CPROPA SIMULATIONS FOR UHECR ANISOTROPY STUDIES

CRPROPA WORKSHOP 2023 – BOCHUM, GERMANY

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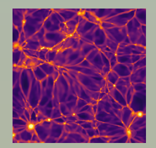
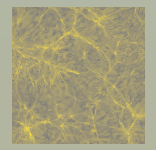
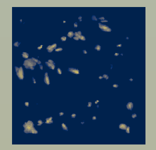
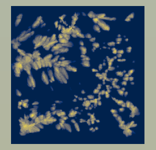
Federal Ministry of Education and Research

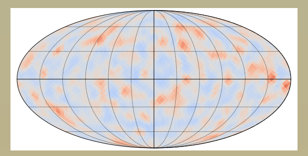
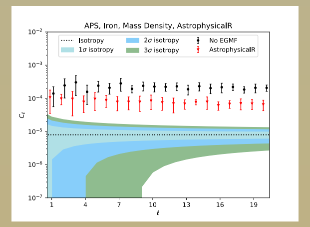
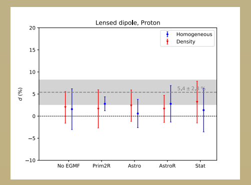
OUTLOOK

CONSTRAINED MAGNETOHYDRODYNAMIC SIMULATIONS

- BARYON DENSITY 
- EXTRAGALACTIC MAGNETIC FIELD   

CRPROPA SIMULATIONS

RESULTS

- SKY MAPS 
- ANGULAR POWER SPECTRUM 
- DIPOLE 

CONCLUSIONS

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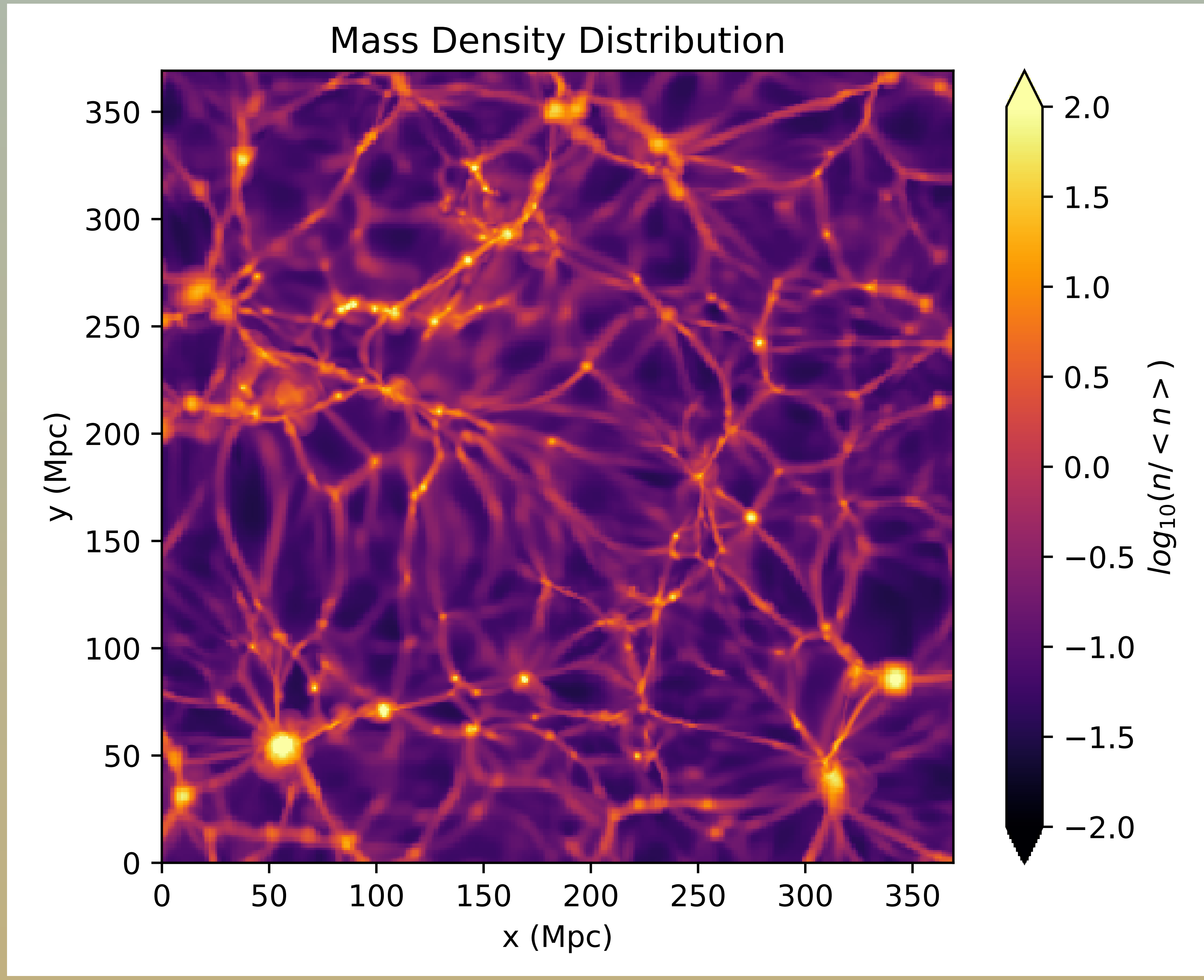
CONSTRAINED MHD SIMULATIONS



Constrained initial condition of the local Universe at back to z=60 in a comoving volume of 500 Mpc each side (**ENZO**).

