Anisotropy studies of the arrival directions of cosmic rays at the highest energies with the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

UFRJ

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TeVPA - Chicago, 26-30 August 2024

Other talks from the Pierre Auger Observatory

The energy spectrum of ultra-high energy cosmic rays measured using the Pierre Auger Observatory

Fiona Ellwanger (Karlsruhe Instiute of Technology)

Mass Composition Interpretation with the Pierre Auger Observatory

Miguel Alexandre Martins (Instituto Galego de Física de Altas Enerxias)

AugerPrime - the new Phase of the measurements at the Pierre Auger Observatory

Nataliia Borodai (Institute of Nuclear Physics, Polish Academy of Sciences)

The search for UHECR sources

- ⋆ Cosmic rays: observed at energies of more than **10^{20} eV**
- ⋆ Most **energetic** particles known in the universe

    - ⋆ Search for sources is challenging: charged particles deflected by **magnetic fields**
    - ⋆ Magnetic fields: **difficult to study** and their modeling is far from being complete

- ⋆ Above a few tens of EeV: **deflections small enough**, directional information for small charges can be preserved
- ⋆ The cosmological **volume** within which UHECRs sources should be sought is **limited**
- ⋆ CR interact with photon backgrounds, **mean free path** for energy losses depends on their mass and energies
- ⋆ At 100 EeV, protons and iron: **200-300 Mpc**, intermediate nuclei He, N: **3-6 Mpc**
- ⋆ Sources of UHECRs must be in the **local universe**!

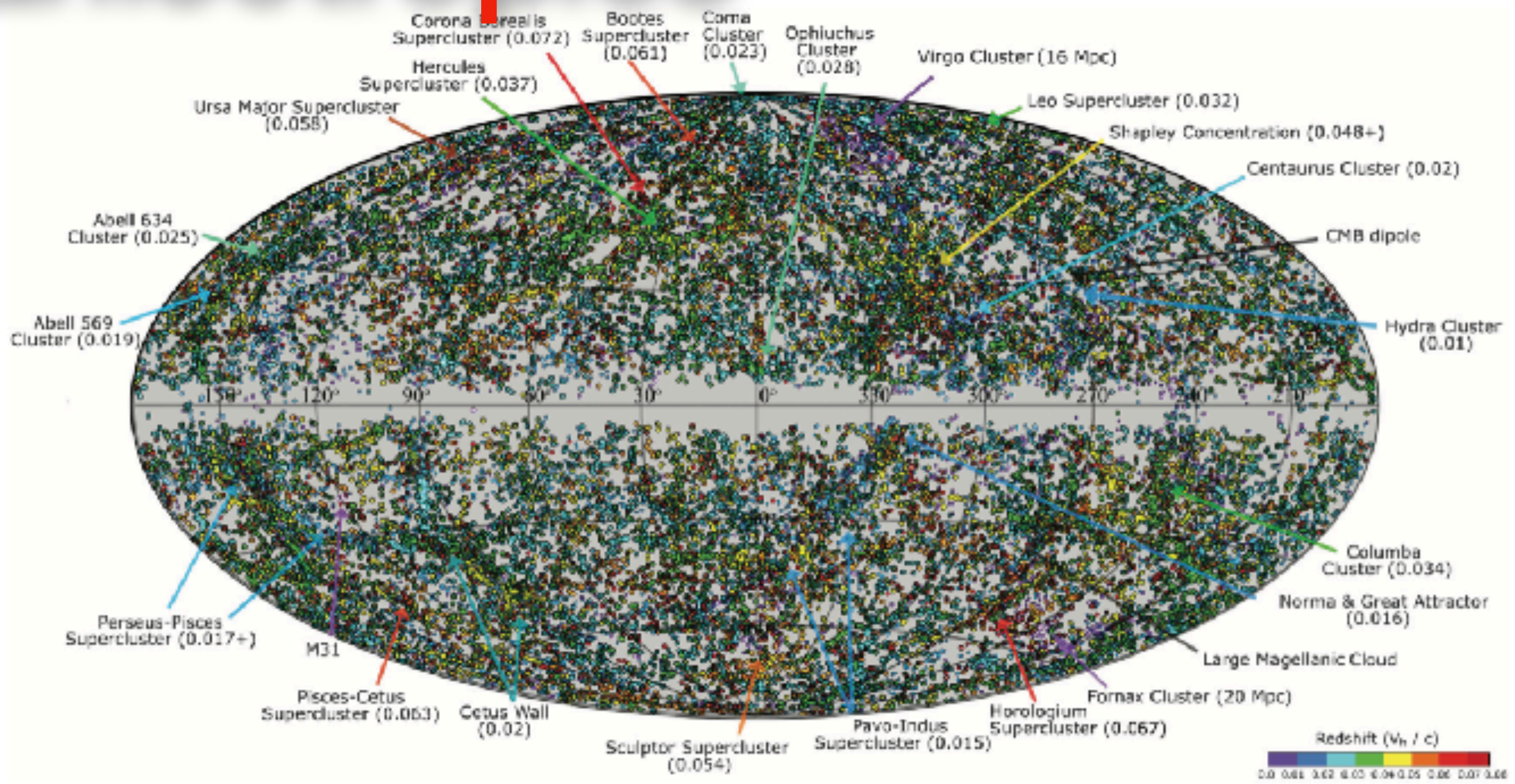
Two approaches to search for anisotropies

Small-intermediate scale anisotropies can be present in the suppression region

At UHE, cosmic rays have reduced horizon and maybe enough rigidity ***to point back to their sources***

Method: Comparison of UHECR arrival directions with catalogues of astronomical objects

Challenge: control of exposure and trial factor (energy, angle...)



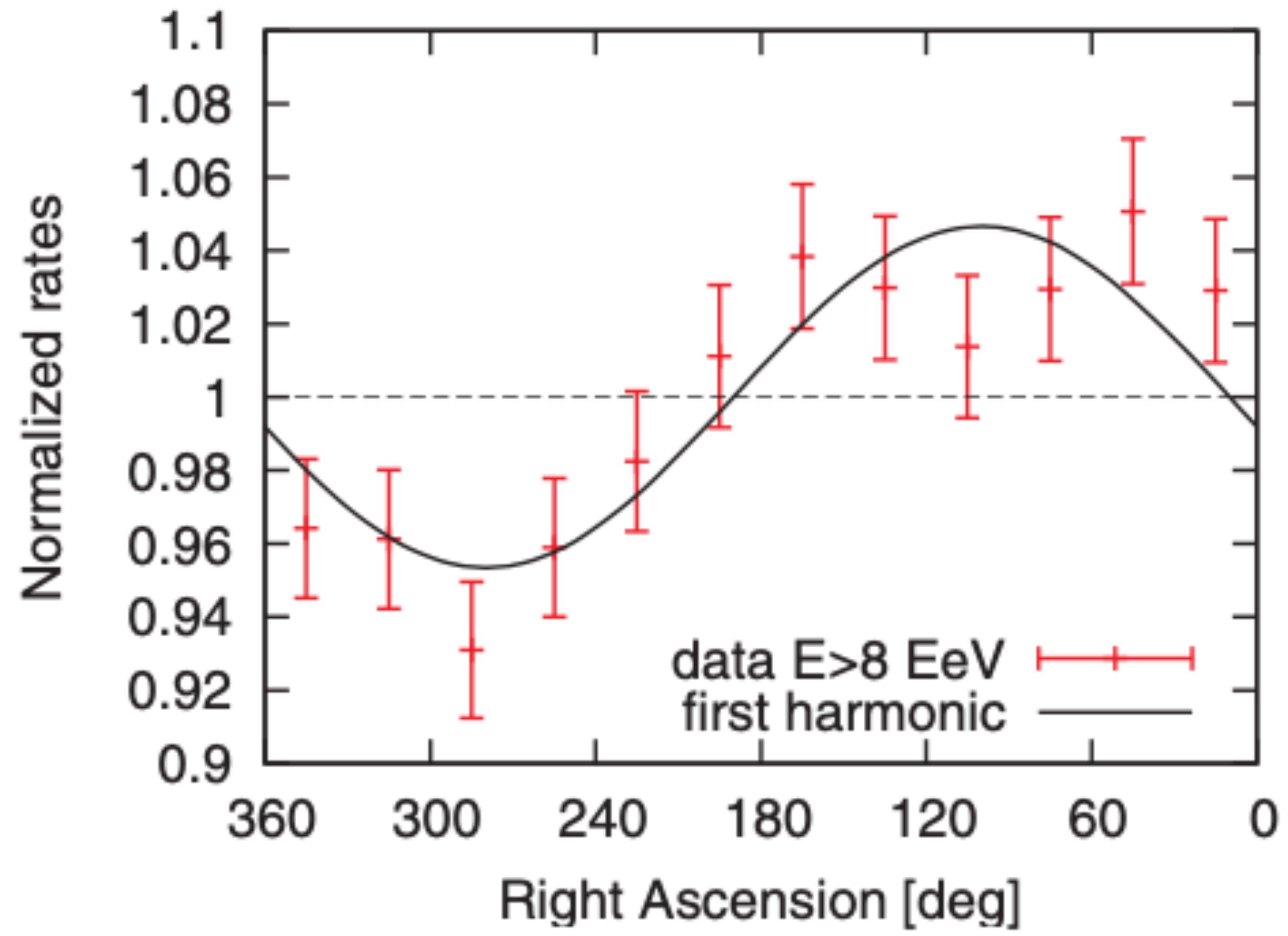
2MASS Survey, Astrophys. J., 2011

Large scale anisotropies can be present at all energies

- ⋆ **Propagation** from **extragalactic sources** distributed anisotropically
- ⋆ **Diffusion** from individual extragalactic sources
- ⋆ **Diffusive escape** from Galaxy of CRs from galactic sources
- ⋆ **Compton-Getting** effect due to the Earth motion in the CR rest frame

Method: Rayleigh analysis in right ascension (and azimuth)

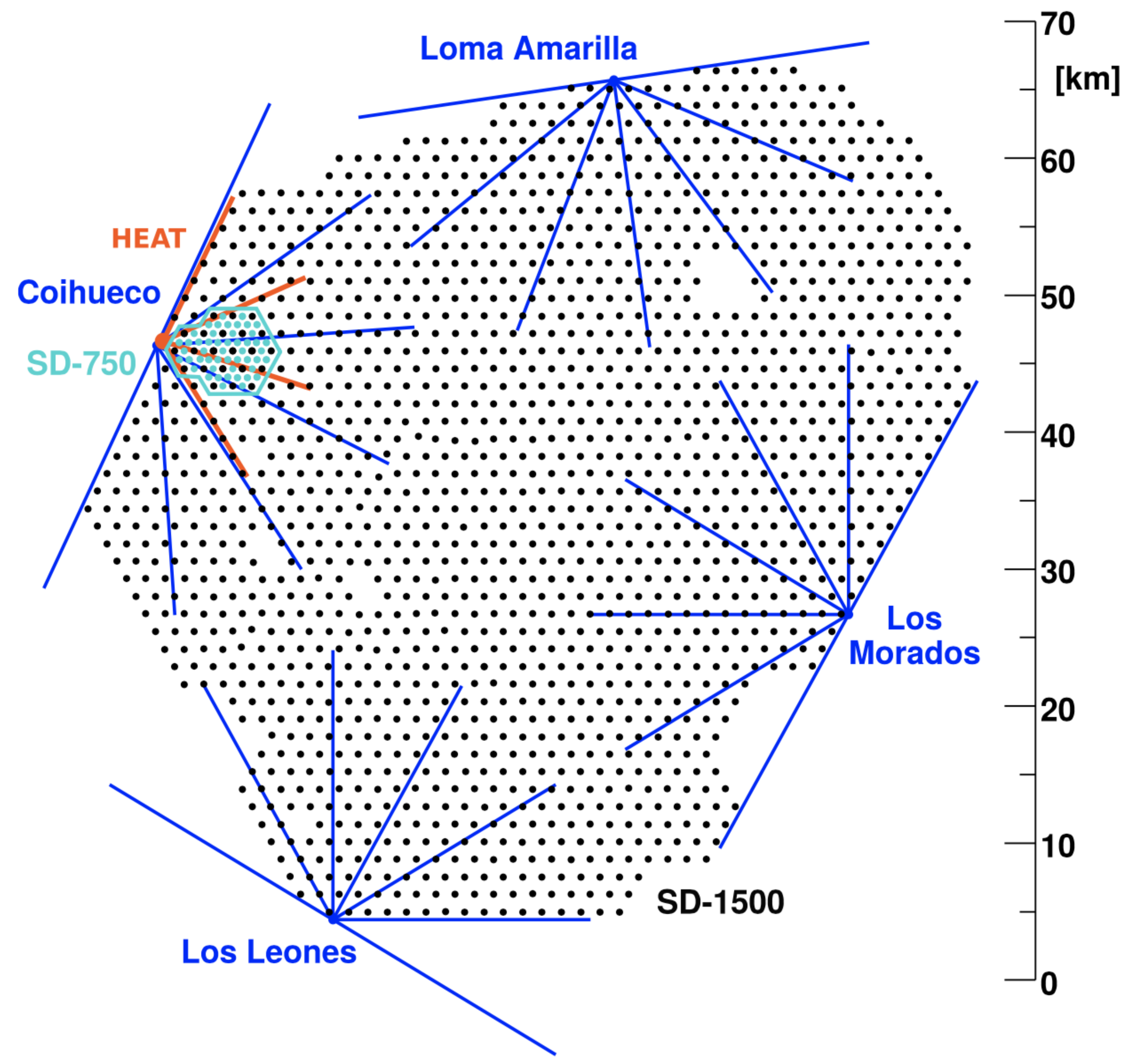
Challenge: control exposure and event rate down below < % level



Pierre Auger Collab., Science, 2017

The Pierre Auger Observatory dataset

⋆Water-Cherenkov surface detectors data.
⋆From Jan. 2004 to Dec. 2022.
⋆2021-2022 (AugerPrime installation underway):
only those detectors in which the electronics have not been updated (~1.6 yr of exposure).



