Federal Ministry
of Education
and Research

Ultra-high energy cosmic ray propagation in a structured Universe

Anisotropy study above 8 EeV

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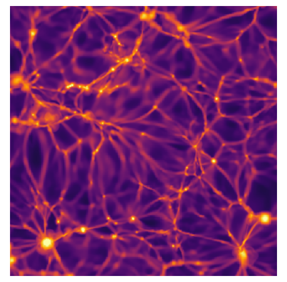
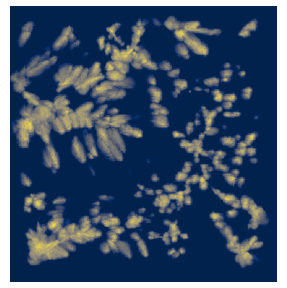
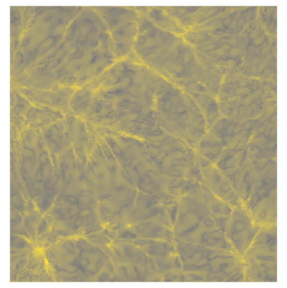
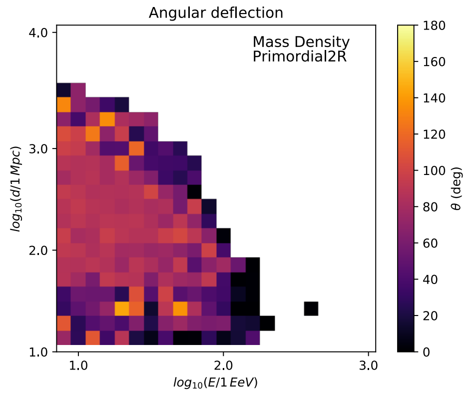
Outlook

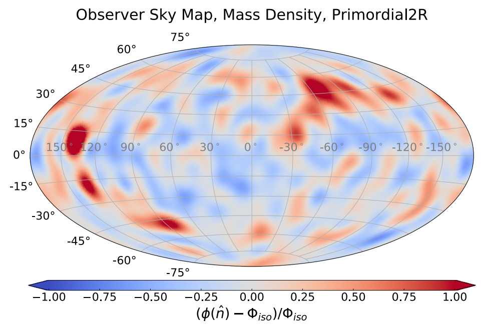
- Constrained MHD simulations: structured Universe

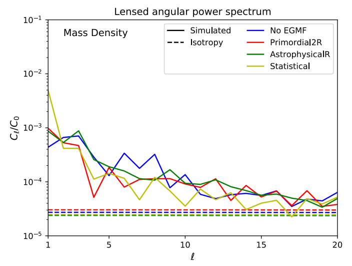




- CRPropa simulations CRPropa

- Results: deflection, sky map, anisotropies

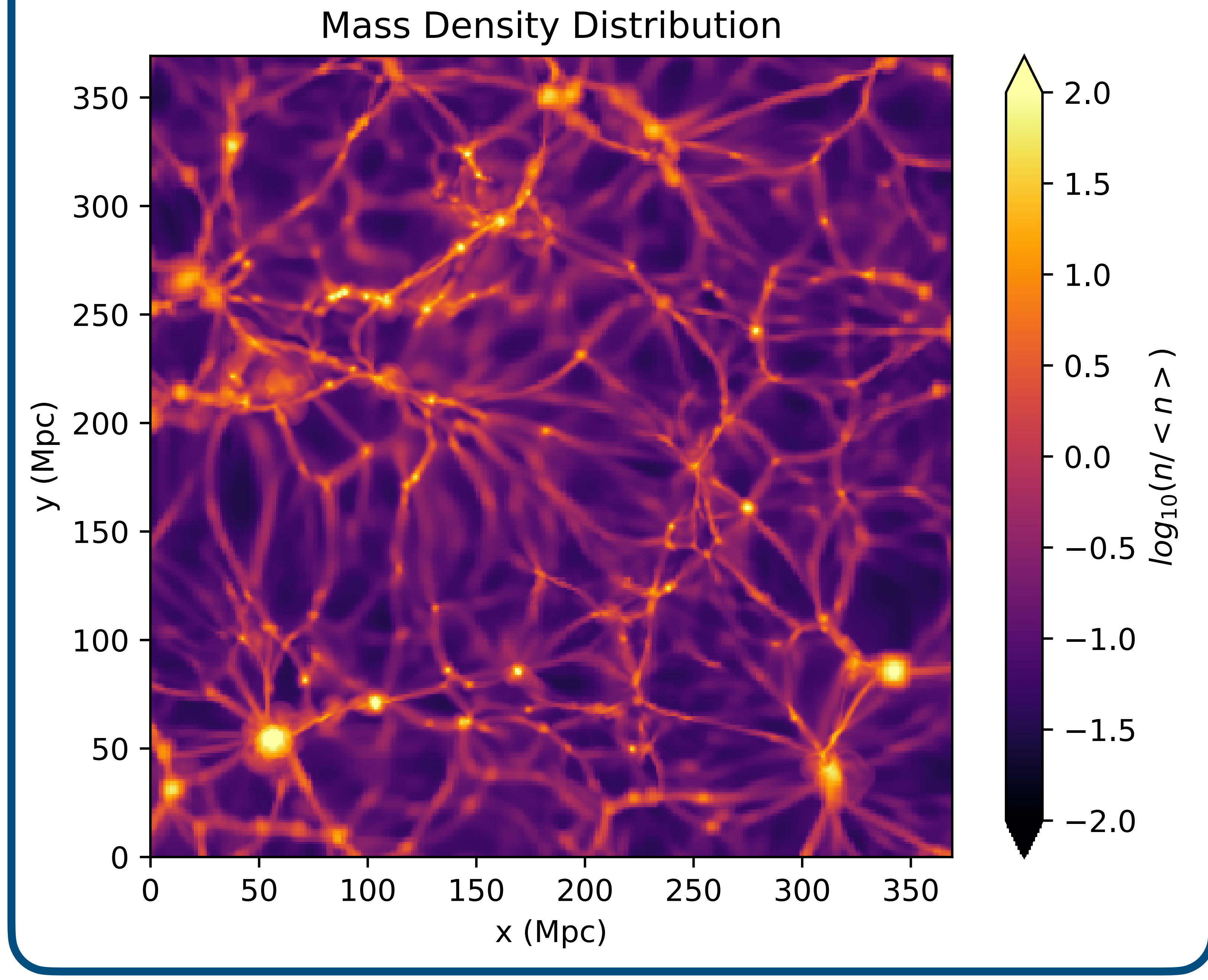




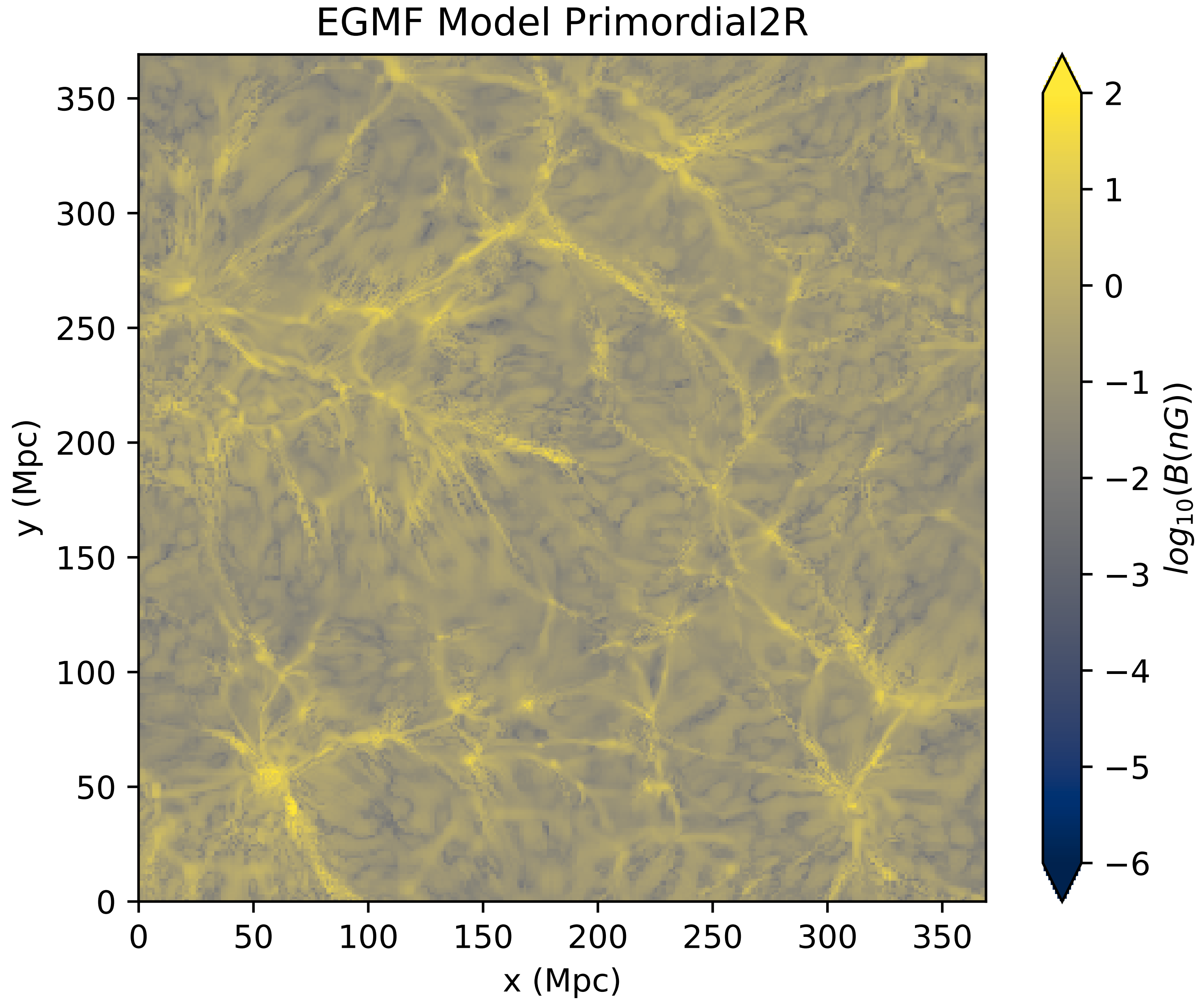


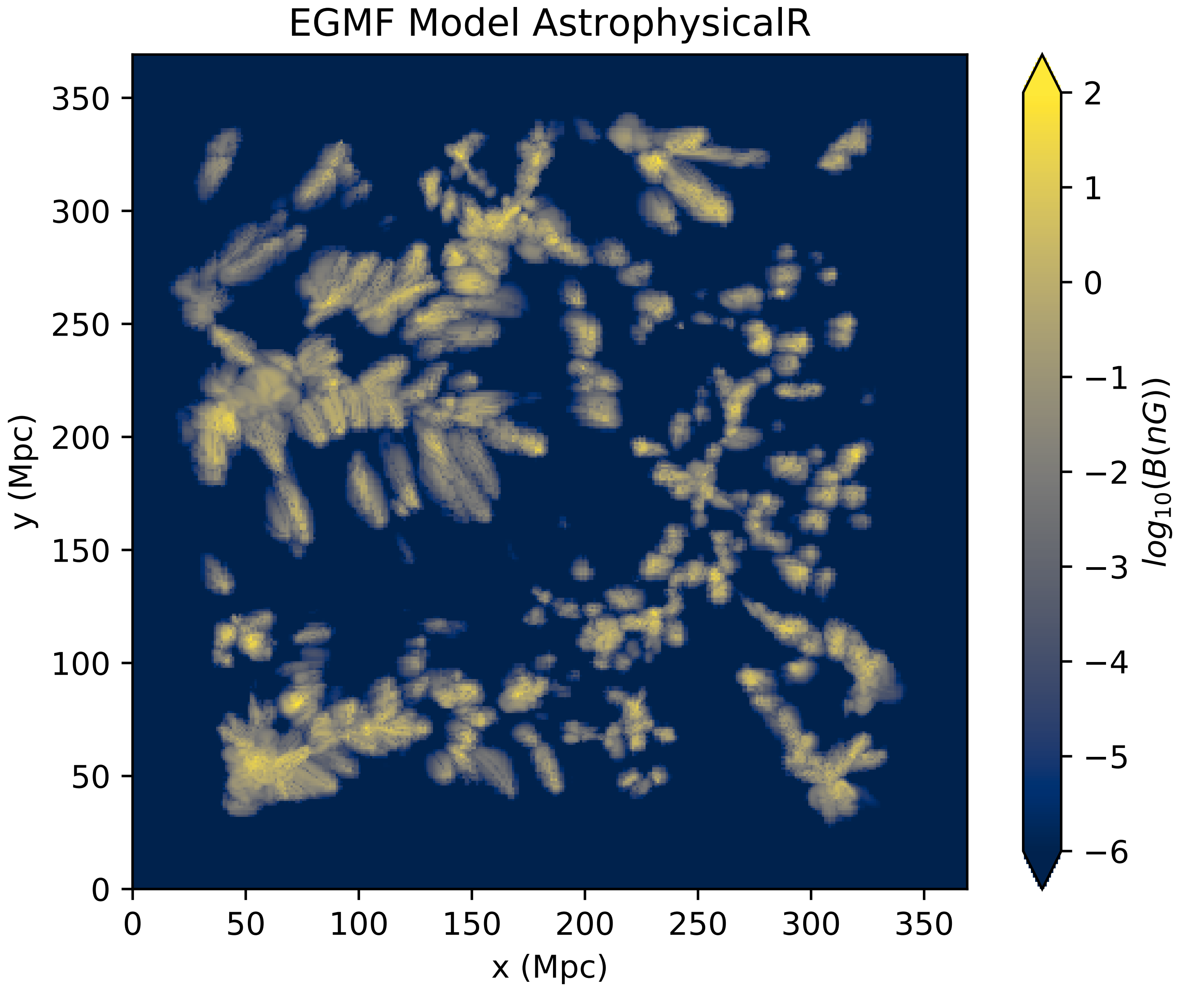
Constrained MHD simulations

Baryonic distribution



Extragalactic magnetic field





Constrained baryonic distribution at z=60 in a comoving volume of $(500\,Mpc)^3$ (**ENZO**)

Primordial2R: EGMF seeded at z=60 uniform along each axis or described by a spectral power law.