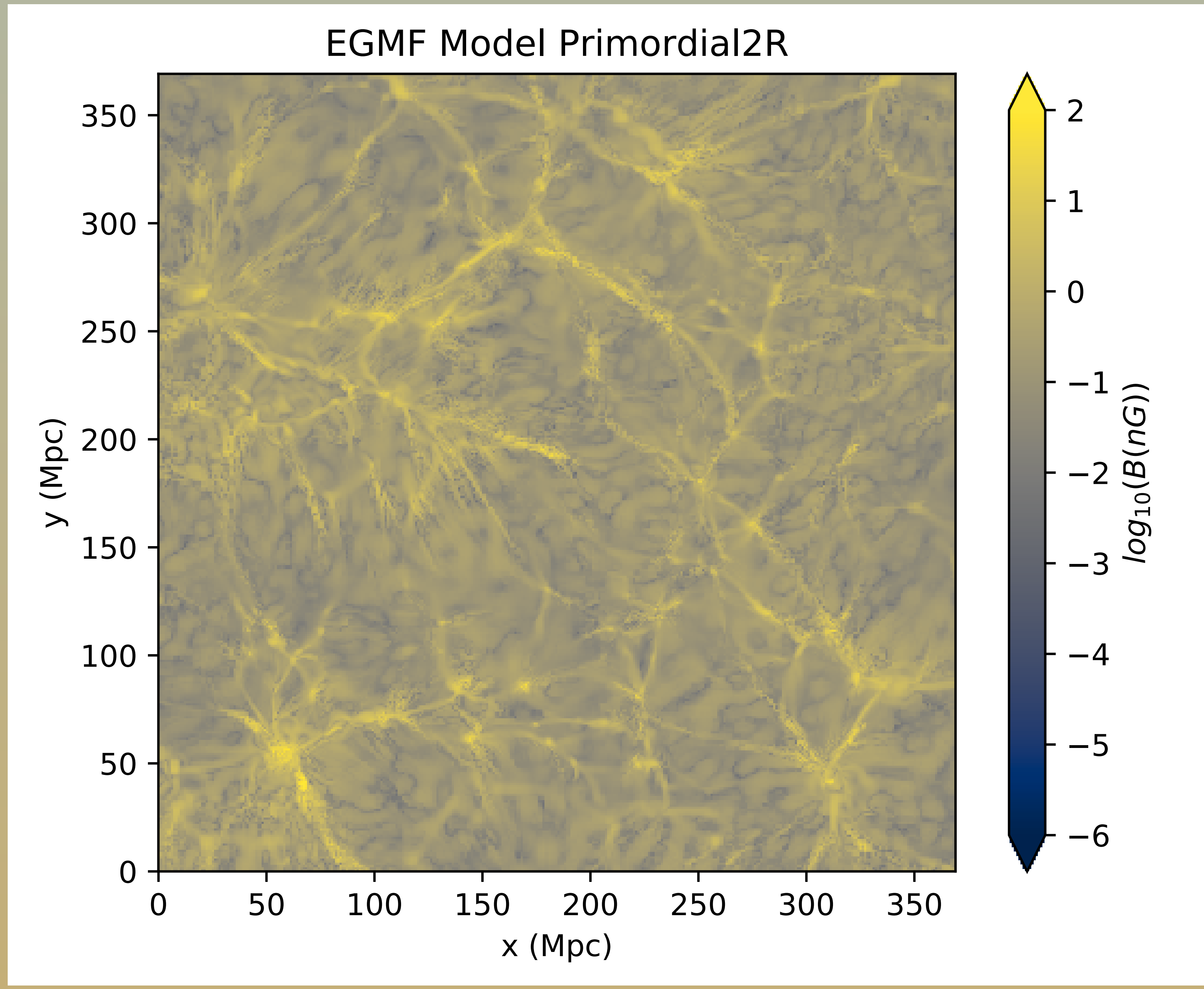
The ENZO Collaboration: G.L.Bryan et al, ApJS (2013)
J.G.Source et al, Mon. Not. R. Astron. Soc. (2015)

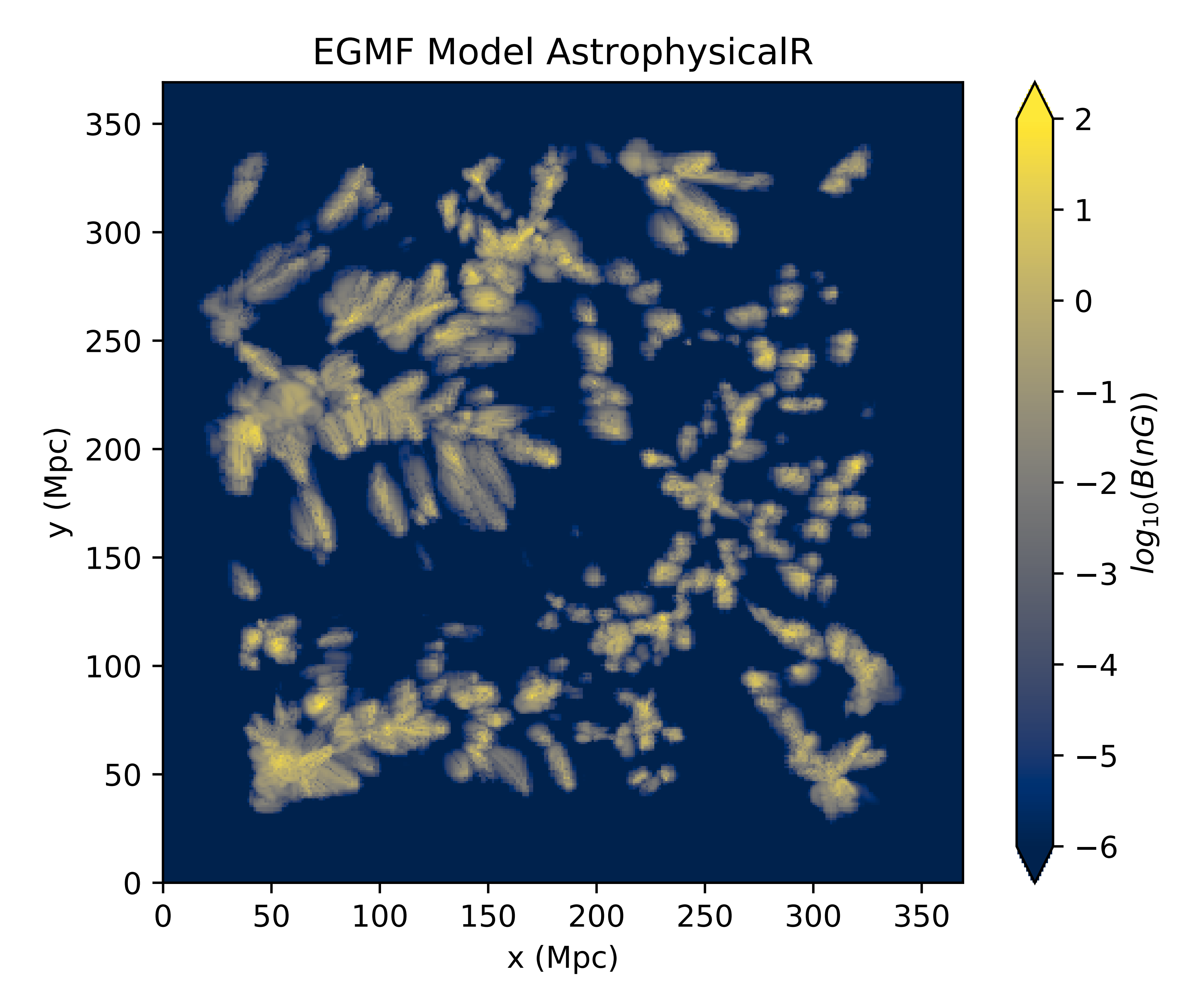
UHECRs propagation within a comoving volume of 250 Mpc each side (Milky Way at the center).

