Constraints on UHECR sources and extragalactic magnetic fields

from directional anisotropies

Teresa Bister & Glennys Farrar

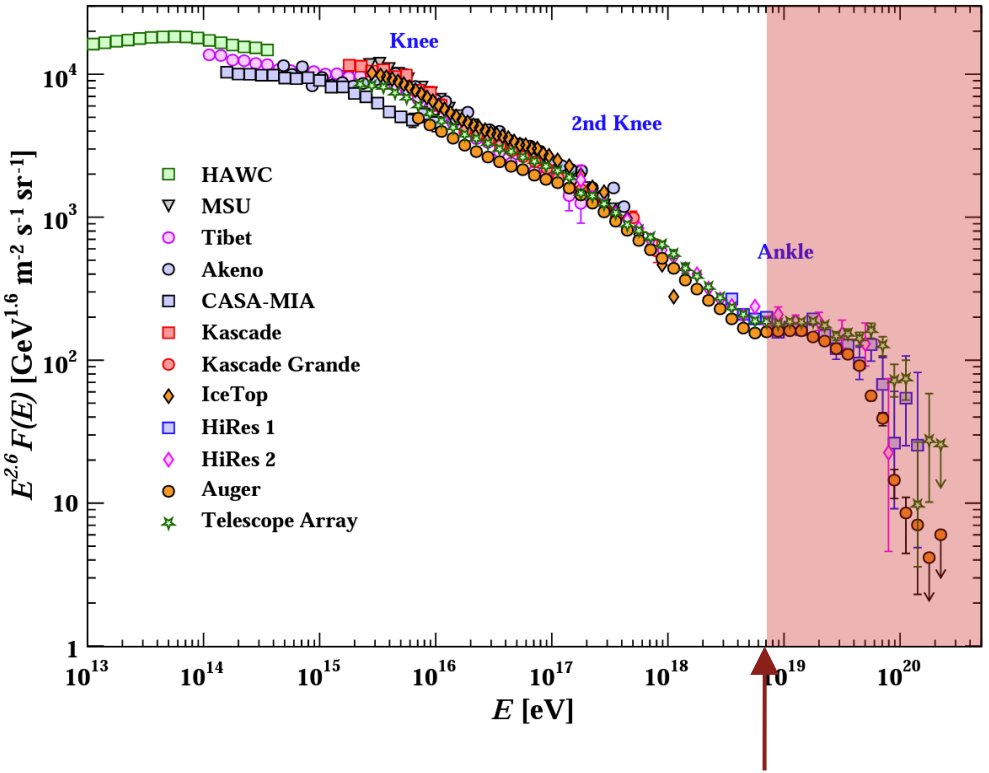
based on ApJ 966 1 (2024)

CRIS-MAC 2024

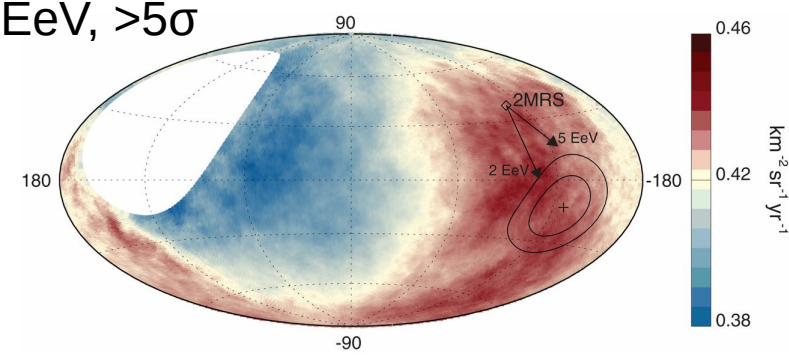
Radboud University

Nikhef

Ultra-high-energy cosmic ray data



dipole > 8 EeV, >5σ

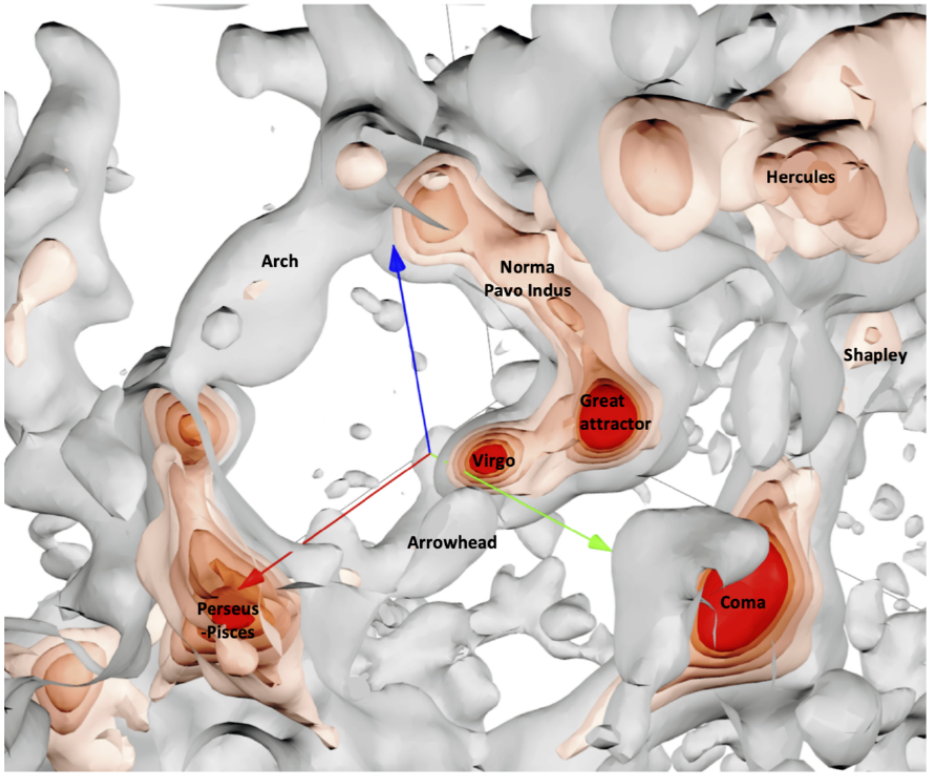


The Pierre Auger Collaboration, Science 2017

- amplitude ~ 7%, rising with the energy
- **no significant quadrupole or higher moments!**
- phase shifts from Galactic center to anticenter

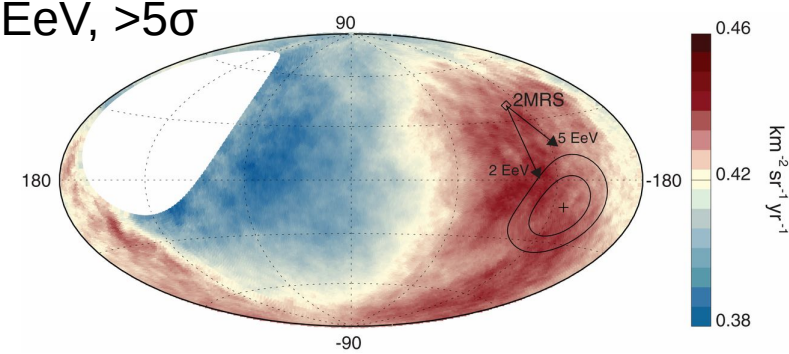
  → **sources extragalactic!**

UHECR flux from Large Scale Structure



extragalactic matter density

dipole > 8 EeV, >5σ



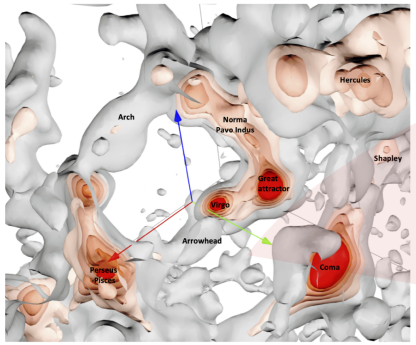
dipole can be explained by extragalactic sources following the **large-scale structure of the universe**

