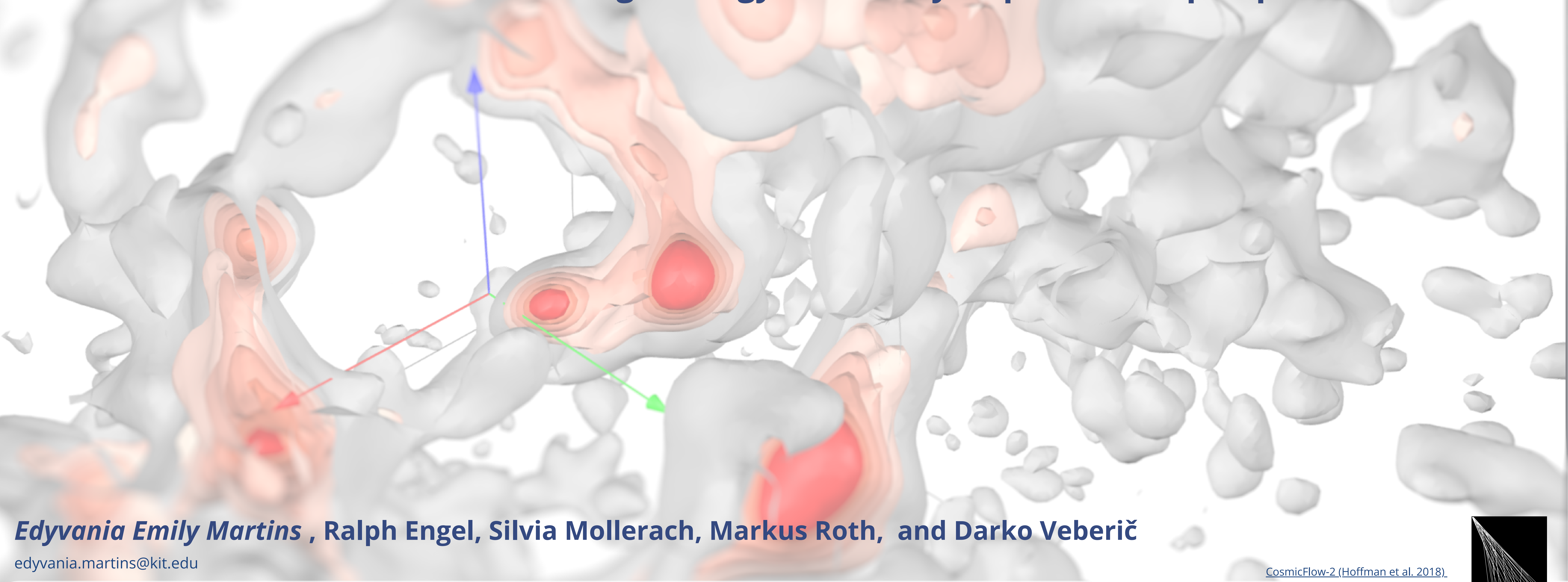
Search for mass-enhanced anisotropy

on the arrival directions of ultra-high-energy cosmic rays: updates and prospects



CosmicFlow-2 (Hoffman et al. 2018)

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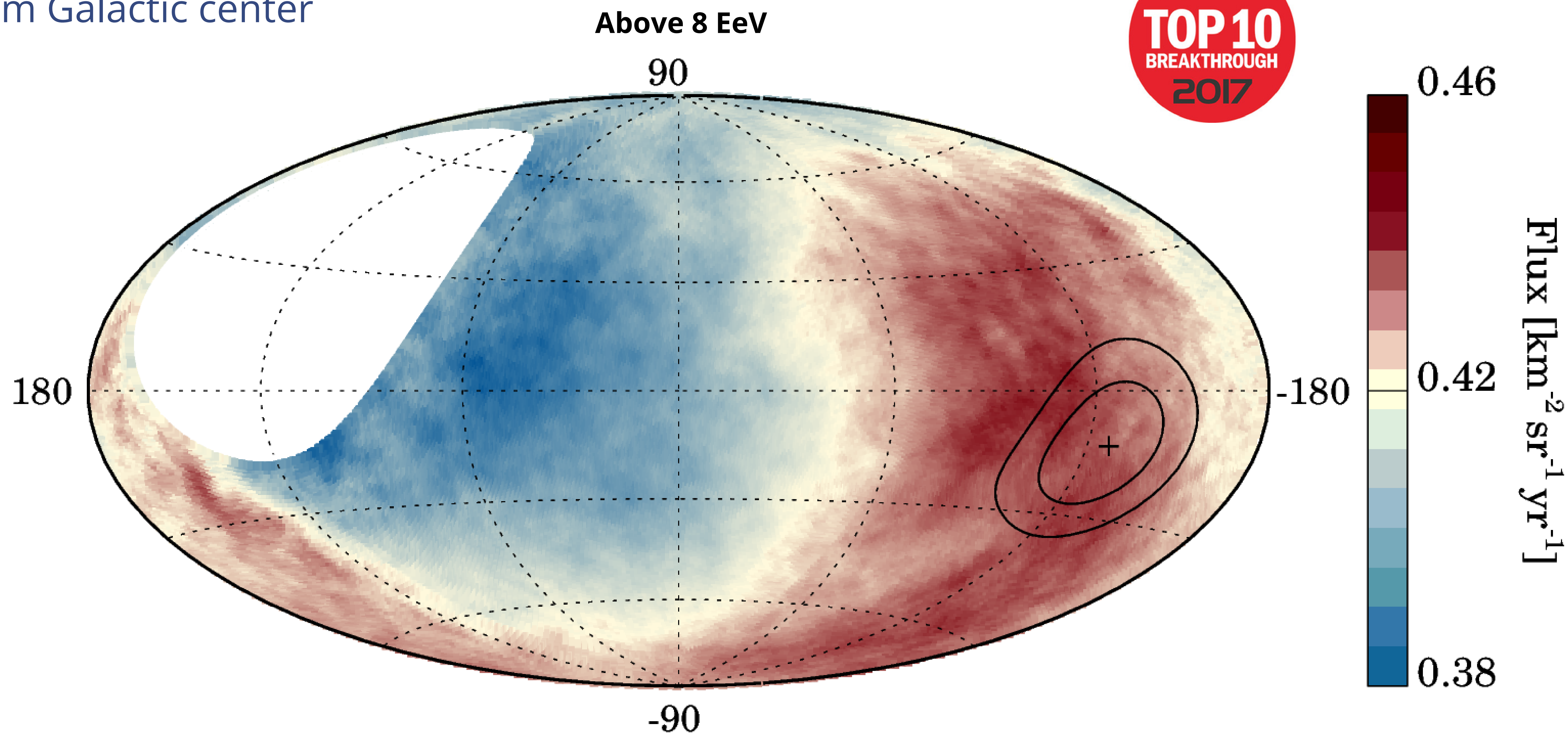
Karlsruher Institut für Technologie | UNSAM | Double Doctoral degree in Astrophysics DDAp | HIRSAP Helmholtz International Research School for Astroparticle Physics | cuaa-dahz deutsch-argentinisches hochschulzentrum | centro universitario argentino-alemán | PIERRE AUGER OBSERVATORY

Extragalactic UHECR

- Higher-order multipoles not significant
- Excess away from Galactic center
- Above 8 EeV



physicsworld TOP 10 BREAKTHROUGH 2017

Science 357 (2017) 1266

Harmonic Analysis

- Modulation of event rate in RA (α)
- Dominated by first-harmonic Fourier components

$$a_k^x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos(kx_i) \qquad b_k^x = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin(kx_i)$$

- Amplitude and phase:

RA

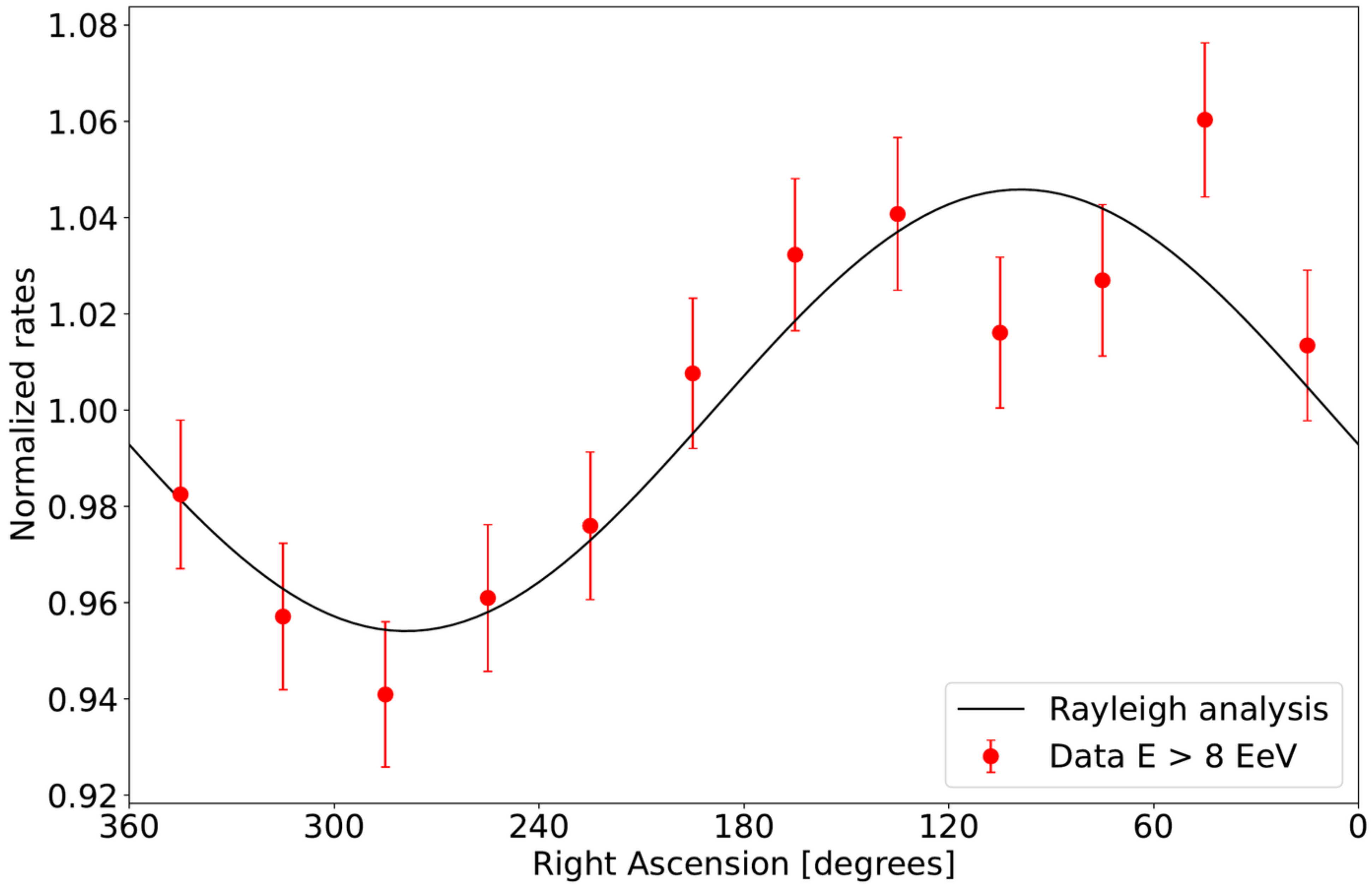
$$r_1^\alpha = \sqrt{a_\alpha^2 + b_\alpha^2} \qquad \tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$

- **3D dipole amplitude**

Φ: Azimuth, N/S

$$d_\perp \simeq \frac{r_1^\alpha}{\langle \cos \delta \rangle} \qquad d_z \simeq \frac{b_1^\phi}{\cos \ell_{\text{obs}} \langle \sin \theta \rangle}$$

