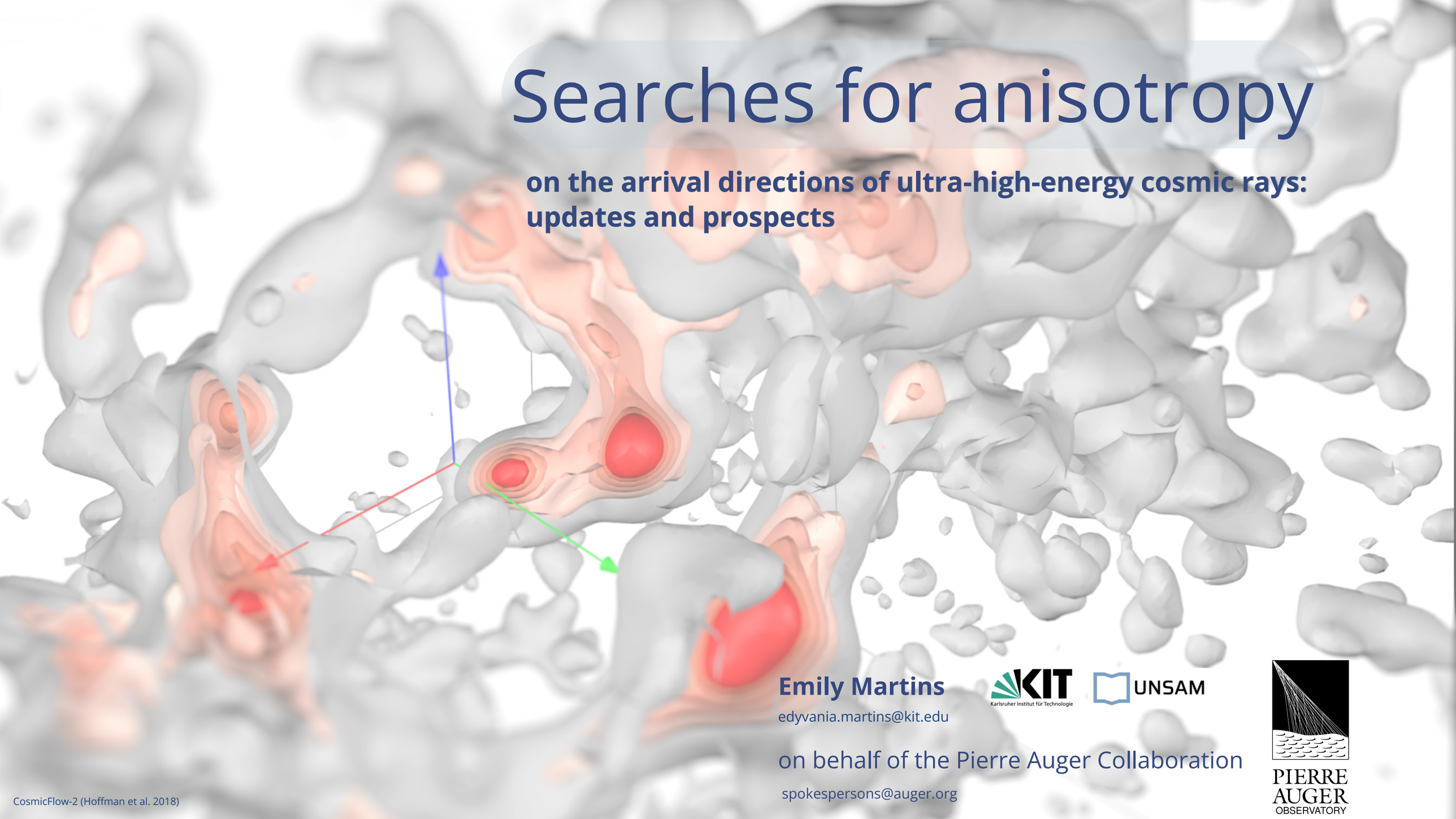
Searches for anisotropy

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



Emily Martins

edyvania.martins@kit.edu

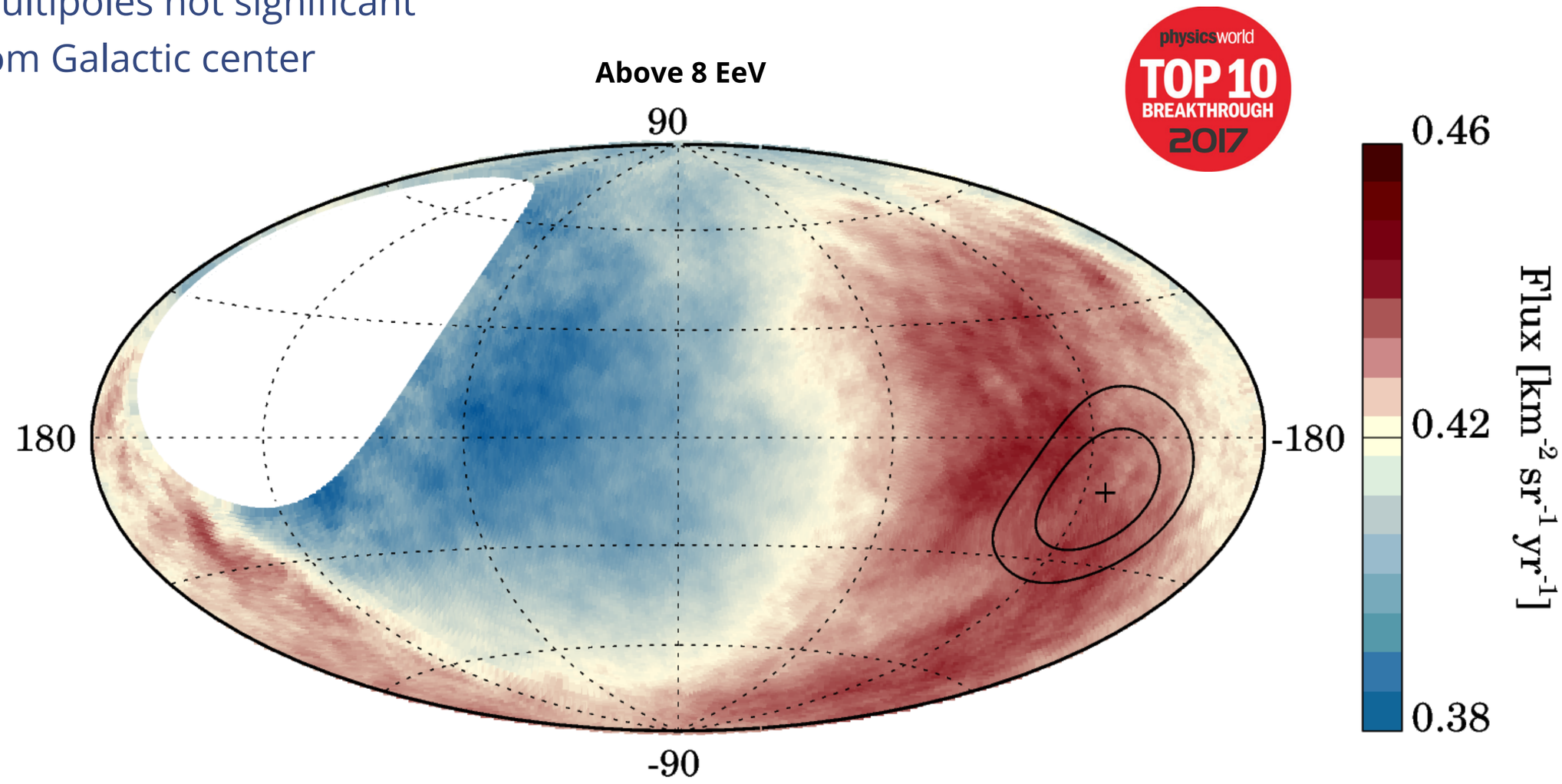
on behalf of the Pierre Auger Collaboration

