Constraining the sources of ultra-high-energy cosmic rays

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

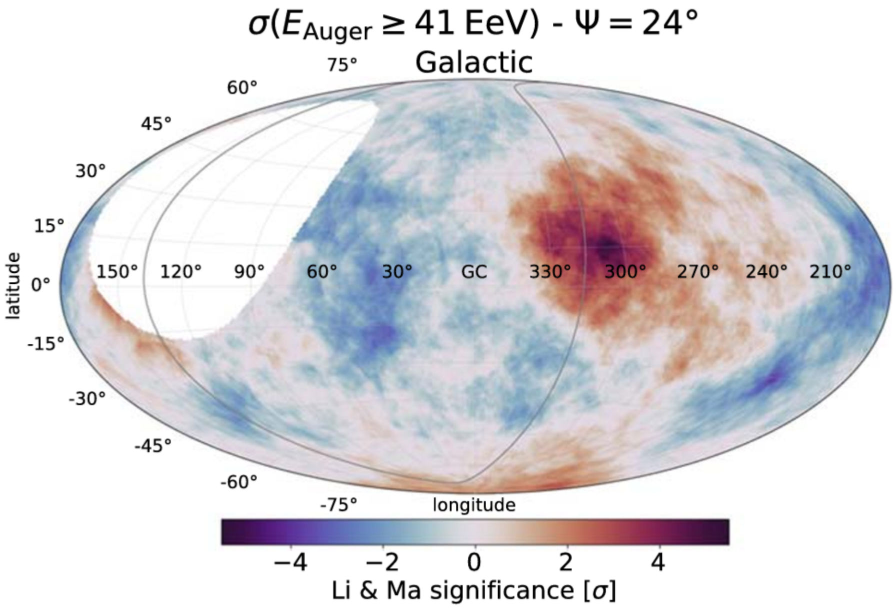
Radboud University

PIERRE AUGER OBSERVATORY

Teresa Bister, June 2023

27th Symposium on Astroparticle Physics in the Netherlands

Introduction



search for overdensities in the UHECR flux measured at the Pierre Auger Observatory

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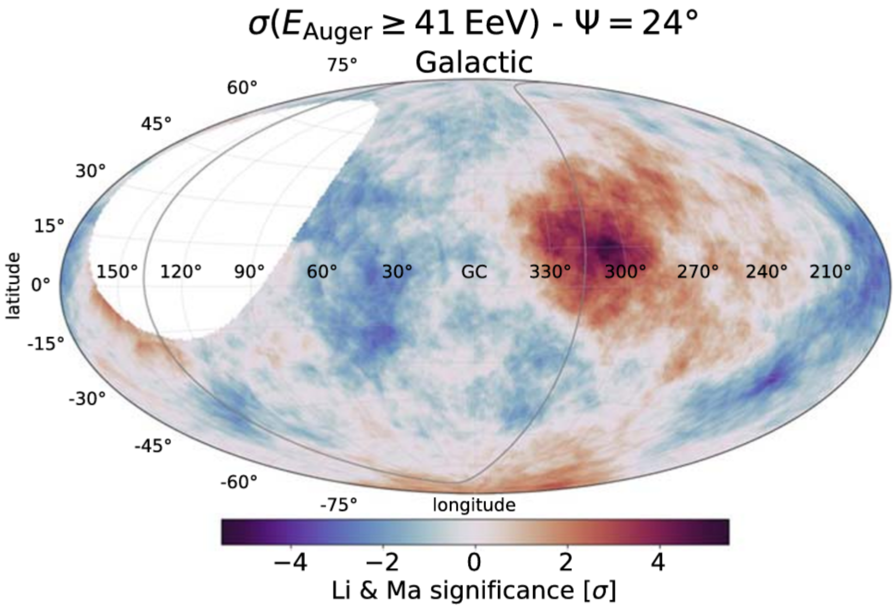

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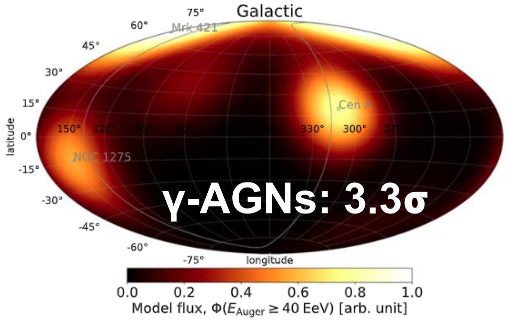
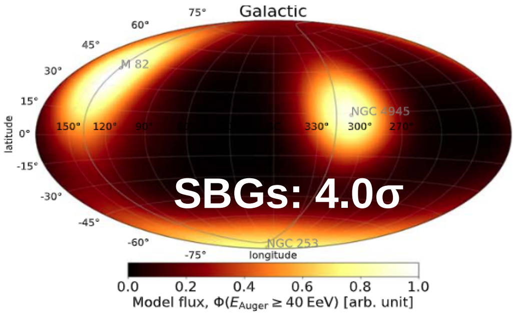
- intermediate-scale anisotropies in UHECR flux correlate with catalogs of source candidates





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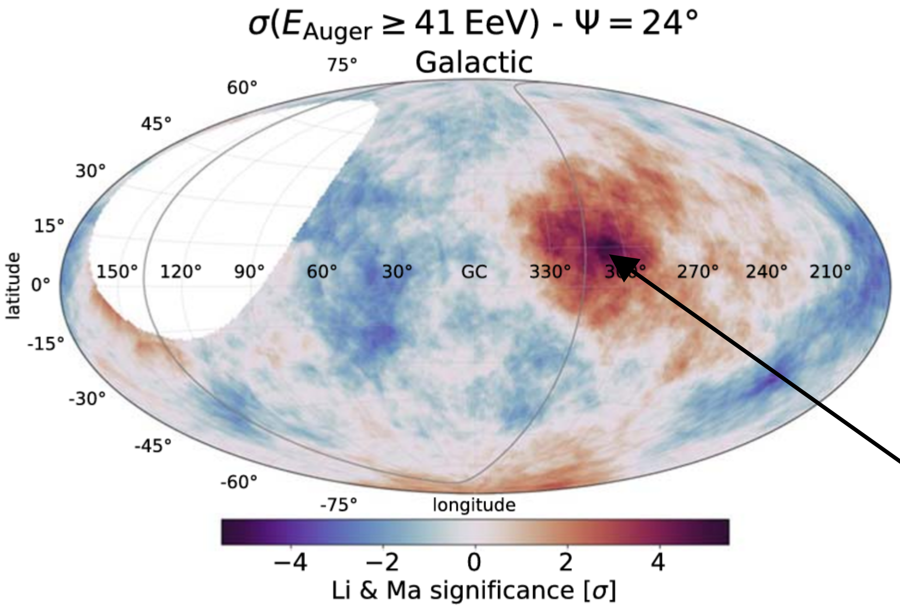

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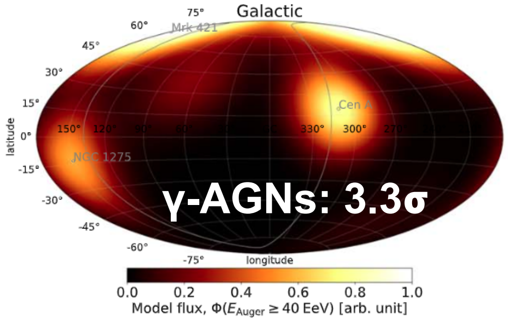

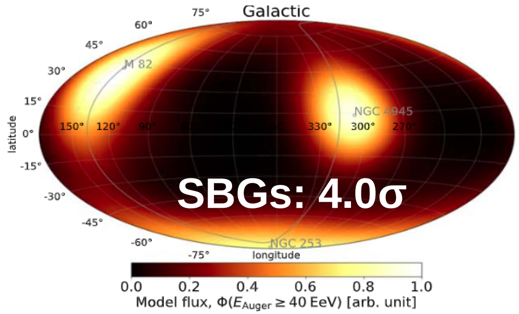

- correlation with **Cen A region: 4.1σ**

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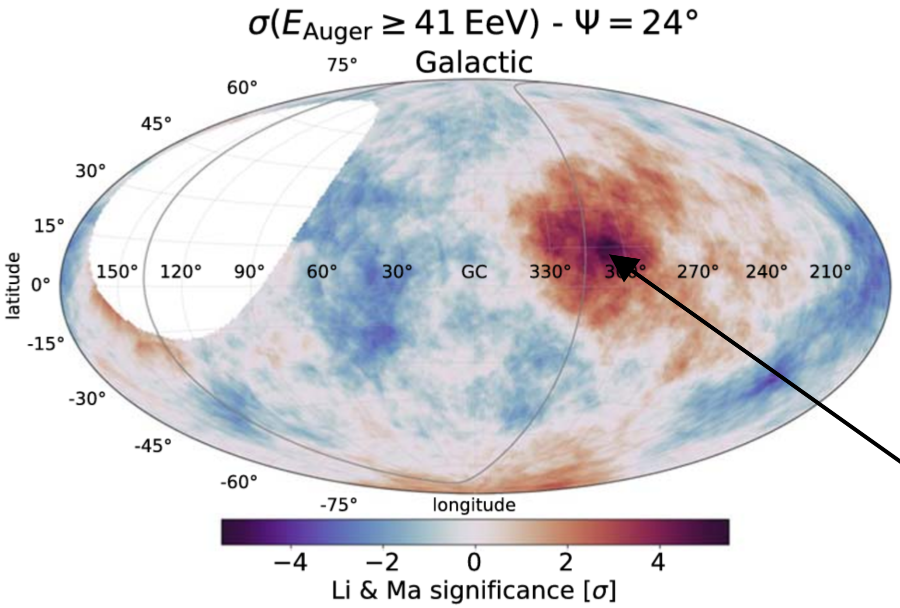

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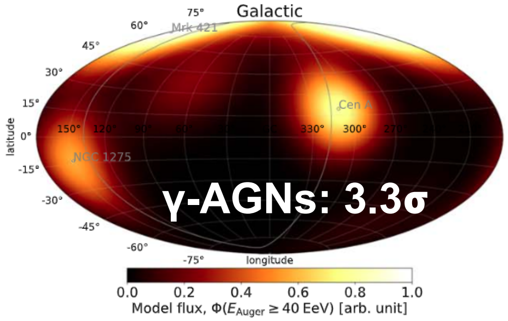

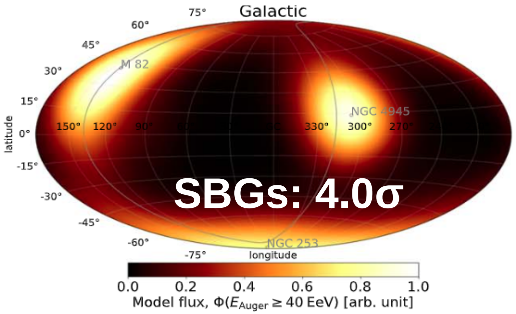

- correlation with **Cen A region: 4.1σ**

Idea:

- investigate possibility of SBGs / γ-AGNs / Cen A as sources of overdensities
- build one coherent model for injection → propagation → detection
- describe arrival directions + spectrum + composition data at the same time

Astrophysical model and combined fit

injection:

$$Q_{\mathrm{inj}}(E_{\mathrm{inj}}, A_{\mathrm{inj}}) = Q_0\, a_A \cdot \left(\frac{E_{\mathrm{inj}}}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} f_{\mathrm{cut}}\left(\frac{E_{\mathrm{inj}}}{Z_A R_{\mathrm{cut}}}\right)$$