CONSTRAINED MHD SIMULATIONS

Primordial models: EGMF seeded at z=60 uniform along each axis or described by a spectral power law.

Astrophysical models: EGMF produced by magnetic feedback within halos with high number density.





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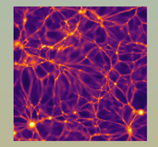
3D CRPropa SIMULATIONS

R.A.Batista et al, JCAP (2016)

PIERRE AUGER OBSERVATORY

Source Models

- Homogeneous
- Mass Density 

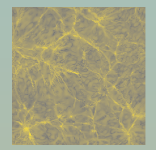
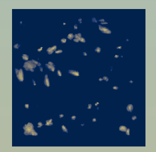
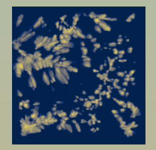
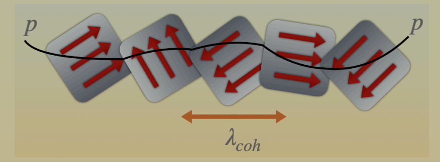
$n_s = 1.6 \cdot 10^{-4}\, Mpc^{-3}\, h^3$

Observer

- Spherical observer in the center of the simulation volume

$R_0 = 1\, Mpc$

EGMF Models

- No EGMF
- Primordial2R 
- Astrophysical 
- AstrophysicalR 
- Statistical 

$B_{rms} = 1\, nG$

$\lambda_c = 1\, Mpc$

GMF Model

- Jansson and Farrar 2012

LENSING TECHNIQUE

Propagation

- 3D propagation
- Periodic boundary conditions

Interactions

- Pair production
- Photopion
- Photodisintegration

CMB & EBL

- Nuclear decay
- Redshift

Source injection

- Isotropic
- p, He, N, Si, Fe
- between 8 and 1000 EeV.

$dN/dE \propto E^{-1}$

Realisations and Analysis

Observation of 10.000 cosmic rays above 8 EeV.

10 source realisation of each combination of composition, source model and EGMF model.

Cosmic average and variance of anisotropies observables (sky maps, multipoles, ...).