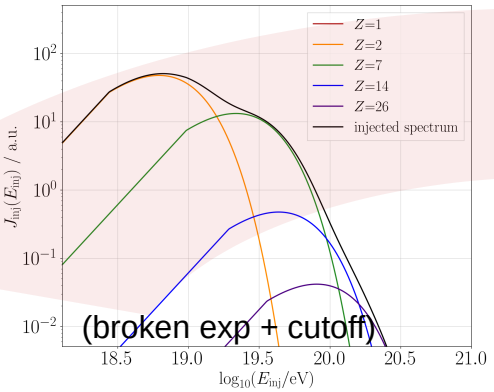
\+ deflection by Galactic magnetic field

[Ding, Globus, Farrar ApJ 2022]

Fit principle

injection following LSS
all sources following **Peters cycle**

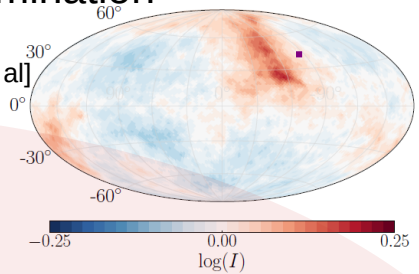




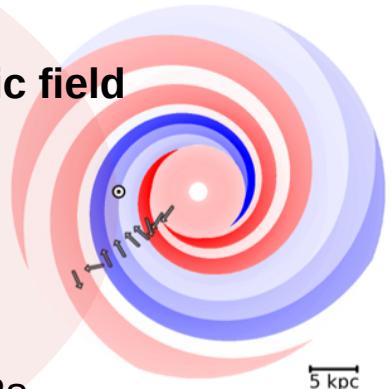
(broken exp + cutoff)

propagation with CRPropa
→ gives illumination

update to [Ding et al]



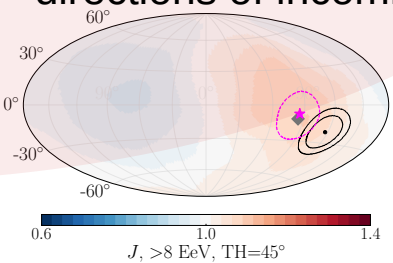
Galactic magnetic field
deflections: JF12



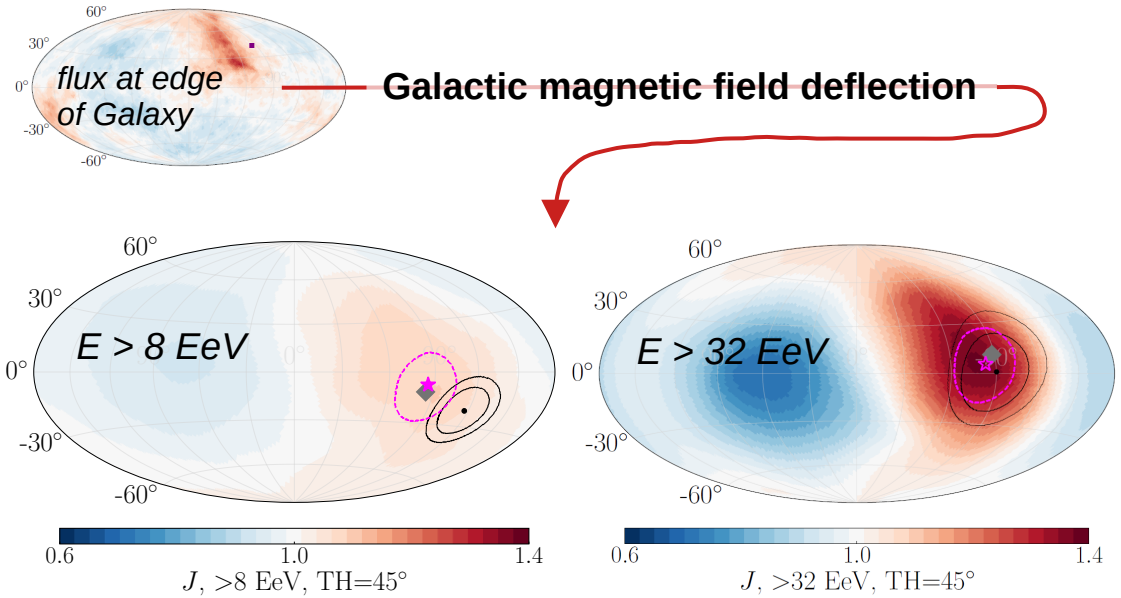
adapt injection, via likelihood:

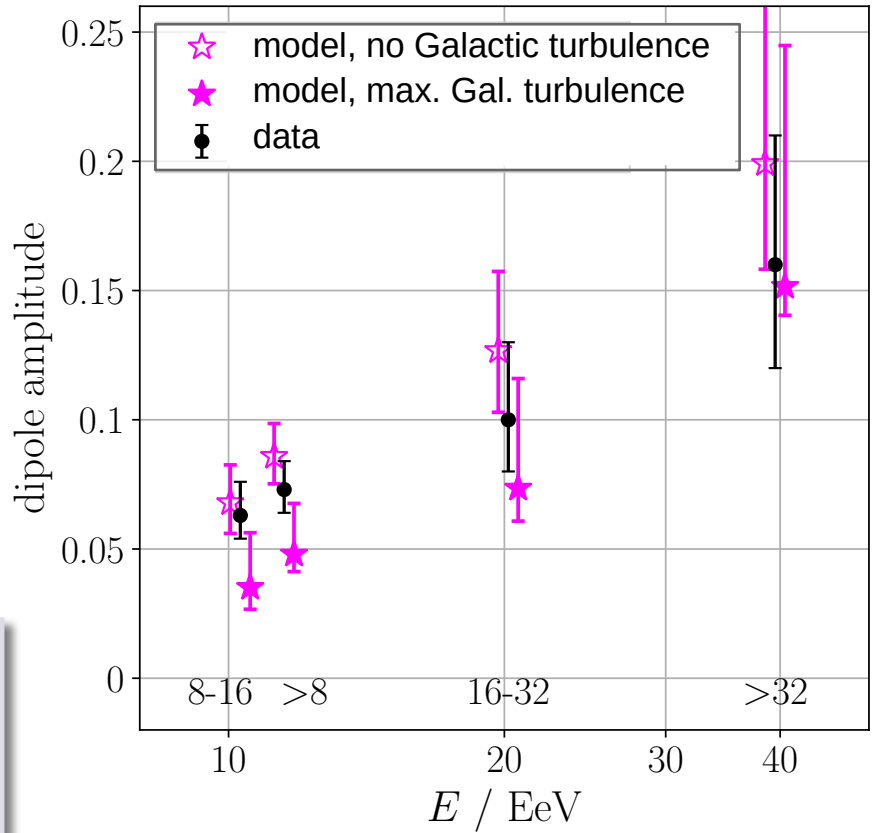
- compare model to data from Pierre Auger Observatory
  - dipole components in 3 E bins
  - energy spectrum
  - mass composition (shower depth distributions)

on Earth: calculate energies, charges + directions of incoming CRs



Measurements at Earth (after Galactic magnetic field)