spokespersons@auger.org

CosmicFlow-2 (Hoffman et al. 2018)

Extragalactic UHECR

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



Science 357 (2017) 1266

Large Scale Anisotropy

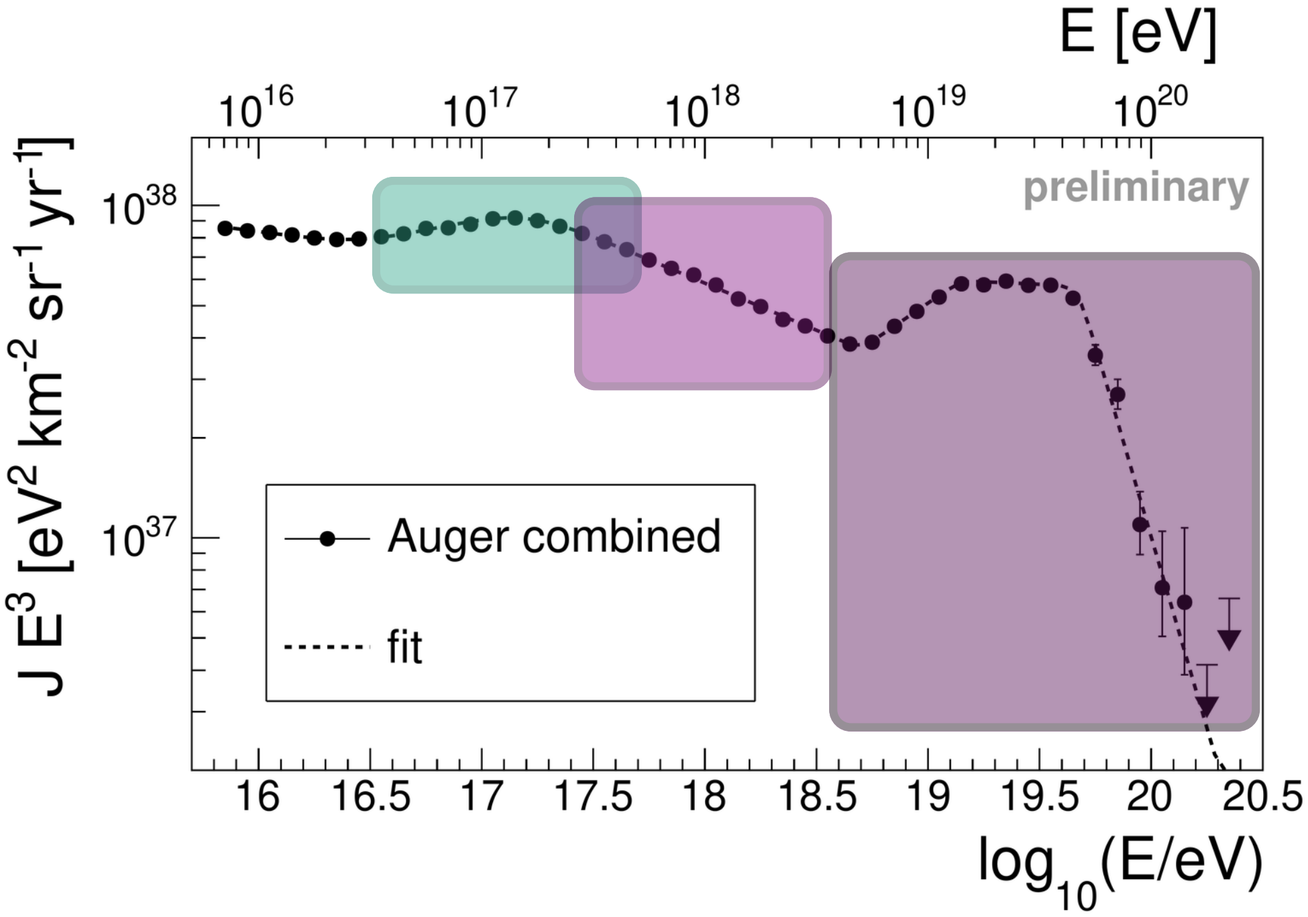
The dataset

- 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



Harmonic Analysis

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

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

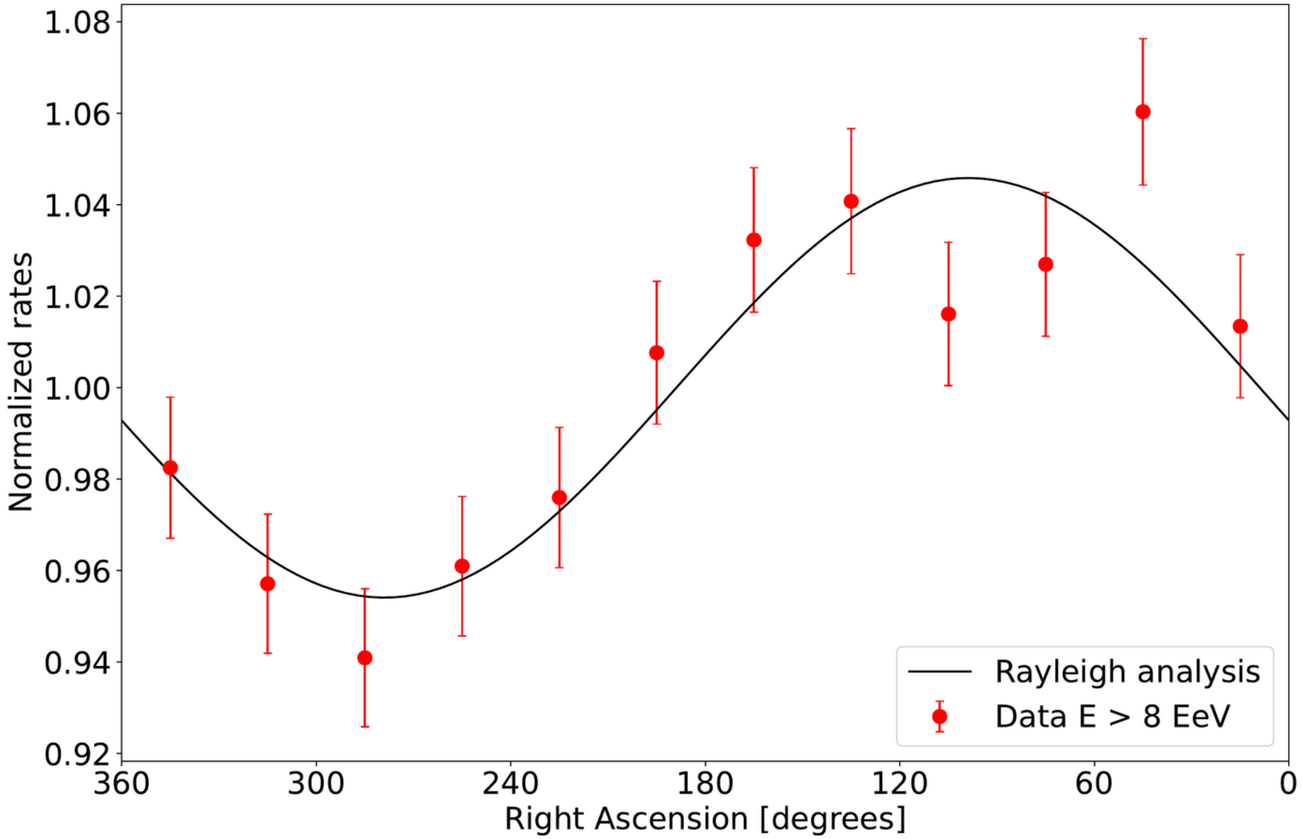
- Amplitude and phase:

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

- **3D dipole amplitude**

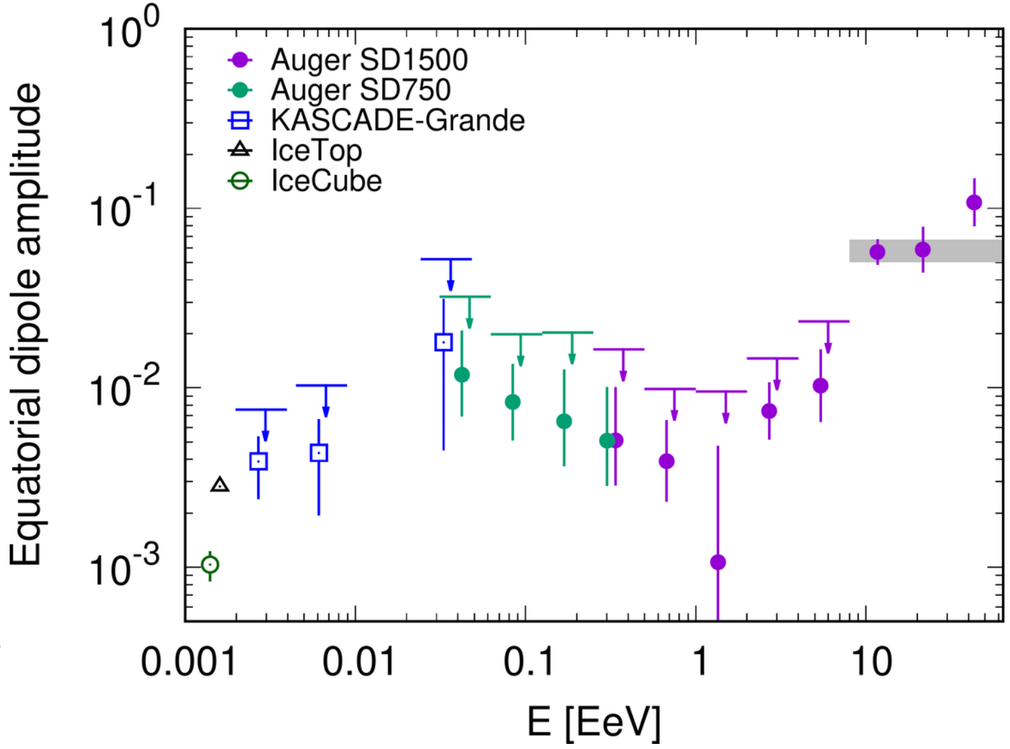
$$d_\perp \simeq \frac{r_1^\alpha}{\langle \cos \delta \rangle} \qquad d_z \simeq \frac{b_1^\phi}{\cos \ell_{\rm obs} \langle \sin \theta \rangle}$$

