HI IM: Power spectrum modelling and foreground cleaning

Paula Soares

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Outline

1. Modelling of HI IM power spectrum
2. Instrumental and systematic effects
3. Cosmological parameter estimation

Simplest *isotropic* model

The **power spectrum** tells us how clustered the matter is a function of inverse separation (k)

HI background temperature

$$P^{\mathrm{HI}}(k) = \overline{T}^2_{\mathrm{HI}} b^2_{\mathrm{HI}} P_m(k)$$

$\propto \Omega_{\mathrm{HI}}(z)$

HI power spectrum

HI bias

Underlying dark matter power spectrum

Anisotropic model - RSD

The **power spectrum** tells us how clustered the matter is as a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

Kaiser effect

$$P^{\mathrm{HI}}(k,\mu) = \frac{(\overline{T}_{\mathrm{HI}} b_{\mathrm{HI}} + \overline{T}_{\mathrm{HI}} f \mu^2)^2}{1 + (k\mu\sigma_v / H_0)^2} P_m(k)$$

Angle between k and line-of-sight of observer

Fingers-of-God effect

Anisotropic model - σ_8

The **power spectrum** tells us how clustered the matter is as a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

$$P^{\mathrm{HI}}(k,\mu) = \frac{(\overline{T}_{\mathrm{HI}} b_{\mathrm{HI}} \sigma_8 + \overline{T}_{\mathrm{HI}} f \sigma_8 \mu^2)^2}{1 + (k\mu\sigma_v/H_0)^2} \frac{P_m(k)}{\sigma_8^2}$$

Multiply by: $\frac{\sigma_8^2}{\sigma_8^2}$

RMS of matter fluctuations within a sphere of radius 8 Mpc/*h*

Alcock-Paczynski effect

An effect introduced when we convert from redshift to distance

- We need to assume a *fiducial cosmology* to do this
- If this is different from the *true cosmology*, our power spectrum measurements will be distorted by the factors:

$$\alpha_{\perp} = \frac{D_A(z)}{D_A(z)^{\mathrm{f}}}$$

$$\alpha_{||} = \frac{H(z)^{\mathrm{f}}}{H(z)}$$

Anisotropic model - AP

The **power spectrum** tells us how clustered the matter is as a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

Alcock-Paczynski effect

$$P^{\mathrm{HI}}(k^f,\mu^f) = \alpha_{\parallel}^{-1}\alpha_{\perp}^{-2}\left[\frac{(\overline{T}_{\mathrm{HI}}b_{\mathrm{HI}}\sigma_8 + \overline{T}_{\mathrm{HI}}f\sigma_8\mu^2)^2}{1+(k\mu\sigma_v/H_0)^2}\frac{P_m(k)}{\sigma_8^2} + P_{\mathrm{SN}}\right]$$

Shot noise

Anisotropic model

The **power spectrum** tells us how clustered the matter is a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

$$P^{\mathrm{HI}}(k^f, \mu^f) = \alpha_{\parallel}^{-1}\alpha_{\perp}^{-2}\left[\frac{(\overline{T}_{\mathrm{HI}} b_{\mathrm{HI}}\sigma_8 + \overline{T}_{\mathrm{HI}} f\sigma_8 \mu^2)^2}{1 + (k\mu\sigma_v/H_0)^2}\frac{P_m(k)}{\sigma_8^2} + P_{\mathrm{SN}}\right]$$

HI bias

Growth rate of structure

Hubble constant

Angular diameter distance

Anisotropic model

The **power spectrum** tells us how clustered the matter is a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

$$P^{\mathrm{HI}}(k^f, \mu^f) = \alpha_{\parallel}^{-1} \alpha_{\perp}^{-2} \left[\frac{(\overline{T}_{\mathrm{HI}} b_{\mathrm{HI}} \sigma_8 + \overline{T}_{\mathrm{HI}} f \sigma_8 \mu^2)^2}{1 + (k \mu \sigma_v / H_0)^2} \frac{P_m(k)}{\sigma_8^2} + P_{\mathrm{SN}} \right]$$

$$\vec{\theta} = \{\alpha_{\parallel},\ \alpha_{\perp},\ \overline{T}_{\mathrm{HI}} f \sigma_8,\ \overline{T}_{\mathrm{HI}} b_{\mathrm{HI}} \sigma_8,\ \sigma_v,\ P_{\mathrm{SN}}\}$$

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Telescope beam

- Because the beam damps small scales, we can model it as a Gaussian (very idealised!):

Beam size (determines resolution)

$$\tilde{B}_\perp(k, \mu) = \exp\left(\frac{-k^2R^2(1-\mu^2)}{2}\right)$$

Anisotropic model - beam

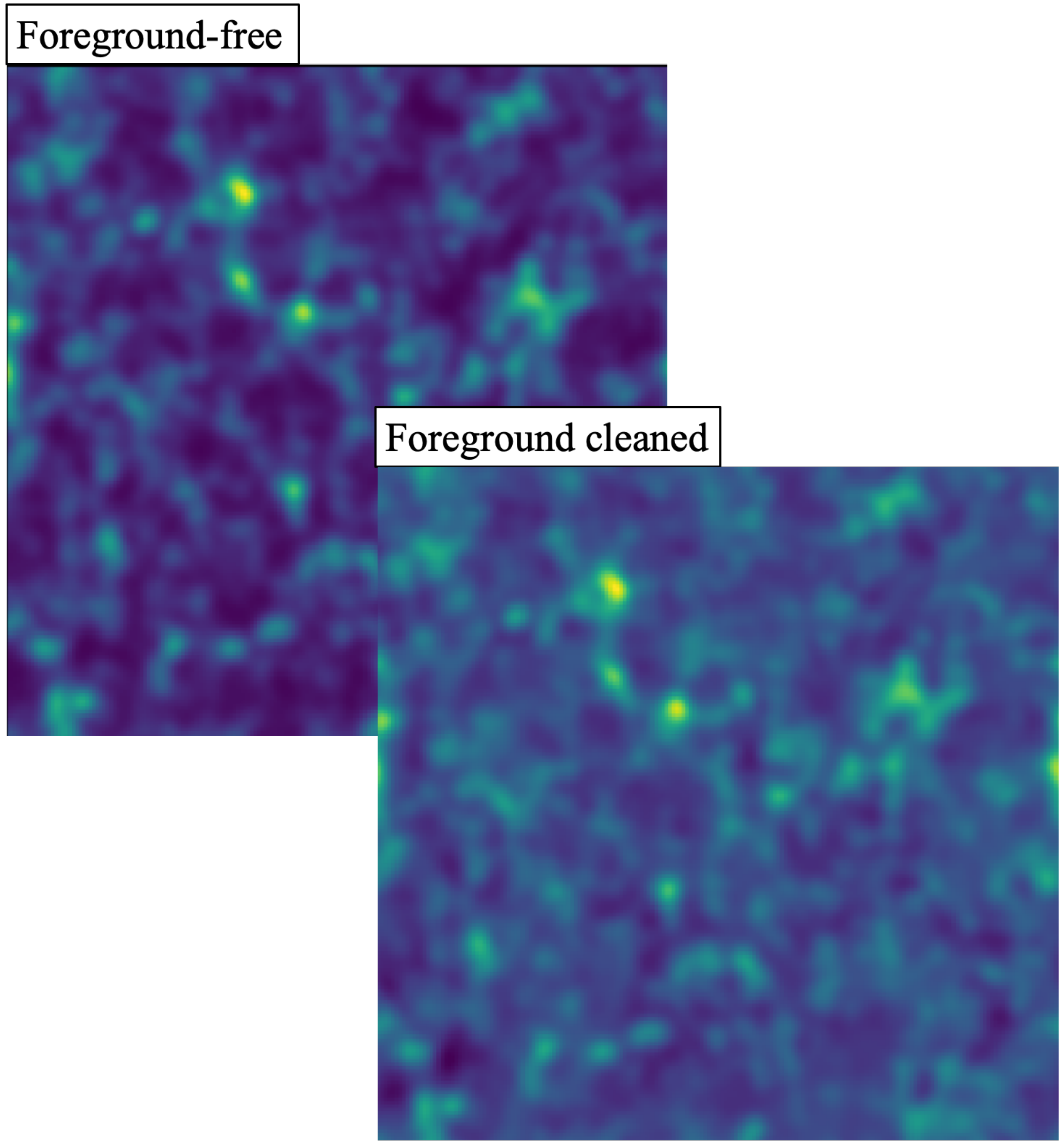
The **power spectrum** tells us how clustered the matter is a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

