COSMOLOGICAL PARAMETER ESTIMATION WITH 21CM INTENSITY MAPPING

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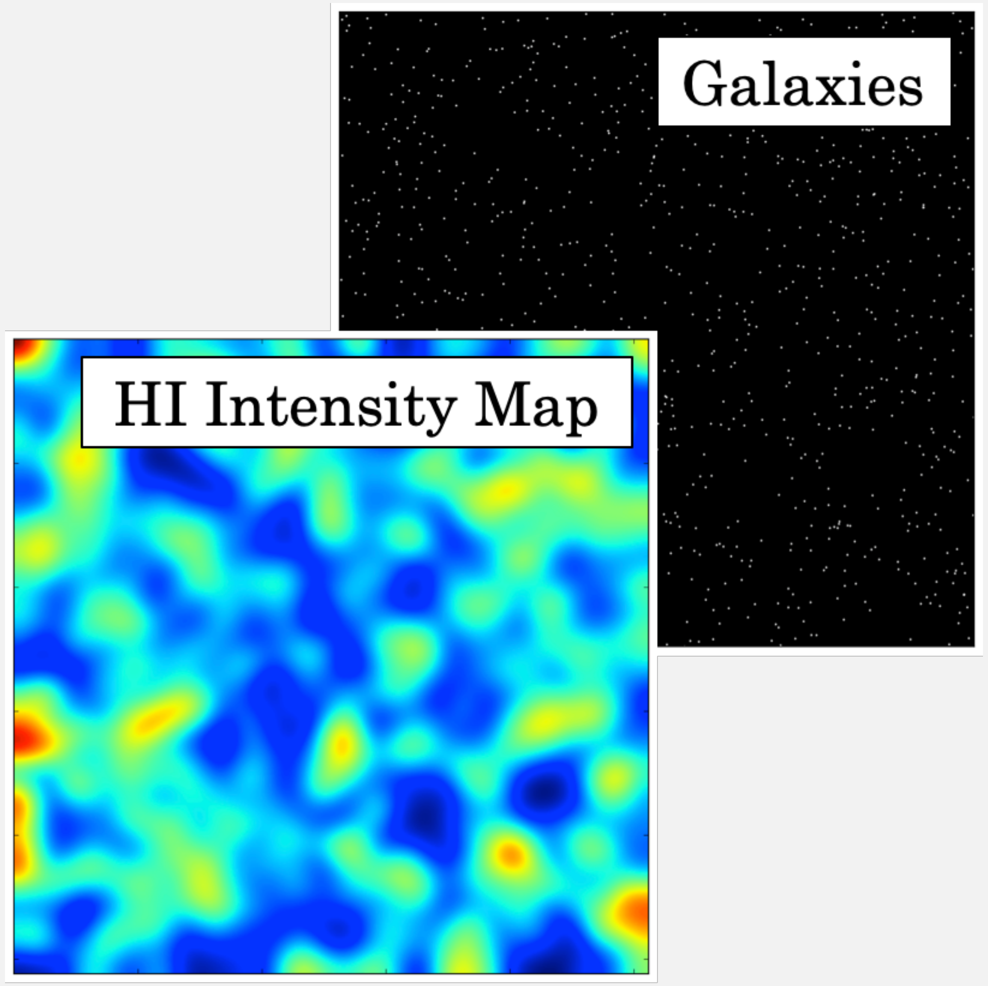
OUTLINE

1. Motivation
   - Why 21cm Intensity Mapping?
2. Modelling
   - How to model the 21cm IM power spectrum
     - Including instrumental and systematic effects
     - Comparing the modelling to simulated data which includes these effects
3. Covariance Matrix
   - How to model the uncertainty in our 21cm IM power spectrum
4. Parameter estimation results

INTENSITY MAPPING

- Measures the intensity and redshift of the HI 21cm line across the sky
- Does not detect individual galaxies, can scan large volumes of the sky quickly
- Biased tracer for the underlying matter distribution
- Can use HI to map the 3D LSS of the Universe



Francisco Villaescusa-Navarro

Isotropic

Simplest model:

$$P^{\mathrm{HI}}(k) = \overline{T}_{\mathrm{HI}}^{2} b_{\mathrm{HI}}^{2} P_{\mathrm{m}}(k)$$

HI power spectrum as a function of inverse length (k)

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

HI bias

Underlying matter power spectrum

HI IM POWER SPECTRUM

Anisotropic

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

Redshift space distortions

Angle between k and line of sight of observer

$\mu \equiv \cos\theta$

Alcock-Paczynski effect

Shot noise

HI IM POWER SPECTRUM

Parameters: $\{\alpha_{\parallel},\ \alpha_{\perp},\ \overline{T}_{\rm HI}f\sigma_8,\ \overline{T}_{\rm HI}b_{\rm HI}\sigma_8,\ \sigma_v,\ P_{\rm SN}\}$