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

The ENZO Collaboration: G.L.Bryan et al, ApJS (2013)
J.G.Source et al, Mon. Not. R. Astron. Soc. (2015)
S.Hackstein et al, Mon. Not. R. Astron. Soc. (2017)

UHECR interactions

Cosmic background photon fields (CMB & EBL)

- Pair production

$$p + \gamma_{bg} \rightarrow p + e^+ + e^-$$

- Photopion production

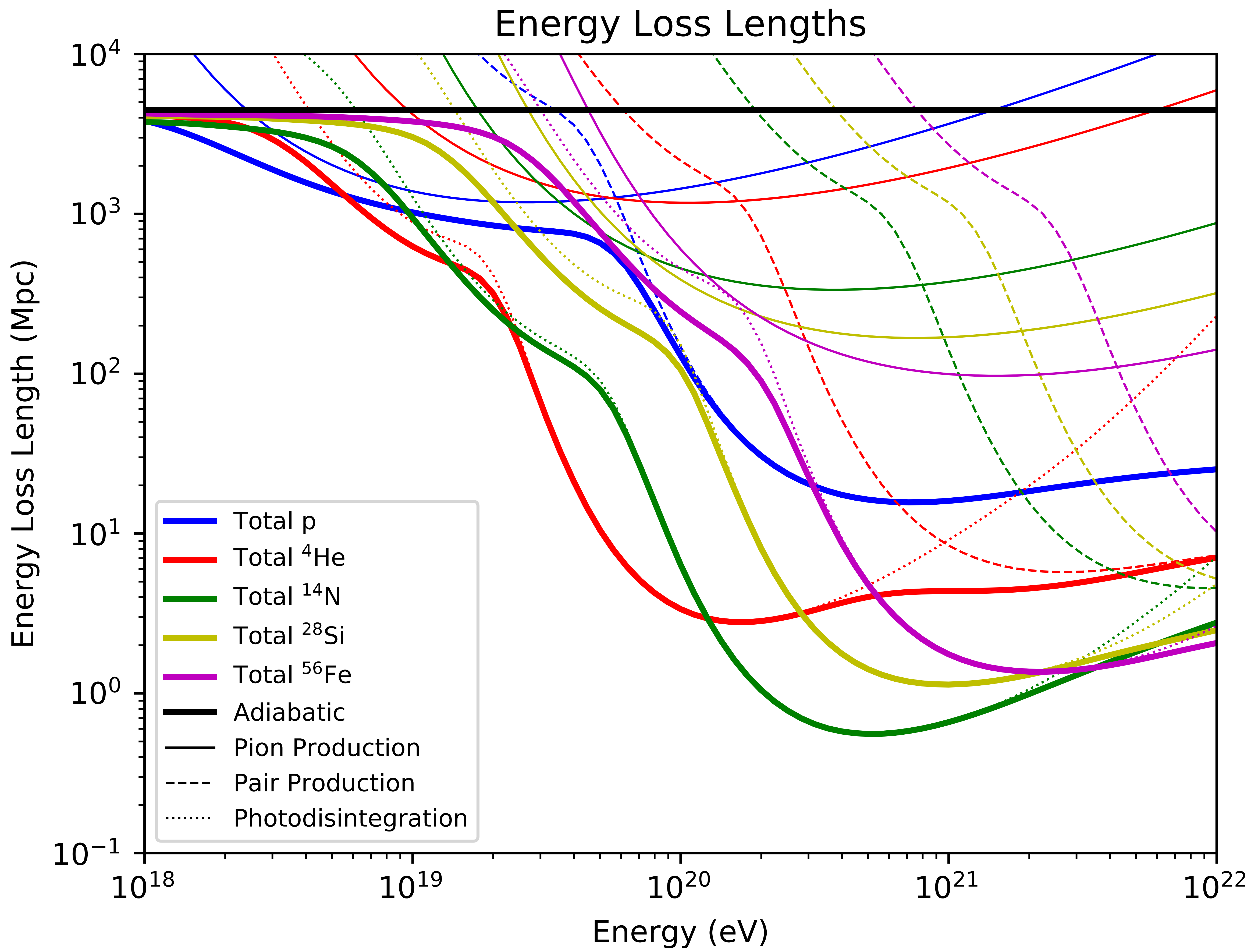
$$p + \gamma_{bg} \rightarrow p(n) + \pi^0(\pi^+)$$

- Photodisintegration

$$(A, Z) + \gamma_{bg} \rightarrow (A - n, Z - m) + nN$$

- Adiabatic energy loss

$$-\frac{1}{E}\frac{dE}{dt} = H_0$$



$$\tau^{-1}(\Gamma) = \frac{c}{2\Gamma^2}\int_{\epsilon'_{th}}^{\infty} \epsilon'\sigma(\epsilon')\nu(\epsilon')\int_{\epsilon'/2\Gamma}^{\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon d\epsilon'$$

CRPropa simulations

- Structured source distribution following LSS with $n \simeq 10^{-2}\,Mpc^{-3}$
- Structured and statistically homogeneous EGMF with $B_{rms} = 1\,nG$, $\lambda_c = 1\,Mpc$
- Galactic magnetic field JF12 (*lensing*)

- Spherical observer in the center with radius $R_O = 1\,Mpc$
- 3D propagation
- Periodic boundary conditions

- Photohadronic interactions (CMB & EBL), nuclear decay and redshift
- Isotropic injection of p, He, N, Si and Fe
- Simulated spectrum above 8 EeV

R.A. Batista et al, JCAP (2016)
R.A. Batista et al, JCAP (2022)

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- Correction for the finite size of the observer
- Weighting of the simulations with combined fit of energy spectrum and mass composition

	baseline	**JF12 reg**	**homogeneous**
sources	LSS	LSS	homogenous
HIM	EPOS-LHC	EPOS-LHC	EPOS-LHC
cutoff $f_{\rm cut}$	b.e.	b.e.	b.e.
GMF	reg+rand	reg only	reg+rand
γ	−1.17	−1.23	−1.34
$\log_{10} R_{\rm cut}$	18.2	18.2	18.2
$I_{\rm H}$	0.01	0.02	0.02
$I_{\rm He}$	0.27	0.27	0.24
$I_{\rm N}$	0.57	0.56	0.58
$I_{\rm Si}$	0.12	0.12	0.13
$I_{\rm Fe}$	0.01	0.04	0.04
$\nu_{X_{\rm max}}/\sigma$	−0.88	−0.93	−0.95
$\ln \mathcal{L}_E$	−92.3	−91.1	−92.4
$\ln \mathcal{L}_{X_{\rm max}}$	−228.7	−229.2	−229.3
$\ln \mathcal{L}_d$	12.1	11.8	−8.5
$\ln \mathcal{L}_{\rm syst}$	−0.4	−0.4	−0.5
$\ln \mathcal{L}_{\rm sum}$	−309.3	−308.9	−330.6

T. Bister & G. Farrar, Astrophys.J. (2024)

$$Q_A(E) \propto a_A \left(\frac{E}{E_0}\right)^{-\gamma} f_{cut}\left(\frac{E}{Z_A R_{cut}}\right)$$