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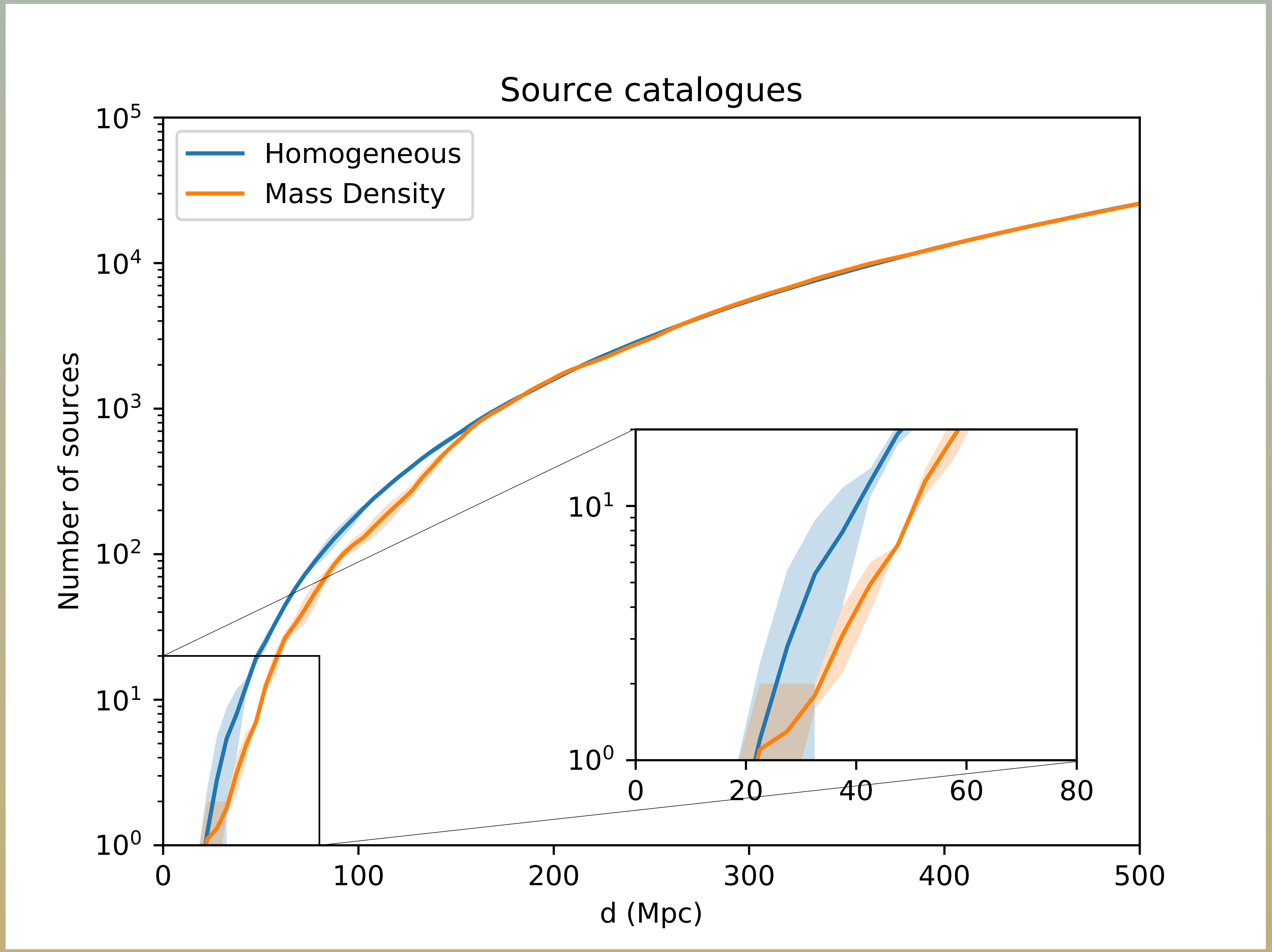
SOURCE DISTRIBUTION MODELS

Difference in the local distribution due to the different probability densities.

Same large distance behaviour: cosmological principle.



UHH

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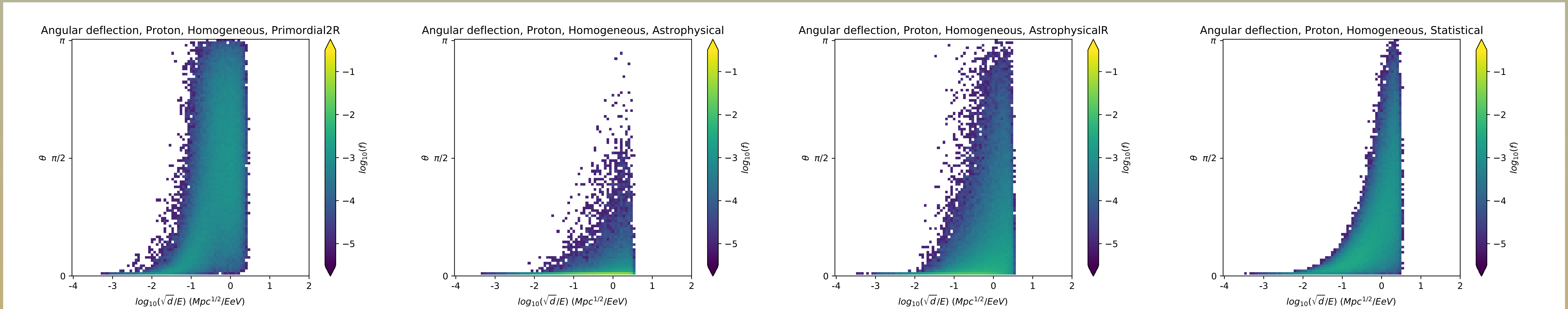
PIERRE AUGER OBSERVATORY

MAGNETIC DEFLECTION

Angular distribution between injected momentum
and observed momentum of detected particles

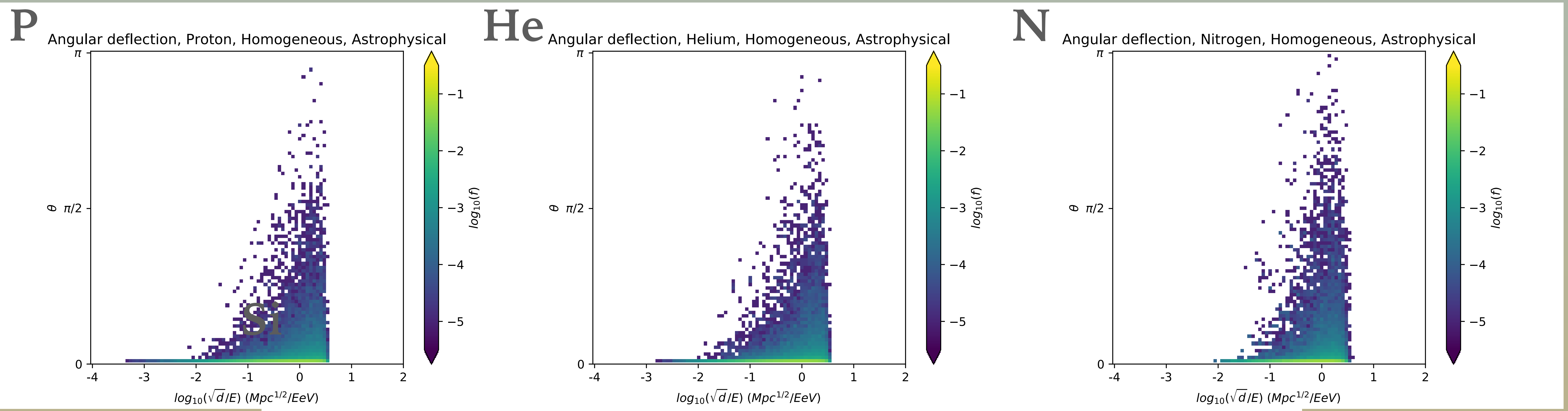
Primordial2R | Astrophysical | AstrophysicalR | Statistical