MULTIPOLE EXPANSION

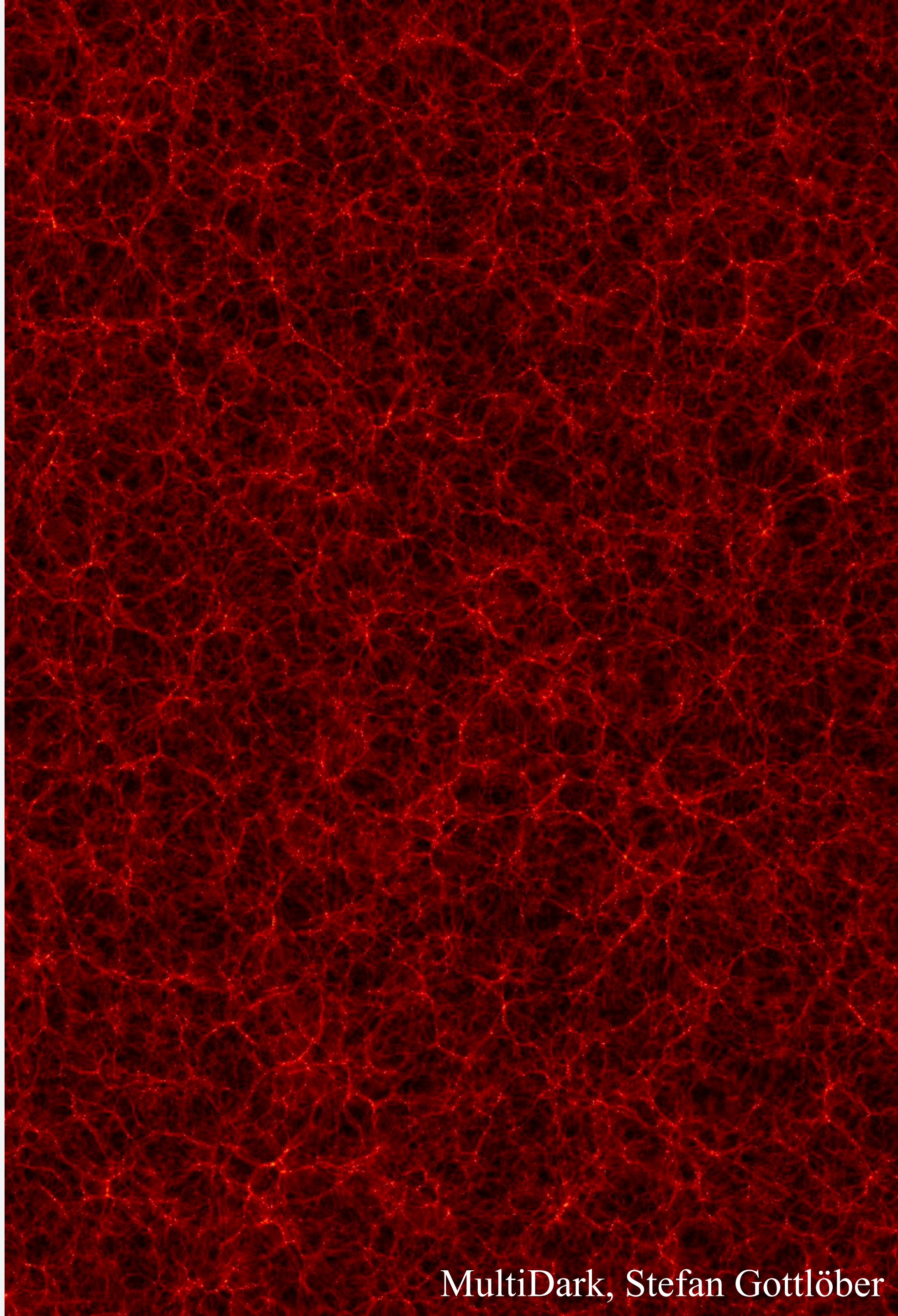
- Useful analysis tool:
  - Decomposing power spectrum into multipoles using Legendre polynomials

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

$$\ell = 0, 2, 4$$

SIMULATING SINGLE DISH HI IM

- MultiDark N-body simulation:
  - $z = 0.82$
  - $L_x = L_y = L_z = 1000$ Mpc h^{-1}
  - $N_x = N_y = N_z = 225$
  - Map the cold gas mass of galaxies to HI mass
  - Smooth with a large telescope beam of $R = 26$ Mpc h^{-1}
    - Equivalent to what an SKA1-MID telescope beam at this redshift would look like

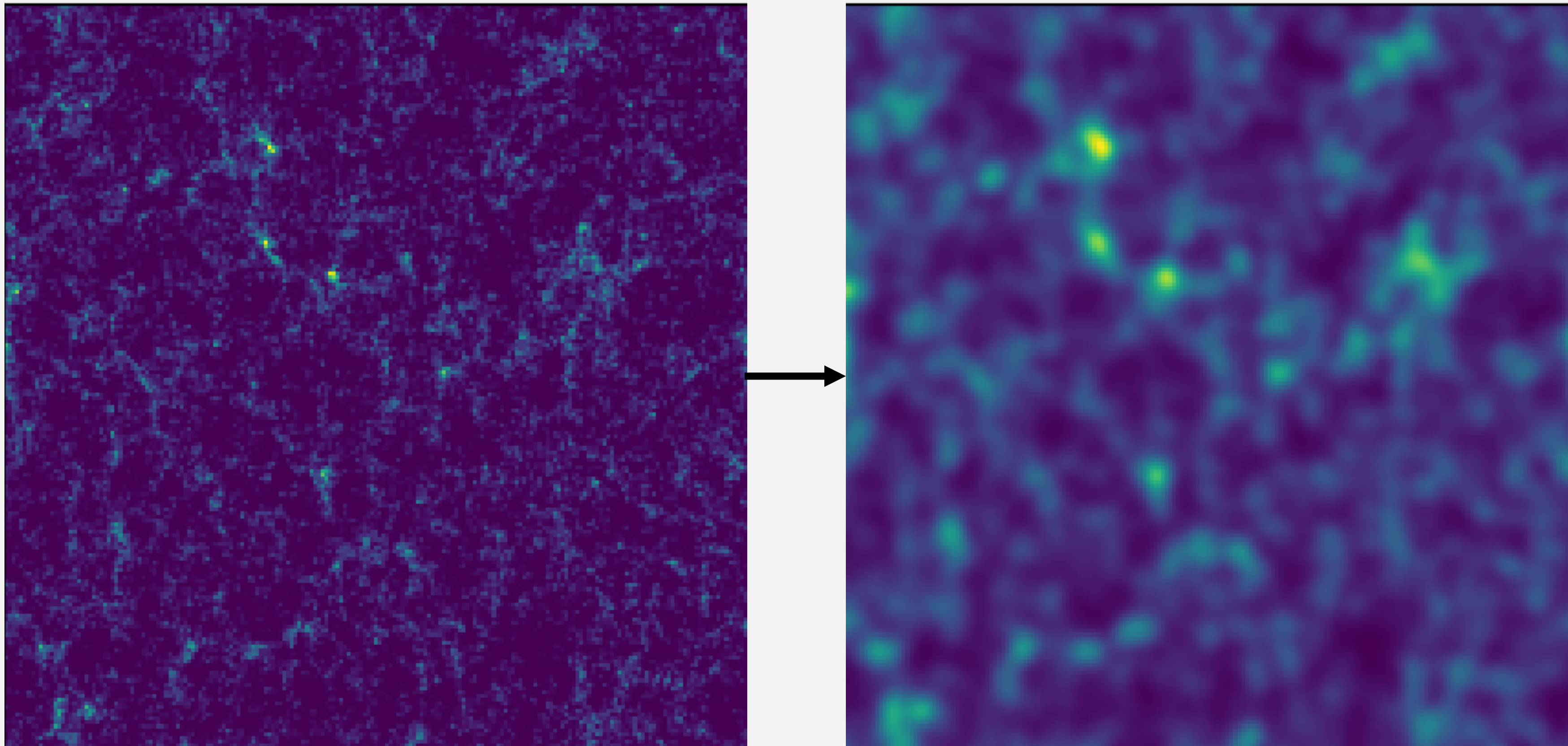


See https://www.cosmosim.org/ and https://arxiv.org/abs/1411.4001 for more details on MultiDark