Beam effect ↑

$$P^{\mathrm{HI}}(k^f, \mu^f) = \tilde{B}_{\perp}^2(k, \mu)\alpha_{\parallel}^{-1}\alpha_{\perp}^{-2} \left[\frac{(\overline{T}_{\mathrm{HI}} b_{\mathrm{HI}} \sigma_8 + \overline{T}_{\mathrm{HI}} f \sigma_8 \mu^2)^2}{1 + (k\mu\sigma_v/H_0)^2} \frac{P_m(k)}{\sigma_8^2} + P_{\mathrm{SN}} \right]$$

Foreground removal

- We remove foregrounds using the fact that foregrounds are **smooth** in frequency and very **bright**, and HI is not
  - However, the **largest** HI modes are smooth so get confused with foregrounds and **removed**
  - **Power is damped on large scale modes**



Foreground model

Similar to the *beam* which damps power on **small** scales, we model foreground removal by damping power on **large** scales:

$$\tilde{B}_{\rm FG}(k,\mu) = \left(1 - \exp\left[-\left(\frac{k}{N_\perp k_\perp^{\rm min}}\right)^2 (1-\mu^2)\right]\right) \times \left(1 - \exp\left[-\left(\frac{k}{N_\parallel k_\parallel^{\rm min}}\right)^2 \mu^2\right]\right)$$

Free parameter ($N_\perp$)

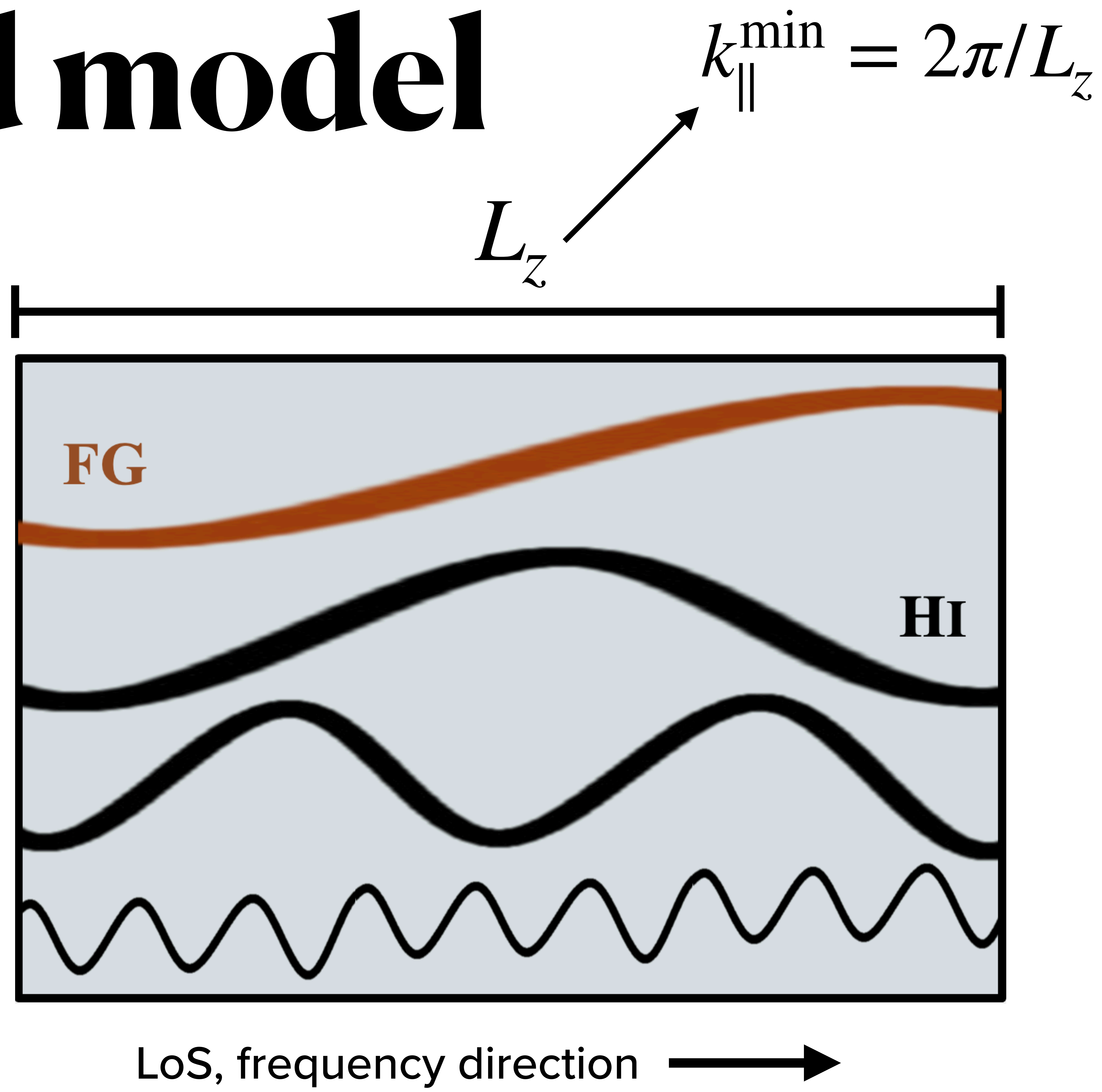
Largest physical scale you can fit in this direction ($k_\perp^{\rm min}$)

Foreground model

Along the line of sight direction:

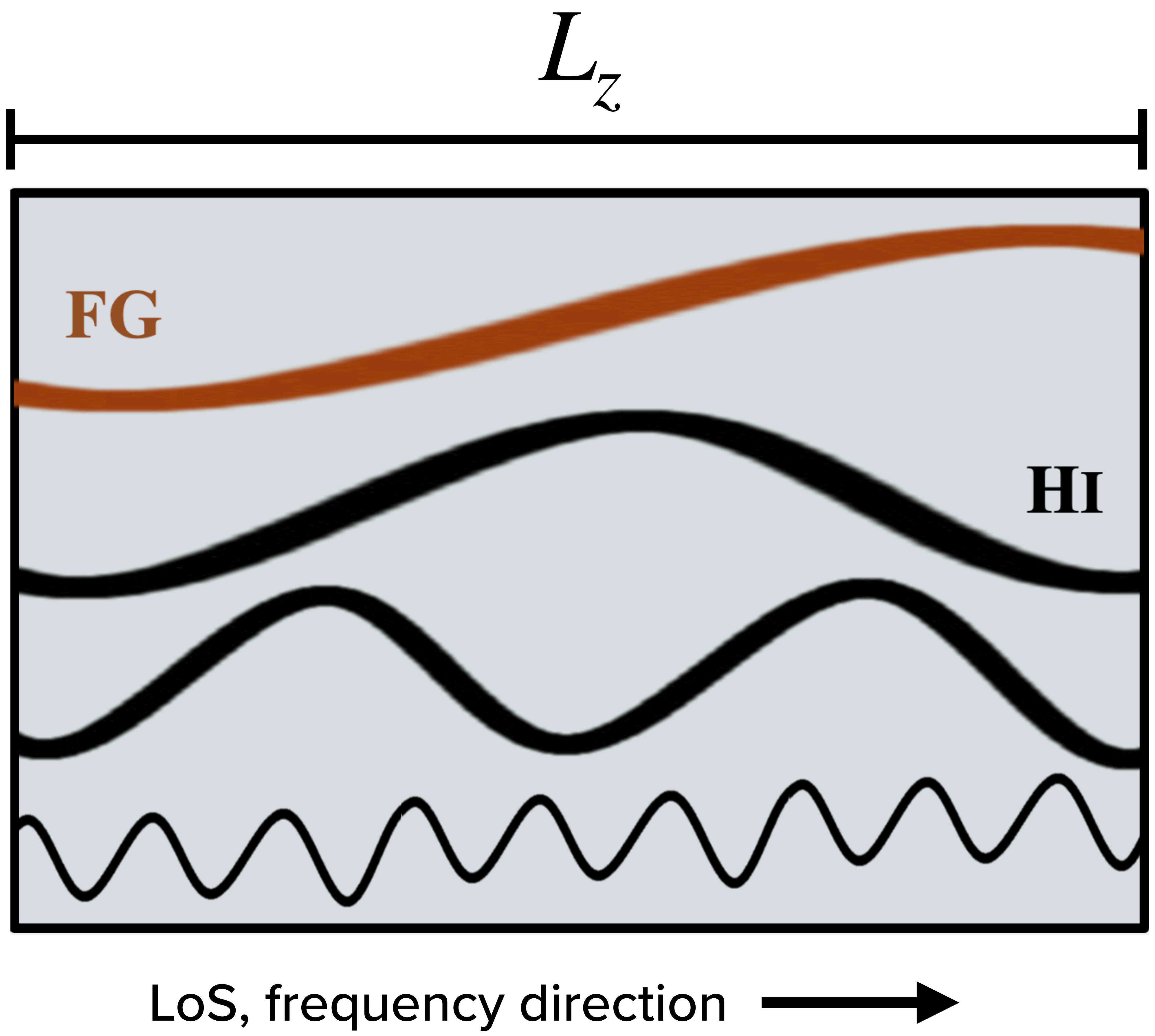
- **FGs are spectrally smooth**
- **HI signal is not smooth**
  - However, the largest HI signal fluctuations that fit inside the box may appear smooth
  - So the threshold for differentiating it from FGs would be *half of the largest fluctuations we can fit in the box*

