Reconstructing signal loss from foreground cleaning

Steve Cunnington - University of Manchester

21 cm Cosmology Workshop 2023 &
Tianlai Collaboration Meeting

Northeastern University - 18th July 2023

Karoo Desert, South Africa

MANCHESTER 1824
The University of Manchester

UK Research and Innovation

Steve Cunnington [steven.cunnington@manchester.ac.uk]

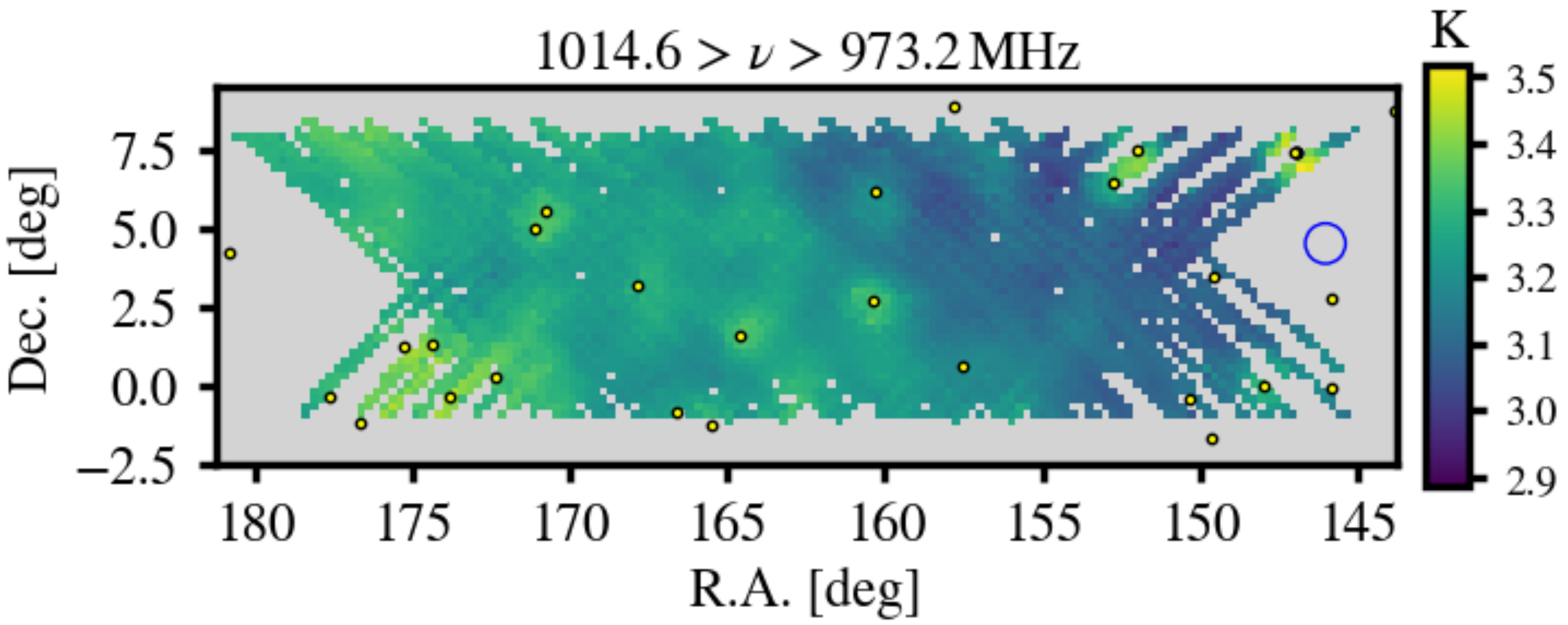
SKAO Pathfinder: MeerKAT

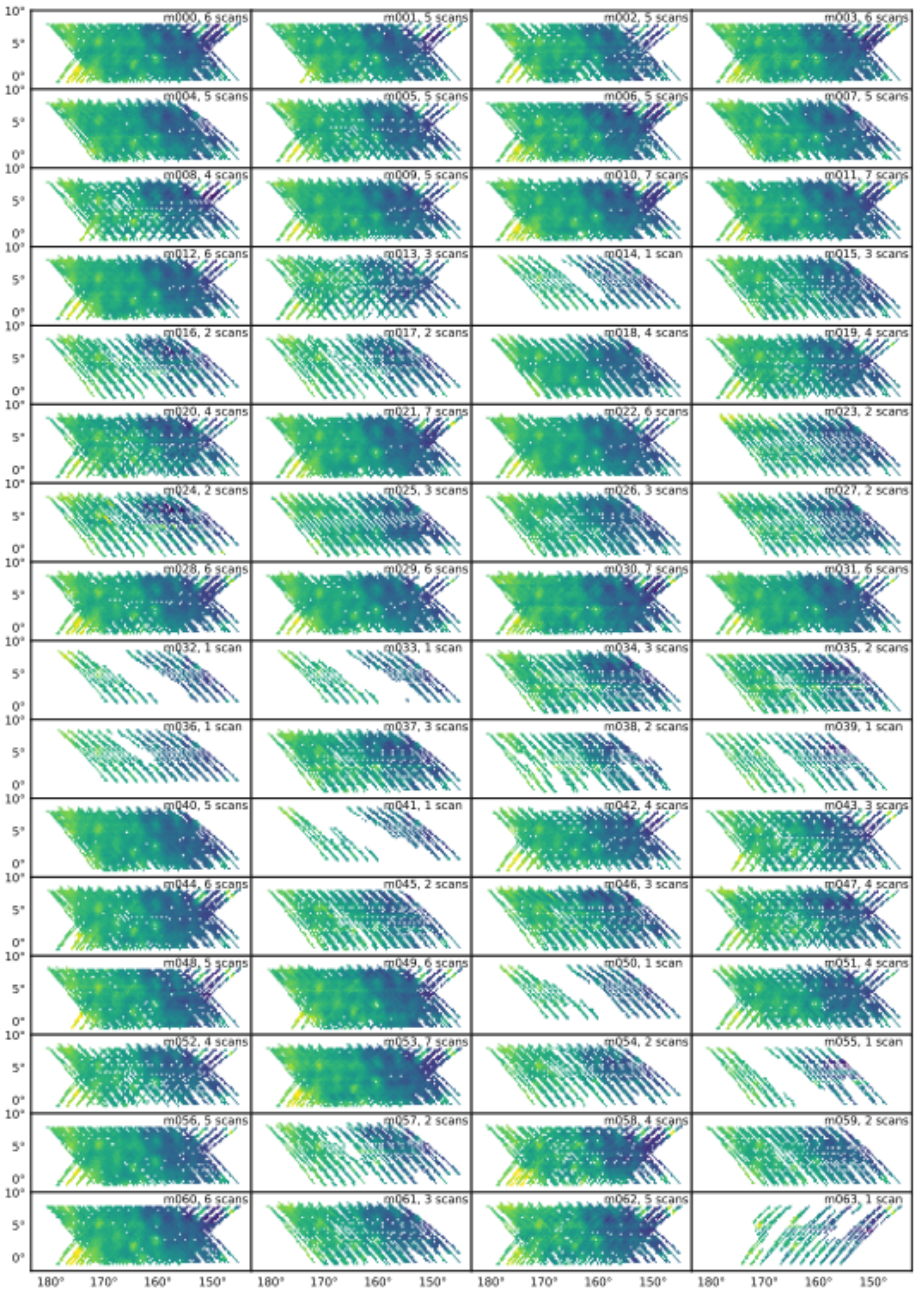
- 64 dishes
- Will become part of SKA-MID
- $0.2 < z < 0.58$ (L-band)
- $0.4 < z < 1.45$ (UHF-band)
- >4000 sq.deg surveys

Single-dish MeerKAT observations provides 64 maps for each dish

Pilot survey data:

- 10.5 hours of data from six nights of observations
- Overlapping with the WiggleZ11hr field (~200 deg^2)
- We use data in range 973-1015 MHz ($0.40 < z < 0.46$)