$\langle \cos \delta \rangle = 0.78$



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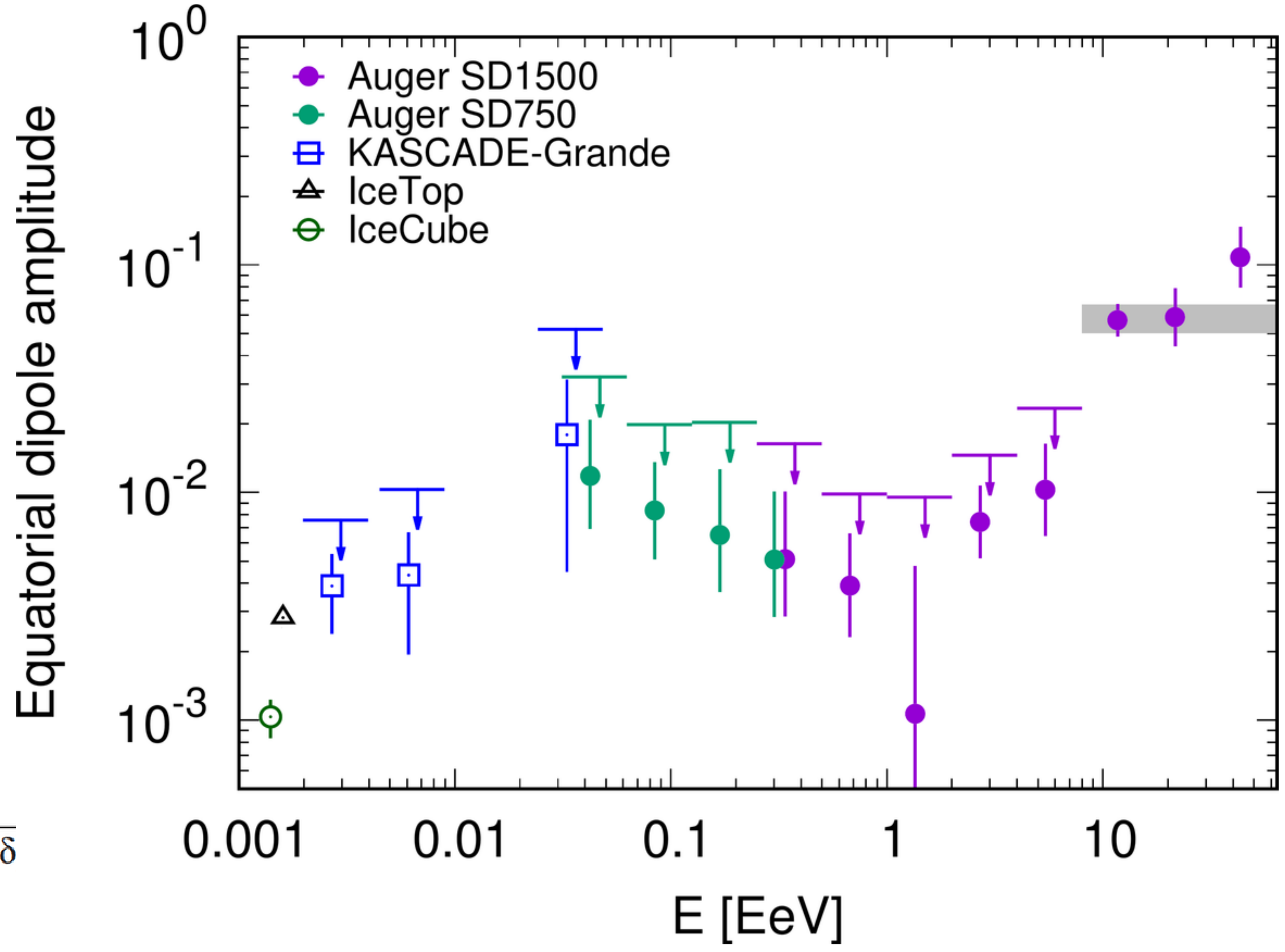
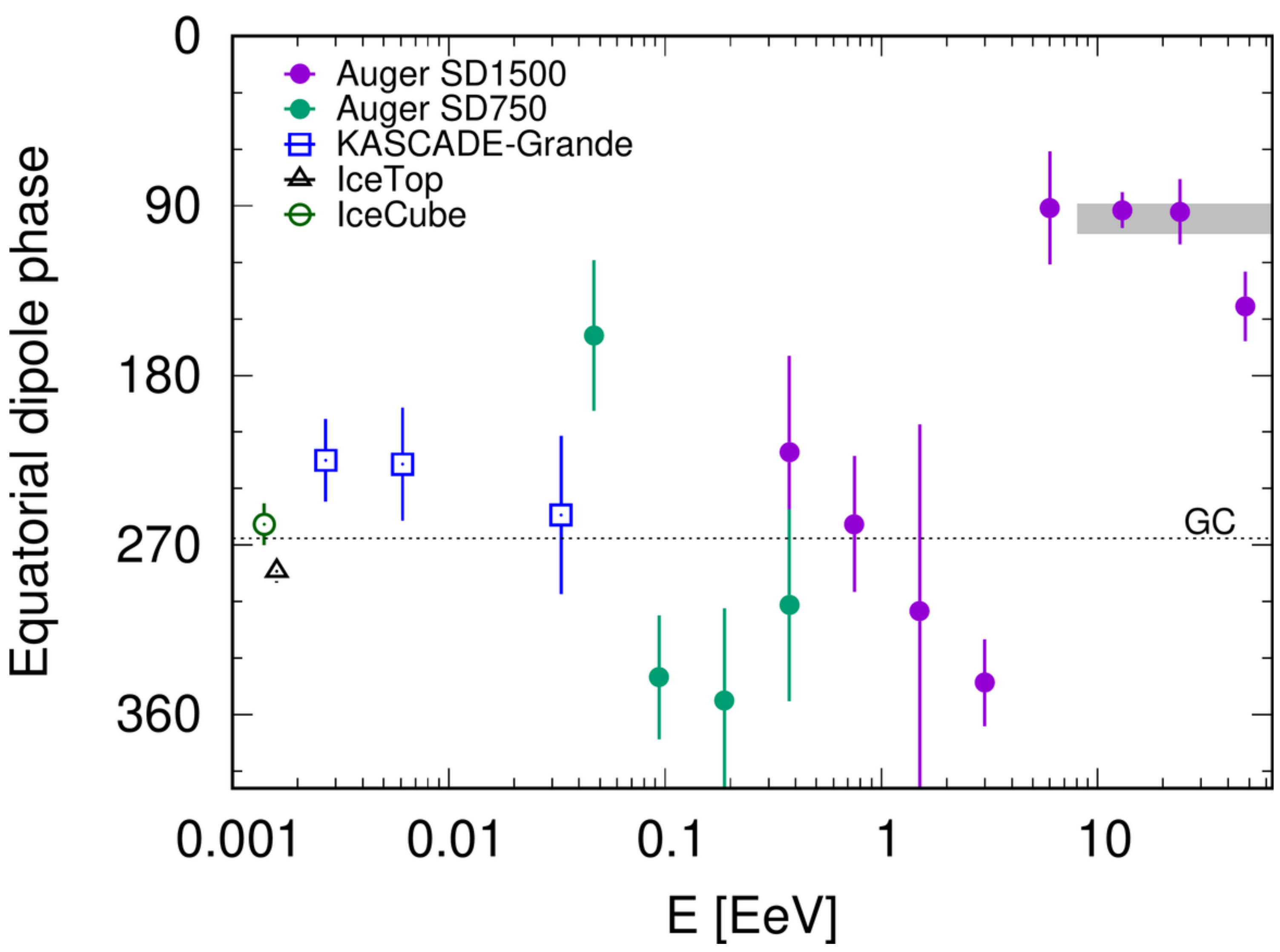
Amplitude & phase



$$d_\perp \approx \frac{r_\alpha}{\langle \cos\delta \rangle}$$



Increasing amplitude above 2 EeV + Phase shifted away from Galactic centre

Suggests shift from galactic to extra-galactic origin of UHECR anisotropy

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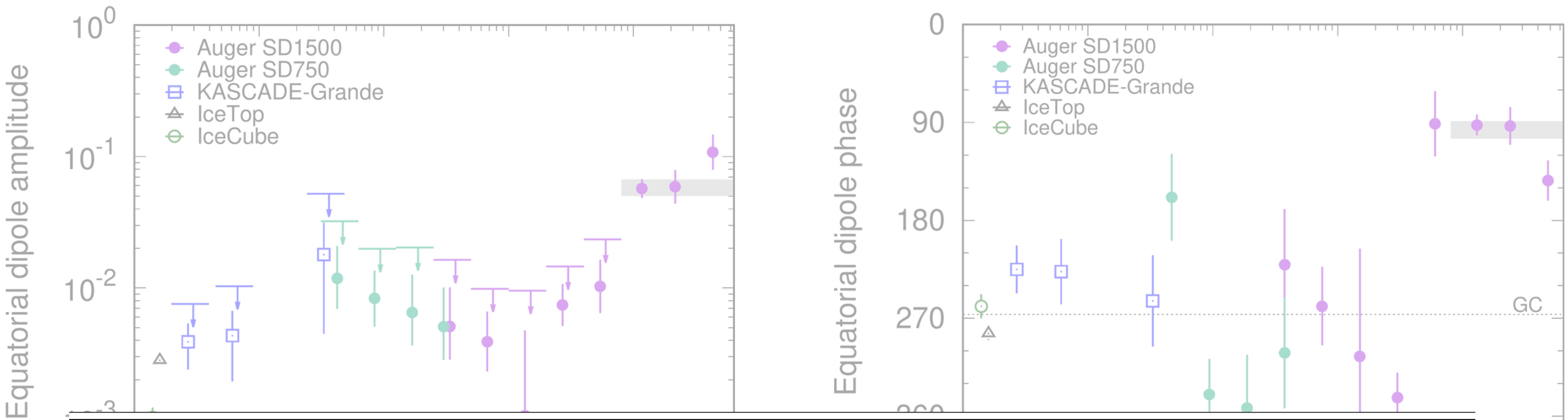
Amplitude & phase



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
$\geq$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}	**6.9 σ**
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}	**5.7 σ**
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}
$\geq$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}

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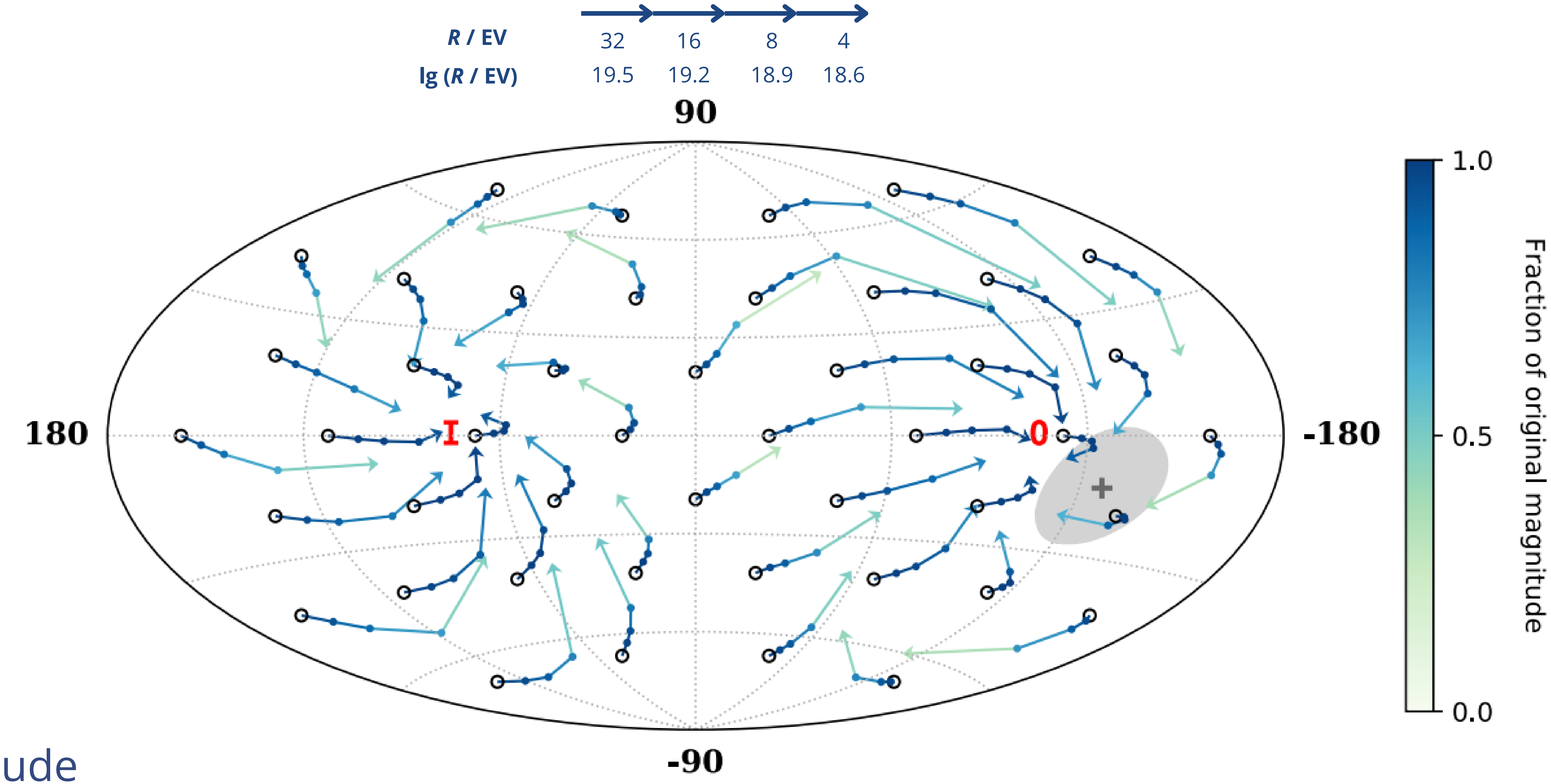
Galactic magnetic field effects



- Damping of dipole amplitude
- Direction shifted towards the plane
- Rigidity-dependent = composition-sensitive
- B is *modeled*

APJ 868:4 (2018)

UNTANGLING

To probe the effects of A/Z on the anisotropy, separate data into *light* and *heavy* populations

- Separation method

AI generated image with Canva Magic Studio

UNTANGLING

To probe the effects of A/Z on the anisotropy, separate data into *light* and *heavy* populations

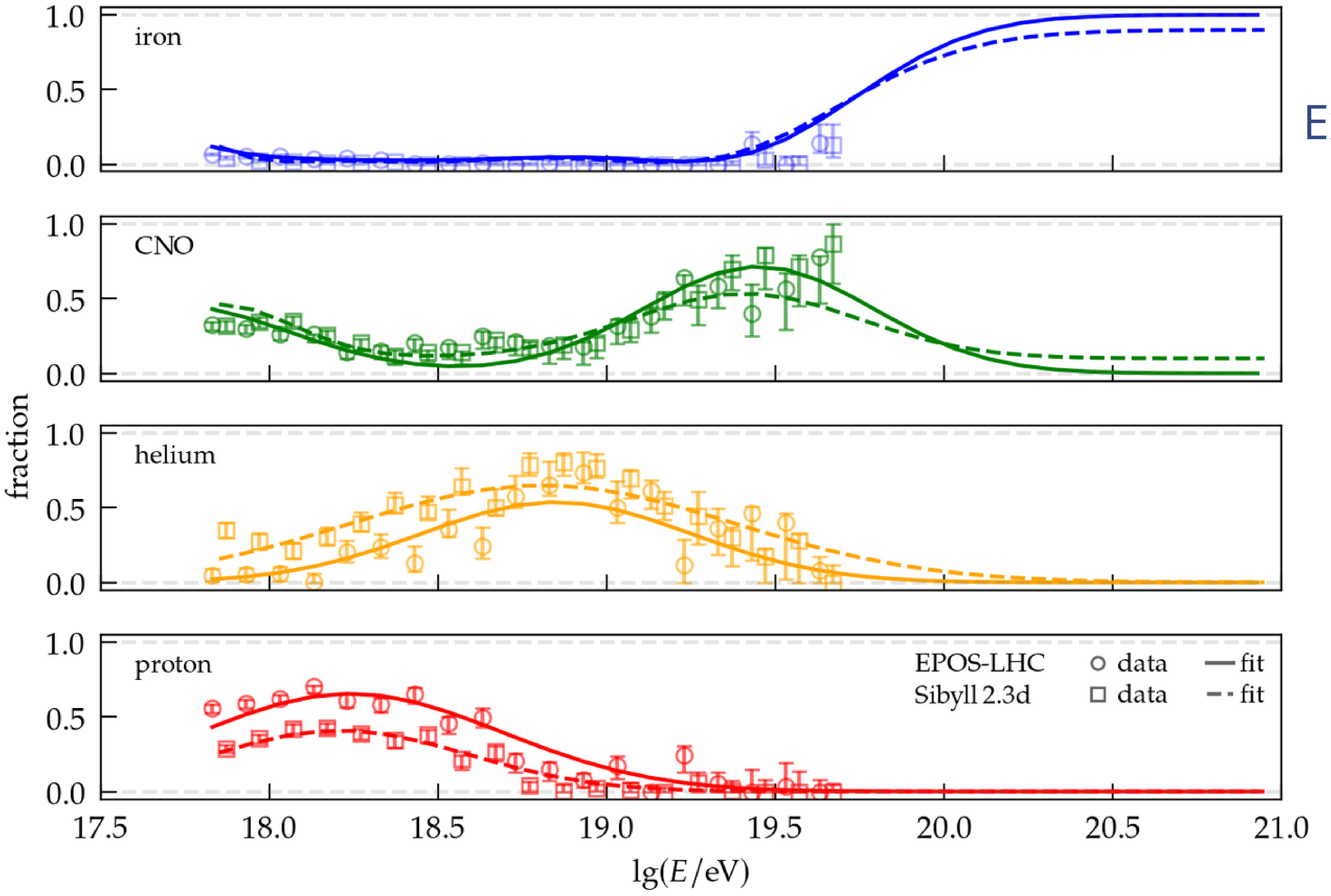
- Separation method

To probe the feasibility of measuring such effects with Auger data:

- Scrutinize separation on 'Auger-like' simulation dataset
- Composition model
- R-dependent dipole amplitude model

AI generated image with Canva Magic Studio

Extended Auger mix

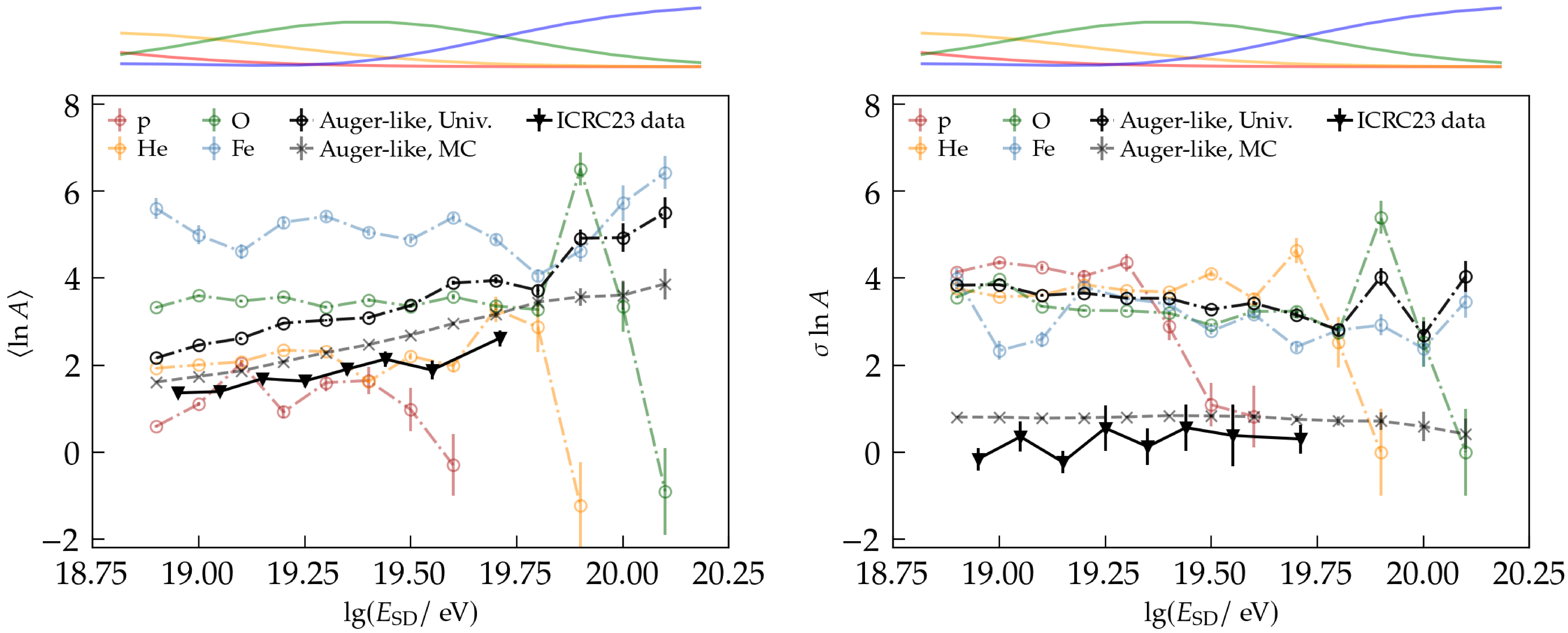


Extending the FD-based composition fractions

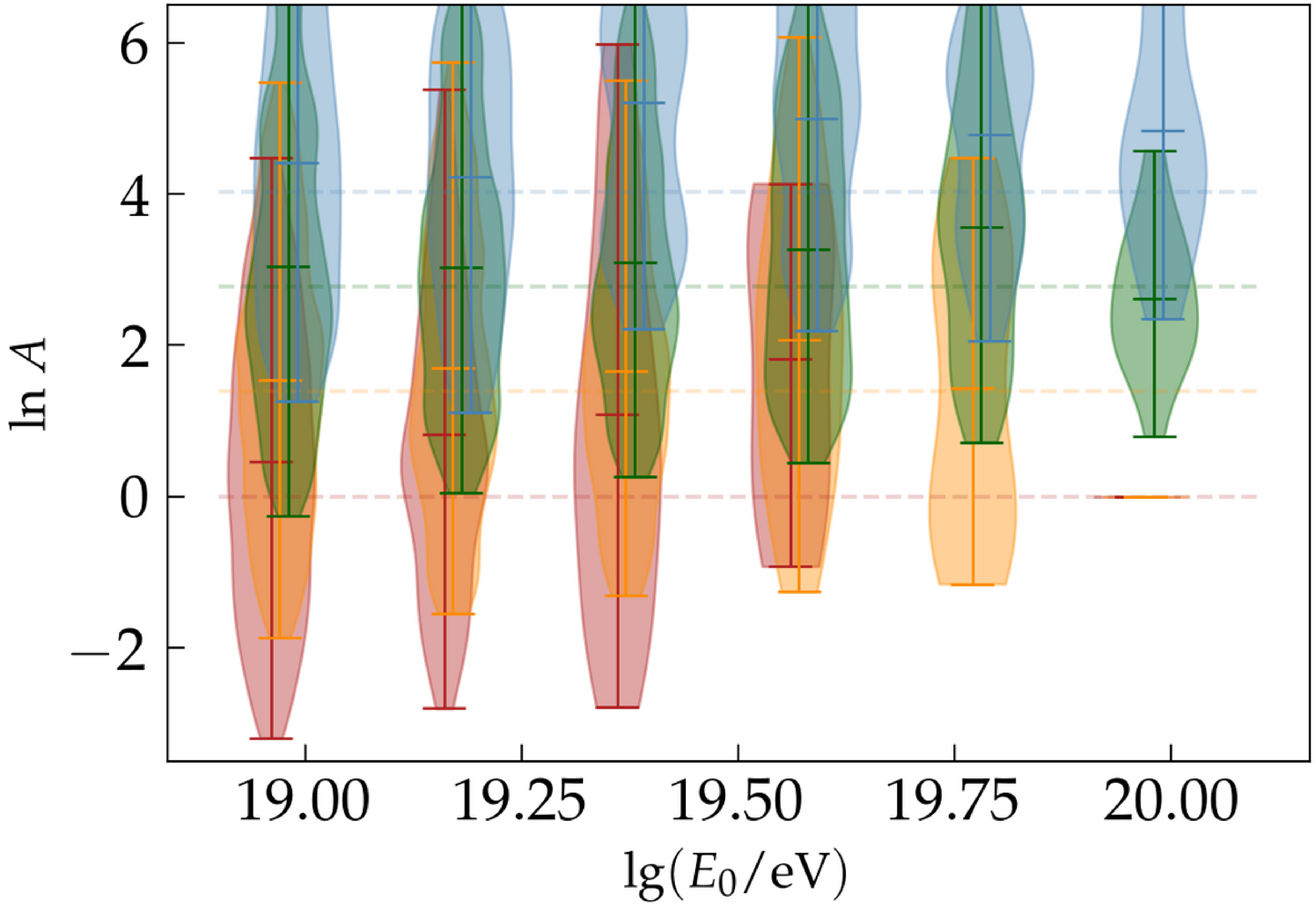
- MCMC fraction fit of Xmax distributions from FD measurements by Olena Tkachenko, PoS ICRC2023 (2023) 438
- Mass-ordering of components as seen in GAP-2022-007
- HIM-dependent but no assumption on sources, GMF, EGMF