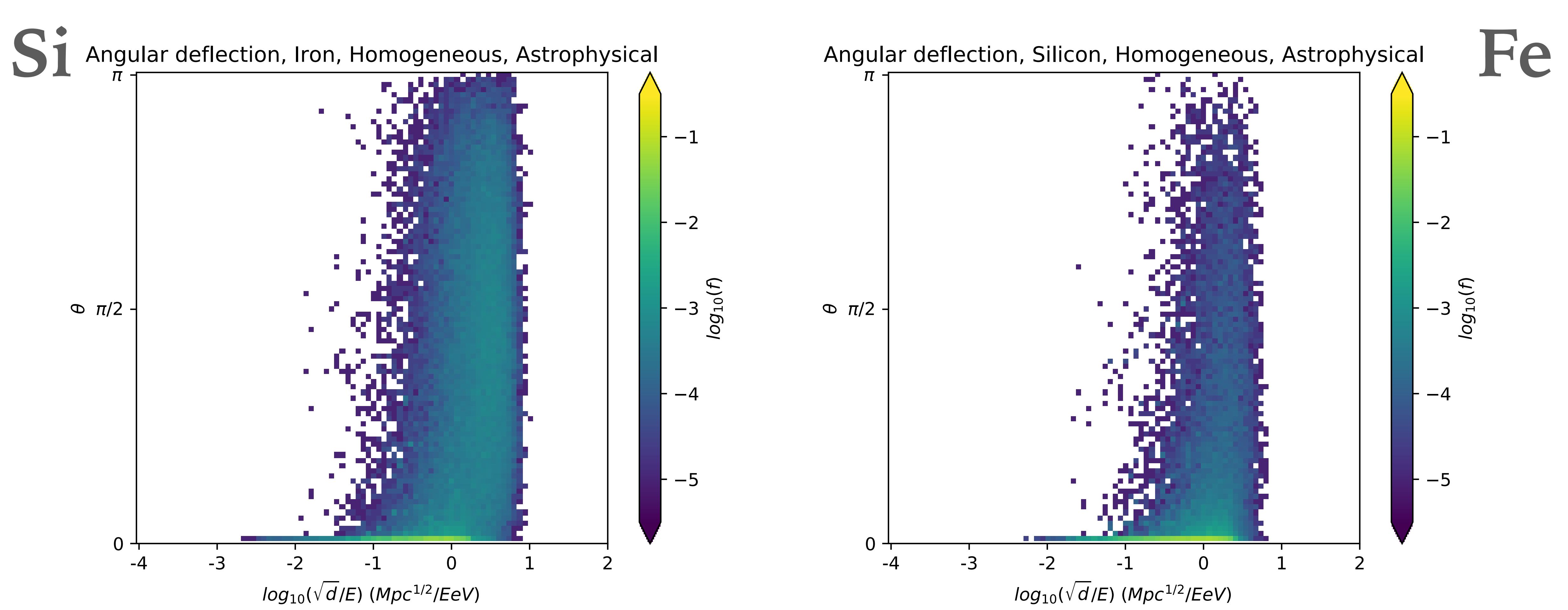


Protons, Homogeneous

MAGNETIC DEFLECTION

Homogeneous, Astrophysical





SKY MAPS

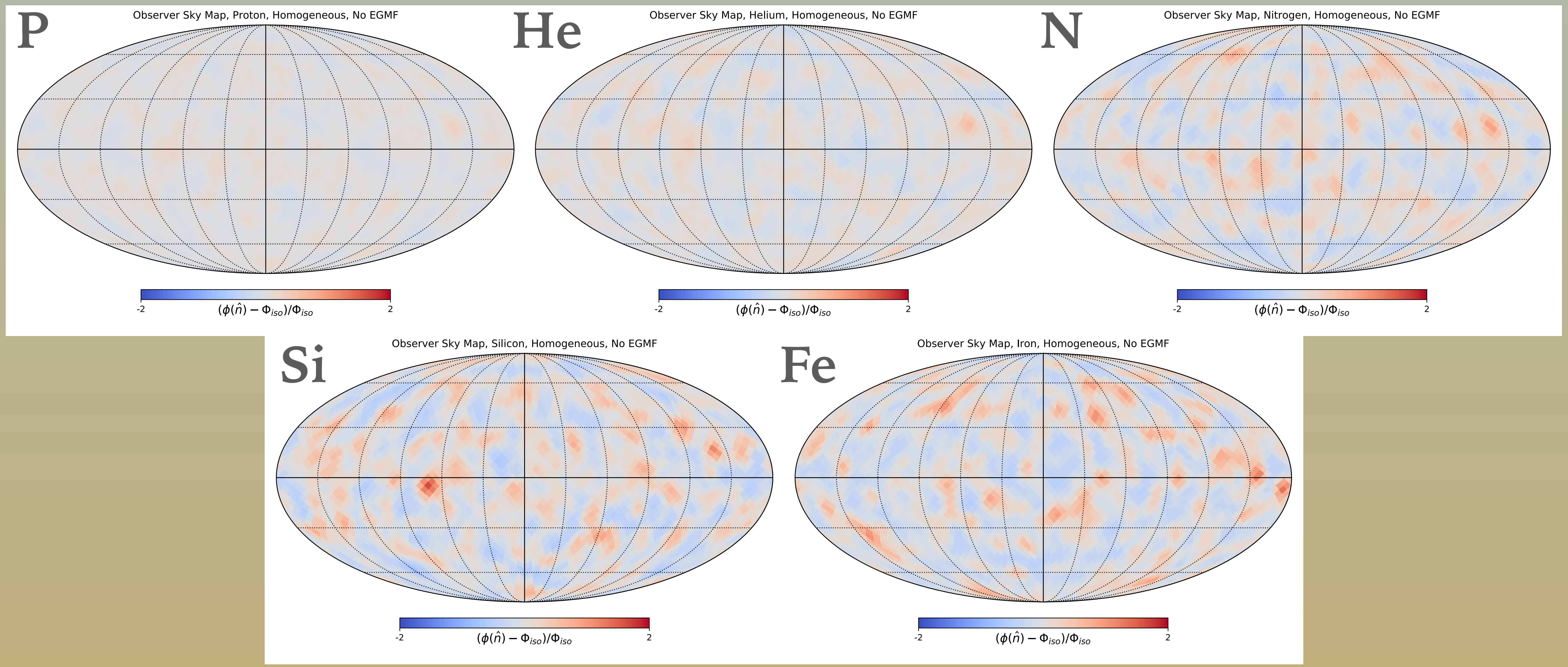
$$\phi(\hat{n}) = \frac{1}{N}\sum_{i=0}^{N}\delta(\hat{n}-\hat{n}_i) \simeq \frac{N_{i,j}}{N\cdot\Delta\Omega}$$