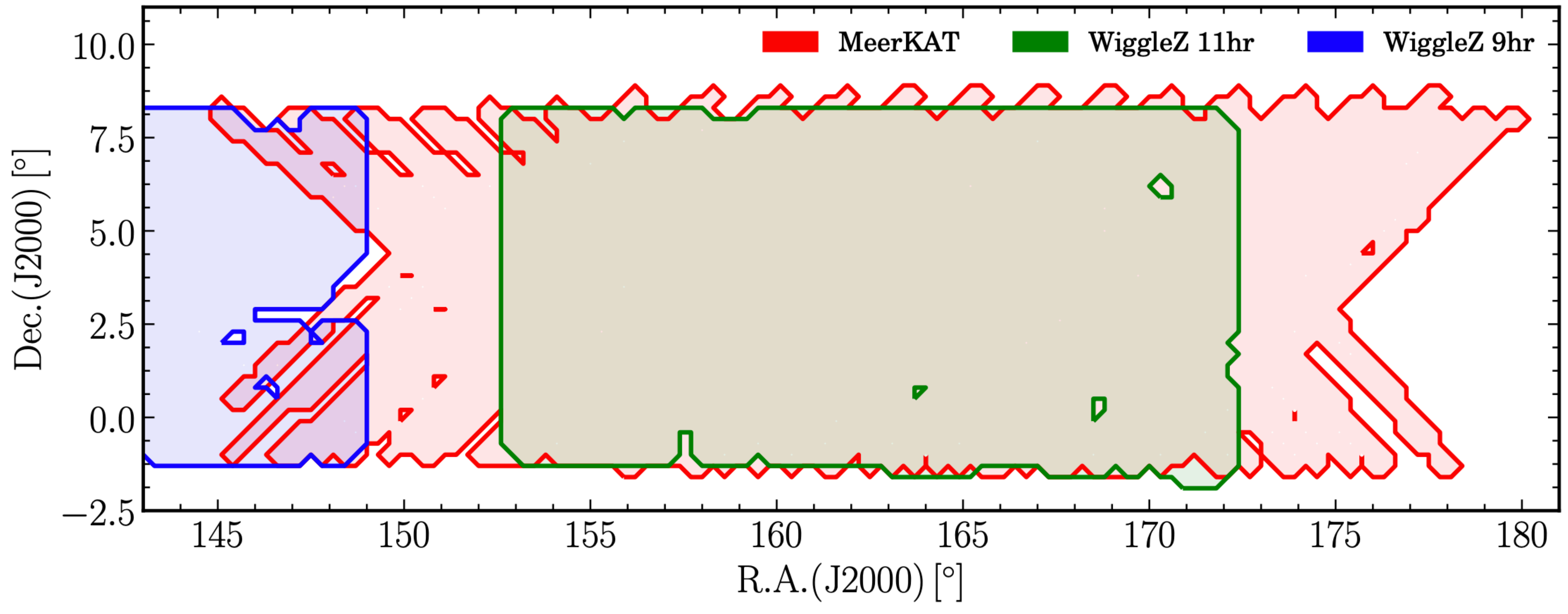




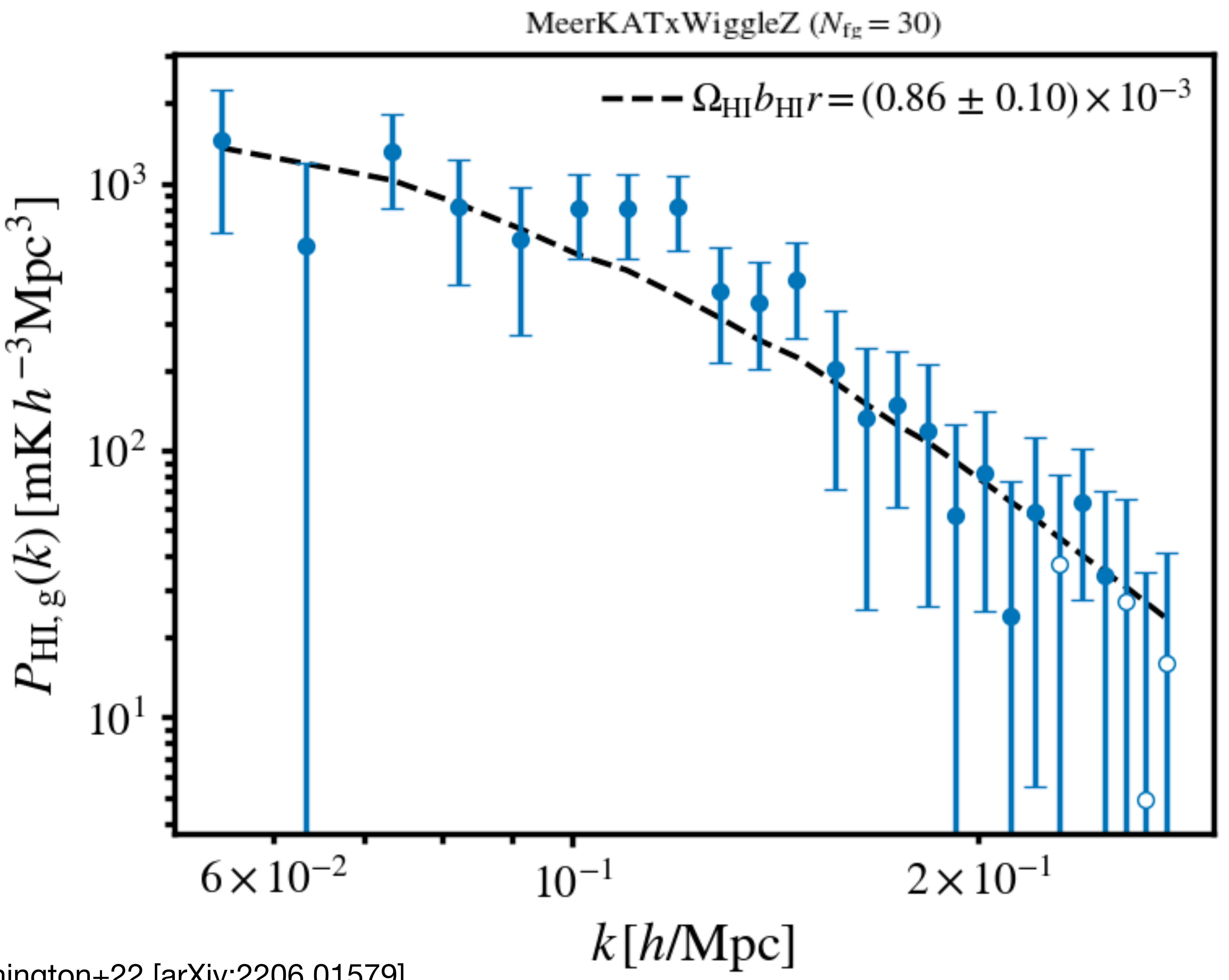
J.Wang, …, SC+21 [arXiv:2011.13789]

Steve Cunnington [steven.cunnington@manchester.ac.uk]

Detecting cosmological clustering with MeerKAT pilot intensity mapping survey



- Positive correlation (7.7σ) between galaxy survey and array of dishes in single-dish mode
- The first detection of its kind
- Important milestone for doing LSS cosmology with SKA intensity mapping



S.Cunnington+22 [arXiv:2206.01579]

Steve Cunnington [steven.cunnington@manchester.ac.uk]

Challenges to overcome with intensity mapping

Foreground cleaning with Principal Component Analysis (PCA)

Mixing matrix

$$\mathbf{X}_{\text{clean}} = \mathbf{X}_{\text{obs}} - \hat{\mathbf{A}}(\hat{\mathbf{A}}^{\text{T}}\mathbf{X}_{\text{obs}})$$

Observed data

The **mixing matrix** is a set of functions we assemble to project out dominant modes within the data.

- Aim for the foregrounds to be contained within these modes we are projecting out

Obtaining a mixing matrix with PCA:

$$\mathbf{C} = \mathbf{X}^{\text{T}}_{\text{obs}}\mathbf{X}_{\text{obs}}/(N_\theta - 1) \xrightarrow{\text{Diagonalise / Eigendecompose}} \mathbf{CV} = \mathbf{V\Lambda}$$

The first N_{FG} column vectors $\boldsymbol{v}_i$ from the eigenvector matrix $\mathbf{V}$ represent the set of smooth functions to construct the $[N_\nu, N_{\text{FG}}]$ mixing matrix i.e. $\hat{\mathbf{A}} = [\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_{N_{\text{FG}}}]$.

- [ ] Can we know how much (HI) signal is lost in foreground cleaning?

- [ ] Can we correct for this to avoid biased results?

☐ Can we know how much (HI) signal is lost in foreground cleaning?

The focus of this paper (and talk)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Royal Astronomical Society

MNRAS **523,** 2453–2477 (2023)
Advance Access publication 2023 May 24

https://doi.org/10.1093/mnras/stad1567

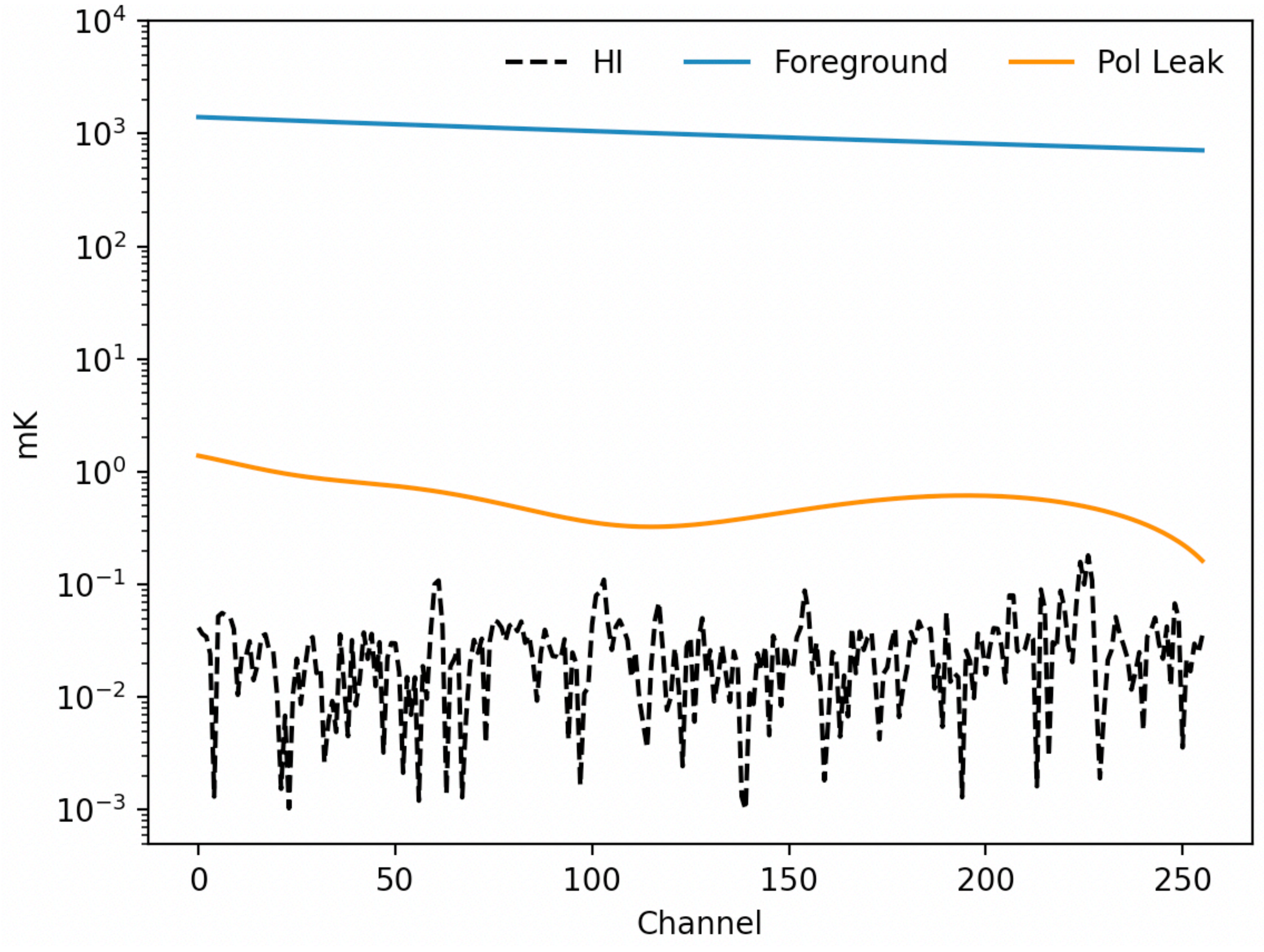
The foreground transfer function for H I intensity mapping signal reconstruction: MeerKLASS and precision cosmology applications

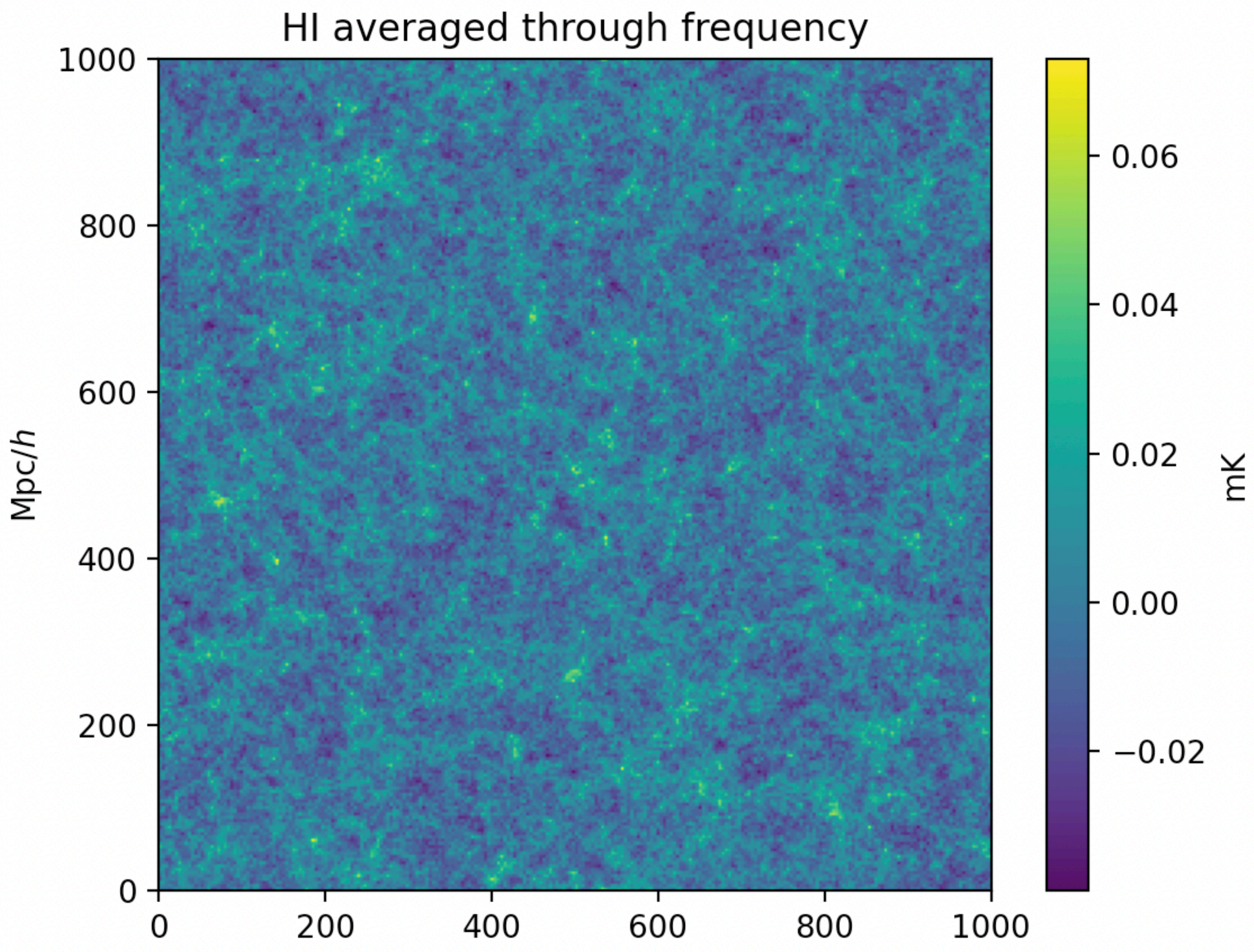
Steven Cunnington,[1★†] Laura Wolz,[1] Philip Bull,[1,2] Isabella P. Carucci,[3,4] Keith Grainge,[1] Melis O. Irfan,[2,5] Yichao Li,[6,2] Alkistis Pourtsidou,[7,8,2] Mario G. Santos,[2,9] Marta Spinelli[10,2] and Jingying Wang[11,2]

