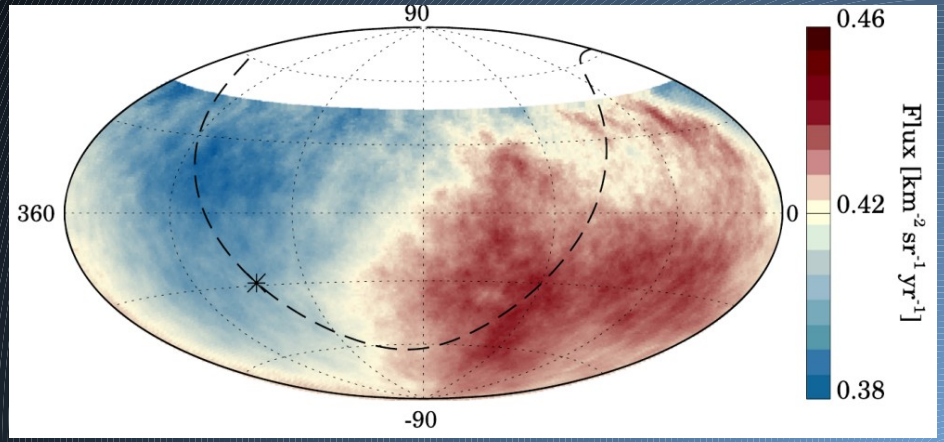
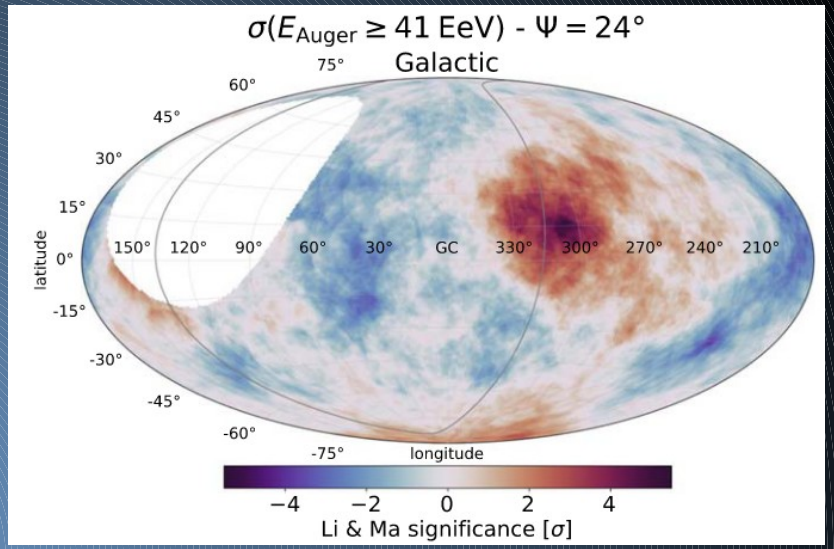
Propagation of UHECRs from sources

Alexander Korochkin, ULB Brussels &
K. Dolgikh, G. Rubtsov, D. Semikoz, I. Tkachev

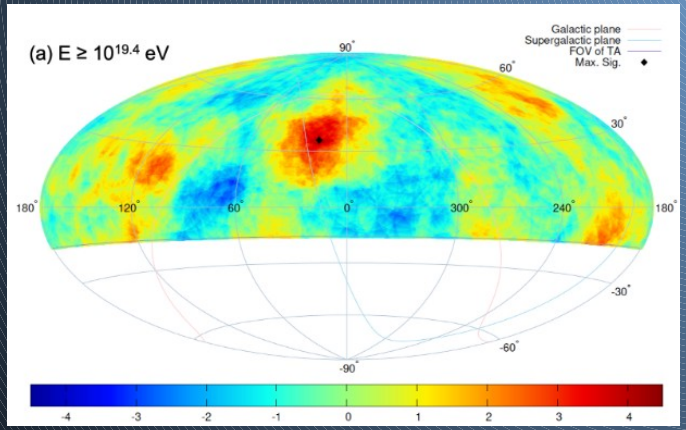
UHECR anisotropies



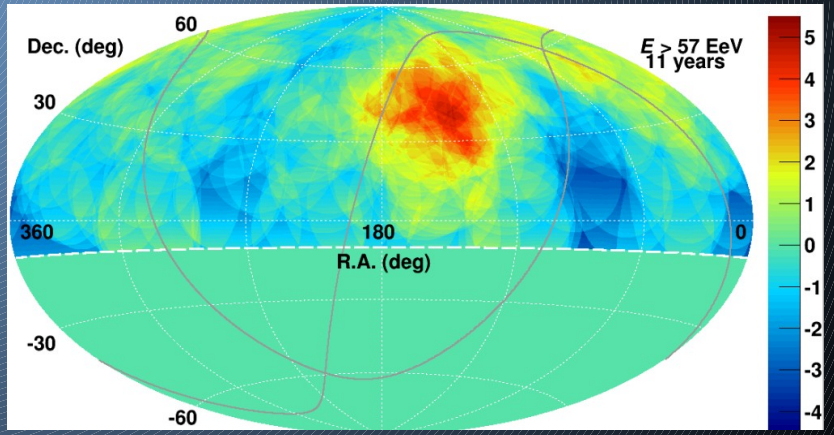
Auger Coll. 2017



Auger Coll. 2022



TA 2022



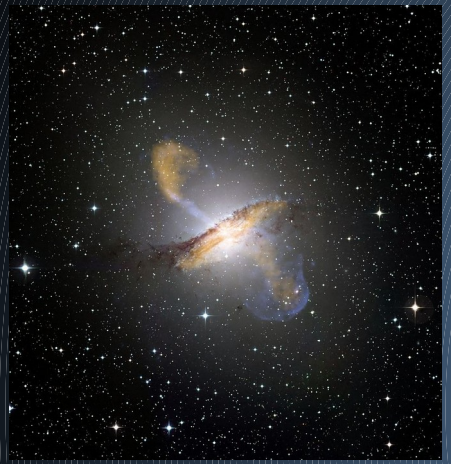
TA 2020

UHECR anisotropies

Satisfactory UHECR model should explain the observed level of isotropy and the absence of obvious sources

