Constraining the sources of ultra-high-energy cosmic rays

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Nikhef
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NNV meeting
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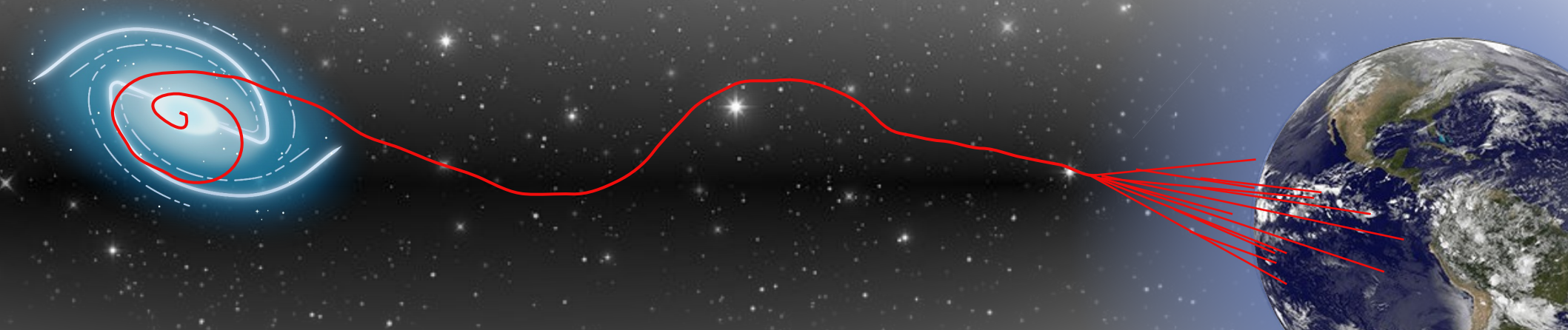
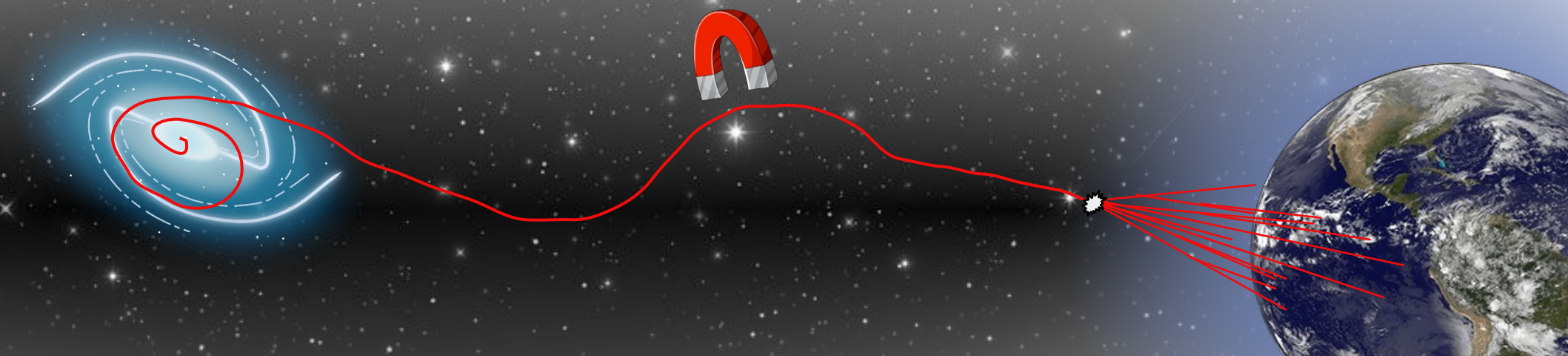


Ultra-high-energy cosmic rays…

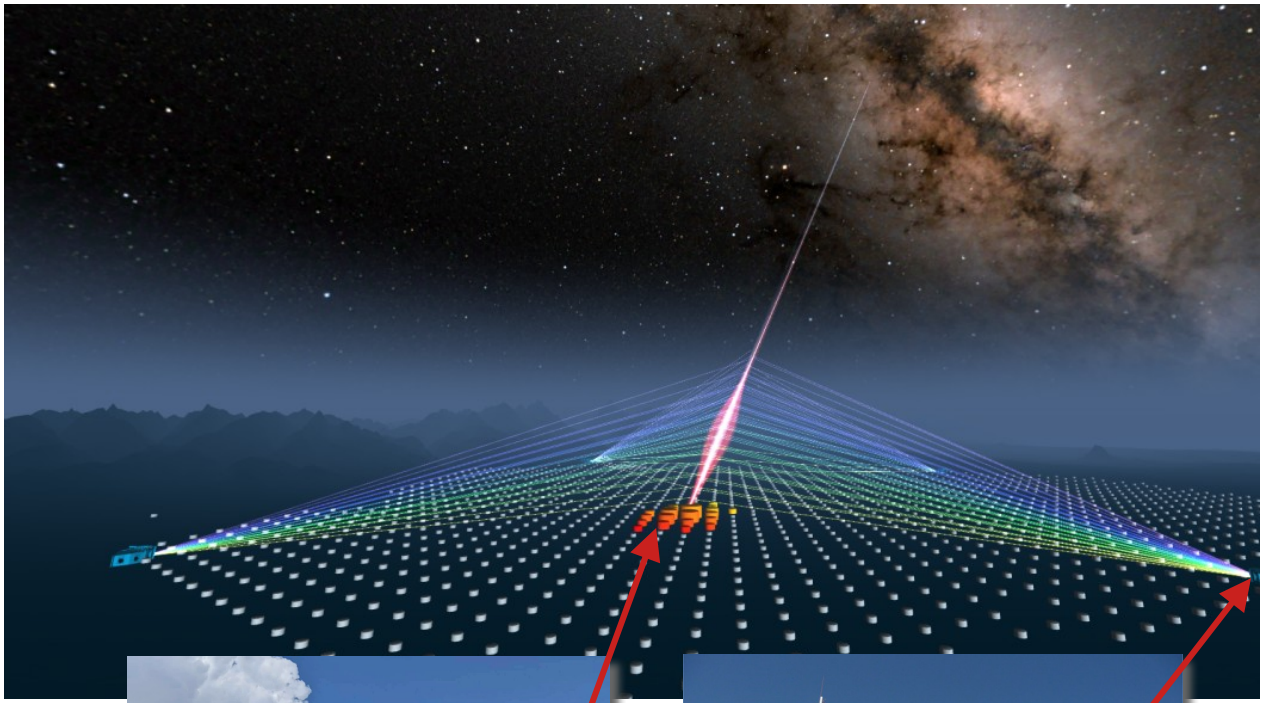
- are the highest energetic particles we know
- come from somewhere outside the Milky Way

- are charged and therefore deflected
- do not point back to sources

- interact with the atmosphere and produce air showers
- ~10^{10} secondary particles!

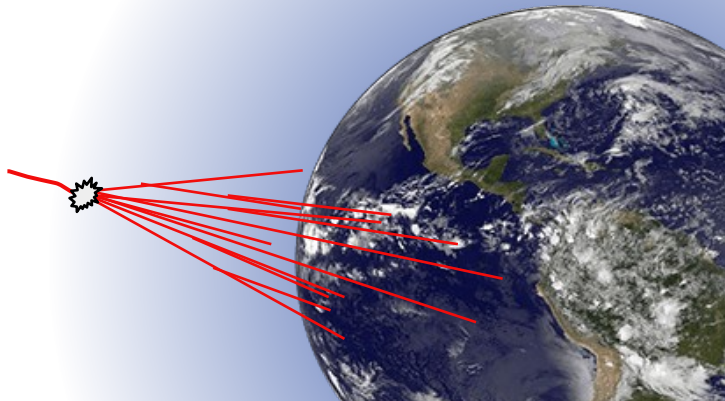


Measuring extensive air showers at the Pierre Auger Observatory

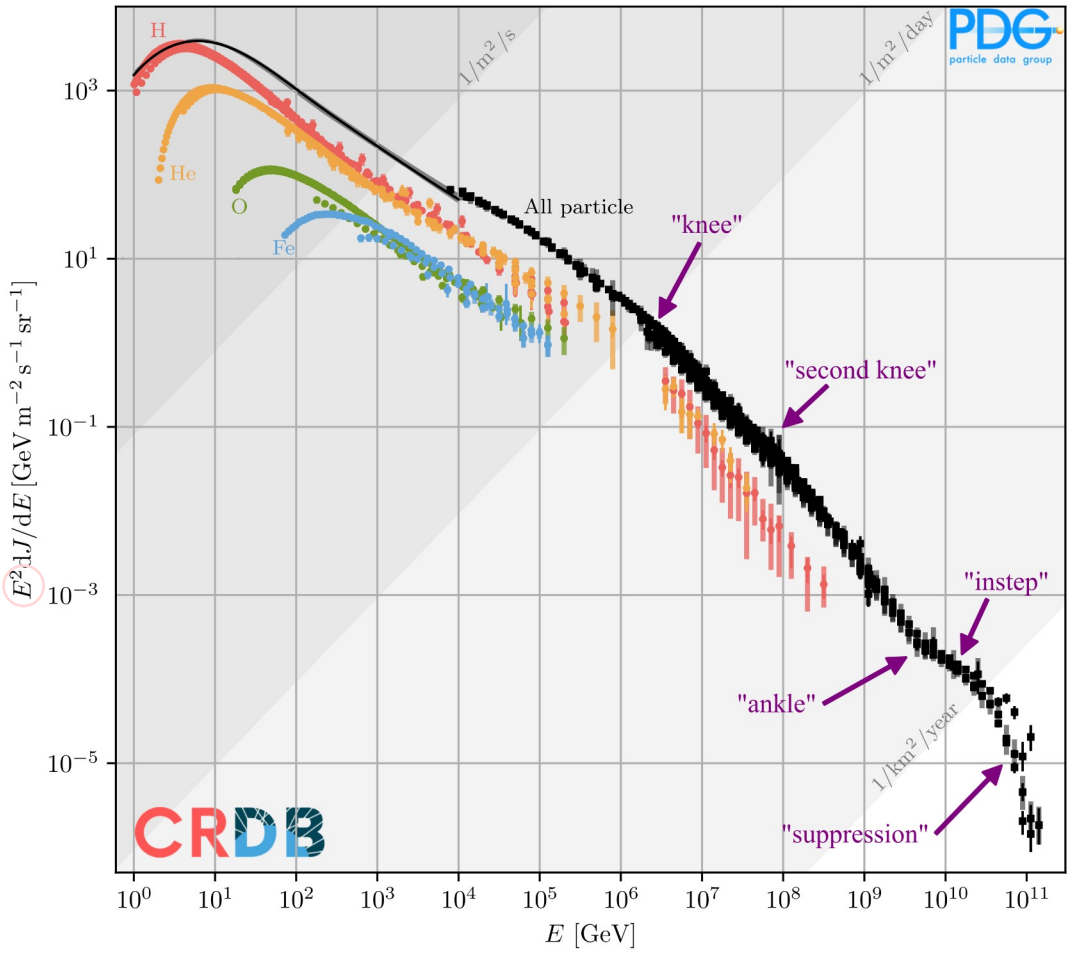


- **Pierre Auger Observatory:**
  - close to Malargüe, Argentina
  - 1660 surface detector stations, 4 fluorescence detector sites
  - 3000 km² → largest Observatory in the world

- <u>reconstruction of:</u>
  - ➔ energy
  - ➔ arrival direction
  - ➔ depth → mass / charge



Cosmic ray energy spectrum



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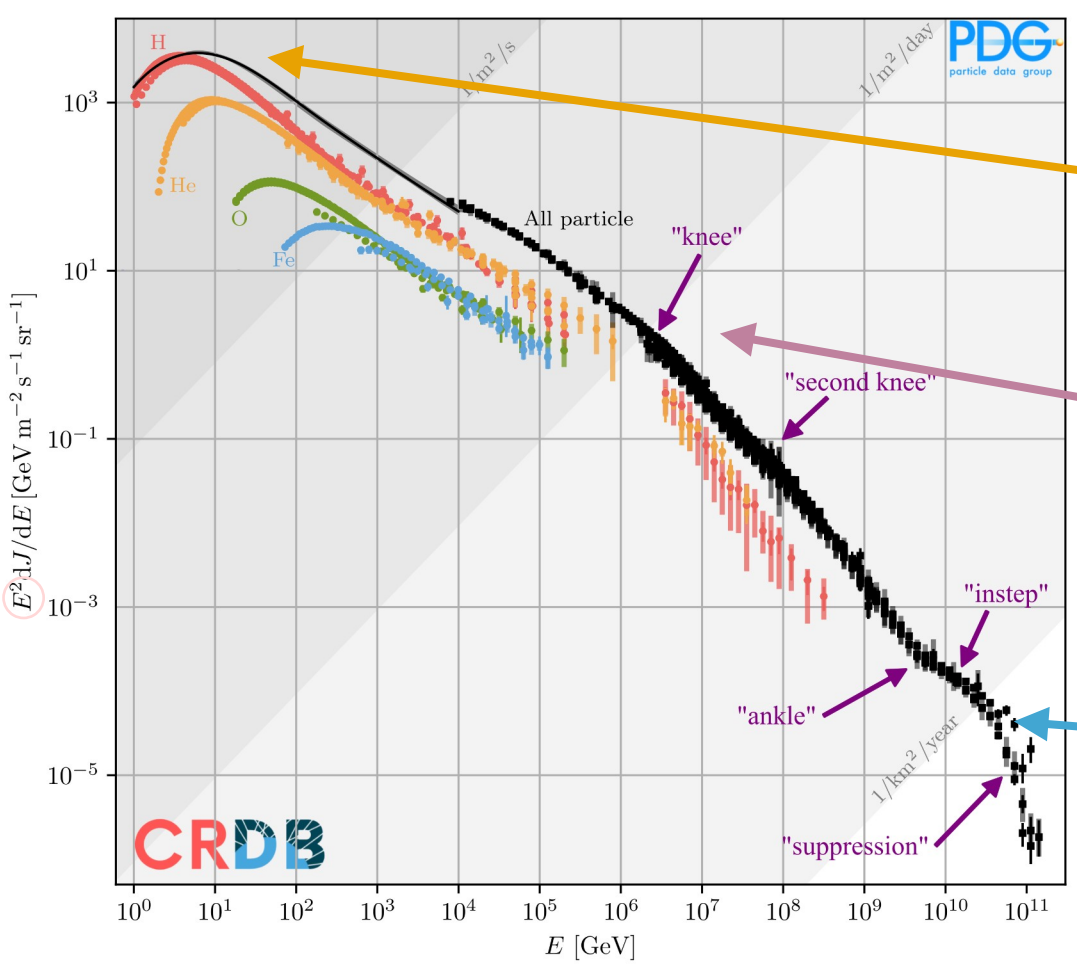
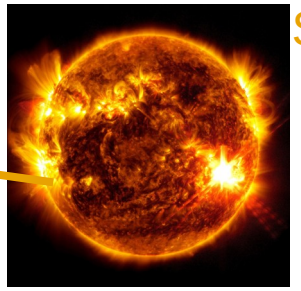
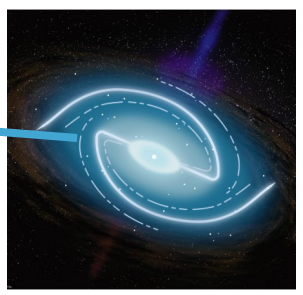