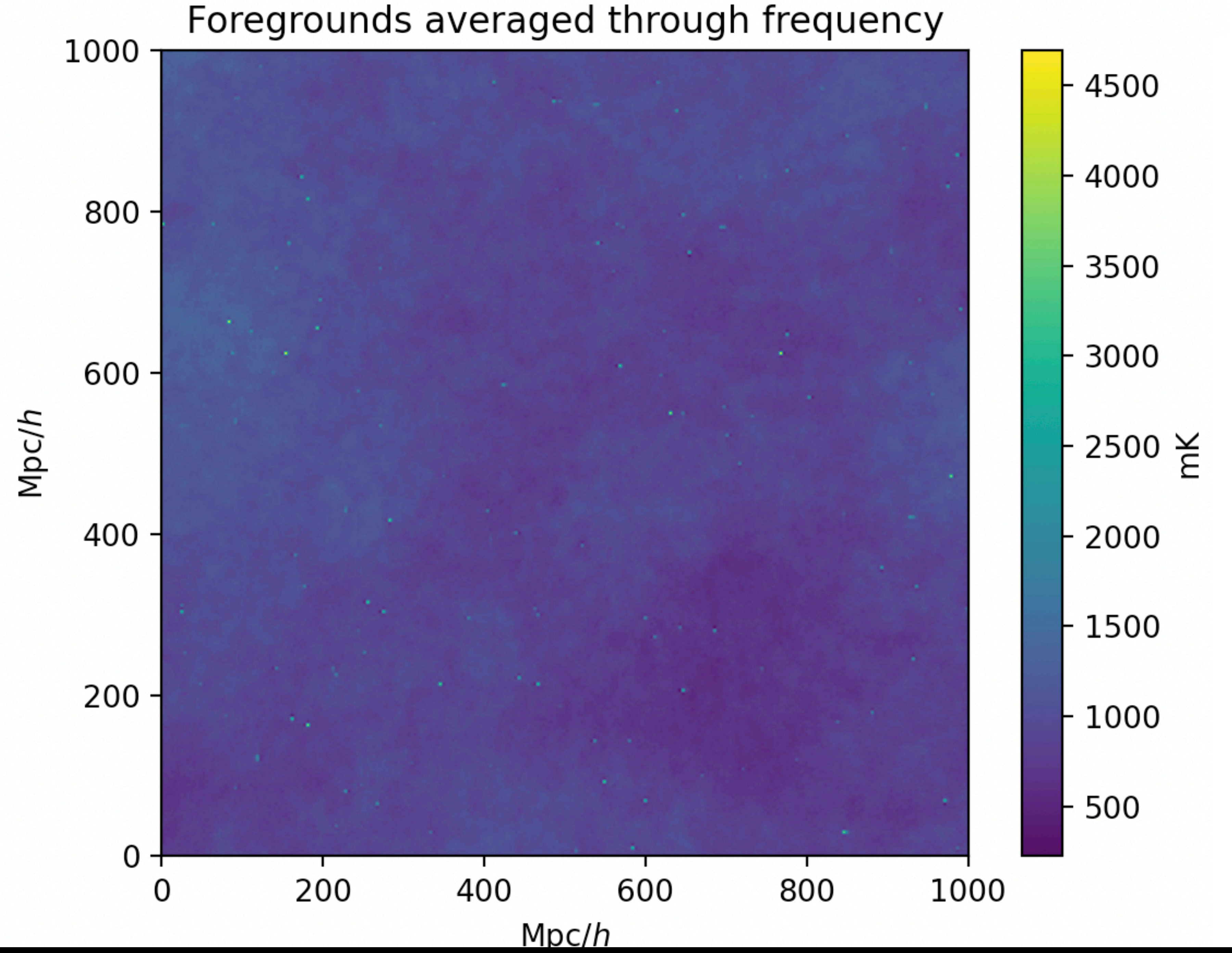
☐ Can we correct for this to avoid biased results?

Simulation-based data

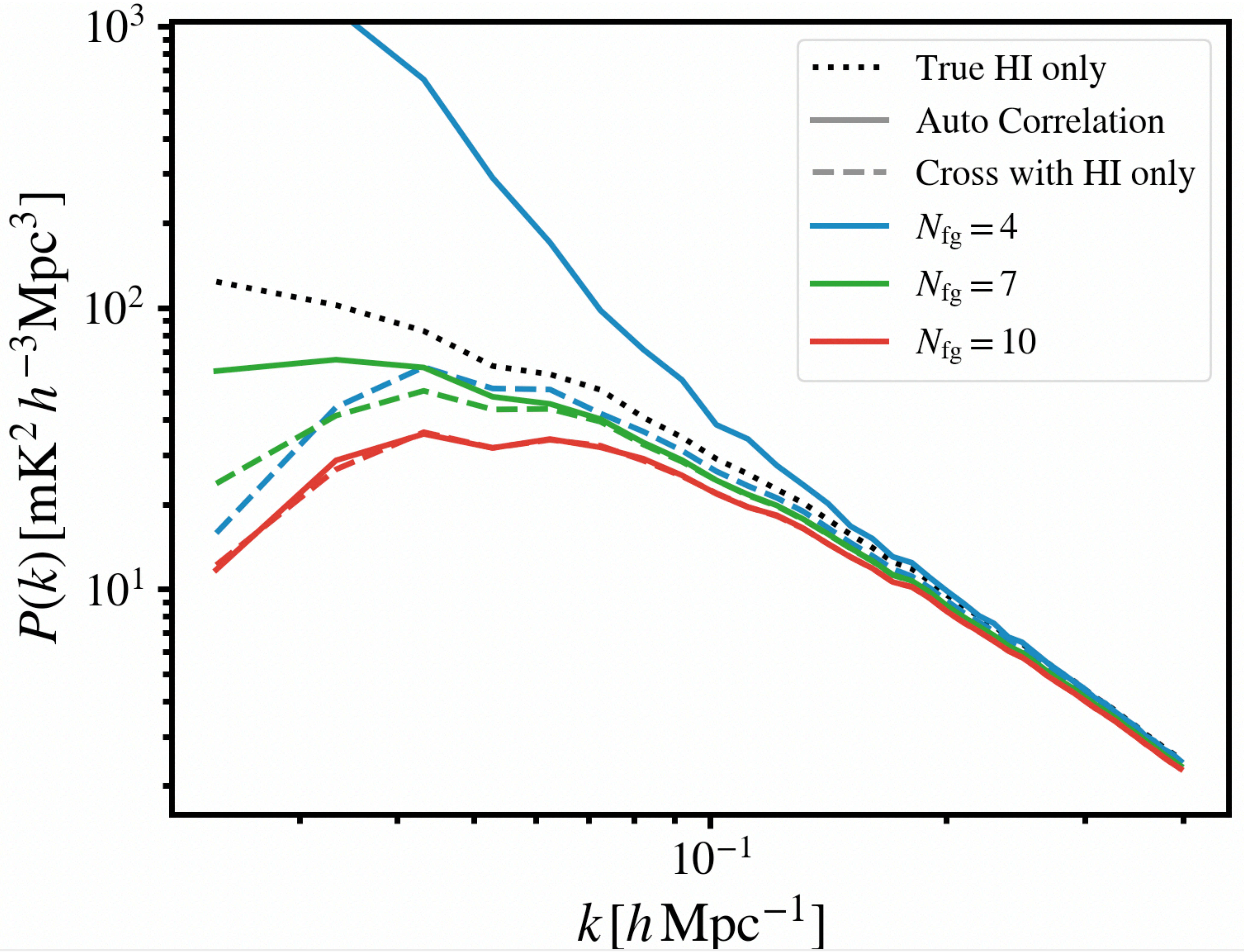
- 1 (Gpc/h)^3 box at z=0.39 (consistent with MeerKAT L-band)
- For the HI: use Multi-Dark semi-analytical N-body simulation
- For the Foregrounds:
  - Planck Sky Model
  - + Point source model
  - + CRIME (polarisation leakage)







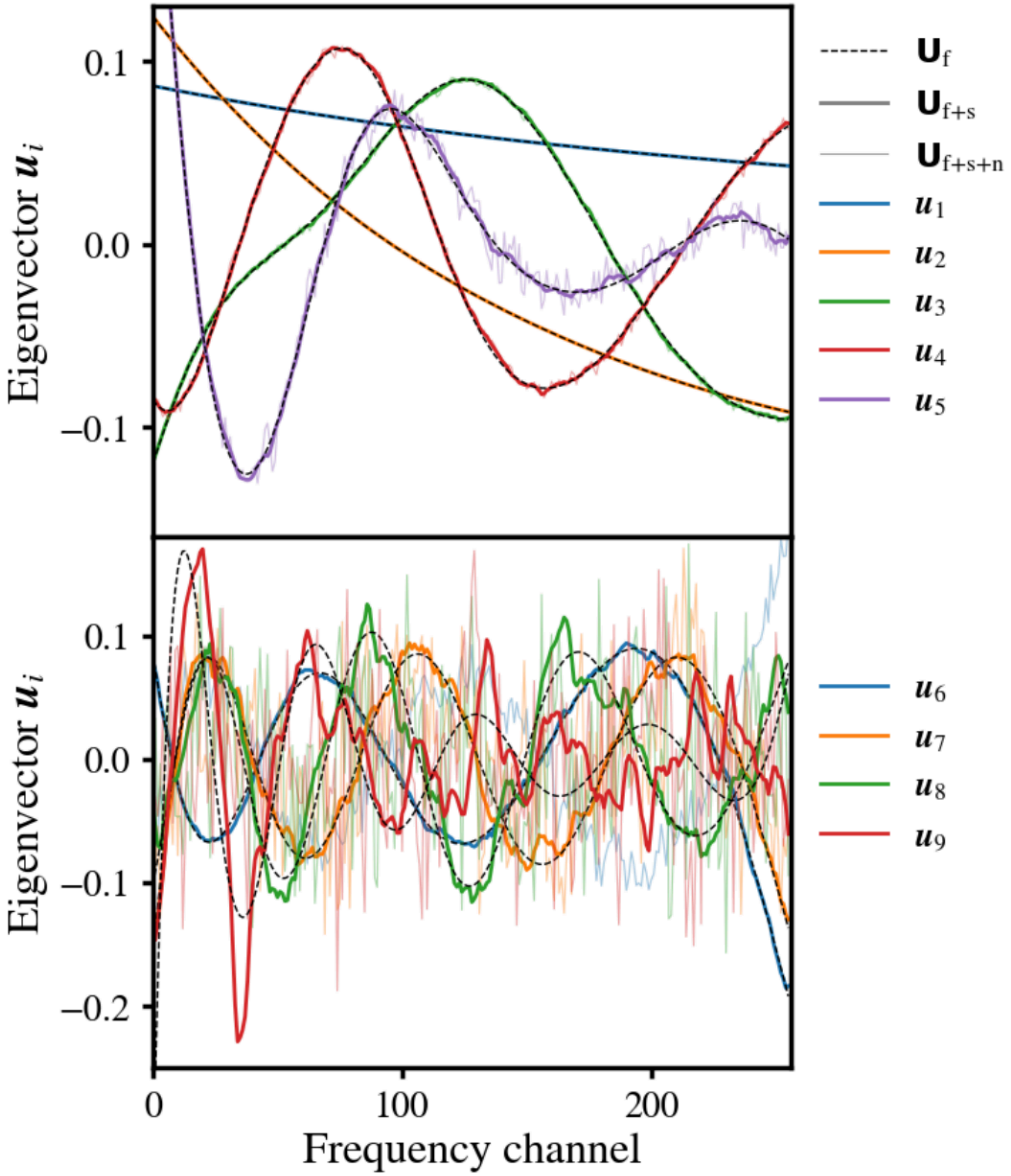
Foreground cleaning the simulations



Imperfect foreground cleaning

$$\hat{\mathbf{C}} = \hat{\mathbf{C}}_{\mathrm{f}} + \mathbf{C}_{\Delta}$$

$$\longrightarrow \quad \mathbf{U}_{\mathrm{f+s}} = \mathbf{U}_{\mathrm{f}} + \Delta$$



Steve Cunnington [steven.cunnington@manchester.ac.uk]

Constructing a transfer function for signal loss correction

Inject mocks into real observational data and clean:

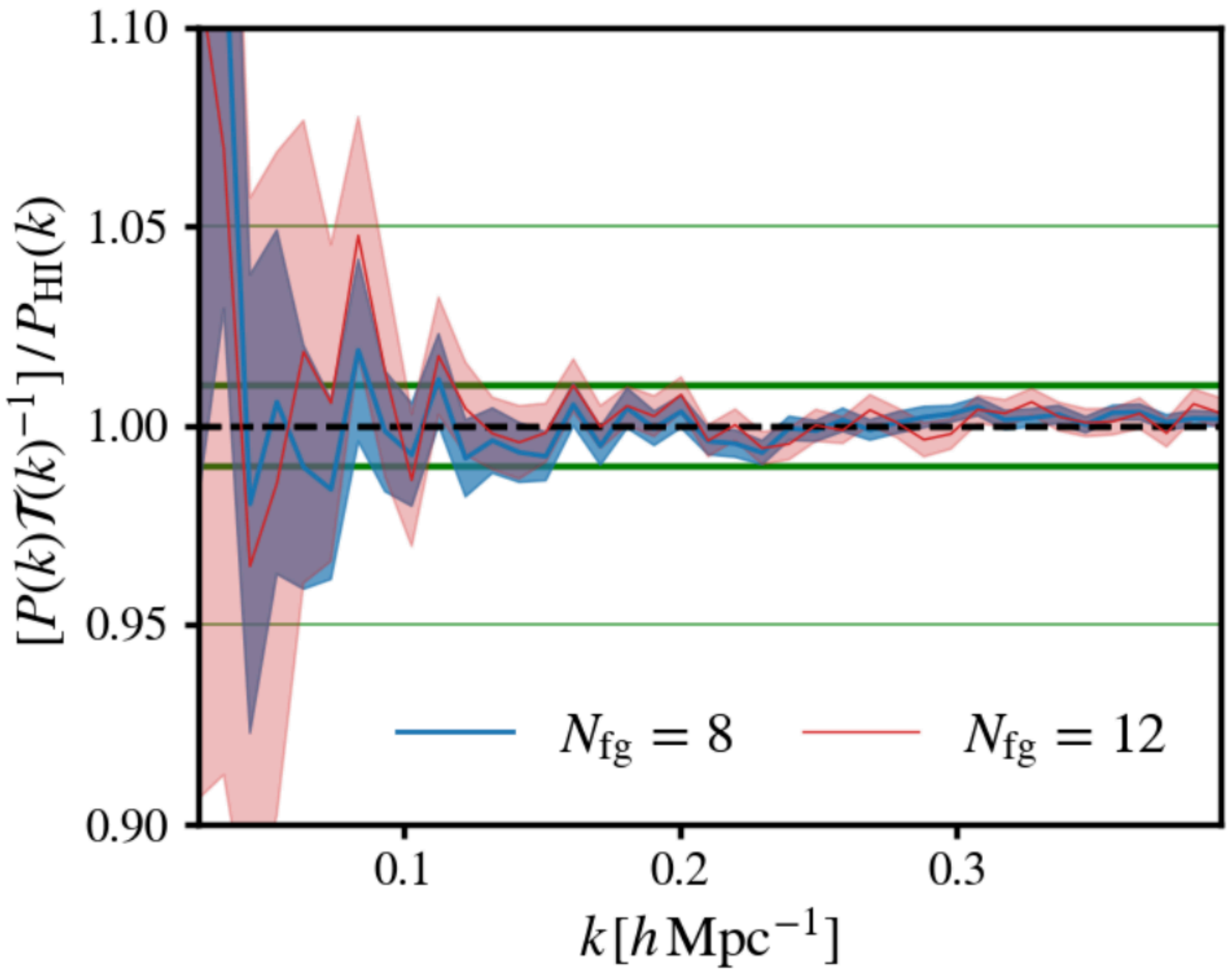
$$\mathbf{X}^{\mathrm{m}}_{\mathrm{clean}} = \mathbf{X}_{\mathrm{f+s+m}} - \mathbf{U}_{\mathrm{f+s+m}}\mathbf{S}\mathbf{U}^{\mathrm{T}}_{\mathrm{f+s+m}}\mathbf{X}_{\mathrm{f+s+m}}$$

"Cleaned" mock

Uncleaned (original) mock

$$\mathcal{T}(k) = \left\langle \frac{\mathcal{P}(\mathbf{X}^{\mathrm{m}}_{\mathrm{clean}}\,,\,\mathbf{X}_{\mathrm{m}})}{\mathcal{P}(\mathbf{X}_{\mathrm{m}}\,,\,\mathbf{X}_{\mathrm{m}})} \right\rangle$$

$$P_{\mathrm{corrected}}(k) = P_{\mathrm{cleaned}}(k)\,/\,\mathcal{T}(k)$$

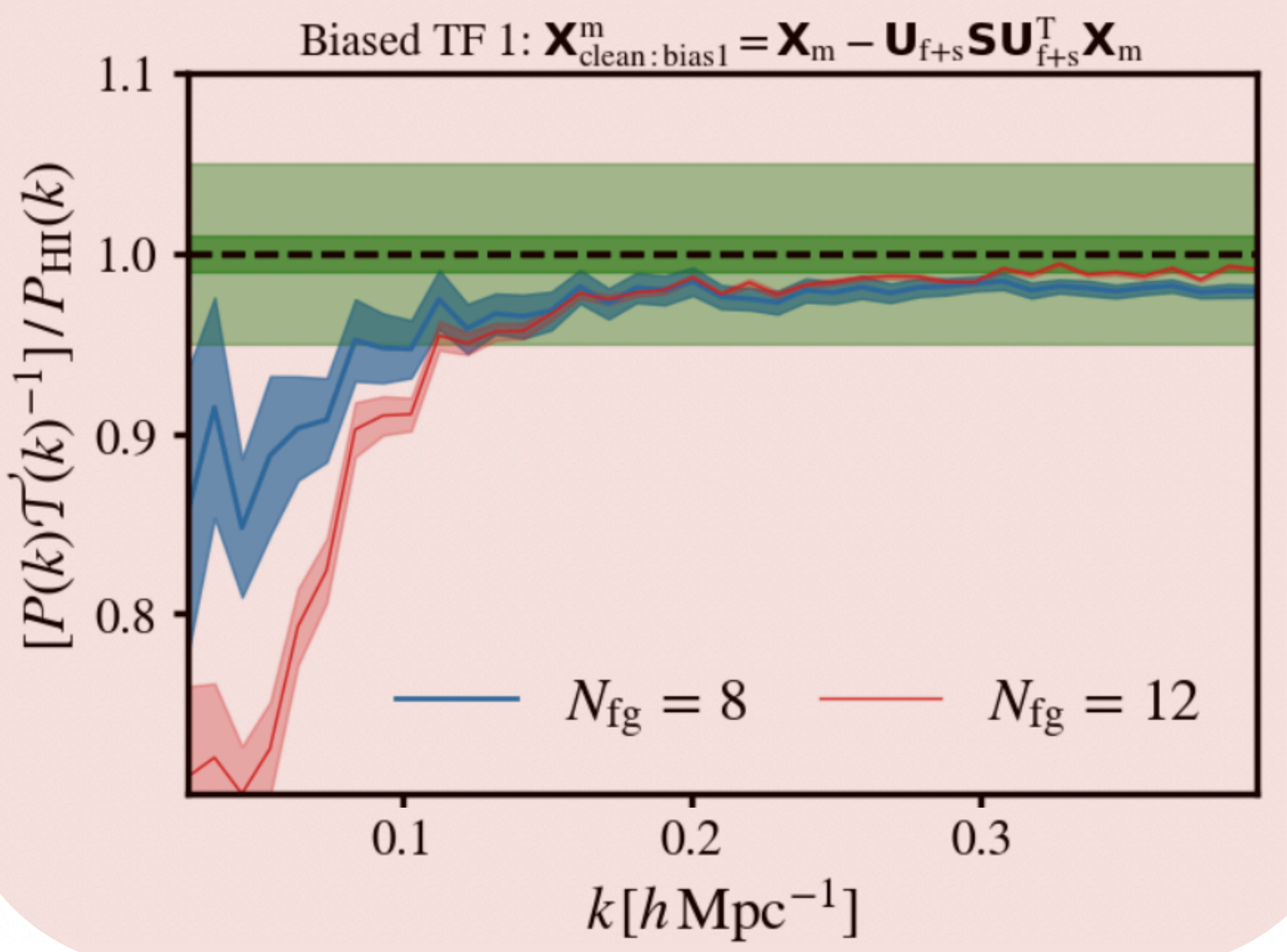


Biased transfer functions:
What to avoid

Unbiased approach

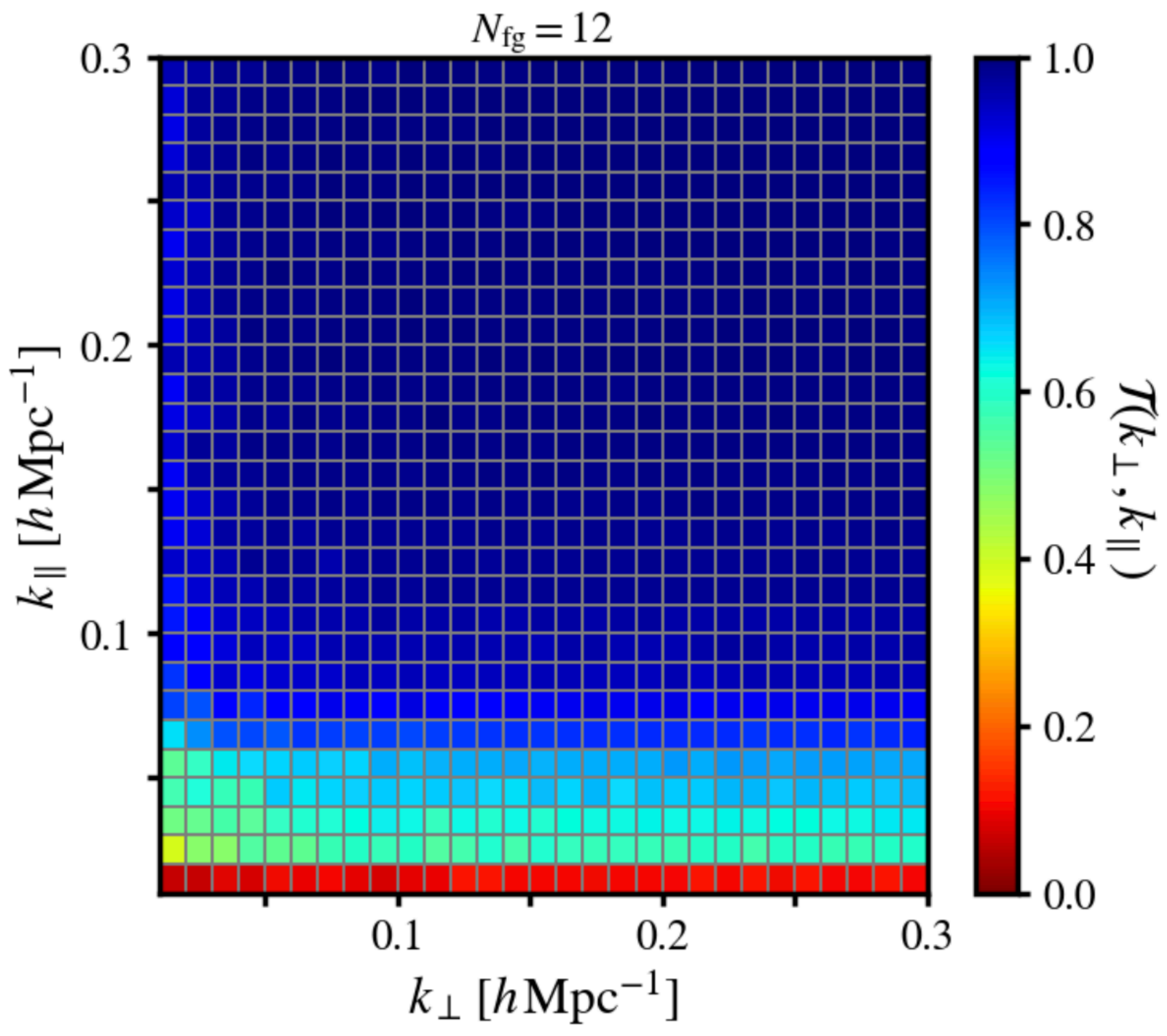
$$\mathbf{X}^{\mathrm{m}}_{\mathrm{clean}} = \mathbf{X}_{\mathrm{f+s+m}} - \mathbf{U}_{\mathrm{f+s+m}}\mathbf{S}\mathbf{U}^{\mathrm{T}}_{\mathrm{f+s+m}}\mathbf{X}_{\mathrm{f+s+m}}$$

$$\mathcal{T}(k) = \left\langle \frac{\mathcal{P}(\mathbf{X}^{\mathrm{m}}_{\mathrm{clean}}\,,\,\mathbf{X}_{\mathrm{m}})}{\mathcal{P}(\mathbf{X}_{\mathrm{m}}\,,\,\mathbf{X}_{\mathrm{m}})} \right\rangle_{N_{\mathrm{mock}}}$$



Steve Cunnington [steven.cunnington@manchester.ac.uk]

☑ Can we know how much (HI) signal is lost in foreground cleaning?

