PIERRE AUGER OBSERVATORY

Large and intermediate scale anisotropies of ultra-high-energy cosmic rays with the Pierre Auger Observatory

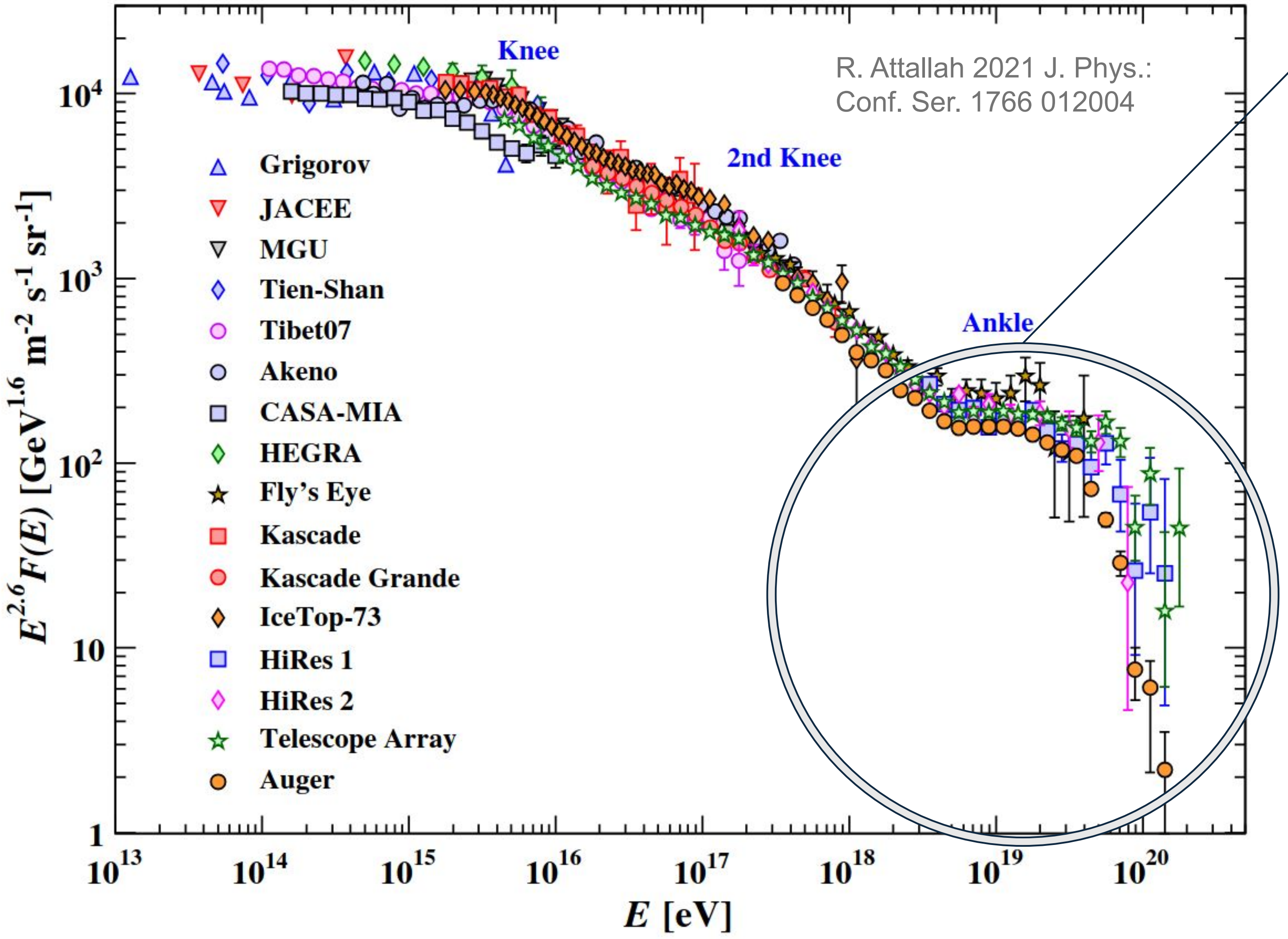
Luca Deval

for the Pierre Auger Collaboration

TeVPA - Valencia

Istituto Nazionale di Fisica Nucleare

Ultra-high energy cosmic rays (UHECRs)



- Ultra-high energy cosmic rays (UHECRs) have **energies E ≥ 10^{18} eV**

Challenges:

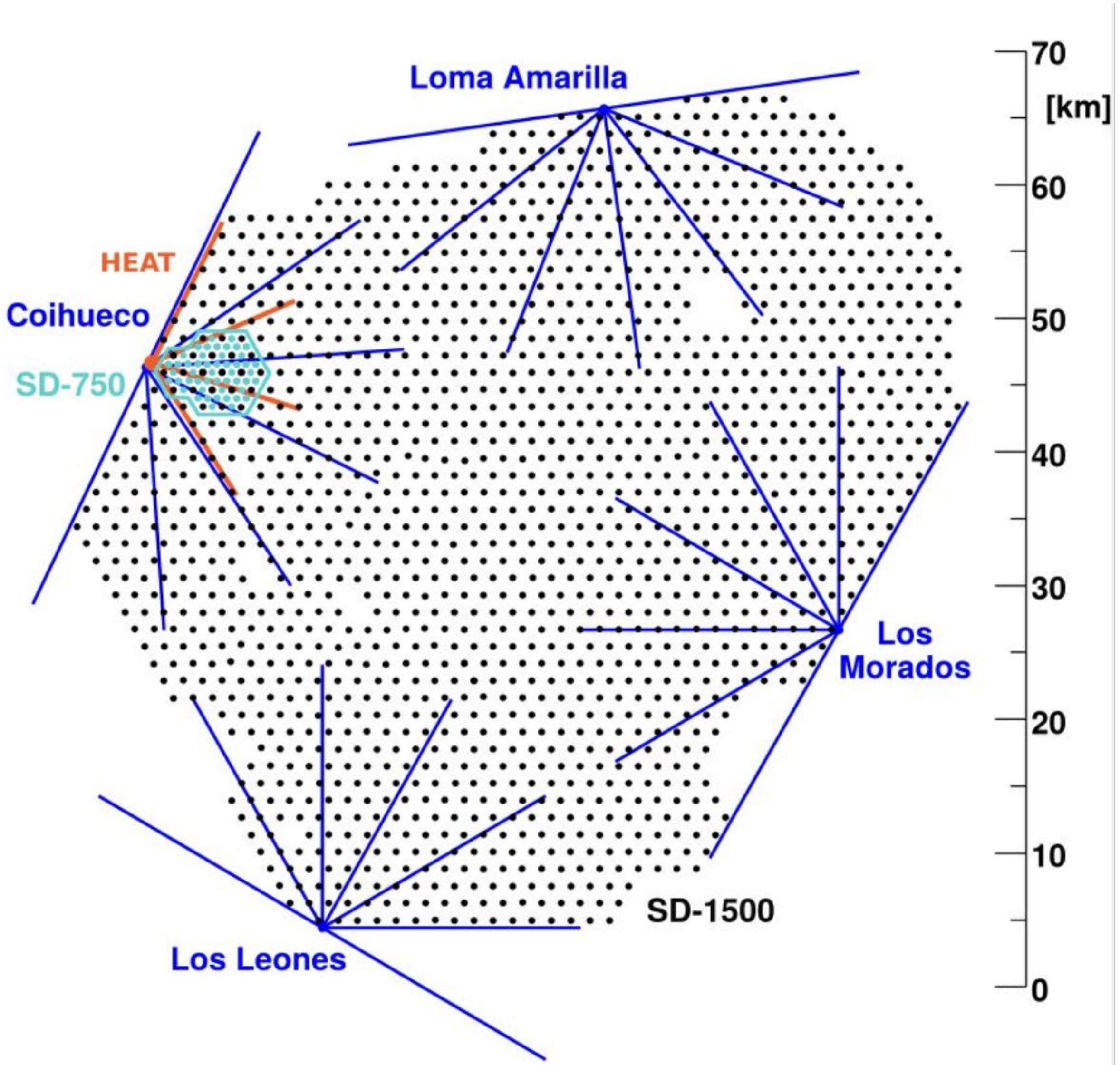
- **Very low flux** at the highest energies (~1 particle per 1000 km^2 per year)
- **Deflections** by the Galactic and extragalactic **magnetic fields**
- **Arrival directions** do **not point** directly to **sources**
- **Large numbers** of **events** needed to detect **anisotropies** over the statistical **noise**

Pierre Auger Observatory

- **Largest UHECR detector:** its area is 3000 km^2

- **Hybrid detection**:
  - 27 **fluorescence telescopes** with ~10-15% duty cycle
  - 1660 **water-Cherenkov detectors** with ~100% duty cycle

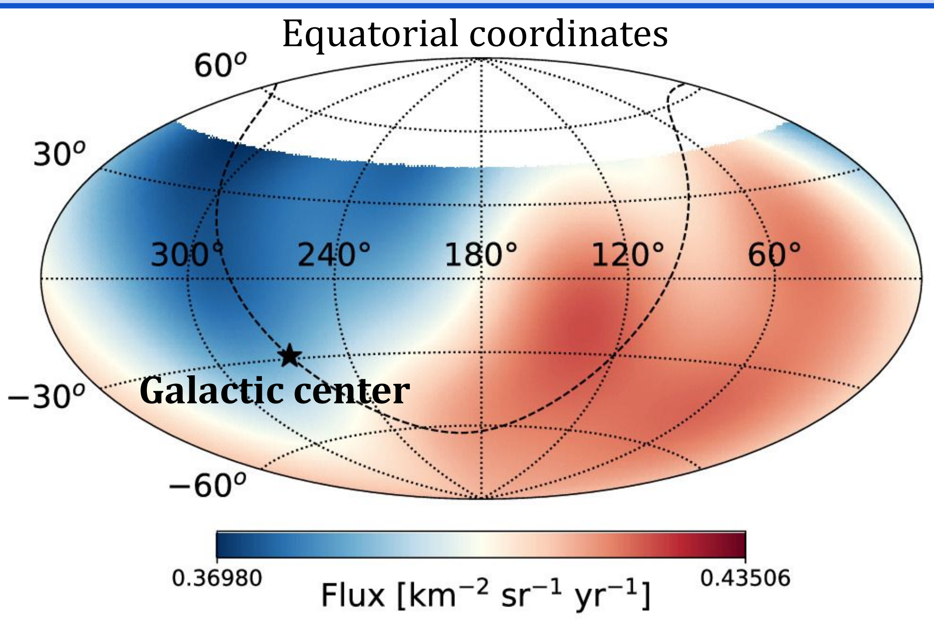
- **AugerPrime upgrade**:
  - **Scintillator** and **radio antenna** added to each surface station
  - Underground **muon detectors** in the infill area
  - Upgraded **electronics**



