Constraining the sources of ultra-high-energy cosmic rays

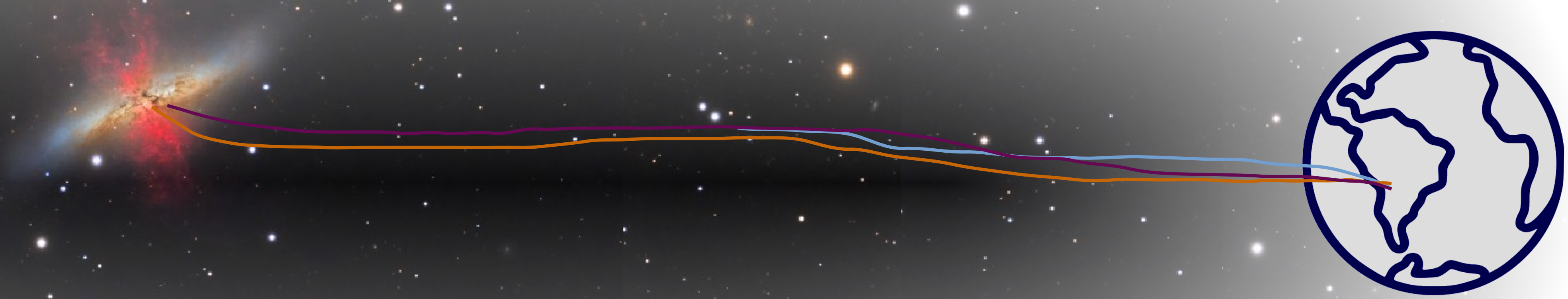
with arrival direction, spectrum, and composition data measured at the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

Radboud University

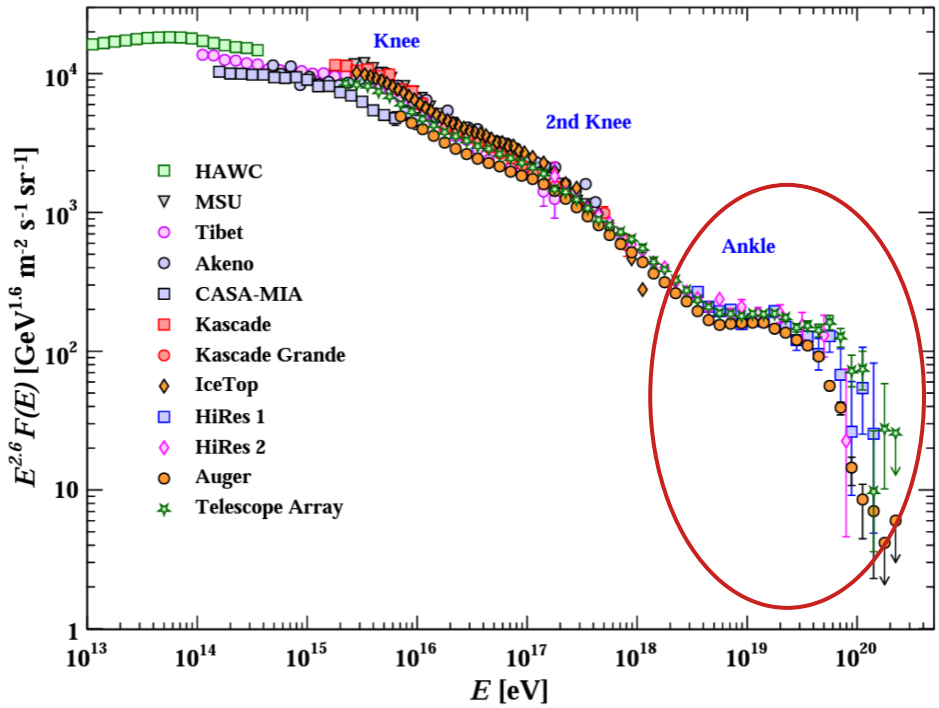
Teresa Bister for the Pierre Auger Collaboration

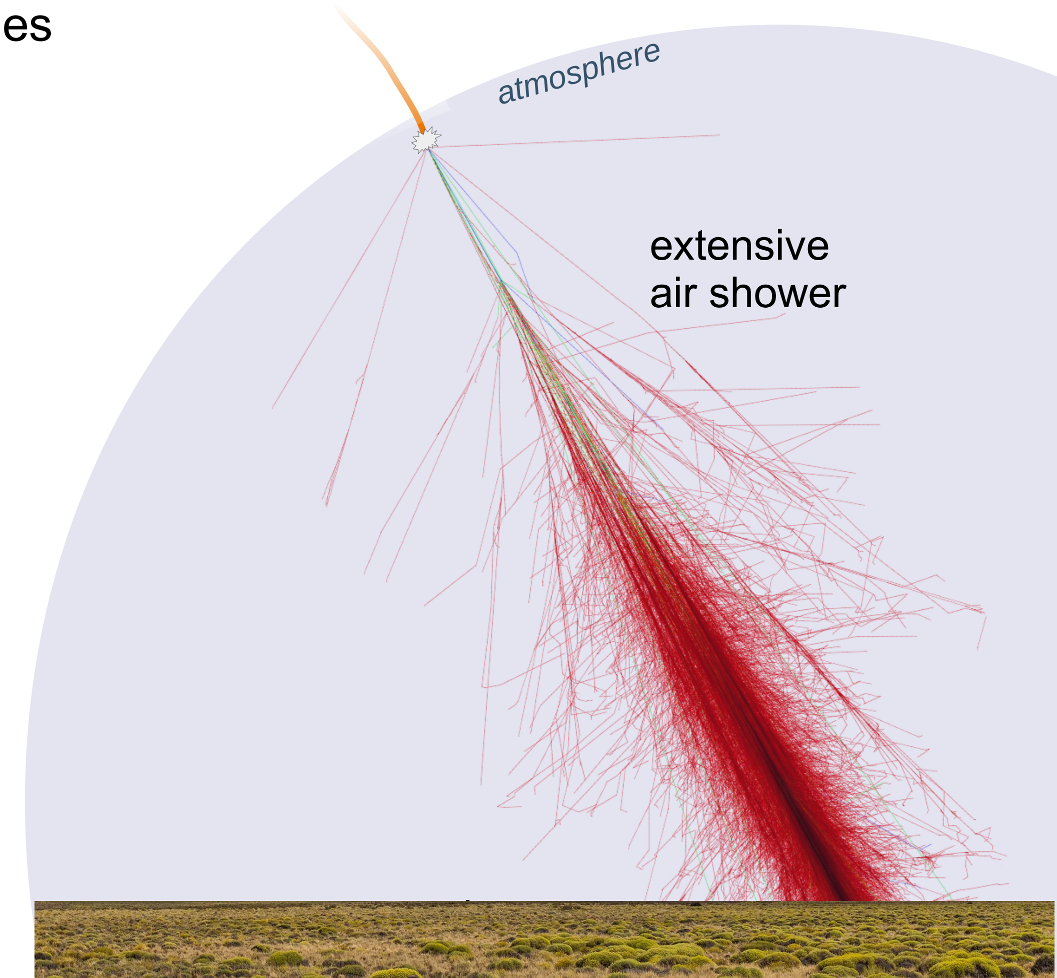
17.05.2023, Cosmic ray anisotropy workshop, Chicago



Measurement of UHECRs

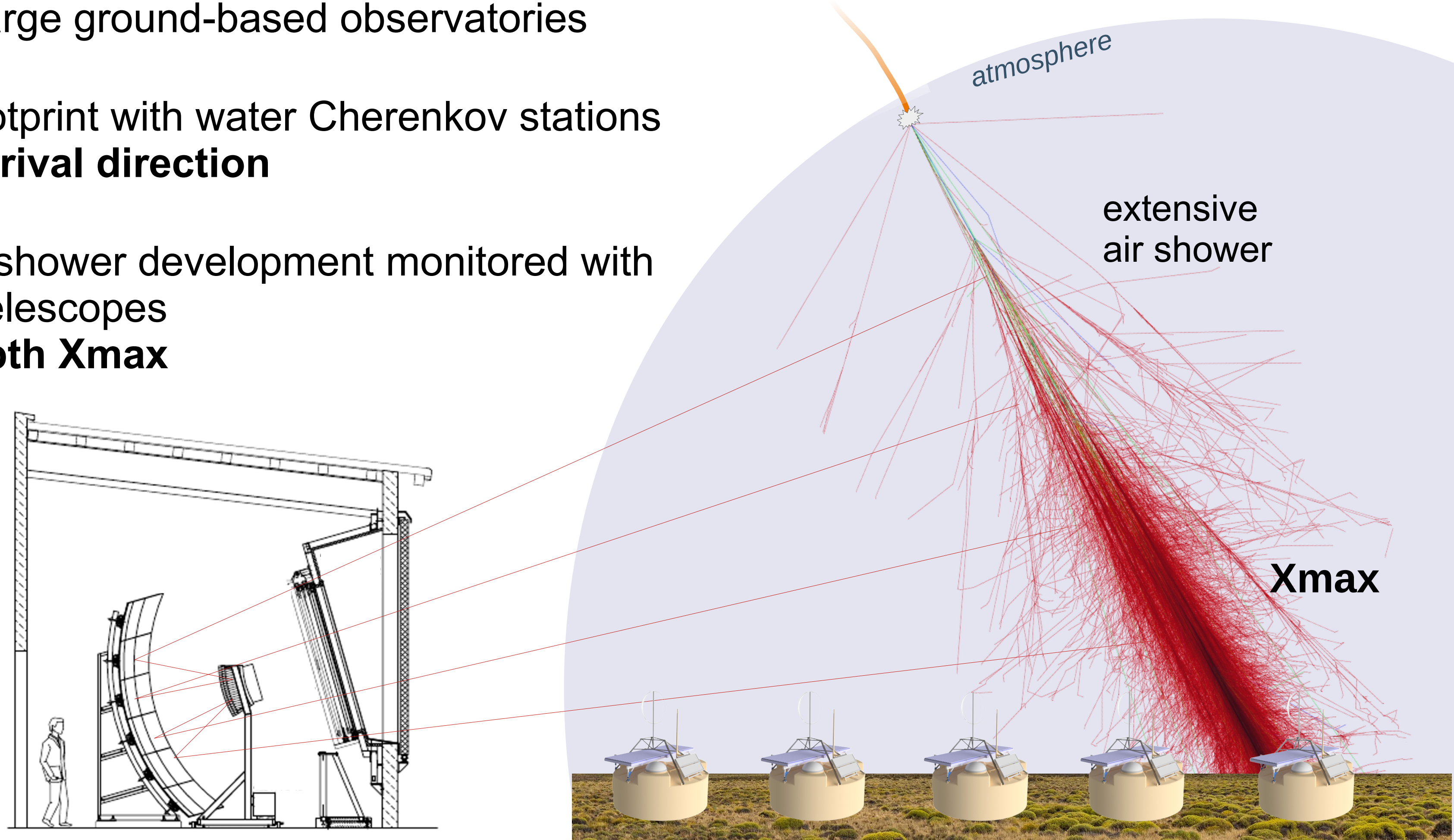
- ultra-high-energies: flux only few particles per century per km²
  → need very large ground-based observatories





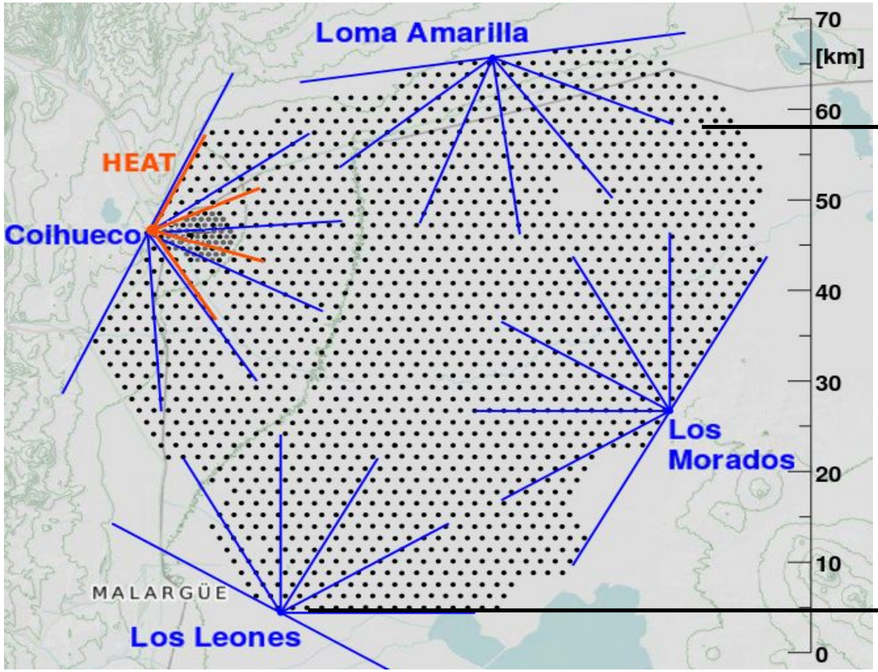
Measurement of UHECRs (on the example of the Pierre Auger Observatory)

- ultra-high-energies: flux only few particles per century per km²
  → need very large ground-based observatories
- detection of footprint with water Cherenkov stations
  → **energy + arrival direction**
- in dark nights: shower development monitored with fluorescence telescopes
  → **shower depth Xmax**



The Pierre Auger Observatory

- largest observatory for UHECRs in the world (3000 km^2)
- located in Argentina, close to Malargüe



hybrid detection:

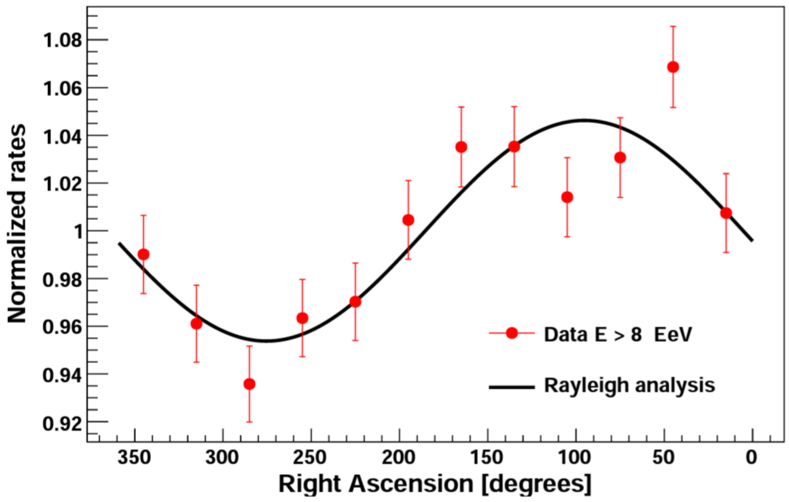
1660 water cherenkov detectors (SD)

