Anisotropy studies of ultra-high-energy cosmic rays measured at the Pierre Auger Observatory

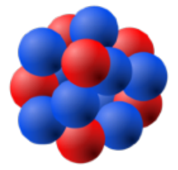
Josina Schulte on behalf of the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

TAUP VIENNA 2023

30.08.2023

Ultra-high-energy cosmic rays

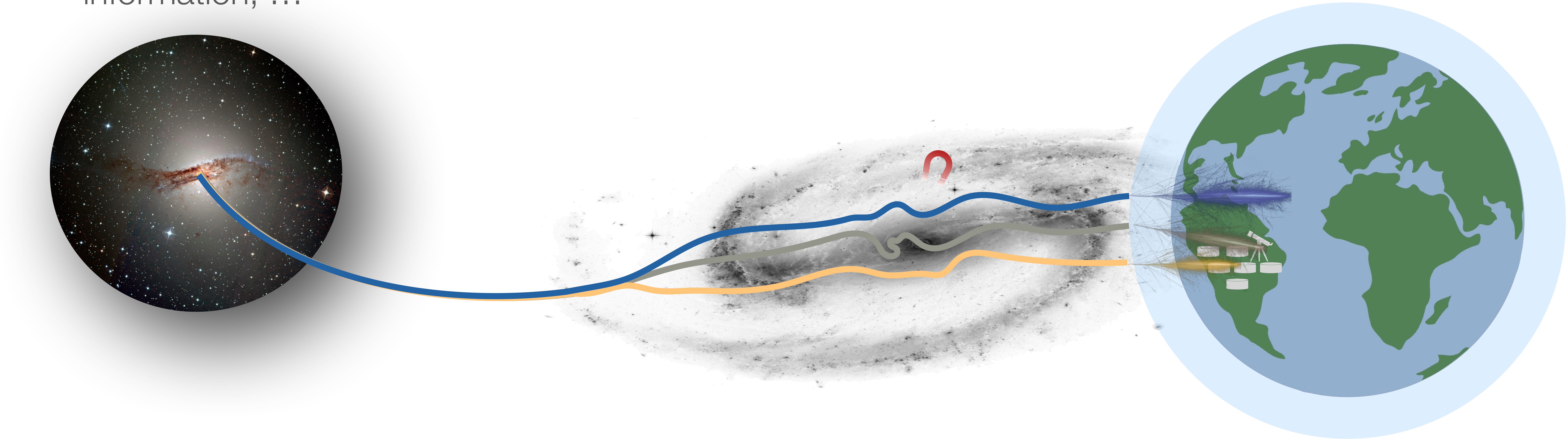
nuclei with energies $\geq 10^{18}$ eV inducing **extensive air showers** on Earth 

open questions:

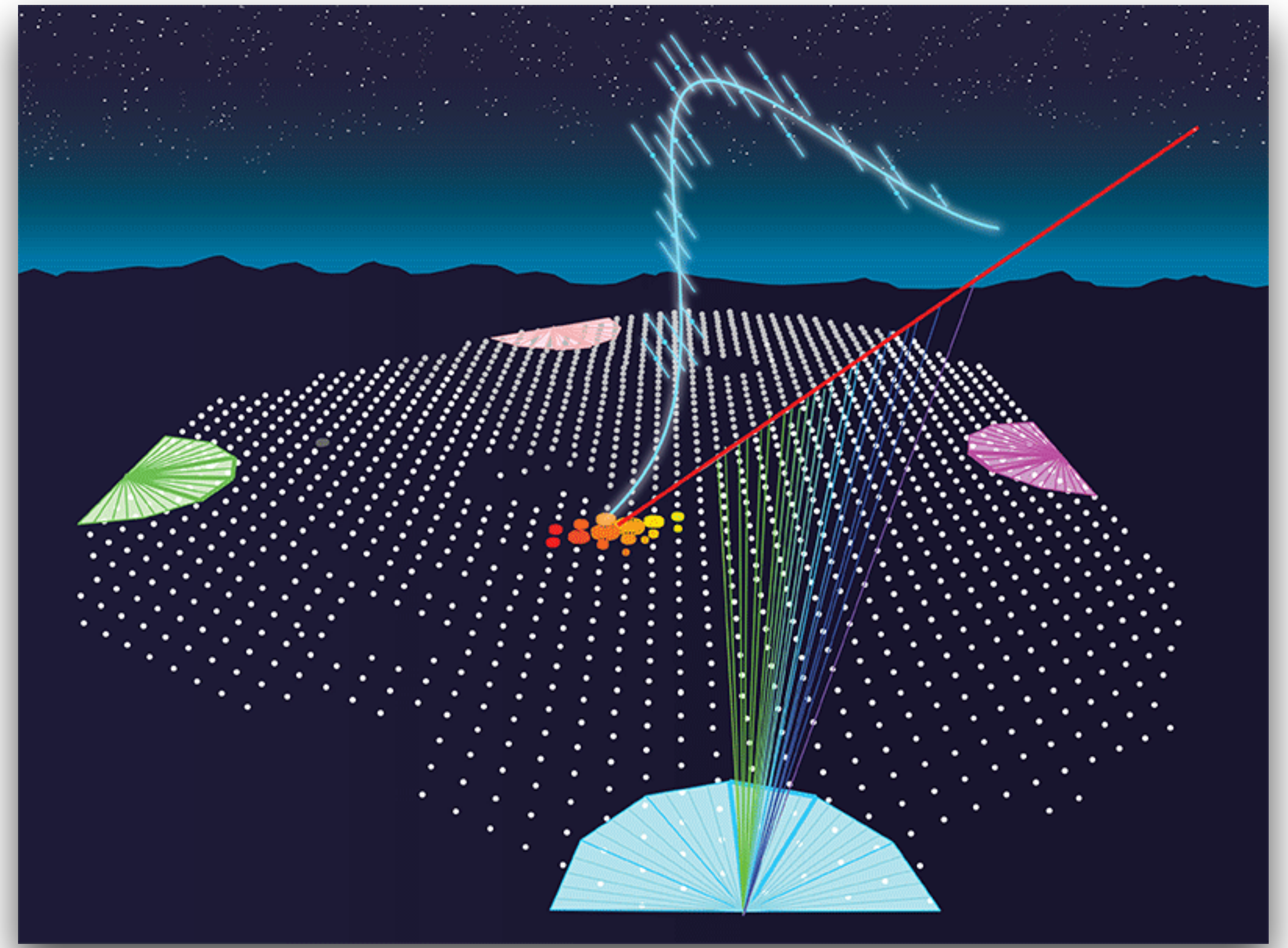
- what are their sources? how are they accelerated? what is the mass composition at highest energies?

challenges:

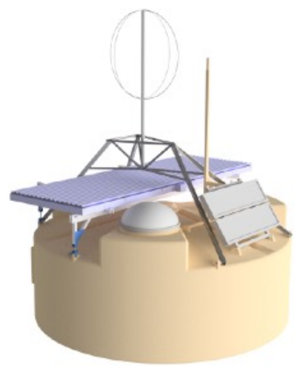
- deflections in magnetic fields, interactions with photon fields during propagation, limited charge information, …

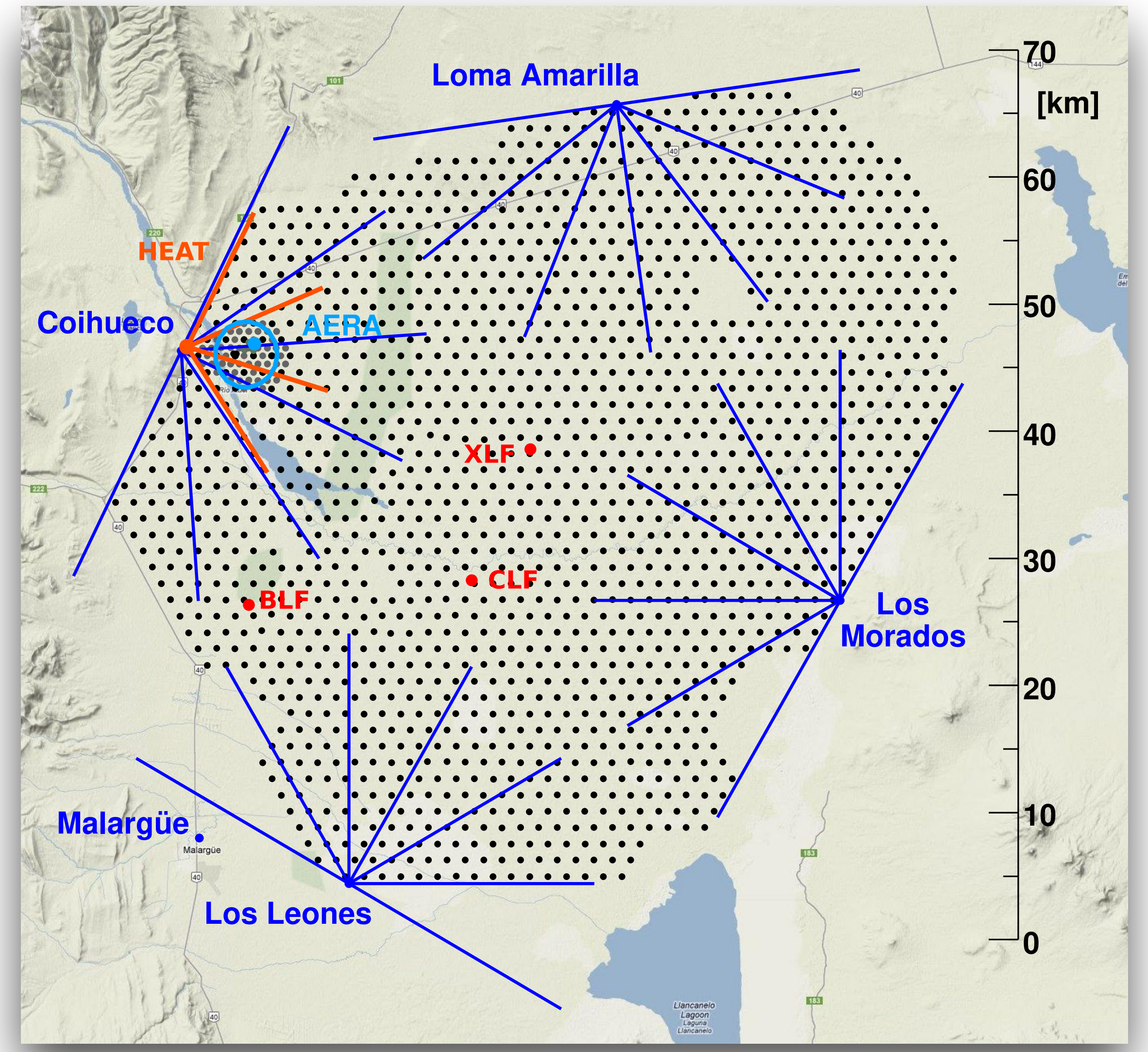


Pierre Auger Observatory



- largest UHECR detector: area of 3,000 km²
- located in **Argentina**
- **hybrid detection** of extensive air showers
  - **Surface Detector Array** *(SD)*
    - 1660 water-Cherenkov stations
    - ~ 100% duty cycle
  - **Fluorescence Detector** *(FD)*
    - 27 telescopes at 4 sites around the perimeter overlooking the array
    - ~ 15 % duty cycle
- **AugerPrime**
  - upgrade nearly finished
    - updated electronics
    - radio antennas
    - scintillation detectors