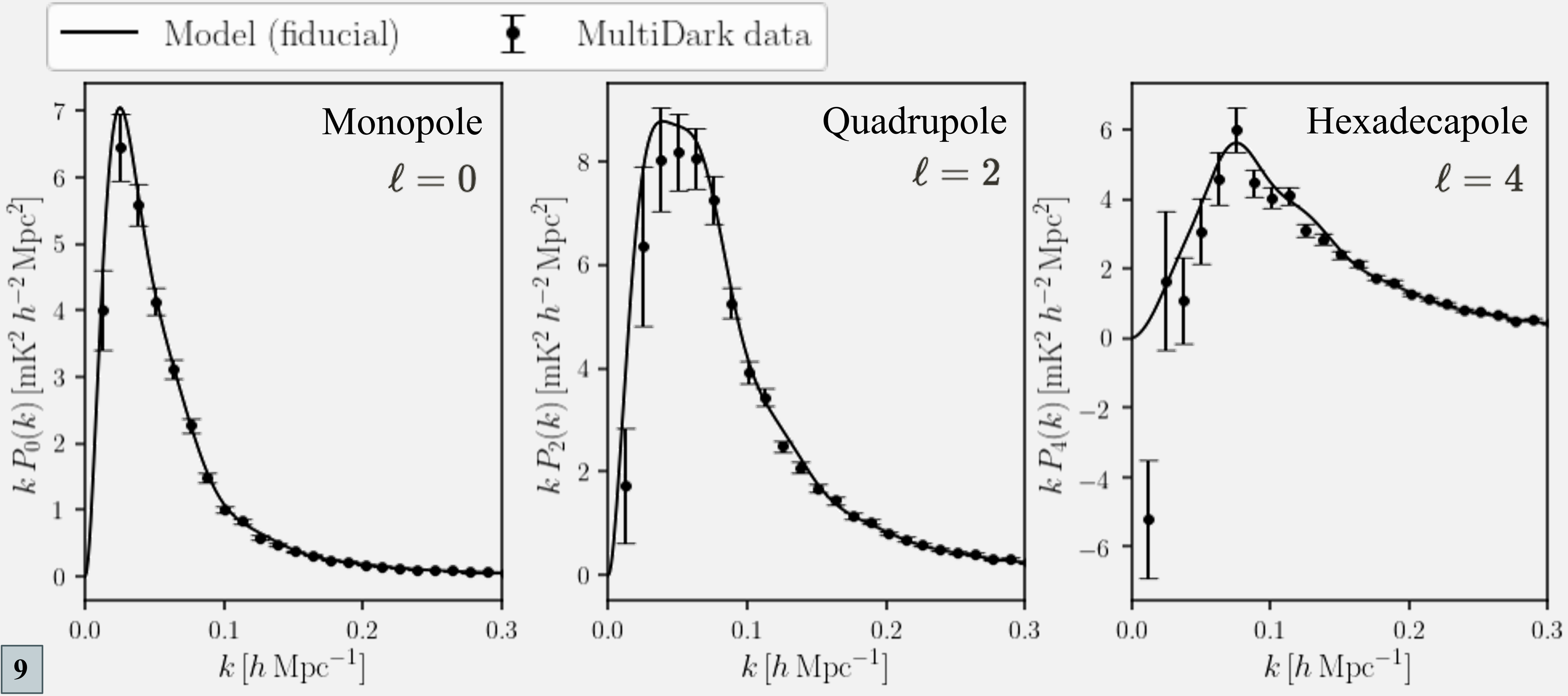
INSTRUMENTAL EFFECTS
TELESCOPE BEAM

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

- The telescope beam damps power on small physical scales
- The beam acts on the direction perpendicular to the LoS, adding further anisotropies to the power spectrum



Agreement between model and simulation:

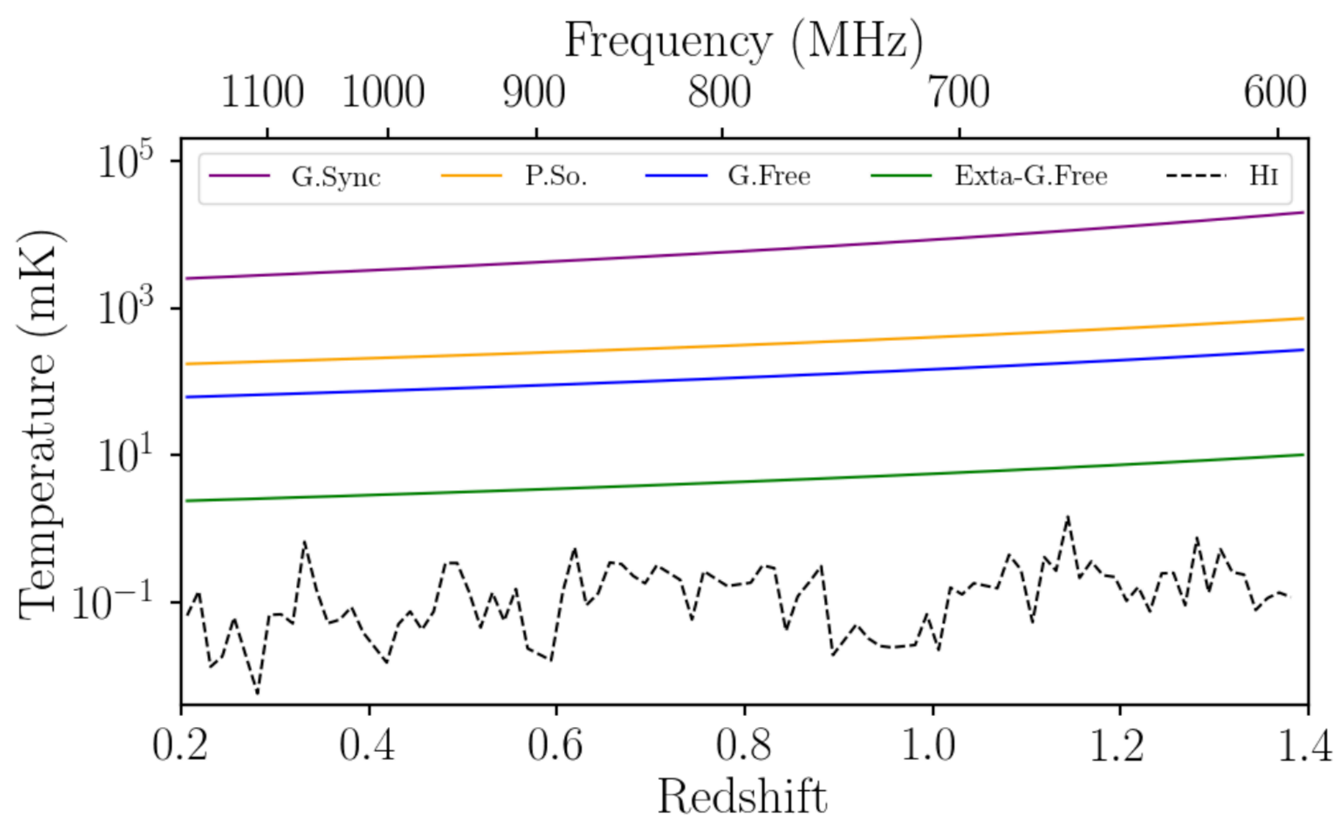


SYSTEMATIC EFFECTS
FOREGROUND REMOVAL

- To actually measure this HI signal, we need to separate it from foregrounds that we end up observing in the same frequencies
  - Some of which are 5 order of magnitude larger!
- Main foreground sources:
  - **Synchrotron emission**: high energy electrons accelerated by magnetic field
  - **Extragalactic point sources** (e.g. AGNs)
  - **Galactic free-free emission**: electrons being scattered off ions
  - **Extragalactic free-free emission**: electrons being scattered off ions
    - We can simulate these!

