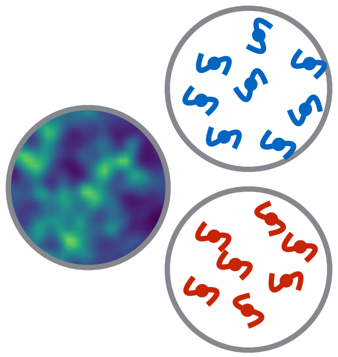


GBT - eBOSS cross-correlation

26.05.2022

Laura Wolz - University of Manchester

with **Alkistis Pourtsidou, Kiyo Masui, Tzu-Ching Chang,** Julian Bautista, Eva-Maria Mueller, Will Percival, Santiago Avila, David Bacon, Steve Cunnington and others

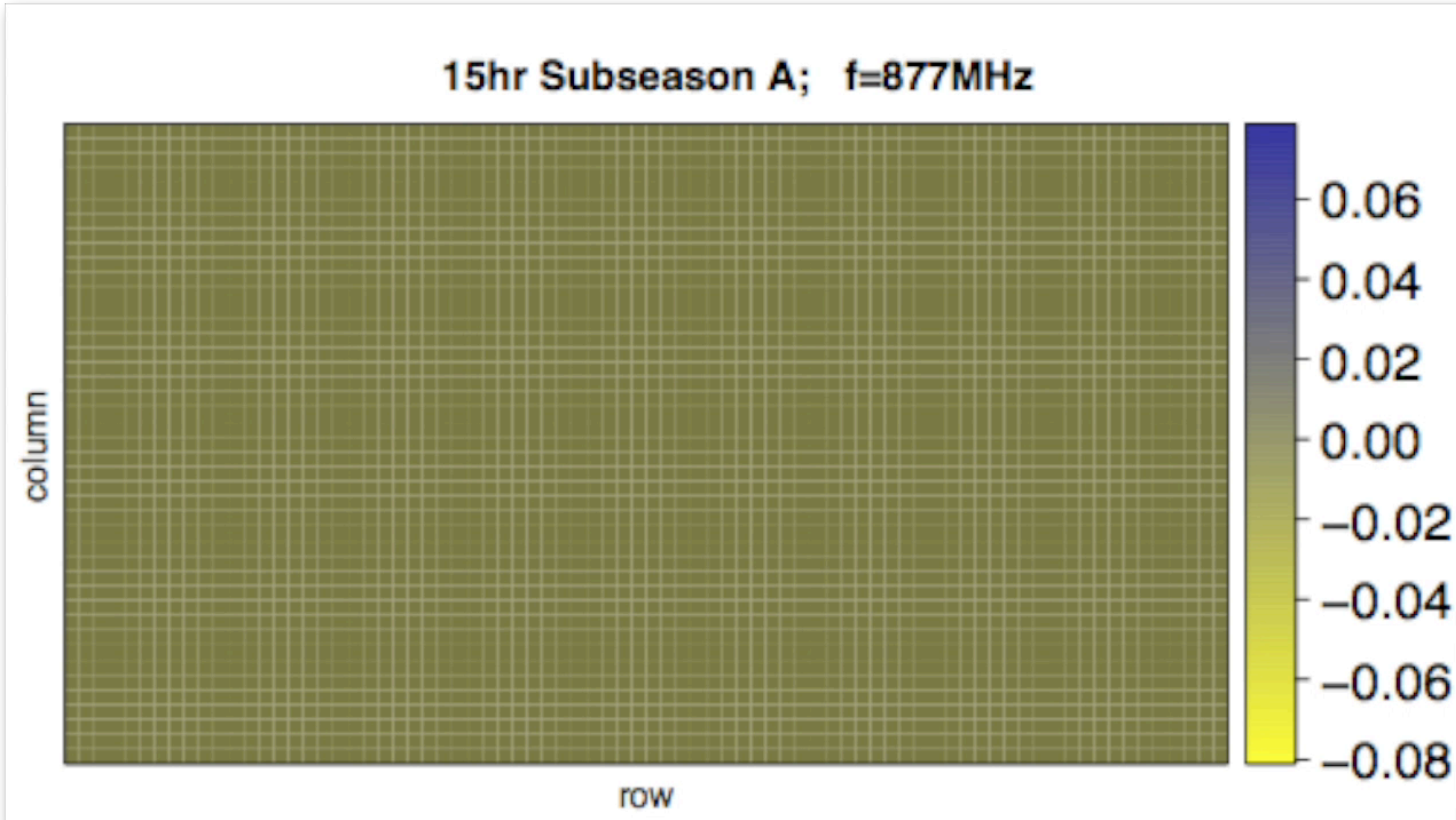
GBT data

Data by GBT IM team; Wolz et al 2017 1510.05453