GAP2023-050

Extended Auger mix



Universality-based mass-estimator

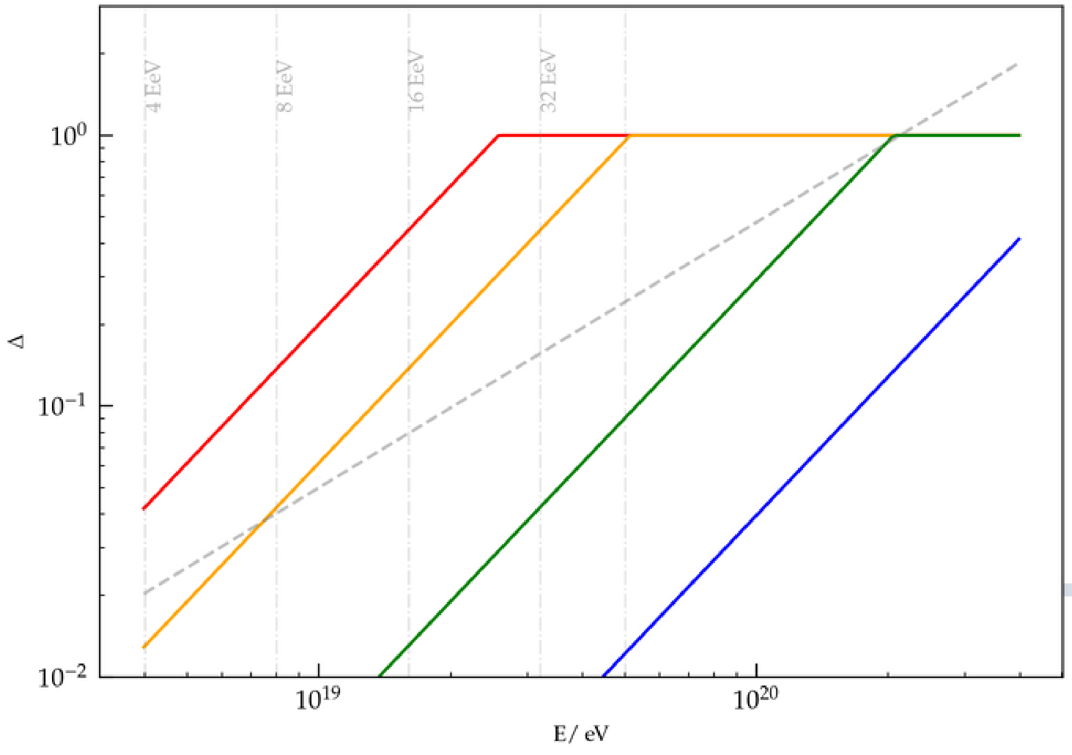


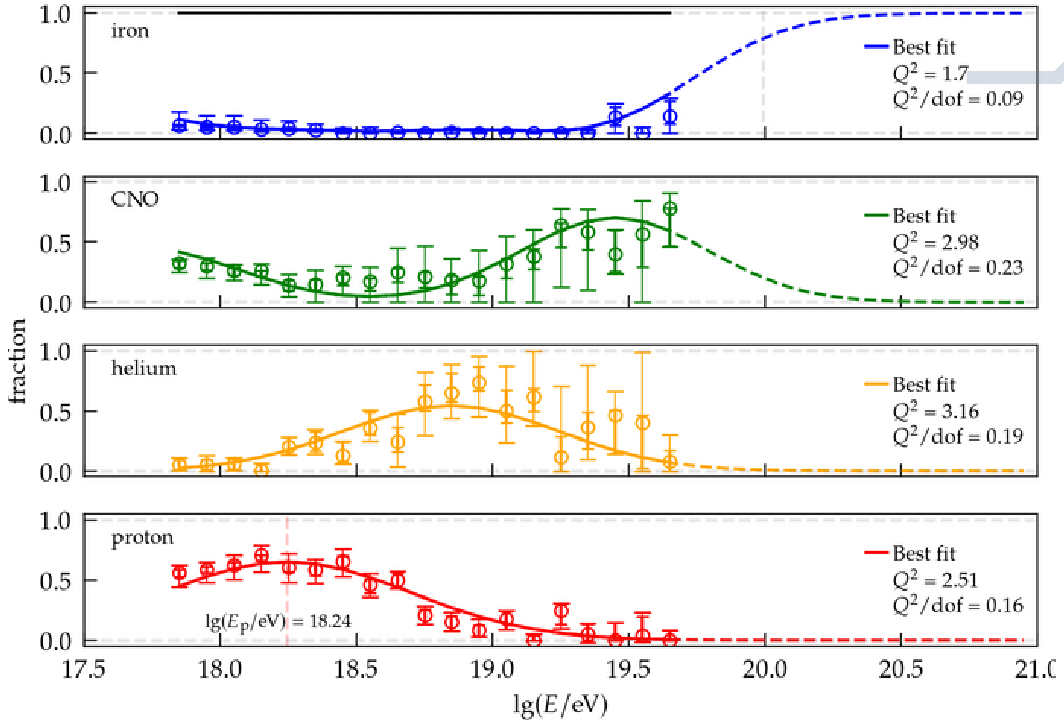
Extended Auger mix + Spectrum

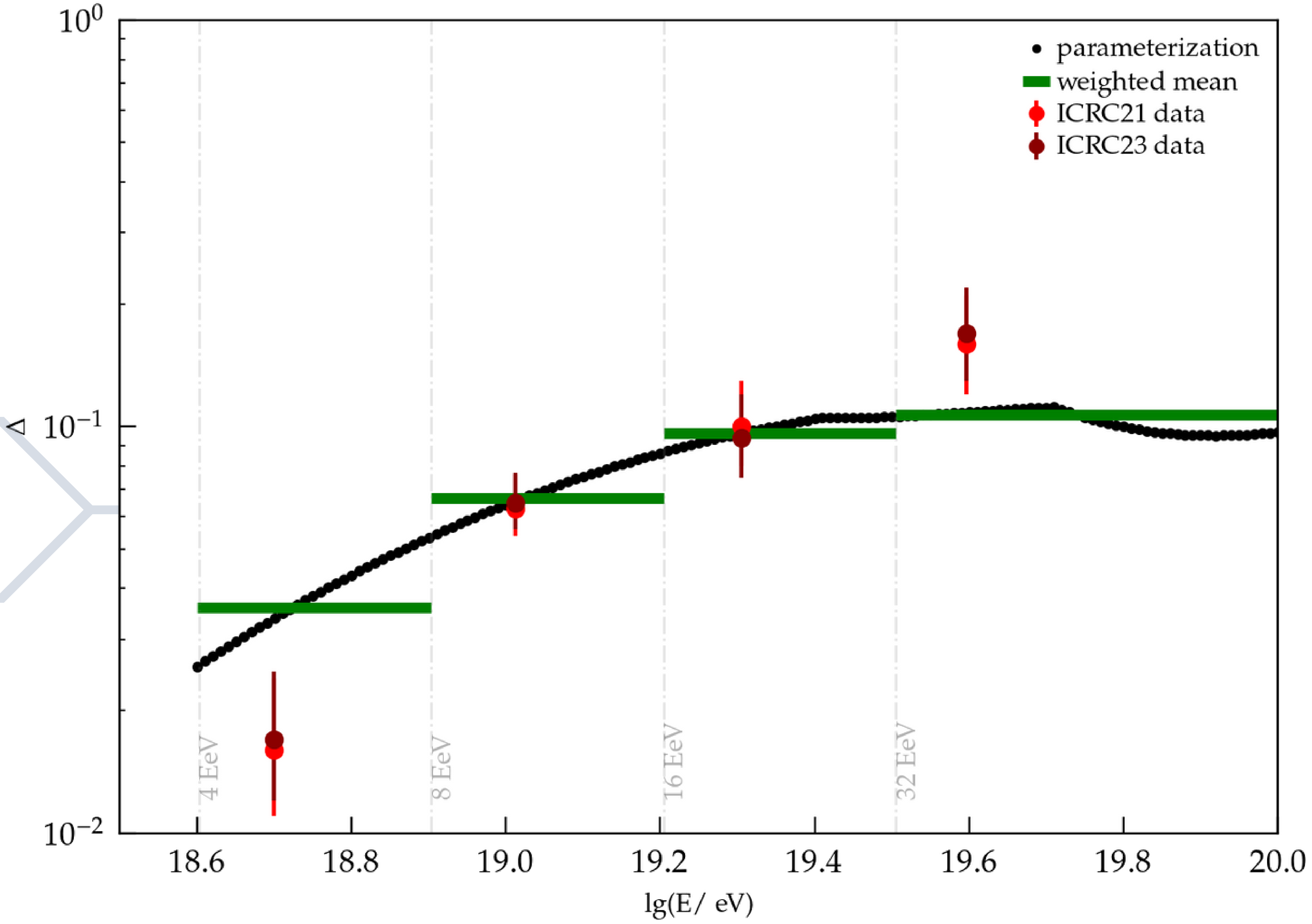
Reconstruct Xmax and Rμ with WCD (+SSD in AugerPrime)

- Xmax and Rμ are independent
- From cascade equations, combine both into ln *A* estimator
- Select tails of distributions = *light* vs *heavy*

R-dependent dipole amplitude model



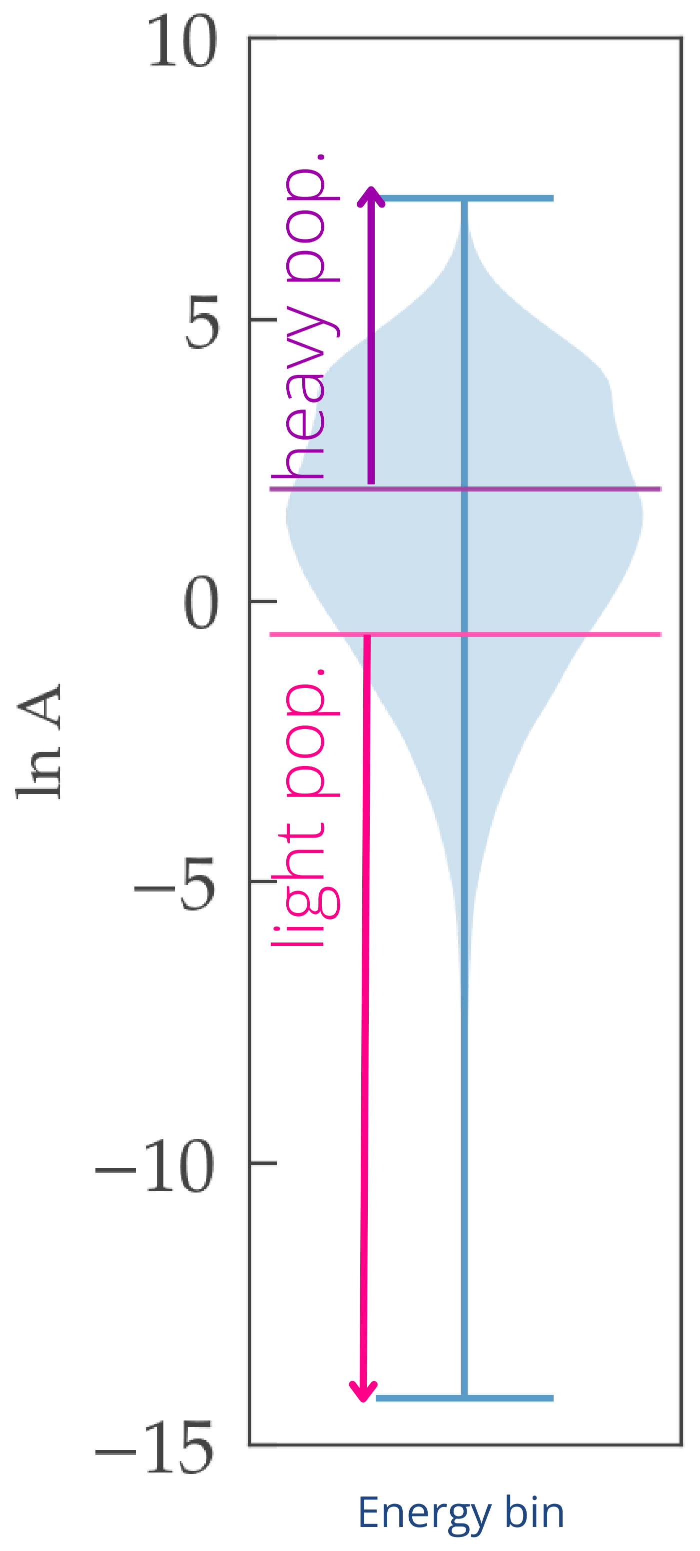




$$d = d_R \left(\frac{E}{Z\,\mathrm{EeV}} \right)^{\beta_R}$$

- Scanned parameters, given composition model
- Spectrum-weighted average in large E-bins
- No assumption on sources

Light & heavy separation



8 - 16 EeV (N=33873, 15% p, 48% He, 33% CNO, 4% Fe)

Method	Value	ln A_l^{th}	N_l	d_l	p_l (%)	He_l (%)	O_l (%)	Fe_l (%)	ln A_h^{th}	N_h	d_h	p_h (%)	He_h (%)	O_h (%)	Fe_h (%)
SMD	1.88	-0.6	3942	0.1026	26.76	55.48	17.07	0.68	2.4	8775	0.0517	8.59	40.39	44.55	6.47

~12% ~26%

16 - 32 EeV (N=9555, 4% p, 27% He, 65% CNO, 4% Fe)

Method	Value	ln A_l^{th}	N_l	d_l	p_l (%)	He_l (%)	O_l (%)	Fe_l (%)	ln A_h^{th}	N_h	d_h	p_h (%)	He_h (%)	O_h (%)	Fe_h (%)
SMD	1.99	0.6	1266	0.1713	8.61	45.02	45.66	0.71	2.2	3175	0.0776	2.33	20.41	71.46	5.8

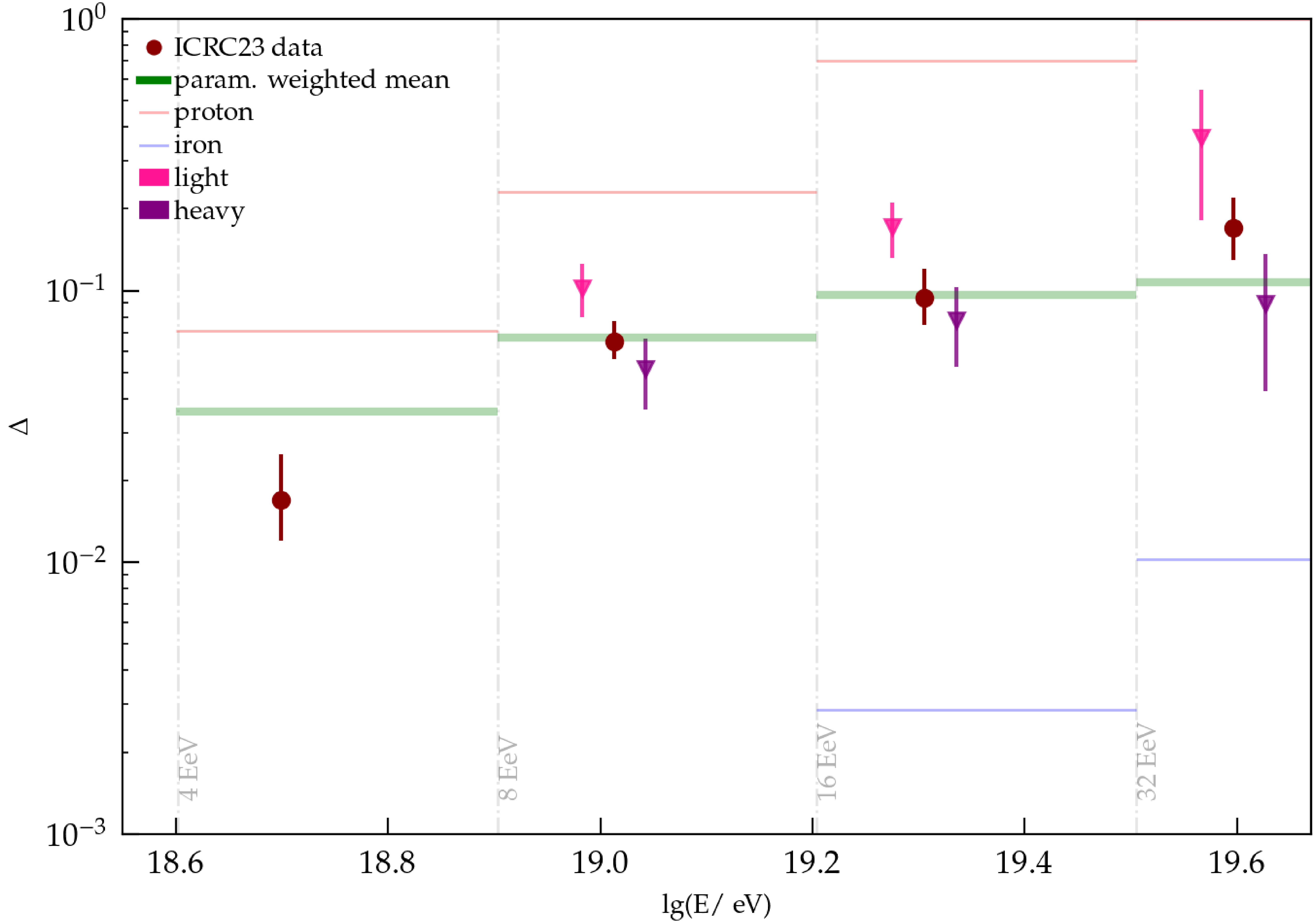
~13% ~33%

above 32 EeV (N=2391, 0.7% p, 9% He, 61% CNO, 29% Fe)

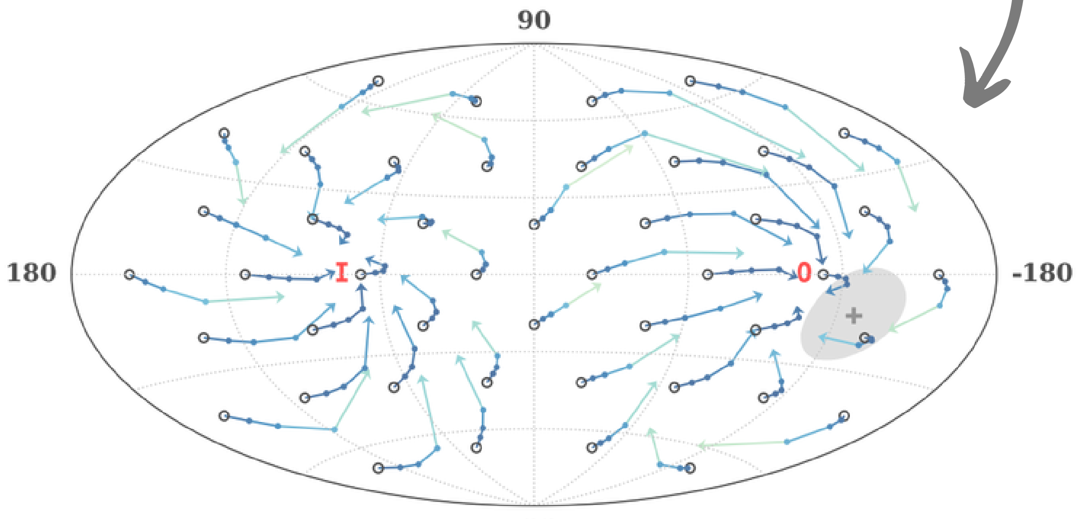
Method	Value	ln A_l^{th}	N_l	d_l	p_l (%)	He_l (%)	O_l (%)	Fe_l (%)	ln A_h^{th}	N_h	d_h	p_h (%)	He_h (%)	O_h (%)	Fe_h (%)
SMD	1.46	-1.0	59	0.3665	1.69	45.76	47.46	5.08	2.6	914	0.0894	0.66	5.47	54.6	39.28

~2% ~38%

Expected separation in dipole amplitude



- Interplay: purity vs statistics
- Phase I separation power 1 - 2 σ
- Dipole direction can also add information!



