Probing for anisotropies at different angular scales in the arrival directions of the cosmic rays detected at the Pierre Auger Observatory

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Overview

- Cosmic rays have an anisotropy in their arrival directions on Earth
- How can we better parametrize it?
- Do the anisotropies occur differently at different angular scales or different energy bins?
- Are they just statistical fluctuations?

Cosmic ray anisotropy

Cosmic ray **flux** as a function of its **arrival direction:**

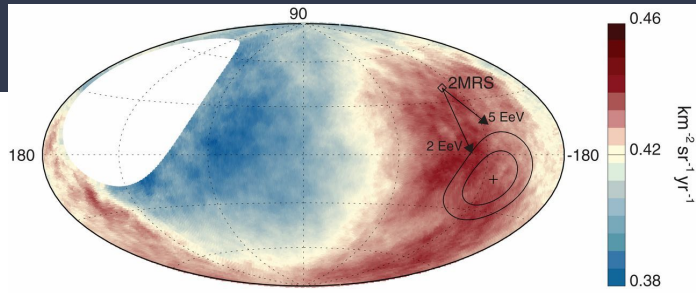
$$\Phi(\hat{u}) = \Phi_0(1 + \Delta\hat{u})$$

Assuming that the dominant anisotropy in the *distribution* of arrival directions is given by a **dipolar** and **quadrupolar** component,

$$\Delta\hat{u} = \mathbf{d} \cdot \hat{u} + \frac{1}{2}\sum_{i,j} Q_{i,j} u_i u_j$$

To search for anisotropies across various angular scales, we separate the **isotropic** and **anisotropic** components of the differential observed events per solid angle,

$$\frac{dN}{d\Omega}(\hat{u}) = \frac{N}{4\pi f_1} W(\hat{u})(1 + \Delta\hat{u})$$



$\mathrm{Amplitude}(E \geq 8 \times 10^{18} eV) : 7.4^{+1.0}_{-0.8}\%; 6.8\sigma_{stat}$

Pierre Auger Observatory detected anisotropies at the highest energies, demonstrating its Extragalactic origins

Science 357 (2017) 1266, ApJ 891 (2020) 2, ApJ 976 (2024) 48

Where, f_1 is the normalized **relative exposure** of the observatory

$$f_1 = \frac{1}{4\pi}\int W(\hat{u})d\hat{u}$$

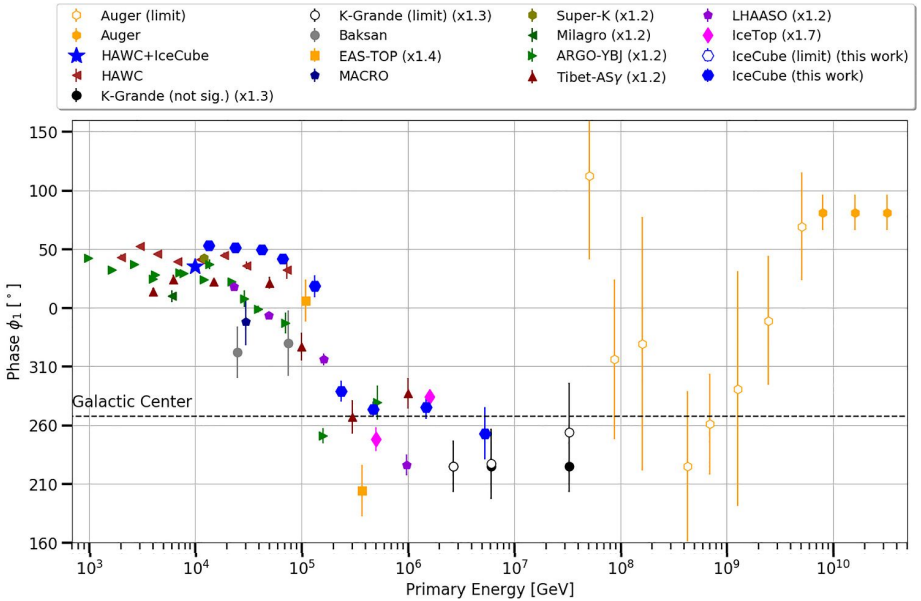
the **angular power spectrum** of the scalar field *u* is defined by

