QUARKS-2026

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Images of ultra-high-energy cosmic ray sources in a turbulent intergalactic magnetic field

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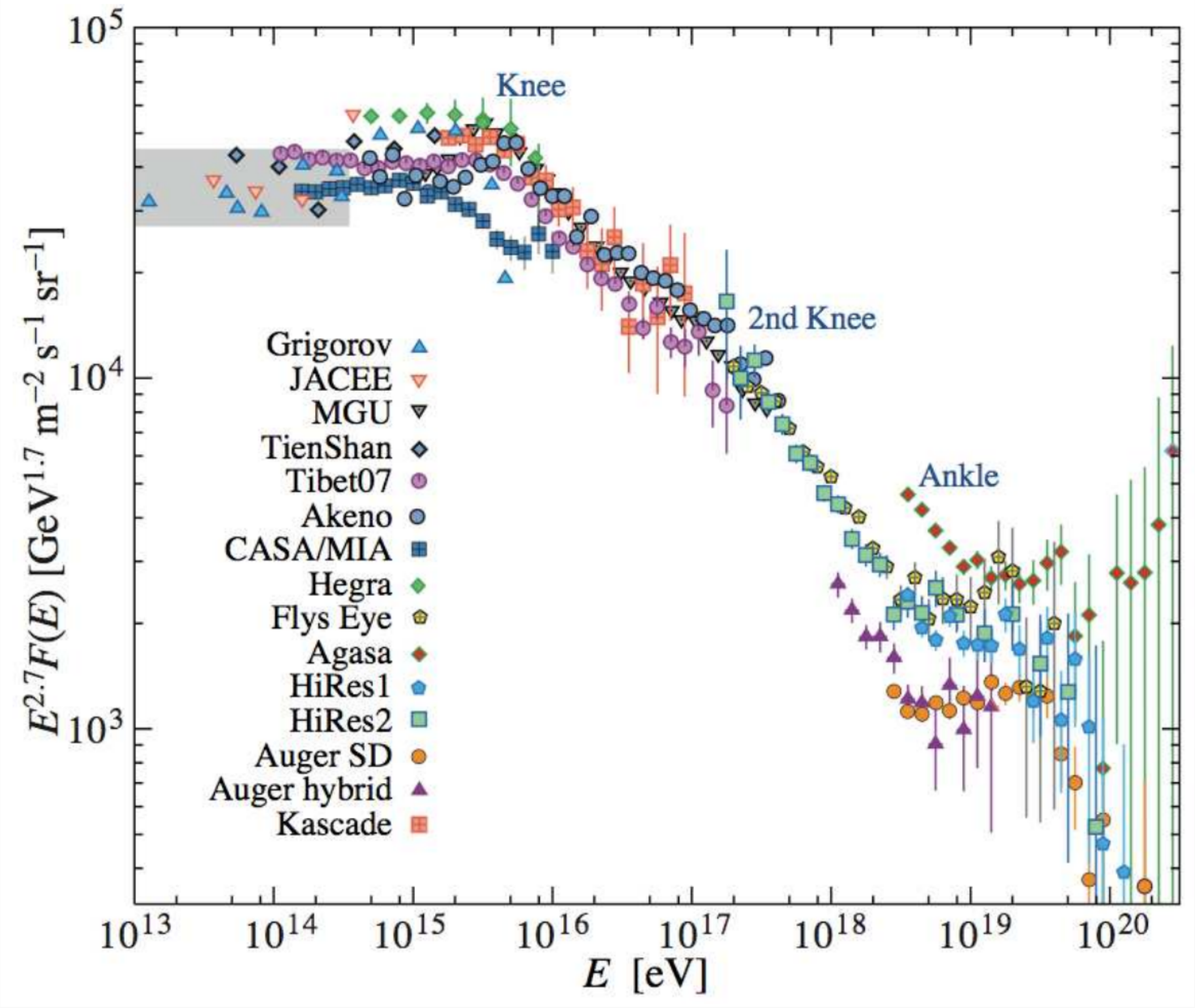
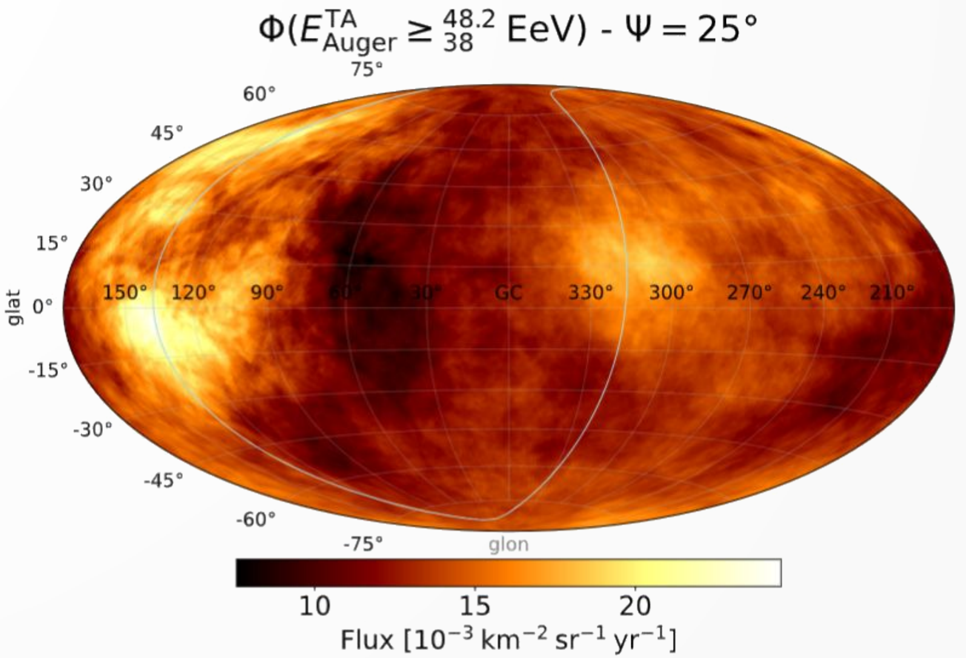
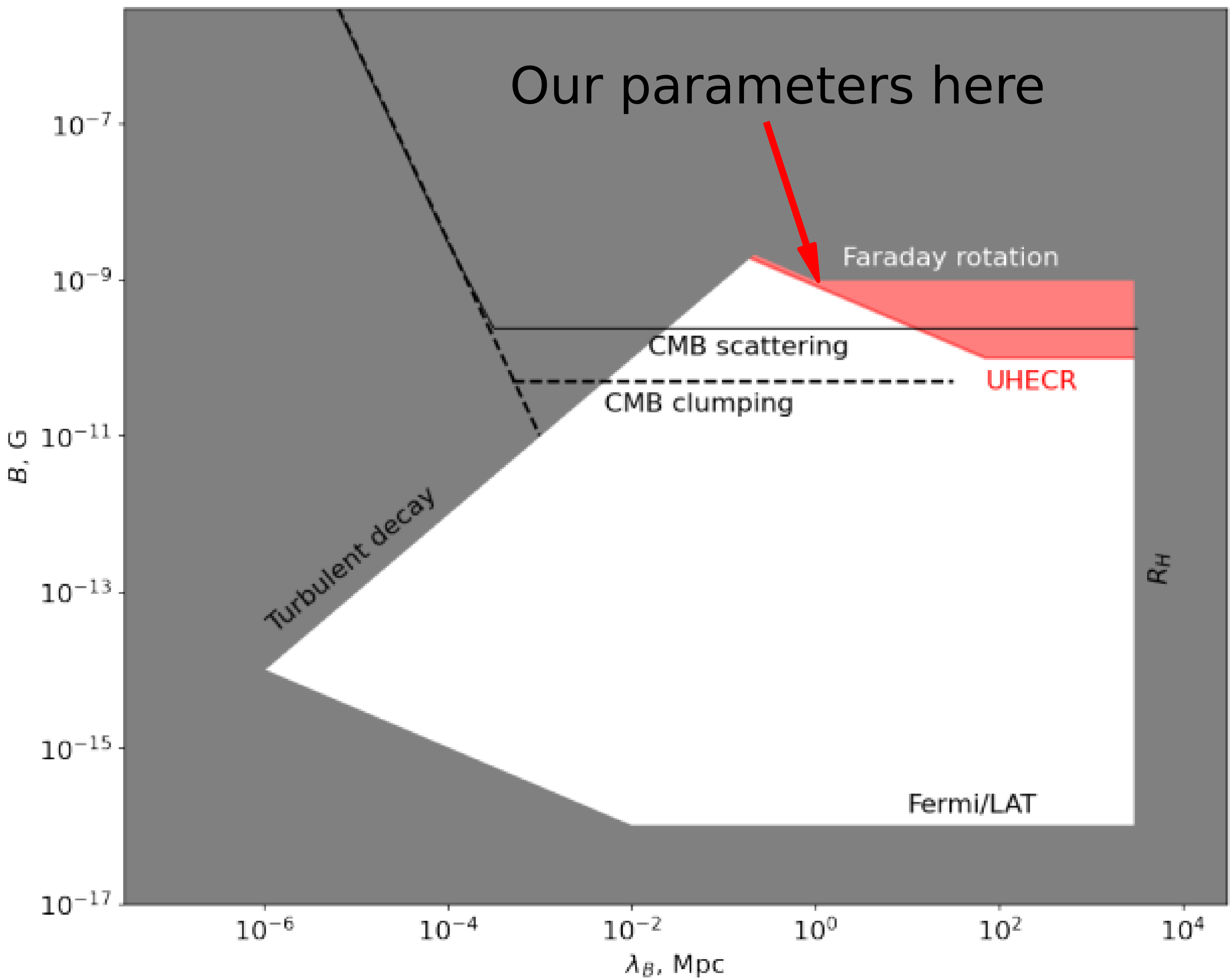
Motivation: TA & PAO hotspots



E > 3.8·10^{19} eV



Constraints on the IGMF



Neronov+21

Is it possible that observed UHECR hotspots are due to propagation in a strong IGMF?