	E [EeV]	θ_{max} [°]	Exposure [$km^2 yr sr$]	Increase [%]
SD1500	> 32	80	135,000	11[1]
	> 4	80	123,000	11[2]
	$0.25 < E < 4$	60	81,000	40[3]
SD750	> 0.03	55	337	33[3]

85% coverage of the sky

71% coverage of the sky

Previous results: [1] Astrophys. J. 935 (2022) 170, [2] PoS(ICRC2021)335, [3] Astrophys. J. 891 (2020) 142

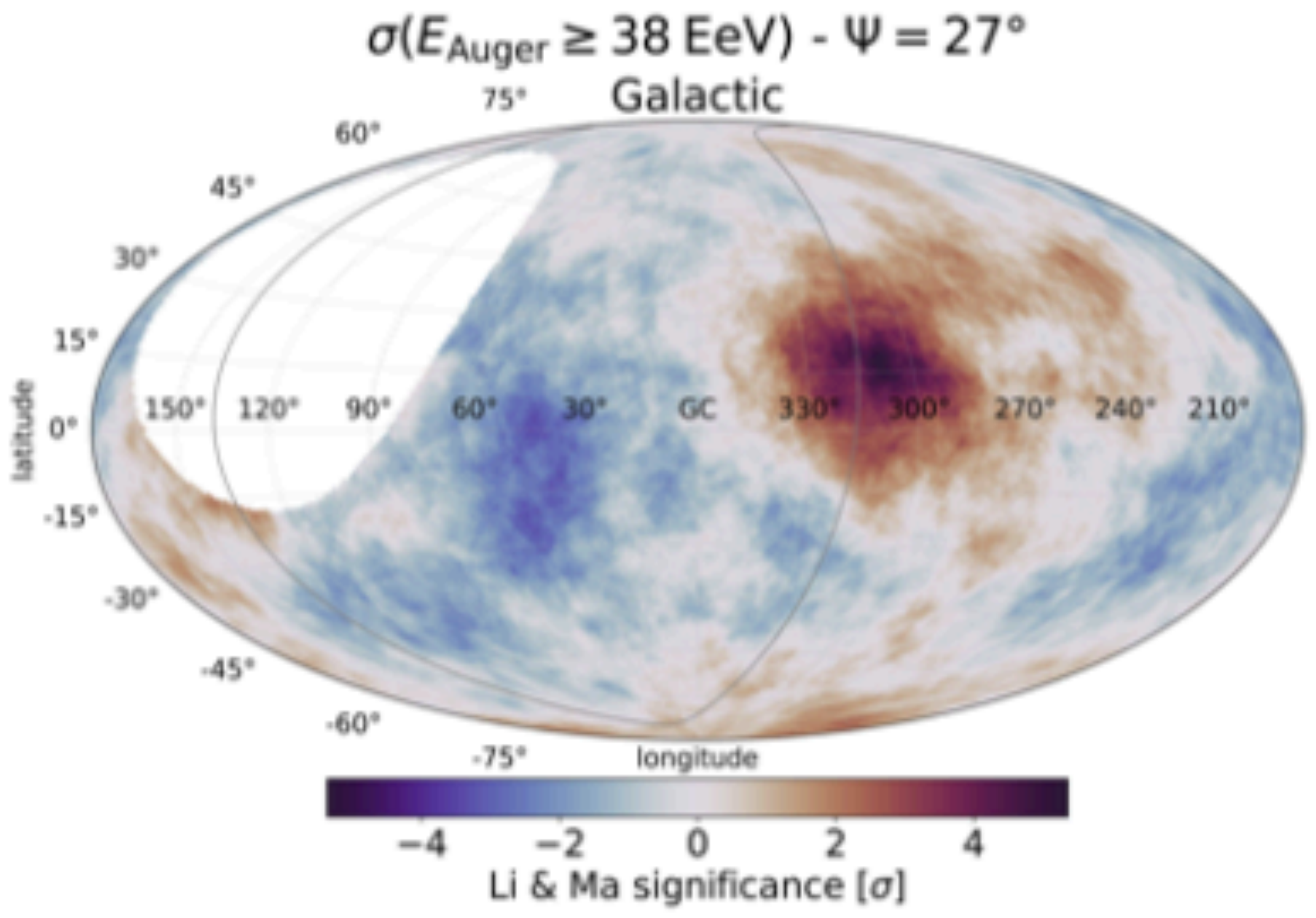
Anisotropy studies E > 32 EeV

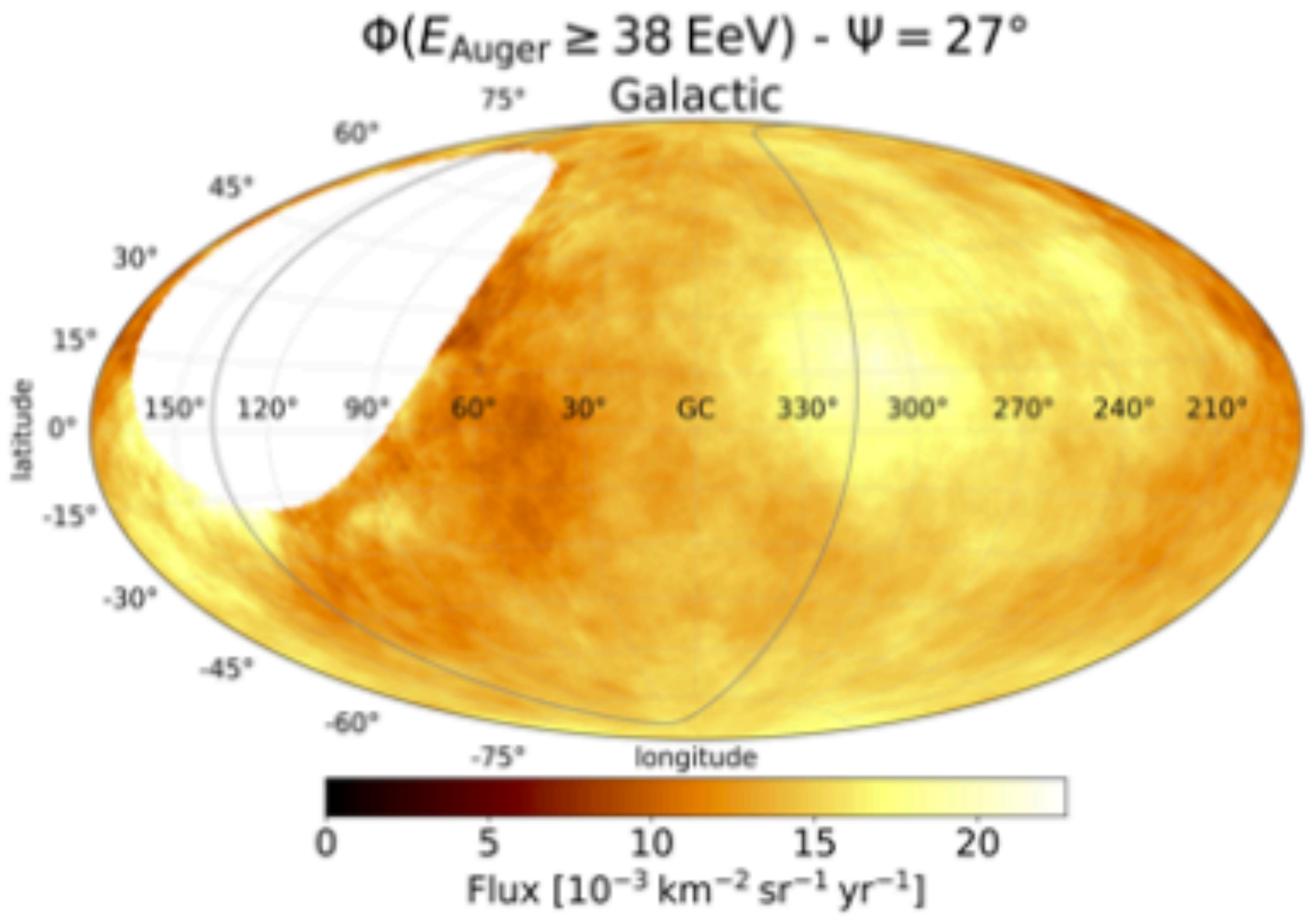
- ⋆ Binomial probability to measure N_{obs}, inside a circular window, compared to N_{exp} from isotropic simulations.
- ⋆ Scan in E_{th} in [32, 80] EeV, steps of 1 EeV and in top-hat search angle Ψ in [1°, 30°], steps of 1° (for the Centaurus region 0.25° steps between 1° and 5°).

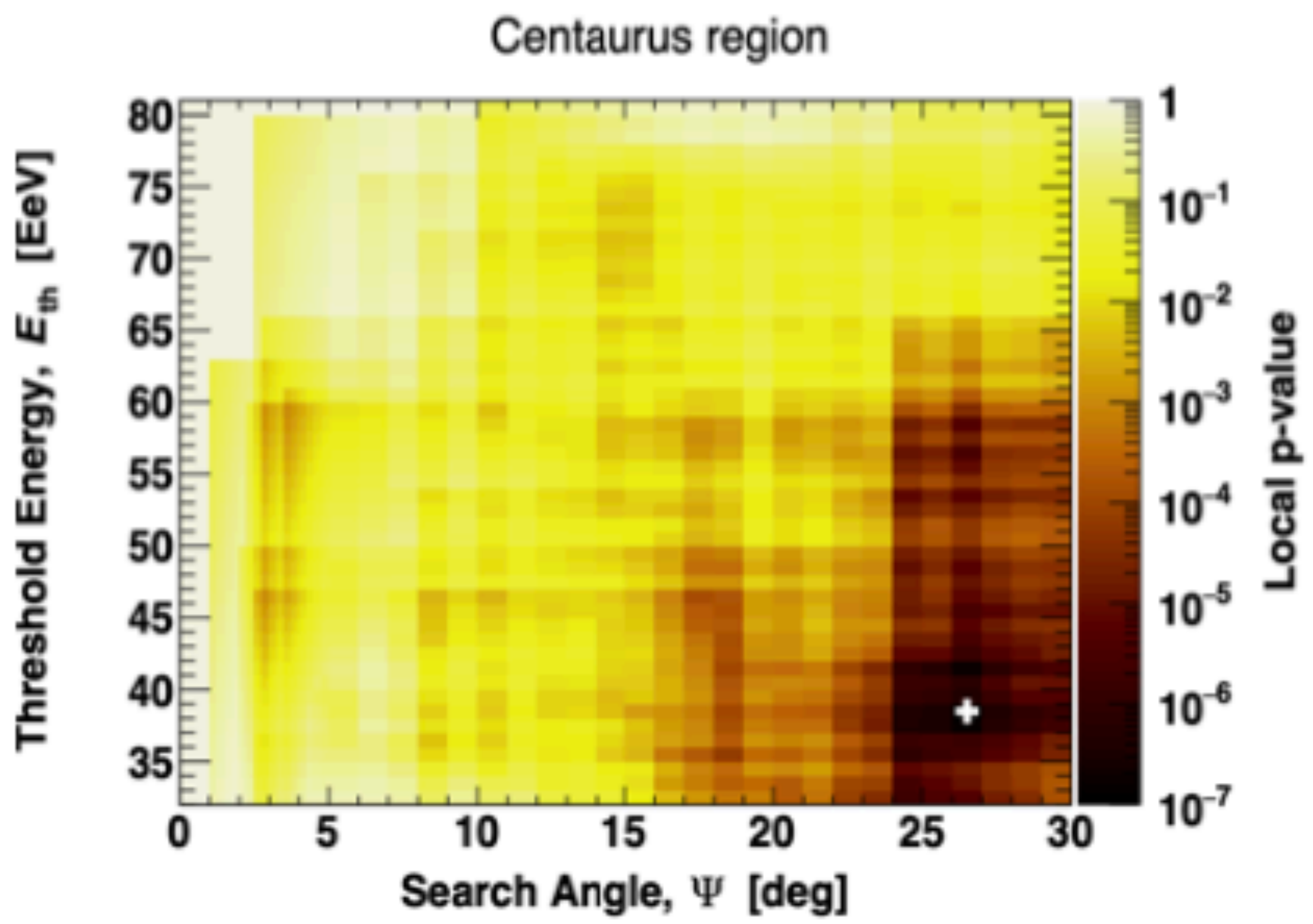
Analysis	E_{th} [EeV]	Ψ [°]	N_{obs}	N_{exp}	Local p-value	Post-trial p-value
Overdensity	38	27	245	172.0	1.8×10^{-8}	0.02
Cen A	38	27	237	169.0	1.1×10^{-7}	3.0×10^{-5}

2.1 σ, 2° from Cent A

4.0 σ







Pierre Auger Collab., 38th ICRC , 2023

Catalog-based searches E > 32 EeV

- ★ Probability maps built weighting objects by their relative flux in the corresponding e.m. band and an attenuation due to their different distances (Auger spectral-composition modeling) **Pierre Auger Collab, JCAP, 2017**
- ★ Parameters: Fisher search radius Θ (ψ =1.59 Θ) and the signal fraction α. Scan in E_{th} in [32, 80] EeV, steps of 1 EeV.
- ★ Catalogs (and their flux proxy):

  "all galaxies (IR)" from 2MRS (K-band)
  "starbursts (radio)" based on Lunardini+19 (1.4 GHz)
  "all AGNs (X-rays)" from Swift-BAT (14-195 keV)
  "jetted AGNs (γ-rays)" from Fermi 3FLHE (E>10 GeV)