Large-scale anisotropy analyses

- Analysis above **4 EeV:**
  - **Flux** parametrized following:
    $$\Phi = \Phi_0 \times (1 + \mathbf{d} \cdot \mathbf{n} + \cdots))$$
    - **RA** sensitive to $\mathbf{d}_\perp$
    - **Azimuth** sensitive to $\mathbf{d}_z$

Direction dipole pointing **away** from Galactic Center → **Extragalactic origin of UHECRs**

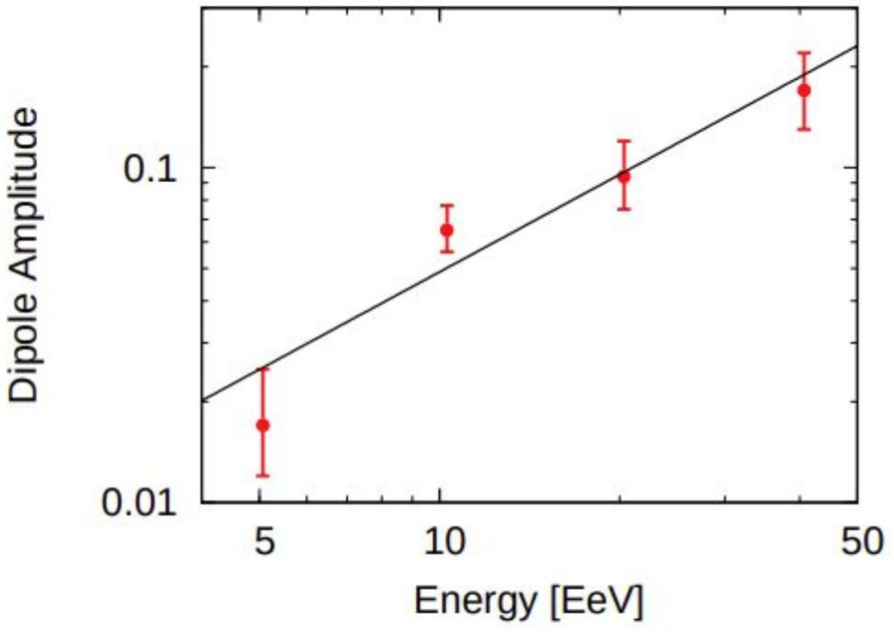


Auger Collab, 2024, *ApJ* 976 48

E [EeV]	N	$d_\perp$ [%]	d_z [%]	d [%]	α_d [°]	δ_d [°]	$P(\geq r_1^\alpha)$
4-8	118,722	$1.0^{+0.6}_{-0.4}$	-1.3 ± 0.8	$1.7^{+0.8}_{-0.5}$	92 ± 28	-52^{+21}_{-19}	0.14
≥8	49,678	$5.8^{+0.9}_{-0.8}$	-4.5 ± 1.2	$7.4^{+1.0}_{-0.8}$	97 ± 8	-38^{+9}_{-9}	8.7×10^{-12} → **6.8σ**
8-16	36,658	$5.7^{+1.0}_{-0.9}$	-3.1 ± 1.4	$6.5^{+1.2}_{-0.9}$	93 ± 9	-29^{+11}_{-12}	1.4×10^{-8} → **5.7σ**
16-32	10,282	$5.9^{+2.0}_{-1.8}$	-7 ± 3	$9.4^{+2.6}_{-1.9}$	93 ± 16	-51^{+13}_{-13}	4.3×10^{-3}
≥32	2,738	11^{+4}_{-3}	-13 ± 5	17^{+5}_{-4}	144 ± 18	-51^{+14}_{-14}	9.8×10^{-3}

Large-scale anisotropy analyses

- Analysis above **4 EeV:**
  - Energy evolution**:**
    - Amplitude **increases** with **energy**



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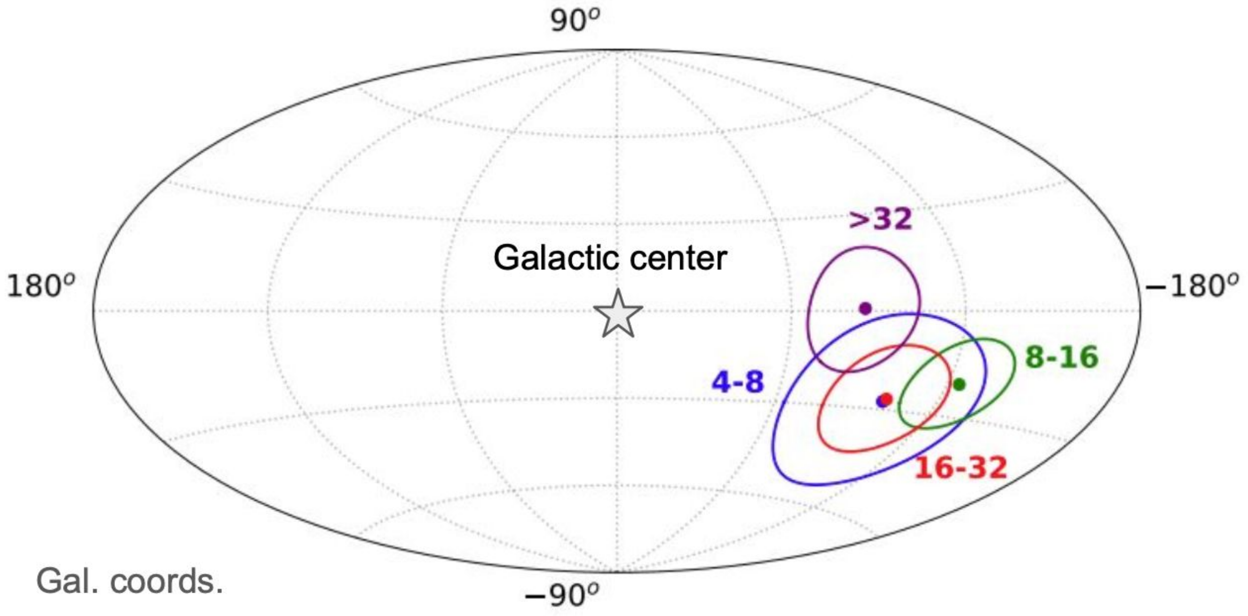


