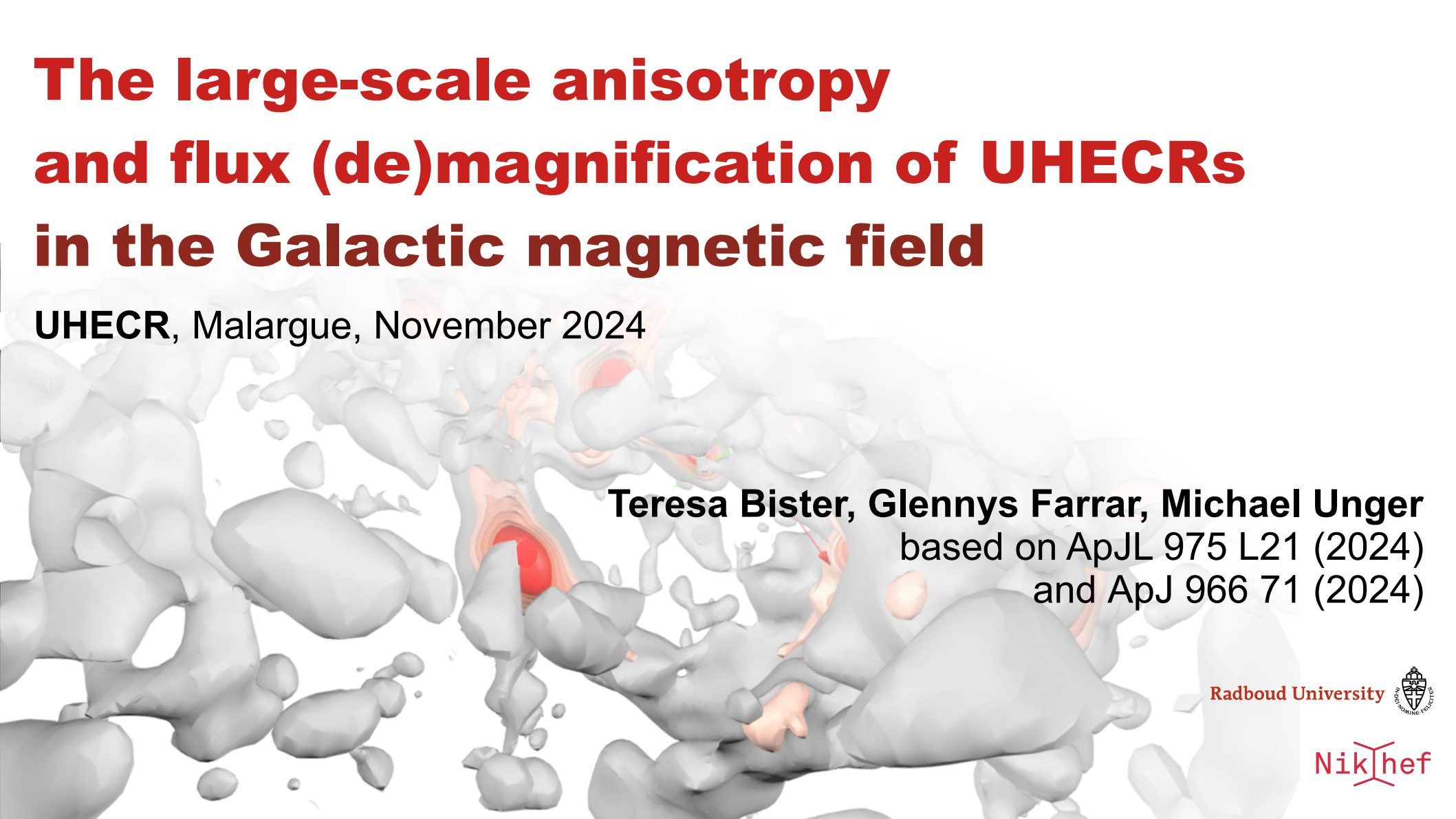
# The large-scale anisotropy and flux (de)magnification of UHECRs in the Galactic magnetic field

**UHECR**, Malargue, November 2024



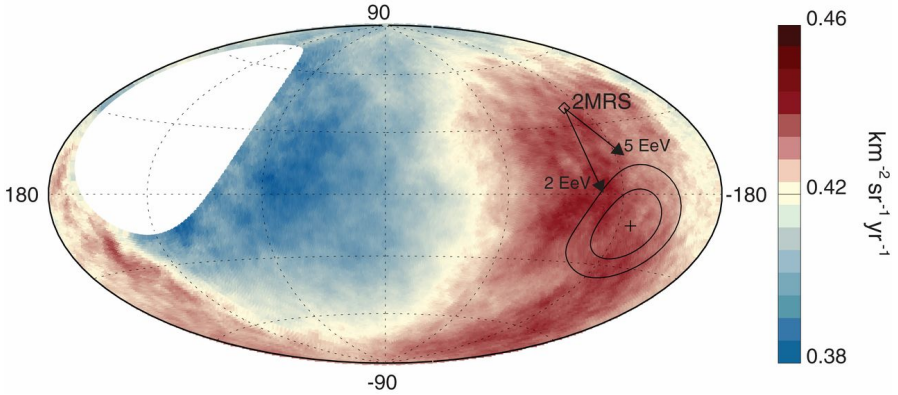
**Teresa Bister, Glennys Farrar, Michael Unger**

based on ApJL 975 L21 (2024)
and ApJ 966 71 (2024)

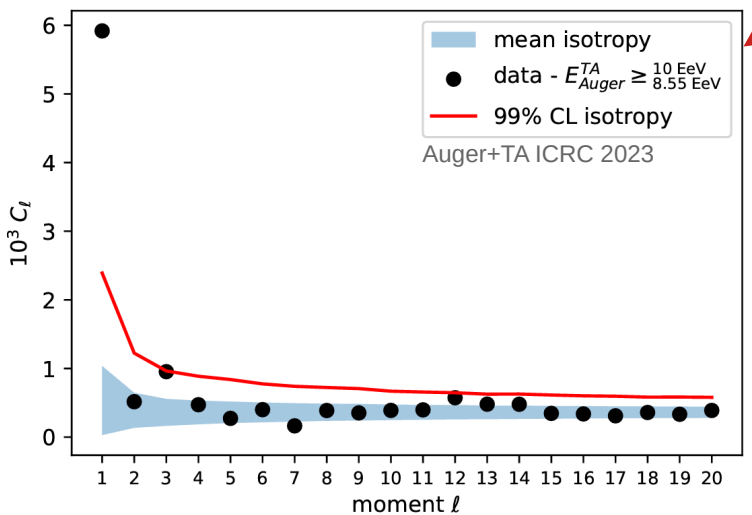
Radboud University

Nikhef

# UHECR large-scale anisotropies




The Pierre Auger Collaboration, Science 2017




**large-scale anisotropy at E > 8 EeV:**

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

➔ **can be explained by:**

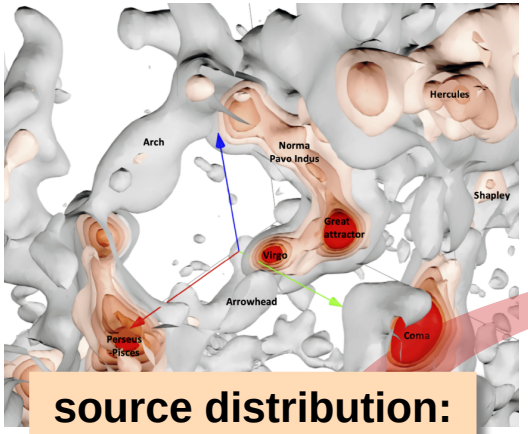
➔ extragalactic sources following the LSS

➔ plus deflection by **Galactic magnetic field**

see e.g.:

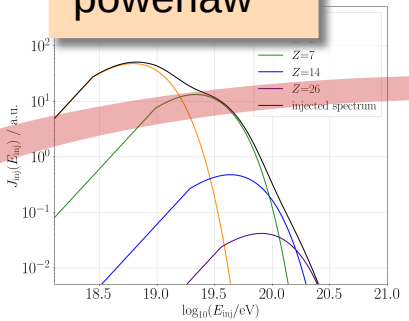

Mollerach & Roulet 2015, Phys. Rev. D, 92, 06301 (2015)
Tinyakov, & Urban, J. Exp. Theor. Phys., 120, 533 (2015)
Globus & Piran, ApJL, 850, L25 (2017)
Globus, Piran, Hoffman, Carlesi, Pomarede MNRAS 484 (2019)
Ding, Globus, Farrar ApJL 913 L13 (2021)
Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)
The Pierre Auger Collaboration, arXiv:2408.05292
Bister & Farrar ApJ 966 71 (2024)
Bister, Farrar, Unger ApJL 975 L21 (2024)