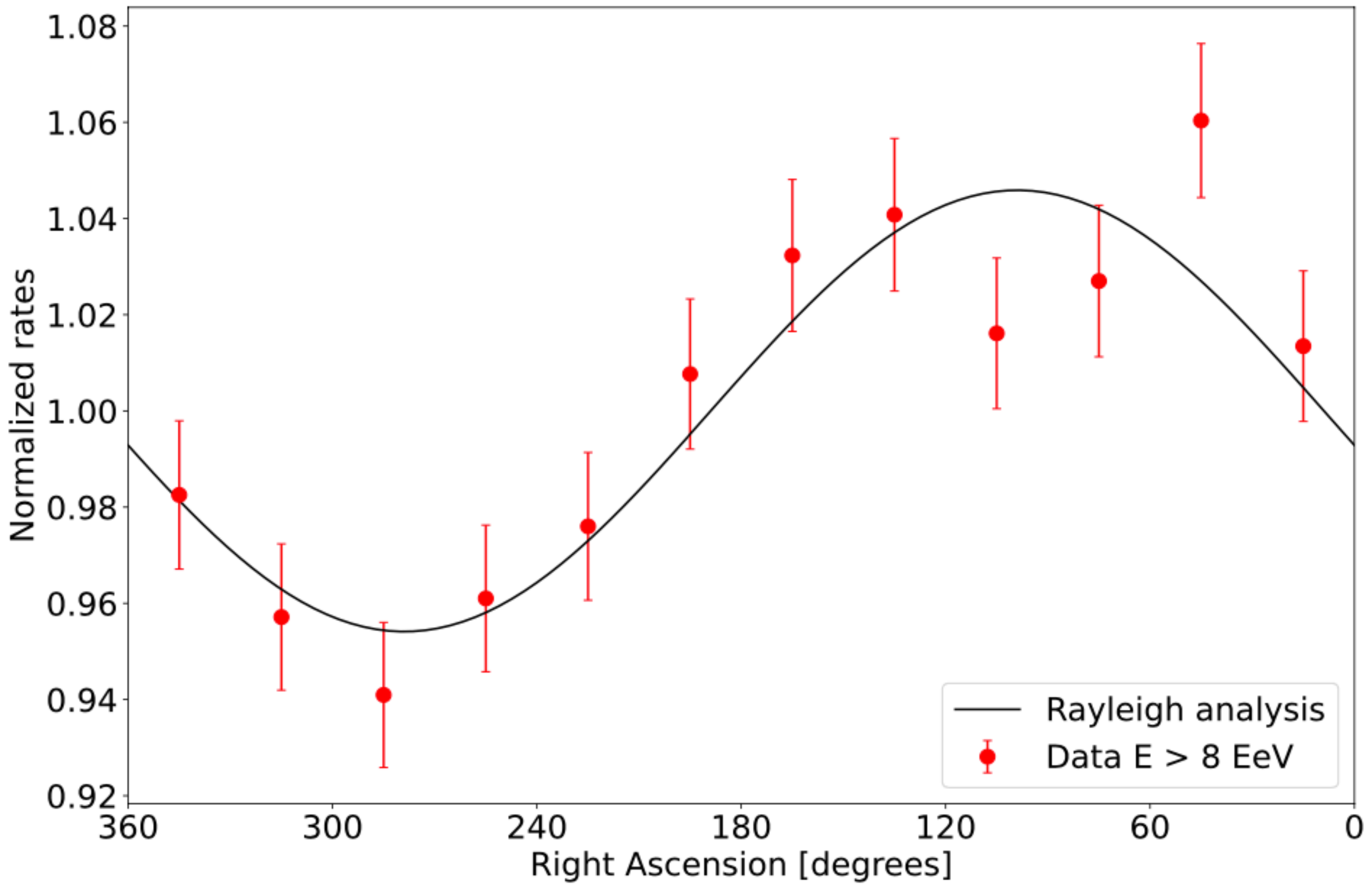
→ observables

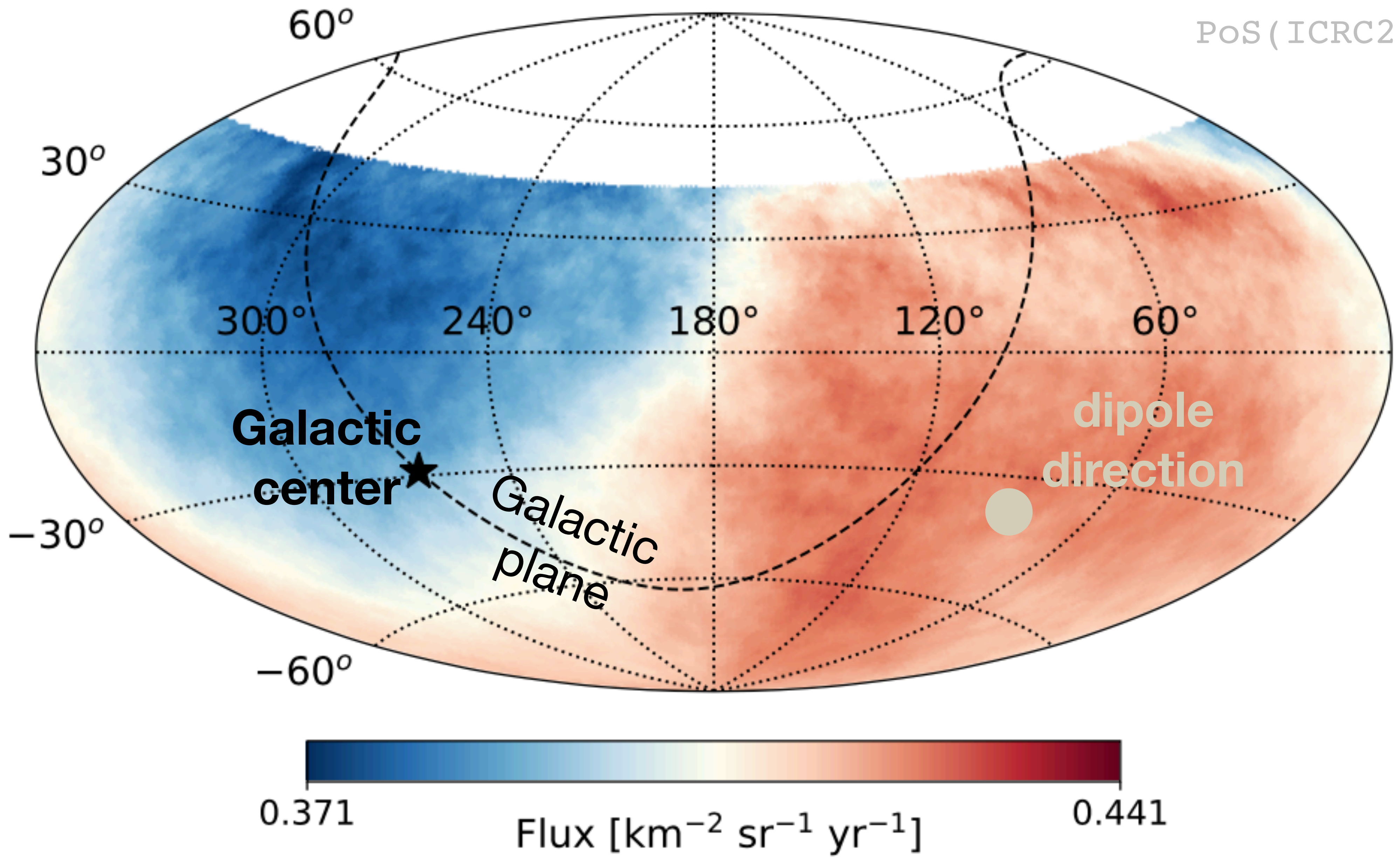
- depth of shower maximum (**mass**)
- **energy** of primary particle
- **arrival direction**

Large-scale anisotropy

→ **harmonic analysis** in right ascension & azimuth of measured UHECR flux **above 8 EeV** with data from 1/1/2004 to 31/12/2022 *(~50,000 events)*

PoS(ICRC2023)252





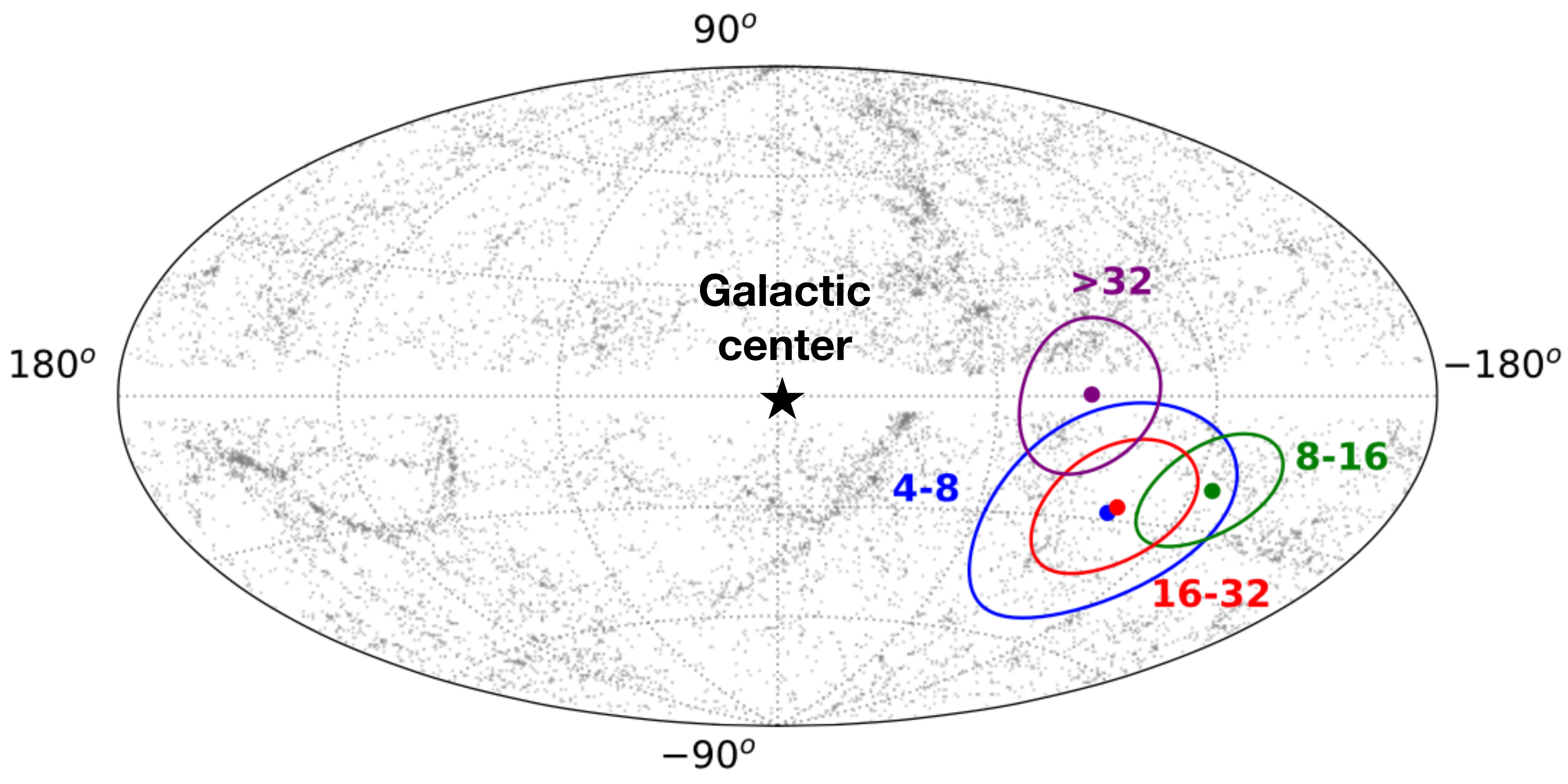
measured flux above 8 EeV
in equatorial coordinates smoothed with 45° tophat

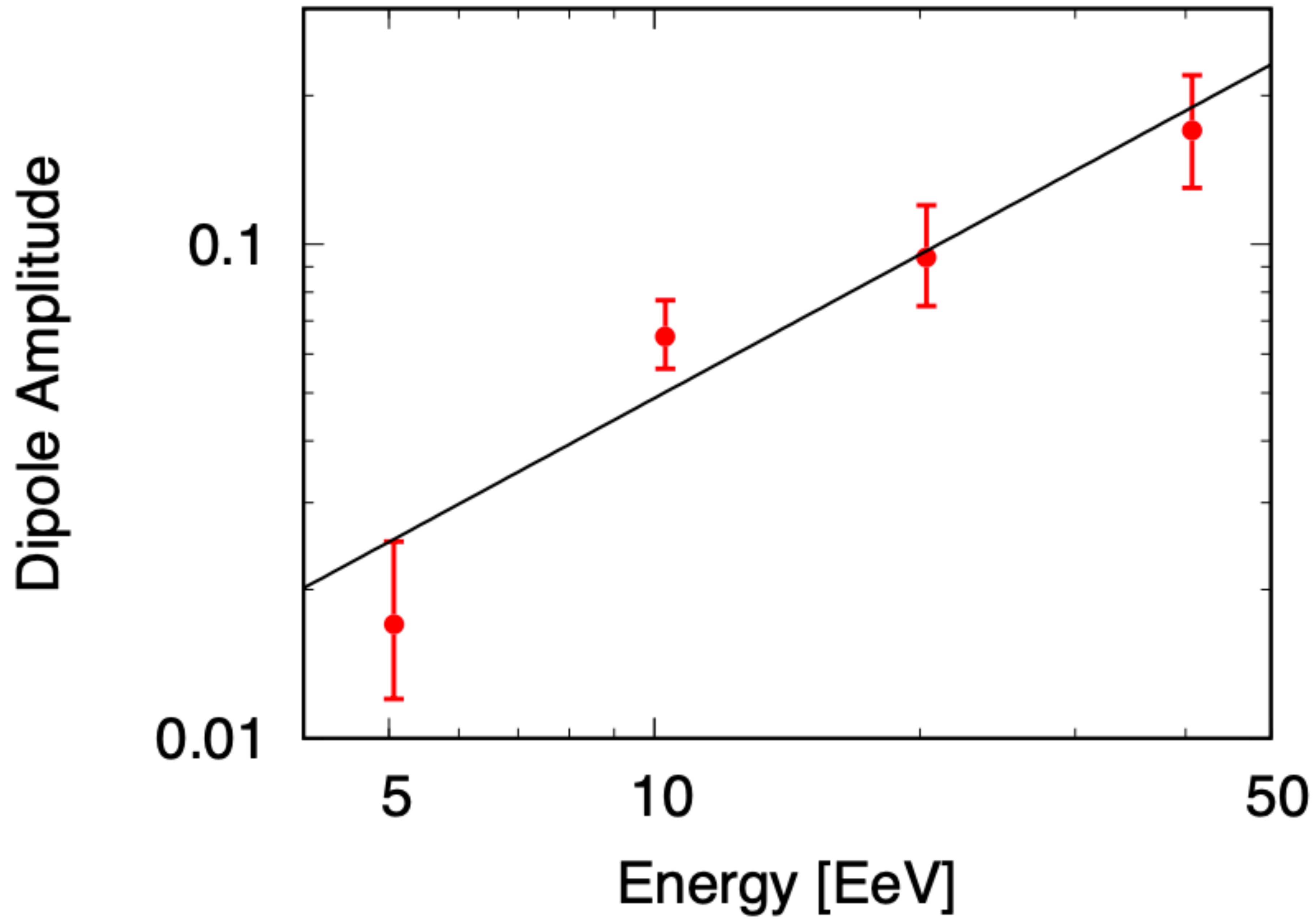
- dipolar modulation in right ascension: $6.9\,\sigma$ **significance**
- dipole **amplitude**: $7.3^{+1.0}_{-0.8}\,\%$
- dipole **direction**: $113°$ from the Galactic center
- no significant quadrupole components

