Global fit of UHECR spectrum, composition & anisotropies

measured at the Pierre Auger Observatory

Teresa Bister

RICAP, Rome, September 2024

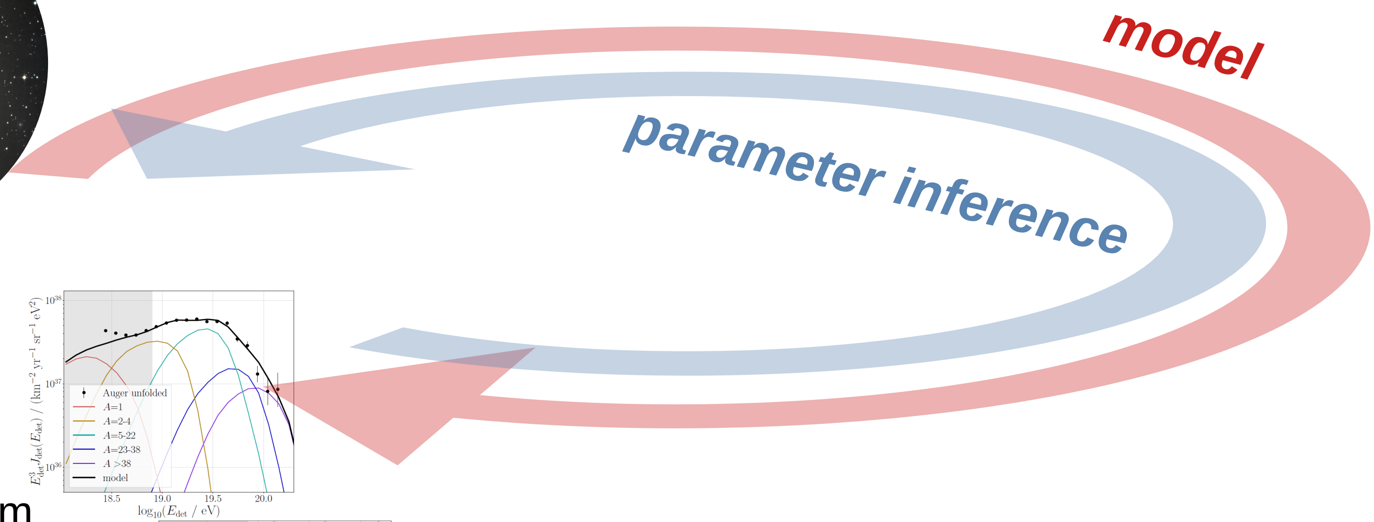
PIERRE AUGER OBSERVATORY

Radboud University

Nikhef

Modeling UHECRs from sources to detection

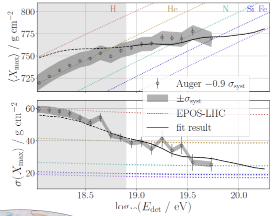
sources emit UHECRs



PIERRE AUGER OBSERVATORY

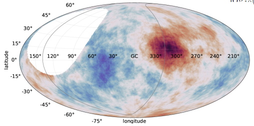
compare to data

- energy spectrum
- mass composition
- arrival directions



→ see Vladimir Novotny's talk later today

→ for general introduction to the Pierre Auger Observatory: see Marcus Roth's talk on Thursday morning

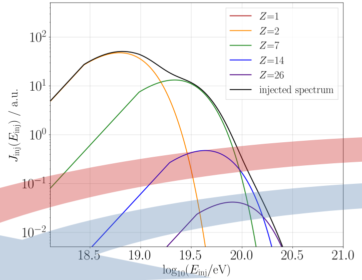


→ see Federico Mariani's & Marta Bianchiotti's talks later today

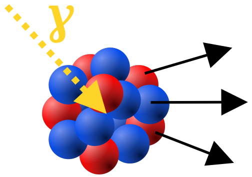
Modeling UHECRs from sources to detection

source distribution

injection

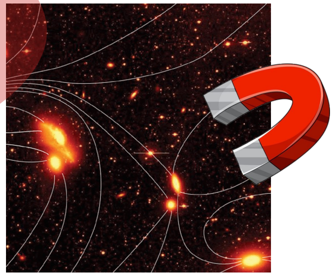


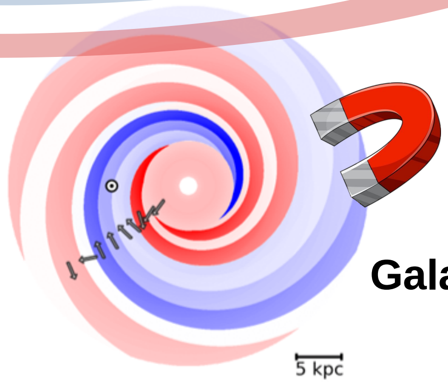
propagation through extragalactic space



model

extragalactic magnetic fields

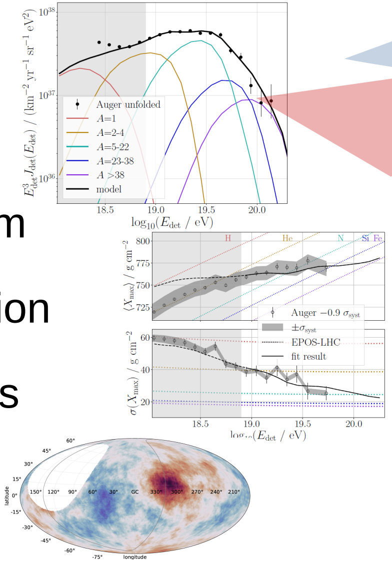




Galactic magnetic fields

compare to data

- energy spectrum
- mass composition
- arrival directions

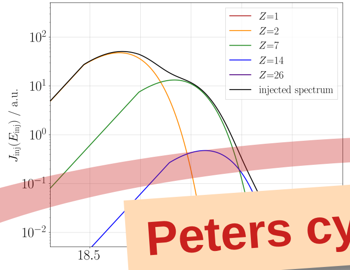


Combined fit of spectrum and composition

source distribution

homogeneous

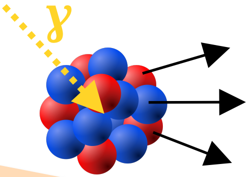
injection



Peters cycle

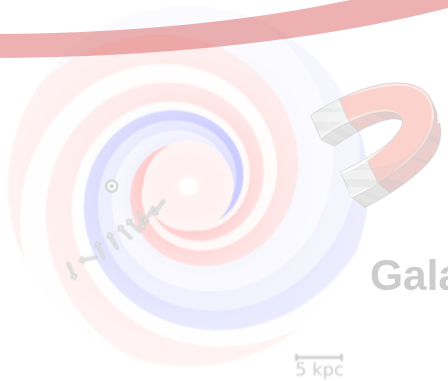
maximum energy prop. to charge number Z

propagation through extragalactic space



CRPropa

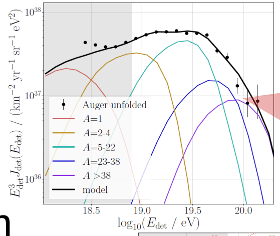
extragalactic magnetic fields

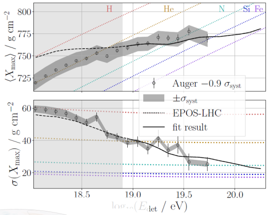


Galactic magnetic fields

compare to data

- energy spectrum
- mass composition
- arrival directions





Combined fit of spectrum and composition

spectral index

rigidity cutoff

$R:=E/Z$

$$\widetilde{Q}_A(E) = \widetilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \leq Z_A R_{\mathrm{cut}} \\ \exp\left(1 - \frac{E}{Z_A R_{\mathrm{cut}}}\right), & E > Z_A R_{\mathrm{cut}} \end{cases}$$

element contributions

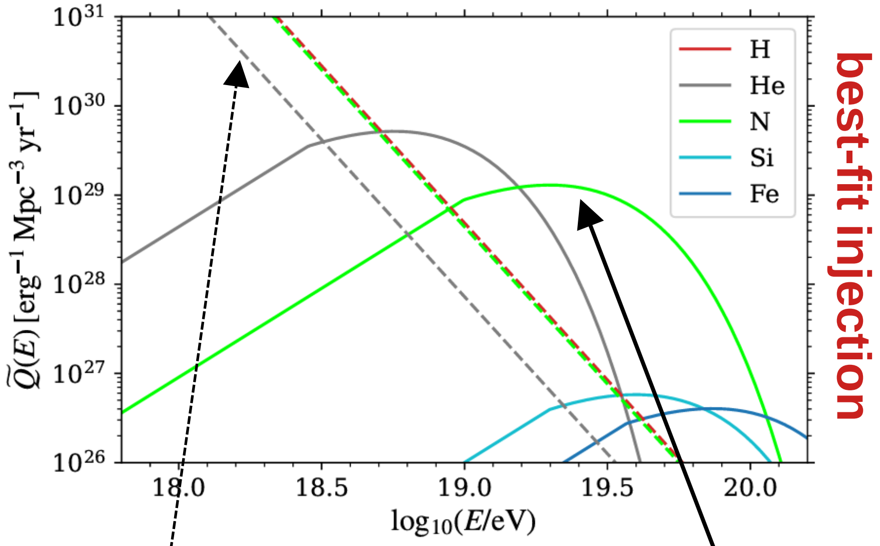
- **injection: Peters cycle** + broken exp. cutoff
- two populations of **extragalactic sources**

Combined fit of spectrum and composition

$$\widetilde{Q}_A(E) = \widetilde{Q}_{0A}\left(\frac{E}{E_0}\right)^{-\gamma}\begin{cases}1, & E \le Z_A R_{\rm cut}\\ \exp\left(1-\frac{E}{Z_A R_{\rm cut}}\right), & E > Z_A R_{\rm cut}\end{cases}$$

spectral index (γ), rigidity cutoff ($R_{\rm cut}$), element contributions ($\widetilde{Q}_{0A}$)