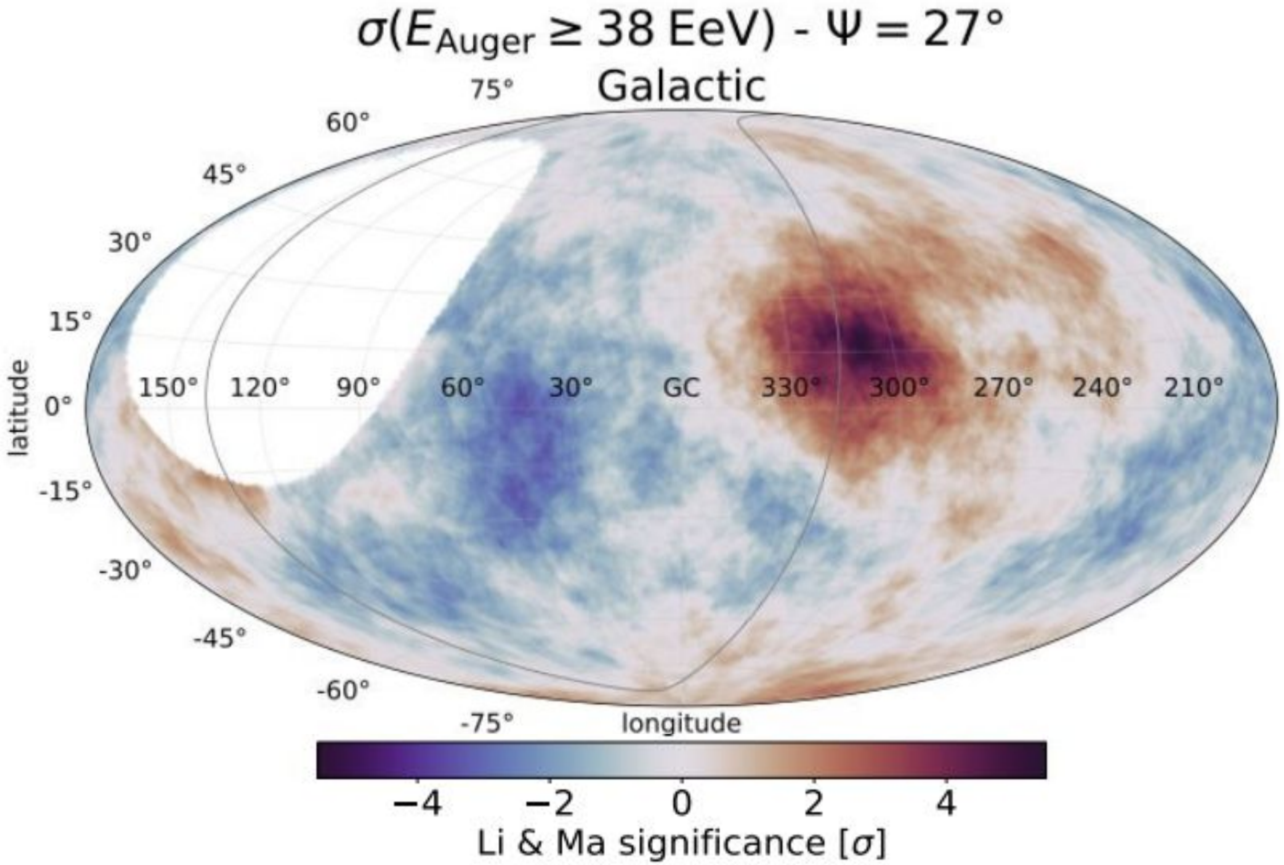
<u>Possible explanations</u>:

- **Reduced** mean **free path** in photon backgrounds → **less contribution** from distant, more isotropically distributed **sources**
- **Higher rigidity** ($R = E/Z$) → **reduced magnetic deflections** ($\Delta\Theta \propto B/R$)

Intermediate-scale anisotropy analyses

- **Search** for **excesses** with intermediate angular scale**:**
  - **Blind search** over the sky employing a search radius (Ψ)
  - **Event counts** compared to **isotropic expectation** at different energy thresholds

Results:
- **Overdensity** in the Centaurus region (post-trial significance: 4σ)
- **E_{th} = 38 EeV**
- **Ψ = 27°**
- **(l, b) = (305.4° , 16.2°)**