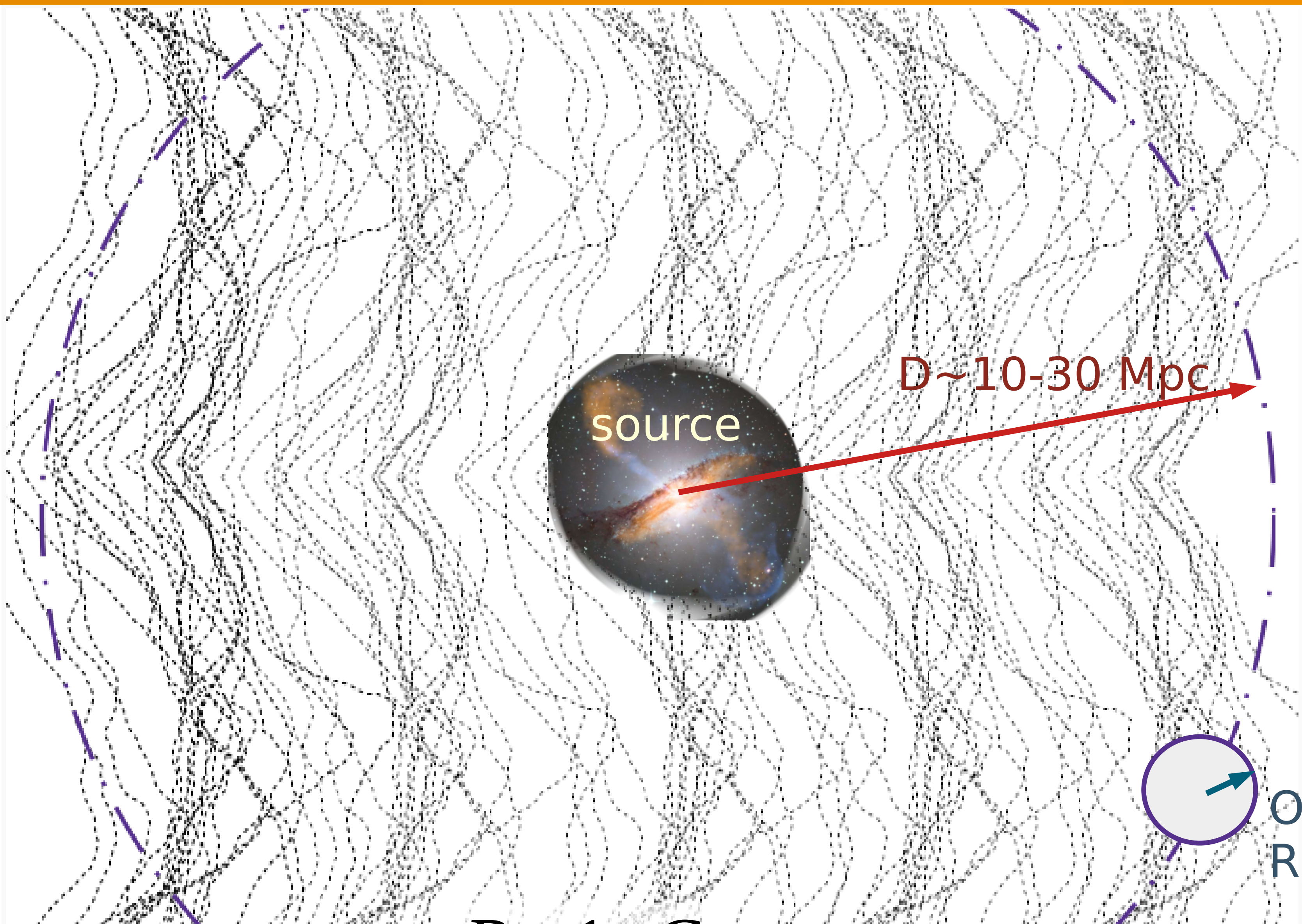
$$E \geq 10^{19}\, eV$$

$$B = 1\, nG$$

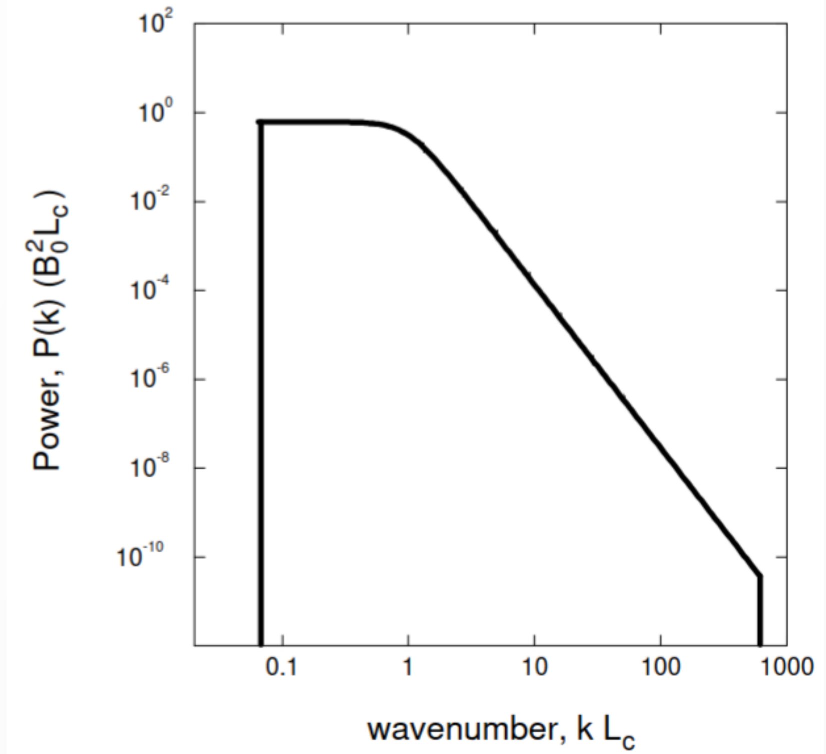
$$\lambda_C \geq 1\, Mpc$$

$$Z = 1$$

Simulation setup



$B = 1nG$



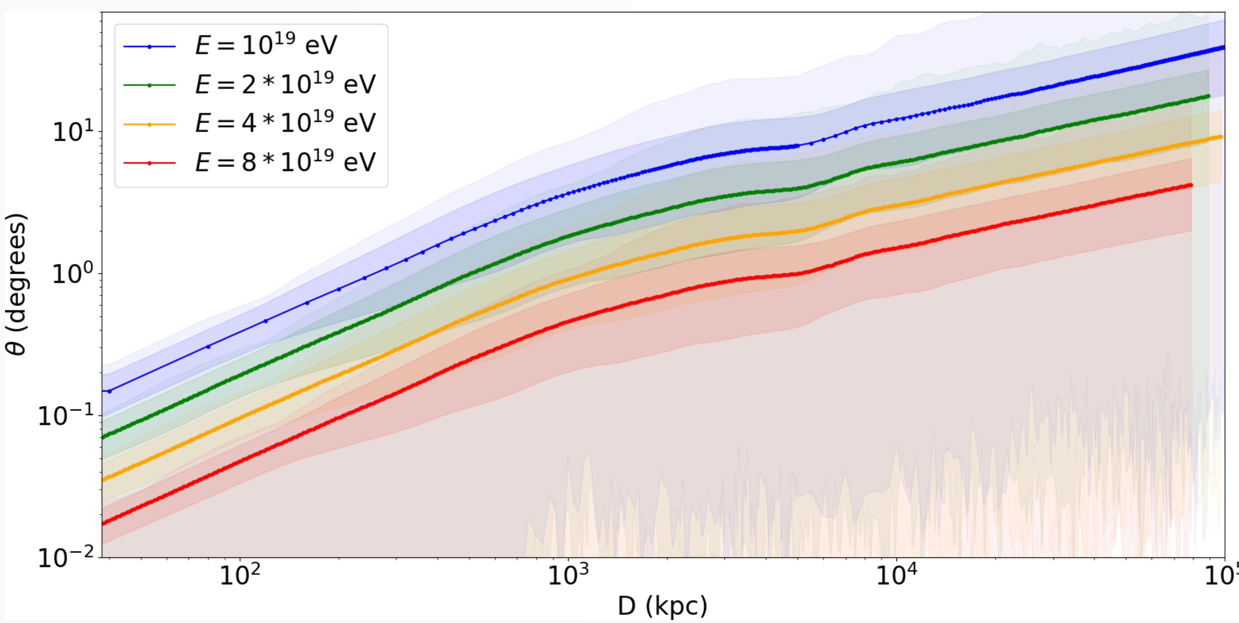
No losses,
magnetic field
deflection only

Pic from Giacalone&Jokipii99

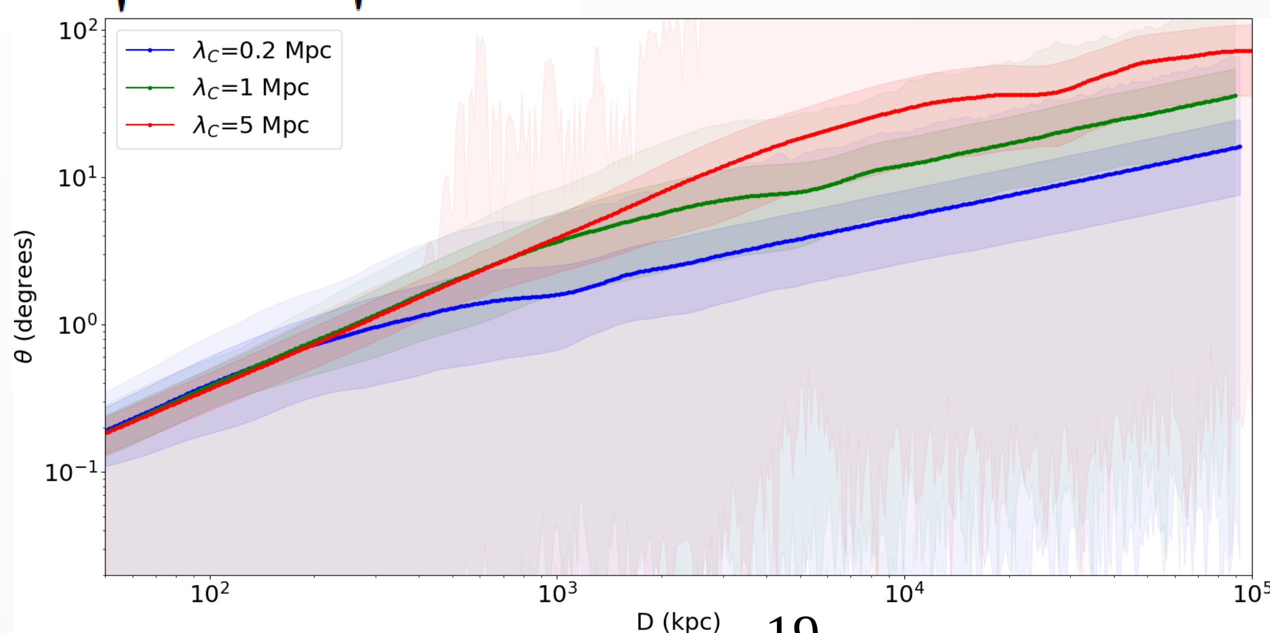
1D picture

Average deflection angle of UHECR protons after propagation in turbulent MF is given by analytic formula:

$$\theta \sim 4^\circ \; Z \frac{B}{\mathrm{nG}} \frac{10\ \mathrm{EeV}}{E} \sqrt{\frac{D}{\mathrm{Mpc}}} \sqrt{\frac{\lambda_C}{\mathrm{Mpc}}}$$



