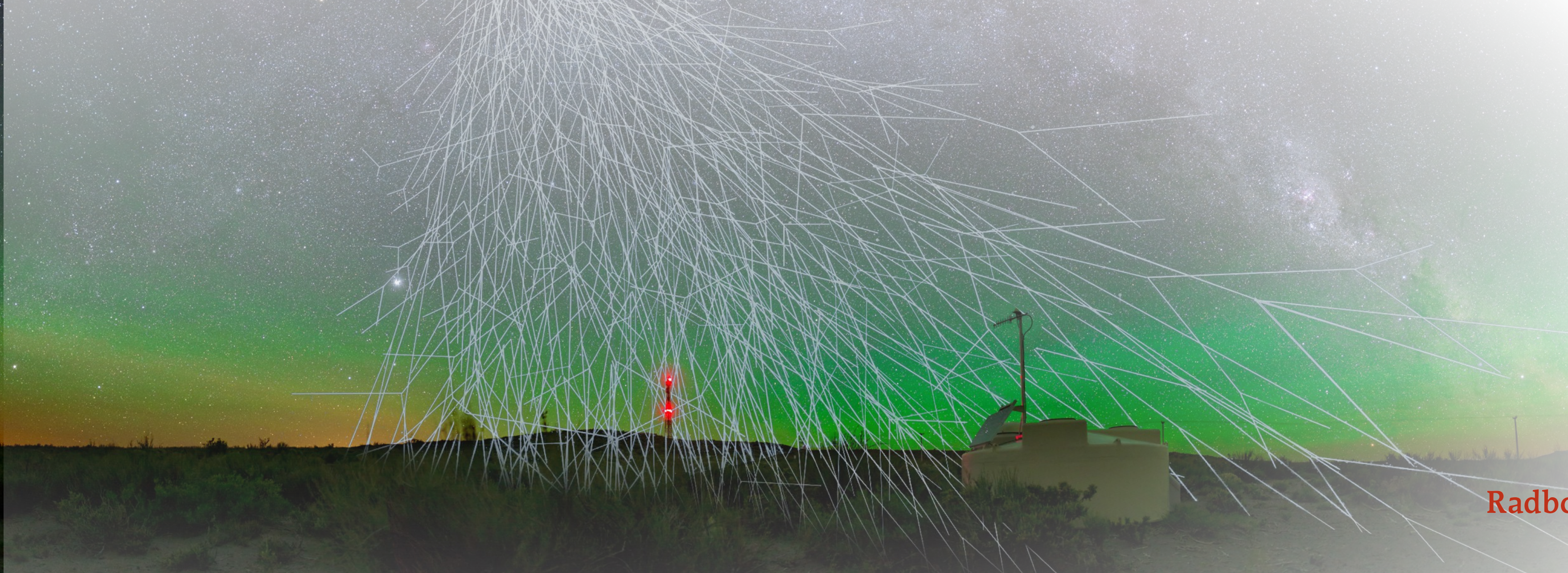
Astrophysical interpretations

of the data measured at the Pierre Auger Observatory

Teresa Bister for the Pierre Auger Collaboration

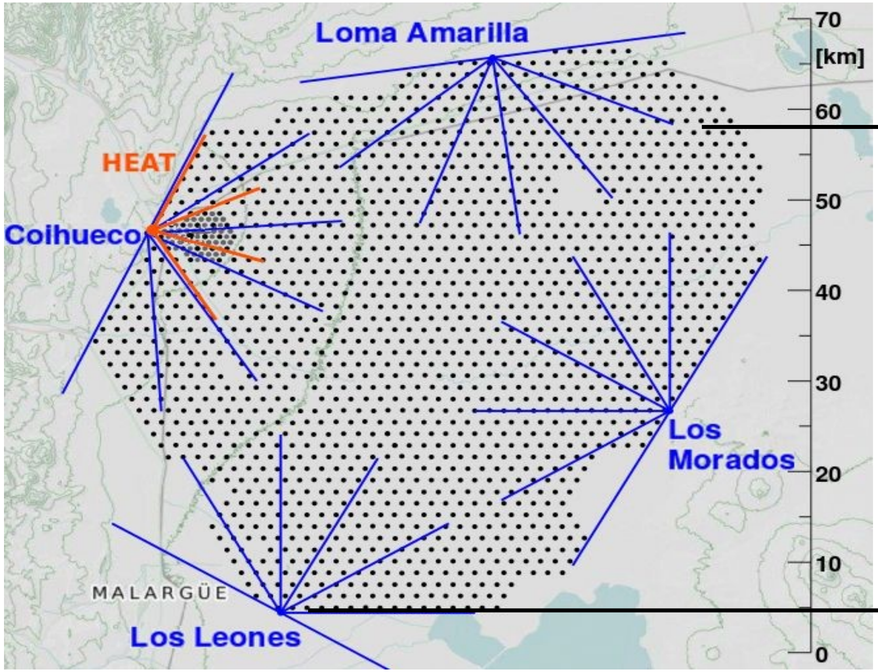
TAUP, August 2025



Nikhef
Radboud University

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)

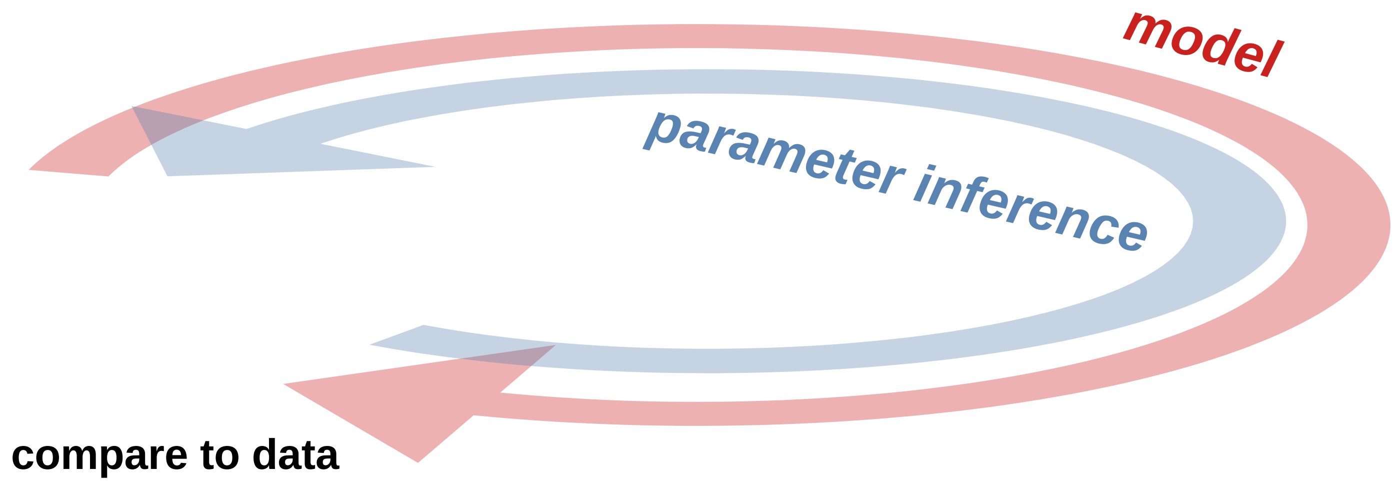
27 fluorescence telescopes (FD)