# The LSS model and fit to the data

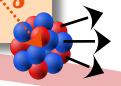



**source distribution:**
following LSS from CosmicFlows

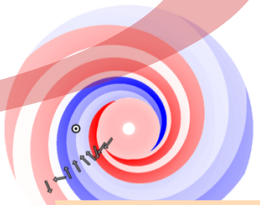
**injection:**
broken-exp. powerlaw



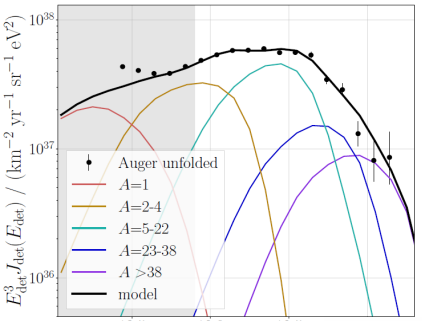

**propagation:**
CRPropa

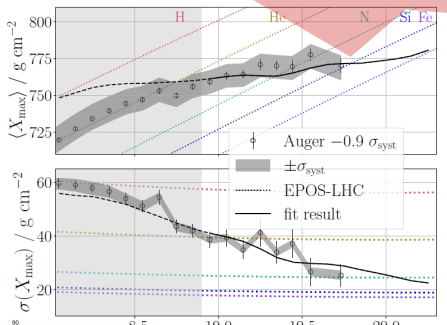


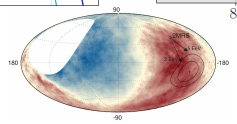

**extragalactic magnetic field:**
neglected /
turbulent approximation



**Galactic magnetic field:**
JF12 & UF23 models



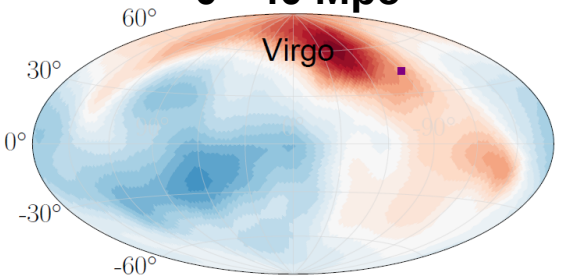



**likelihood fit, E>8 EeV**

- energy spectrum
- mass composition
  Xmax distr. + scale uncertainty
- dipole moments
  8-16 EeV, 16-32 EeV, >32 EeV

# UHECR flux from the Large Scale Structure

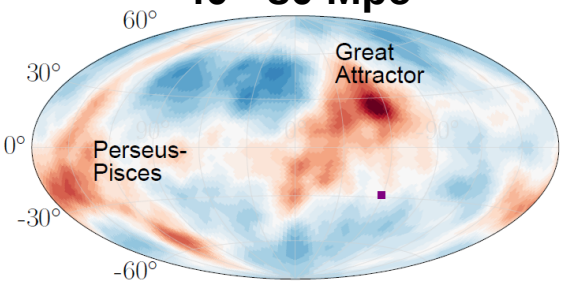
**0 - 40 Mpc**




~10% of flux >8 EeV
~40% of flux >32 EeV

+

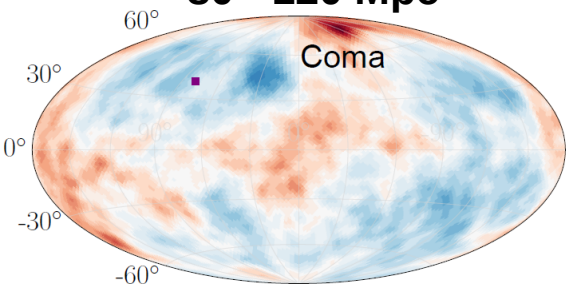
**40 - 80 Mpc**




~10% of flux >8 EeV
~20% of flux >32 EeV

+

**80 - 120 Mpc**

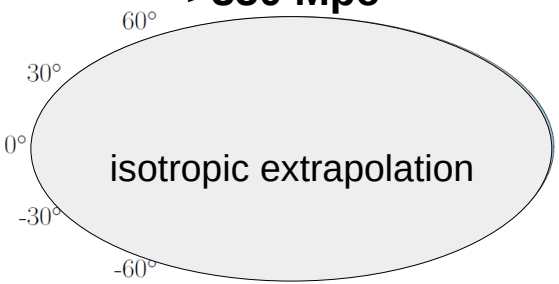



~8% of flux >8 EeV
~15% of flux >32 EeV

+ ...

+

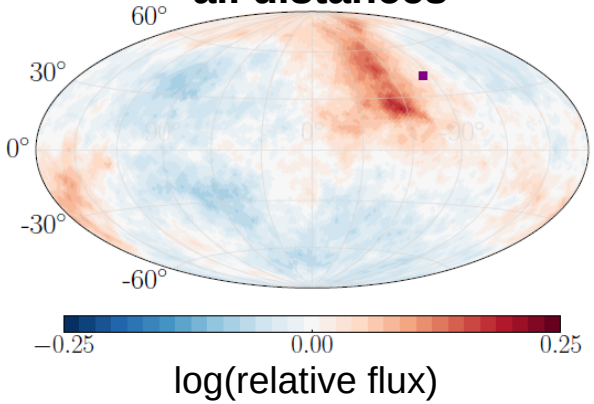
**>350 Mpc**




~30% of flux >8 EeV
~5% of flux >32 EeV

=

**all distances**

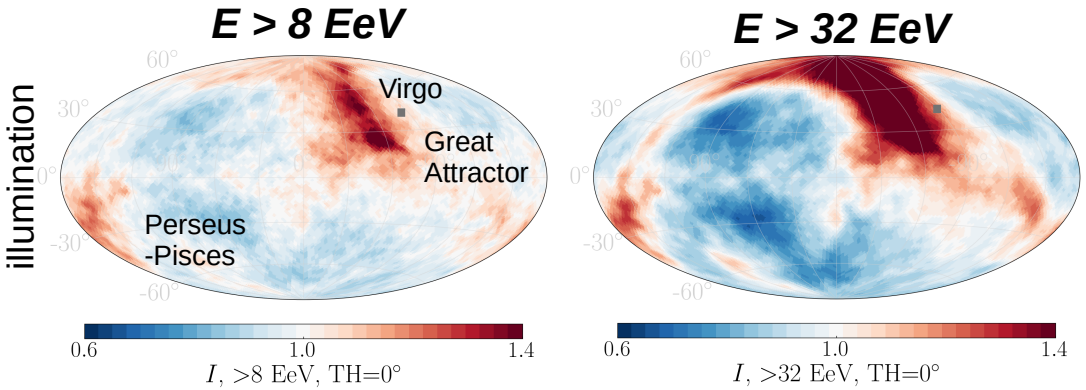



**expected flux at the edge of our Galaxy**

**„illumination“**

skymaps for E>8 EeV

# Predicted dipole directions (JF12)



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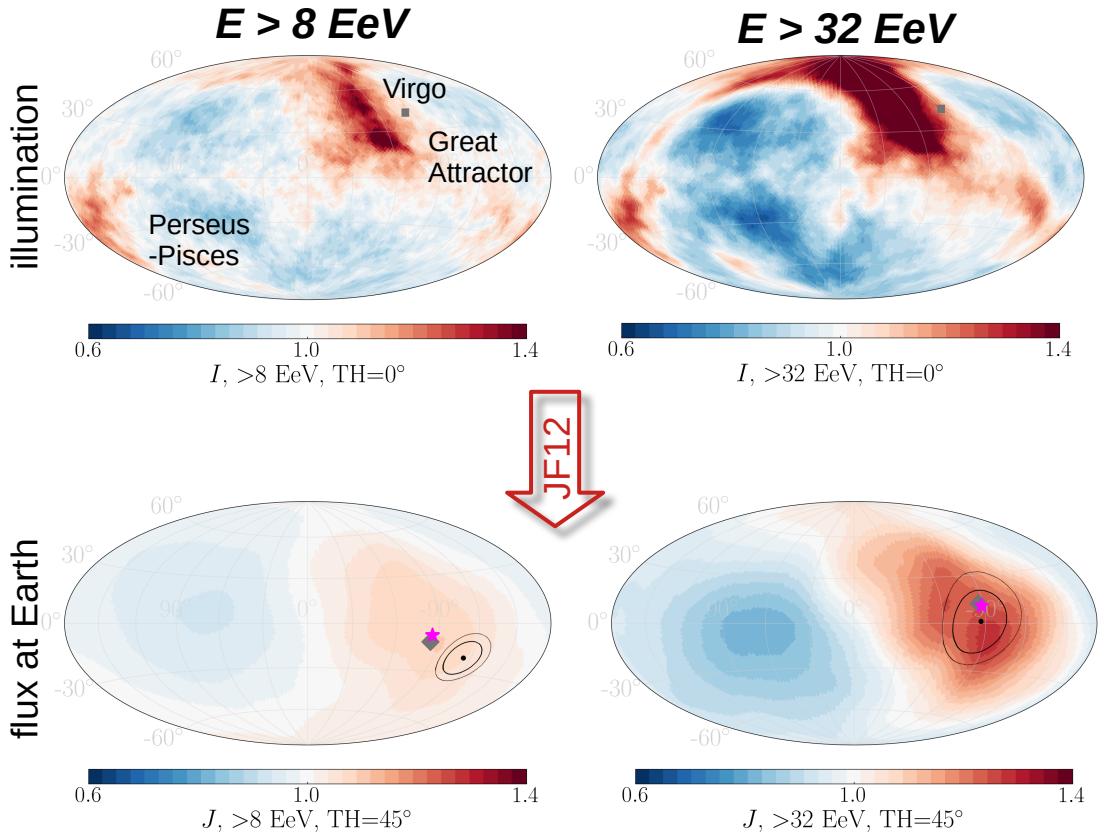
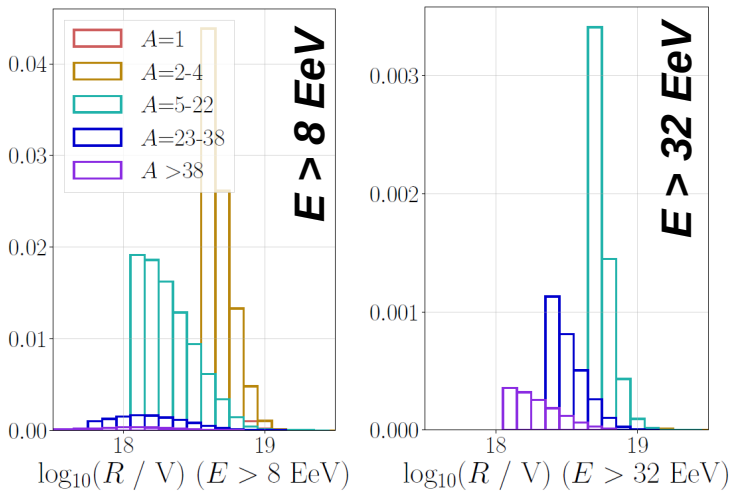