Deflections of UHECRs in magnetic fields can significantly complicate the picture

UHECR deflections by magnetic fields



UHECR source

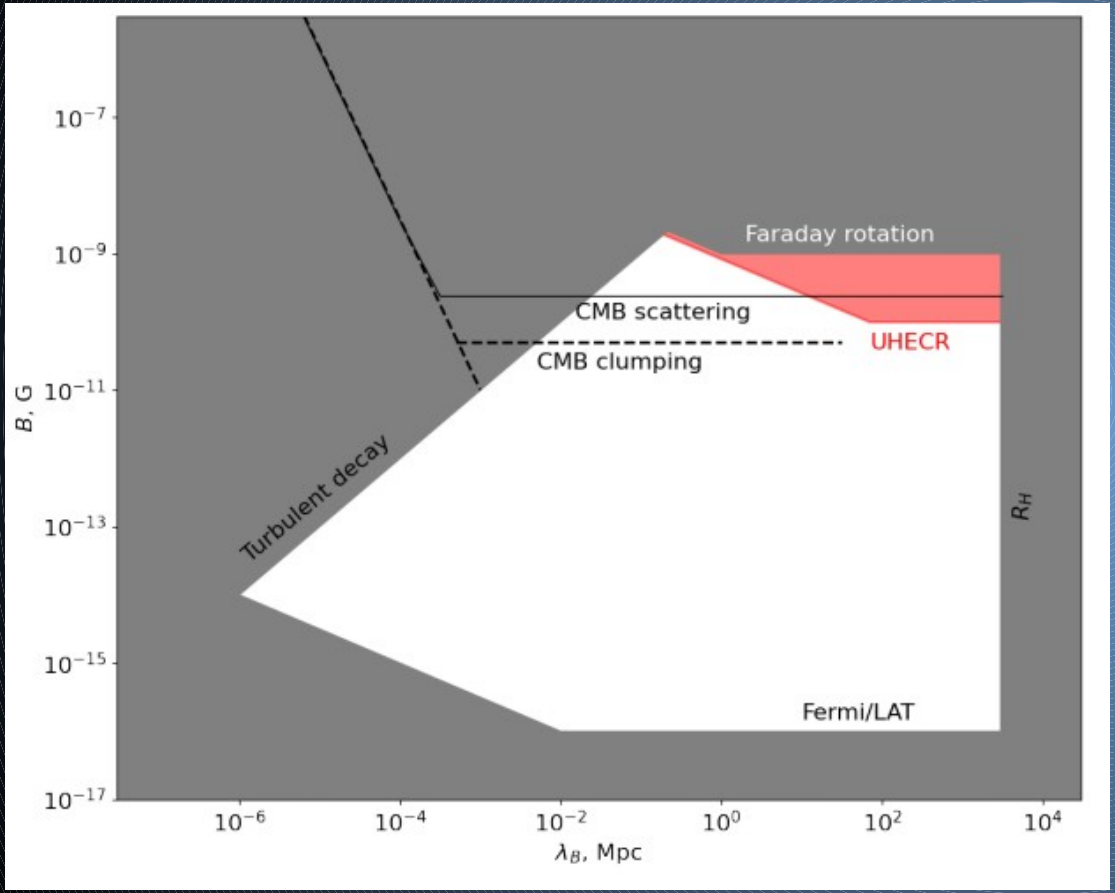
Deflection of the UHECR can be divided into three stages:

IGMF

Deflection in our Galaxy

If the magnetic field in the source located in a galaxy cluster or supercluster is strong enough it may randomize the directions of UHECR particles in energy-dependent way and change observational appearance of a source and it's spectrum, *Dolag+09, Hussain+21*

Intergalactic Magnetic Fields (IGMF)