- Hence we expect $N_{\perp}, N_{\parallel} = 2$



Foreground model

- Keeping these as **free parameters** means it can model different types and levels of foreground removal
  - However, we only tested this on **one** simulation and foreground removal method



Anisotropic model - foregrounds

The **power spectrum** tells us how clustered the matter is a function of inverse separation (k) and angle between k and observer's line-of-sight (μ)

Foreground removal effect

$$P^{\rm HI}(k^f,\mu^f) = \tilde{B}_\perp^2(k,\mu)\tilde{B}_{\rm FG}(k,\mu)\alpha_\parallel^{-1}\alpha_\perp^{-2}\left[\frac{(\overline{T}_{\rm HI}b_{\rm HI}\sigma_8 + \overline{T}_{\rm HI}f\sigma_8\mu^2)^2}{1+(k\mu\sigma_v/H_0)^2}\frac{P_m(k)}{\sigma_8^2} + P_{\rm SN}\right]$$

Multipole expansion

Useful way to **decompose** the power spectrum using Legendre polynomials

$$P_\ell^{\mathrm{HI}}(k^f) = \frac{2\ell + 1}{2} \int_{-1}^{1} d\mu^f \mathscr{L}_\ell(\mu^f) P^{\mathrm{HI}}(k, \mu)$$

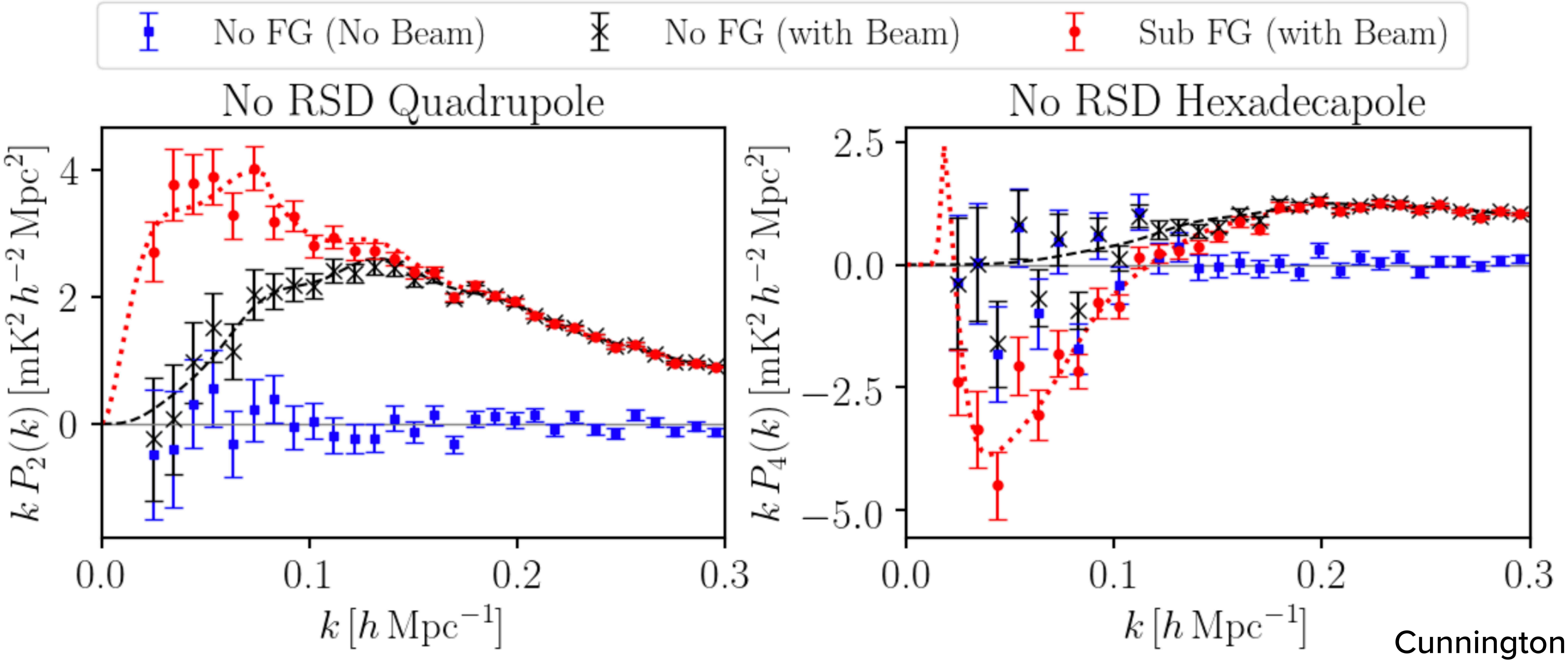
Legendre polynomial

We look at $\ell = 0,2,4$:

- As ℓ increases, we get **increasingly anisotropic information** (which can be harder to model), and should be fainter

Multipole expansion

Higher multipoles should disappear without any RSD, but instrumental and systematic effects mean this is not true:



Cunnington et al. 2020

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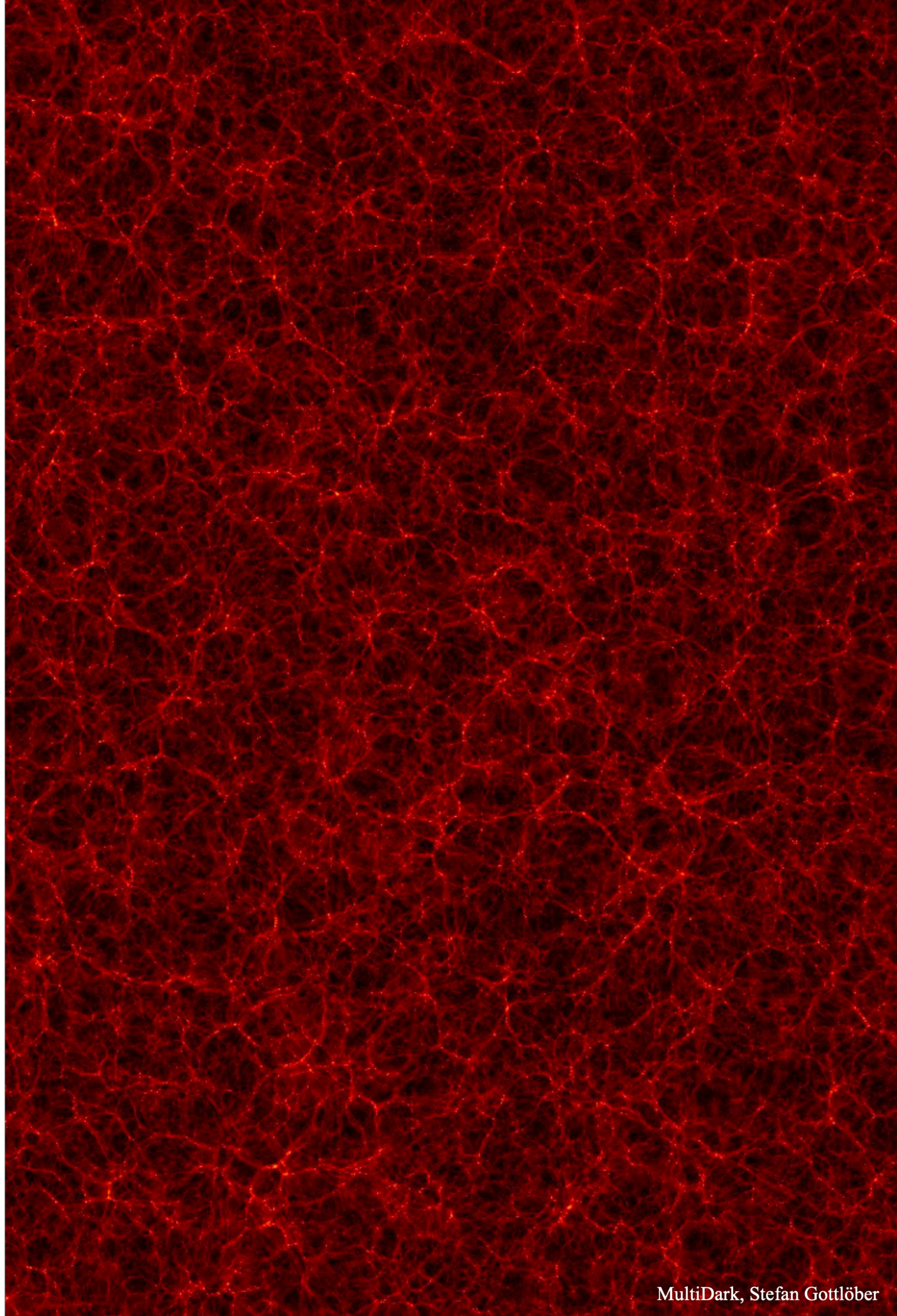
Simulations