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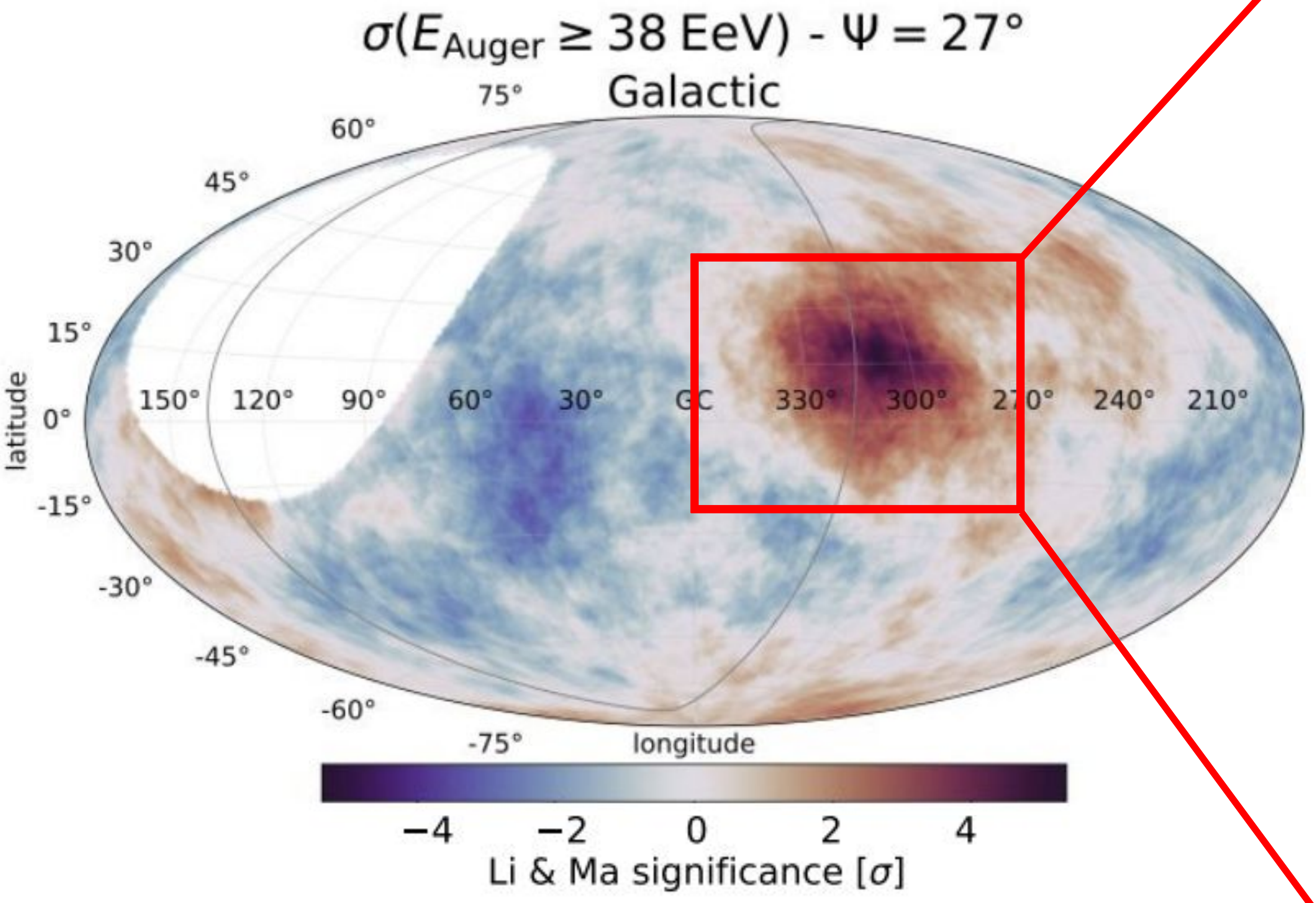
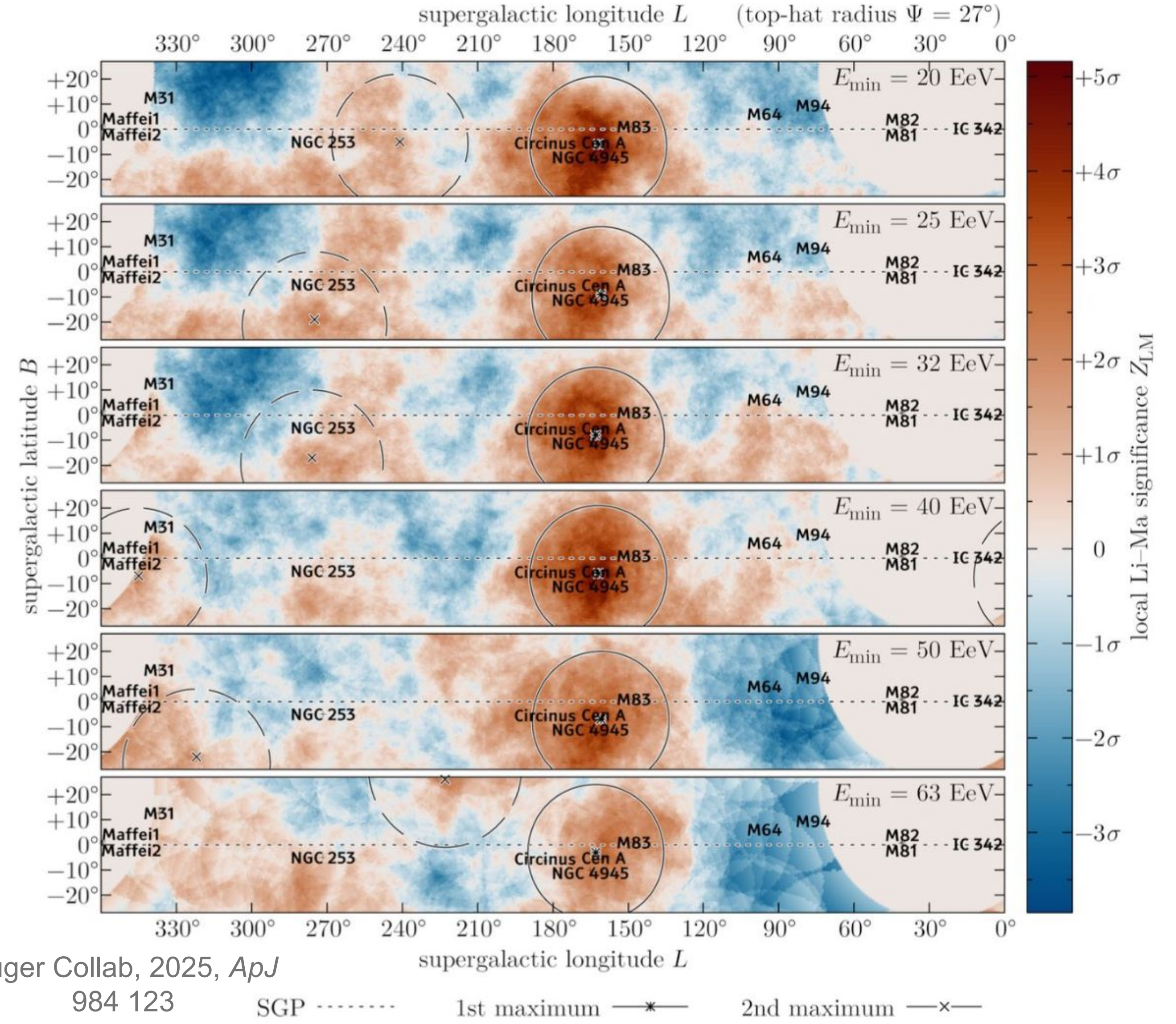
Intermediate-scale anisotropy analyses