- **injection: Peters cycle** + broken exp. cutoff
- two populations of **extragalactic sources**



low-energy component:
→ very soft spectrum
→ rigidity cutoff unconstrained

high-energy component:
→ very hard spectrum ɣ<0
→ low rigidity cutoff ~1 EV

Combined fit of spectrum and composition

spectral index — rigidity cutoff

$$\widetilde{Q}_A(E) = \widetilde{Q}_{0A}\left(\frac{E}{E_0}\right)^{-\gamma}\begin{cases}1, & E \leq Z_A R_{\rm cut}\\ \exp\left(1-\frac{E}{Z_A R_{\rm cut}}\right), & E > Z_A R_{\rm cut}\end{cases}$$

element contributions

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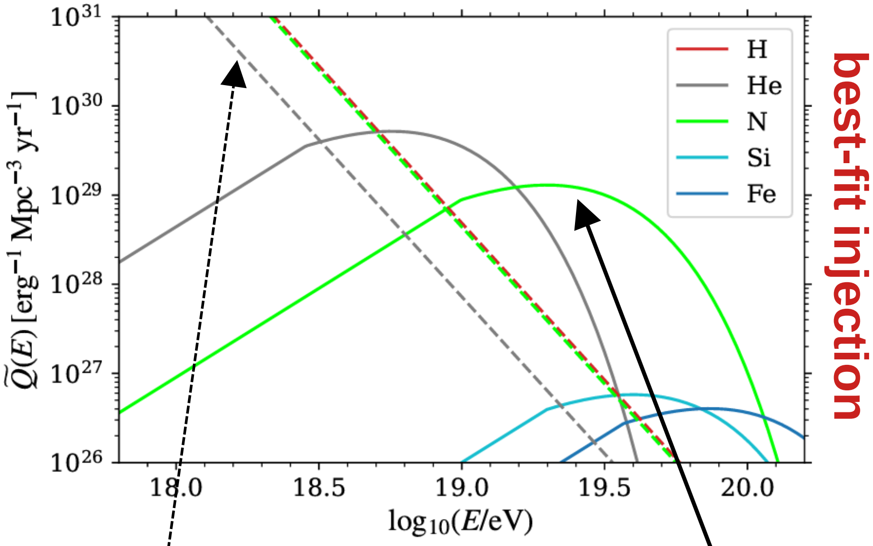

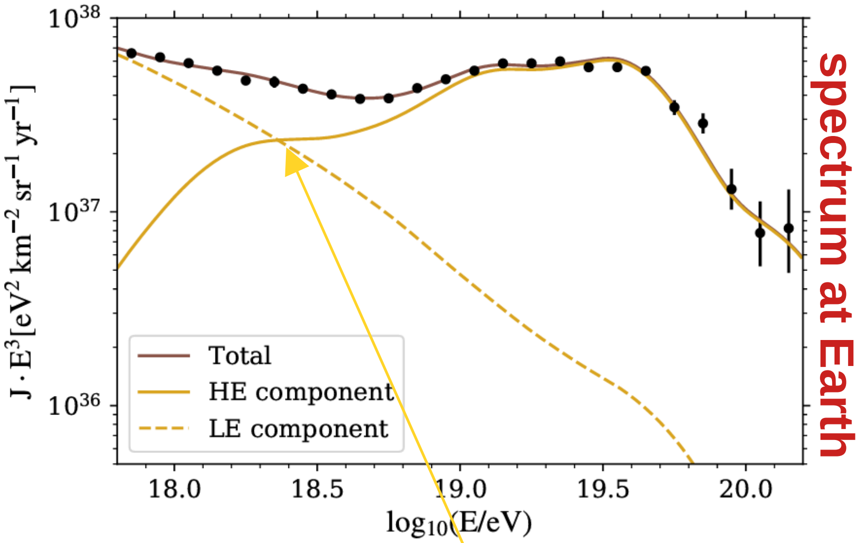

low-energy component:
→ very soft spectrum
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high-energy component:
→ very hard spectrum γ<0
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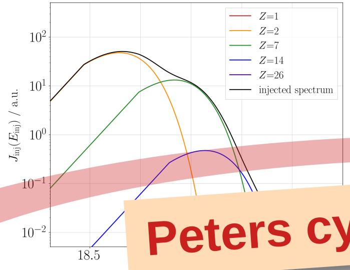
ankle: transition between populations

Adding arrival directions as an observable

source distribution

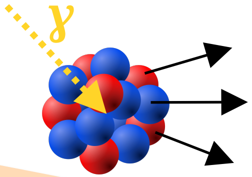
homogeneous

injection



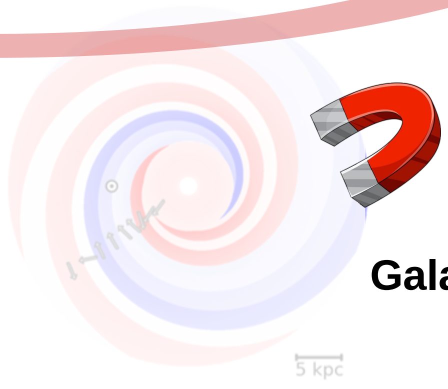
Peters cycle

propagation through extragalactic space



CRPropa

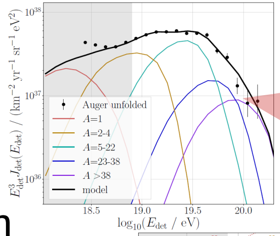
extragalactic magnetic fields

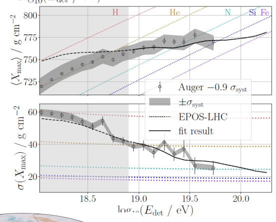


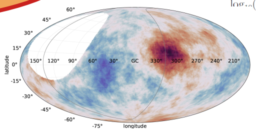
Galactic magnetic fields

compare to data

- energy spectrum
- mass composition
- **arrival directions**



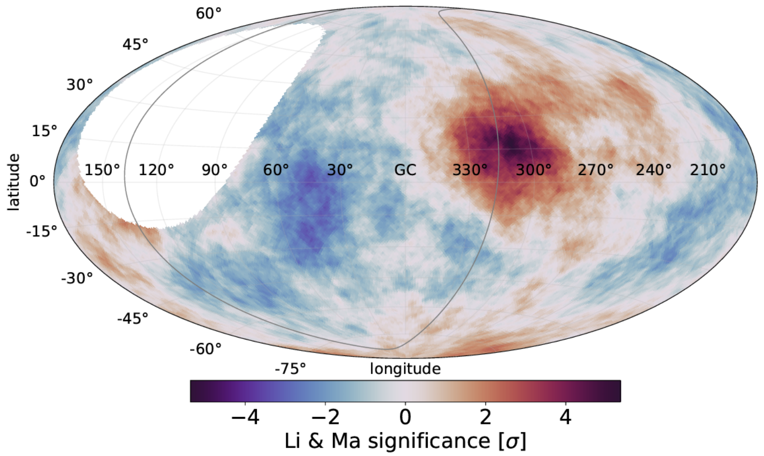




What do the arrival directions look like at ~40 EeV?

→ see Federico Mariani's talk later today

sky in cosmic rays at E > 40 EeV:



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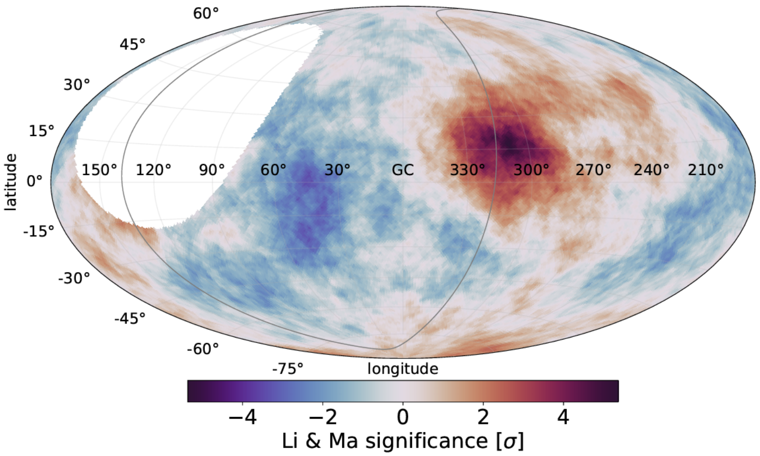
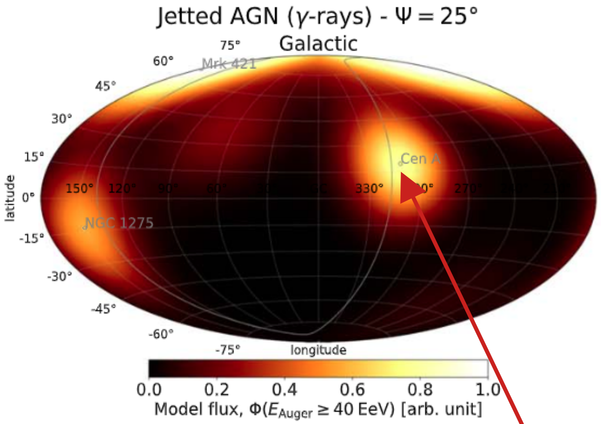
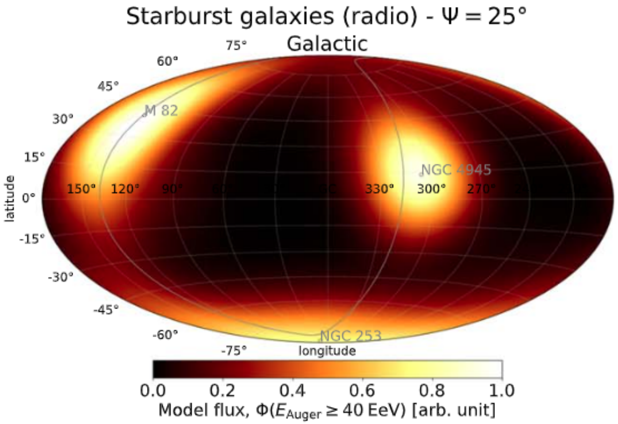


jetted active galactic nuclei (γ-AGNs):



nearest AGN: *Centaurus A*

starburst galaxies (SBGs):



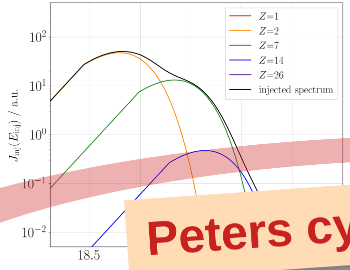
Nearby starburst galaxies or active galactic nuclei could explain the measured arrival directions based on their directions & fluxes