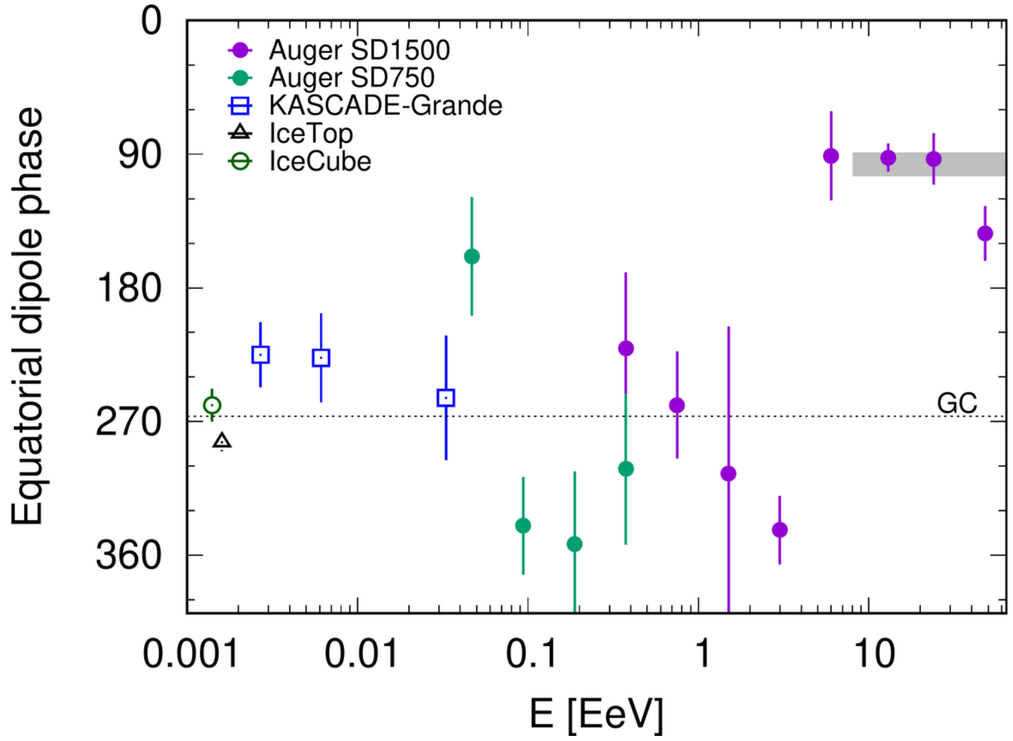
$\langle \cos \delta \rangle = 0.78$



Amplitude & phase

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



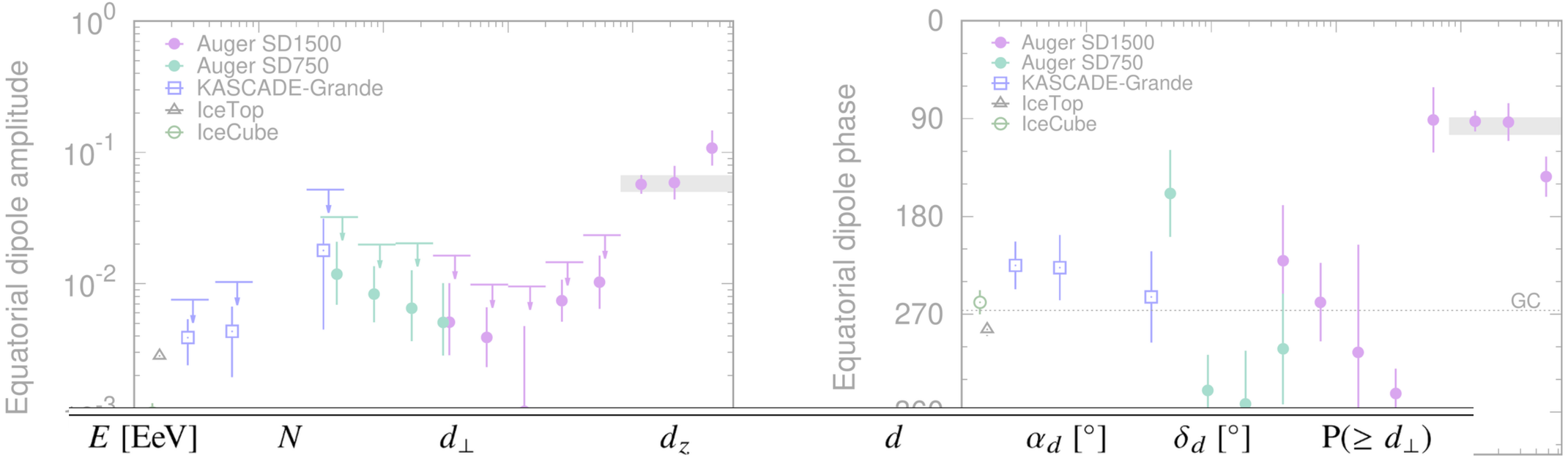


Increasing amplitude above 2 EeV + Phase shifted away from Galactic centre

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

PoS(ICRC2023) 252

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	
≥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}	
≥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}	