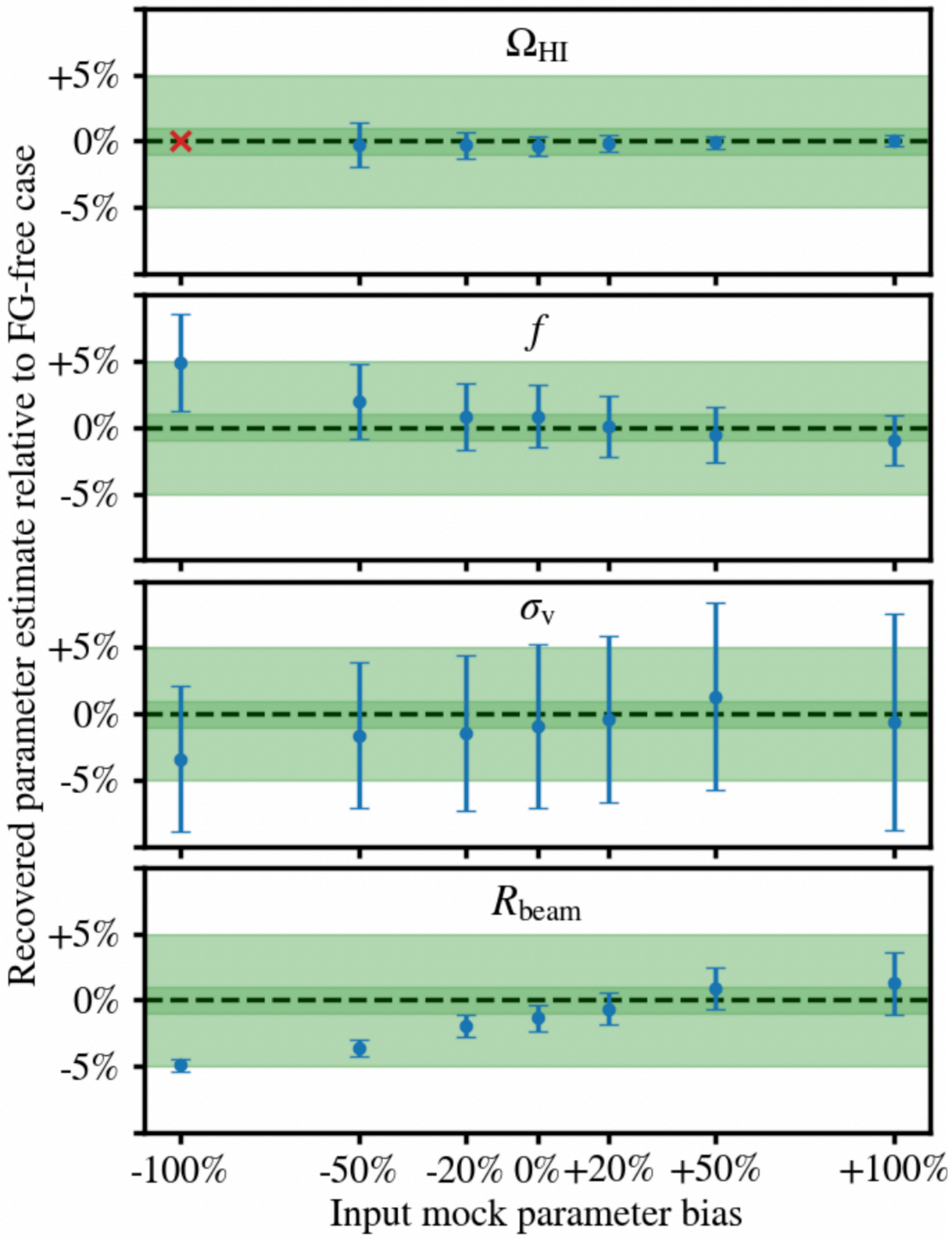


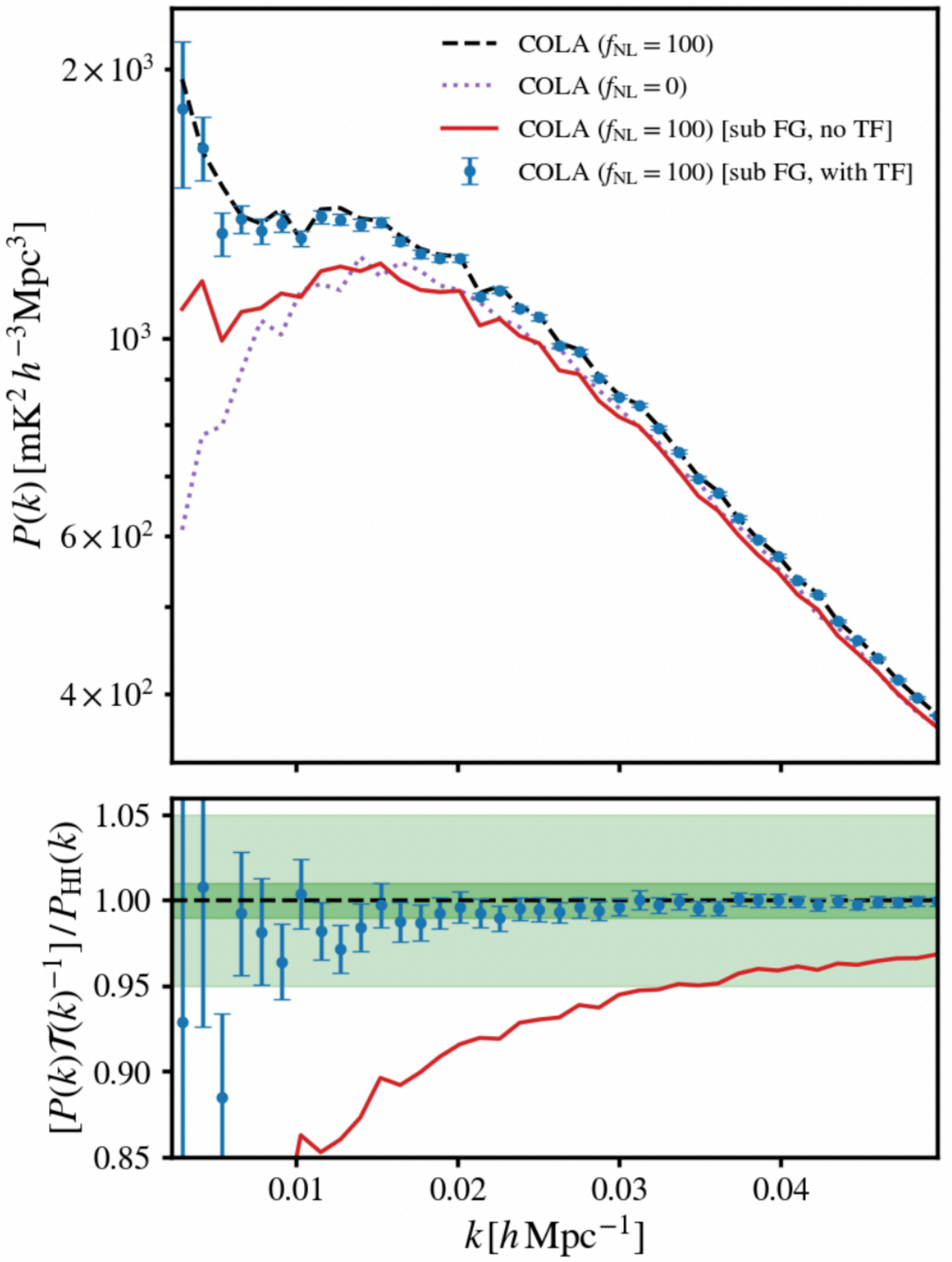
☐ Can we correct for this to avoid biased results?

- To what extent can a transfer function be used for precision cosmology?

Steve Cunnington [steven.cunnington@manchester.ac.uk]