Adding arrival directions to the model

source distribution

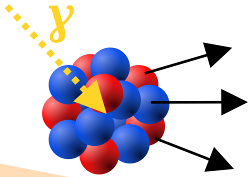
homogeneous + catalog

injection



Peters cycle

propagation through extragalactic space

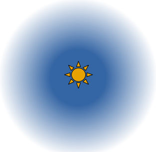


CRPropa

extragalactic magnetic fields

turbulent: blurring prop. to *1/R*: = *Z/E*

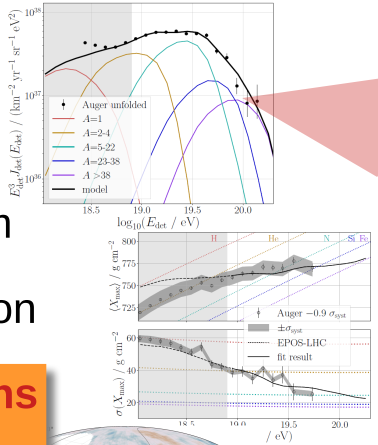
$$\delta = \frac{\delta_0}{R/10\ \mathrm{EV}}$$

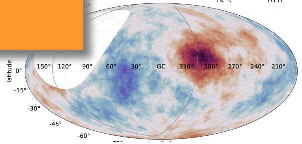


Galactic magnetic fields

compare to data

- energy spectrum
- mass composition
- **arrival directions E>20 EeV**





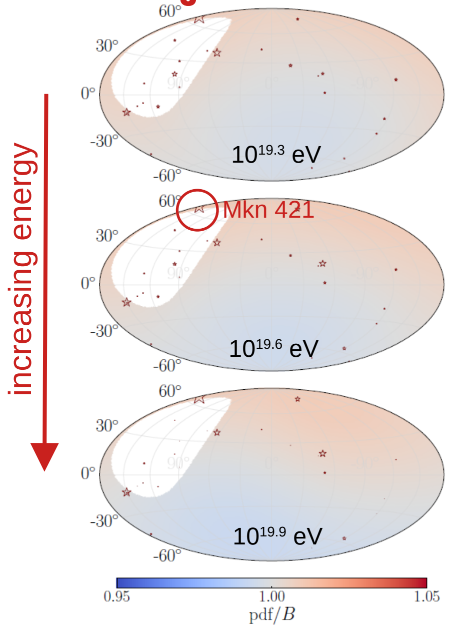
TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration JCAP01(2024)022

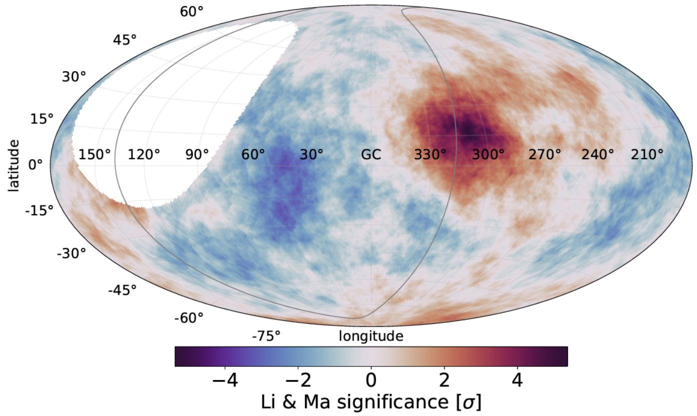
Best-fit model: arrival directions

γ-AGNs

Centaurus A

Starburst Galaxies





Best-fit model: arrival directions

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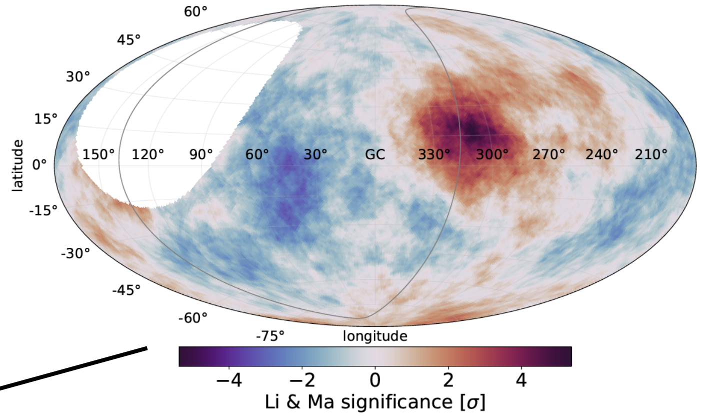
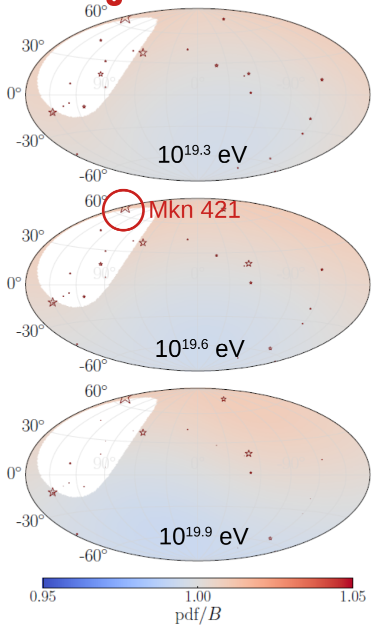
Centaurus A

Starburst Galaxies



increasing energy

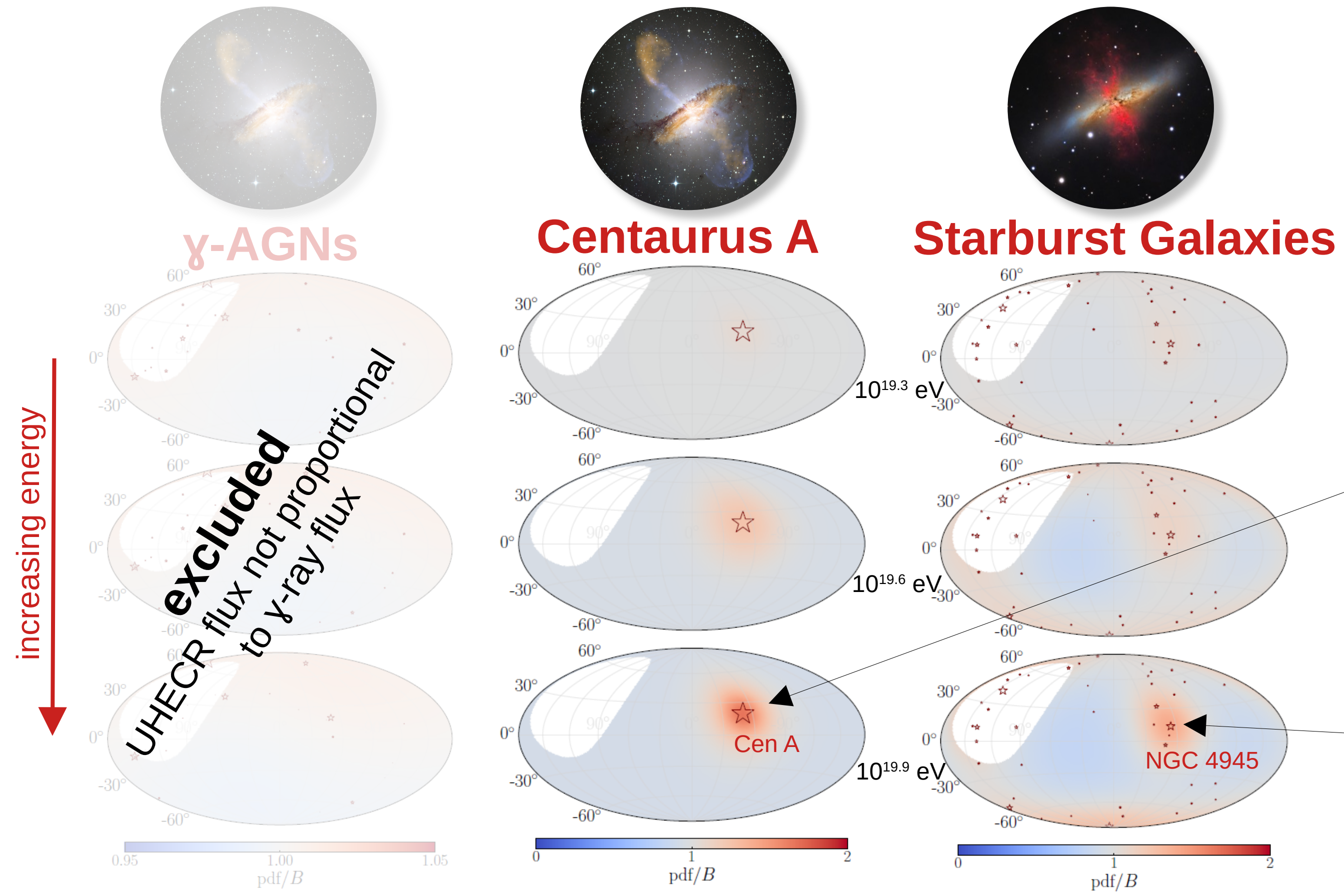


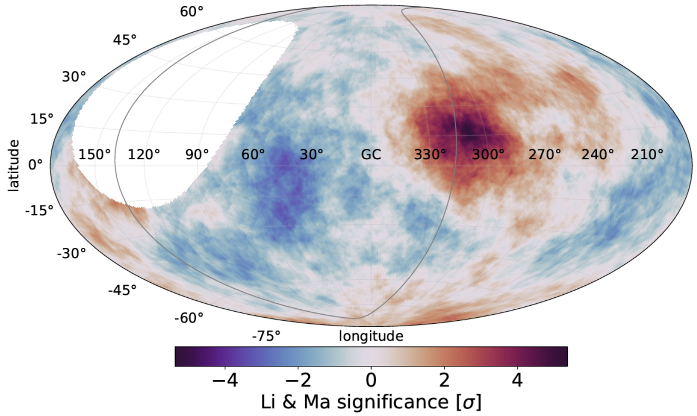
does not describe data well!

- blazar Mkn 421 severely overweighted
- UHECR flux not proportional to γ-ray flux

TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration JCAP01(2024)022

Best-fit model: arrival directions

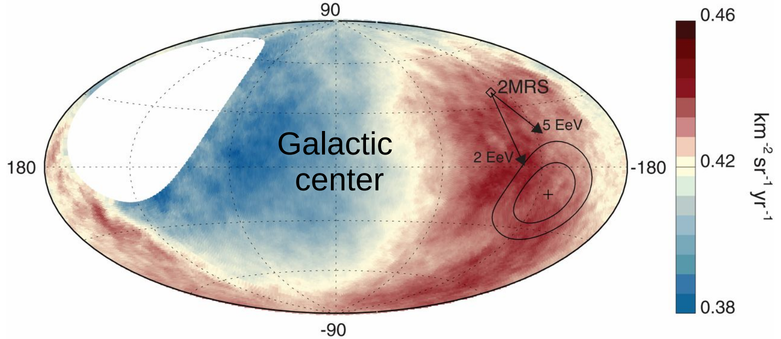




- **starburst galaxy model favored with 4.5σ significance over homogeneous model!**
- mostly due to Centaurus A / NGC 4945 region

What about lower energies?