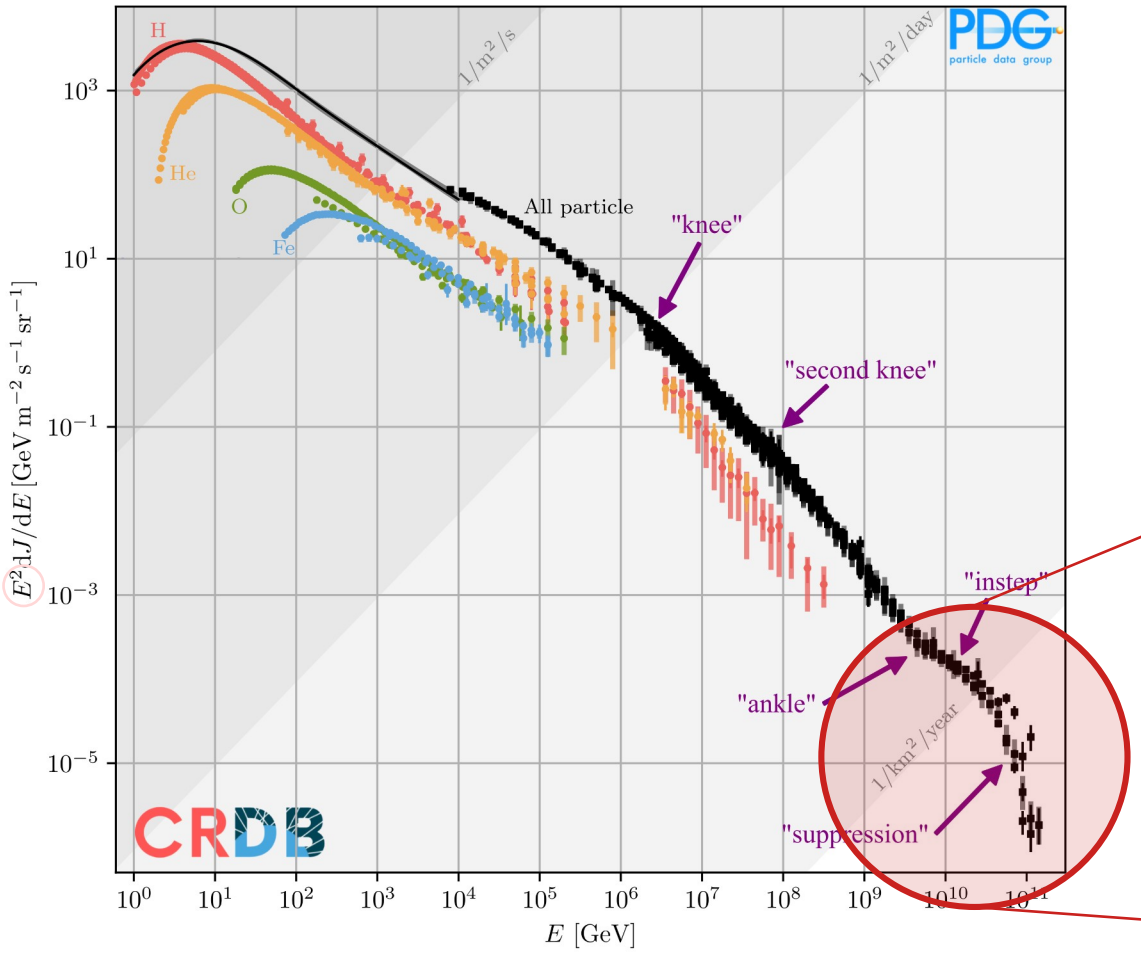
Sun

Milky Way

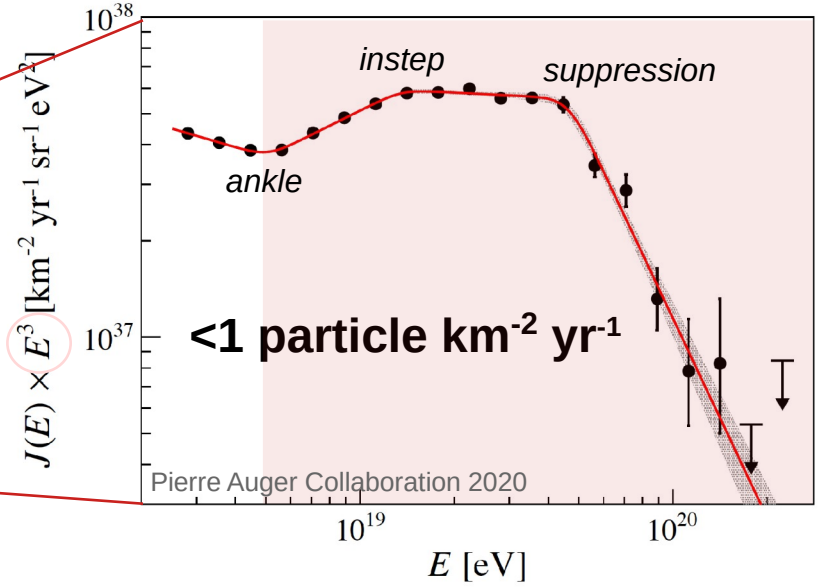


powerful extragalactic sources

Ultra-high-energy cosmic rays

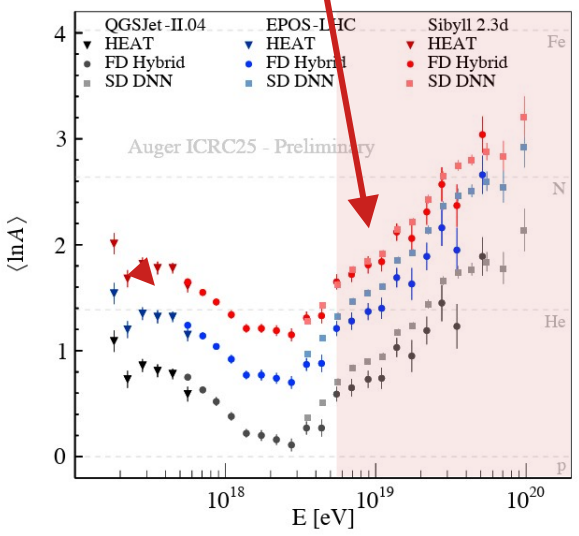


What does the spectrum, in combination with the mass composition, tell us about the sources?

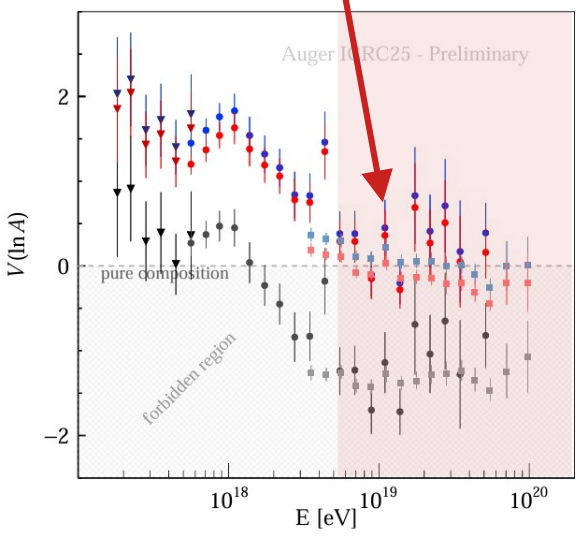


Ultra-high-energy cosmic ray data

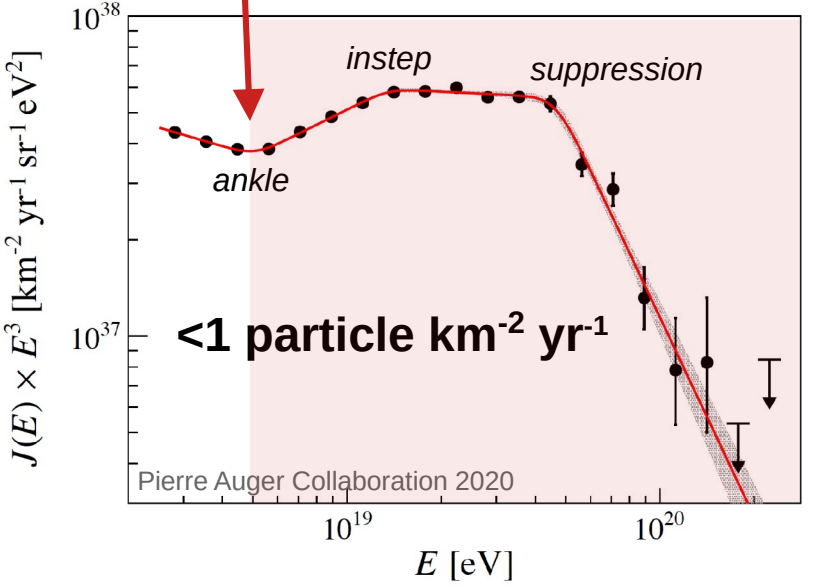
transition from light composition at the ankle to **heavy composition** at the suppression



composition becomes **purer** with energy



pronounced features in the energy spectrum

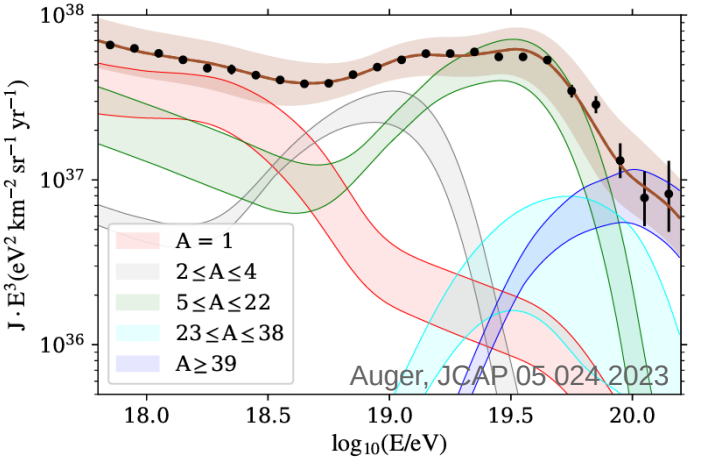


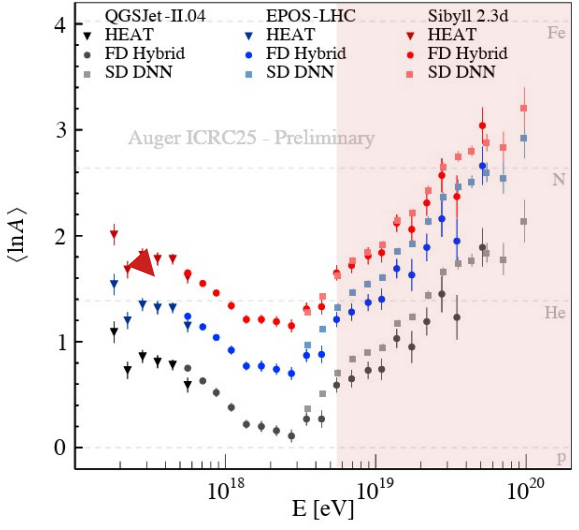
What we know about the sources

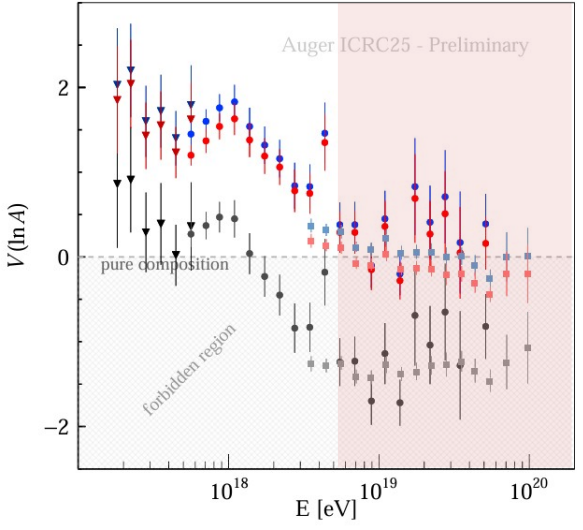
from spectrum and mass composition measurements

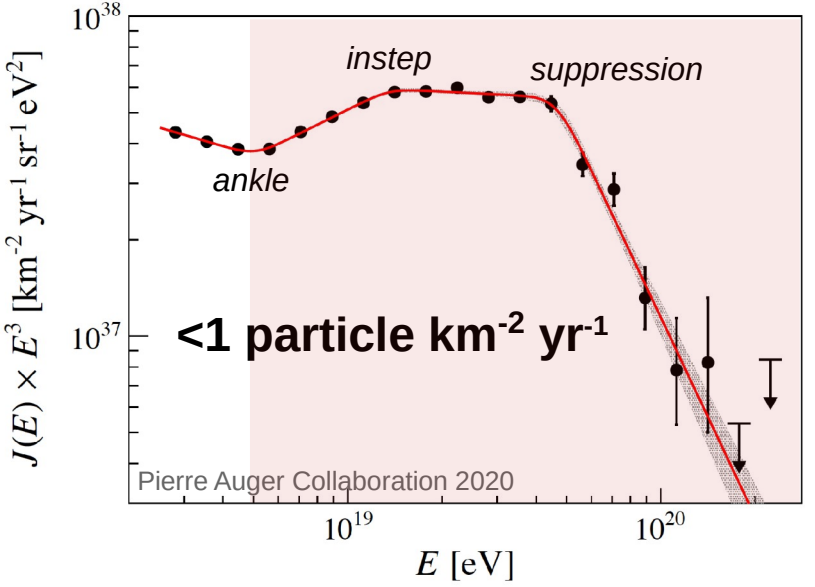
spectrum & composition data can be described by:

- population of **extragalactic** sources dominating above ankle
- **acceleration ∝ Z** → mass composition gets heavier
- **hard injection spectrum & almost identical sources** to describe pronounced spectrum features and small composition variance [Ehlert, Oikonomou, Unger 2023]









