Update on full-sky searches for large- and medium-scale anisotropies in the UHECR flux using the Pierre Auger Observatory and the Telescope Array

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for the Pierre Auger and Telescope Array collaborations

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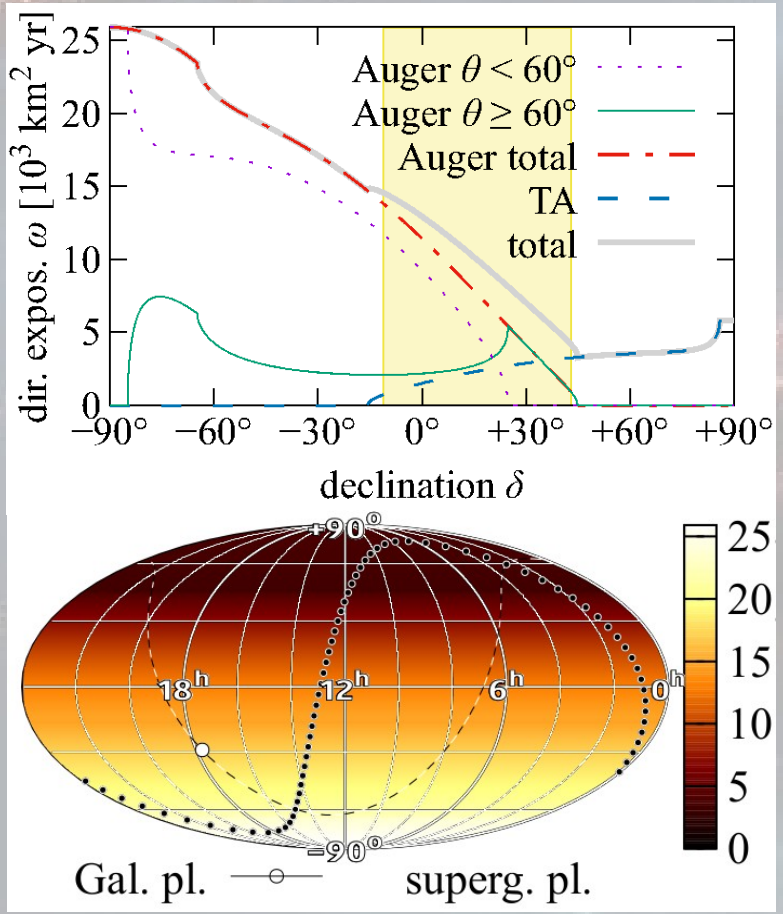
Search for the origin of the UHECR with the largest Auger+TA dataset

- Two large scale experiments are operating: Pierre Auger Observatory and Telescope Array.
- The Joint Auger+TA dataset is the world's largest UHECR dataset. This is the only dataset with full sky coverage.
- The results of the two analyses are presented:
  - Large-scale anisotropy analysis: angular power spectrum, including dipole and quadrupole
  - Medium-scale anisotropy analysis: correlations with all galaxies and starburst galaxies

Joint Auger+TA dataset

- **Telescope Array data:**
  - 16 years, 2008-05-11 — 2024-05-11, θ < 55° (two years added since ICRC 2023)
    - 6712 events for E_{TA} > 10 EeV
    - 461 events for E_{TA} > 40.96 EeV
  - effective exposure 19 500 km^2 sr yr
- **Pierre Auger data:**
  - 19 years, 2004-01-01 – 2022-12-31, θ < 80° (same as at ICRC 2023)
  - For large scale anisotropies (stricter cuts):
    - 44309 events for E_{Auger} > 8.53 EeV
    - geometrical exposure 123,000 km^2 sr yr
  - For medium scale anisotropies (looser cuts):
    - 2936 events for E_{Auger} > 32 EeV
    - geometrical exposure 135,000 km^2 sr yr