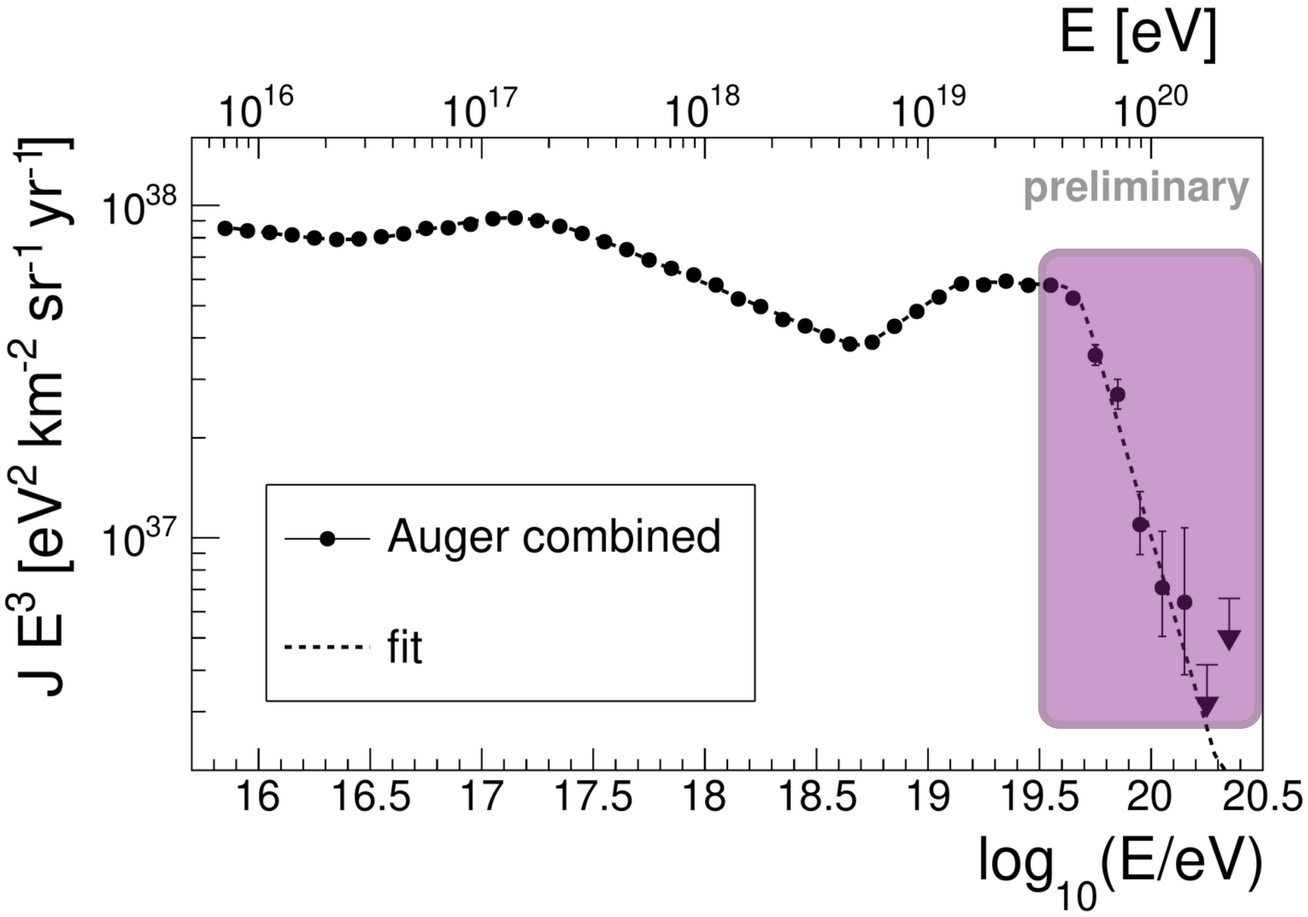
Intermediate Scale Anisotropy

The dataset

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

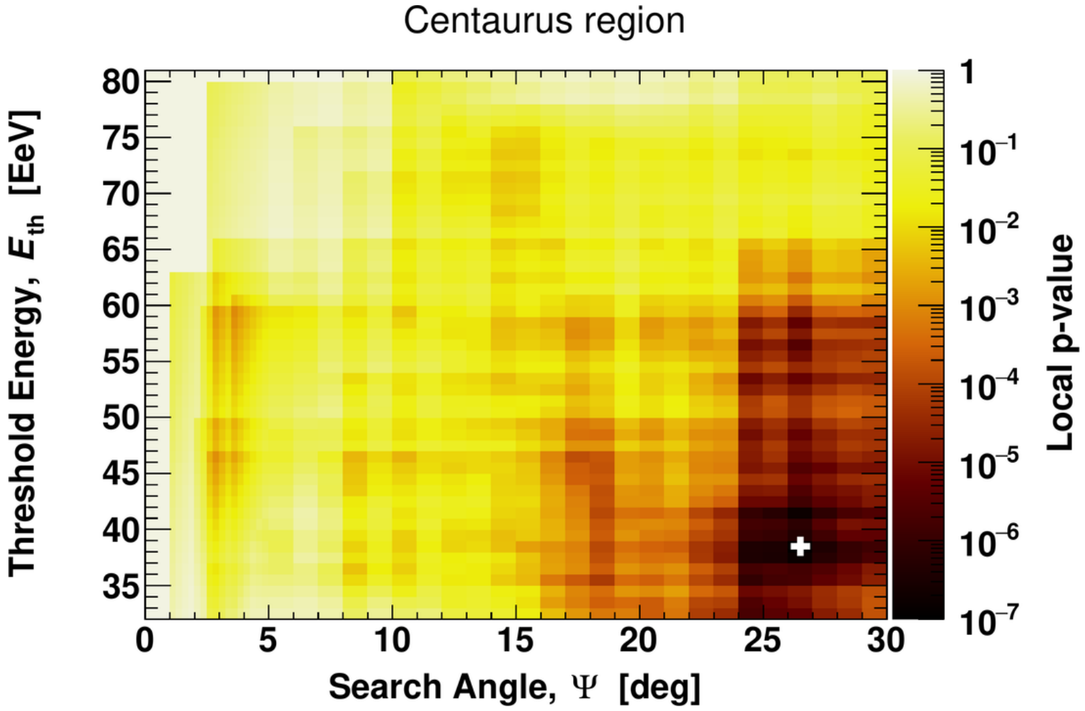
Exposure