REMOVING FOREGROUNDS

- We can separate the foregrounds from the underlying signal because the **foregrounds are spectrally smooth in frequency**
  - Independent Component Analysis (ICA) can do this by separating components in the data that are **statistically independent**

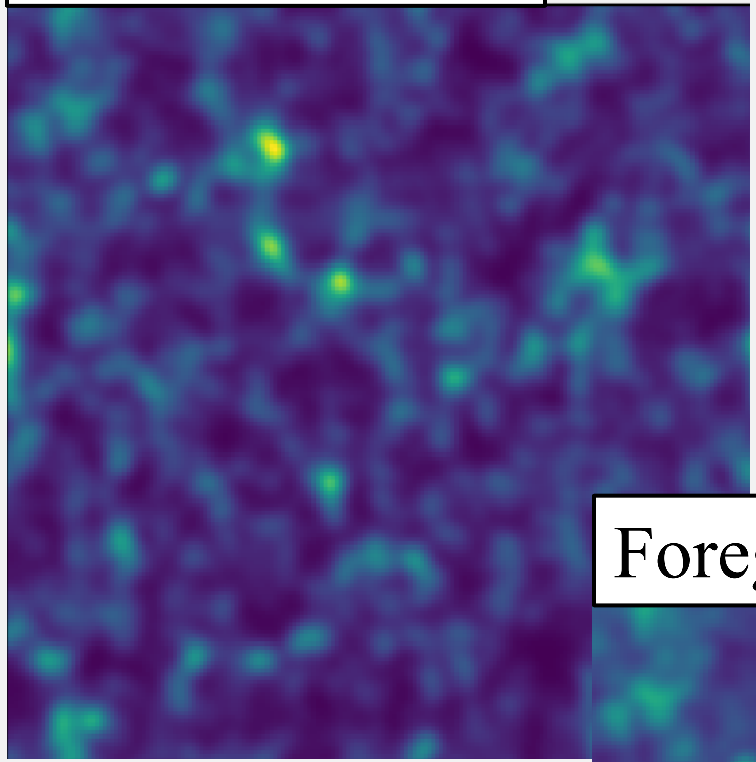


S. Cunnington et al. 2019

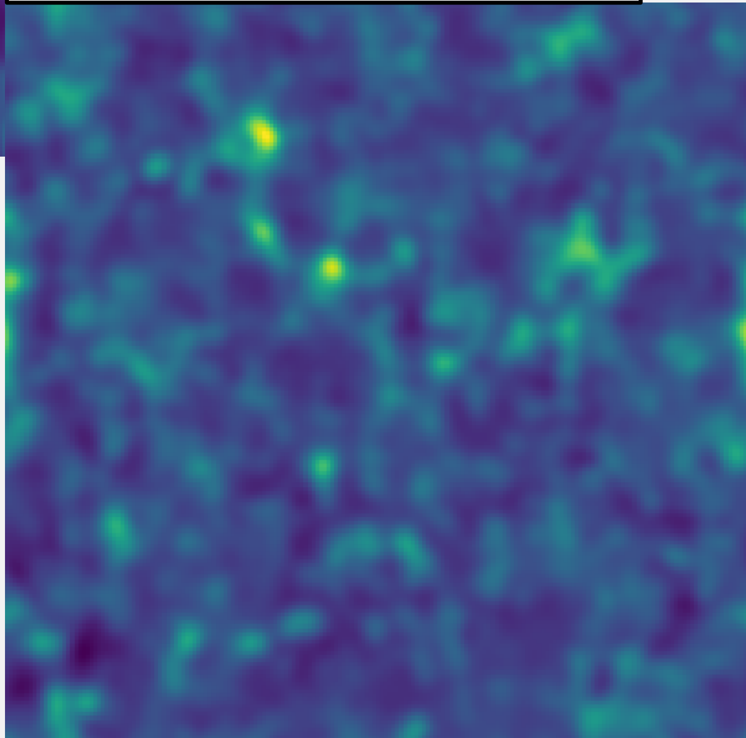
EFFECTS OF FOREGROUND CLEANING

- When we perform foreground cleaning with an ICA algorithm, large radial modes of the HI signal are also smooth with frequency
  - This is because they are large so cover a large frequency range), so will get removed.
  - This means power is damped on large scale modes.