$$\Phi_{iso} = (4\pi)^{-1}$$

$$\Downarrow$$

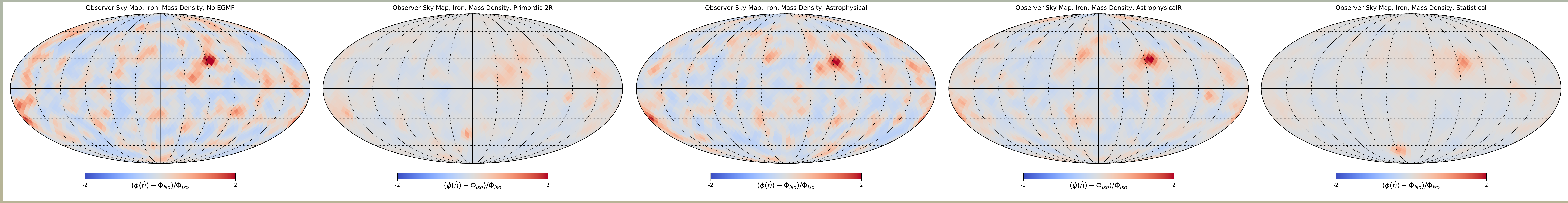
$$\delta_\phi(\hat{n}) = \frac{\phi(\hat{n})-\Phi_{iso}}{\Phi_{iso}}$$