- **dipole mostly originates from Virgo + Great Attractor**
- no significant overdensity in Perseus-Pisces direction after GMF
- **change with amplitude from changing propagation horizon,** not changing rigidity



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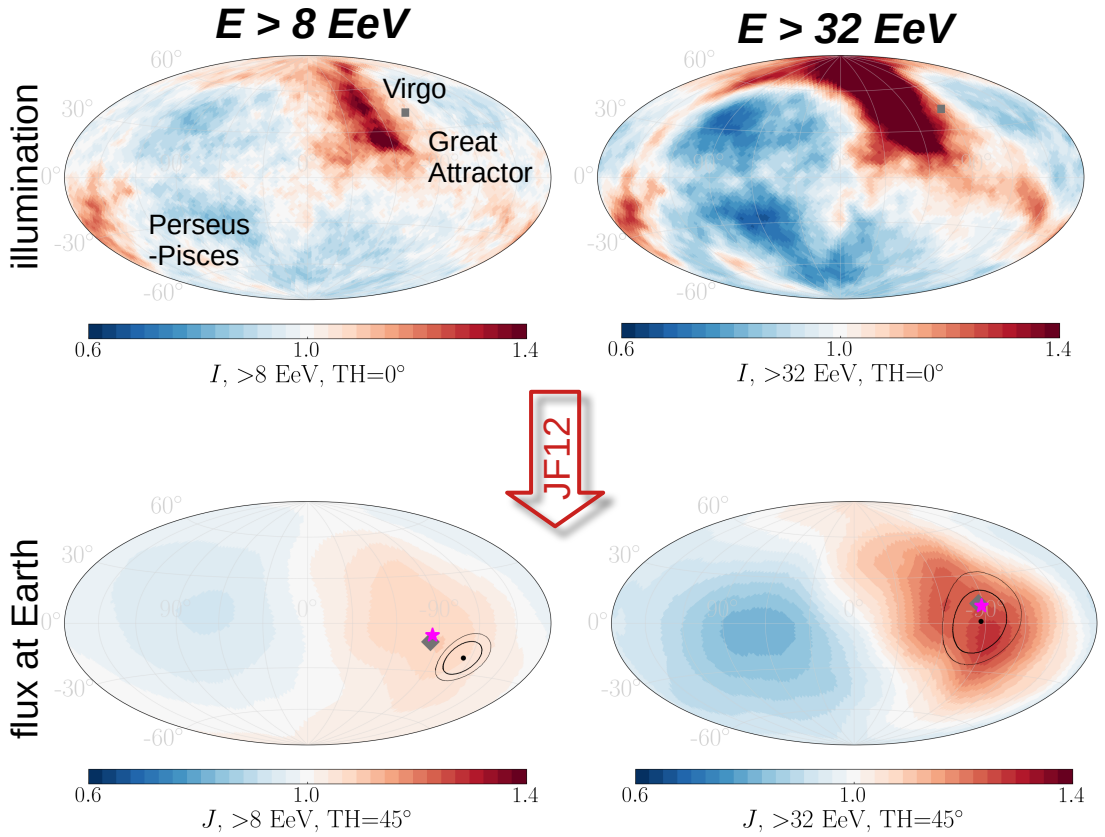


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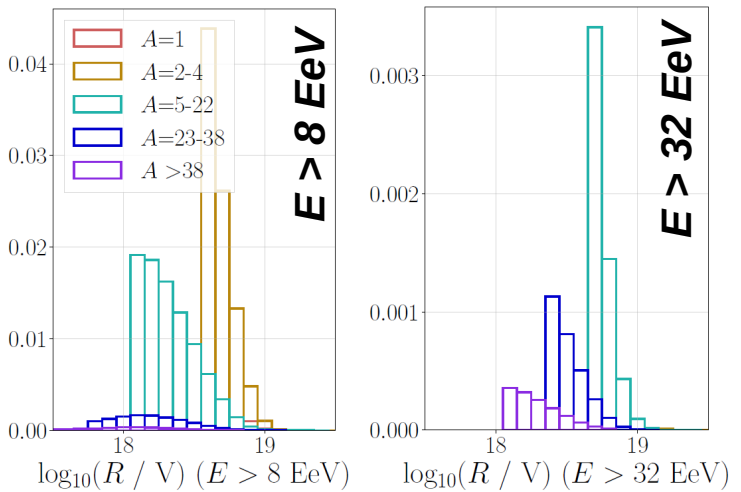
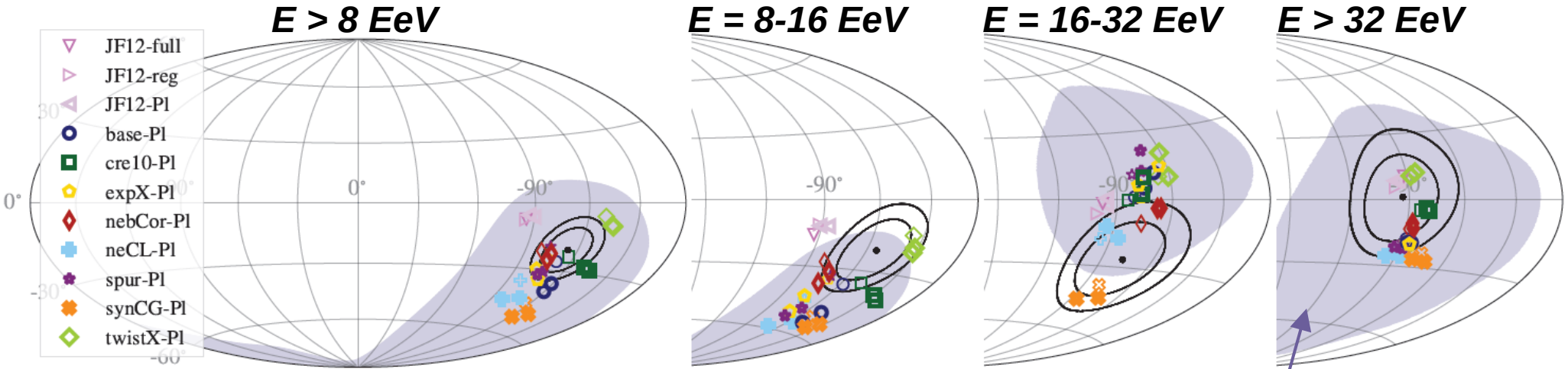



**dipole direction close to measured with JF12 ✔**
**What about newer models?**

# Predicted dipole directions

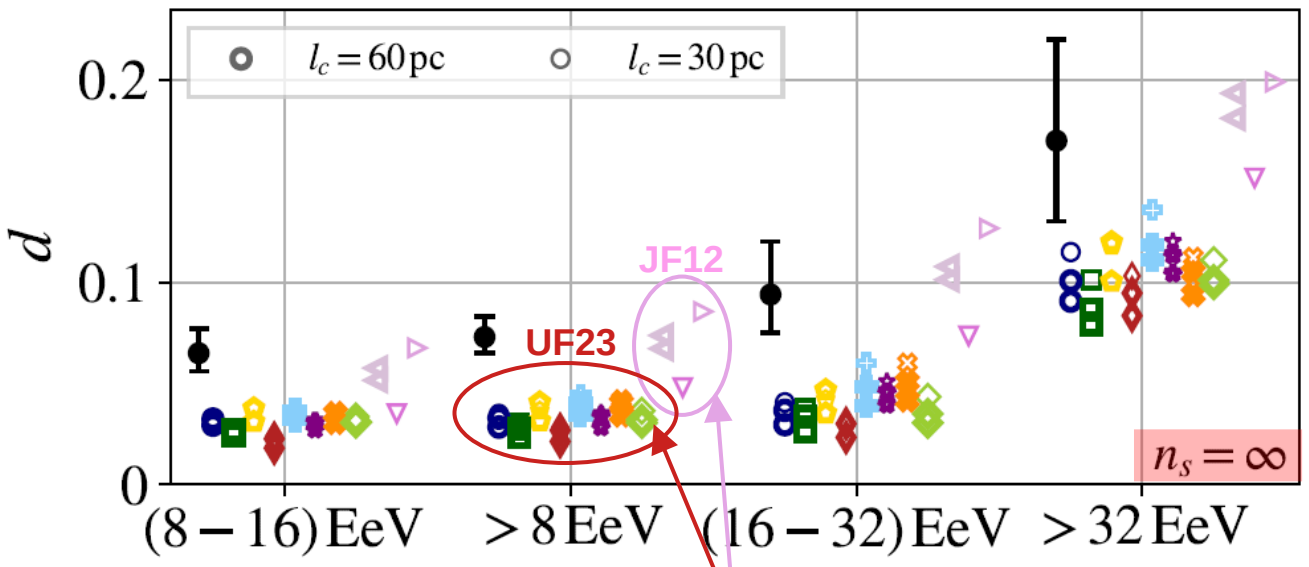


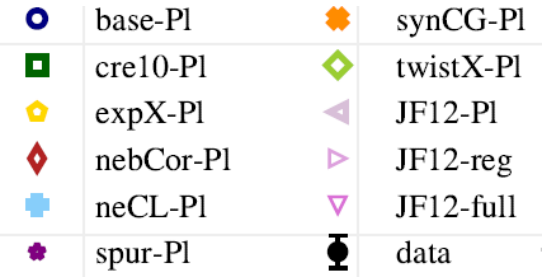

- **all UF23 models predict the dipole direction close to measured one**
  - → but, none fits perfectly at all energies
  - → the models are quite similar
- → **uncertainties on GMF (random & turbulent) do not obstruct conclusions on sources**