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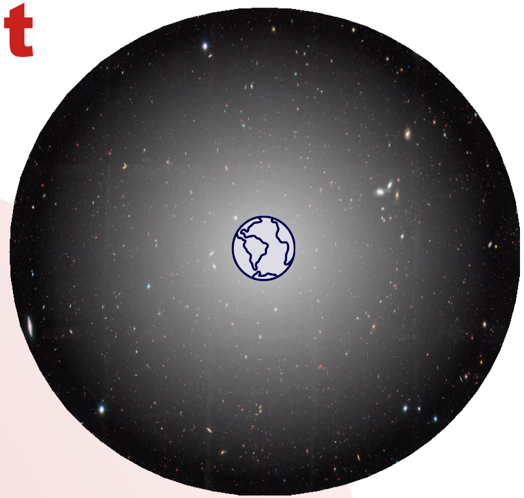
3d setup:

- homogeneous background
  → SFR or flat evolution



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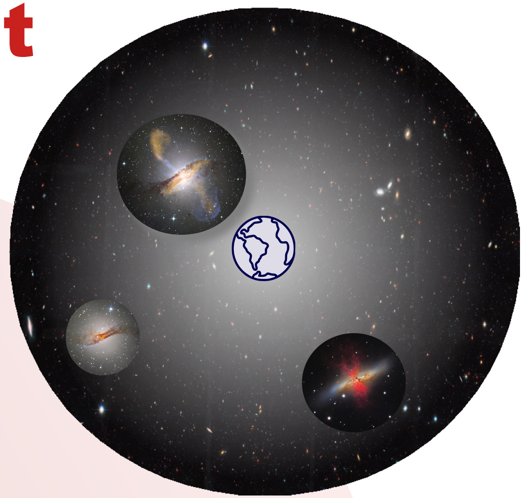

distance, flux weight, direction

Astrophysical model and combined fit

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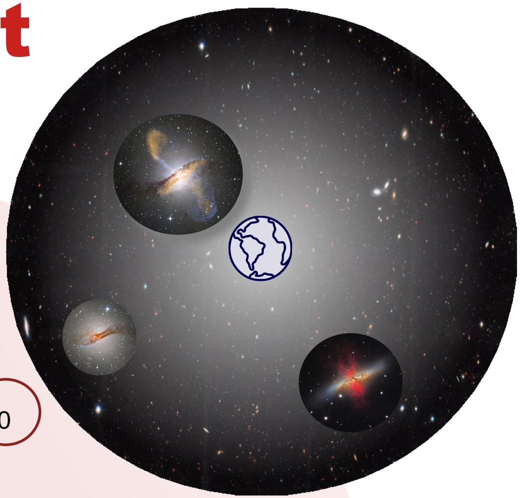
3d setup:

- homogeneous background → SFR or flat evolution
- + catalog sources (SBGs / ɣ-AGNs / Cen A)
- weight with signal fraction f_0 *(defined at 40 EeV)*



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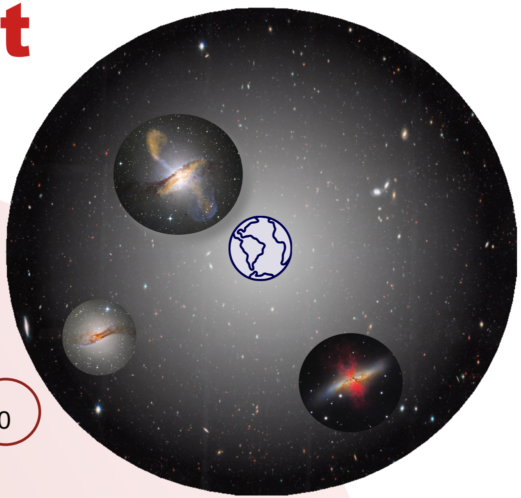
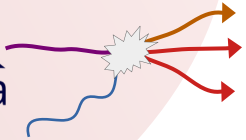


propagation:

- database CRPropa 1d + reweighting



- rigidity-dependent magnetic field blurring

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

$R = E/Z$

Astrophysical model and combined fit

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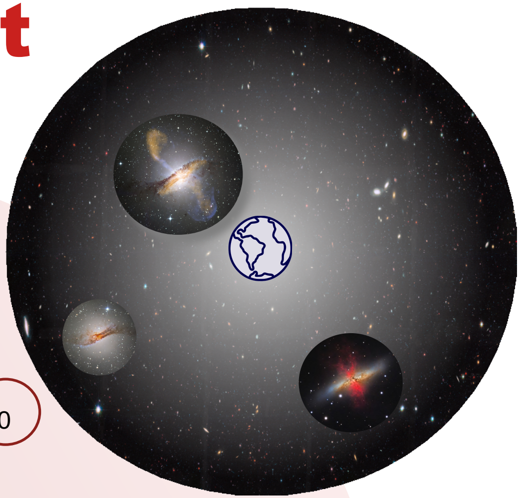
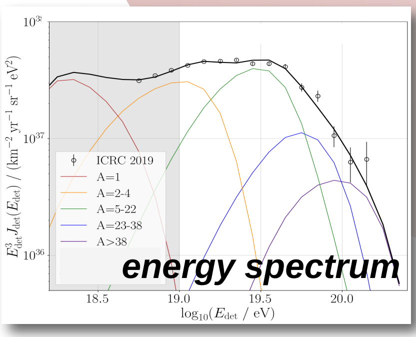
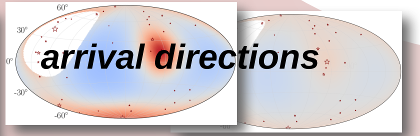
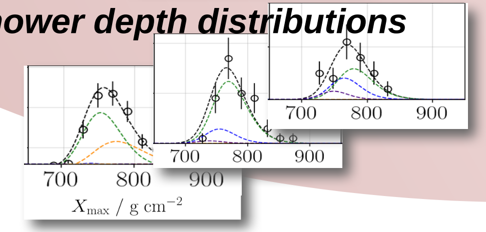


modeled observables:
(include detector effects)







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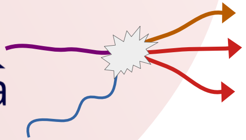

- database CRPropa 1d + reweighting
- rigidity-dependent magnetic field blurring

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

Astrophysical model and combined fit

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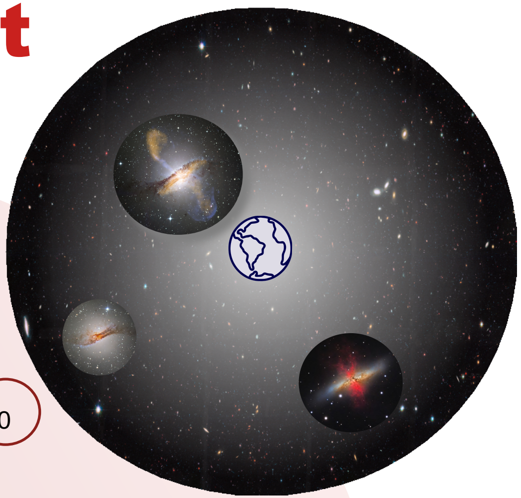

Likelihood function:
→ determine free parameters

$$\log \mathcal{L} = \log \mathcal{L}_E + \log \mathcal{L}_{X_{\max}} + \log \mathcal{L}_{\mathrm{ADs}}$$

propagation:

- database CRPropa 1d + reweighting
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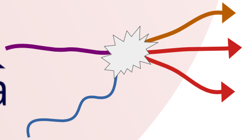

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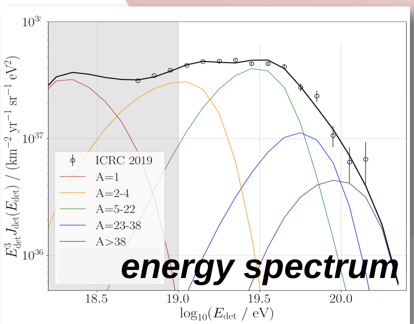
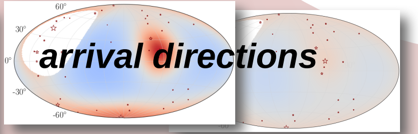
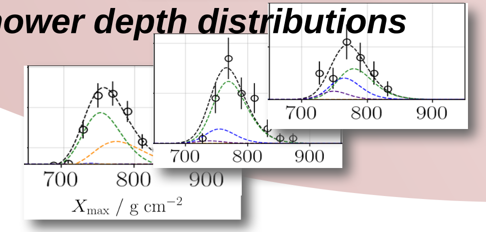






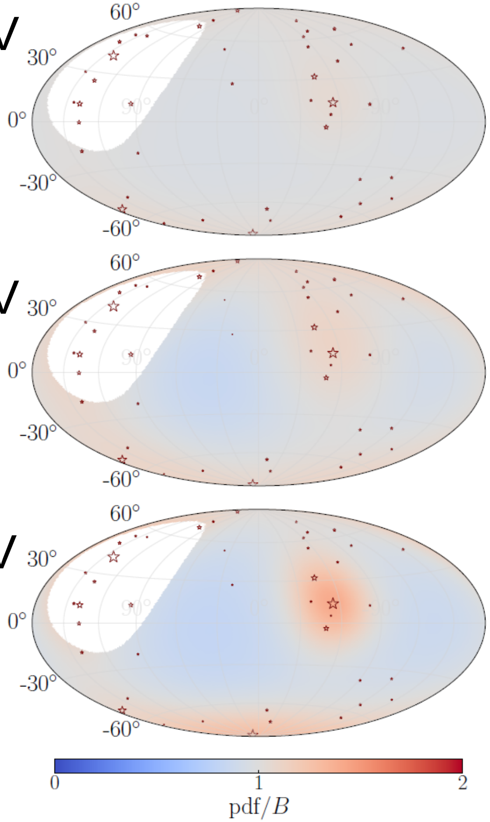
Best-fit arrival directions

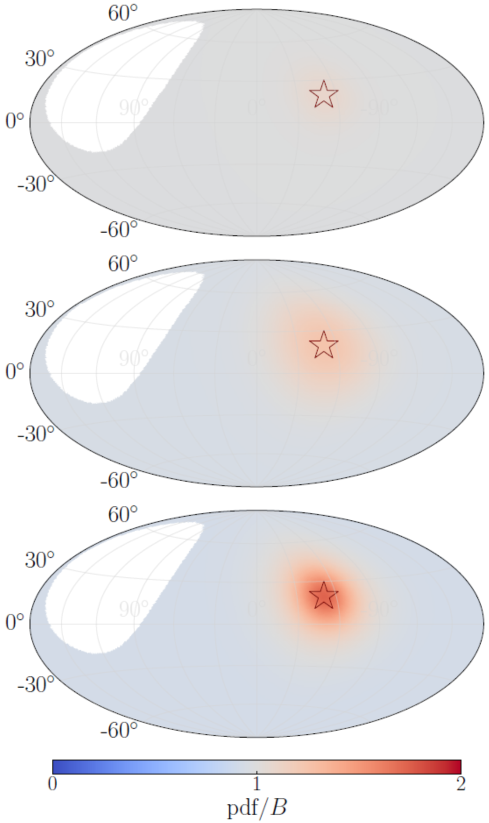
SBG model (SFR) | Cen A model (flat) | Cen A model (SFR)