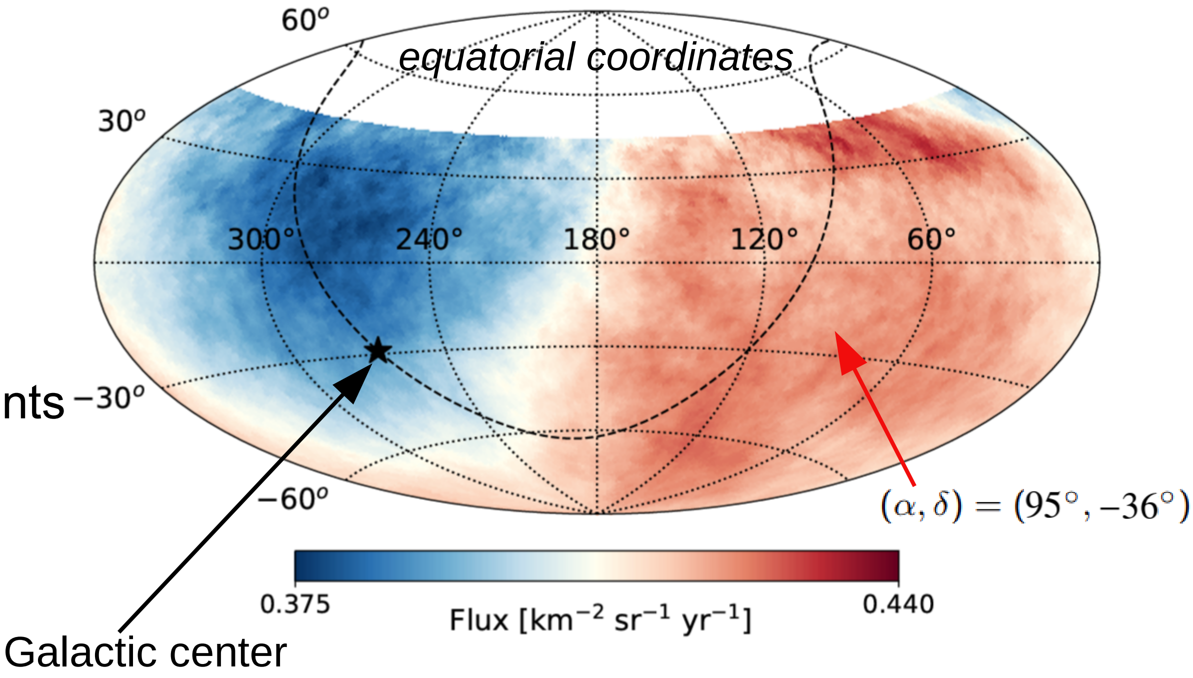
27 fluorescence telescopes (FD)

AugerPrime upgrade

Large-scale anisotropy

- harmonic analysis in right ascension
  → **dipolar modulation**
- data above 8 EeV:
  - significance > 5σ
  - amplitude ~7%
  - no significant quadrupolar components

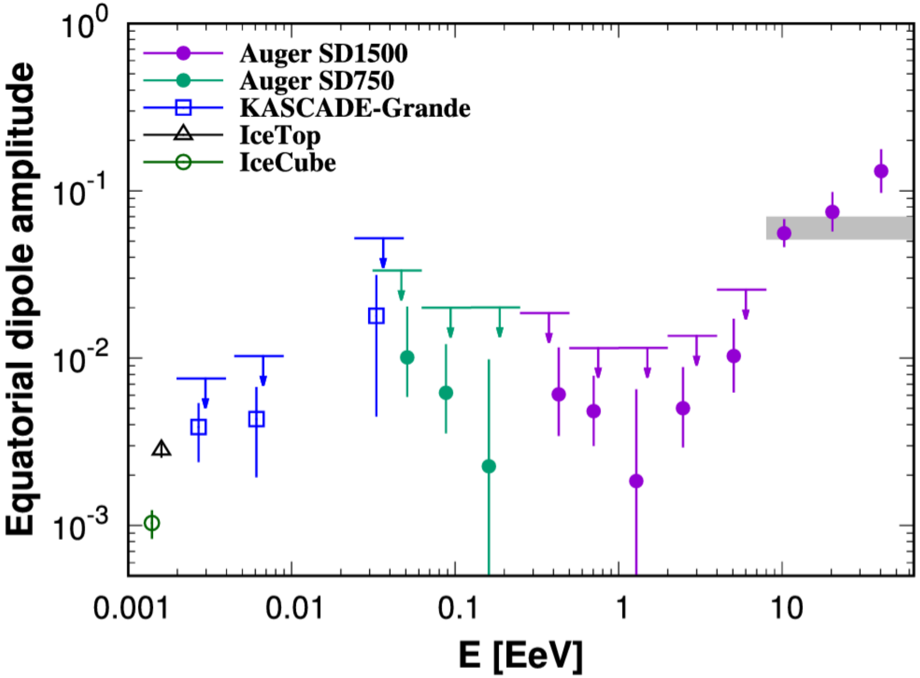


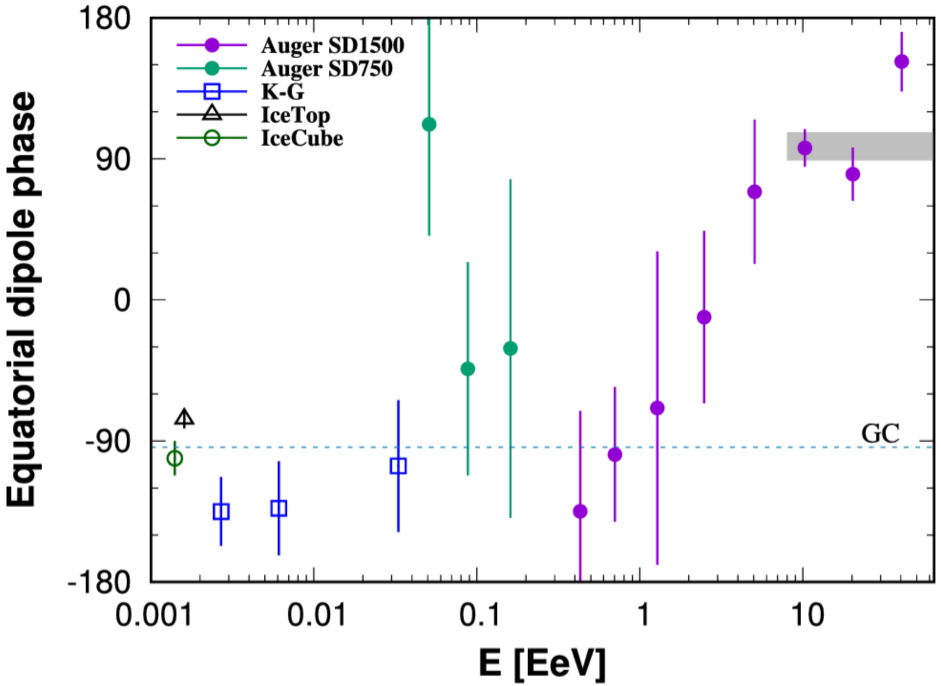


dipole points 115° away from Galactic center
→ indication for **extragalactic origin of UHECRs**

A. Aab et al. Science 357 6357 (2017)
R. de Almeida for the Pierre Auger Collaboration, PoS (ICRC2021)

Large-scale anisotropy: energy dependency





amplitude grows with energy
(lower energy amplitudes not significant)

phase moves from Galactic center to opposite
transition from Galactic to extragalactic injection at few EeV

A. Aab et al., ApJ 891 142 (2020)

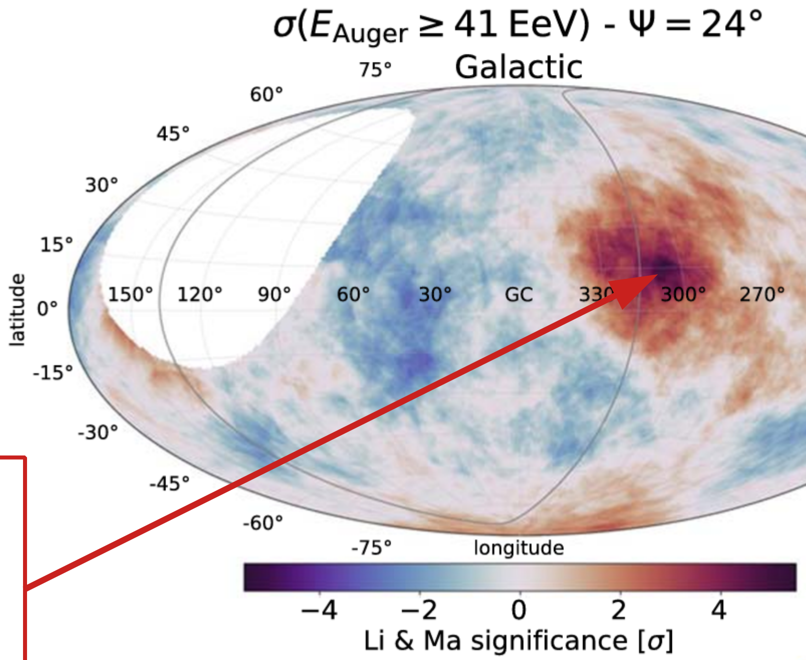
Small-scale anisotropies

- **blind search** over 1° pixels
- 2 scan parameters:
  - energy threshold
    32 EeV ≤ E_{th} ≤ 80 EeV
  - circular tophat window
    1° ≤ ψ ≤ 30°

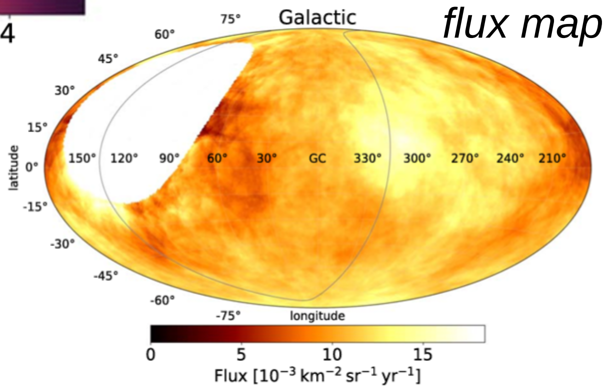
most significant excess:

local Li-Ma significance 5.4σ

post-trial **p=3%**



LiMa significance map



flux map

large trial factor due to whole-sky scan
→ comparison to source candidates

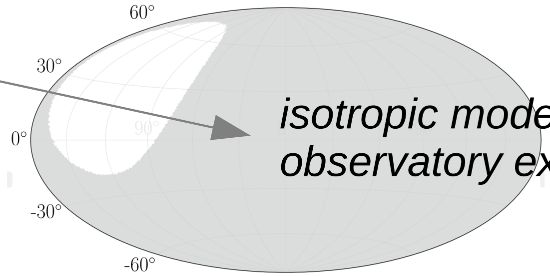
Correlations with source candidates

comparison of measured ADs with **model flux maps**:

$$\mathrm{pdf}_{\mathrm{AD-only}} = f_{\mathrm{AD-only}} \cdot S_{\delta_{\mathrm{AD-only}}} + (1 - f_{\mathrm{AD-only}}) \cdot B$$

signal fraction

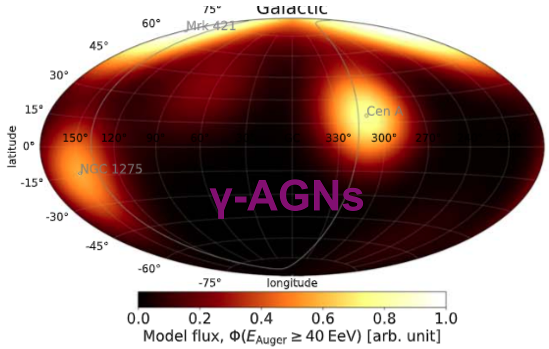
magnetic field blurring

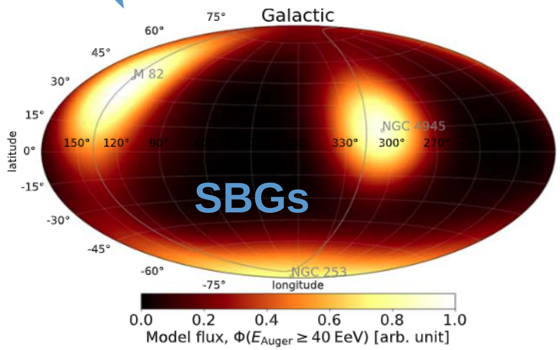


isotropic model: observatory exposure

jetted active galactic nuclei ***γ-AGNs***

starburst galaxies ***SBGs***





likelihood function:

$$\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}}, \delta_{\mathrm{AD-only}}) = \prod_i \mathrm{pdf}_i(\vec{v}_i))$$

test statistic:

$$\mathrm{TS}_{\mathrm{AD-only}} = 2 \log \frac{\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}}, \delta_{\mathrm{AD-only}})}{\mathcal{L}_{\mathrm{AD-only}}(f_{\mathrm{AD-only}} = 0)}$$

P. Abreu et al ApJ 935 170 (2022) Link to Data and Code

Correlations with source candidates

comparison of measured ADs with **model flux maps**:

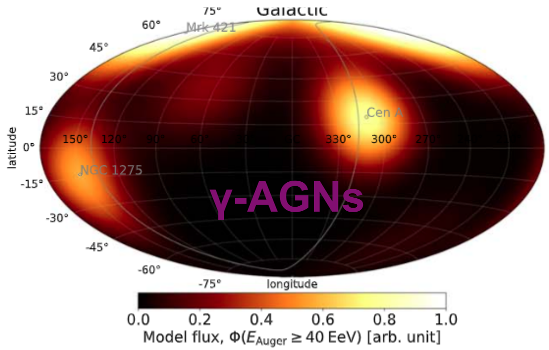
$$\mathrm{pdf}_{\mathrm{AD-only}} = f_{\mathrm{AD-only}} \cdot S_{\delta_{\mathrm{AD-only}}} + (1 - f_{\mathrm{AD-only}}) \cdot \ldots$$