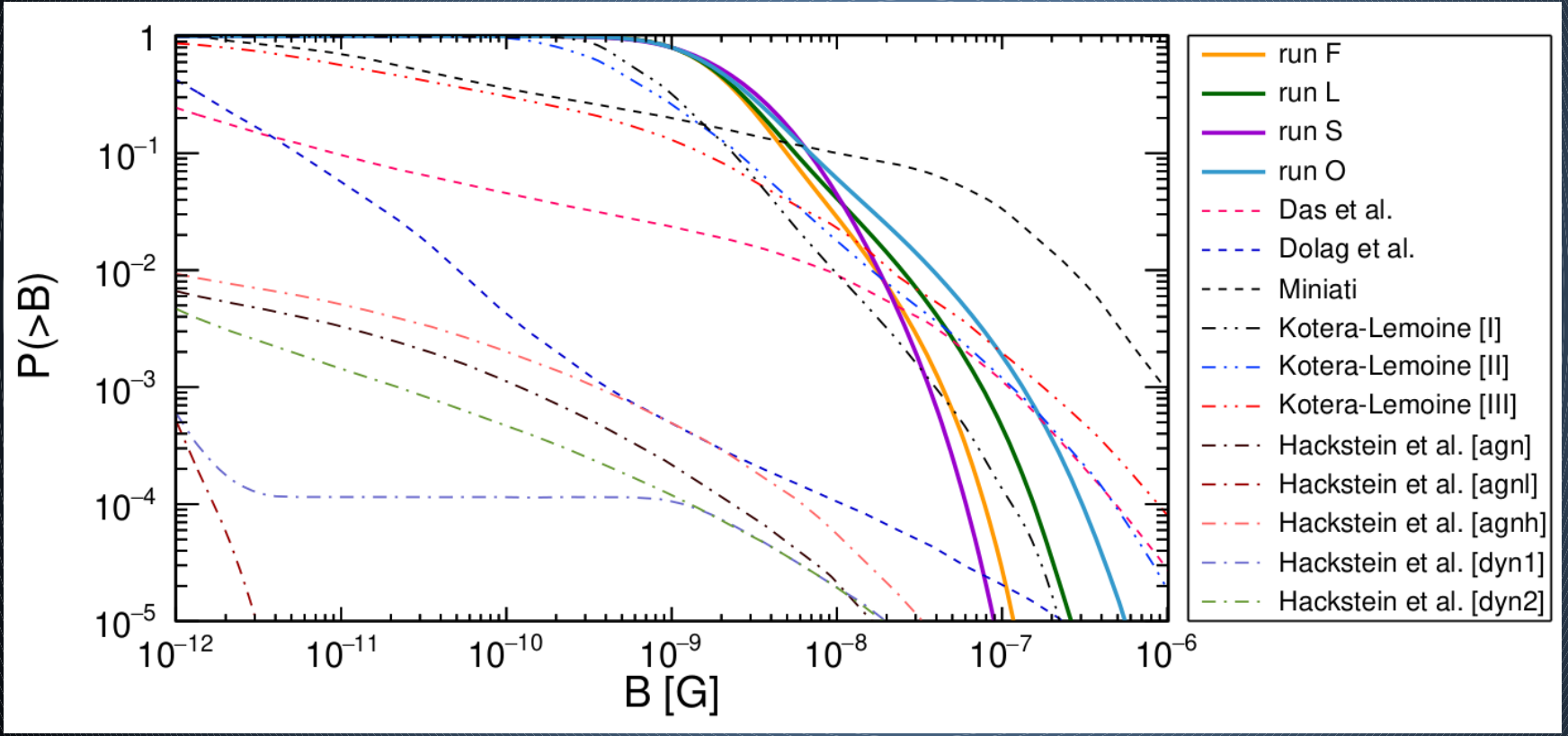
Neronov+21

Low redshift IGMF constraints:
1e-16 G < B < 1e-9 G,
MAGIC+21, Fermi/LAT+16,
Blasi+99, Pshirkov+16

High redshift data (CMB) give stronger upper bounds
Jedamzik+18

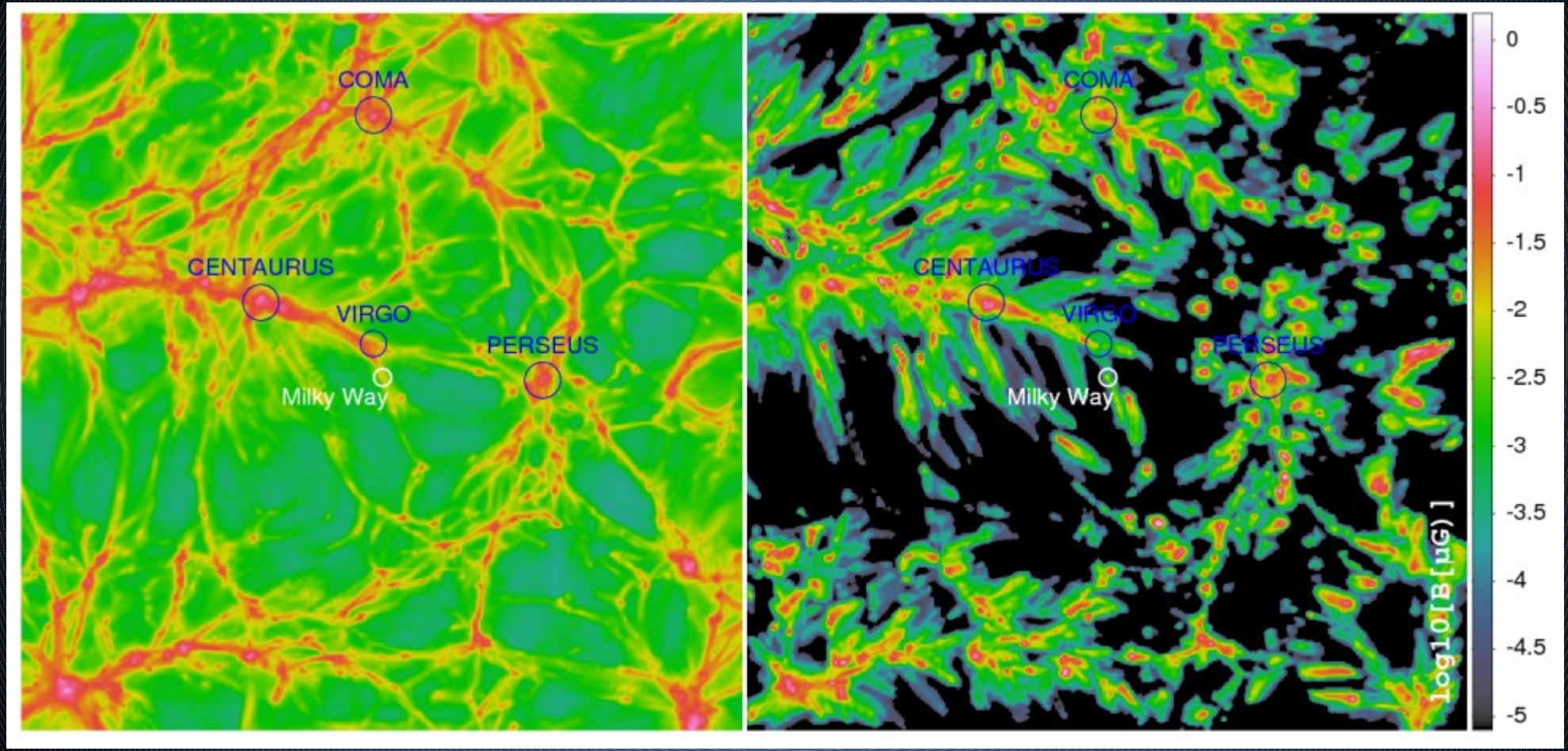
MHD simulations

Simulations: Sigl+04, Dolag+06, Ryu+09, Vazza+16, Rafael Batista+17, Hackstein+17...