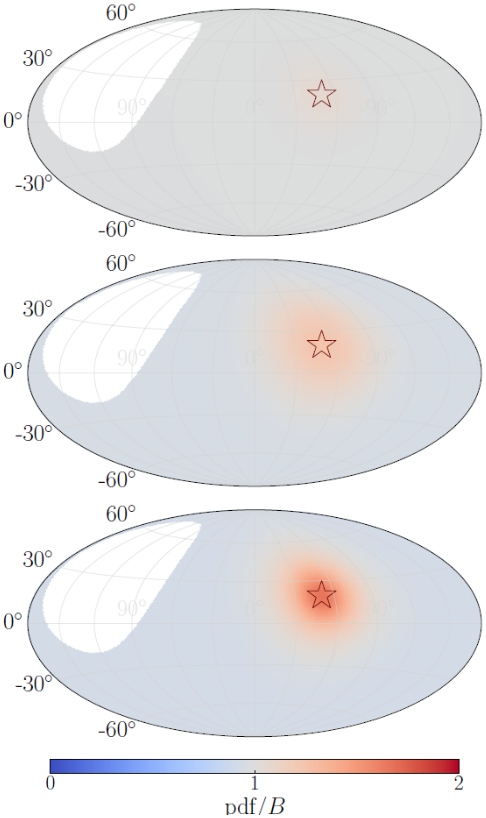
$10^{19.3}$ eV

$10^{19.6}$ eV

$10^{19.9}$ eV





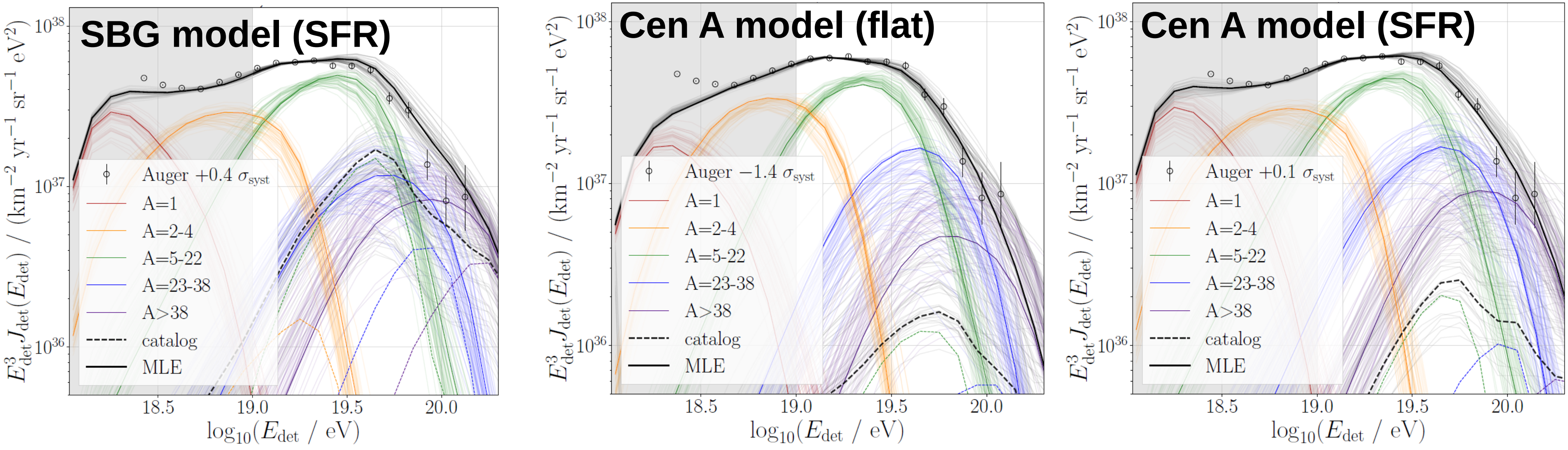


best-fit magnetic field blurring: **δ_0~20°**

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

Fitted energy spectra

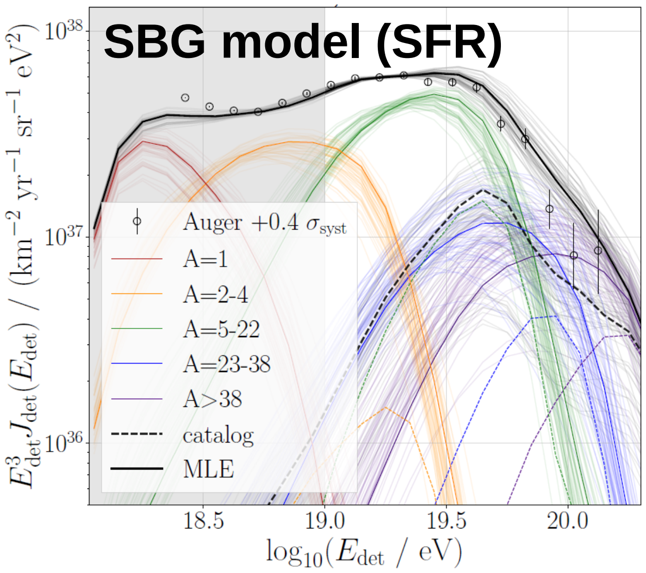
dashed line: catalog contribution
thin lines: uncertainties

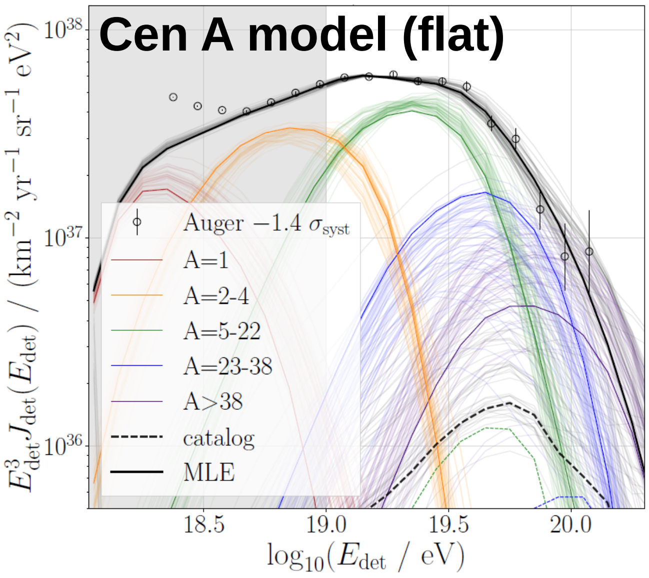


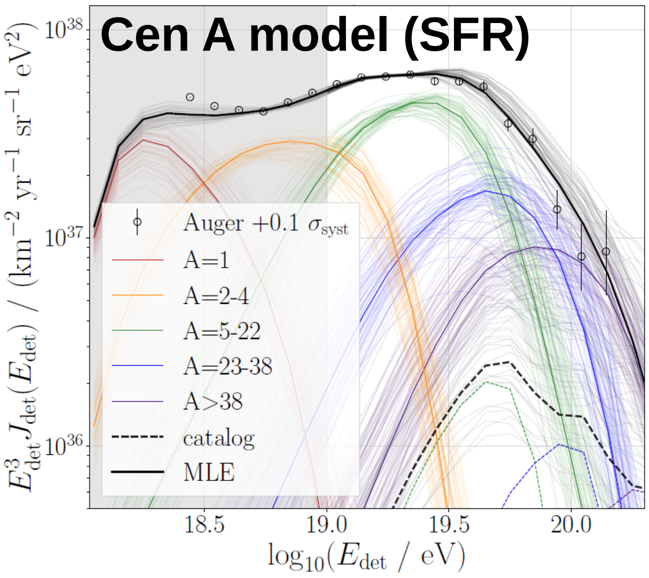
- **hard injected spectrum ∝E¹, dominant N contribution, small maximum energy ~2 EeV**

- **contribution of Cen A region fitted consistently: f_0 ~ 3%**
  - ➔ independent of systematics & evolution

Significance







„How much better does the model with catalog sources fit than one with just homogeneous background?“

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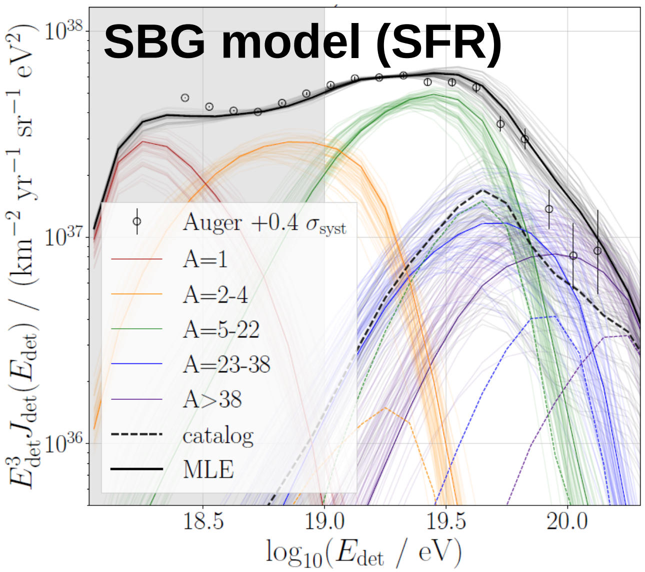
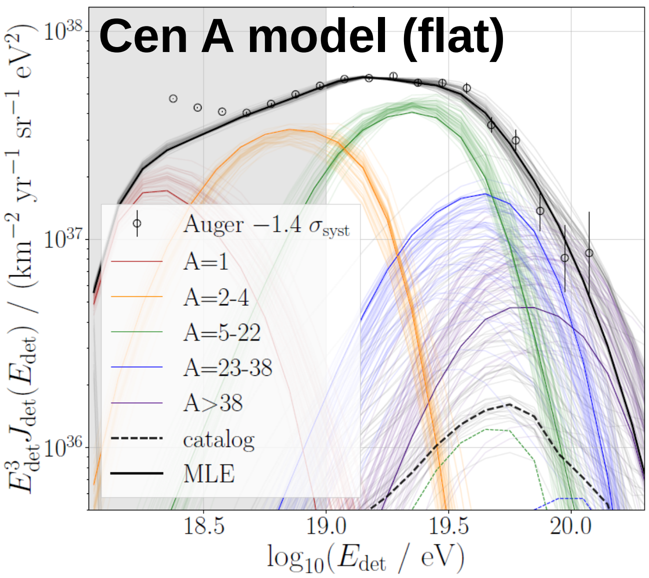
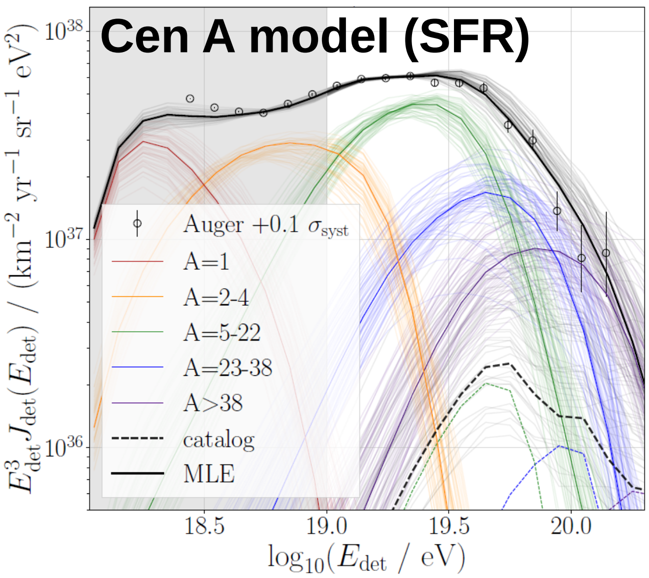