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

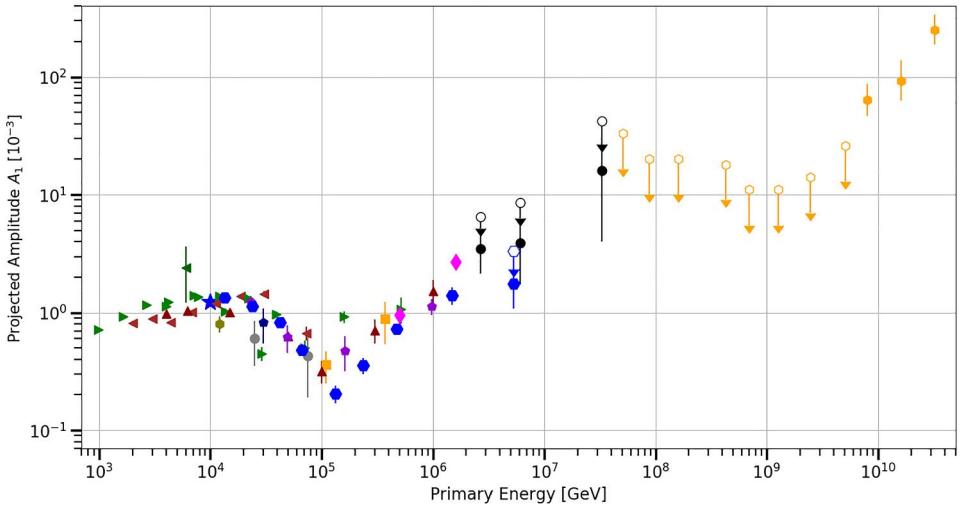
coefficients a_{lm} is the **multipolar expansion** of *u*