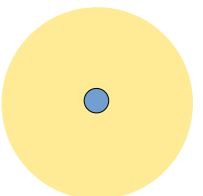
$n_s = 10^{-3}$ Mpc$^{-3}$

**biggest uncertainty on dipole direction: from cosmic variance**

# Predicted dipole amplitude: continuous sources



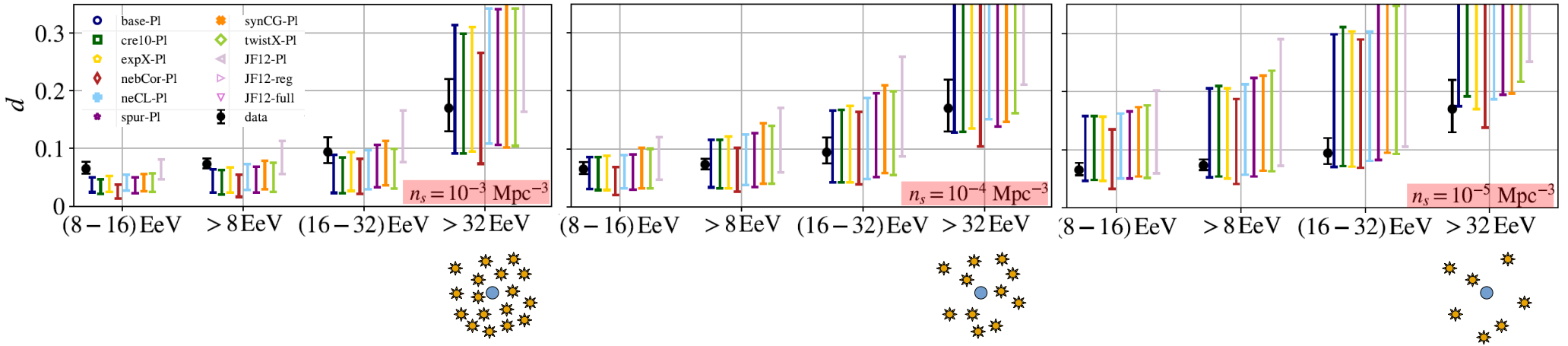



continuous souce distribution

**dipole amplitudes for UF23 models are around half of JF12**

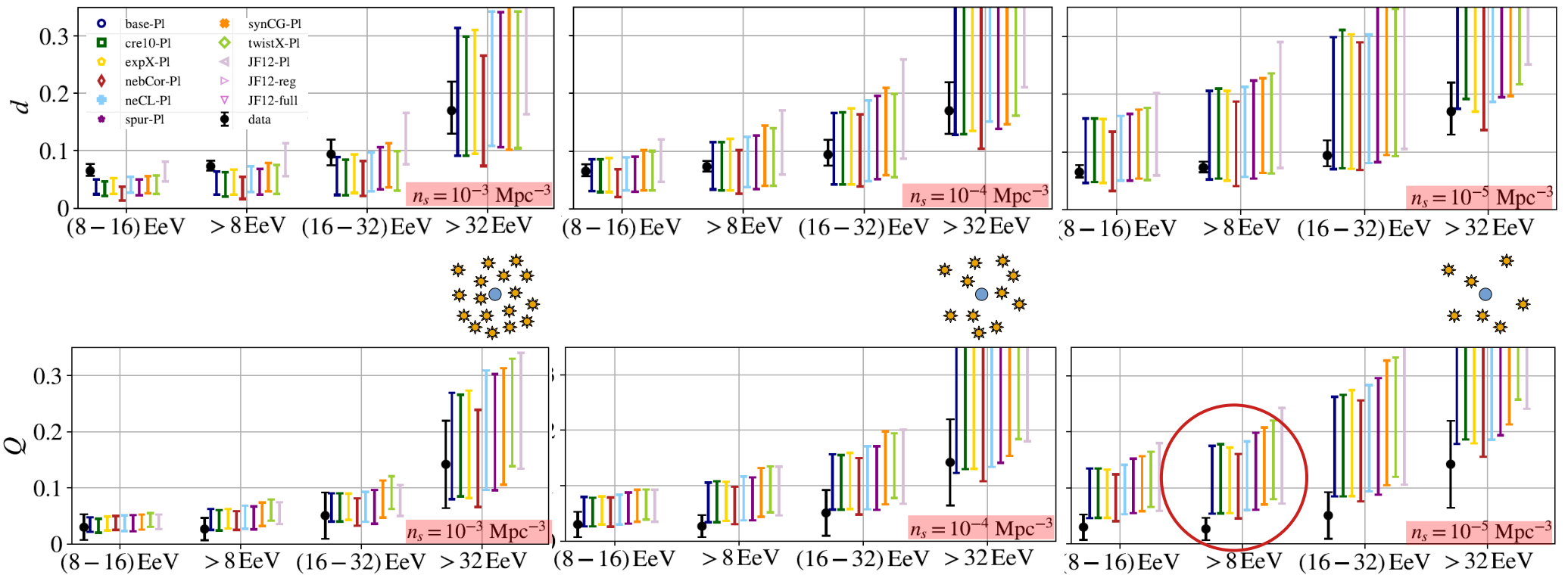
**→ for UF23 models: continuous model disfavored**

# Predicted dipole amplitude: source density




for **densities ~($10^{-3}$ to $10^{-5}$) Mpc$^{-3}$**
→ compatibility with dipole amplitude

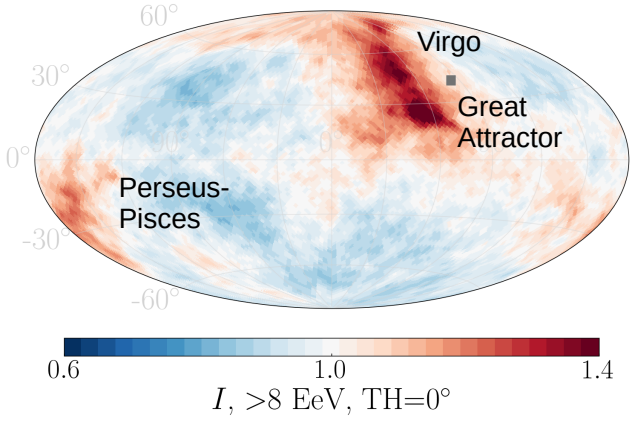
# Predicted dipole & quadrupole amplitudes



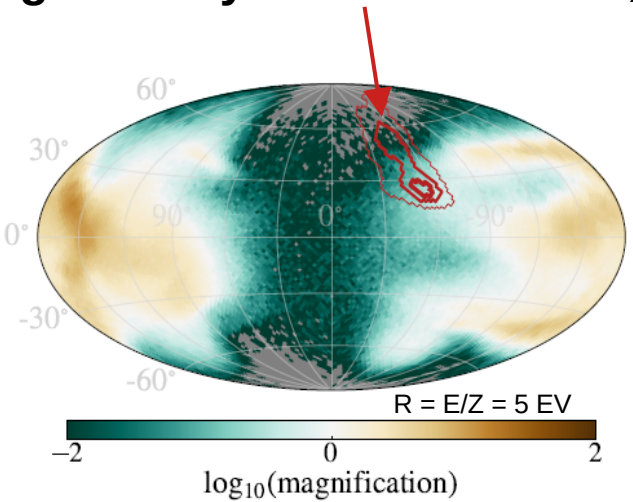

for **densities ~$10^{-3}$ Mpc$^{-3}$ to >$10^{-5}$ Mpc$^{-3}$**
→ compatibility with dipole and quadrupole amplitudes
→ note: dipole direction more random for smaller densities

# Why is the dipole amplitude so small with UF23?

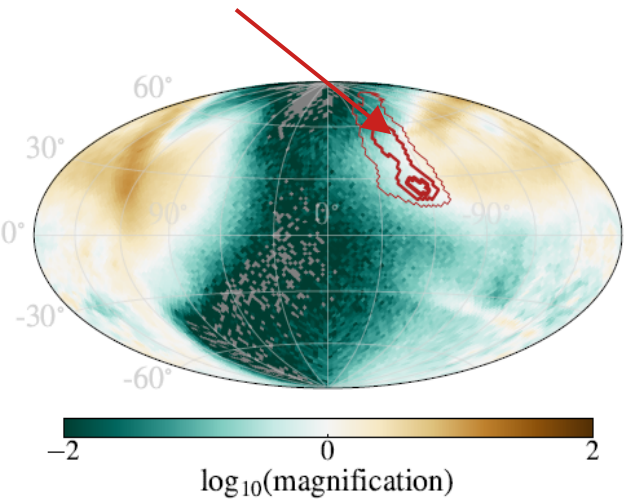
highest flux illumination is **demagnified by *all* UF23 models**, different to JF12