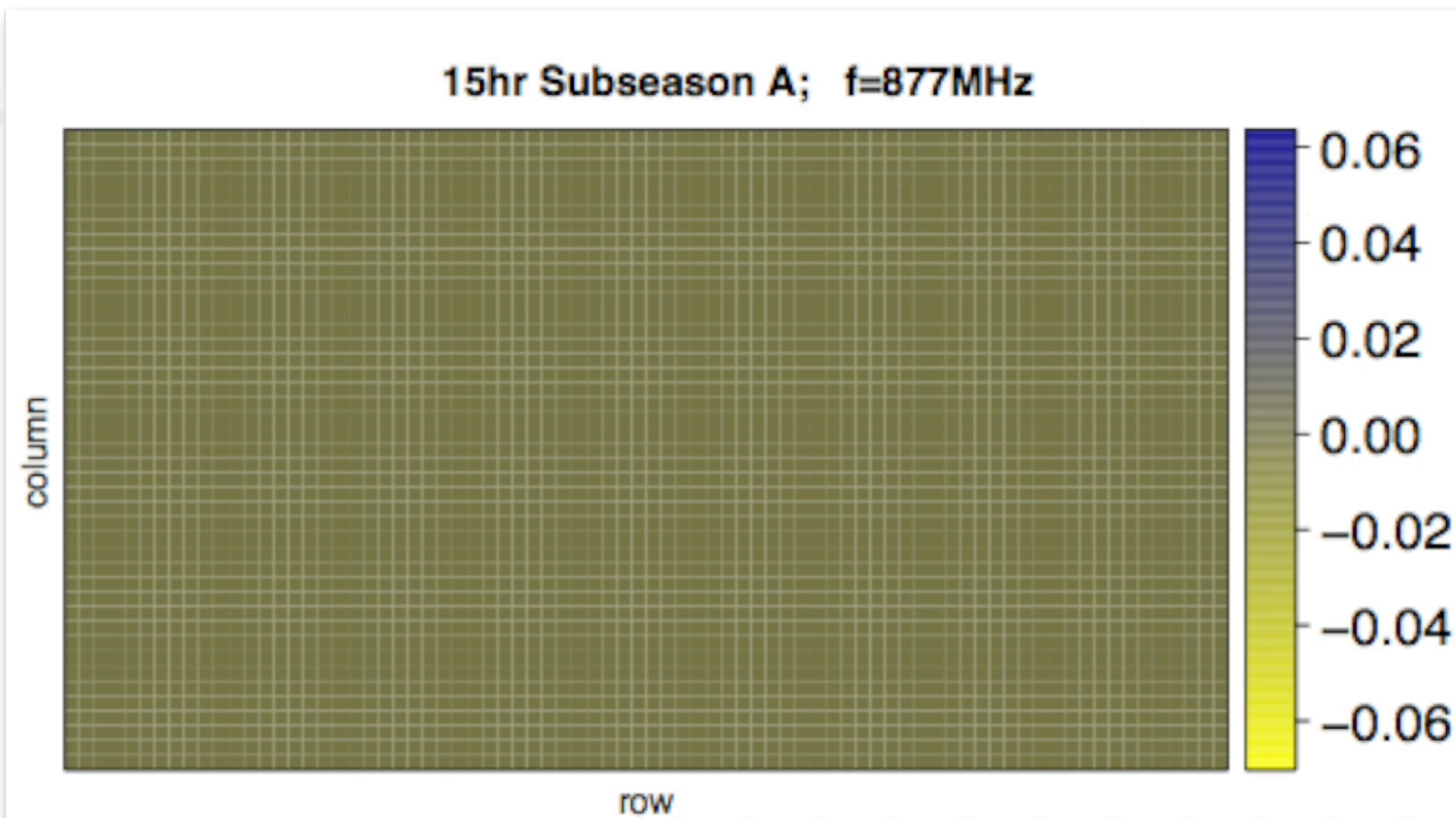
- Intensity Maps in two fields 1hr (85hrs) and 15hr (105hrs) overlapping with WiggleZ fields totalling 40 sq deg
- Frequency channels from 700-900MHz
- Observed in 4 sub-seasons such that each season has independent noise characteristics
- Incoherent scanning strategy results in noise patterns
- Effective beam of 0.44 deg

Masui et al. (2013), Switzer et al. (2013)