- Nearest source luminosity 10 times greater

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

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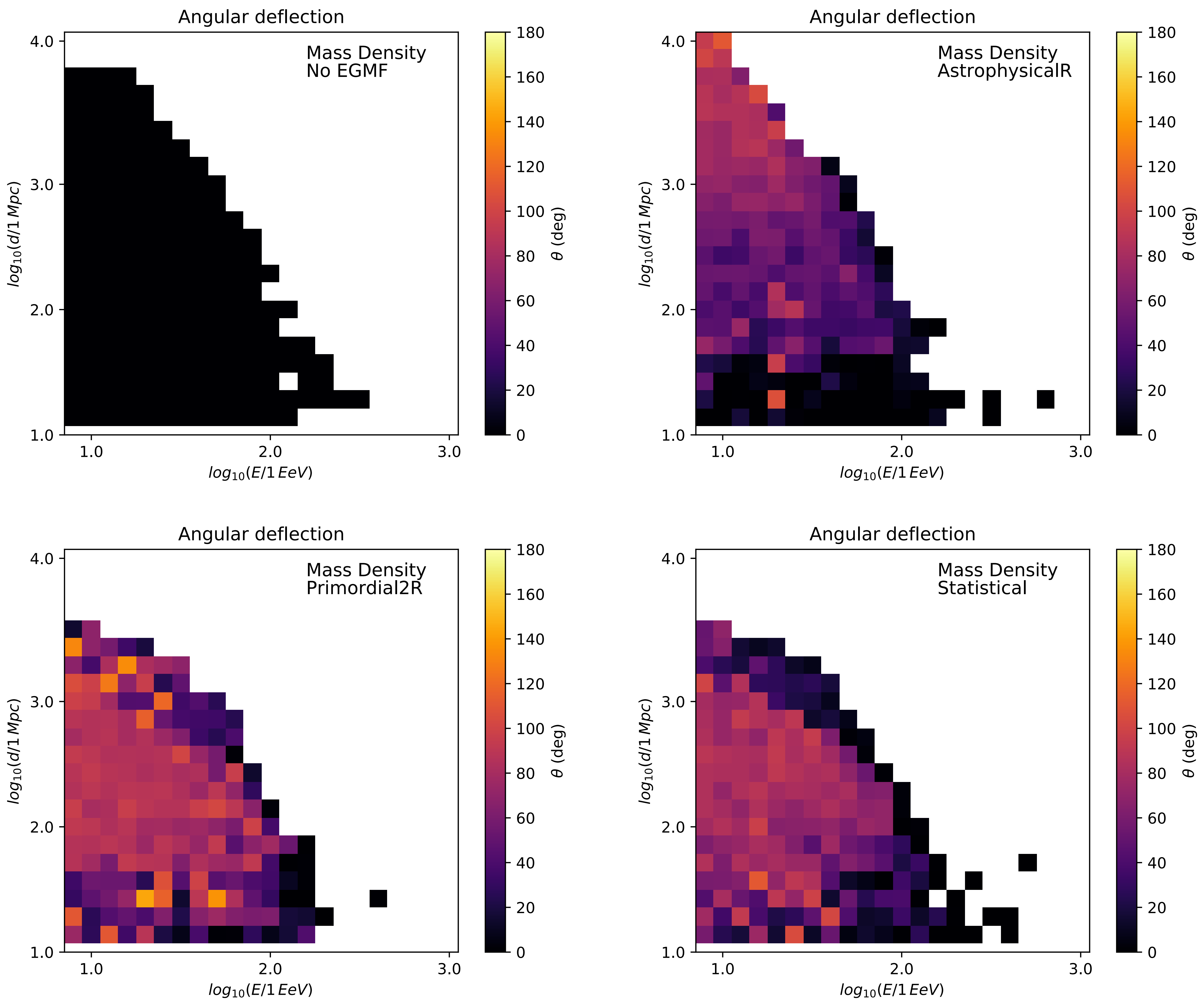
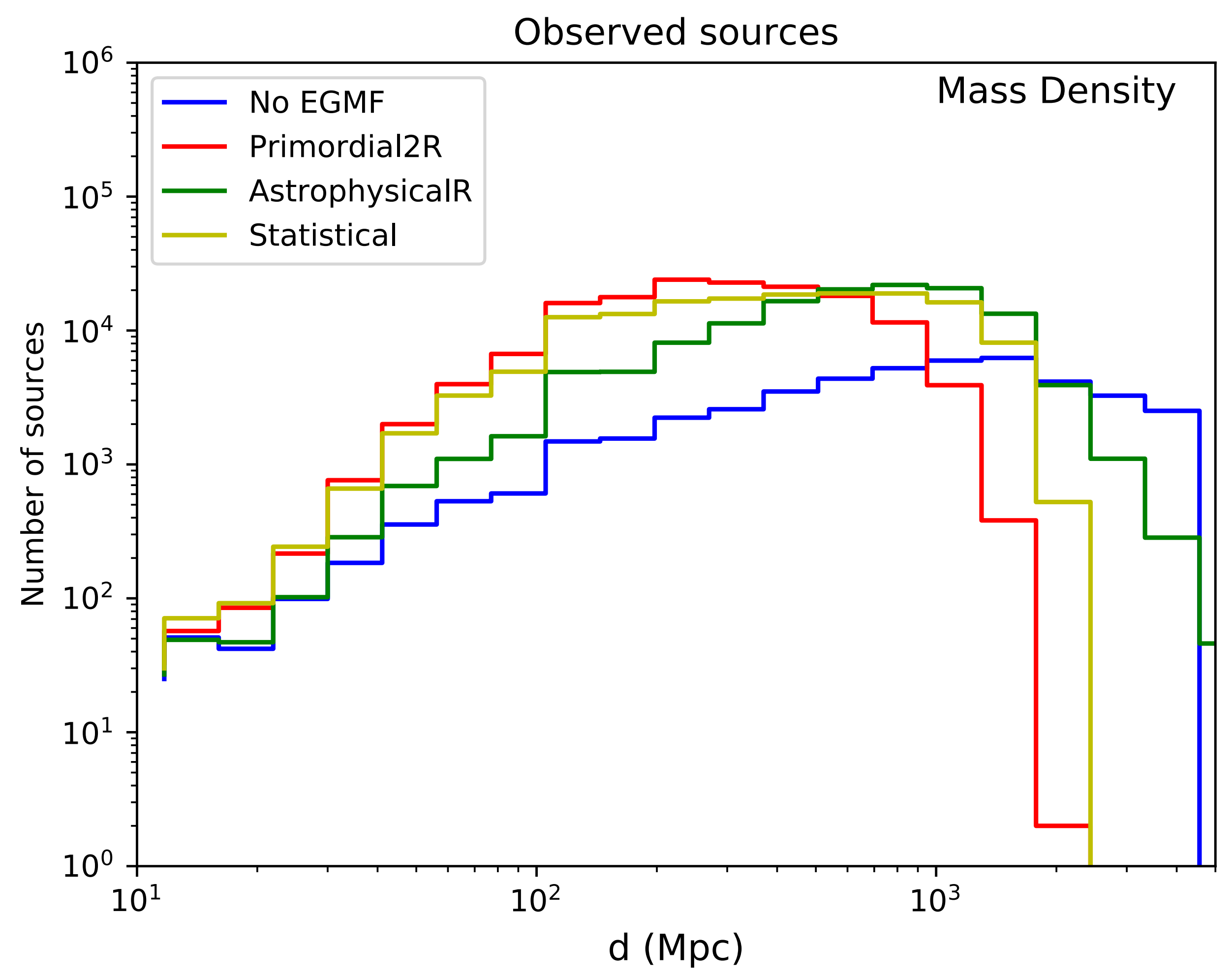
Magnetic deflection and horizon



Angle distribution between injected momentum and observed momentum of detected particles

Magnetic horizon: suppression of the maximum source distance



Arrival direction distribution

Effective number of particles with weight factor ω_i given by

$$\mathcal{N} = \sum_{i=1}^{N} \omega_i$$

If N_p is the number of pixels in the sky with angular size $\Delta\Omega$

$$\phi(\hat{n}) = \frac{1}{\mathcal{N}} \sum_{i=1}^{N_p} \mathcal{N}_i \cdot \Delta(\hat{n} - \hat{p}_i)$$

Effective number of particles in the pixel i $\mathcal{N}_i$ and

$$\Delta(\hat{n} - \hat{p}_i) = \frac{1}{\Delta\Omega_i} \quad , \quad for\ \hat{n}\ in\ the\ pixel\ \hat{p}_i$$

Fractional deviation of arrival direction distribution

$$\delta_\phi(\hat{n}) = \frac{\phi(\hat{n}) - \phi_{iso}}{\phi_{iso}} \quad , \quad \phi_{iso} = \frac{1}{4\pi}$$

Spherical decomposition of the sky map distribution

$$\phi(\hat{n}) = \sum_{l=0}^{+\infty} \sum_{m=-l}^{l} a_{lm} Y_{ml}(\hat{n})$$

$$a_{lm} = \int d\hat{n}\, \phi(\hat{n})\, Y^*_{lm}(\hat{n}) \quad \Rightarrow \quad C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} \left| a_{lm} \right|^2$$

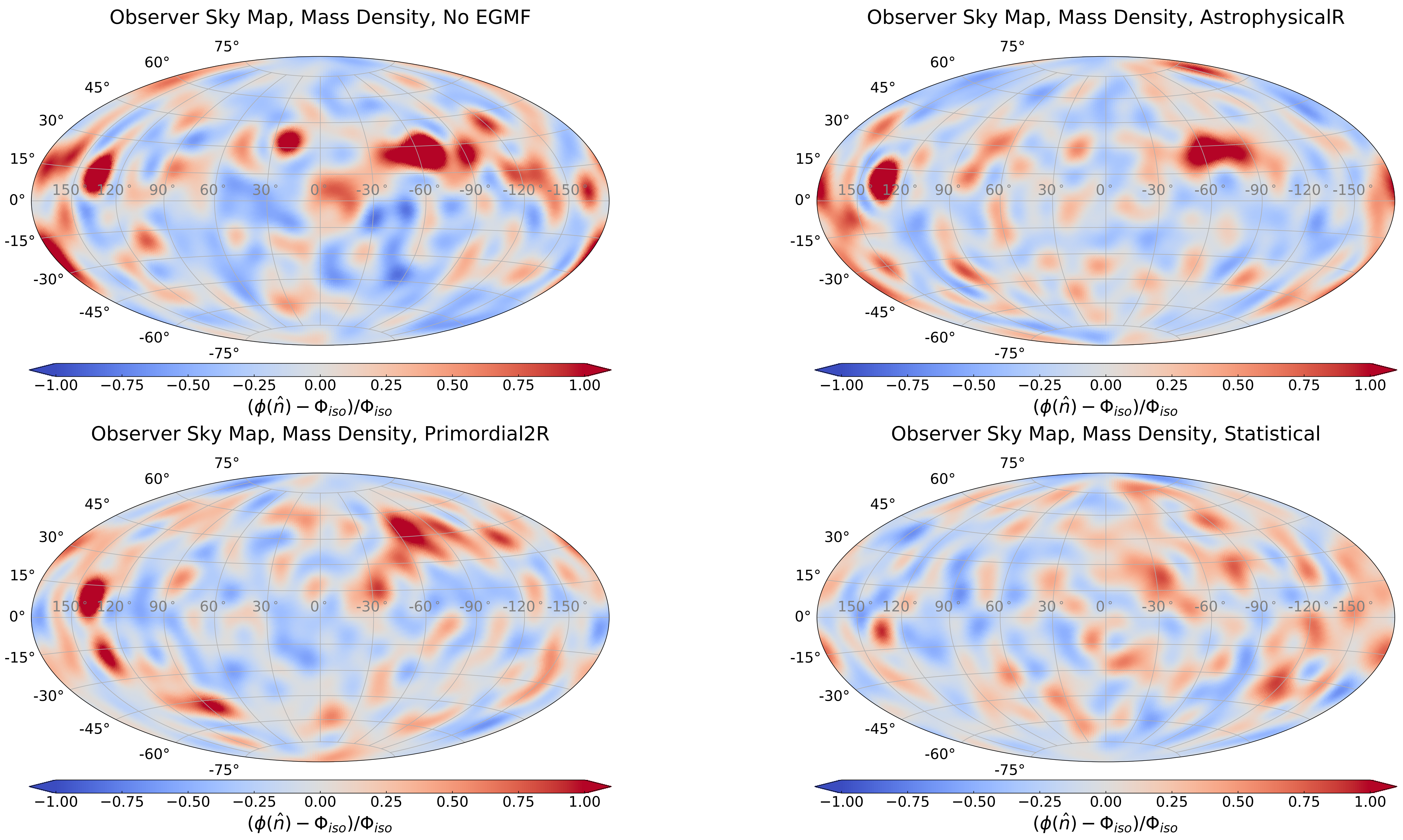
Expected angular power spectrum under isotropic assumption

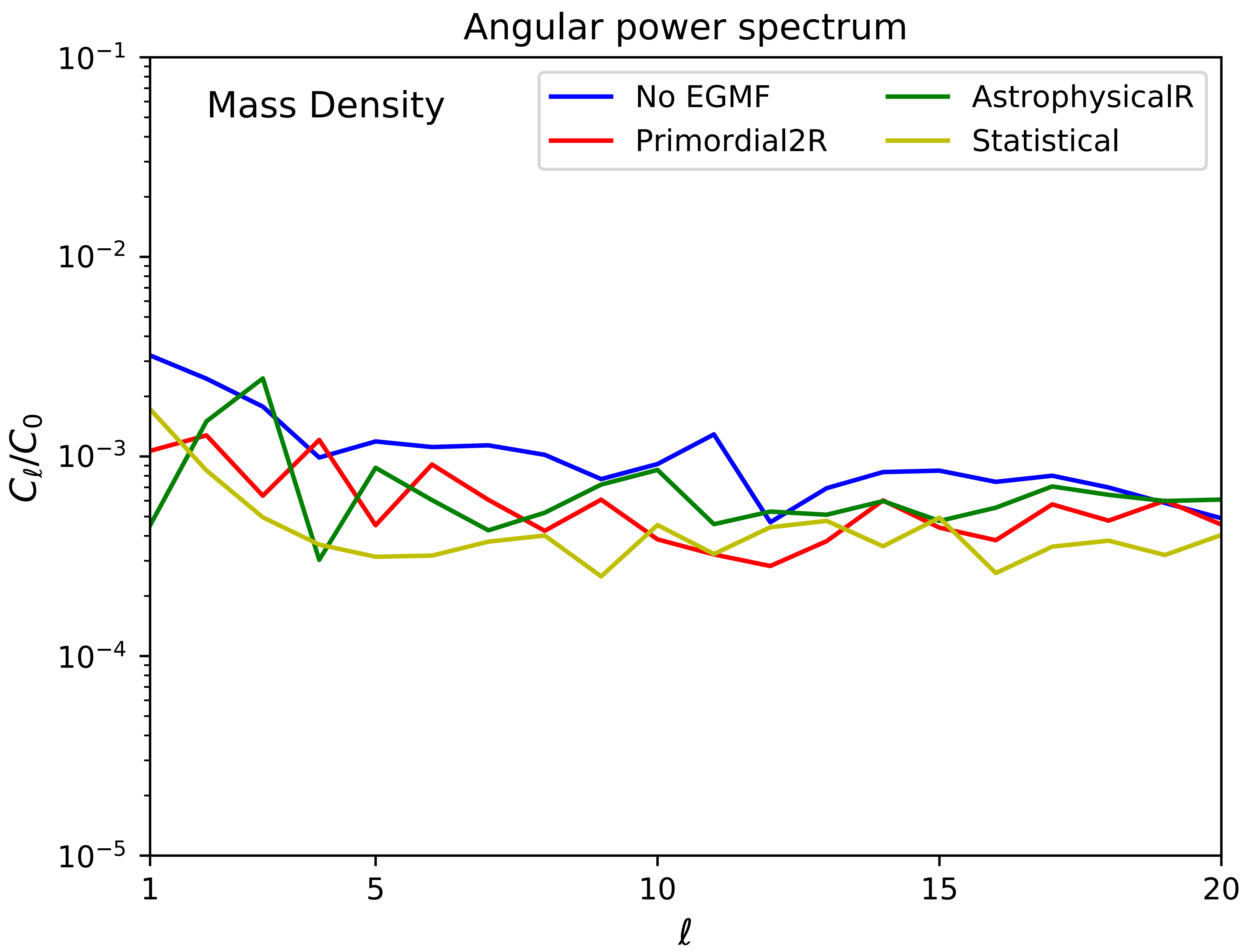
$$\left\langle C_l \right\rangle_{\phi_{iso}} = \frac{1}{2l+1} \frac{\Delta\Omega}{4\pi} \frac{\sum_{j=1}^{N} \omega_j^2}{\mathcal{N}^2} \sum_{m=-l}^{l} \sum_{i=1}^{N_p} \left| f_{lm,i} \right|^2$$