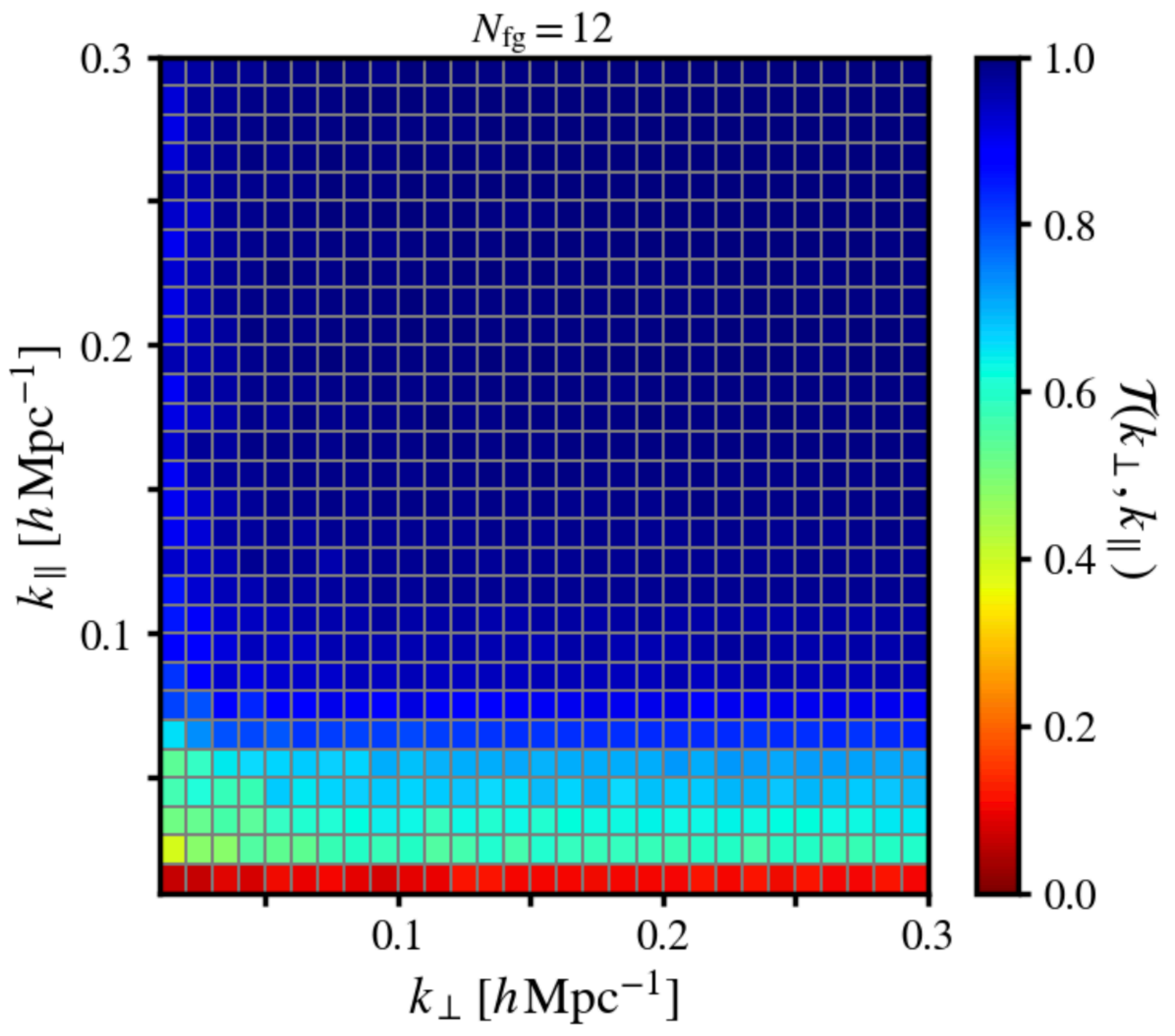
Precision cosmology applications

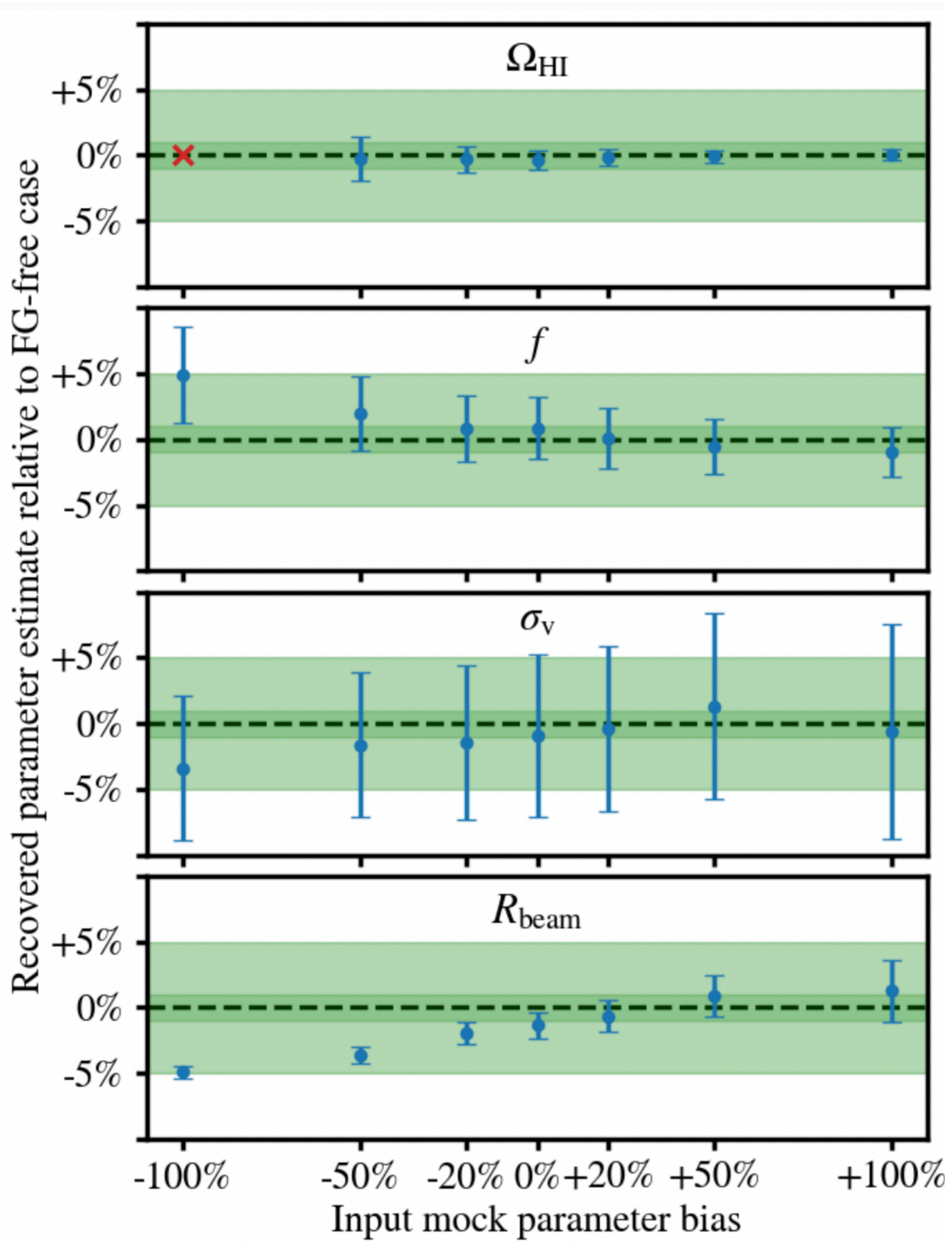




Steve Cunnington [steven.cunnington@manchester.ac.uk]

☑ Can we know how much (HI) signal is lost in foreground cleaning?



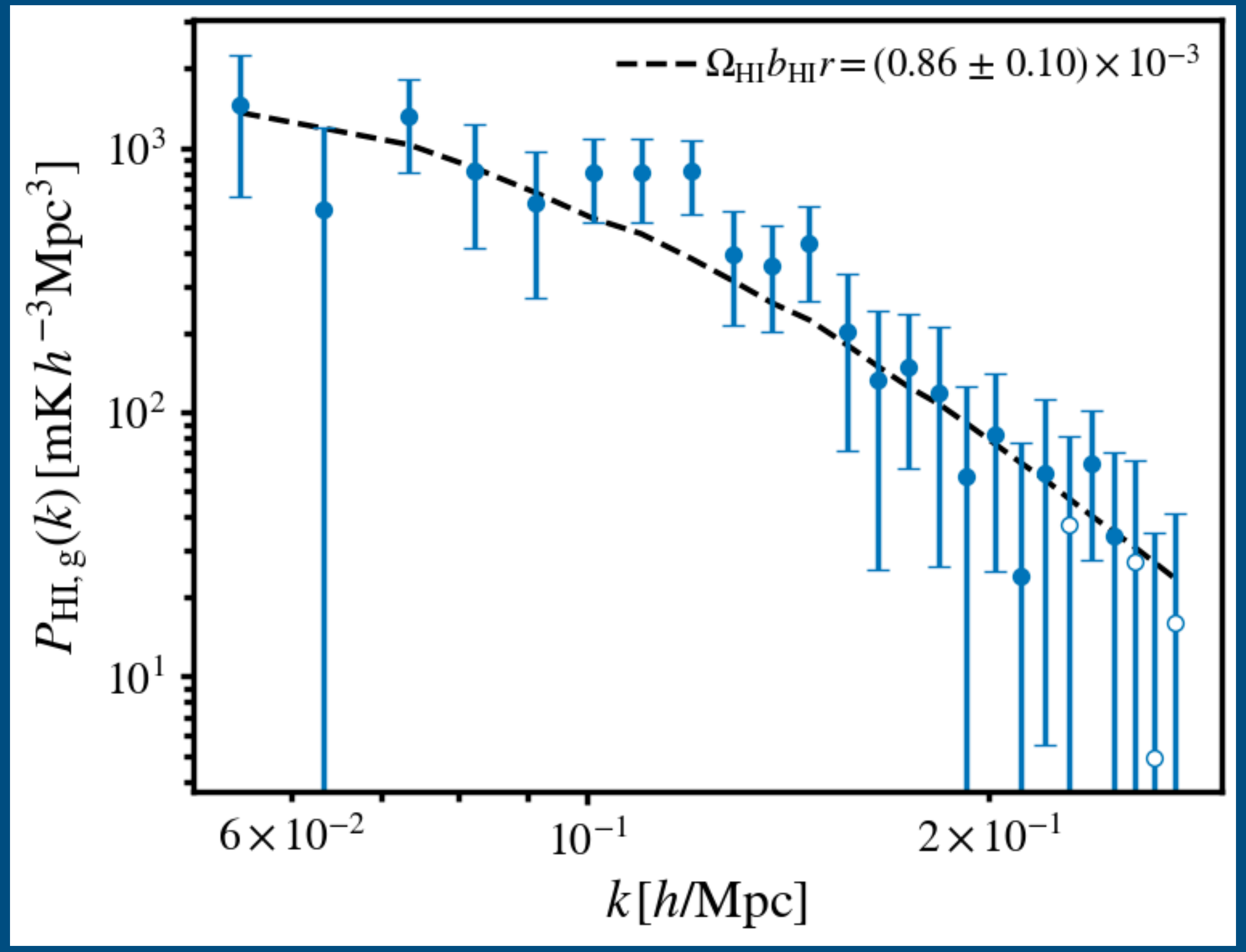


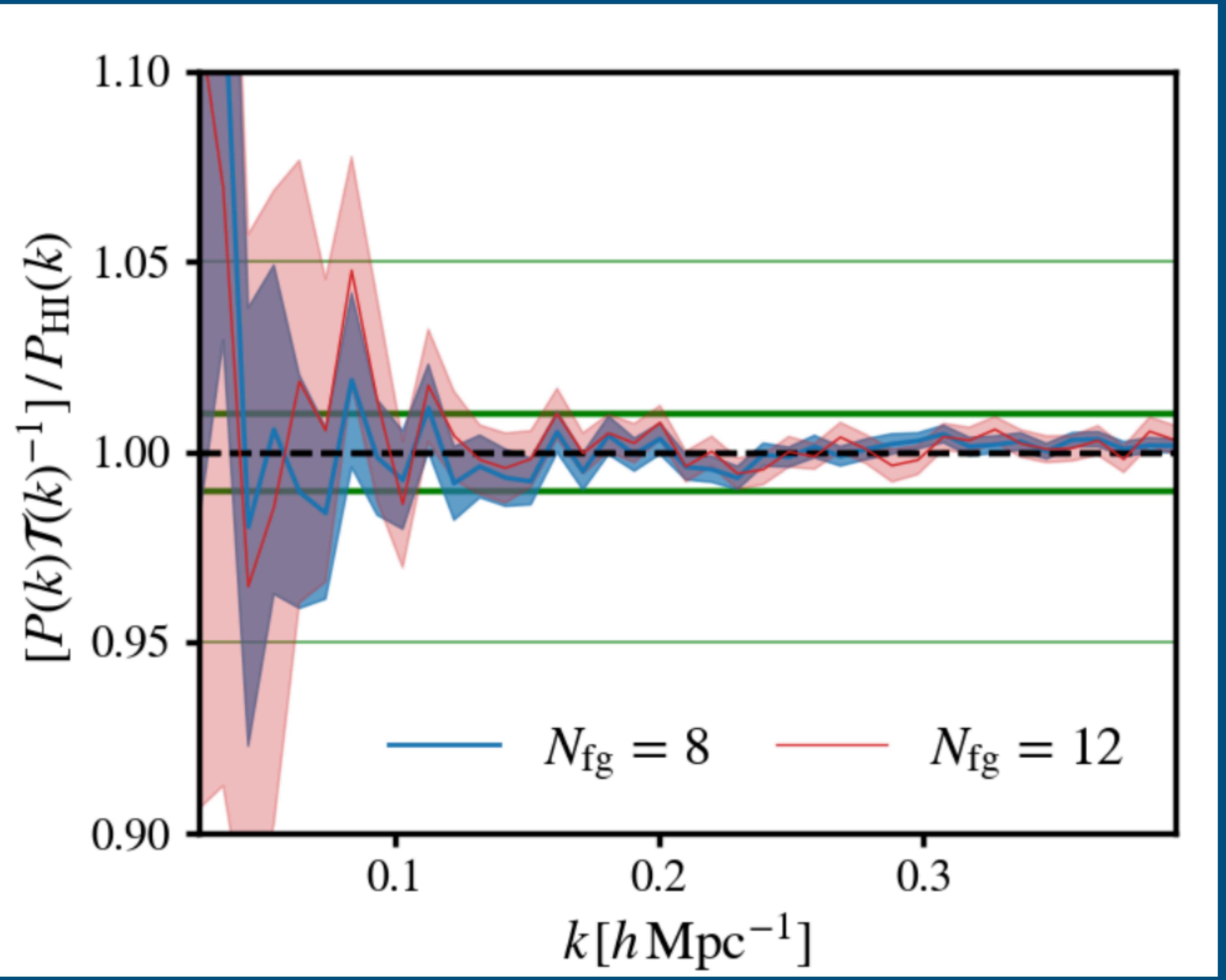
☑ Can we correct for this to avoid biased results?

- To what extent can a transfer function be used for precision cosmology?

In Summary…

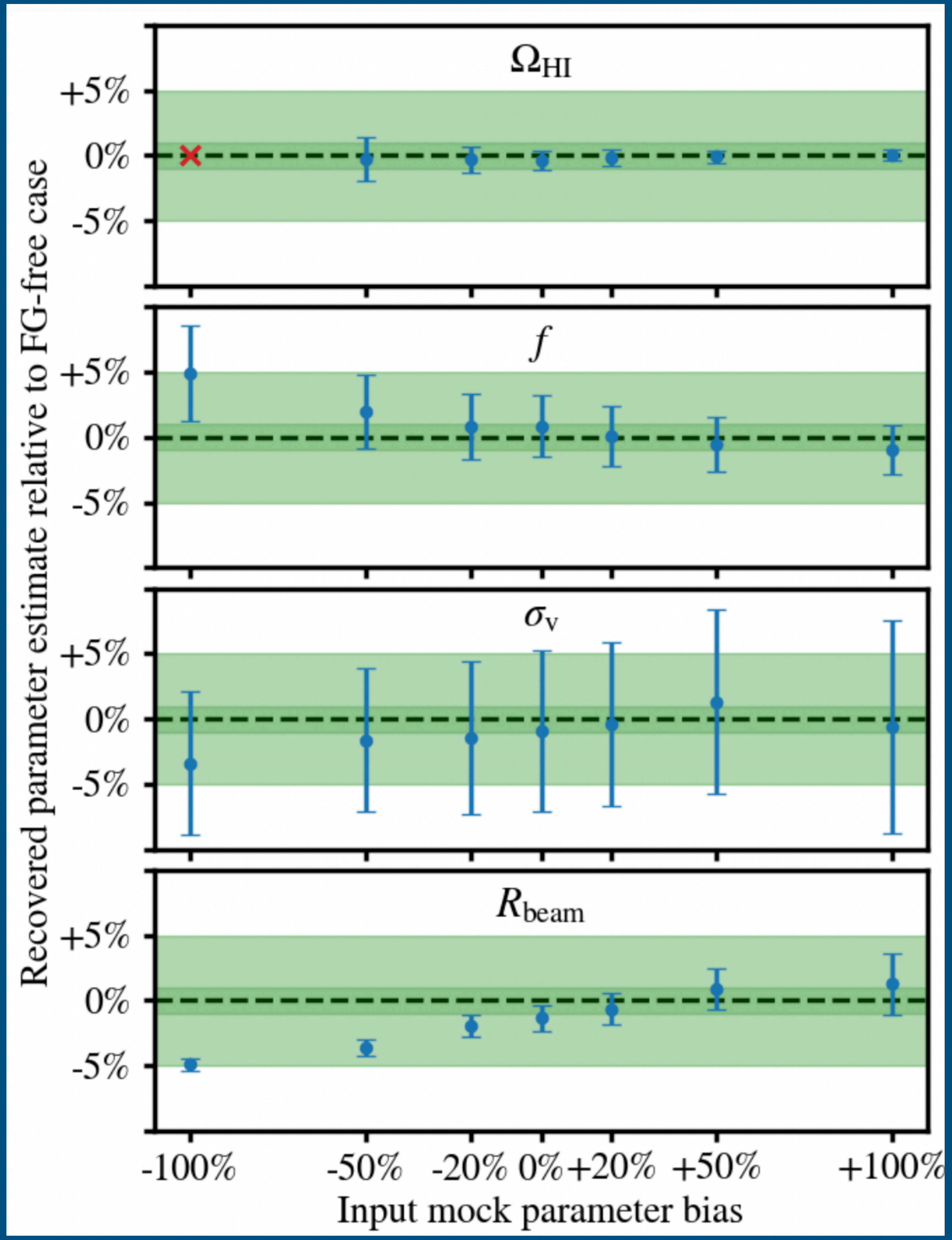
Telescopes like **MeerKAT** will continue to improve 21cm intensity mapping applications