Homogeneous, No EGMF

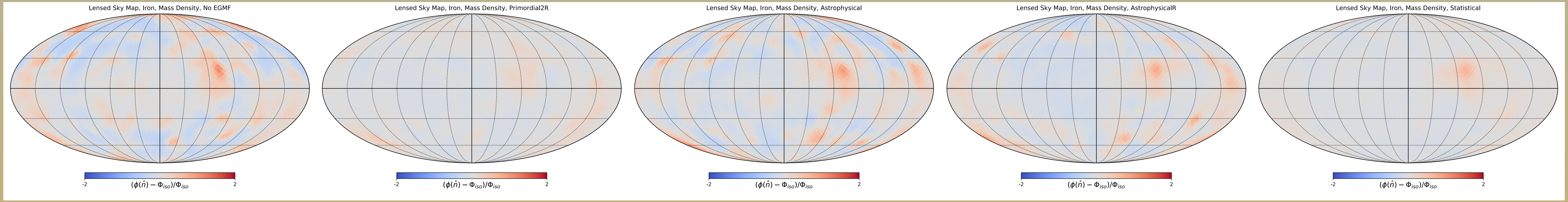


SKY MAPS

Irons, Mass Density, Observer



No EGMF | Primordial2R | Astrophysical | AstrophysicalR | Statistical



Irons, Mass Density, at Earth

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MULTIPOLE EXPANSION

Spherical Decomposition

$$a_{lm} = \int d\hat{n}\, \phi(\hat{n})\, Y^*_{lm}(\hat{n})$$

Angular power spectrum

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} \left| a_{lm} \right|^2$$

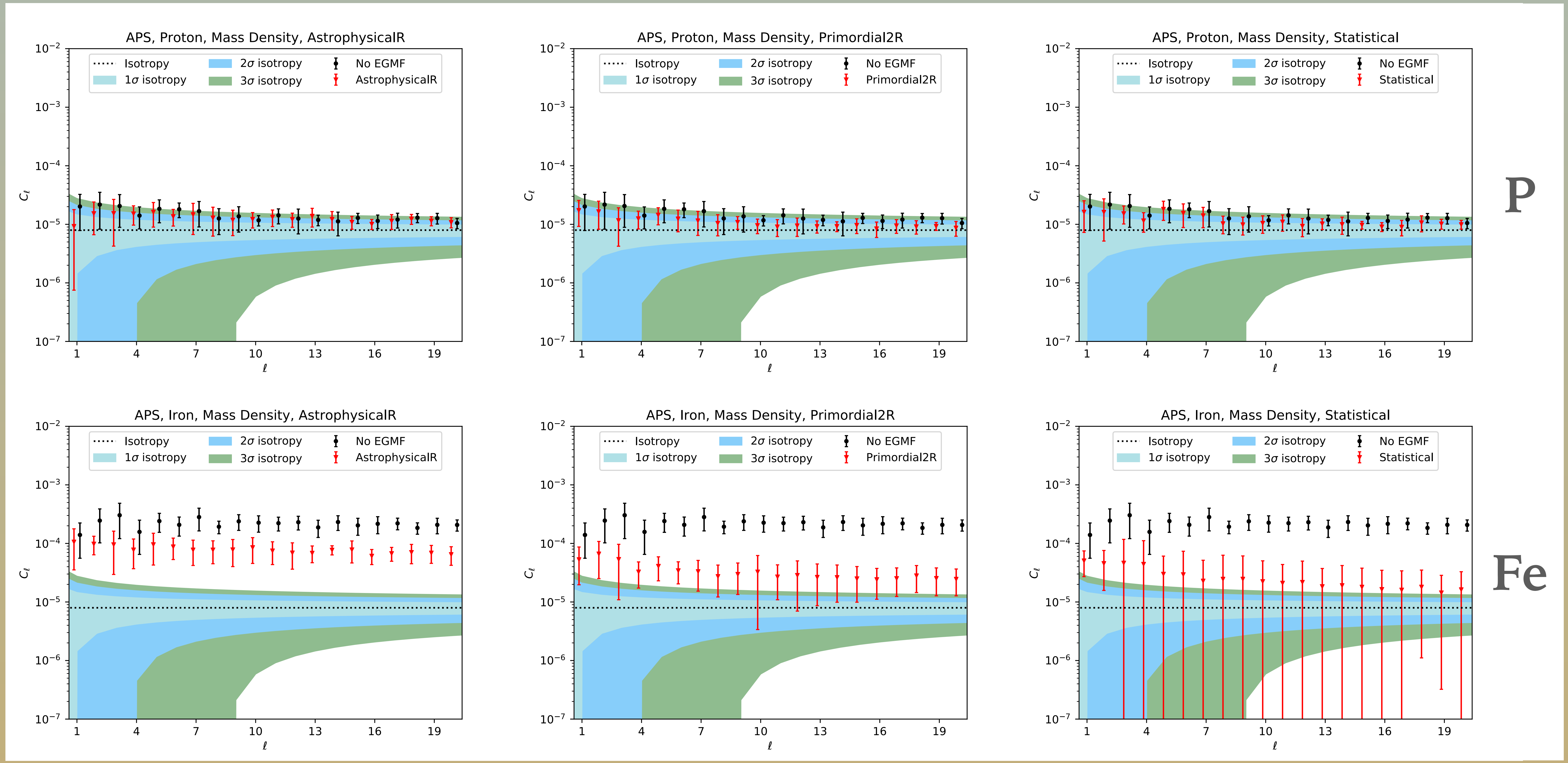
Multipoles contribution (dipole, quadrupole, …)

$\theta \sim 180°/l$

Isotropic prediction

$$C_l^{iso} = (4\pi N)^{-1}$$

AstrophysicalR Primordial2R Statistical



All the maps contain one EGMF model (red) and the case without EGMF. The source model is Mass Density

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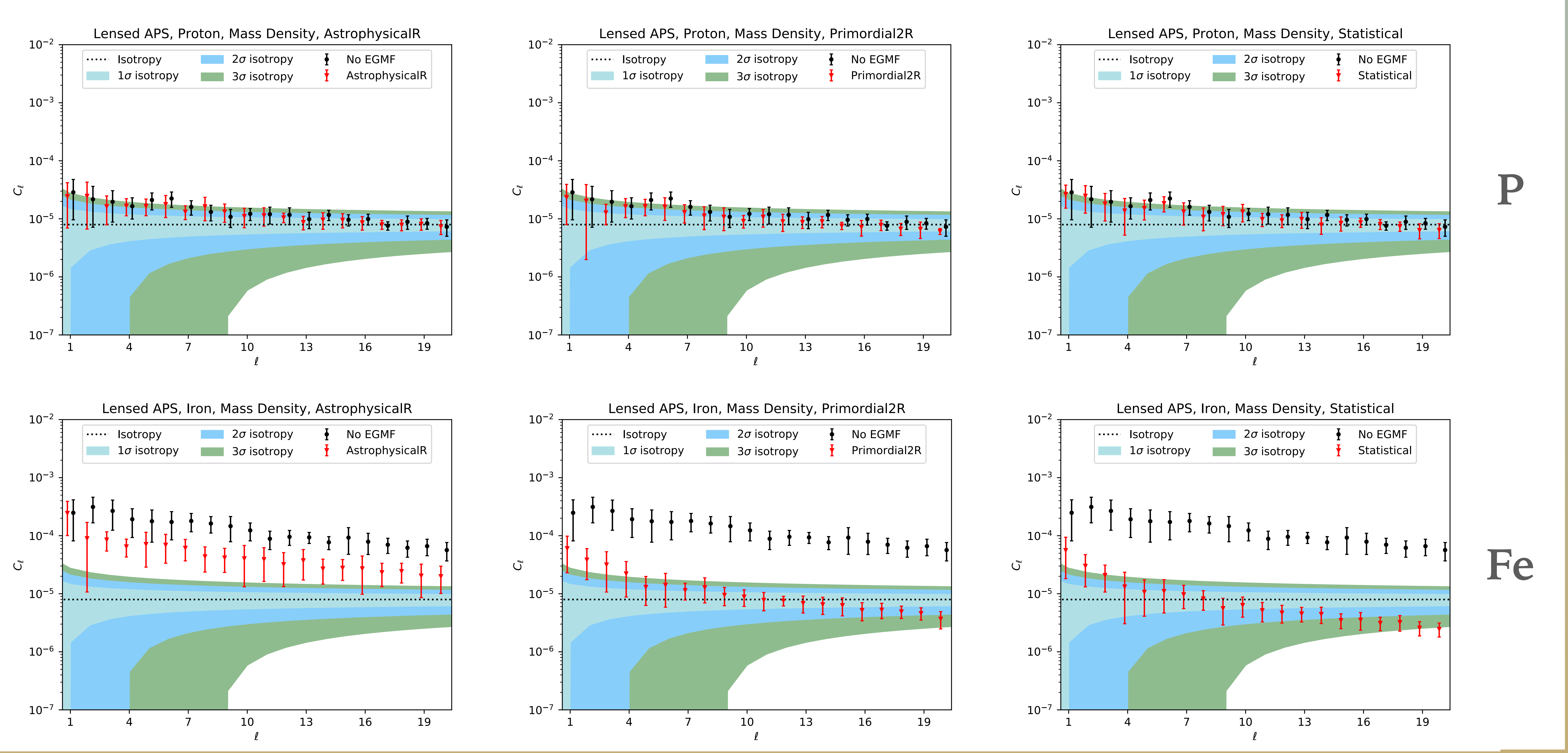
MULTIPOLE EXPANSION WITH THE GALACTIC LENSING