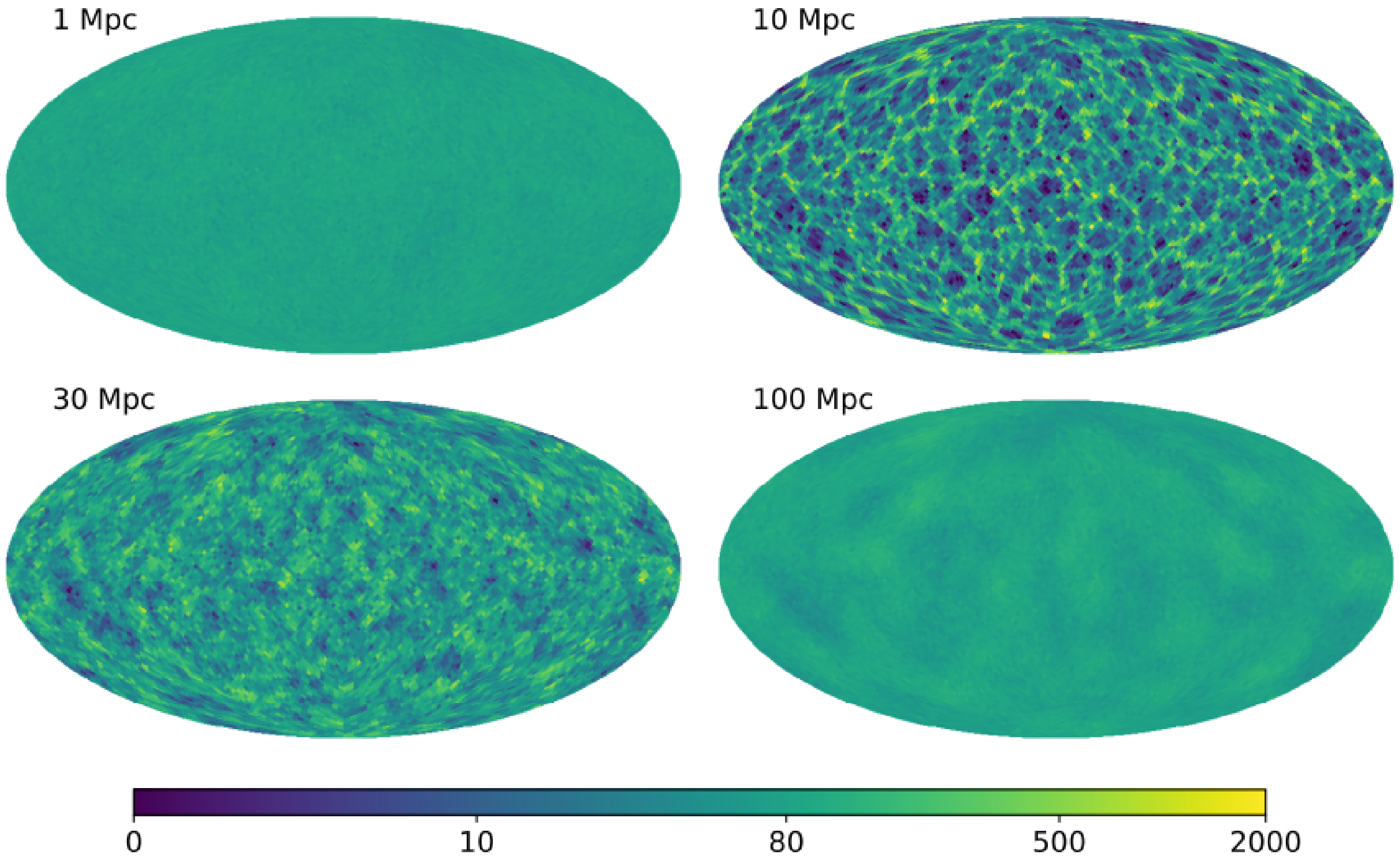
$\lambda_C = 1\,Mpc \quad B = 1\,nG$



$B = 1\,nG \quad E = 10^{19}\,eV$

Linear grow at small distances and √D at large distances: good agreement between theoretical prediction and simulations

2D: Caustic-like structure



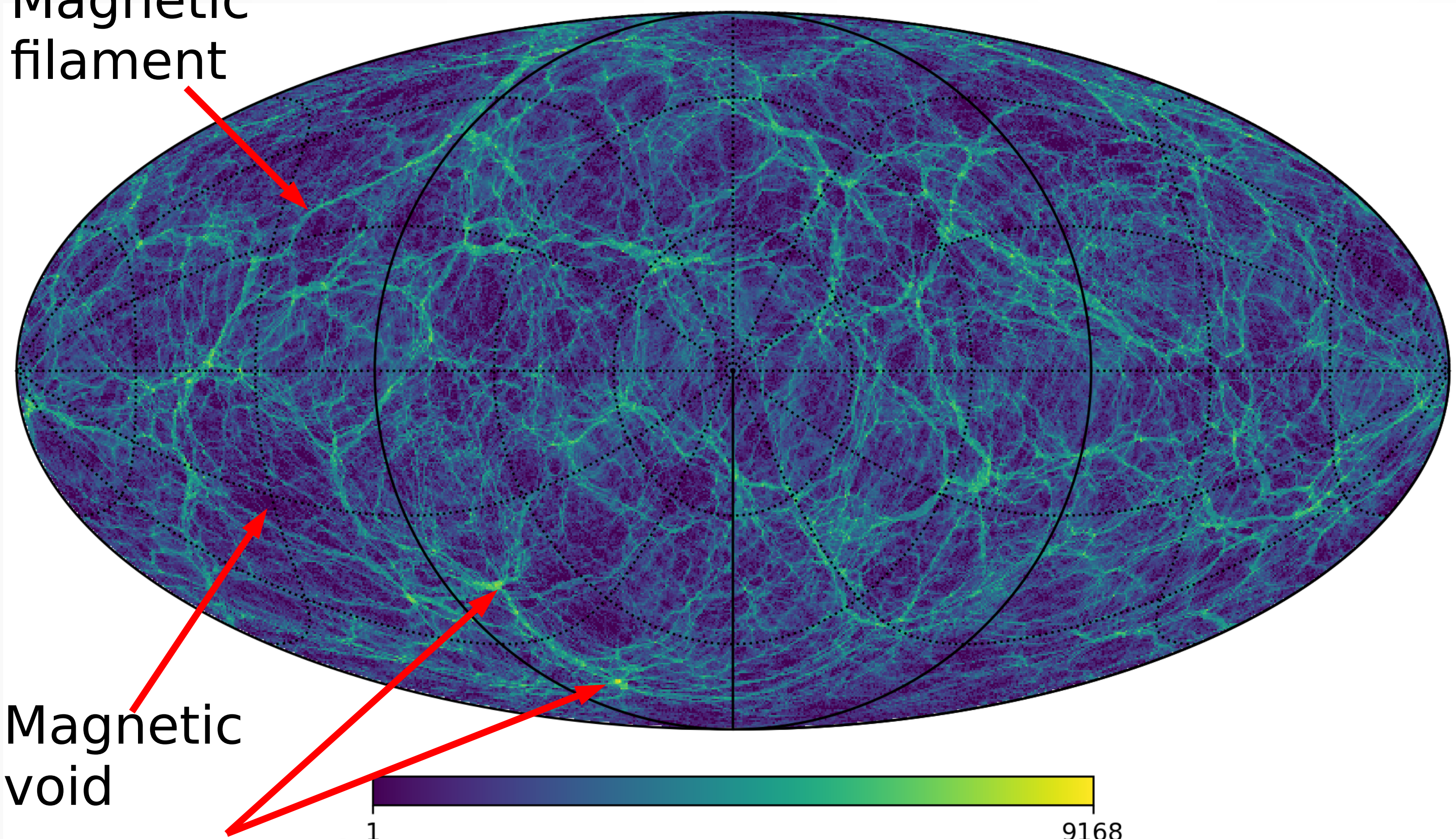
Distribution of cosmic rays on the spheres of different radius around the source

Medium-scale anisotropies first increase and then blur

$$B = 1\,nG$$
$$\lambda_C = 0.3\,Mpc$$
$$E = 10^{19}\,eV$$

2D: Caustic-like structure

Magnetic filament



Magnetic void

Magnetic knots

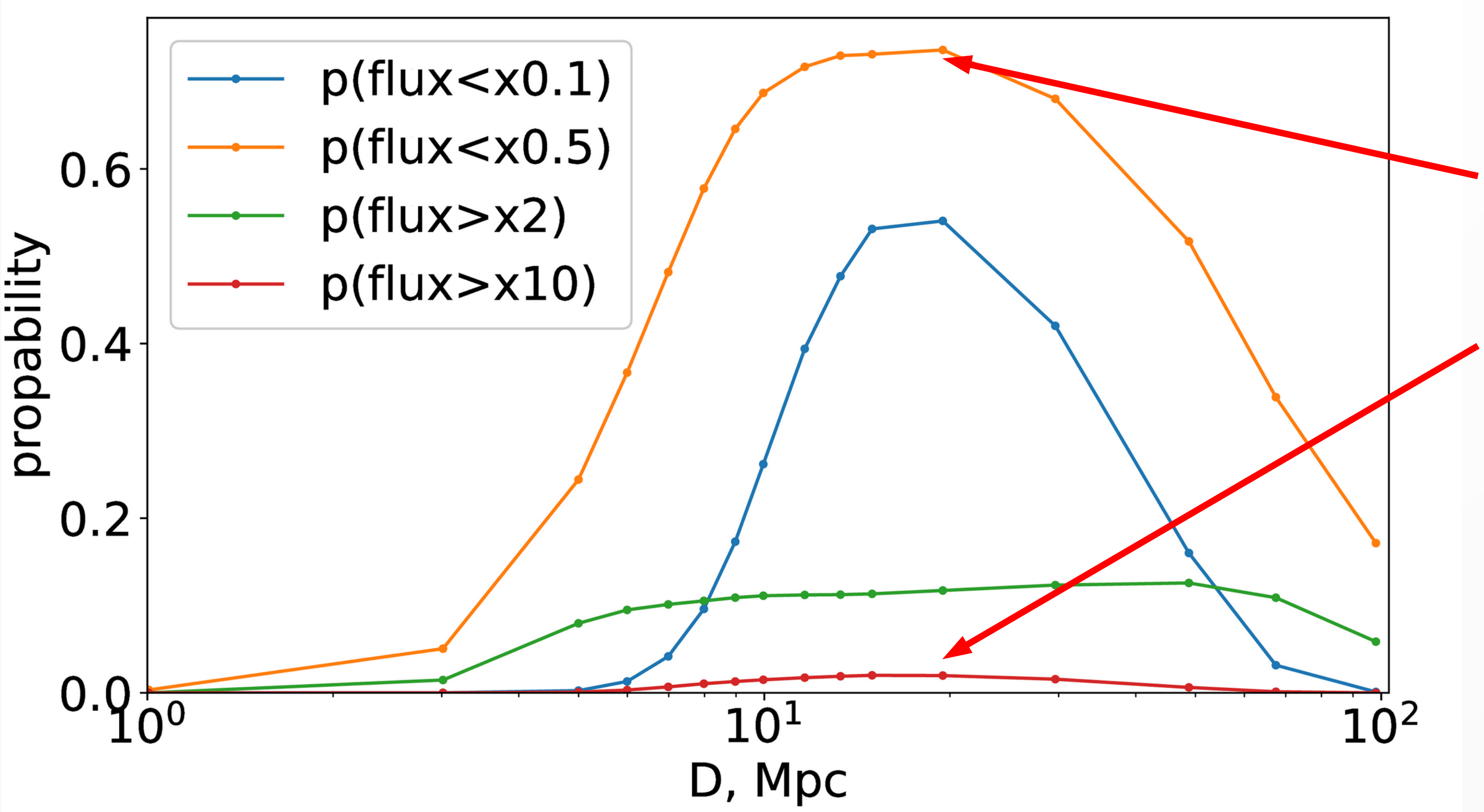
Magnetic void – large region with flux deficit

Magnetic filament – sausage-like structure with moderately amplified flux

Magnetic knot – small region with the strongest flux amplification

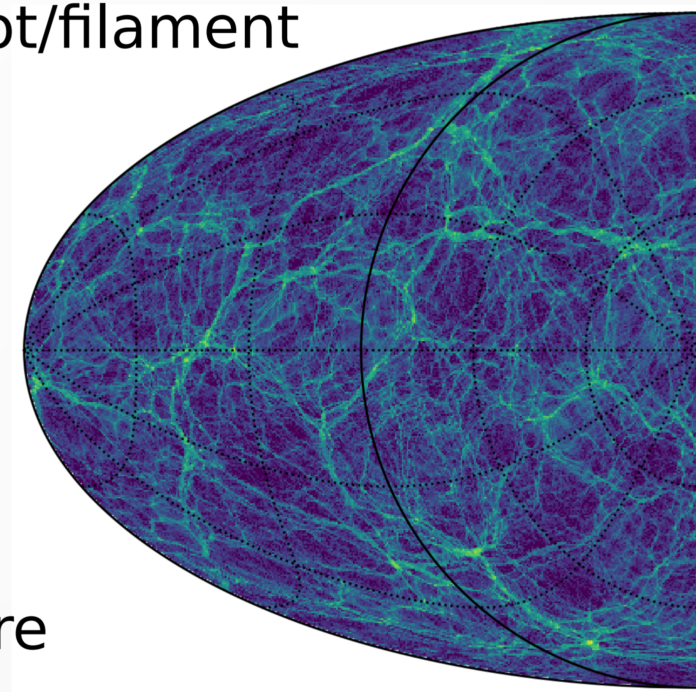
Observed brightness of the source strongly depends on the position of the observer!