where

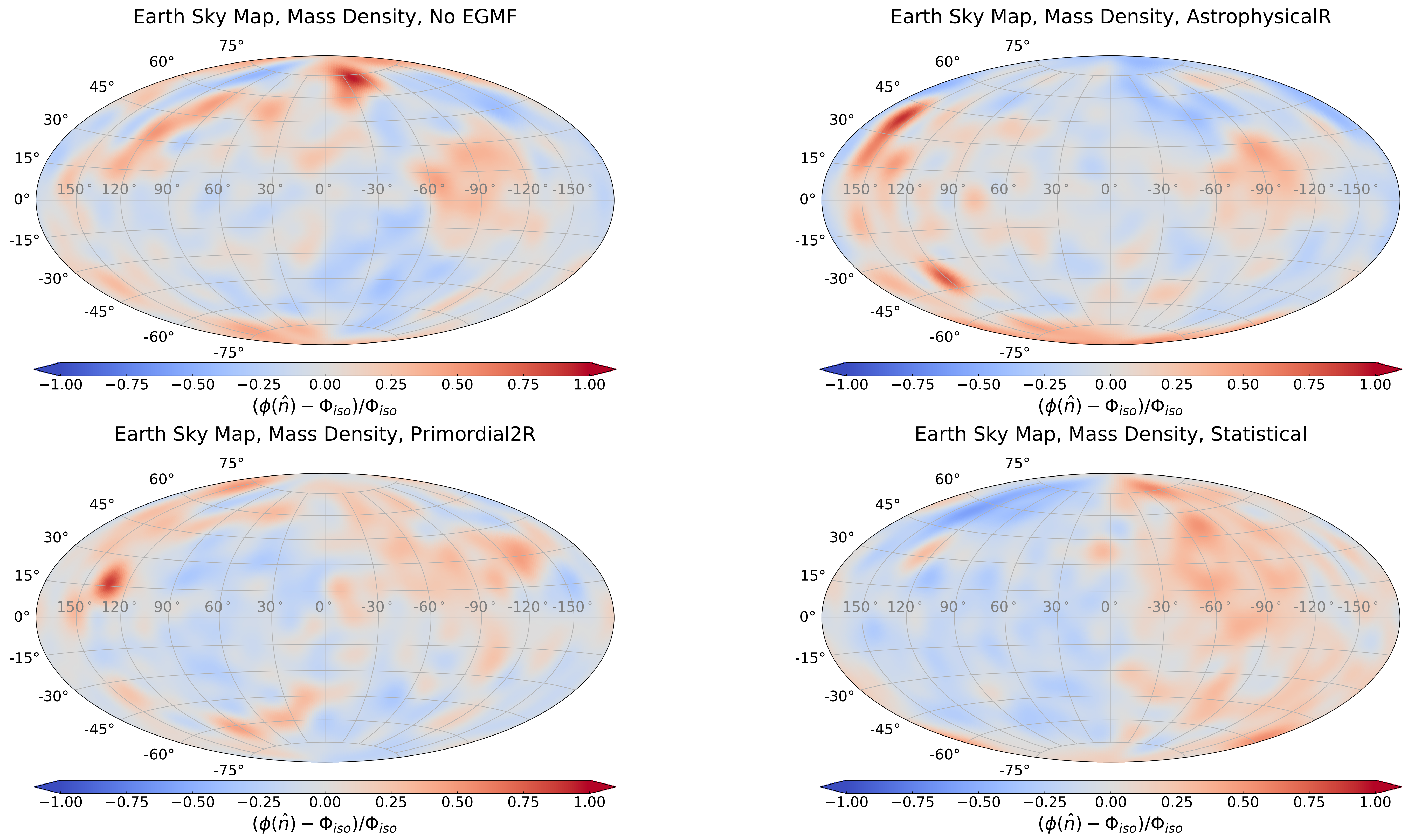
$$f_{lm,i} = \frac{1}{\Delta\Omega_i} \int_{\Delta\Omega_i} d\hat{n}\, Y_{lm}(\hat{n})$$

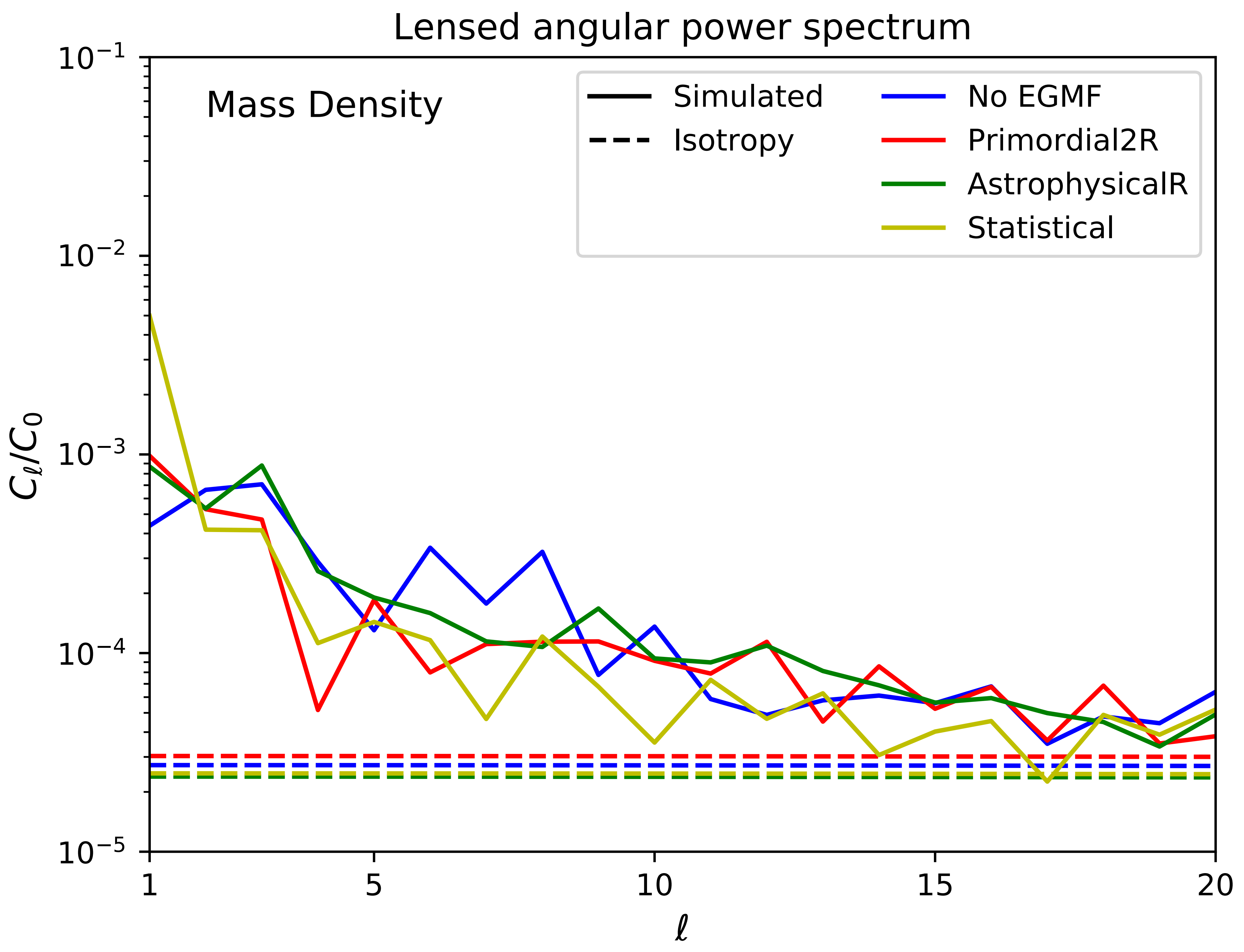
Arrival direction distribution



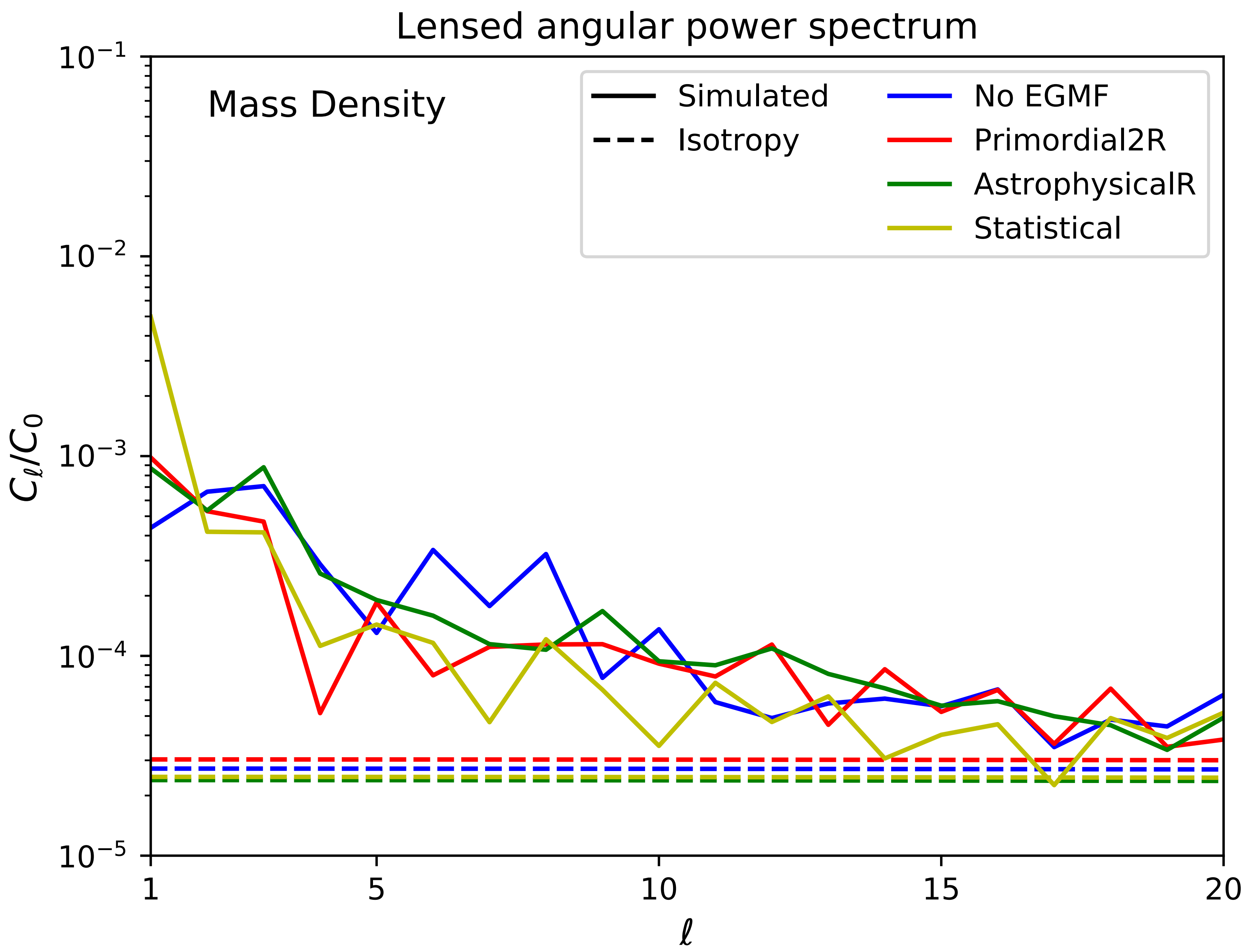


Lensed arrival direction distribution





Dipole and quadrupole



Dipole strength $d = 3\sqrt{\frac{C_1}{C_0}}$

Quadrupole strength $Q = \sqrt{150\frac{C_2}{C_0}}$

	Dipole	Quadrupole
No EGMF	6%	32%
AstrophysicalR	9%	27%
Primordial2R	9.5%	27%
Statistical	21%	21%
Auger	**(6.5±0.1)%**	**(1.5±1.6)%**