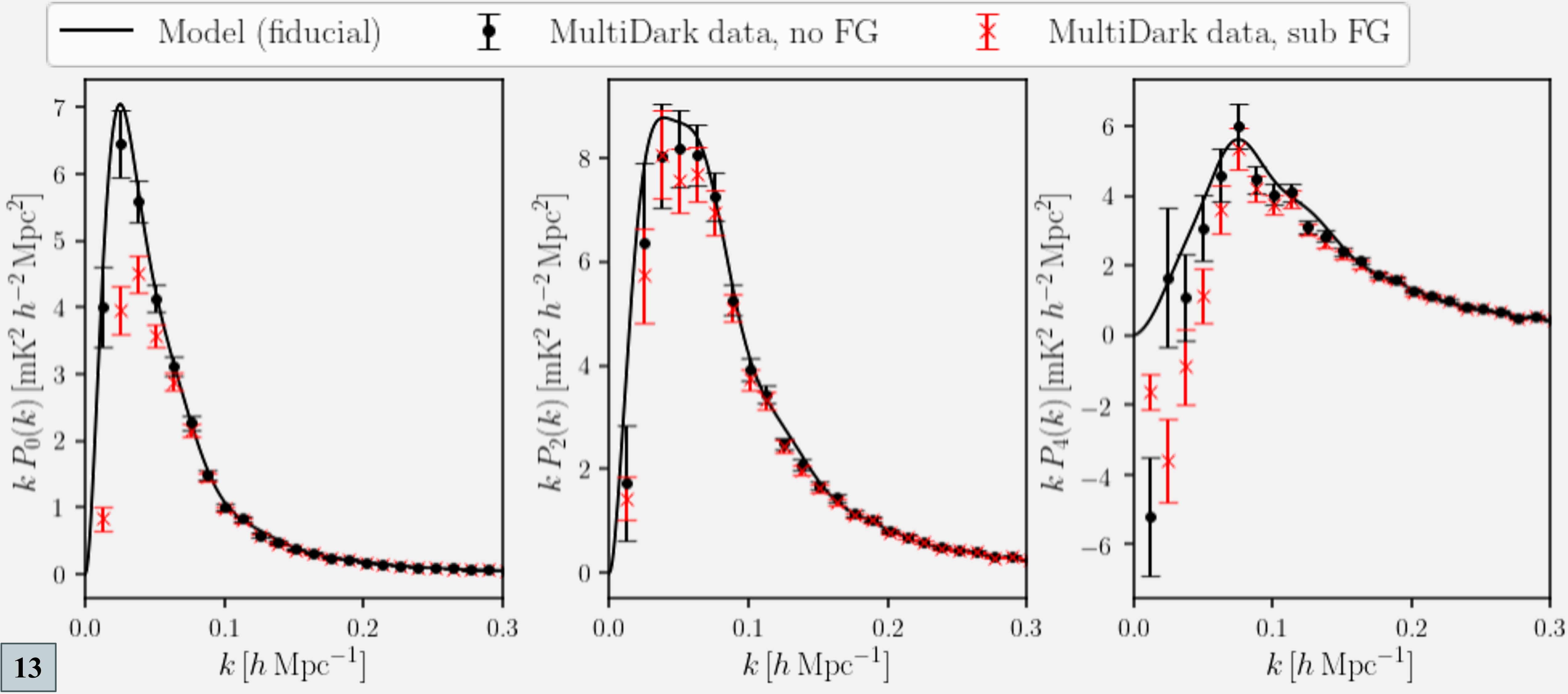
Foreground-free



Foreground cleaned



Effect of foreground removal on the power spectrum:

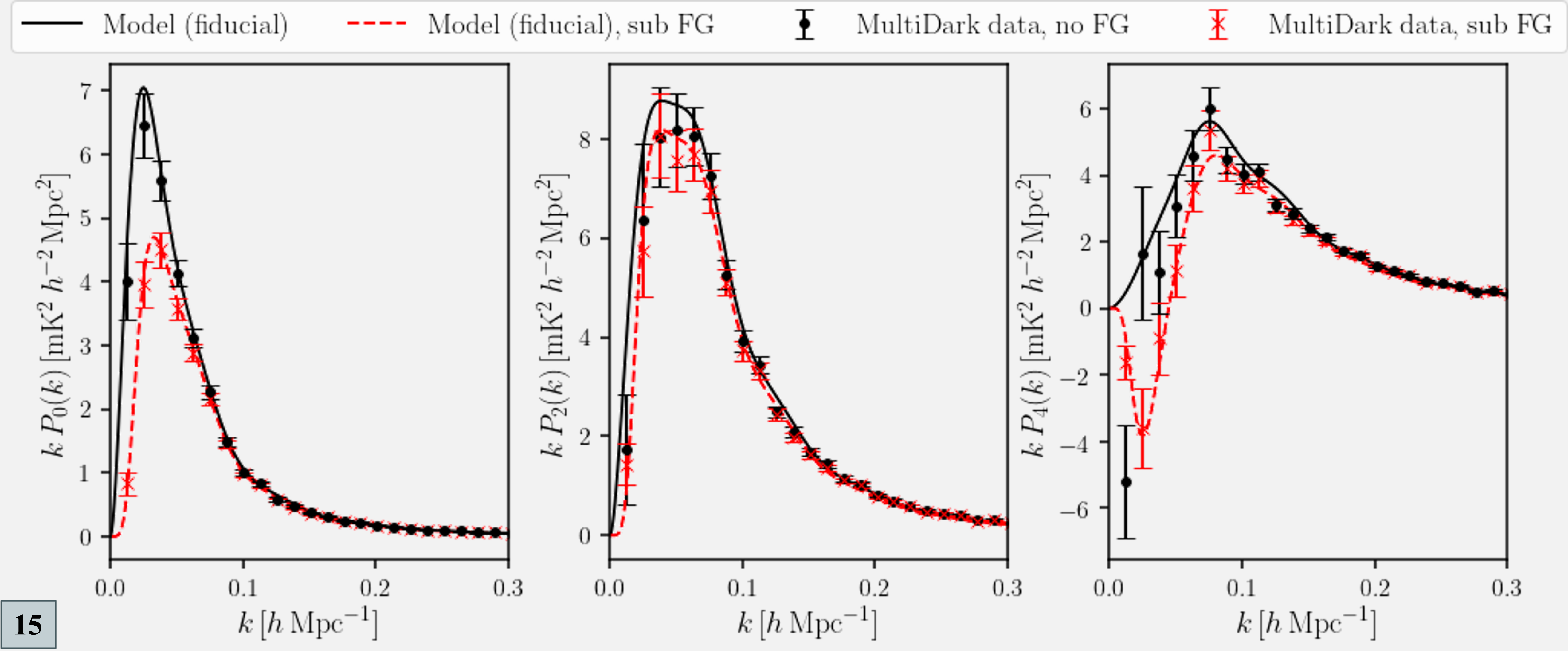


MODELLING FOREGROUND REMOVAL

- Model loss of power due to foreground removal as a damping function
  - Gaussian function in Fourier space, which damps large scale modes:

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

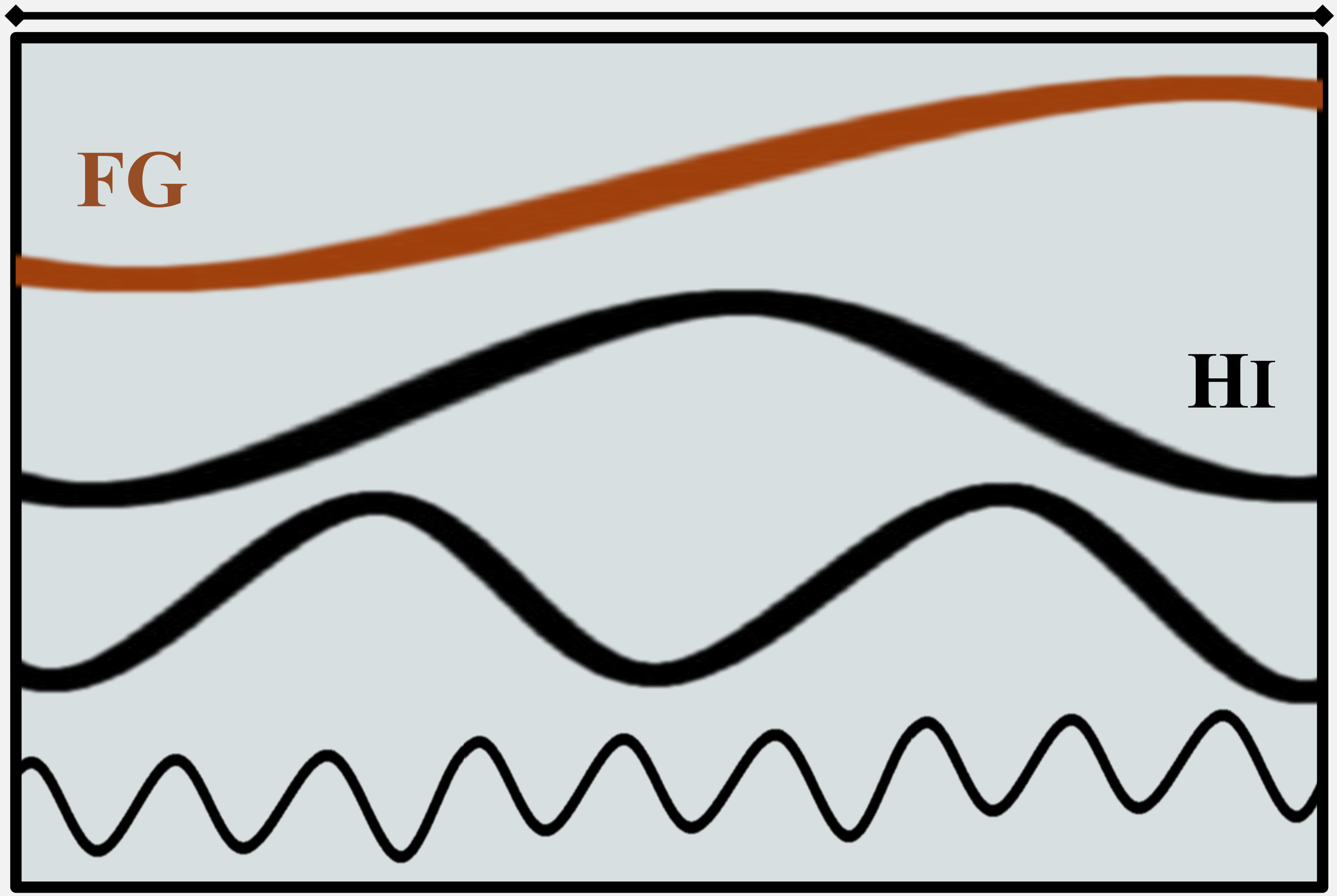
BEST FITTING FOREGROUND MODEL $N_\perp = 2,\ N_\parallel = 2$



WHY $N_\perp = 2,\ N_\parallel = 2$?

- 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 seems to be *half of the largest fluctuations we can fit in the box*
      - Hence $N_\parallel = 2$

$L_z = 1000\,\mathrm{Mpc}\,h^{-1} \quad k_\parallel^{\mathrm{min}} = 2\pi/L_z$



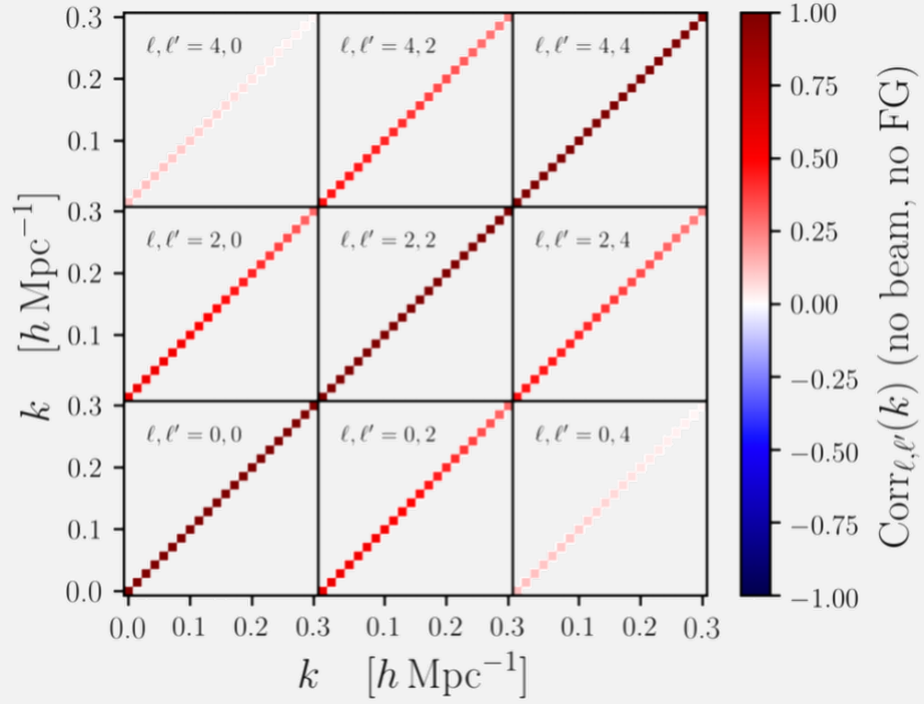
LoS direction, redshift/frequency

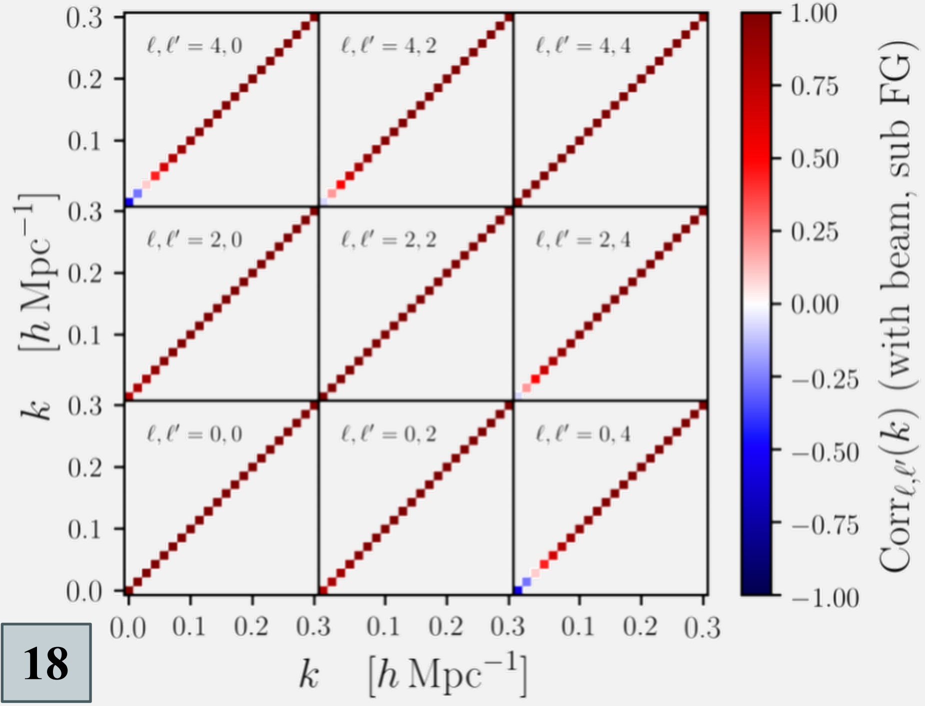
COVARIANCE MATRIX

- Covariance between *k* and *μ* bins (assuming no mode coupling):