AugerPrime upgrade

main aim: discover and characterize the sources of ultra-high-energy cosmic rays

Modeling UHECRs from sources to detection

main aim: characterize the sources of UHECRs

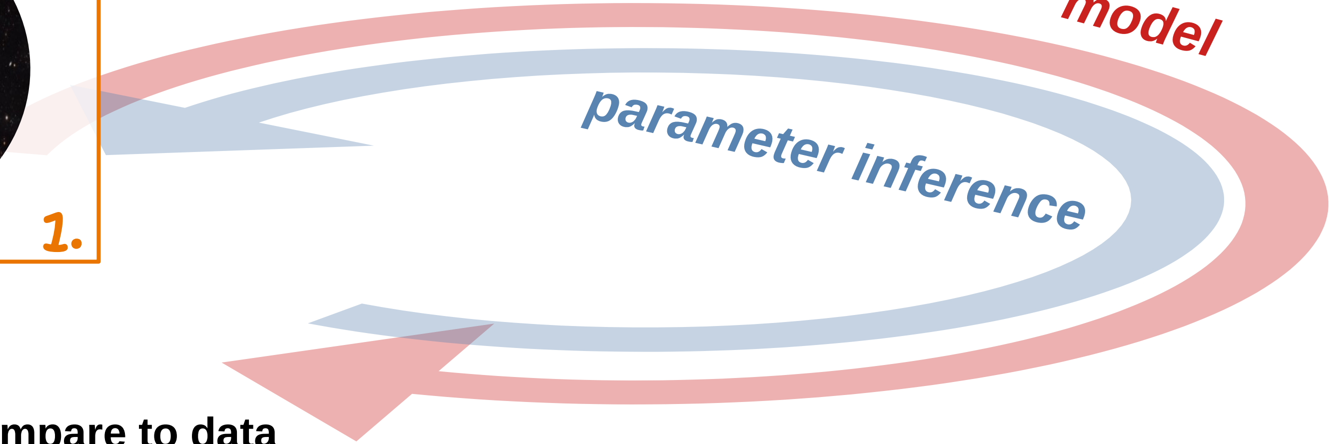


Modeling UHECRs from sources to detection

homogeneous source population(s)

1.

main aim: characterize the sources of UHECRs

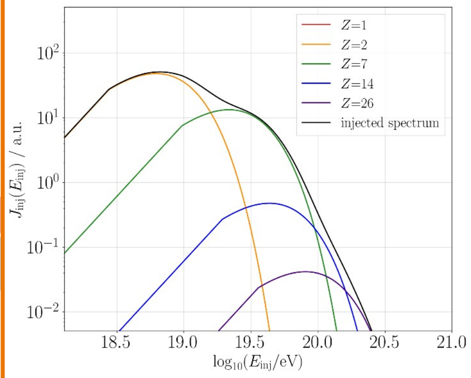


compare to data

Modeling UHECRs from sources to detection

homogeneous source population(s)

2. emission



usual assumptions:

- **maximum energy prop. to charge number *Z*: "Peters cycle"**
- shape: power-law + cutoff:

spectral index

rigidity cutoff
R=E/Z

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

element contributions

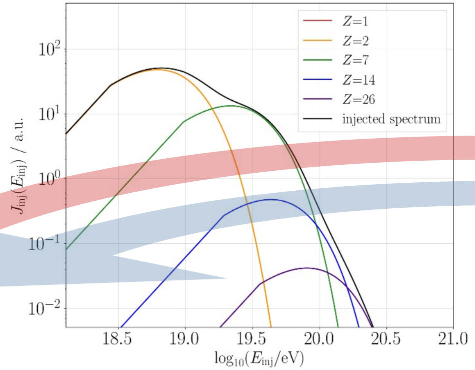
- model 5 representative elements (H, He, N, Si, Fe)

compare to data

Modeling UHECRs from sources to detection

homogeneous source population(s)

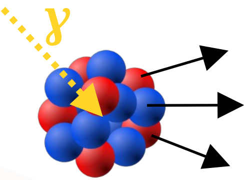
emission



3.

propagation through extragalactic space

→ interactions & deflections



compare to data

Modeling UHECRs from sources to detection

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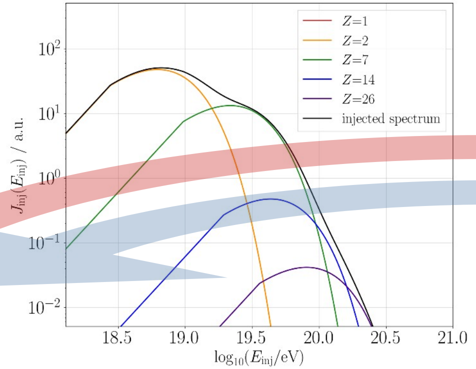
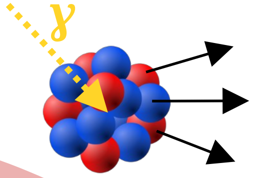


propagation through extragalactic space
→ interactions & deflections

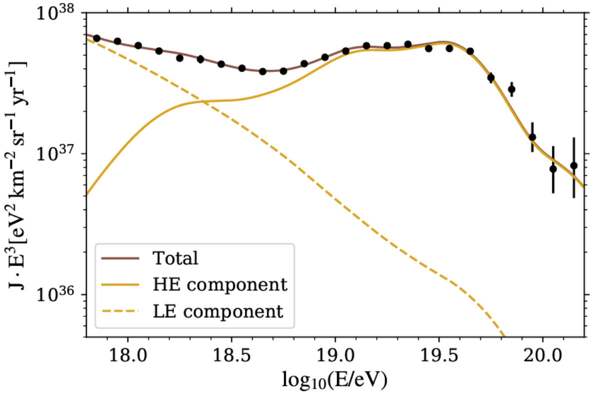


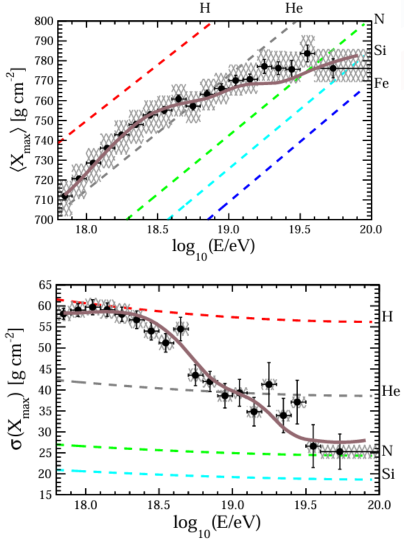
4.

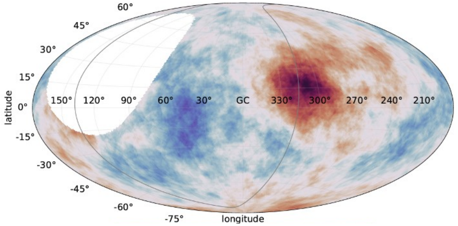
compare to data

- energy spectrum
- mass composition
- arrival directions

likelihood







Modeling UHECRs from sources to detection

homogeneous source population(s)

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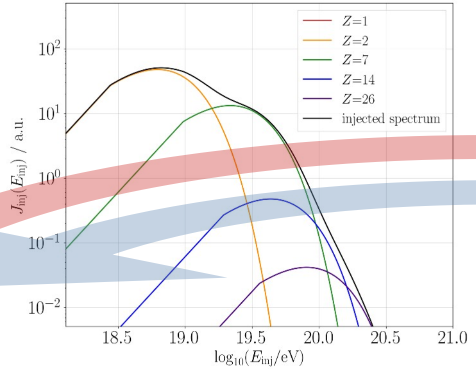
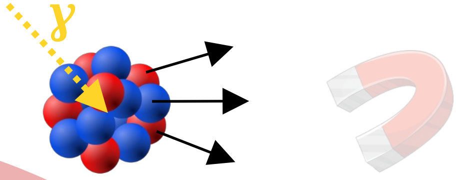


propagation through extragalactic space

→ interactions (& deflections)