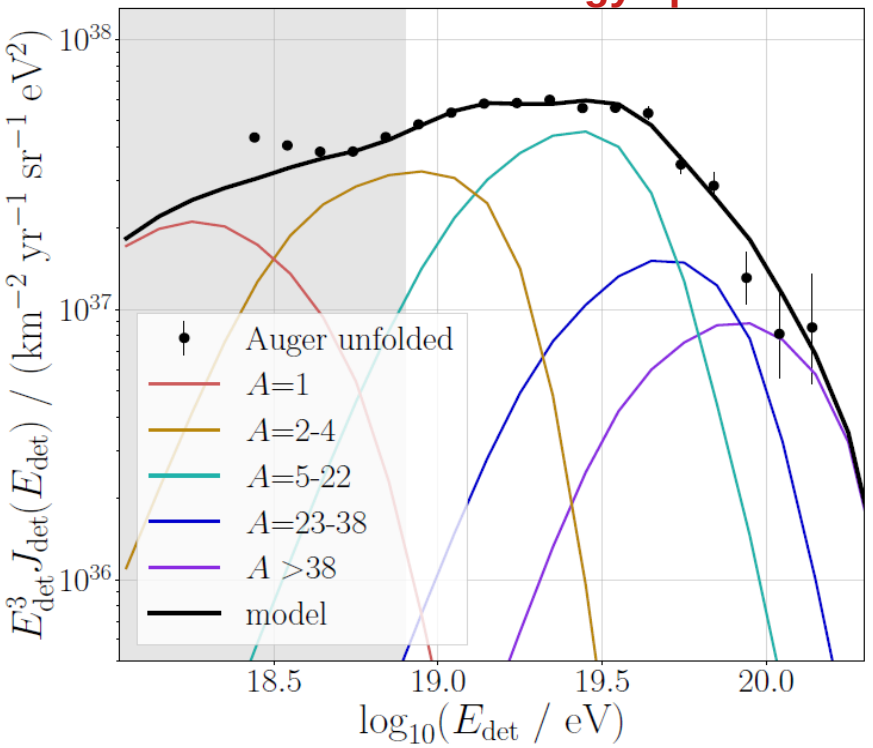




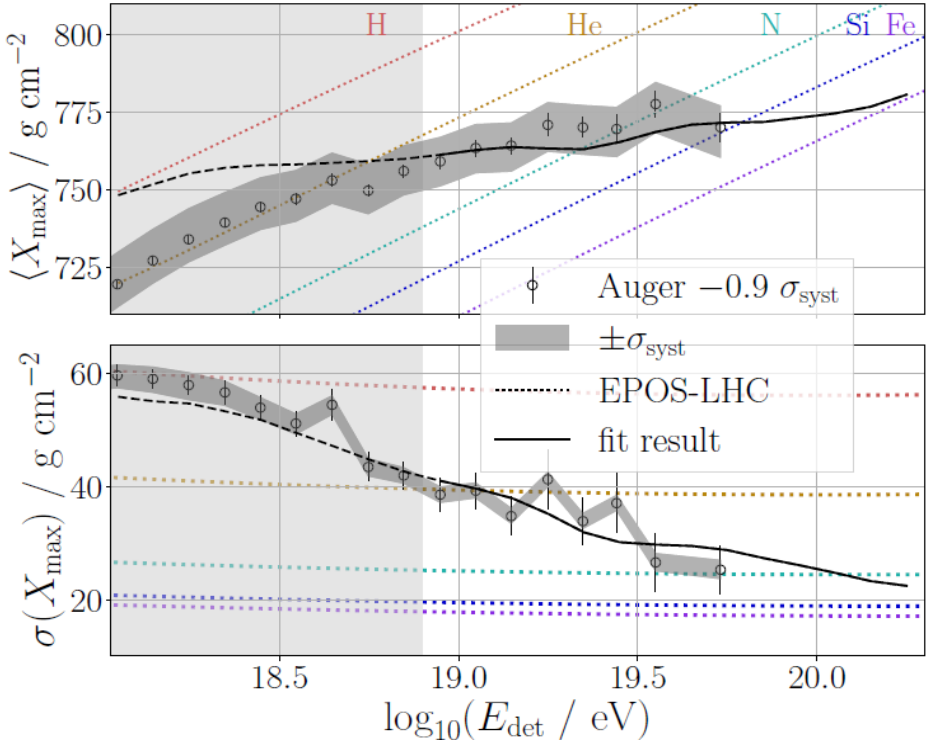
- **dipole amplitude + energy evolution** ✓
- **dipole direction not perfect** at lower energy
  → update of GMF model [Unger & Farrar 2024]

Measurements at Earth (after Galactic magnetic field)

energy spectrum ✔



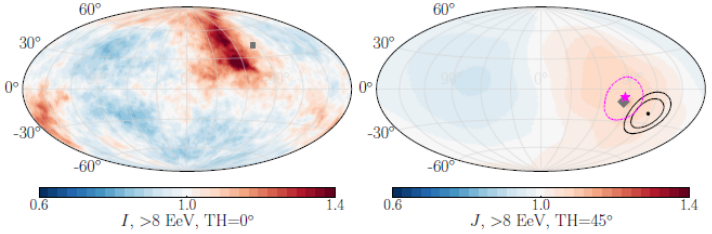
mass composition ✔



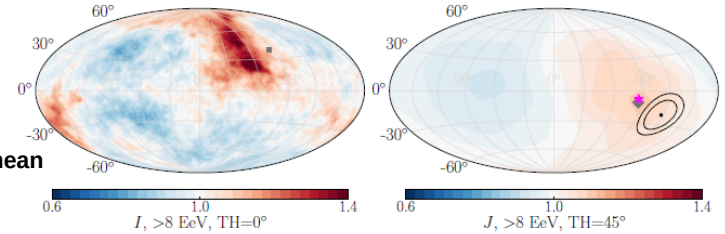
LSS model can describe spectrum, composition and arrival directions. What else can we learn…?