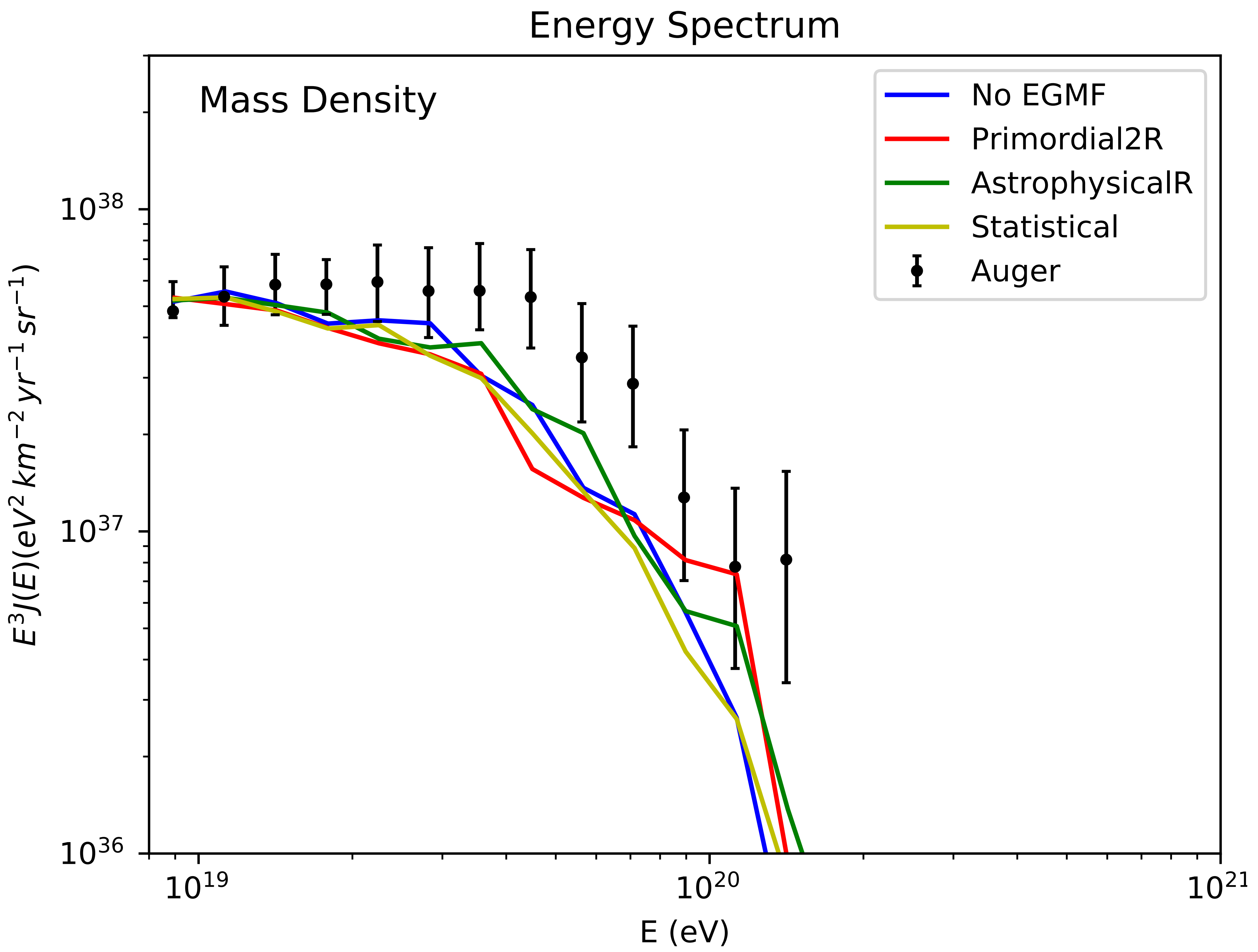
R. de Almeida, PoS ICRC (2021)

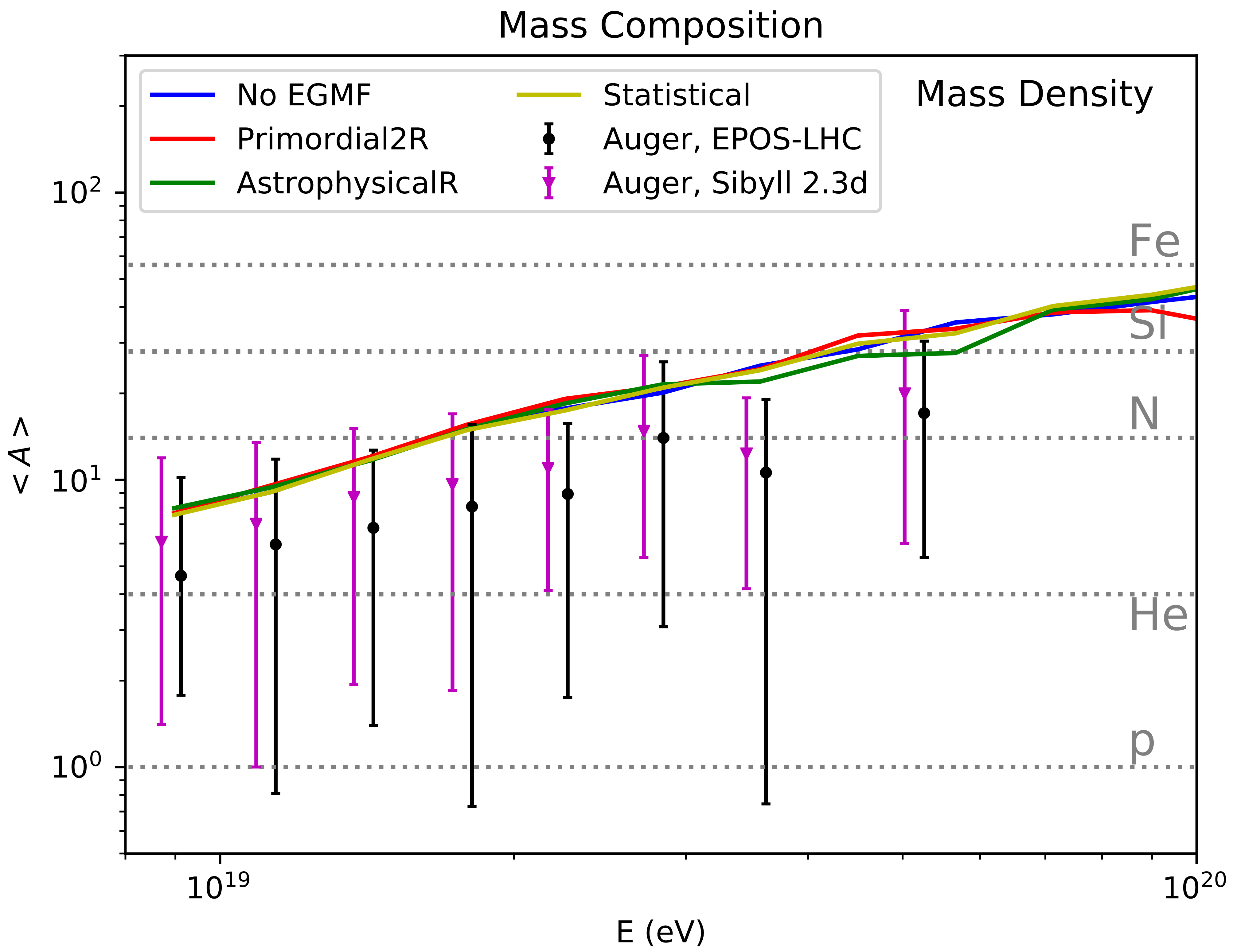
Results

- Magnetic horizon due to the magnetisation of the extragalactic space. The higher the magnetisation, the lower the horizon.
- The galactic magnetic field suppresses small angular scale anisotropies
- Large angular scale anisotropies due to the intrinsic source distribution and interaction horizon are still present after the propagation