Combined Auger+TA exposure

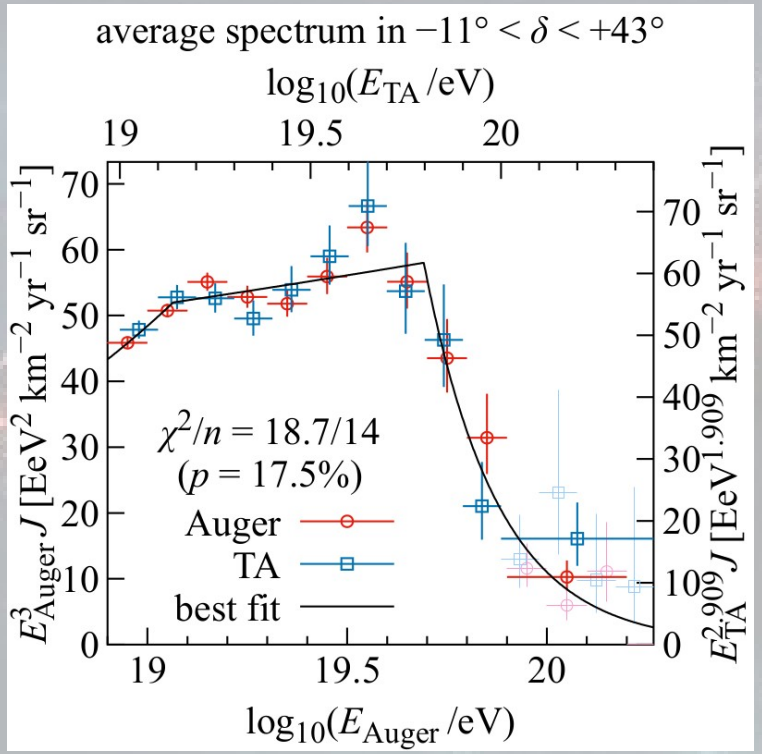


Energy scale cross-calibration

- There is a systematic uncertainty for the absolute energy calibration of each observatory: ±14% for Auger, ±21% for TA
- We require that the binned energy spectrum in the common declination band $-11^\circ < \delta < 43^\circ$ agrees in both observatories:
- We assume a mapping between the two energy scales of the form

$$\frac{E_{Auger}}{10\,EeV} = a\left(\frac{E_{TA}}{10\,EeV}\right)^{b}$$

- We simultaneously fit the parameters a and b and a spectrum model to both Auger and TA data



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- We require that the binned energy spectrum in the common declination band $-11^\circ < \delta < 43^\circ$ agrees in both observatories:
- The parameters a,b are obtained from the fit $\frac{E_{Auger}}{10\,EeV} = a\left(\frac{E_{TA}}{10\,EeV}\right)^b$
- The boundaries of energy ranges are fixed:
- $\ln a = -0.159 \pm 0.011$
  $b = 0.954 \pm 0.015$

	E_1, EeV	E_2, EeV	E_3, EeV
E_{Auger}	8.53	16	32
E_{TA}	10	19.3	40.0

dataset	$\ln a$	b	χ^2/n	p	$\frac{E_1}{\mathrm{EeV}_{Auger}}$	$\frac{E_2}{\mathrm{EeV}_{TA}}$	$\frac{E_3}{\mathrm{EeV}_{TA}}$	$\frac{1-b}{\sigma_b}$
ICRC 2023	−0.157	0.949	19.3/14	0.15	8.545	19.36	40.18	3.1σ
UHECR 2024	−0.159	0.954	18.7/14	0.17	8.529	19.33	39.96	2.9σ

Large-scale anisotropy: motivation

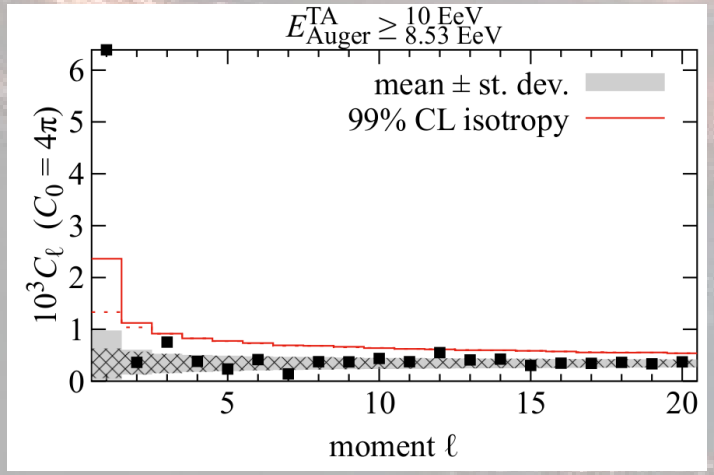
- The most of the UHECRs are charged particles, they undergo deflections in the Galactic and extragalactic magnetic fields.
- It has been proposed that the dipole and quadrupole anisotropy are robust with respect to the magnetic field models:

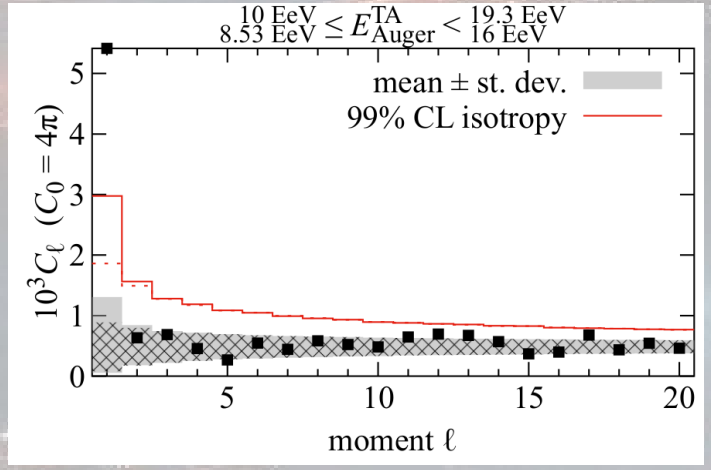
  di Matteo, Tinyakov, MNRAS 476 (2018) 1, 715-723

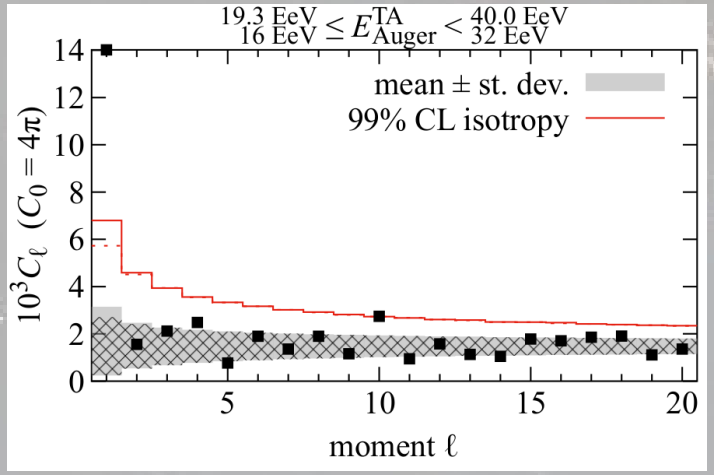
- The dipole modulation in RA for E > 8 EeV was discovered by Pierre Auger collaboration in 2017 and has now reached 6.8σ significance.
  The quadrupole anisotropy is an important signature of the UHECR origin models, but it has not been detected so far.

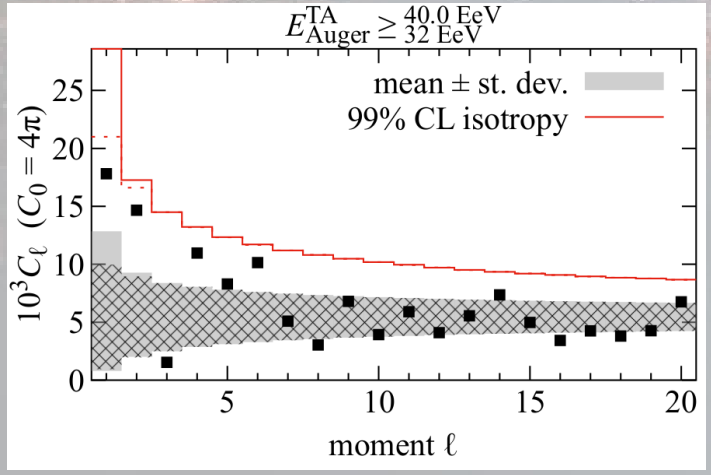
  Pierre Auger collaboration, Science 357 (2017) 6357;
  ApJ 868 (2018) 4; arXiv:2408.05292 accepted in ApJ

Large-scale: angular power spectrum









- Only the dipole stands out
- The isotropic prediction accounts for the statistical uncertainty of the Auger-TA energy calibration.
- Hatched region and dashed red line show isotropy predictions without accounting for this effect.