To summarize

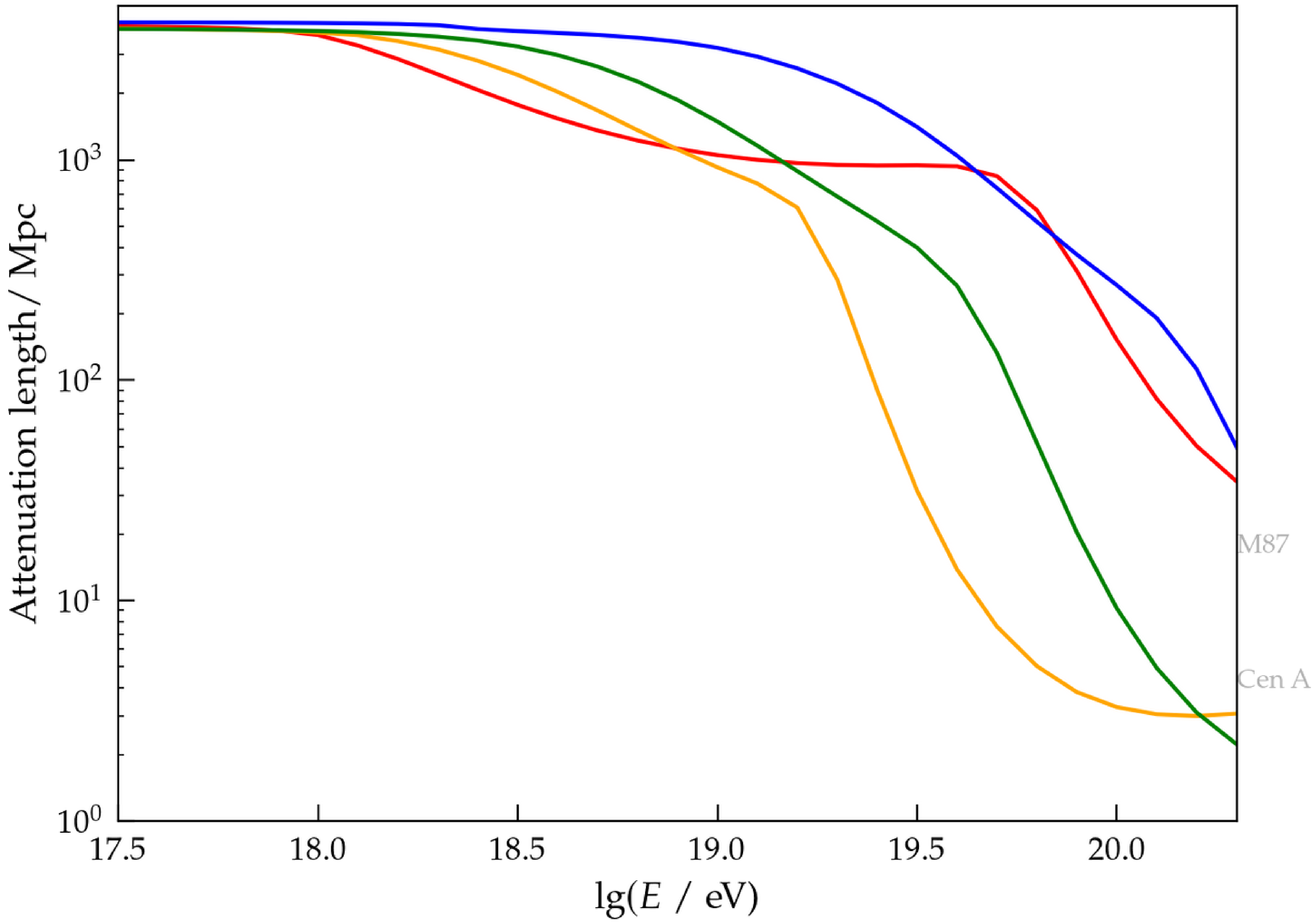
- Defined a method to separate data into *light* and *heavy* populations
- Created an ‘Auger-like’ simulation data set
  - Extended Auger mix model (with *A*-ordering) + spectrum
- Modeled an R-dependent dipole amplitude that reproduces the data
- Probed the feasibility of measuring mass effects on dipole amplitudes of *A*-distinct populations
- + cross-checks between Universality and DNN reconstructions in the MEAD context

We concluded that…

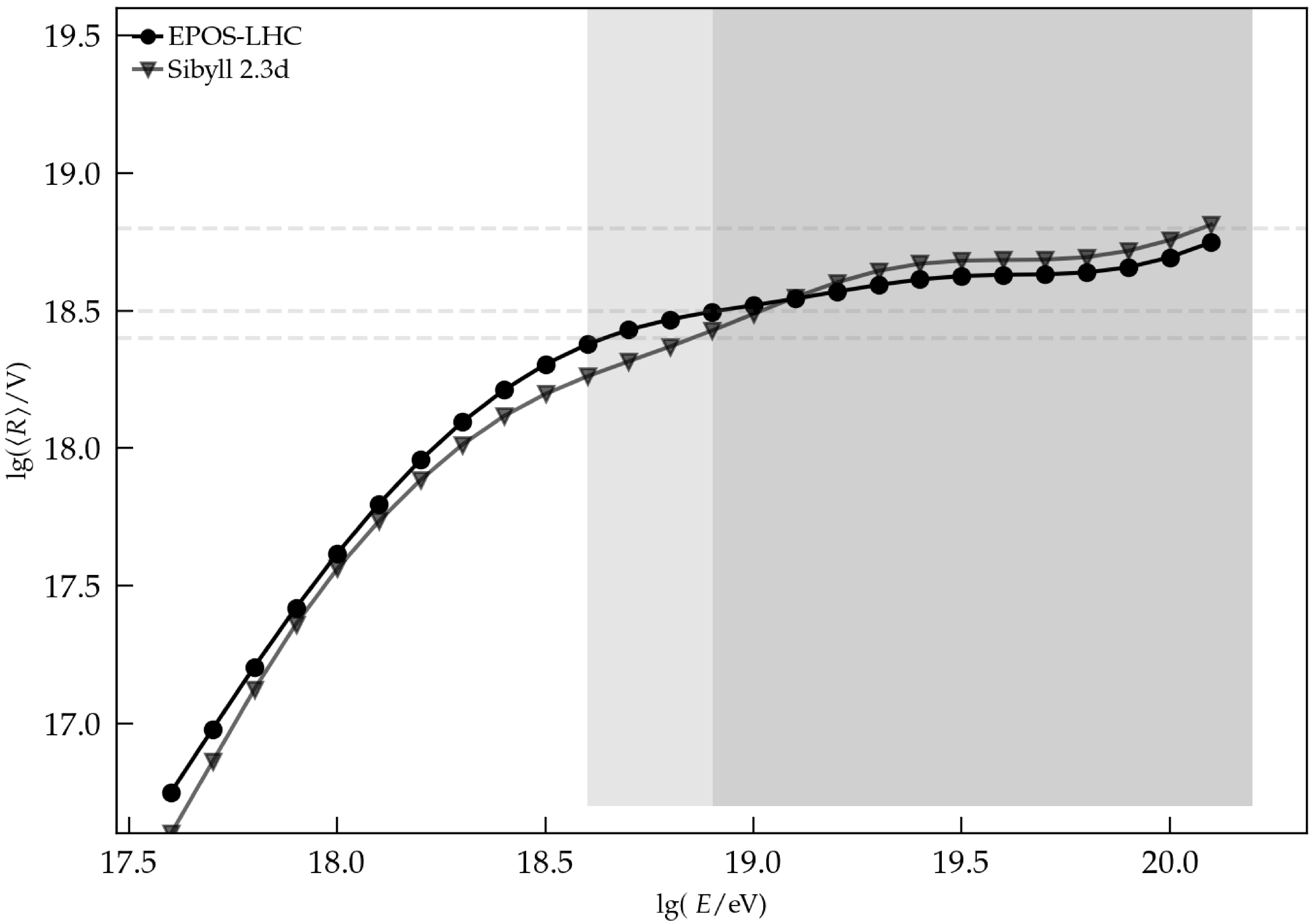

We are ready to search for
mass-enhanced anisotropy!

Thank you

Additional material



- Photodisintegration -> primary CR horizon



- Small changes in rigidity above 4 EeV

Large Scale Anisotropy

The dataset

- Jan. 2004 - Dec. 2022
- Energy ranges

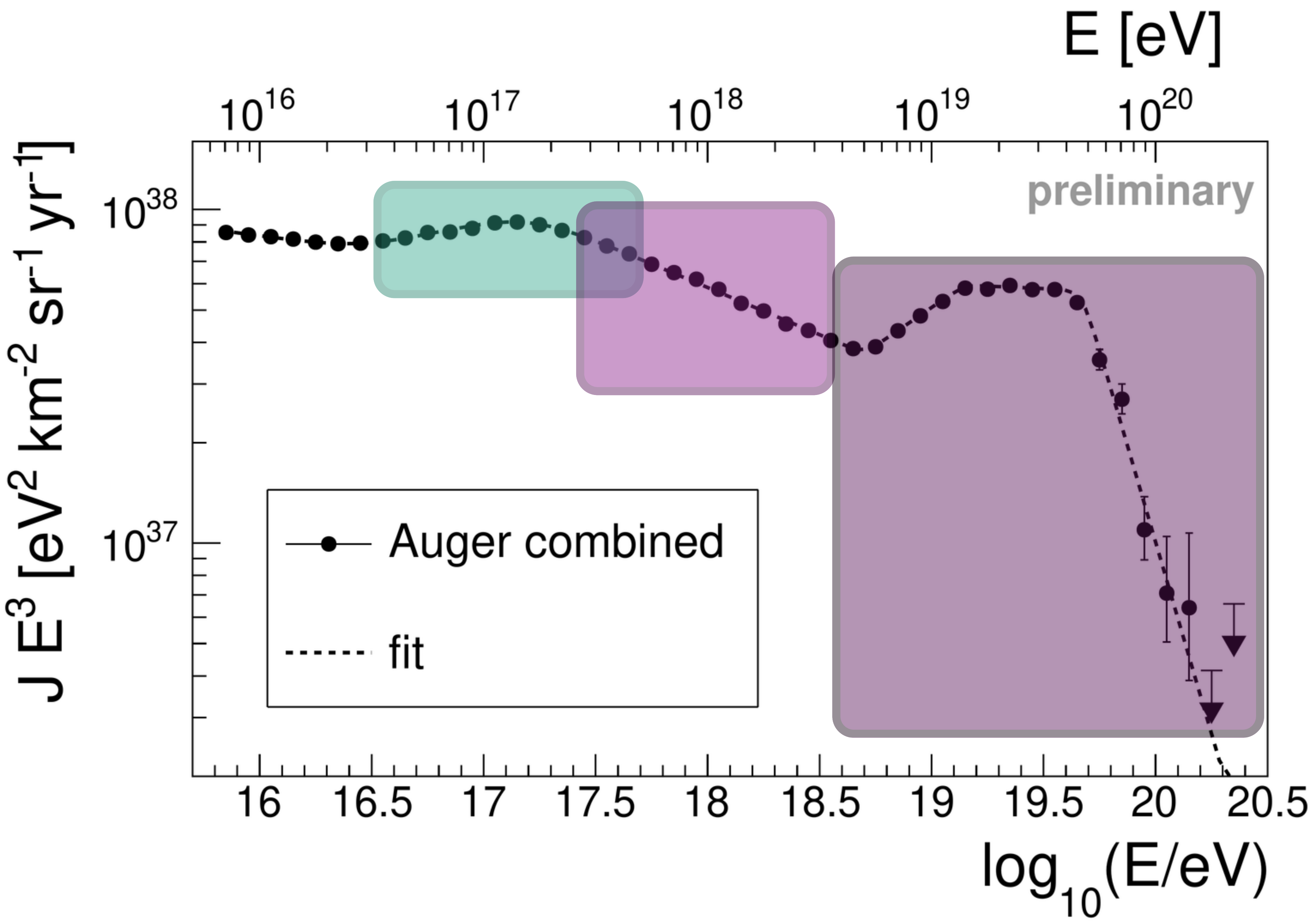
1/32 EeV	to	1/2 EeV	$\theta < 55°$
1/4 EeV	to	4 EeV	$\theta < 60°$
	above	4 EeV	$\theta < 80°$

Exposure

SD 750 array = 337 km² yr sr

SD 1500 array = 81 000 km² yr sr

123 000 km² yr sr



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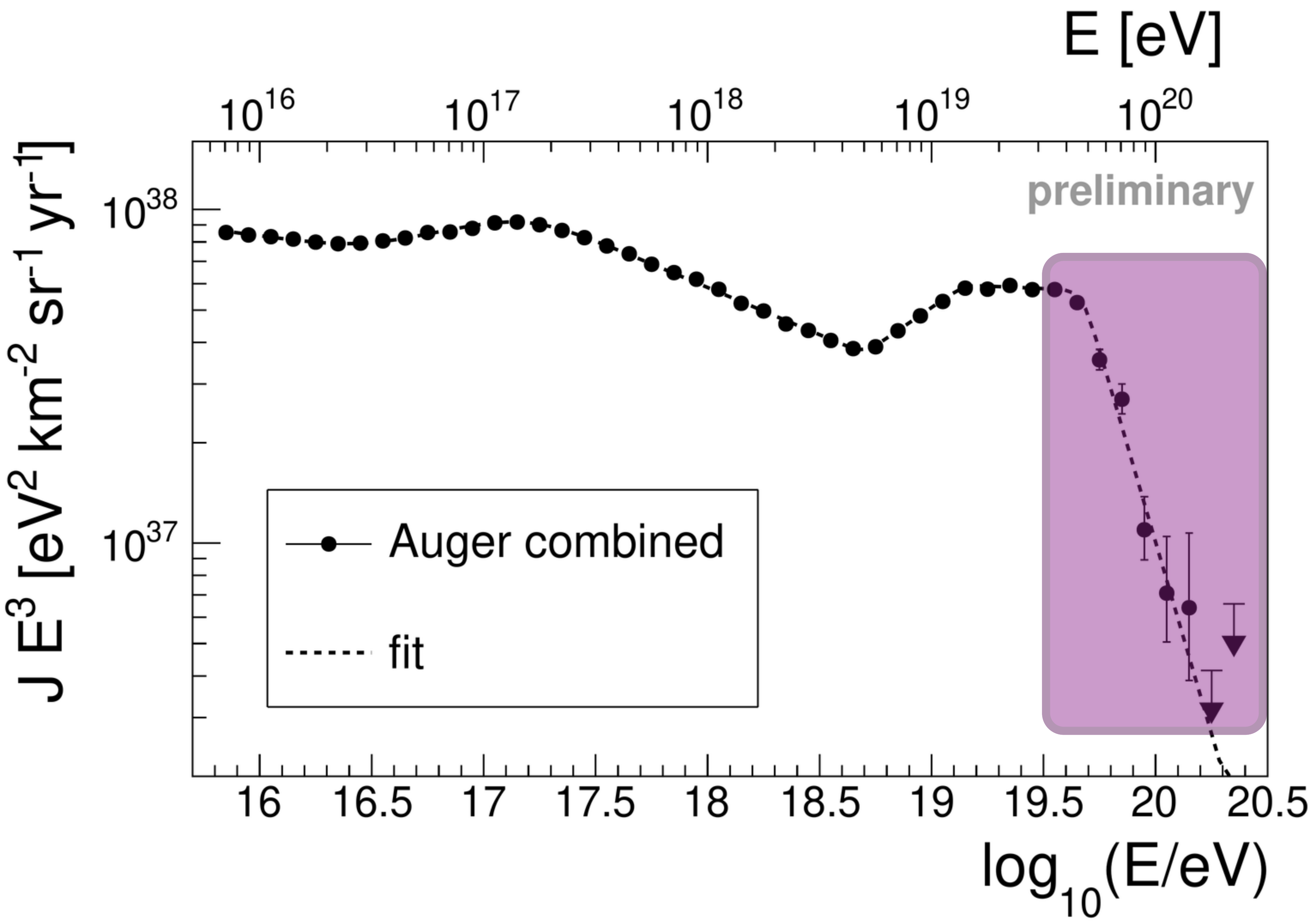
Intermediate Scale Anisotropy