Intermediate-scale anisotropy analyses

- **Supergalactic plane (SGP) analysis:**
  - **SGP** should contain all major **sources**
  - **Blind search** over the SGP with a fixed search radius at different energy thresholds

<u>**Results:**</u>
- Most **significant overdensity** always in the **Centaurus region**
- **Position** approximately **stable** as a function of the energy threshold
- **No hint** for excesses in **TA "spots"** with data of comparable size



Auger Collab, 2025, *ApJ* 984 123

Intermediate-scale anisotropy analyses

- **Maximum likelihood analysis:**
  - Investigate the **correlation** with **source catalogs**
  - Test **nested hypothesis**: Model hypothesis describes data better than isotropy?

$$\mathrm{TS} = 2\sum_i k_i \times \ln \frac{n^{H_1}(\mathbf{u}_i)}{n^{H_0}(\mathbf{u}_i)}$$

$$n^{H_1}(\mathbf{u}) = (1-\alpha) \times n^{H_0}(\mathbf{u}) + \alpha \times \frac{\sum_j s_j(\mathbf{u};\Theta)}{\sum_i \sum_j s_j(\mathbf{u_i};\Theta)}$$

$$n^{H_0}(\mathbf{u}) = \frac{\omega(\mathbf{u})}{\sum_i \omega(\mathbf{u}_i)}$$

  - **Model hypothesis**: **signal** contribution (**α**) with average **angular dispersion** due to magnetic fields (**θ**)
  - **Null hypothesis**: normalized **exposure**

Intermediate-scale anisotropy analyses

Results:

- **Highest significance** (Test statistic) found for **Starburst galaxies** catalog (SBG) at **38 EeV**

- **Best-fit parameters:**
  - Signal fraction (α): 9^{+7}_{-4} %
  - Angular dispersion (Ψ): 25^{+13}_{-7}°