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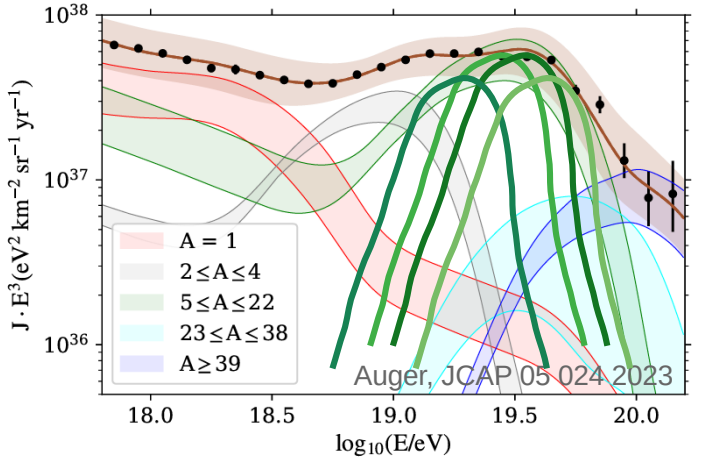
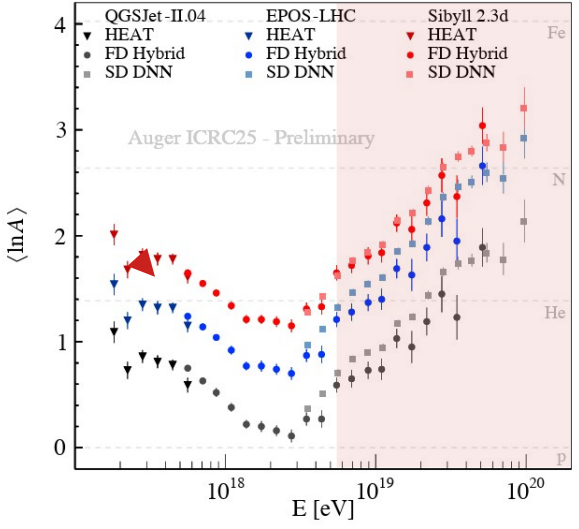
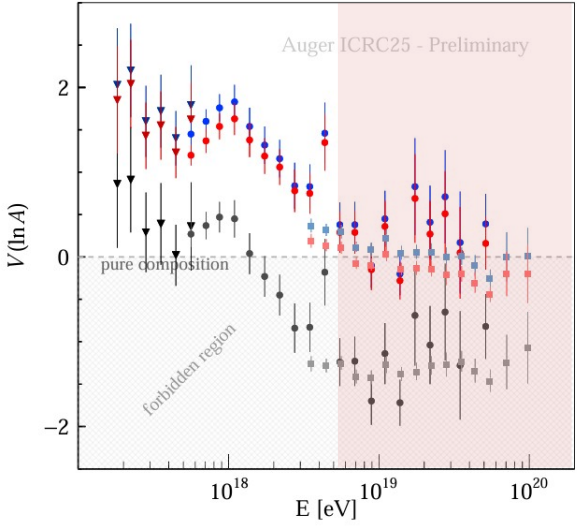
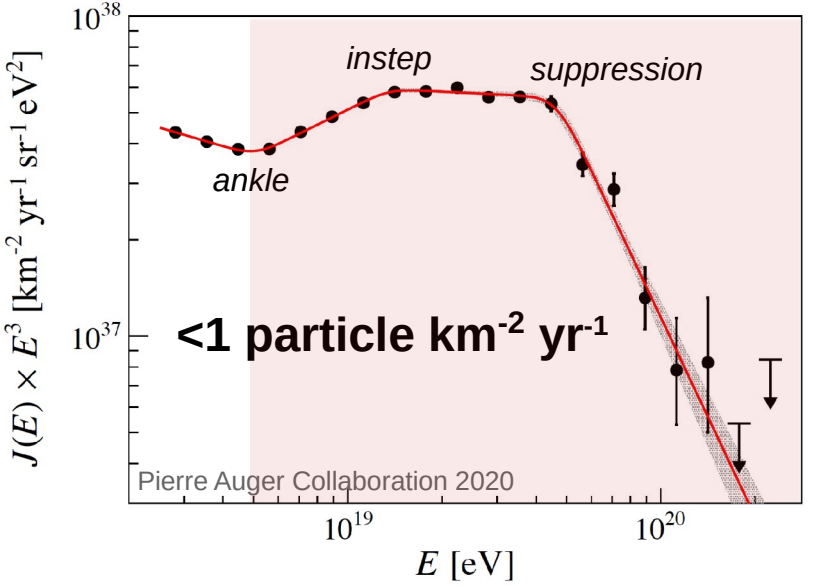








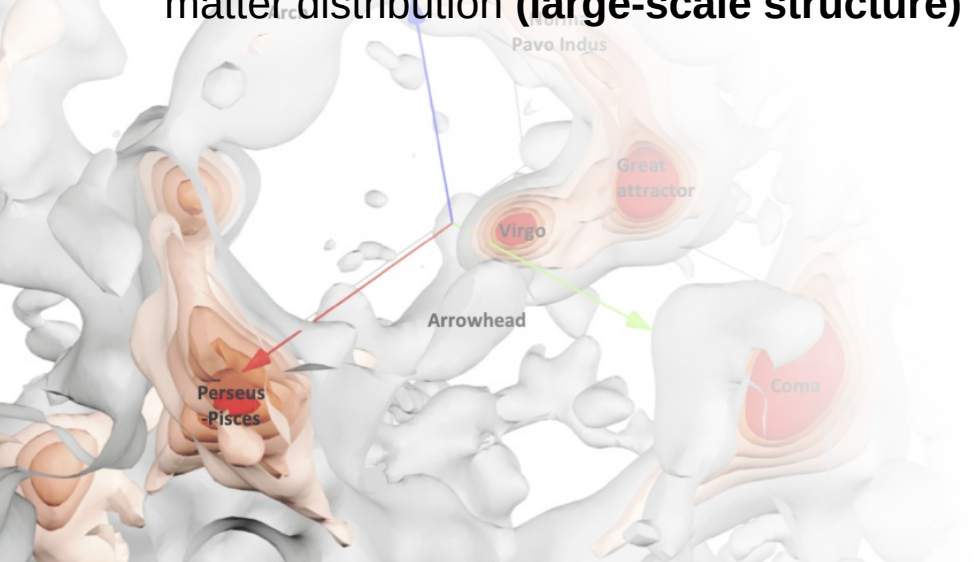
What can we learn from the arrival directions?

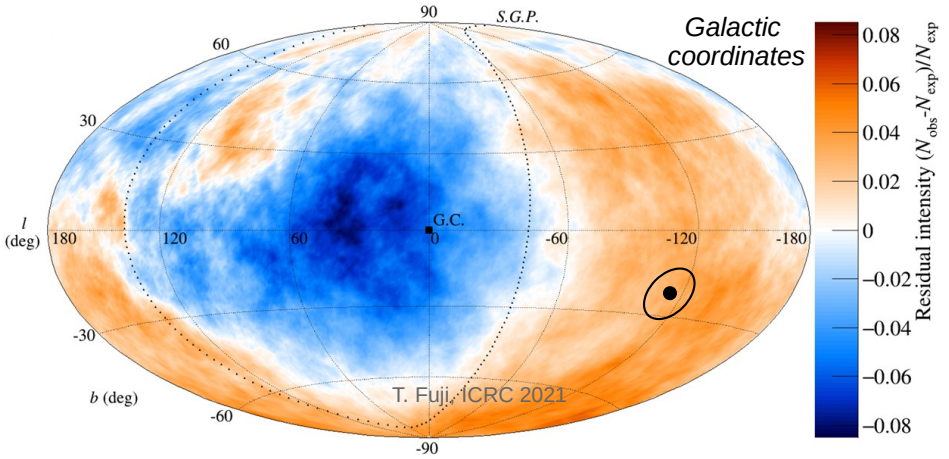
most important:
Galactic magnetic field (GMF)

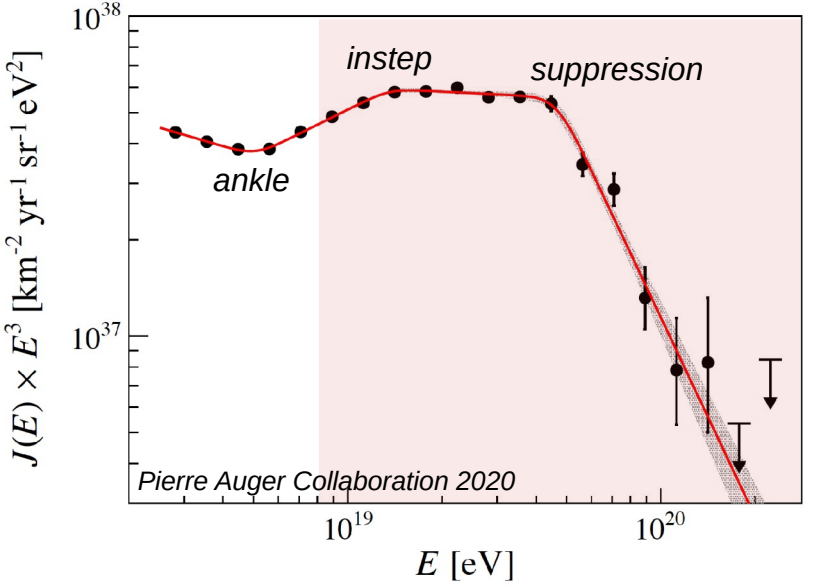
The UHECR sky >8 EeV

- **> 8 EeV, the sky is dominated by a dipole**
  - ➔ points ~125° away from Galactic center
    - ➔ extragalactic! Auger, Science 2017
- no higher multipoles present

- at these energies, propagation length $\gtrsim$1000 Mpc
  - ➔ dipole is likely an **imprint** of anisotropic extragalactic matter distribution **(large-scale structure)**



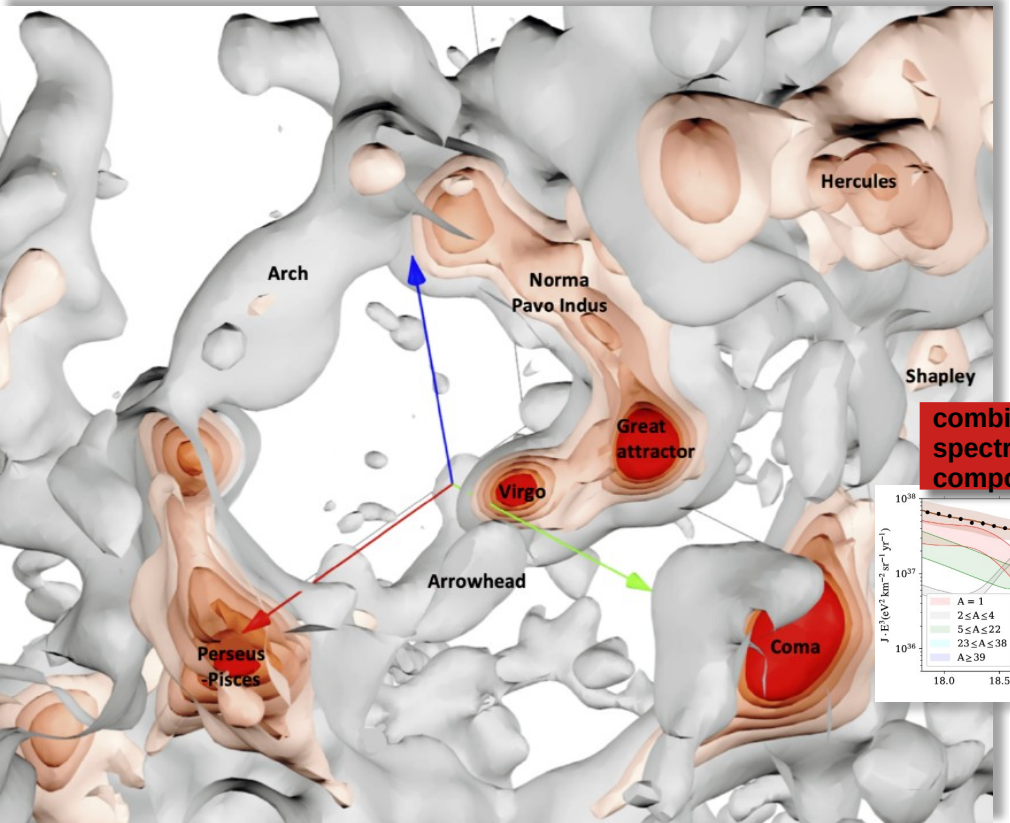




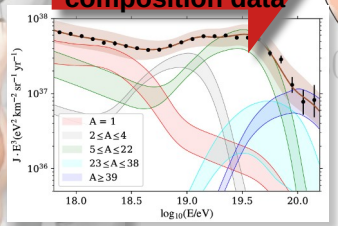
The UHECR sky >8 EeV

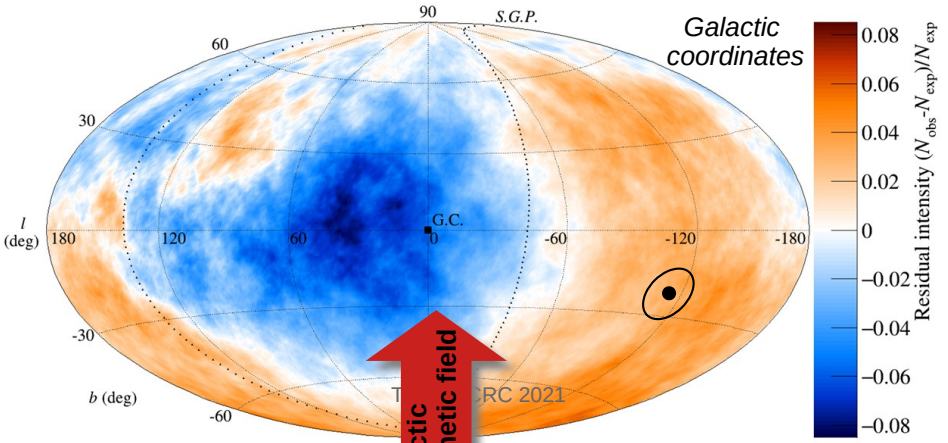
The large-scale structure
→ use as proxy for UHECR source distribution