→ ***suggests extragalactic origin of UHECRs at these energies***

Large-scale anisotropy: energy evolution

→ investigate **energy dependence of dipole direction & amplitude** above 4 EeV



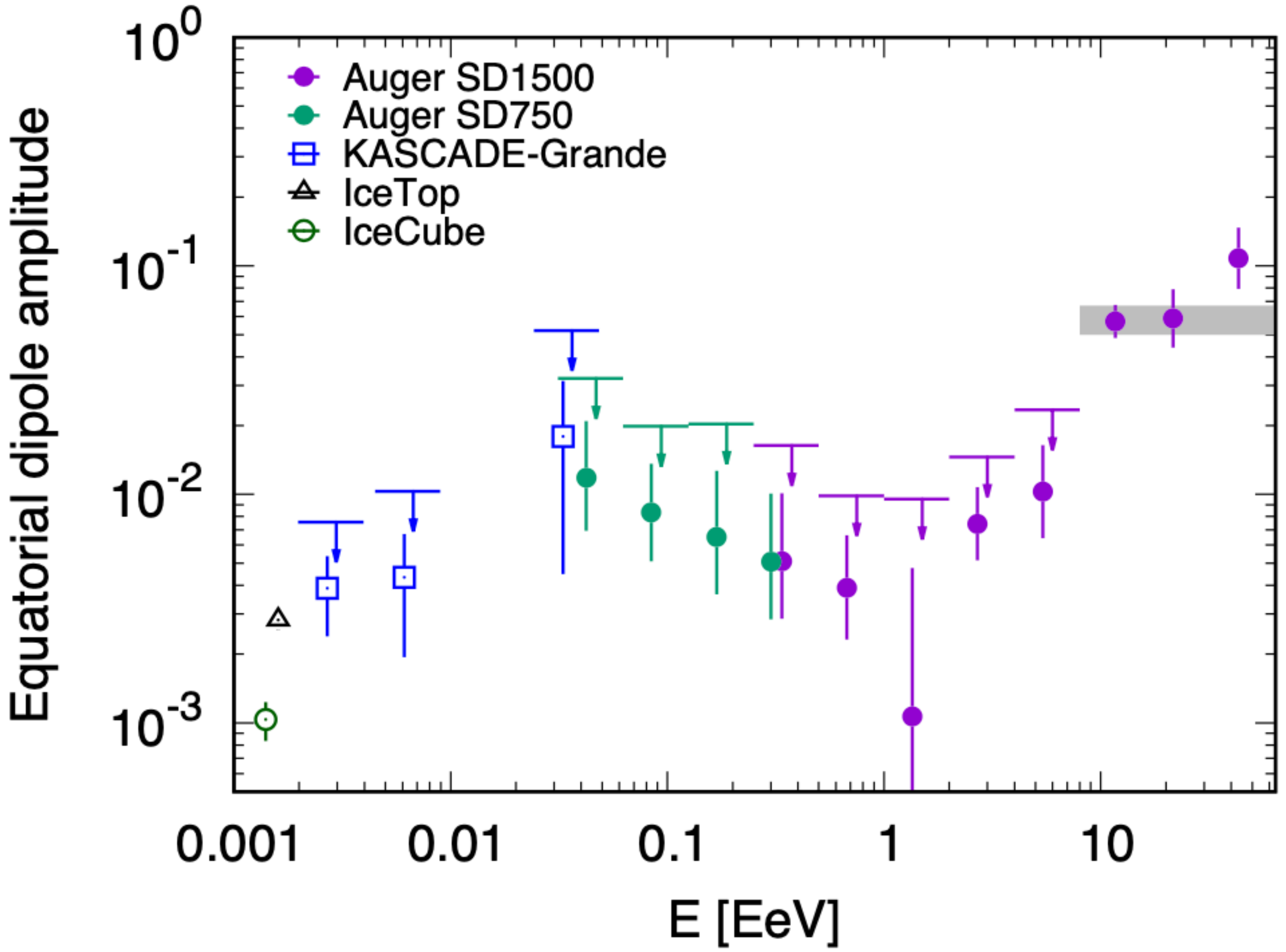


PoS(ICRC2023)252

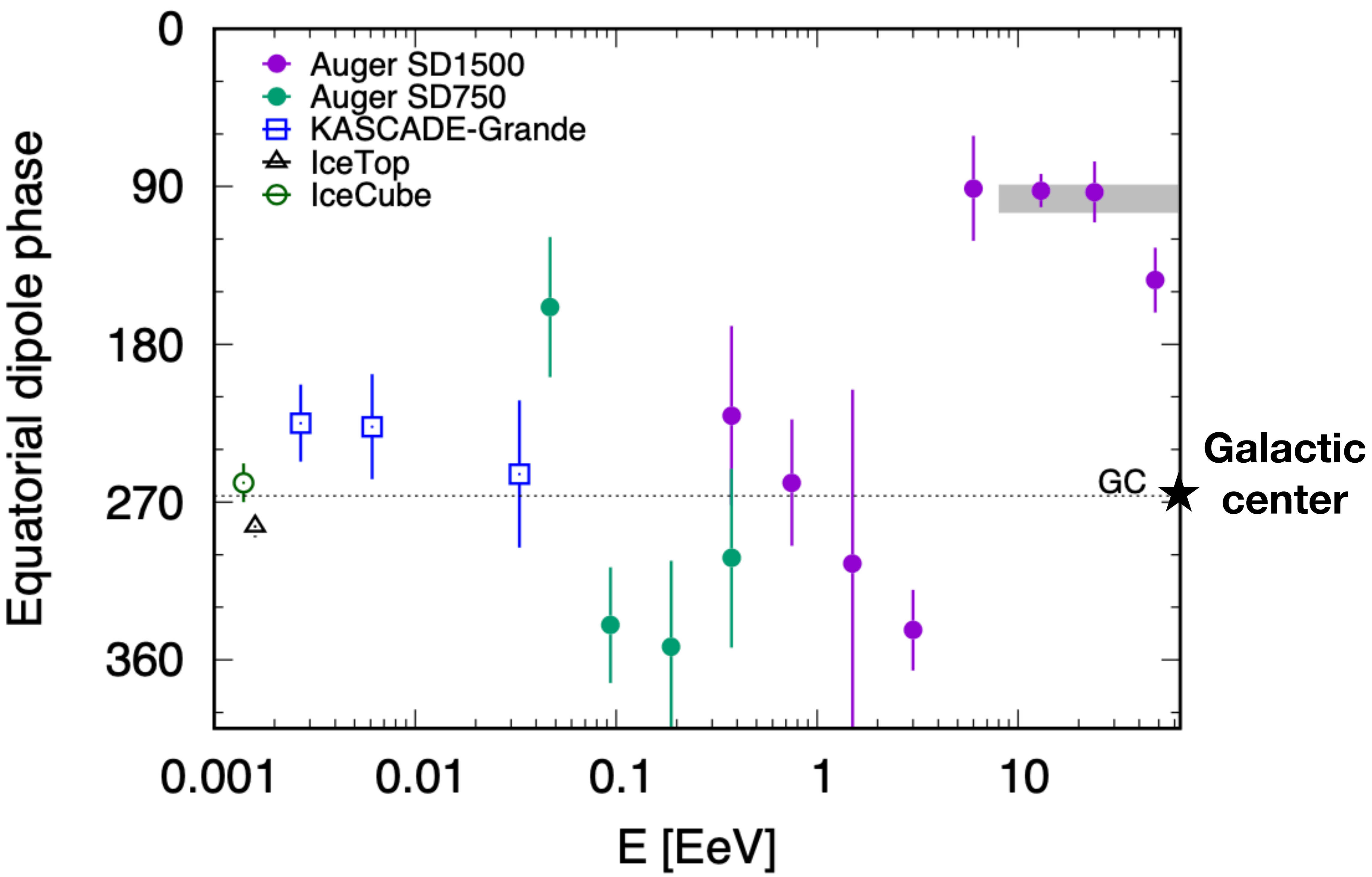
- **no** clear trend in **dipole direction**
- **rise** of **dipole amplitude** with energy
  - possible explanation: **larger relative contribution of nearby sources** with rising energy + particles with **higher rigidities** being **less deflected** by magnetic fields

Large-scale anisotropy: low-energy extension

→ energies down to 0.03 EeV



PoS(ICRC2023)252



PoS(ICRC2023)252

- **amplitude** increase from <1% to >10%
  (results for energies <8 EeV: P>1%)

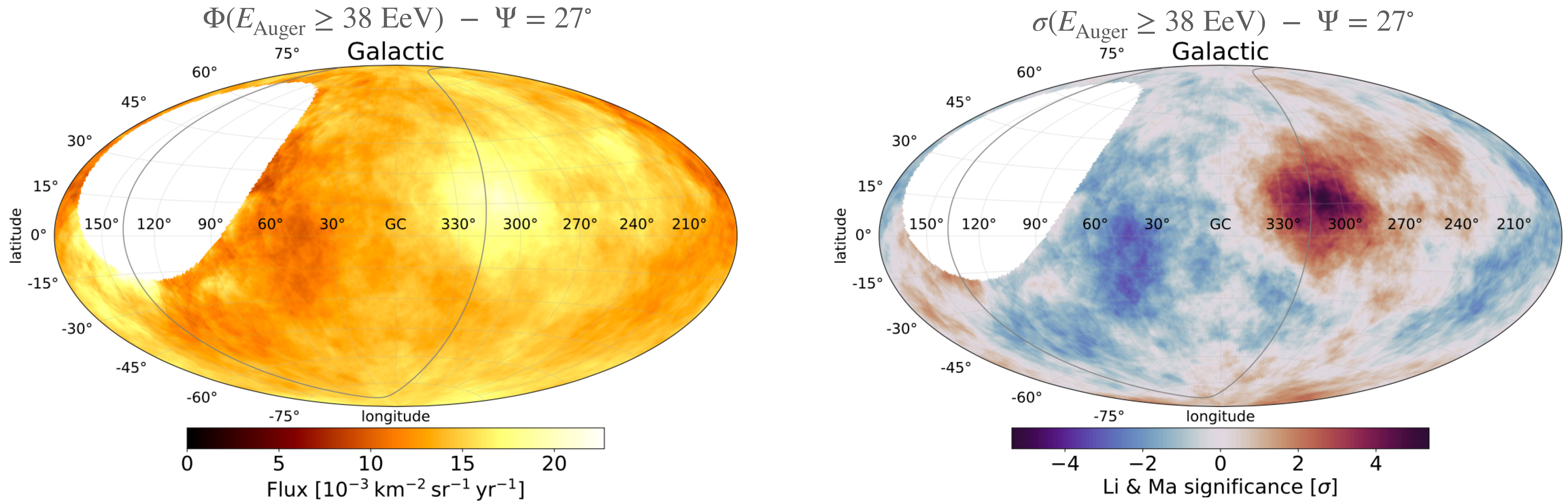
- **phase** shift from ~ Galactic center
  to opposite direction

→ *suggests **transition** from **Galactic to extragalactic origin** at few EeV*

Overdensity search

blind search with 2 free parameters:

- energy threshold: $32\ \mathrm{EeV} \leq E_{\mathrm{th}} \leq 80\ \mathrm{EeV}$ *(~2,700 events above* $32\ \mathrm{EeV}$*)*
- search radius: $1^\circ \leq \Psi \leq 30^\circ$