$$a_{\ell m} = \int \Delta\hat{u} Y_{\ell m}(\hat{u}) d\hat{u}$$

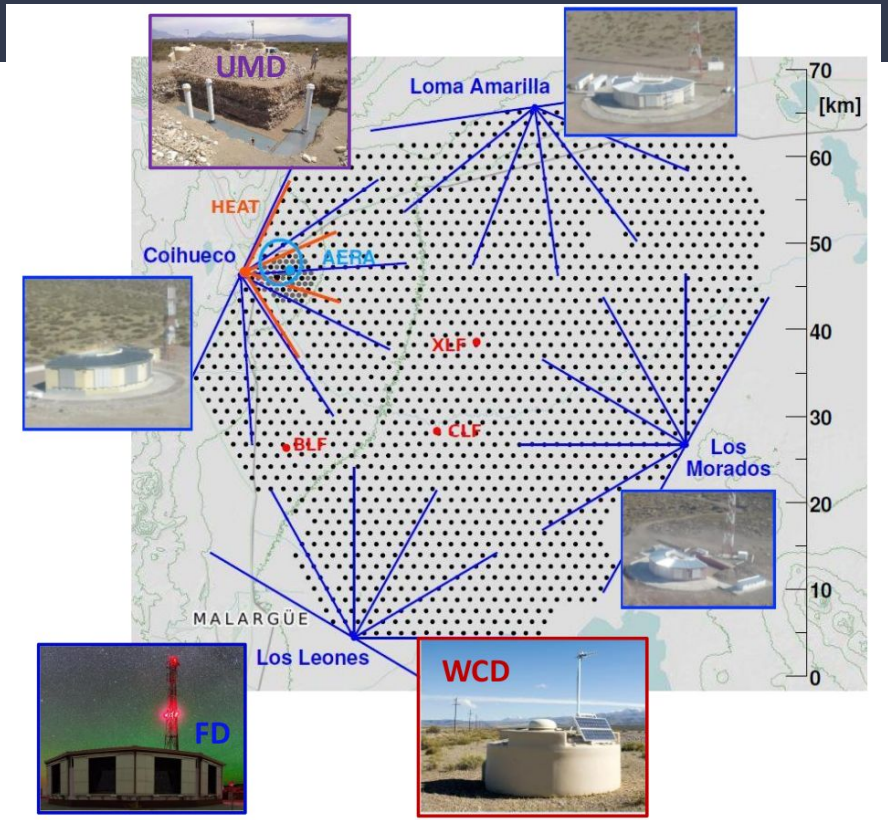
Cosmic-ray anisotropy for E > 1 TeV



IceCube 2025



Pierre Auger Observatory
The largest observatory of UHE Cosmic Rays



Multi hybrid detector

Phase I (2004-2023)

Phase II (2023-)

- **Surface Detector (SD)**
  - **Water-Cherenkov detectors (WCD)**
    - ~1600 stations, 1.5 km grid, **3000 km² (SD-1500)**
    - 2 additional grids of 750 m and 433 m spacing
  - **Scintillator Surface Detector (SSD)**
  - **Radio Detector (RD)**
- **Fluorescence Detector (FD)**
  - 4 sites, 27 telescopes
- **Underground Muon Detector (UMD)**

\+ Atmospheric monitoring devices

Characterization of the anisotropy with von Mises-Fisher distribution

A localized source signal distribution is considered over an isotropic background. The von Mises-Fisher distribution, a generalization of a Gaussian function over a sphere, is used

$$\frac{dN}{d\cos\Theta} = \frac{N}{2}\left[(1-\alpha) + \alpha\frac{\kappa}{\sinh\kappa}\exp\kappa\cos\Theta\right] \qquad f_{p=3}(\mathrm{x};\mu,\kappa) = C_{p=3}(\kappa)\exp(\kappa\mu^{\top}x)$$

This gives 2 asymptotic regimes, based on the **concentration parameter**, κ

1. κ << 1, **nearly isotropic** $\quad \frac{dN}{d\cos\Theta} \approx \frac{N}{2}\left[1 + d\cos\Theta + q\left(\cos^2\Theta - \frac{1}{3}\right)\right]$

with d = $\alpha\kappa$, q = $\alpha\kappa^2/2$

2. κ >> 1, anisotropic can be *approximated* in a **small angular** region, by a **Gaussian** of width, $1/\sqrt{\kappa}$

Likelihood Ratio Test

The likelihood of the events distribution is defined by using the von Mises-Fisher function and the **directional exposure** of the array, *w*

$$\mathcal{L}(\alpha, \kappa, \boldsymbol{u_0}) = \prod_{j=1}^{N} \left[(1-\alpha) + \alpha \frac{\kappa}{\sinh \kappa} e^{\kappa \boldsymbol{u_j} \cdot \boldsymbol{u_0}} \right] \frac{\omega(\boldsymbol{u_j})}{\mathcal{N}(\alpha, \kappa, \boldsymbol{u_0})}$$

The **likelihood ratio test** is used between the isotropic case (α = 0) and one with anisotropy $\mathrm{TS} = -2 \log \left(\frac{\mathcal{L}(\alpha = 0)}{\mathcal{L}(\alpha, \kappa, u_0)} \right)$