Probability of voids/knots



Probability to be in void

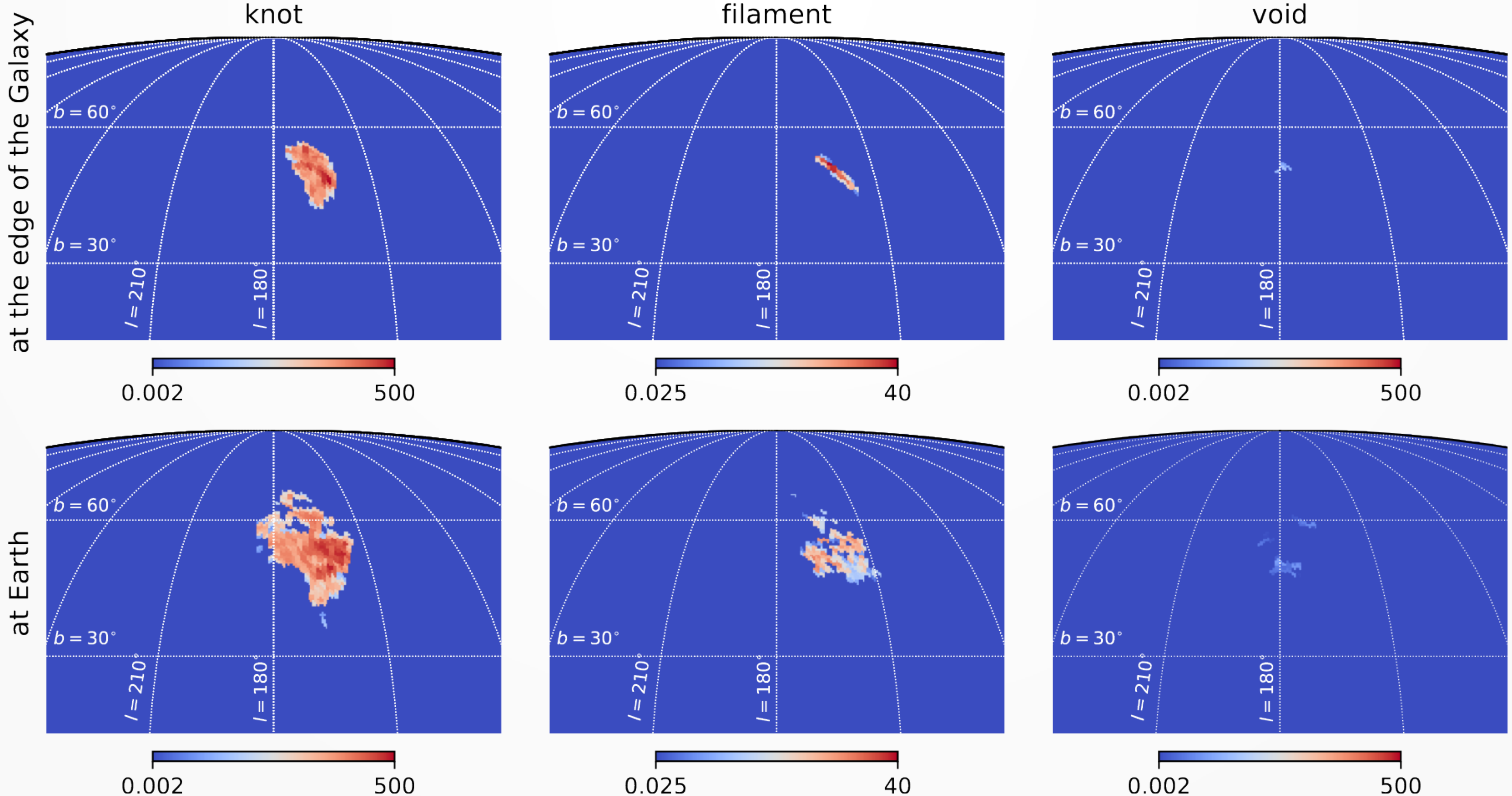
Probability to be in knot/filament



$$\lambda_C = 1\,Mpc$$
$$B = 1\,nG$$

The average flux on the entire sphere around the source remains constant

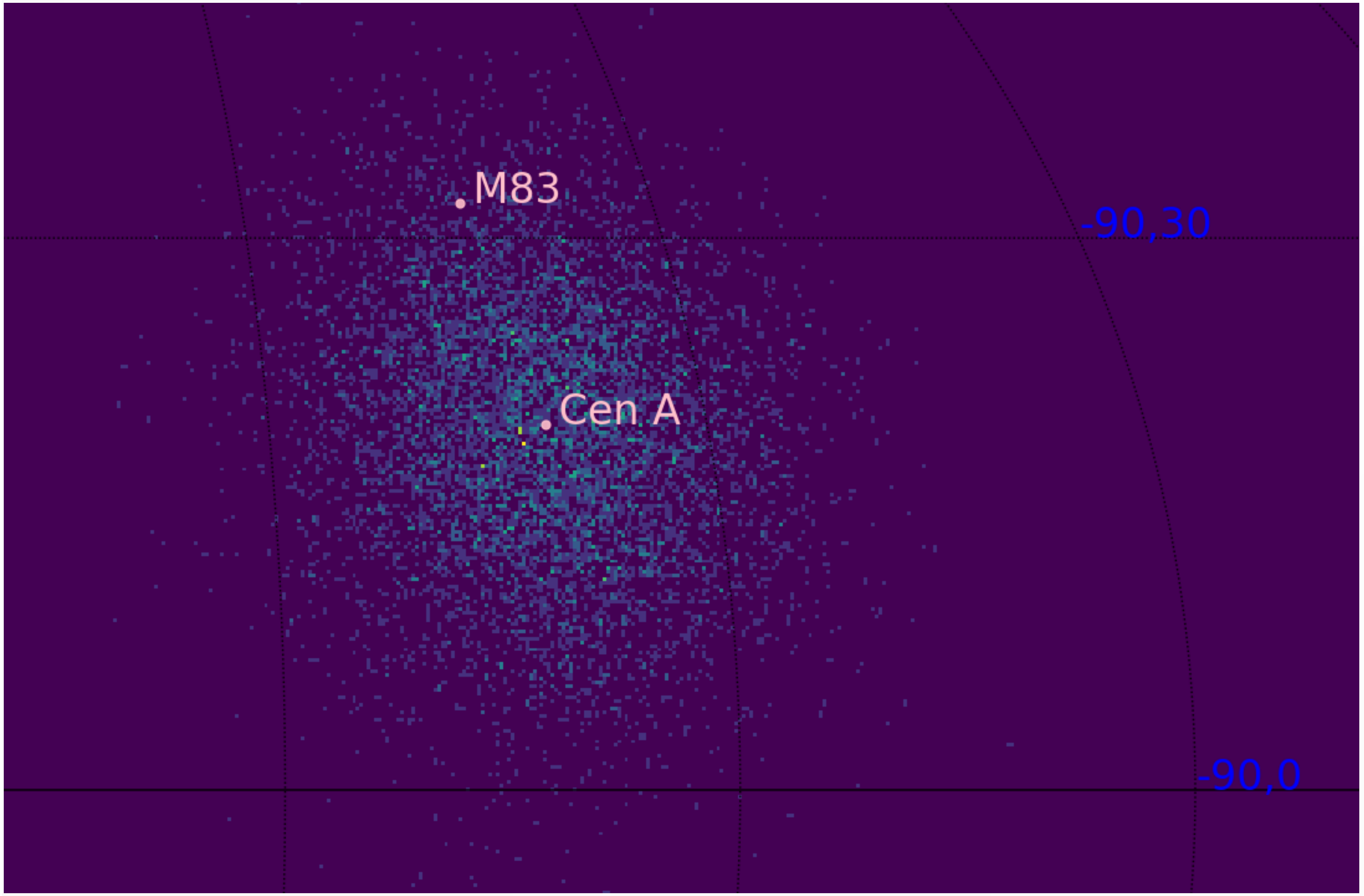
What does observer see? GMF



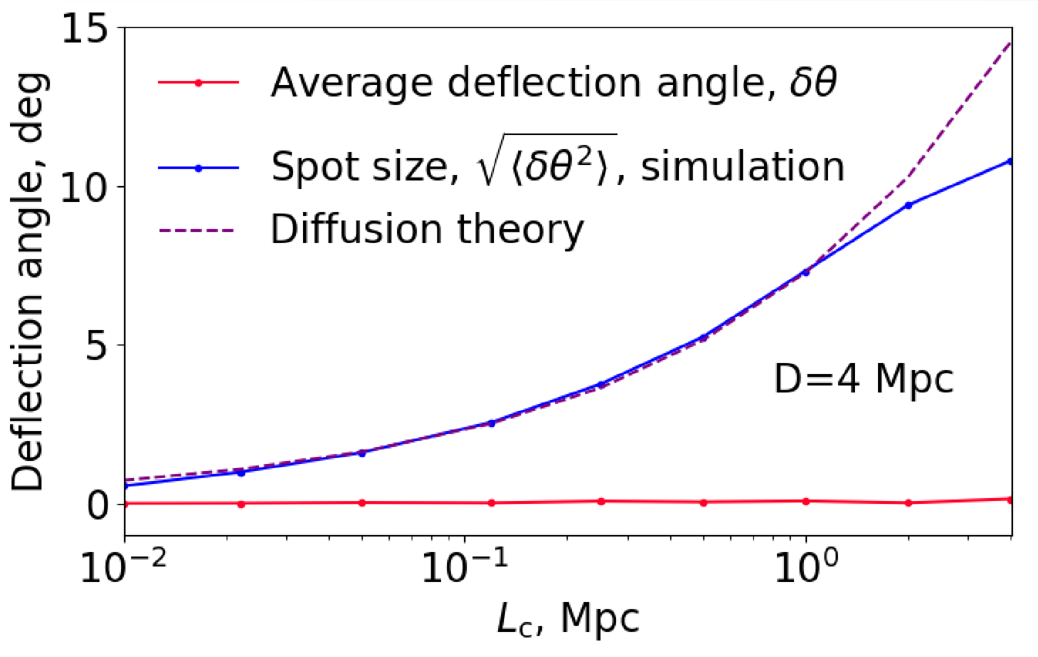
The position of the source in the sky was chosen to approximately coincide with the position of the TA hotspot