Cosmic-ray sky at E > 8 EeV:



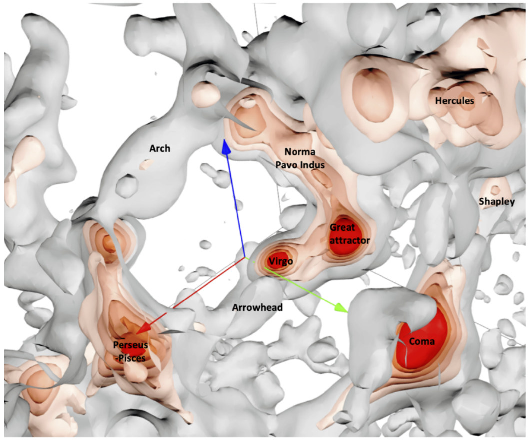
The Pierre Auger Collaboration, Science 2017

- **dipole with significance** >5σ
- no significant quadrupole or higher moments
- not aligned with Galactic center
  - ➔ **sources extragalactic!**

→ see Marta Bianchiotti's talk later today

sources at lower energy:

- ➔ larger horizon
- ➔ more sources contribute, not dominated by nearby candidates



dipole can be explained by extragalactic sources following the **large-scale structure of the universe**

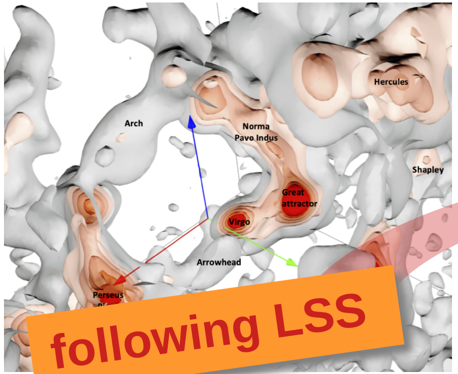
+ deflection by Galactic magnetic field

e.g. Ding, Globus, Farrar ApJL 913 L13 (2021)
Globus, Piran, Hoffman, Carlesi, Pomarede MNRAS 484 (2019)
Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)
The Pierre Auger Collaboration arXiv:2408.05292
...

Bister & Farrar, ApJ 966 71 2024

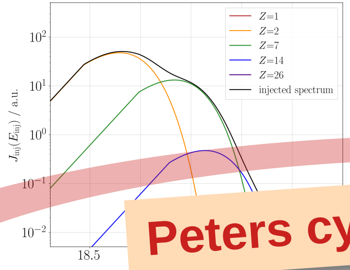
Model for large-scale anisotropies >8 EeV

source distribution



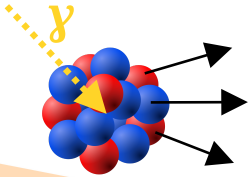
following LSS

injection



Peters cycle

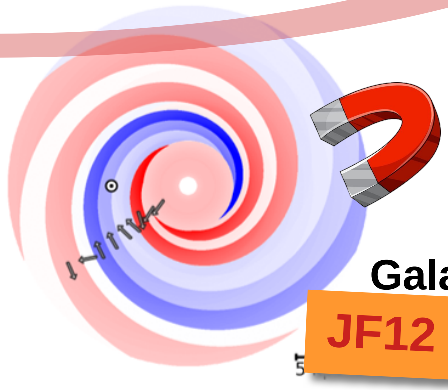
propagation through extragalactic space



CRPropa

extragalactic magnetic fields

turbulent

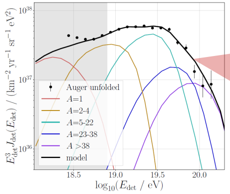


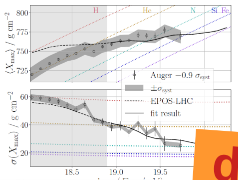
Galactic magnetic field

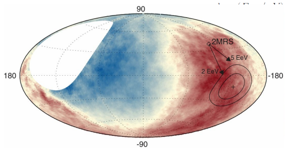
JF12 (& UF23 models)

compare to data

- energy spectrum
- mass composition
- arrival directions

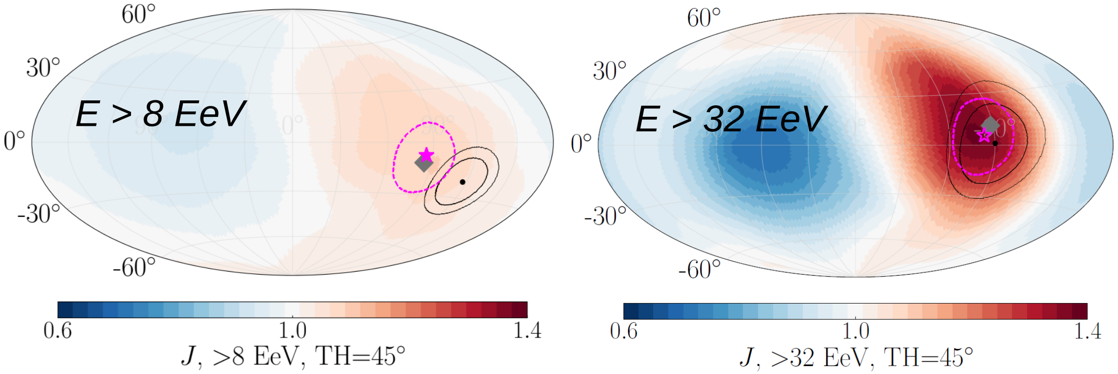


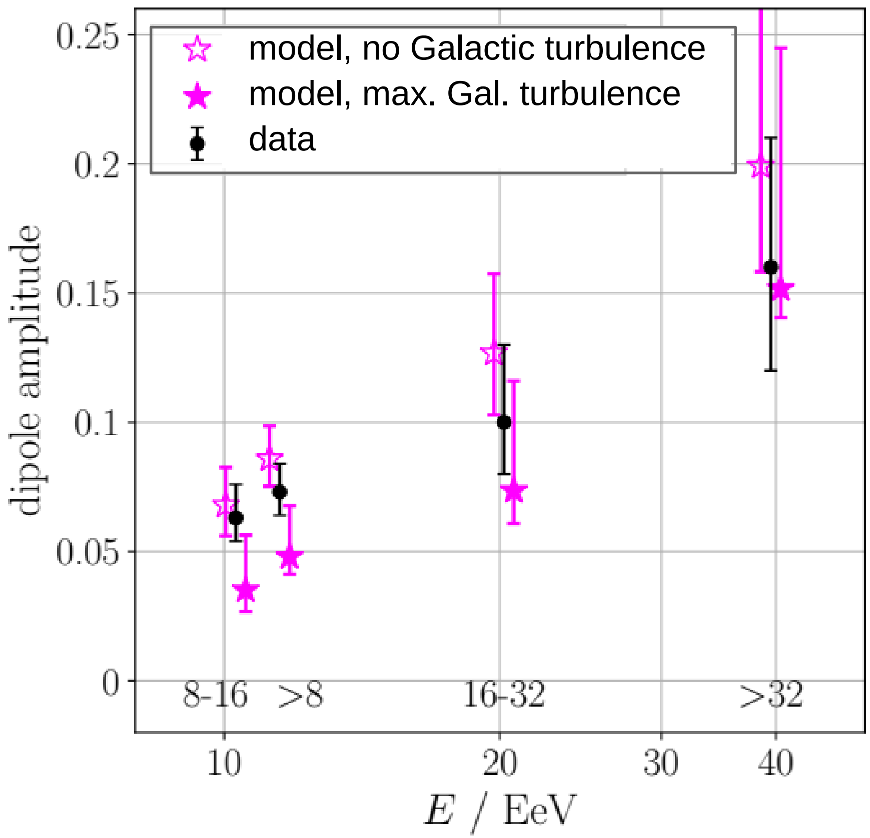




dipole
E>8 EeV

Best-fit model: predictions



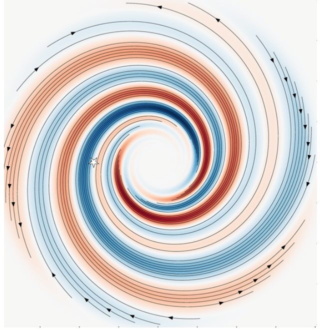


- dipole amplitude + energy evolution ✓
- dipole direction not perfect at lower energy
  → **updated GMF models?**

Bister, Farrar, Unger submitted to ApJL

Using new magnetic field models

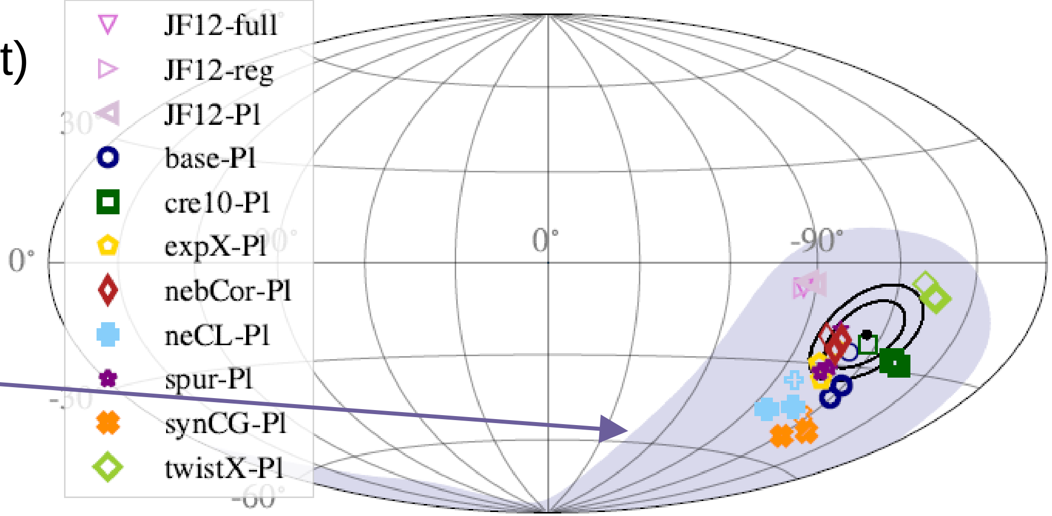
8 new GMF models recently became available (UF23)



Unger & Farrar, ApJ 2024 970 95

- all predict the dipole direction close to measured one!
  - ➔ but none fits perfectly at all energies
- **models quite similar**
  - ➔ uncertainties on GMF (random & turbulent) do not obstruct conclusions on sources
  - ➔ cannot reject any model
- **biggest uncertainty: from cosmic variance**