**illumination** E>8 EeV




**UF23 base** + Planck



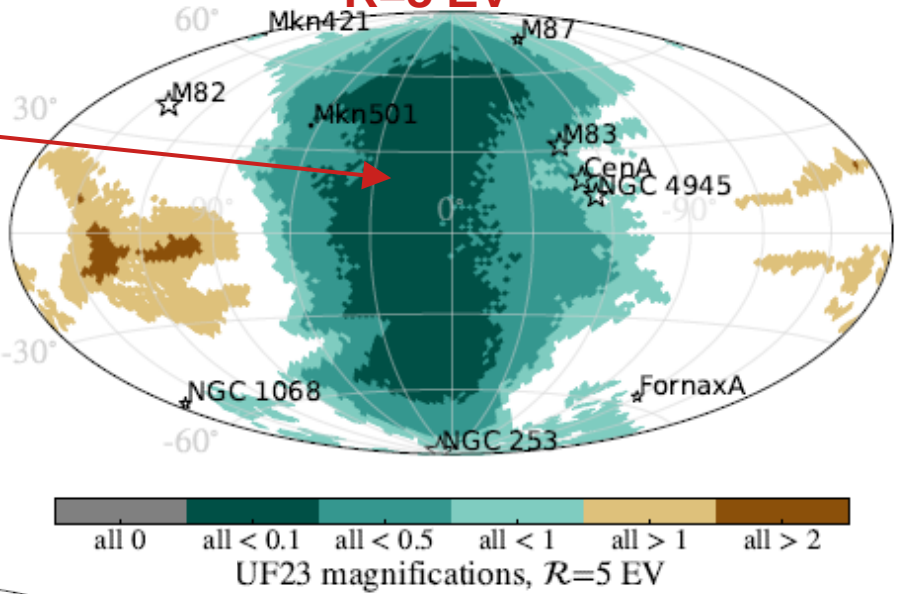

**JF12** + Planck

- magnification has unexpectedly large influence on dipole amplitude
- **caution: due to uncertainties on LSS model + random magnetic field model + EGMF:**
  **→ preferred source density with large uncertainties!**

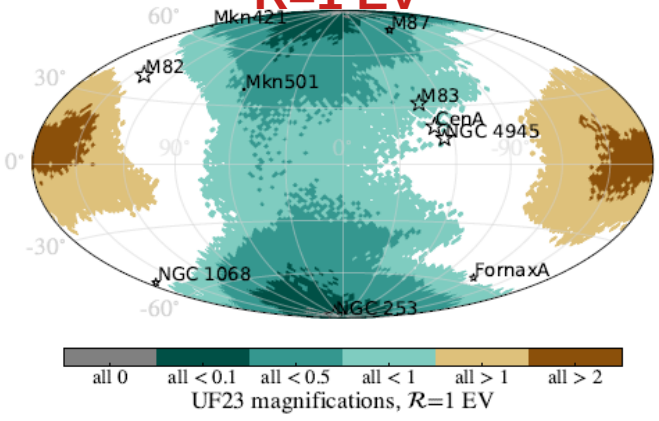
# Demagnification - agreement & source candidates

- all UF23 models + random field variations agree on central magnification area
  - → **many source candidates in central demagnification area**
  - → might not see many CRs from them, at least not with rigidity R <= 5 EV

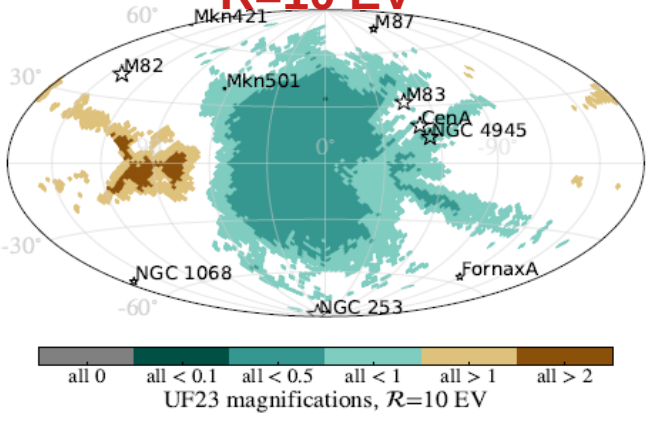
R=5 EV




R=1 EV



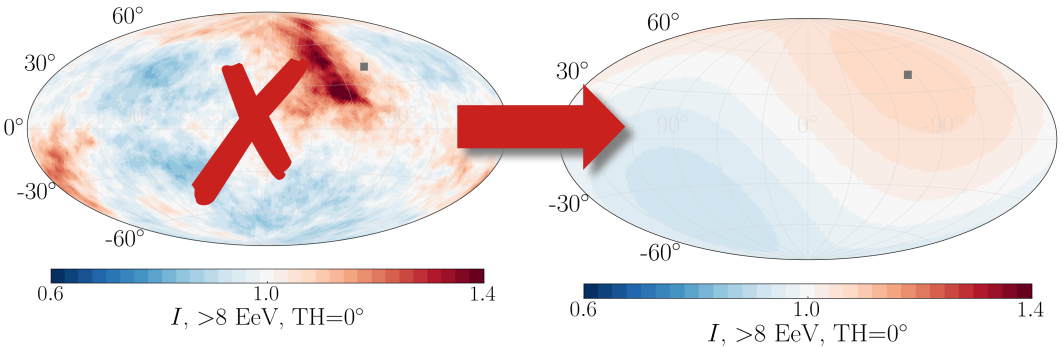

R=10 EV




*white region:*
*no agreement between all 8 UF23 models*

# Sensitivity to the LSS model illumination

**replace the illumination by dipole component:**



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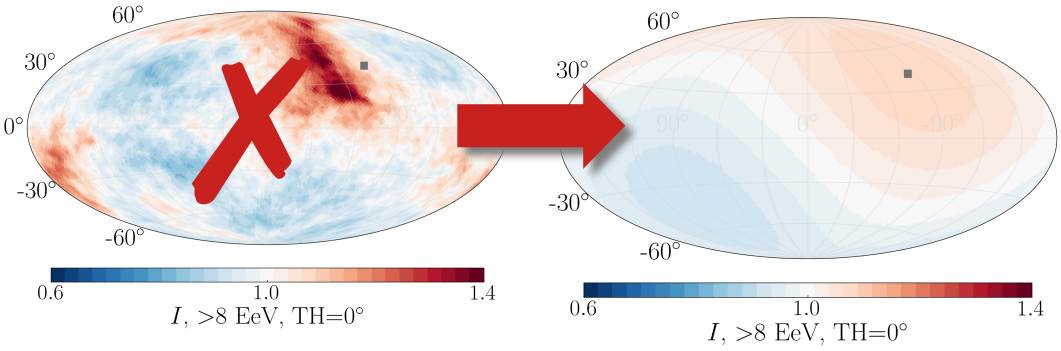
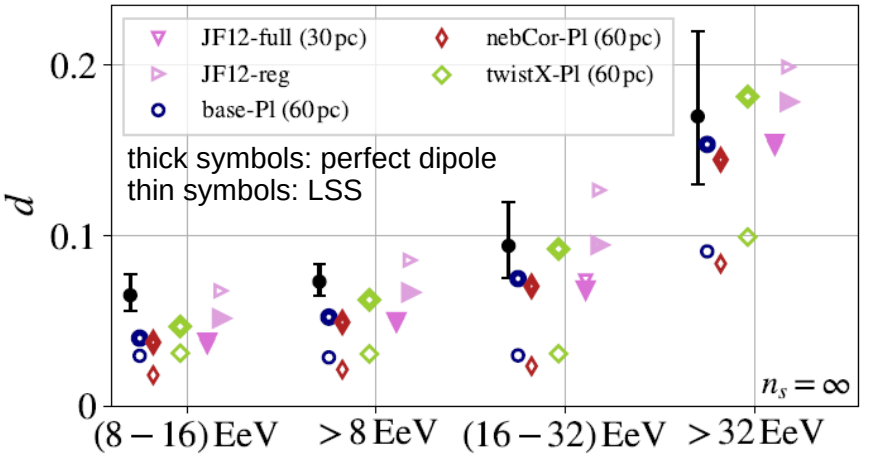
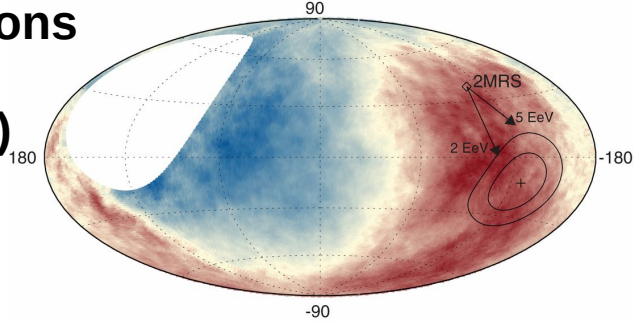
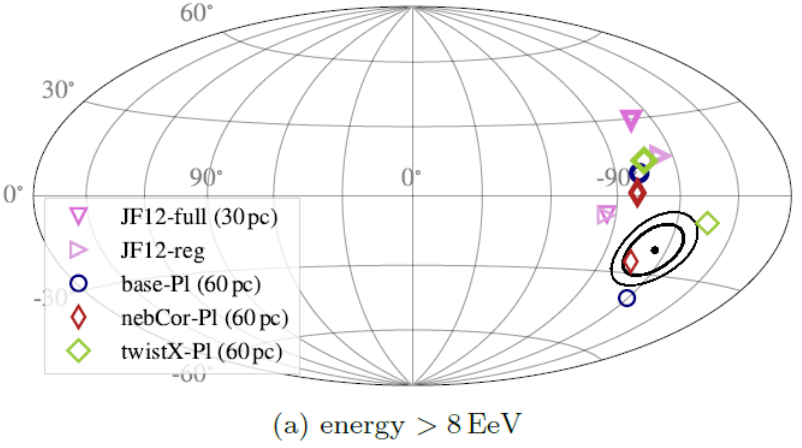



- consequence of sensitive interplay between illumination & magnification
  - **quite different predictions of amplitude (factor 2) & direction (by 20°-60°)**