Bias between matter density and UHECR sources

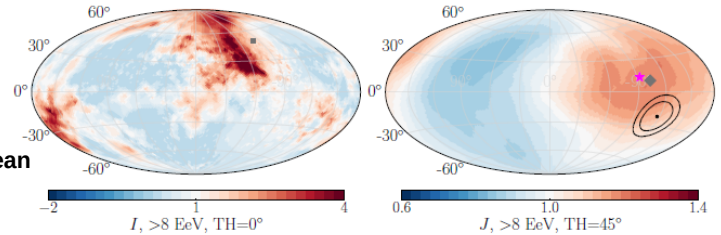
no cut



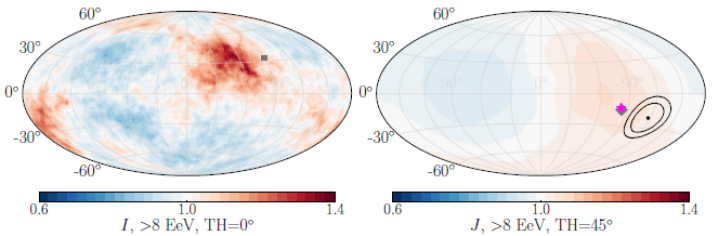
cut
< 0.5 ρ_{mean}



cut
< 1.5 ρ_{mean}

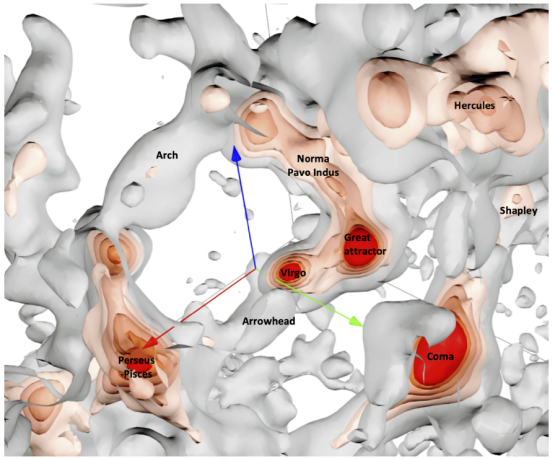


cut
> 4 ρ_{mean}

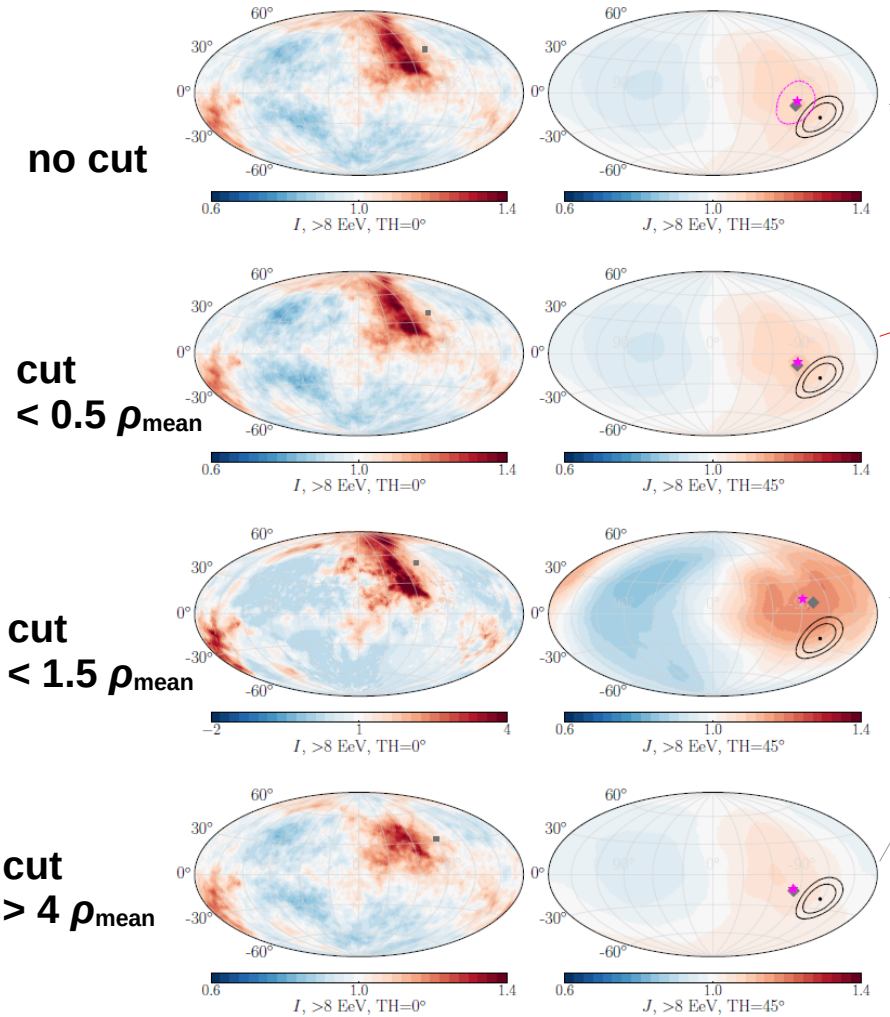


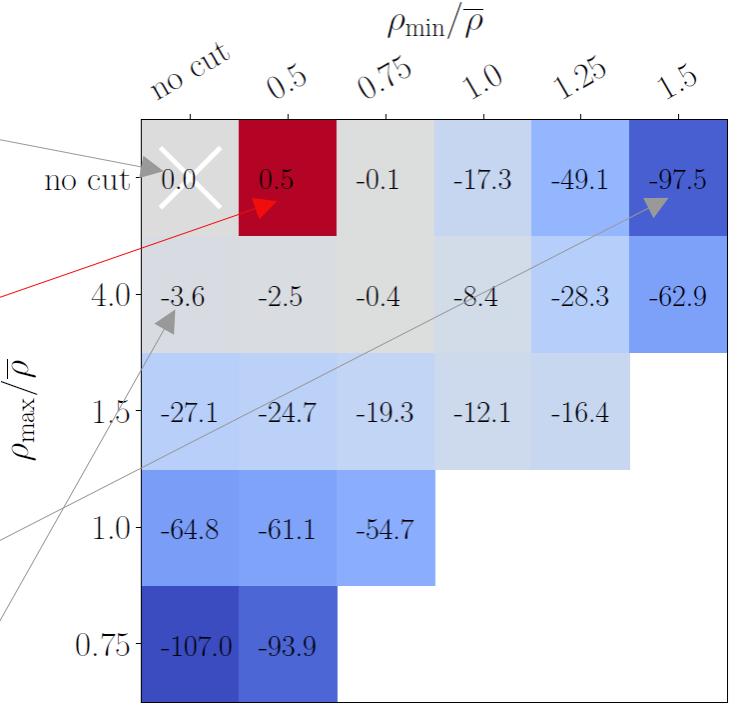
*Is there a **bias** between the UHECR source distribution and the (dark) matter distribution / LSS?*

→ simple test:
cut away densest / least dense regions of LSS



Bias between matter density and UHECR sources





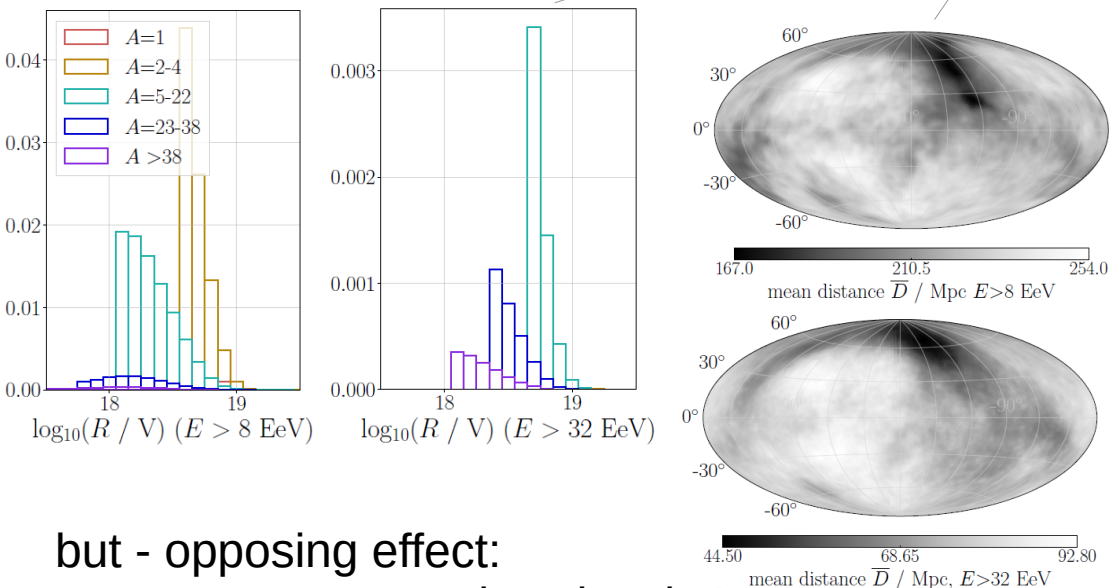
color: likelihood

- sources in matter-dense and average regions, no definite conclusion on low-density regions
- **(dark) matter density (almost) unbiased proxy for UHECR source density**

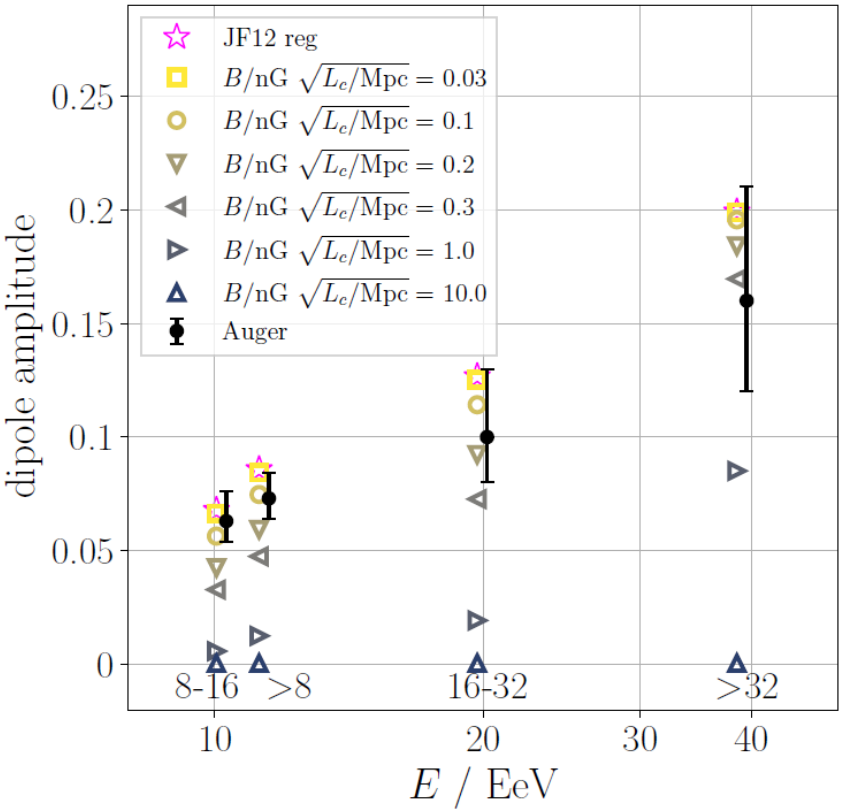
Extragalactic magnetic field effect?