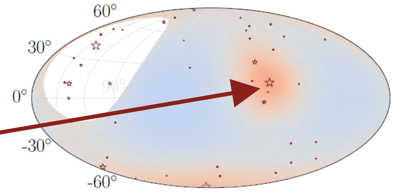
„How much better does the model with catalog sources fit than one with just homogeneous background?“

TS = 25.6

TS = 17.3

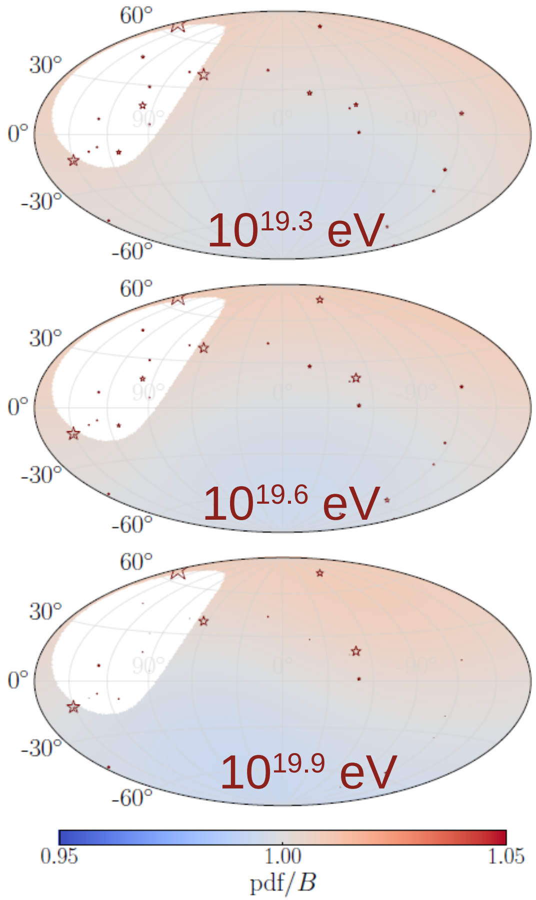
TS = 19.1

- **SBG model fits best (≙4.5σ significance)**
- main contribution from well described arrival directions in Cen A region



The γ-AGN model with strong evolution $\propto(1+z)^5$

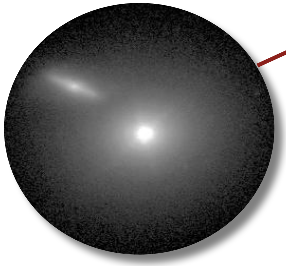
- **arrival directions test statistic negative**

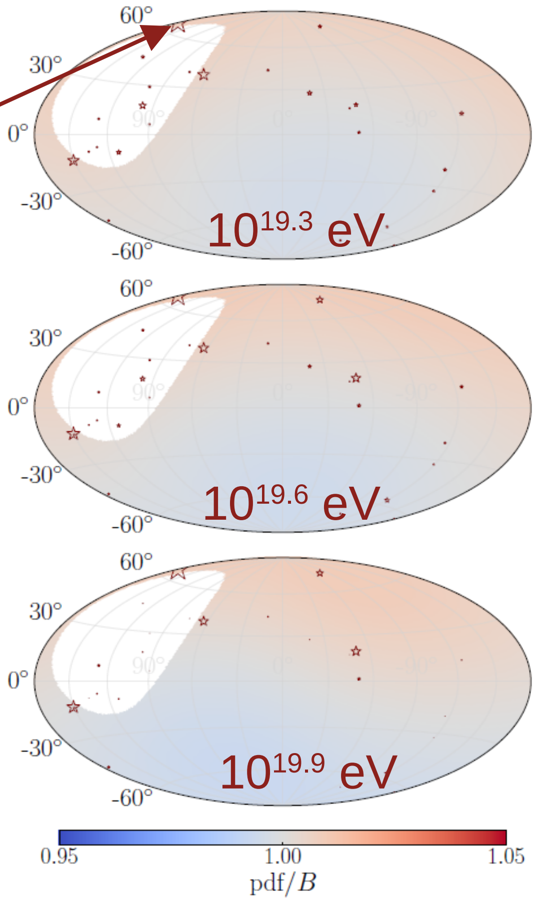


The ɣ-AGN model with strong evolution $\propto(1+z)^5$

- **arrival directions test statistic negative**

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





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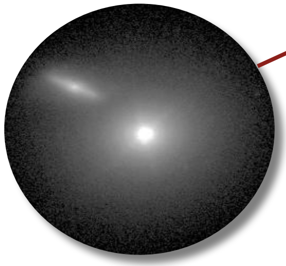
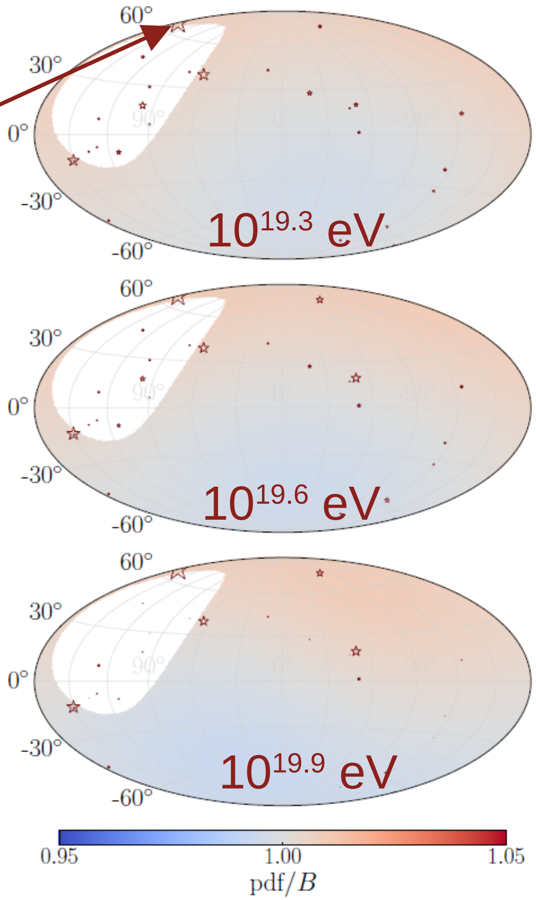
- **influence of EGMF?**
  - ➔ best-fit extremely strong
  - ➔ arrival directions still not well enough described
  - ➔ mainly Cen A present





→ **discard ɣ-AGN model with flux $\propto$ ɣ-ray emission**

Conclusion

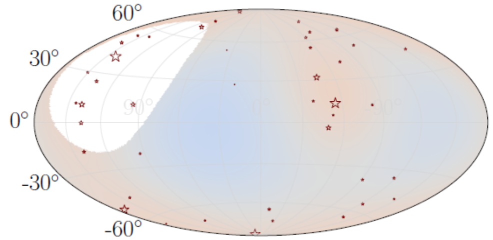
- **first-time combination of all 3 observables in 1 model**

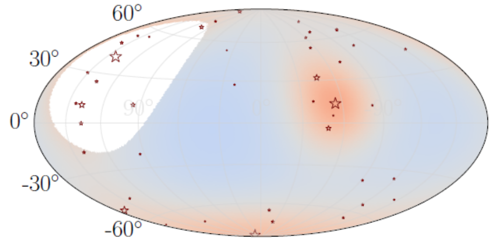
- **SBG model: 4.5σ** (including exp. syst. uncertainties)
  - ➔ **main contribution to TS (~20 of 26) from Cen A region**

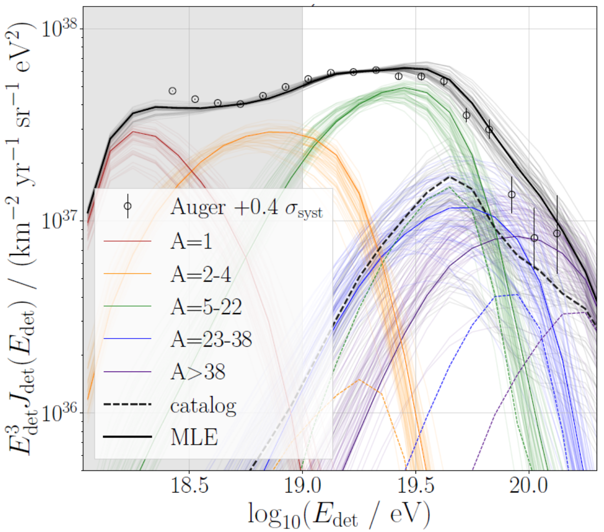
- **γ-AGN catalog can be discarded** for the first time
  - ➔ CR flux proportional to γ-ray flux disfavored

- results under assumption of **turbulent » coherent Galactic magnetic field** (at least in source directions)