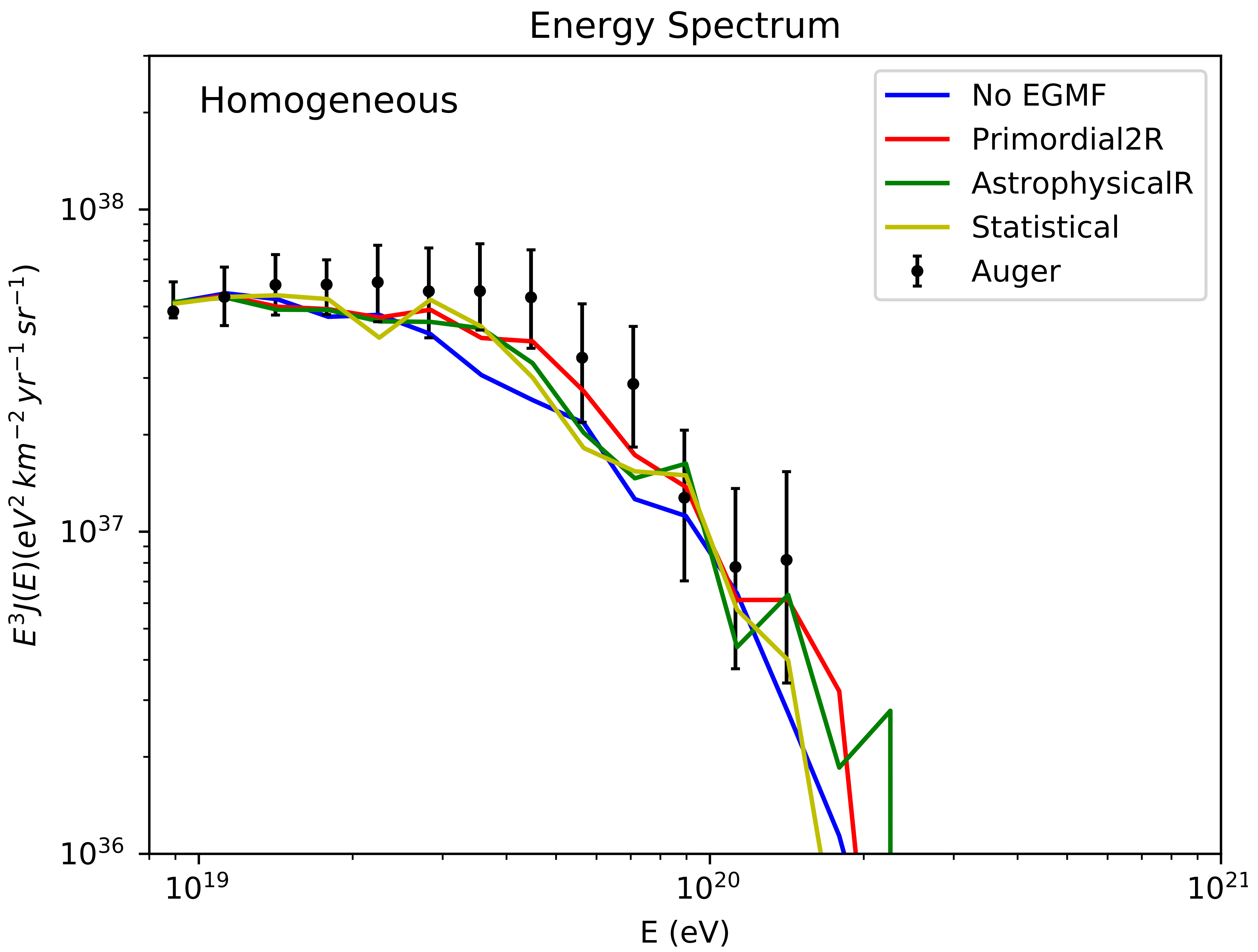
Backup slides

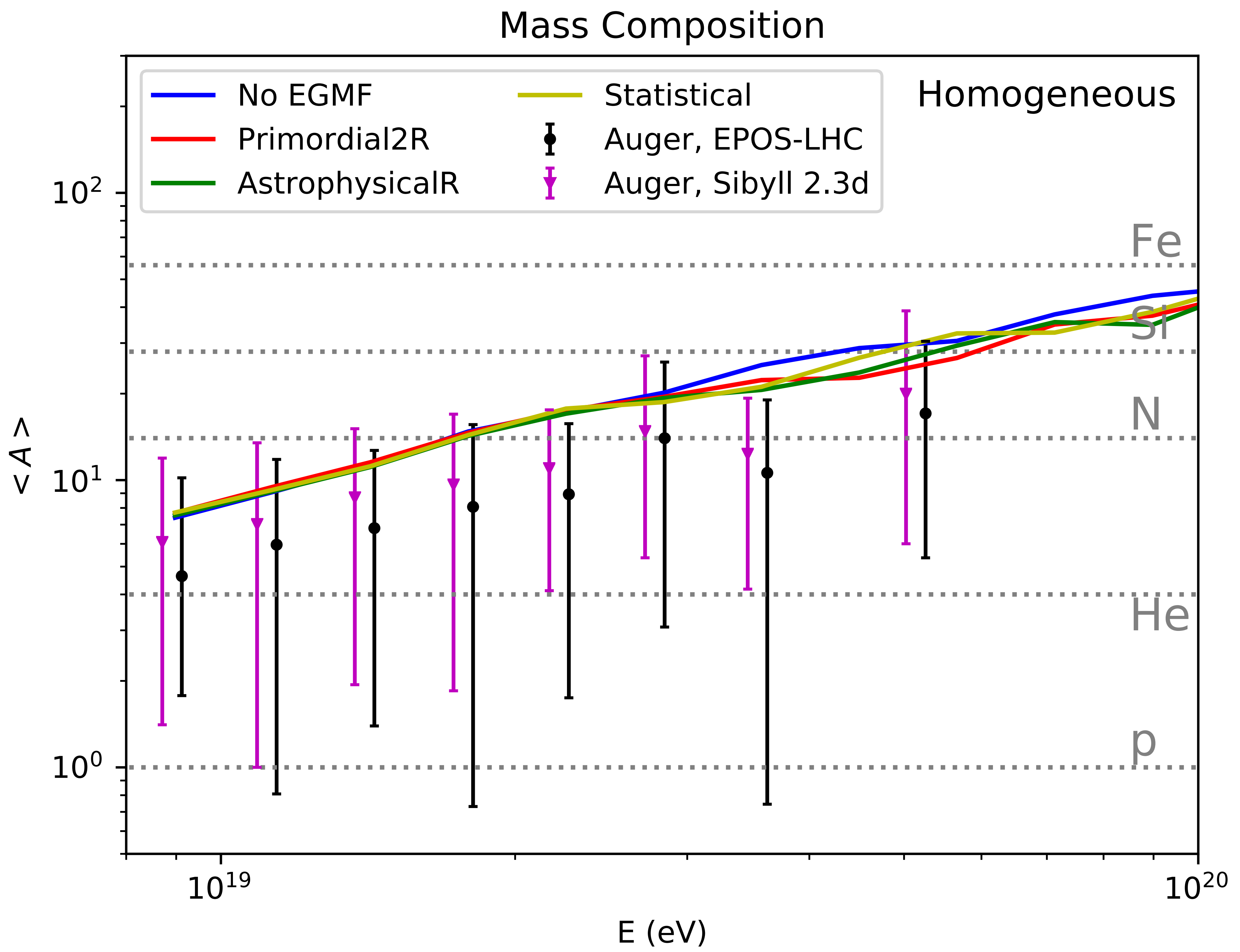
Spectrum and composition



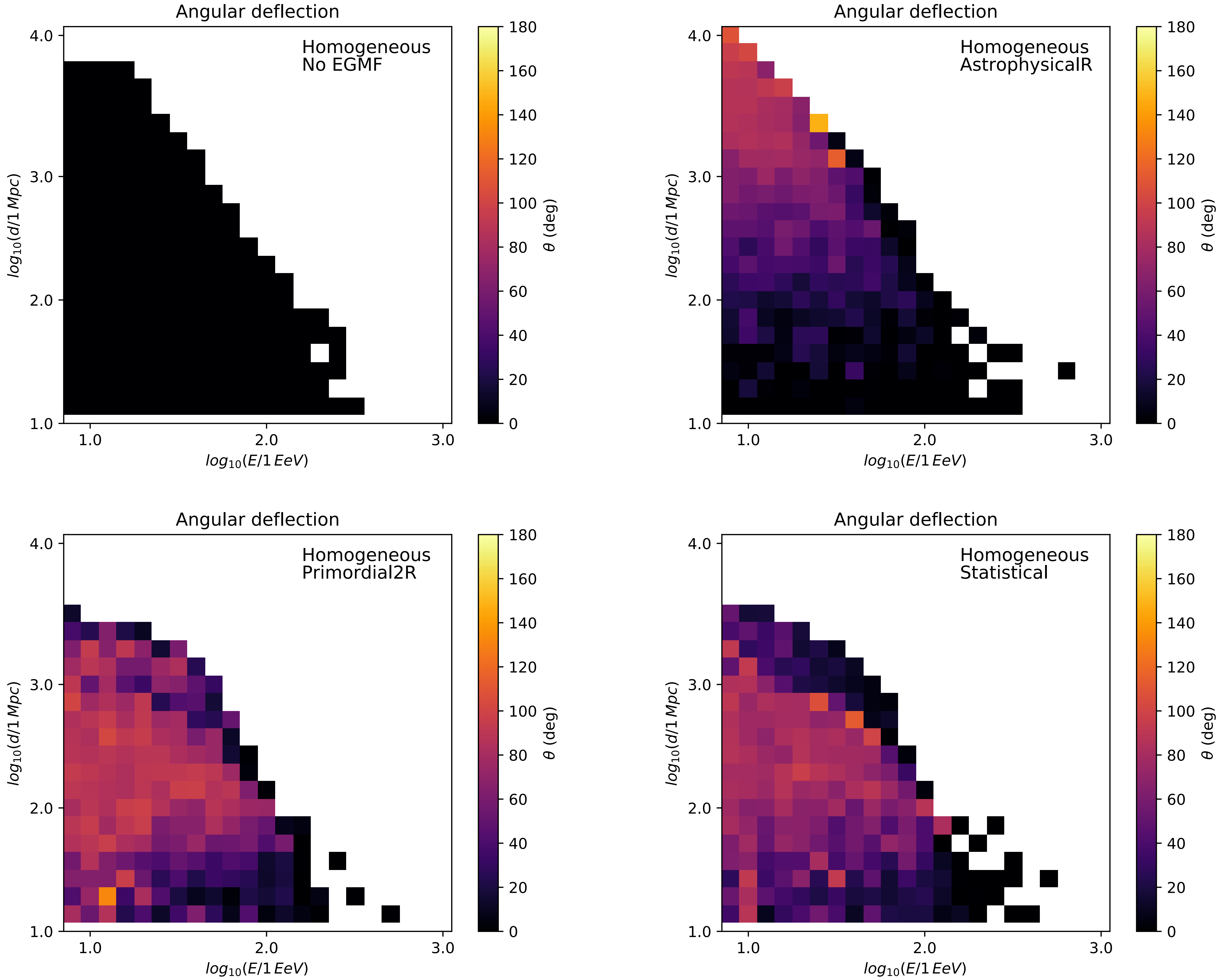


Spectrum and composition homogeneous

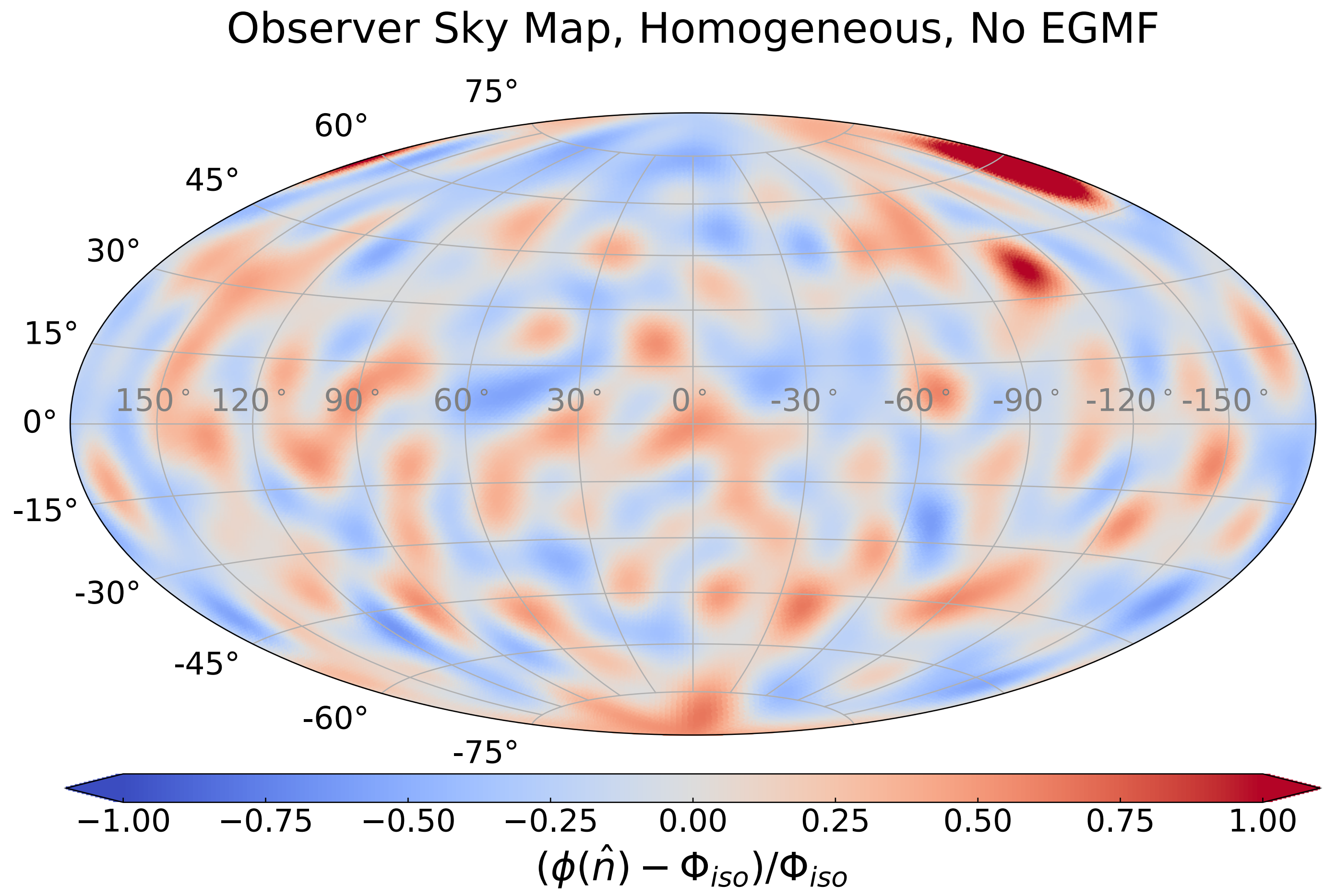