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

- We assume a noise power spectrum based on what we can expect for a future SKA1-MID single dish IM experiment
- We include our modelling of instrumental and systematic effects
- We don't ignore the covariance between different multipoles





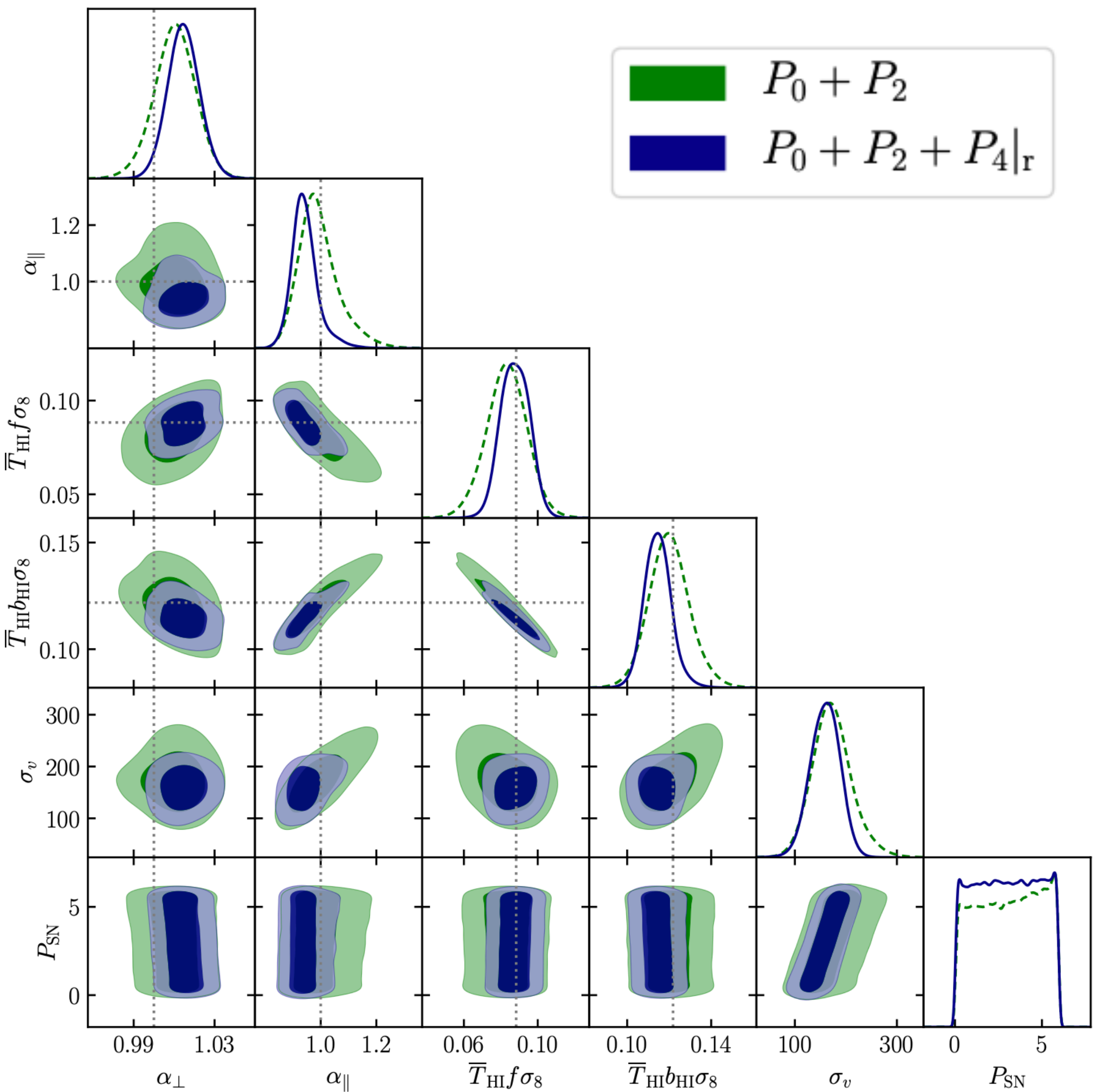
CORRELATION MATRIX

- The telescope beam effect increases correlations between different multipoles significantly
- The FG removal effect also significantly affects the correlation matrix, at small *k*
  - However, more work is required in order to fully understand the effect of FG removal on the HI IM power spectrum covariance matrix

PARAMETER ESTIMATION
FOREGROUND-FREE CASE

- Parameter estimation using our simulation data and model
  - MCMC analysis
  - Unbiased results
  - Sub-10% errors on all cosmological parameters of interest