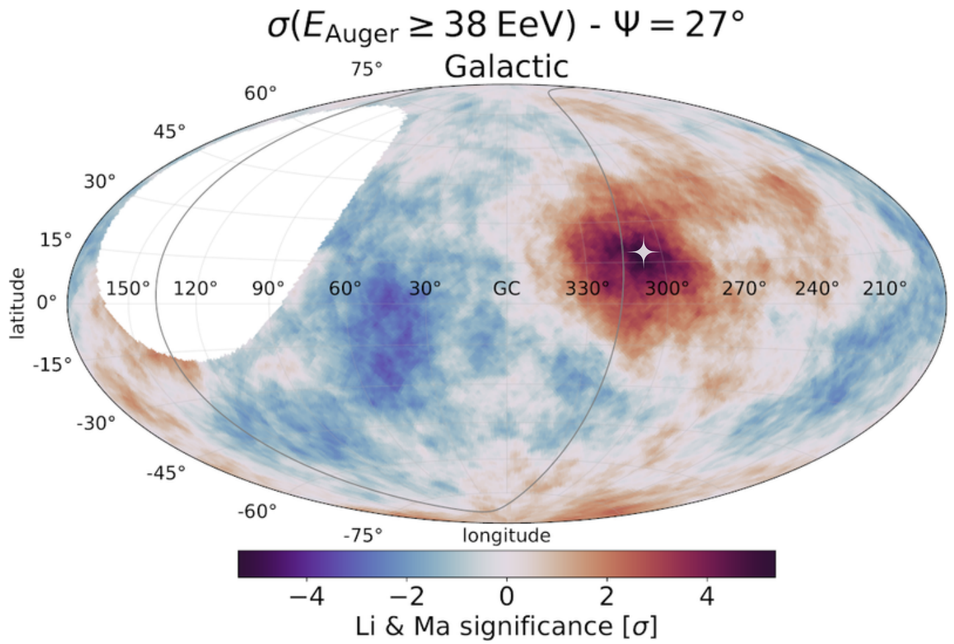
SD 1500 array = 135 000 km^2 yr sr

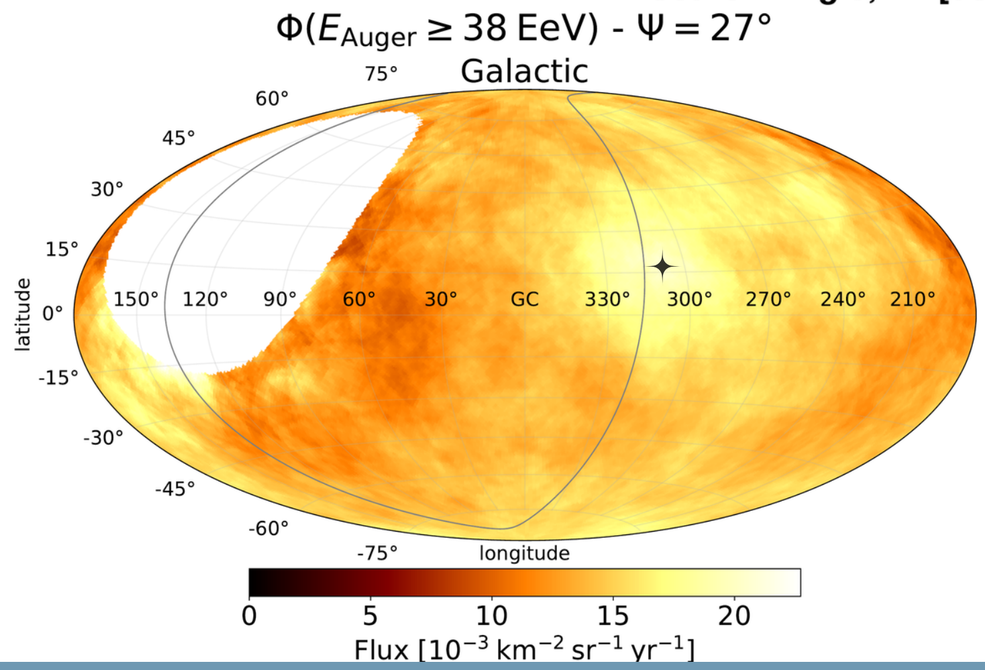


Centaurus excess

- 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**)