- **publication submitted to JCAP, available at:**
  arXiv: 2305.16693





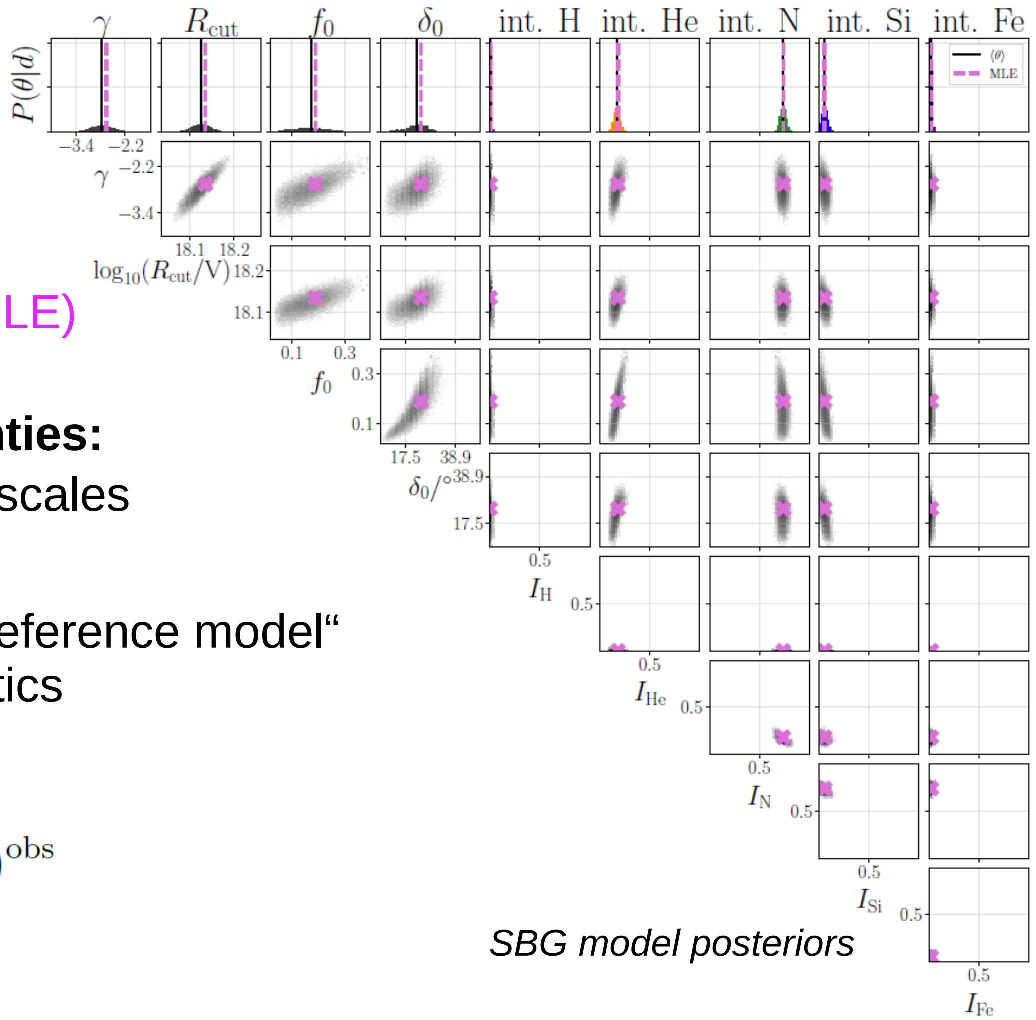


Backup

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:**

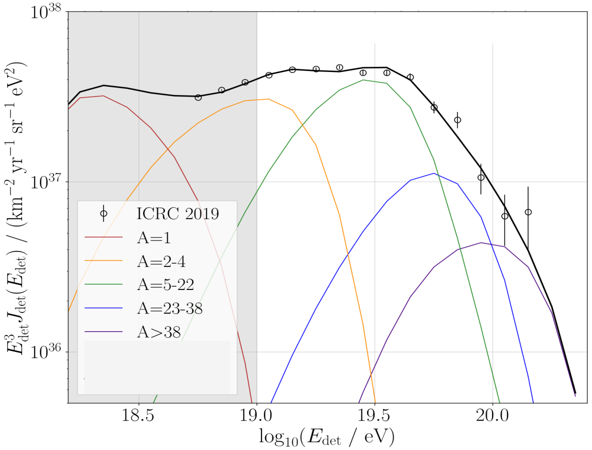
$$\mathrm{TS}_{\mathrm{tot}} = \sum_{\mathrm{obs}=E,X_{\mathrm{max}},\mathrm{ADs}} 2(\log \mathcal{L}^{m=x} - \mathcal{L}_{\mathrm{ref}}^{m=x})^{\mathrm{obs}}$$



SBG model posteriors

Modeling 3 observables

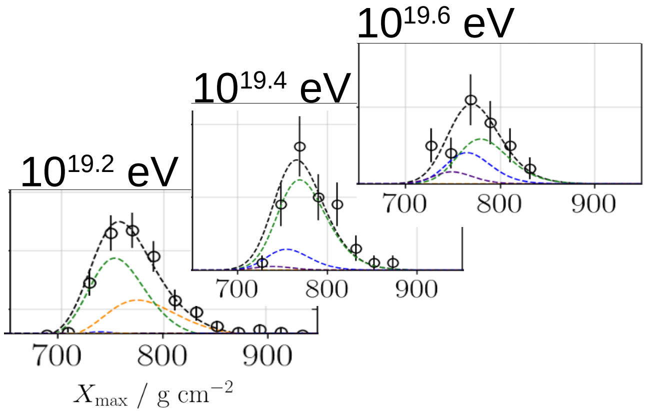
energy spectrum



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

$$\log \mathcal{L}_E = \sum_e k^e \log(p^e) - \log(k^e!) - p^e$$

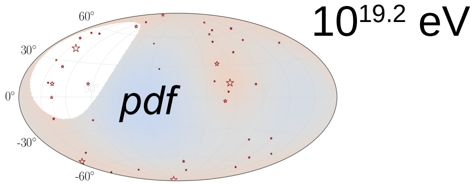
shower depth distributions

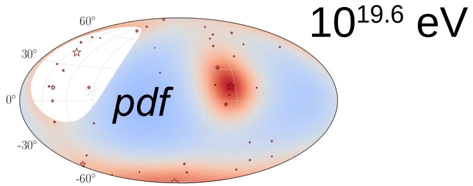


- parameterize with Gumbel distributions (EPOS-LHC)
- fold with detector resolution & acceptance
- Multinomial likelihood function:

$$\mathcal{L}_{\rm Xmax} = \prod_{\tilde{e}} k^{\tilde{e}}! \prod_x \frac{(p^{\tilde{e},x})^{k^{\tilde{e},x}}}{k^{\tilde{e},x}!}$$

arrival directions





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

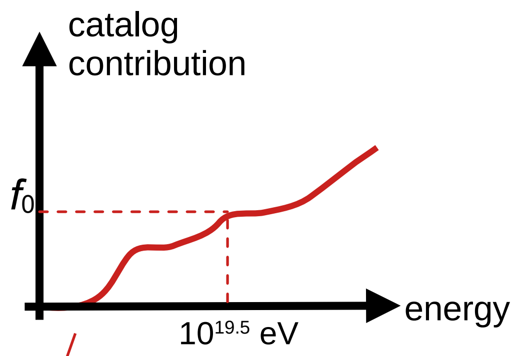
$$\mathcal{L}_{\rm AD} = \prod_e \prod_p {\rm pdf}^{e,p}(v^{e,p})$$

Signal fraction & arrival directions

→ define signal fraction:

weight catalog and background

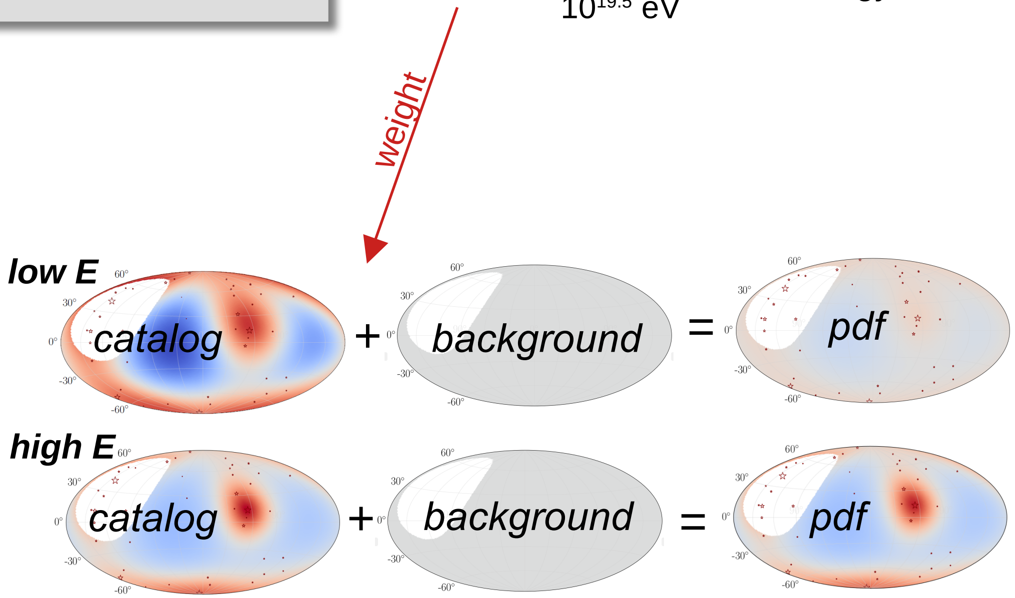
- catalog contribution shaped by propagation
- define signal fraction f_0
- free model parameter



→ calculate arrival directions:

- arrival direction blurring anti-prop. to rigidity: $$\delta = \frac{\delta_0}{R/10\ \mathrm{EV}}$$
- for <u>each source</u> in <u>each *E*-bin:</u> add Fisher distribution <u>weight with contribution</u>

example:
Fe + Si + N



Reference models: results

	Reference, $m=0$ (flat)		Reference, $m=3.4$ (SFR)		Reference, $m=5.0$ (AGN-like)	
	posterior	MLE	posterior	MLE	posterior	MLE
γ	$-2.18^{+0.31}_{-0.33}$	-2.25	$-3.23^{+0.24}_{-0.21}$	-3.09	$-3.92^{+0.01}_{-0.08}$	-4.0
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	$18.18^{+0.03}_{-0.03}$	18.17	$18.09^{+0.02}_{-0.02}$	18.10	$18.04^{+0.01}_{-0.01}$	18.04
I_{H}	$6.5^{+2.0}_{-1.6}\times10^{-2}$	7.0×10^{-2}	$9.0^{+2.2}_{-9.0}\times10^{-3}$	$<10^{-10}$	$1.8^{+0.3}_{-1.8}\times10^{-3}$	$<10^{-10}$
I_{He}	$2.0^{+0.3}_{-0.3}\times10^{-1}$	2.0×10^{-1}	$1.3^{+0.2}_{-0.2}\times10^{-1}$	1.4×10^{-1}	$4.5^{+1.8}_{-1.8}\times10^{-2}$	$<10^{-10}$
I_{N}	$6.0^{+0.4}_{-0.3}\times10^{-1}$	6.0×10^{-1}	$7.2^{+0.3}_{-0.3}\times10^{-1}$	7.1×10^{-1}	$8.1^{+0.3}_{-0.3}\times10^{-1}$	8.8×10^{-1}
I_{Si}	$1.2^{+0.2}_{-0.3}\times10^{-1}$	1.2×10^{-1}	$1.2^{+0.3}_{-0.2}\times10^{-1}$	1.3×10^{-1}	$1.0^{+0.3}_{-0.3}\times10^{-1}$	8.2×10^{-2}
I_{Fe}	$2.1^{+0.6}_{-0.9}\times10^{-2}$	1.9×10^{-2}	$2.6^{+0.7}_{-0.9}\times10^{-2}$	2.3×10^{-2}	$3.8^{+1.1}_{-1.1}\times10^{-2}$	3.6×10^{-2}
$\log b$	-270.6 ± 0.2		-277.7 ± 0.3		-297.0 ± 1.3	
D_E ($N_J=14$)		22.2		28.1		63.2
$D_{X_{\max}}$ ($N_{X_{\max}}=74$)		126.8		132.4		134.1
D		149.0		160.5		197.3
$\log \mathcal{L}_{\mathrm{ADs}}$		0		0		0
$\log \mathcal{L}$		-250.5		-256.2		-274.6

Table 4. Results for the reference models of only homogeneously distributed sources.