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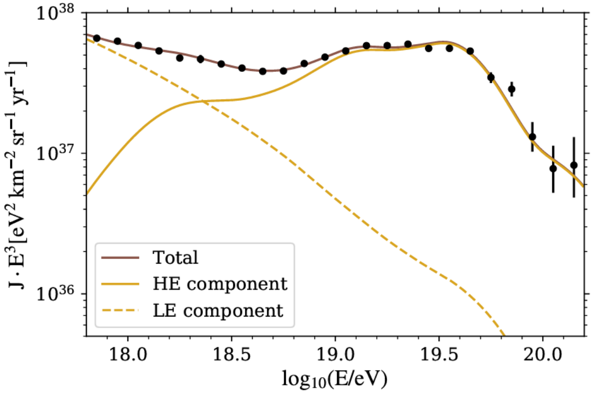
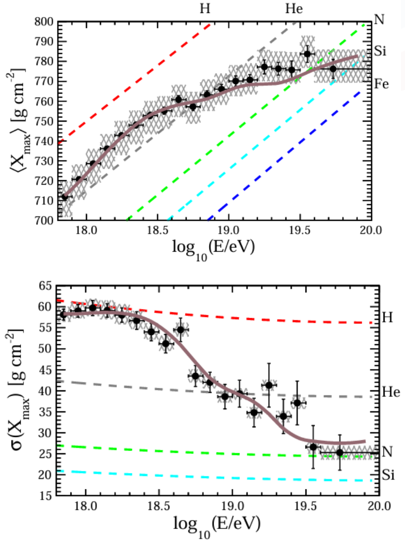
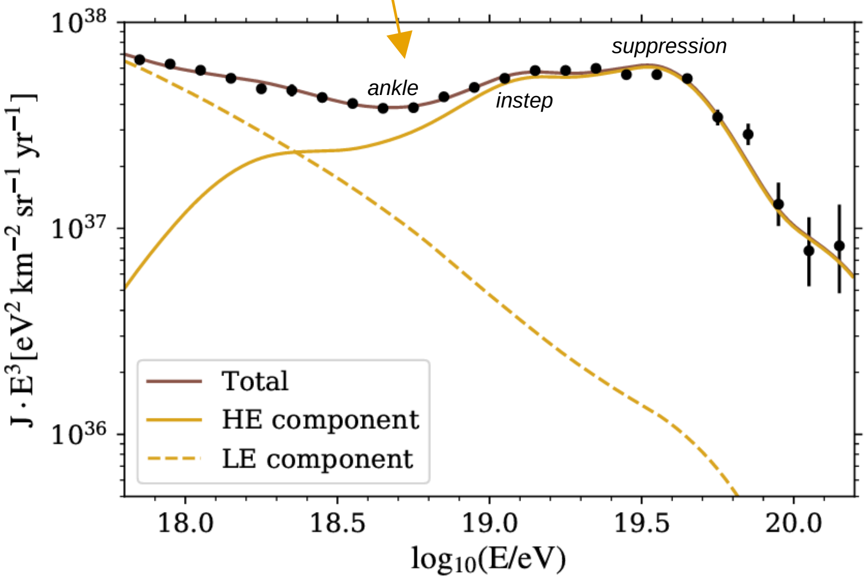




Source populations & emission

ankle explained by transition between source populations



measured spectrum at Earth

Source populations & emission

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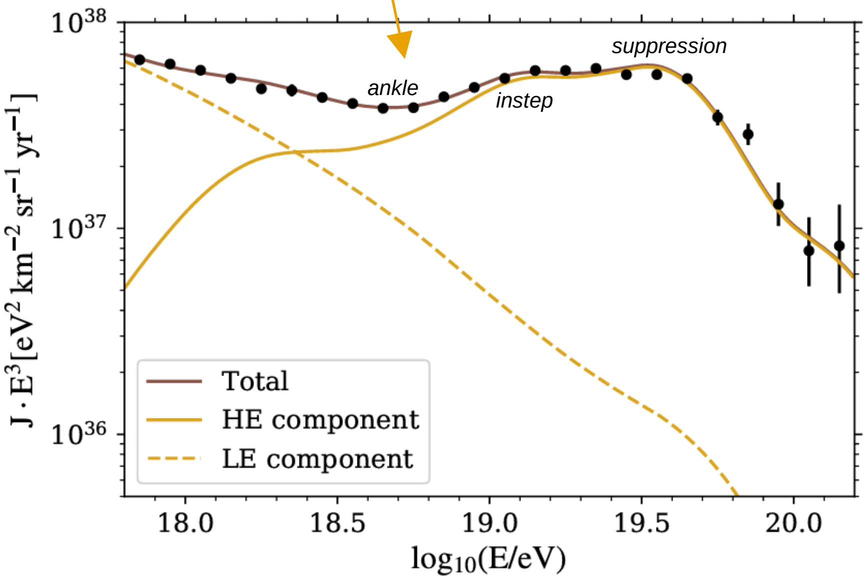
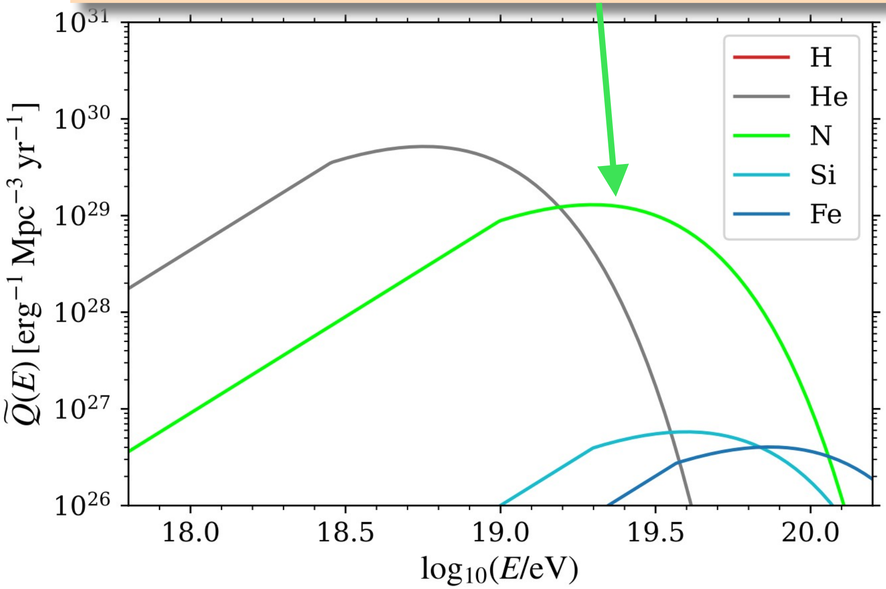


measured spectrum at Earth

above the ankle *(high-energy):*

- extragalactic, Nitrogen-dominated
- very hard spectrum
  - diffusion in extragalactic magnetic field?