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

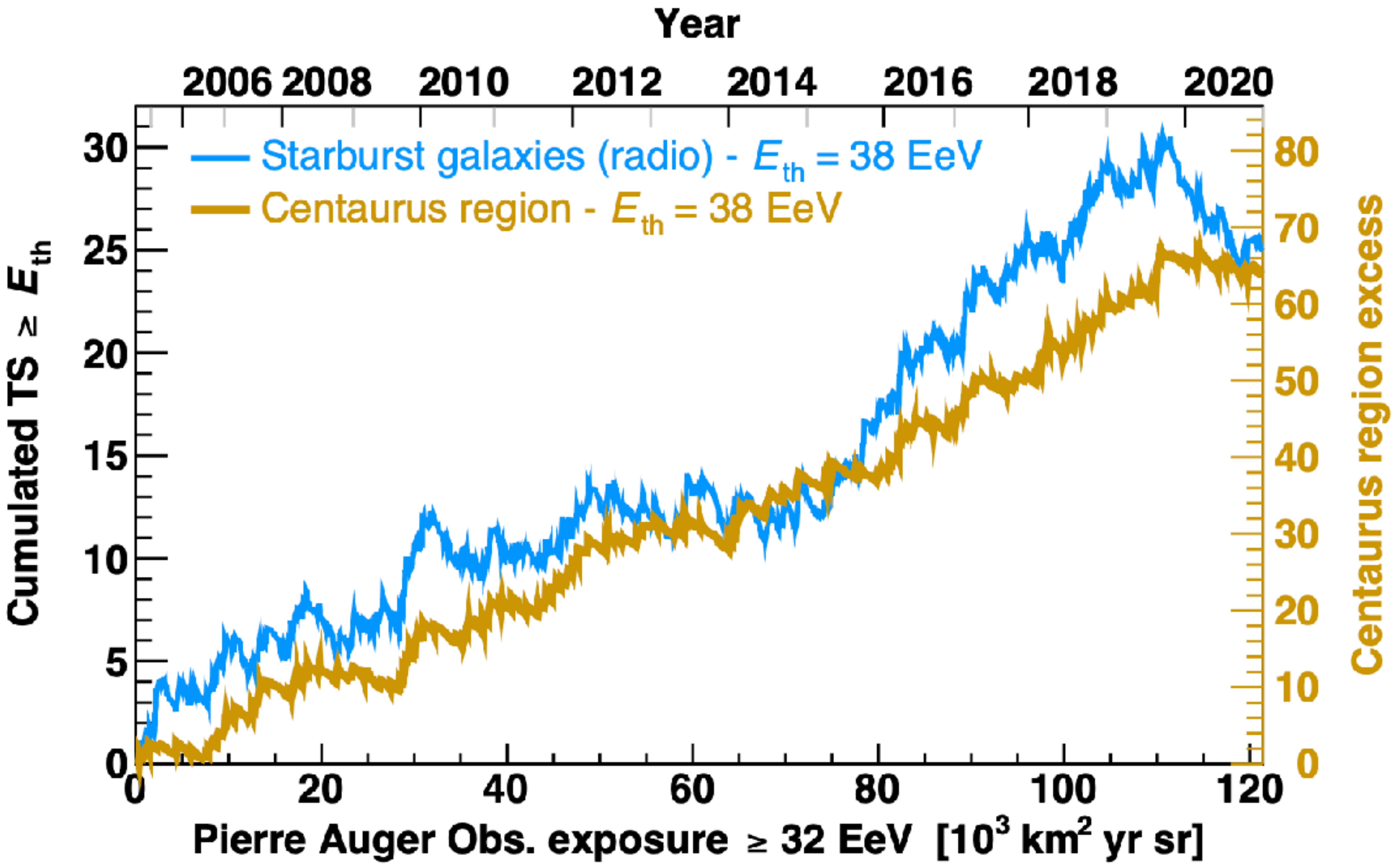
Pierre Auger Collab., ApJL, 2018

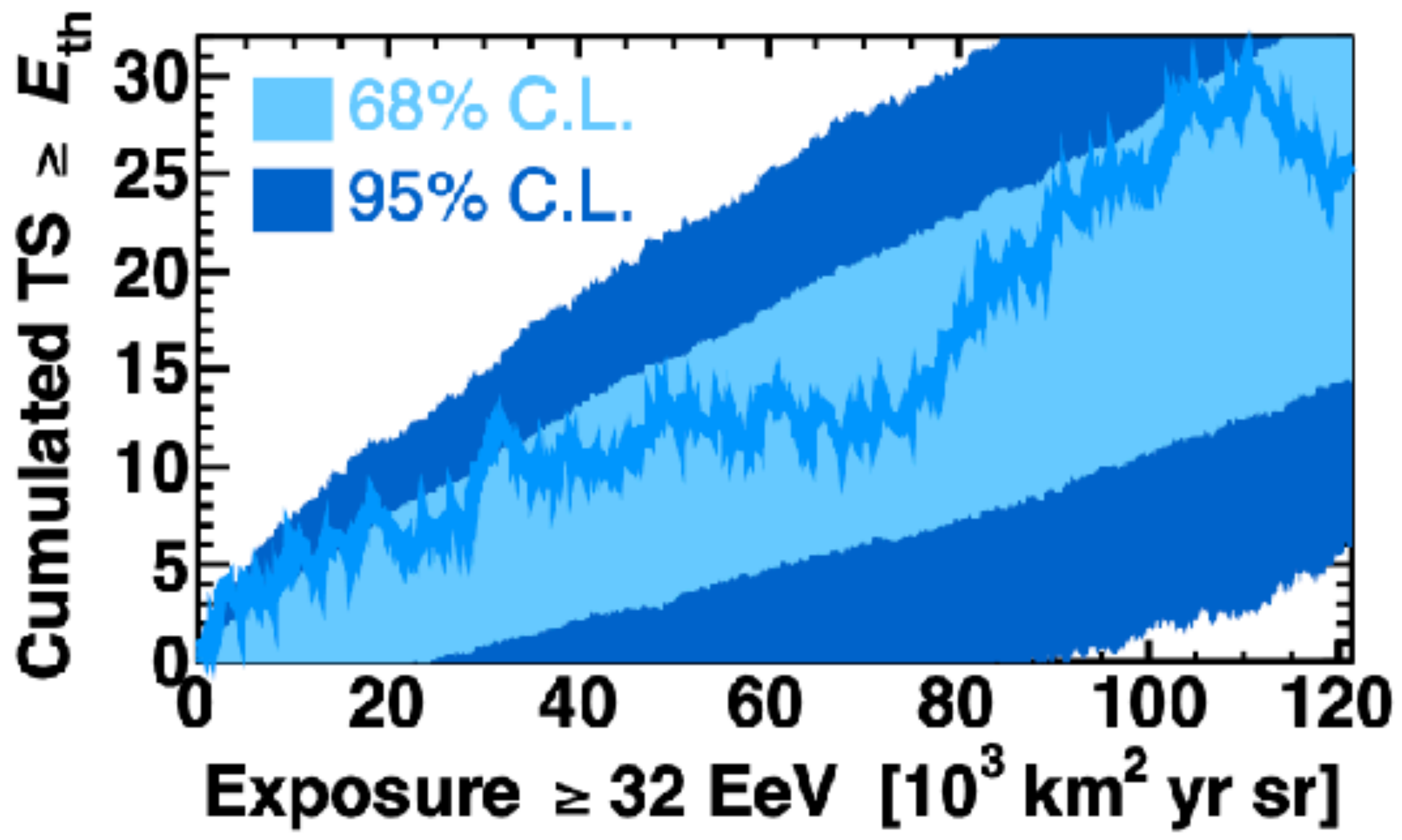
All excesses happen at the same Eth and at the same angular scale