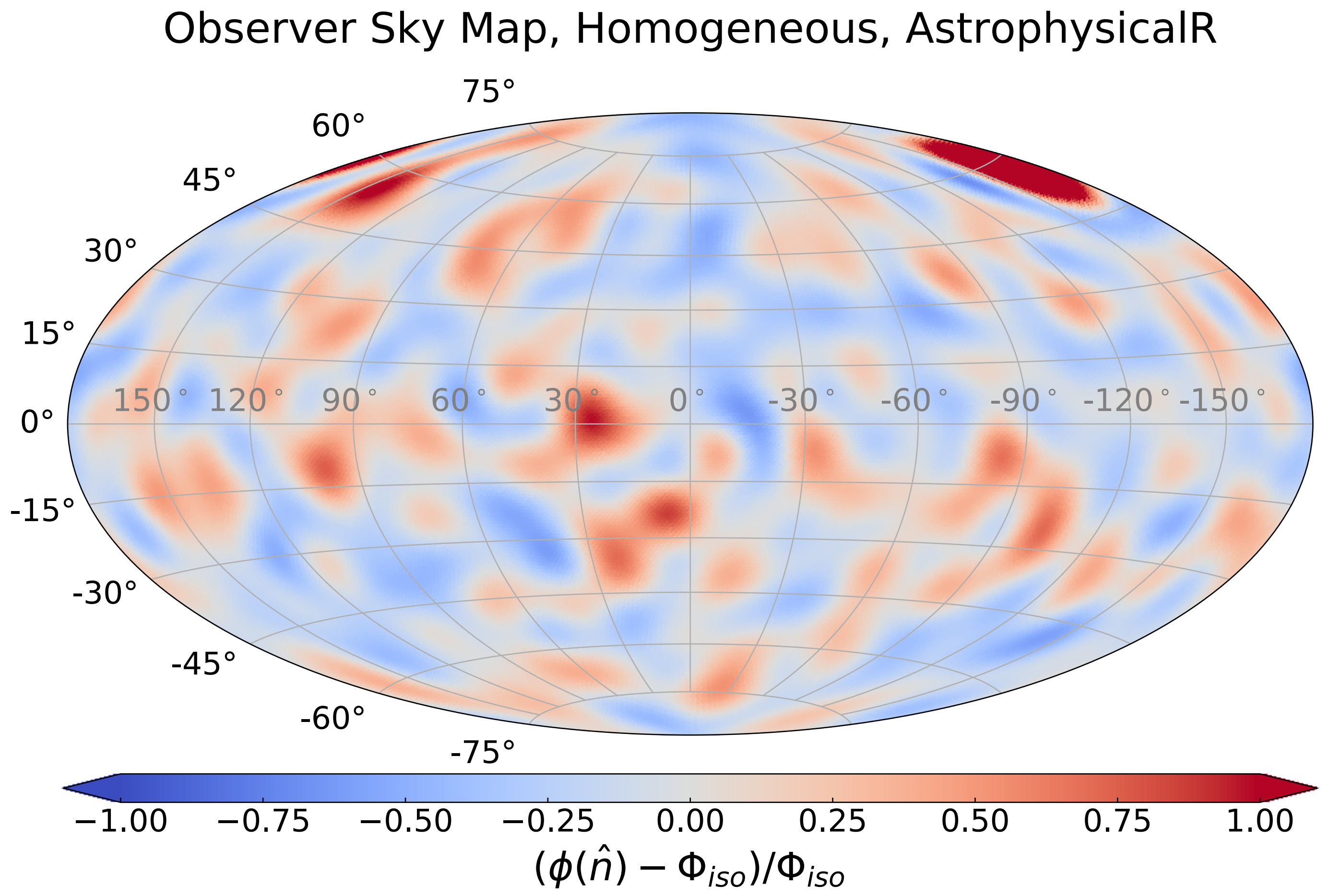


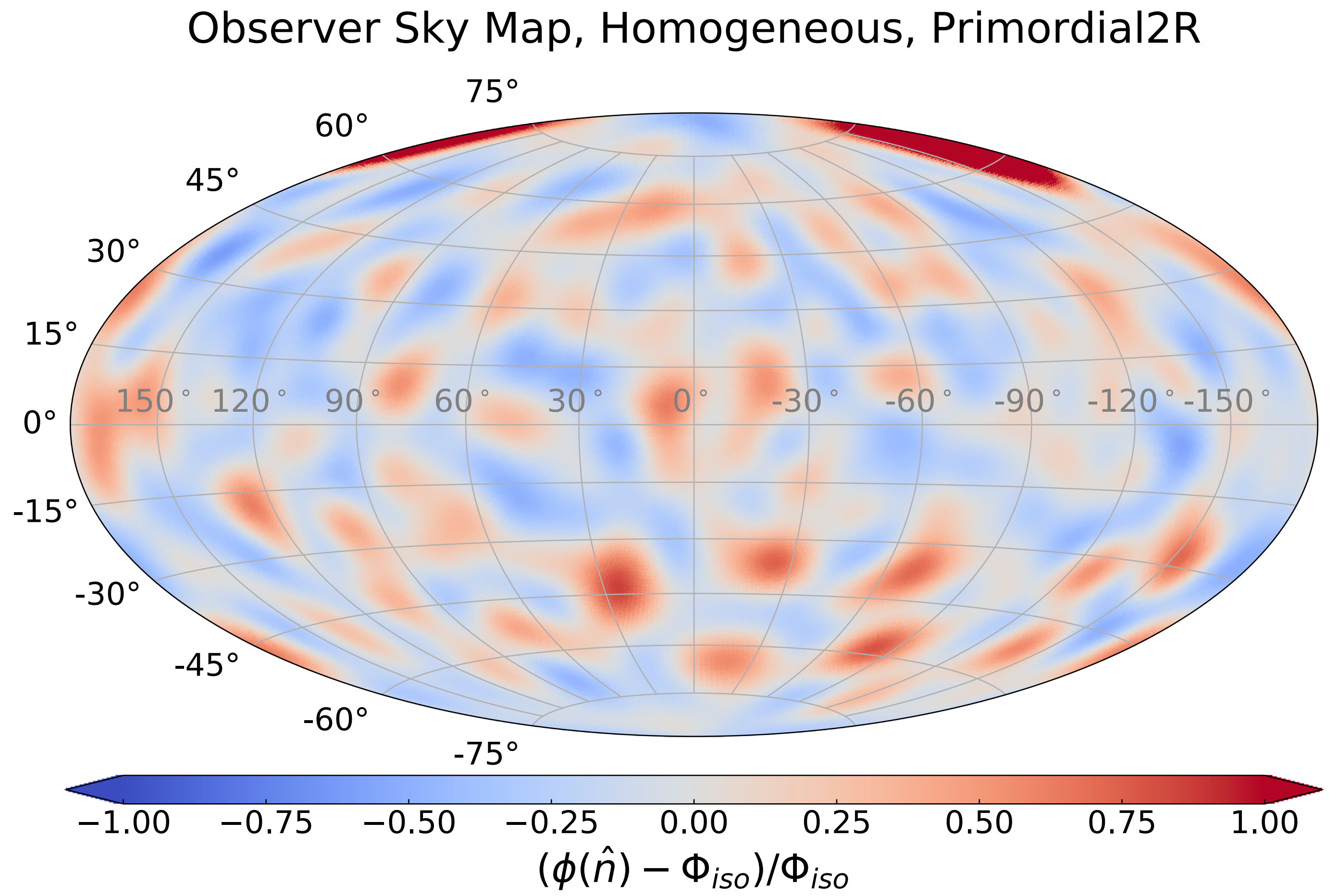
Magnetic deflection homogeneous

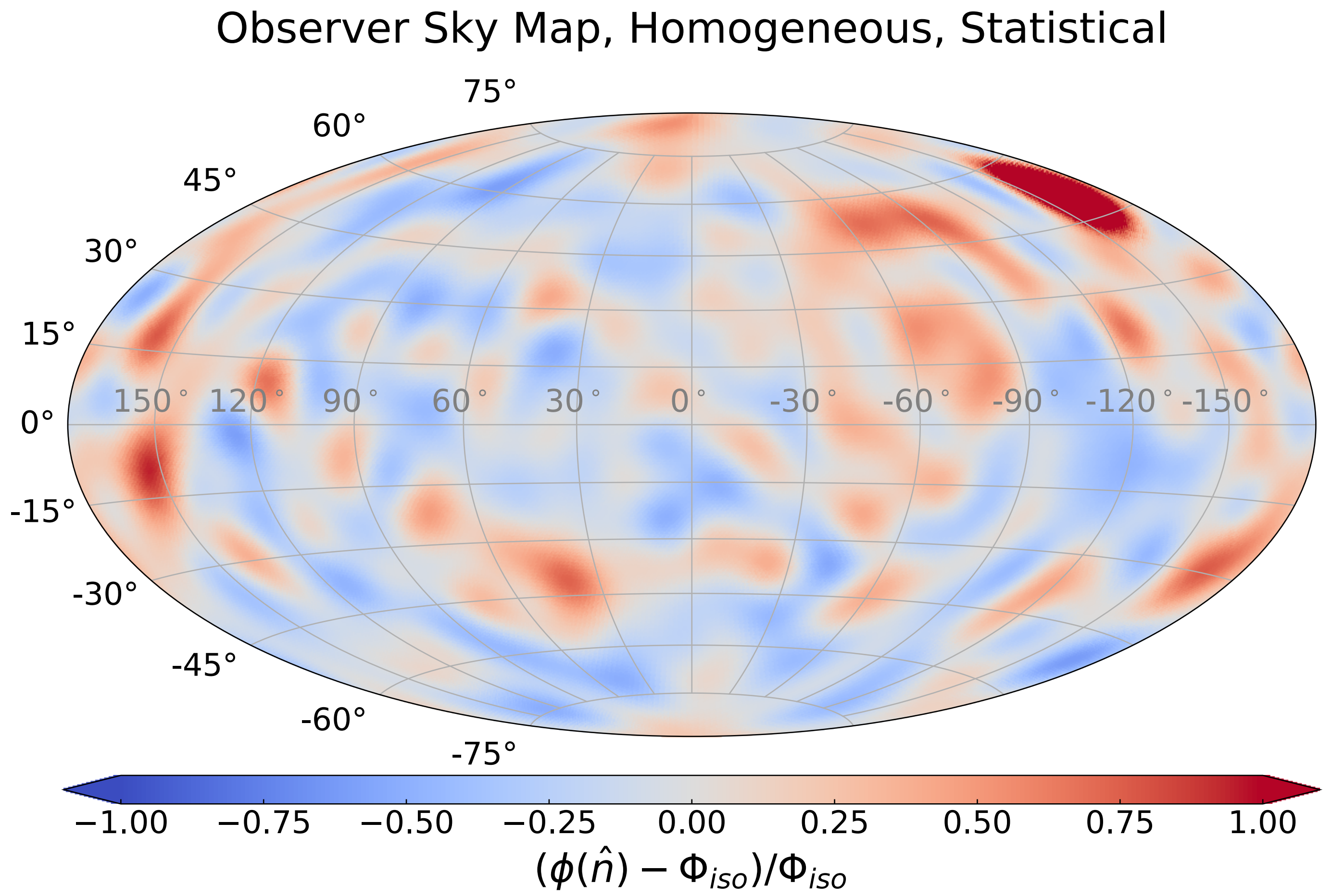


Arrival direction distribution homogeneous