	Reference, $m=0$ (flat)		Reference, $m=3.4$ (SFR)		Reference, $m=5.0$ (AGN-like)	
	posterior	MLE	posterior	MLE	posterior	MLE
γ	$-1.01^{+0.41}_{-0.33}$	-1.13	$-1.34^{+0.63}_{-0.50}$	-1.39	$-1.19^{+0.41}_{-0.34}$	-1.40
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	$18.19^{+0.03}_{-0.05}$	18.19	$18.20^{+0.05}_{-0.06}$	18.19	$18.25^{+0.04}_{-0.05}$	18.25
I_{H}	$4.8^{+2.3}_{-3.2}\times10^{-2}$	5.1×10^{-2}	$1.1^{+0.1}_{-1.1}\times10^{-2}$	$<10^{-10}$	$1.1^{+0.2}_{-1.1}\times10^{-2}$	3.5×10^{-8}
I_{He}	$2.9^{+0.4}_{-0.4}\times10^{-1}$	2.9×10^{-1}	$1.1^{+0.4}_{-0.3}\times10^{-1}$	1.3×10^{-1}	$3.5^{+0.8}_{-3.5}\times10^{-2}$	5.7×10^{-4}
I_{N}	$5.3^{+0.4}_{-0.4}\times10^{-1}$	5.2×10^{-1}	$6.4^{+0.7}_{-0.7}\times10^{-1}$	6.4×10^{-1}	$5.9^{+0.7}_{-0.5}\times10^{-1}$	6.8×10^{-1}
I_{Si}	$1.2^{+0.4}_{-0.4}\times10^{-1}$	1.2×10^{-1}	$1.8^{+0.6}_{-0.5}\times10^{-1}$	1.8×10^{-1}	$2.8^{+0.5}_{-0.5}\times10^{-1}$	2.4×10^{-1}
I_{Fe}	$2.2^{+0.9}_{-1.1}\times10^{-2}$	1.7×10^{-2}	$5.7^{+1.4}_{-2.2}\times10^{-2}$	4.8×10^{-2}	$9.3^{+1.9}_{-2.2}\times10^{-2}$	8.3×10^{-2}
ν_E/σ	$-1.43^{+0.57}_{-0.67}$	-1.37	$0.19^{+0.39}_{-0.60}$	0.18	$1.21^{+0.29}_{-0.30}$	1.17
$\nu_{\mathrm{Xmax}}/\sigma$	$-0.88^{+0.33}_{-0.28}$	-0.78	$-1.62^{+0.34}_{-0.36}$	-1.53	$-2.23^{+0.27}_{-0.24}$	-2.00
$\log b$	-257.9 ± 0.1		-267.0 ± 0.1		-280.3 ± 1.6	
D_{syst}		2.5		2.4		5.4
D_E ($N_J=14$)		12.2		20.8		21.8
$D_{X_{\max}}$ ($N_{X_{\max}}=74$)		107.6		114.6		123.4
D		122.3		137.8		150.6
$\log \mathcal{L}_{\mathrm{ADs}}$		0		0		0
$\log \mathcal{L}$		-237.2		-244.9		-251.3

Table 5. Results for the reference models of only homogeneously distributed sources including experimental systematic uncertainties as nuisance parameters.

Source models: results

	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
$\delta_0/°$	$30.5^{+2.0}_{-20.2}$	14.4	$27.4^{+4.2}_{-17.0}$	14.3	$18.8^{+5.9}_{-3.6}$	21.9
I_{H}	$5.8^{+2.9}_{-2.6}\times10^{-2}$	4.2×10^{-4}	$1.2^{+0.2}_{-1.2}\times10^{-2}$	3.0×10^{-4}	$1.2^{+0.1}_{-1.2}\times10^{-2}$	1.0×10^{-4}
I_{He}	$2.7^{+0.4}_{-0.4}\times10^{-1}$	3.5×10^{-1}	$9.9^{+3.8}_{-2.9}\times10^{-2}$	1.2×10^{-1}	$1.1^{+0.3}_{-0.4}\times10^{-1}$	1.4×10^{-1}
I_{N}	$5.6^{+0.4}_{-0.4}\times10^{-1}$	5.0×10^{-1}	$6.7^{+0.7}_{-0.7}\times10^{-1}$	6.8×10^{-1}	$7.2^{+0.6}_{-0.6}\times10^{-1}$	7.3×10^{-1}
I_{Si}	$9.0^{+3.9}_{-3.4}\times10^{-2}$	1.4×10^{-1}	$1.5^{+0.5}_{-0.6}\times10^{-1}$	1.6×10^{-1}	$1.2^{+0.5}_{-0.5}\times10^{-1}$	9.8×10^{-2}
I_{Fe}	$2.3^{+0.9}_{-1.2}\times10^{-2}$	1.8×10^{-2}	$5.1^{+1.5}_{-1.8}\times10^{-2}$	4.4×10^{-2}	$4.7^{+1.3}_{-1.7}\times10^{-2}$	3.8×10^{-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
$\nu_{X\max}/\sigma$	$-0.94^{+0.29}_{-0.24}$	-0.97	$-1.60^{+0.30}_{-0.25}$	-1.45	$-1.55^{+0.26}_{-0.25}$	-1.33
$\log b$	-254.6 ± 0.1		-264.5 ± 0.2		-258.6 ± 0.2	
D_{syst}		2.8		2.1		1.9
D_E ($N_J=14$)		13.6		21.9		25.3
$D_{X_{\max}}$ ($N_{X_{\max}}=74$)		107.4		113.6		112.7
D		123.8		137.7		139.9
$\log\mathcal{L}_{\mathrm{ADs}}$		-9.4		-9.5		-13.5
$\log\mathcal{L}$		-228.51		-235.3		-232.4

	Cen A, $m=0$ (flat)		Cen A, $m=3.4$ (SFR)		SBG, $m=3.4$ (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
$\delta_0/°$	$56.5^{+29.4}_{-12.8}$	16.5	$27.6^{+2.7}_{-16.3}$	16.8	$22.2^{+5.3}_{-4.0}$	24.3
I_{H}	$5.9^{+2.5}_{-1.7}\times10^{-2}$	7.1×10^{-2}	$8.3^{+2.0}_{-8.3}\times10^{-3}$	1.6×10^{-5}	$6.4^{+1.3}_{-6.4}\times10^{-3}$	4.3×10^{-5}
I_{He}	$2.3^{+0.3}_{-0.5}\times10^{-1}$	1.9×10^{-1}	$1.3^{+0.2}_{-0.2}\times10^{-1}$	1.4×10^{-1}	$1.7^{+0.3}_{-0.4}\times10^{-1}$	1.8×10^{-1}
I_{N}	$6.3^{+0.3}_{-0.3}\times10^{-1}$	6.2×10^{-1}	$7.4^{+0.3}_{-0.3}\times10^{-1}$	7.3×10^{-1}	$7.4^{+0.3}_{-0.3}\times10^{-1}$	7.4×10^{-1}
I_{Si}	$6.5^{+3.6}_{-3.3}\times10^{-2}$	9.9×10^{-2}	$9.2^{+3.2}_{-2.3}\times10^{-2}$	1.1×10^{-1}	$5.7^{+2.5}_{-3.1}\times10^{-2}$	5.4×10^{-2}
I_{Fe}	$1.6^{+0.7}_{-1.0}\times10^{-2}$	2.0×10^{-2}	$2.5^{+0.8}_{-0.9}\times10^{-2}$	2.3×10^{-2}	$2.5^{+0.8}_{-0.9}\times10^{-2}$	2.3×10^{-2}
$\log b$	-264.0 ± 0.2		-272.6 ± 0.2		-266.9 ± 0.1	
D_E ($N_J=14$)		22.3		28.5		33.3
$D_{X_{\max}}$ ($N_{X_{\max}}=74$)		124.9		130.6		126.2
D		147.2		159.1		159.5
$\log\mathcal{L}_{\mathrm{ADs}}$		-10.5		-10.4		-13.3
$\log\mathcal{L}$		-239.1		-245.1		-242.4

Source contributions to TS

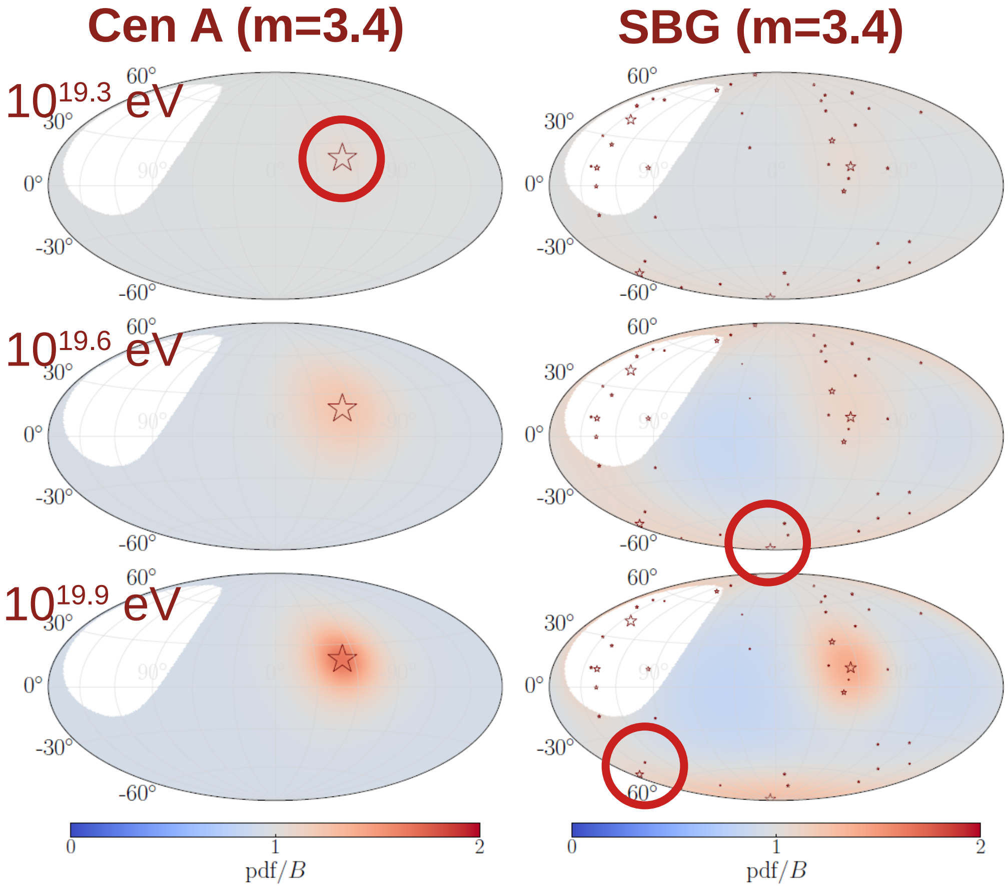
Cen A region contributes TS_{AD} ~ 20

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

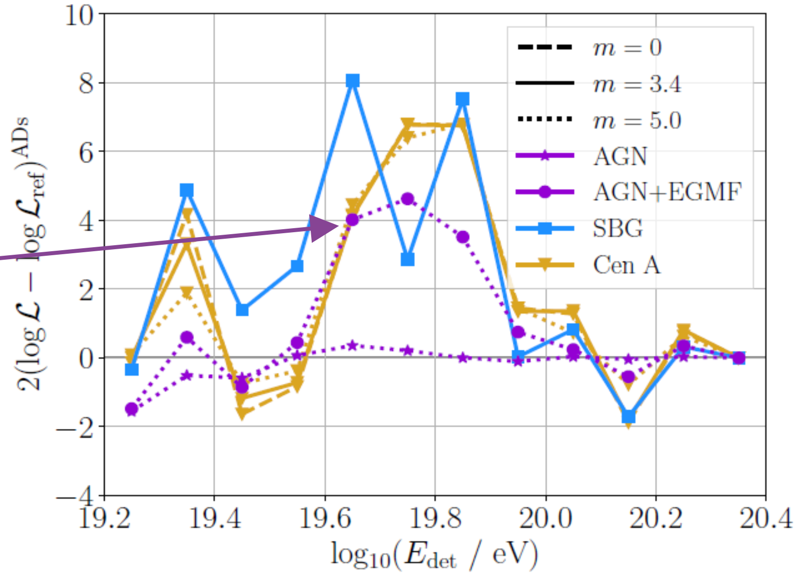


The γ-AGN model with EGMF / distance-dependent blurring

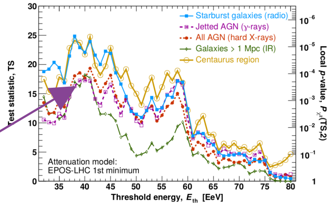
- include **distance-dependent blurring:**