The dataset

- Jan. 2004 - Dec. 2022
- Energy above 32 EeV, $\theta < 80°$
- Looser selection of events

Exposure

SD 1500 array = 135 000 km^2 yr sr



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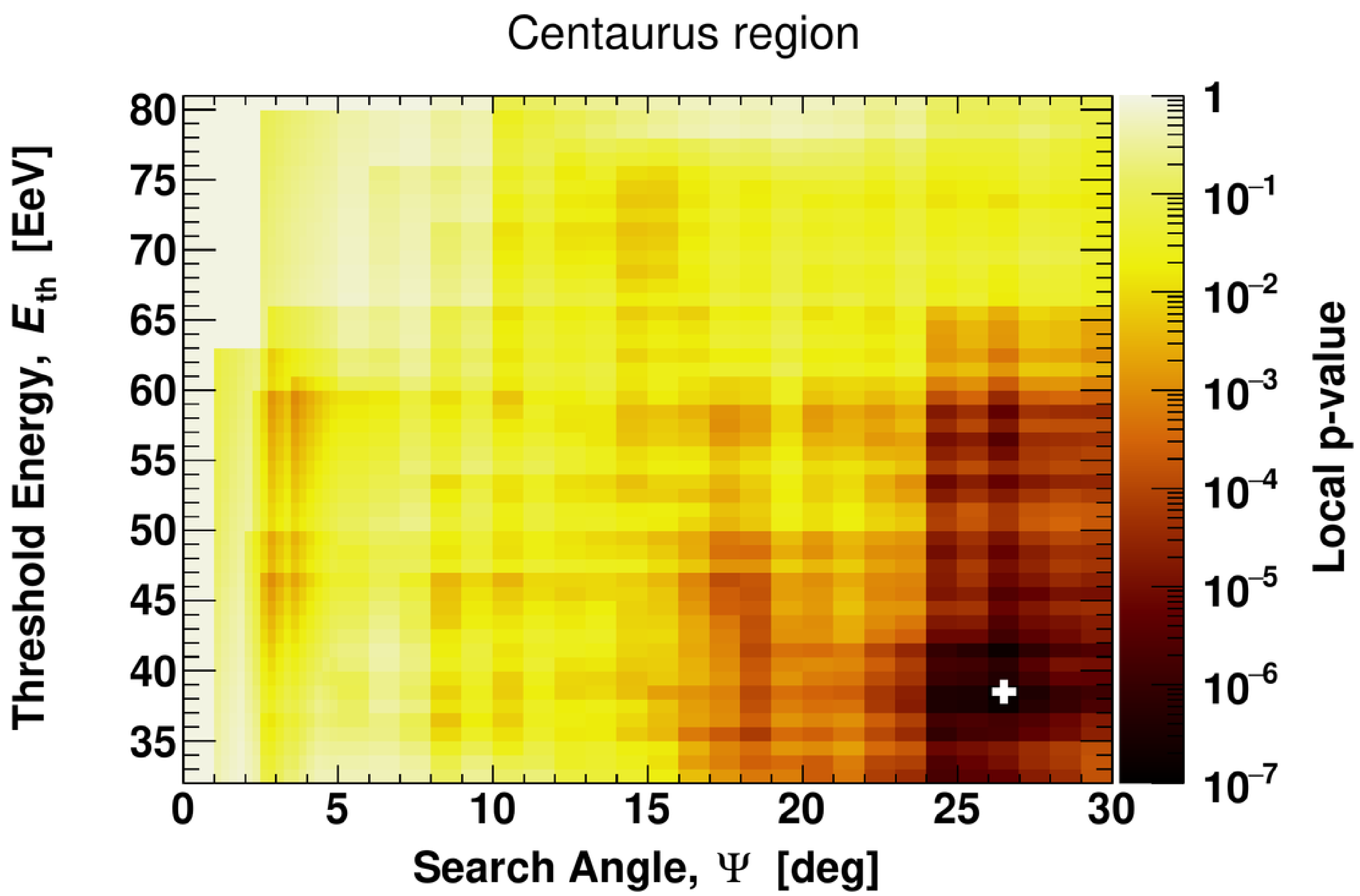
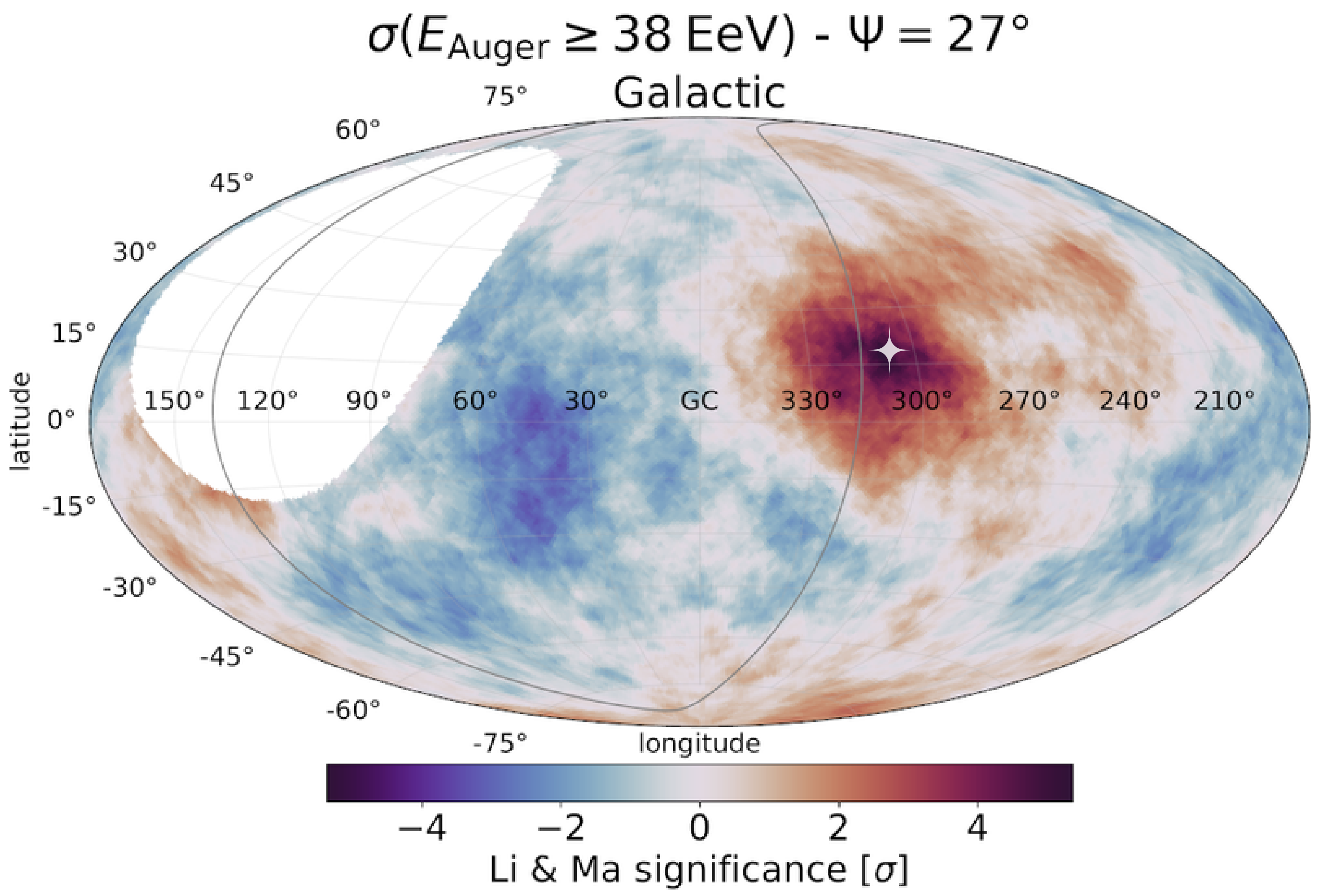
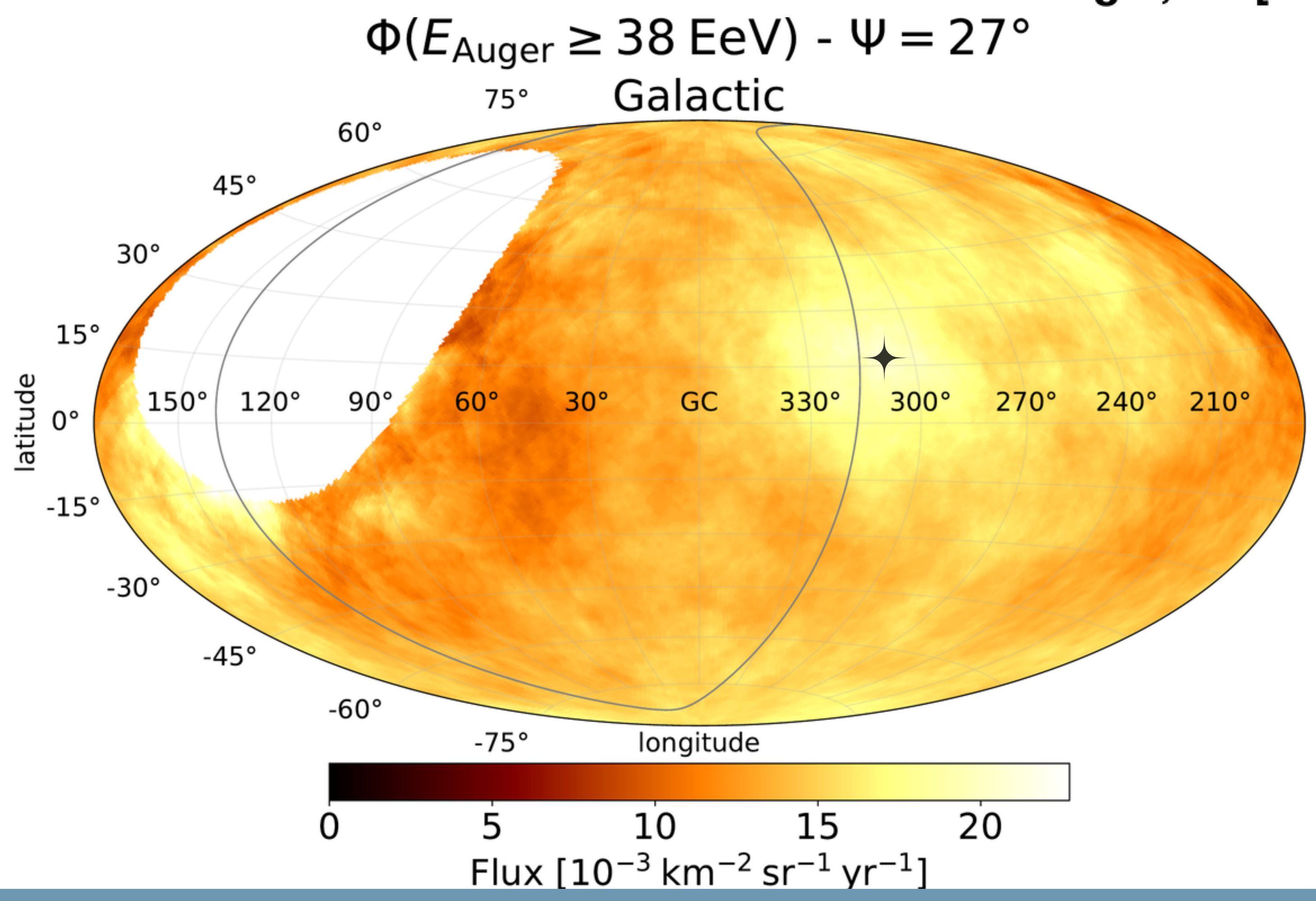
Centaurus excess

- CenA ≈ 4 Mpc away
- Scan in Centaurus region
- Significance: 3.9σ (ApJ2022) → **4.0σ** (ICRC23)
- If signal is real, reach 5σ significance at (165 000 ± 15 000) km^2 yr sr (**2025 ± 2 years**)