Simulations do not unambiguously predict the magnitude of IGMF

MHD simulations



Pic from Hackstein+17

Kotera & Lemoine 07

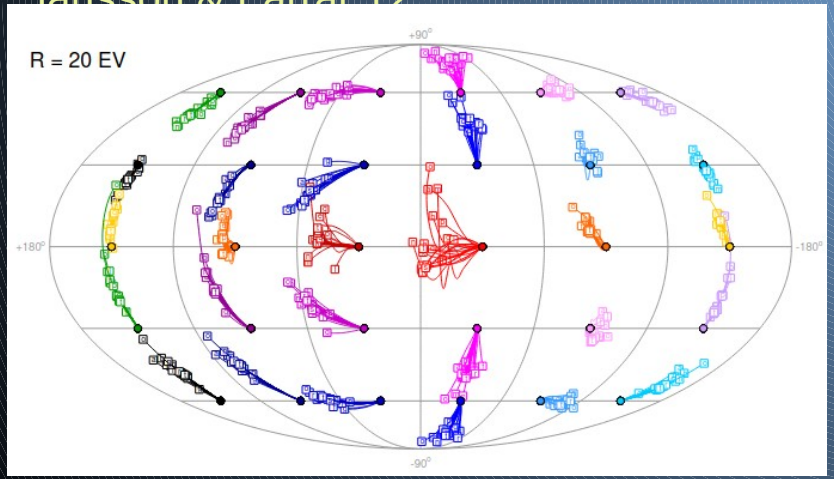
see Klaus Dolag talk

Galactic magnetic field

see Michael Unger talk

Regular component displaces the source image from its original position on the sky, Jansson & Farrar 12

Turbulent component broadens the source extent, Pshirkov+13



Unger & Farrar
UHECR 2018

UHECR lensing by GMF

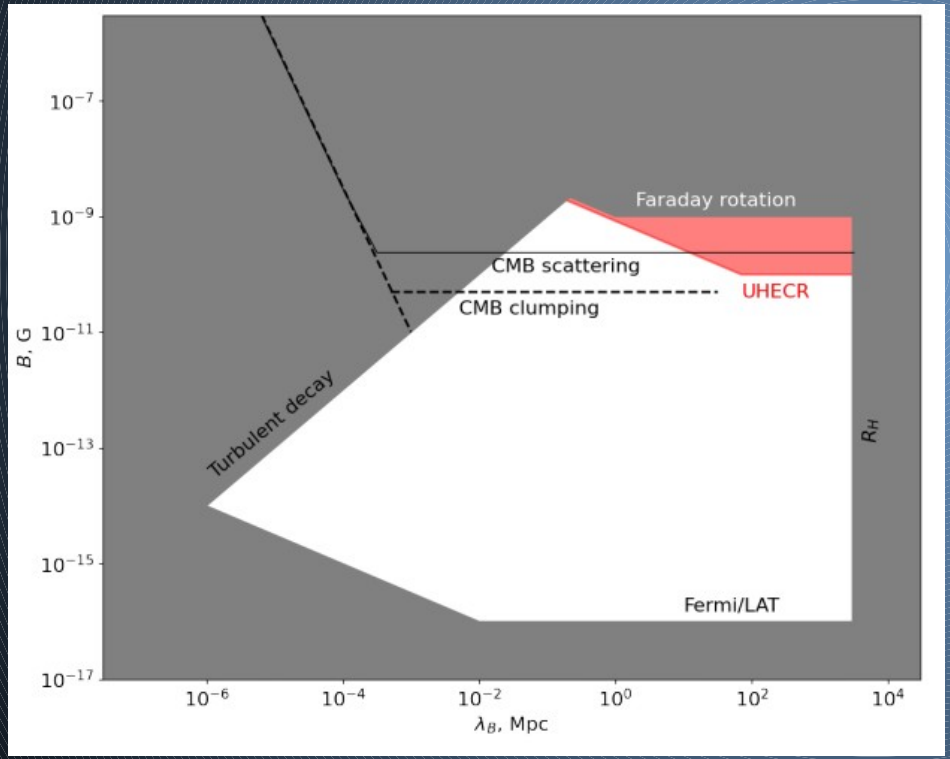
Deflections of the cosmic ray trajectories can lead to amplification or deamplification of the cosmic ray fluxes by lensing effects

Harari+99,01,02...