2ICs

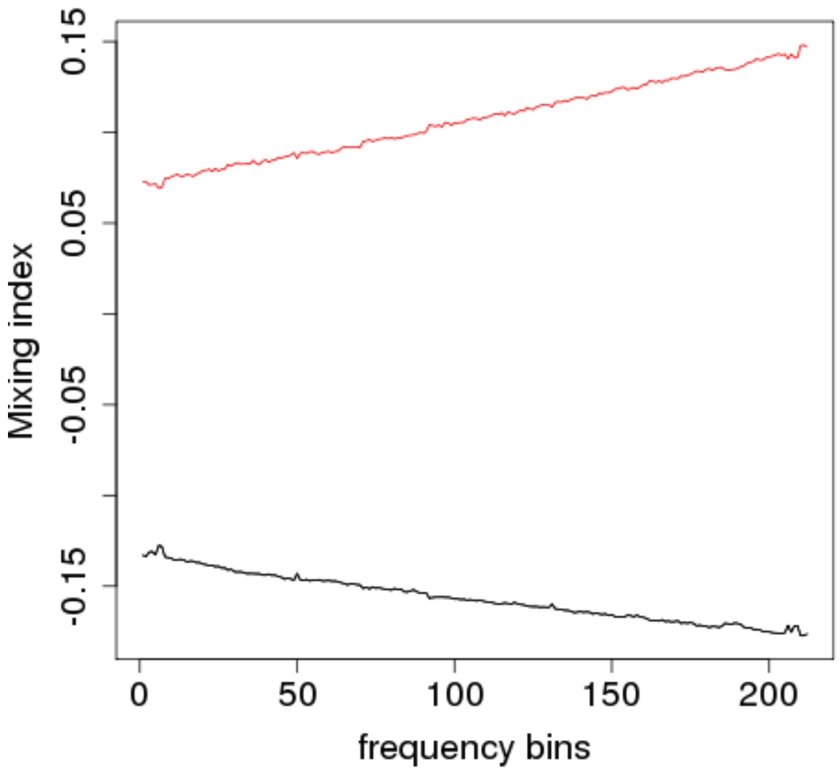


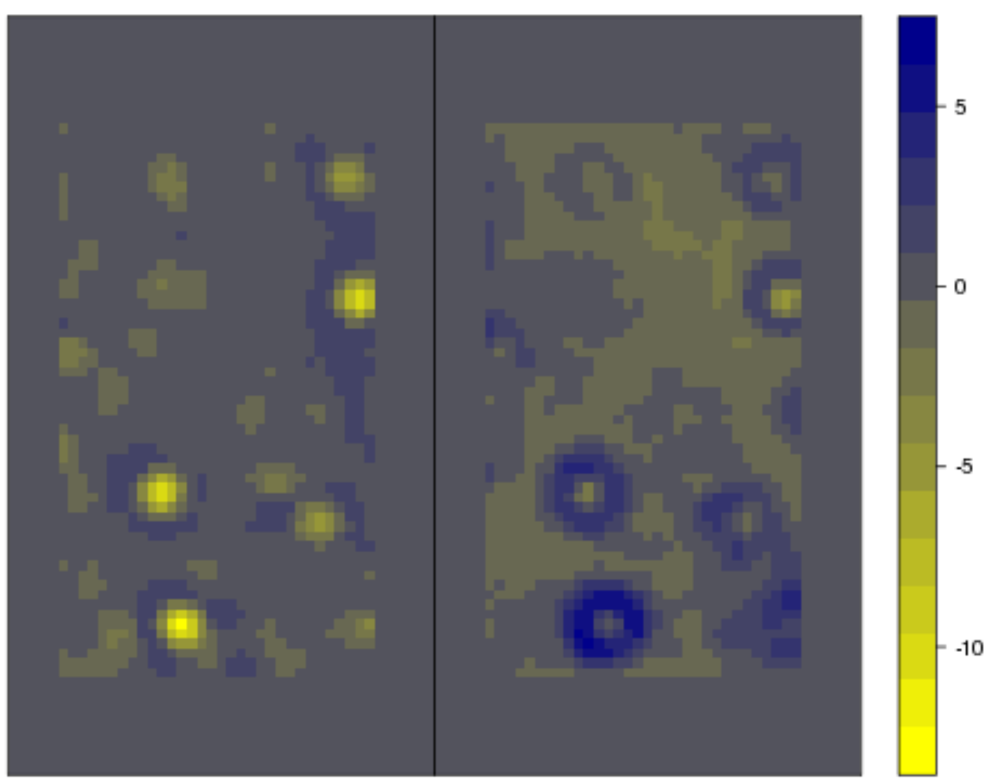
10ICs



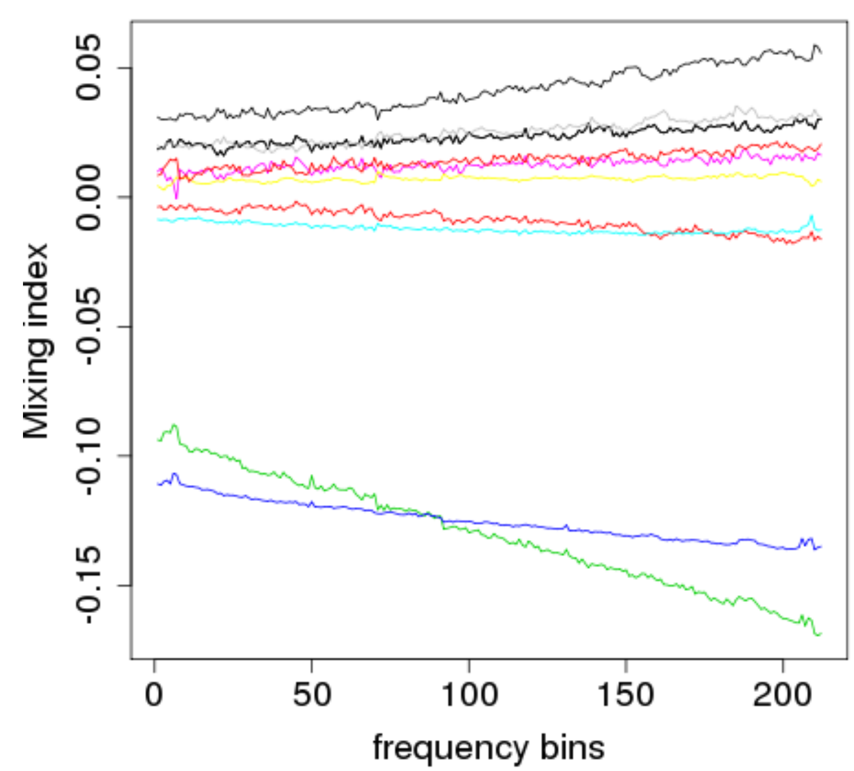
14h31m28.5s RA and 2 deg 0' DEC

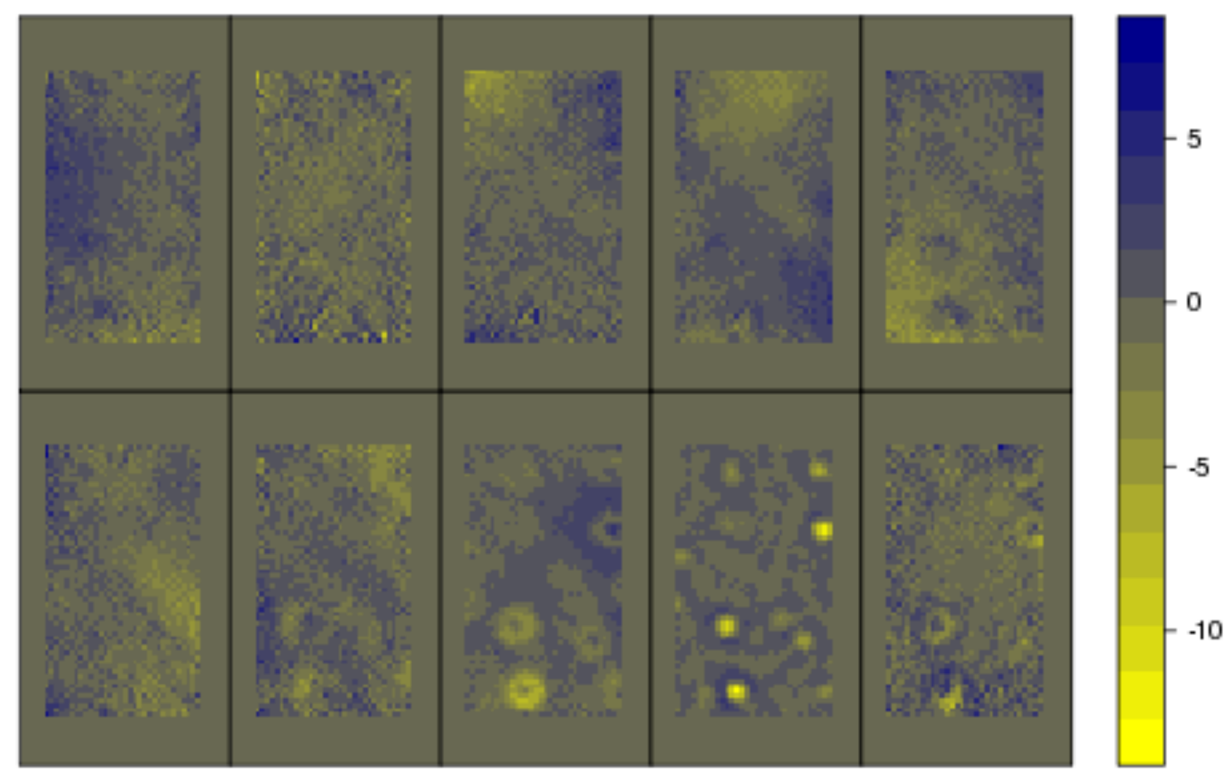
2ICs





10ICs