Pierre Auger Collaboration JCAP95(2024)094

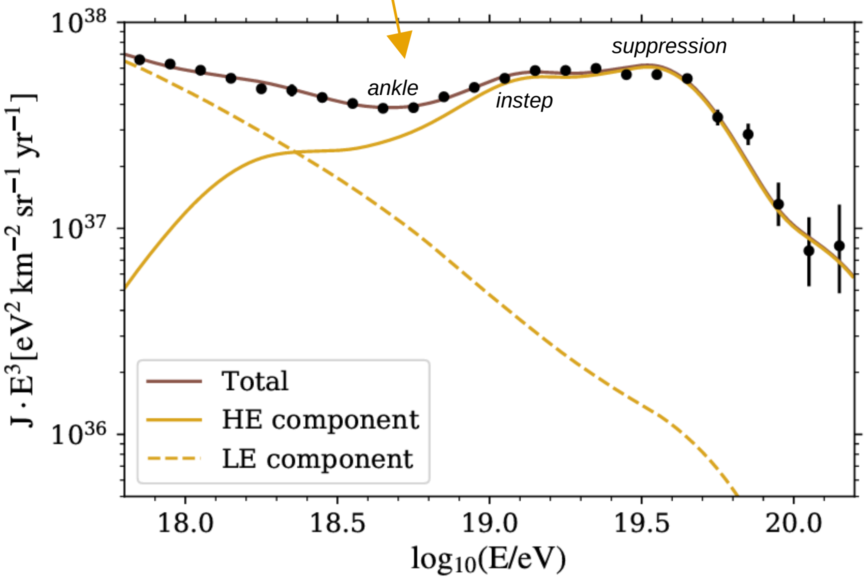


best-fit emission spectrum

Pierre Auger Collaboration JCAP05(2023)024

Source populations & emission

ankle explained by transition between source populations



above the ankle *(high-energy):*

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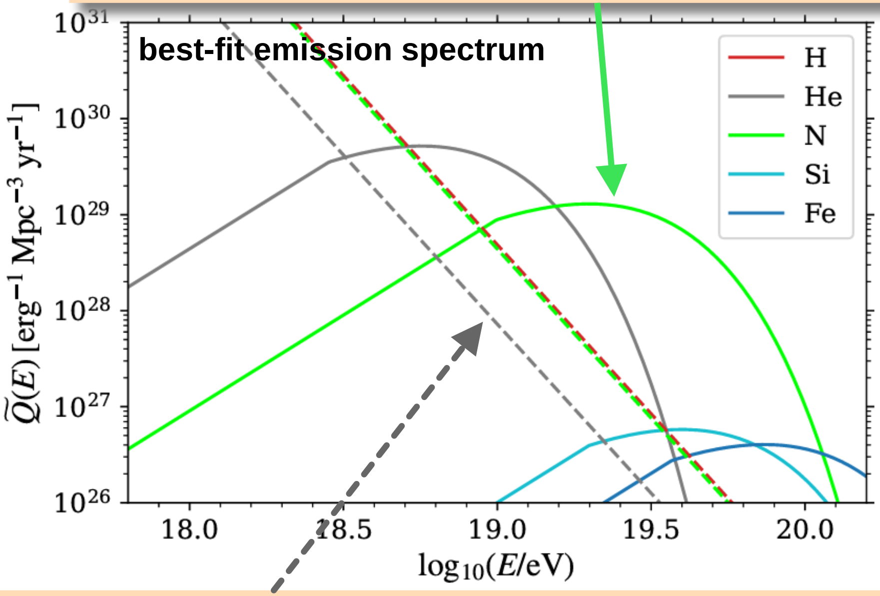
Pierre Auger Collaboration JCAP95(2024)094



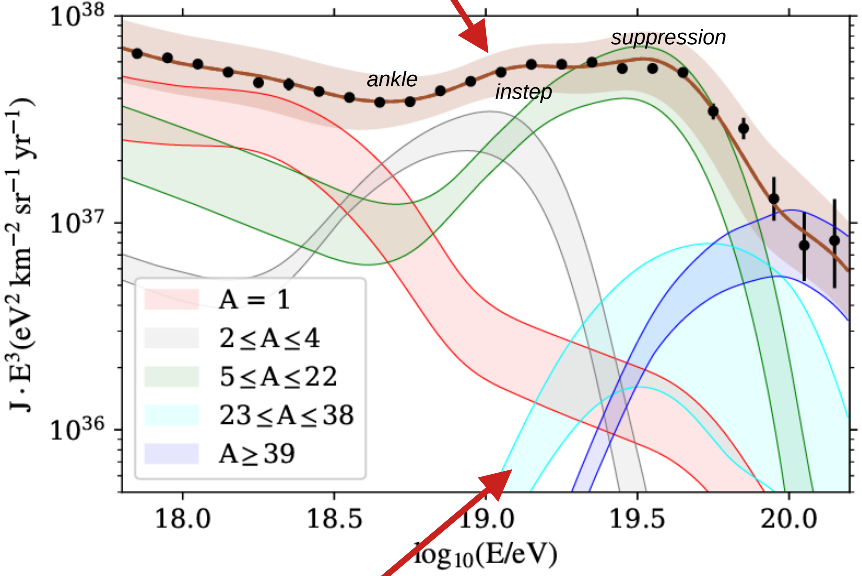
below the ankle *(low-energy):*

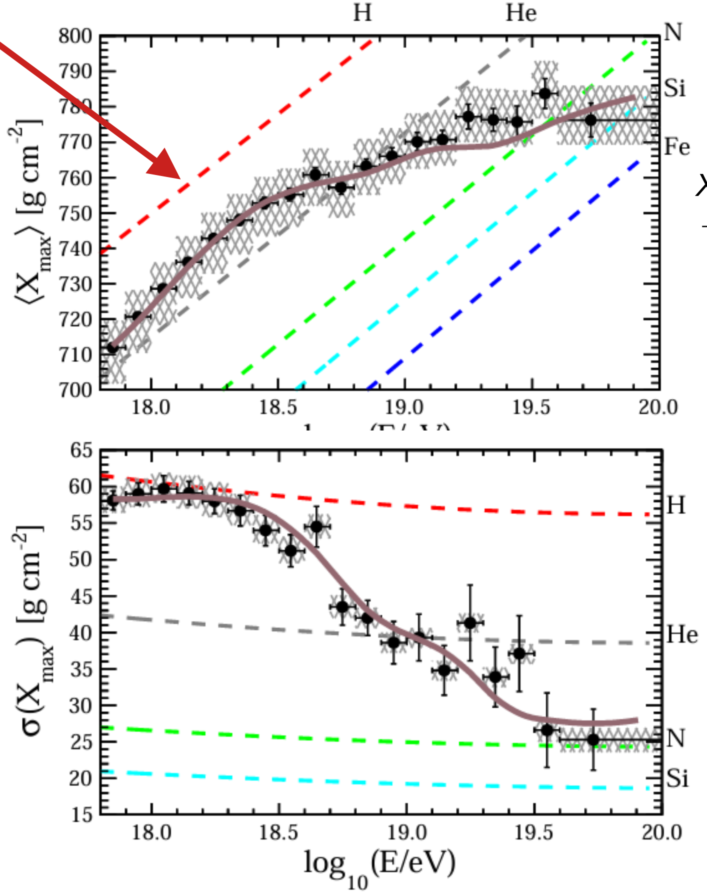
- another mixed very soft extragalactic population
- *or* light extragalactic plus heavier Galactic population

Modeled Observables on Earth

fast transition between element groups

to describe composition getting heavier + small variance
+ pronounced features in spectrum