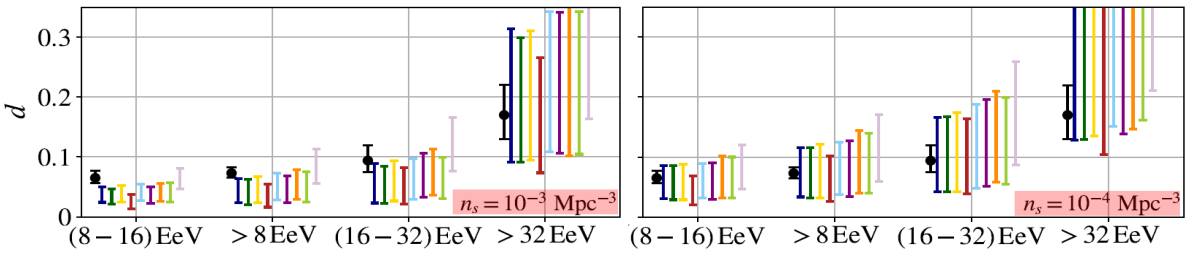


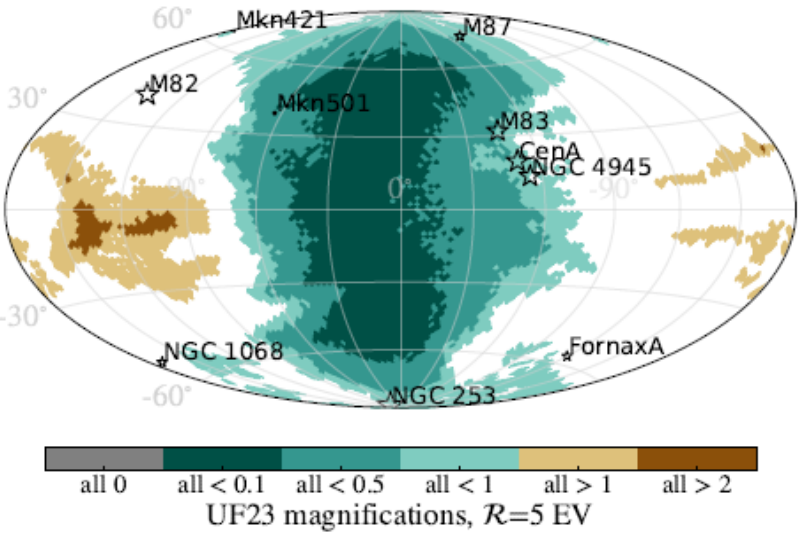



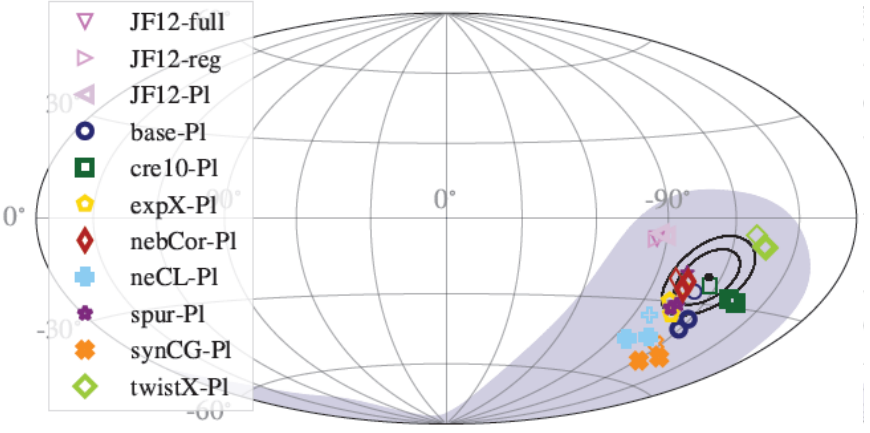

(a) energy $> 8$ EeV

# Conclusions

- large-scale anisotropies can be well explained if UHECR sources follow the large-scale structure
- **dipole amplitude is significantly reduced with new UF23 GMF models**
  - ➔ due to **demagnification** in Virgo direction
  - ➔ preferred source number density $n_s \sim 10^{-4}$ Mpc$^{-3}$
- **sensitive interplay** of flux predicted by LSS model and demagnification heavily influences dipole
  - future: updated random GMF models, update of LSS model from CosmicFlows...