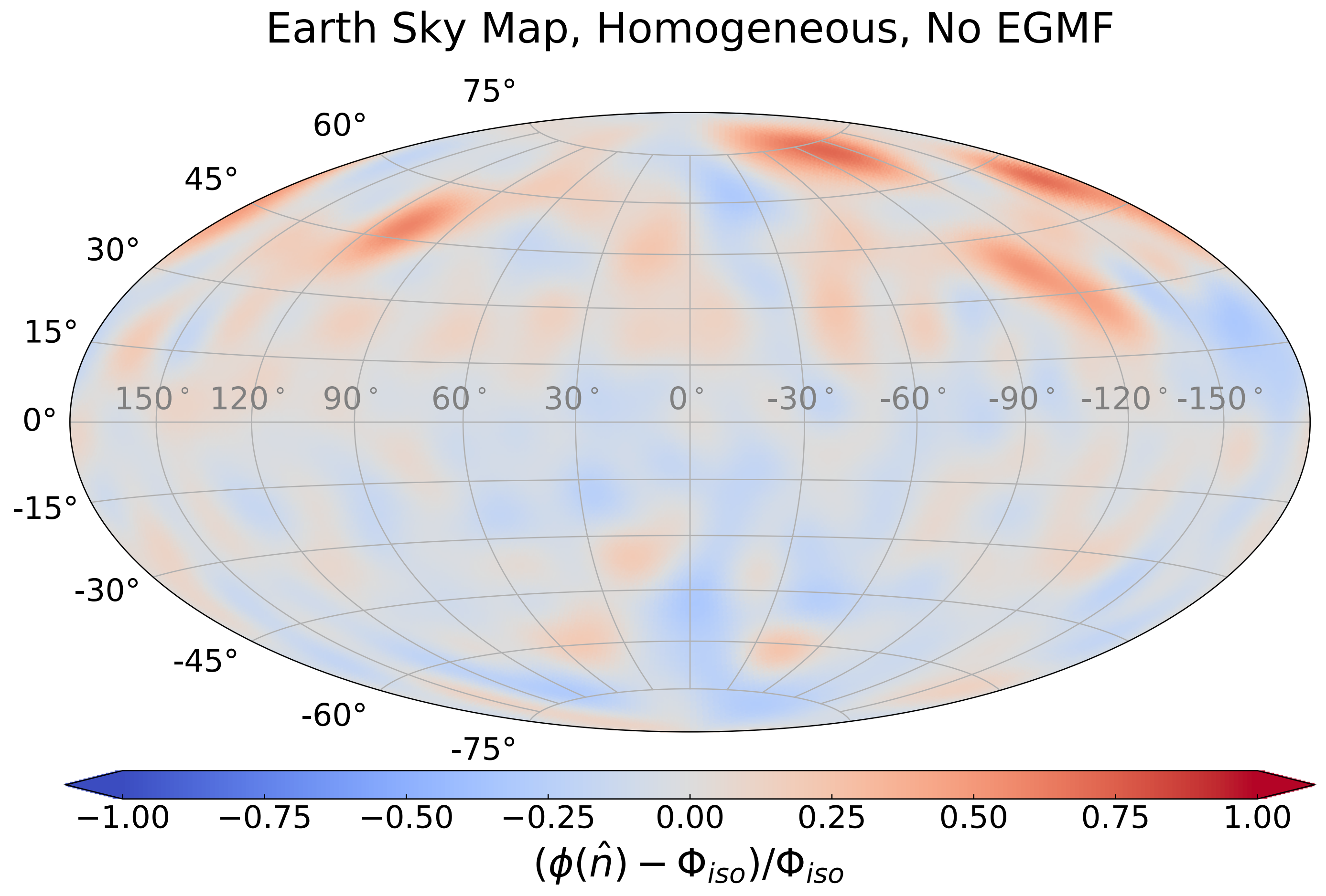


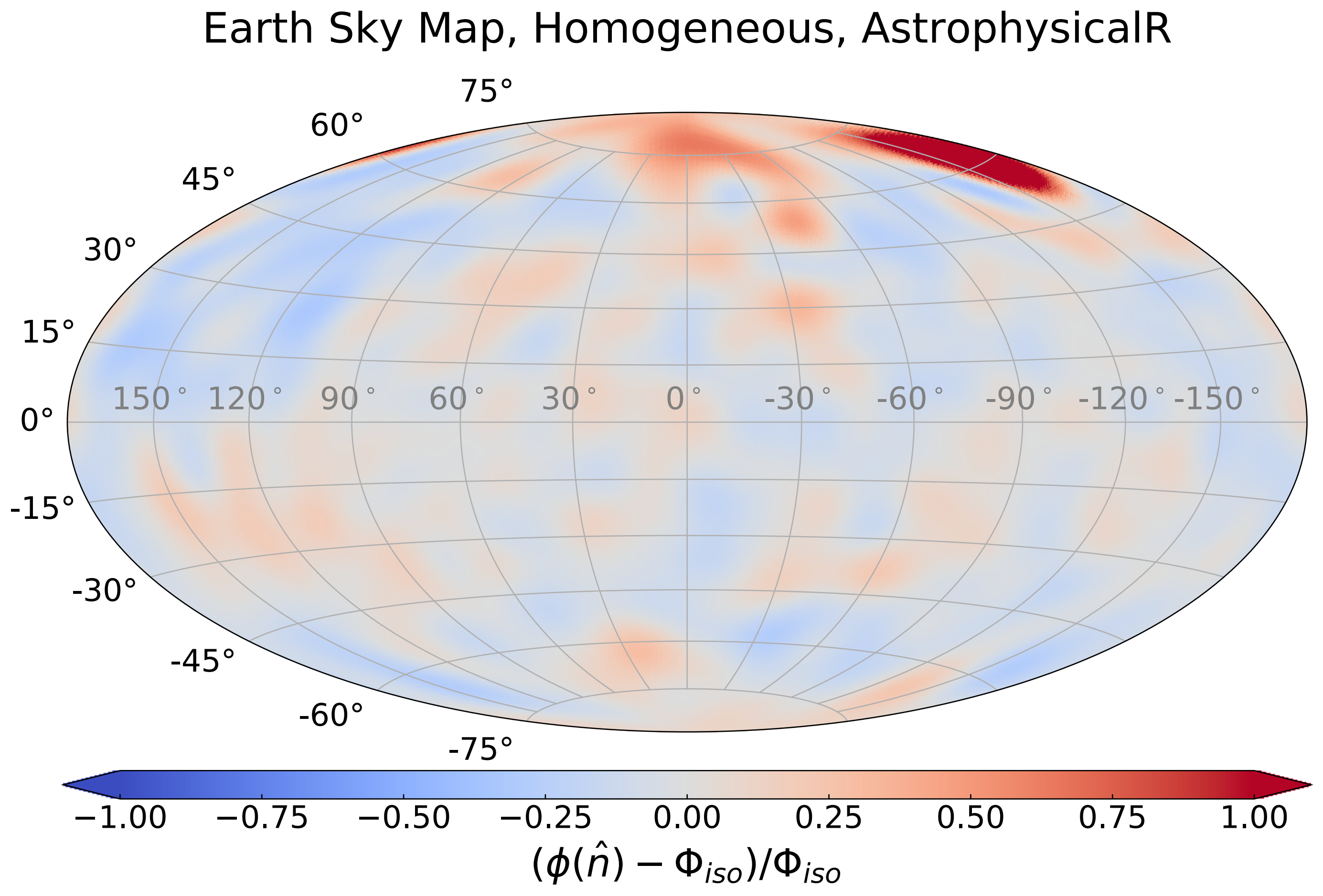


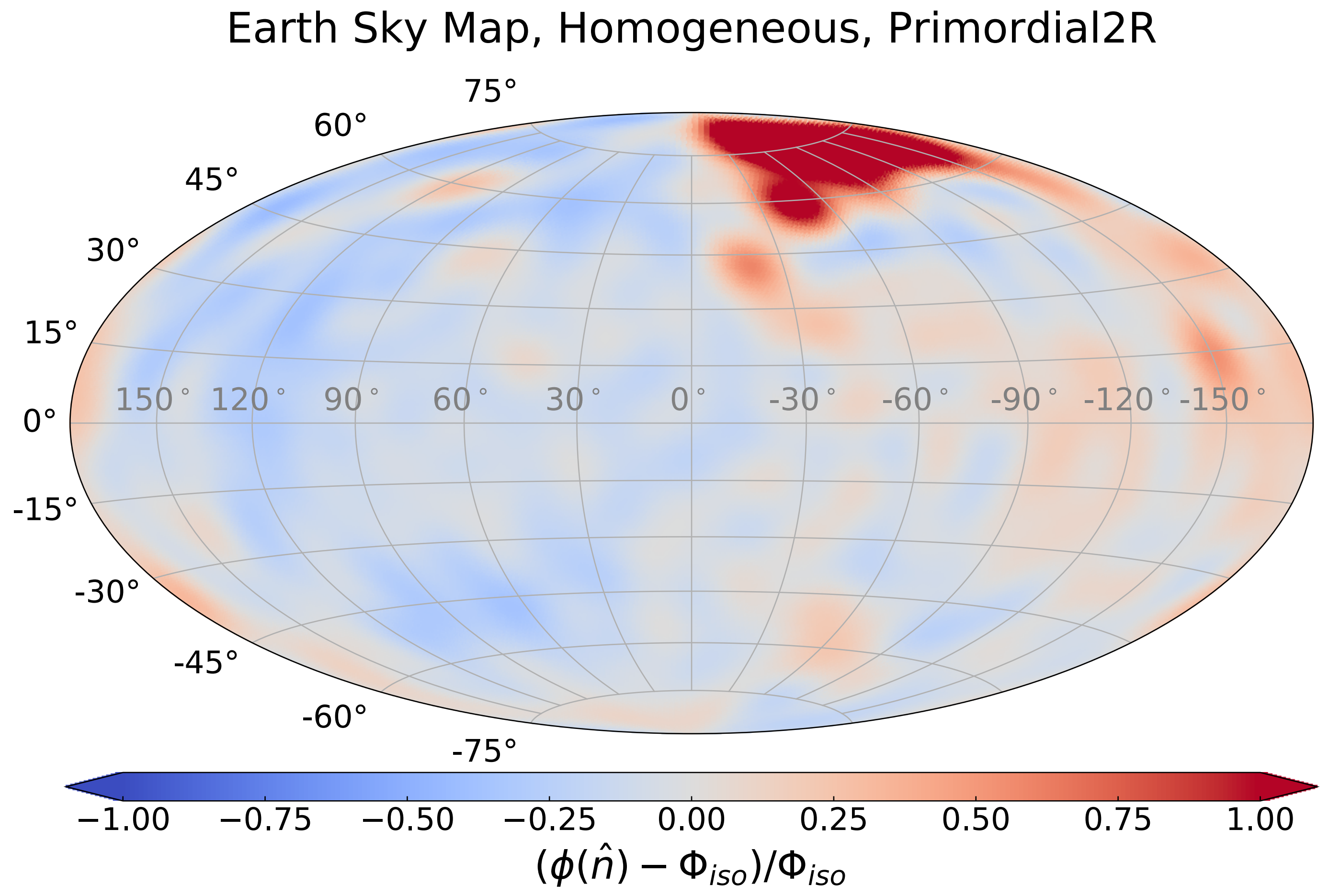


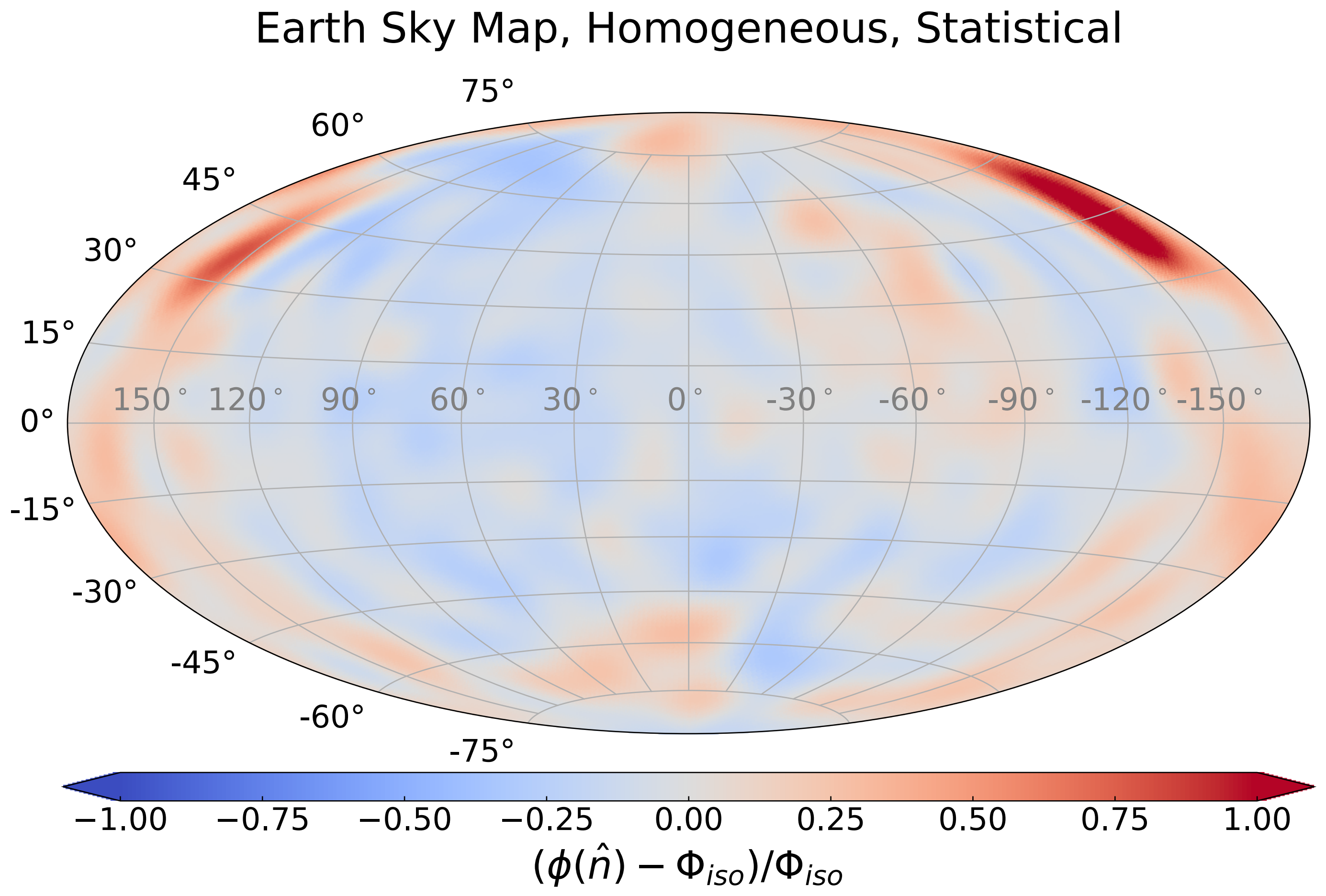


Arrival direction distribution (lensed)









Angular power spectrum homogeneous