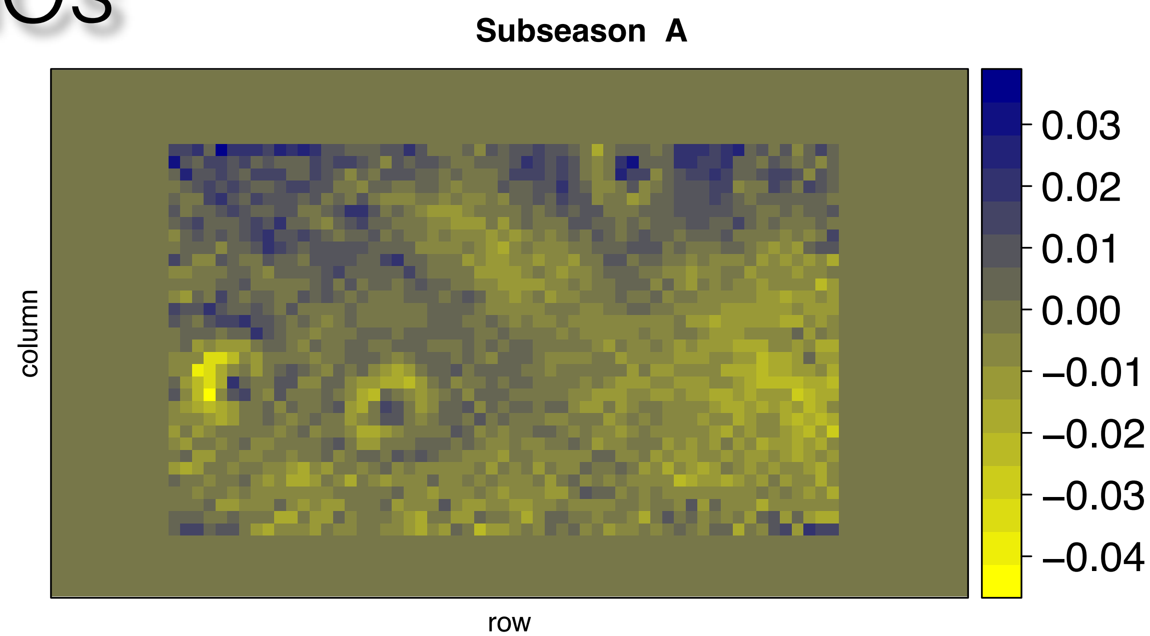


Sub-season A15hr-field 14h31m28.5s RA and 2 deg 0′ DEC

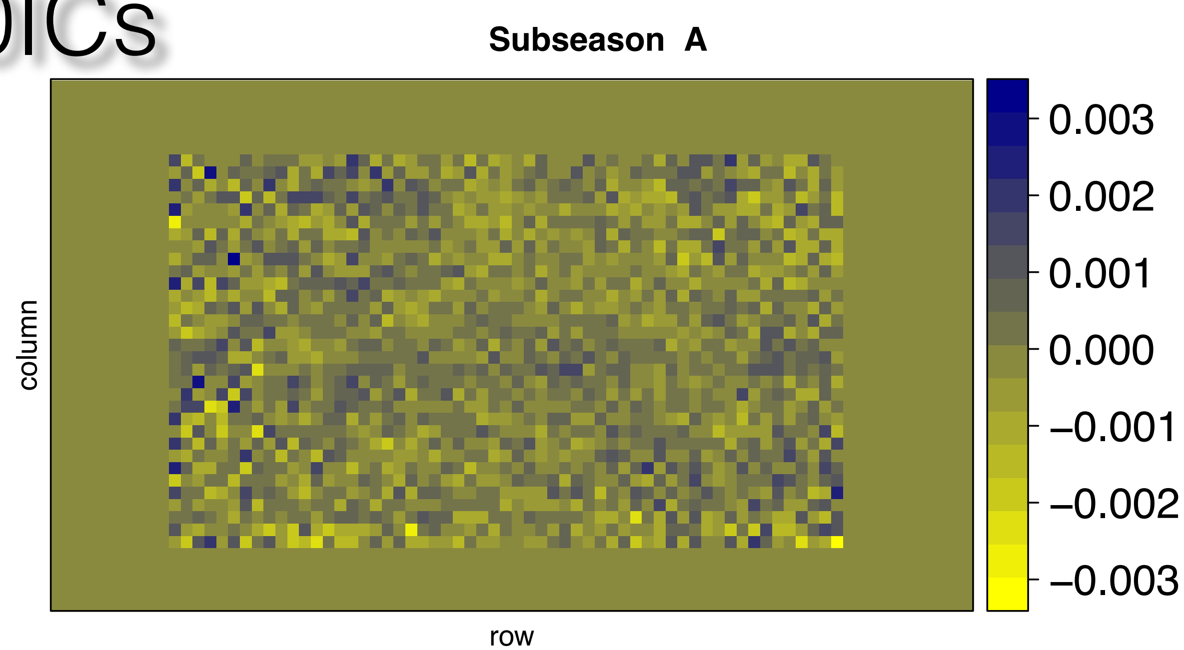
Residual analysis

Total sum

2ICs

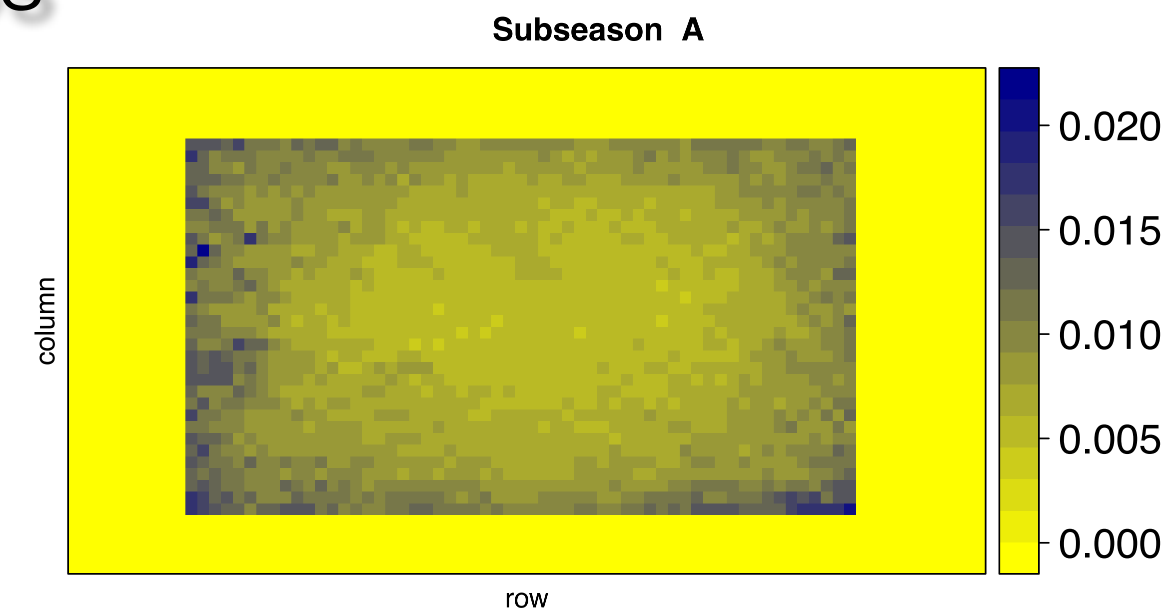


10ICs