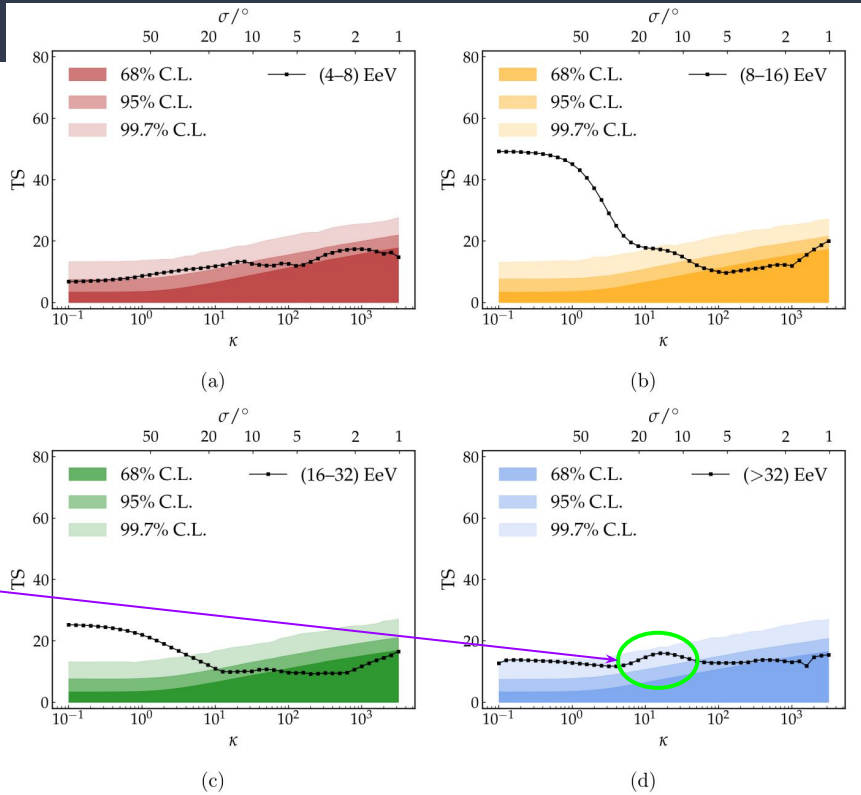
As the concentration parameter, κ, controls the angular width of the tested distribution, the **likelihood is profiled with κ**, in the range of **$\log_{10}\kappa$ = [-1.0, 3.5]** -> **purely dipolar flux** (20x stronger than quadrupole term) to the **limit of the angular resolution** of the observatory, σ = 1.0°

For each step in κ-parameter space, an **isotropic chance probability ρ_{iso}** is derived by performing 10^4 isotropic Monte-Carlo simulations

The **uncertainties in *d*** is evaluated by profiling the likelihood over α, as $d = \alpha\kappa$