Large-scale: angular power spectrum

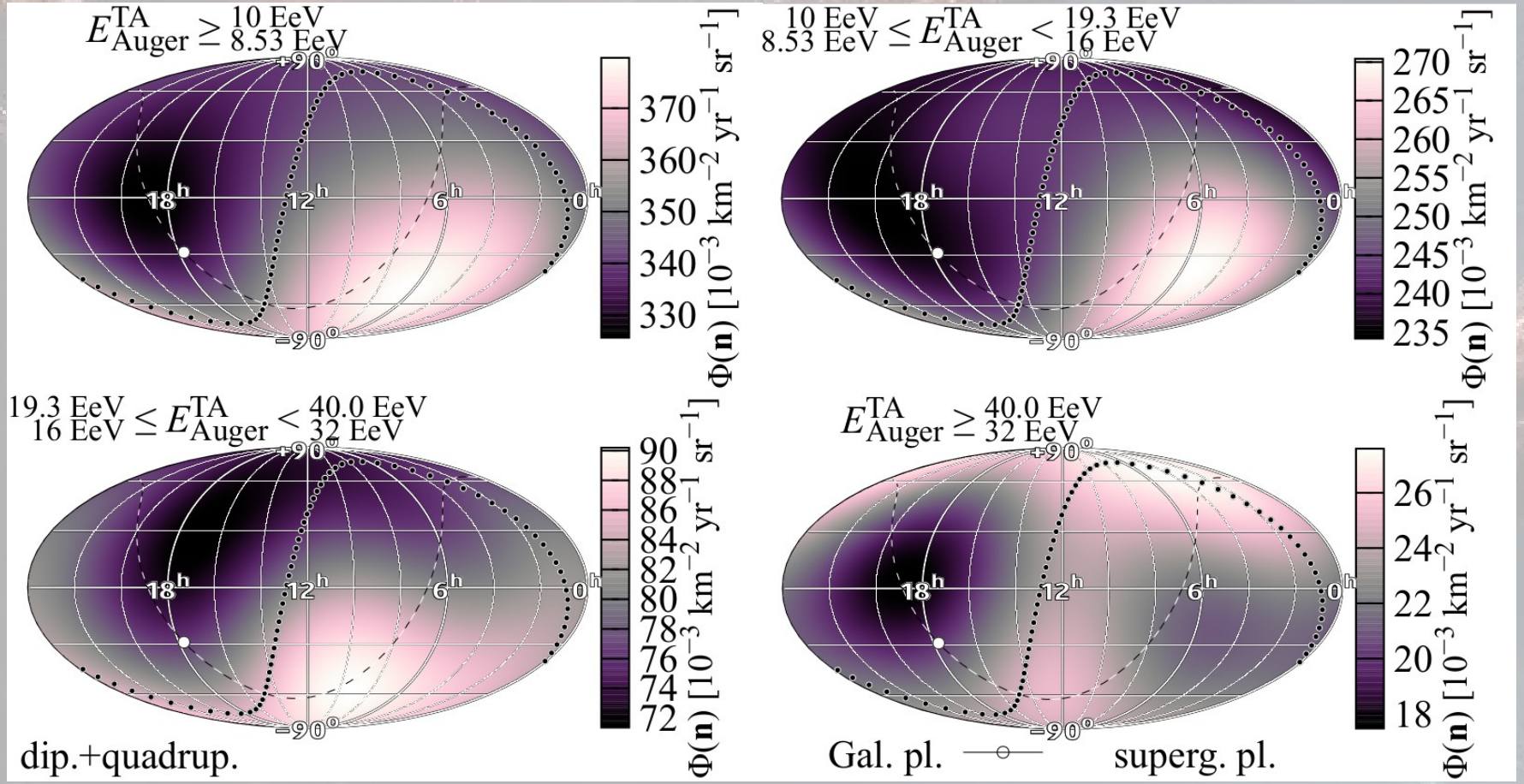
$$\begin{cases} E_1 = 10\,\text{EeV}_{\text{TA}} \\ E_2 = 16\,\text{EeV}_{\text{Auger}} \\ E_3 = 32\,\text{EeV}_{\text{Auger}} \end{cases}$$

Most significant multipole moments

		UHECR 2024		ICRC 2023	
energy bin	ℓ	p	signif.	p	signif.
$[E_1, +\infty)$	1	3.9×10^{-6}	4.6σ	2.6×10^{-5}	4.2σ
	3	3.1×10^{-2}	2.2σ	1.0×10^{-3}	3.3σ
$[E_1, E_2)$	1	3.3×10^{-4}	3.6σ	5.0×10^{-4}	3.5σ
$[E_2, E_3)$	1	7.8×10^{-5}	4.0σ	1.2×10^{-3}	3.2σ
	10	9.6×10^{-3}	2.6σ	5.0×10^{-3}	2.8σ

- The dipole got more significant, especially in the middle energy bin.
- Still nothing else jumping out