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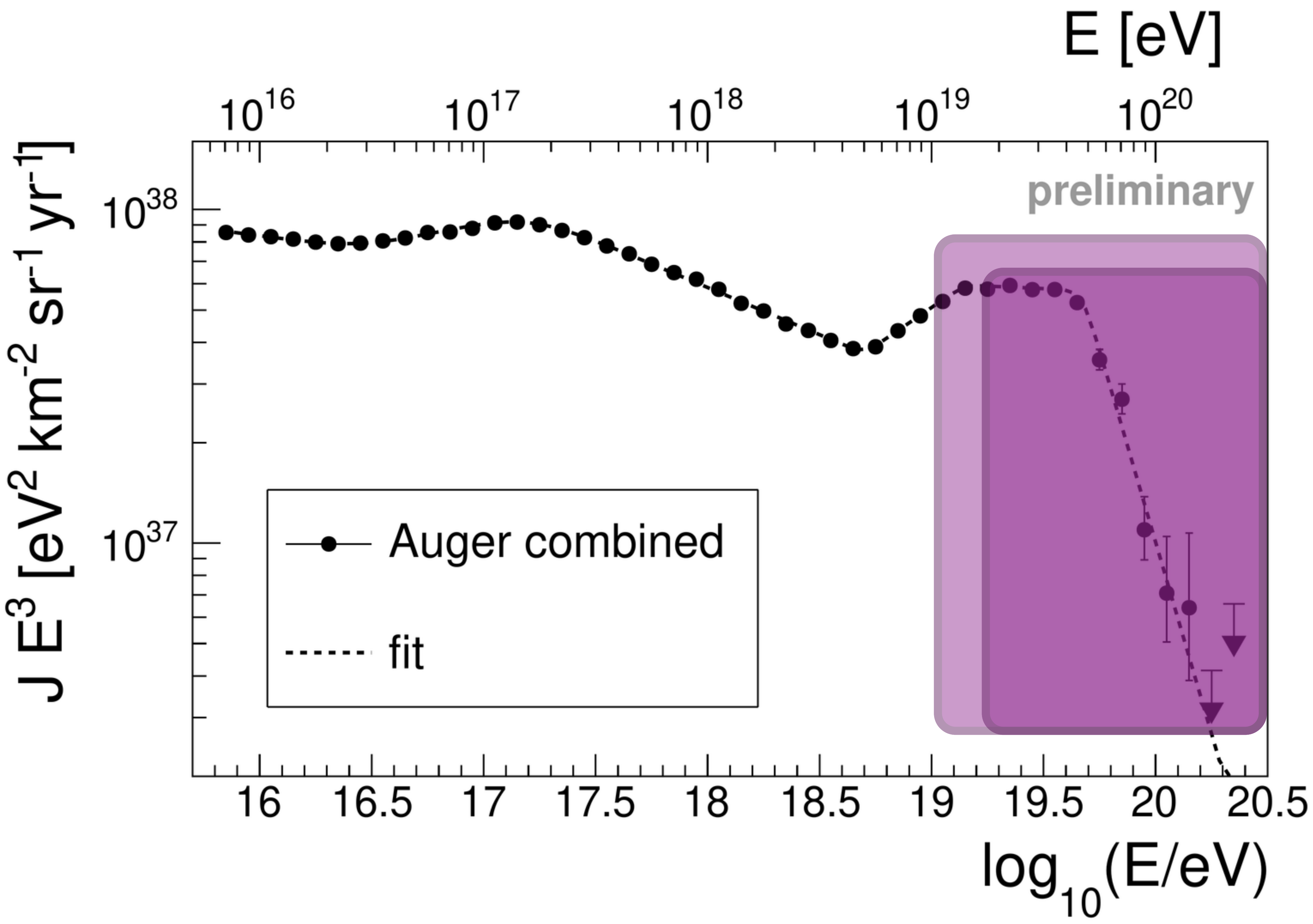
The next step: combining observables

The dataset

- **Arrival directions**
  - >16 EeV
  - Jan. 2004 to Dec. 2020
  - Exposure 95 700 km² yr sr ($\theta < 60°$) and 26 300 km² yr sr ($60° < \theta < 80°$)
- **Energy**
  - >10 EeV
  - Jan. 2004 to Aug. 2018, $\theta < 60°$
  - Exposure 60 426 km² yr sr
- **Shower-maximum depth distribution**
  - >10 EeV
  - FD measurements



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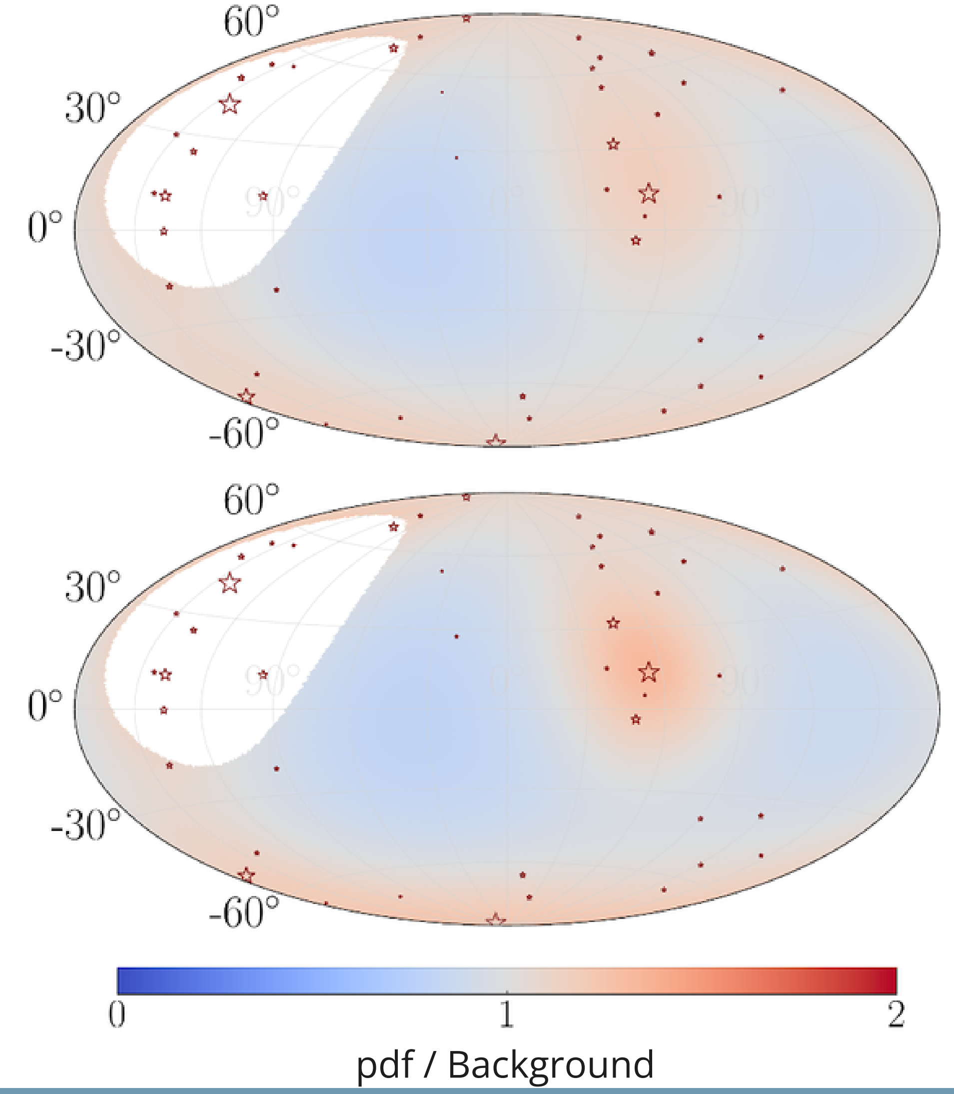
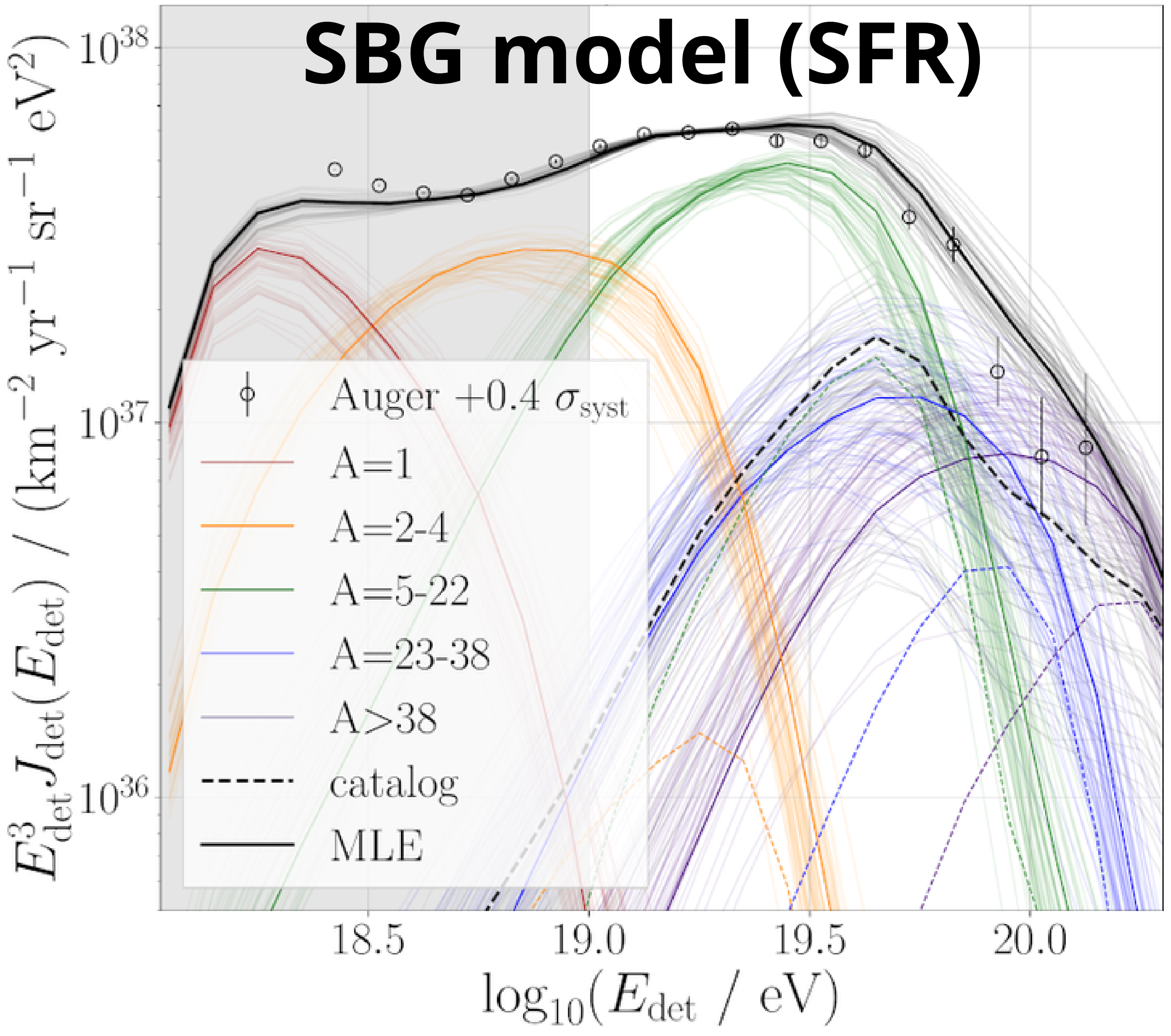
The next step: combining observables

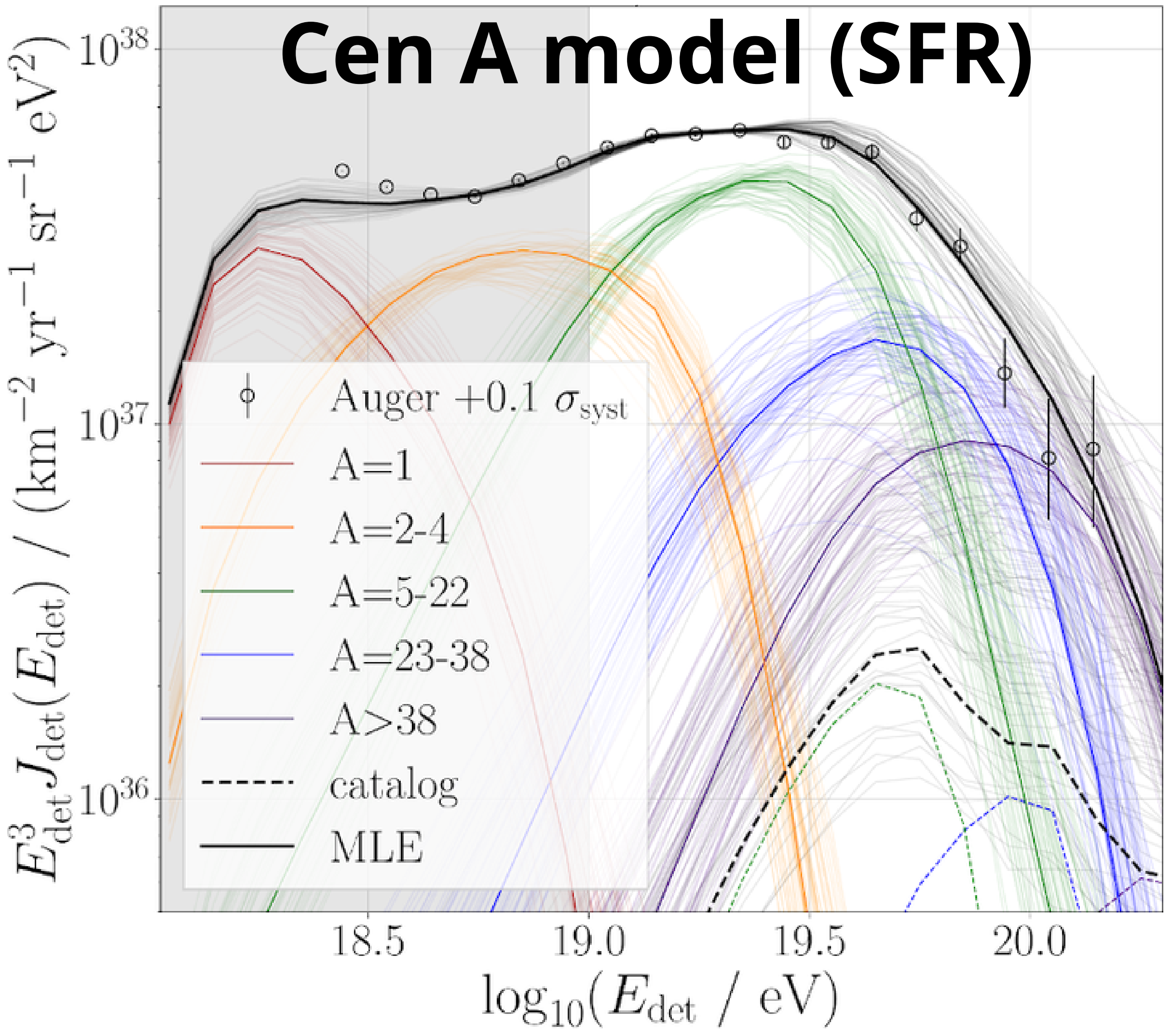
- Energy, X_{max} and arrival direction
- Homogeneous background + Source catalogs (SBG / γ-AGN) or single source (Cen A)
- Blurring of ~14° to 20° at a rigidity of 10 EV