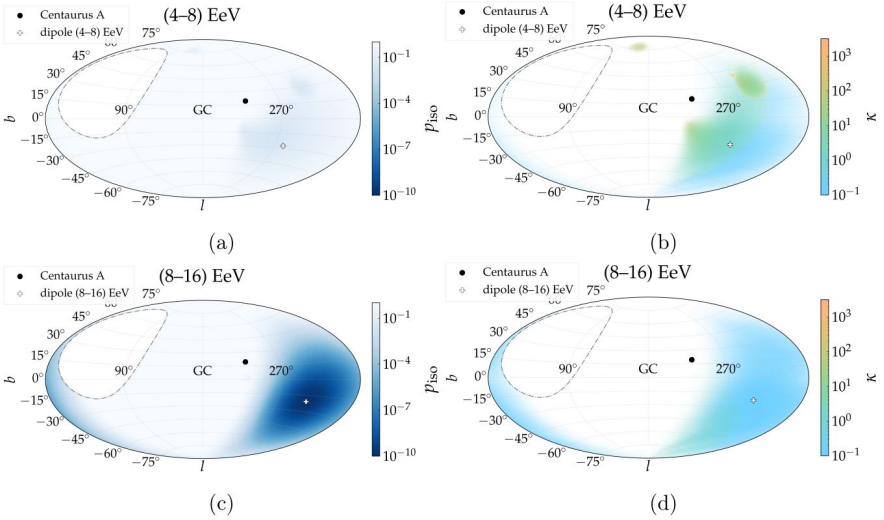
Results

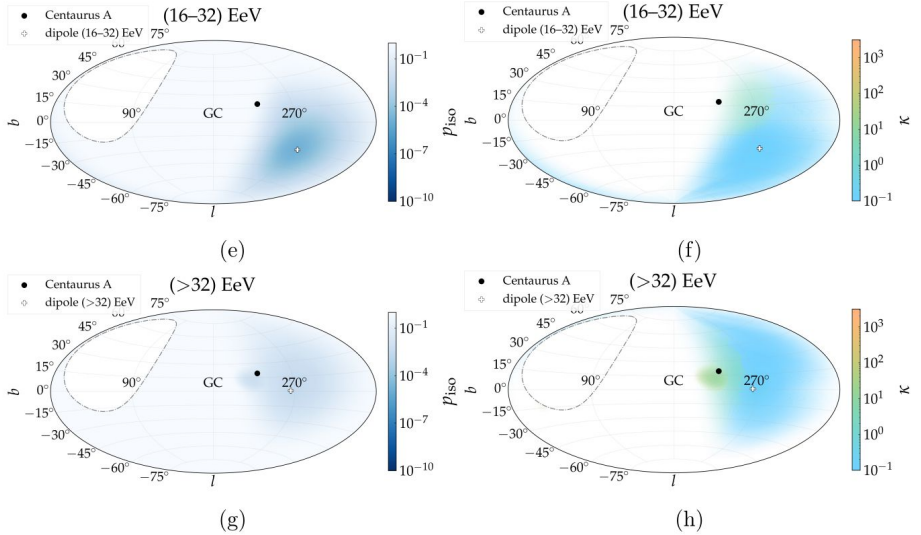
E/ EeV	κ	α (%)	R.A./°	dec/°	TS	d (%)	σ/°	$p_{\rm iso}$
4–8	2.5	$0.7^{+0.2}_{-0.2}$	112^{+26}_{-33}	-65^{+16}_{-13}	10.1	—	36.2	0.023
8–16	0.10	67^{+10}_{-10}	94^{+9}_{-9}	-28^{+10}_{-10}	49.2	$6.7^{+1.0}_{-1.0}$	—	$1.1 \times 10^{-10*}$
16–32	0.10	100_{-17}	95^{+17}_{-16}	-53^{+11}_{-10}	25.2	10^{+2}_{-2}	—	$1.3 \times 10^{-5*}$
32–∞	0.16	90^{+10}_{-25}	141^{+19}_{-19}	-44^{+18}_{-15}	13.8	14^{+4}_{-4}	—	3.0×10^{-3}



Centered around RA, Dec: (209°, -50°), with κ=1.1, corresponding 25.44° away from Centaurus A (201.4°, -43°). Compatible with the overdensity observed on an intermediate angular scale of 27° from the source