Large scale sky: dipole and quadrupole

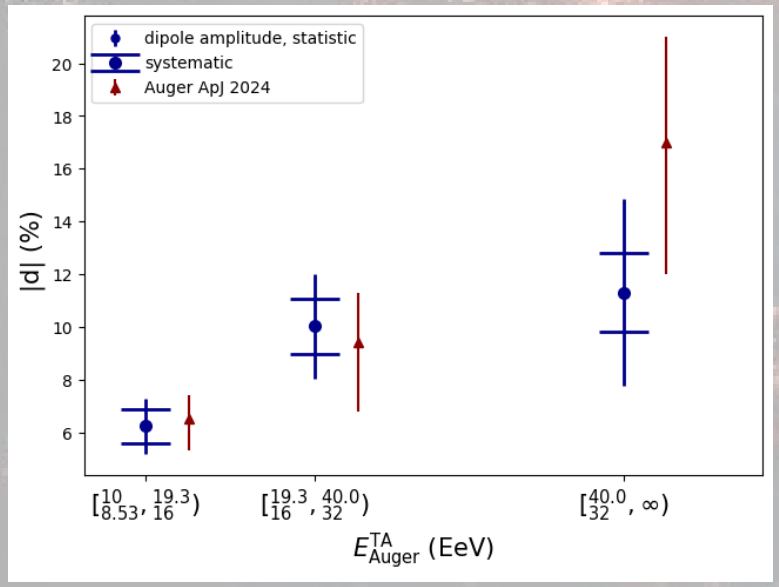


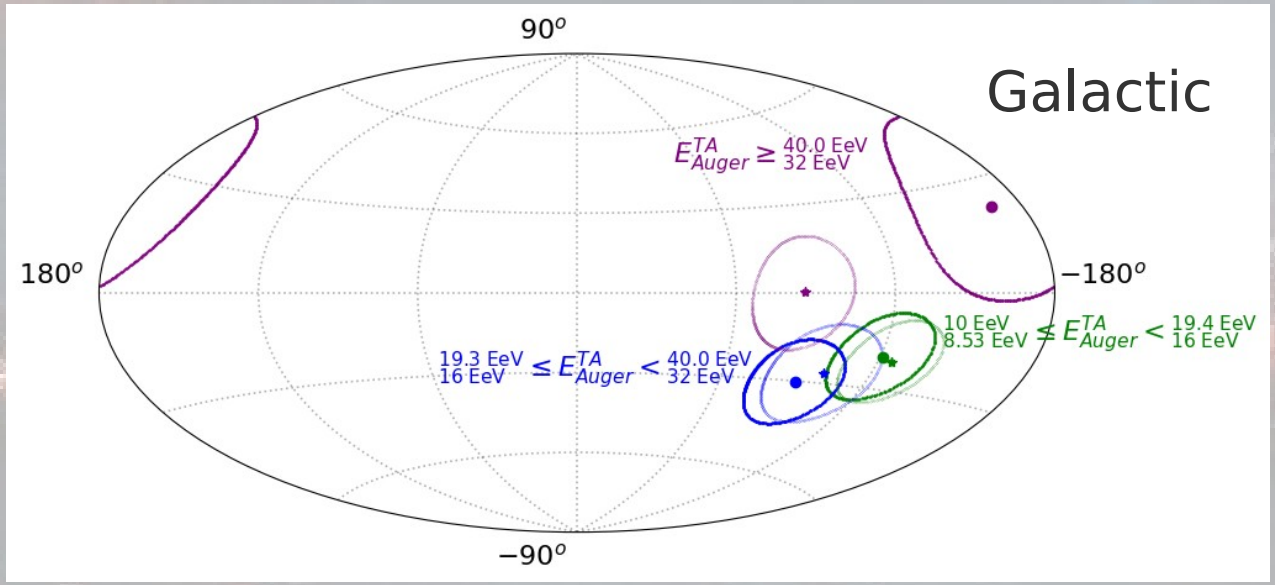
Large scale sky: dipole and quadrupole values