$n = 10^{-3}$ Mpc^{-3}

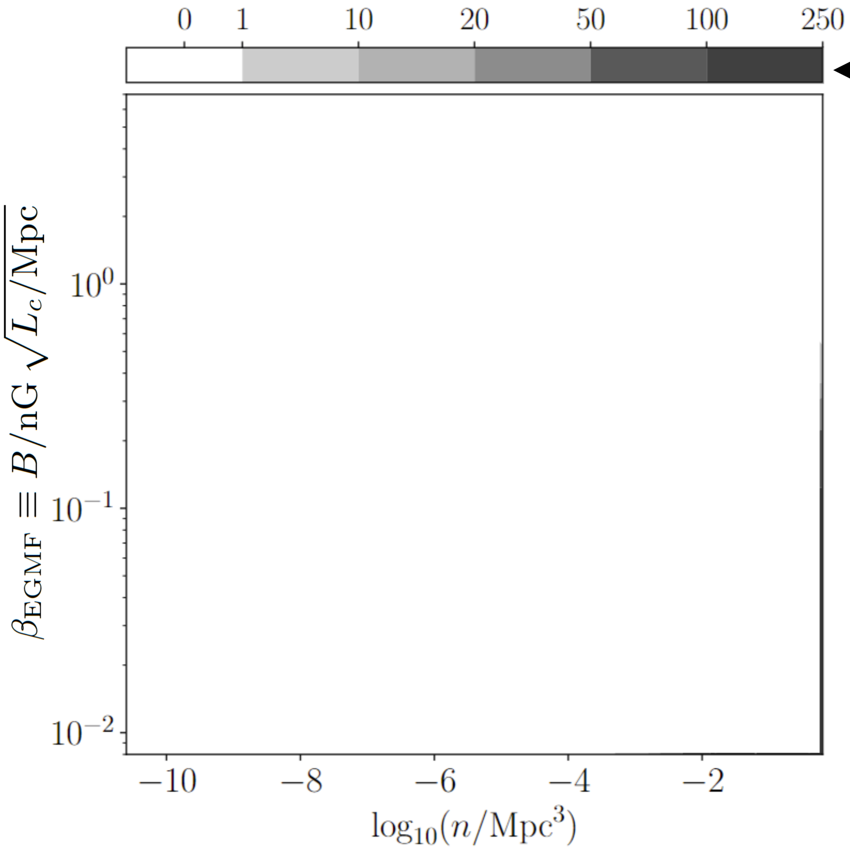


E > 8 EeV

➔ *What value is realistic for the source density n?*

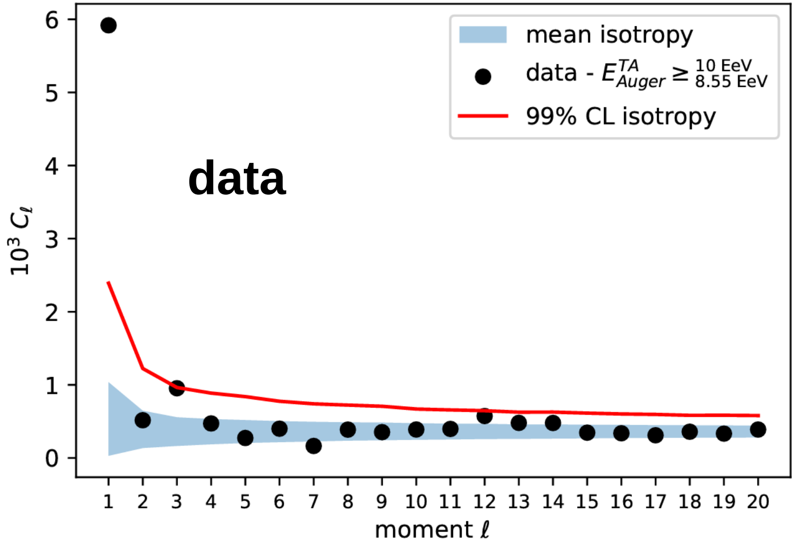
Source density and extragalactic magnetic field

extragalactic magnetic field



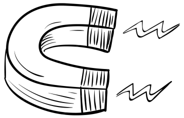
source number density

„How many of 1000 random simulations have a large enough dipole and small enough higher multipole moments?“

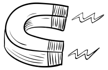


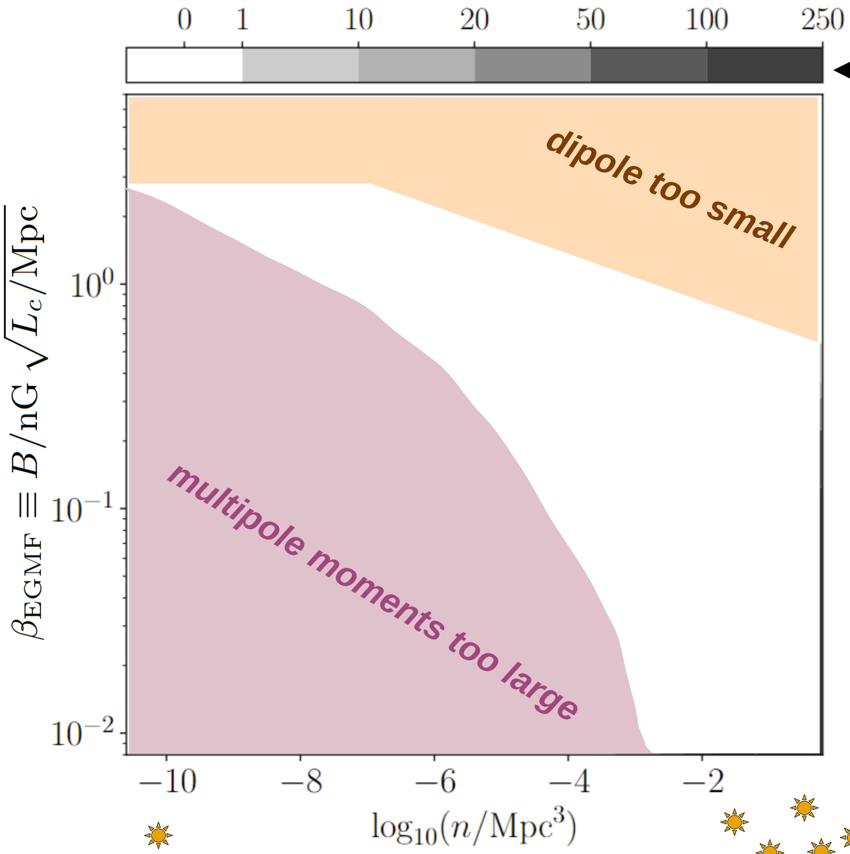
Bister & Farrar, ApJ 966 71 2024

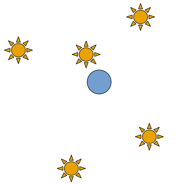
Source density and extragalactic magnetic field



extragalactic magnetic field







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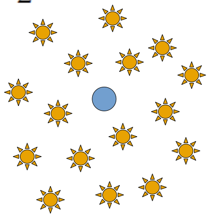

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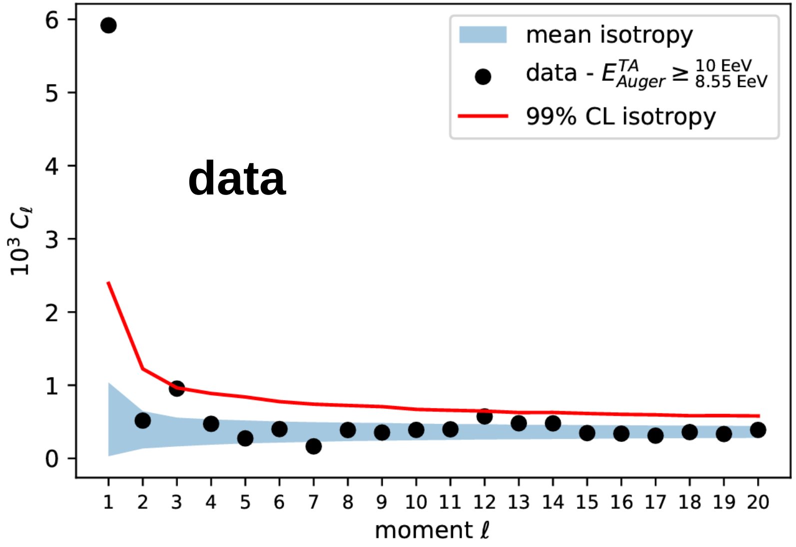
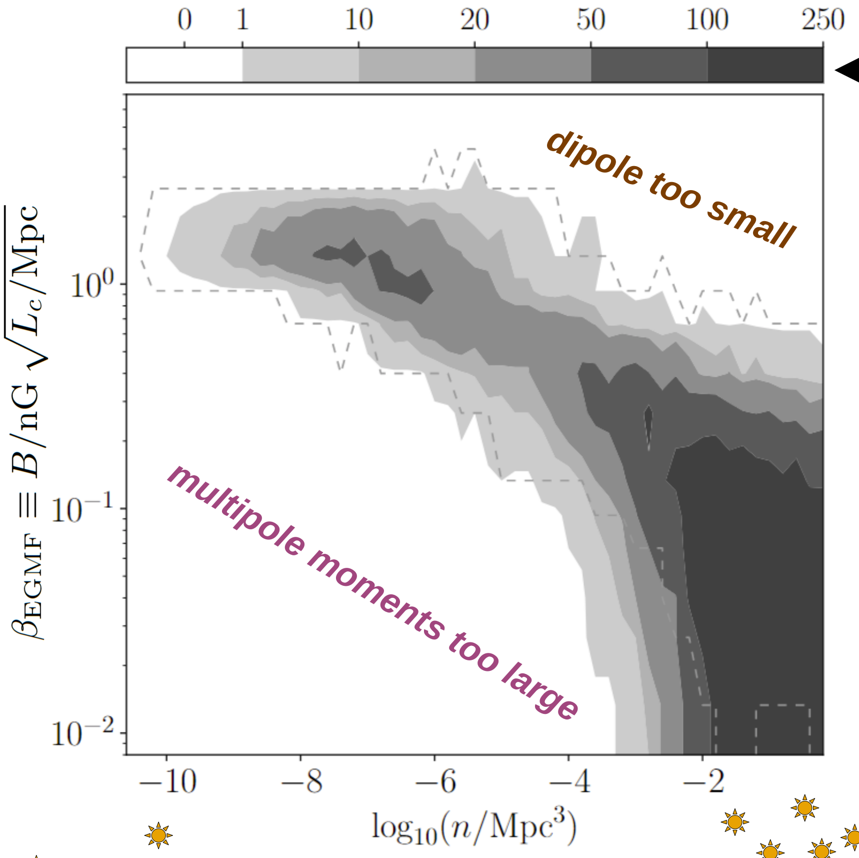