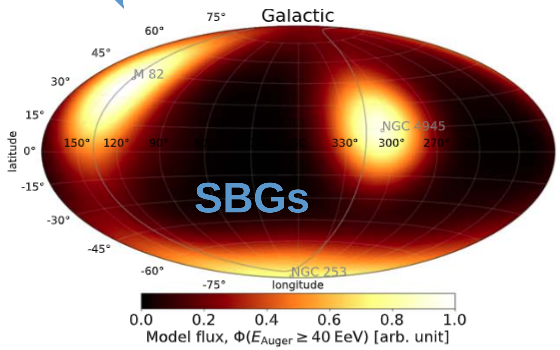
signal fraction

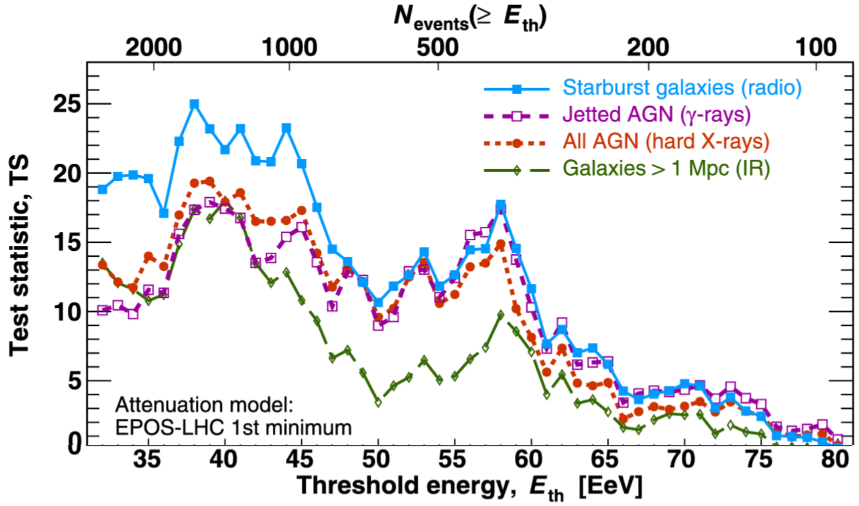
magnetic field blurring

jetted active galactic nuclei ***γ-AGNs***

starburst galaxies ***SBGs***



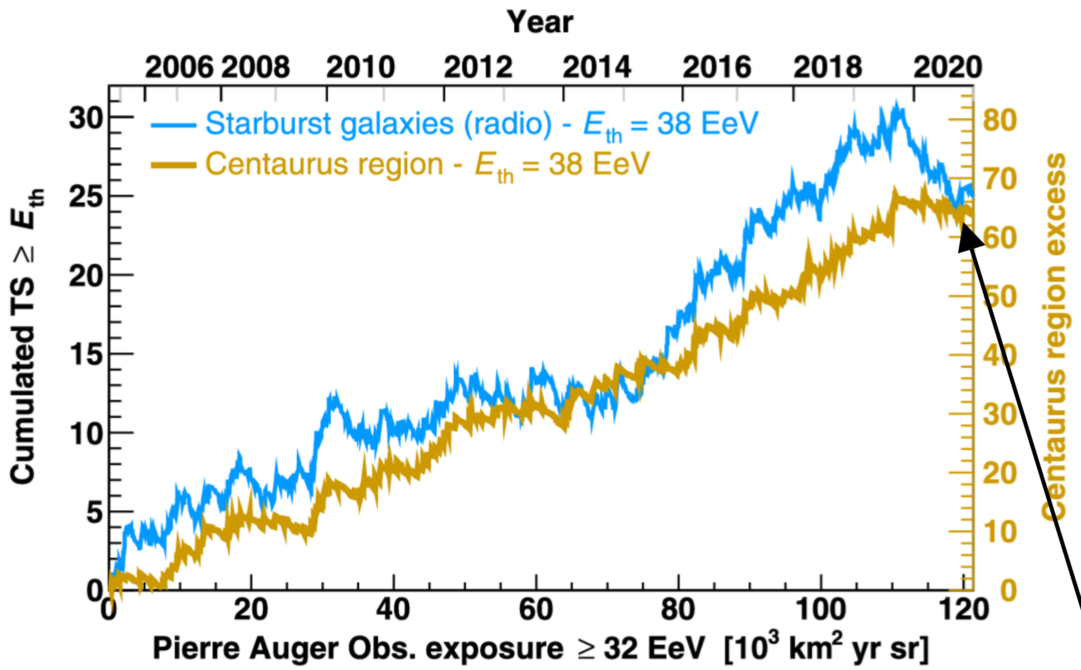


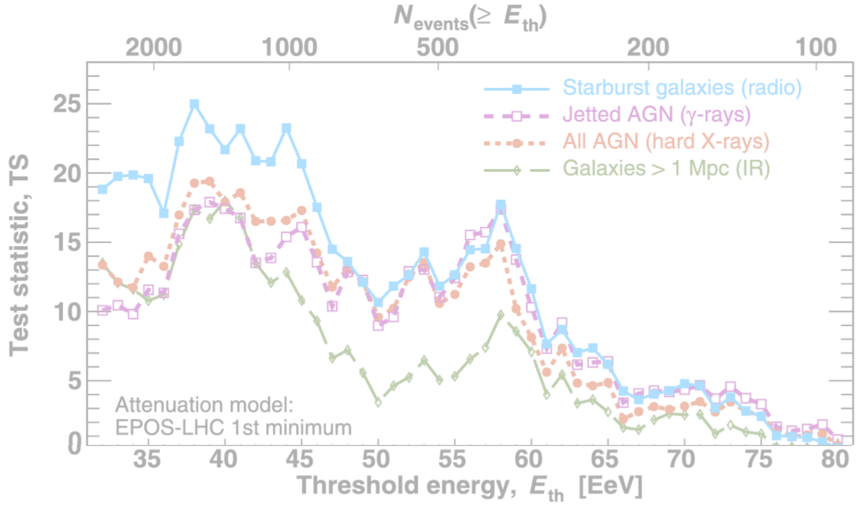


- SBG with largest significance → **4.0σ, δ=15°, f=9%**
- large contribution from NGC 4945 / **Cen A region**
- ***cannot distinguish catalogs significantly***

P. Abreu et al ApJ 935 170 (2022) Link to Data and Code

Correlations with source candidates





p_{CenA} = 4.5 x 10^{-5}

p_{SBG} = 3.2 x 10^{-5}

- SBG with largest significance → **4.0σ, δ=15°, f=9%**
- large contribution from NGC 4945 / **Cen A region**
- ***cannot distinguish catalogs significantly***

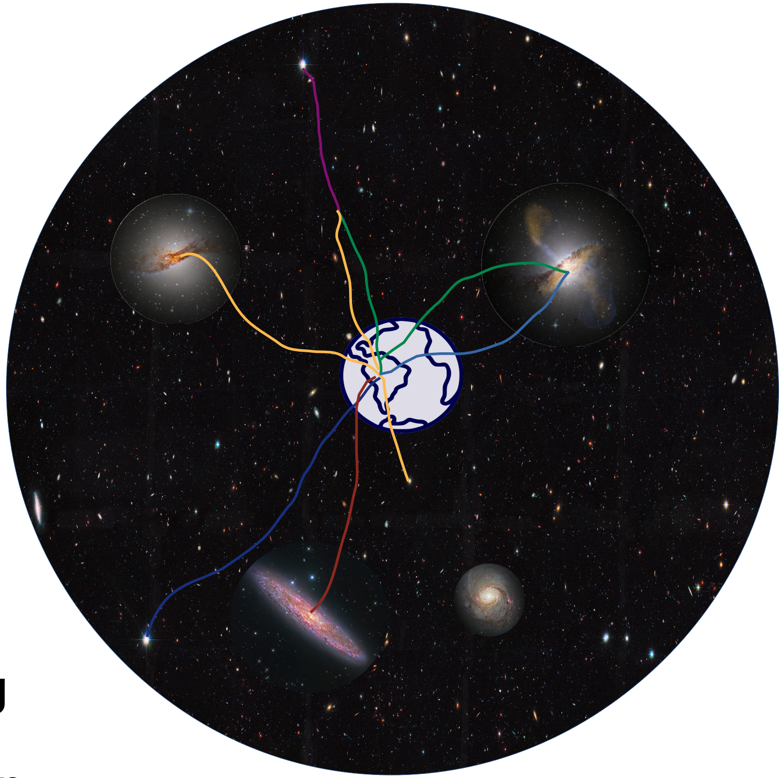
P. Abreu et al ApJ 935 170 (2022) Link to Data and Code

Idea of the combined fit

of arrival directions + spectrum + composition

- investigate scenario: source candidates as sources of the medium-scale overdensities around them
  - ➔ investigate SBGs / ɣ-AGNs / Centaurus A
  - ➔ include also spectrum and composition data
- **model whole process: source emission + propagation + detection**
  - ➔ possibility to constrain parameters of sources
  - ➔ contribution of each source shaped by flux weight + propagation influence
  - ➔ include **rigidity-dependent magnetic field blurring**

➔ **explain arrival directions + spectrum + composition with <u>one</u> model!**

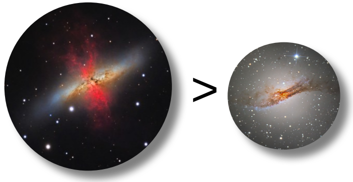


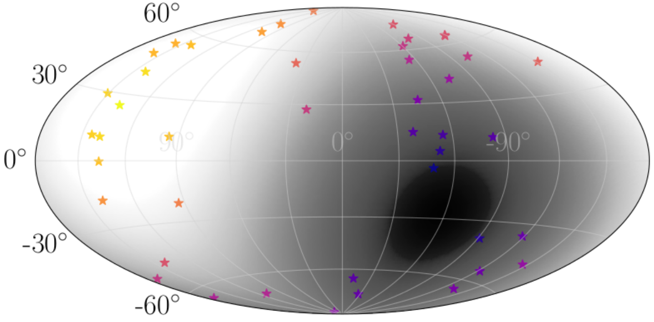
The astrophysical model: setup

inject UHECRs from candidate sources

include effects of:

1. distance
2. flux weight
3. direction

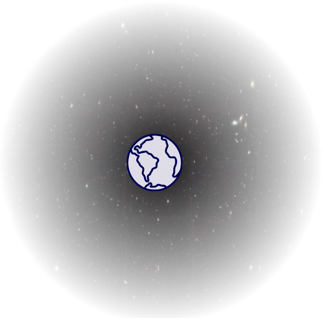




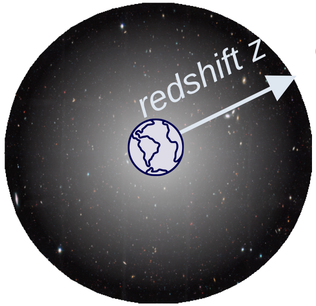
+

homogeneous background sources

include effect of source evolution:



less sources in past



more sources in past

$\propto (1+z)^m$

for SBGs: *m~3.4*

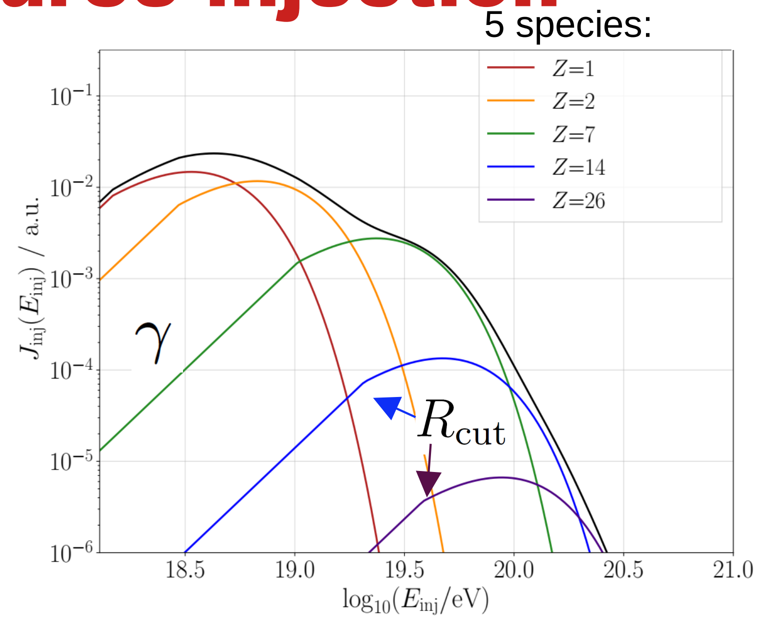
for AGNs: *m~5.0*

The astrophysical model: source injection

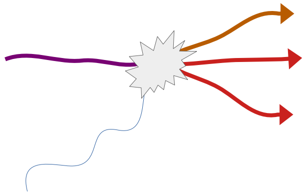
→ **injection** (same for all sources+background):

$$J_{\rm inj}(E_{\rm inj}, A_{\rm inj}) = J_0 \cdot a_A \cdot \left(\frac{E_{\rm inj}}{10^{18}\ {\rm eV}}\right)^{-\gamma} f_{\rm cut}\left(\frac{E_{\rm inj}}{Z_A R_{\rm cut}}\right)$$

free model parameters



→ **propagation** (from sources to Earth):



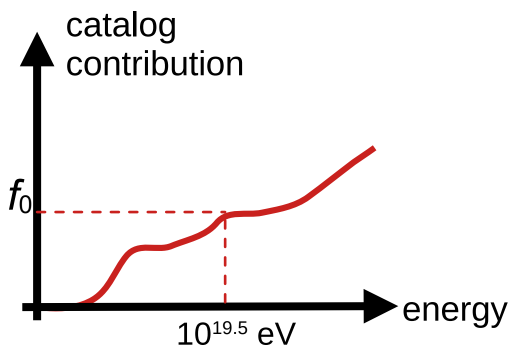
- simulate "**propagation database**" with CRPropa
- maps injected energies & masses to detected ones at Earth $P(E^h_{\rm inj}, A^i_{\rm inj}, E^e_{\rm det}, A^k_{\rm det}, d^l)$

Signal fraction & arrival directions

→ define signal fraction:

weight catalog and background

- catalog contribution shaped by propagation
- define signal fraction f_0
- free model parameter