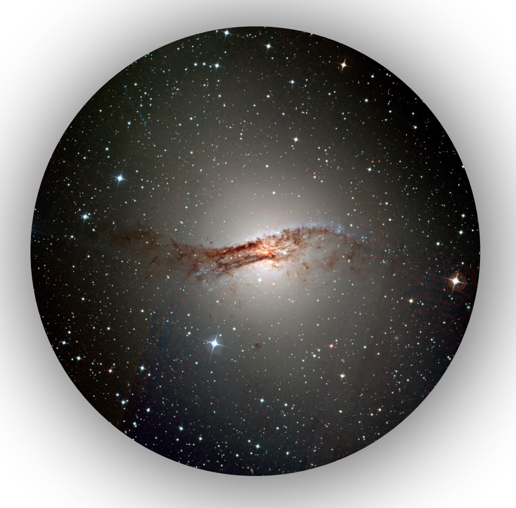
PoS(ICRC2023)252

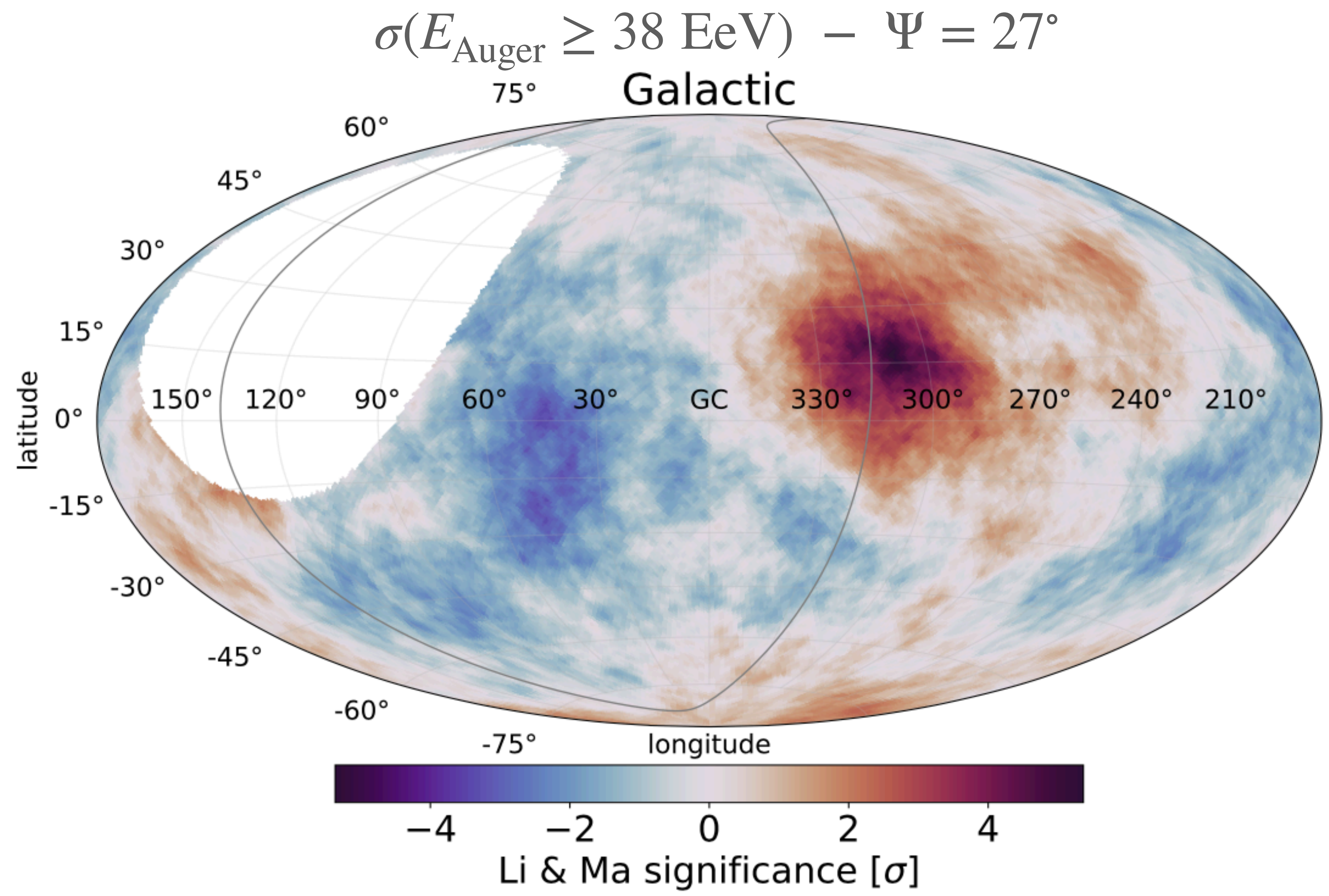
→ *most significant excess:* $E_{\mathrm{th}} = 38\ \mathrm{EeV}$, $\Psi = 27^\circ$ *with* 2.1σ *post-trial significance, 2° away from* ***Centaurus A***

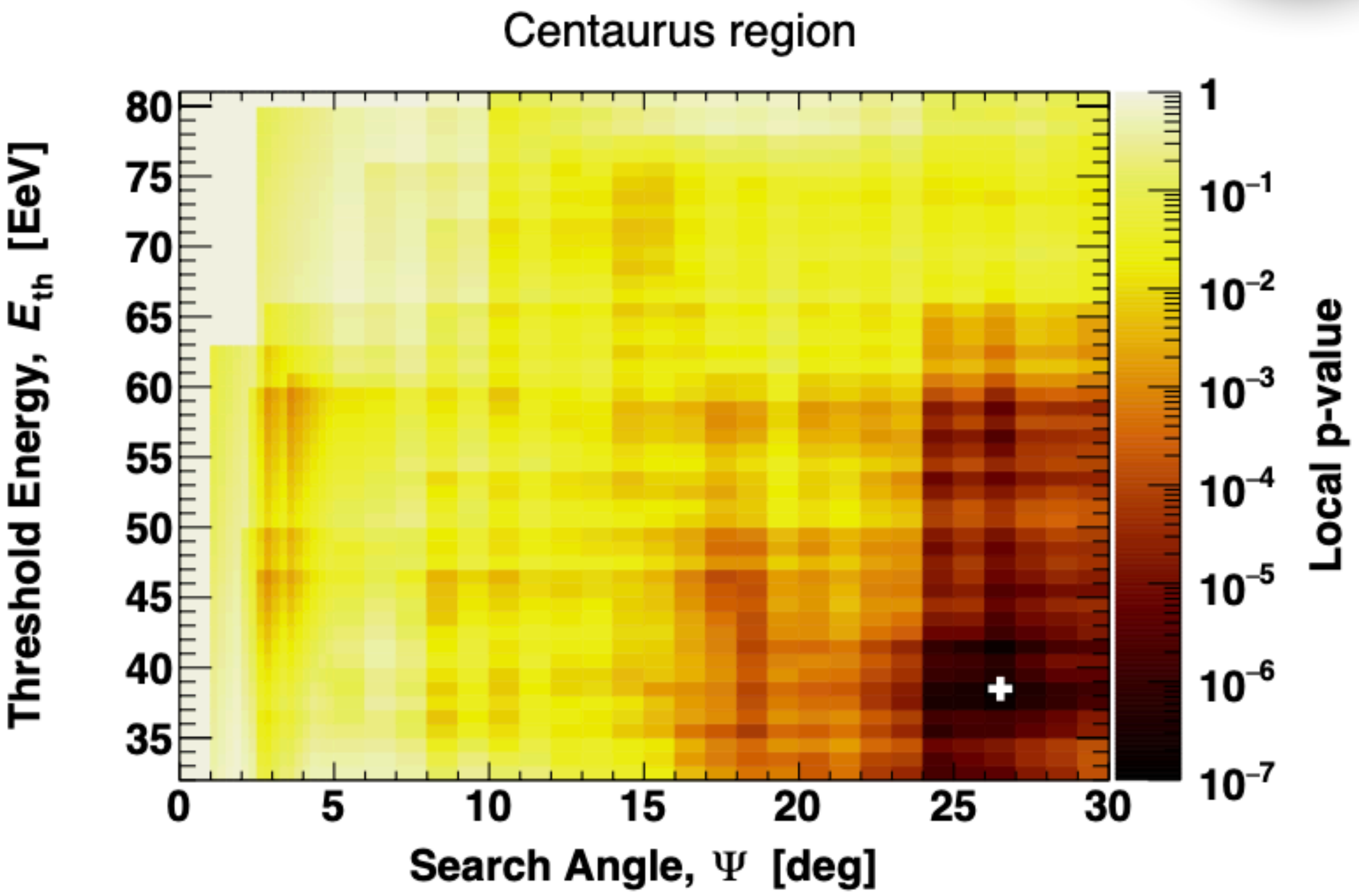
Overdensity search: Centaurus A

Centaurus region with 2 free parameters:

- energy threshold: $32\ \mathrm{EeV} \leq E_{\mathrm{th}} \leq 80\ \mathrm{EeV}$
- search radius: $1^{\circ} \leq \Psi \leq 30^{\circ}$







PoS(ICRC2023)252

→ ***Centaurus region****: also $E_{\mathrm{th}} = 38\ \mathrm{EeV}$, $\Psi = 27^{\circ}$, with 4σ post-trial significance*

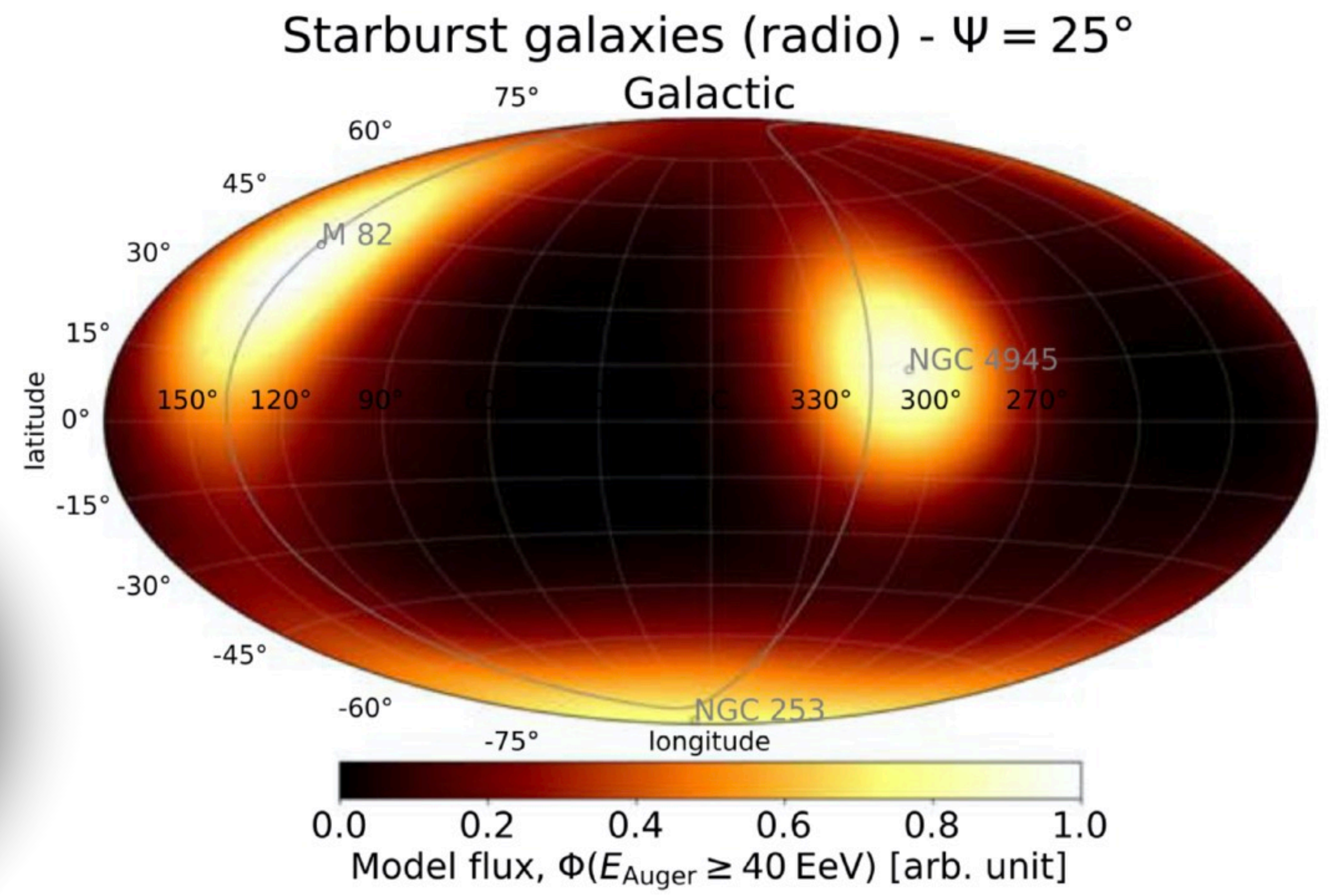
Catalog-based likelihood analyses

compare measured flux with isotropic **models** + **catalog contribution**

free model parameters:

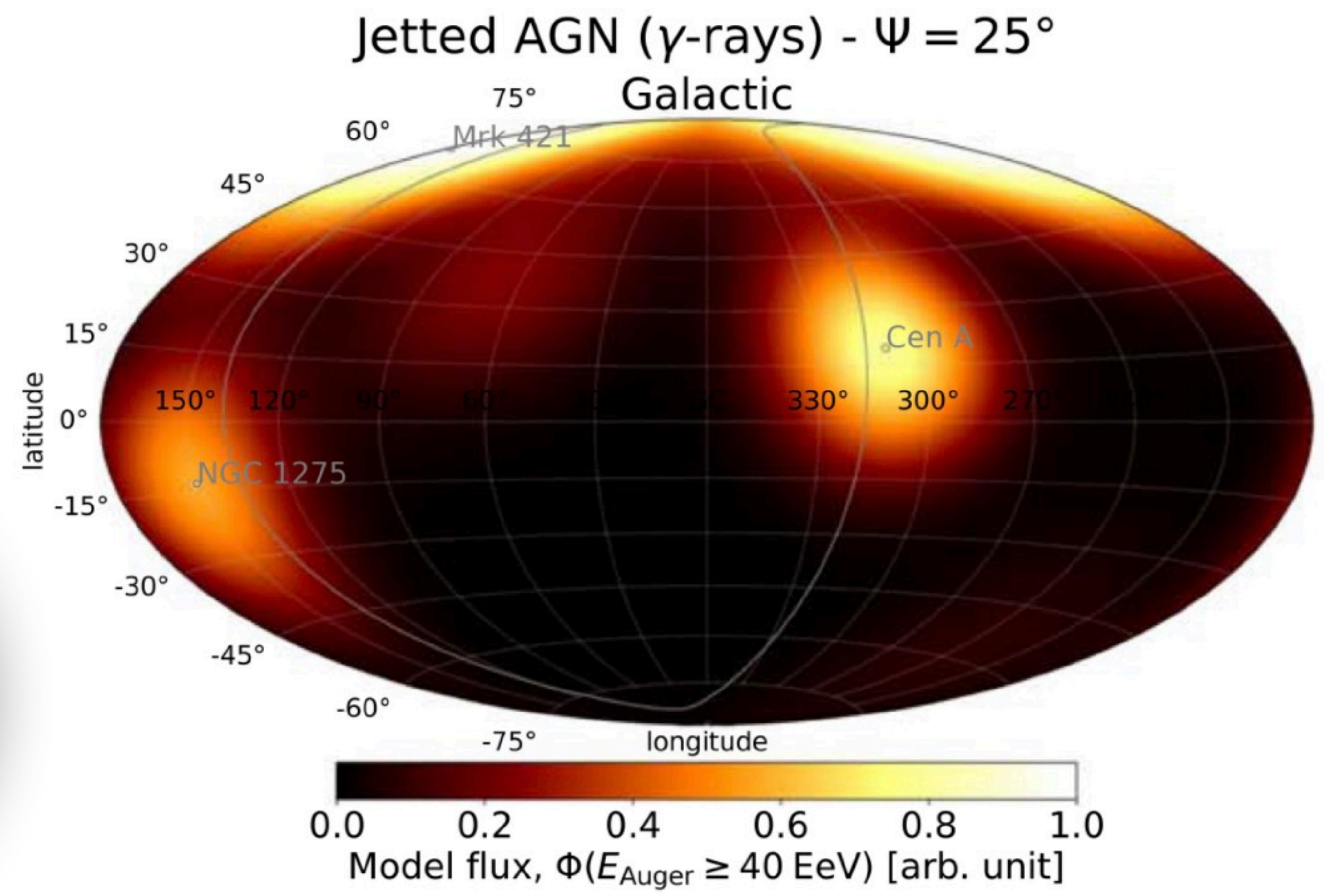
- signal fraction from catalog α
- search radius Θ *(magnetic field influence)*

with scan of energy threshold ($E_{\text{th}} \in [32\ \text{EeV}, 80\ \text{EeV}]$)



tested catalogs based on:

- near-infrared emission of galaxies (2MASS Redshift Survey): **„all galaxies“**
- radio emission from starburst galaxies (SBGs): **„starbursts“**
- X-rays from AGNs (Swift-BAT): **„all AGNs“**
- γ-rays from jetted AGNs: **„jetted AGNs“**



P. Abreu et al 2022 ApJ 935 170

Catalog-based likelihood analyses

compare measured flux with isotropic **models** + **catalog contribution**

free model parameters:

- signal fraction from catalog α
- search radius Θ *(magnetic field influence)*

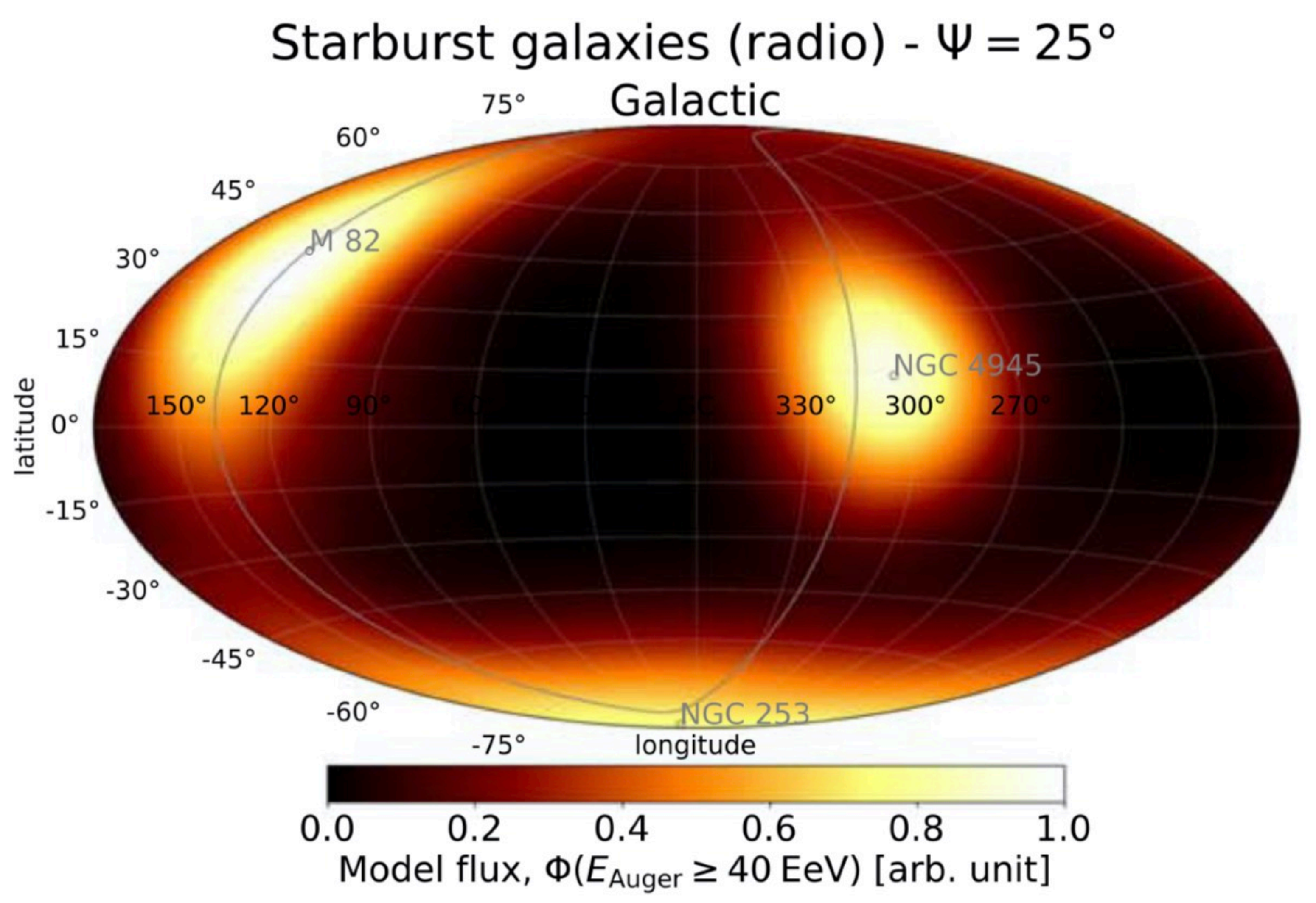
results:

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

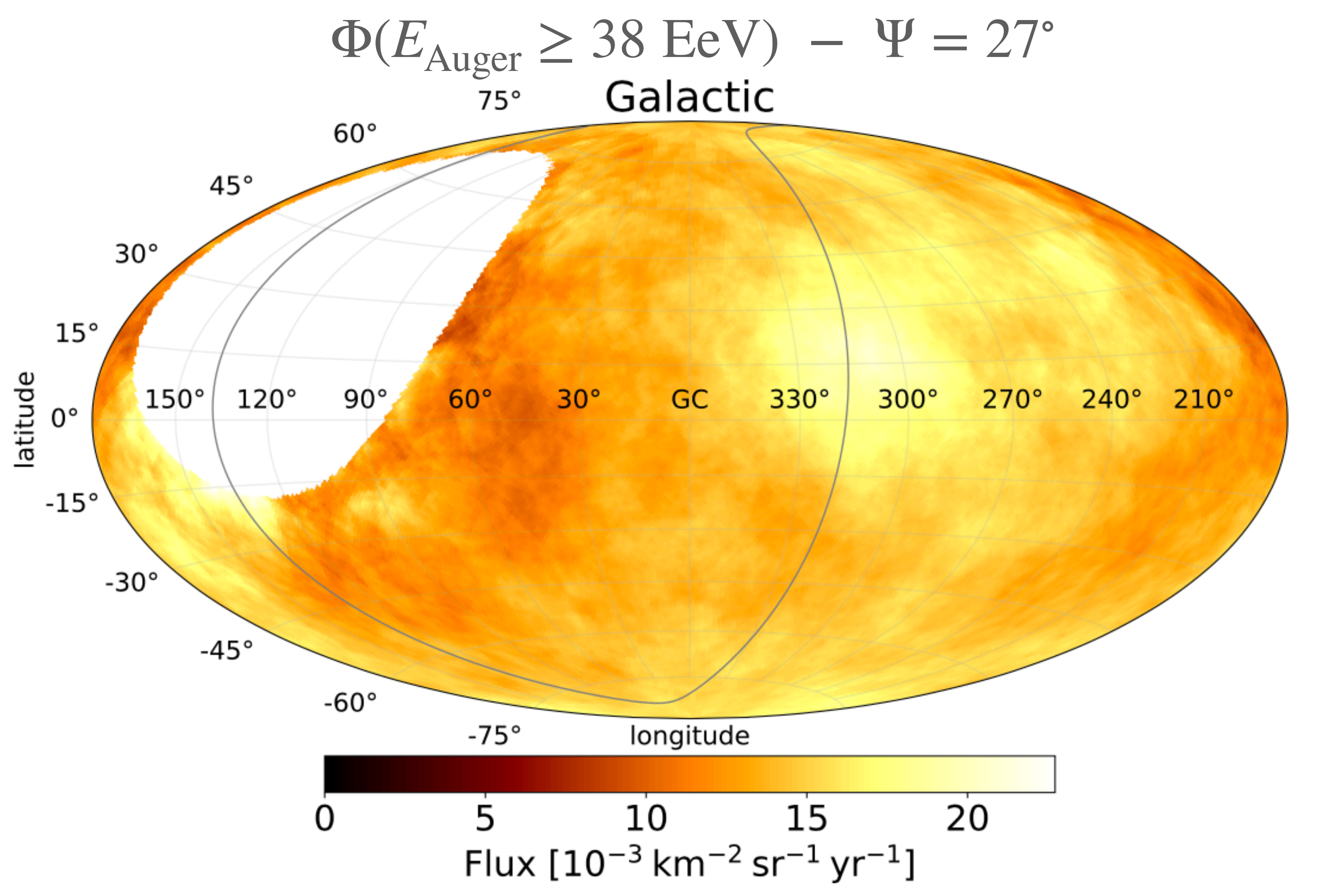
PoS(ICRC2023)252

→ similar angular scale & energy threshold for all tested catalogs

→ overdensity of Centaurus region captured by all models, SBG model adds subtle overdensity at Galactic South Pole

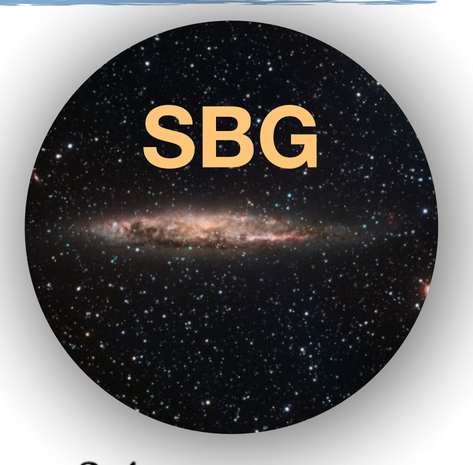


P. Abreu et al 2022 ApJ 935 170



PoS(ICRC2023)252

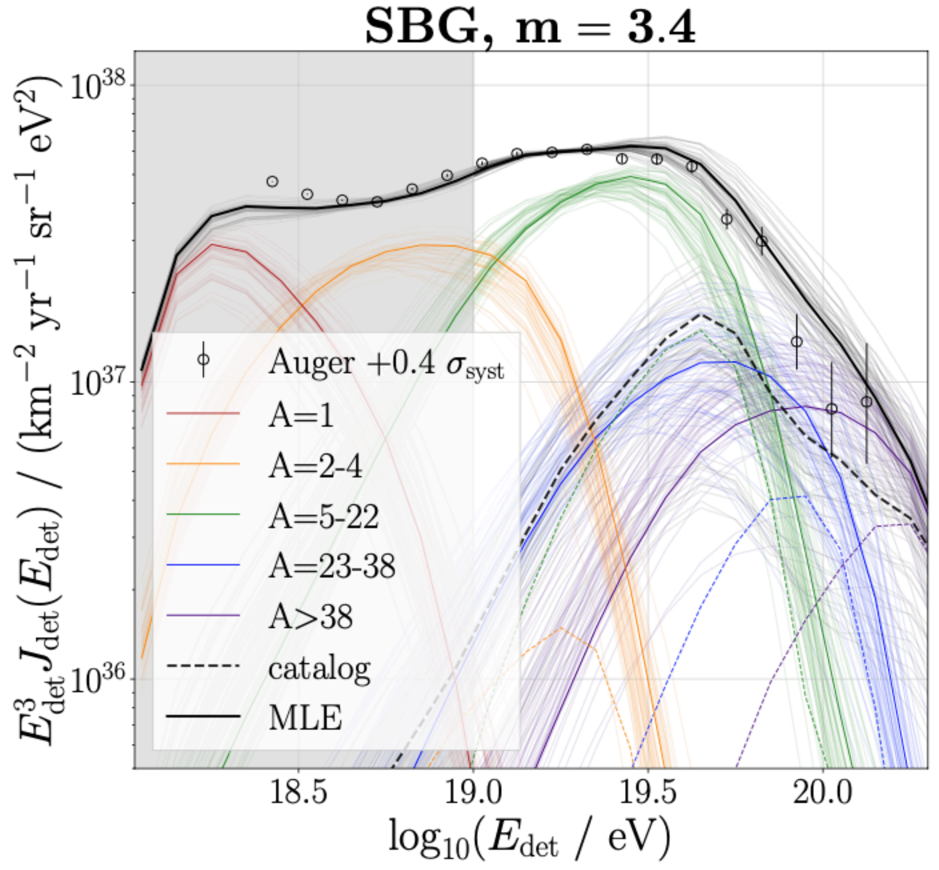
Combination of anisotropy with spectrum & composition

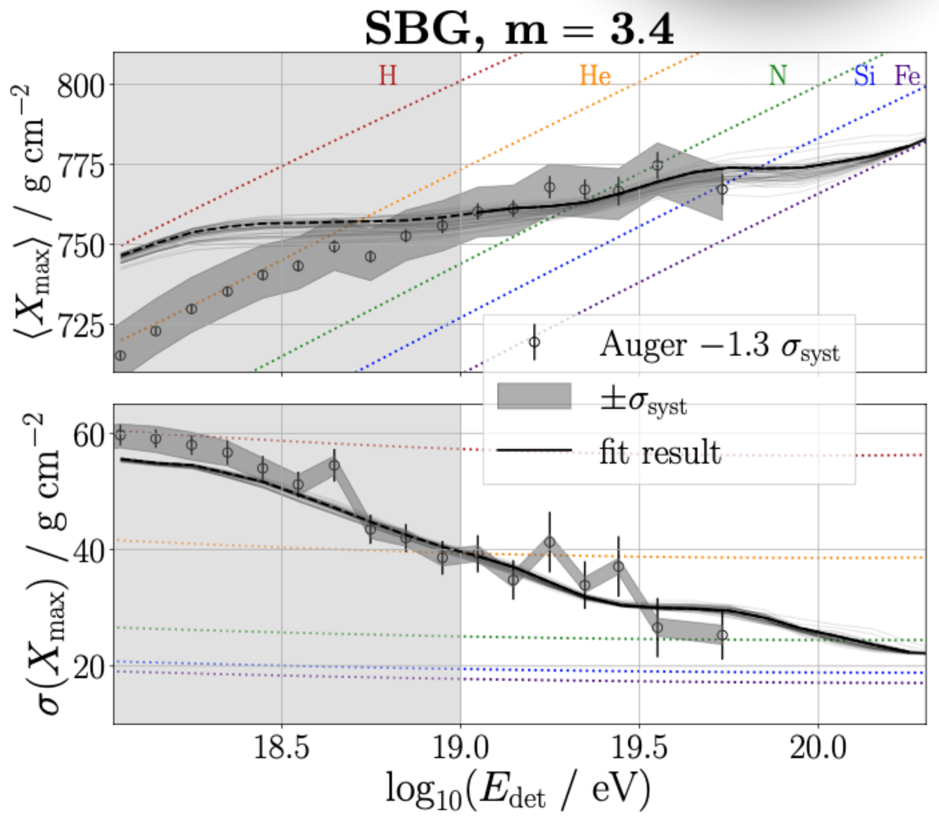


use **energy spectrum** & **composition** measurements as additional information

improved astrophysical model:

- energy-dependent catalog contribution
- modeling of propagation effects
- rigidity-dependent magnetic field blurring

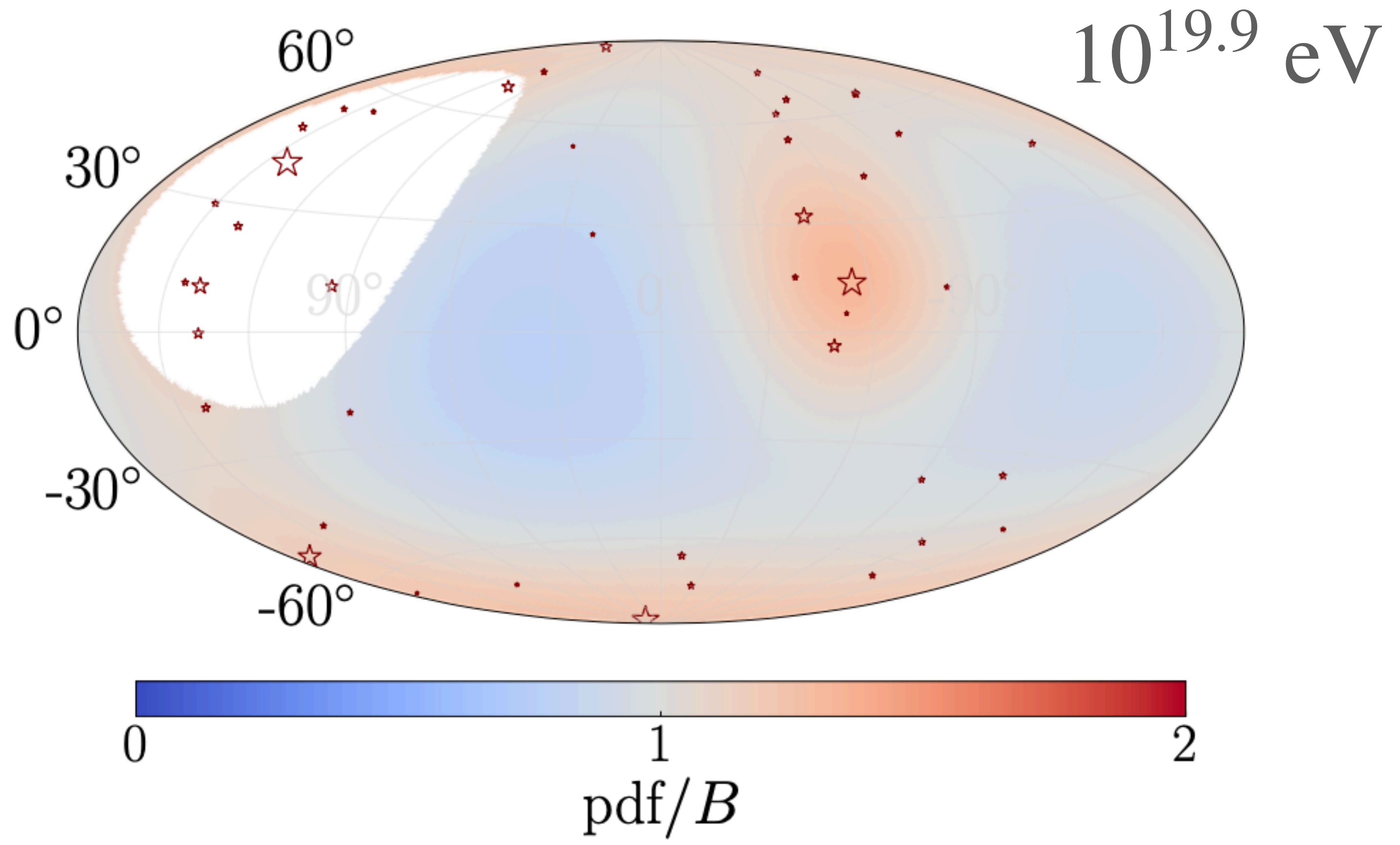




results:

- γ-AGN catalog:
  - more strongly disfavored than with AD-only analysis
  - **CR flux proportional to γ-ray flux disfavored**
- **SBG model**: favored with 4.5σ over homogeneous model
  - main contribution to significance: Centaurus region

ADs in best-fit SBG model

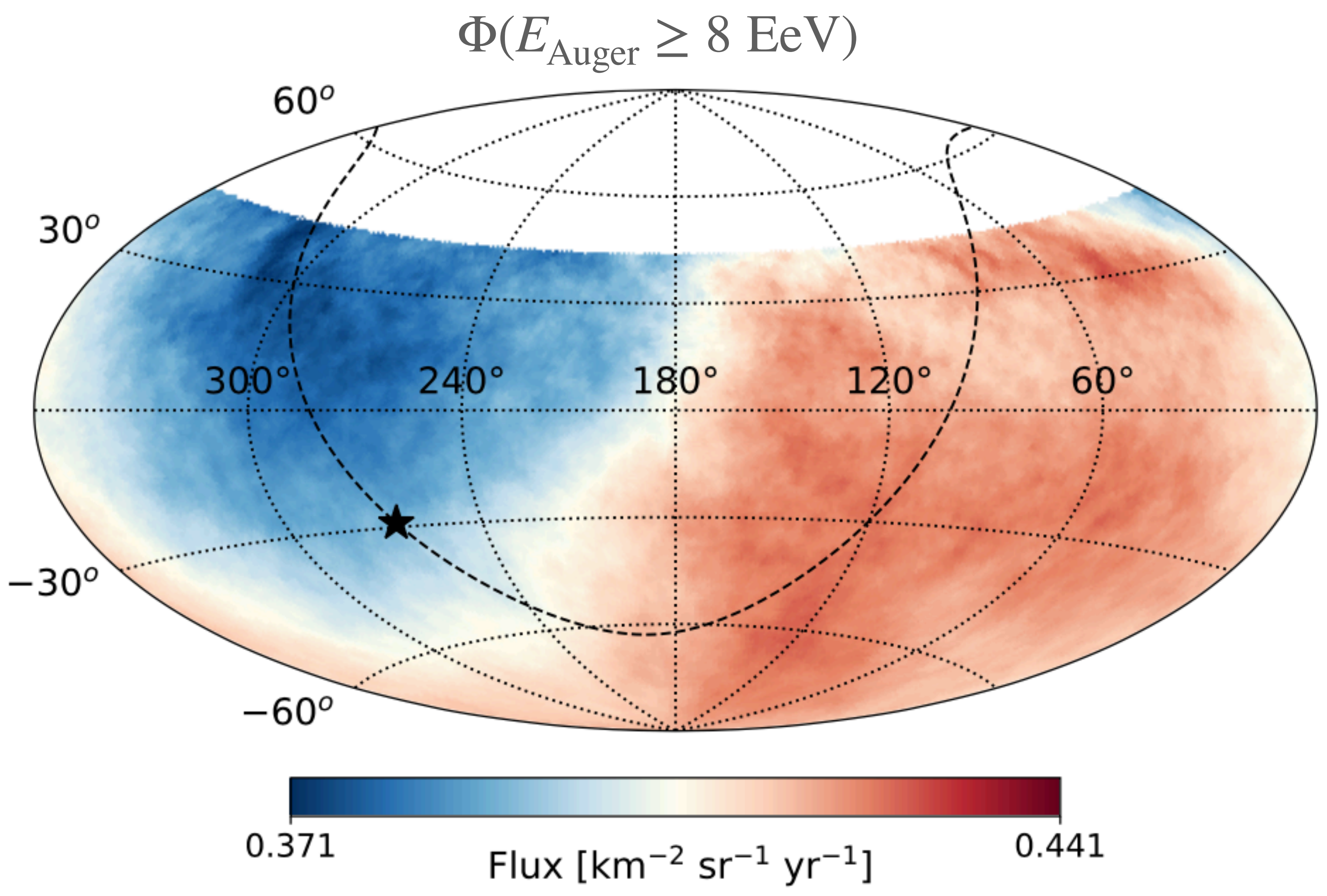


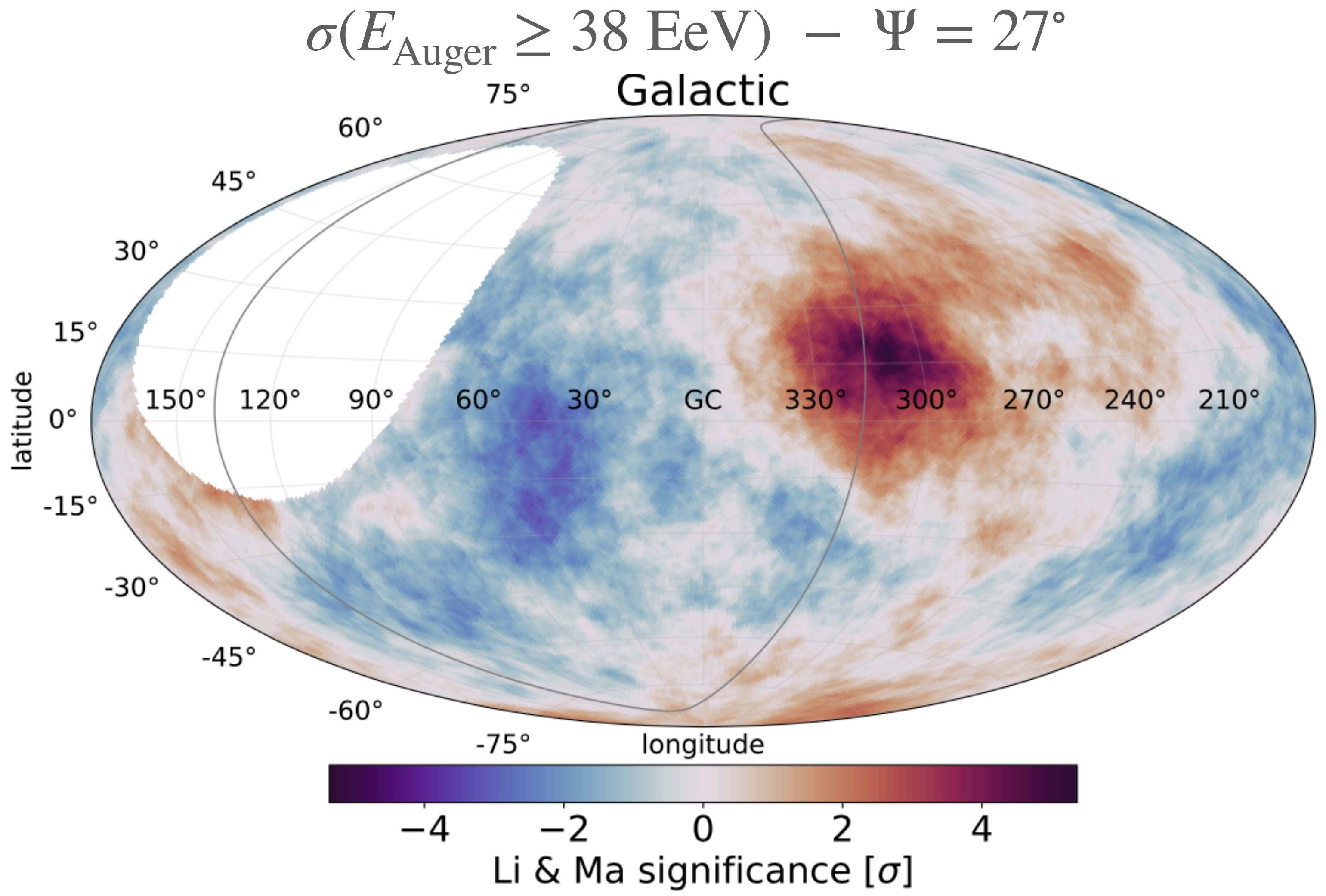
→ ***good description of all 3 observables with one model***

PoS(ICRC2023)258

Conclusions & Outlook

- 6.9σ **large-scale dipole anisotropy** above $8\ \mathrm{EeV}$ pointing away from the Galactic center indicating **extragalactic origin** of UHECRs
  - amplitude rising with energy
- 4σ **overdensity in Centaurus region** above $38\ \mathrm{EeV}$
- 3.8σ **correlation with starburst galaxy catalog** above $38\ \mathrm{EeV}$
  - 4.5σ including energy spectrum & composition





PoS(ICRC2023)252

future perspectives:

- event-by-event mass estimates using deep-learning techniques & AugerPrime upgrade
- improved Galactic magnetic field models will be released soon
- exciting prospects for unveiling the sources of UHECRs!