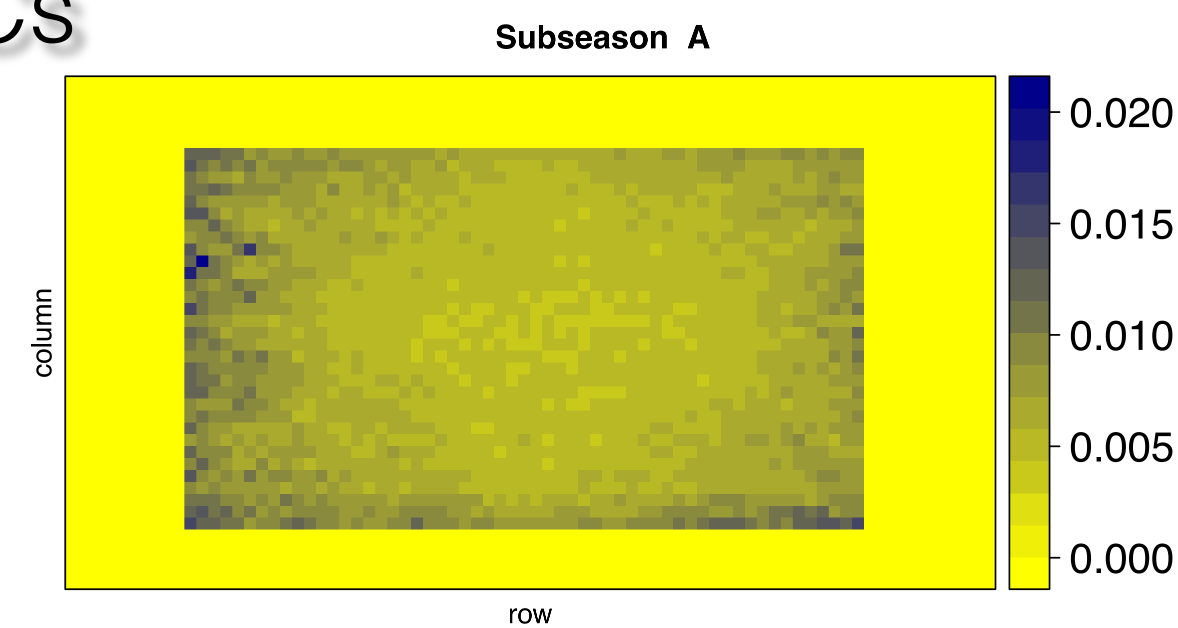


Standard deviation

2ICs



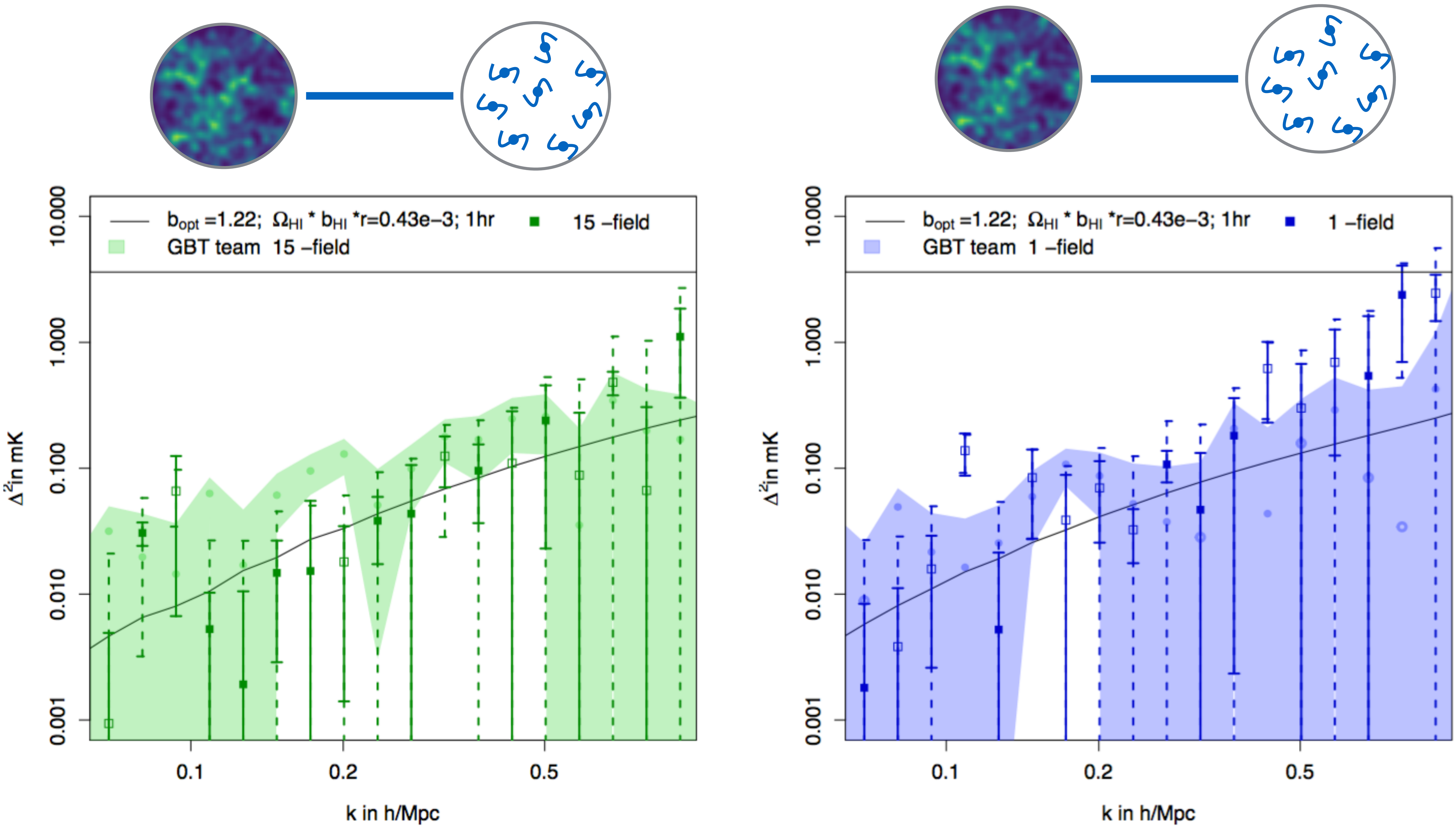
10ICs



Sub-season A15hr-field 14h31m28.5s RA and 2 deg 0′ DEC

Masui et al, 2013, Switzer et al 2013, Wolz et al 2017