X_{max} is the shower depth
→ correlated with mass

conclusions stable with regards
to **systematic effects**

Pierre Auger Collaboration JCAP05(2023)024

Modeled Observables on Earth

fast transition between element groups

to describe composition getting heavier + small variance
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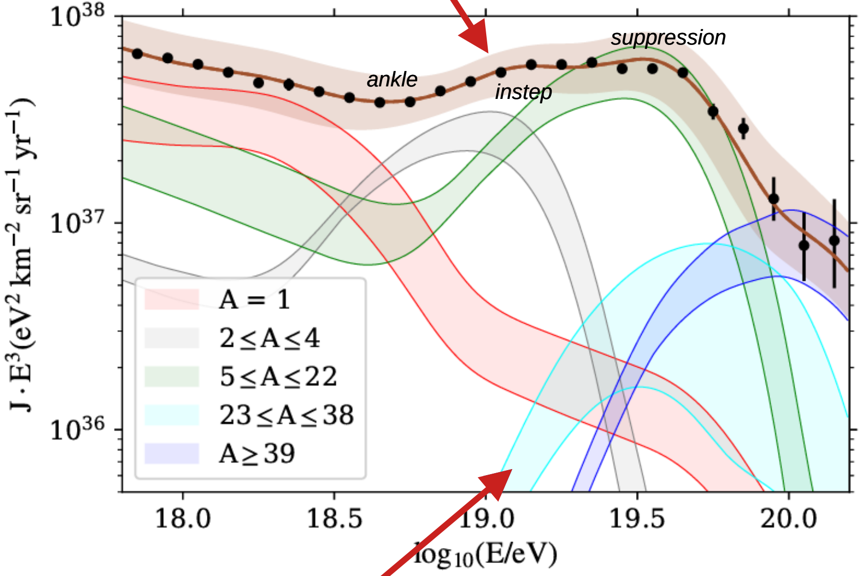
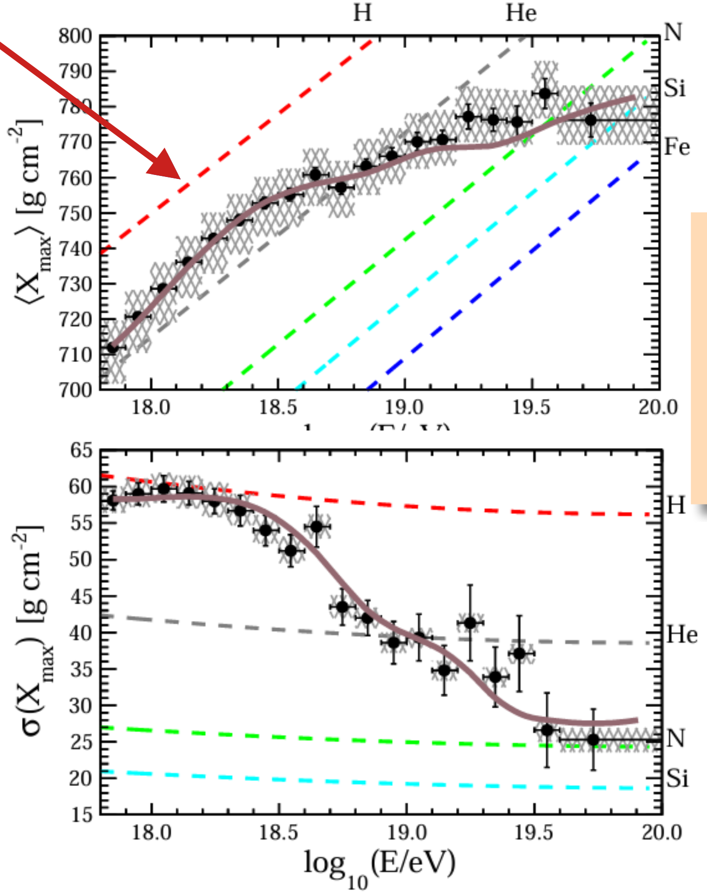
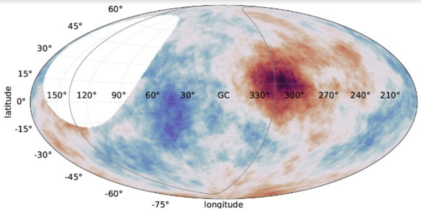




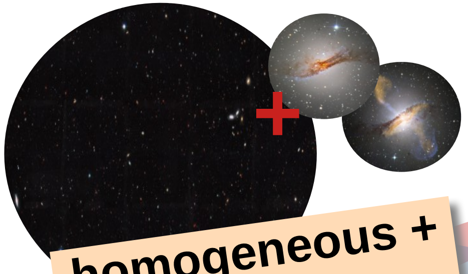
What can we learn from the arrival directions as an additional observable?



conclusions stable with regards
to **systematic effects**

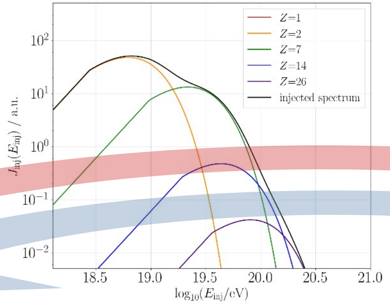
Adding arrival directions to the model

source distribution

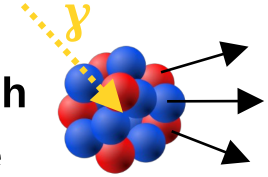


homogeneous + catalogs

emission



propagation through extragalactic space
→ interactions & deflections

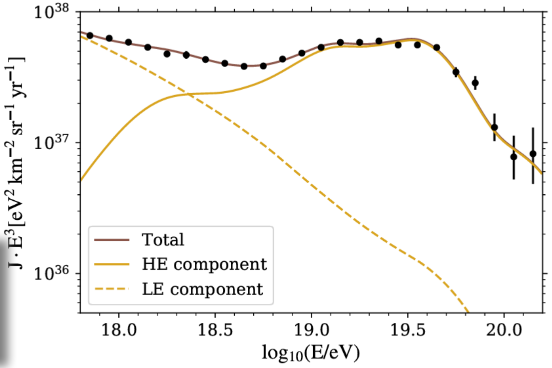


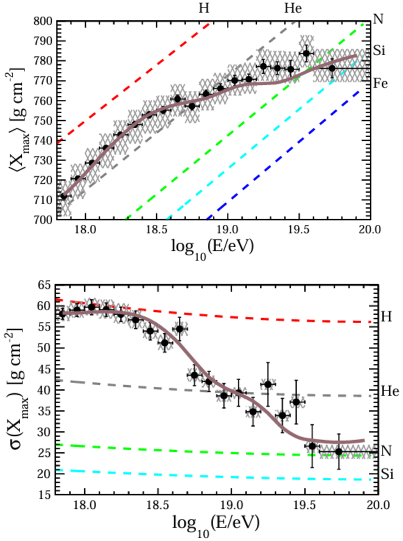
4.

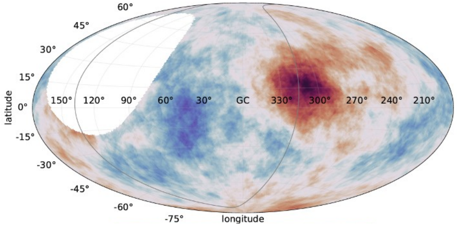
compare to data

- energy spectrum
- mass composition
- **arrival directions**
  >16 EeV in energy bins

likelihood







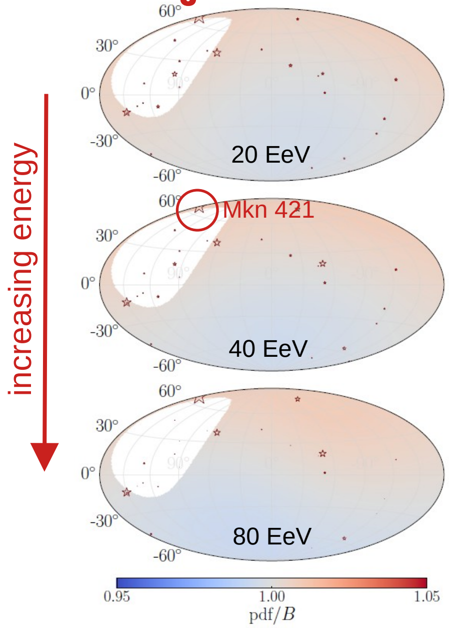
TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration JCAP01(2024)022