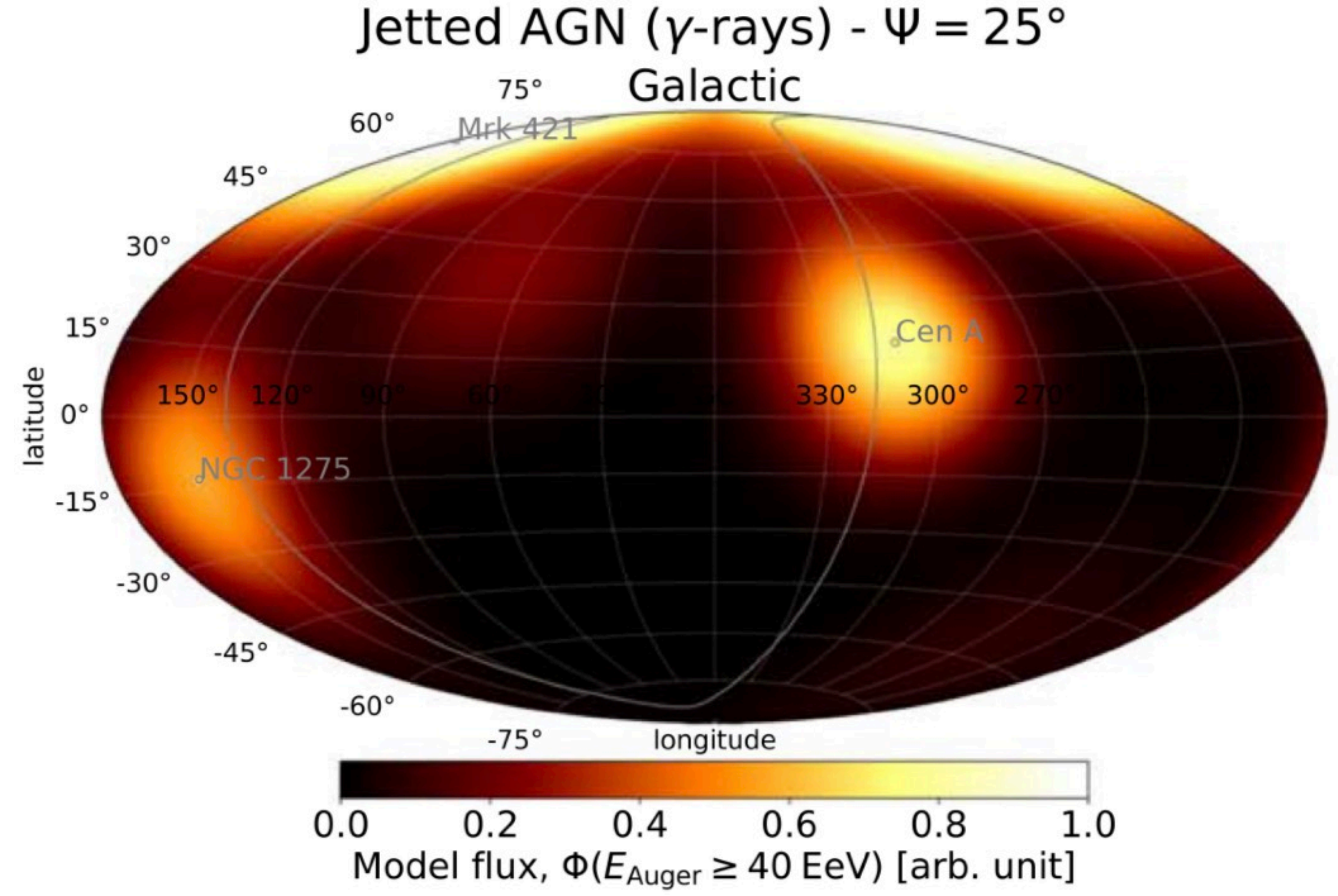
Backup

Catalogs for likelihood analyses: jetted AGNs

Jetted AGNs (Fermi-LAT 3FHL)

3FHL Name	Counterpart	Jetted AGN Type	R.A. °	Decl. °	$(m - M)$ mag	$\sigma(m - M)$ mag	d_L Mpc	$\sigma(d_L)/d_L$	$\Phi(0.01 - 1$ TeV) 10^{-10} cm^{-2} s^{-1}	$\sigma(\Phi)$ 10^{-10} cm^{-2} s^{-1}	flag: in Pierre Auger Collaboration (2018b)? (No/Yes)
J1325.5-4300	CenA	RDG	201.37	−43.02	27.83	0.03	3.68	0.014	1.54	0.25	Y
J1230.8+1223	M87	RDG	187.71	12.39	31.12	0.06	16.7	0.028	0.98	0.20	Y
J0322.6-3712e	FornaxA	RDG	50.67	−37.21	31.55	0.03	20.4	0.014	0.48	0.16	N
J1346.2-6026	CenB	RDG	206.70	−60.41	33.71	0.29	55.2	0.134	0.64	0.18	N
J0319.8+4130	NGC1275	RDG	49.95	41.51	34.46	0.08	78.0	0.037	14.17	0.67	Y
J0316.6+4120	IC310	RDG	49.18	41.32	34.60	0.19	83.2	0.087	0.43	0.13	Y
J0153.5+7115	TXS0149+710	BCU	28.36	71.25	35.07	0.15	103.3	0.069	0.44	0.12	Y
J0308.4+0408	NGC1218	RDG	47.11	4.11	35.48	0.13	124.7	0.060	0.54	0.16	N
J1104.4+3812	Mkn421	BLL	166.10	38.21	35.63	0.12	133.7	0.055	59.35	1.38	Y
J1653.8+3945	Mkn501	BLL	253.47	39.76	35.91	0.10	152.1	0.046	19.17	0.76	Y
J0131.1+5546	TXS0128+554	BCU	22.81	55.75	36.06	0.10	162.9	0.046	0.33	0.12	N
J1543.6+0452	CGCG050-083	BCU	235.89	4.87	36.26	0.09	178.6	0.041	0.69	0.17	N
J0223.0-1119	1RXSJ022314.6-111741	BLL	35.81	−11.29	36.31	0.09	182.8	0.041	0.40	0.13	N
J2347.0+5142	1ES2344+514	BLL	356.76	51.69	36.47	0.08	196.8	0.037	3.32	0.31	Y
J0816.4-1311	PMNJ0816-1311	BLL	124.11	−13.20	36.51	0.08	200.4	0.037	2.71	0.33	N
J1136.5+7009	Mkn180	BLL	174.11	70.16	36.54	0.08	203.2	0.037	1.74	0.21	Y
J1959.9+6508	1ES1959+650	BLL	299.97	65.16	36.63	0.08	211.8	0.037	8.43	0.46	Y
J1647.6+4950	SBS1646+499	BLL	251.90	49.83	36.64	0.08	212.8	0.037	0.48	0.12	N
J1517.6-2422	APLibrae	BLL	229.42	−24.37	36.68	0.07	216.8	0.032	3.76	0.37	Y
J0214.5+5145	TXS0210+515	BLL	33.55	51.77	36.70	0.11	218.8	0.051	0.42	0.12	Y
J1806.8+6950	3C371	BLL	271.71	69.82	36.77	0.07	225.9	0.032	1.30	0.18	N
J1353.0-4413	PKS1349-439	BLL	208.24	−44.21	36.79	0.07	228.0	0.032	0.33	0.12	N
J0200.1-4109	1RXSJ020021.0-410936	BLL	30.09	−41.16	36.85	0.07	234.4	0.032	0.51	0.14	N
J0627.1-3528	PKS0625-35	BLL	96.78	−35.49	36.89	0.07	238.8	0.032	1.81	0.26	Y
J2039.4+5219	1ES2037+521	BLL	309.85	52.33	36.89	0.07	238.8	0.032	0.58	0.15	N
J0523.0-3627	PKS0521-36	BLL	80.76	−36.46	36.91	0.07	241.0	0.032	1.17	0.21	N

Note. 26 entries within 250 Mpc, 6 entries at $d_L < 100$ Mpc, and 14 at $d_L < 200$ Mpc. The full data set is available in the same format at https://doi.org/10.5281/zenodo.6504276 and in machine-readable format in the online article.



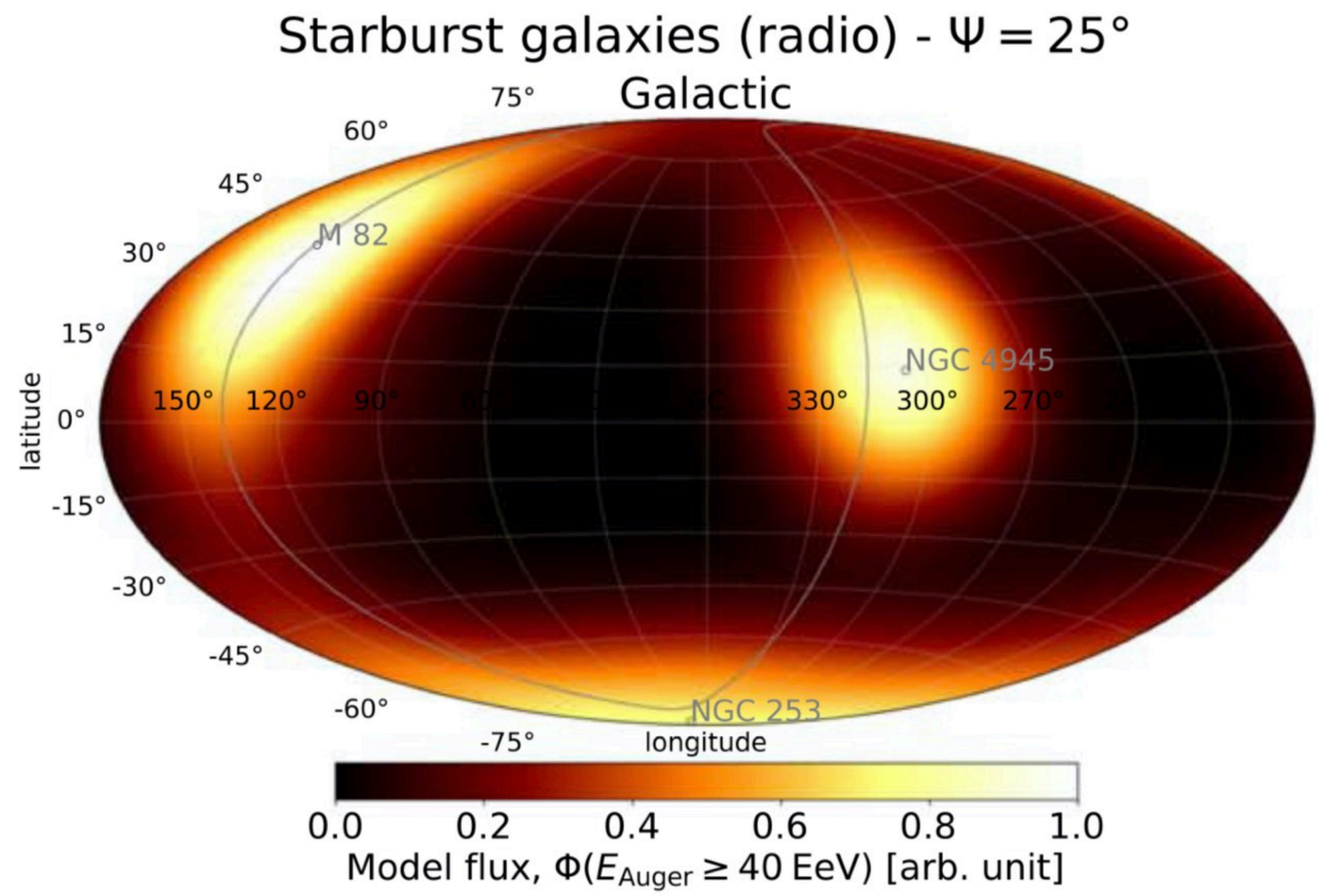
P. Abreu et al 2022 ApJ 935 170

Catalogs for likelihood analyses: SBGs

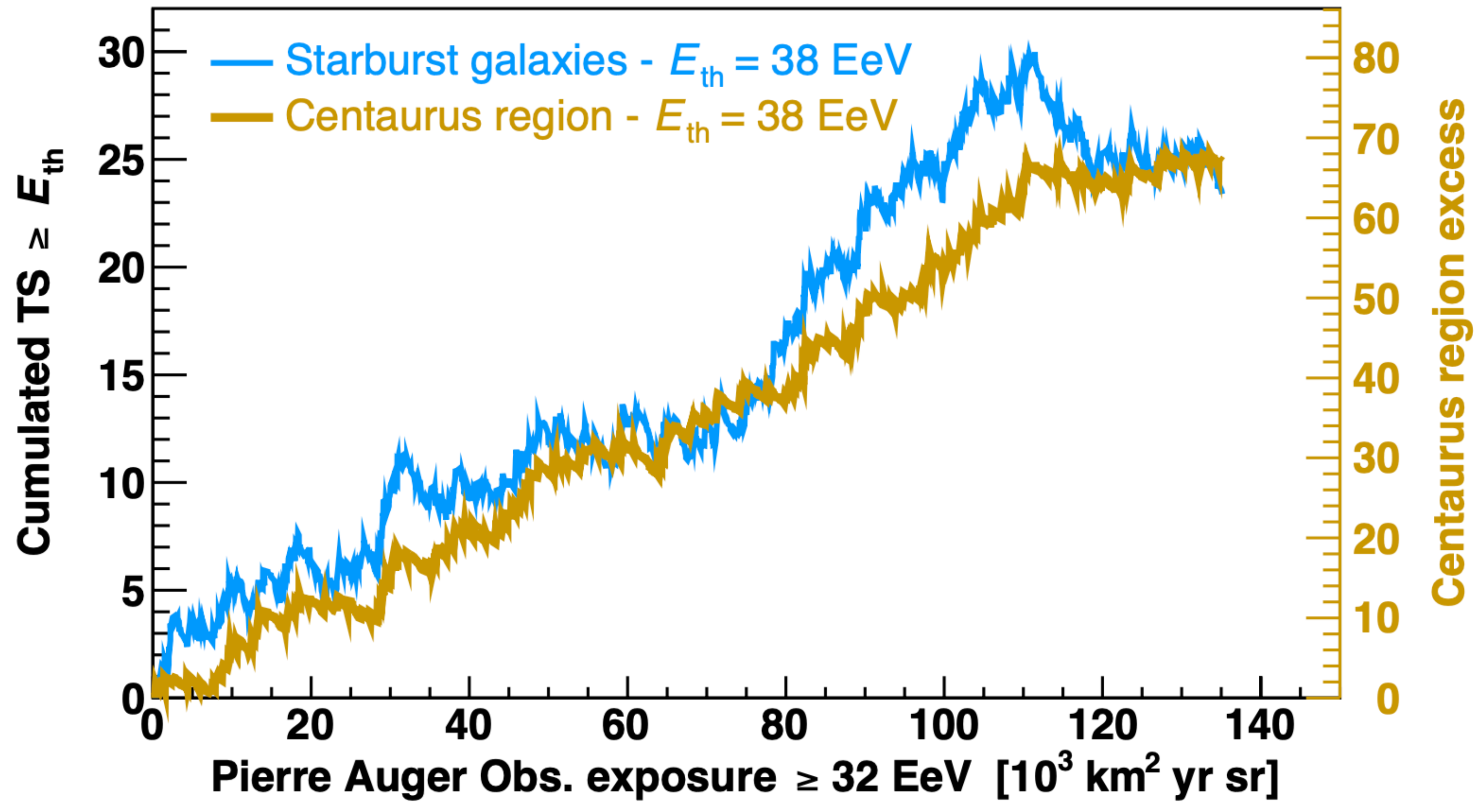
Starburst Galaxies (Lunardini+ '19)

