Caustic-like Structures in UHECR Flux after Propagation in Turbulent IGMF

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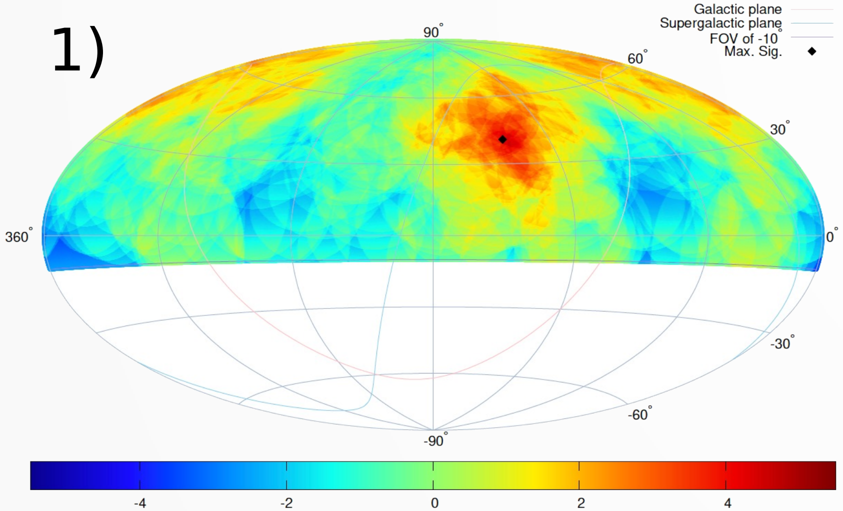
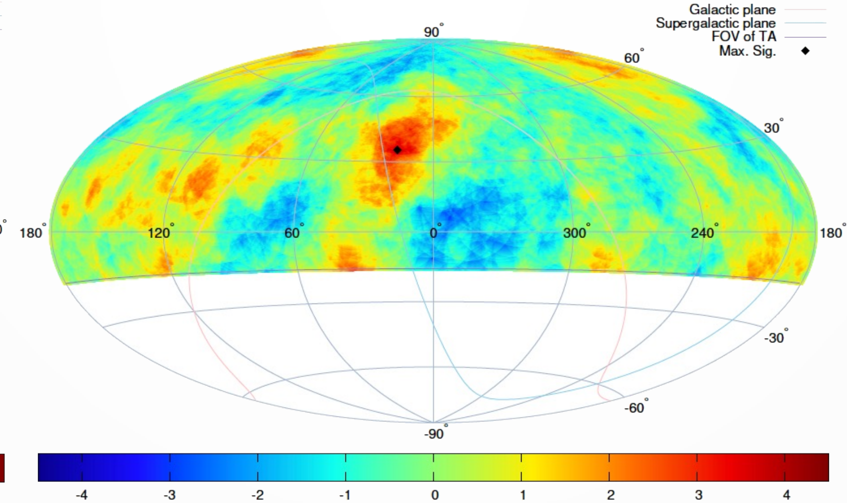
Motivation: TA & PAO hotspots

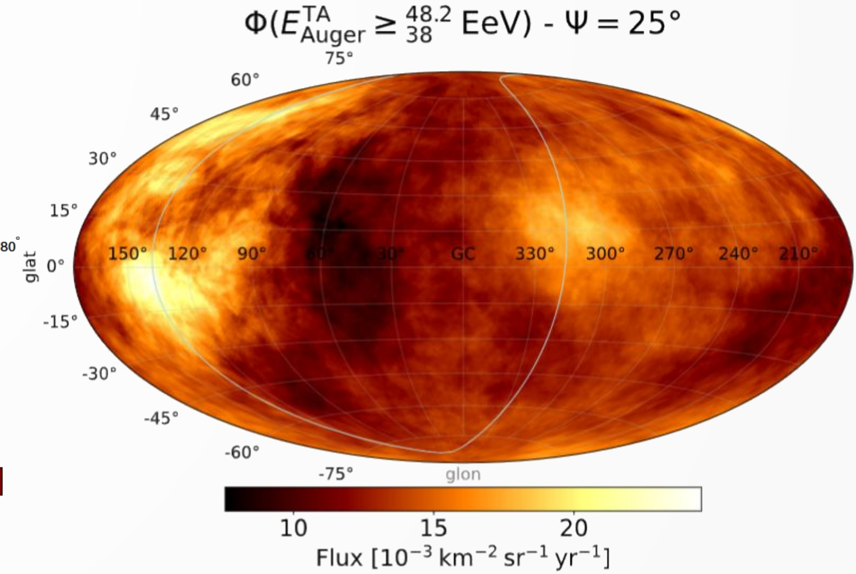
1)