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

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

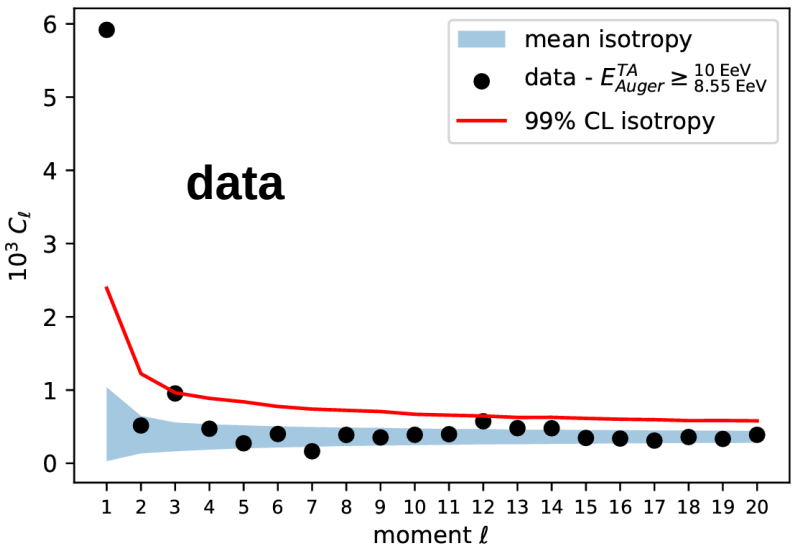


but - opposing effect:
sparser source number density!

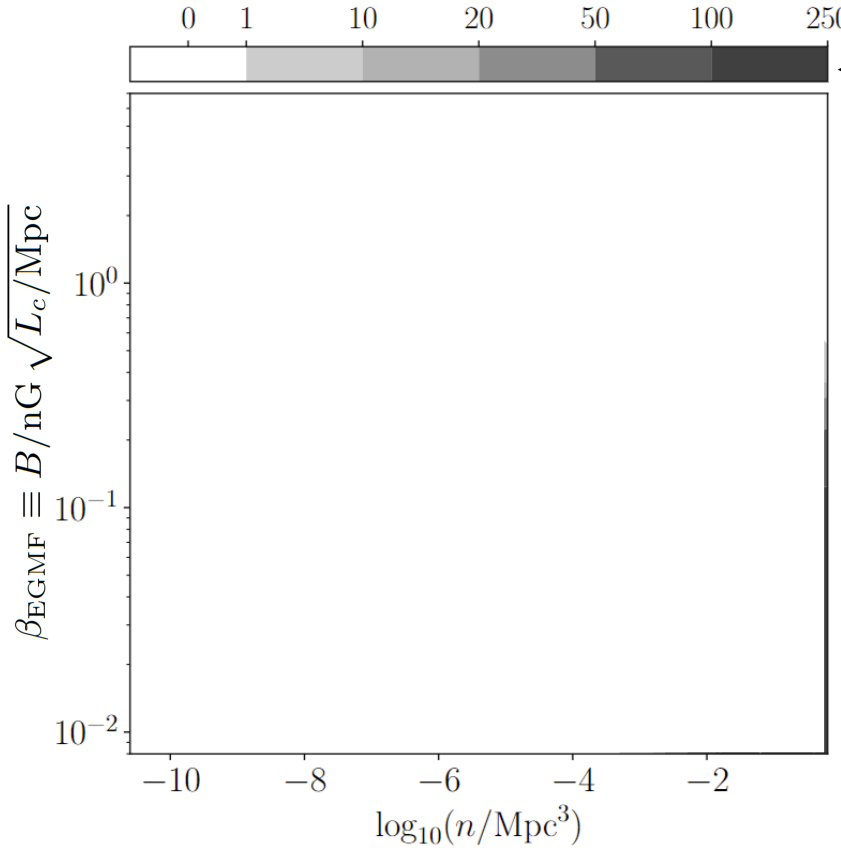


Source density and extragalactic magnetic field

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



Source density and extragalactic magnetic field



extragalactic magnetic field

source number density

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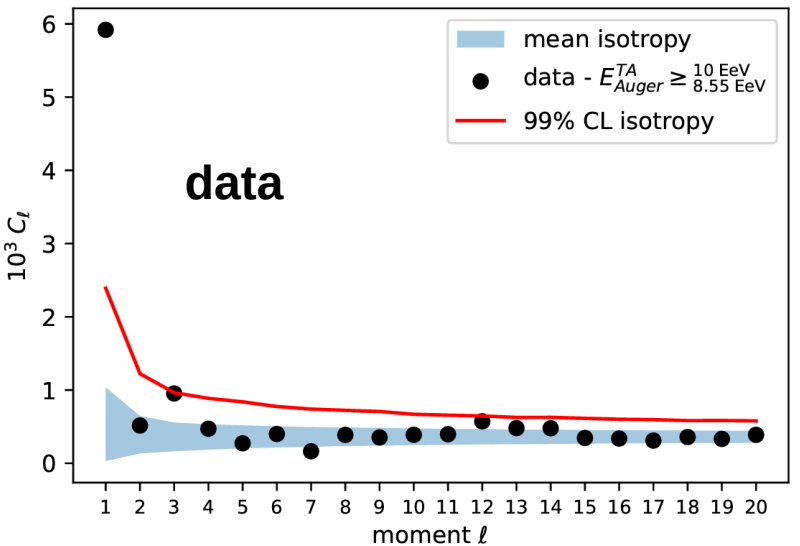
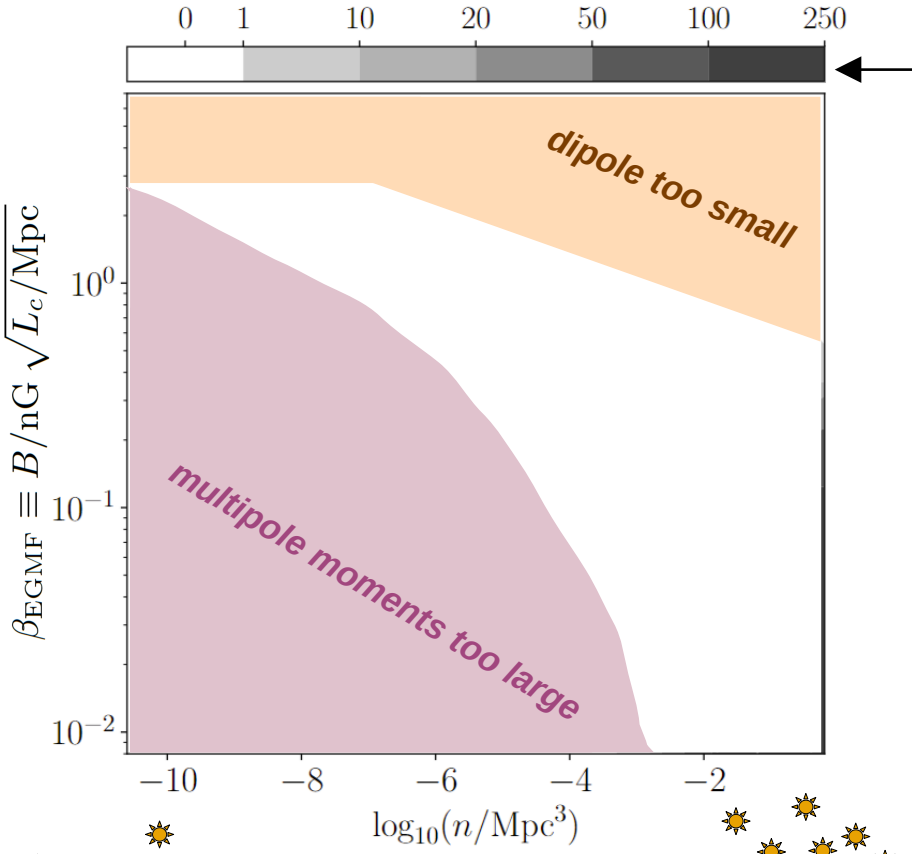
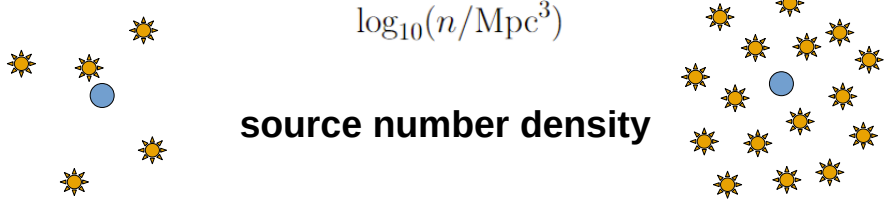