Signal loss from foreground cleaning will be one of the most crucial things to control in these experiments

Constructing **transfer functions** with mock signal injection is now a **validated** method



This process is **robust to incorrect fiducial cosmology** assumptions meaning biased parameter inference is low risk

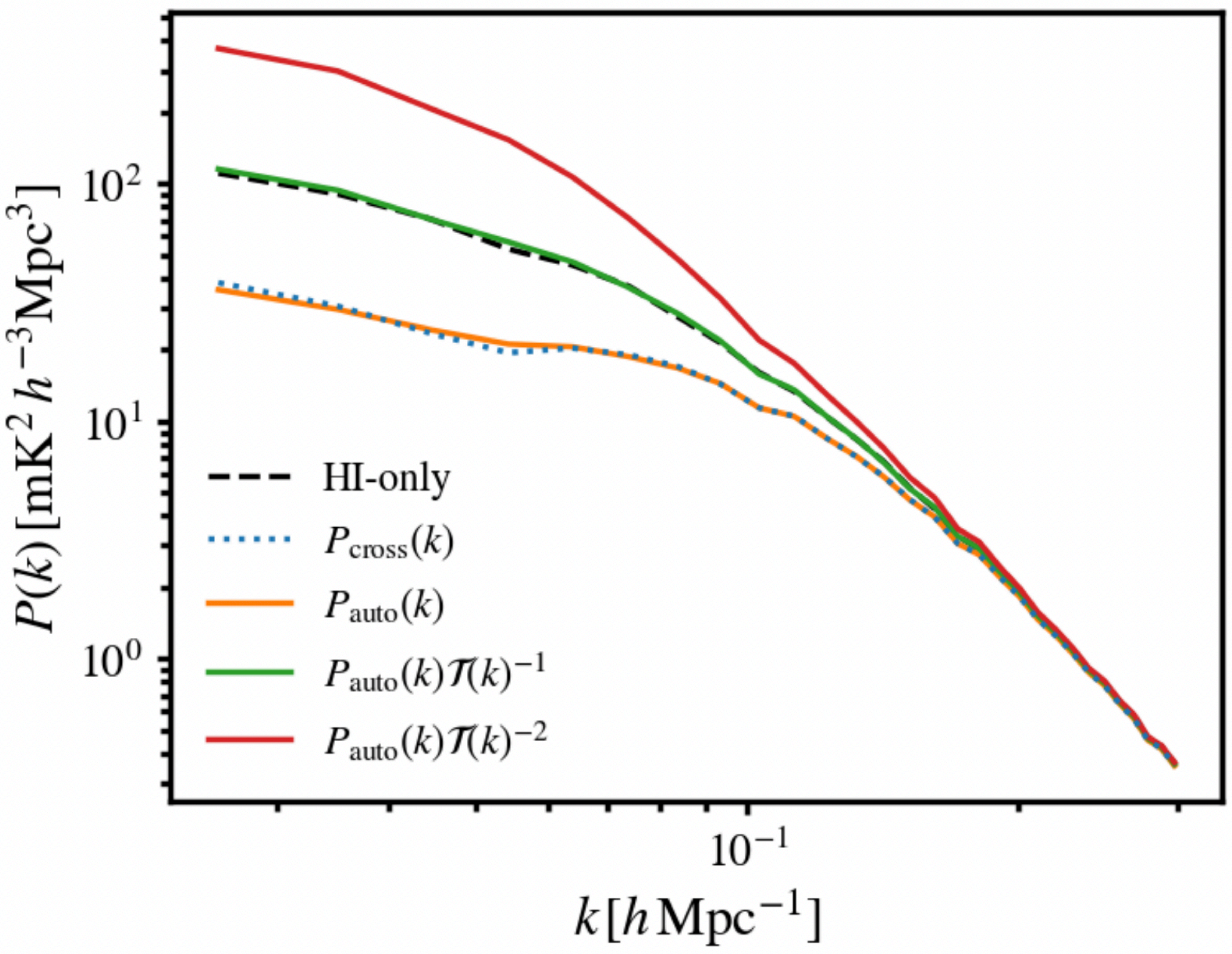
Thank you

SC+2023 [arXiv:2302.07034]

Steve Cunnington [steven.cunnington@manchester.ac.uk]

Backup Slides

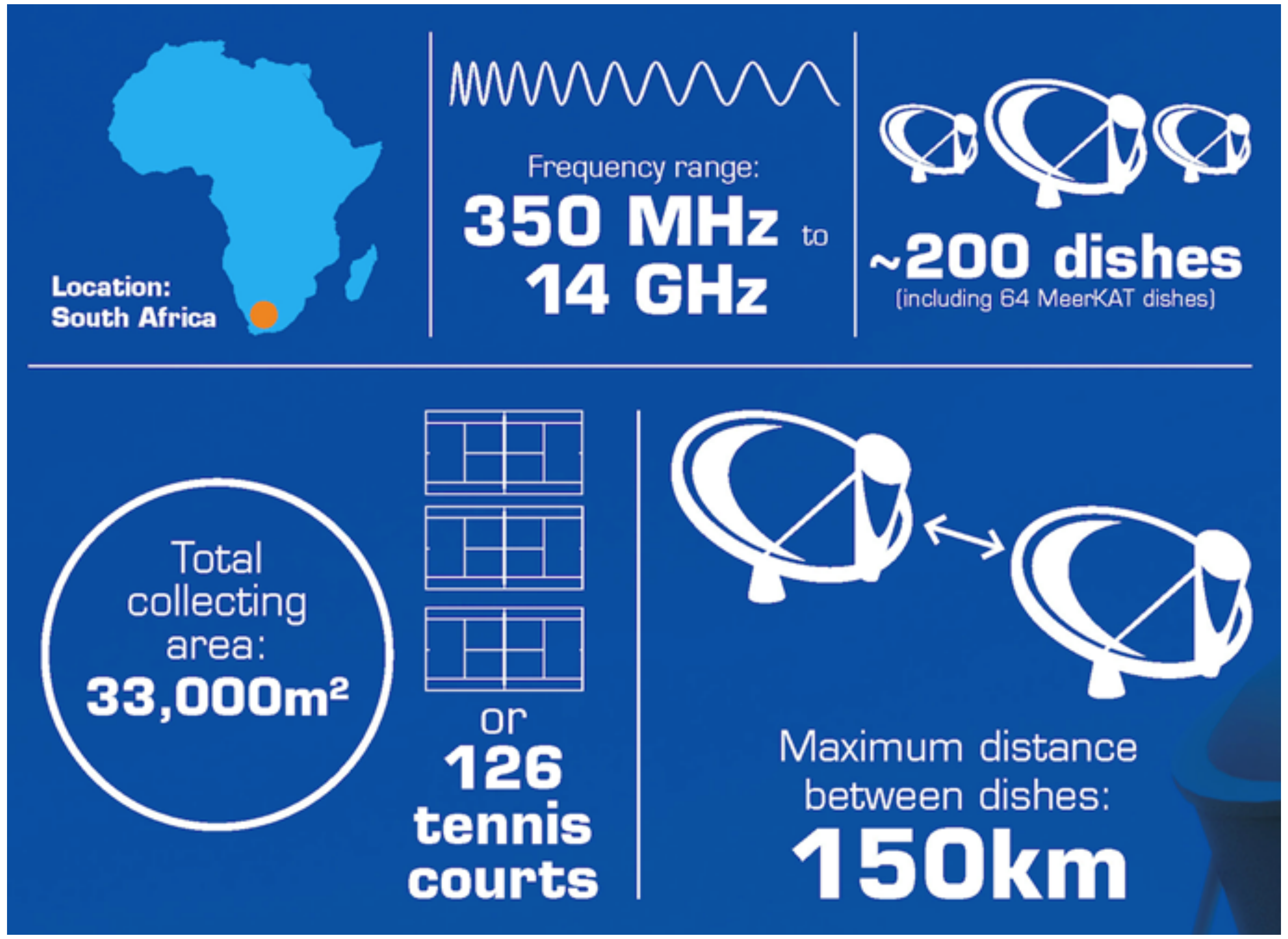
Auto v Cross Signal Loss



 Steve Cunnington [steven.cunnington@manchester.ac.uk]

"SKA Observatory"

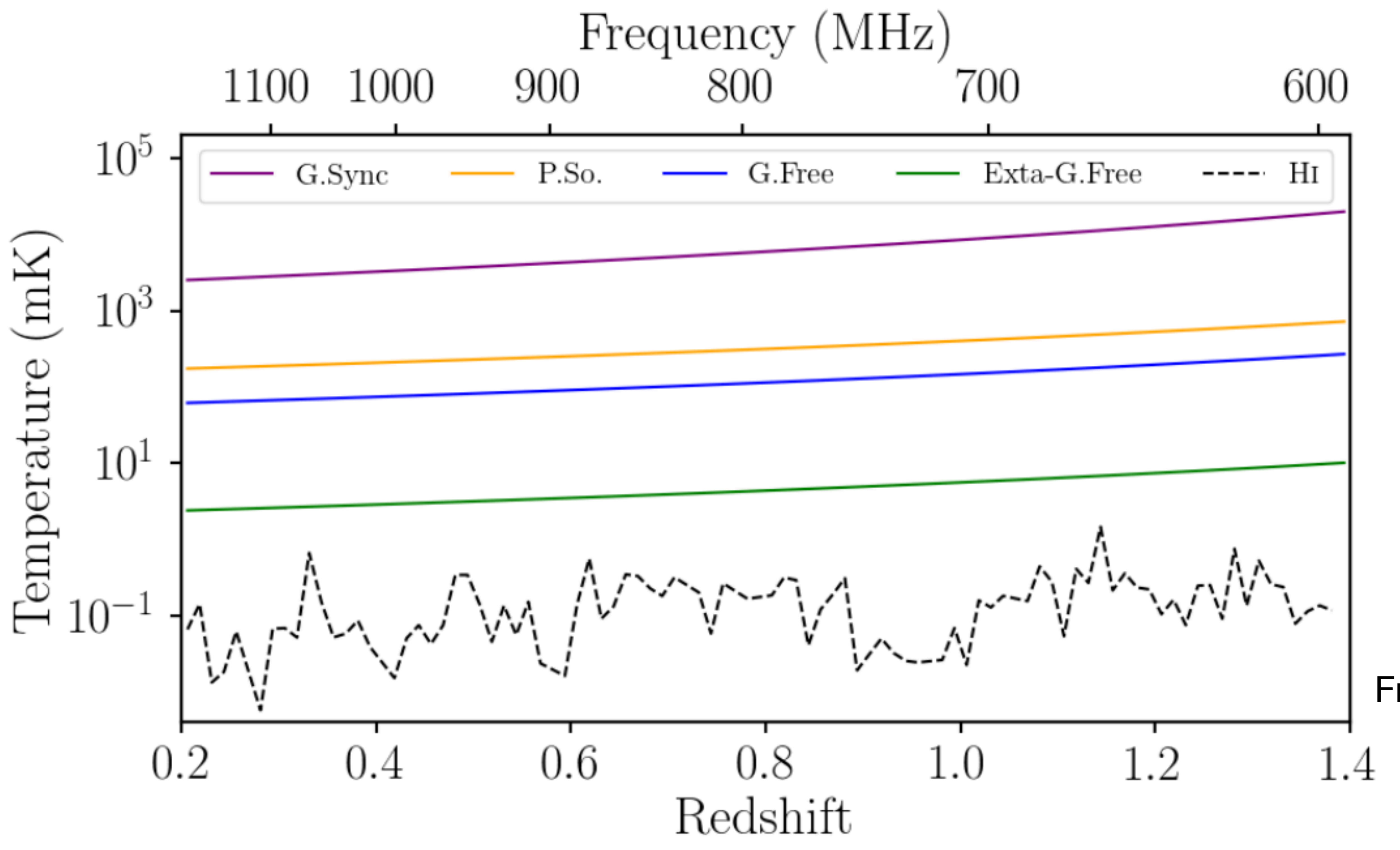
SKA1 - MID (South Africa)