Case of strong IGMF: B = 1 nG, L = 1 Mpc

Strongest possible IGMF

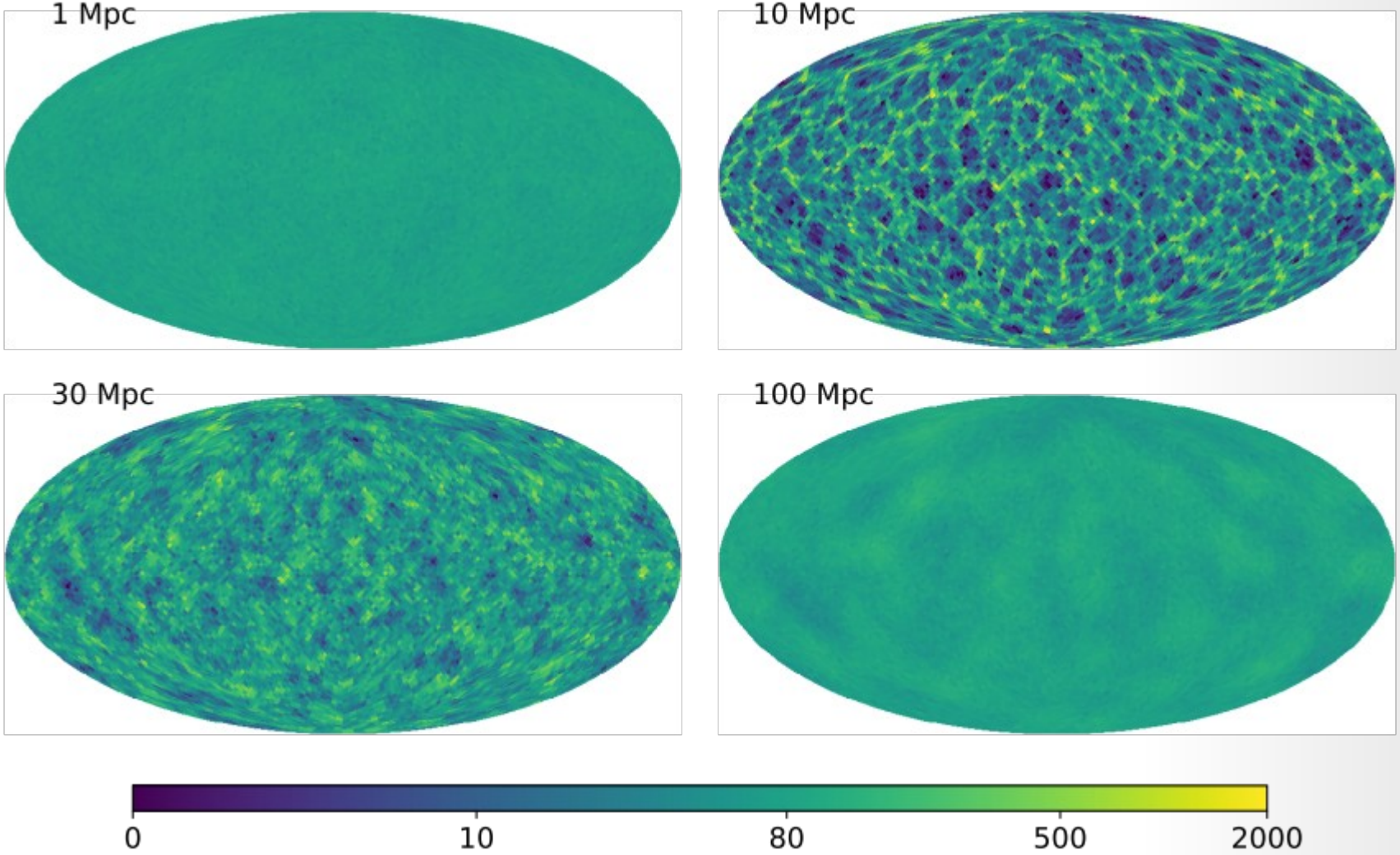
Consider UHECR with E=10 EeV

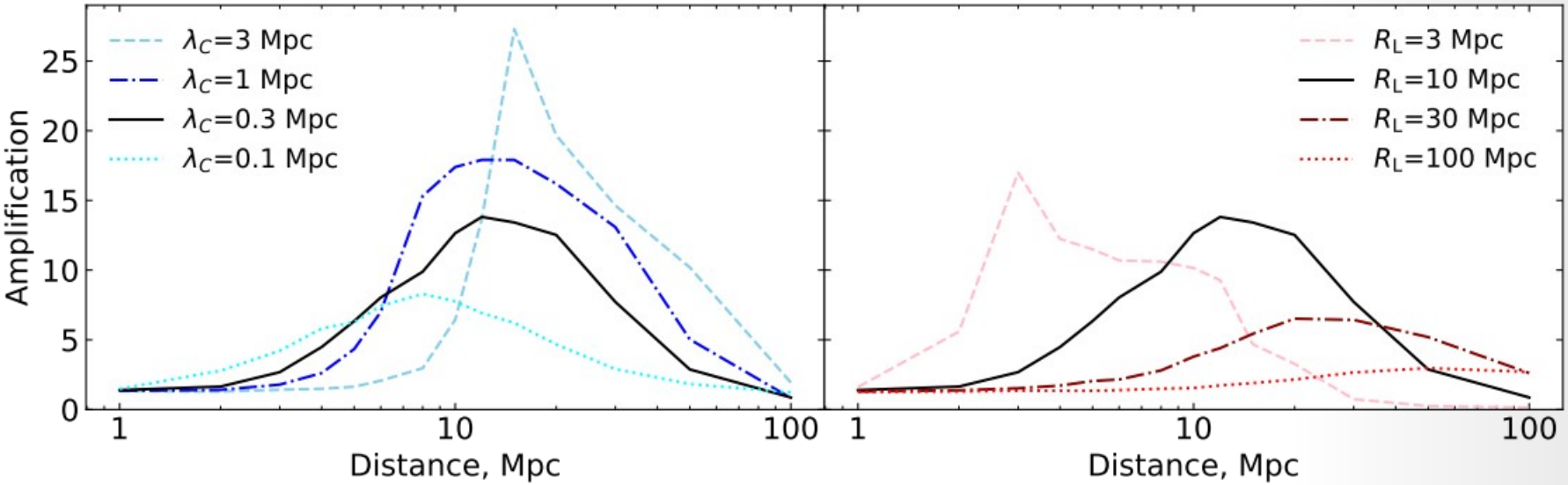


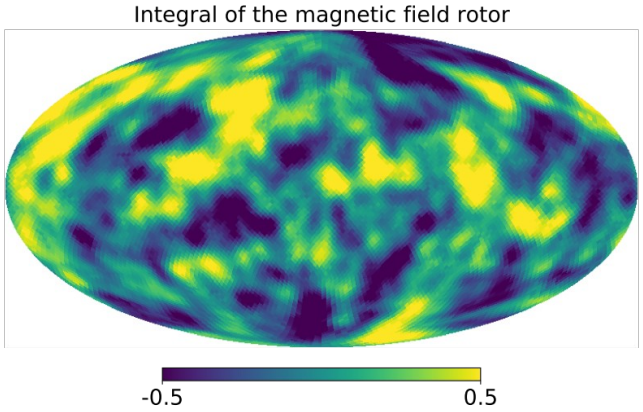
$$\theta \sim 4^\circ \, Z \frac{B}{\mathrm{nG}} \frac{10\ \mathrm{EeV}}{E} \sqrt{\frac{D}{\mathrm{Mpc}}} \sqrt{\frac{\lambda_C}{\mathrm{Mpc}}}$$