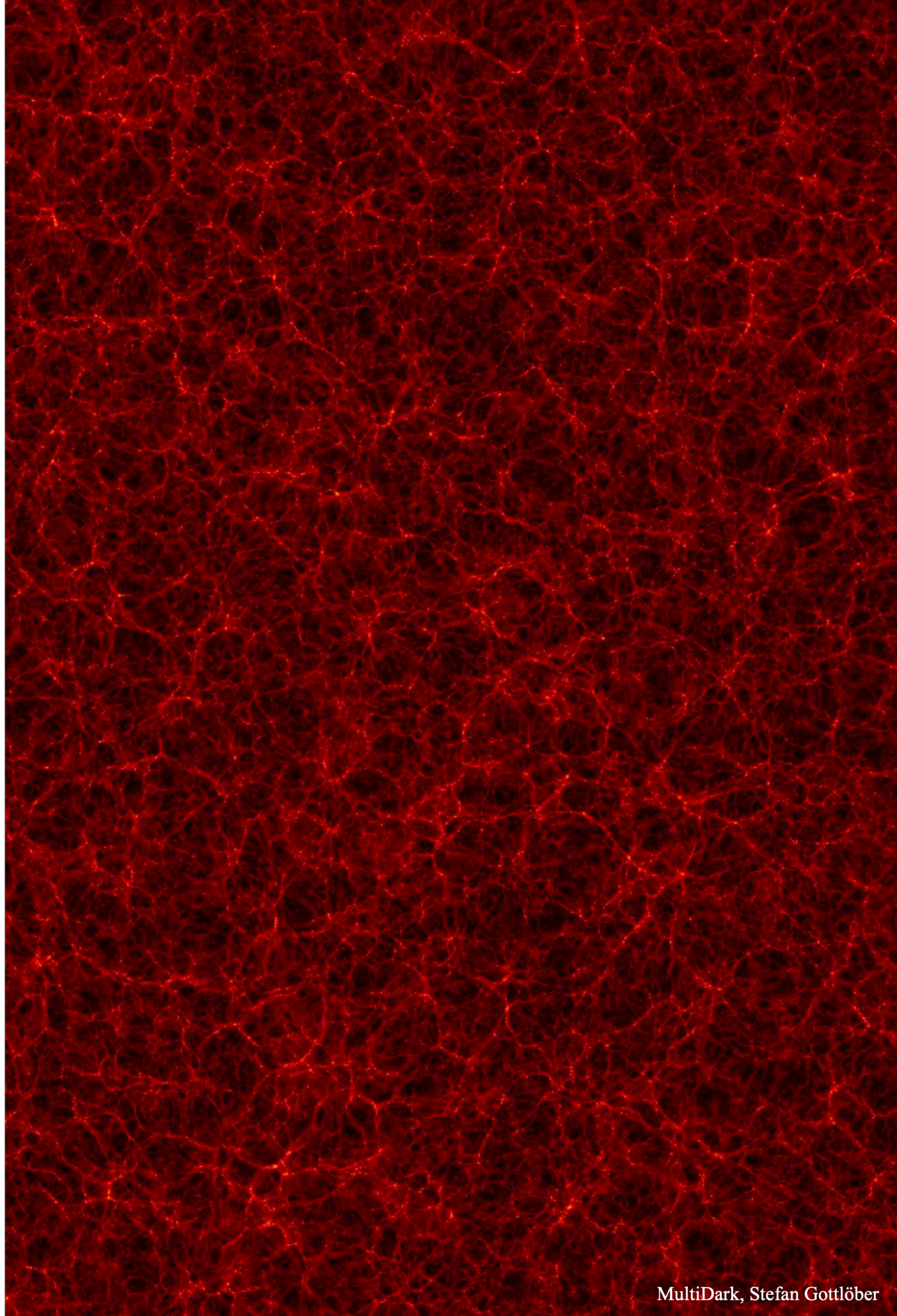
- **MultiDark-Galaxies** have used **MultiDark-Planck** N-body simulations and applied SAGE semi-analytical model
- Each galaxy has an associated cold gas mass, which we convert to HI mass, and then to HI brightness temperature

$z = 0.82$
$L_x = L_y = L_z = 1000$ Mpc h^{-1}
$N_x = N_y = N_z = 225$



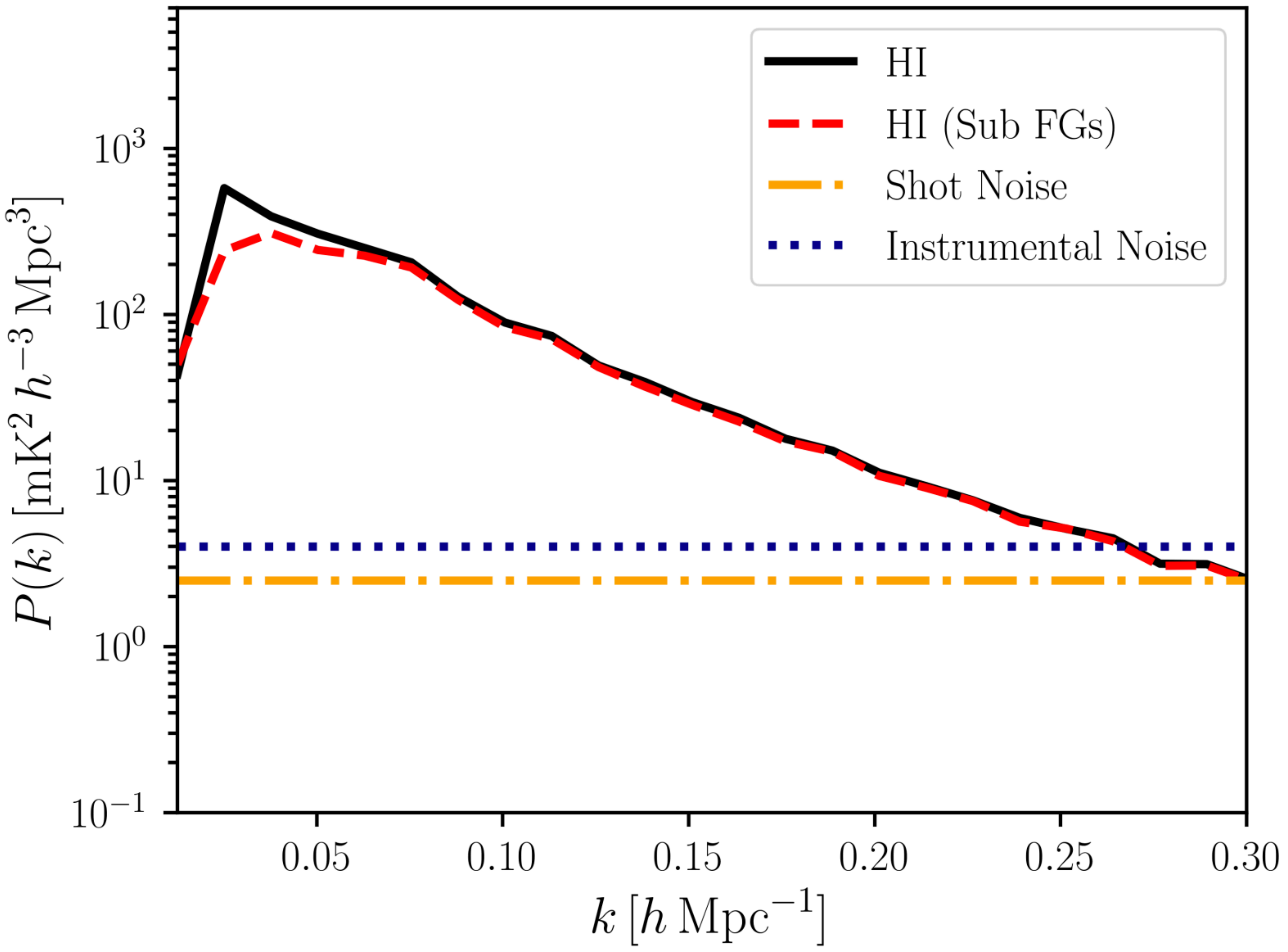
Simulations

- We simulate foregrounds using the **Global Sky Model** and also realisations of a diffuse emission model power spectrum for finer detail
- No **noise** is added but we instead consider this in our modelling
- Add HI + foregrounds, then **smooth** each frequency slice with a telescope beam of SKA-like size
- Remove foregrounds using **FastICA**