GMF model Jansson&Farrar+12

Approximation of uncorrelated trajectories

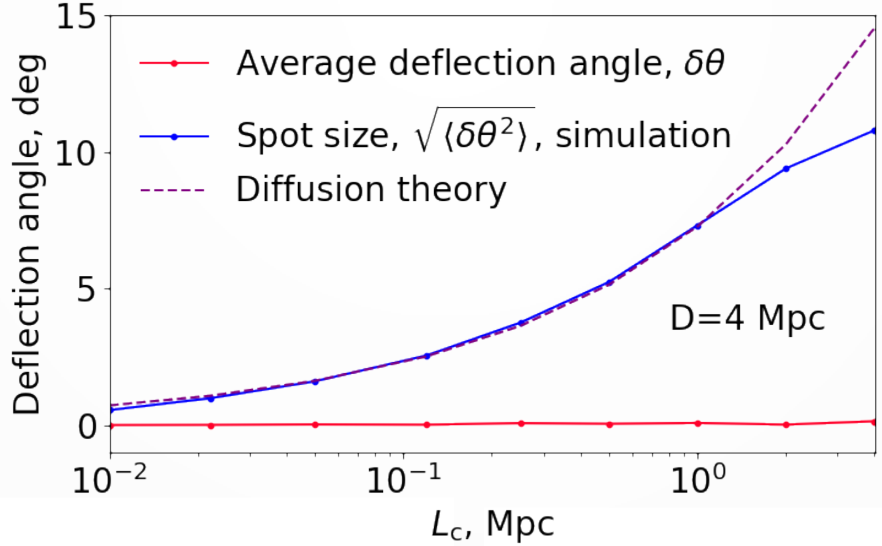


Random IGMF for every particle is not realistic

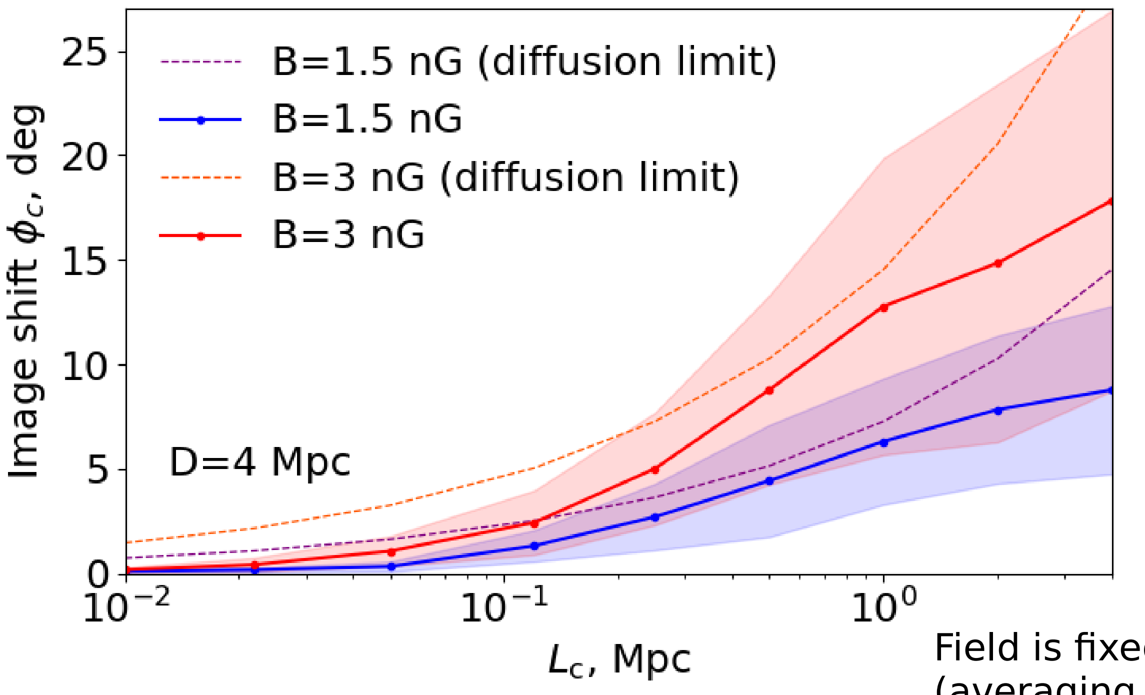


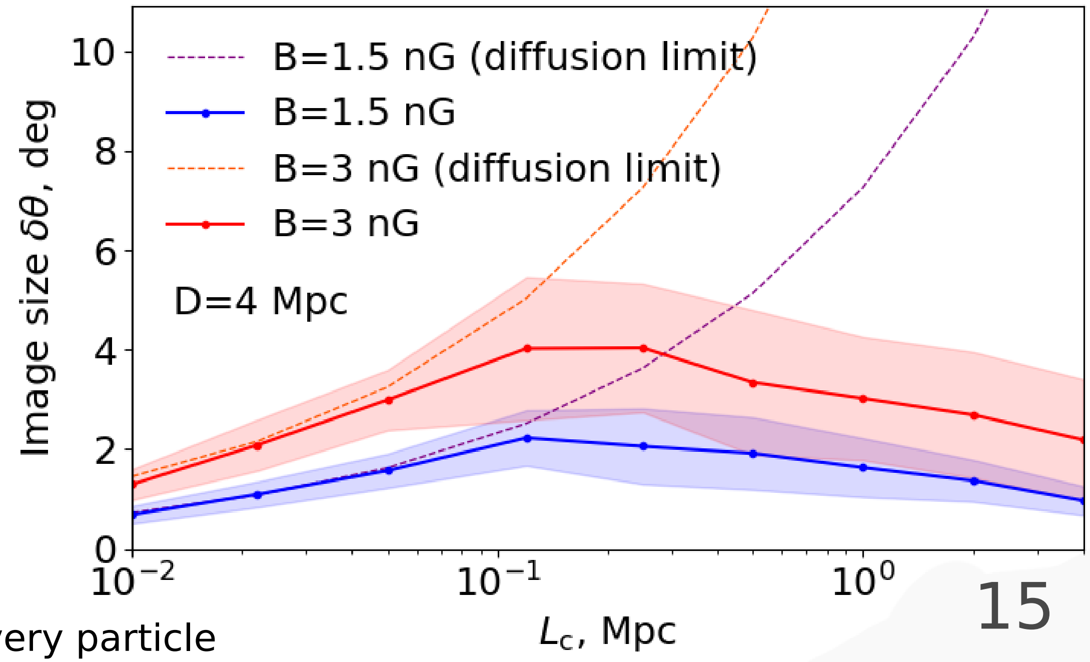
If each particle has its own implementation of the magnetic field, then the spot shift is zero.

Image shift in turbulent IGMF



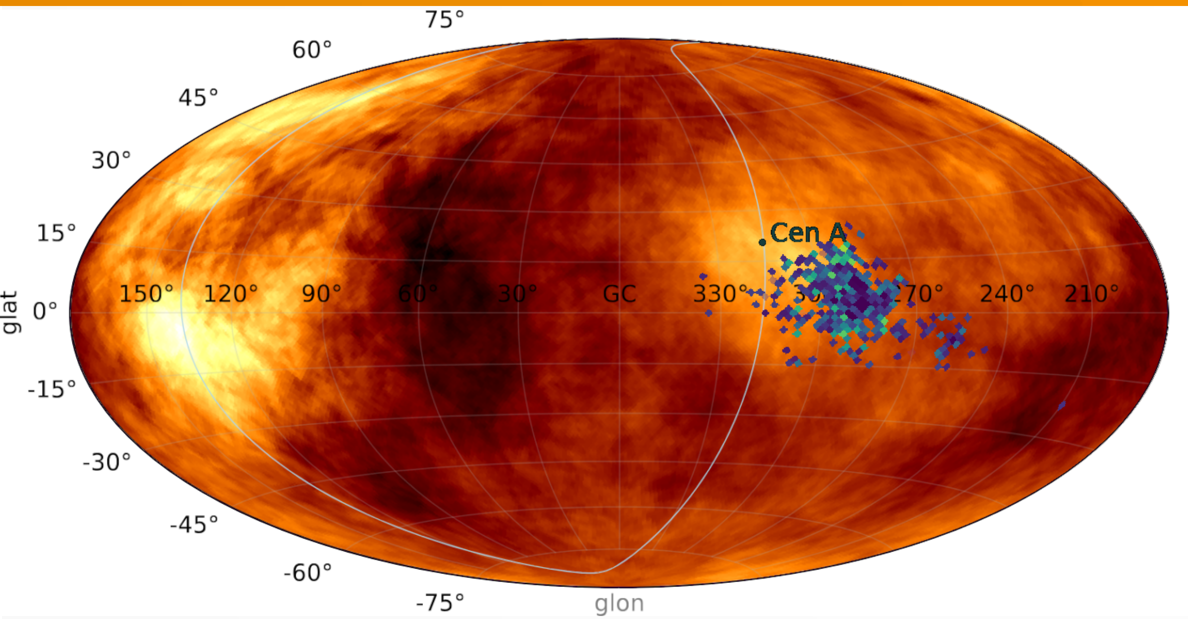
Random field for every particle

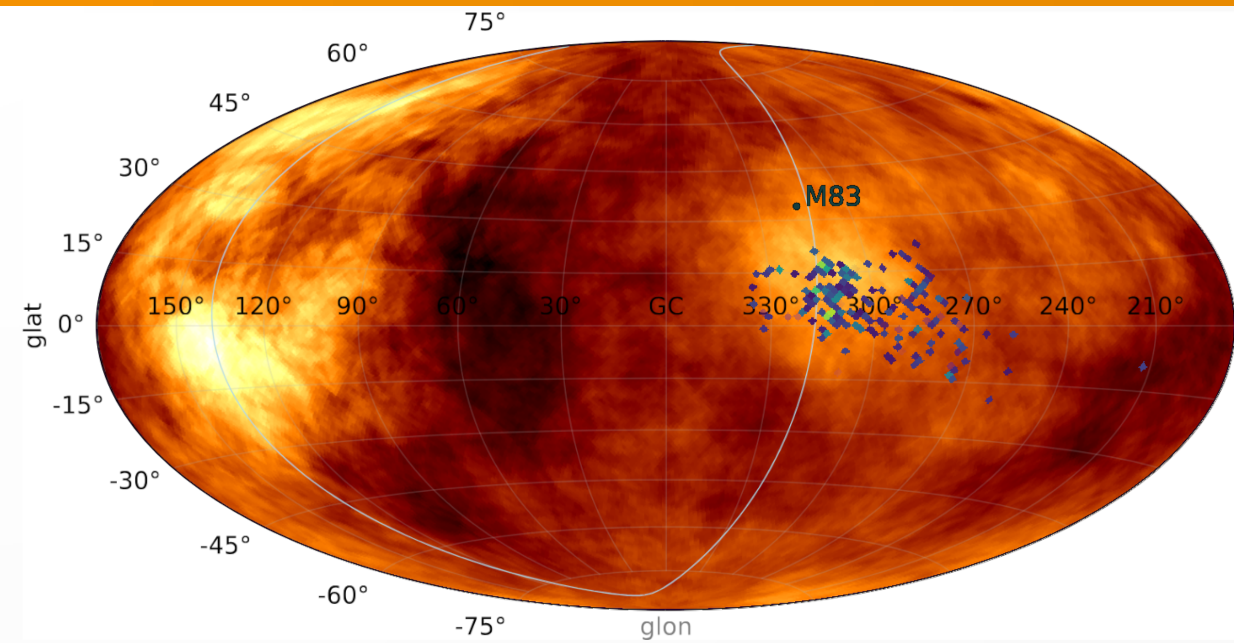




Field is fixed for every particle
(averaging over 20+ realizations)

"Cen A" hotspot: M83 or Cen A?