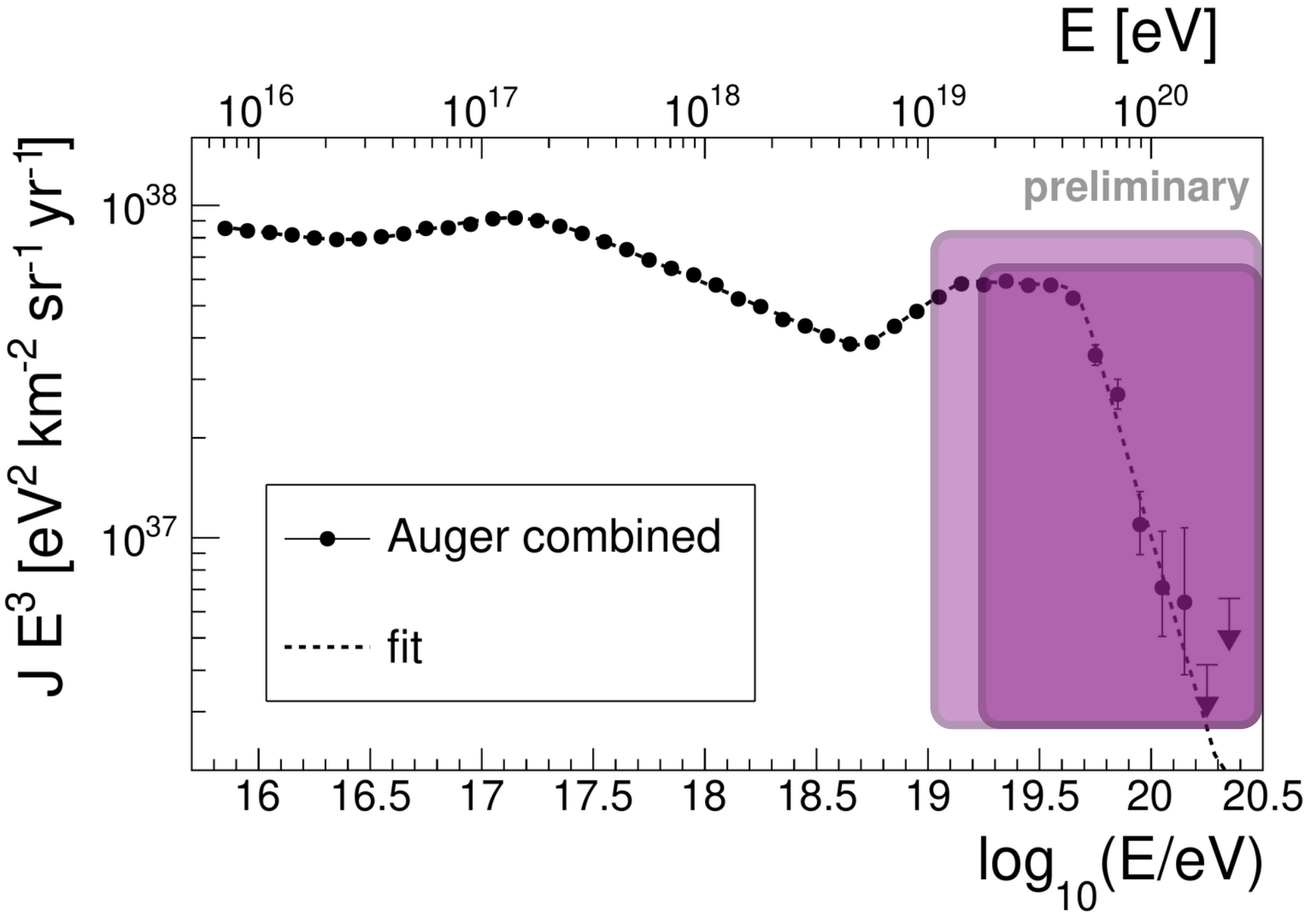


PoS(ICRC2023) 252

The next step: combining observables

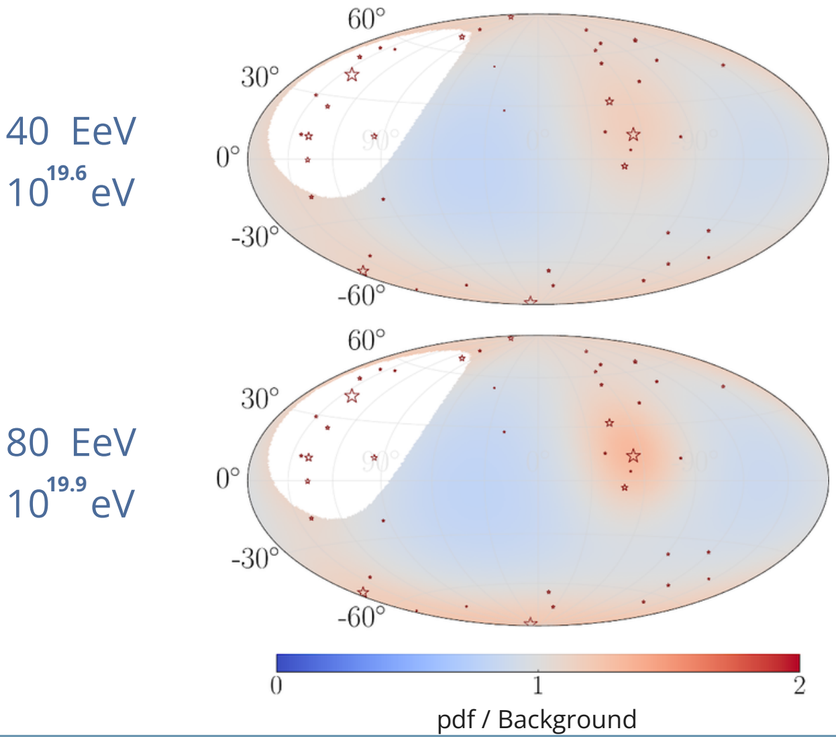
The dataset

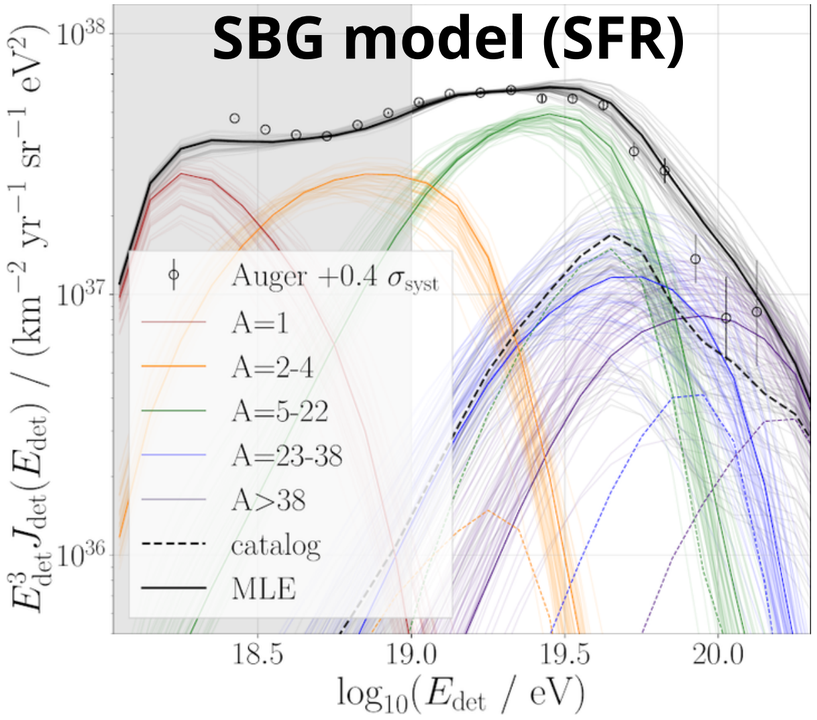
- **Arrival directions**
  - >16 EeV
  - Jan. 2004 to Dec. 2020
  - Exposure 95 700 km^2 yr sr ($\theta < 60°$) and 26 300 km^2 yr sr ($60° < \theta < 80°$)
- **Energy**
  - >10 EeV
  - Jan. 2004 to Aug. 2018, $\theta < 60°$
  - Exposure 60 426 km^2 yr sr
- **Shower-maximum depth distribution**
  - >10 EeV
  - FD measurements