Bister & Farrar, ApJ 966 71 2024

Source density and extragalactic magnetic field

extragalactic magnetic field

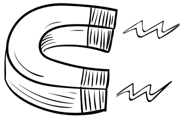


source number density

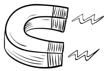
„How many of 1000 random simulations have a large enough dipole and small enough higher multipole moments?“

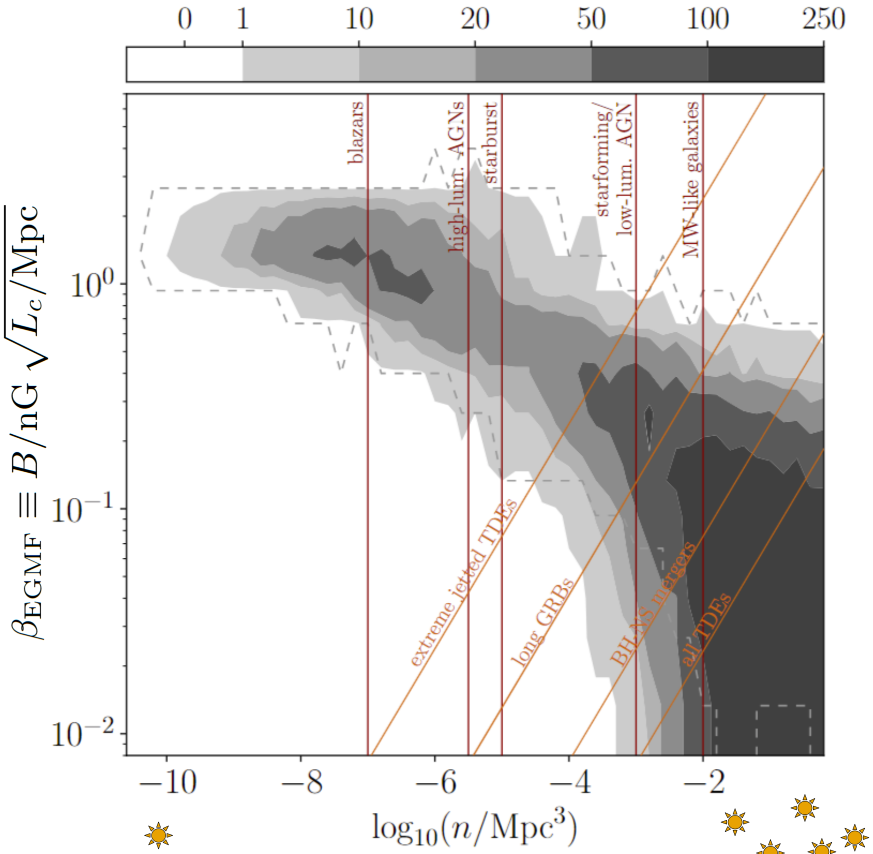
Bister & Farrar, ApJ 966 71 2024

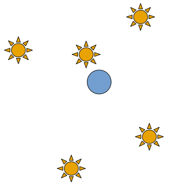
Source density and extragalactic magnetic field



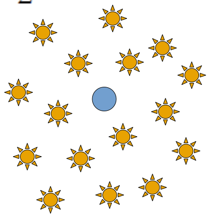
extragalactic magnetic field







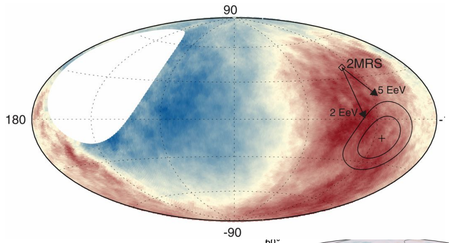
source number density

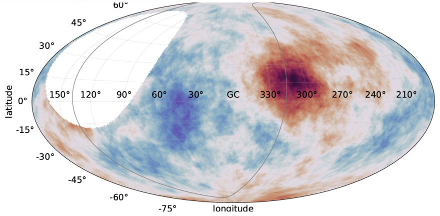


- **rare sources** (e.g. starbursts) ↔ **strong EGMF**
  - max. 3 nG $\mathrm{Mpc}^{1/2}$
- **negligible EGMF** ↔ sources must be **common**, (e.g. Milky-Way-like galaxies)
  - or: **frequent** in case of **transients** like BH-NS mergers, tidal disruption events

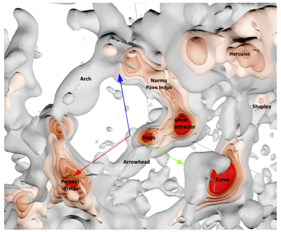
Conclusions

- **Global fit of spectrum, composition <u>& arrival directions</u> can constrain models for UHECR origin**

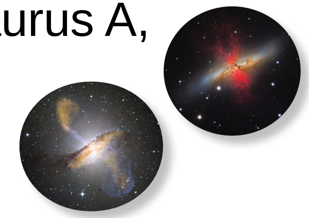




- **>8 EeV: sources most likely follow large-scale structure**
  - can infer information on cosmic magnetic fields & source number density



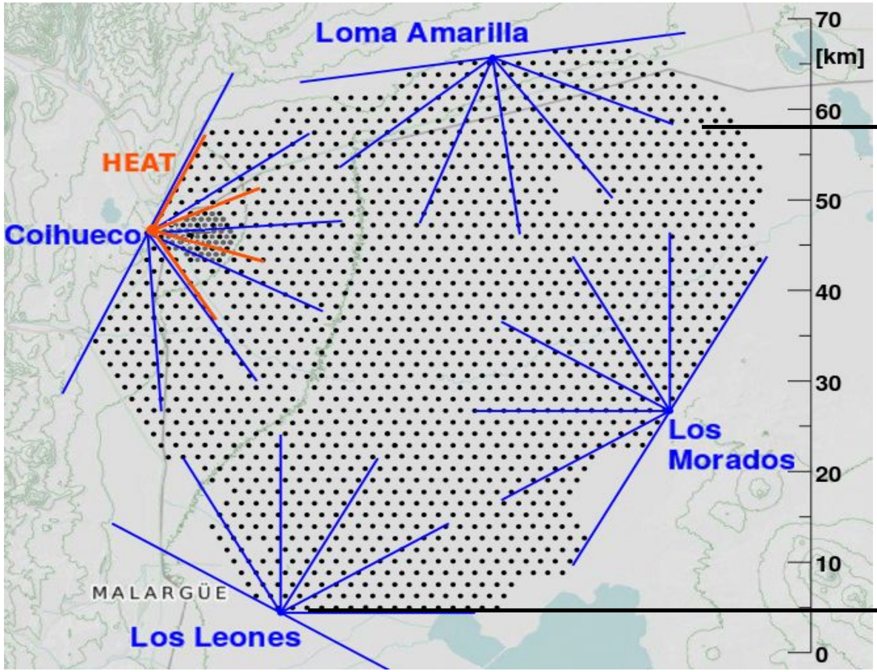
- **>40 EeV: individual source candidates describe data**
  - starburst galaxies, Centaurus A, ~4.5σ significance



Backup

The Pierre Auger Observatory

- largest observatory for UHECRs in the world (3000 km²)
- located in Argentina, close to Malargüe



hybrid detection:

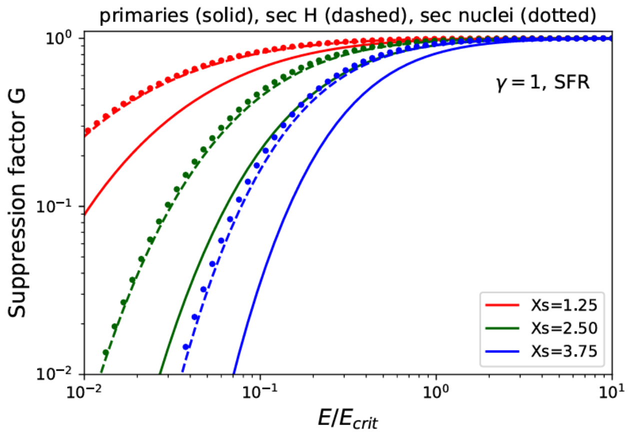
1660 water cherenkov detectors (SD)

27 fluorescence telescopes (FD)

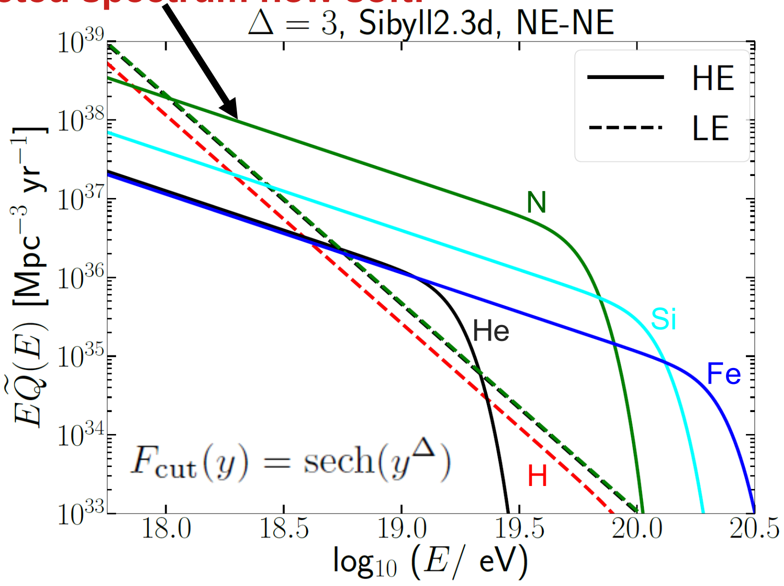
AugerPrime upgrade

Combined fit of spectrum and composition including EGMF

- extragalactic magnetic field can suppress lower energy particles (diffusion)
- include suppression factor G
  - +2 parameters (critical energy + norm. source density)



high-energy population injected spectrum now soft!