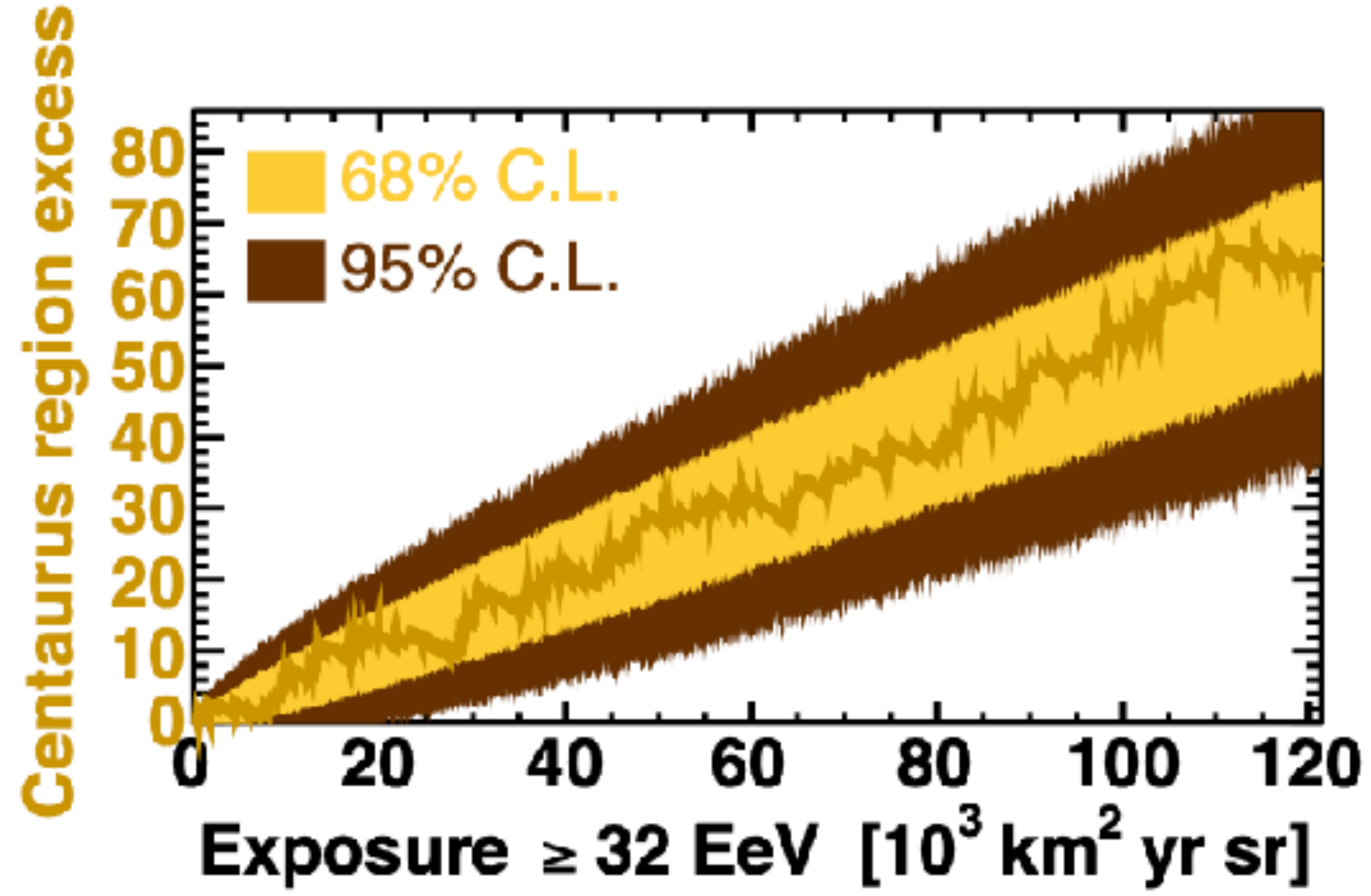
Pierre Auger Collab., 38th ICRC , 2023

Evolution of the signal

Considering the best-fit parameters of the Centaurus region search





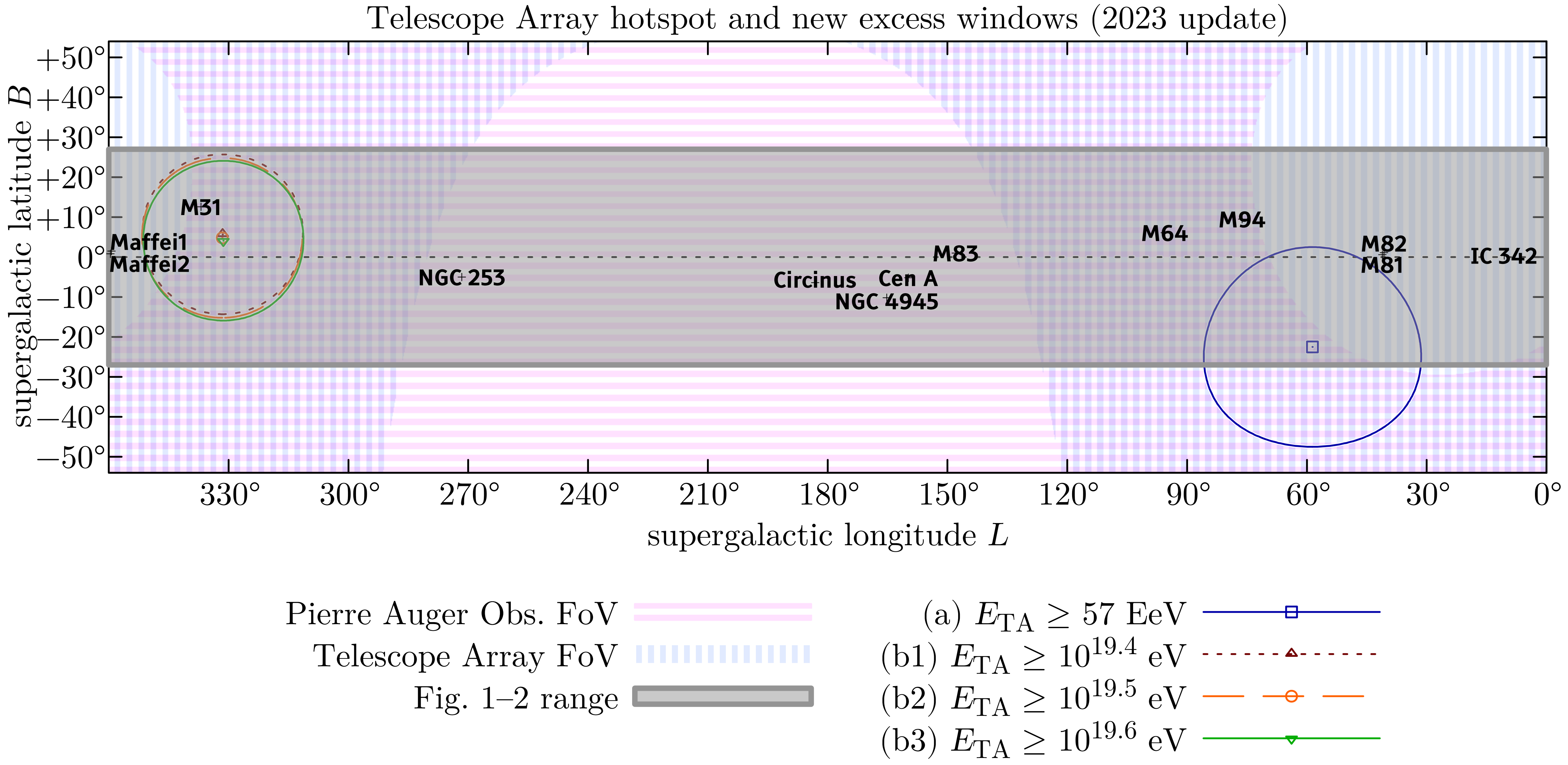


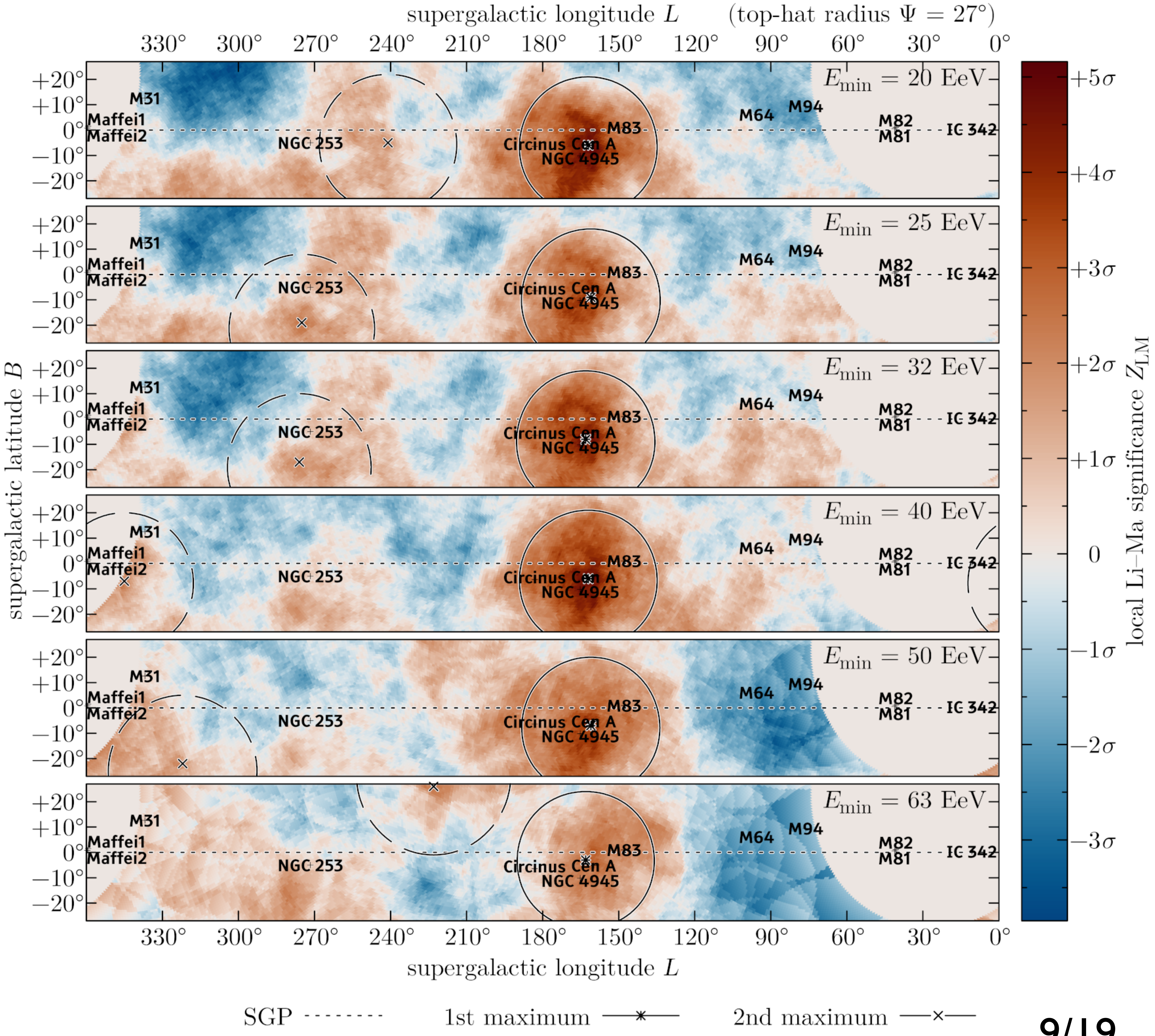
Compatible with linear growth within the expected variance

5 sigma deviation from isotropy at 2025 ± 2 years

Pierre Auger Collab., 38th ICRC , 2023

Regions of Telescope Array excesses with Auger data





- ★ E_{min} = 20, 25, 32, 40, 50, 63 EeV
- ★ top-hat windows with radius Ψ = 27°
- ★ SGP intersect the window
- ★ center of the window be inside the FoV

Pierre Auger Collab., arXiv 2407.06874

Regions of Telescope Array excesses with Auger data

The excesses reported by TA in the windows a and b , as of their latest update and the corresponding results in our data

Telescope Array Collab., 38th ICRC, 2023

Correcting the energy thresholds for the known mismatch between the energy scales of the two observatories

Pierre Auger Collab. Telescope Array Collab, 38th ICRC, 2023

	Telescope Array (Telescope Array Collaboration 2023)									Pierre Auger Observatory (this work)							
	$E_{\rm min}$	$N_{\rm tot}$	$\frac{\mathcal{E}_{\rm in}}{\mathcal{E}_{\rm tot}}$	$N_{\rm bg}$	$N_{\rm in}$	$\frac{\Phi_{\rm in}}{\Phi_{\rm out}}$	$Z_{\rm LM}$	99% L.L.	post-trial	$E_{\rm min}$	$N_{\rm tot}$	$\frac{\mathcal{E}_{\rm in}}{\mathcal{E}_{\rm tot}}$	$N_{\rm bg}$	$N_{\rm in}$	$\frac{\Phi_{\rm in}}{\Phi_{\rm out}}$	$Z_{\rm LM}$	99% U.L.
(a)	57 EeV	216	9.47%	18.0	44	$2.44^{+0.44}_{-0.39}$	$+4.8\sigma$	1.60	2.8σ	44.6 EeV	1074	1.00%	10.7	9	$0.84^{+0.31}_{-0.25}$	-0.5σ	1.76
(b1)	$10^{19.4}$ eV	1125	5.88%	64.0	101	$1.58^{+0.17}_{-0.16}$	$+4.1\sigma$	1.22	3.3σ	20.5 EeV	8374	0.84%	70.1	65	$0.93^{+0.12}_{-0.11}$	-0.6σ	1.23
(b2)	$10^{19.5}$ eV	728	5.87%	41.1	70	$1.70^{+0.22}_{-0.20}$	$+4.0\sigma$	1.25	3.2σ	25.5 EeV	5156	0.84%	43.5	39	$0.90^{+0.15}_{-0.14}$	-0.7σ	1.29
(b3)	$10^{19.6}$ eV	441	5.84%	24.6	45	$1.83^{+0.31}_{-0.27}$	$+3.6\sigma$	1.23	3.0σ	31.7 EeV	2990	0.87%	26.0	27	$1.04^{+0.21}_{-0.19}$	$+0.2\sigma$	1.61

We actually obtain always $-0.7\sigma \lesssim Z_{\rm LM} < +0.2\sigma$, in excellent agreement with the isotropic null hypothesis.

Pierre Auger Collab,, arXiv 2407.06874

Regions of Telescope Array excesses with Auger data

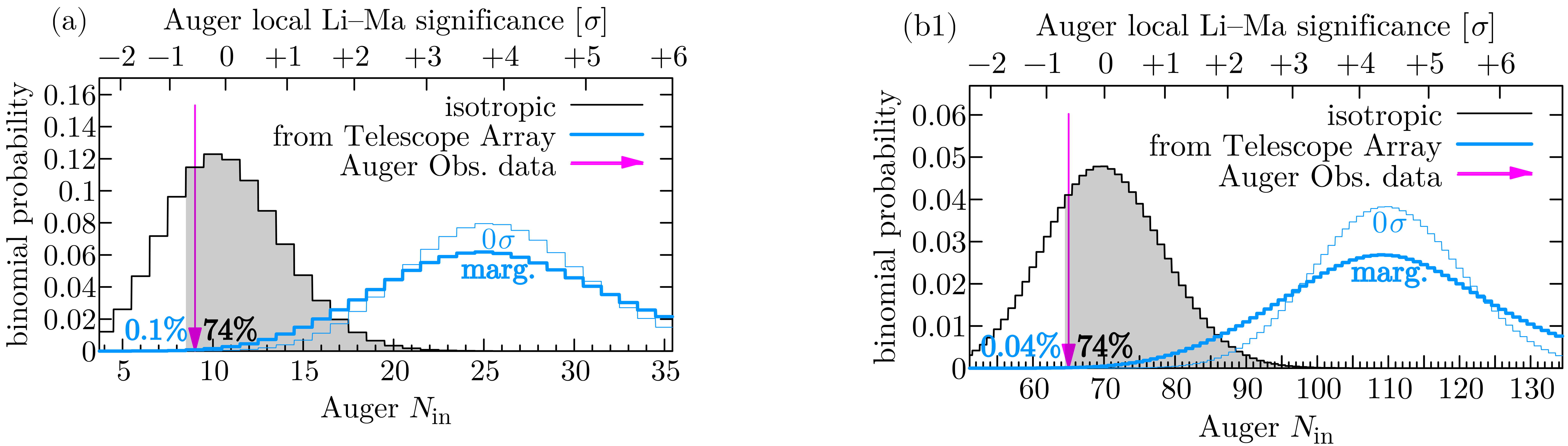
We computed the distribution of the number N_{in} of events in our dataset expected in each of these windows based on

(i) isotropy ($\Phi_{in}/\Phi_{out} = 1$),

(ii) the TA value of Φ_{in}/Φ_{out} that can be computed from their numbers of events N_{in}, N_{tot} as reported in their last update

Telescope Array Collab., 38th ICRC, 2023

(iii) the marginal distribution of Φ_{in}/Φ_{out} over TA statistical uncertainties.



Pierre Auger Collab,, arXiv 2407.06874

Large scale: weighted harmonic analysis E>4 EeV

- ⋆ Search for harmonic modulation in right ascension and azimuth: $x = \alpha \text{ or } \phi$
- ⋆ Fourier coefficients of order k (1 or 2) $a_x^k = \frac{2}{N}\sum_{i=1}^{N} w_i \cos(kx_i), \; b_x^k = \frac{2}{N}\sum_{i=1}^{N} w_i \sin(kx_i)$
- ⋆ Amplitude, $r_k^x = \sqrt{(a_k^x)^2 + (b_k^x)^2}$, phase $\varphi_k^x = \frac{1}{k}\tan^{-1}\frac{b_k^x}{a_k^x}$
- ⋆ Weights: small variations in coverage and tilt of the array