Hotspot
$E > 5.7 \cdot 10^{19}$ eV



Perseus-Pisces direction
$E \geq 10^{19.4}$ eV $\approx 2.5 \cdot 10^{19}$ eV

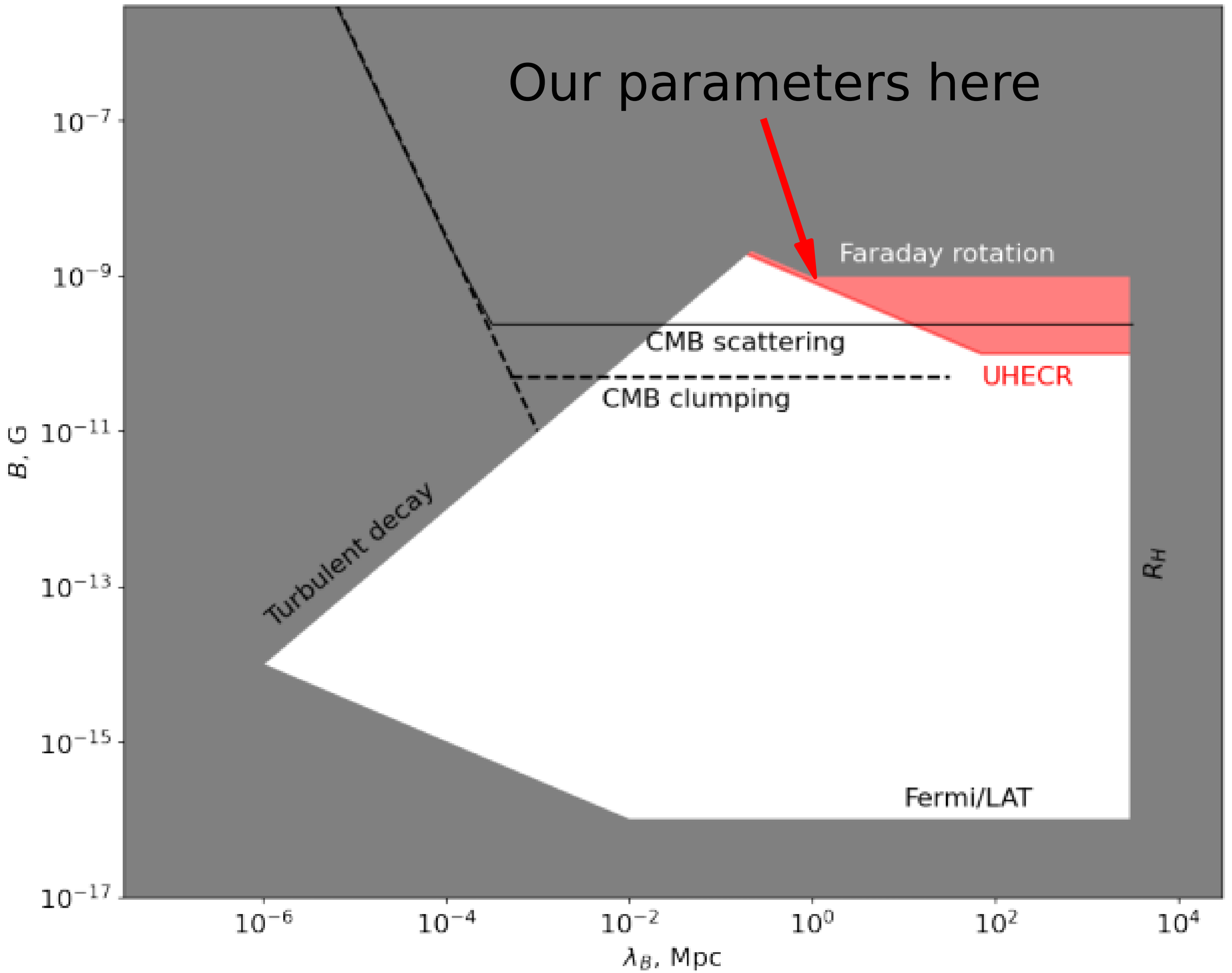


Cen A direction
$E > 3.8 \cdot 10^{19}$ eV

2) Absence of obvious point sources

See more: https://pos.sissa.it/444/521/

Constraints on the IGMF



Neronov+21

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

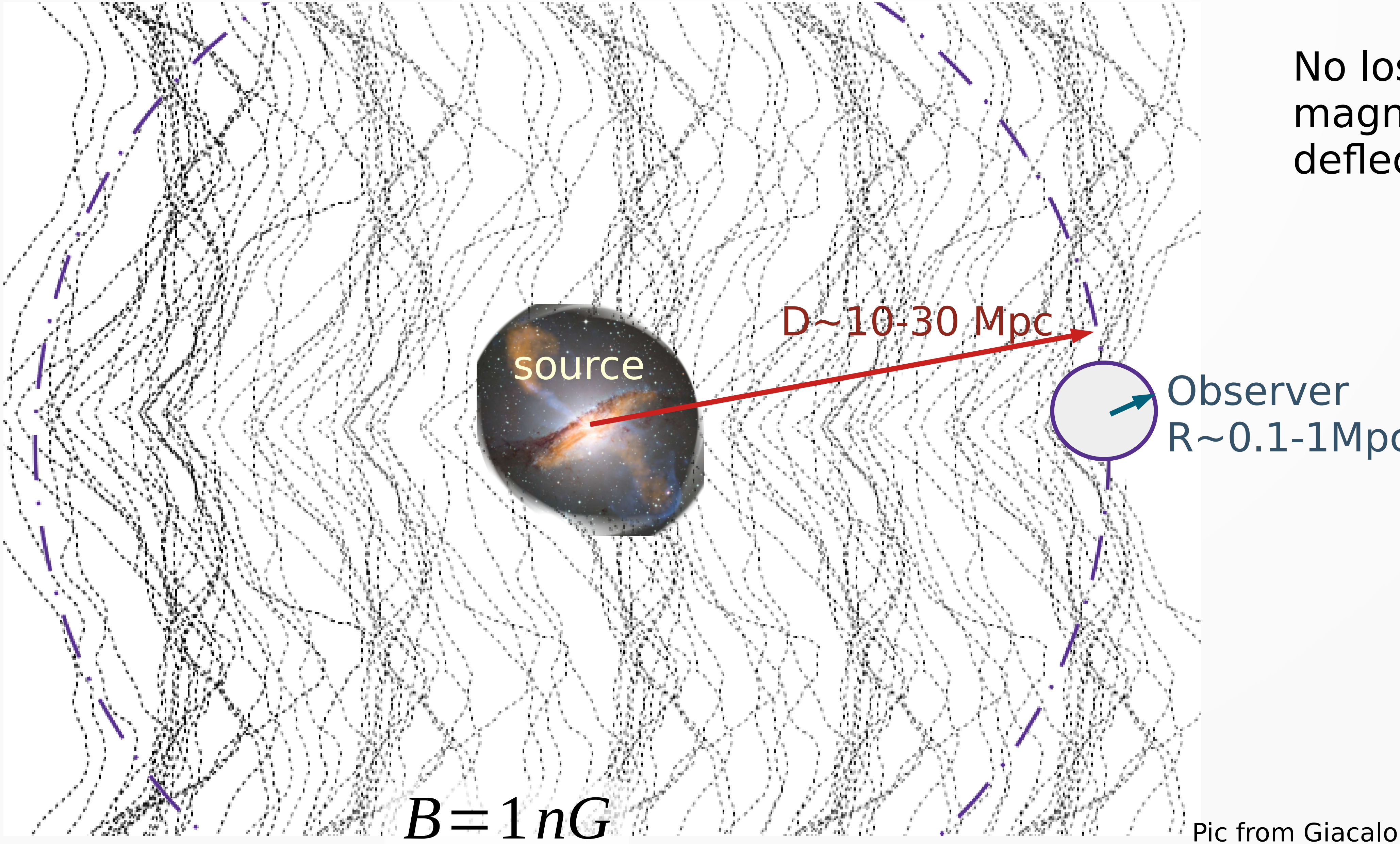
$$E \geq 10^{19}\, eV$$

$$B = 1\, nG$$

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

$$Z = 1$$

Simulation setup



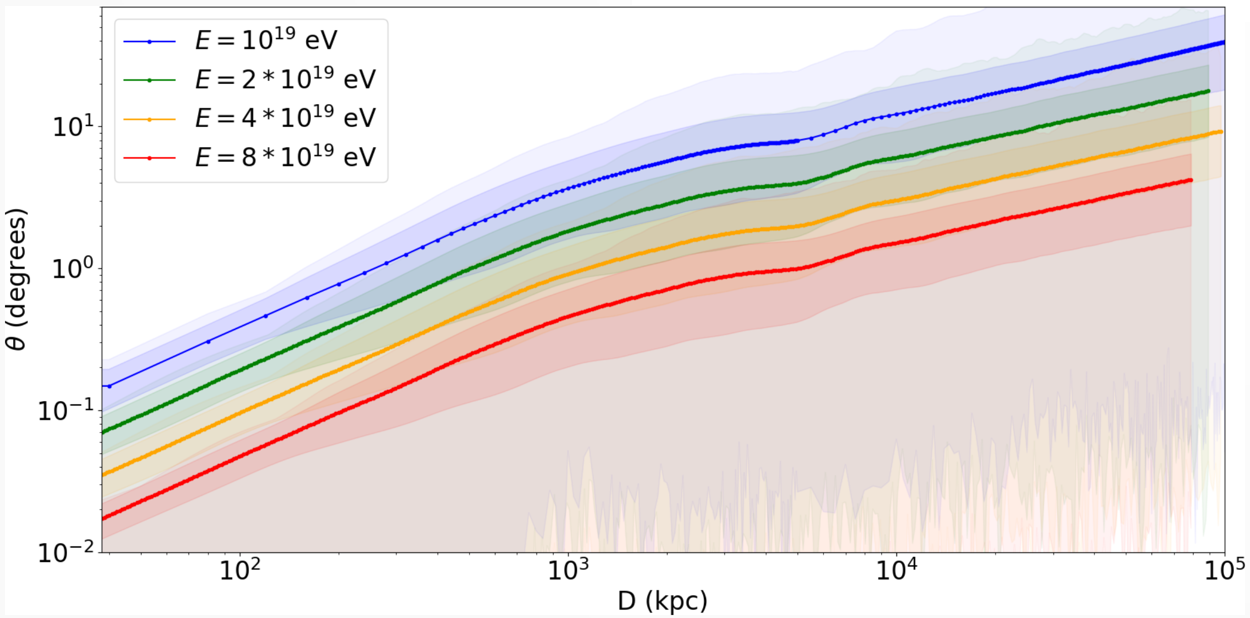
No losses, magnetic field deflection only