Source density and extragalactic magnetic field

extragalactic magnetic field





source number density

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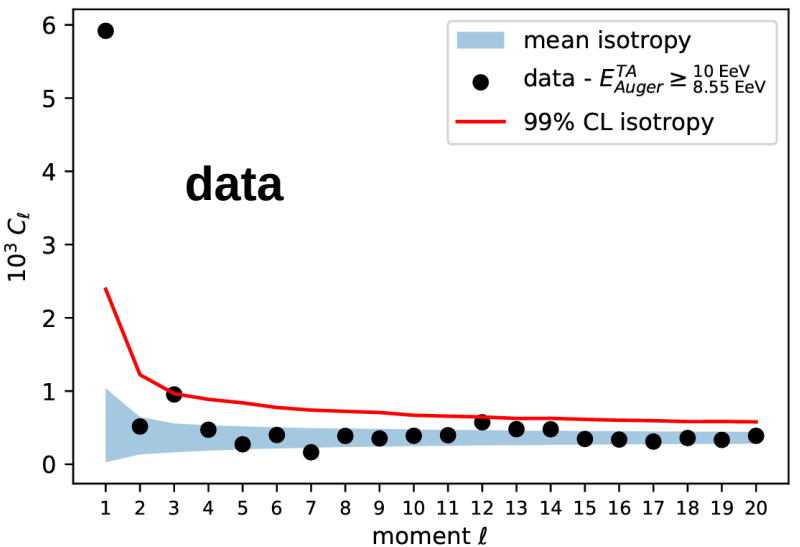
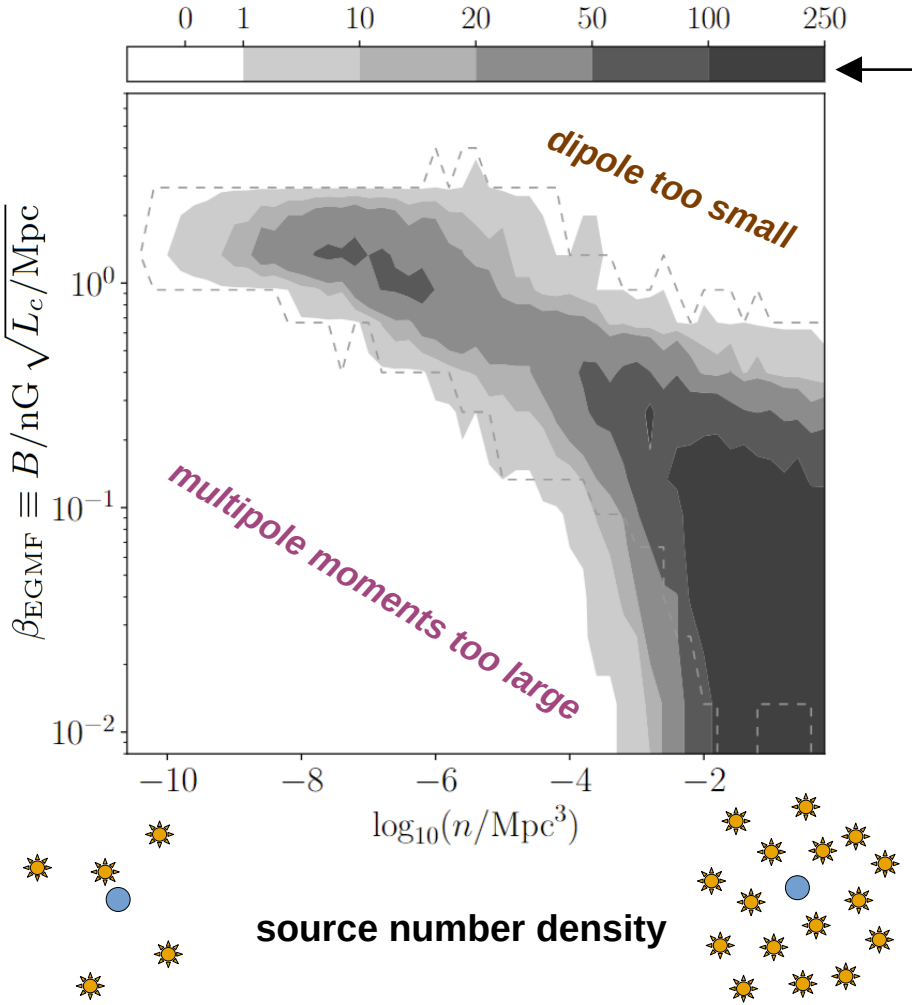


Source density and extragalactic magnetic field

extragalactic magnetic field



source number density

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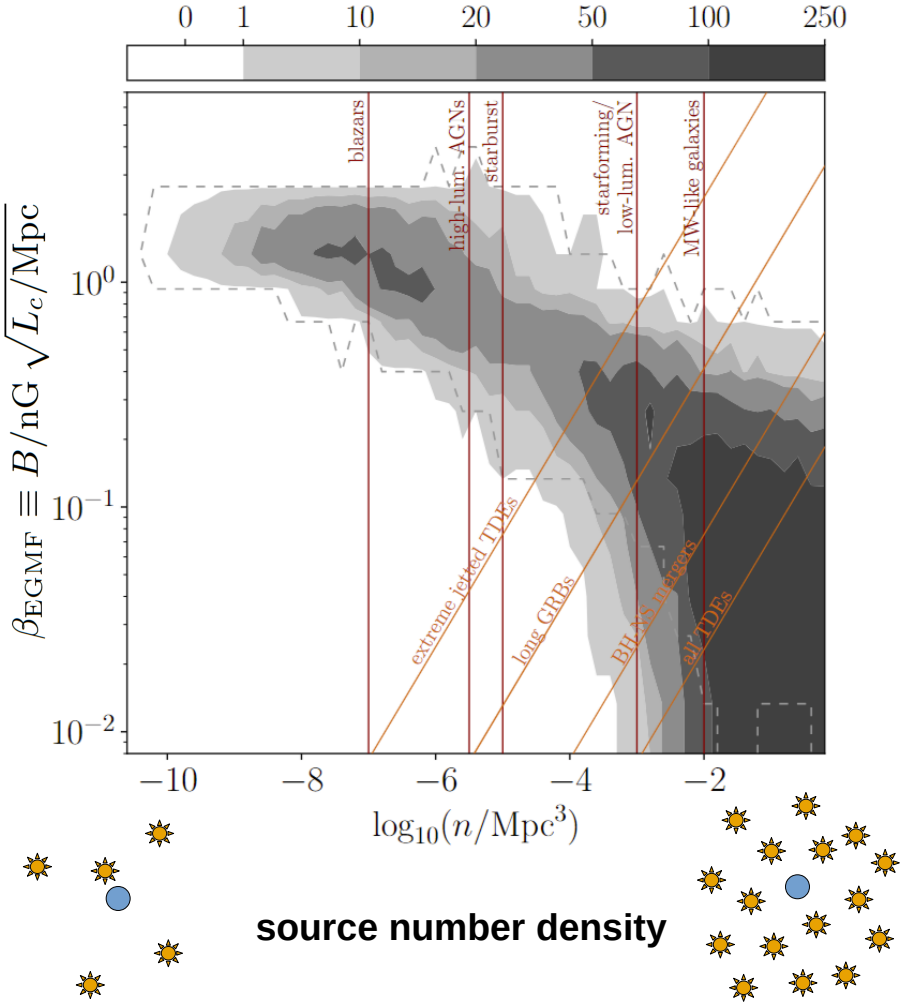
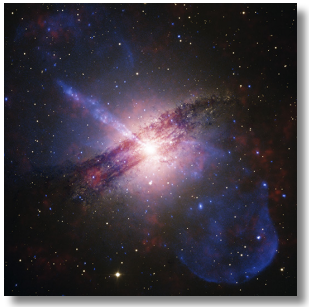
Source density and extragalactic magnetic field