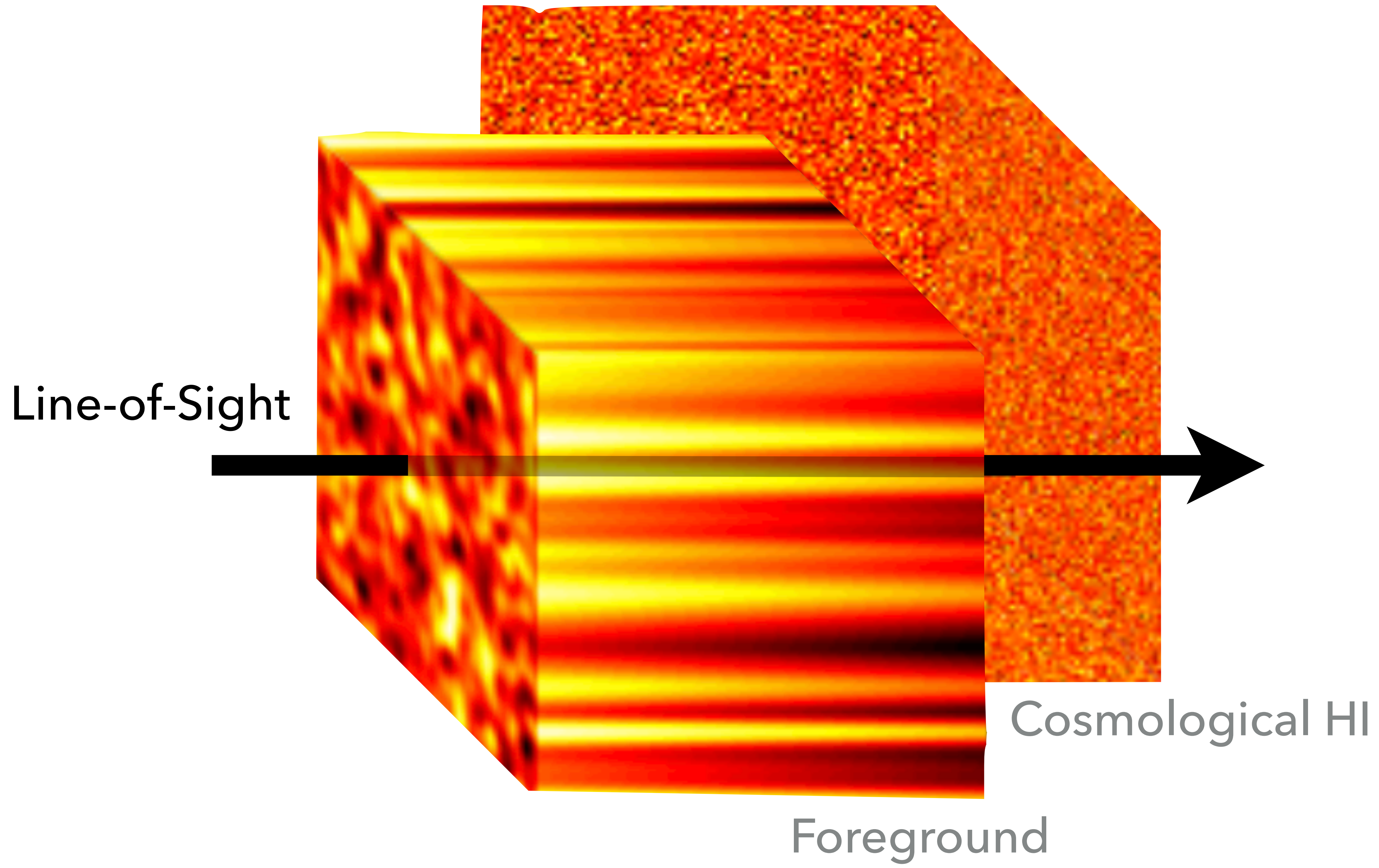


Redshift range: $0 < z < 3$

Foreground cleaning MeerKAT HI intensity maps

Idealised simulation demo:

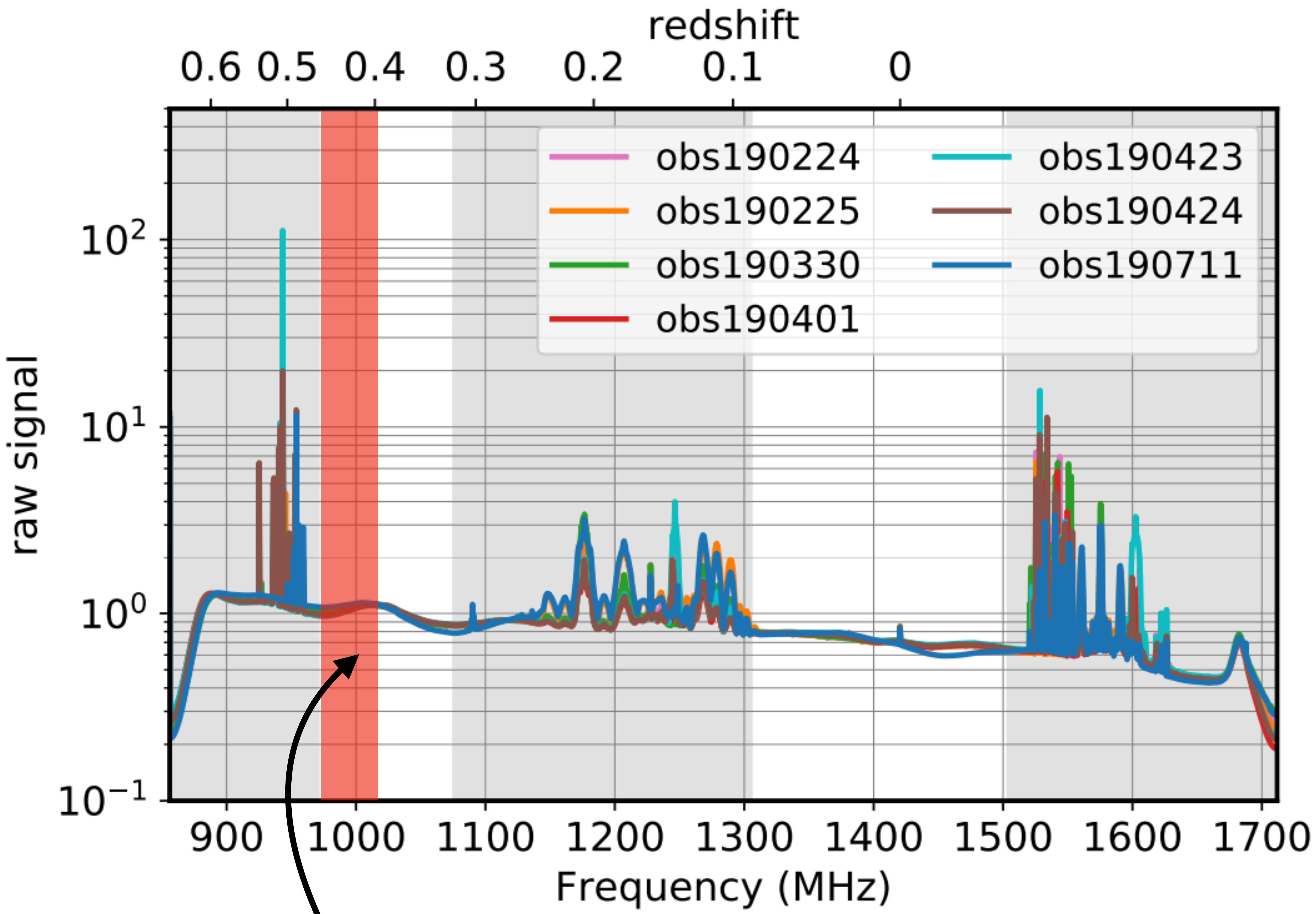




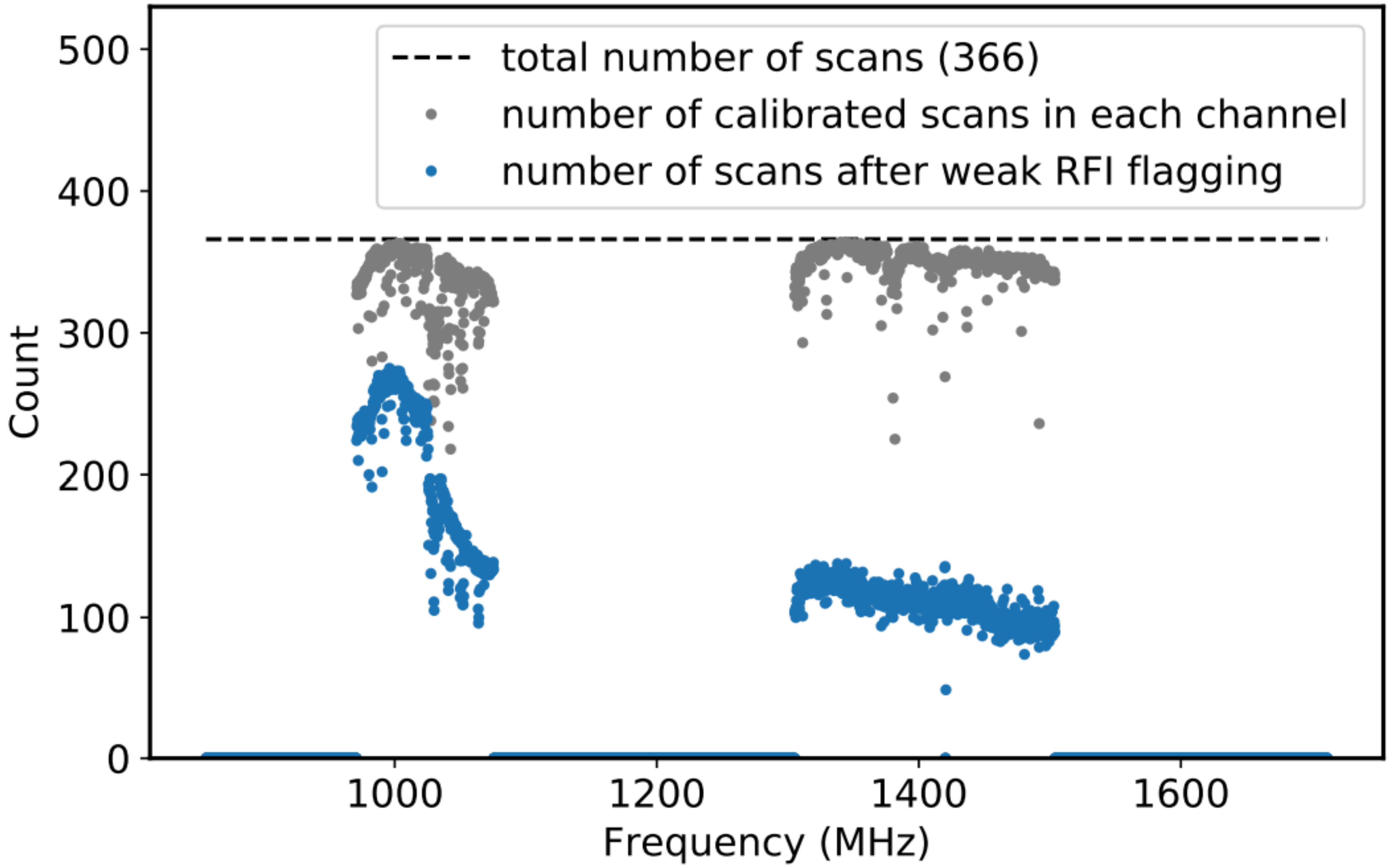
From S.Cunnington+19 [arXiv:1904.01479]

- We utilise smooth foreground spectra to distinguish them from cosmological signal

Radio Frequency Interference (RFI) flagging



J.Wang, …, SC+21 [arXiv:2011.13789]



Channels used for analysis

199 frequency channels at 973.2 – 1014.6 MHz.

- A further 32 within this range are also removed due to their dominant contributions

Steve Cunnington [steven.cunnington@manchester.ac.uk]