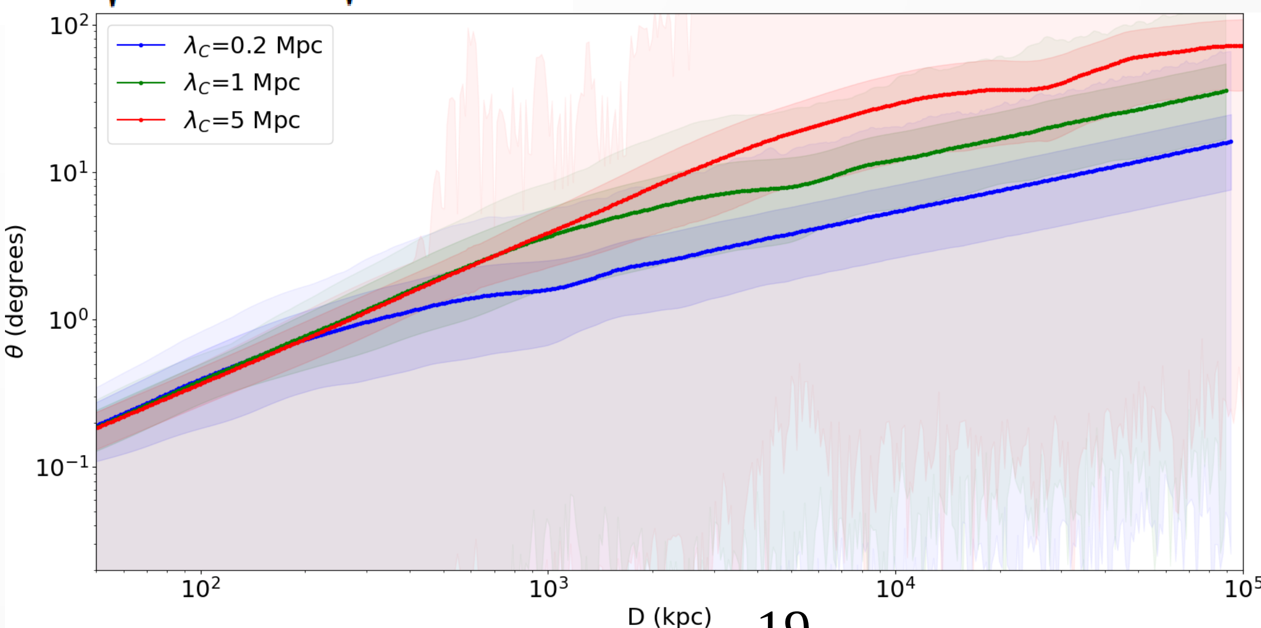
Pic from Giacalone&Jokipii99

1D picture

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

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

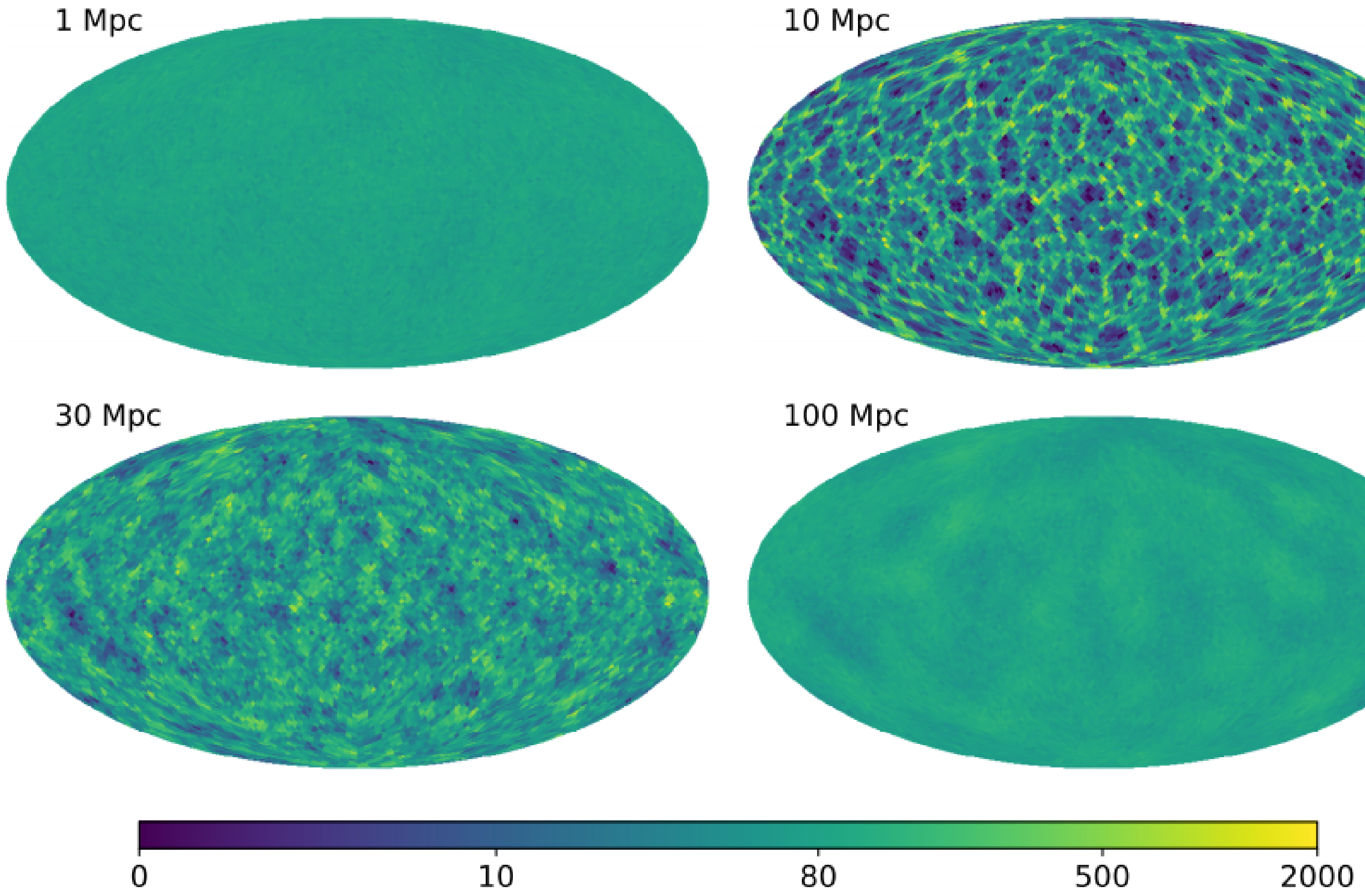




$\lambda_C = 1\,Mpc \quad B = 1\,nG$ $\qquad$ $B = 1\,nG \quad E = 10^{19}\,eV$

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

2D picture

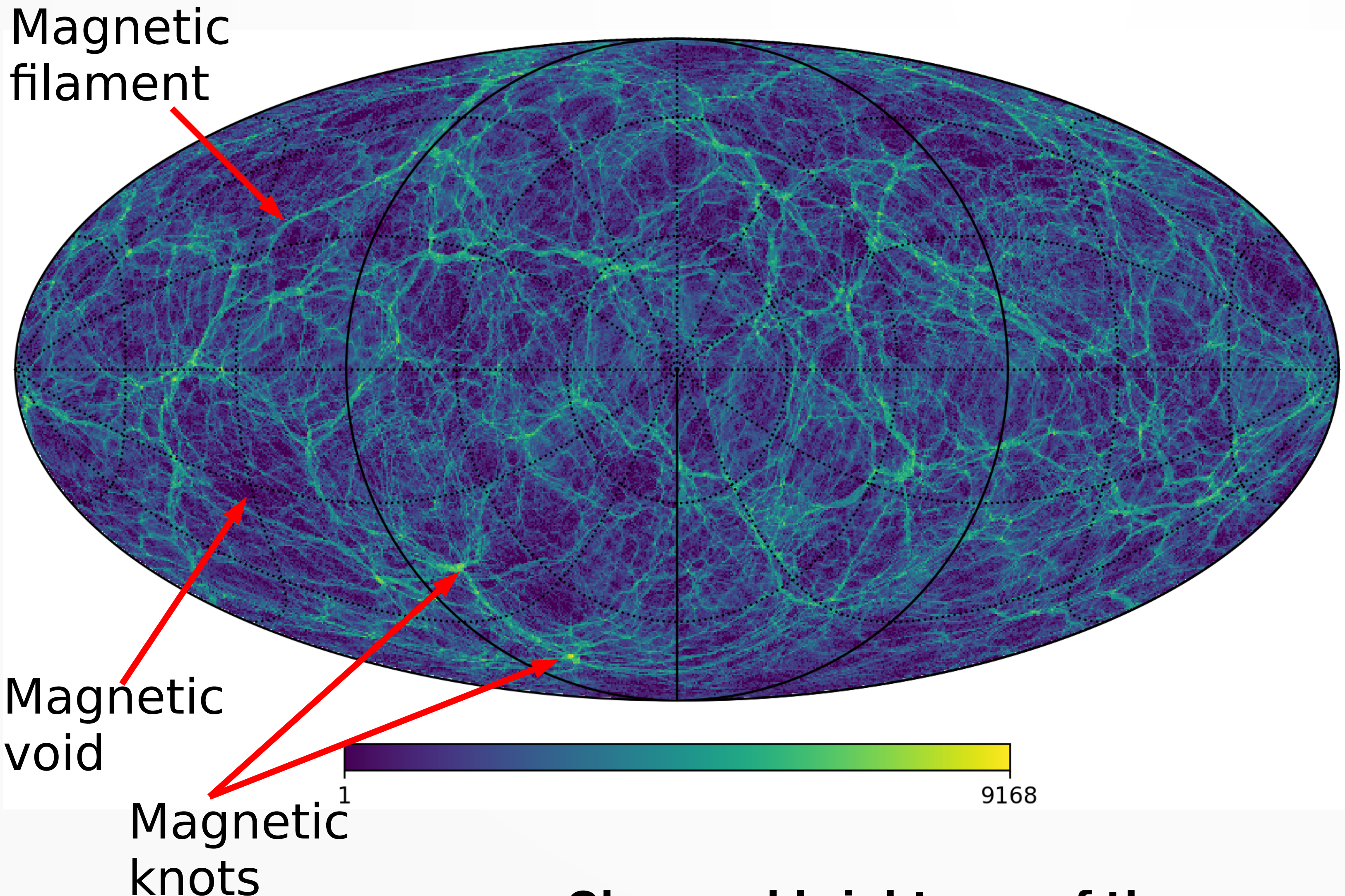


Distribution of cosmic rays on the spheres of different radius around the source

Medium-scale anisotropies first increase and then blur

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

2D picture



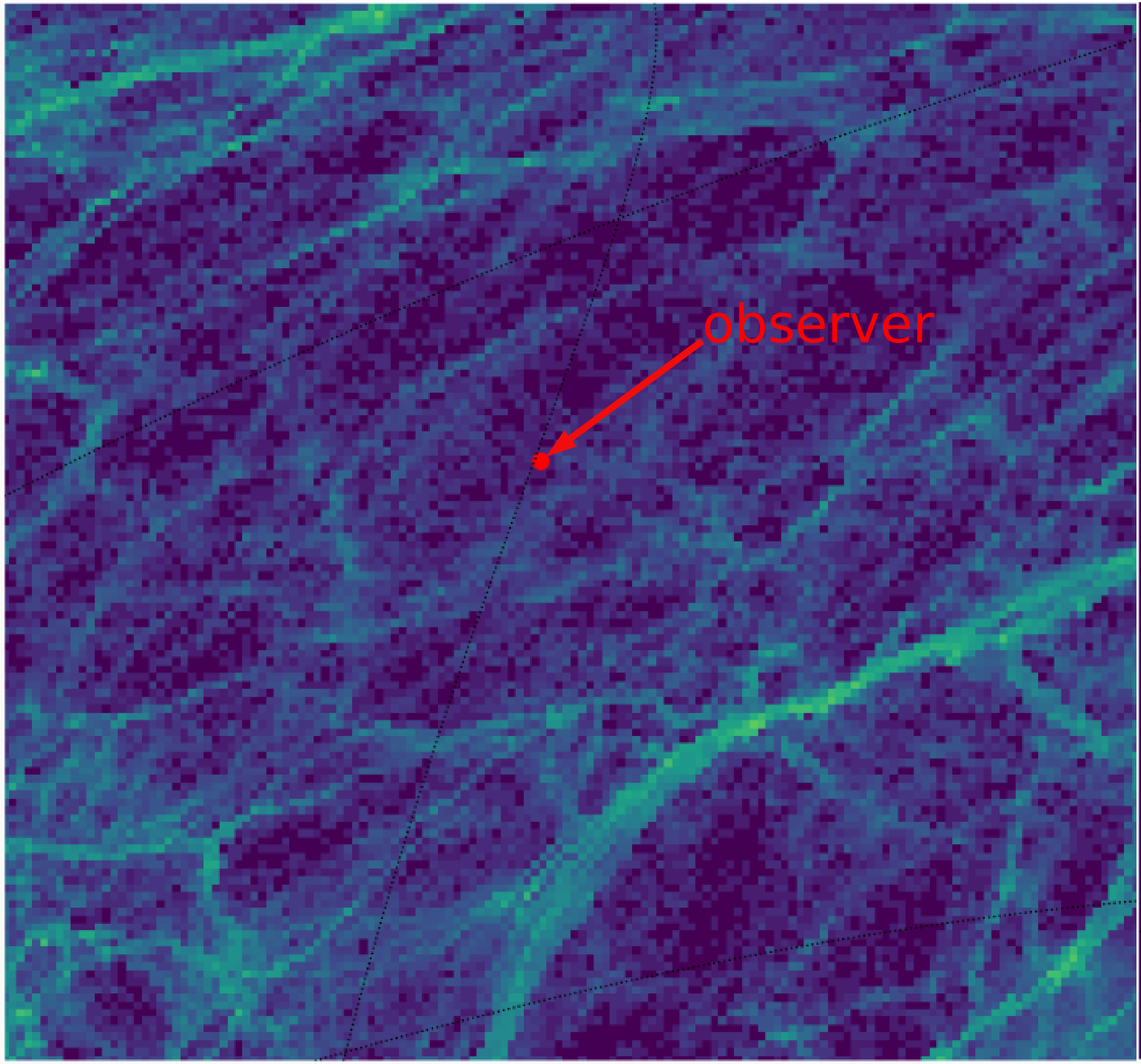
Magnetic void – large region with flux deficit