from Cosmic Flows, Hoffman et al. Nature Astronomy 2018

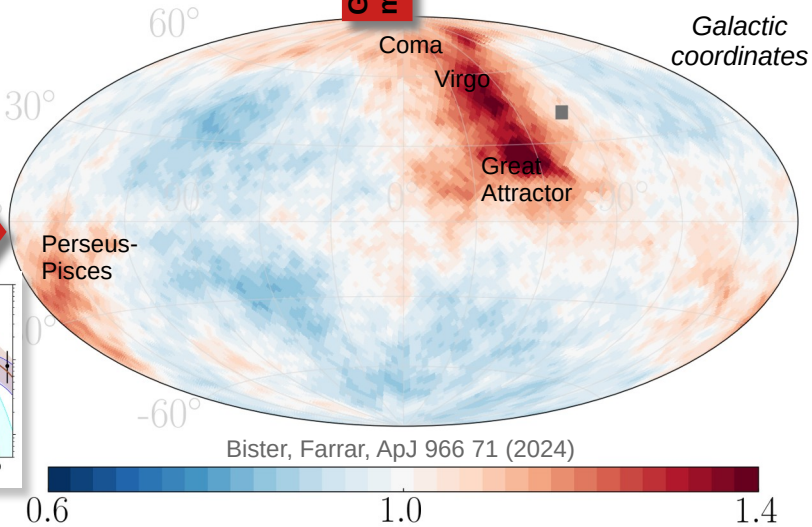


combined fit to spectrum and composition data





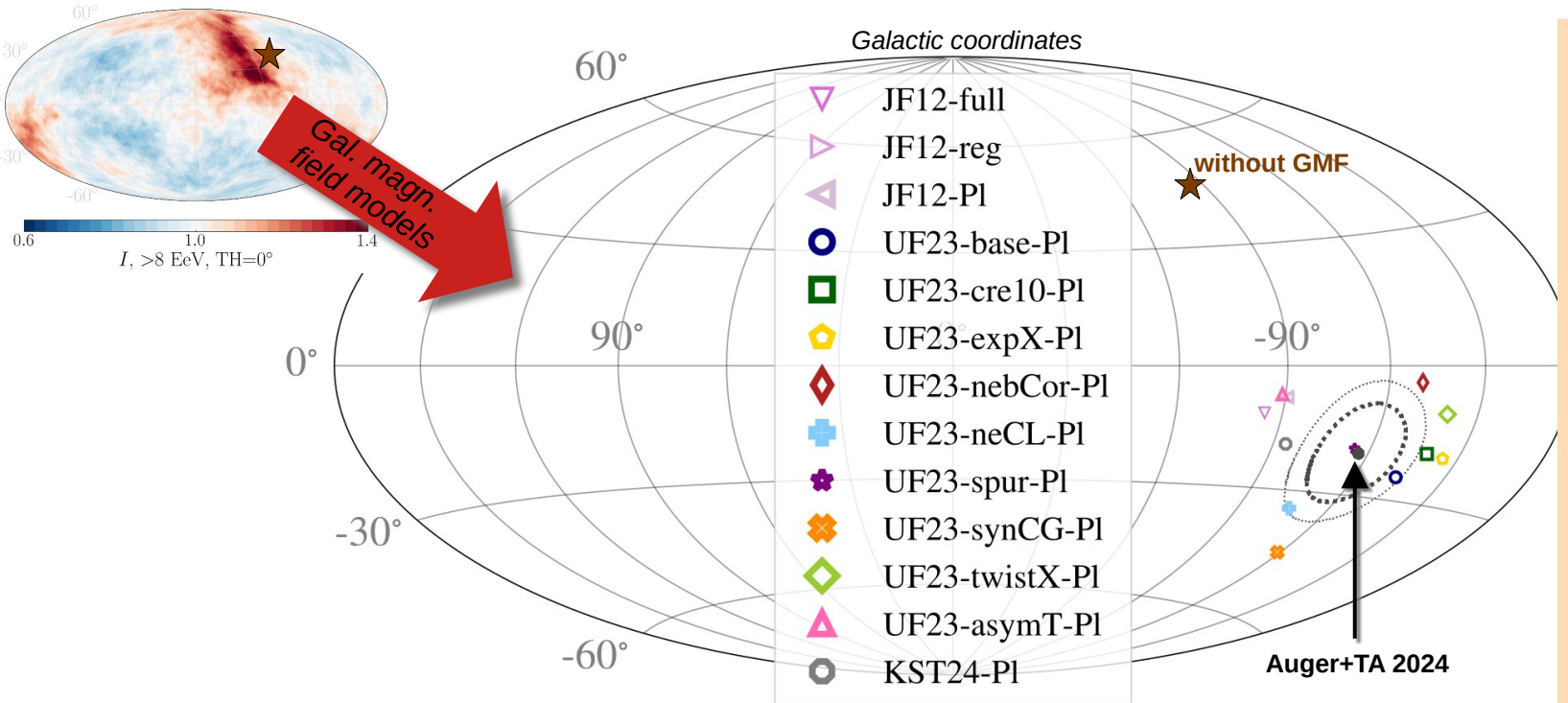
Galactic magnetic field



Bister, Farrar, ApJ 966 71 (2024)

model flux at the edge of the Galaxy

Dipole direction > 8 EeV



lots of new Galactic magnetic field models became available in recent years!

all models predict dipole direction close to measured one ✓

uncertainty estimate of GMF model ✓

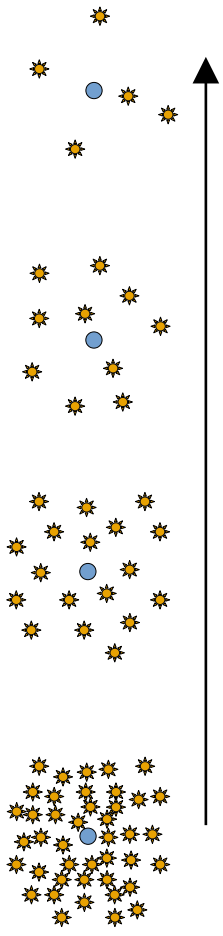
Note: cannot get predicted dipole direction to match measurements with **proton-only composition or no GMF deflections ✘**

Ding, Globus, Farrar ApJL 913 (2021)

T. Bister, Universe 2025

Bister, Farrar, Unger ApJL 975 L21 (2024)
+ KST24 model from Korochkin et al. A&A 693 (2025)
+ UF23-asymT model from Unger & Farrar UHECR (2024)

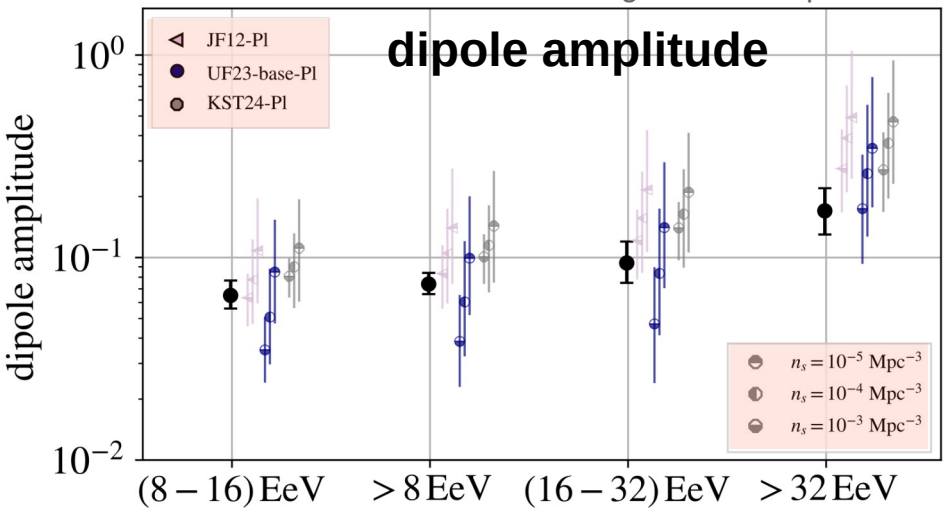
Source number density

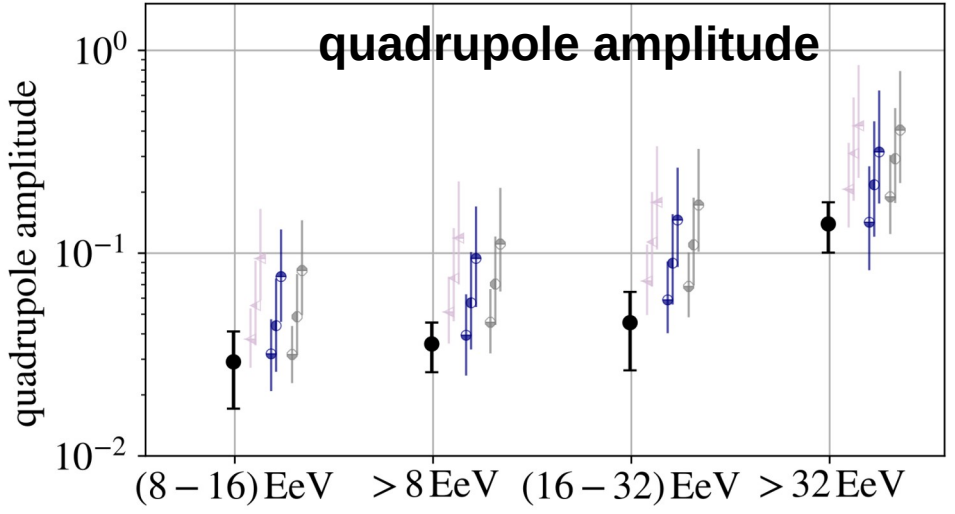


smaller density
→ larger multipole moments (on average)

larger density
→ smoother, smaller multipole moments (on average)

Bister, Unger, Farrar, ApJL 2024





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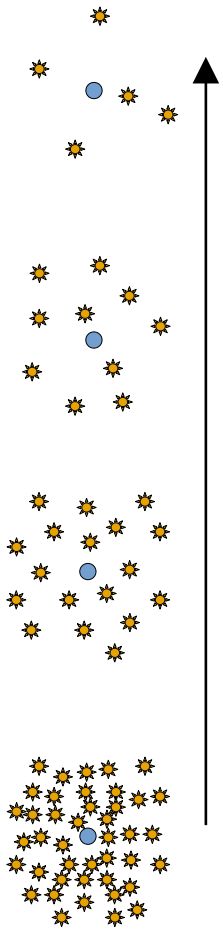


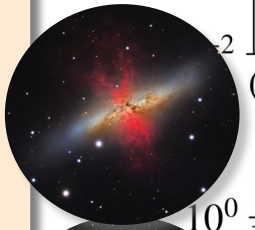
smaller density
→ larger multipole moments (on average)

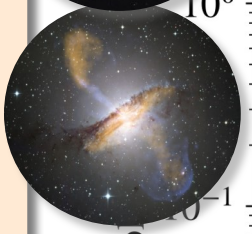
densities of **~(10^{-3} - 10^{-4}) Mpc^{-3}** work best for most GMF models

for comparison:
starburst galaxies ~10^{-5} Mpc^{-3}
active galactic nuclei ~10^{-6} Mpc^{-3}

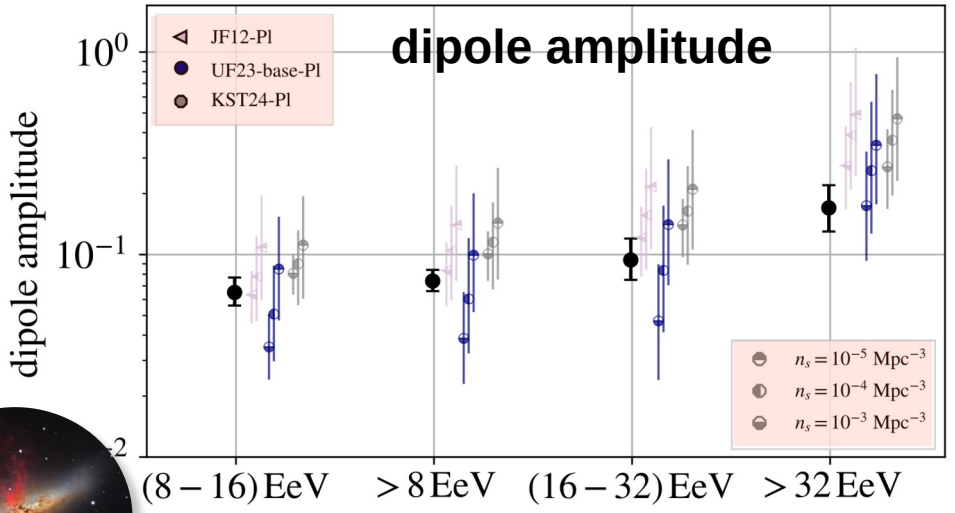
→ UHECR sources quite common at $\gtrsim$ 8 EeV!
(if there is no very strong extragalactic magnetic field)

larger density
→ smoother, smaller multipole moments (on average)



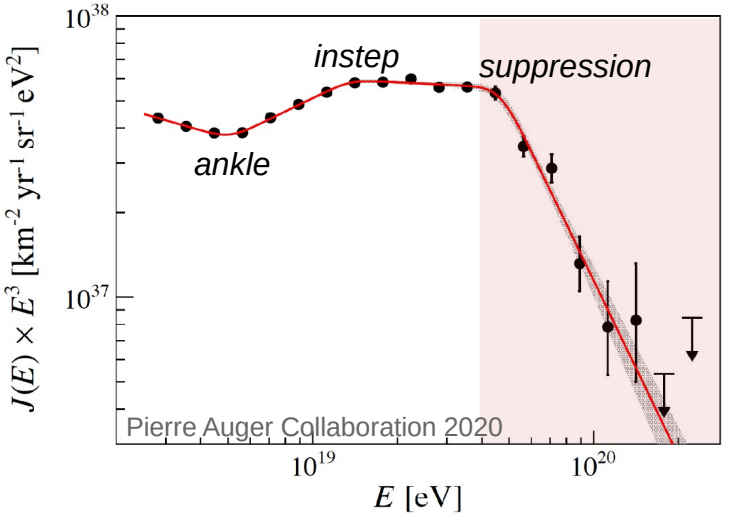


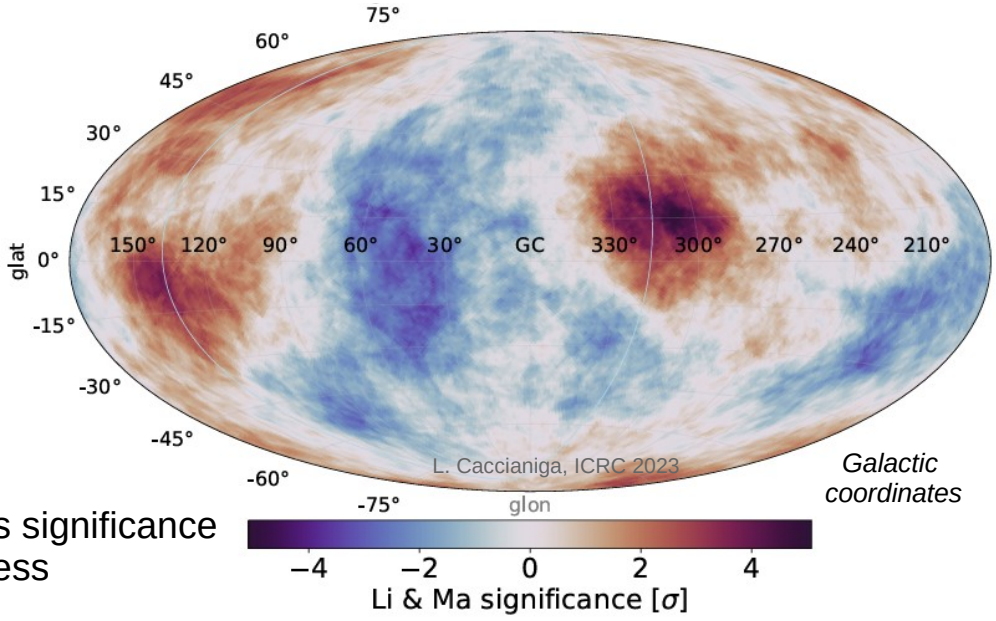
Bister, Unger, Farrar, ApJL 2024



The UHECR sky >40 EeV

- $\gtrsim$ **40 EeV, the UHECR sky is dominated by smaller-scale warmspots**
- at these energies, propagation length $\lesssim$ 200 Mpc
  - ➔ **imprints of nearby sources?**