	$E > E_1$	$E_1 < E < E_2$	$E_2 < E < E_3$	$E > E_3$
d_x [%]	$-0.5 \pm 1.0 \pm 0.0$	$+0.1 \pm 1.8 \pm 0.0$	$-4.3 \pm 3.4 \pm 0.1$	$-0.6 \pm 0.9 \pm 0.0$
d_y [%]	$+5.3 \pm 1.0 \pm 0.0$	$+5.1 \pm 1.8 \pm 0.0$	$+9.0 \pm 3.3 \pm 0.0$	$+5.5 \pm 0.8 \pm 0.0$
d_z [%]	$-3.3 \pm 1.2 \pm 1.2$	$-8.6 \pm 2.1 \pm 1.2$	$+5.3 \pm 4.1 \pm 3.3$	$-3.9 \pm 1.0 \pm 1.1$
$Q_{xx} - Q_{yy}$ [%]	$-3.8 \pm 4.4 \pm 0.0$	$+12.7 \pm 7.6 \pm 0.0$	$+26.8 \pm 14.1 \pm 0.1$	$+1.9 \pm 3.7 \pm 0.0$
Q_{xz} [%]	$-1.9 \pm 2.5 \pm 0.0$	$+5.8 \pm 4.4 \pm 0.0$	$+9.4 \pm 9.2 \pm 0.0$	$+0.6 \pm 2.1 \pm 0.0$
Q_{yz} [%]	$-5.3 \pm 2.6 \pm 0.0$	$-3.1 \pm 4.4 \pm 0.0$	$+11.5 \pm 8.6 \pm 0.2$	$-3.7 \pm 2.1 \pm 0.0$
Q_{zz} [%]	$+0.6 \pm 2.9 \pm 1.4$	$+3.0 \pm 5.1 \pm 1.4$	$+24.7 \pm 9.7 \pm 4.0$	$+2.7 \pm 2.4 \pm 1.3$
Q_{xy} [%]	$+1.6 \pm 2.2 \pm 0.0$	$-1.6 \pm 3.8 \pm 0.0$	$+4.1 \pm 7.3 \pm 0.1$	$+1.1 \pm 1.8 \pm 0.0$