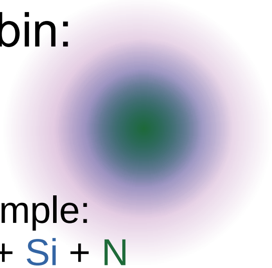


→ calculate arrival directions:

- arrival direction blurring anti-prop. to rigidity:

$$\delta = \frac{\delta_0}{R/10\ \mathrm{EV}}$$

- for each source in each energy bin: add Fisher distribution & weight with contribution



example:
Fe + Si + N

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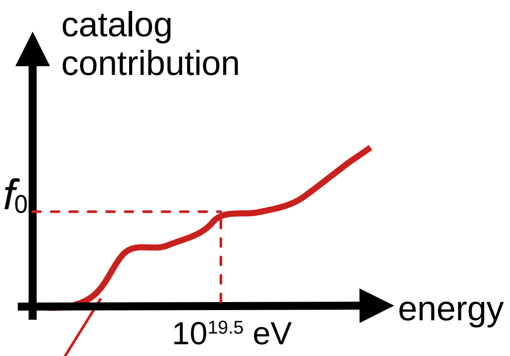

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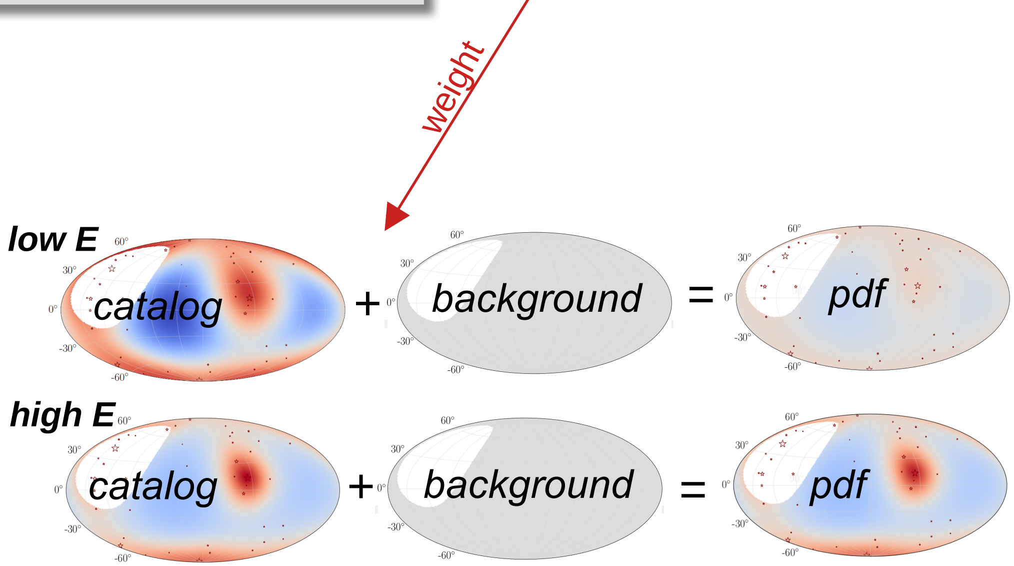
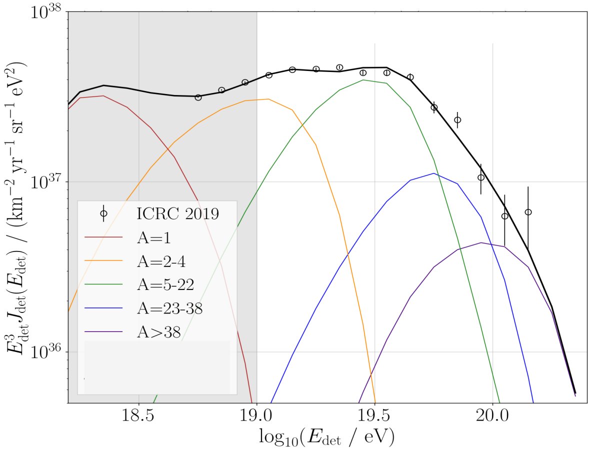


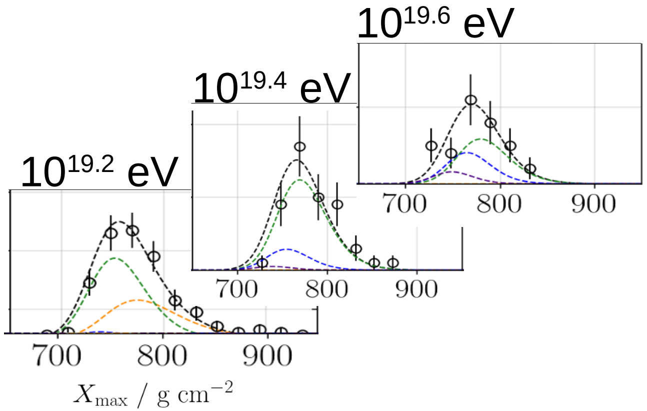
Modeling 3 observables

energy spectrum



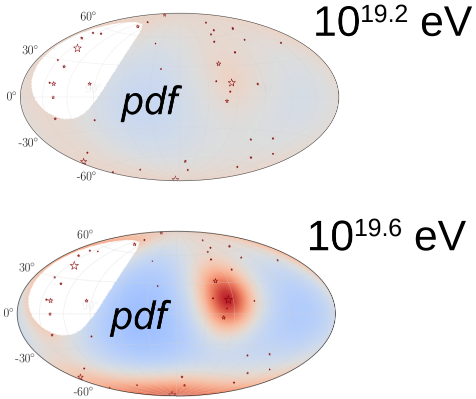
- energy spectrum
  = sum over detected particles
- fold with detector resolution
- Poissonian likelihood

shower depth distributions



- parameterize with Gumbel distributions (EPOS-LHC)
- fold with detector resolution & acceptance
- Multinomial likelihood function

arrival directions



- likelihood function similar to previous analysis
- but: pdf energy dependent
- in healpy pixels p:

$$\mathcal{L}_{\mathrm{AD}} = \prod_e \prod_p \mathrm{pdf}^{e,p}(v^{e,p})$$

Results

Paper to be uploaded to arXiv within the next days

PRELIMINARY

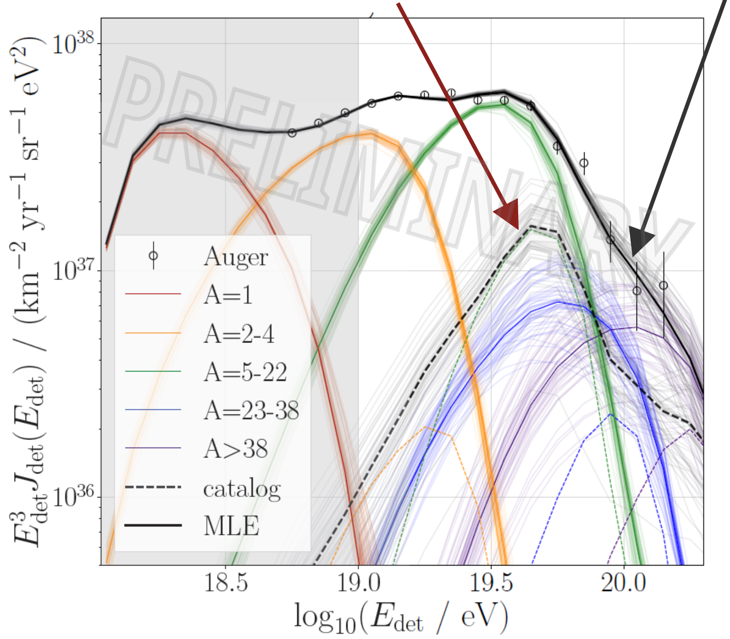
Starburst Galaxy model: results

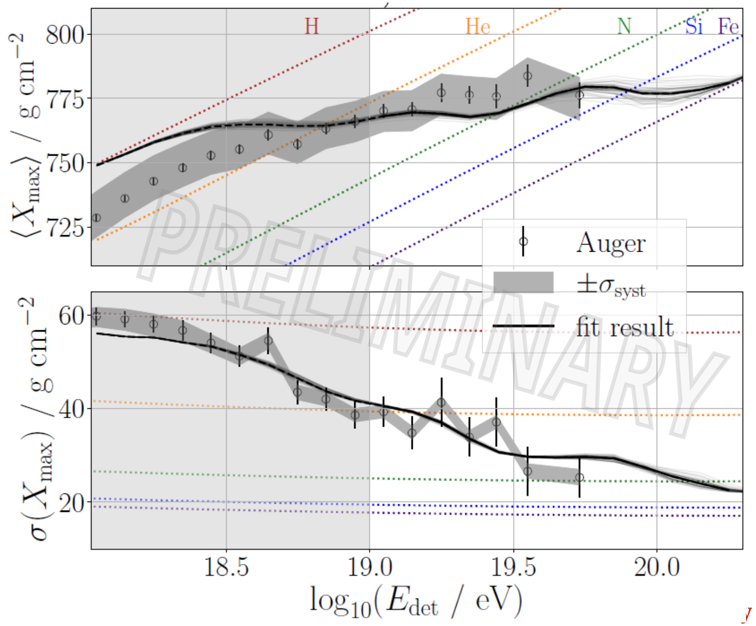
- hard emission spectrum, nitrogen-dominated
- signal fraction: **f_0~20% at 40 EeV**
- magnetic field blurring: **δ_0~20° for 10 EV**

	posterior	MLE
γ	$-2.77^{+0.27}_{-0.29}$	-2.67
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	$18.13^{+0.02}_{-0.02}$	18.13
f_0	$0.17^{+0.06}_{-0.08}$	0.19
$\delta_0/°$	$22.2^{+5.3}_{-4.0}$	24.3
I_{H}	$6.4^{+1.3}_{-6.4} \cdot 10^{-3}$	$4.3 \cdot 10^{-5}$
I_{He}	$1.7^{+0.3}_{-0.4} \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$
I_{N}	$7.4^{+0.3}_{-0.3} \cdot 10^{-1}$	$7.4 \cdot 10^{-1}$
I_{Si}	$5.7^{+2.5}_{-3.1} \cdot 10^{-2}$	$5.4 \cdot 10^{-2}$
I_{Fe}	$2.5^{+0.8}_{-0.9} \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$

dashed line = catalog contribution

thin lines = uncertainties



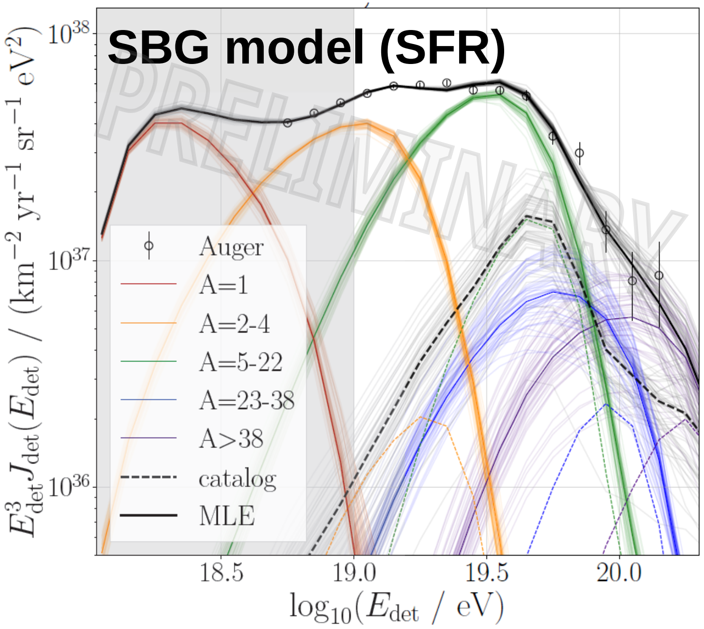


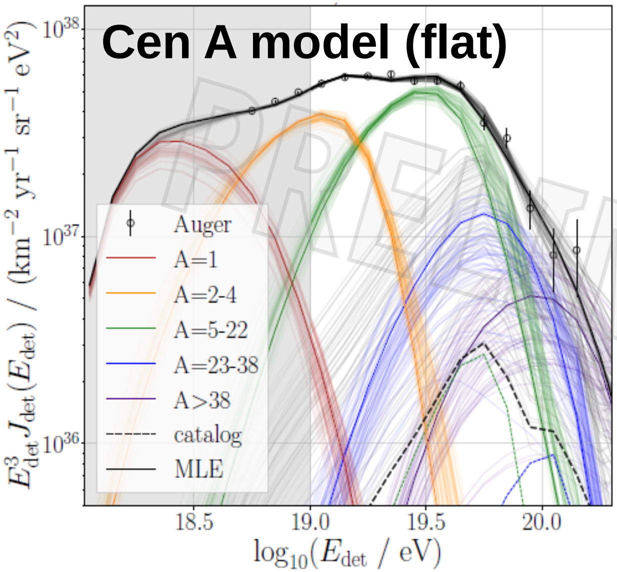
accordance with measured data increases when including a systematic shift of the Xmax scale of around -1.5σ