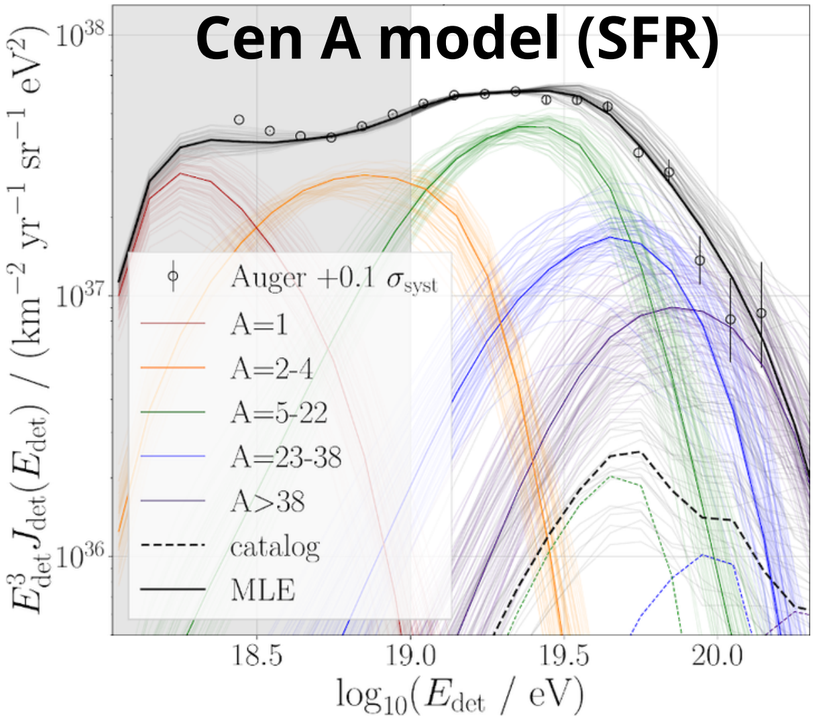


The next step: combining observables

- 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



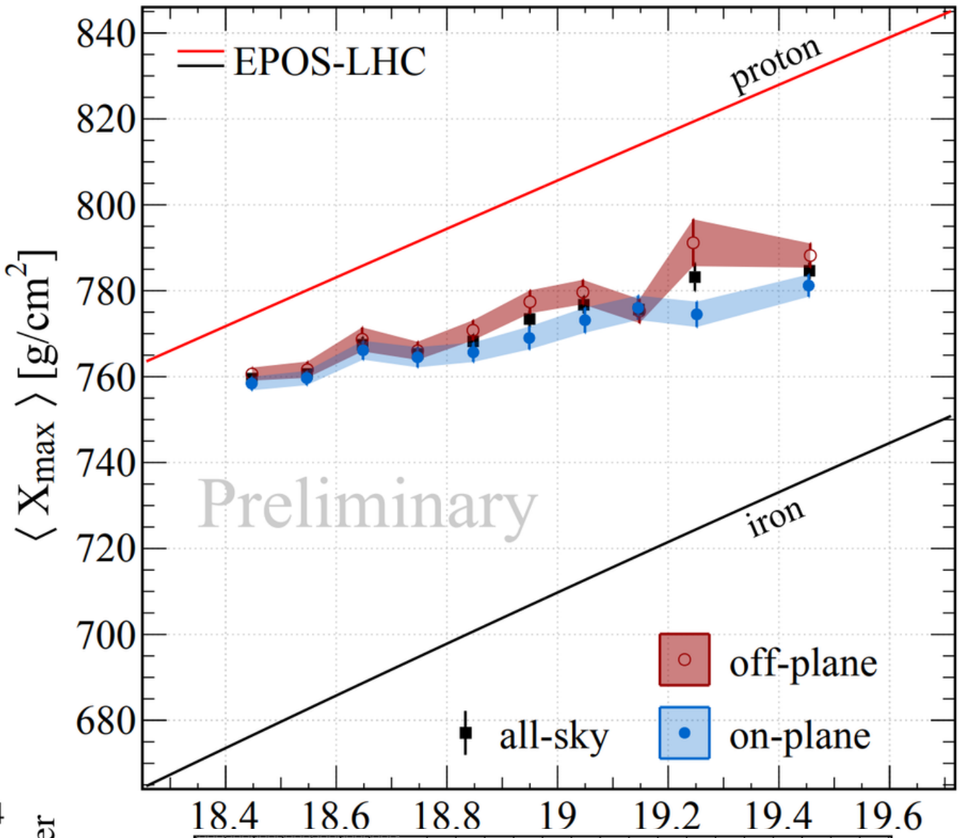


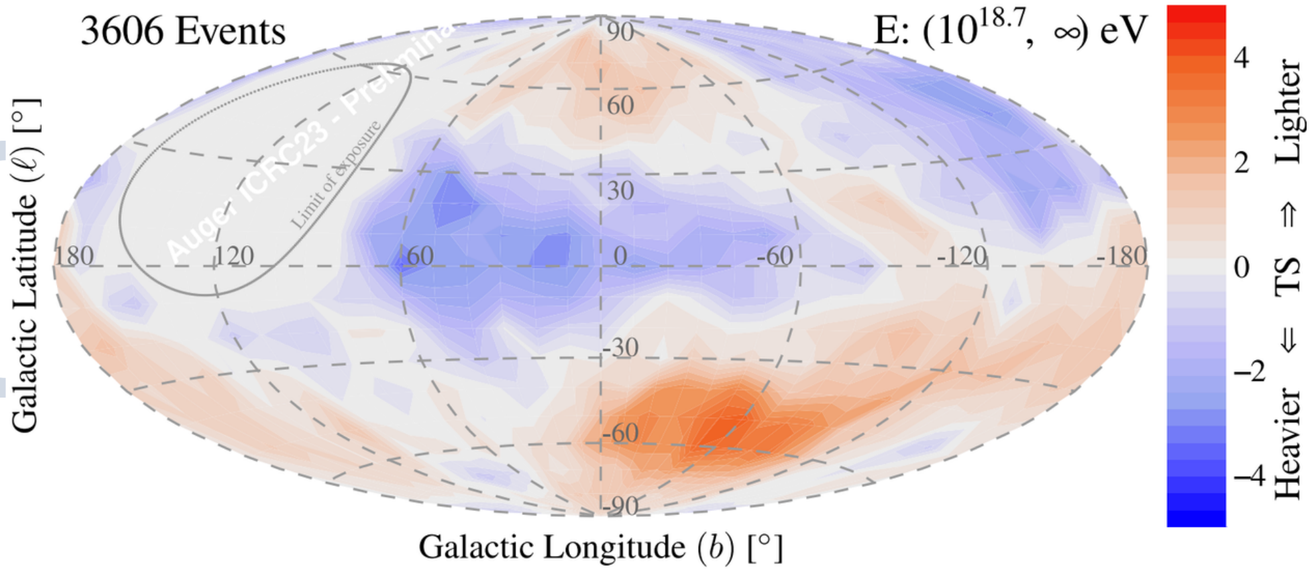


- SBGs model preferred at 4.5σ. Centaurus region contributes most
- Overdensity in Centaurus region described either by NGC4945 (SBG), or by Cen A
- In both, source contributes to ~3% of flux at 40 EeV

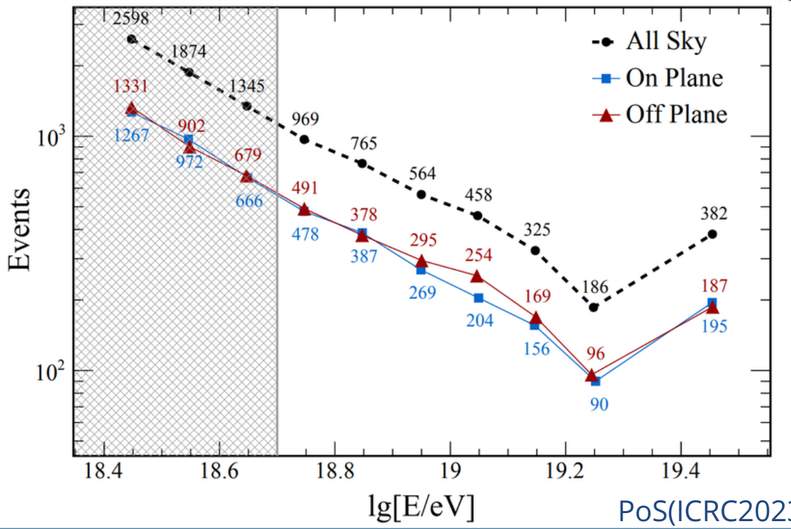
On- / Off-plane analysis

- 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



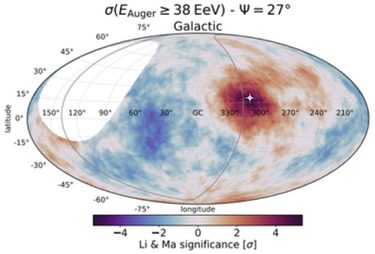


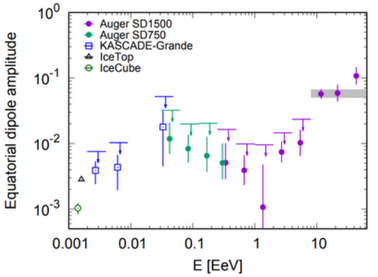
