catalogue)
# The Dataset (SD-based)

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<tr>
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<th>Exposure km² sr y</th>
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<tr>
<td>I</td>
<td>1 Jan 2004 - 26 May 2006</td>
<td>4390</td>
<td>14</td>
</tr>
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<td>II</td>
<td>27 May 2006 - 31 Aug 2007</td>
<td>4500</td>
<td>13</td>
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<td>1 Sept 2007 - 31 Dec 2009</td>
<td>11480</td>
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Zenith angle < 60 deg  
Fiducial cut: ≥ 5 active stations around the EAS core  
Minimal energy: 55 EeV
Recap: Exploratory scan
1 Jan 2004-27 May 2006 (period I)

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- To demonstrate anisotropy: search for correlation with AGNs in the Veron-Cetty & Veron catalogue (quasars and active nuclei)
- VCV tracer of nearby matter (but not homogenous and incomplete)
- Helpful tool to test anisotropy with small statistics (but not to identify sources unambiguously)
Recap: Exploratory scan
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- Scan in $\psi$ (angular distance between CR and AGN), $E_{th}$ (CR energy), $z_{max}$ (AGN distance) to minimize the binomial probability $P$ that $\geq k$ out of $N$ evs correlate by chance
- Minimum value of $P$ found for $E_{th} = 56$ EeV, $\psi = 3.1^\circ$, $z_{max} = 0.018$
- 12/14 events correlate (3.2 expected by chance, $p(z, \psi) = 0.21$)
- Scan -> proper penalization difficult to calculate -> Prescription adopted
**Recap: Independent data:**

**27/5/2006-31/8/2008 (period II)**

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- Test on independent data with a-priori fixed parameters: $E_{th} = 56$ EeV, $\psi = 3.1^\circ$, $z_{max} = 0.018$, built to have 1% probability to incorrectly reject isotropy.
- 9/13 events correlated (2.7 expected by chance)
- Probability to happen by chance from an isotropic flux: $P \approx 1.7 \times 10^{-3}$
- Test passed: 99% c.l. anisotropy
Post-prescription data: 27/5/2006-31/12/2009 (period II + III)

**Updated event reconstruction:** $56$ EeV $\rightarrow 55$ EeV

**55 post-prescription events**

**A-priori fixed parameters:** $E_{th} = 55$ EeV, $\psi = 3.1^\circ$, $z_{max} = 0.018$

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Post-prescription data: 27/5/2006-31/12/2009 (period II + III)

Degree of correlation ($p=k/N$) vs total number of time-ordered events

The amount of observed correlation has decreased.

Probability that an isotropic flux would yield $\geq 21$ correlations: $P=0.003$
NEW DATA (Post-prescription): 27/5/2006-31/12/2009 (Period II + III)

VCV catalogue increasingly incomplete near the GP (dust extinction) + CRs arriving close to the GP are expected to be more deflected

9/55 events are within 10° from the Galactic Plane
None of them correlates: 21/46 correlations (46±6% vs 24% isotropic)
Arrival directions:
Examination versus other source scenarios
Different potential sources:

1. AGNs detected in X-rays in 58-months SWIFT catalogue (373 objects within 200 Mpc)
2. Galaxies in the 2MRS compilation (22000 most luminous galaxies from 2MASS, full-sky, IR). GP excluded (|b| > 10°)

Different methods:

I. Cross-correlation
II. Log-likelihood

Different models:

a. No weight by flux or distance
b. Weight by flux and distance (GZK-based attenuation)

N.B. A posteriori analysis
I. Cross-correlation

- No weight by distance or luminosity (equal contribution to CR flux from each source)
- Measures the excess of pairs within a given angular separation wrt isotropy (departures are larger if CRs correlate with denser regions of the catalogues)
- Excesses of pairs wrt to isotropic expectations in both cases
II. Log-Likelihood.  
Building catalogue smoothed maps

For each catalogue: build probability maps of CRs arrival directions expected by the objects, weighted by exposure&flux&GZK attenuation

SWIFT AGNs (stars): dimensions depend on flux, Auger exposure and GZK attenuation
II. Log-Likelihood.

Building catalogue smoothed maps

2 free parameters:
- smoothing angle $\sigma$ (to account for unknown magnetic deflections)
- isotropic background $f_{\text{iso}}$ (to account for an isotropic CR component and/or exclusion of possible other sources)

E.g. SWIFT density map: $\sigma=5^\circ$, $f_{\text{iso}}=0\%$
II. Log-Likelihood.