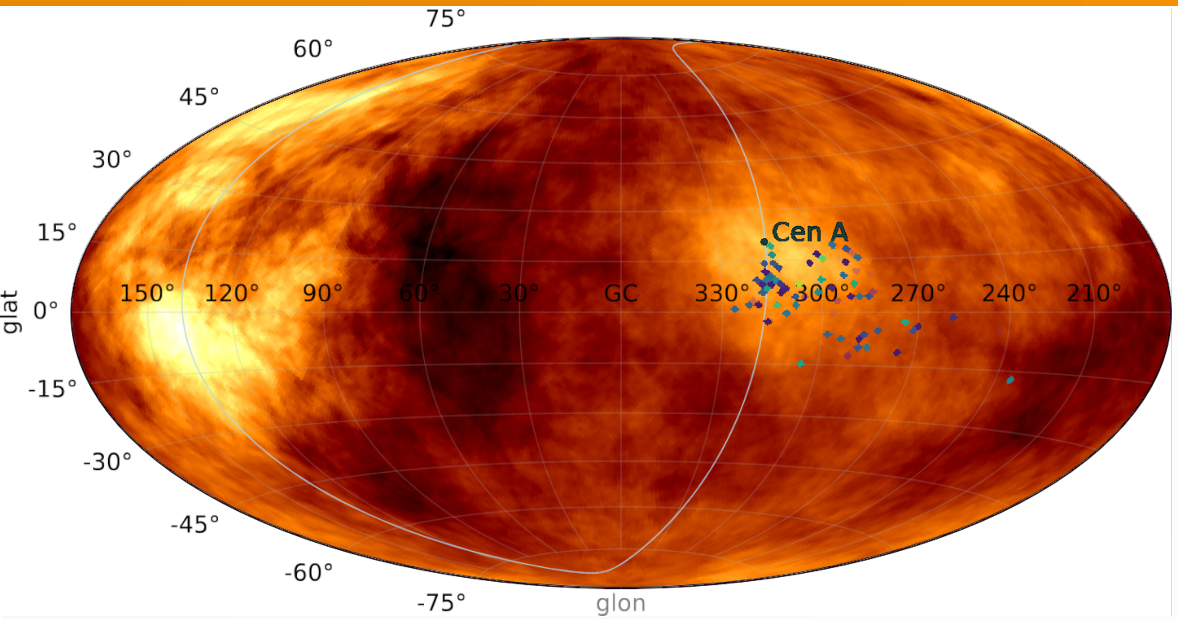


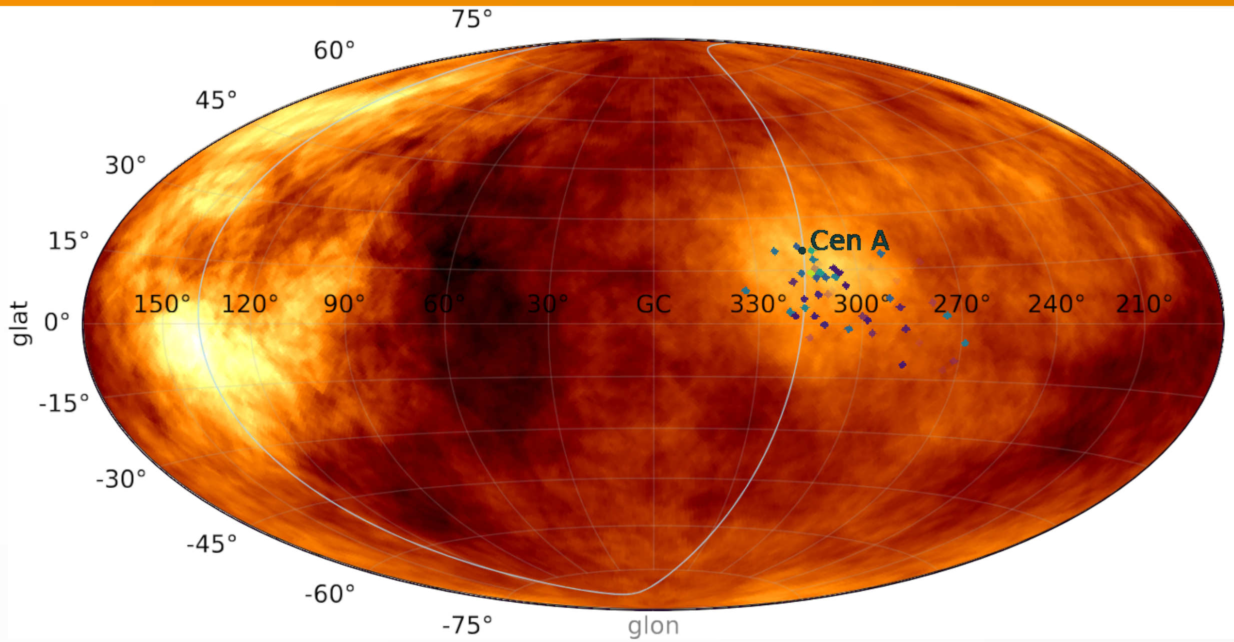


Carbon nuclei with E = 60 EeV
from Cen A
B=1.5 nG
Lc=0.05 Mpc
GMF in JF12 model

Carbon nuclei with E = 60 EeV
from M83
B=1.5 nG
Lc=0.05 Mpc
GMF in JF12 model

“Cen A” hotspot: Cen A tuning





Carbon nuclei with E = 60 EeV
from Cen A
B=1.5 nG
Lc=3.35 Mpc
GMF in JF12 model

Carbon nuclei with E = 60 EeV
from Cen A
B=3 nG
Lc=0.3 Mpc
GMF in JF12 model

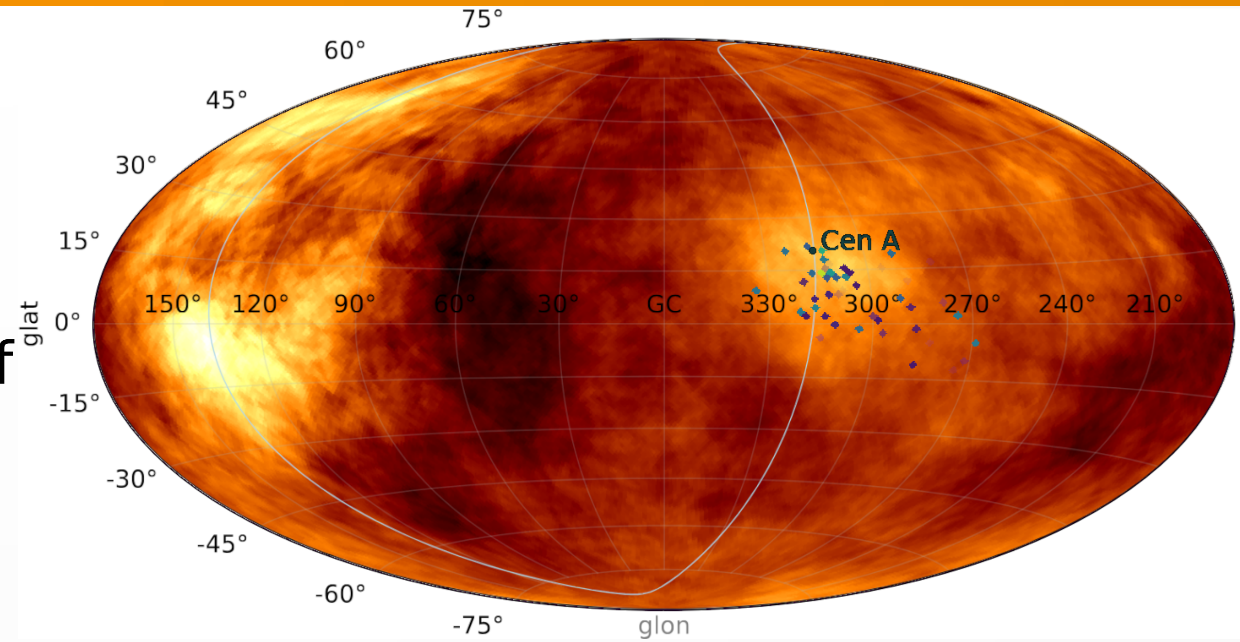
The angular distance between Cen A and M83 is about 12.5 degrees.
Deviations in IGMF can provide this shift.

Application for Cen A hotspot

The probability of a shift in the MGMP by more than 12° → 13%

The probability of matching the direction of deviation is approximately 15°/360° → 4%

Final probability → about 0.5%



Carbon nuclei with E = 60 EeV
from Cen A
B=3 nG
Lc=0.3 Mpc
GMF in JF12 model

The angular distance between Cen A and M83 is about 12.5 degrees.
Deviations in IGMF can provide this shift.

Conclusions

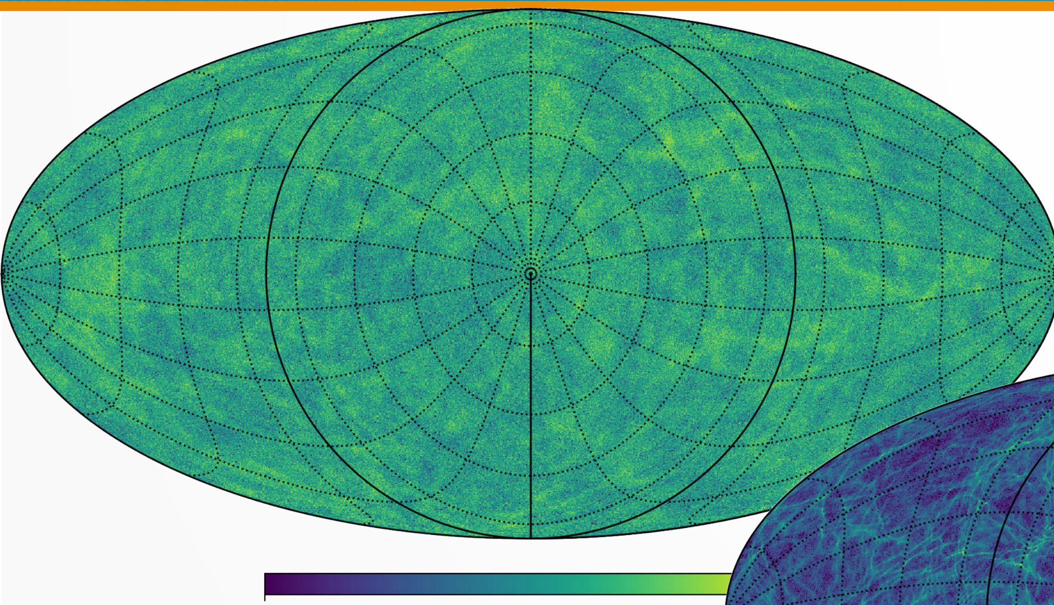
We can explain

- size of observed UHECR hotspots by propagation effect in strong IGMF
- absence of point sources
- possible explanations of CenA hotspot

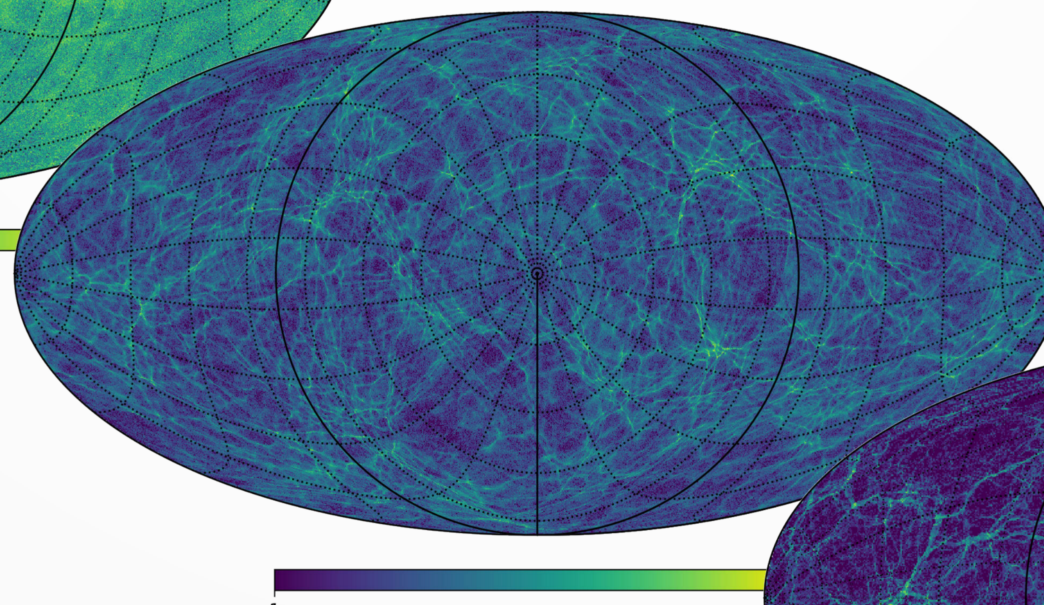
Thank you for your attention

Backup: Forming the structure

What if turn off magnetic field after some distances?