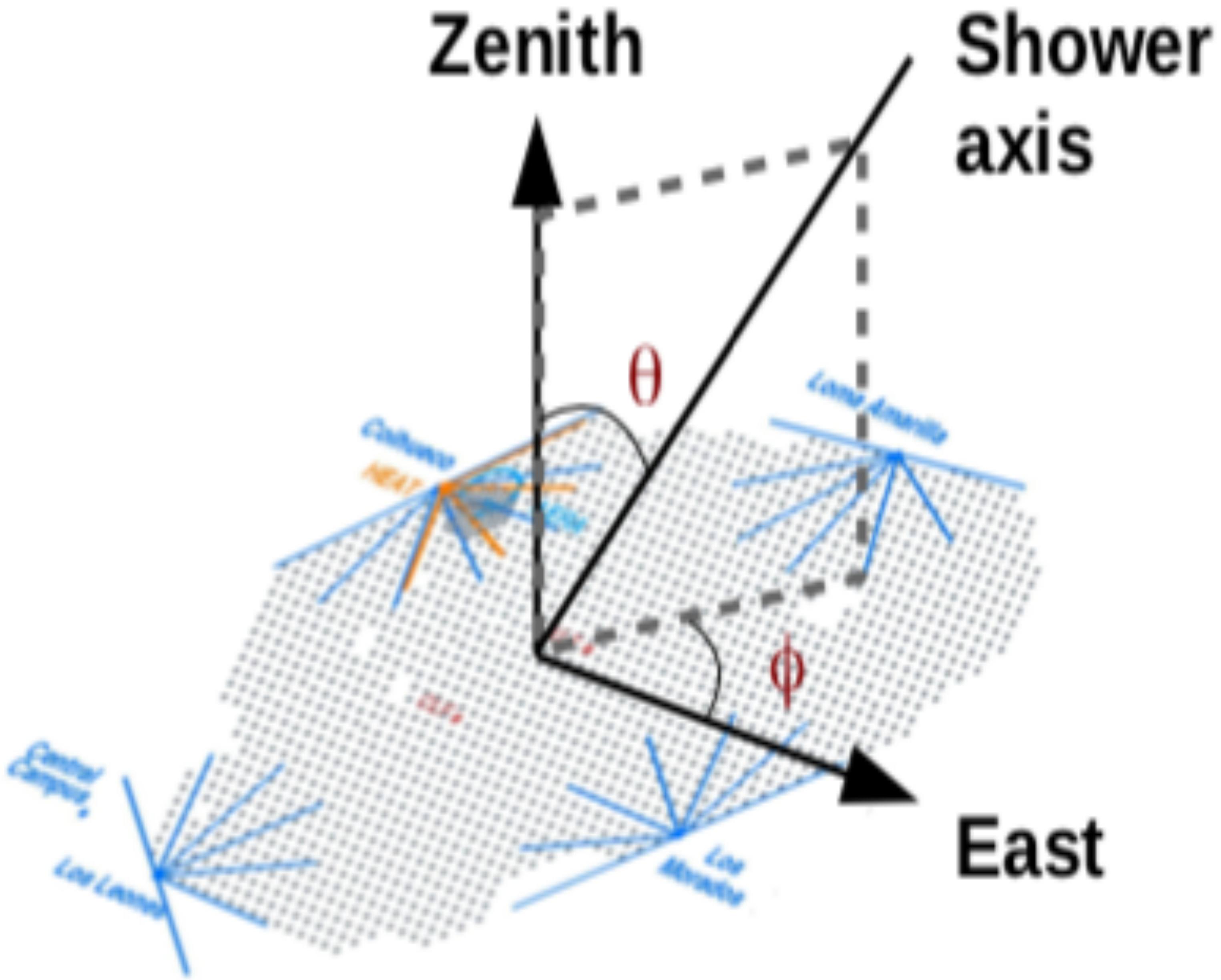
$$w_i = \left[\Delta N_{cell}(\alpha_i^0)(1 + 0.003\tan\theta_i\cos(\phi_i - \phi_0))\right]^{-1}$$

number of active detector cells

right ascension of the zenith of the observatory

average tilt of the array $\phi_0 = -30^\circ$

Dipolar modulation: $d_\perp \simeq \frac{r_1^\alpha}{\langle\cos\delta\rangle}$ $d_z \approx \frac{b_1^\varphi}{\cos\ell_{\text{obs}}\langle\sin\theta\rangle}$



Pierre Auger Collab., APJ, 2020

Harmonic analysis above 4 EeV

E [EeV]	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]	$P(\geq d_\perp)$
4-8	118,835	$0.010^{+0.006}_{-0.004}$	-0.014 ± 0.008	$0.017^{+0.008}_{-0.005}$	91 ± 30	-53^{+21}_{-19}	0.15
≥8	49,710	$0.058^{+0.009}_{-0.008}$	-0.045 ± 0.012	$0.073^{+0.010}_{-0.008}$	97 ± 8	-37^{+9}_{-9}	7.4×10^{-12}
8-16	36,683	$0.057^{+0.010}_{-0.009}$	-0.030 ± 0.014	$0.065^{+0.012}_{-0.009}$	92 ± 10	-28^{+11}_{-12}	1.2×10^{-8}
16-32	10,288	$0.059^{+0.020}_{-0.015}$	-0.07 ± 0.03	$0.094^{+0.026}_{-0.019}$	93 ± 18	-51^{+13}_{-13}	4.5×10^{-3}
≥32	2,739	$0.11^{+0.04}_{-0.03}$	-0.13 ± 0.05	$0.17^{+0.05}_{-0.04}$	143 ± 19	-51^{+14}_{-13}	8.4×10^{-3}

→ 6,9 σ

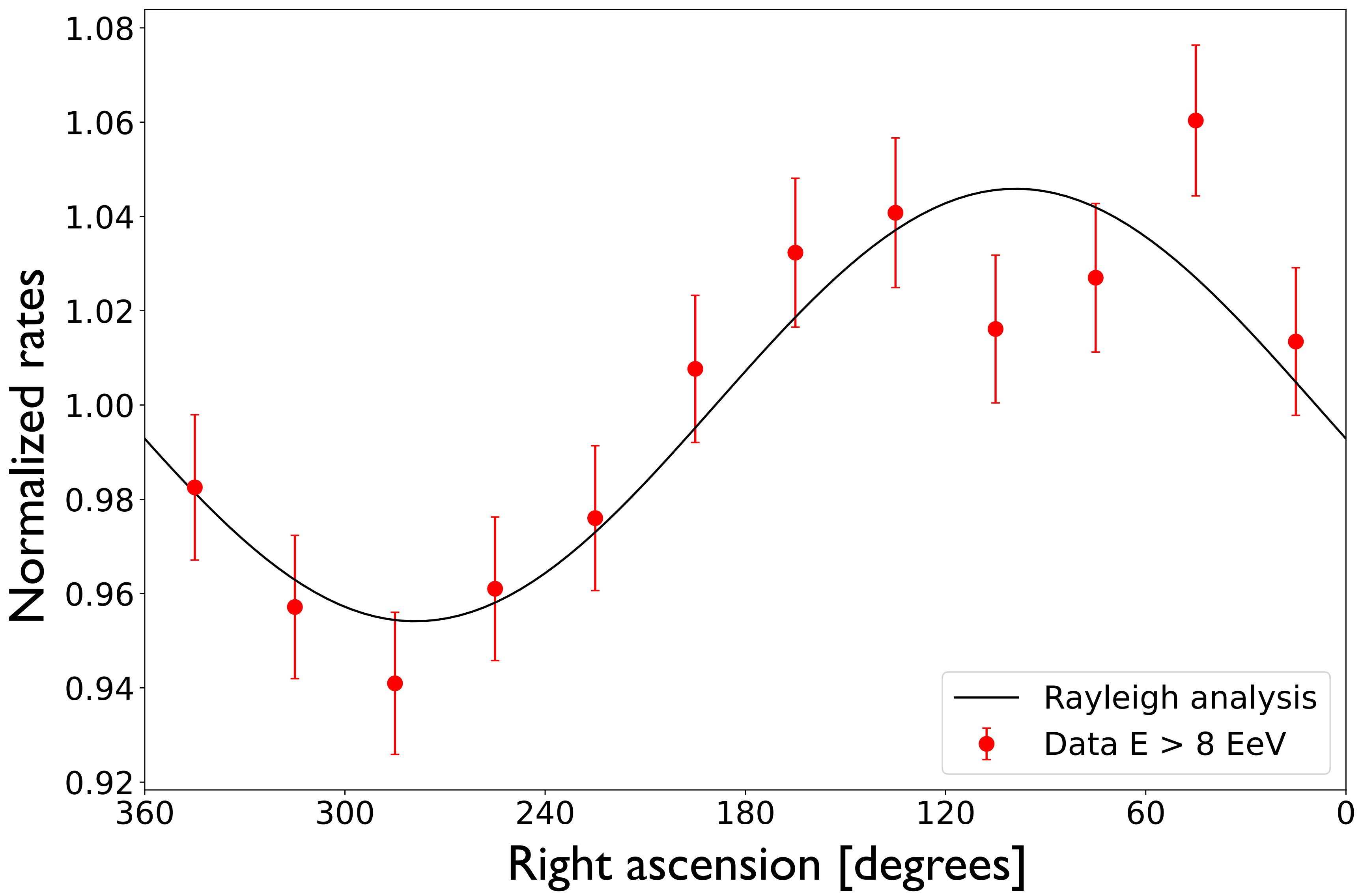
→ 5,7 σ

Significance of the first harmonic modulation became larger as the exposure increase

1.4×10^{-9} **ApJ 2020**

2.6×10^{-8} **Science 2017**

6×10^{-5} **ApJ 2015**



4-8 EeV bin: consistent with isotropy

> 8 EeV bin: $P(\geq d_\perp) \geq 7.4 \times 10^{-12}, \quad \alpha = 97° \pm 8°$

Evidence of large scale anisotropies above 8 EeV

Pierre Auger Collab., 38th ICRC , 2023

Large-scale analysis E>4 EeV: dipole + quadrupole

Results for the two energy bins with more than 5σ significance

E [EeV]	d_i	Q_{ij}	Q_{ij}
≥ 8	$d_x = -0.002 \pm 0.011$	$Q_{zz} = 0.04 \pm 0.05$	$Q_{xz} = 0.016 \pm 0.025$
	$d_y = 0.059 \pm 0.011$	$Q_{xx} - Q_{yy} = 0.07 \pm 0.04$	$Q_{yz} = 0.005 \pm 0.025$
	$d_z = -0.02 \pm 0.03$	$Q_{xy} = 0.024 \pm 0.019$	
8-16	$d_x = -0.002 \pm 0.012$	$Q_{zz} = 0.10 \pm 0.06$	$Q_{xz} = 0.001 \pm 0.029$
	$d_y = 0.049 \pm 0.012$	$Q_{xx} - Q_{yy} = 0.03 \pm 0.04$	$Q_{yz} = -0.028 \pm 0.029$
	$d_z = 0.02 \pm 0.04$	$Q_{xy} = 0.039 \pm 0.022$	

Quadrupolar component not significant

Dipolar amplitudes consistent with dipole only results

Dipole reconstruction E> 4 EeV

E [EeV]	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]	P($\geq d_\perp$)
4-8	118,835	$0.010^{+0.006}_{-0.004}$	-0.014 ± 0.008	$0.017^{+0.008}_{-0.005}$	91 ± 30	-53^{+21}_{-19}	0.15
≥8	49,710	$0.058^{+0.009}_{-0.008}$	-0.045 ± 0.012	$0.073^{+0.010}_{-0.008}$	97 ± 8	-37^{+9}_{-9}	7.4×10^{-12}
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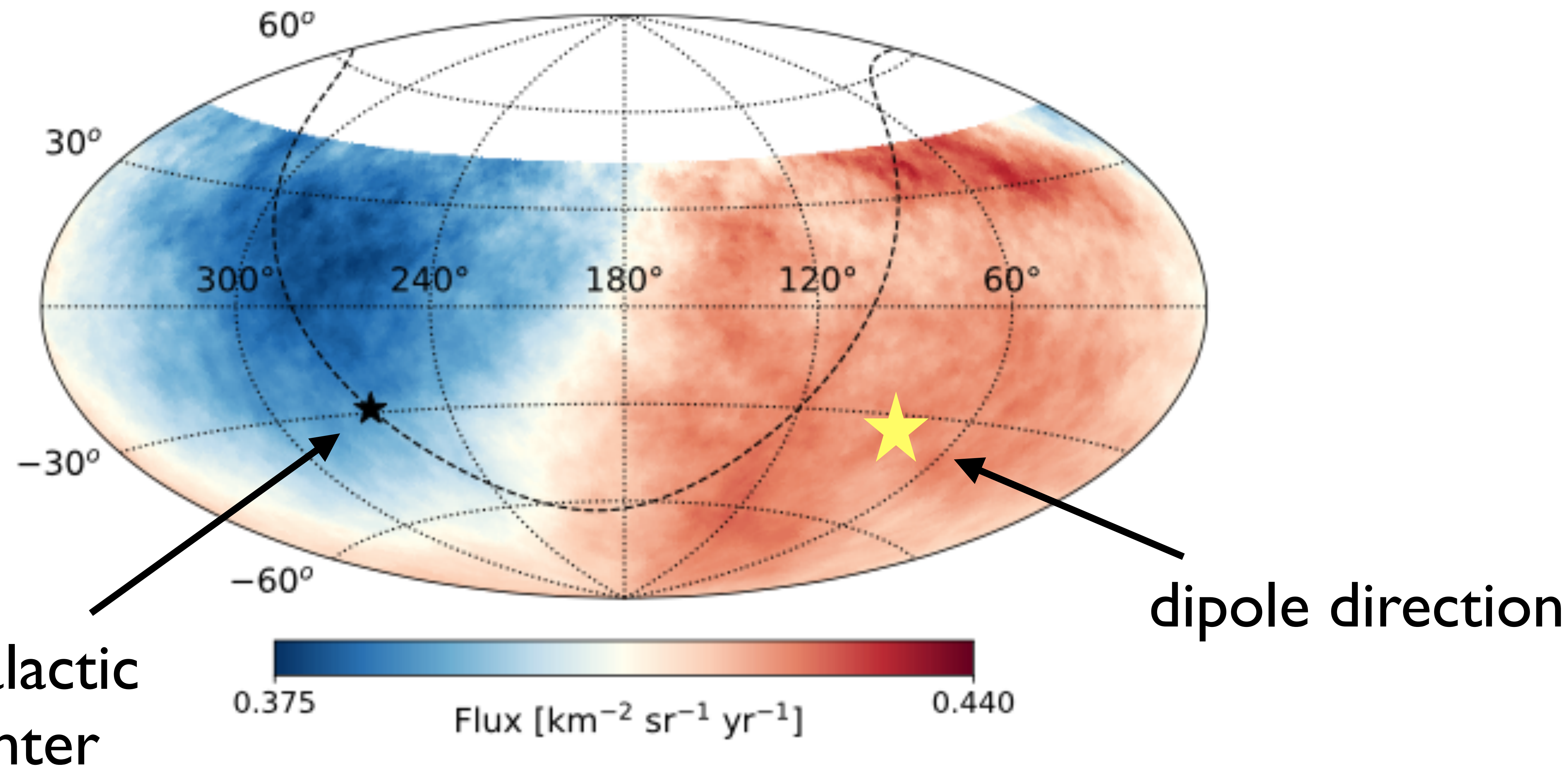
suposing a pure dipolar distribution

E > 8 EeV:

dipole amplitude:

$7.3^{+1.1}_{-0.9}$ %

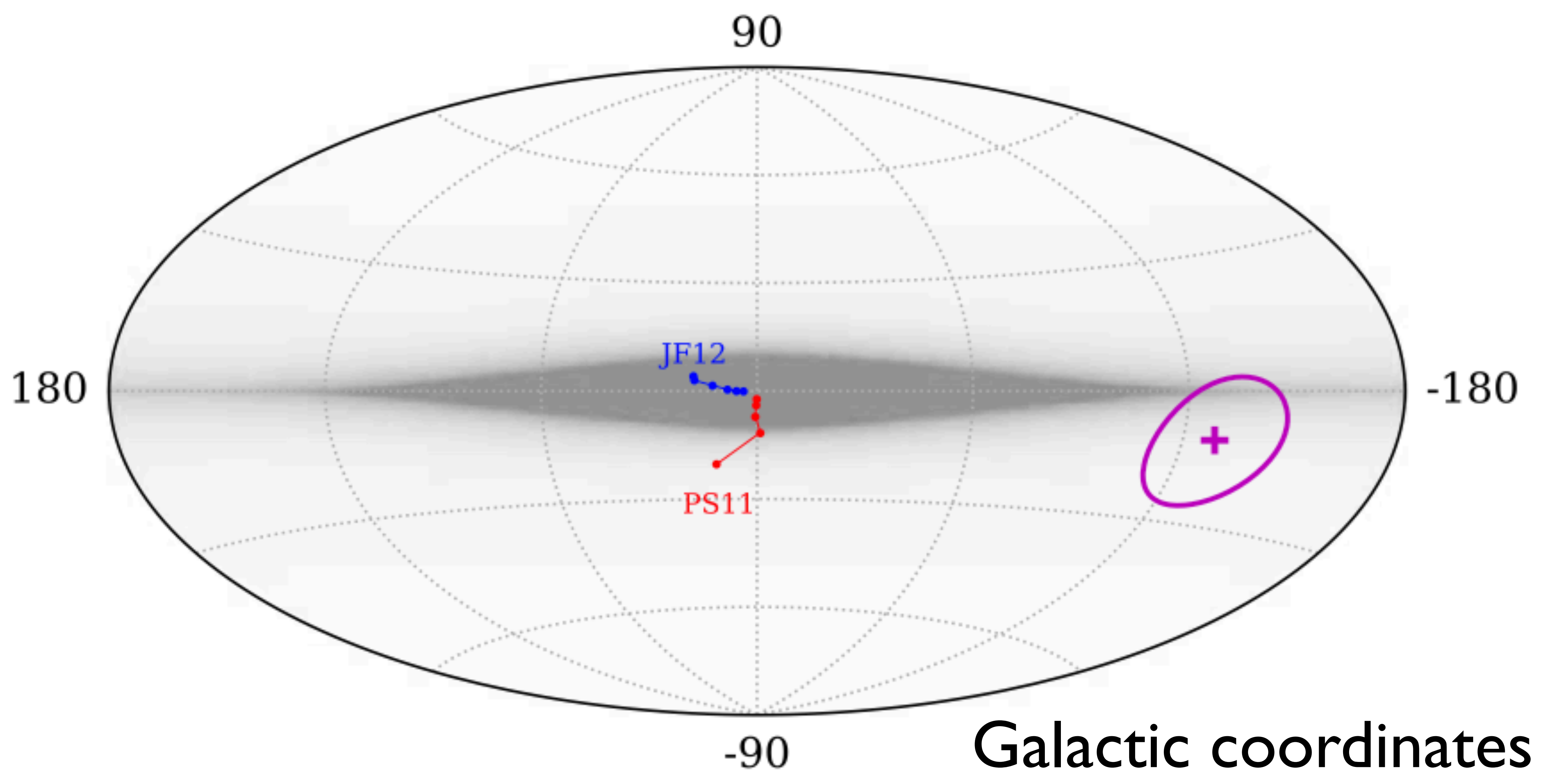
Flux sky map E > 8 EeV



Galactic center

Equatorial coordinates

Dipole directions in galactic scenario

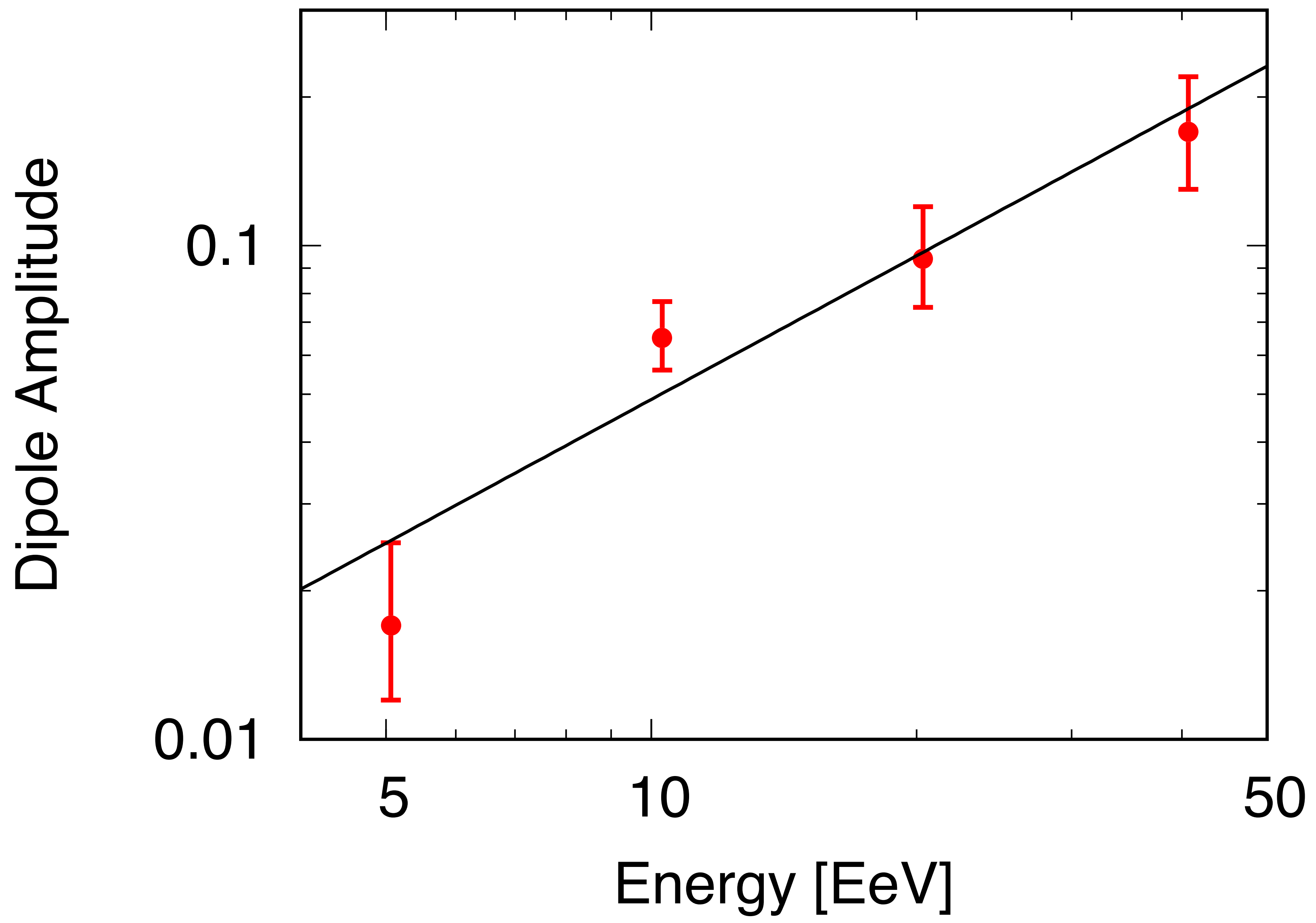


Galactic coordinates

Extragalactic origin

Energy dependence of dipolar modulation

Split the E>8 EeV bin in three

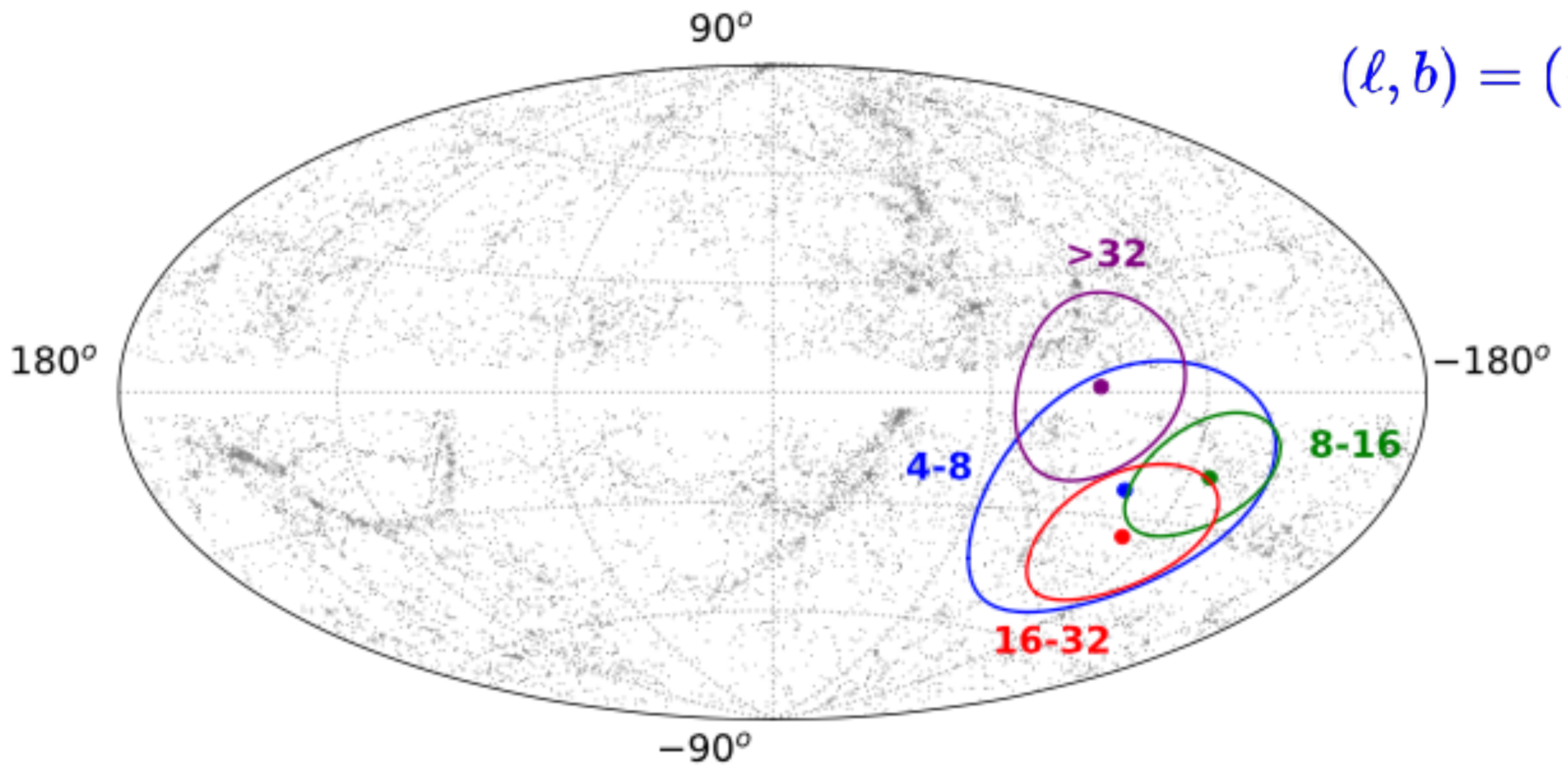


$$d(E) = d_{10} \times \left(\frac{E}{10\text{EeV}}\right)^{\beta} \qquad d_{10} = 0.049 \pm 0.009 \quad \beta = 0.97 \pm 0.21$$

dipole amplitude increases with energy

(energy-independent fit disfavored above 5σ)