40 EeV
$10^{19.6}$ eV

80 EeV
$10^{19.9}$ eV







- SBGs model preferred at 4.5σ. Centaurus region contributes most
- Overdensity in Centaurus region described either by NGC4945 (SBG), or by Cen A
- In both, source contributes to ~3% of flux at 40 EeV

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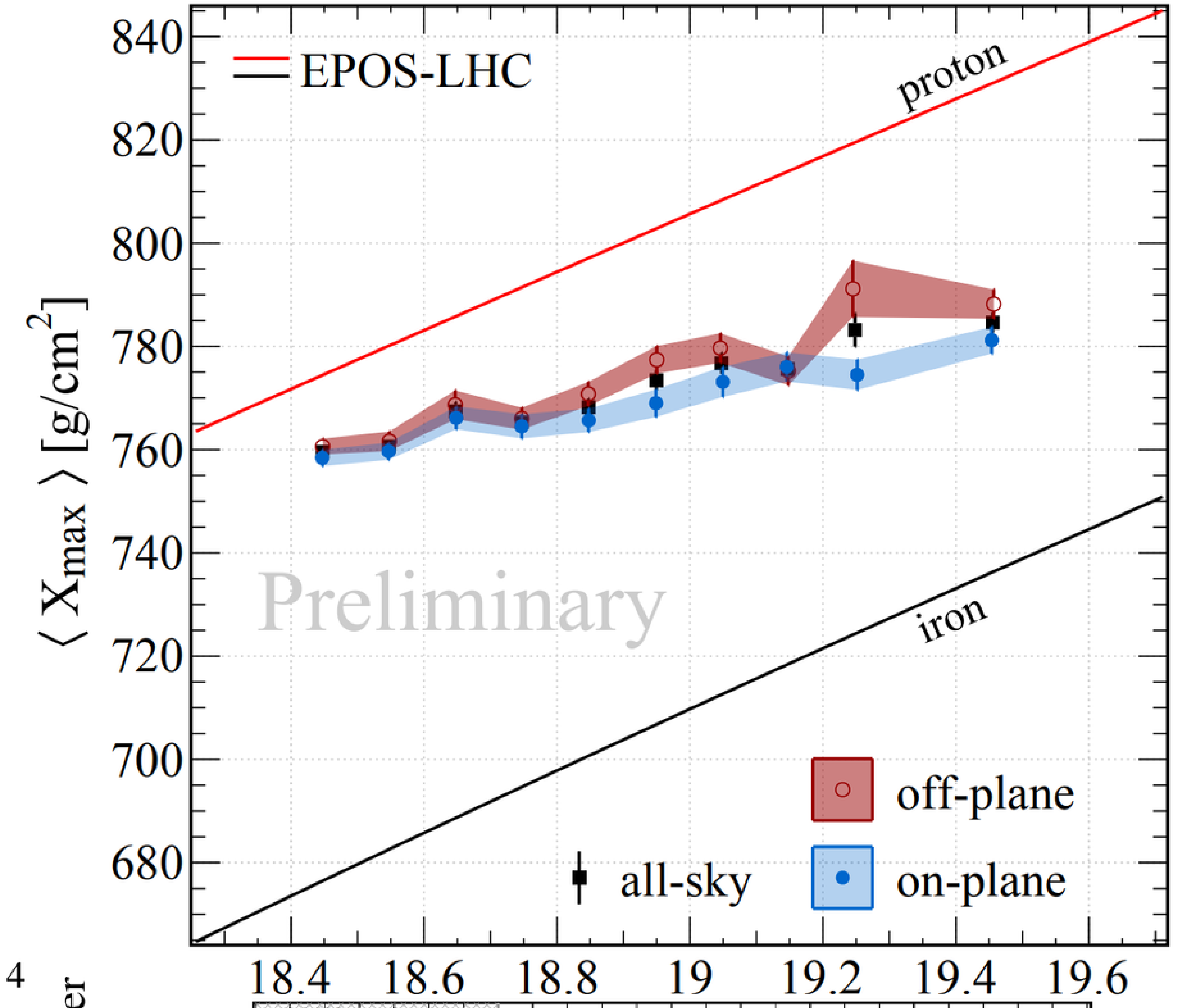
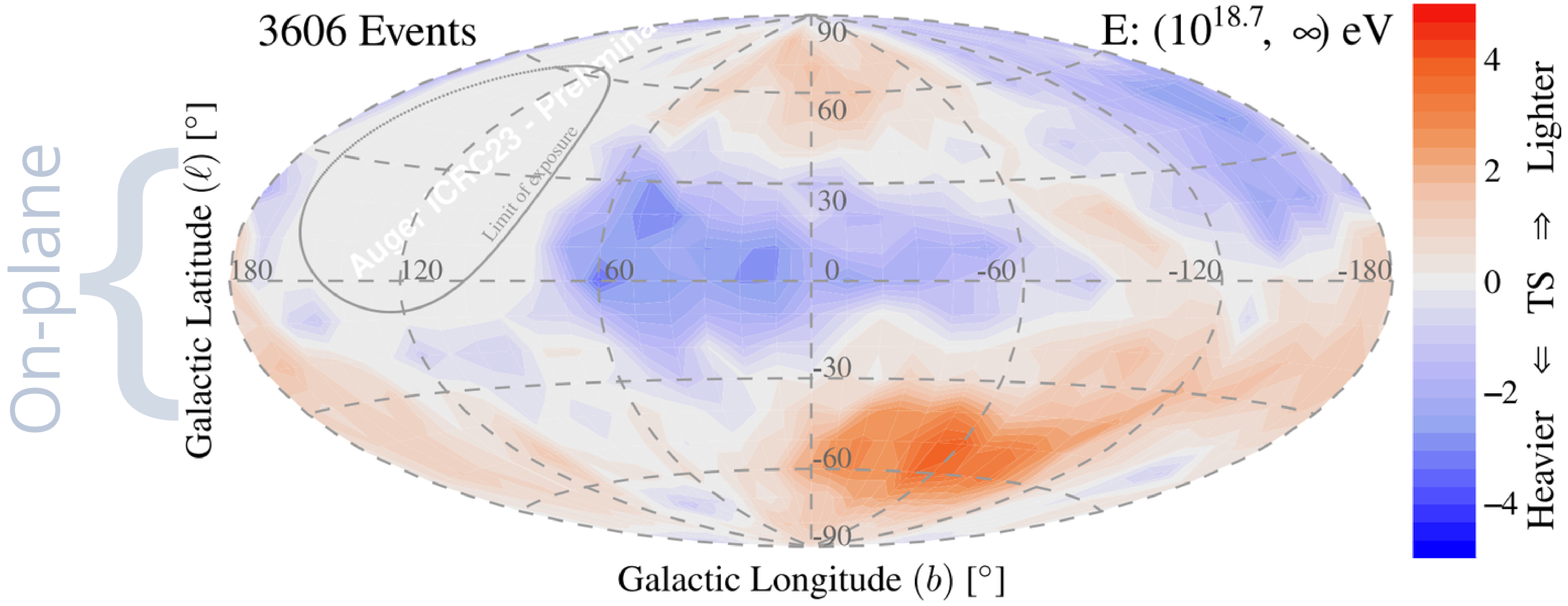
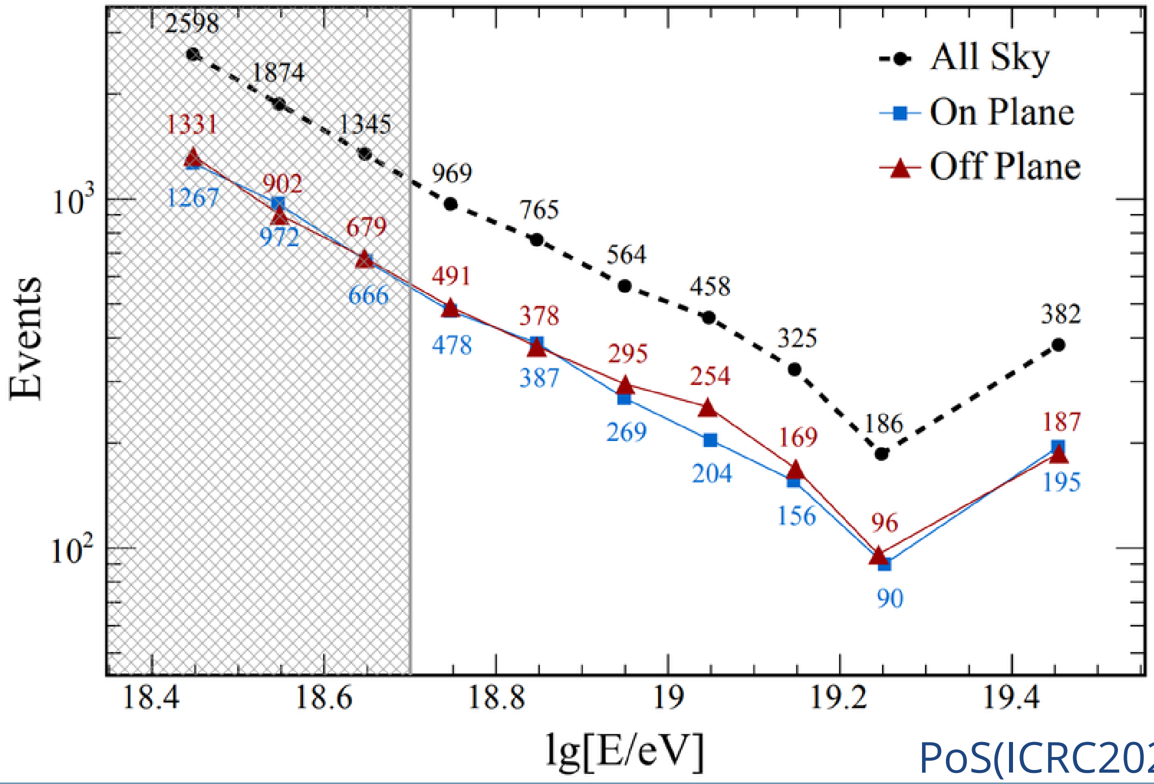
On- / Off-plane analysis

- Hybrid data: FD & SD combined
- X_{max} as mass proxy
- Probe mass-dependent anisotropies
- Current significance 2.5σ
- With this method, 5σ not reached by 2035: mass estimator from SD needed







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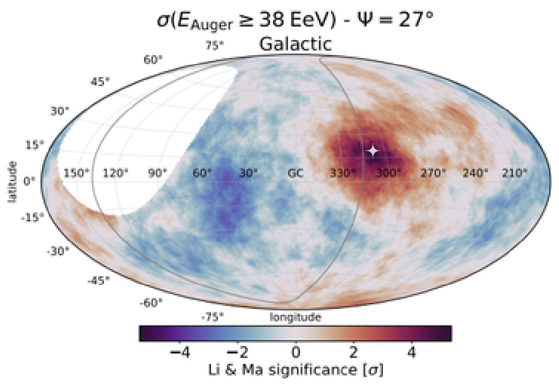
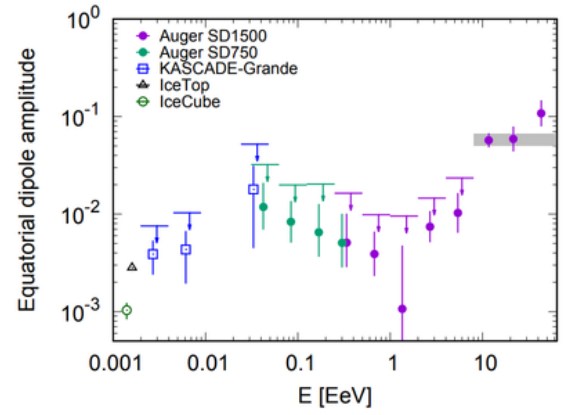
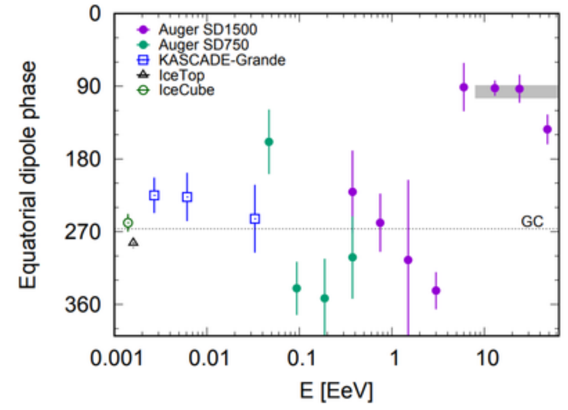
Summary



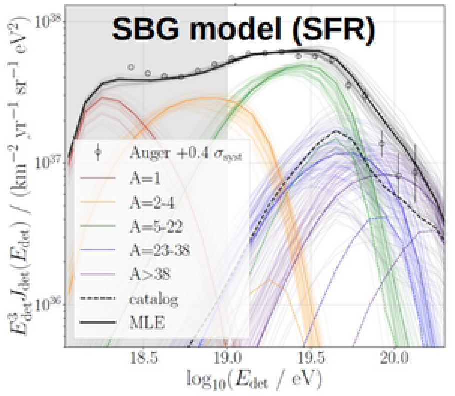
- Arrival direction anisotropies are relevant in different scales:
  - Intermediate scale: increasing excess in the Centaurus region (**4.0σ**)
  - Large scale: significant dipole structure in 8 to 16 EeV (**5.7σ**) and > 8 EeV (**6.9σ**)



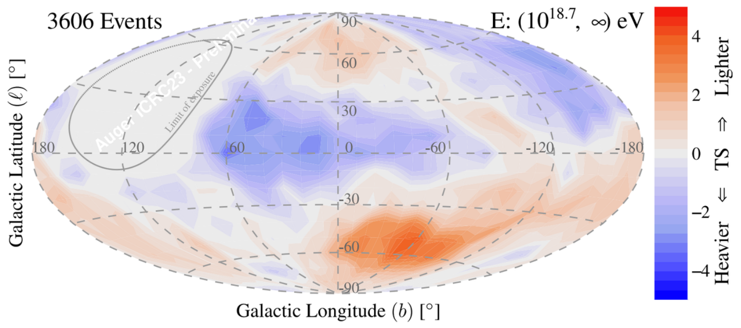


- Strong indications of a transition from galactic- to extra-galactic origin of the observed anisotropies of cosmic rays in the EeV region

- Complementary information is being used to further investigate:
  - Combined fit with energy and X_{max} points to favorable astrophysical scenarios



- Next on probing the origin of CRs: propagation effects are mass- and charge-dependent
  → **AugerPrime**



Thank you
Muito obrigada

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UNSAM
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CosmicFlow-2 (Hoffman et al. 2018)