map shows significance of flux excess

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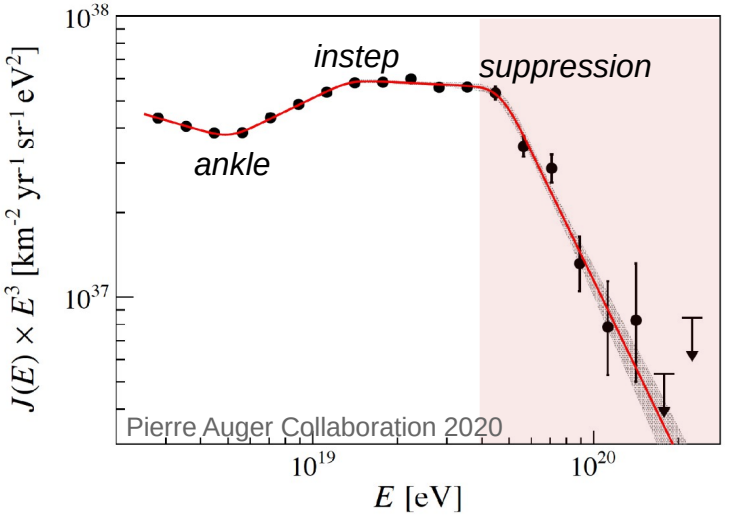
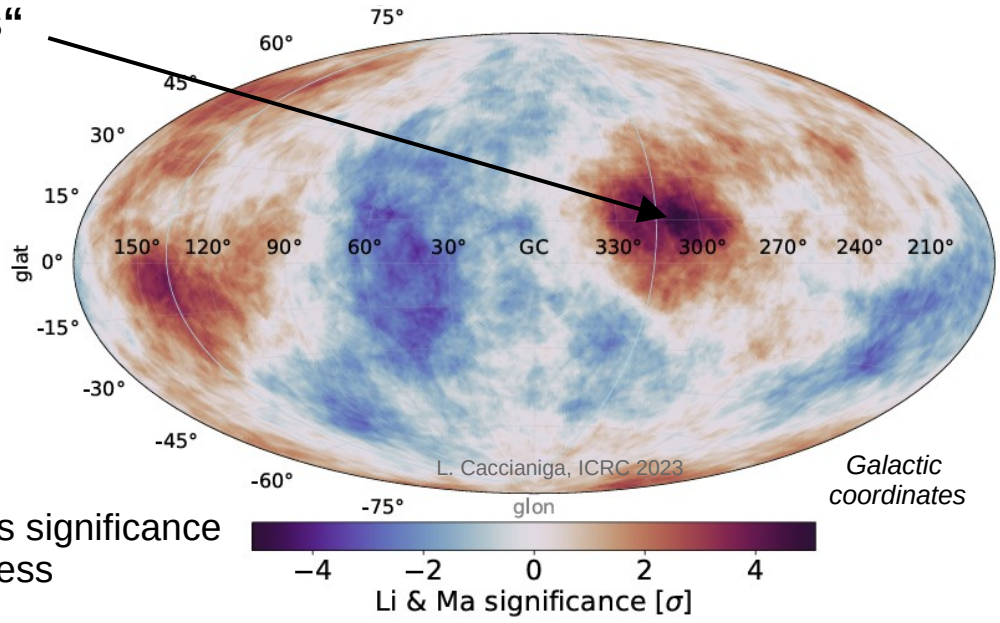
- none of the warmspots significant when penalizing for scan
  - ➔ most significant one: **„Centaurus region excess“**





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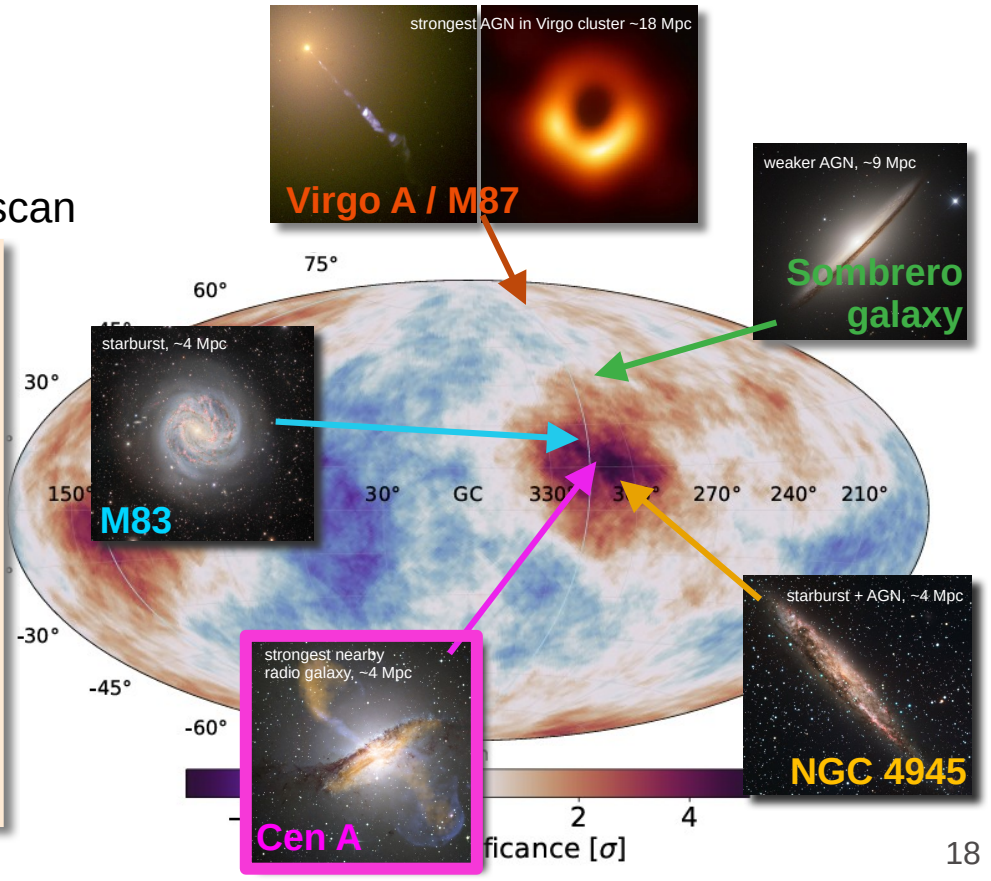
  - ➔ imprints of nearby sources?

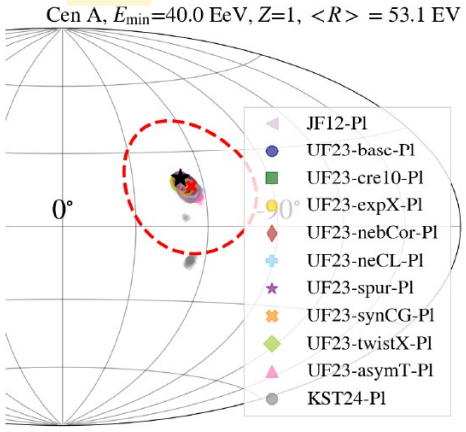
- none of the warmspots significant when penalizing for scan
  - ➔ most significant one: **„Centaurus region excess“**
  - ➔ **several source candidates have been proposed**
    - ➔ **But which one is compatible with newest Galactic magnetic field models?**
    - ➔ What **charge** do the particles need to have?
    - ➔ How large is the **extragalactic magnetic field**?
    - ➔ How large is the source contribution?

T. Bister 2025, https://arxiv.org/abs/2509.06594
submitted to Astroparticle Physics



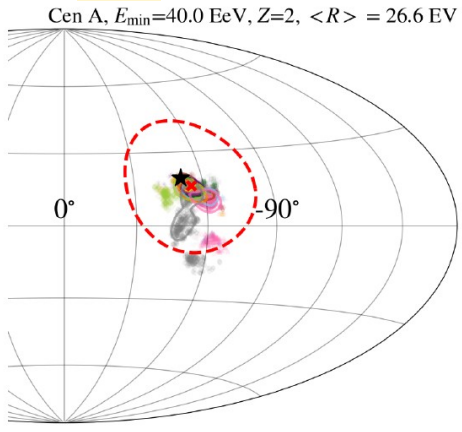
UHECRs from Cen A & magnetic field deflections

Z=1



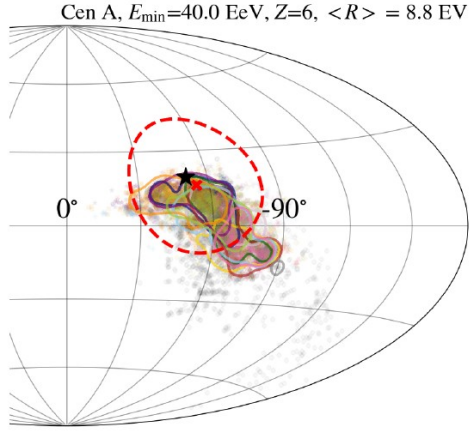
agrees well with excess direction ✔

Z=2



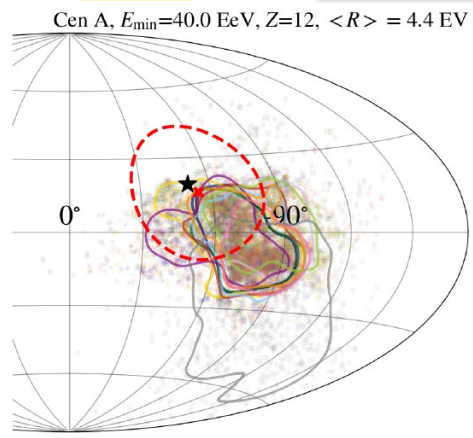
agrees well with excess direction ✔

Z=6



still fits for some GMF models ✔

Z=12

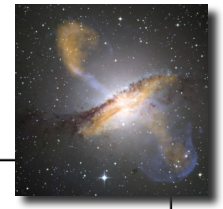


deflections too large ✘

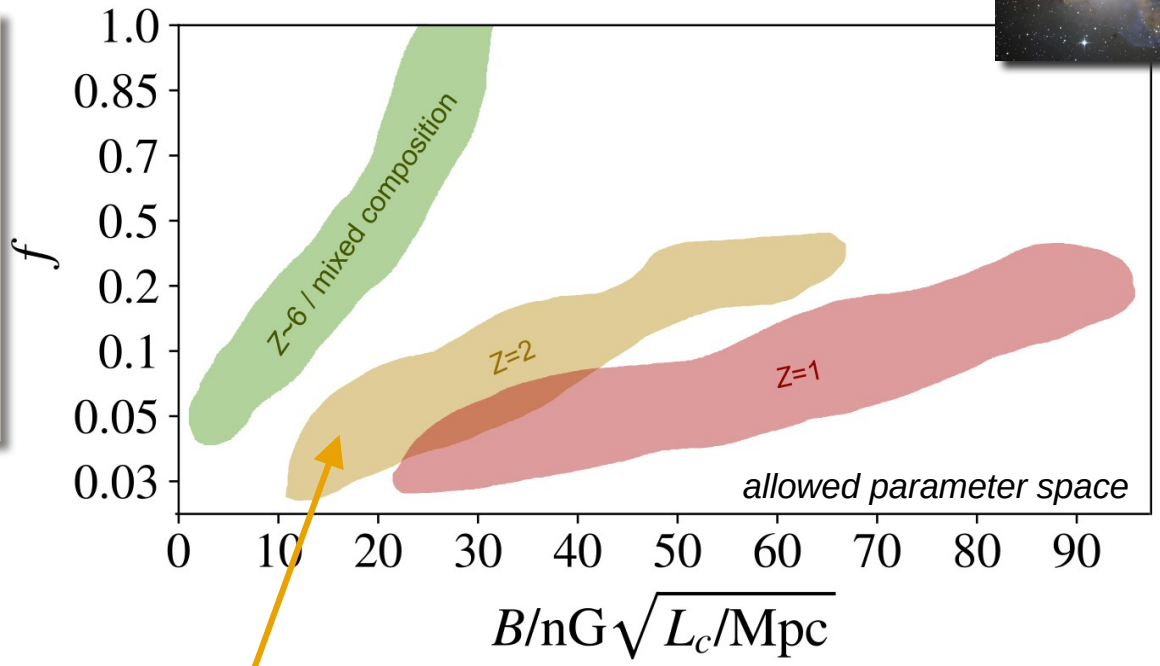
- charge needs to be **Z** $\lesssim$ **6** to be compatible with excess direction for Cen A
  - for KST24 GMF model, only Z=1 compatible
- figures are for **extragalactic magnetic field zero** → clearly does not reproduce angular scale!
  - ➔ add 2d Gaussian distribution to mimic turbulent EGMF:

$$\vartheta = 29^\circ \frac{\mathrm{EV}}{E/Z} \frac{B}{\mathrm{nG}} \frac{\sqrt{d\,L_c}}{\mathrm{Mpc}}$$

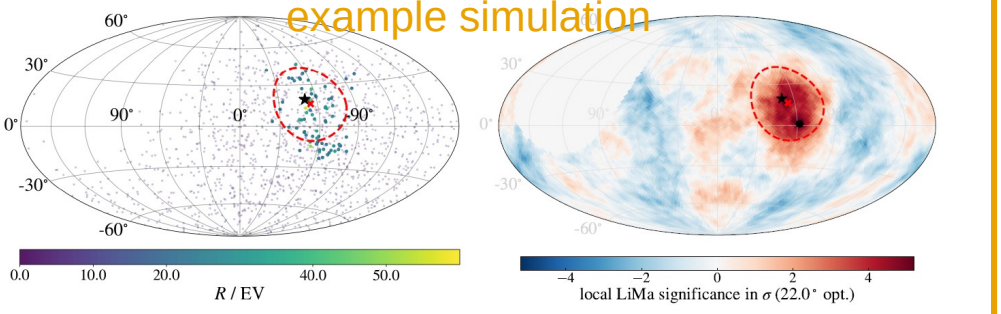
Constraints on the signal fraction



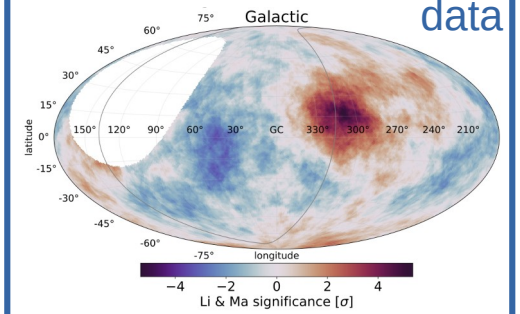
- can reproduce strength, size, direction & energy dependency of excess with Cen A as the source with $Z \lesssim 6$
  - extragalactic magnetic field of zero not allowed
  - **best current constraints** for field between Earth and nearby source