Dipole directions above 4 EeV



outer
spiral arm

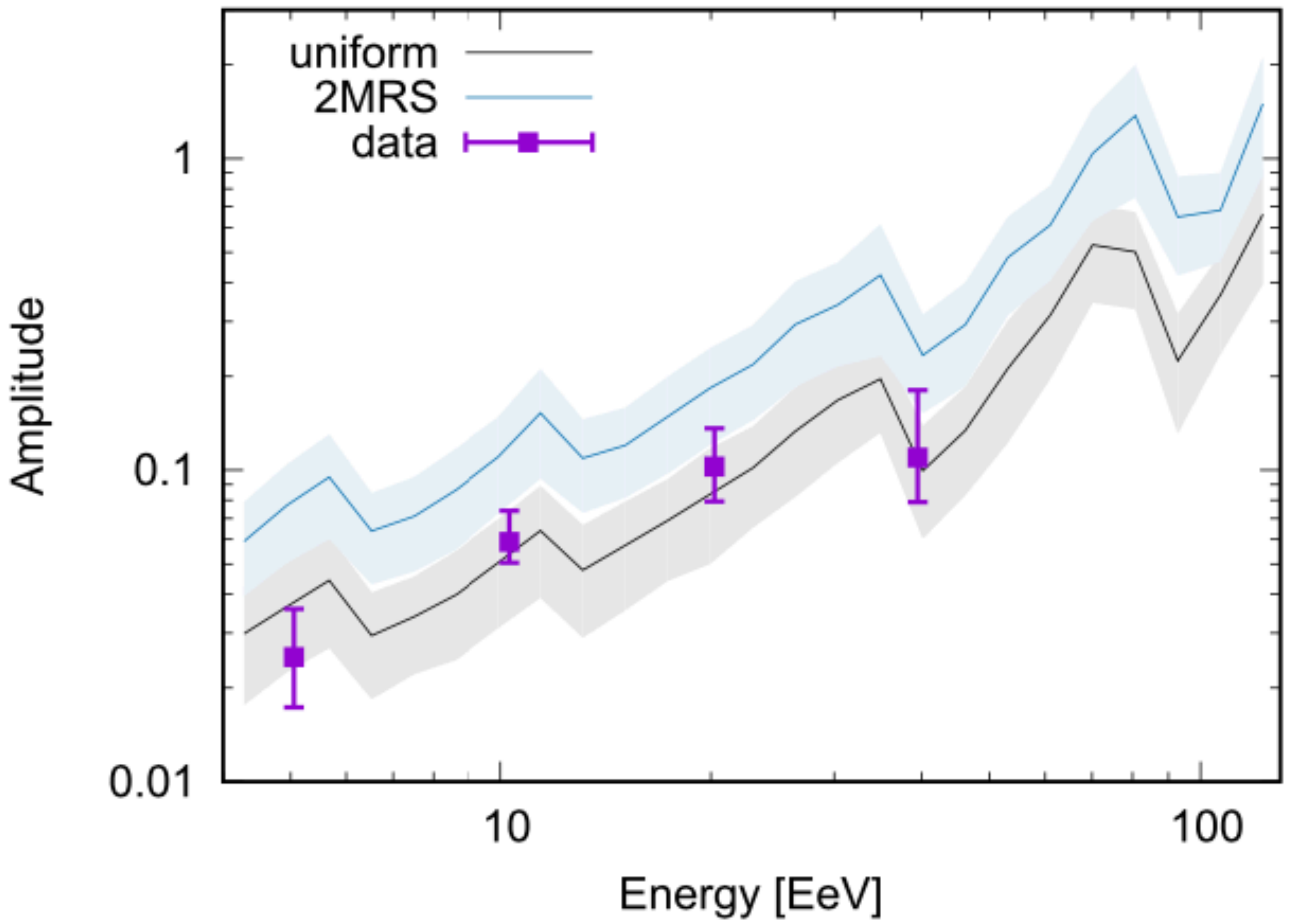
$(\ell, b) = (-100°, 0°)$

Galactic coordinates

No clear trend in the evolution of dipole direction with energy

Dipole interpretation

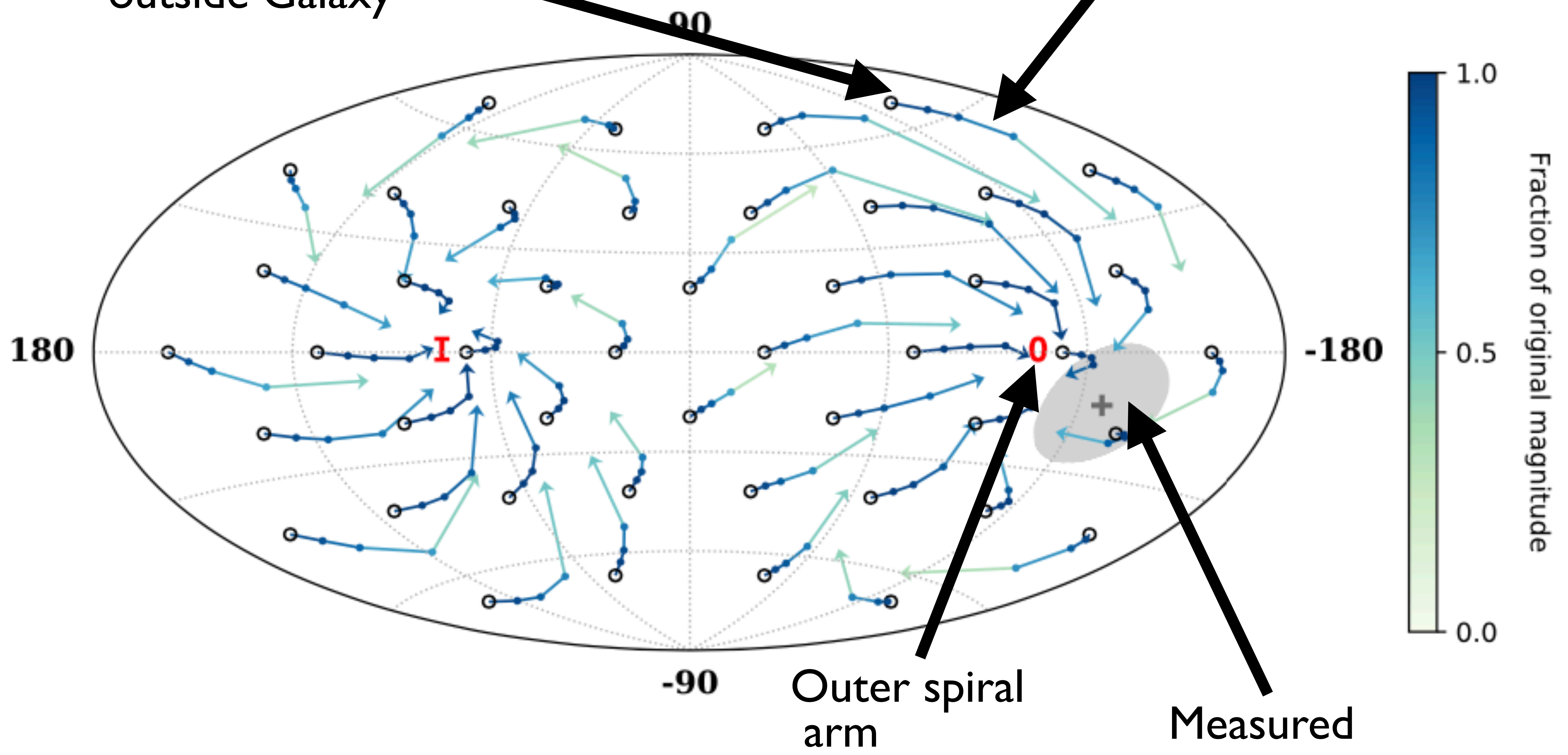
Models with mixed composition,
R_{max} = 6 EV, source density 10^{-4} Mpc^{-3}



Consistent with expectations

Harari, Molerach, Roulet, PRD, 2014)

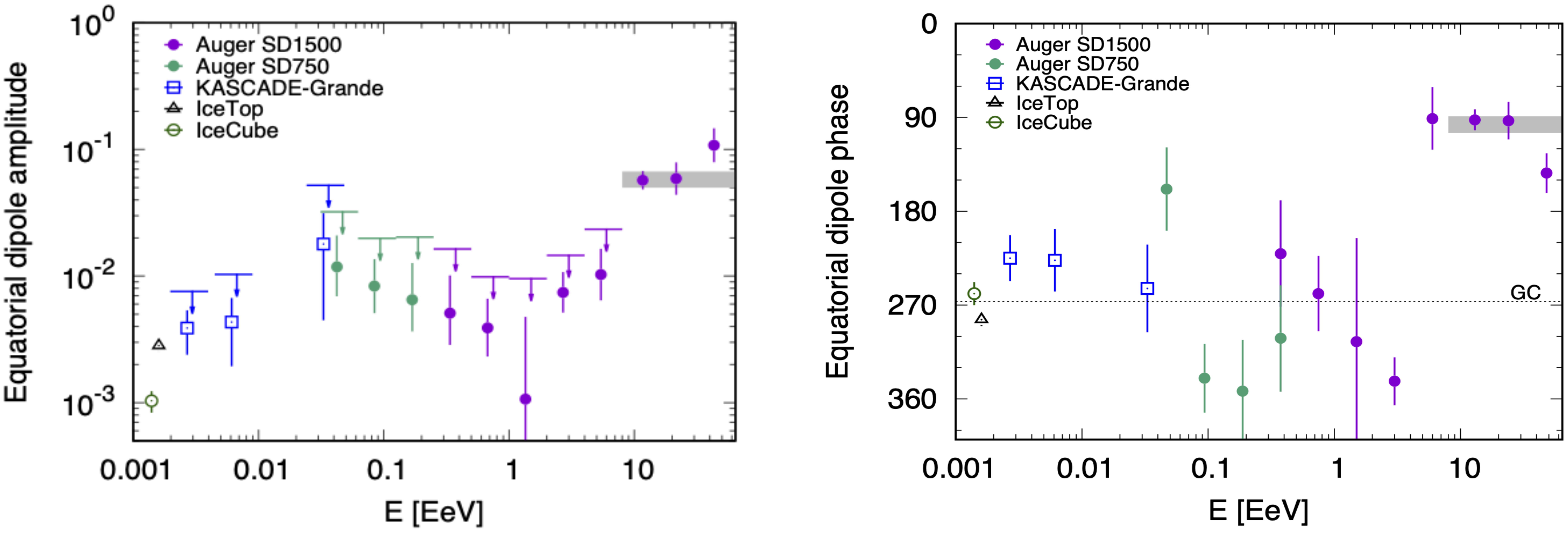
Extragalactic Dipole and GMF



Extragalactic dipole direction gets shifted towards spiral arms

Possibly due to the larger relative contribution from nearby sources to the flux at higher energies

Large-scale analysis in R.A. at E > 0.03 EeV



Even though the results for the lower E have a P>1%, amplitudes grow from below 1% to above 10% and phases shift from ~GC to the opposite direction.

⟹ suggests a transition of the origin of the anisotropies from galactic to extragalactic

Conclusions and prospects

- ★ Highest energies: Centaurus region at 4.0 σ (3.0×10^{-5}), could reach 5.0 σ by (165 ± 15) x 10^3 km^2sr yr. SBG catalog at 3.8 σ (6.6×10^{-5}).
- ★ TA excesses: with comparable statistics, no significant results have been found.
- ★ Dipole: >8 EeV at 6.9 σ and 8-16 EeV at 5.7σ. Quadrupolar moments not signifcant.
- ★ Large-scale analysis above 0.03 EeV: results suggest that the anisotropy has a predominant galactic origin below 1 EeV and a predominant extragalactic one above few EeV.
- ★ Promising inclusion of mass composition estimators on an event-by-event basis with AugerPrime (and improved mass estimators with Phase1 data)

Thank you!

Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro

Backup slides

Catalog-based searches E > 32 EeV

Analysis strategy

Sky model probability maps:

Null hypothesis H_0: **isotropy**

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

Single population **signal** model H_1:

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

(free parameters: α and Θ)

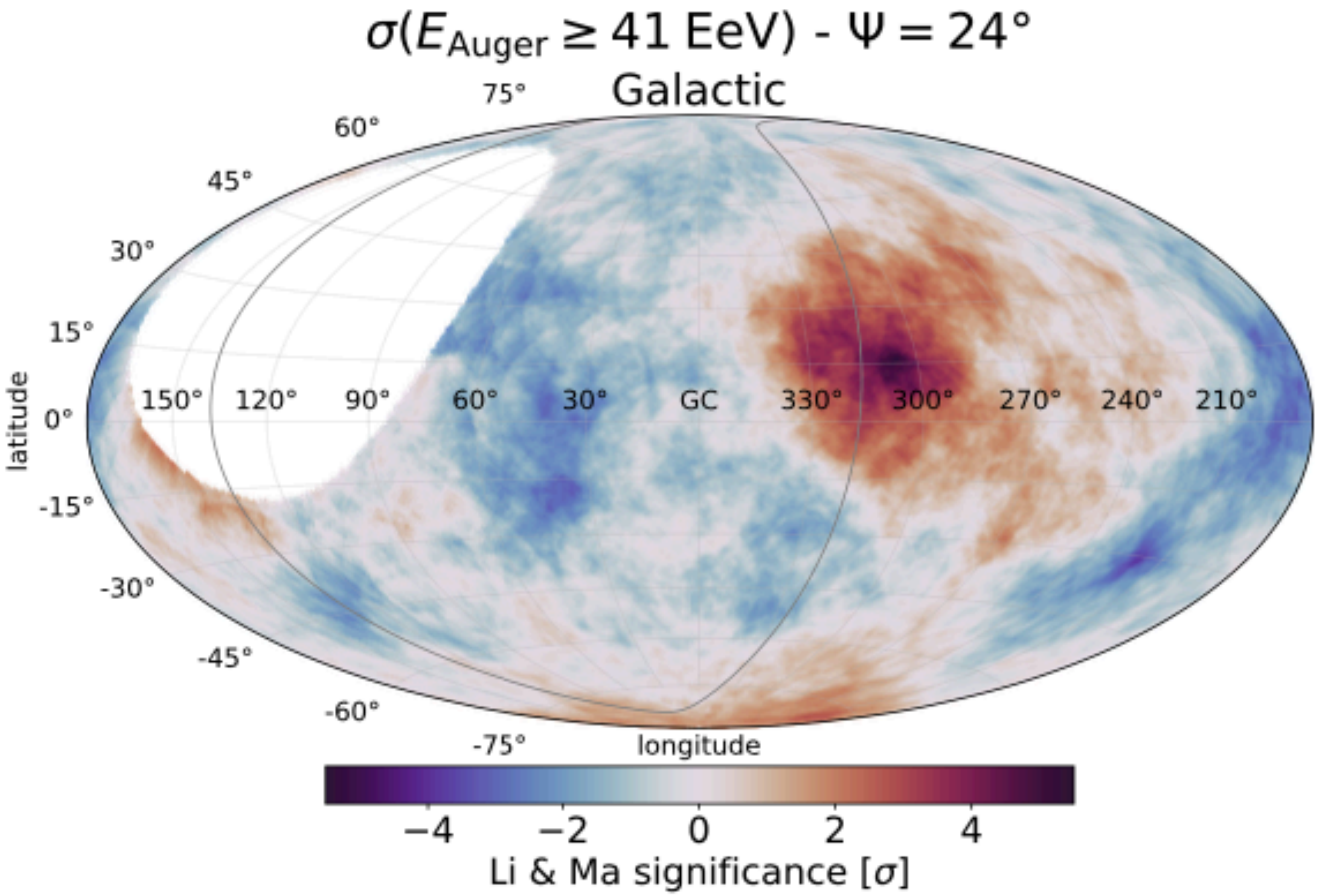
Contribution to the UHECR flux from each galaxy:

$$s_j(\mathbf{u};\Theta) = \omega(\mathbf{u}) \times \phi_j a(d_j) \times \exp\left(\frac{\mathbf{u}\cdot\mathbf{u}_j}{2(1-\cos\Theta)}\right)$$