Statistical uncertainty and uncertainty of energy calibration are shown

Large scale anisotropies: dipole amplitude and position





Stars are the position of Auger dipole

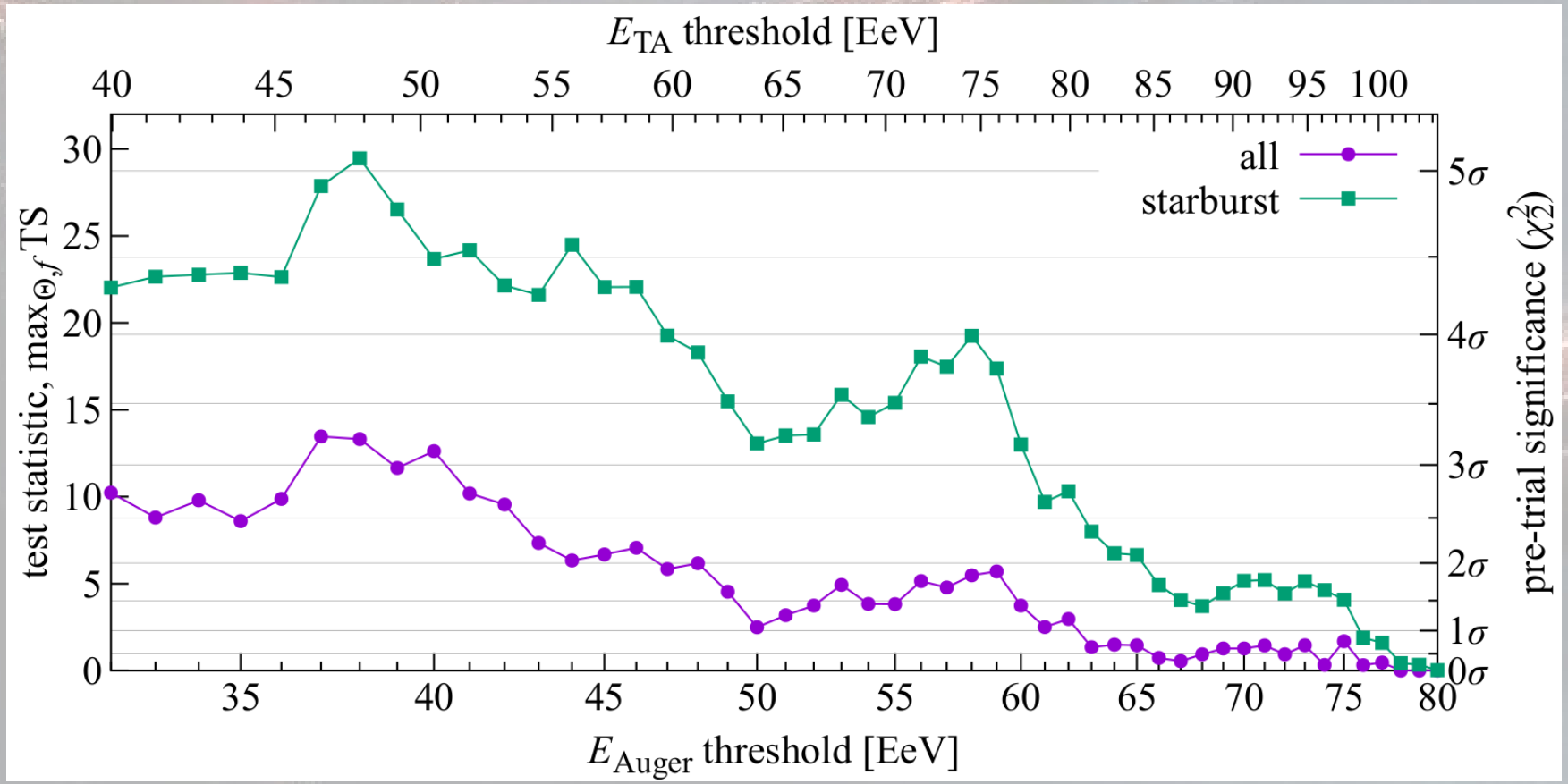
Search for medium-scale anisotropy

- Different type of analysis is used for searching for medium-scale anisotropy: the likelihood analysis.
- Test statistics is defined with the two free parameters:
  - Θ – angular scale (Mises-Fisher)
  - f – fraction of correlating events (f=0 – pure isotropy)

$$\mathrm{TS}(\Theta, f) = 2 \ln \frac{\mathcal{L}(\Theta, f)}{\mathcal{L}(f = 0)}$$

- The likelihood analysis is performed with two catalogs of galaxies:
  - all types of galaxies at 1 Mpc ≤ D < 250 Mpc based on 2MASS >44,000 galaxies, weighted based on their K-band flux (2.16 μm)
  - starburst galaxies (SBG) at 1 Mpc ≤ D < 130 Mpc (based on Lunardini et al. 2019), SMC and LMC removed, Circinus added from the Parkes telescope 44 galaxies, weighted based on flux in the 1.4 GHz band

The results of the medium-scale search



Searches for medium-scale anisotropy: results

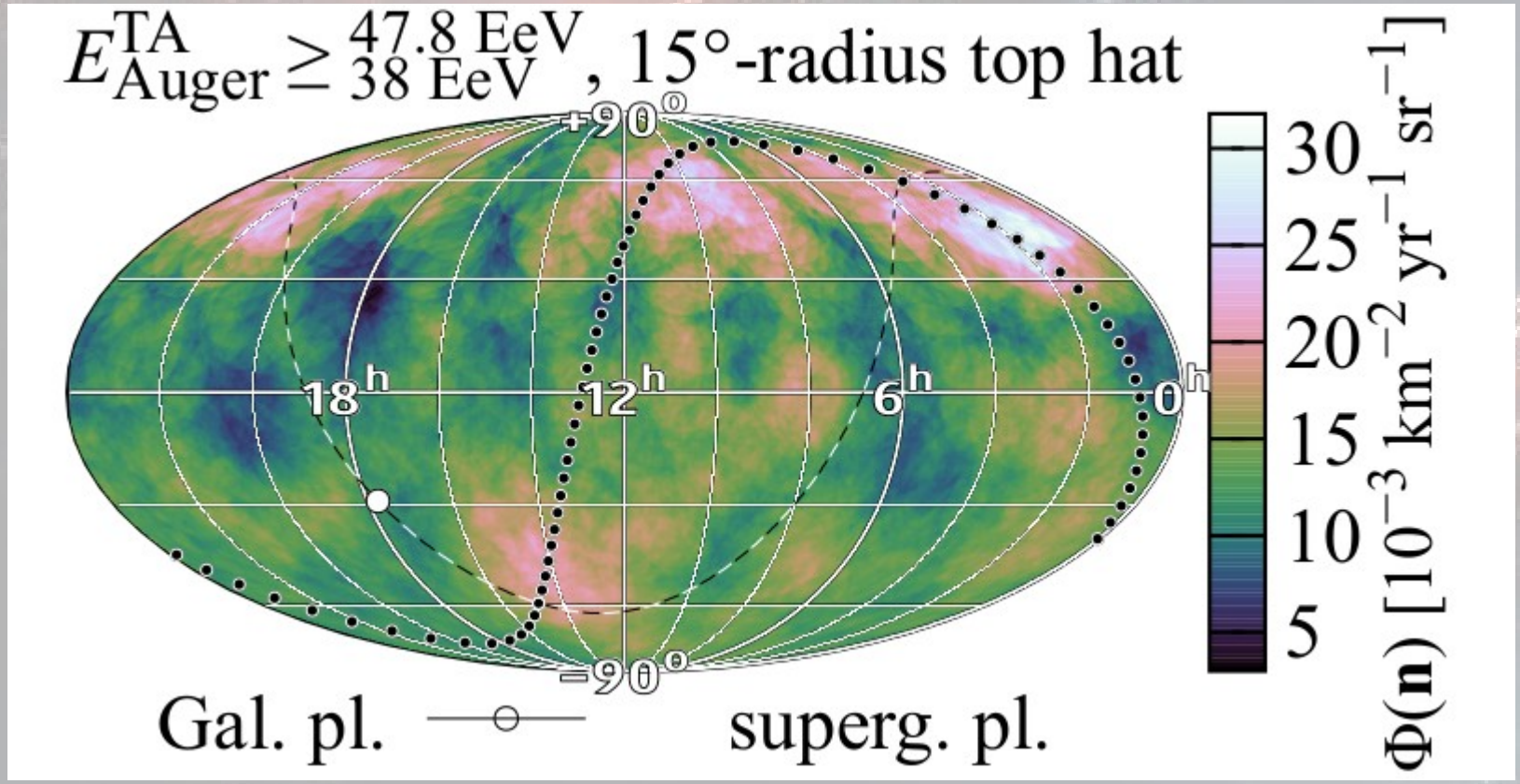
Correlation with all galaxies $1\,\mathrm{Mpc} \leq D < 250\,\mathrm{Mpc}$ (2MRS catalog)