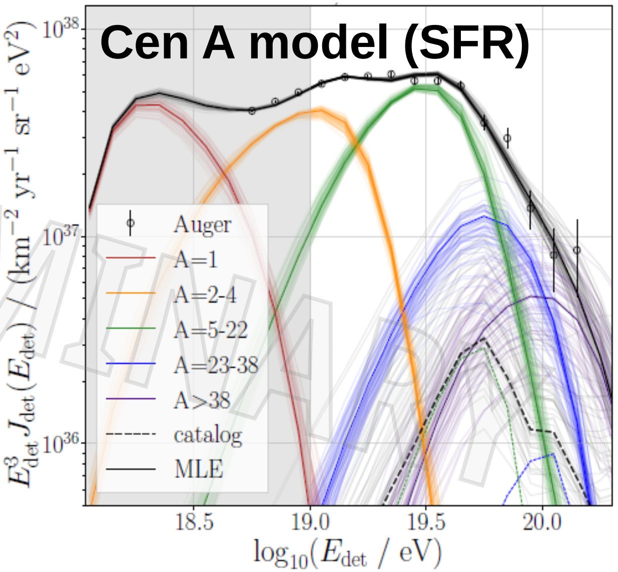
→ see backup for systematic study

Starburst Galaxy ↔ Centaurus A model

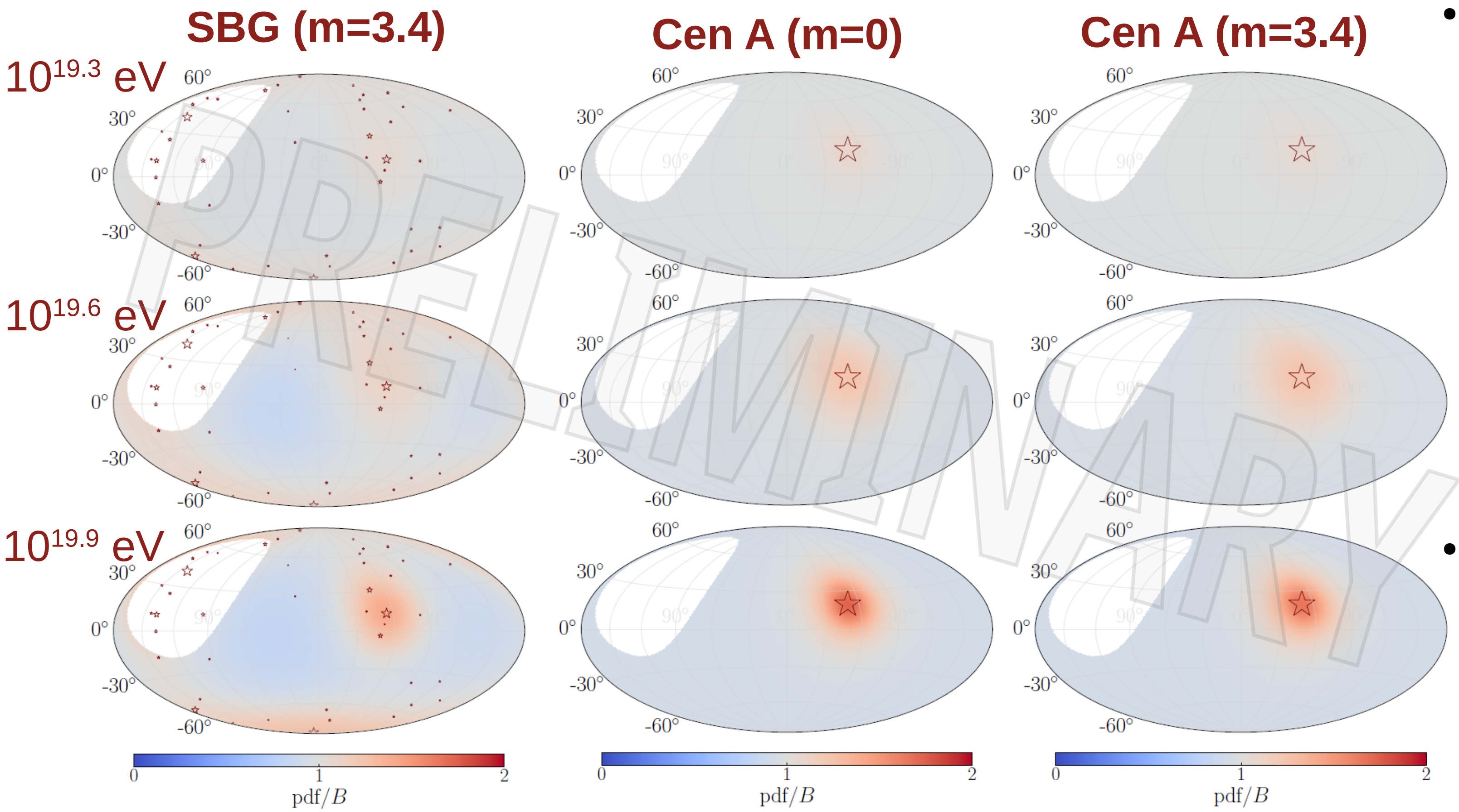
- **Cen A region spectrum fitted consistently**
  - independent of evolution & systematics $\mathbf{f_0 \sim 3\%}$
  - Cen A region contribution also similar in SBG model
- in all models: **nitrogen up to high energies** with R ~ 10 EV
  - light elements cut off above ~30 EeV due to hard spectrum







SBG & Centaurus A models: arrival directions



- **level of anisotropy rises with energy**
  - ➔ signal fraction increases (propagation effect)
  - ➔ blurring decreases (rigidity dependency)
- **Cen A / NGC 4945 region modeled consistently**

Likelihood ratio / test statistic

How much better do models with catalog sources fit than a model with only homogeneous background sources?

	SBG, m = 3.4		Cen A, m = 0.0		Cen A, m = 3.4	
		+ syst		+ syst		+ syst
TS_{tot}	27.6	25.6	22.8	17.3	22.2	19.7
TS_E	−5.2	−0.5	−0.1	−1.4	−0.4	2.9
$TS_{X_{max}}$	6.2	0.1	1.9	0.2	1.8	−0.9
TS_{ADs}	26.6	27.1	20.9	18.7	20.8	19.0

PRELIMINARY

arrival directions most important for source identification

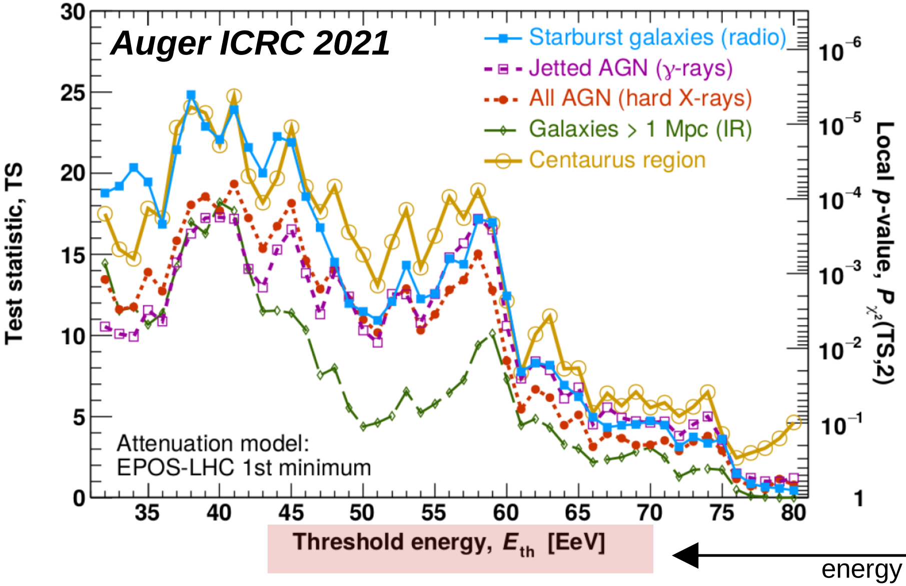
SBG model has highest TS=27.6 ↔ 4.7σ

- **4.5σ with systematics**
- increase compared to AD-correlation analysis: 4.0σ (all 1-sided)

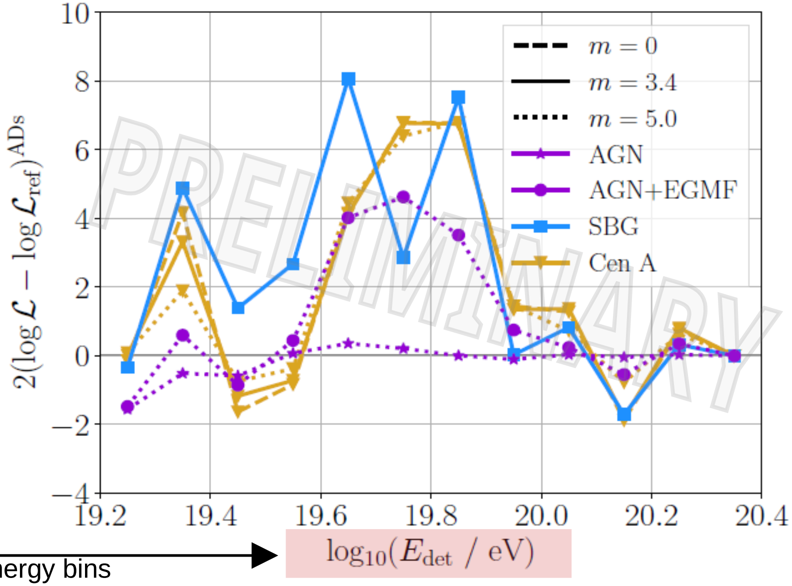
Cen A region contributes dominant part with TS~20

- despite small f_0=3%

Arrival directions TS energy dependency



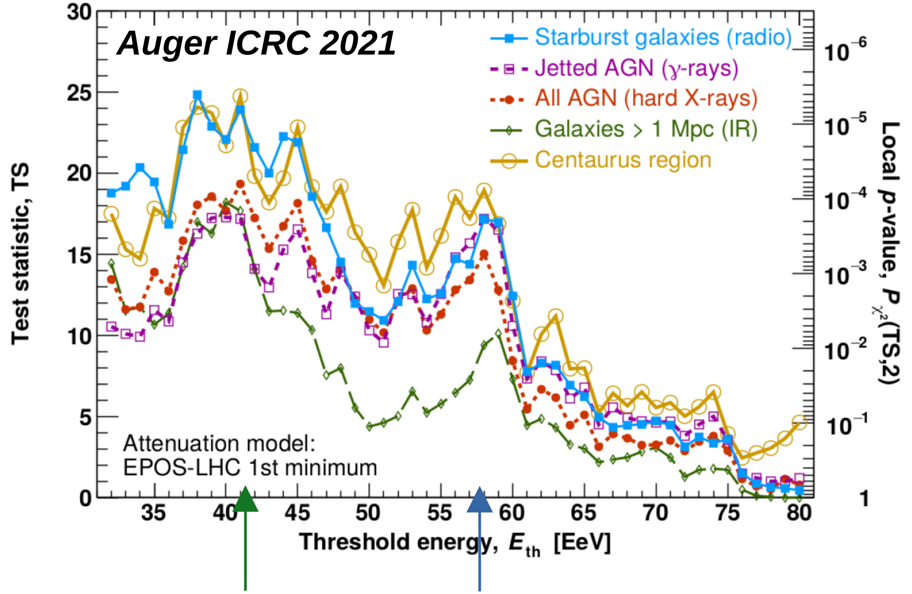
energy threshold ≠ energy bins

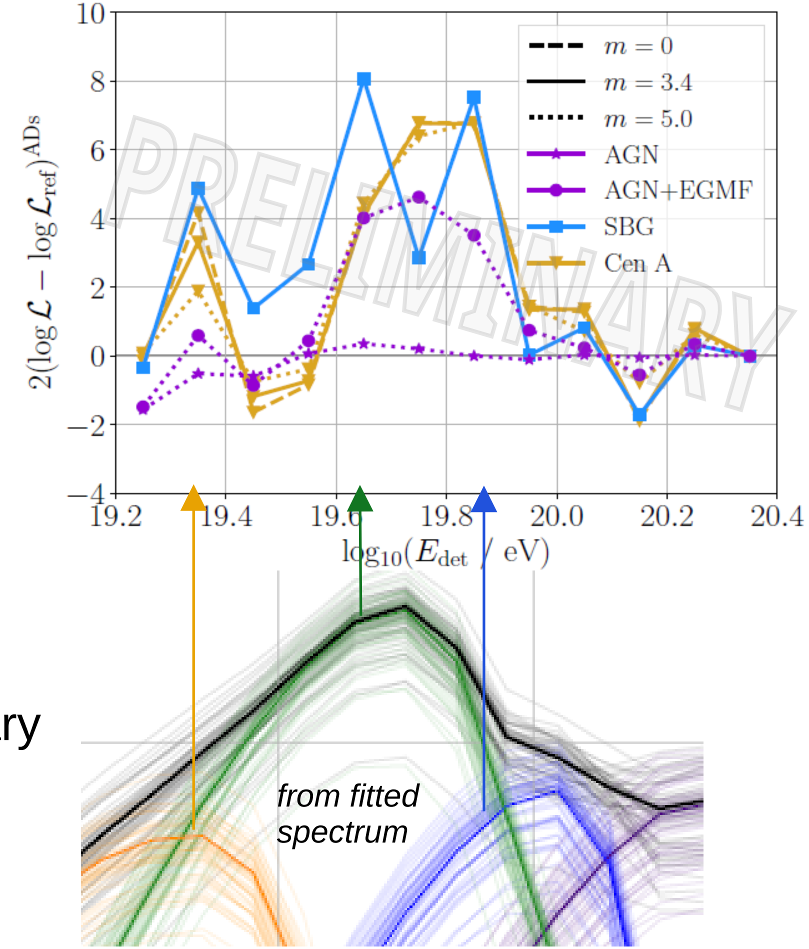


energy dependency of AD test statistics

- sum over all bins gives TS_{tot} → no scan necessary
  → catch whole signal by rigidity-dependency

Arrival directions TS energy dependency



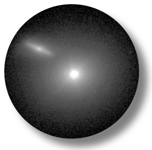


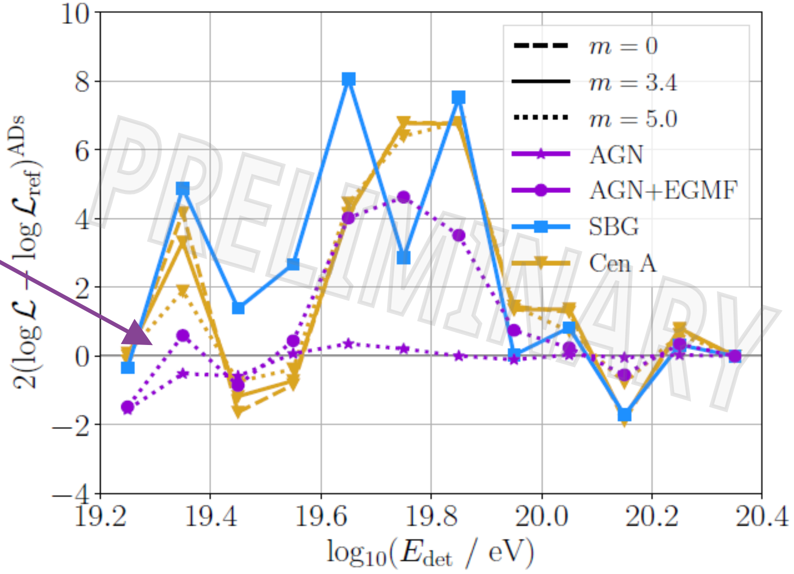
energy dependency of AD test statistics

- sum over all bins gives TS_{tot} → no scan necessary
- peaks: **could correspond to He, N, Si peak**
- but: statistical fluctuations of TS large
  (→ UHECR 2022 Symposium [EPJ Web Conf. 283 03008 (2023)])