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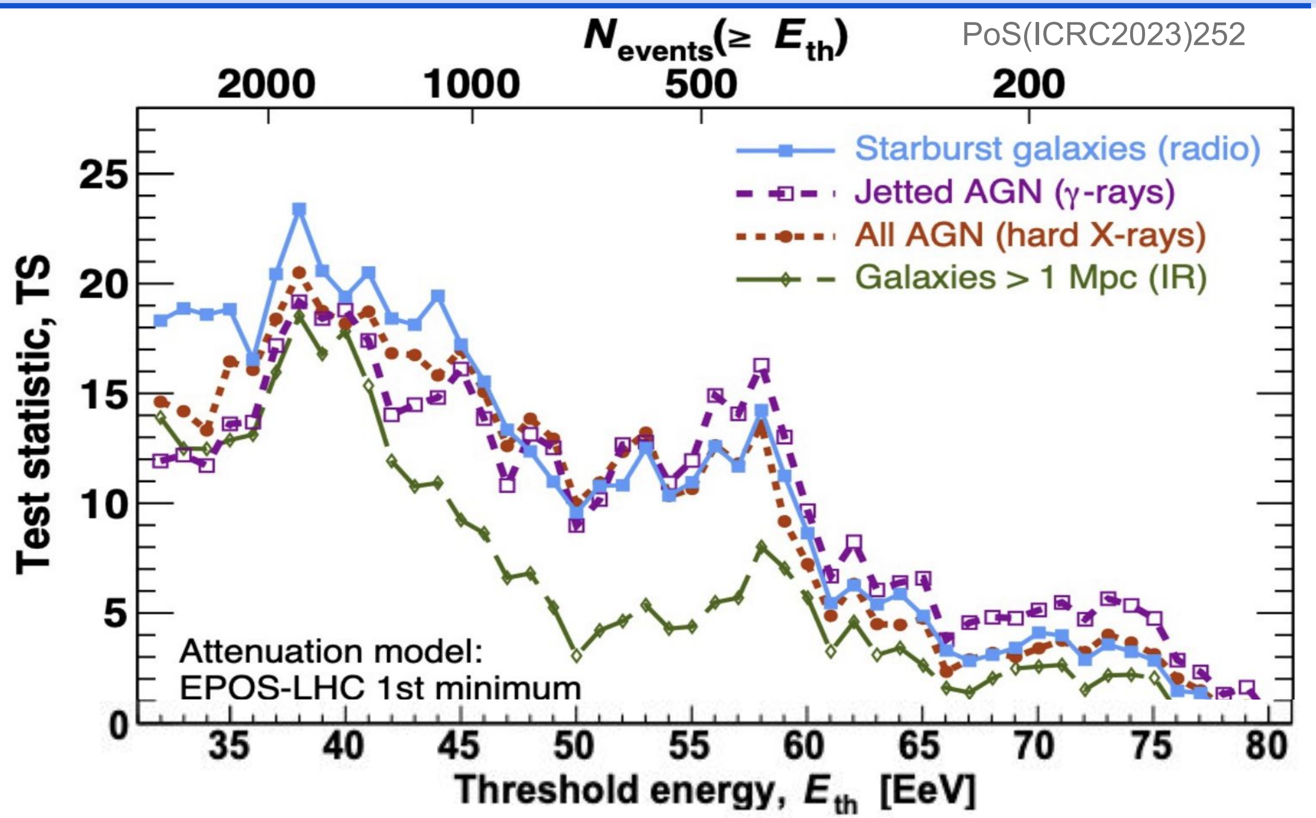
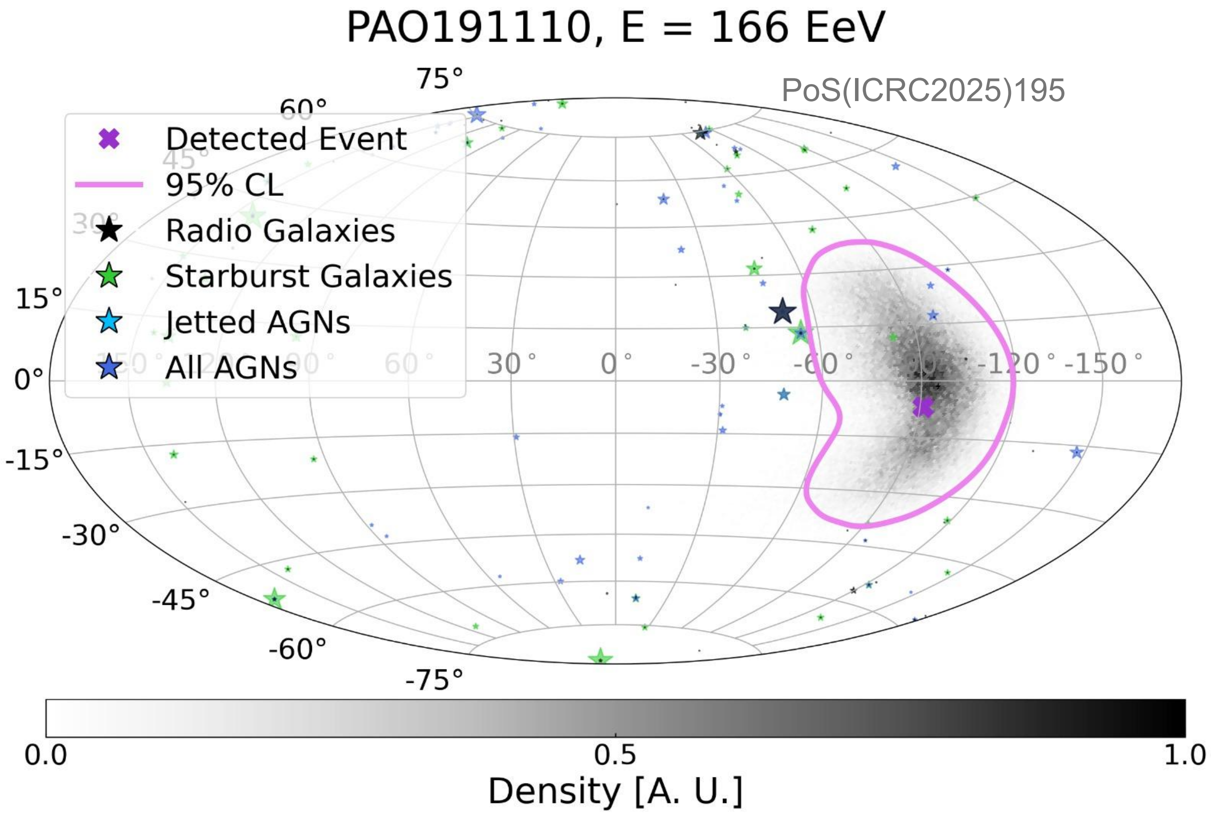


Catalog	E_{th} [EeV]	Ψ [°]	α [%]	TS	Post-trial p-value	
All galaxies (IR)	38	24^{+15}_{-8}	14^{+8}_{-6}	18.5	6.3×10^{-4}	→ 3.2σ
Starbursts (radio)	38	25^{+13}_{-7}	9^{+7}_{-4}	23.4	6.6×10^{-5}	→ 3.8σ
All AGNs (X-rays)	38	25^{+12}_{-7}	7^{+4}_{-3}	20.5	2.5×10^{-4}	→ 3.5σ
Jetted AGNs (γ-rays)	38	23^{+8}_{-7}	6^{+3}_{-3}	19.2	4.6×10^{-4}	→ 3.3σ