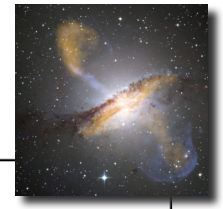
example simulation



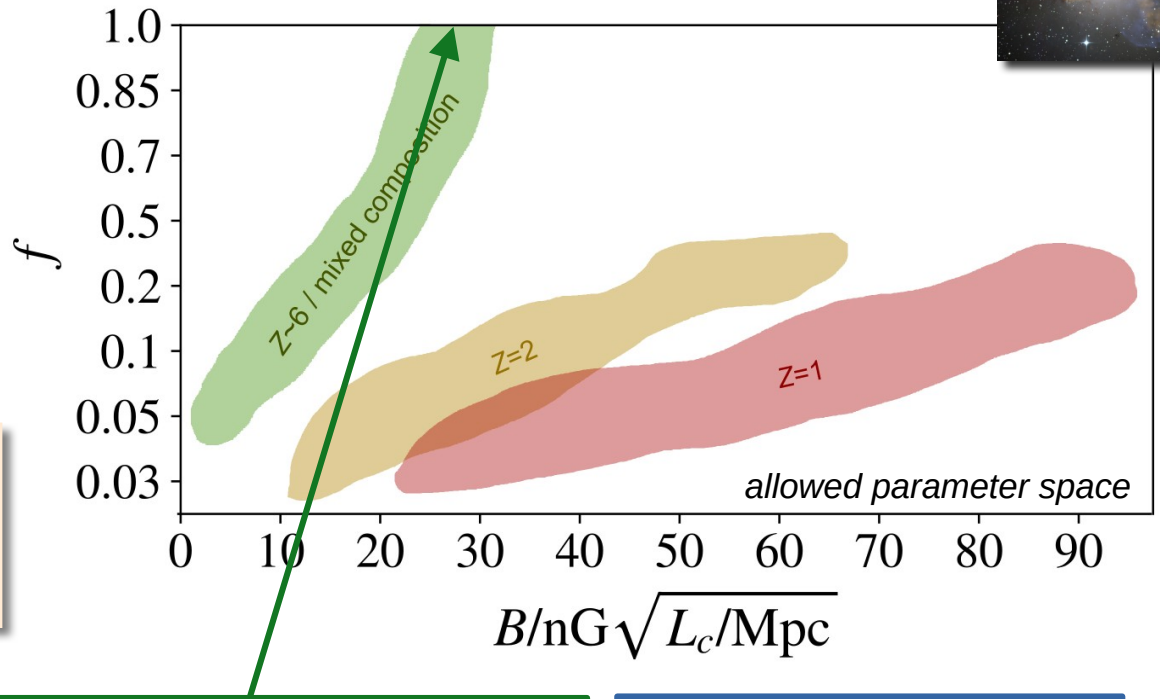
data

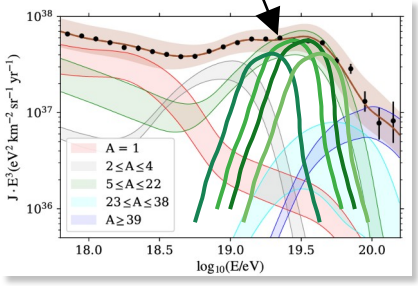


Constraints on the signal fraction

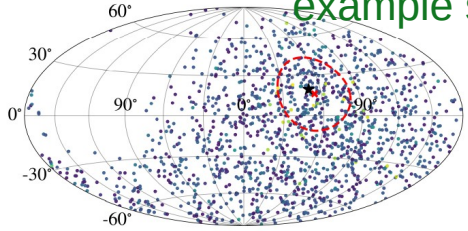


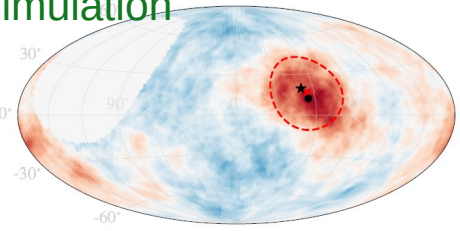
- can reproduce strength, size, direction & energy dependency of excess with Cen A as the source with $Z \lesssim 6$
  - extragalactic magnetic field of zero not allowed
  - **best current constraints** for field between Earth and nearby source
- signal fraction of Cen A up to **100%!**
  - very attractive: would explain „similarity“ of sources



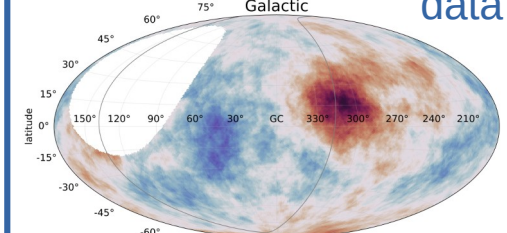


example simulation



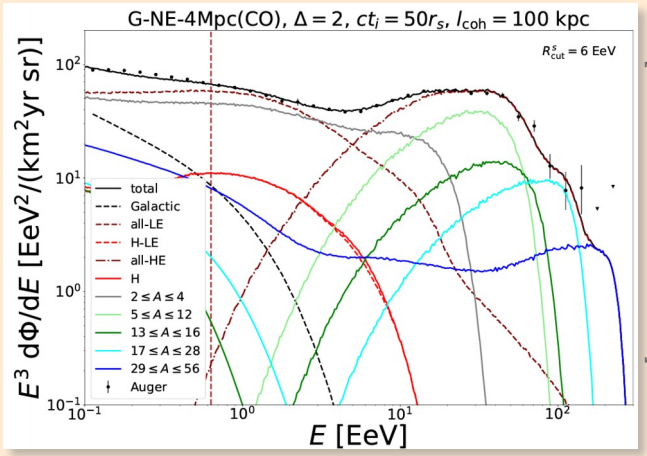


data

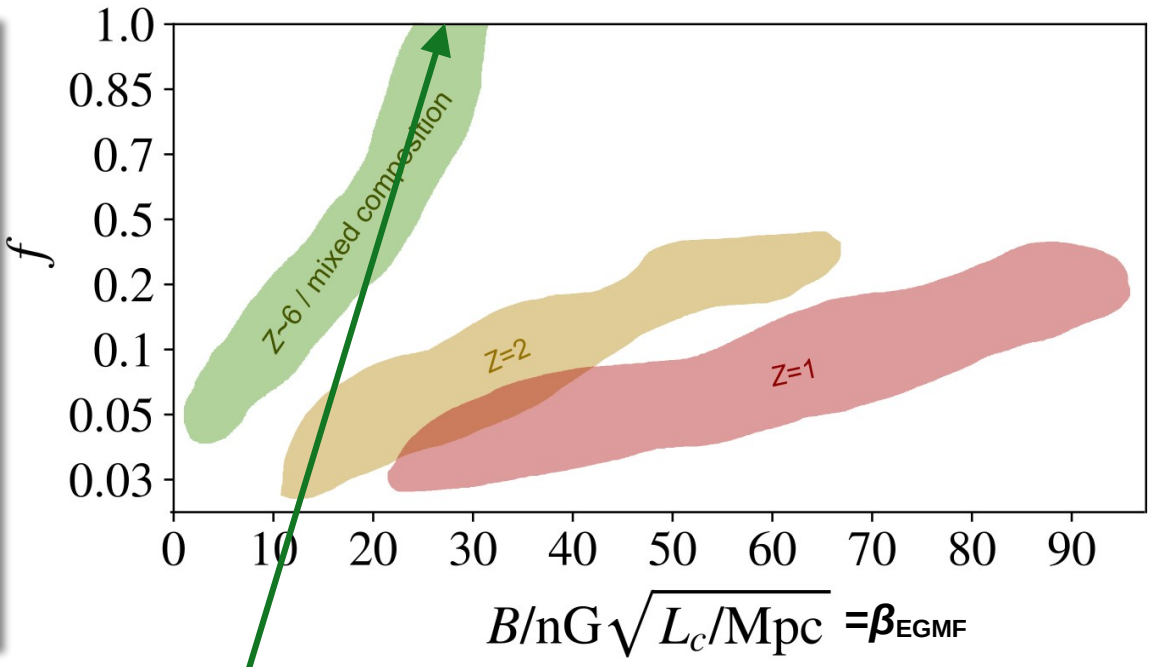


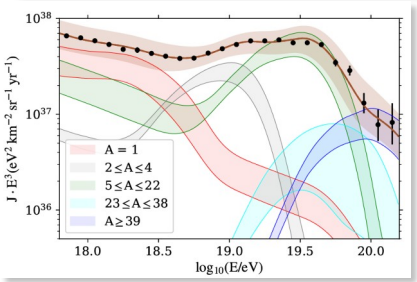
Conditions on signal fraction and EGMF: Cen A

Cen A as only source above the ankle also fits well with spectrum and mass composition for B/nG sqrt(L_c/Mpc) ~5-15

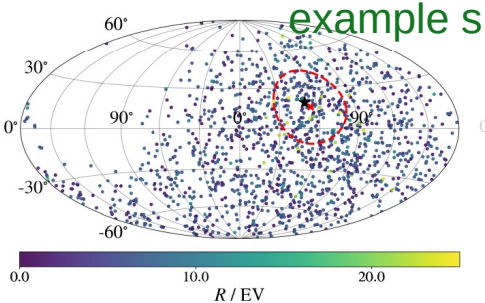


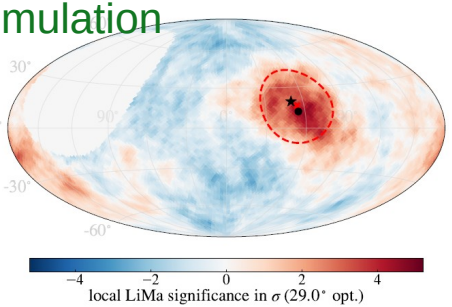
[Mollerach & Roulet 2024]





example simulation





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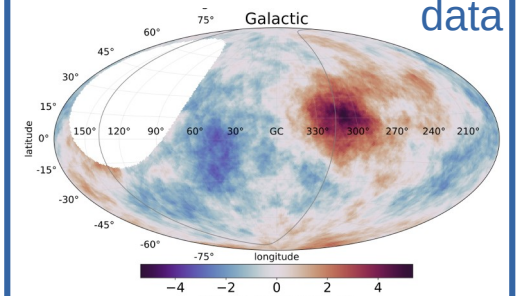
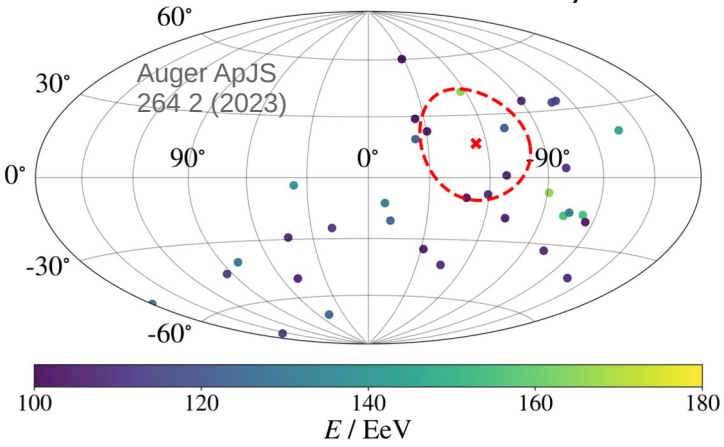
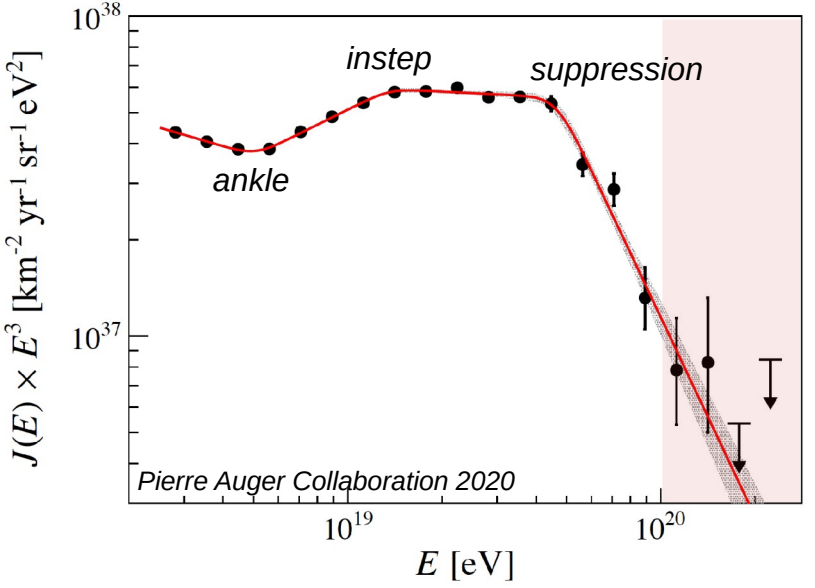


Cen A dominates sky - highest energy events?

measured distribution of events, E>100 EeV



- **unexpectedly isotropic,** do not correlate well with any source candidates after correcting for Galactic magnetic field
  [M. Bianciotto for Auger, ICRC 2025]
  - ➔ transient sources? ultra-heavy elements? BSM physics? ...