$\Omega_{HI} b_{HI} = [0.62^{+0.23}] \times 10^{-3}$



GBT x WiggleZ - 40sqdeg - z~0.8

THE UNIVERSITY OF MELBOURNE

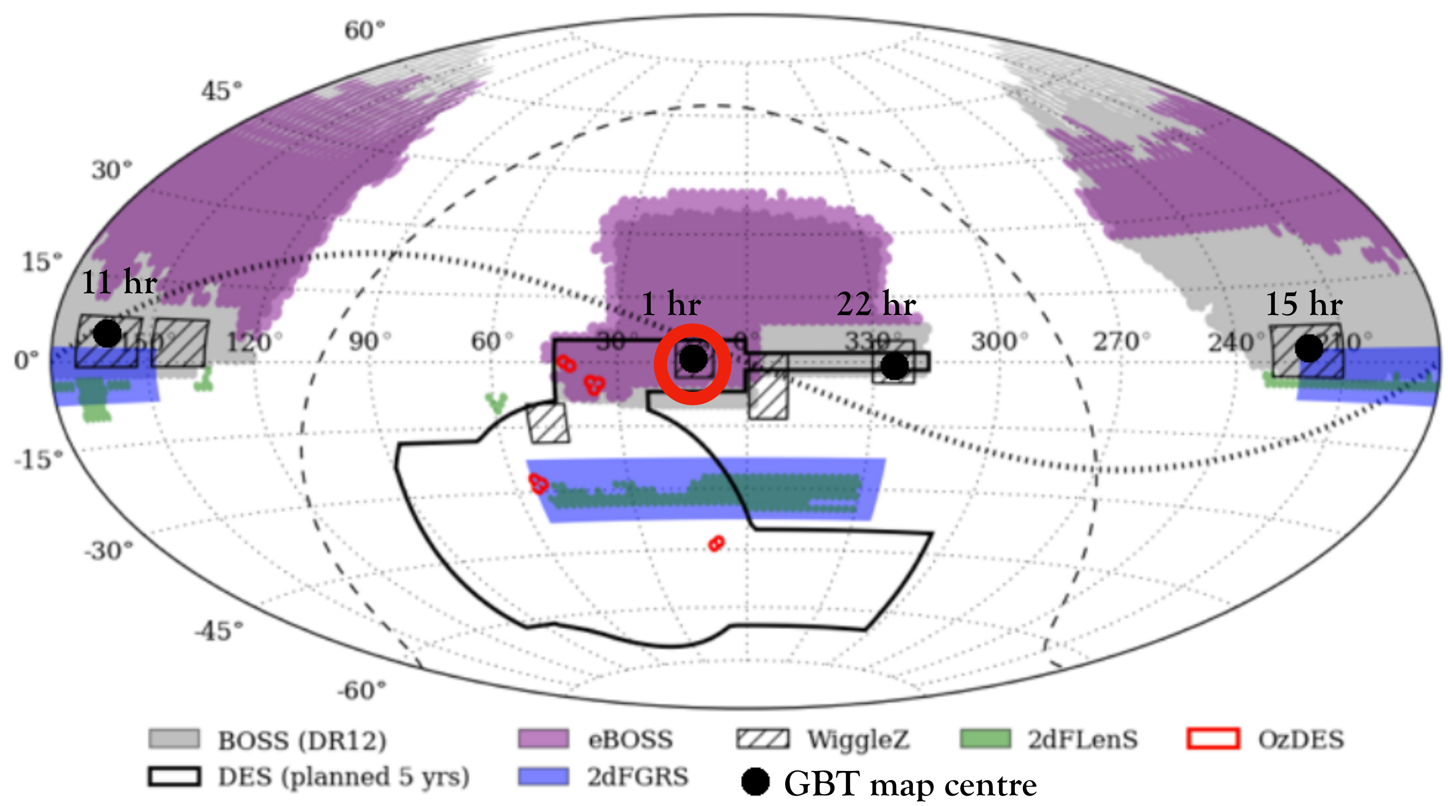
GBT updated HI intensity mapping data with **0.6<z<1**

Three galaxy samples for cross-correlation:

eBOSS ELGs: 0.7<z<1.1; LRGs: 0.6<z<0.9; WiggleZ: 0.6<z<1.0

Area overlap: **100 square degrees**

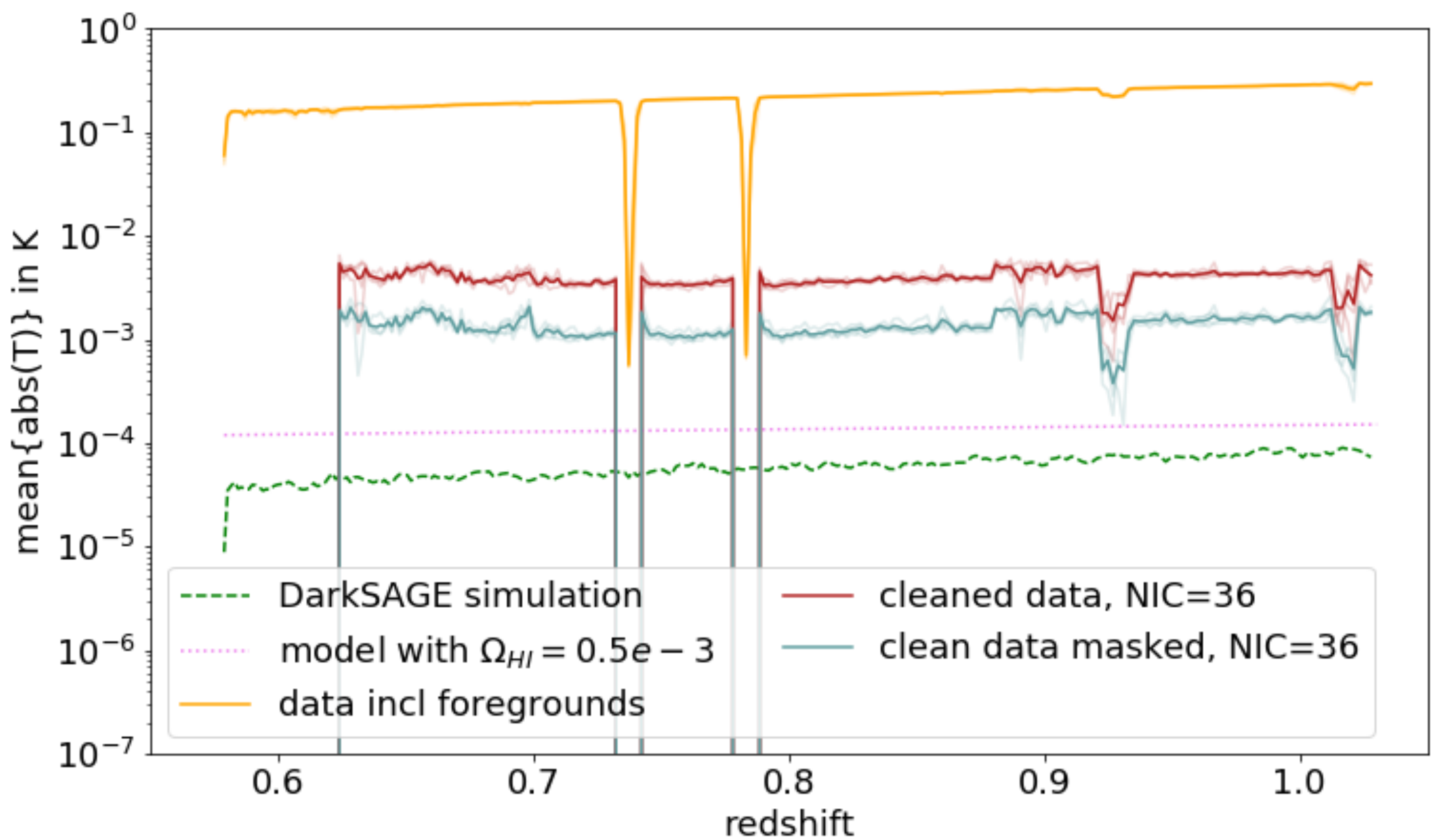
Figure adapted from Anderson et al 2015



See Switzer et al 2013, Masui et al 2013 for previous data and Wolz et al 2016 for analysis pipeline

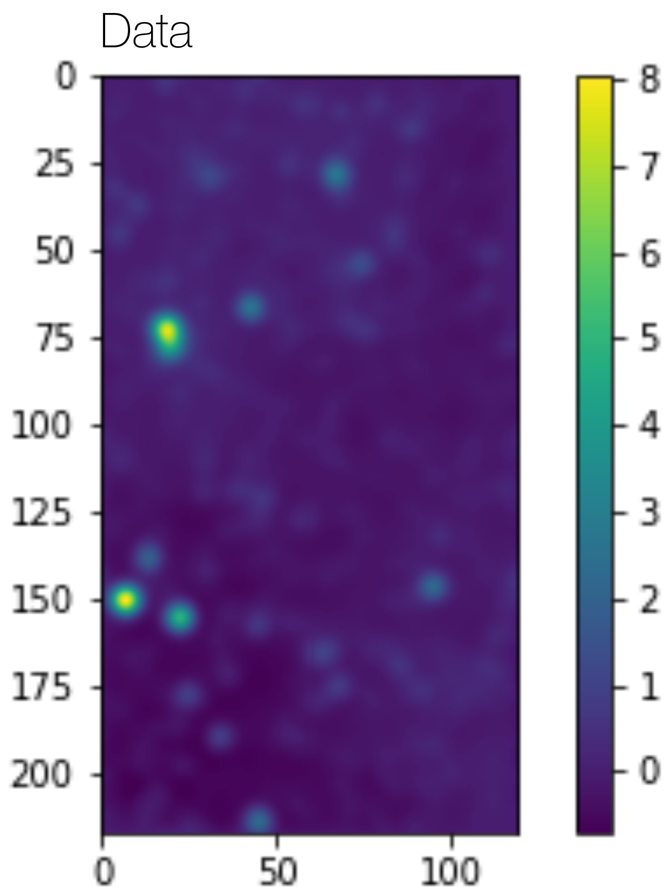
- GBT data is divided into 4 seasons {A, B, C, D} (independent noise realisations), results are averaged over all seasons
- Data is masked around spatial edges to reduce systematics
- All power spectra use data from 30<f<220 -> **0.62<z<0.95** (reduce RFI)