Lunardi Name	Counterpart	Host Type	R.A. °	Decl. °	$(m-M)$ mag	$\sigma(m-M)$ mag	d_L Mpc	$\sigma(d_L)/d_L$	Φ(1.4 GHz) Jy	$\sigma(\Phi)$ Jy	flag: in Pierre Auger Collaboration (2018b)? (No/Yes/Xcheck)
NGC0055	NGC0055	SBm	3.72	−39.20	26.62	0.01	2.11	0.005	0.37	N/A	N
NGC1569	NGC1569	IB	67.70	64.85	27.53	0.05	3.21	0.023	0.40	N/A	X
NGC2403	NGC2403	SABc	114.21	65.60	27.53	0.01	3.21	0.005	0.39	N/A	X
IC342	IC342	SABc	56.70	68.10	27.68	0.03	3.44	0.014	2.25	N/A	Y
NGC4945	NGC4945	Sbc	196.37	−49.47	27.70	0.02	3.47	0.009	6.60	N/A	Y
NGC3034 (M82)	M82	S?	148.97	69.68	27.79	0.01	3.61	0.005	7.29	N/A	Y
NGC0253	NGC253	SABc	11.89	−25.29	27.84	0.02	3.70	0.009	6.00	N/A	Y
N/A	Circinus	Sb	213.29	−65.34	28.12	0.36	4.21	0.166	1.50	N/A	Y
NGC5236 (M83)	M83	Sc	204.25	−29.87	28.45	0.02	4.90	0.009	2.44	N/A	Y
Maffei2	Maffei2	Sbc	40.48	59.60	28.79	0.12	5.73	0.055	1.01	N/A	X
NGC6946	NGC6946	SABc	308.72	60.15	29.14	0.05	6.73	0.023	1.40	N/A	Y
NGC4631	NGC4631	SBcd	190.53	32.54	29.33	0.02	7.35	0.009	1.12	N/A	Y
NGC5194 (M51)	M51	SABb	202.48	47.20	29.67	0.02	8.59	0.009	1.31	N/A	Y
NGC5055 (M63)	NGC5055	Sbc	198.96	42.03	29.78	0.01	9.04	0.005	0.35	N/A	Y
NGC2903	NGC2903	Sbc	143.04	21.50	29.85	0.11	9.33	0.051	0.44	N/A	Y
NGC891	NGC891	Sb	35.64	42.35	29.94	1.72	9.73	0.792	0.70	N/A	Y
NGC1068	NGC1068	Sb	40.66	0.00	30.12	0.34	10.6	0.157	4.85	N/A	Y
NGC3628	NGC3628	SBb	170.07	13.59	30.21	0.34	11.0	0.157	0.47	N/A	Y
NGC4818	NGC4818	SABa	194.20	−8.53	30.27	0.33	11.3	0.152	0.45	N/A	N
NGC3627	NGC3627	Sb	170.06	12.99	30.30	0.04	11.5	0.018	0.46	N/A	Y
NGC1808	NGC1808	Sa	76.93	−37.51	30.45	0.36	12.3	0.166	0.50	N/A	X
NGC4303	M61	Sbc	185.48	4.47	30.45	0.10	12.3	0.046	0.44	N/A	X
NGC3521	NGC3521	SABb	166.45	−0.04	30.47	0.29	12.4	0.134	0.35	N/A	N
NGC0660	NGC660	Sa	25.76	13.65	30.50	1.31	12.6	0.603	0.37	N/A	Y
NGC4254	NGC4254	Sc	184.71	14.42	30.77	1.13	14.3	0.520	0.37	N/A	N
…	…	…	…	…	…	…	…	…	…	…	…
NGC6240	NGC6240	S0-a	253.26	2.40	35.18	0.15	108.6	0.069	0.65	N/A	Y

Note. 44 entries within 250 Mpc, 43 entries at $d_L < 100$ Mpc, and 44 at $d_L < 200$ Mpc. The full data set is available in the same format at https://doi.org/10.5281/zenodo.6504276 and in machine-readable format in the online article.



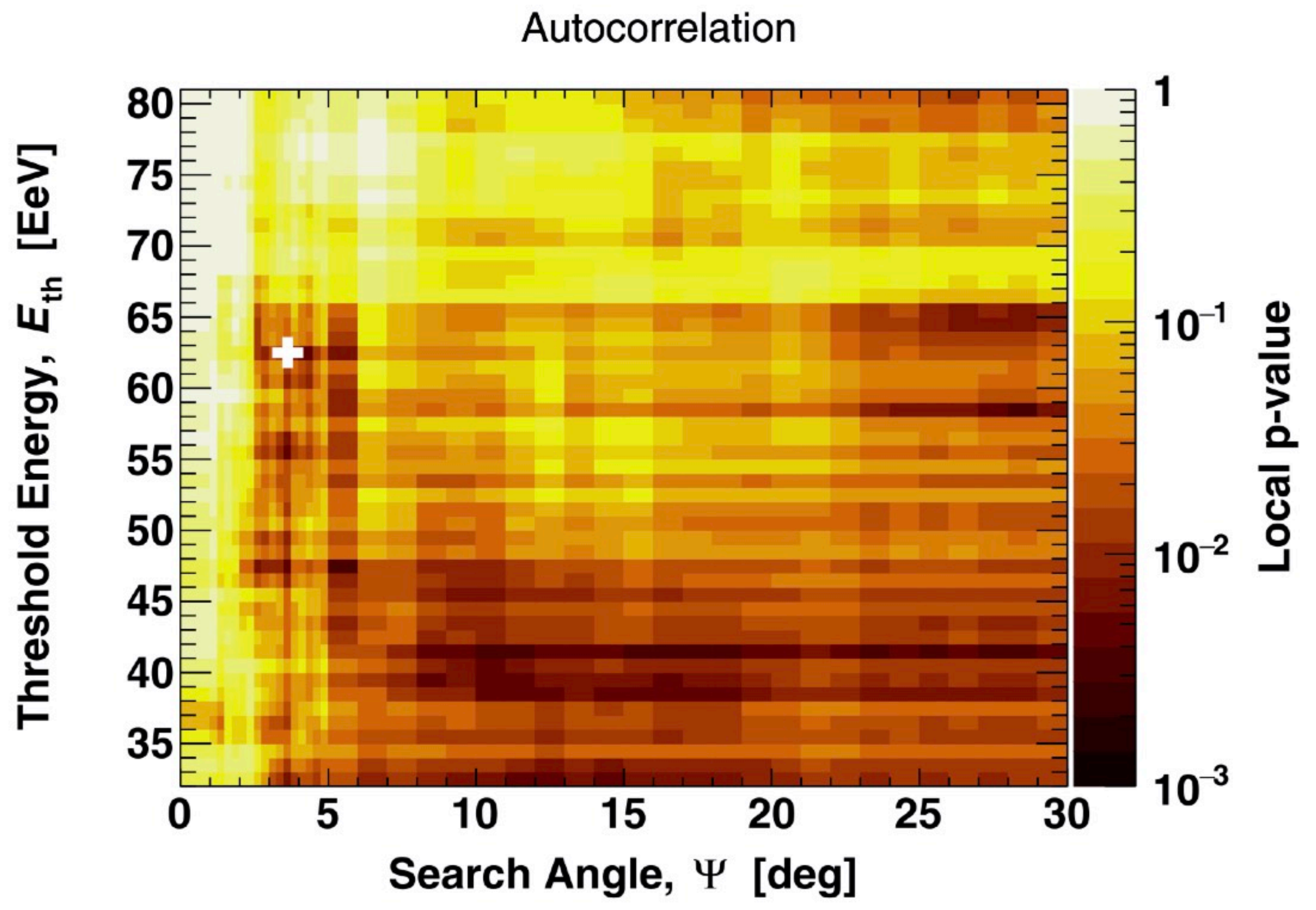
P. Abreu et al 2022 ApJ 935 170



Correlation studies

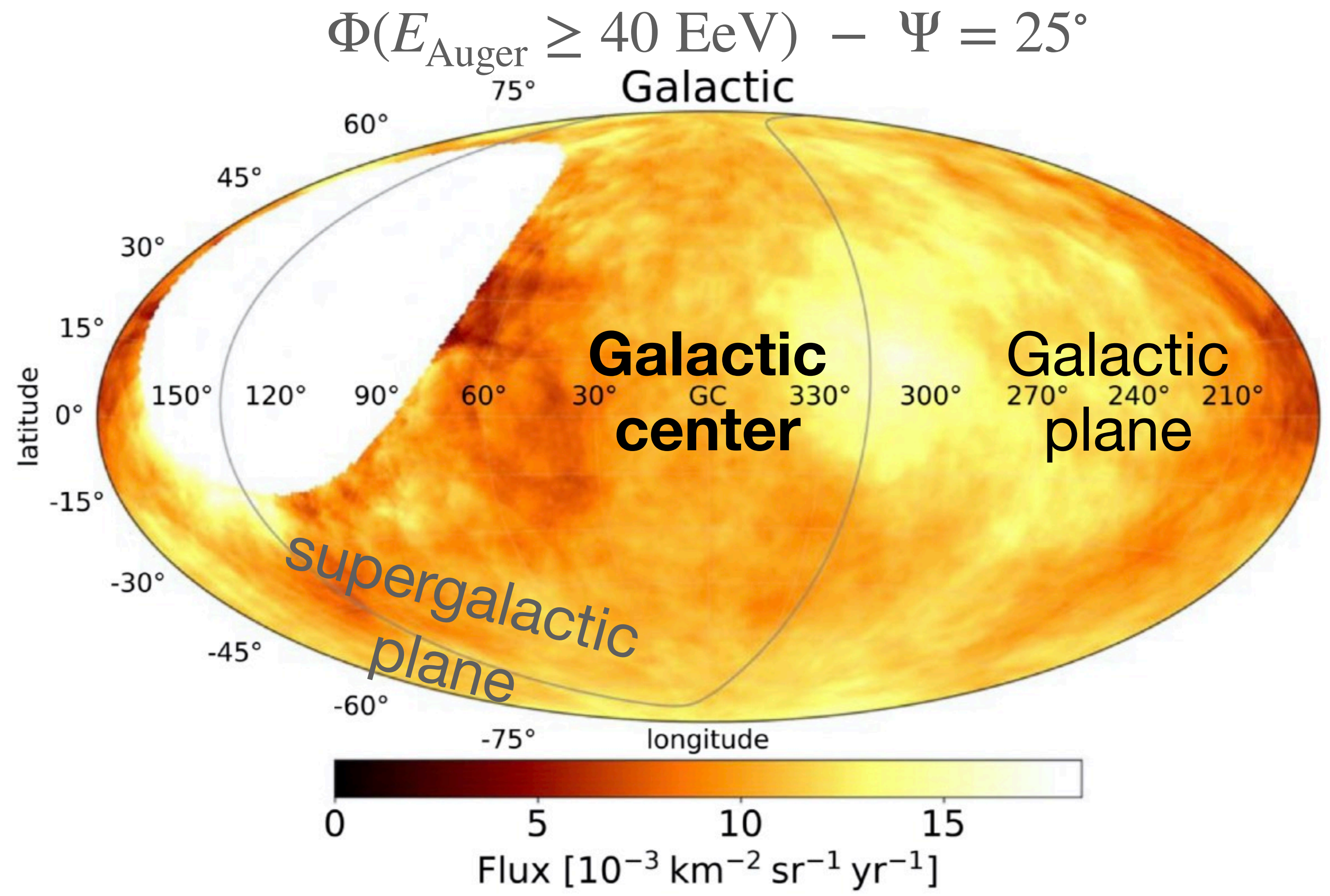
autocorrelation study

- count events separated by less than an angle Ψ above an energy threshold E_{th} & compare to simulations of isotropy
  - post-trial p-value: 0.24



correlation with local astrophysical structures

	post-trial p-value
• Galactic plane	0.13
• Galactic center	0.44
• supergalactic plane	0.57



scan in $\Psi \in [1^{\circ}, 30^{\circ}]$,
$E_{\mathrm{th}} \in [32\ \mathrm{EeV}, 80\ \mathrm{EeV}]$

P. Abreu et al 2022 ApJ 935 170

→ *no significant departures from isotropy found*