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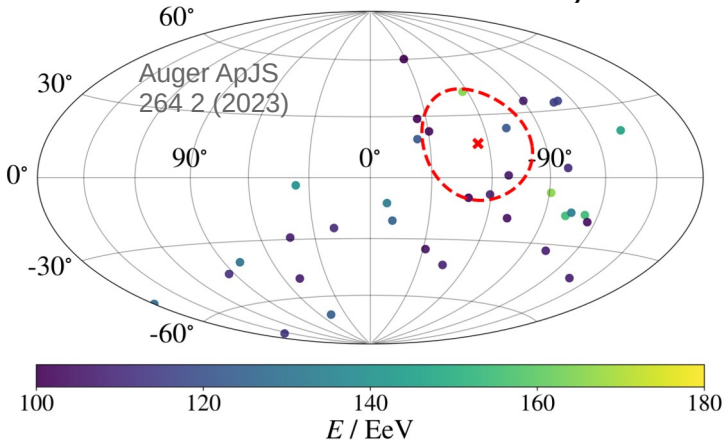
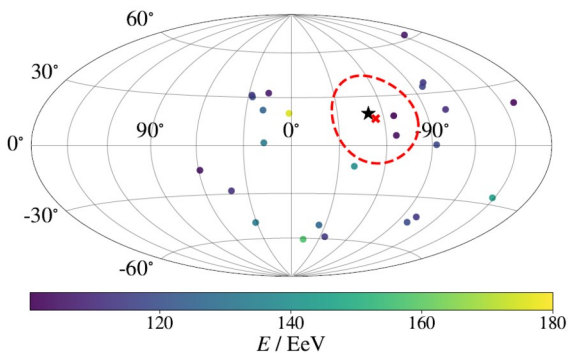
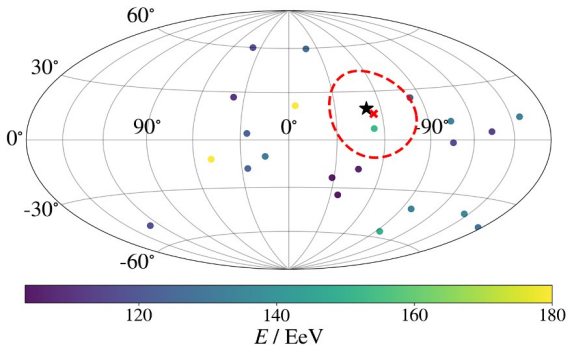
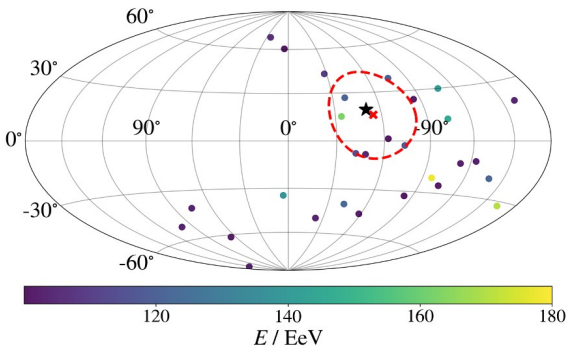


- **unexpectedly isotropic,** do not correlate well with any source candidates after correcting for Galactic magnetic field
  [M. Bianciotto for Auger, ICRC 2025]
  - ➔ transient sources? ultra-heavy elements? BSM physics? ...
- <u>or just one source and very strong local EGMF!</u>



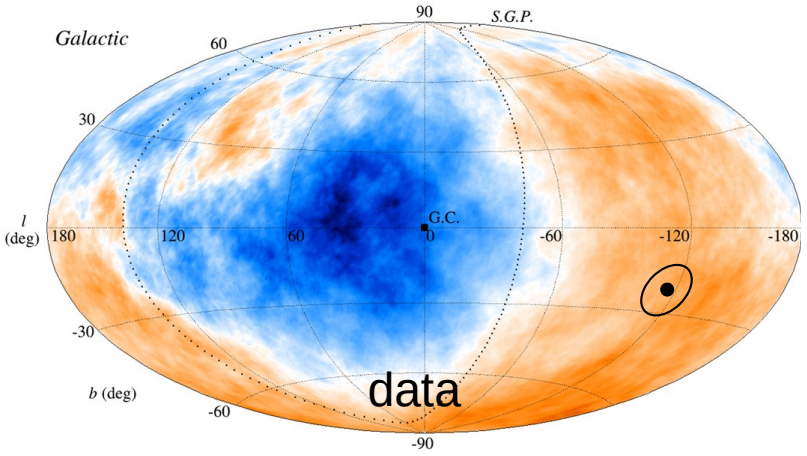




simulated distributions of events with E>100 EeV ✔

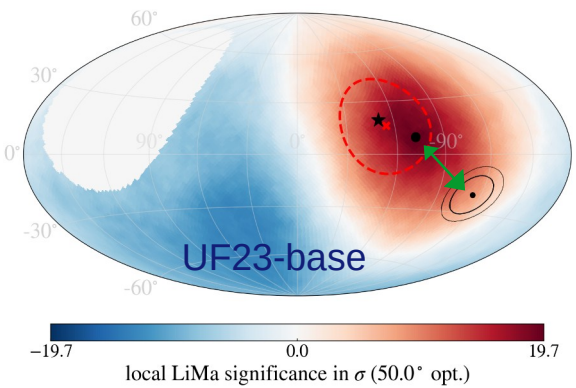
(3 simulations with UF23-base, β_{EGMF}=26, mixed composition)

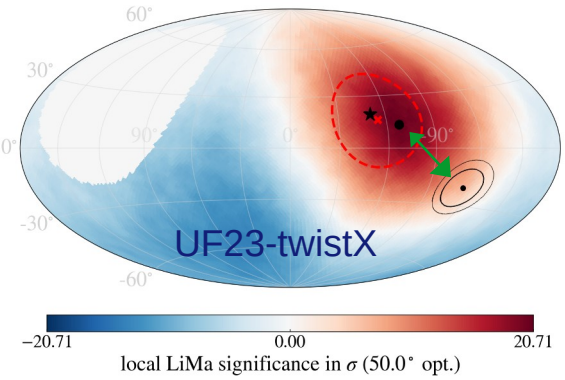
Cen A dominates sky - lower energies and dipole?

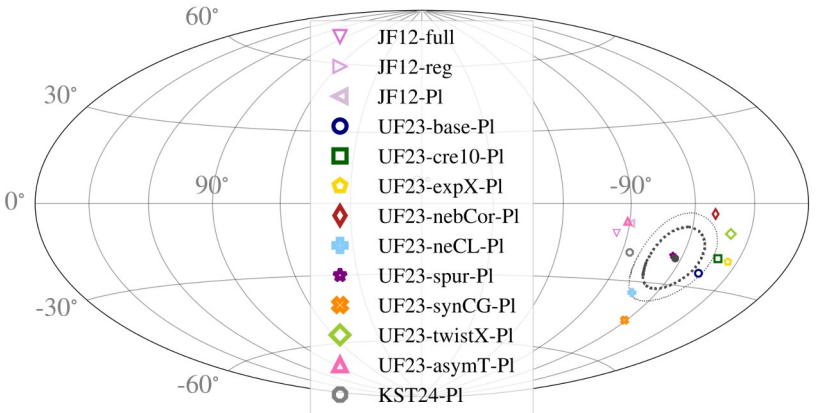


- dipole direction <u>not</u> well reproduced by only Cen A as single source
- **need other sources to explain data <30 EeV**
  - e.g. individual sources in the south (e.g. Fornax A), or following large-scale structure? [Bister & Farrar ApJ 2024]

2 simulations, β_{EGMF}=26, mixed composition:



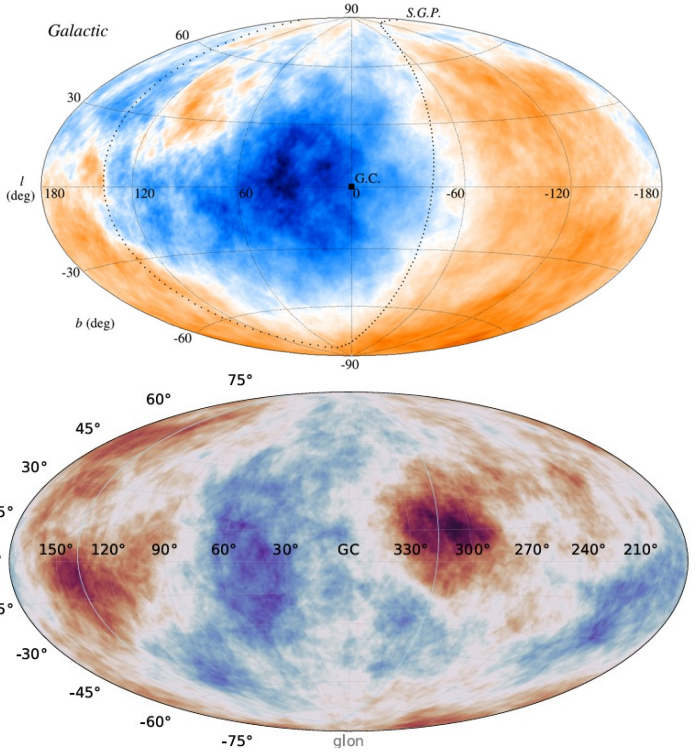




with large-scale-structure based model:
→ dipole direction way better described

What we have learnt about UHECR sources:

1. they are **extragalactic**
2. they emit (possibly after in-source interactions / magnetic confinement)
   a hard spectrum & mixed composition
   that **does not differ much between sources**
3. at $\gtrsim$ 40 EeV nearby sources like Cen A, M83, Sombrero galaxy can explain the **Centaurus excess**
   - need large local extragalactic magnetic field between source and Milky Way to explain excess size
   - Cen A could even have 100% signal fraction $\gtrsim$ 30 EeV
4. at $\gtrsim$ 8 EeV they probably follow the **large-scale structure** & have relatively **large density** $\gtrsim 10^{-5}$ Mpc^{-3}

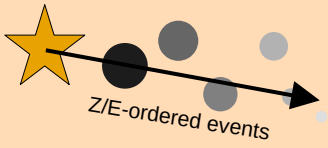


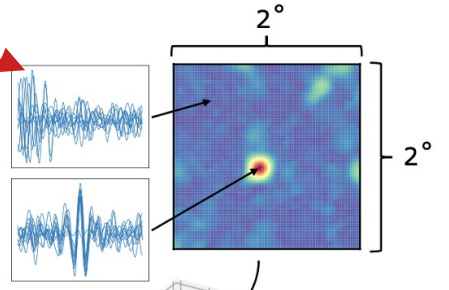
Outlook

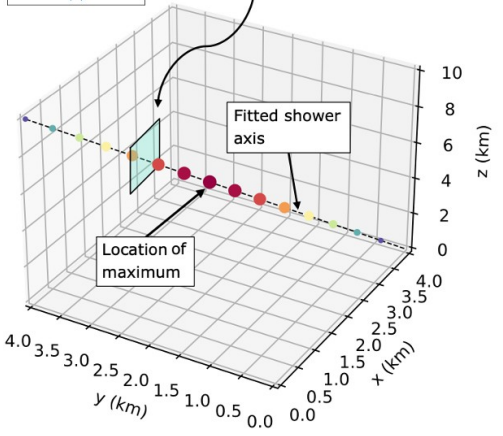
- understanding the mass composition on an event-by-event level soon possible e.g. through:
  - detector upgrade **AugerPrime** (completed last year!)
  - neural networks [Auger PRL 134 2025]
  - **radio interferometry** [through ERC of Harm Schoorlemmer, see Pim's talk earlier]

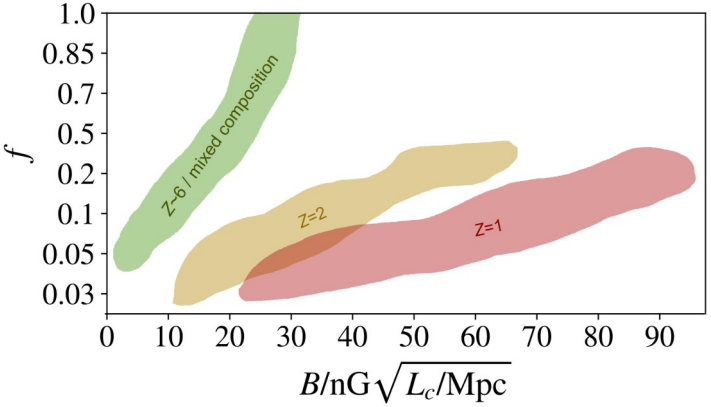
➔ will allow to study charge distribution in interesting regions like Centaurus excess

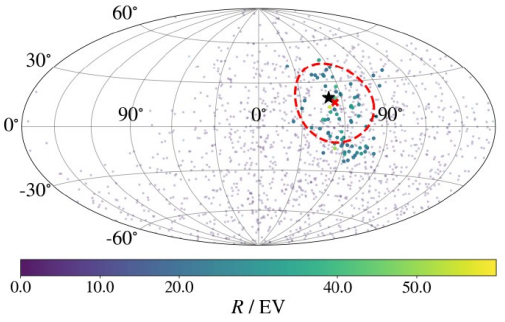
➔ will enable search for orderings in Z / E of individual events to directly reconstruct source direction









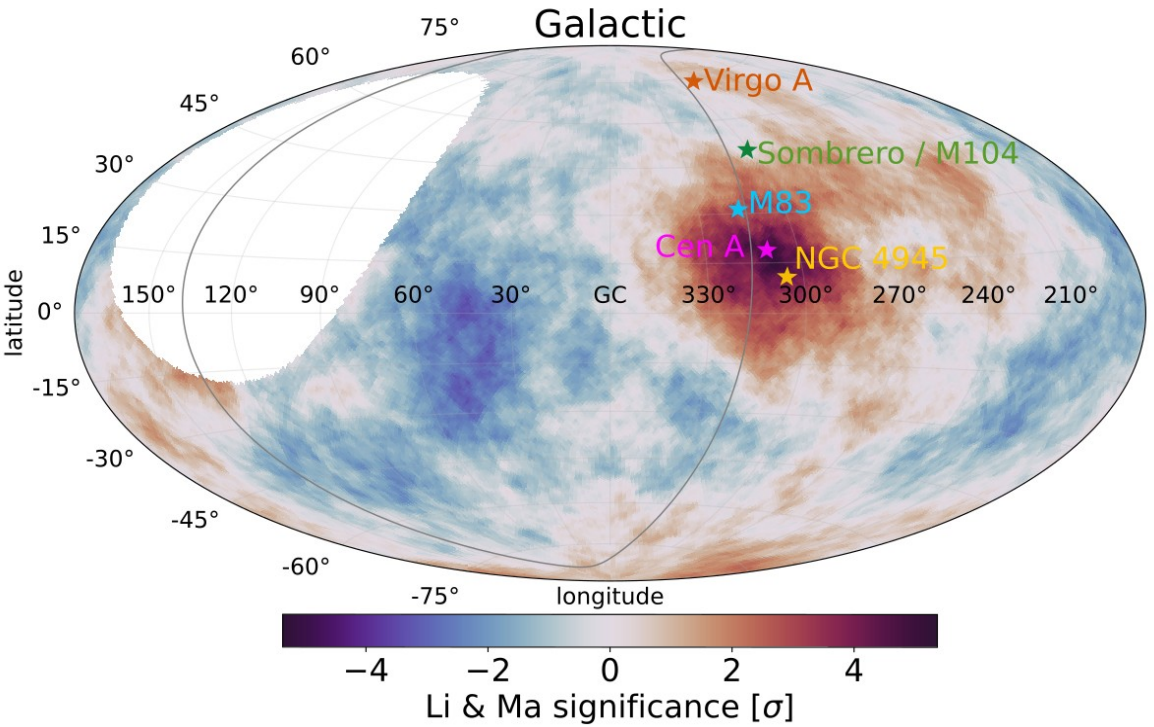


backup

The Centaurus excess

Properties of the excess: [Auger ICRC 2023]

- local significance: 5.1σ for E_{min} = 40 EeV
- angular size: 27° for E_{min} = 40 EeV
- direction: l=305°, b=16°
- **energy dependency:** [Auger ApJ 984 2025]
  - ➔ excess extends to E_{min} = 20 EeV
  - ➔ direction only varies by ~3°
  - ➔ angular size was kept fixed in scan