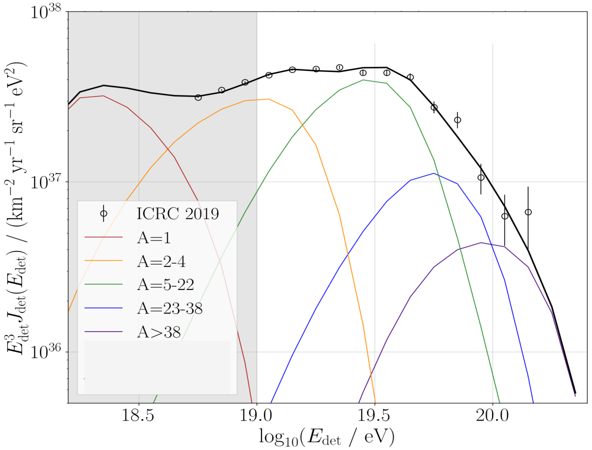
EGMF can have strong effect on injection, but only for:

- steep injection cutoff
- & source densities < 10^{-3} Mpc^{-3}
- & very strong field strengths B~10-200 nG between nearest sources & Earth

➔ then: can reach γ=2

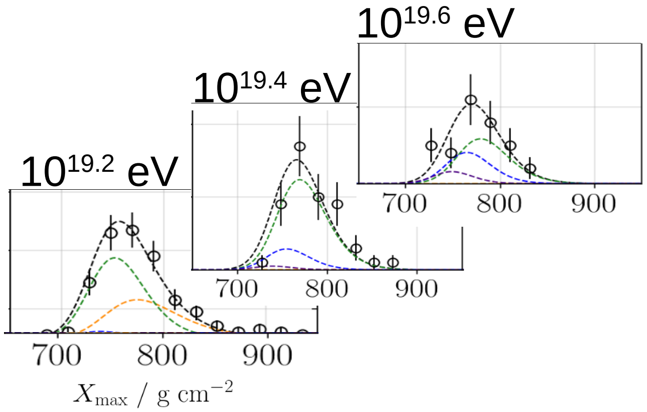
Modeling 3 observables

energy spectrum



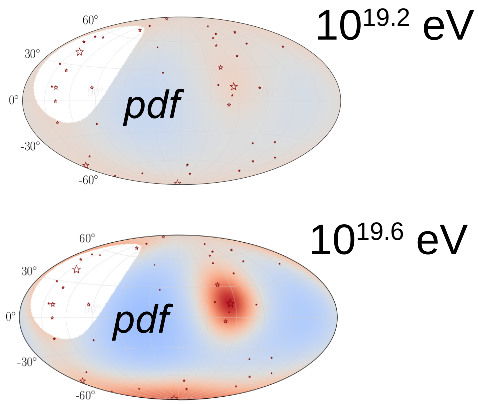
- energy spectrum
  = sum over detected particles
- fold with detector resolution
- Poissonian likelihood

shower depth distributions



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

arrival directions



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

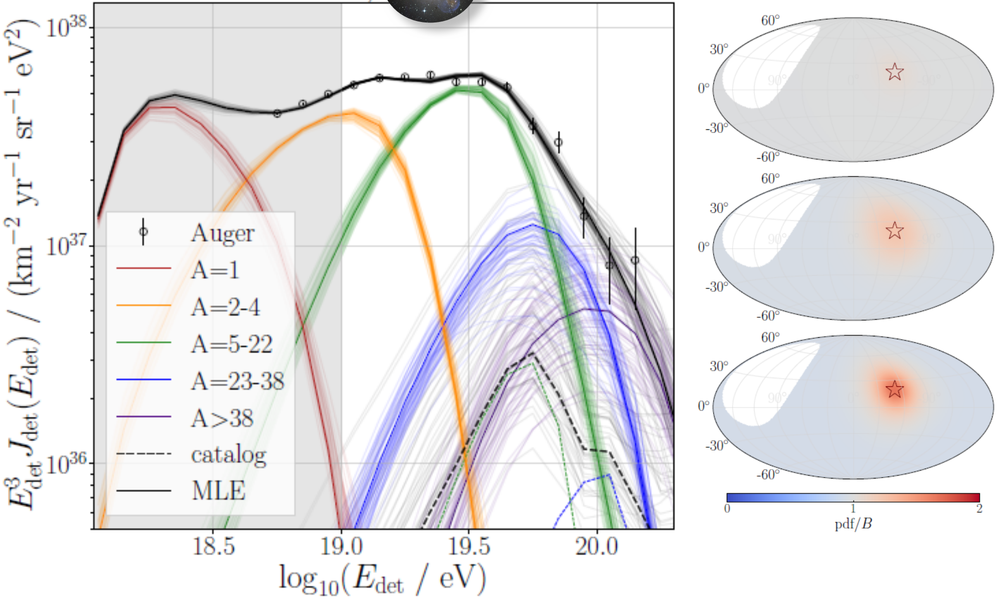
$$\mathcal{L}_{\mathrm{AD}} = \prod_e \prod_p \mathrm{pdf}^{e,p}(v^{e,p})$$

Best-fit model: spectrum

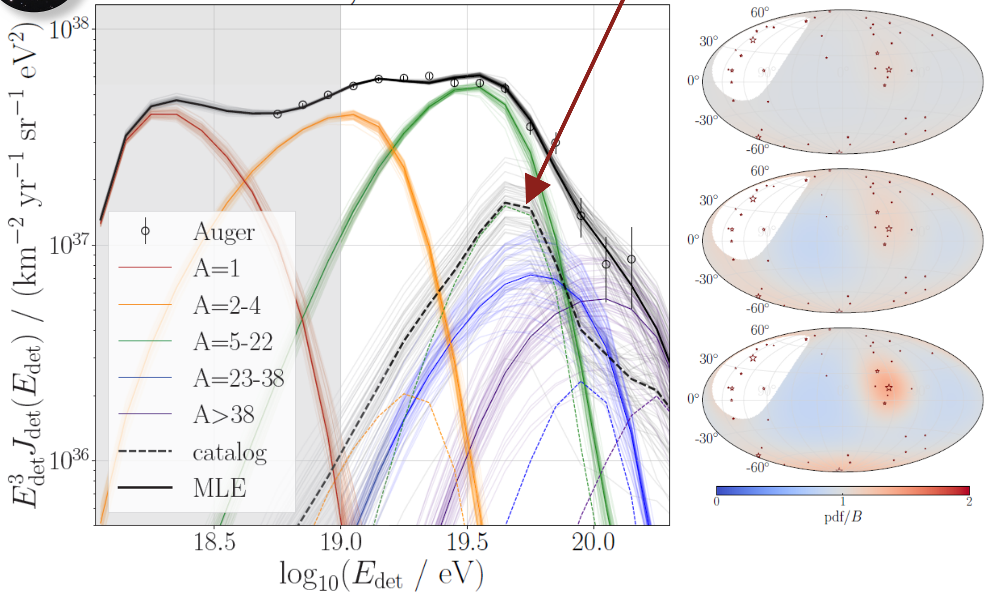
- **best-fit:** hard injection spectrum dN/dE ~ E^{-1}, N-dominated, 20° magnetic field blurring for proton with 10 EeV
- signal fraction ~20% from SBGs, 3% from Centaurus region (at 40 EeV, increases with E)
  - **independent of evolution & systematic effects**

dashed line = catalog contribution

Centaurus A



Starburst Galaxies



Test statistic

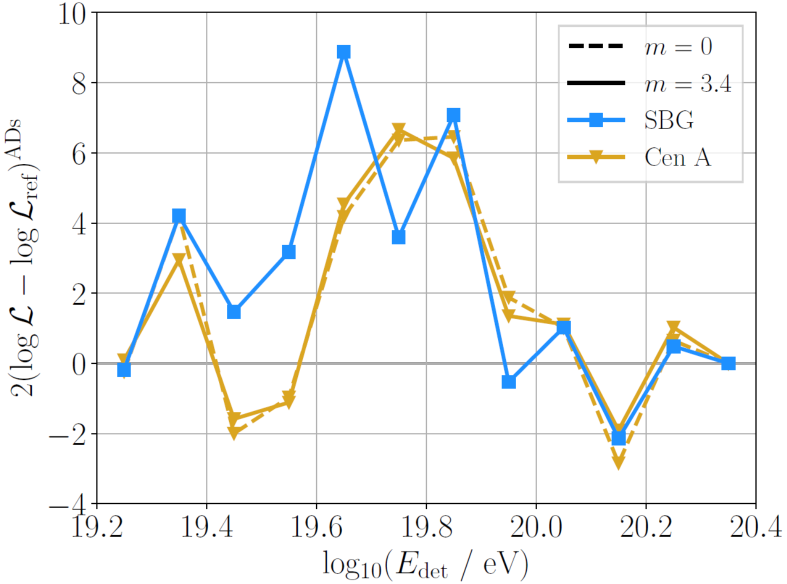
compare likelihood to ref. model (just background sources):

	SBG	Cen A *(flat)*	Cen A *(SFR)*
$\mathrm{TS}_{\mathrm{tot}}$	25.6	17.3	19.1
TS_E	-4.5	-1.4	-1.1
$\mathrm{TS}_{X_{\mathrm{max}}}$	2.0	0.2	1.0
$\mathrm{TS}_{\mathrm{ADs}}$	27.1	18.7	19.0