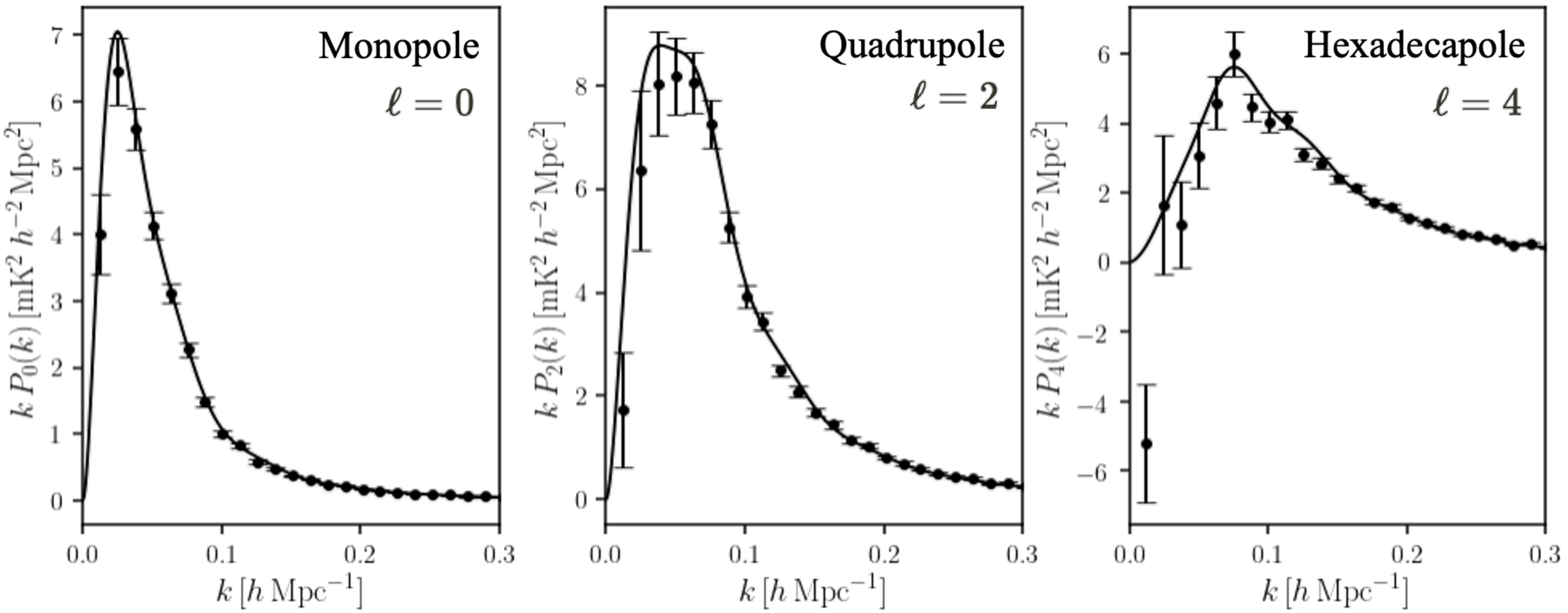
MultiDark, Stefan Gottlöber

Simulations



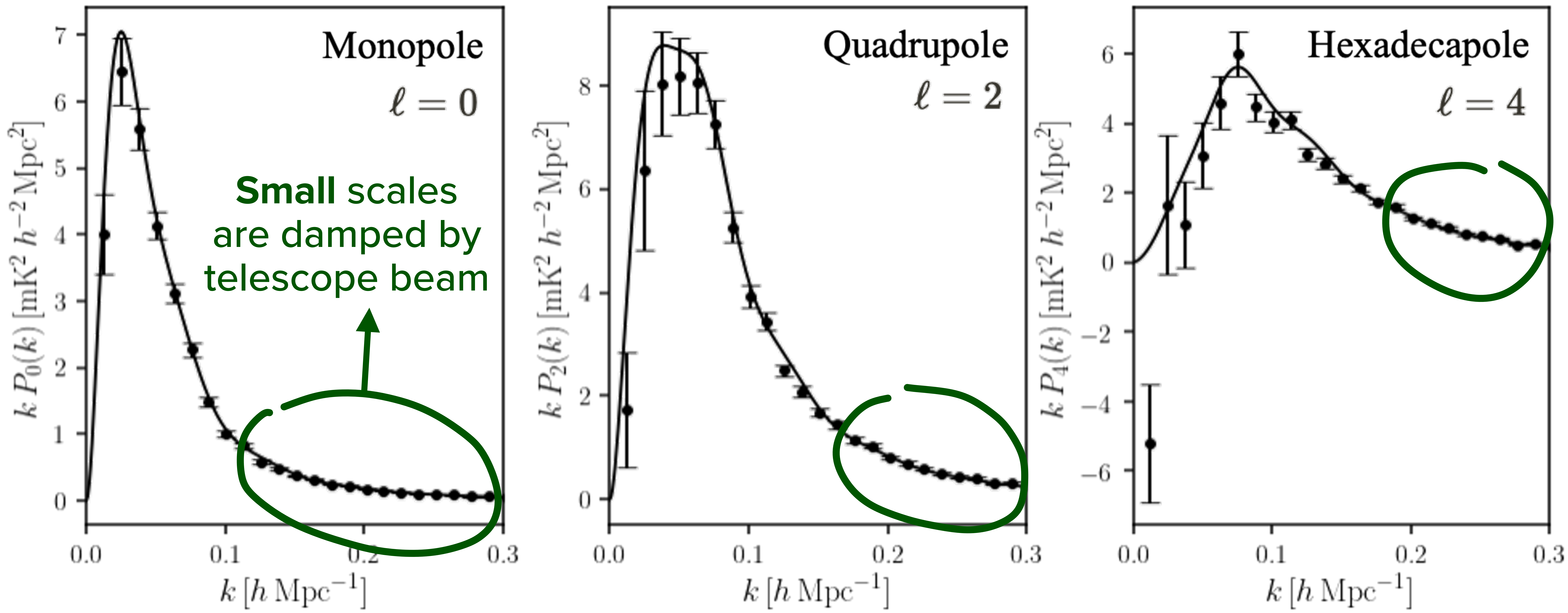
Model vs. simulation

Good agreement



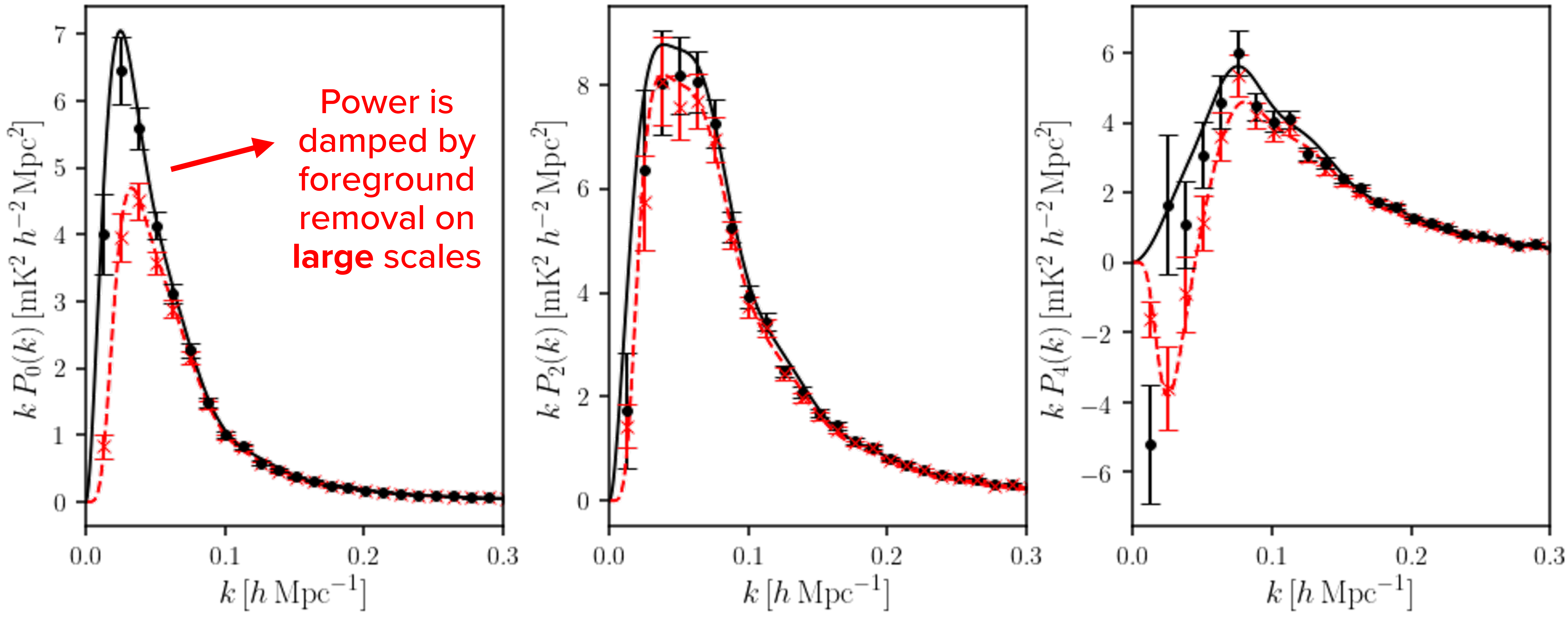
Model vs. simulation

Good agreement

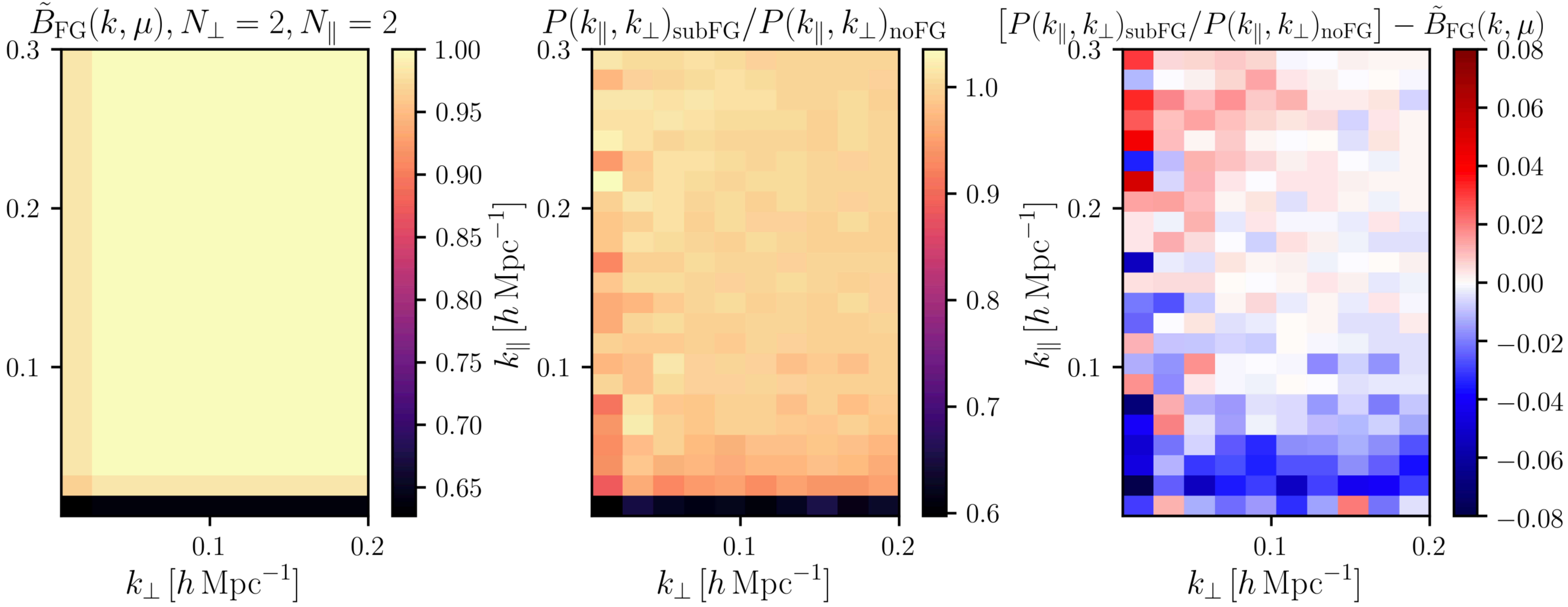


Foreground model vs. simulation

Also good agreement between model and data (using $N_\perp, N_\parallel = 2$).



Foreground model vs. simulation



Covariance matrix

Covariance of our power spectrum:

$$\sigma^2(k, \mu) = \frac{(P^{\mathrm{HI}}(k, \mu) + P_N)^2}{N_{\mathrm{modes}}(k, \mu)}$$

HI power spectrum ← $P^{\mathrm{HI}}(k, \mu)$

Instrumental noise (Gaussian) ← P_N