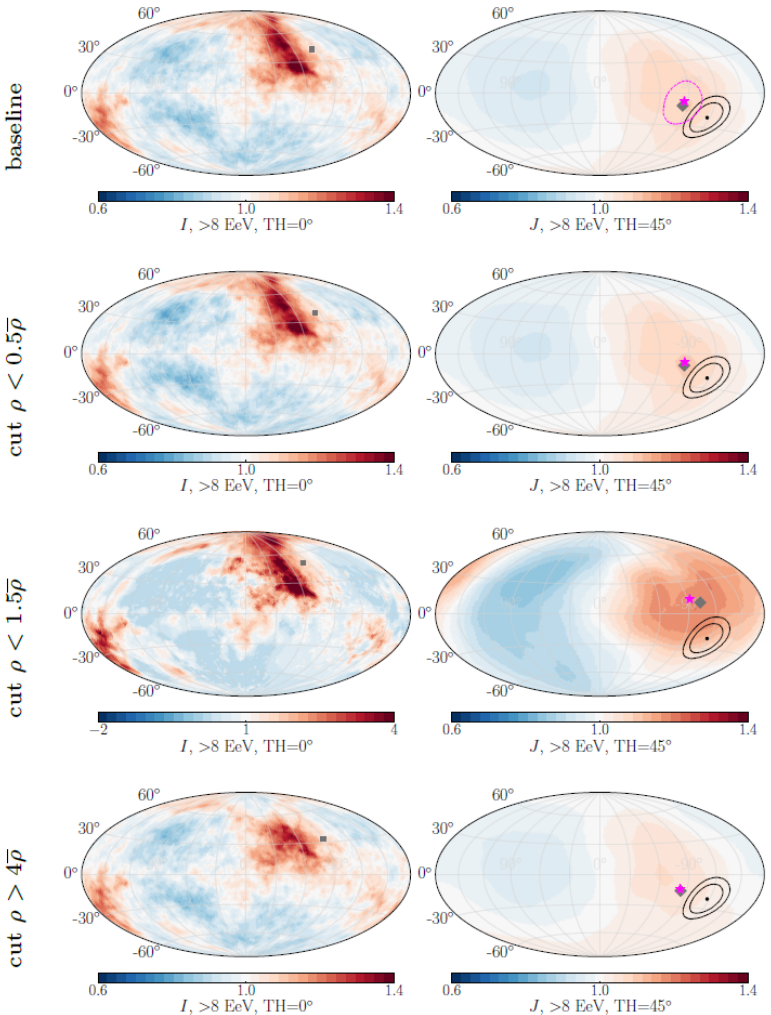


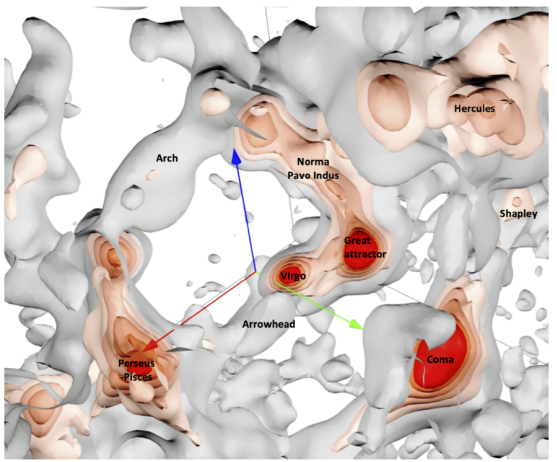
# backup

# Bias between matter density and UHECR sources

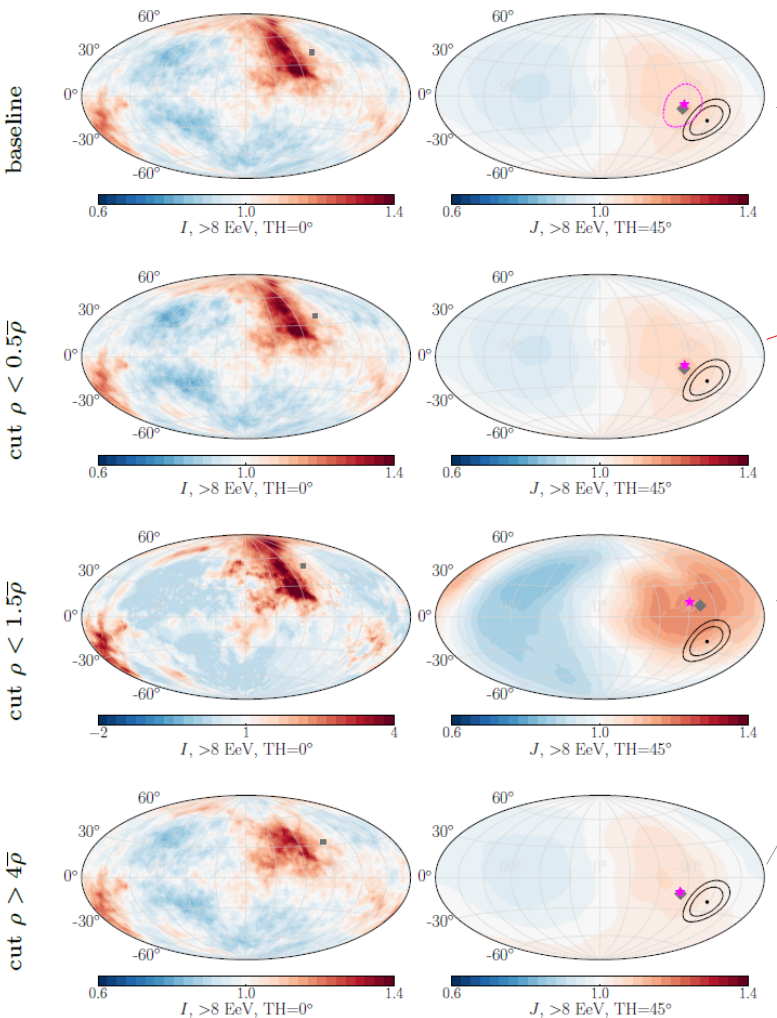


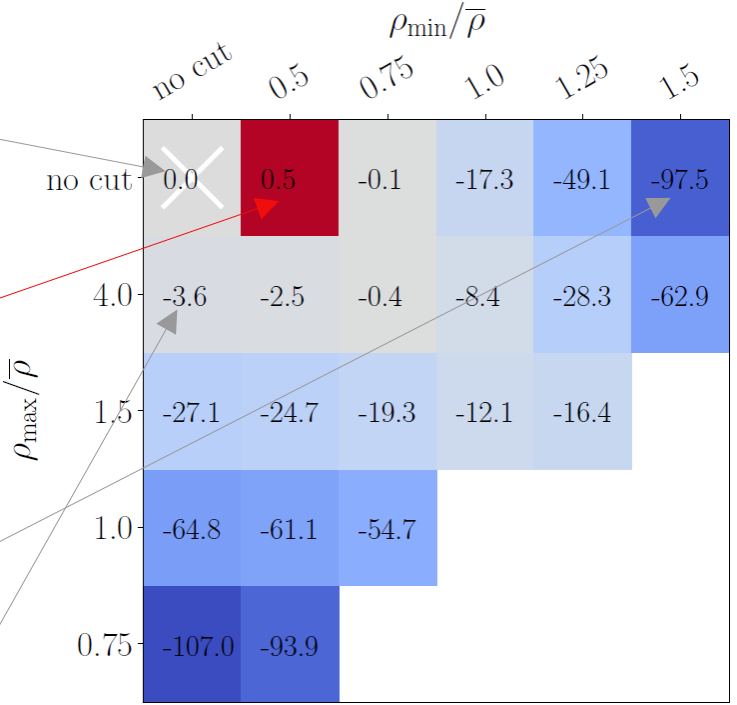

*Is there a **bias** between the UHECR source distribution and the (dark) matter distribution / LSS?*

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



# Bias between matter density and UHECR sources



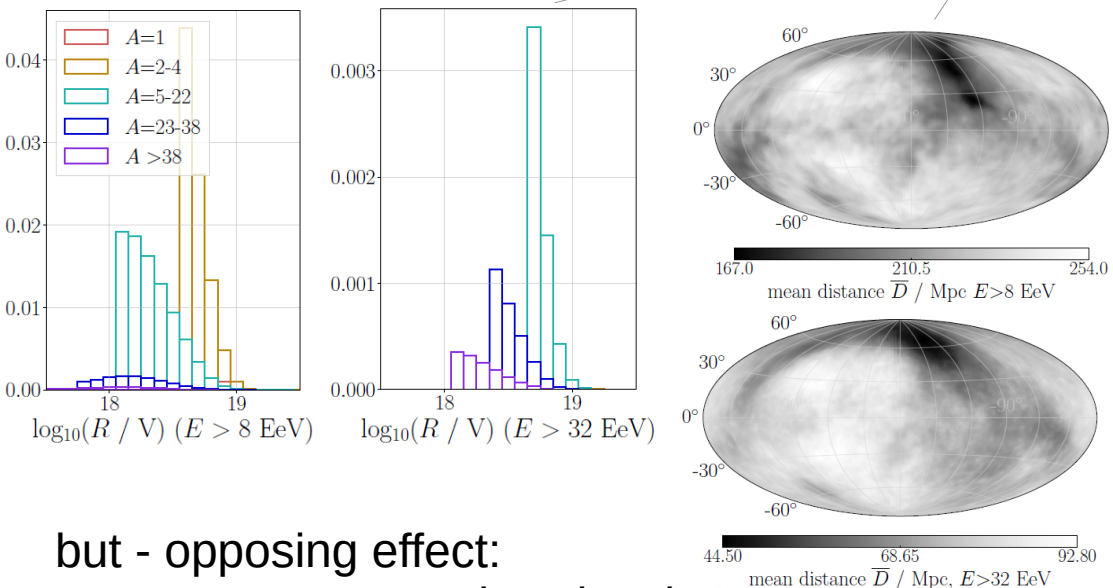

color: likelihood

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

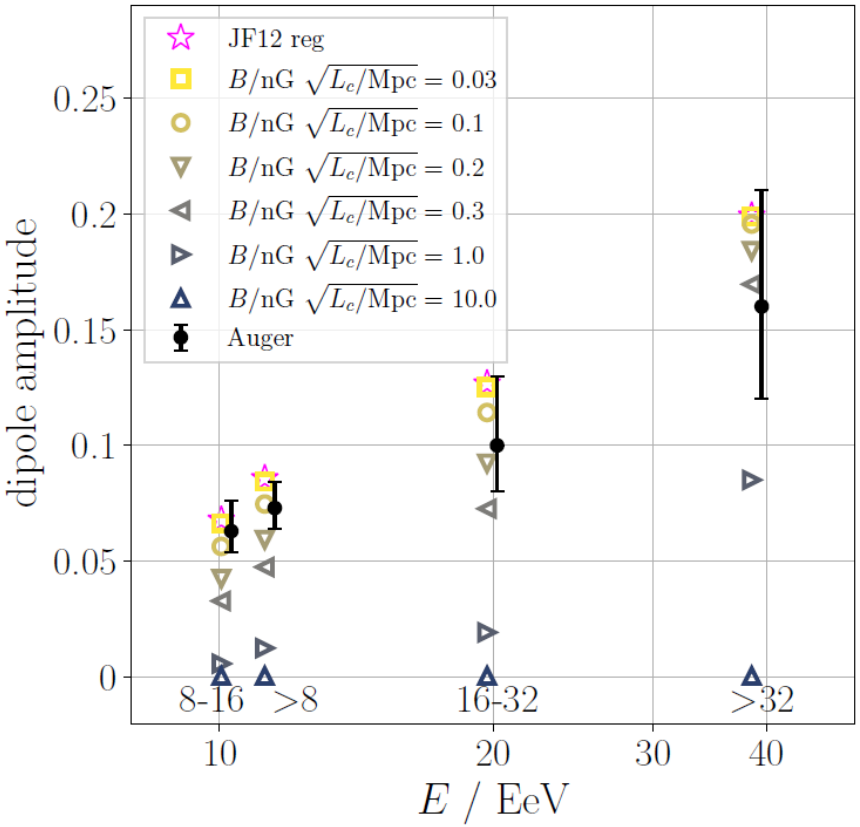
# Extragalactic magnetic field effect?

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

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

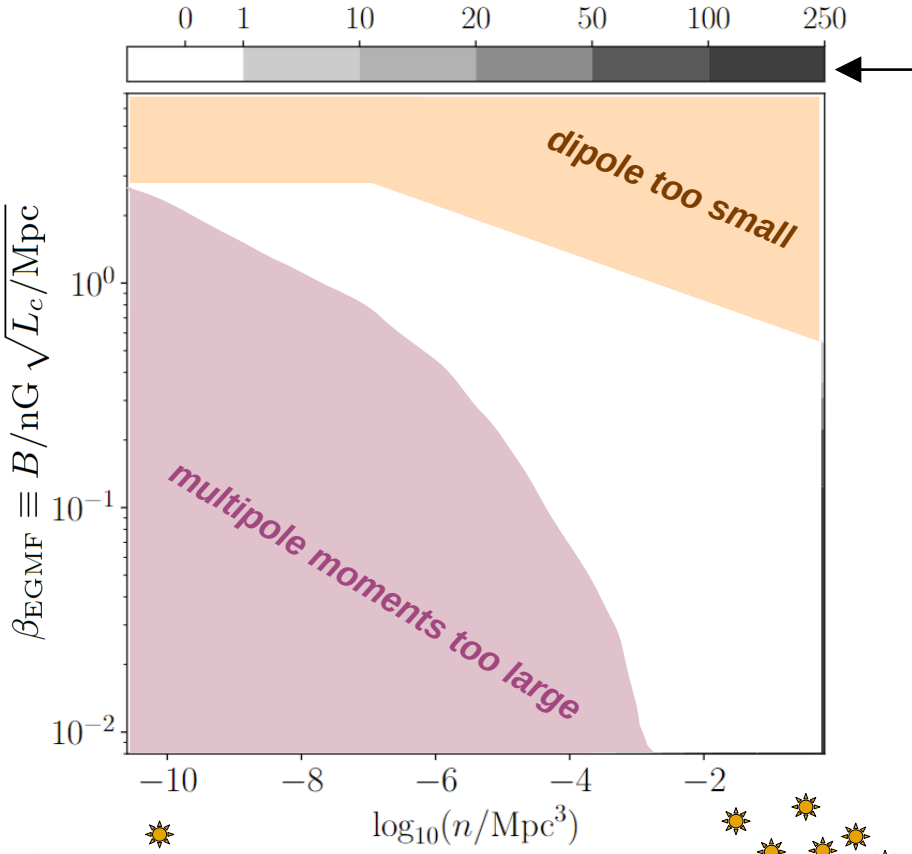



but - opposing effect:
sparser source number density!