SBG model has highest TS = 25.6 ↔ 4.5σ

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

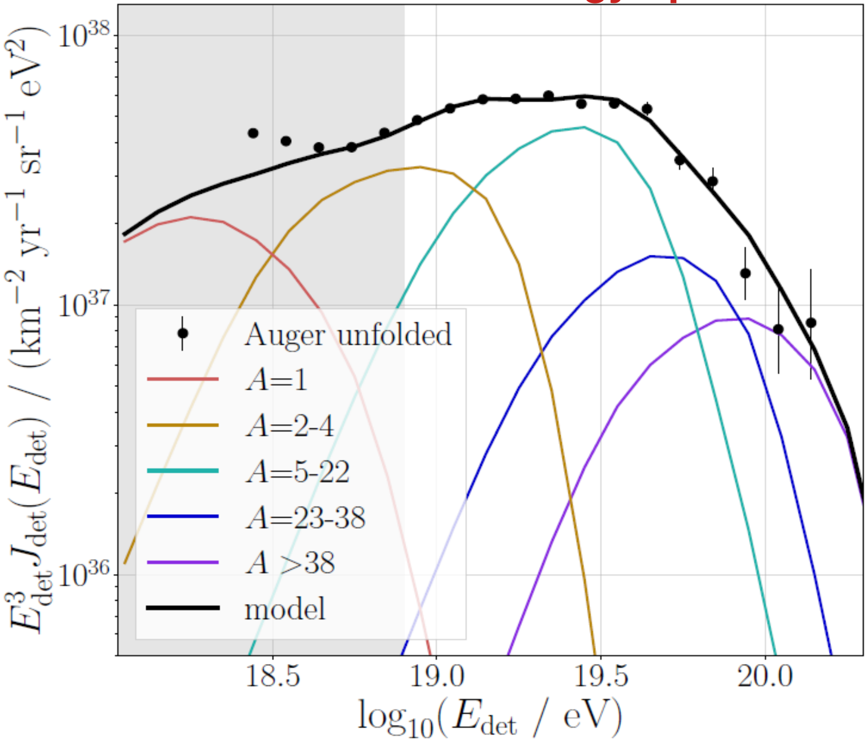
arrival directions test statistic



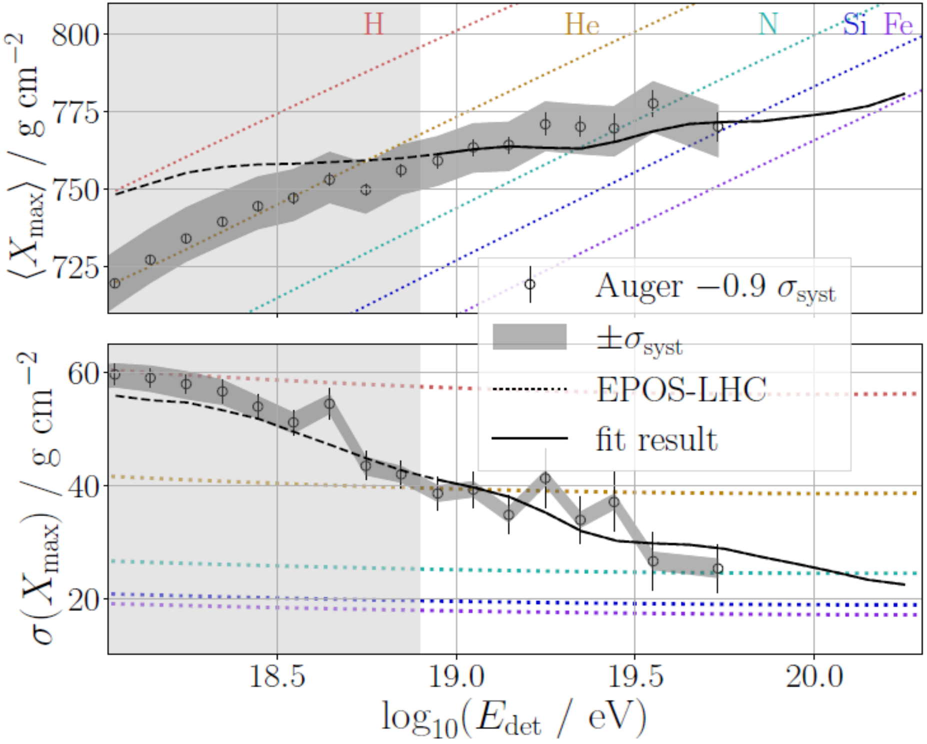
- sum over E bins gives total TS
- peaks could be from He, N, Si
  - ➔ but: large uncertainties

Best-fit model: predictions

energy spectrum ✔



mass composition ✔

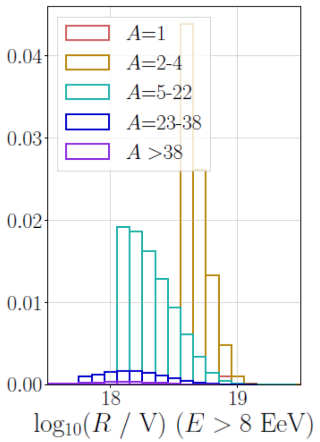


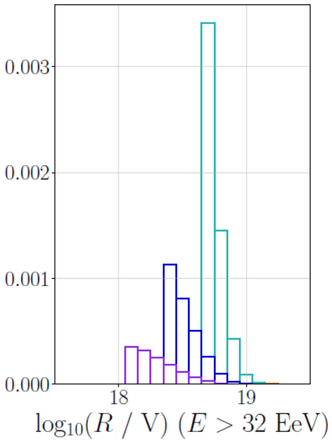
LSS model can describe spectrum, composition and arrival directions >8 EeV.

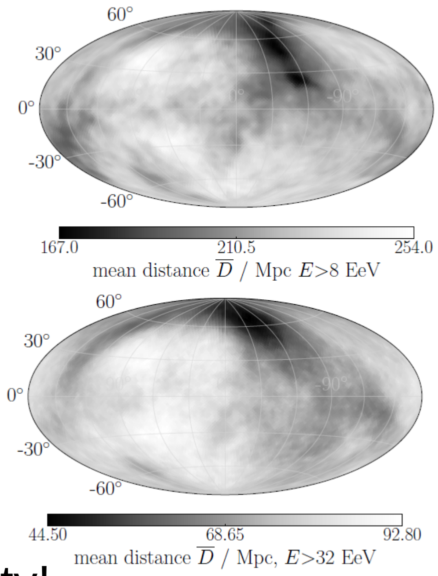
Extragalactic magnetic field effect

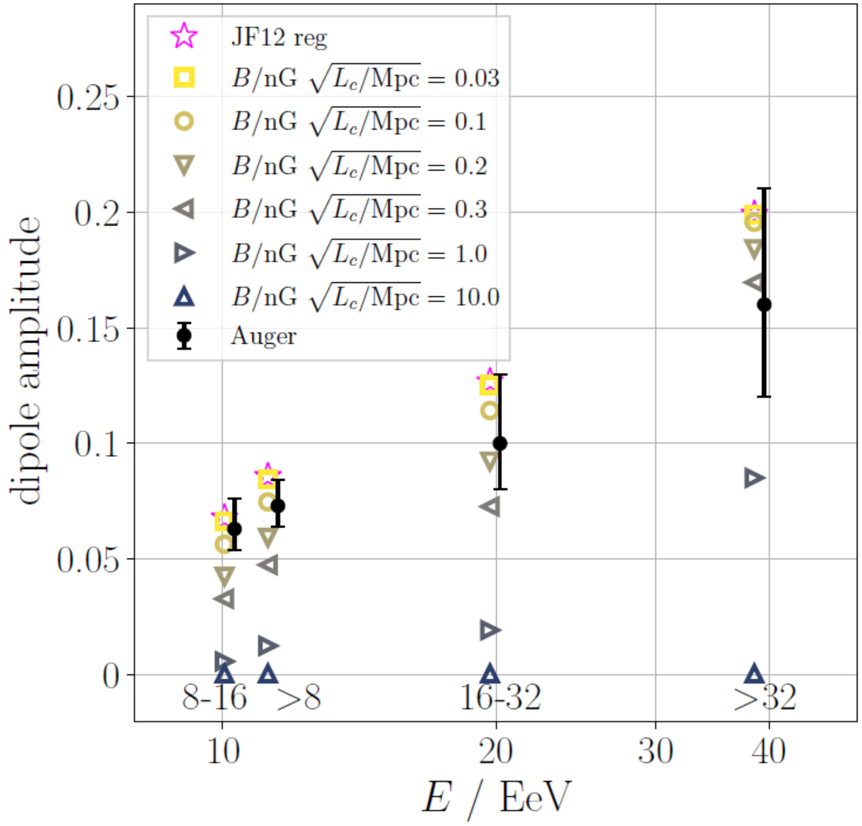
- extragalactic magnetic field „smears out“ arrival directions
- cannot be too strong to not decrease dipole amplitude

$$\delta\theta = 2.9° \frac{B}{\mathrm{nG}} \frac{10\,\mathrm{EV}}{E/Z} \frac{\sqrt{D\ L_c}}{\mathrm{Mpc}}$$





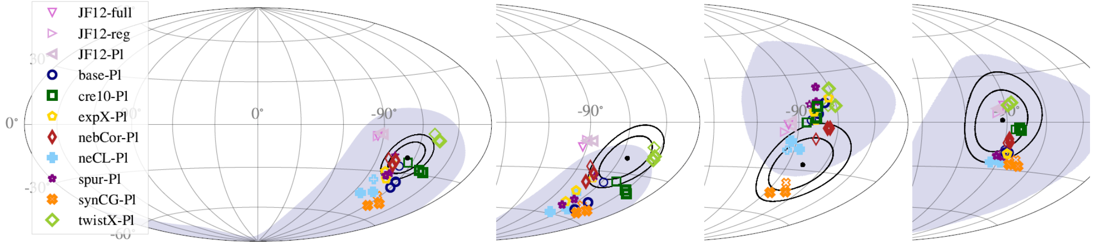




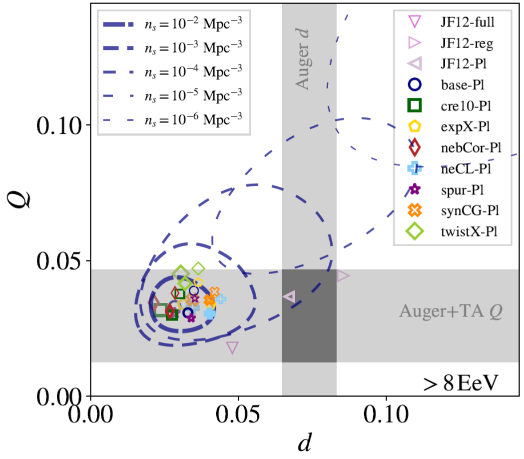
but - opposing effect:
sparser source number density!

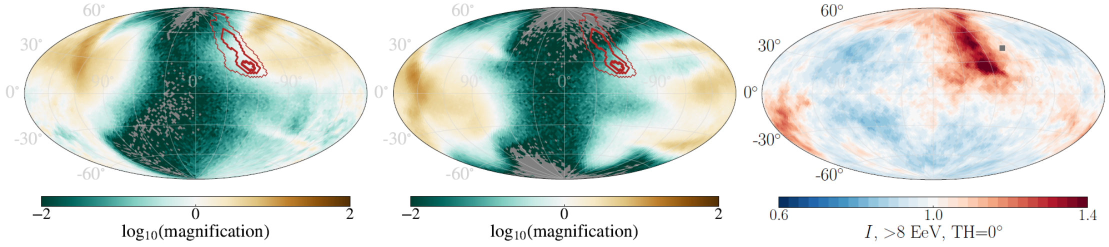
Bister, Farrar, Unger, submitted to ApJL

Further results for UF23 GMF models



(a) energy > 8 EeV (b) (8 – 16) EeV (c) (16 – 32) EeV (d) > 32 EeV





(a) JF12 + Planck $l_c = 60$ pc (b) UF23 base + Planck $l_c = 60$ pc (c) "Illumination" map I