Assumes no coupling between different k bins ← $\sigma^2(k, \mu)$

Number of modes (number of measurements that make up this bin) ← $N_{\mathrm{modes}}(k, \mu)$

Covariance matrix

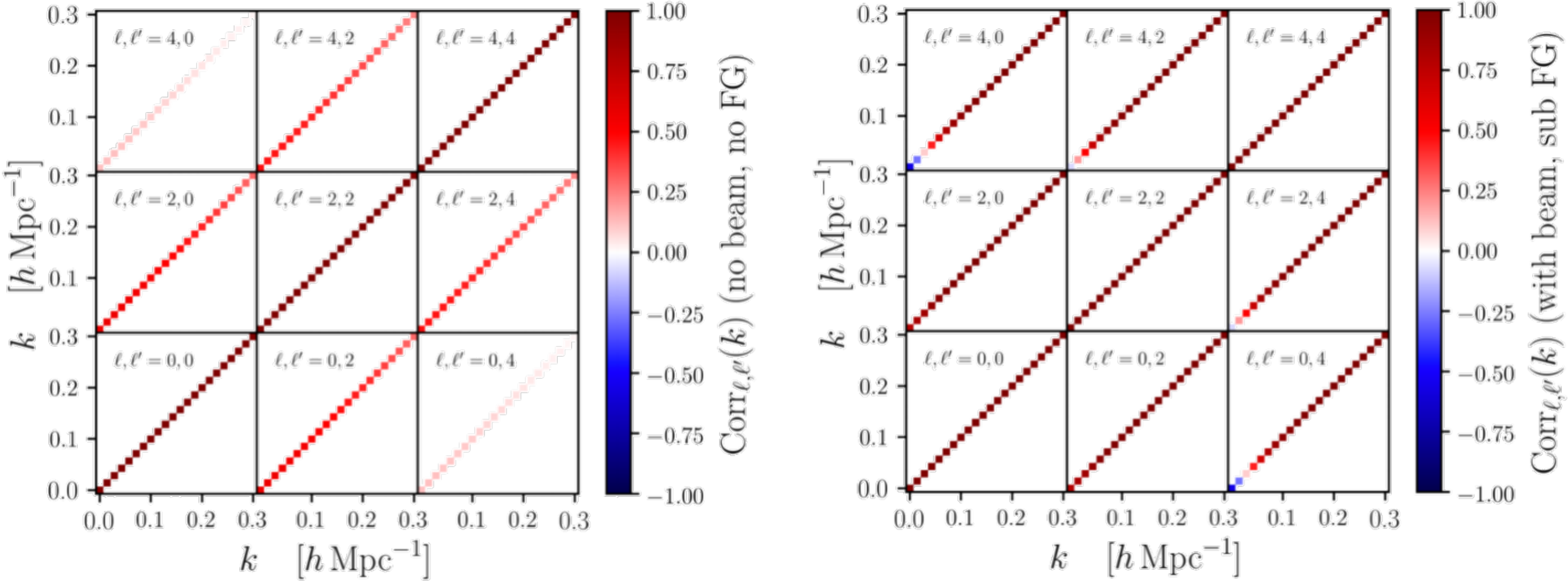
$$C_{\ell\ell'}(k) = \frac{(2\ell+1)(2\ell'+1)}{2} \int_{-1}^{1} d\mu \, \sigma^2(k,\mu) \mathcal{L}_\ell(\mu) \mathcal{L}_{\ell'}(\mu)$$

- **Don't ignore covariance between different multipoles!** Systematic and instrumental effects enhance these.

Correlation matrix

$$\mathrm{Corr}_{\ell\ell'}(k) = \frac{C_{\ell\ell'}(k)}{\sqrt{C_{\ell\ell}(k)C_{\ell'\ell'}(k)}}$$

- Demonstrates how the beam and FG enhance correlation (and hence covariance) between different multipoles.