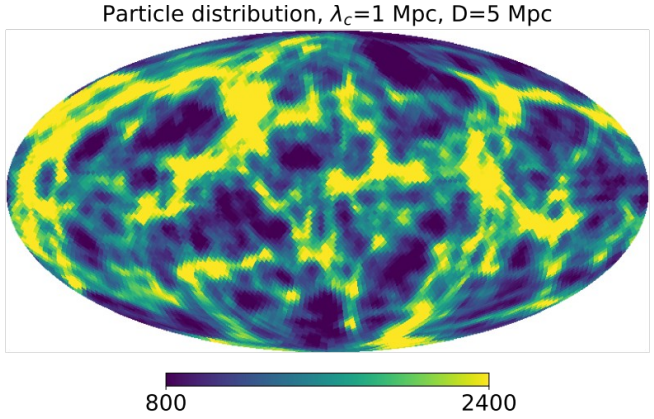
Diffusion and anisotropy from extragalactic sources: Globus+07, Harari+14,15,21

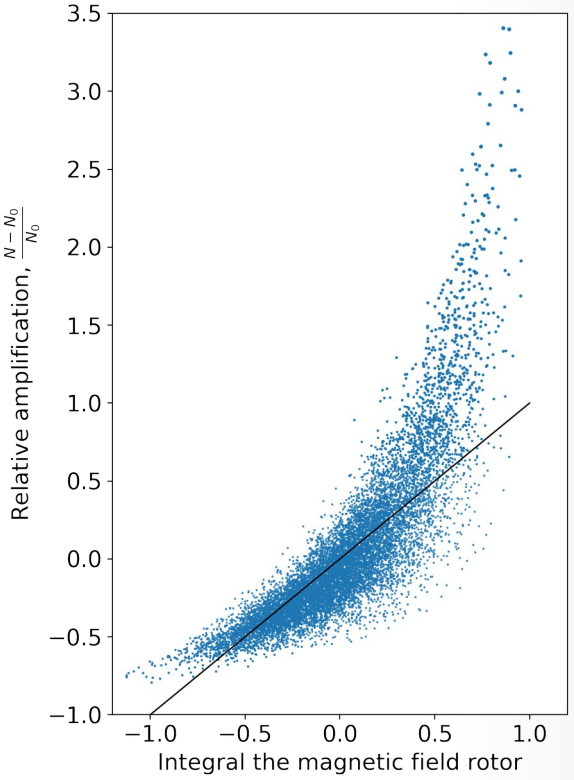
Looking for the 2D picture




Amplification
0
5
10
15
20
25
1
10
100
Distance, Mpc
λ_C=3 Mpc
λ_C=1 Mpc
λ_C=0.3 Mpc
λ_C=0.1 Mpc
1
10
100
Distance, Mpc
R_L=3 Mpc
R_L=10 Mpc
R_L=30 Mpc
R_L=100 Mpc