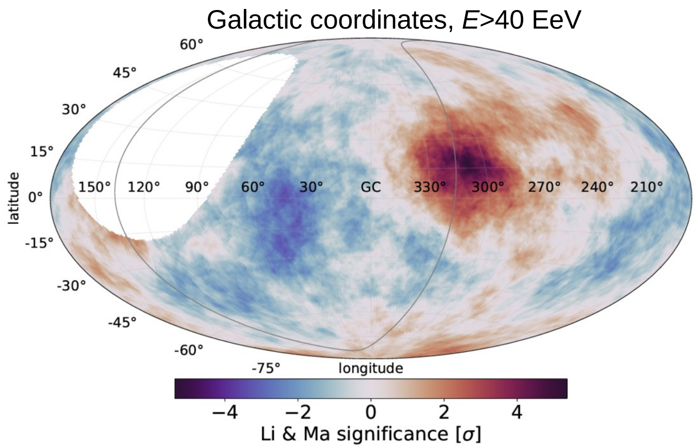
Best-fit model: arrival directions

γ-AGNs

Centaurus A

Starburst Galaxies





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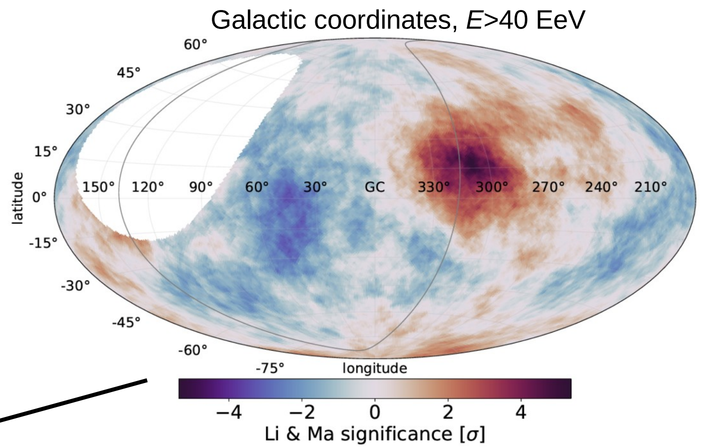
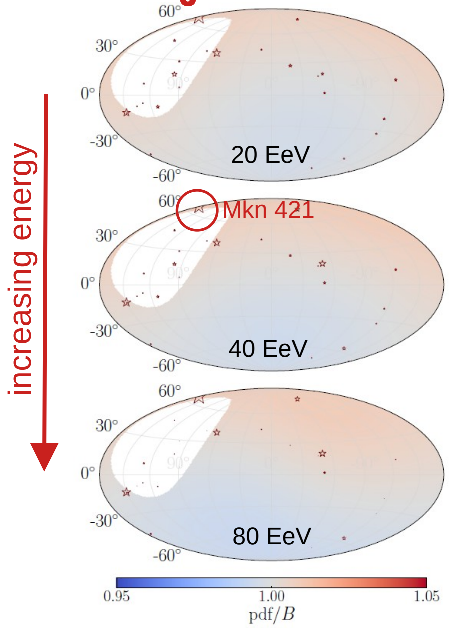


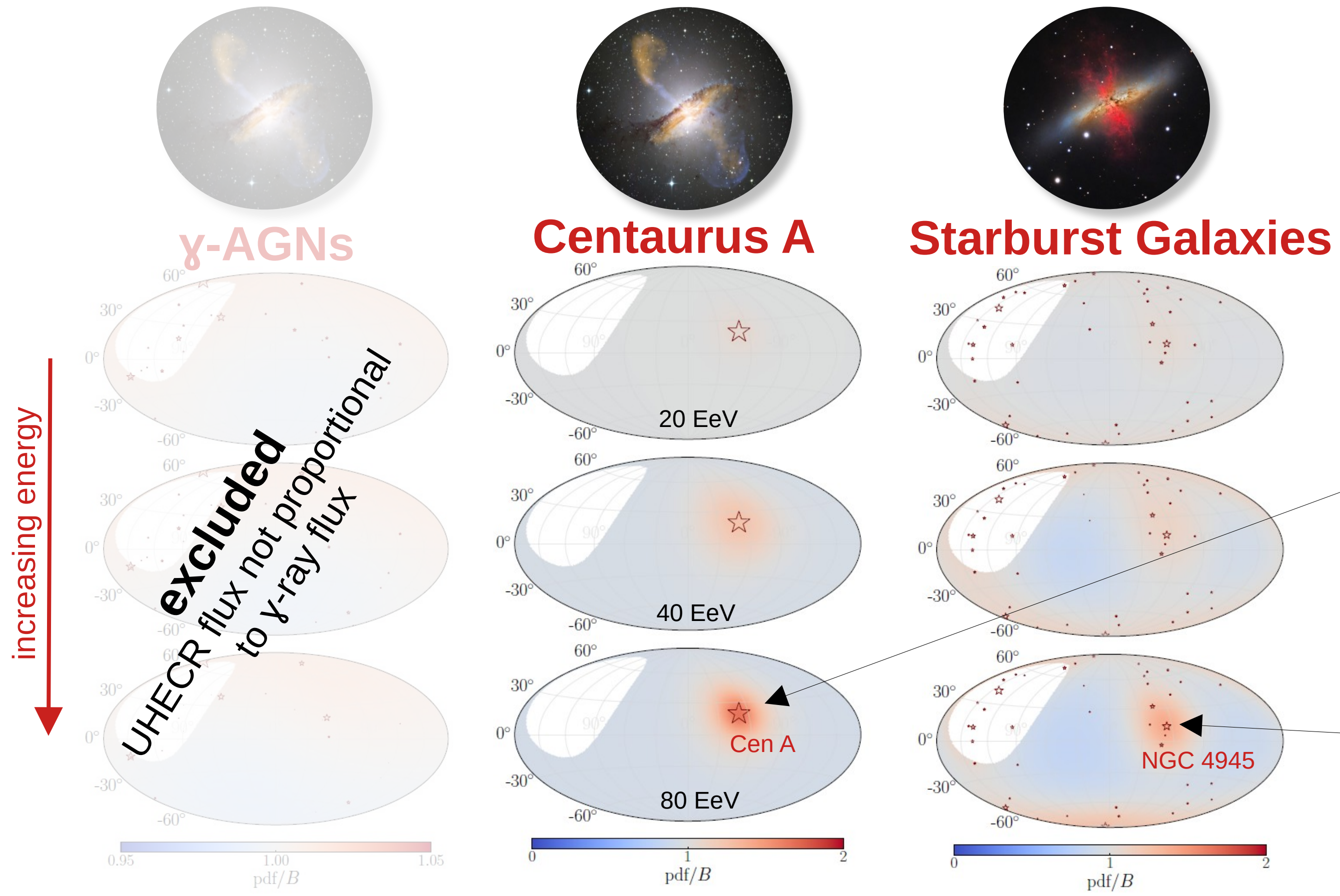


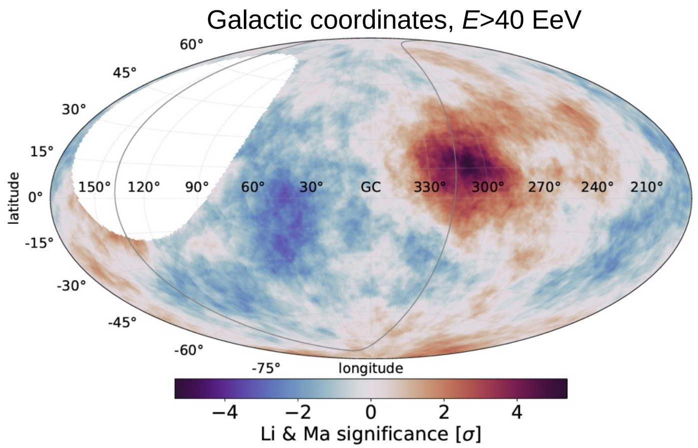
does not describe data well!