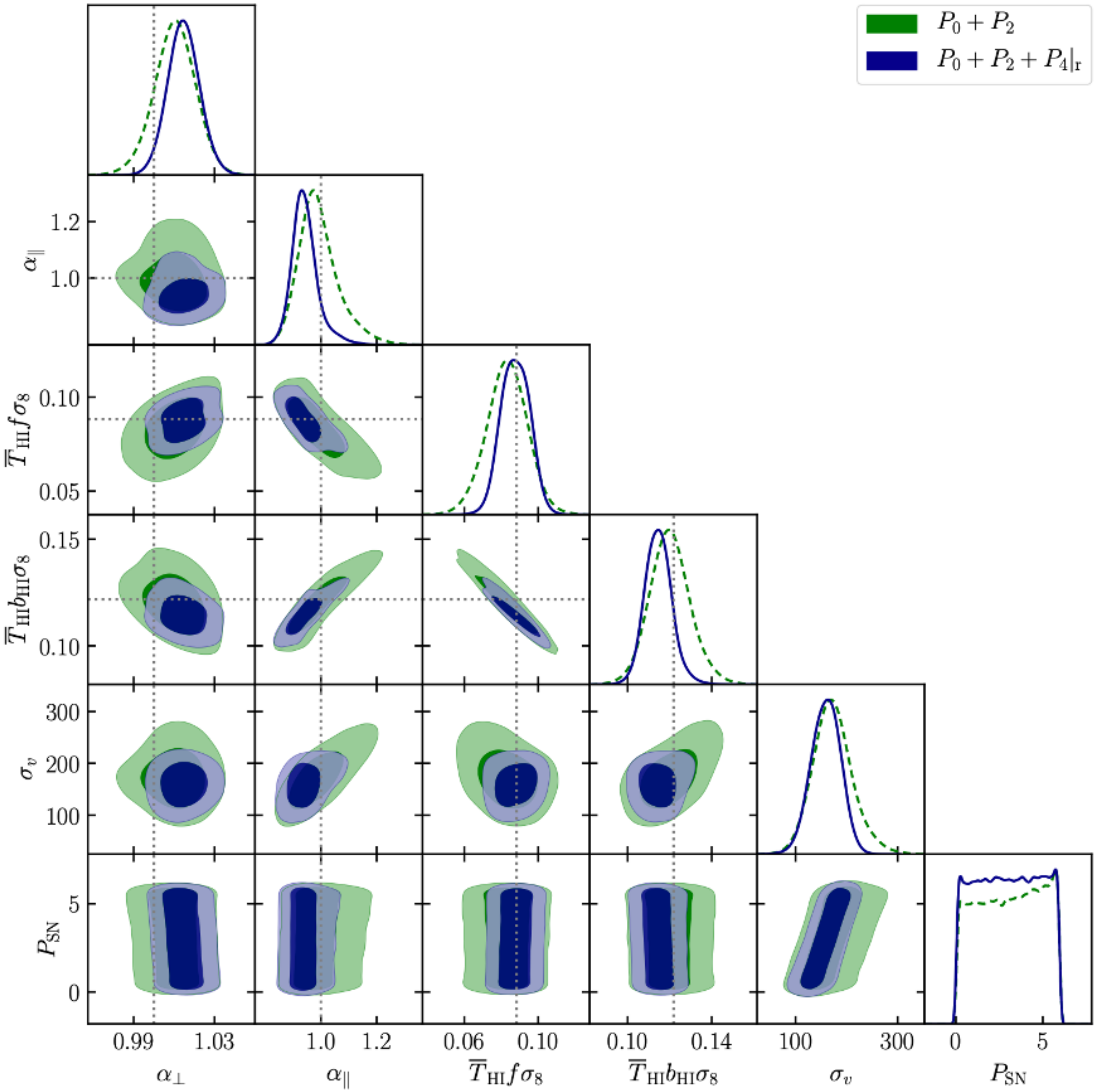


Parameter estimation - FG free

Performed an **MCMC analysis** using our model, covariance, and simulation.

- Unbiased results
- Sub-10% uncertainty on all parameters of interest
- Including the hexadecapole improves constraints, but needs smaller k_{max}

Parameter	$P_0 + P_2$	$P_0 + P_2 + P_4\|_{\mathrm{r}}$
$\alpha_\perp$	1.0%	0.8%
$\alpha_\parallel$	7.6%	5.3%
$\overline{T}_{\mathrm{HI}} f\sigma_8$	13.3%	8.8%
$\overline{T}_{\mathrm{HI}} b_{\mathrm{HI}}\sigma_8$	8.1%	5.7%