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

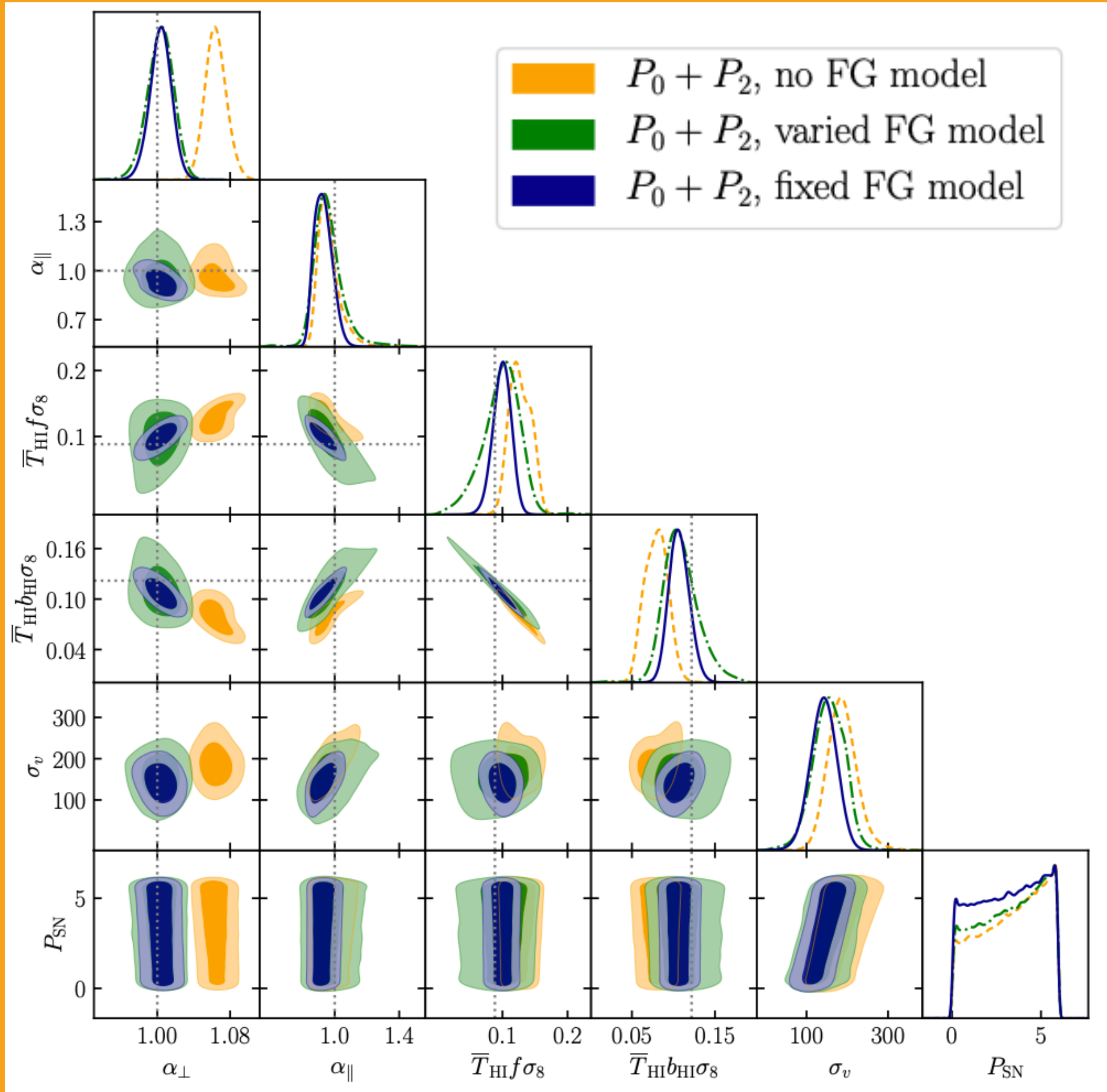


PARAMETER ESTIMATION

FOREGROUND REMOVED CASE

Looking at the monopole and quadrupole:

- If we don't include the foreground model:
  - Biased parameter estimates
- If we include the foreground model:
  - Unbiased parameter estimates
  - Keeping the FG parameters fixed decreases results, but is less realistic

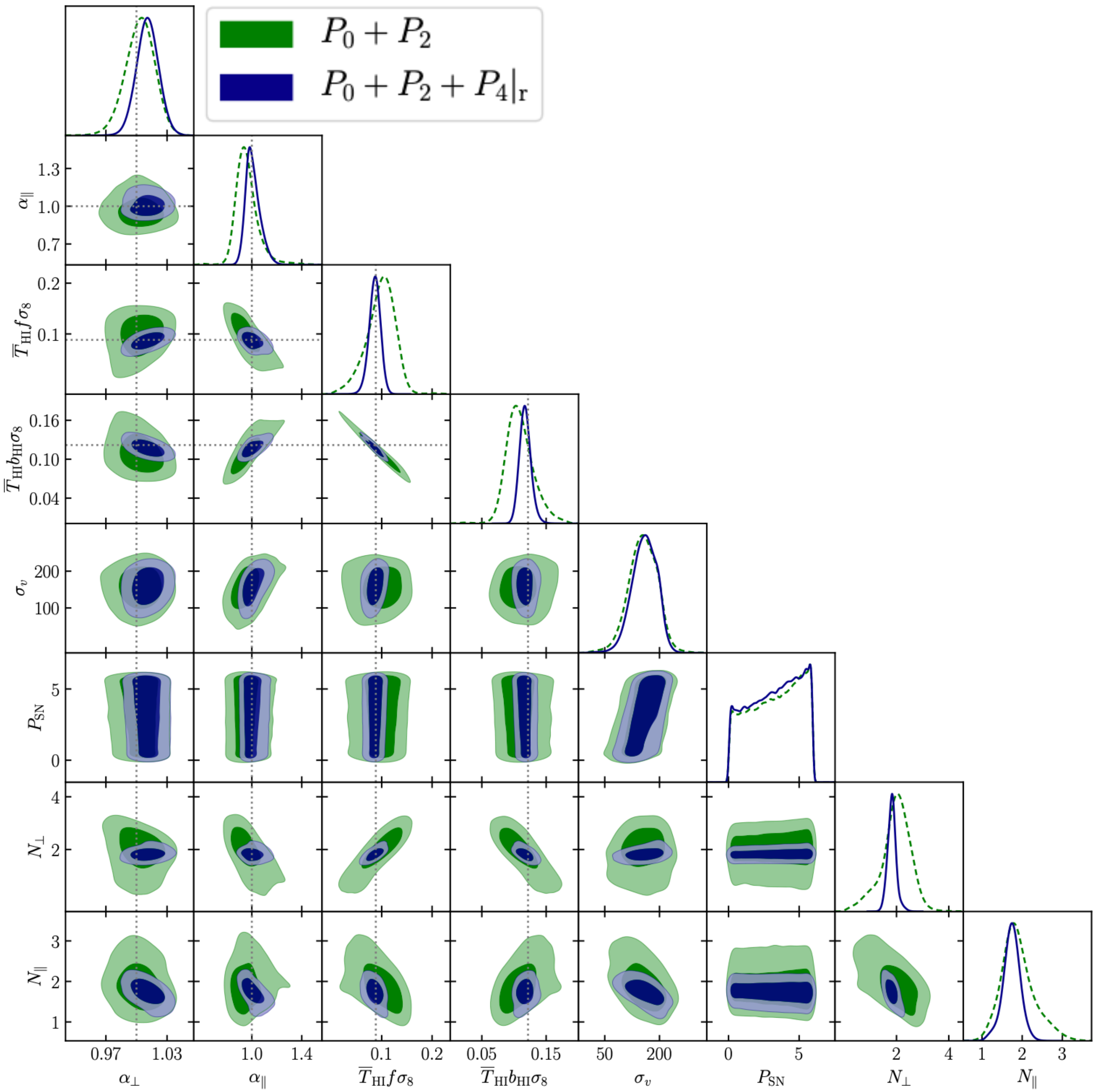


4. Parameter Estimation Results

Including the hexadecapole and letting the FG model vary:

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

- We obtain unbiased parameter results
- The errors on the parameters are larger than on the FG-free case



SUMMARY

- We can model the effects of the telescope beam and foreground removal for a future HI IM single dish experiment
  - This modelling **agrees well with simulated data**
- These instrumental and systematic effects make different HI power spectrum multipoles **more correlated**
  - More research is required to fully understand the effect of FG removal on the covariance matrix
- In the absence of foregrounds, this modelling allows us to obtain **unbiased cosmological parameter results, and sub-10% level uncertainties**
- In the presence of foregrounds, and after they have been removed, we can use our FG model to obtain **unbiased parameter results** but larger uncertainties
  - It would be interesting to test this FG model with other simulations and more complicated foregrounds