Intermediate-scale anisotropy analyses

- **Constraining** the **origin** of the **highest-energy** cosmic-ray **events:**
  - **40 events** above 100 EeV employed
  - **Galactic backtracking** to estimate possible sources
  - Methods applied:
    - **Event by event** analysis
    - **Likelihood-based** analysis



Results:

Event by event: The **backtracked positions** of **39** of **40 events** with **E ≥ 100 EeV** are **compatible** with **one or more sources** within SBGs, AGNs and RGs

Intermediate-scale anisotropy analyses

- **Constraining** the **origin** of the **highest-energy** cosmic-ray **events:**
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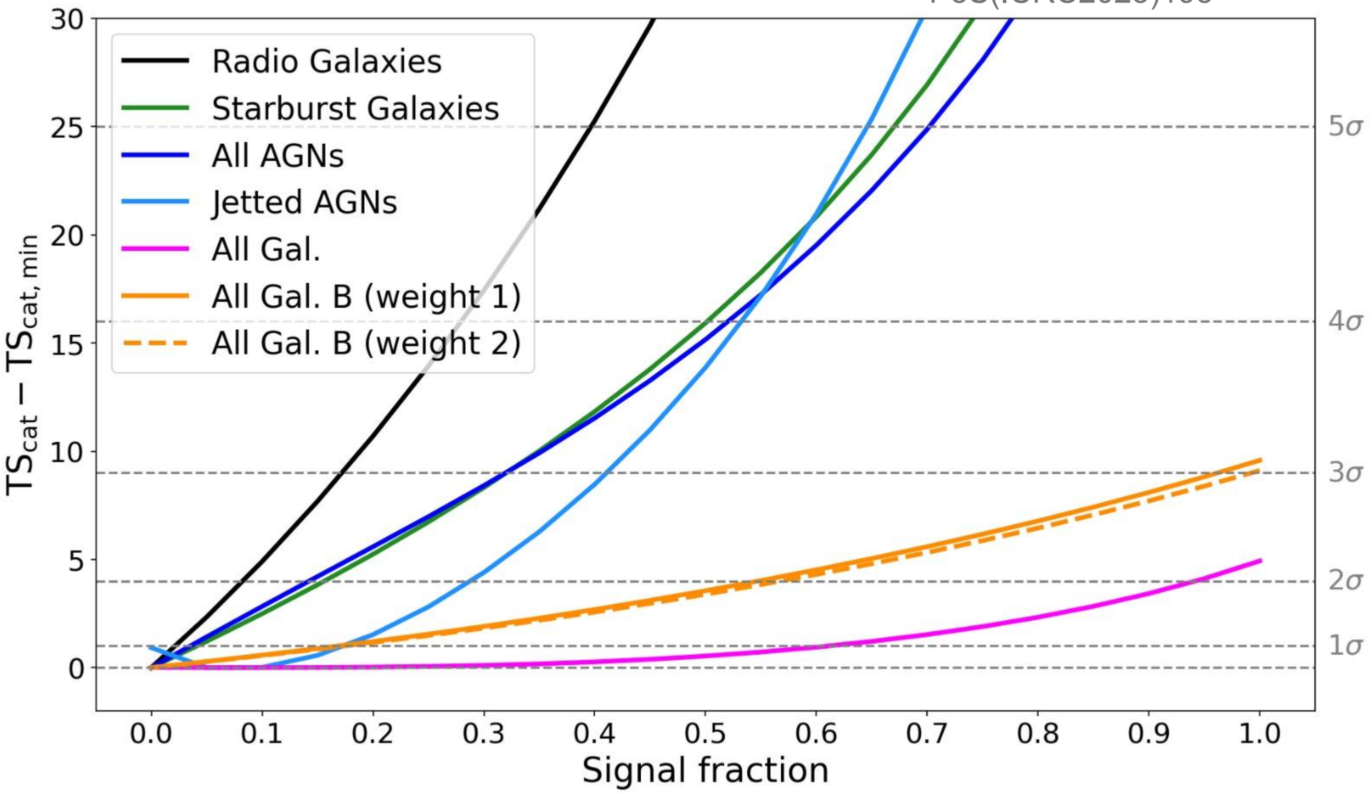

Results:

Likelihood-based: Contributions of: > 40% **RGs**, > 65% **AGNs (jetted)**, > 67% **SBGs**, > 70% **AGNs (all)** are **excluded** at the **5σ level** under the assumption of the Auger 2023 best-fit injection model, negligible EGMF, nominal energy

Conclusions

- **Large-scale anisotropy analyses:**
  - ➢ **Direction** dipole → **Extragalactic** origin of UHECRs
  - ➢ **Amplitude** increases with energy → **contribution** from nearby sources

- **Intermediate-scale anisotropy analyses:**
  - ➢ **Overdensity** in the Centaurus region (4σ)
  - ➢ **Correlation** between **arrival directions** and **Starburst galaxies** catalog (3.8σ)
  - ➢ **Backtracking** of **39** over **40 events** with **E ≥ 100 EeV** shows compatibility with **one or more sources** among SBGs, AGNs and RGs
  - ➢ **A maximum contribution** to the **UHECR flux above 100 EeV** is **excluded at 5σ level** (**RGs** (40%), **jetted–AGNs** (65%), **SBGs** (67%) and **all–AGNs** (70%))