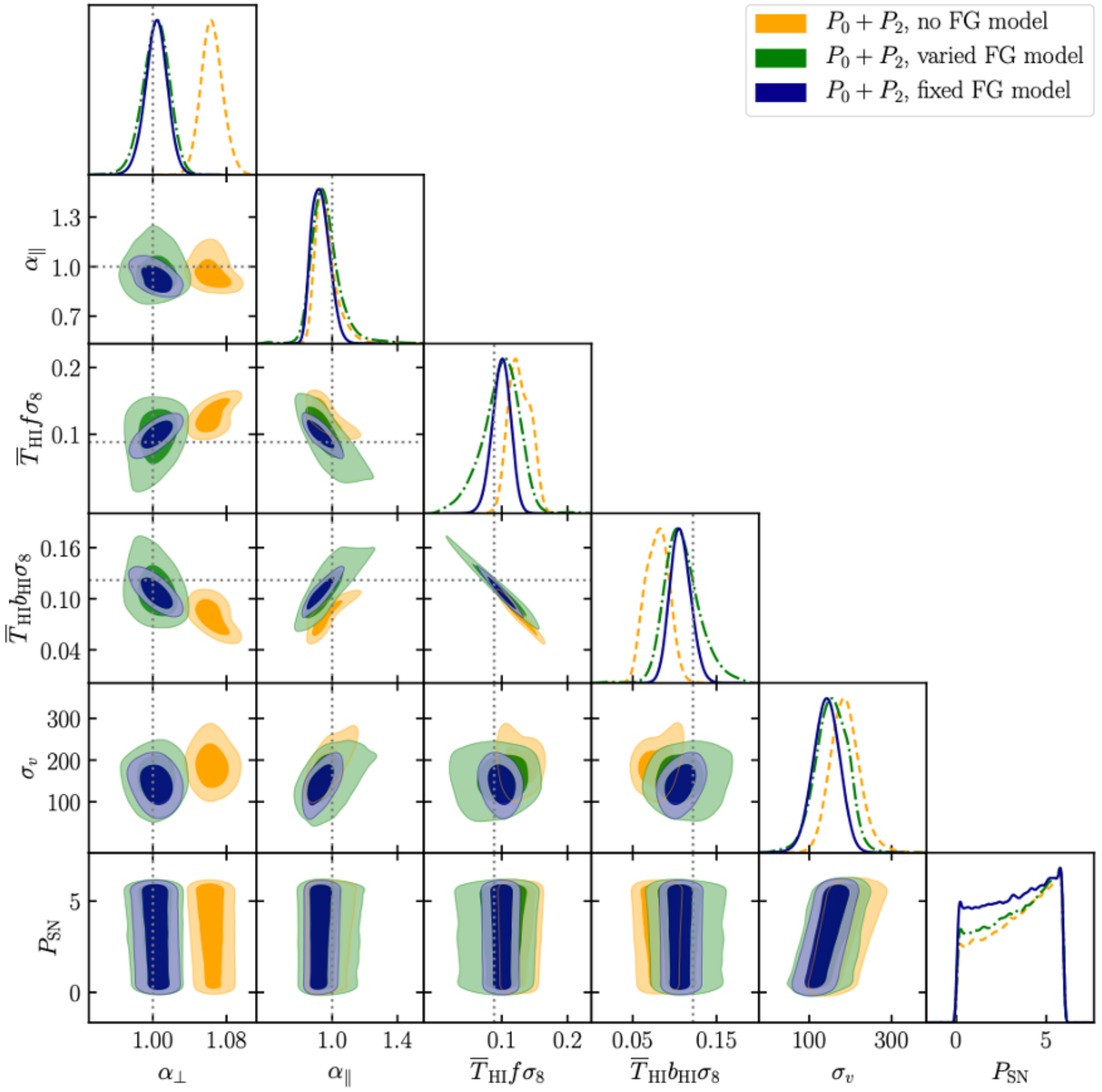


Parameter estimation - FG

If we don't use any foreground damping model, our results are **biased.**

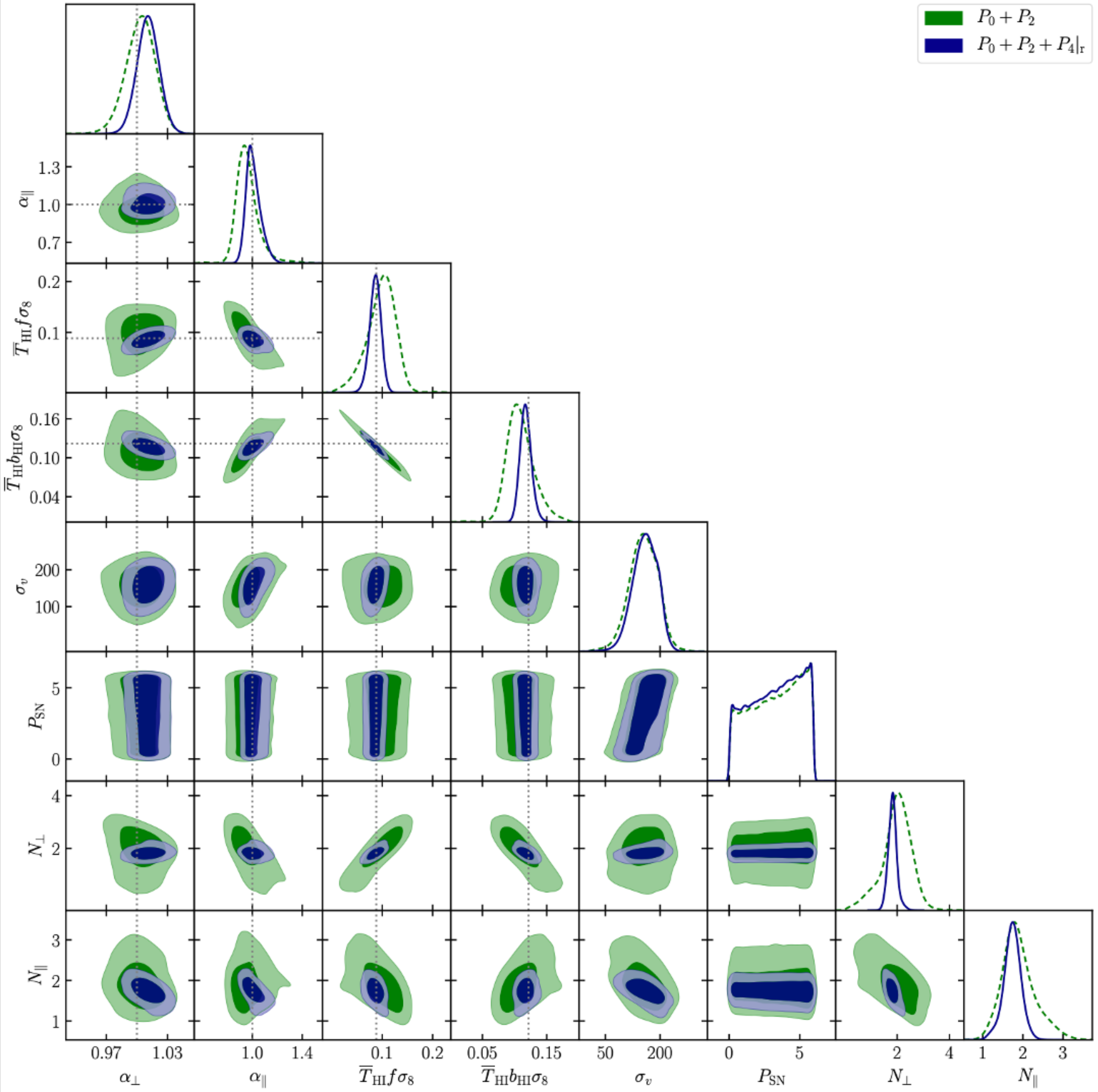
If we use our foreground damping model, results are **unbiased**.

Uncertainties are larger, since we are varying more parameters.



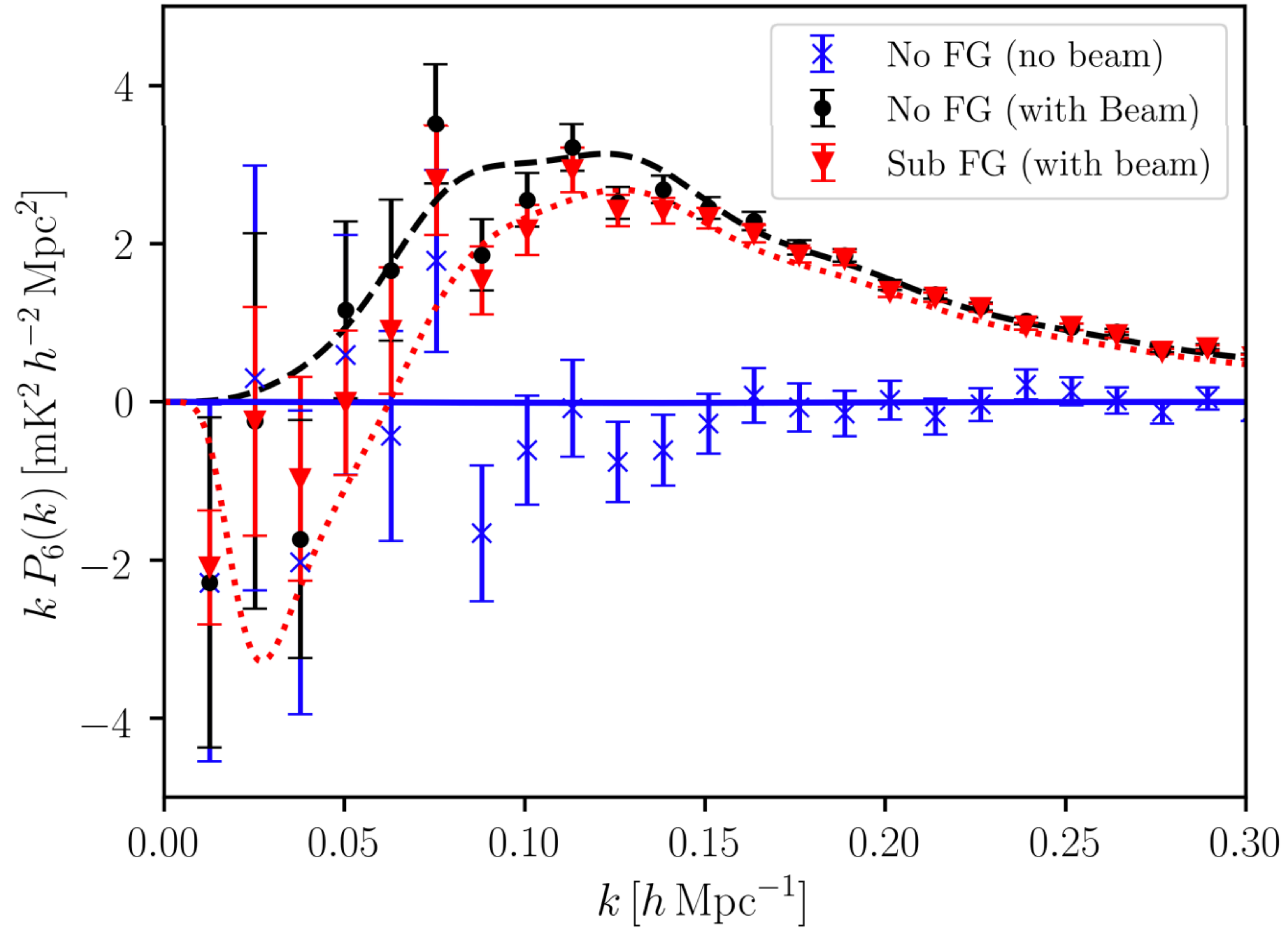
Including the hexadecapole and letting the FG model vary, we again get an improvement on parameter constraints:

Parameter	$P_0 + P_2 + P_4\|_r$ Varied $N_\perp, N_\parallel$
$\alpha_\perp$	1.1%
$\alpha_\parallel$	5.9%
$\overline{T}_{\rm HI} f\sigma_8$	13.3%
$\overline{T}_{\rm HI} b_{\rm HI}\sigma_8$	7.8%



Hexacontatetrapole ($\ell = 6$)

Should be zero for no RSD, but again systematic and instrumental effects enhance it:



Key takeaways

★ It is possible to conduct competitive cosmological parameter estimation with HI IM, but leads to **biased results if foreground removal is not properly accounted for**

★ We present a foreground removal model and show that it **unbiases** results

★ Systematic and instrumental effects significantly impact the covariance between different multipoles, making them more correlated