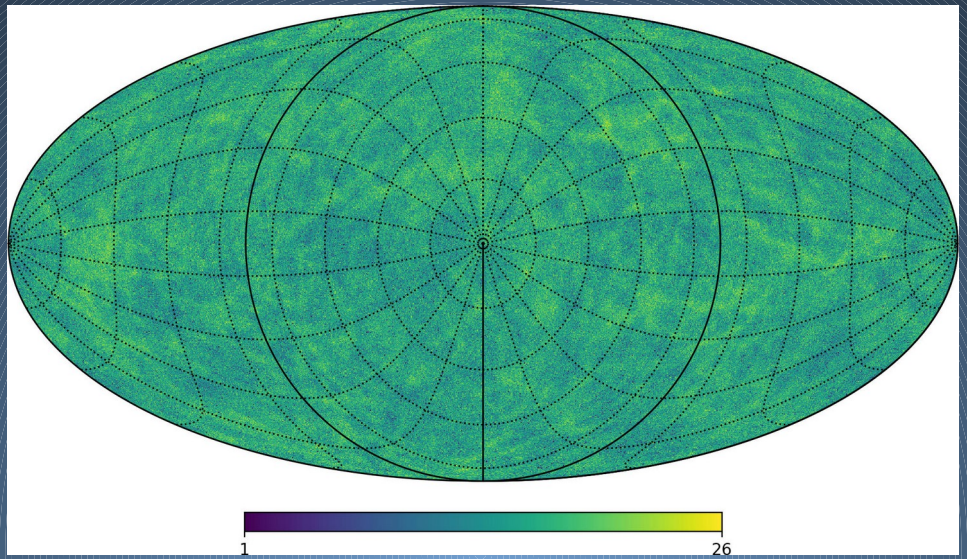


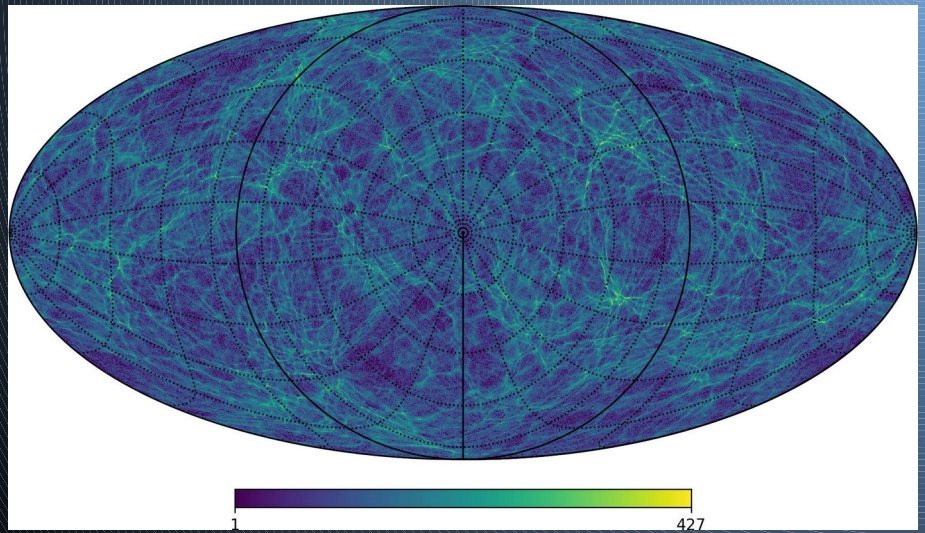


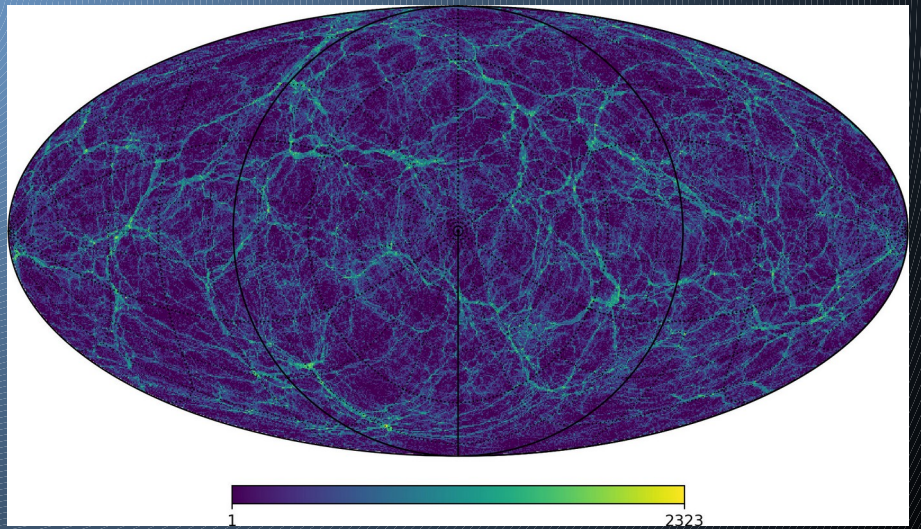


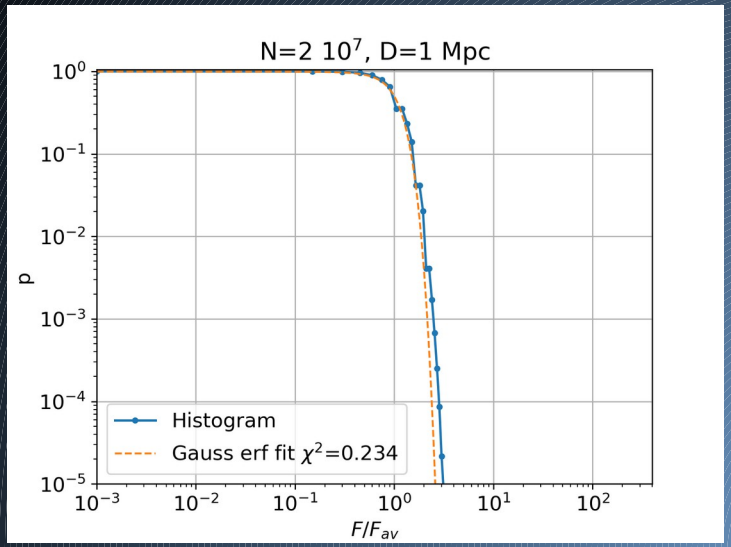
$$A(D) = A_0 \left(1 - \frac{Ze}{E} \int_0^D s \left(1 - \frac{s}{D}\right) (\mathrm{rot}\vec{B} \cdot \mathrm{d}\vec{s})\right)$$