dataset	$E^{\mathrm{min}}_{\mathrm{Auger}}$	$E^{\mathrm{min}}_{\mathrm{TA}}$	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$\left(19^{+15}_{-7}\right)^\circ$	$\left(25^{+24}_{-10}\right)\%$	14.7	2.8σ
UHECR 2024	37 EeV	46.5 EeV	$\left(26^{+13}_{-15}\right)^\circ$	$\left(30^{+26}_{-17}\right)\%$	13.5	2.6σ

Correlation with starburst galaxies $1\,\mathrm{Mpc} \leq D < 130\,\mathrm{Mpc}$ (Lunardini+ '19 catalog)

dataset	$E^{\mathrm{min}}_{\mathrm{Auger}}$	$E^{\mathrm{min}}_{\mathrm{TA}}$	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$\left(15.4^{+5.2}_{-3.0}\right)^\circ$	$\left(11.7^{+4.7}_{-2.9}\right)\%$	30.5	4.6σ
UHECR 2024	38 EeV	47.8 EeV	$\left(15.0^{+5.0}_{-2.9}\right)^\circ$	$\left(11.1^{+4.4}_{-2.8}\right)\%$	29.5	4.4σ

Medium-scale sky map



Conclusions and outlook

- The updated results of the large and medium-scale anisotropy analyses are presented with 16 years of TA data and 19 years of Auger data.
- The dipolar modulation is the only anisotropy that is significantly (4.6σ) identified in the angular power spectrum.
- The hypothesis of correlations with the starburst galaxies is supported at the significance of 4.4σ.
- New types of anisotropy analysis are being conducted. The results are planned to be presented at the ICRC 2025.
- The upcoming data of AugerPrime and TAx4 are crucial for the determination of the origin of UHECR.

Thank you!

Backup slides

The details of the dataset

- **Telescope Array data:**
  - 16 years, 2008-05-11 — 2024-05-11
    (two years added since ICRC 2023)
  - strict cuts, $\theta < 55^{\circ}$ (ApJ 768, 2013, L1)
  - effective exposure 19 500 km^2 sr yr
- **Pierre Auger data:**
  - 19 years, 2004-01-01 – 2022-12-31
    (same as at ICRC 2023)
  - For large scale anisotropies (stricter cuts):
    - 5T5 events (NIM A 798, 2015, 172), $\theta < 80^{\circ}$,
    - geometrical exposure 123,000 km^2 sr yr
  - For medium scale anisotropies (looser cuts):
    - 4T5 events for $\theta < 60^{\circ}$ + 5T5 events for $60^{\circ} < \theta < 80^{\circ}$,
    - geometrical exposure 135,000 km^2 sr yr