On-plane

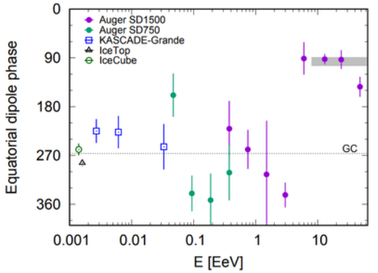


PoS(ICRC2023) 365

Summary



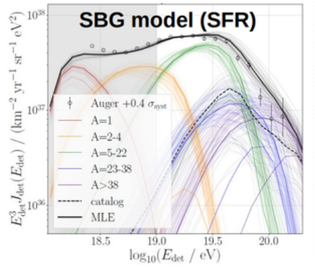




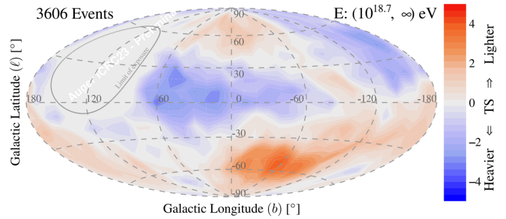
- Arrival direction anisotropies are relevant in different scales:
  - Intermediate scale: increasing excess in the Centaurus region (**4.0σ**)
  - Large scale: significant dipole structure in 8 to 16 EeV (**5.7σ**) and > 8 EeV (**6.9σ**)

- 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

Emily Martins
edyvania.martins@kit.edu

on behalf of the Pierre Auger Collaboration

spokespersons@auger.org

CosmicFlow-2 (Hoffman et al. 2018)