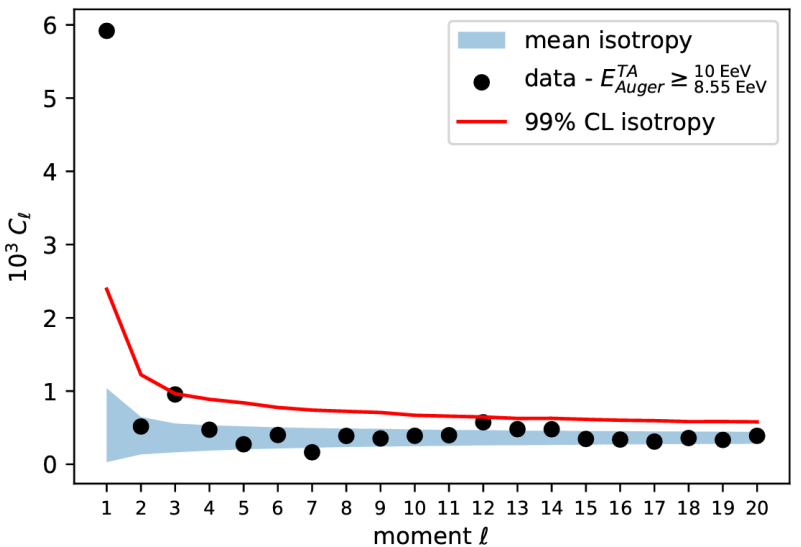
# Source density and extragalactic magnetic field

**extragalactic magnetic field**



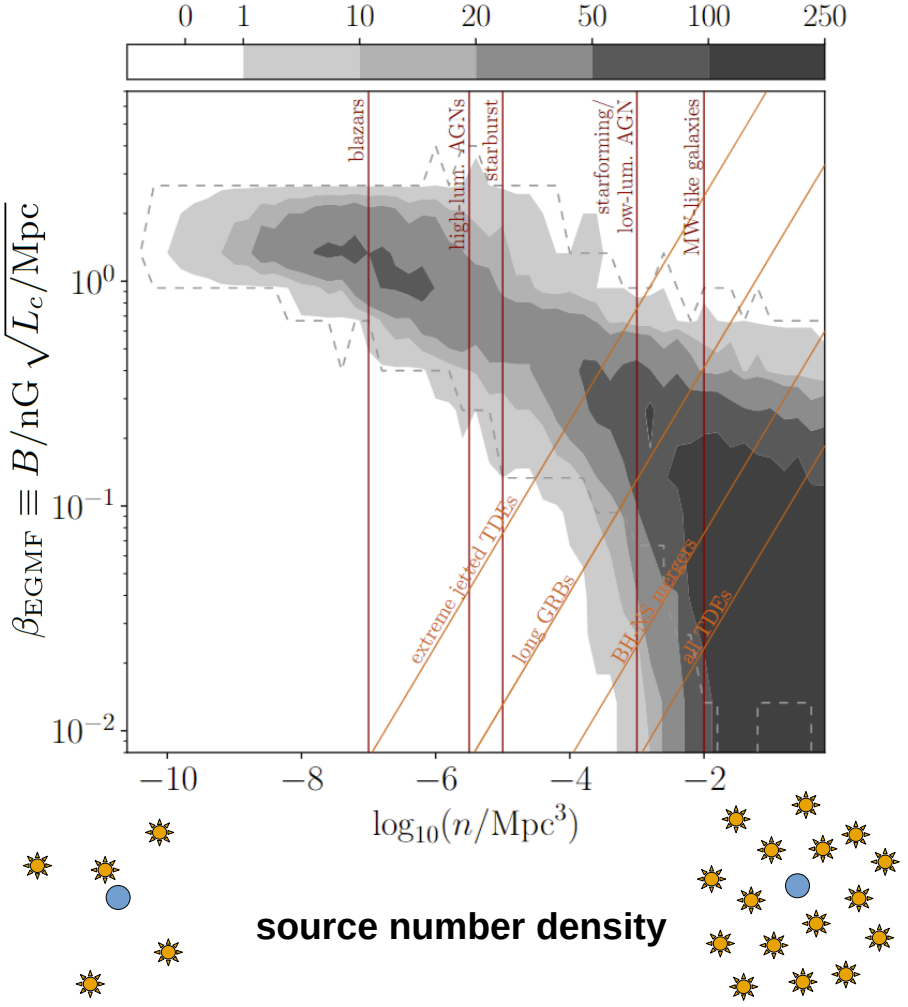

**source number density**

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

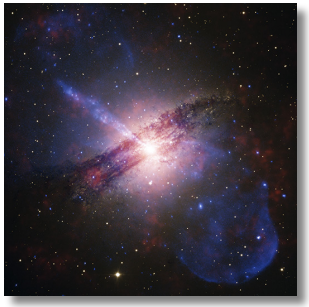


# Source density and extragalactic magnetic field

**extragalactic magnetic field**




- **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



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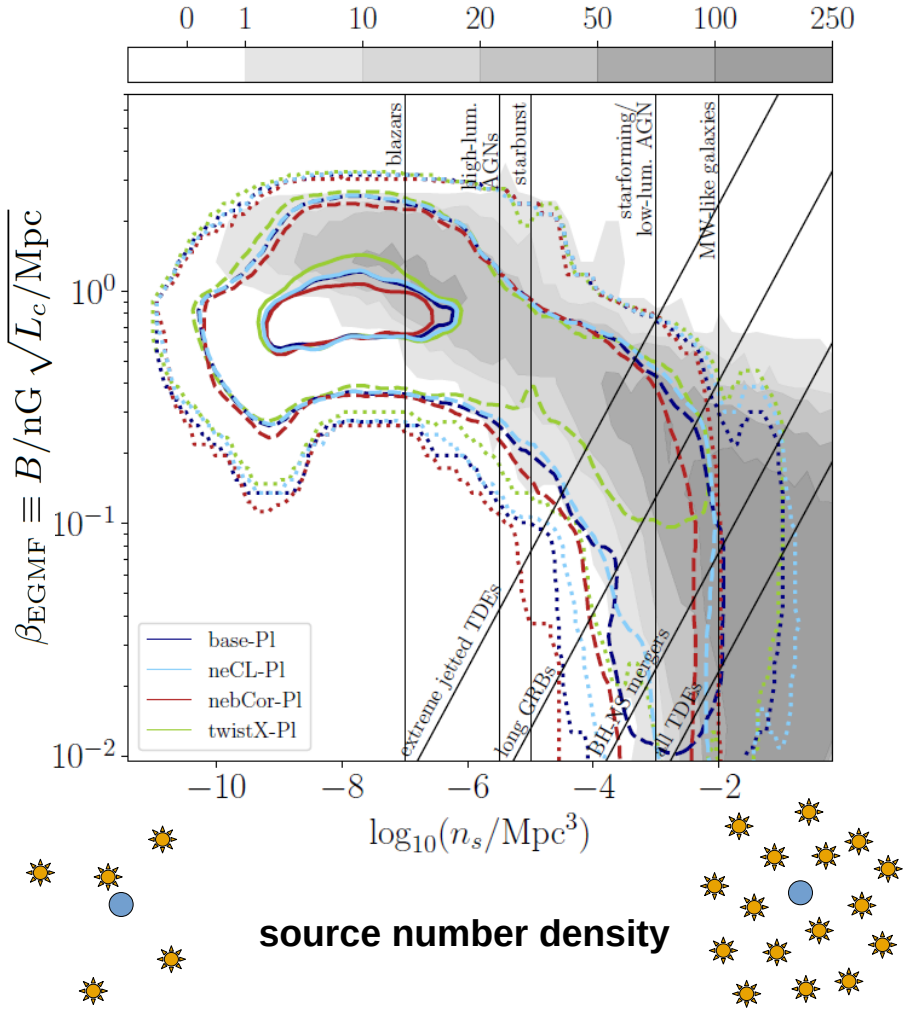
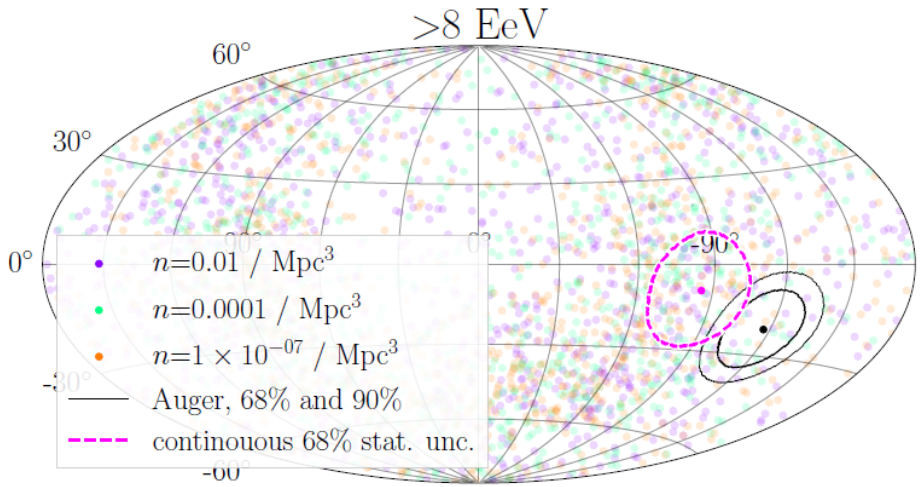



**source number density**

- with UF23 models, smaller source densities are preferred
- due to decreased dipole amplitude (magnification)
- note: large uncertainties due to random GMF model (currently still JF12-Planck) & simplified EGMF treatment

# Homogeneous source distribution?



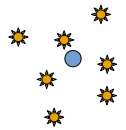




- homogeneous distribution less likely, only for rare sources and considerable EGMF
- dipole direction not predictable

# Dipole & Quadrupole amplitudes

**dipole & quadrupole amplitudes:**

- cosmic variance again dominates over differences between models



- quadrupole amplitude of all UF23 model comparable to JF12 + Planck

- but: **dipole amplitude significantly smaller!**

  → now need approximately $10^{-3}$ Mpc$^{-3}$ to $10^{-4}$ Mpc$^{-3}$ for compatibility

  → continuous model incompatible!