Magnetic filament – sausage-like structure with moderately amplified flux

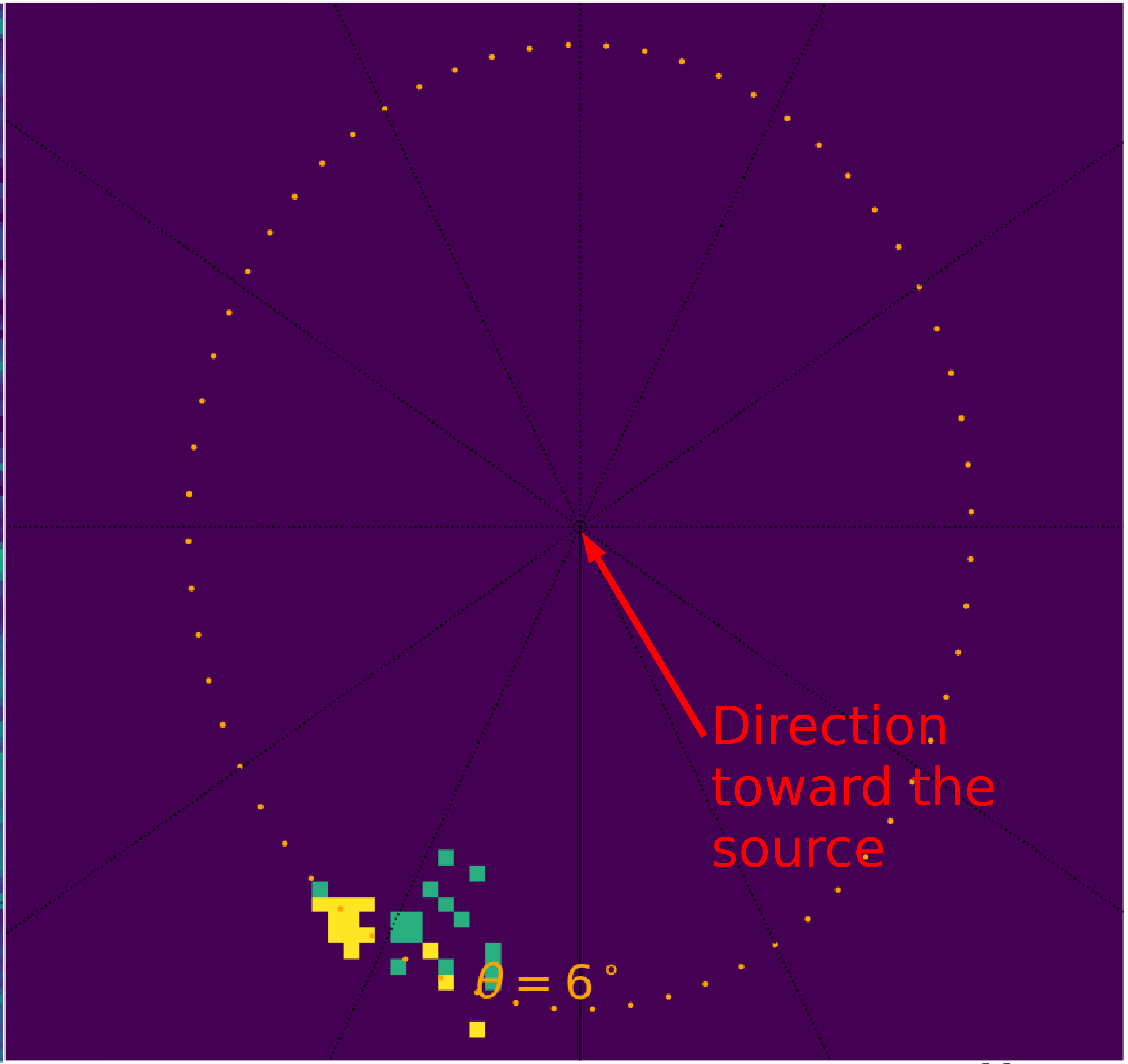
Magnetic knot – small region with the strongest flux amplification