AstrophysicalR | Primordial2R | Statistical

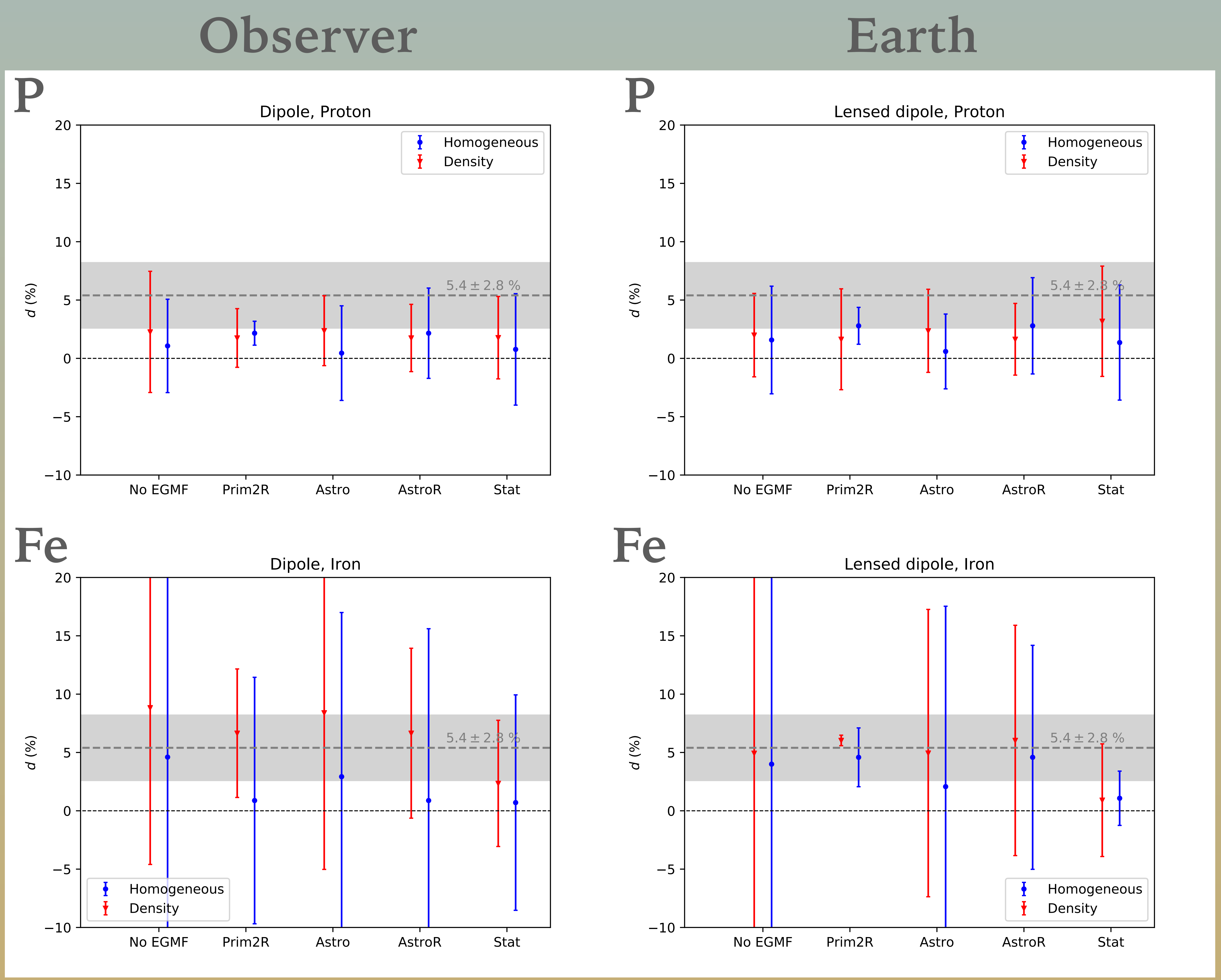


All the maps contain one EGMF model (red) and the case without EGMF. The source model is Mass Density

DIPOLE

$$\phi(\hat{n}) = \phi_0 \left(1 + \hat{n} \cdot \vec{d} + \frac{1}{2} \hat{n} \cdot Q \cdot \hat{n} + \dots \right)$$

The dipole is the strongest indication of UHECR anisotropies
(120° away for the galactic center, energy evolution, …)



A. Aab et al, Astrophys. J. (2018)

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CONCLUSIONS

EGMF: highly magnetised space induces reduction of the anisotropy signal of the source distribution.

Composition: heavy injection implies higher values for the angular power spectrum (photodisintegration). Greater separation induced by the EGMF.

Galactic lensing: suppression of the high- multipole component due to the GMF. Low-multipoles weakly affected by the galactic field.

Dipole: Homogeneous source distribution corresponds to weaker dipole. Less magnetisation corresponds to higher dipole. The galactic deflection slightly increases the dipole signal.

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