Modeled as a von Mises-Fisher distribution centered on the direction of the galaxy with a smearing angle Θ

Test statistics: $\mathrm{TS} = 2\log(\mathrm{H_1}/\mathrm{H_0})$ $\quad \mathrm{TS} = 2\sum_i k_i \times \ln \frac{n^{H_1}(\mathbf{u}_i)}{n^{H_0}(\mathbf{u}_i)}$

Highest energies: blind searches for overdensities



Search for excesses not specifying a priori the targeted regions of the sky

- ★ **Li-Ma**: compare cumulative number of events (Nobs) given the expected on average from isotropic simulations (Nexp)
- ★ Scan in **energy** threshold in [32; 80] EeV, step of 1 EeV
- ★ Scan in top-hat search **angle** Ψ in [1°; 30°], steps of 1°

Most significant local excess over whole observable sky

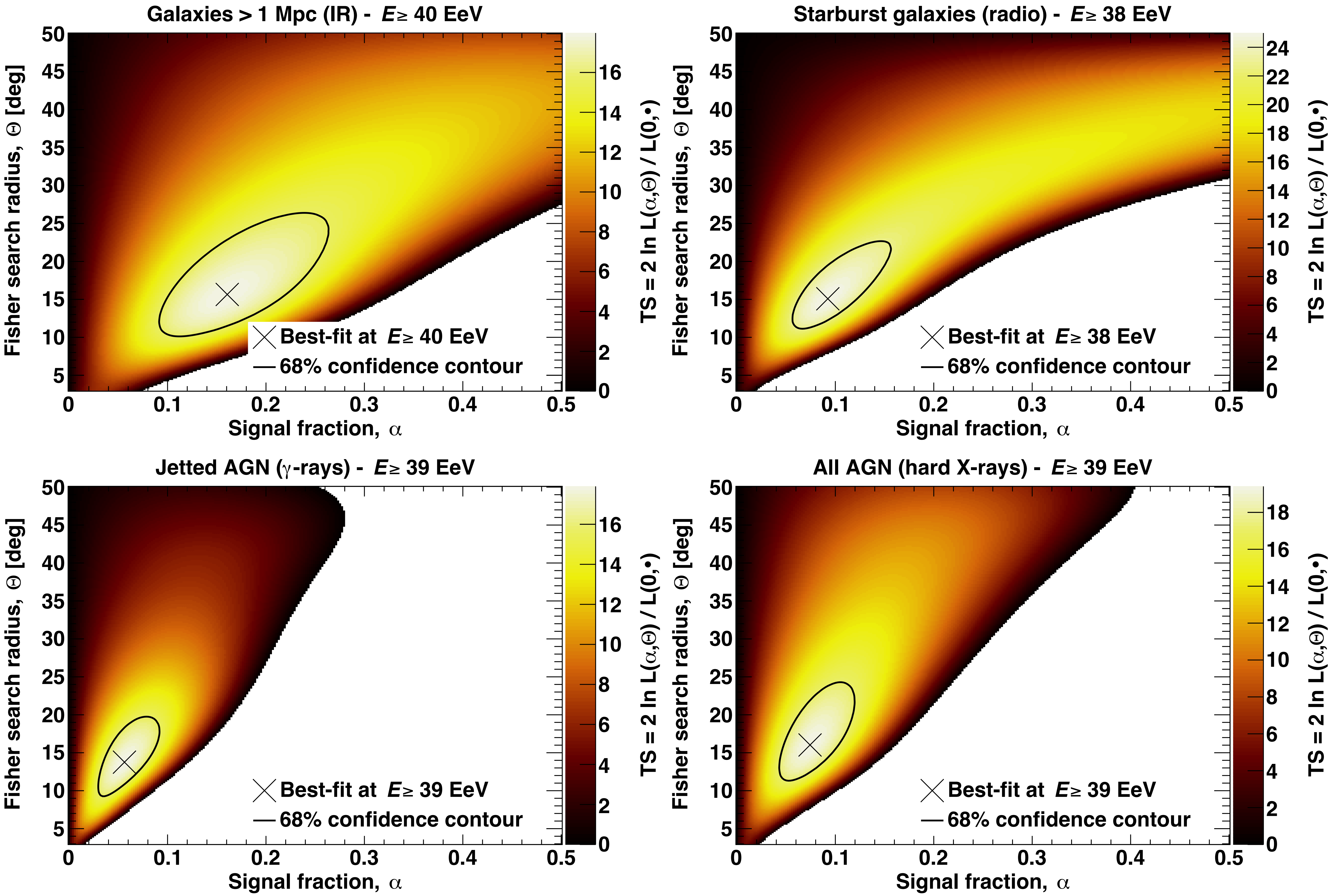
- ★ Eth ≥ 41EeV, Ψ =24°
- ★ (α, δ) = (196.3o, -46.6o), (l, b) = (305.4o, 16.2o)
- ★ Local p-value 3.7×10^{-8}, Li&Ma significance = 5.4σ
- ★ **Global p-value = 3%**
  (after accounting the scan, penalty factor ~$O(10^5)$)

The dataset above 32 EeV is available for public use

- ★ with the code to reproduce the results (link)

P. Auger Collab, ApJ, 2022

Catalogue searches for intermediate scale anisotropies

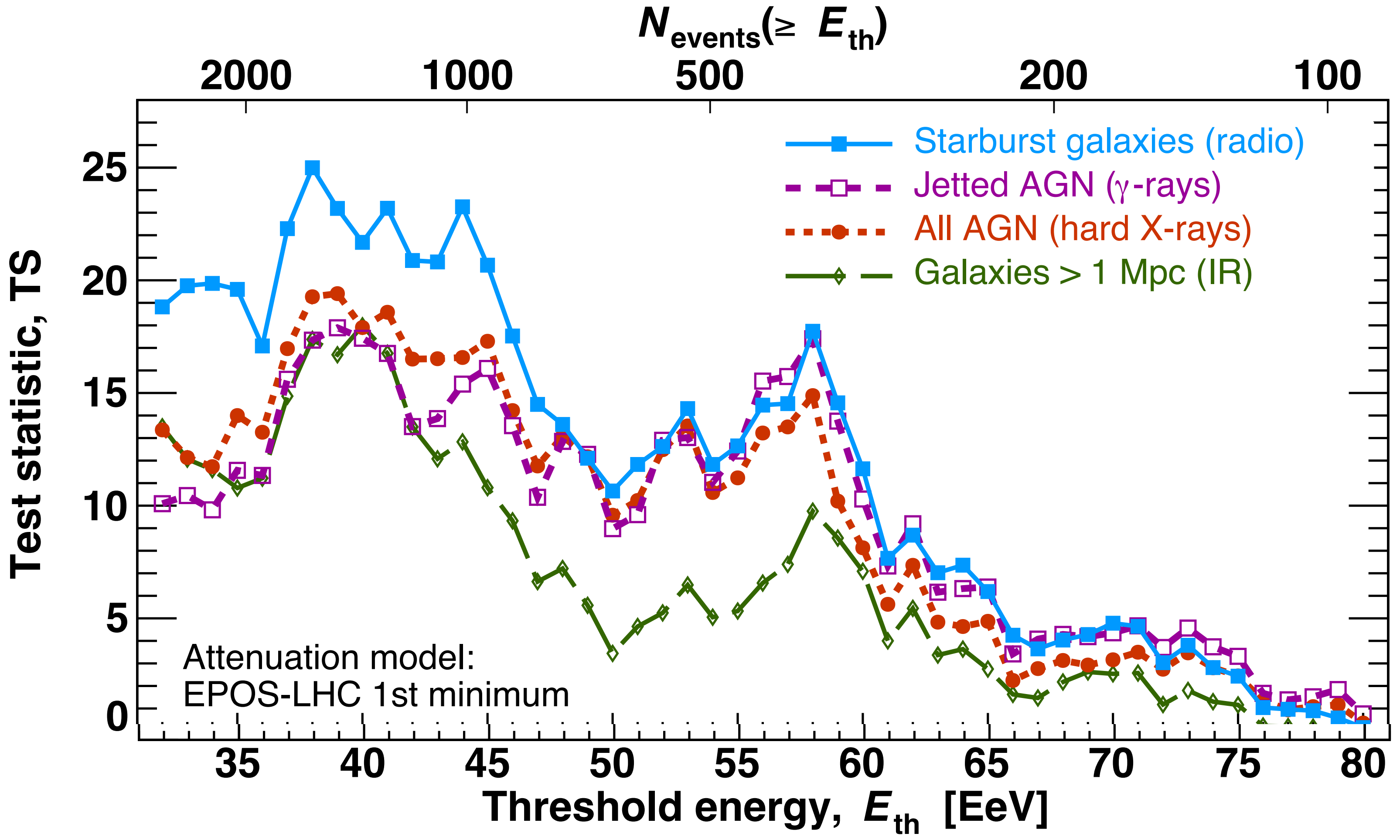


All catalogs have highest test statistics at Eth=38- 41EeV, scale Ψ=23°-27°, signal fraction α=6-15%

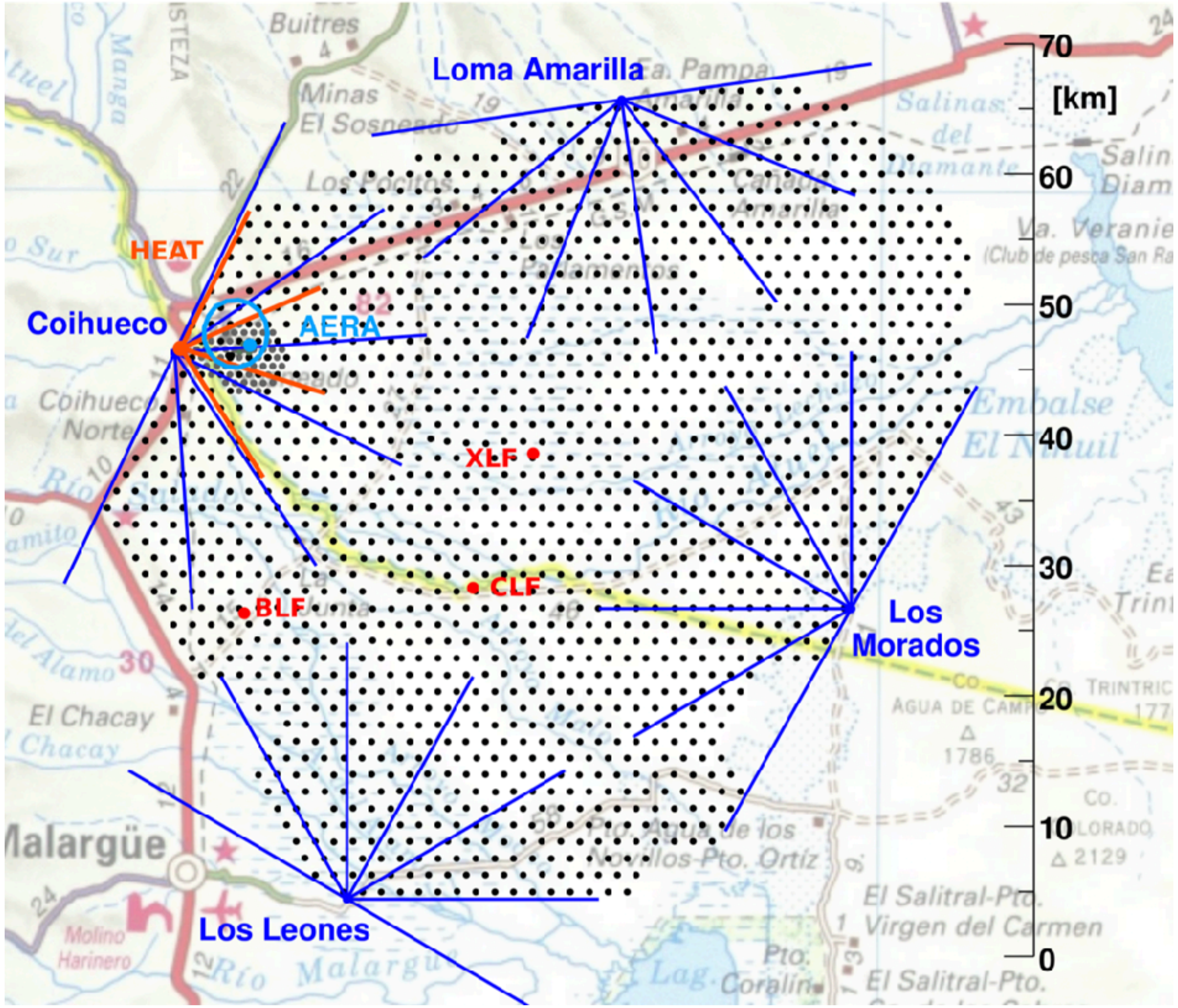
Post-trial significance

3.1σ for jetted AGNs

4.0σ for Starburst galaxies



Pierre Auger Observatory: state-of-the art cosmic ray detector



- ⋆ **Water Cherenkov stations**
  - ⋆ SD1500: 1600, 1.5 km grid, 3000 km^2
  - ⋆ SD750: 61, 0.75 km grid, 23.5 km^2
  - ⋆ **Live time ~ 100%**
- ⋆ **4 Fluorescence sites**
  - ⋆ 24 telescopes, 1-30^0 FOV
  - ⋆ 3 high elevation FD 30^0-60^0 FOV
  - ⋆ **Live time ~ 13%**
- ⋆ **Underground Muon Detectors**
  - ⋆ 7 in engineering array phase
  - ⋆ 61 aside the Infill stations
- ⋆ **AERA radio antennas**
  - ⋆153 antenas in 17 km^2