extragalactic magnetic field

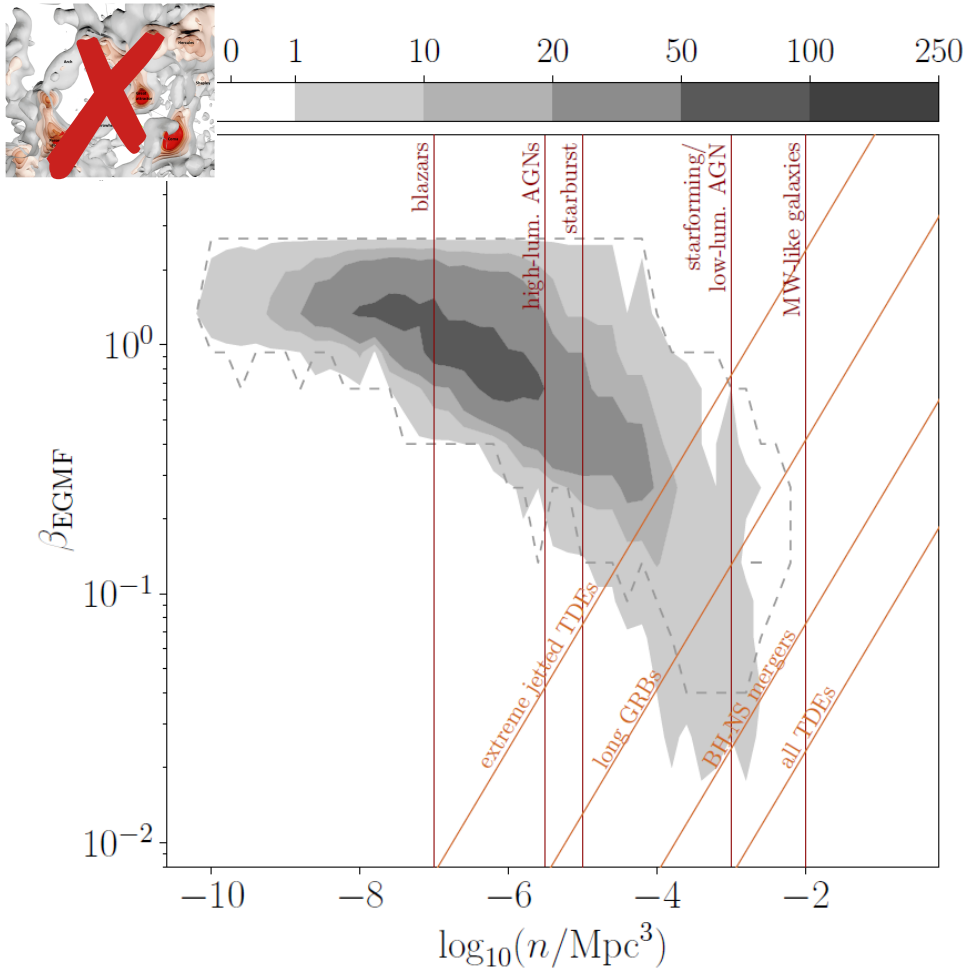


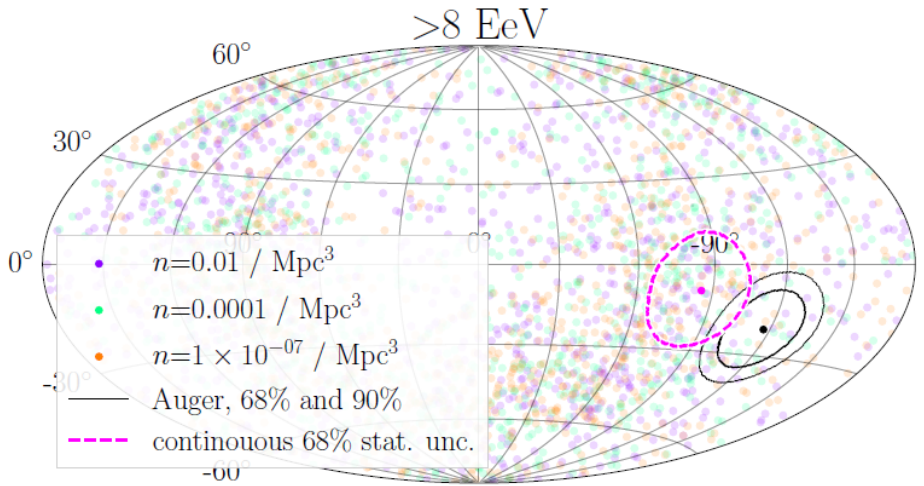
source number density

- **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



Homogeneous source distribution?





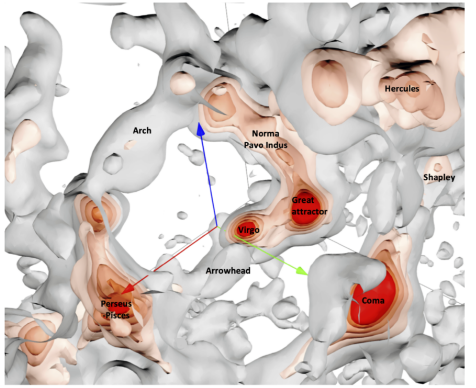
- homogeneous distribution less likely, only for rare sources and considerable EGMF
- dipole direction not predictable

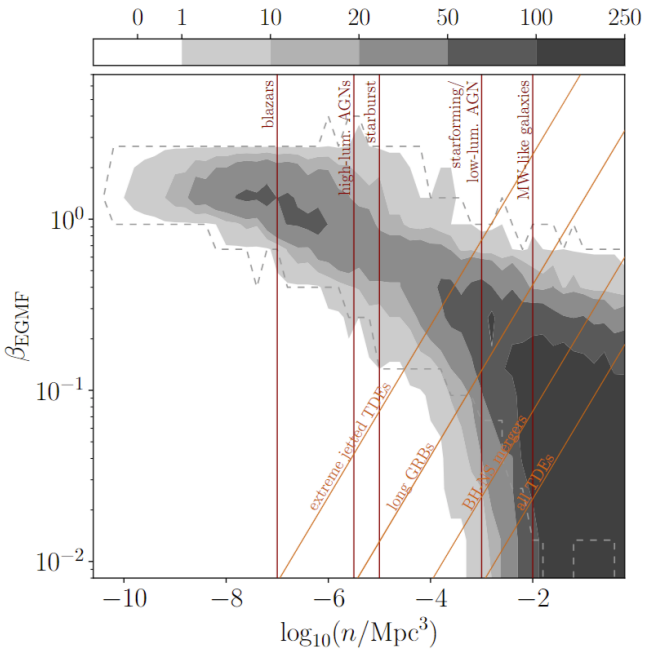
Conclusions

- **sources of UHECRs most likely follow LSS**
  - can describe dipole and absence of higher multipoles
  - LSS bias-free estimator for UHECR source distribution