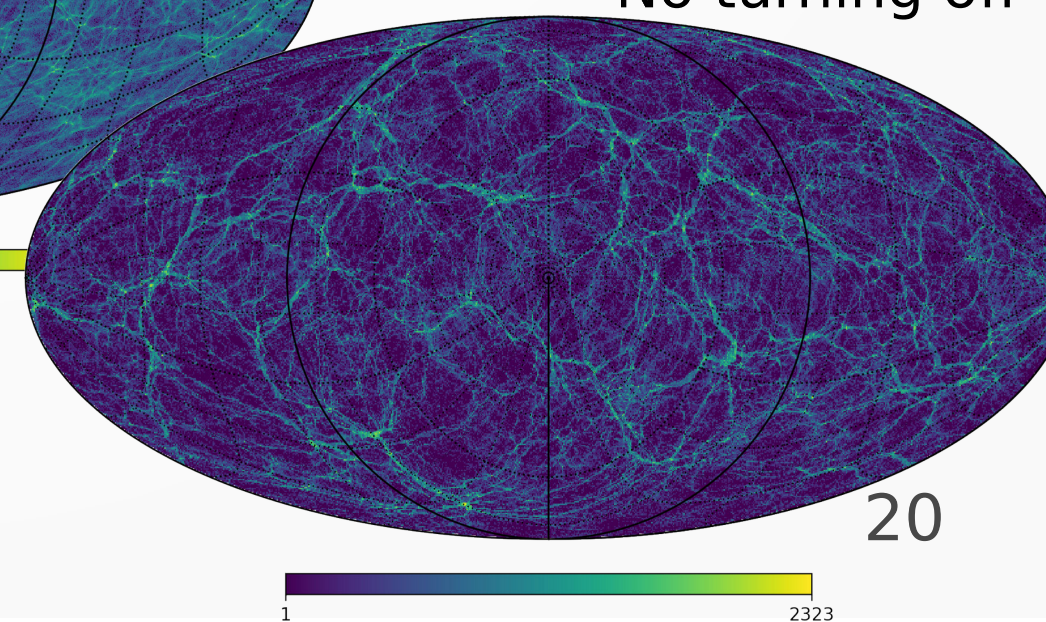


Turning off on D=1 Mpc



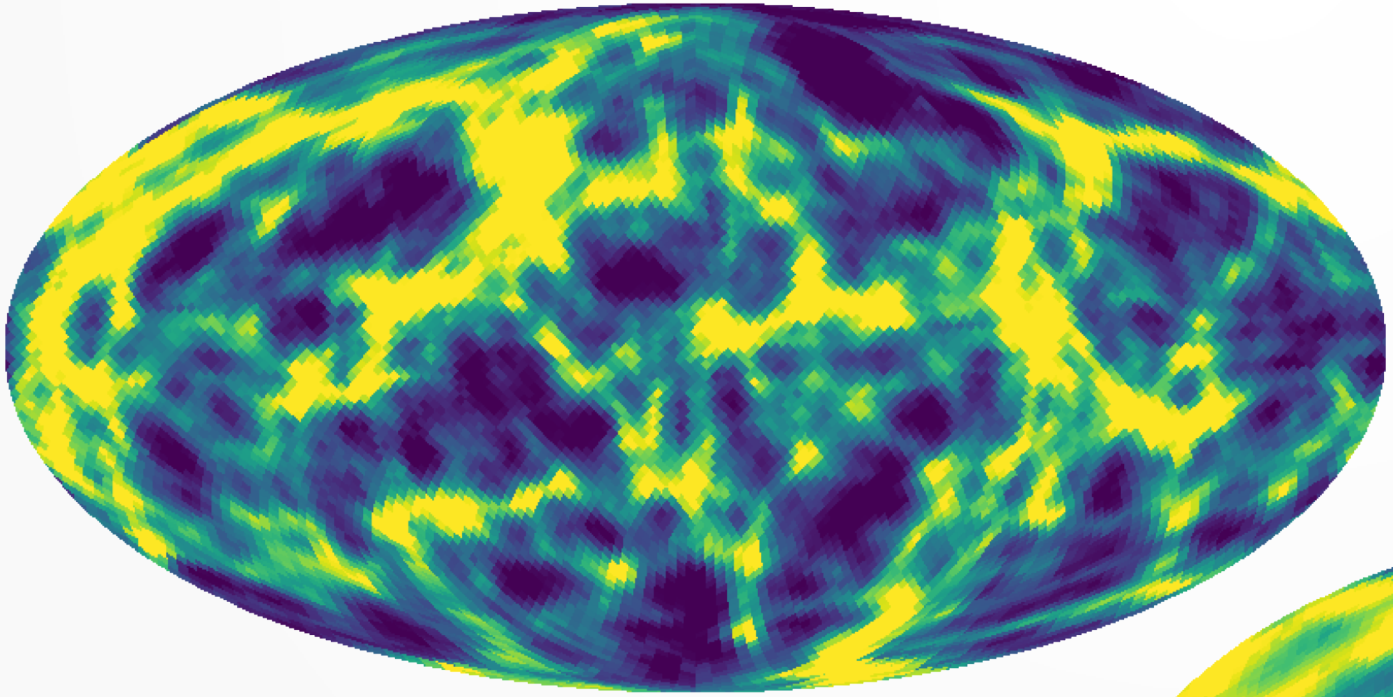
Turning off on D=3 Mpc

No turning off

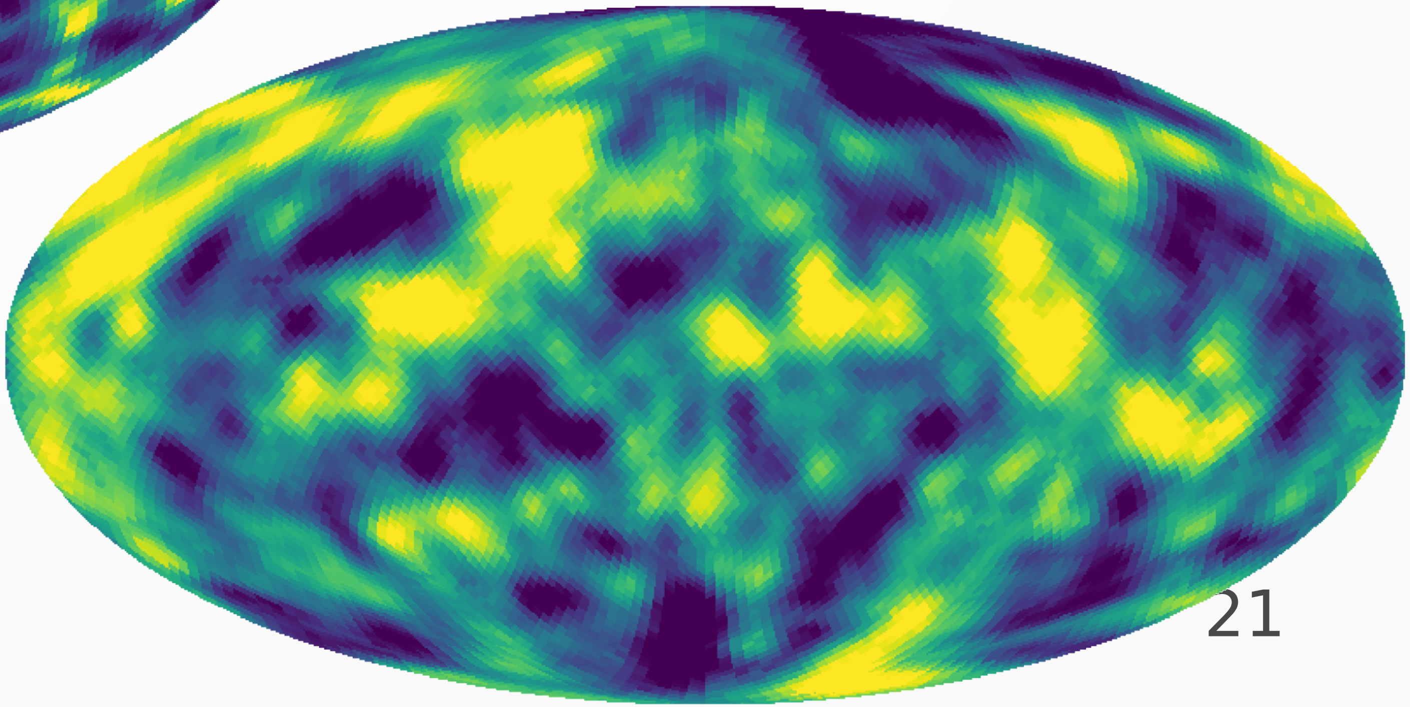


Backup: Correlation with rotB

Particle distribution, λ_c=1 Mpc, D=5 Mpc



Integral of the magnetic field rotor

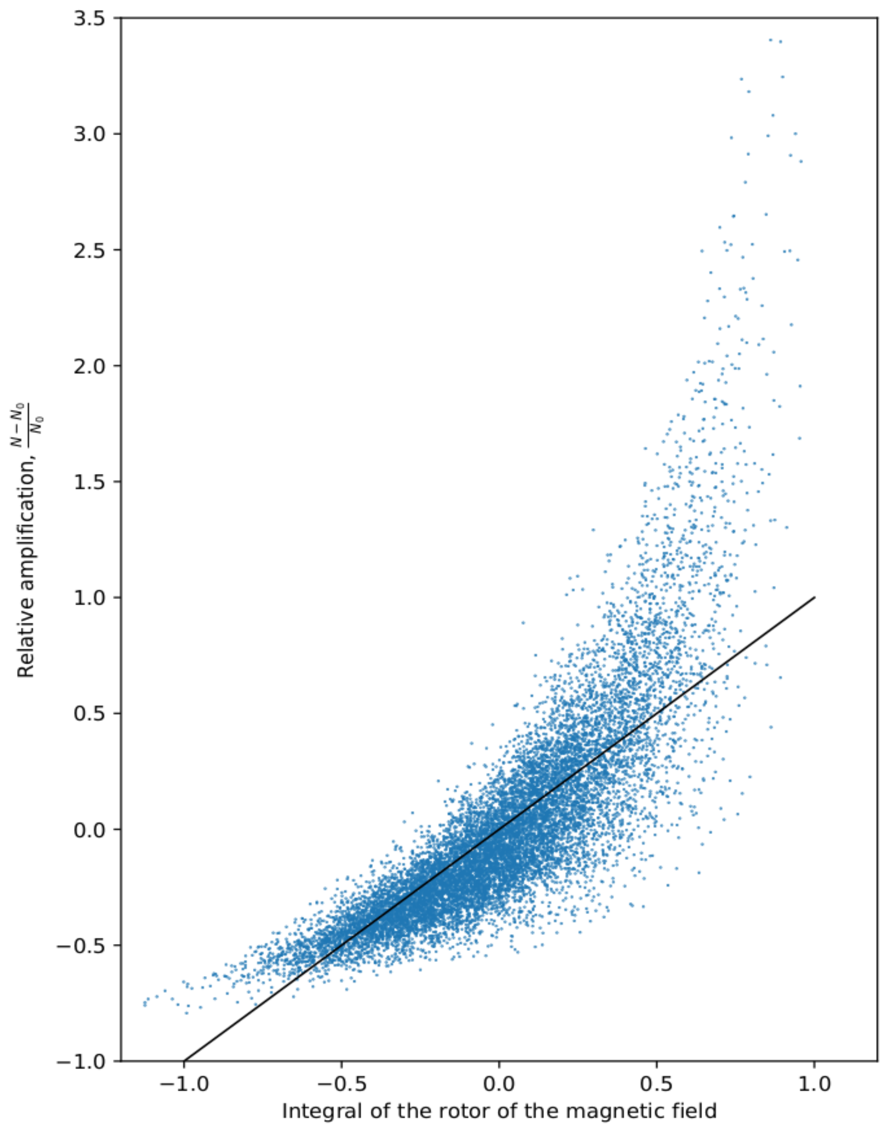


Explanation

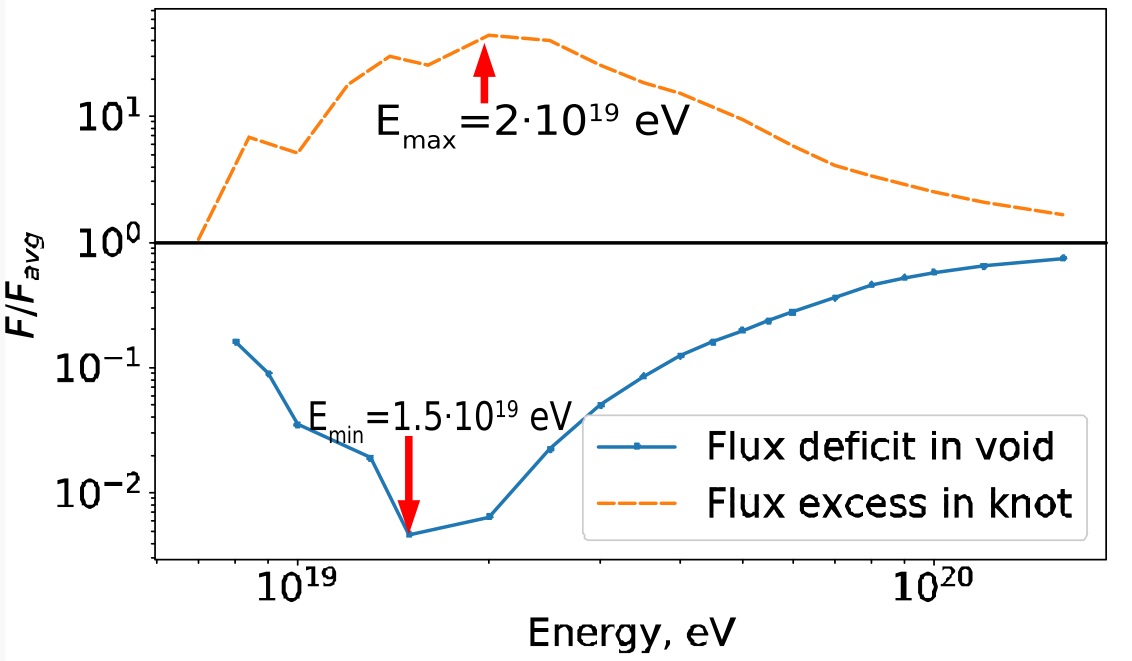
- Similar effect: Diego Harari et al. UHECR lensing in GMF (parallel beam)

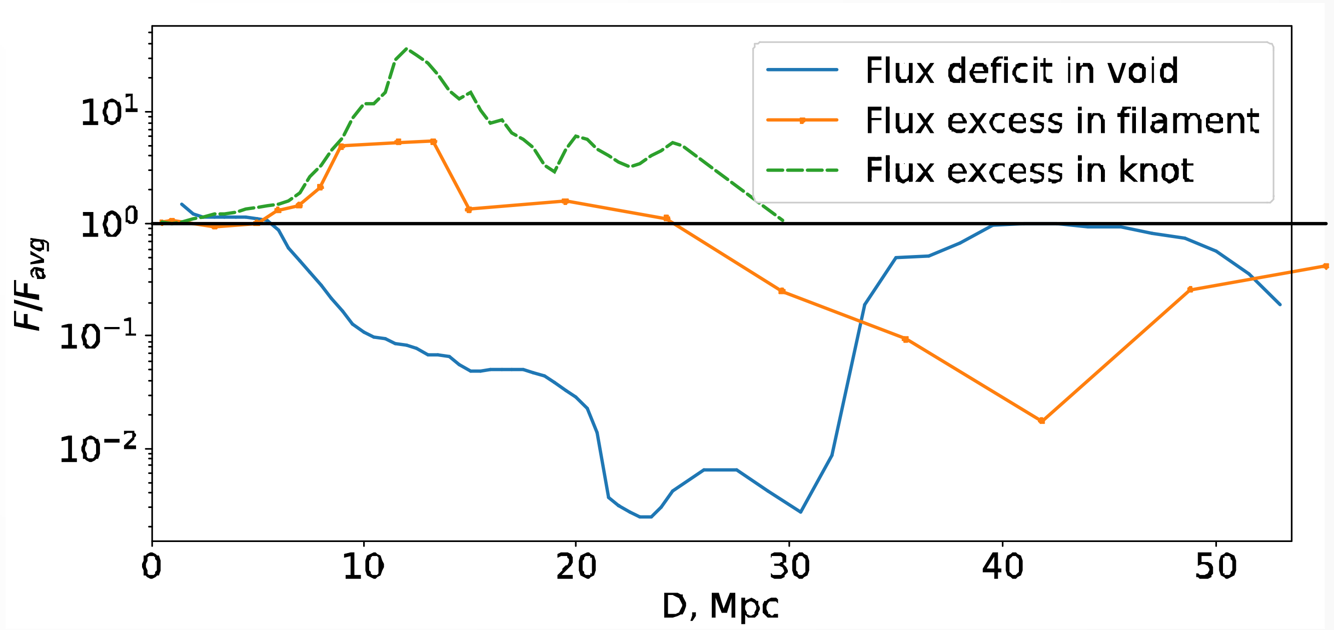