- 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

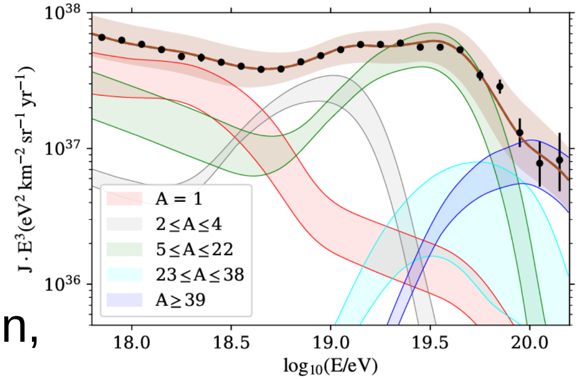
Conclusions

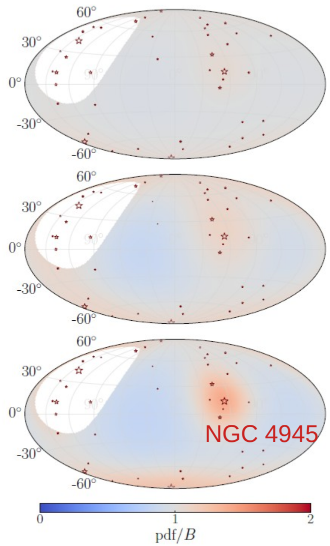
- **UHECR sources better understood**
  - → models important to understand data

→ **combined fit of spectrum and composition:**
  - → above the ankle: extragalactic source population, hard emission spectrum, N-dominated
  - → below the ankle: at least partly extragalactic, lighter composition

→ **including arrival directions:**
  - → nearby source candidates like Centaurus A or catalog of starburst galaxies describe all observables well

- **promising future:** detector upgrades underway (AugerPrime), better mass composition data, machine learning...

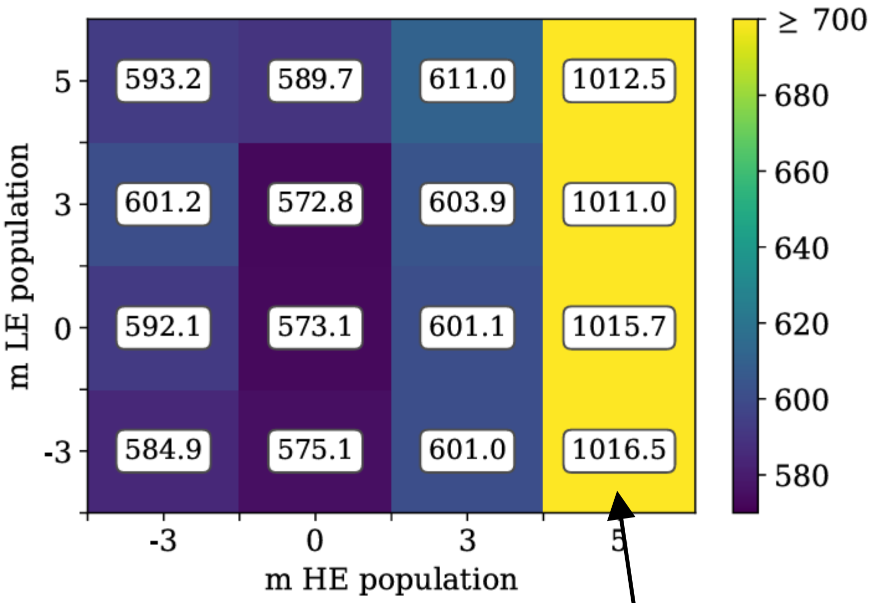


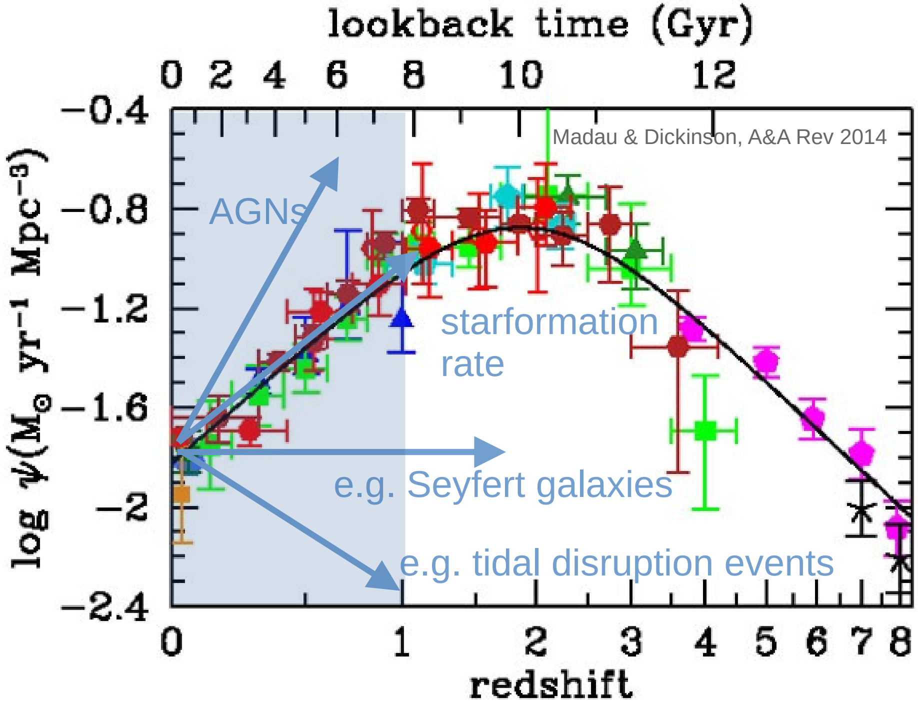


Backup

Model predictions for the source evolution

test cosmological source evolution $\psi(z) \propto (1+z)^m$



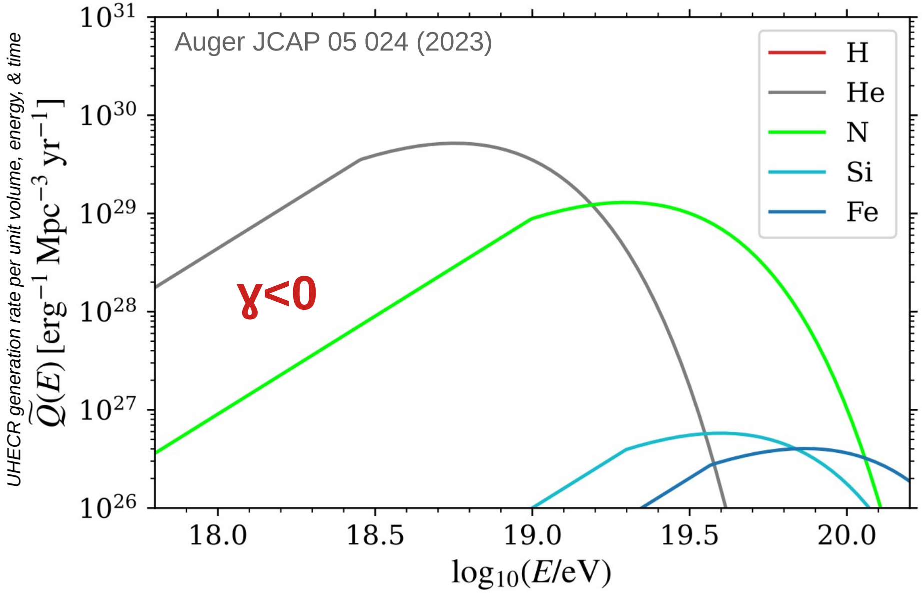


strong evolution of high-energy population disfavored

Why is the spectral index so hard?