Results: Projection on Galactic sky

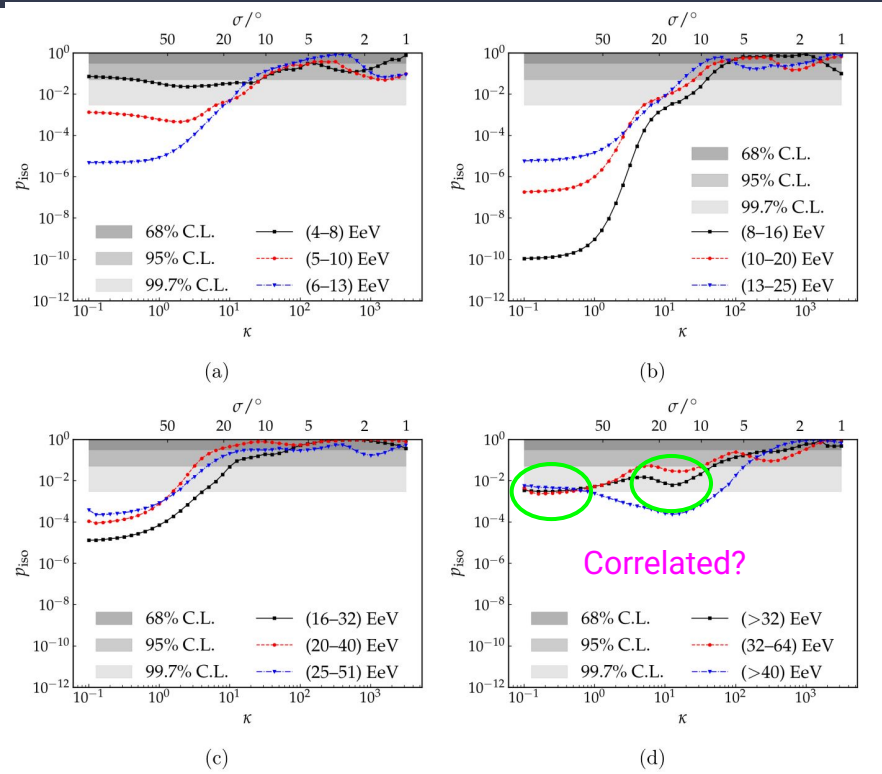




Minimum ρ_{iso} on the left, and the profile of κ on the right

Results: Profile scan over sliding energy bins

Dipole amplitude increases with energy
Corresponding lowest ρ_{iso}, decreases rapidly with energy, and gradually increases after (8-16 EeV)



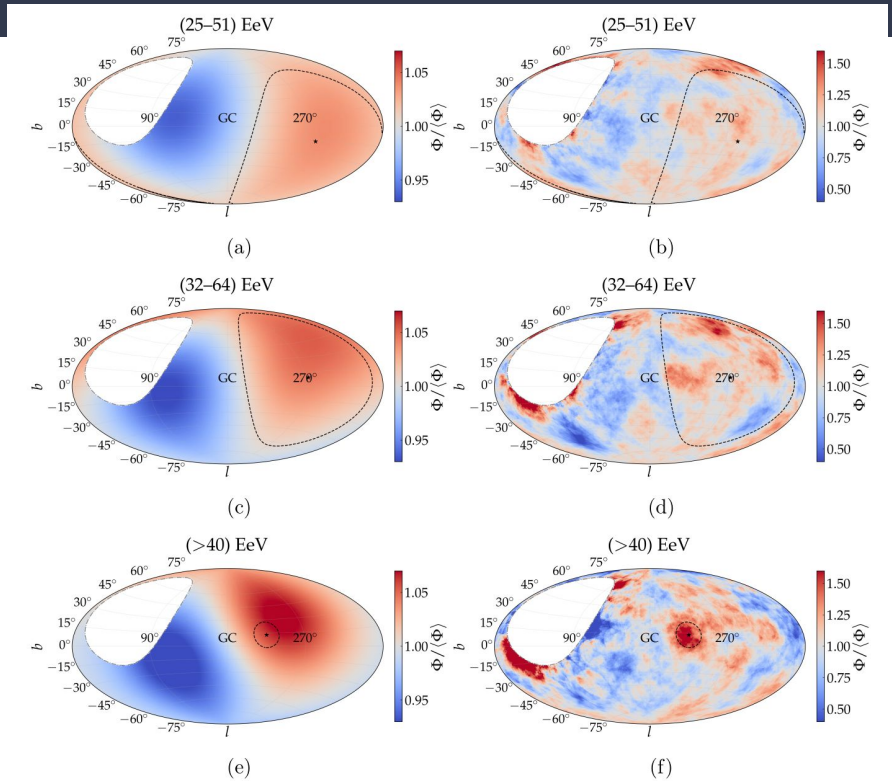
Are the different excesses an artefact of statistical fluctuations?

NO. Based on simulations, the probability of finding an excess at larger angular scale is **similar** whether an intermediate-scale excess is present or not

Normalized Flux: smoothened

Smoothened for easier comparison, by van Mises-Fisher distribution for
1. **Large-scale** excesses, σ = 45º (left)
2. **Intermediate-scale** excesses σ = 15º (right)

Dashed lines contain 39.3% of the normalized flux.
The flux ratio **increases with energy** and has its **maximum in the E > 40 EeV** interval



Summary

- Uniform search for overdensities of cosmic rays at different angular scales in the arrival direction distribution of 19 years of Auger events
- Characterization of the anisotropies with van Mises-Fisher distribution helped in a more thorough understanding
- The overdensities in the Centaurus A region that exceed 95% CL on intermediate angular scales, are also present in (32-64) and (>32) EeV intervals
- No evidence of coexistence of two excesses at different angular scales, with one arising from statistical fluctuations of another
    - Maybe a local dominant source and a far-away population causes this
    - Maybe the mixed mass-composition of CRs at different energies might reveal something?
    - Something else?