- Flux amplification for the diverging beam:

$$A(D) = A_0 \left(1 - \frac{Ze}{E} \int\limits_0^D s \left(1 - \frac{s}{D}\right) (\mathrm{rot}\vec{B} \cdot \mathrm{d}\vec{s}) \right)$$



Length of structures





Knot: D=20 Mpc
Void: D=30 Mpc

Rigidity 10 EV in all cases

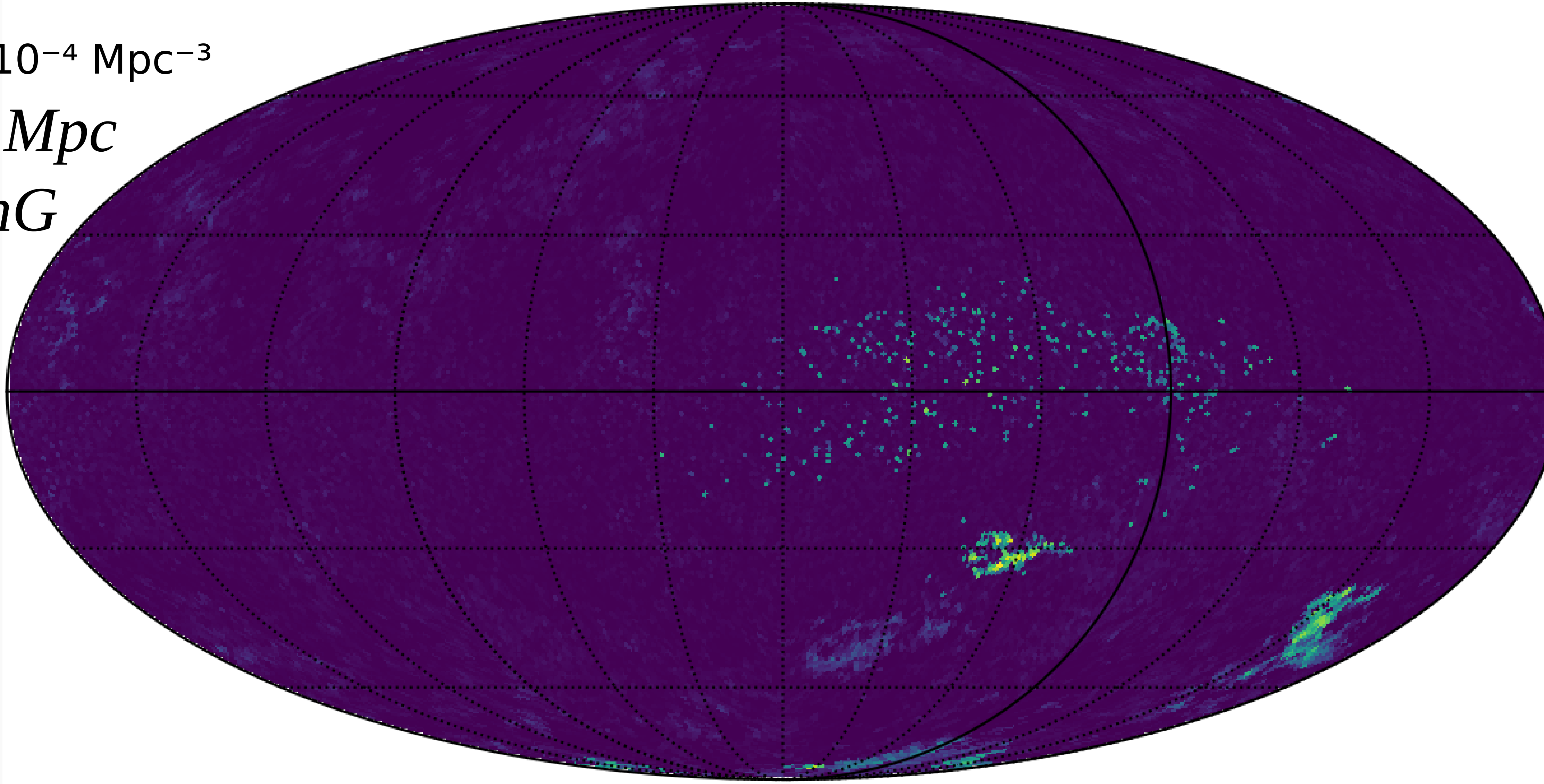
$$\lambda_C = 1\,Mpc$$
$$B = 1\,nG$$

What does observer see? Set of sources

n=1.5*10^{-4} Mpc^{-3}

$\lambda_C = 1\,Mpc$

$B = 1\,nG$



GMF model Jansson&Farrar+12