UHECR data from Auger:

- pronounced features in the energy spectrum
- transition from light composition at the ankle to heavy composition at the suppression
- composition becomes purer with energy



<u>**can be described by:**</u>

1) population of extragalactic sources dominating from ankle energy
2) following Peters cycle (acceleration ∝ Z)
3) very hard injection spectrum

→ ***not expected from shock acceleration!***

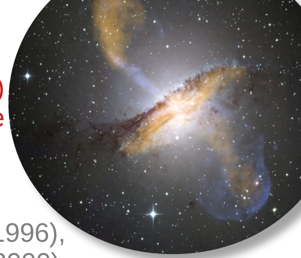
Note that the spectral index γ is highly influenced by:

- **interactions & magnetic confinement** in source environment
  e.g. Unger et al. PRD 92 123001 (2015)
- **extragalactic magnetic field**
  e.g. Auger JCAP 07 094 (2024), Mollerach & Roulet PRD 101 103024 (2020)
- **cutoff shape**
  e.g. Auger JCAP 07 094 (2024), Comisso et al. ApJL 977 L18 (2024)
- **source evolution**
  e.g. Alves Batista et al. JCAP 01 002 (2019), Heinze et al. ApJ 873 88 (2019), Auger JCAP 07 094 (2024)

Pierre Auger Collaboration JCAP 05 024 (2023)

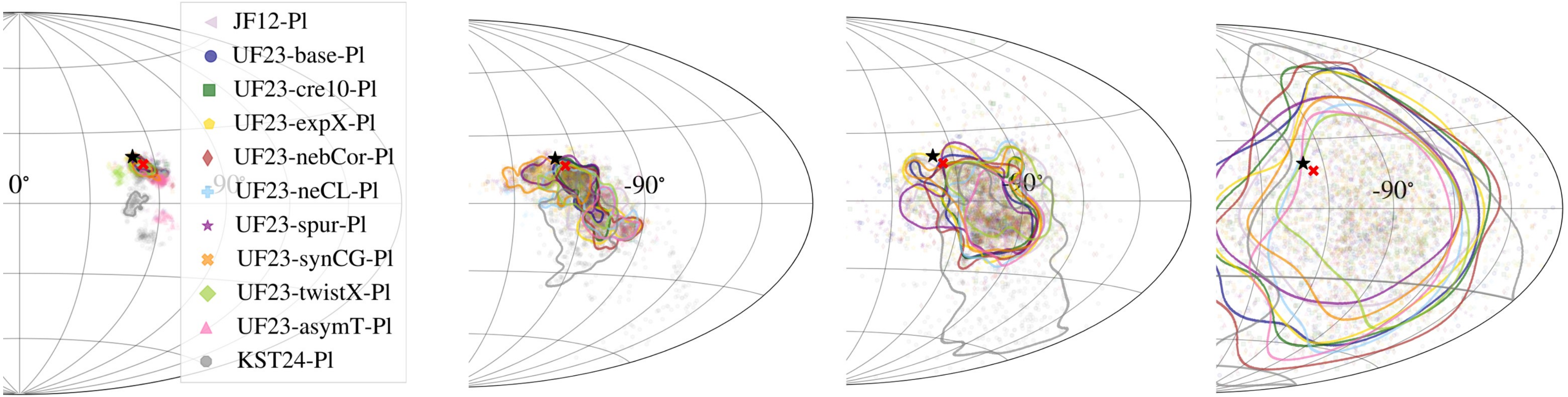
Cen A overdensity

Cen A (radio galaxy) at ~4 Mpc distance



- long-standing **UHECR source candidate** due to powerful radio jets & proximity
  e.g. G. Cavallo A&A 65 (1978) 415, G.E. Romero et al. Astropart. Phys. 5 (1996), G.R. Farrar & T. Piran, arxiv:0010370 (2000)
- correlation with Cen A at 4σ, 27° angular scale Auger ApJ 935 170 (2022)
- **level of anisotropy rises with the energy** Auger ApJ 984 123 (2025)
  - ➔ as expected for close-by source Auger JCAP 01 022 (2024)
- overdensity **direction steady** with energy >20 EeV & **only ~2° from Cen A** Auger ApJ 984 123 (2025)
  - ➔ subdominant coherent magnetic field in that direction? Constant (large) rigidity?

simulation
following Auger energy spectrum



Z=2, $R \approx 26.8$ EV | Z=6, $R \approx 9$ EV | Z=12, $R \approx 4.5$ EV | Z=26, $R \approx 2$ EV

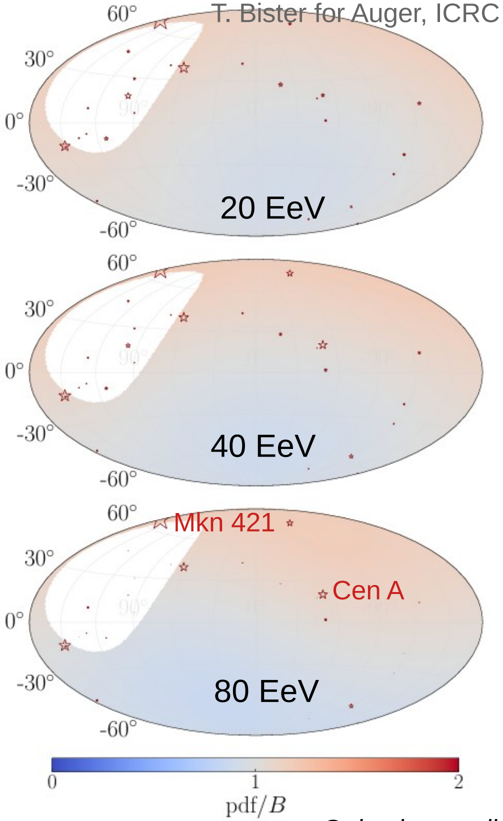
Correlation with AGNs

- AGN lobes or jets are good candidates for UHECR acceleration
- correlation of Auger+TA data with catalog of **all AGNs 3.3σ, jetted AGNs: 3.8σ** (ICRC 2025)

- but: **jetted AGN model (UHECR flux ∝ ɣ-ray)** flux does not describe Auger data well in combined fit model Auger JCAP 01 022 (2024)
  - ➔ correct for magnetic field decollimation? C. de Oliveira et al. ApJ 981 (2025)
  - ➔ UHECR flux anti-proportional to ɣ-ray flux due to heavy losses in ɣ-ray bright sources? L.A. Anchordoqui & K.P. Castillo, arXiv:2503.13315, A. Partenheimer et al. ApJL 967 (2024) L15

- or consider also **weaker AGNs** like FR0 or Seyferts? e.g. L. Merten et al. Astropart. Phys. 128 (2021), R.C. Anjos & C.H. Coimbra-Araujo PRD 96 (2017)
  - ➔ powerful AGNs alone are too sparse (overshoot dipole) & have too strong evolution (overshoot spectrum @ankle)
  - ➔ but, can weaker AGNs accelerate to highest energies?

T. Bister for Auger, ICRC 2023



Galactic coordinates