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

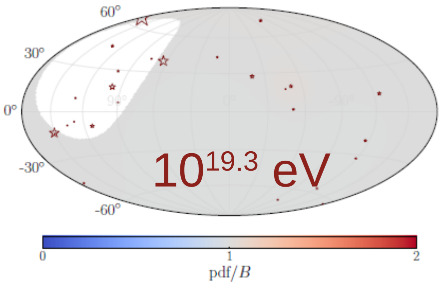
- arrival directions now > isotropy: **TS$_{AD}$=11.7**

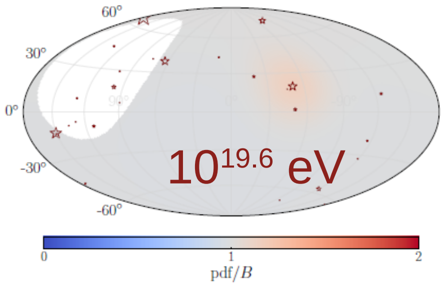


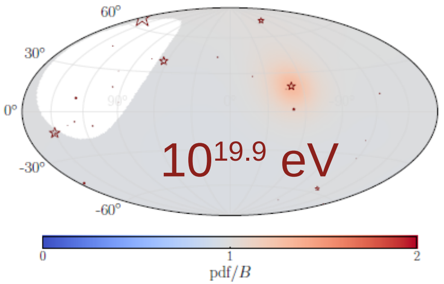
- **but:**
  - ➔ model cannot reproduce



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

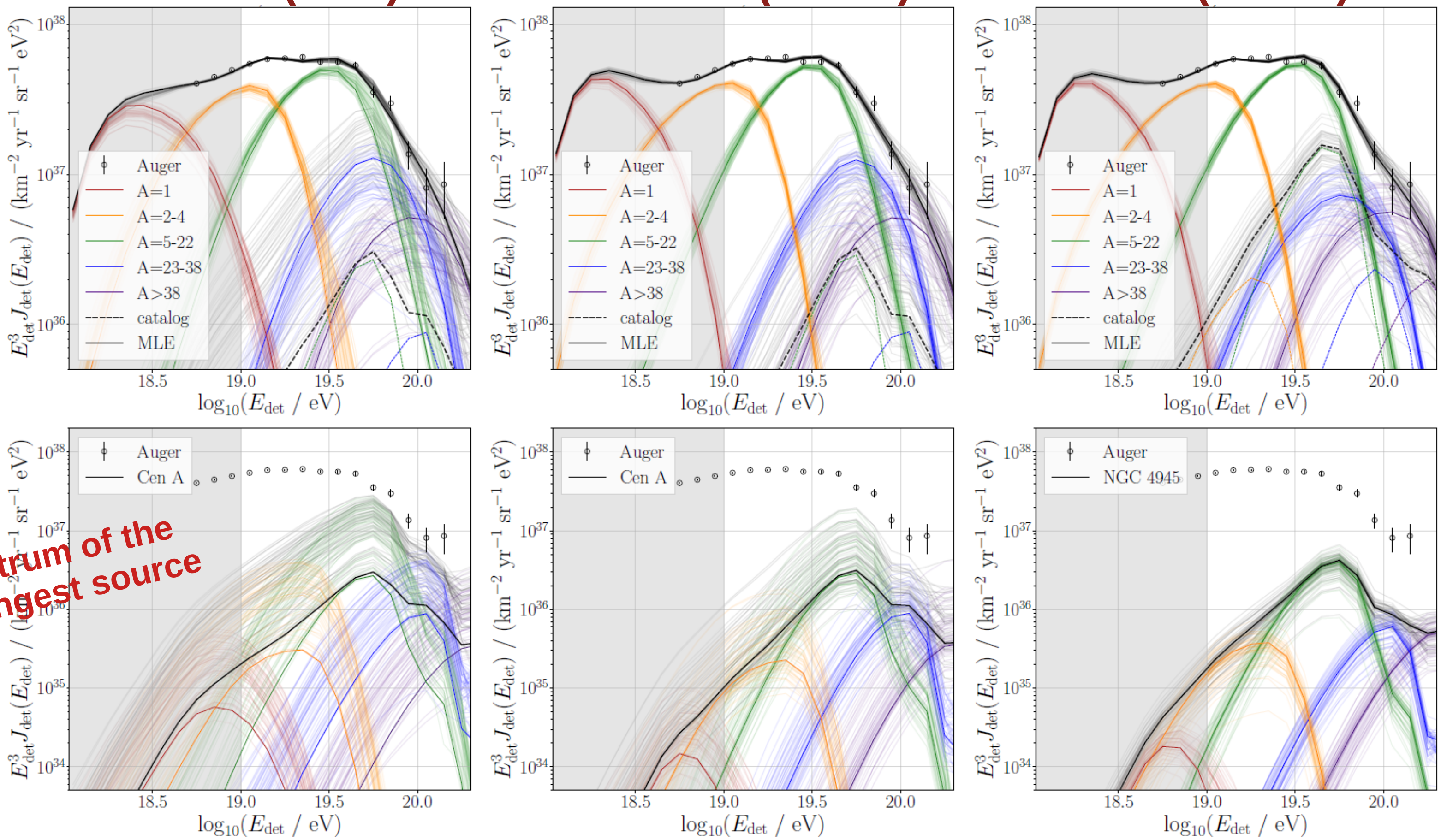






SBG & Centaurus A models: spectra

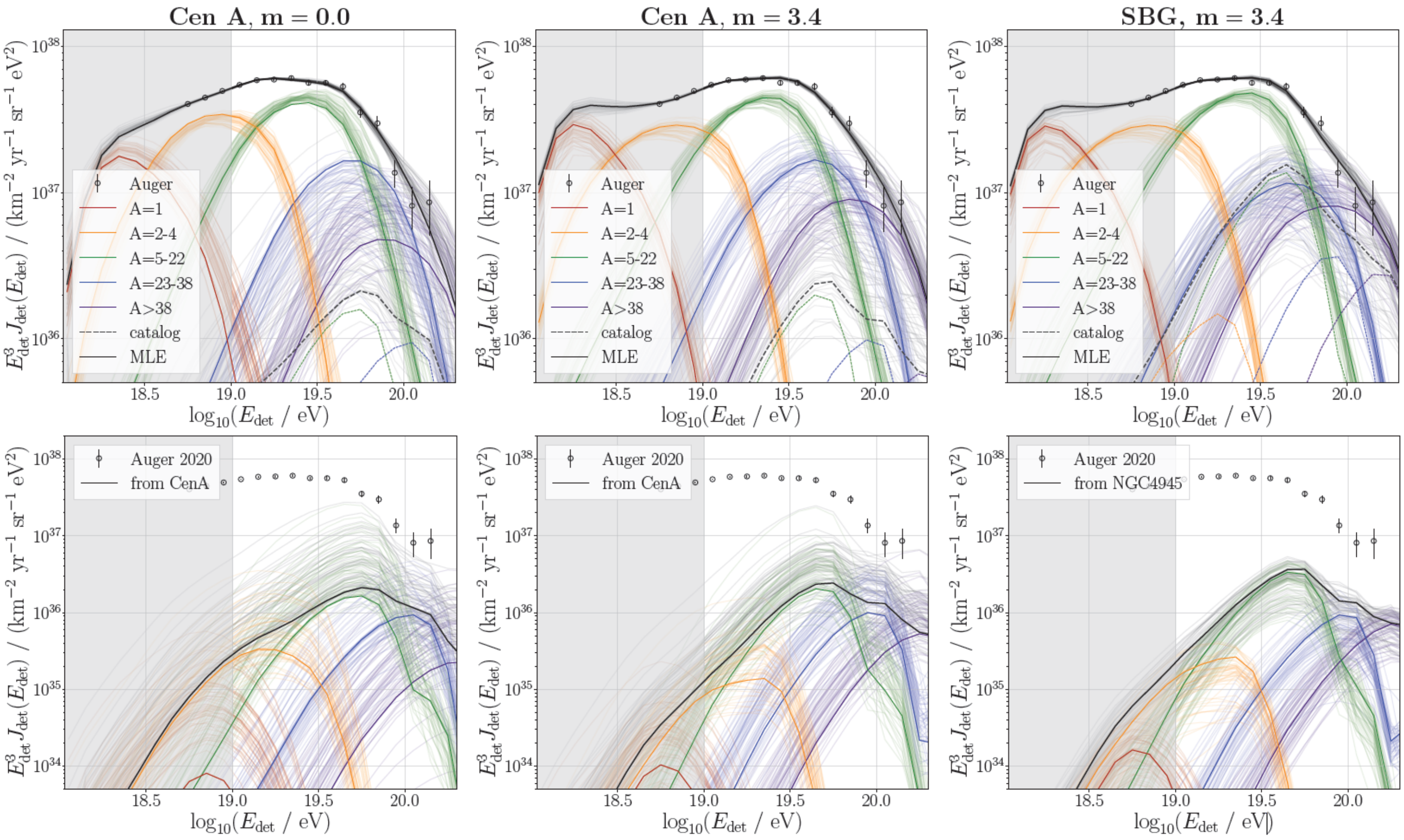
Cen A (m=0) | Cen A (m=3.4) | SBG (m=3.4)