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

Zoom into void

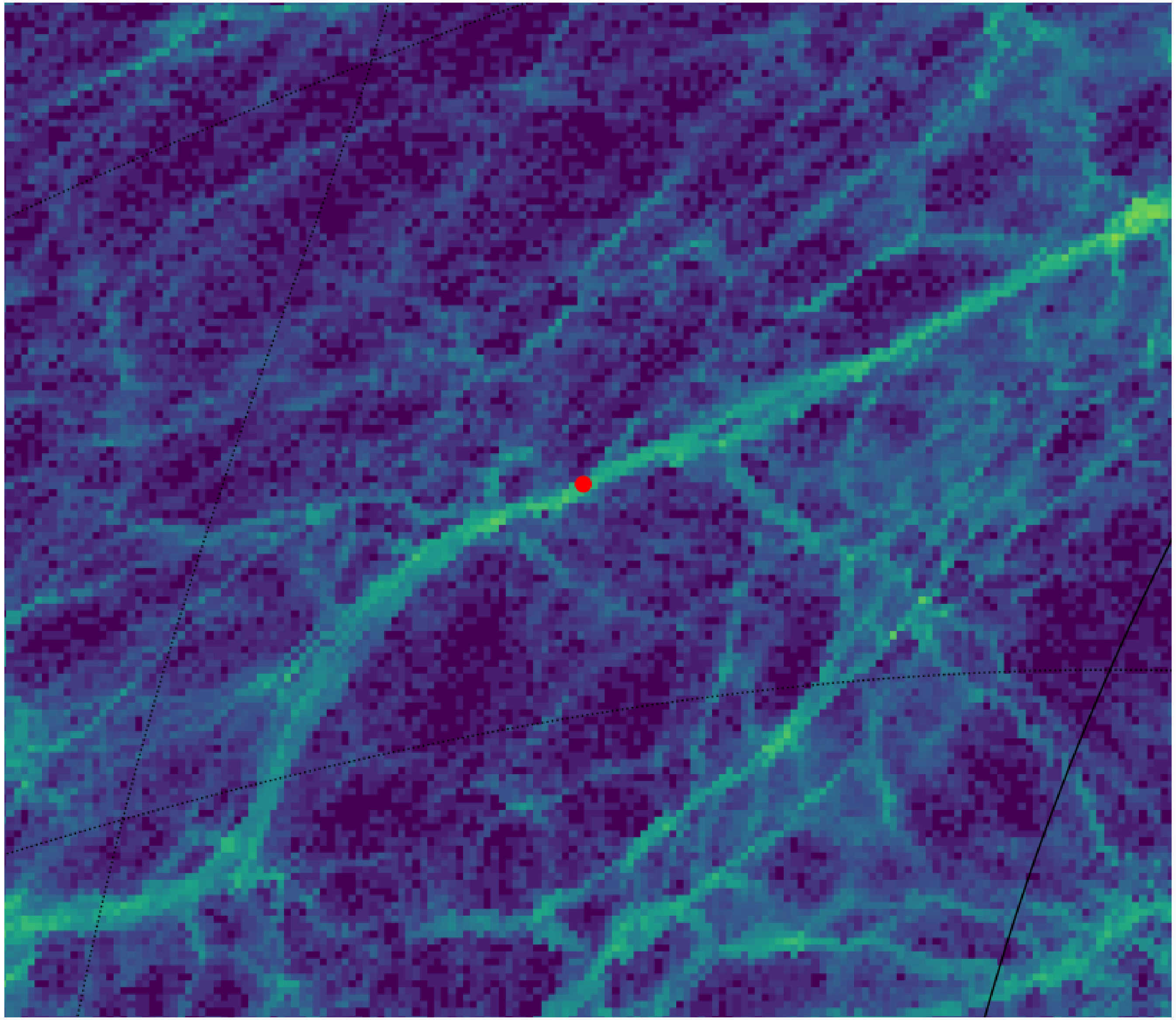


Zoom into void

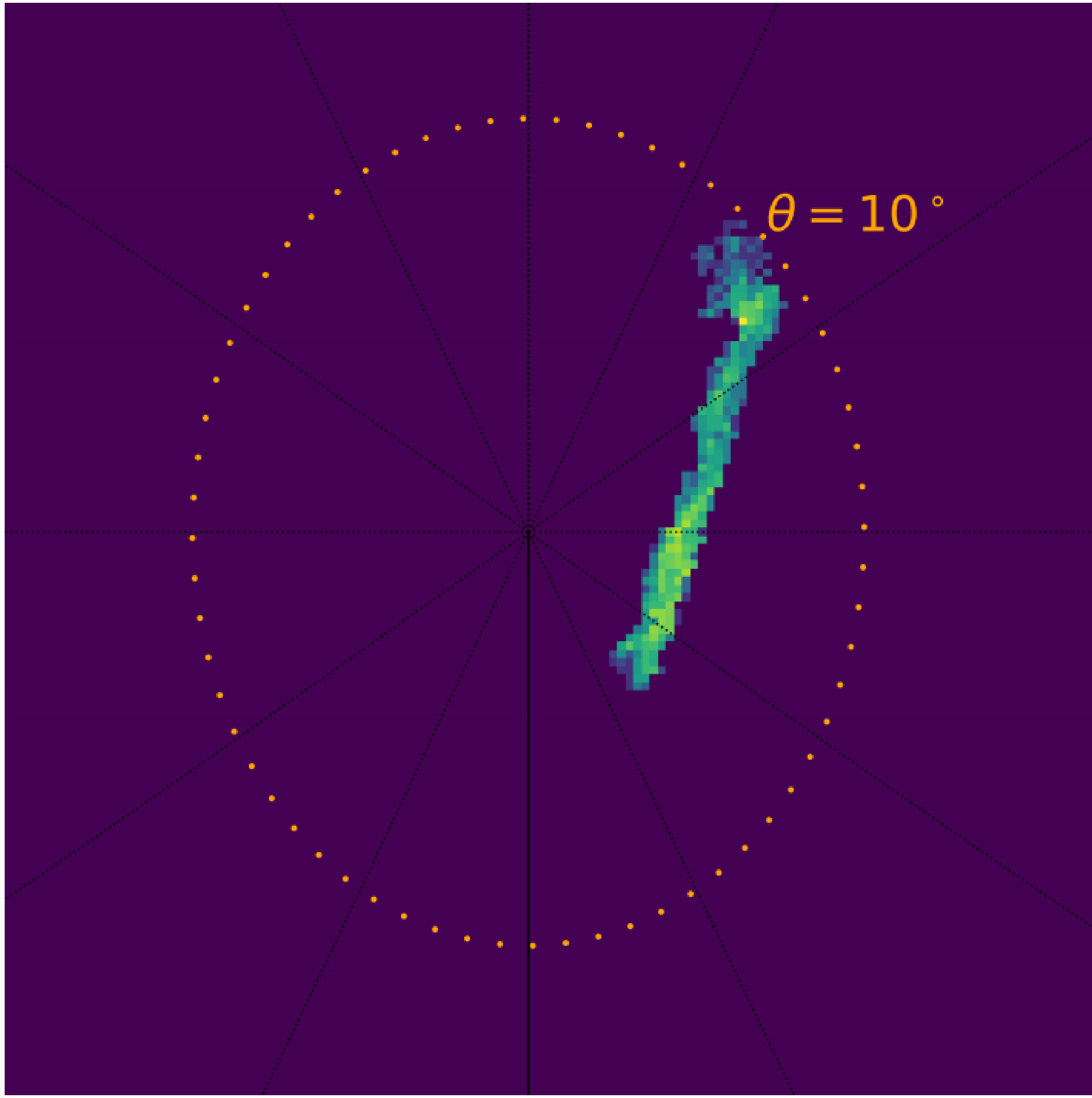


Observer point of view

Zoom into filament

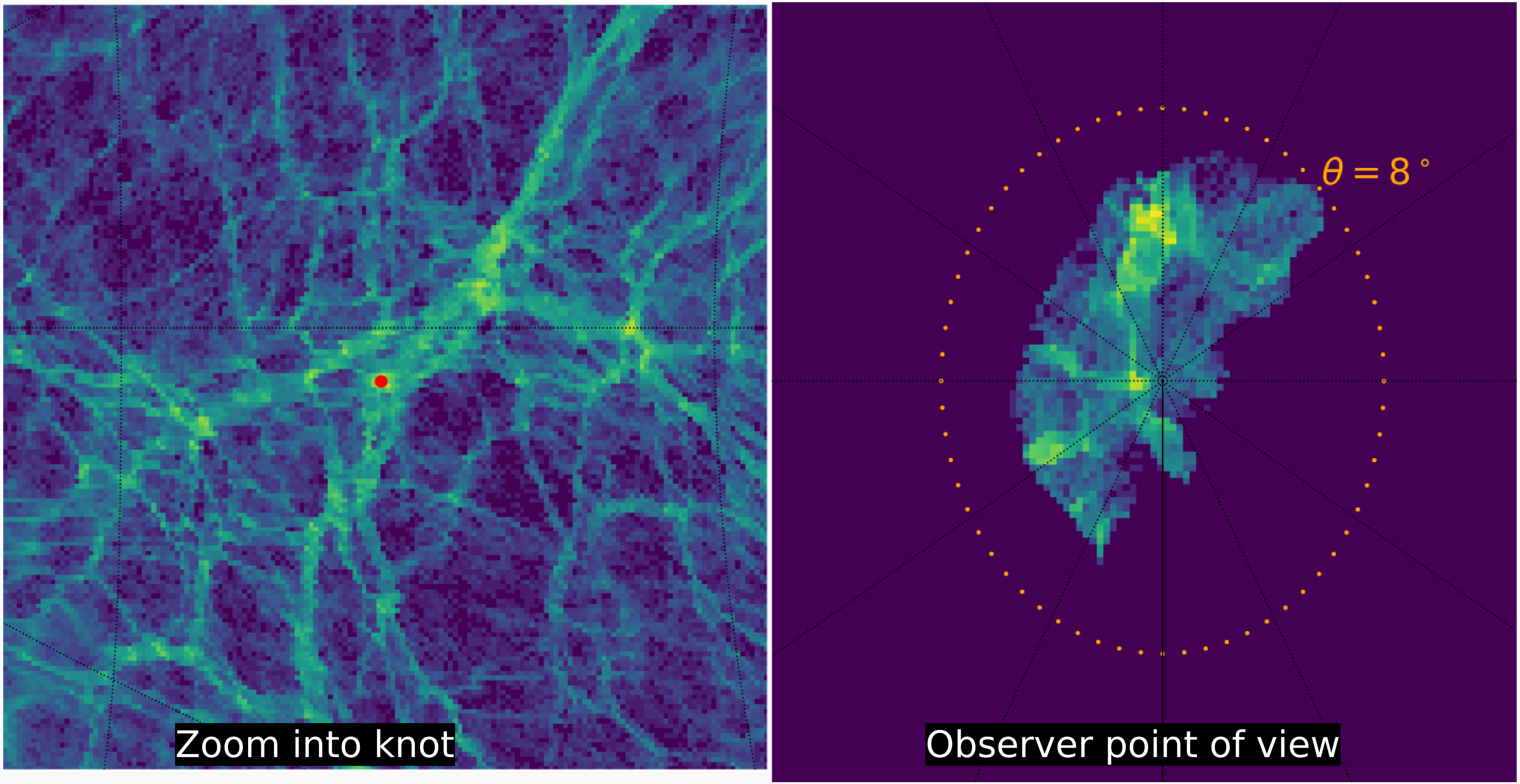


Zoom into filament