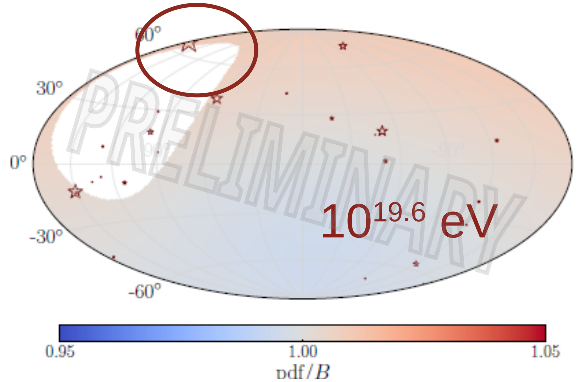
The ɣ-AGN model with strong evolution (m=5.0)

- **arrival directions TS negative**
- flux dominated by faraway **blazar Markarian 421** (~130 Mpc)
  - catalog based on ɣ-ray flux (favors blazars)
  - not compatible with Auger data



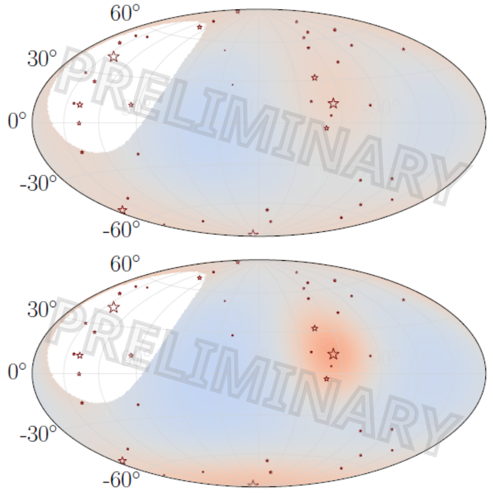


- **influence of EGMF?**
  - best-fit is extremely strong field strength
  - ADs still not well enough described



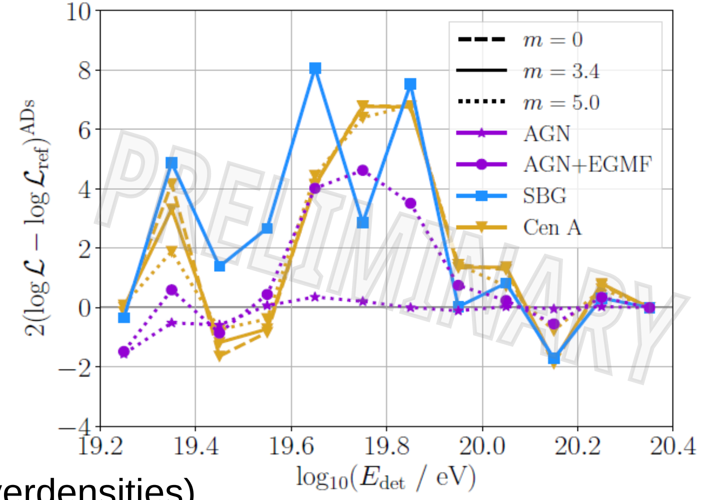
→ **discard ɣ-AGN model with flux ∝ ɣ-ray emission**

Conclusion



- **first-time combination of all 3 observables in 1 model**

- **SBG model: increase of significance** (4.5σ including syst.)
  compared to arrival-directions-only analysis (4.0σ)
  - ➔ E-dependency of catalog contribution, propagation, R-dependent blurring...
  - ➔ **main contribution to TS (~20 of 27.6) from Cen A / NGC 4945 region**
  - ➔ 20% signal fraction at 40 EeV, hard spectrum, N-dominated, 20° blurring at 10 EV



- **ɣ-AGN catalog can be discarded** for the first time
  - ➔ CR flux proportional to ɣ-ray flux disfavored

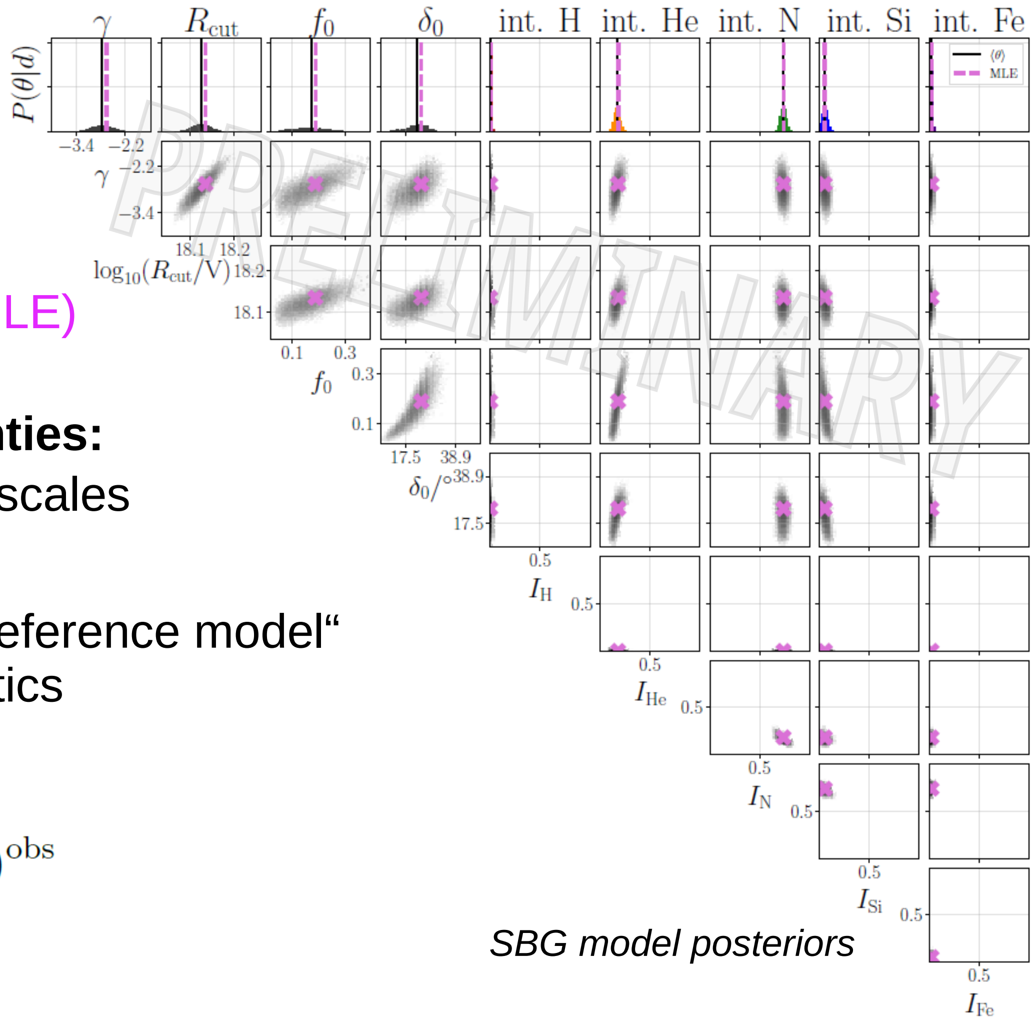
- results under assumption of **turbulent » coherent GMF**
  (at least in source directions, only then source candidates can explain overdensities)

Backup

Fit method

- for each model:
  - ➔ MCMC sampler for uncertainties
  - ➔ gradient-based minimizer for best-fit (MLE)
- estimate influence of **systematic uncertainties:**
  - ➔ let fit determine best shift of E & Xmax scales
- compare model with catalog sources to a „reference model“ with same source evolution & (no) systematics
  - ➔ calculate **test statistic:**

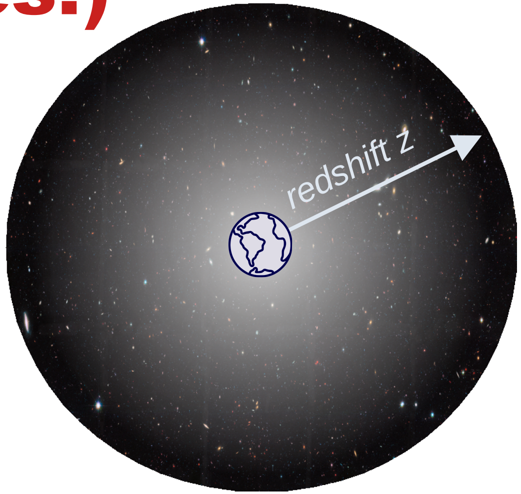
$$\mathrm{TS}_{\mathrm{tot}} = \sum_{\mathrm{obs}=E, X_{\mathrm{max}}, \mathrm{ADs}} 2\left(\log \mathcal{L}^{m=x} - \mathcal{L}^{m=x}_{\mathrm{ref}}\right)^{\mathrm{obs}}$$

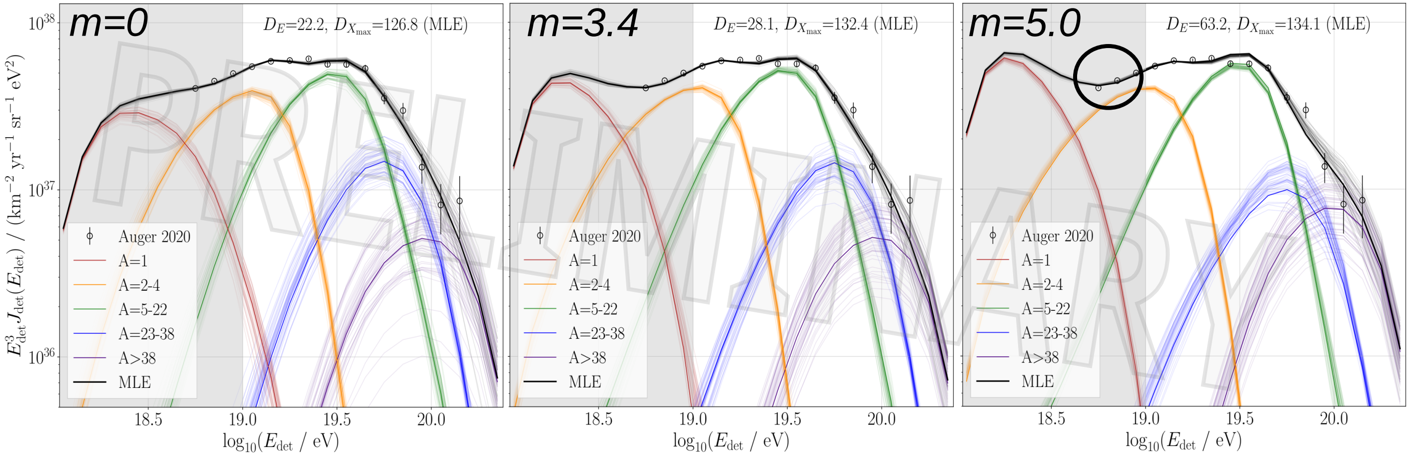


SBG model posteriors

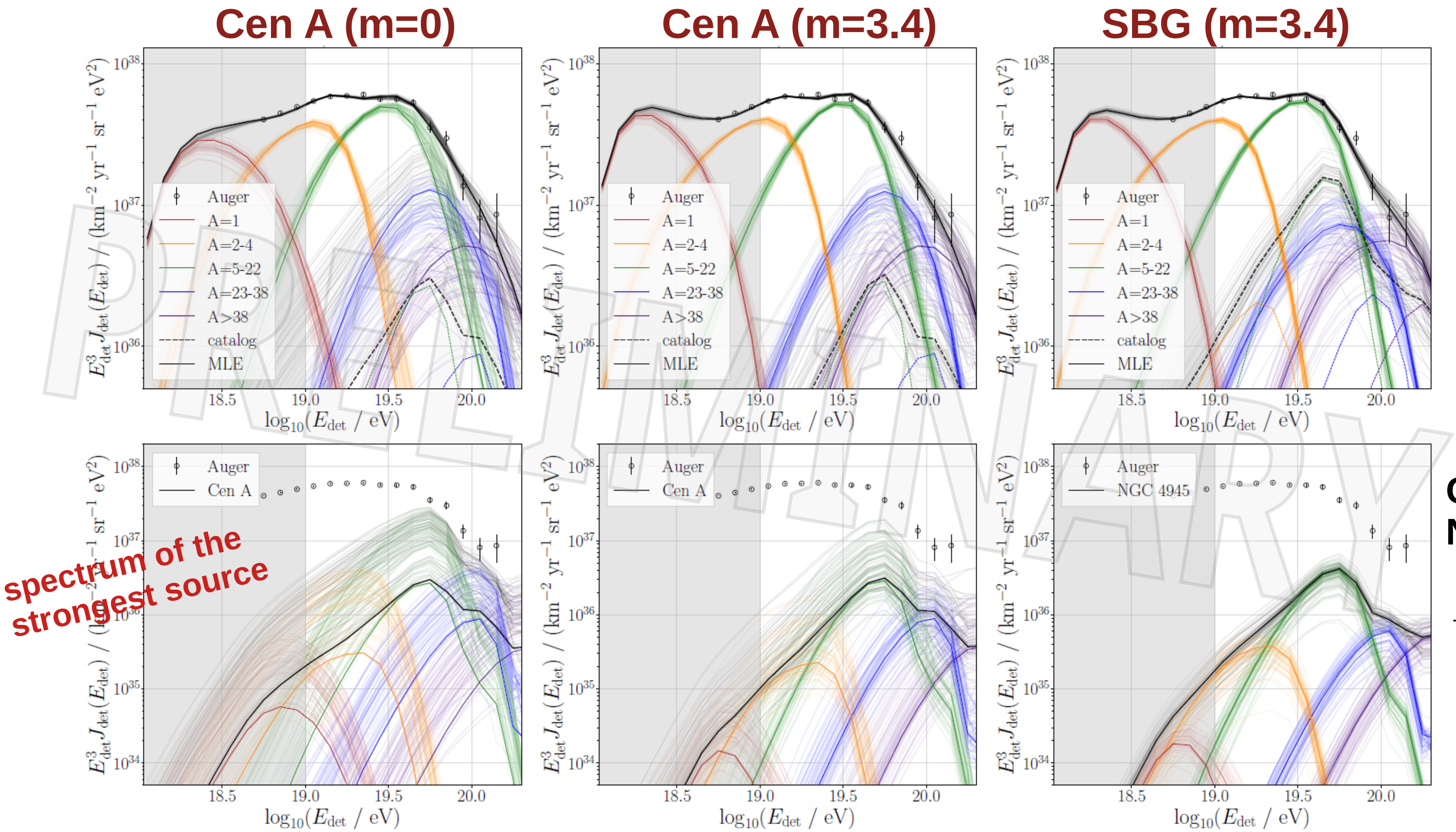
Reference models (no catalog sources!)