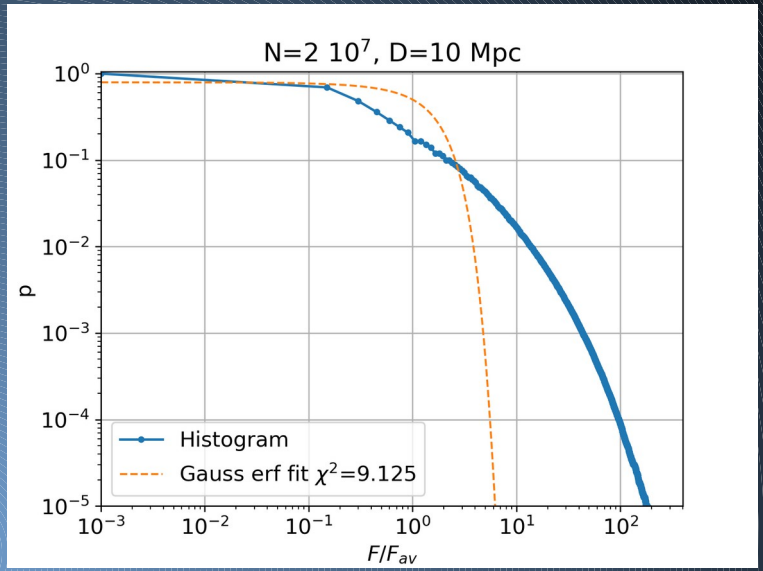
Harari+99,02, Dolgikh+22

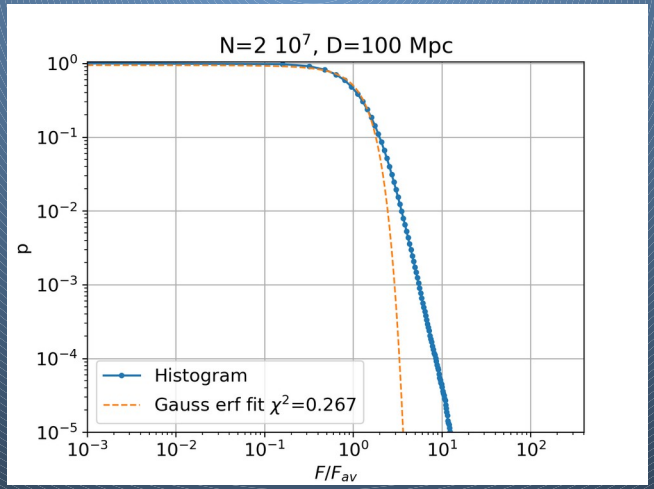

1
26


1
427

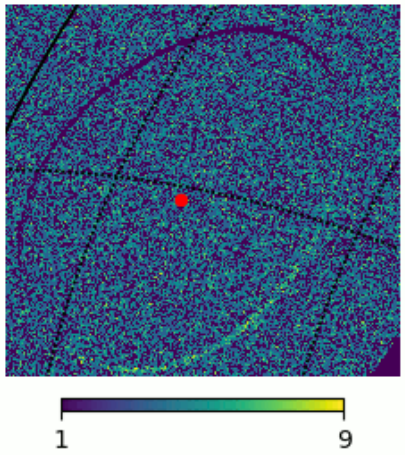

1
2323


N=2 10^7, D=1 Mpc
p
F/F_av
Histogram
Gauss erf fit χ²=0.234

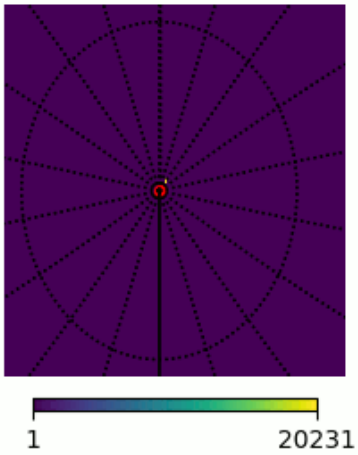

N=2 10^7, D=10 Mpc
p
F/F_av
Histogram
Gauss erf fit χ²=9.125


N=2 10^7, D=100 Mpc
p
F/F_av
Histogram
Gauss erf fit χ²=0.267

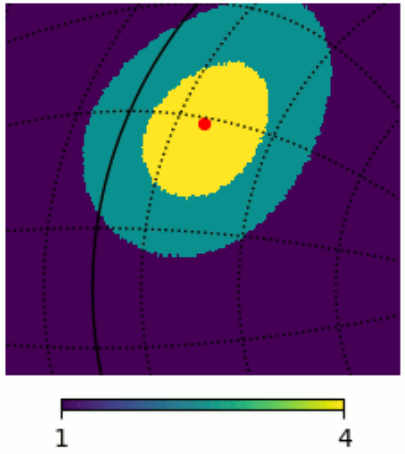
End sphere



What observer see



Initial particles directions



$R_{obs} = 100\,kpc$

$D = 500.0\,kpc$

$\theta_{min} = 1.2\,deg$

$\theta_{max} = 1.8\,deg$

$\alpha_{obs} = 2arctg(R/D) = 22.62\,deg$

$flux_{naive} = 0.97097\,\%$

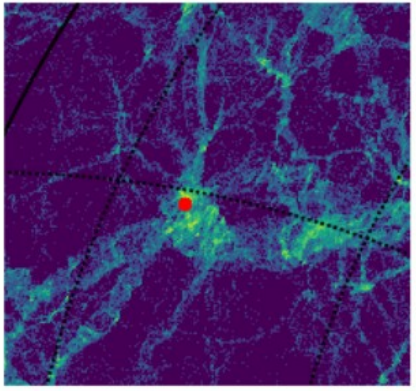
$flux_{real} = 1.0080923076923087\,\%$

$N_{in\,target} = 32763$

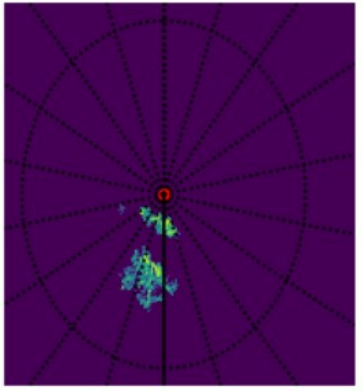
$N_{run} = 125000$

Work in progress: K.Dolgikh et al.

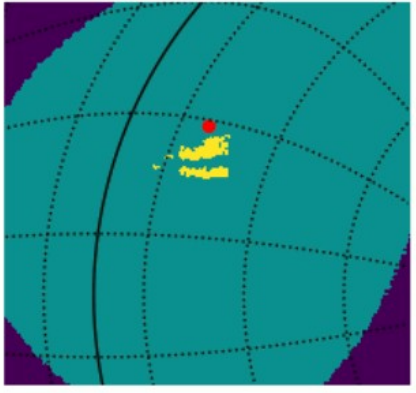
End sphere



What observer see



Initial particles directions



$R_{obs} = 100\,kpc$

$D = 11500.0\,kpc$

$\theta_{min} = 2.5\,deg$

$\theta_{max} = 13.5\,deg$

$\alpha_{obs} = 2arctg(R/D) = 1.0\,deg$

$flux_{naive} = 0.00189\,\%$

$flux_{real} = 0.05532110814332596\,\%$

$N_{in\,target} = 4088$

$N_{run} = 1000000$

Summary

In strong IGMF trajectories of UHECRs form a non-trivial caustic-like pattern with strong deviation from isotropy

Measurements of the flux from a source at a given distance will depend on the position of the observer.

see arXiv:2212.01494, K.Dolgikh et al.