Observer point of view

Zoom into knot

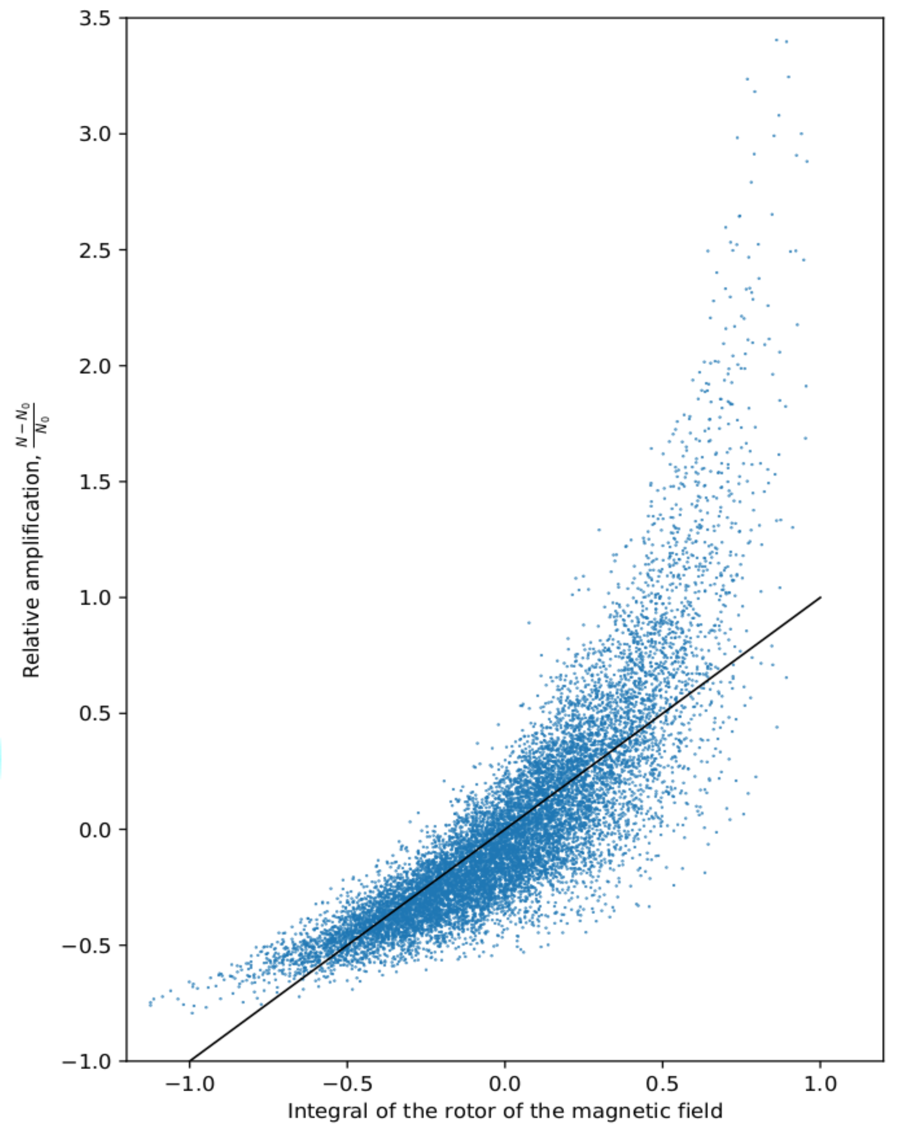


Explanation

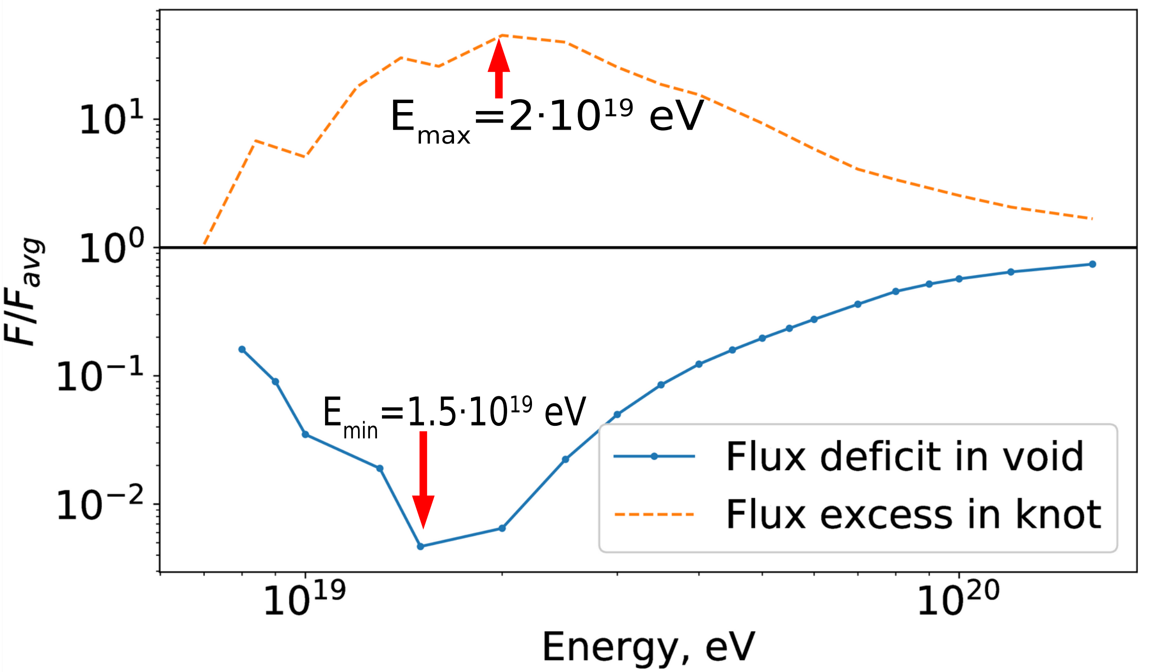
- Similar effect: Diego Harari et al. UHECR lensing in GMF (parallel beam)

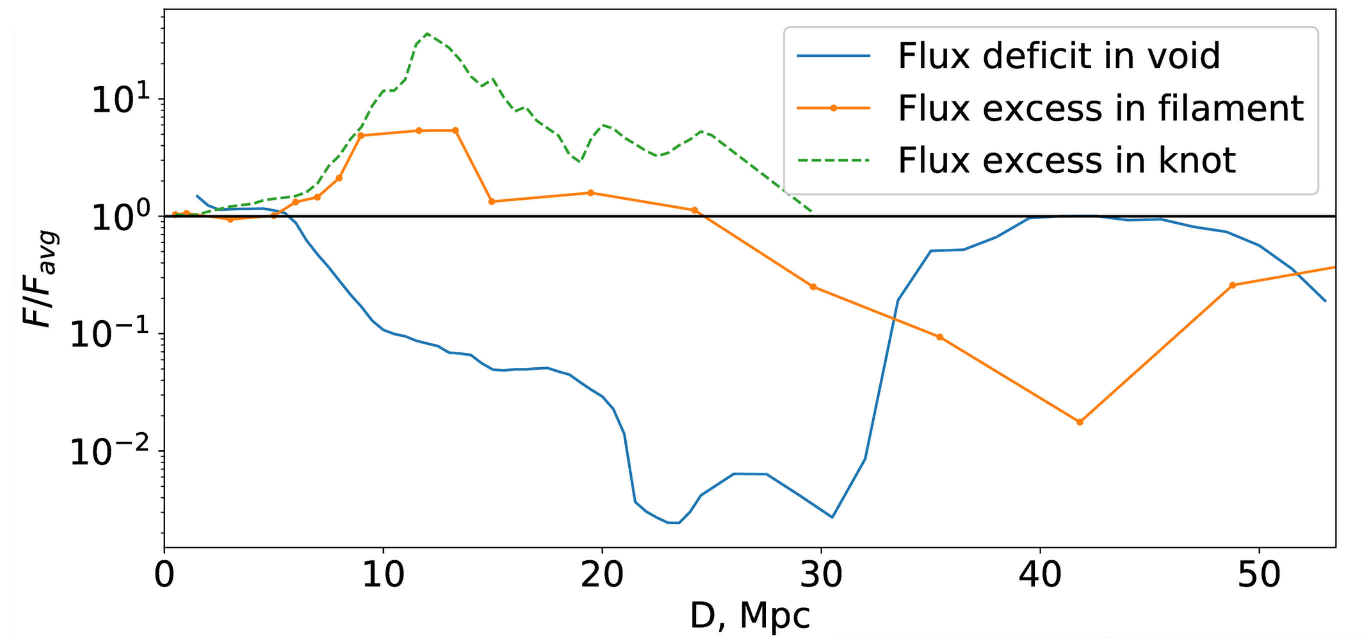
- Flux amplification for the diverging beam:

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



Length of structures



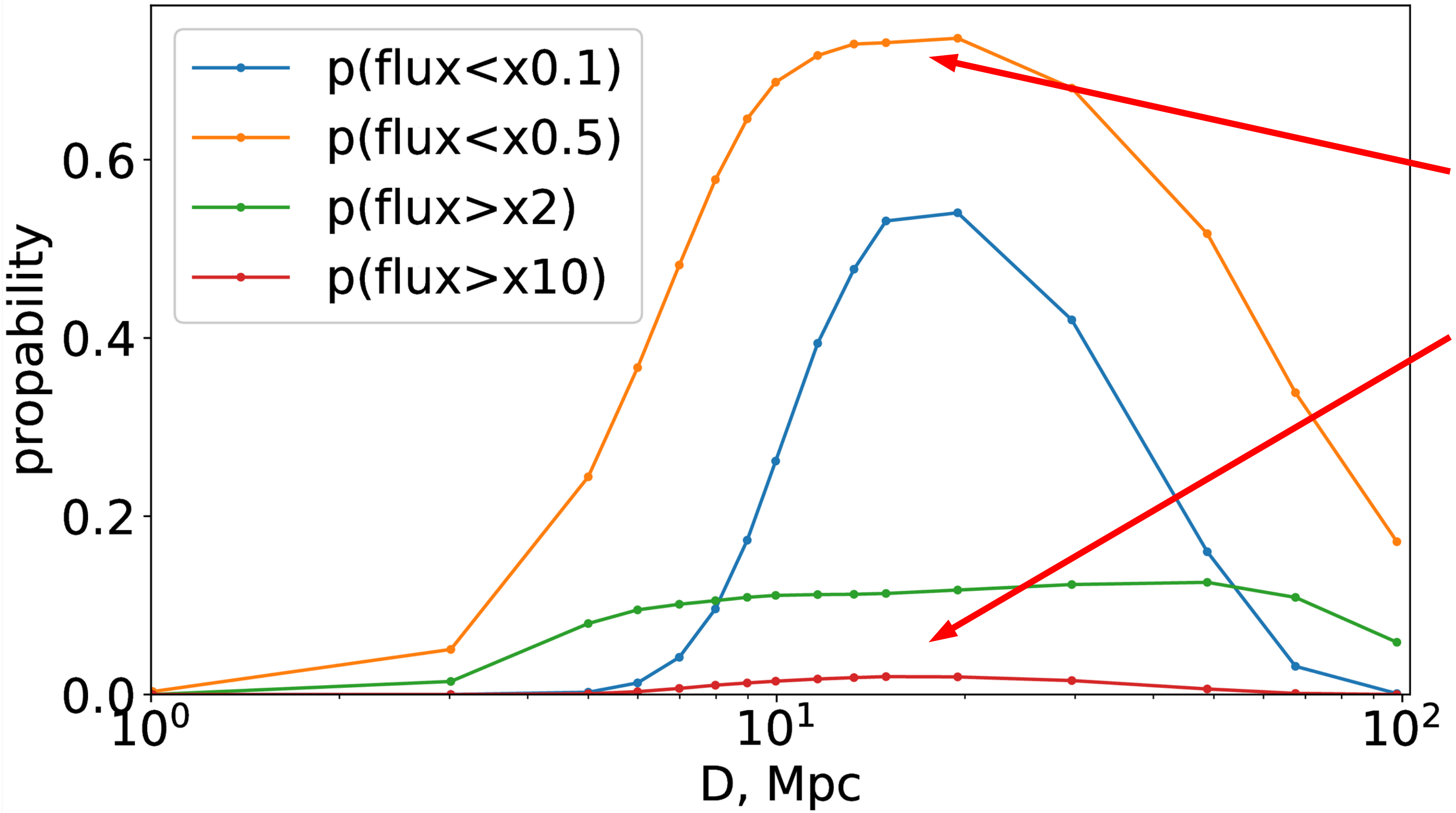


Knot: D=20 Mpc
Void: D=30 Mpc

Rigidity 10 EV in all cases

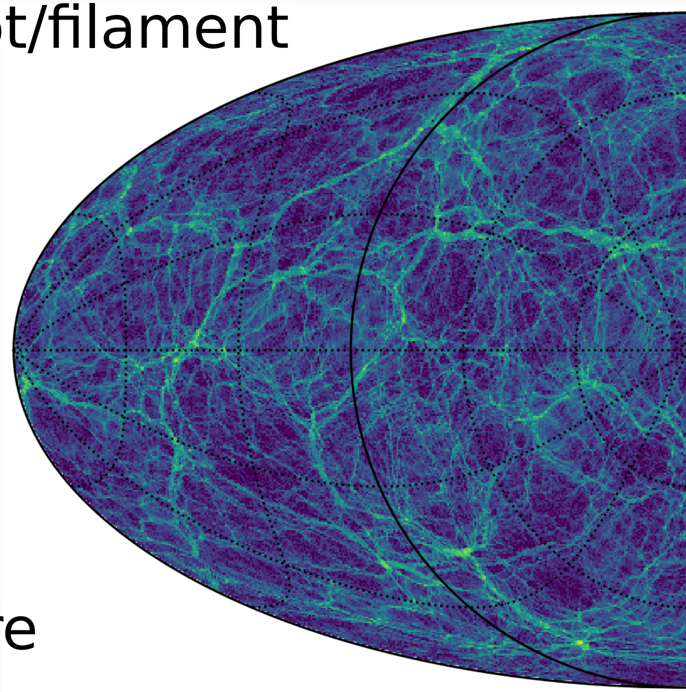
$$\lambda_C = 1\,Mpc$$
$$B = 1\,nG$$

Probability of voids/knots



Probability to be in void

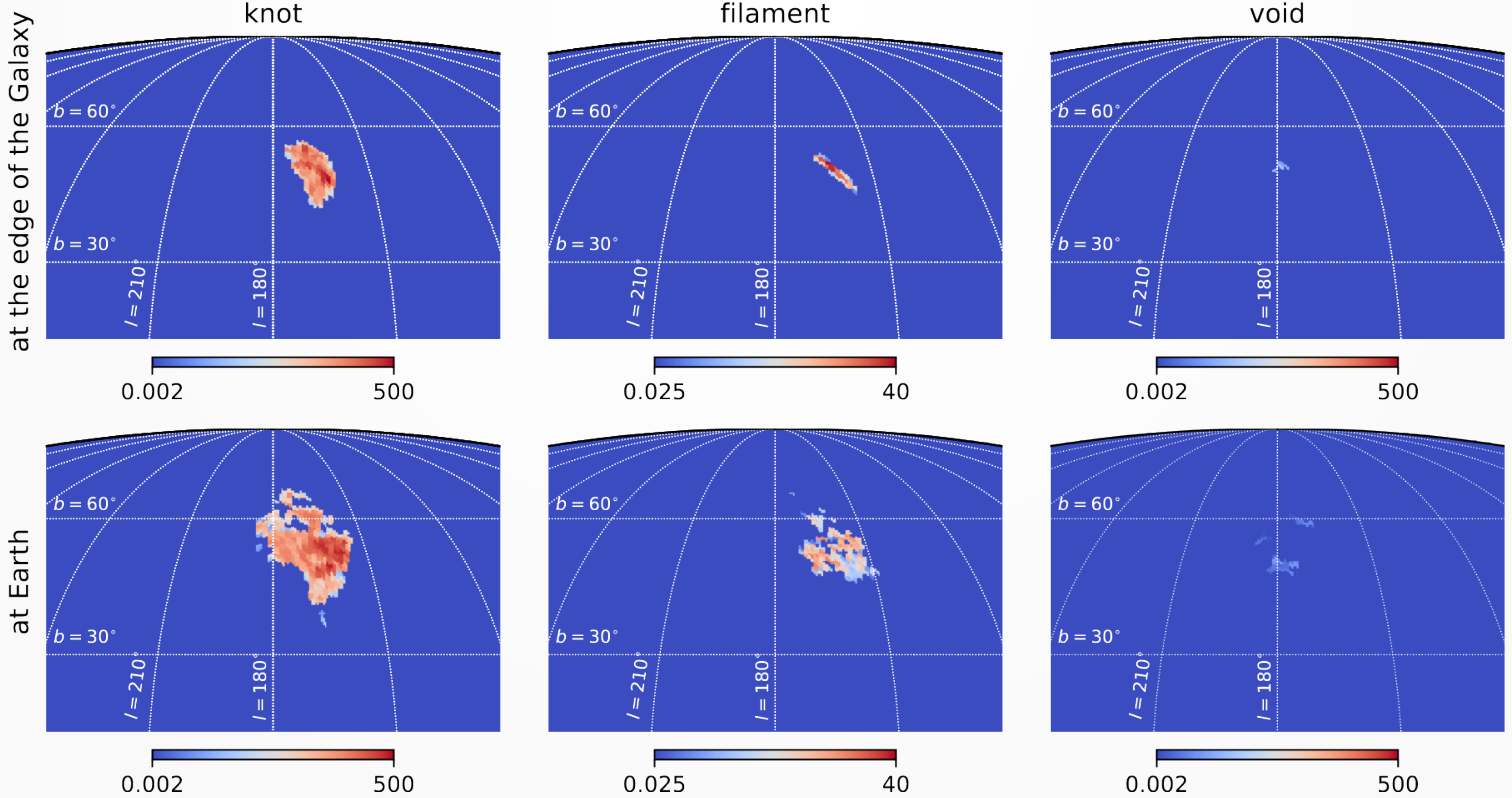
Probability to be in knot/filament



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

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

What does observer see? GMF



GMF model Jansson&Farrar+12

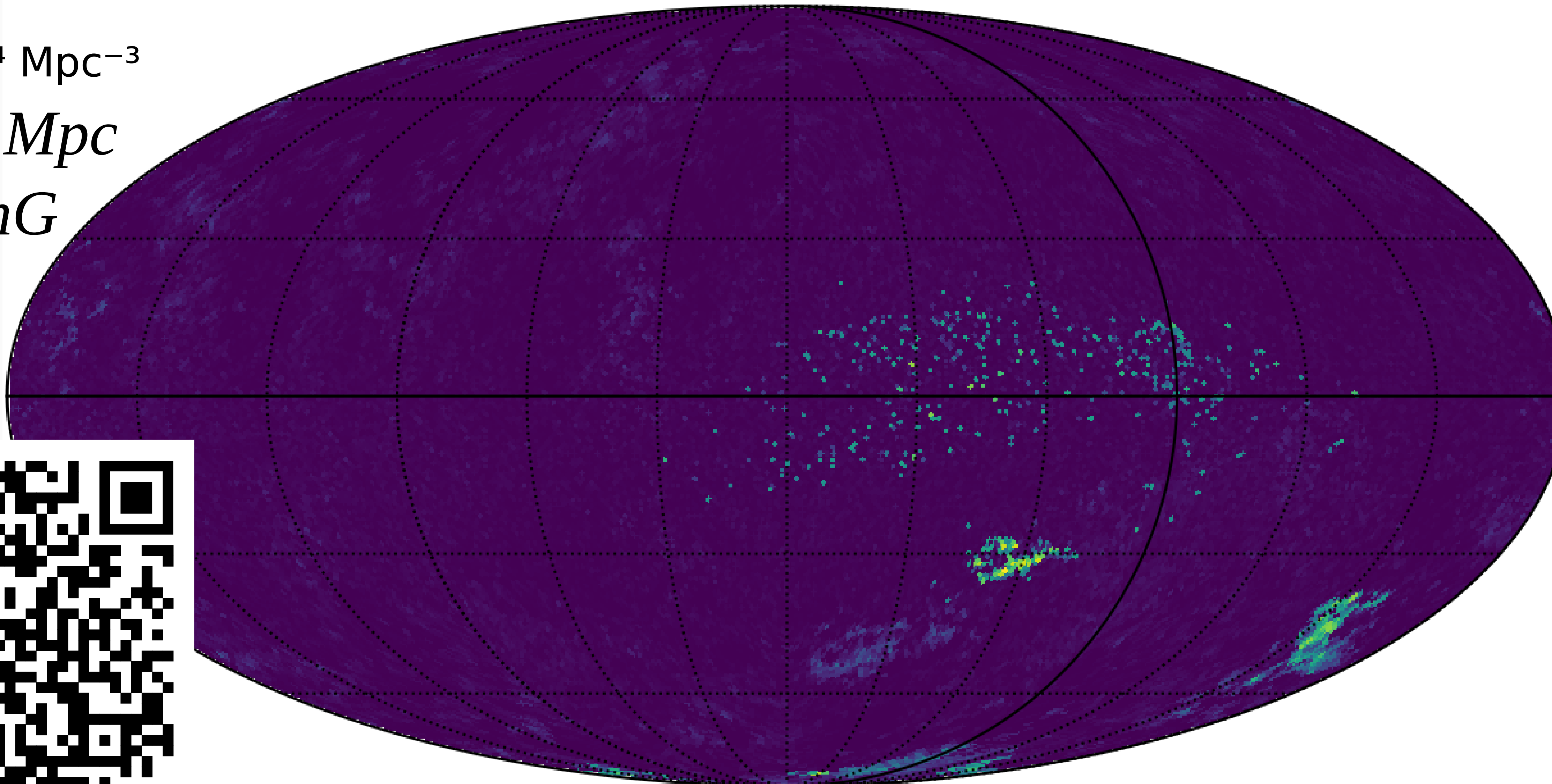
The position of the source in the sky was chosen to approximately coincide with the position of the TA hotspot

What does observer see? Set of sources

$n=1.5^{-4}$ Mpc^{-3}

$\lambda_C = 1\,Mpc$

$B = 1\,nG$



GMF model Jansson&Farrar+12

Online demo: http://85.113.39.151/cosmicRayView/

Conclusions

We can explain

- size of observed UHECR hotspots by propagation effect in strong IGMF
- absence of point sources

Future work:

- Powerful and flexible framework

  CRbeam (https://github.com/potassium-chloride/mcray)
- Realistic IGMF by K.Dolag (see https://arxiv.org/abs/2310.13734)