Finding the best values of \((\sigma, F_{\text{iso}})\)

- \(F_c(n)\): density map value in the direction \(n\)
- Use data to find the best values of \((\sigma, F_{\text{iso}})\) by maximizing the LL

**Best fit:**
- 2MRS -> \((1.5^\circ, 64\%)\)
- Swift -> \((7.8^\circ, 56\%)\)

**Large isotropic fraction favoured**
II. Log-Likelihood test

- Simulate $10^4$ samples with the same number of data as in the real set
- Draw events accordingly to catalogue density map or isotropically
- Compare the likelihood distributions with the value obtained from data
- Data are compatible with the models (fraction of isotropic realizations with a higher LL is 0.0002 for SWIFT, 0.004 for 2MRS)
Arrival directions:
Intrinsic clustering
Largest excess
**Intrinsic clustering: Autocorrelation**

Largest deviation from isotropic expectations @ 11° (P=0.10)

Small scale clustering (a la AGASA) not supported by Auger
The Largest excess

12 events in a 13° cell (1.7 expected): It lies at 4° from CEN A

By contrast, 0/69 observed events within 18° from M87 (but low exposure: 1.1 expected from isotropy)

N.B. Events from this region contributes to the autocorrelation as well as to correlations with all the catalogues.
Arrival directions:
Harmonic analysis of right ascension distribution
**The Dataset (SD-based)**

<table>
<thead>
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<th>$\Delta E$</th>
<th>$N$</th>
</tr>
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<tr>
<td>0.25 - 0.5</td>
<td>553639</td>
</tr>
<tr>
<td>0.5 - 1</td>
<td>488587</td>
</tr>
<tr>
<td>1 - 2</td>
<td>199926</td>
</tr>
<tr>
<td>2 - 4</td>
<td>50605</td>
</tr>
<tr>
<td>4 - 8</td>
<td>12097</td>
</tr>
<tr>
<td>&gt;8</td>
<td>5486</td>
</tr>
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Period: **1/1/2004 - 31/12/2009**

Zenith angle < 60 deg ($\approx$ **1 300 000 events**)

Fiducial cut: 6 active stations around the EAS core

Integrated exposure: **16320 km2 sr y**

Minimal energy: 0.25 EeV
The analysis methods

- First harmonic analysis in right ascension (Rayleigh formalism)
  - Correction for atmospheric effects on EAS
  - Correction for non-uniform exposure in sidereal time
  - Applied to energy > 1 EeV

- East-West analysis
  - Differential method based on the counting rates differences between eastward and westward directions: instrumental effects automatically removed
  - No need for exposure and/or atmospheric corrections
  - Applied to E<1 EeV
Rayleigh analysis: the effects of corrections

After exposure and atmospheric corrections: Solar modulation goes to statistical noise level
Rayleigh and east-west analysis: Results

No statistically significant amplitude at any energy.
Rayleigh and east-west analysis: Derived Upper Limits

90% upper limits to anisotropy amplitude (account taken of detector declination)
Conclusions

- Auger exposure grown to ≈ 20000 km² sr y
- 69 detected CRs with E＞55 EeV
- ＞1 300 000 CRs with E＞0.25 EeV
Conclusions

- On their arrival directions at E>55 EeV:
  - Update of the correlation with VCV objects (a-priori analysis)
  - Degree of correlation lower than in earlier data
  - Probability of finding such a correlation assuming isotropy: P=0.003

- Further (a-posteriori) analysis of the arrival directions distribution:
  - Compatibility with several models for their origin, based on the distribution of nearby extra-galactic matter (over small angular scales and large isotropic fraction): statistics not sufficient yet to identify sources or classes of them
  - Excess of events close to the direction of radio source CEN A
  - No significant excesses from the autocorrelation analysis (many sources and/or large separations)
Conclusions

On the large scale patterns of the arrival directions distribution at $E>0.25$ EeV:

- No significant amplitude detected at any energy
- 99% upper limits derived
  - Not consistent with the 4% anisotropy reported by AGASA at 1 EeV $< E < 2$ EeV
- Exclusion of different models for the galactic magnetic field
- Close to expected amplitude for cosmological Compton-Getting effect
Conclusions

- Auger exposure grown to ≈ 20000 km² sr y
- 69 detected CRs with E>55 EeV
- > 1 300 000 CRs with E>0.25 EeV
- Auger currently attained something more than 1/4 of the foreseen final exposure
- It must run as a “swiss clock/fridge” for the next 3/4
- Great care needed in handling the exposure at “low” energies
- The expected increment of events above 55 EeV is about 2/month
- EAS arrays need patient and long-term dedicated experimenters: PLEASE BE PATIENT