- placed combined constraints on **extragalactic magnetic field & source number density**
  - if EGMF negligible: sources common with $n>10^{-3.5}$ Mpc^{-3} → blazars, SBGs etc too sparse

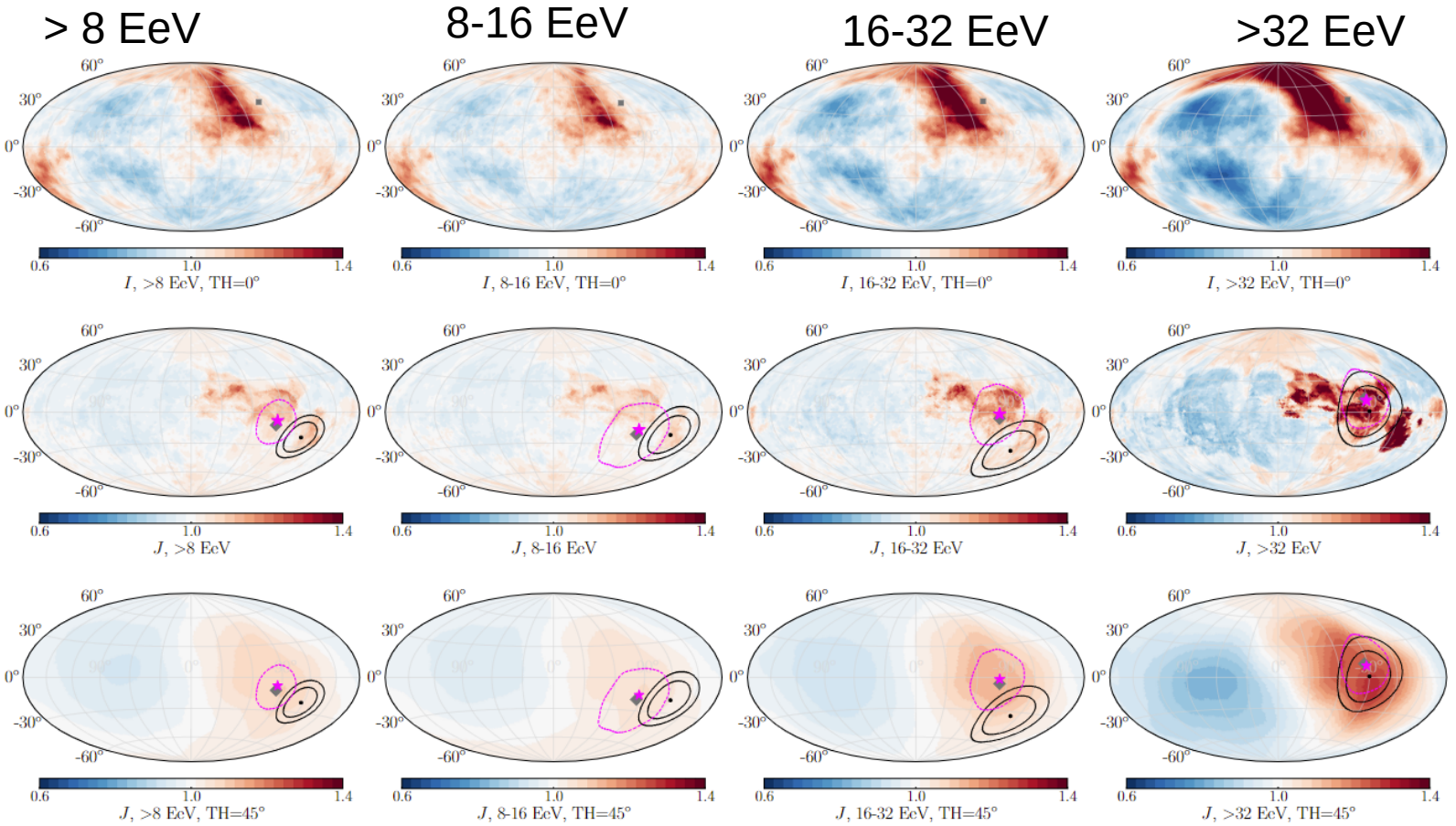
- caution: results dependent on model for the Galactic magnetic field
  - analysis will soon be updated with **new GMF models** [Unger & Farrar 2024]





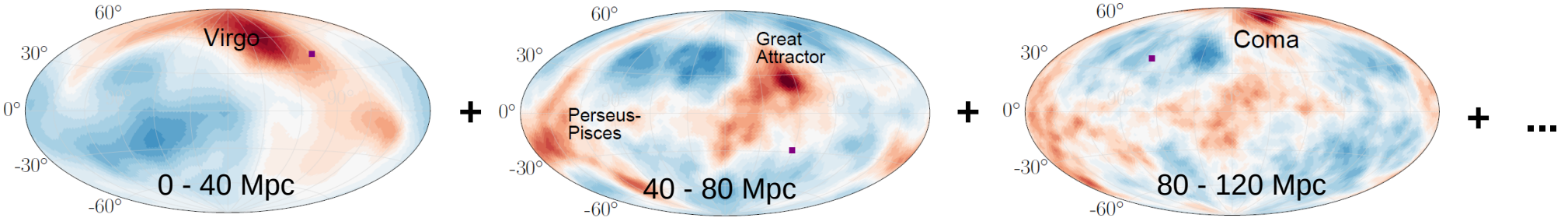
Backup

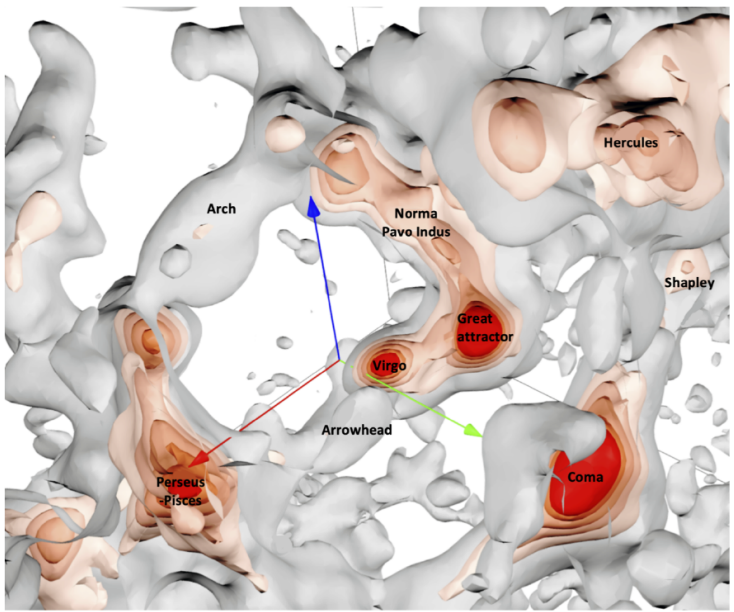
Dipole direction predictions

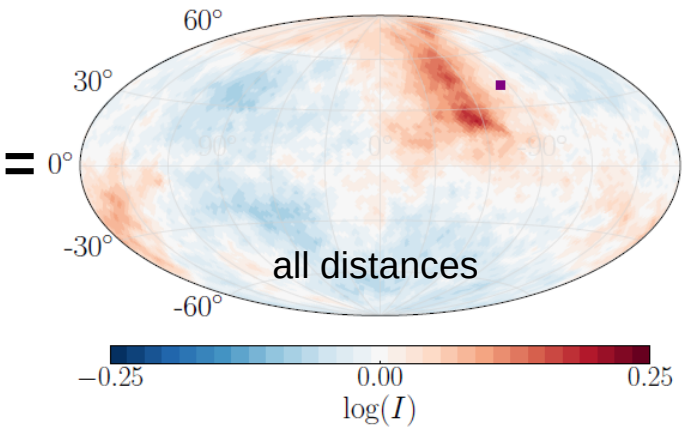


dipole direction at lower energies not perfect (GMF update?)

UHECR flux from Large Scale Structure







expected flux at the edge of our Galaxy

„illumination“