Thank you for your attention

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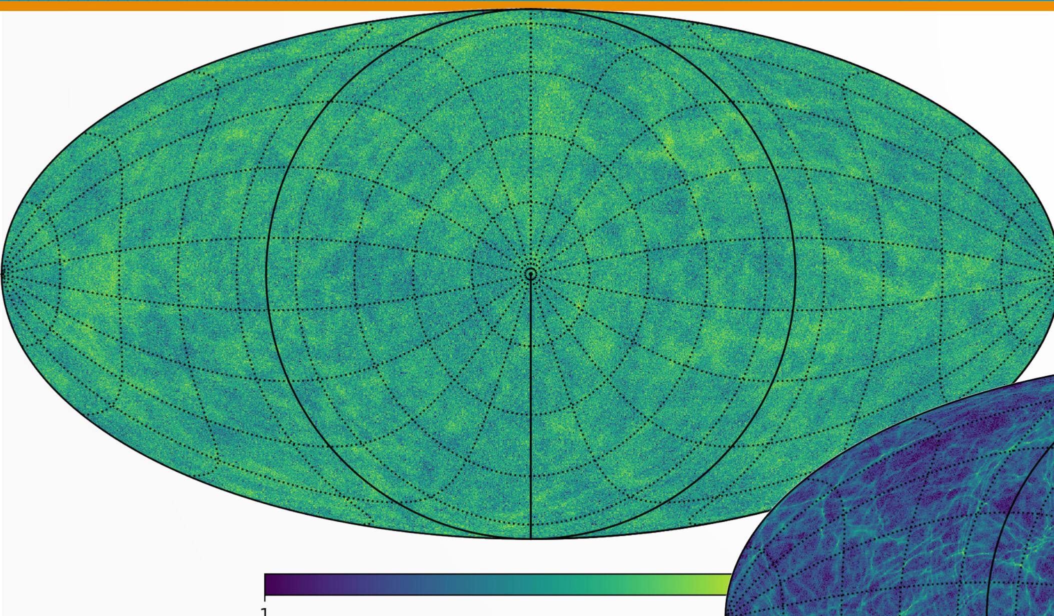
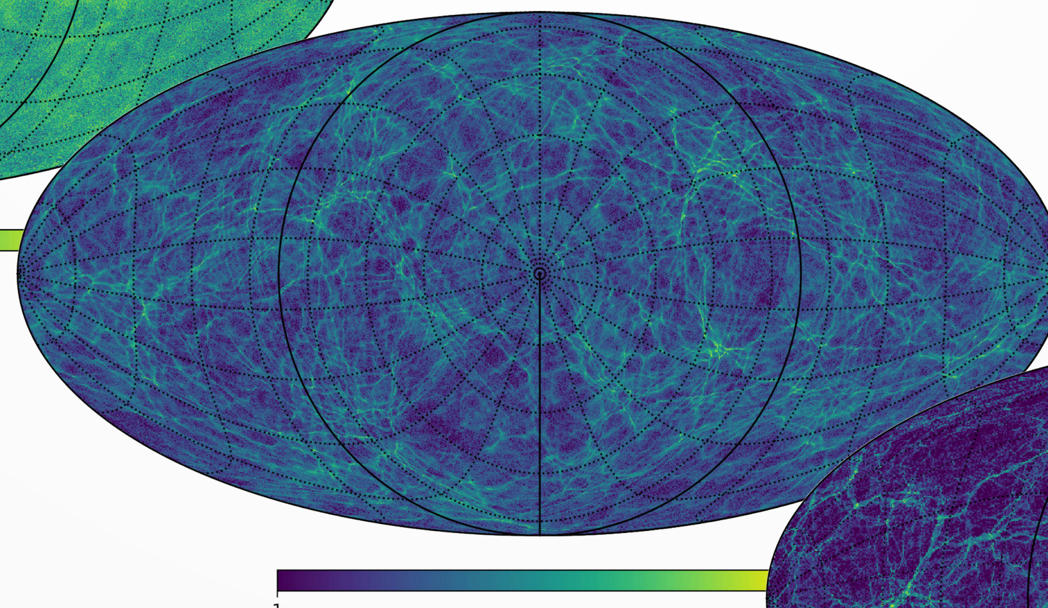
Some of the results have been derived using the CRBeam, CRPropa, healpy and HEALPix packages.

Backup: Forming the structure

What if turn off magnetic field after some distances?

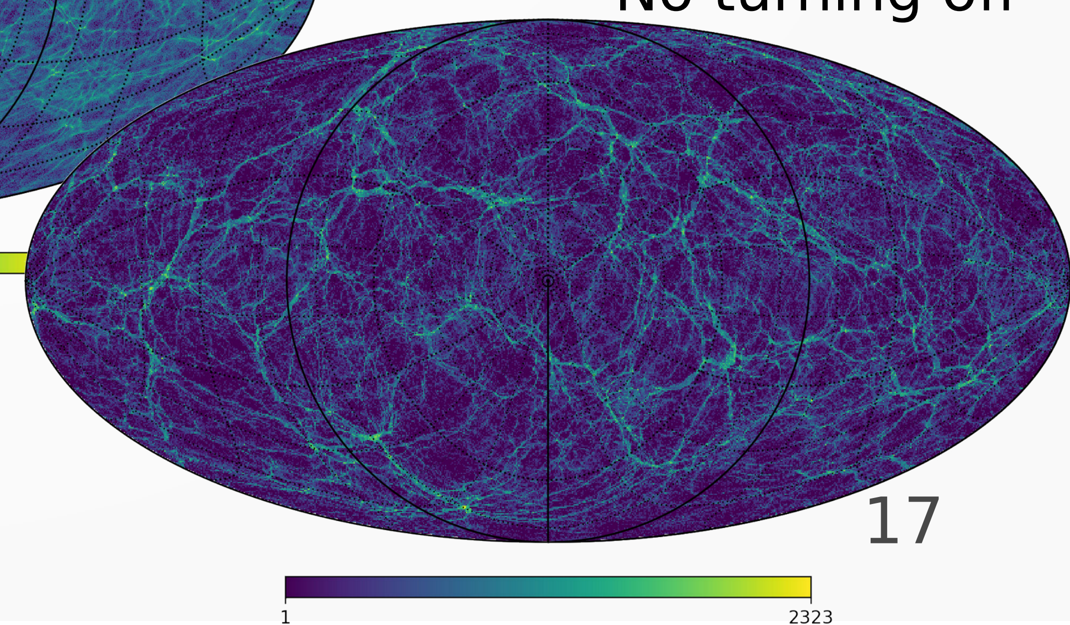


Turning off on D=1 Mpc



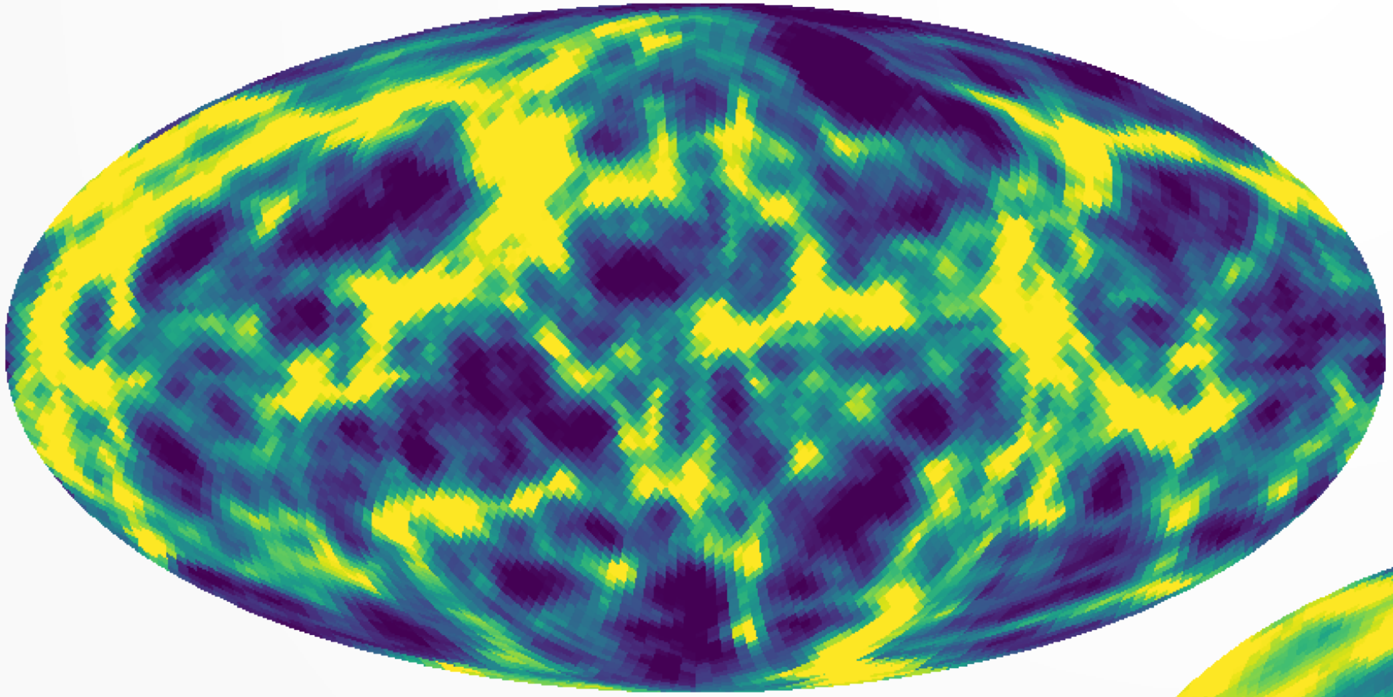
Turning off on D=3 Mpc

No turning off



Backup: Correlation with rotB

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



Integral of the magnetic field rotor