- hard injection spectrum, small R_{cut}, N-dominated
  - ➔ in **agreement with other Auger results**
    link to combined fit across the ankle (Auger 2023)
- **strong evolution discarded**:
  - ➔ too many low-energy secondaries
- with **experimental systematics** (as nuisance parameters):
  - ➔ best shift of X_{max} scale by -10 to -15 g/cm² → D decreases by ~20





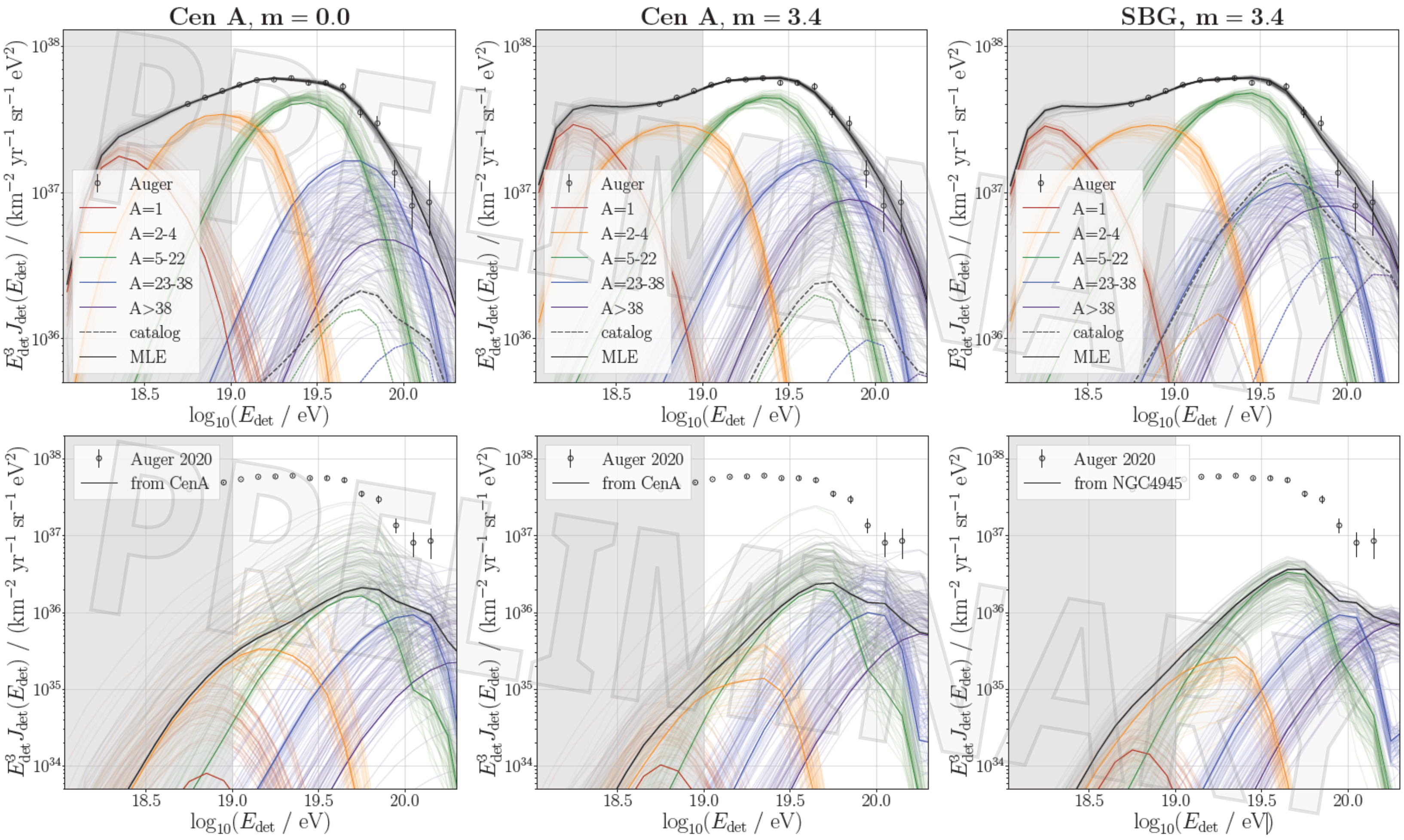
SBG & Centaurus A models: spectra



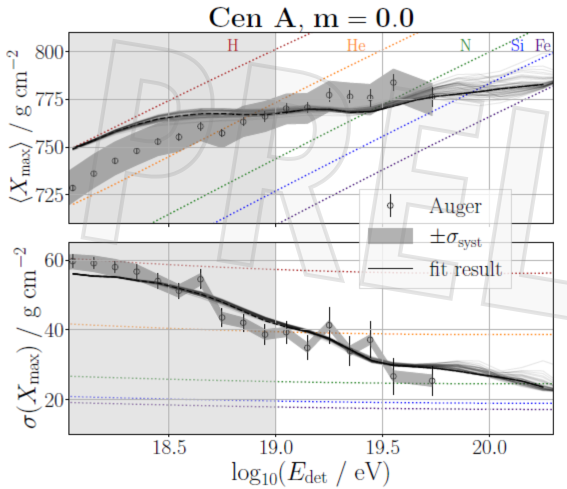
Cen A spectrum = NGC 4945 spectrum

→ flux from that sky region modeled consistently

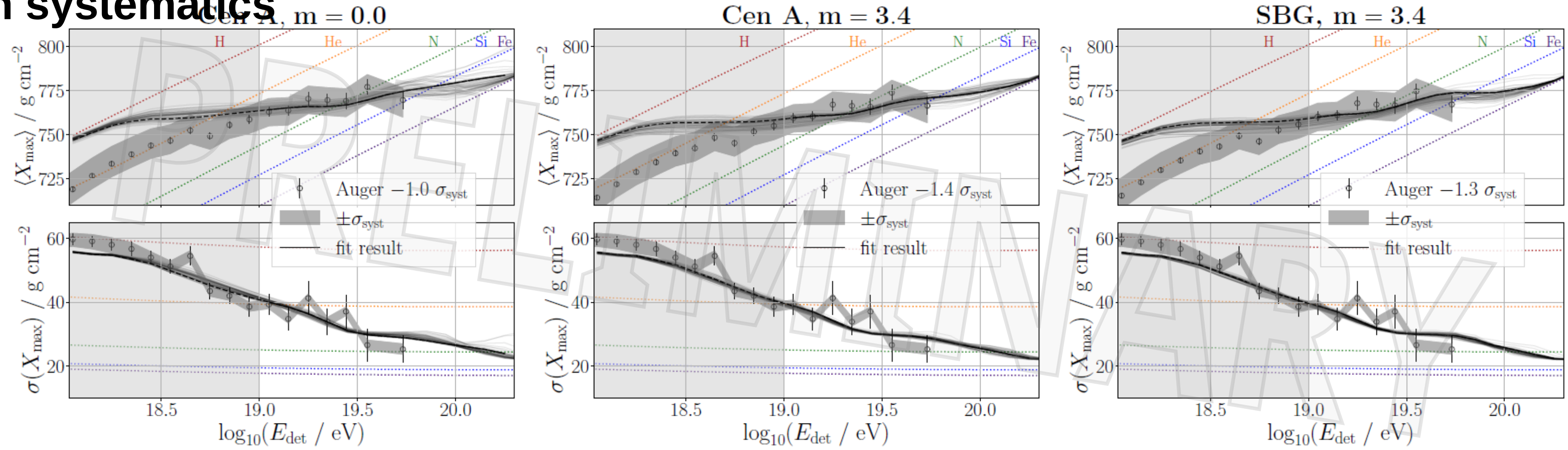
Including systematics: spectra



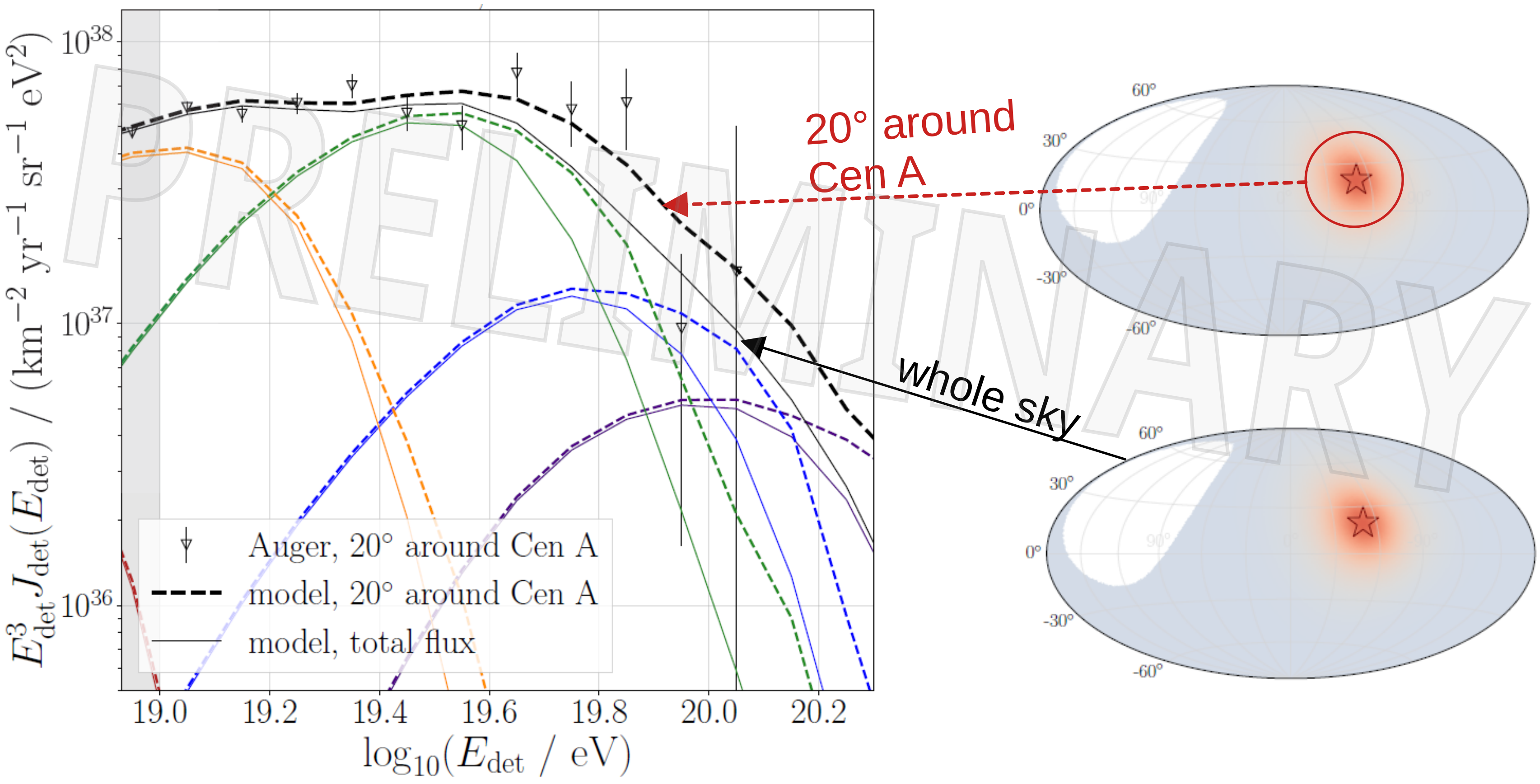
Xmax moments



with systematics



Spectrum in Cen A region



better χ^2 by 10% - 40%

for all angles, Cen A & SBG models

Fit parameters

	Cen A, $m = \mathbf{0}$ (flat)		**Cen A**, $m = \mathbf{3.4}$ (SFR)		**SBG**, $m = \mathbf{3.4}$ (SFR)	
	posterior	MLE	posterior	MLE	posterior	MLE
γ	$-1.67^{+0.48}_{-0.47}$	-2.21	$-3.09^{+0.23}_{-0.24}$	-3.05	$-2.77^{+0.27}_{-0.29}$	-2.67
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	$18.23^{+0.04}_{-0.06}$	18.19	$18.10^{+0.02}_{-0.02}$	18.11	$18.13^{+0.02}_{-0.02}$	18.13
f_0	$0.16^{+0.06}_{-0.14}$	0.028	$0.05^{+0.01}_{-0.03}$	0.028	$0.17^{+0.06}_{-0.08}$	0.19
$\delta_0/^\circ$	$56.5^{+29.4}_{-12.8}$	16.5	$27.6^{+2.7}_{-16.3}$	16.8	$22.2^{+5.3}_{-4.0}$	24.3
I_{H}	$5.9^{+2.5}_{-1.7} \cdot 10^{-2}$	$7.1 \cdot 10^{-2}$	$8.3^{+2.0}_{-8.3} \cdot 10^{-3}$	$1.6 \cdot 10^{-5}$	$6.4^{+1.3}_{-6.4} \cdot 10^{-3}$	$4.3 \cdot 10^{-5}$
I_{He}	$2.3^{+0.3}_{-0.5} \cdot 10^{-1}$	$1.9 \cdot 10^{-1}$	$1.3^{+0.2}_{-0.2} \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$	$1.7^{+0.3}_{-0.4} \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$
I_{N}	$6.3^{+0.3}_{-0.3} \cdot 10^{-1}$	$6.2 \cdot 10^{-1}$	$7.4^{+0.3}_{-0.3} \cdot 10^{-1}$	$7.3 \cdot 10^{-1}$	$7.4^{+0.3}_{-0.3} \cdot 10^{-1}$	$7.4 \cdot 10^{-1}$
I_{Si}	$6.5^{+3.6}_{-3.3} \cdot 10^{-2}$	$9.9 \cdot 10^{-2}$	$9.2^{+3.2}_{-2.3} \cdot 10^{-2}$	$1.1 \cdot 10^{-1}$	$5.7^{+2.5}_{-3.1} \cdot 10^{-2}$	$5.4 \cdot 10^{-2}$
I_{Fe}	$1.6^{+0.7}_{-1.0} \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$2.5^{+0.8}_{-0.9} \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$	$2.5^{+0.8}_{-0.9} \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$
$\log b$	-132379.6 ± 0.2		-132388.2 ± 0.2		-132382.5 ± 0.1	
D_E		22.3		28.5		33.3
$D_{X\mathrm{max}}$		124.9		130.6		126.2
D		147.2		159.1		159.5
$\log \mathcal{L}_{\mathrm{ADs}}$		-132105.1		-132105.2		-132102.3
$\log \mathcal{L}$		-132354.7		-132360.7		-132358.0

Table 1. Fit results for the Centaurus A and SBG models. The best-fit (MLE) parameters and the corresponding deviance and likelihood values are stated. Also, the posterior mean and highest posterior density interval from the MCMC sampler are given (see text).