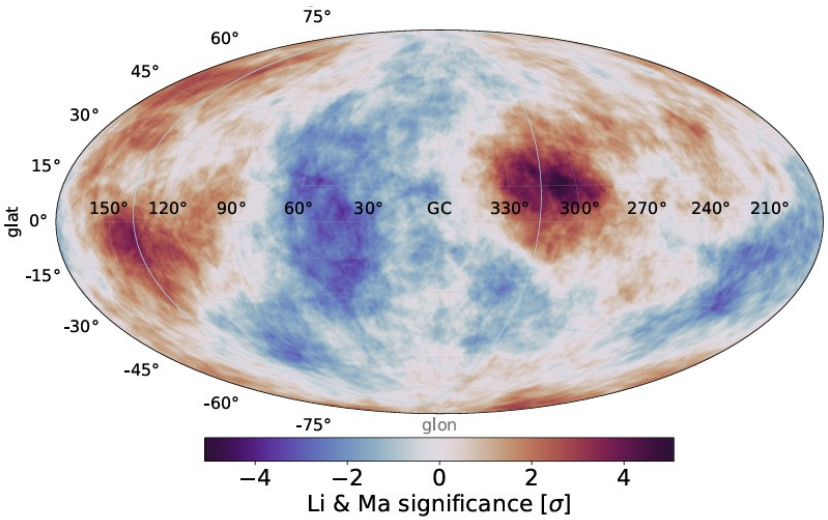


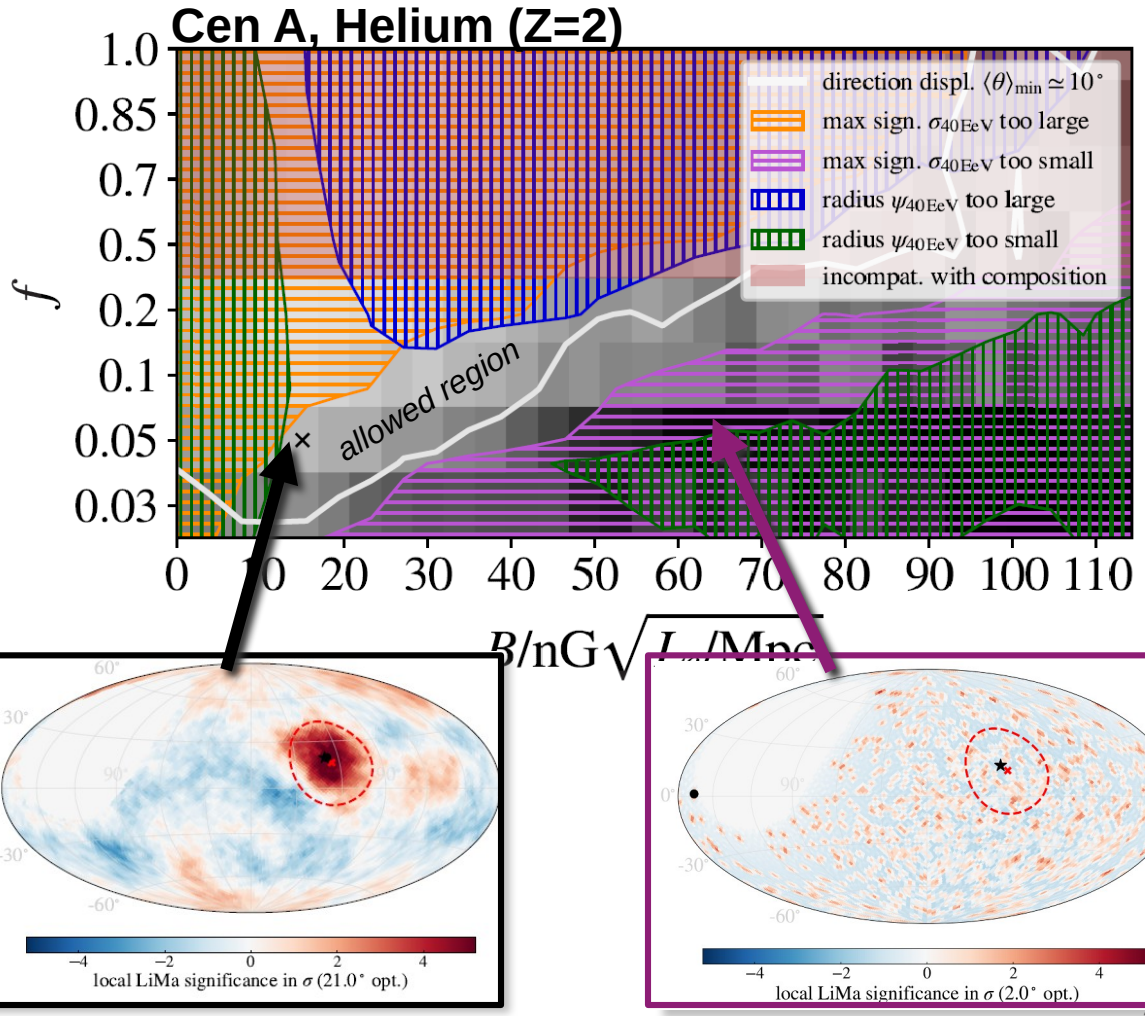
Simulation parameters:

- ➔ Galactic magnetic field
- ➔ charge
- ➔ extragalactic magnetic field
- ➔ signal fraction

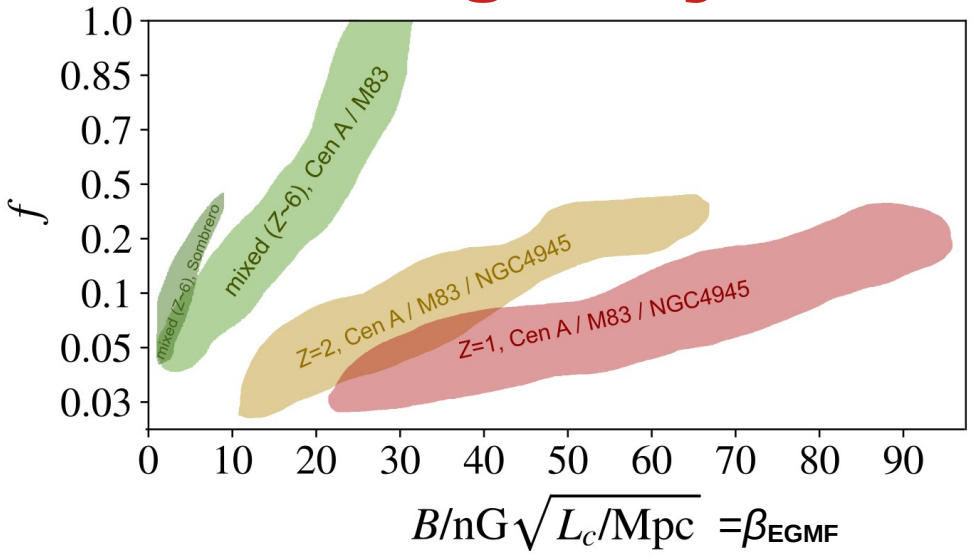
Conditions on signal fraction and EGMF

- for a specific source candidate & charge assumption:
  - ➔ produce 10 random simulations per Galactic magnetic field model
  - ➔ vary signal fraction f and EGMF parameter β_{EGMF}
- apply same analysis as on data and see which ones reproduce excess properties

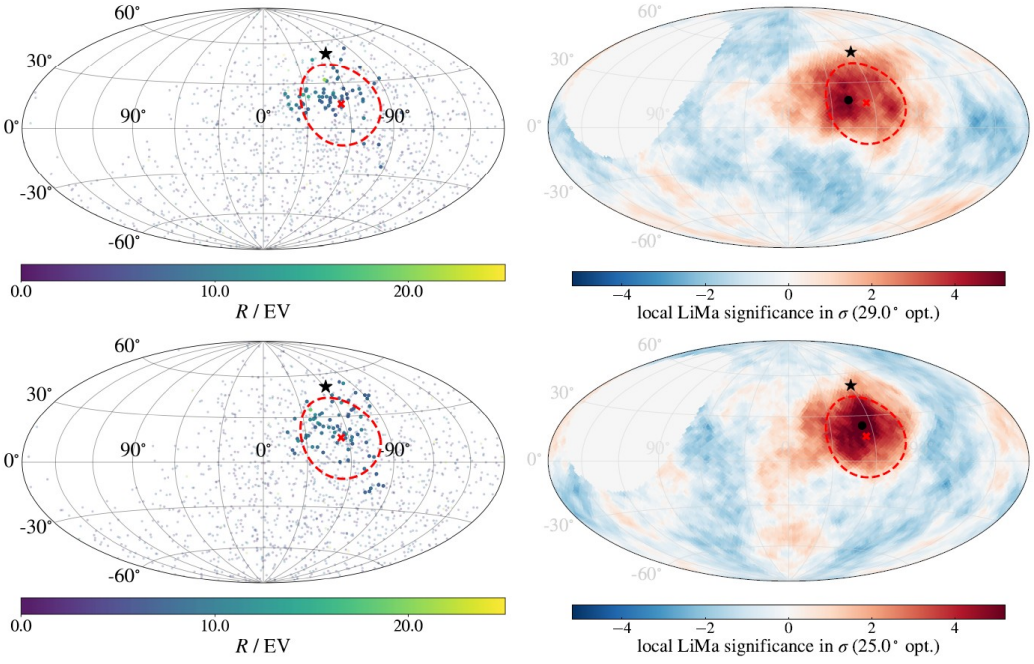




Sombrero galaxy as the source of the Centaurus excess

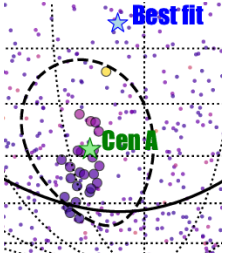


example simulations for E_{min}=40 EeV, UF23-base, Z=6, β_{EGMF}=3

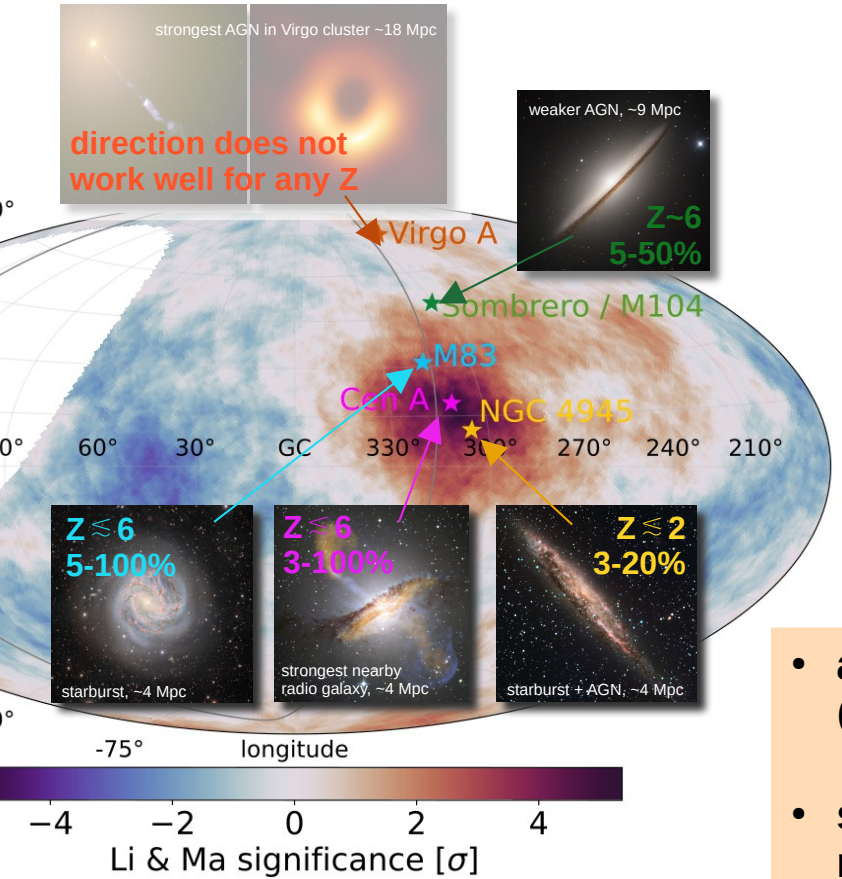


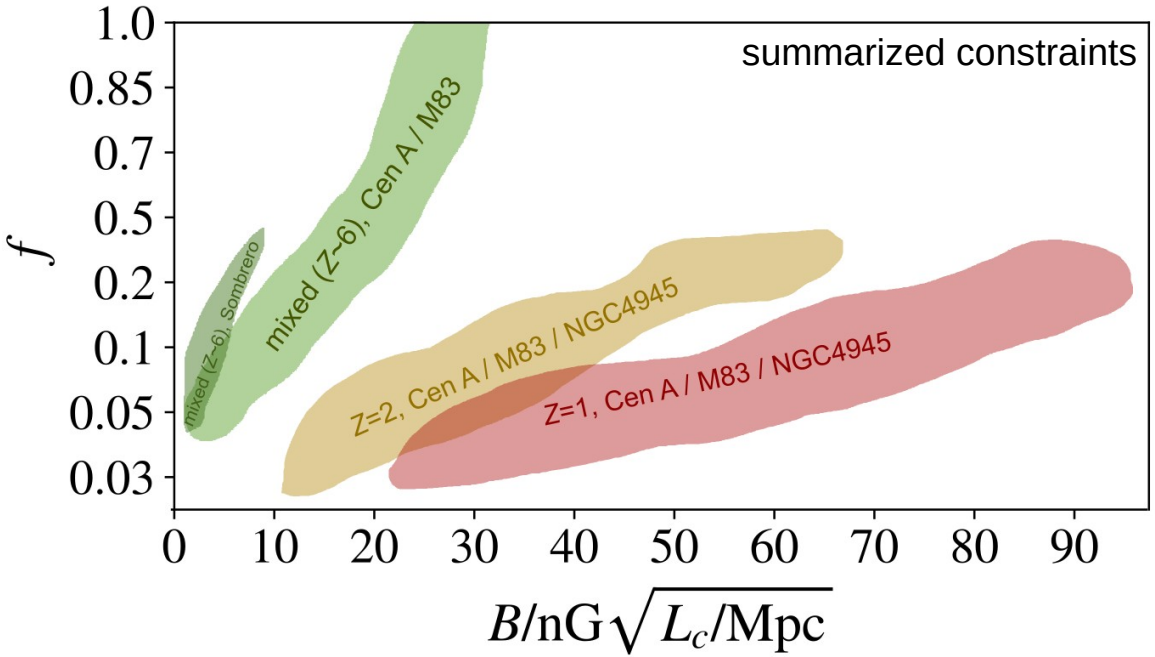
- It is possible to reproduce the Centaurus excess with the Sombrero galaxy for **Z~6, *f*~5-50% ✔**

- but, the EGMF has to be bigger than predicted by [He et al. 2025] to reproduce angular size
  - **β_{EGMF} ~1-10 » 10^{-3}**
  - could improve multiplet method to also capture events further away from the major axis?



Source of the Centaurus region excess





- **always $\beta_{EGMF} > 1$:** realistic between Milky Way and candidates (β_{EGMF} below ~1 in voids, can be » 100 in clusters)
- **sources with very different signal fractions and mass compositions can explain excess**
  - ➔ composition analyses in Centaurus region could differentiate [e.g. L. Apollonio (Auger), ICRC 2025]