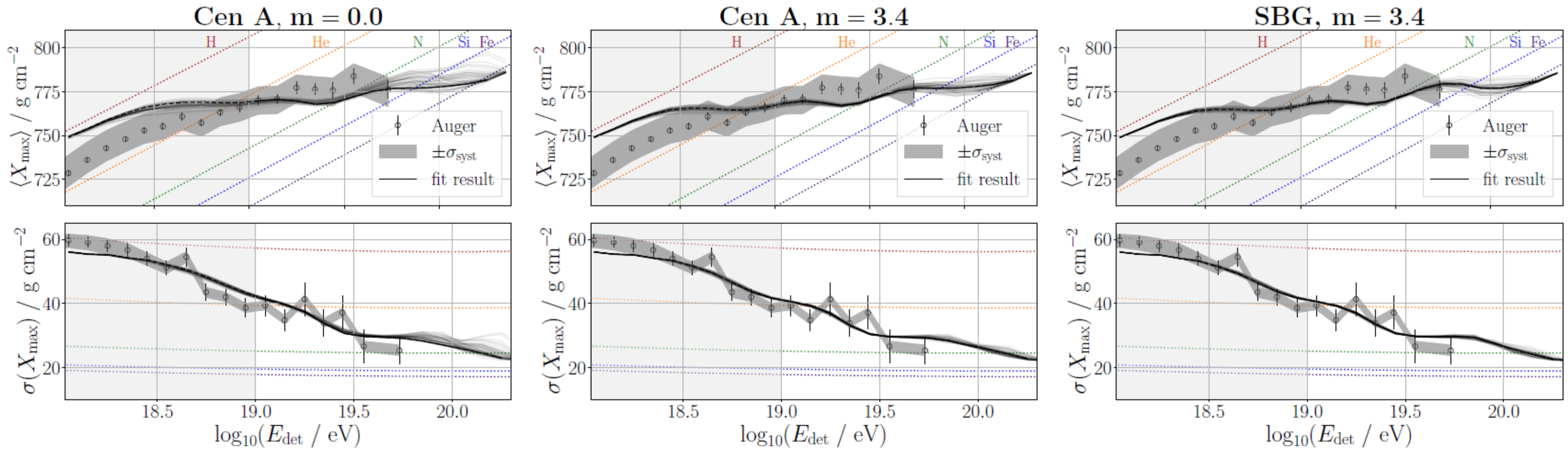
Cen A spectrum = NGC 4945 spectrum

→ flux from that sky region modeled consistently

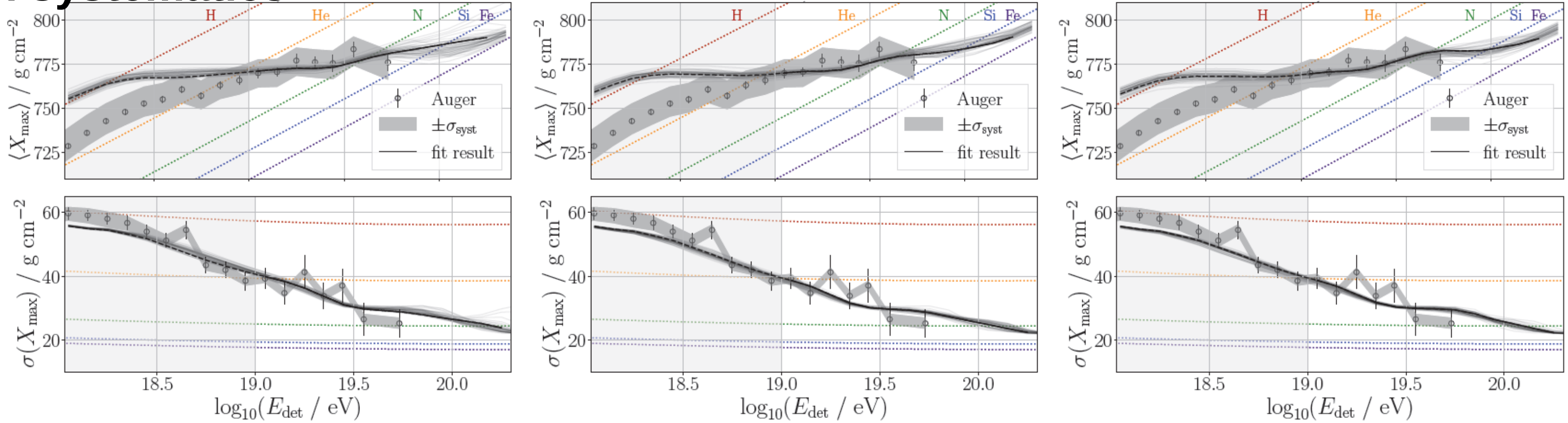
Including systematics: spectra



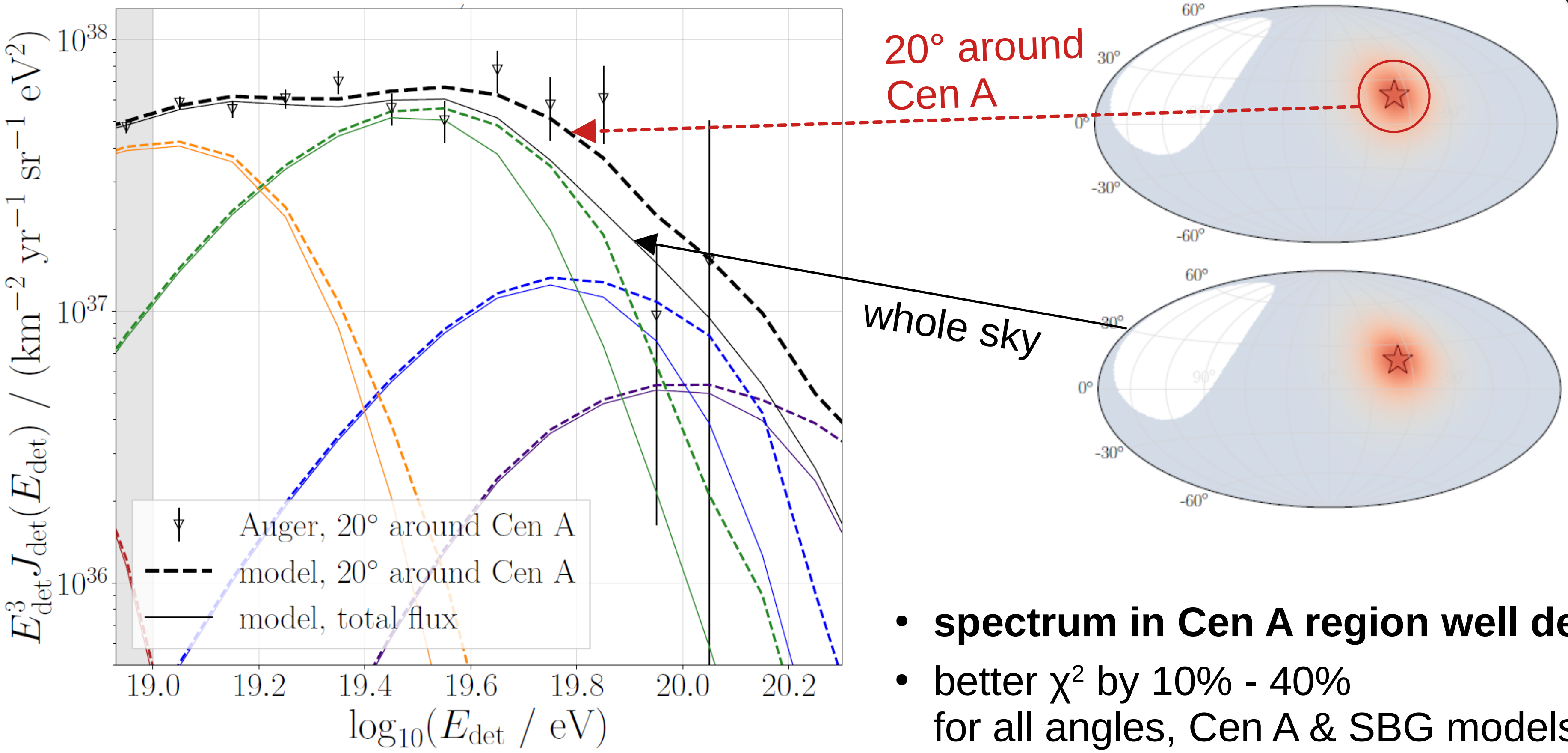
Xmax distributions



with systematics



Spectrum in Cen A region



- **spectrum in Cen A region well described**
- better χ^2 by 10% - 40%
  for all angles, Cen A & SBG models

Test statistic

compare likelihood to ref. model (just background → backup)

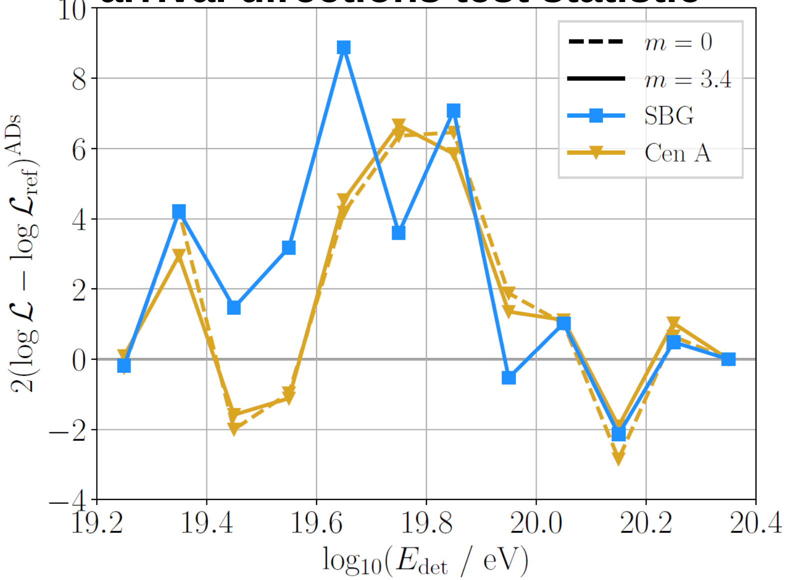
$$\mathrm{TS}_{\mathrm{tot}} = \sum_{\mathrm{obs}=E, X_{\max}, \mathrm{ADs}} 2(\log \mathcal{L}^{m=x} - \mathcal{L}_{\mathrm{ref}}^{m=x})^{\mathrm{obs}}$$

	SBG, $m = 3.4$		**Cen A, $m = 0.0$**		**Cen A, $m = 3.4$**	
		+ syst		+ syst		+ syst
$\mathrm{TS}_{\mathrm{tot}}$	27.6	25.6	22.8	17.3	22.2	19.1
TS_E	−5.2	−4.5	−0.1	−1.4	−0.4	−1.1
$\mathrm{TS}_{X_{\max}}$	6.2	2.0	1.9	0.2	1.8	1.0
$\mathrm{TS}_{\mathrm{ADs}}$	26.6	27.1	20.9	18.7	20.8	19.0

SBG model has highest TS=25.6 ↔ 4.5σ

- ➔ increase compared to AD-only correlation
- ➔ Centaurus region contributes dominant part: **TS~20**
- ➔ (E-dependent) arrival directions most important

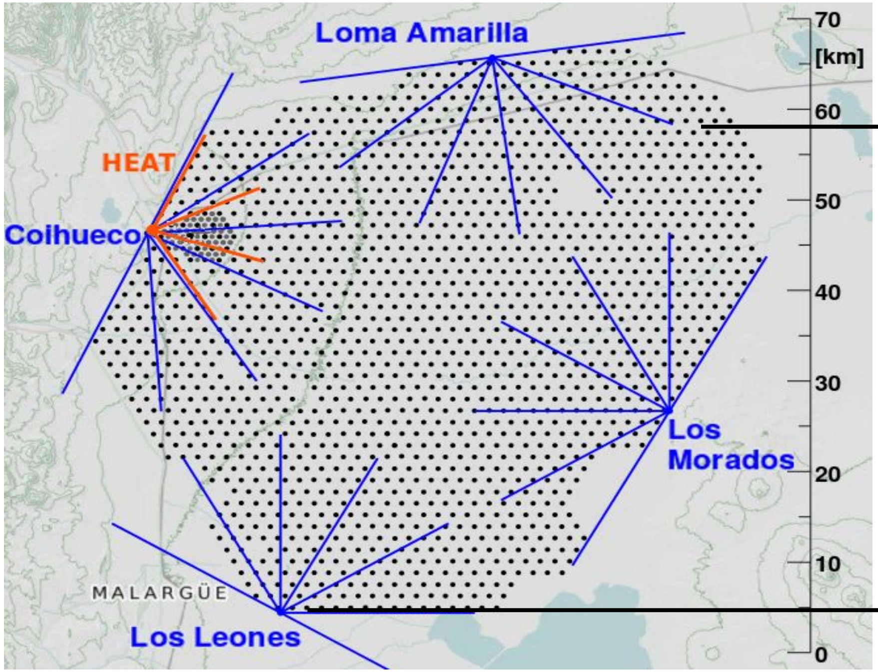
arrival directions test statistic



- sum over E bins gives total TS
  - no E_{thresh} scan!
- peaks could be from He, N, Si
  - ➔ compare to spectrum
  - ➔ but: large uncertainties

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