Fit parameters with systematics included as nuisance parameters

	Cen A, $m = 0$ (flat)		**Cen A, $m = 3.4$** (SFR)		**SBG, $m = 3.4$** (SFR)	
	posterior	MLE	posterior	MLE	posterior	MLE
γ	$-0.89^{+0.37}_{-0.33}$	-0.65	$-1.19^{+0.45}_{-0.39}$	-1.41	$-1.02^{+0.43}_{-0.36}$	-1.25
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	$18.20^{+0.04}_{-0.05}$	18.23	$18.21^{+0.04}_{-0.05}$	18.20	$18.24^{+0.04}_{-0.06}$	18.22
f_0	$0.07^{+0.01}_{-0.05}$	0.029	$0.07^{+0.01}_{-0.05}$	0.031	$0.19^{+0.07}_{-0.11}$	0.23
$\delta_0/^\circ$	$30.5^{+2.0}_{-20.2}$	14.4	$27.4^{+4.2}_{-17.0}$	14.3	$18.8^{+5.9}_{-3.6}$	21.9
I_{H}	$5.8^{+2.9}_{-2.6} \cdot 10^{-2}$	$4.2 \cdot 10^{-4}$	$1.2^{+0.2}_{-1.2} \cdot 10^{-2}$	$3.0 \cdot 10^{-4}$	$1.2^{+0.1}_{-1.2} \cdot 10^{-2}$	$1.0 \cdot 10^{-4}$
I_{He}	$2.7^{+0.4}_{-0.4} \cdot 10^{-1}$	$3.5 \cdot 10^{-1}$	$9.9^{+3.8}_{-2.9} \cdot 10^{-2}$	$1.2 \cdot 10^{-1}$	$1.1^{+0.3}_{-0.4} \cdot 10^{-1}$	$1.4 \cdot 10^{-1}$
I_{N}	$5.6^{+0.4}_{-0.4} \cdot 10^{-1}$	$5.0 \cdot 10^{-1}$	$6.7^{+0.7}_{-0.7} \cdot 10^{-1}$	$6.8 \cdot 10^{-1}$	$7.2^{+0.6}_{-0.6} \cdot 10^{-1}$	$7.3 \cdot 10^{-1}$
I_{Si}	$9.0^{+3.9}_{-3.4} \cdot 10^{-2}$	$1.4 \cdot 10^{-1}$	$1.5^{+0.5}_{-0.6} \cdot 10^{-1}$	$1.6 \cdot 10^{-1}$	$1.2^{+0.5}_{-0.5} \cdot 10^{-1}$	$9.8 \cdot 10^{-2}$
I_{Fe}	$2.3^{+0.9}_{-1.2} \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	$5.1^{+1.5}_{-1.8} \cdot 10^{-2}$	$4.4 \cdot 10^{-2}$	$4.7^{+1.3}_{-1.7} \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$
ν_E/σ	$1.24^{+0.68}_{-0.50}$	1.35	$-0.23^{+0.42}_{-0.60}$	-0.13	$-0.35^{+0.44}_{-0.65}$	-0.40
$\nu_{X\mathrm{max}}/\sigma$	$-0.94^{+0.29}_{-0.24}$	-0.97	$-1.60^{+0.30}_{-0.25}$	-1.45	$-1.55^{+0.26}_{-0.25}$	-1.33
$\log b$	-132370.2 ± 0.1		-132380.1 ± 0.2		-132374.18 ± 0.2	
D_{syst}		2.8		2.1		1.9
D_E		13.6		21.9		25.3
$D_{X\mathrm{max}}$		107.4		113.6		112.7
D		123.8		137.7		139.4
$\log \mathcal{L}_{\mathrm{ADs}}$		-132106.2		-132106.1		-132102.1
$\log \mathcal{L}$		-132344.1		-132350.9		-1323348.0

Table 2. Centaurus A and SBG models with experimental systematic uncertainties included as nuisance parameters

Test statistic

	Cen A, m = 0.0		Cen A, m = 0.0		SBG, m = 3.4		γAGN, m = 5.0		γAGN+EGMF**, m = 5.0	
		+ syst		+ syst		+ syst		+ syst		+ syst
TS_{tot}	22.8	17.3	22.2	19.1	27.6	25.0	23.9*	9.8*	34.3*	33.2*
TS_E	−0.1	−1.4	−0.4	−1.1	−5.2	−4.5	26.8	3.9	18.2	8.4
$TS_{X_{max}}$	1.9	0.2	1.8	1.0	6.2	2.0	−0.8	6.4	4.4	14.7
TS_{ADs}	20.9	18.7	20.8	19.0	26.6	27.1	−2.1	−3.0	11.7	8.6

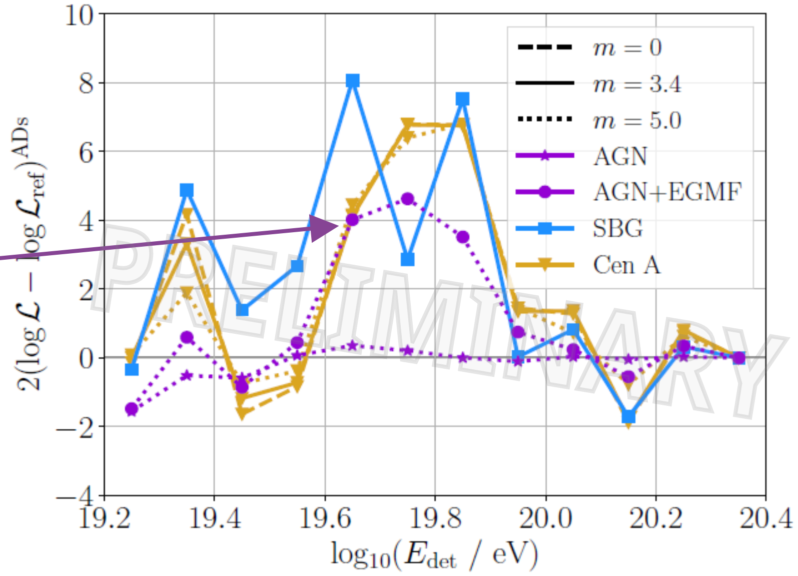
Table 3. Overview of test statistic values for the tested models. In the case with systematics, the contribution from eq. 3.6 is taken into account additionally in TS_{tot}. *Note that the test statistic of each model is always calculated with respect to the reference model with the same source evolution and (no) systematics. This implies that e.g. the test statistics of the γ-AGN model is large only due to the poor fit of the reference model with $m = 5.0$ (compare to Fig. 8). **Note also that the model with EGMF has an additional fit parameter β_e compared to the other models.

The γ-AGN model with EGMF / distance-dependent blurring

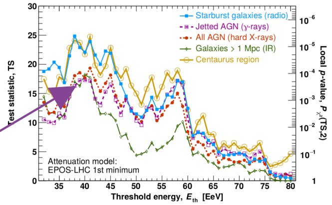
- include **distance-dependent blurring:**

$$\delta_{\rm tot} = \frac{\sqrt{\delta_0^2 + \beta_e^2\ d/\mathrm{Mpc}}}{R/10\ \mathrm{EV}}$$

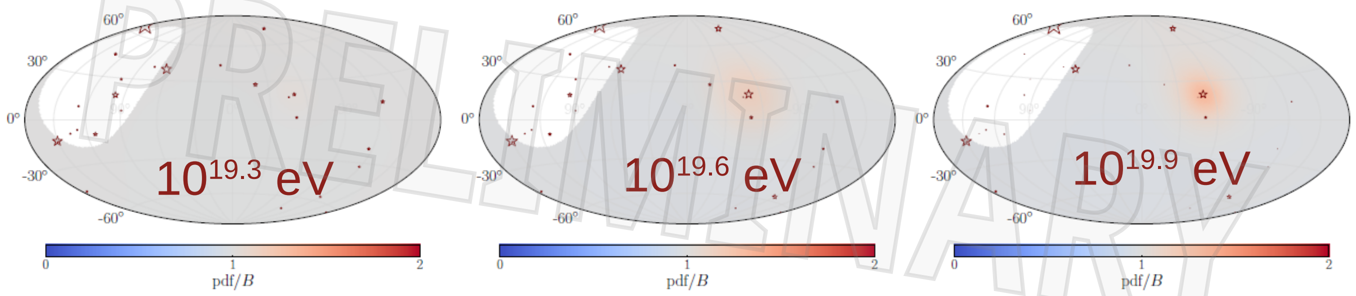
- arrival directions now > isotropy: **TS_{AD}=11.7**



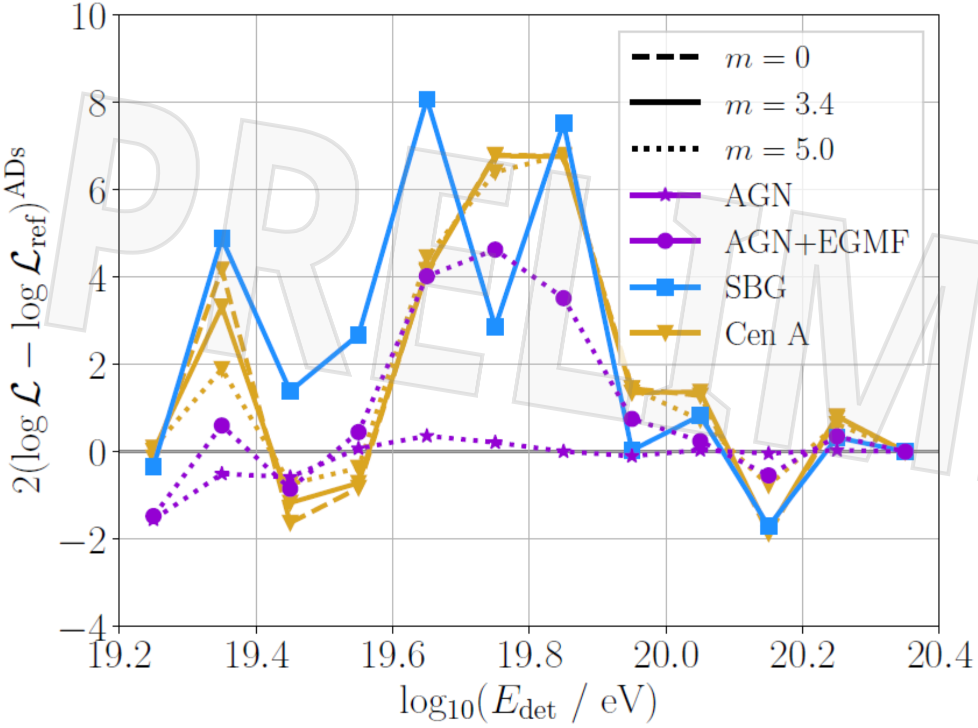
- **but:**
  - ➔ model cannot reproduce



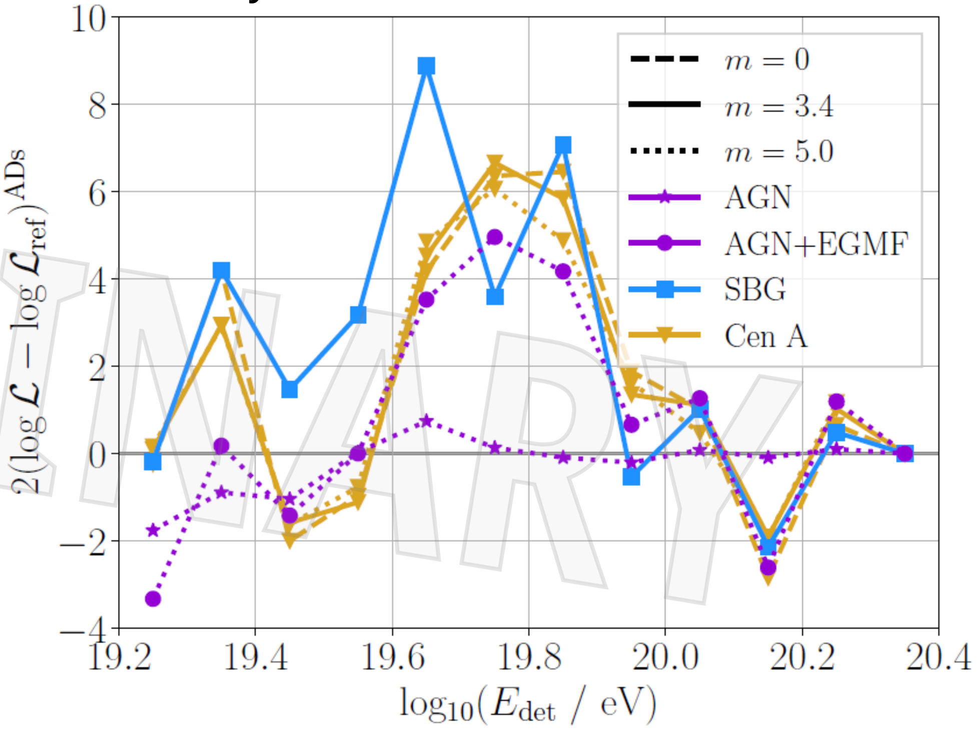
  - ➔ need extremely **strong EGMF** (not compatible with limits in voids)
  - ➔ arrival directions dominated by Cen A,
    - ➔ better as a single source



Arrival directions test statistic



with systematics:



Source contributions to TS

Cen A region contributes TS_{AD} ~ 20

Which other sources are how important?

→ test by removing from the catalog:

NGC 253 contributes TS_{AD} ~ 4-5

NGC 1068 contributes TS_{AD} ~ 1