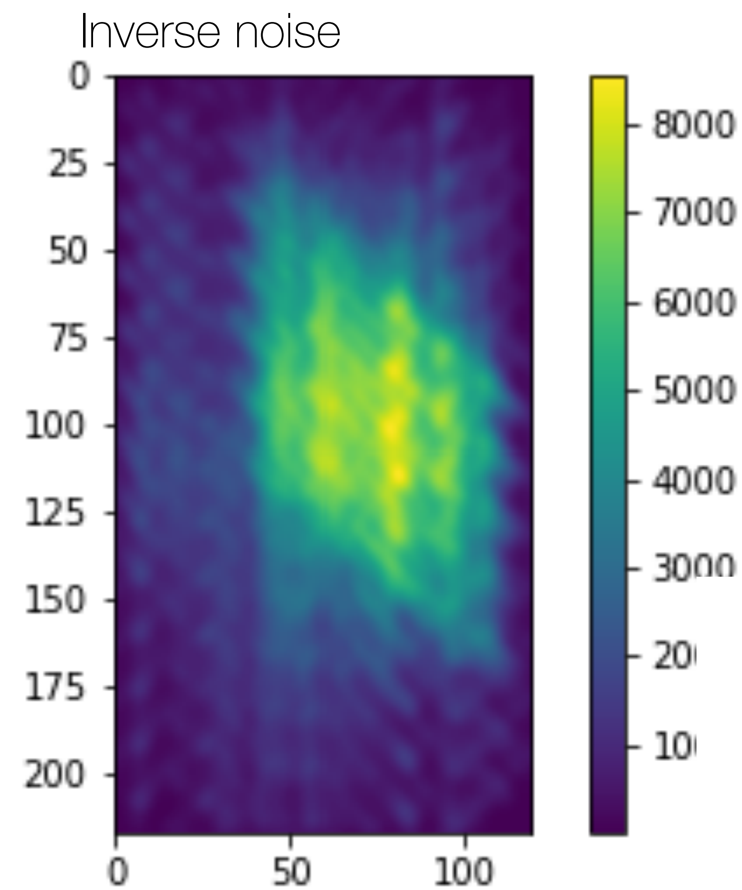
GBT maps mean temperature

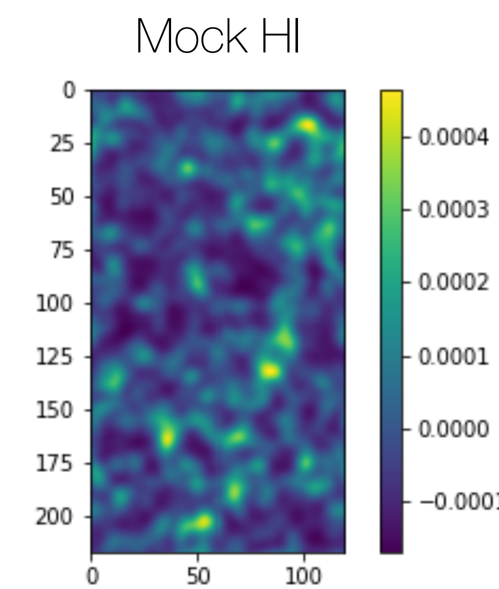


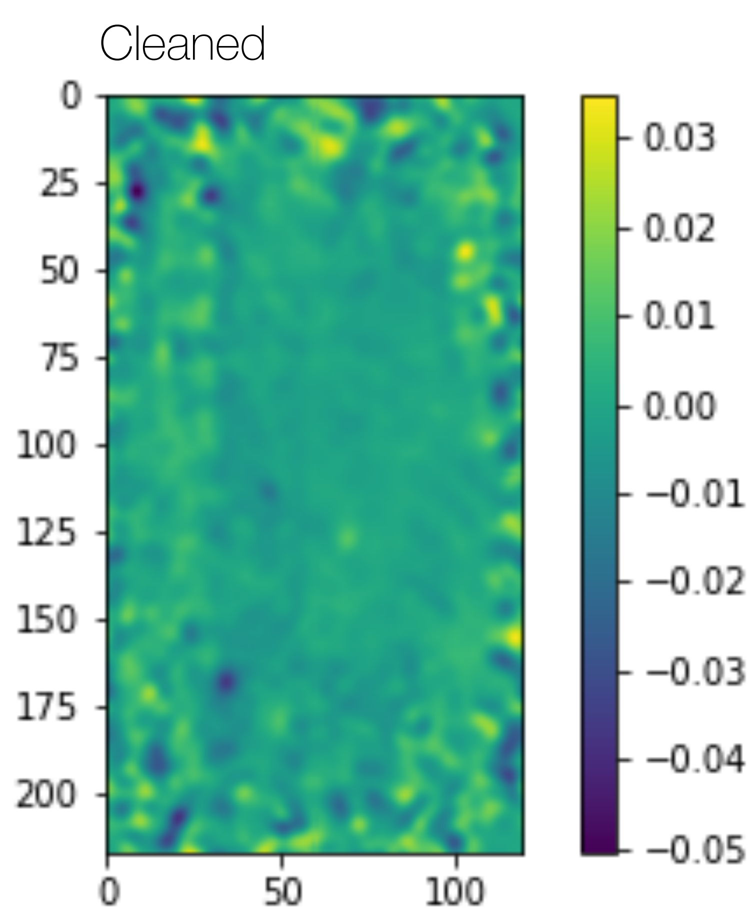
Analysis Pipeline

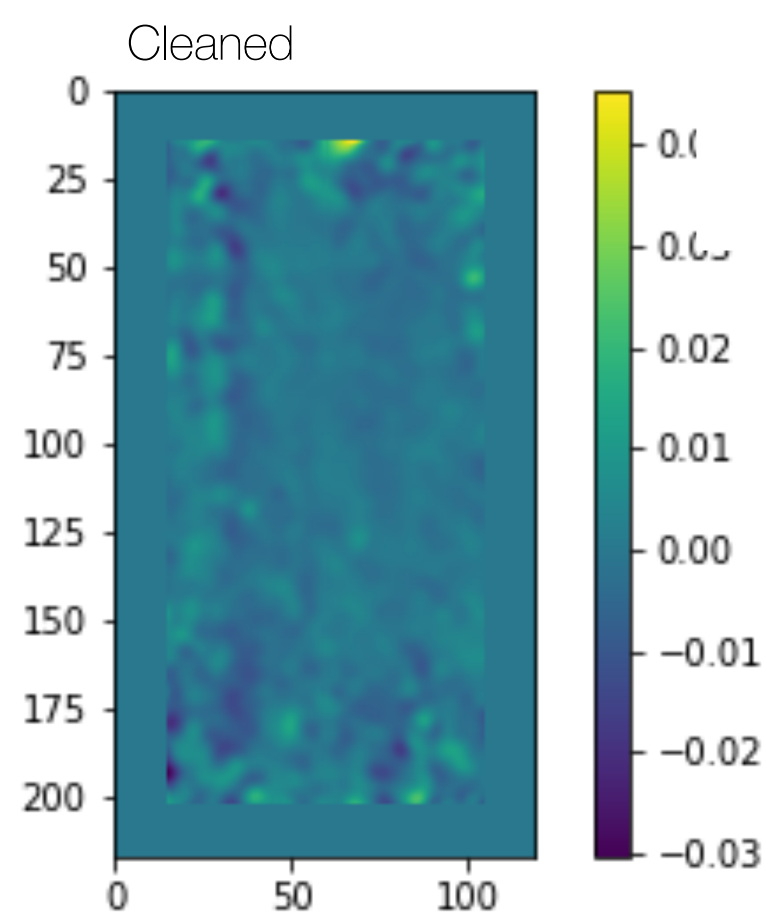
- Start with GBT data after map-making
- Convolve to same angular resolution 1.4*max beam->FWHM~0.44 deg
- Mask out the edges of the 2d-maps (15pix per side)
- Apply fastICA (using N_IC=2 …32)
- Estimate power spectrum using inverse noise variance weighting
- Correct for signal loss with transfer function
- Estimate error bars
- Average over all sub-sections (A,B,C,D)


Data
0
25
50
75
100
125
150
175
200
0
50
100
8
7
6
5
4
3
2
1
0


Inverse noise
0
25
50
75
100
125
150
175
200
0
50
100
8000
7000
6000
5000
4000


Mock HI
0
25
50
75
100
125
150
175
200
0
50
100
0.0004
0.0003
0.0002
0.0001
0.0000
−0.0001


Cleaned
0
25
50
75
100
125
150
175
200
0
50
100
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05

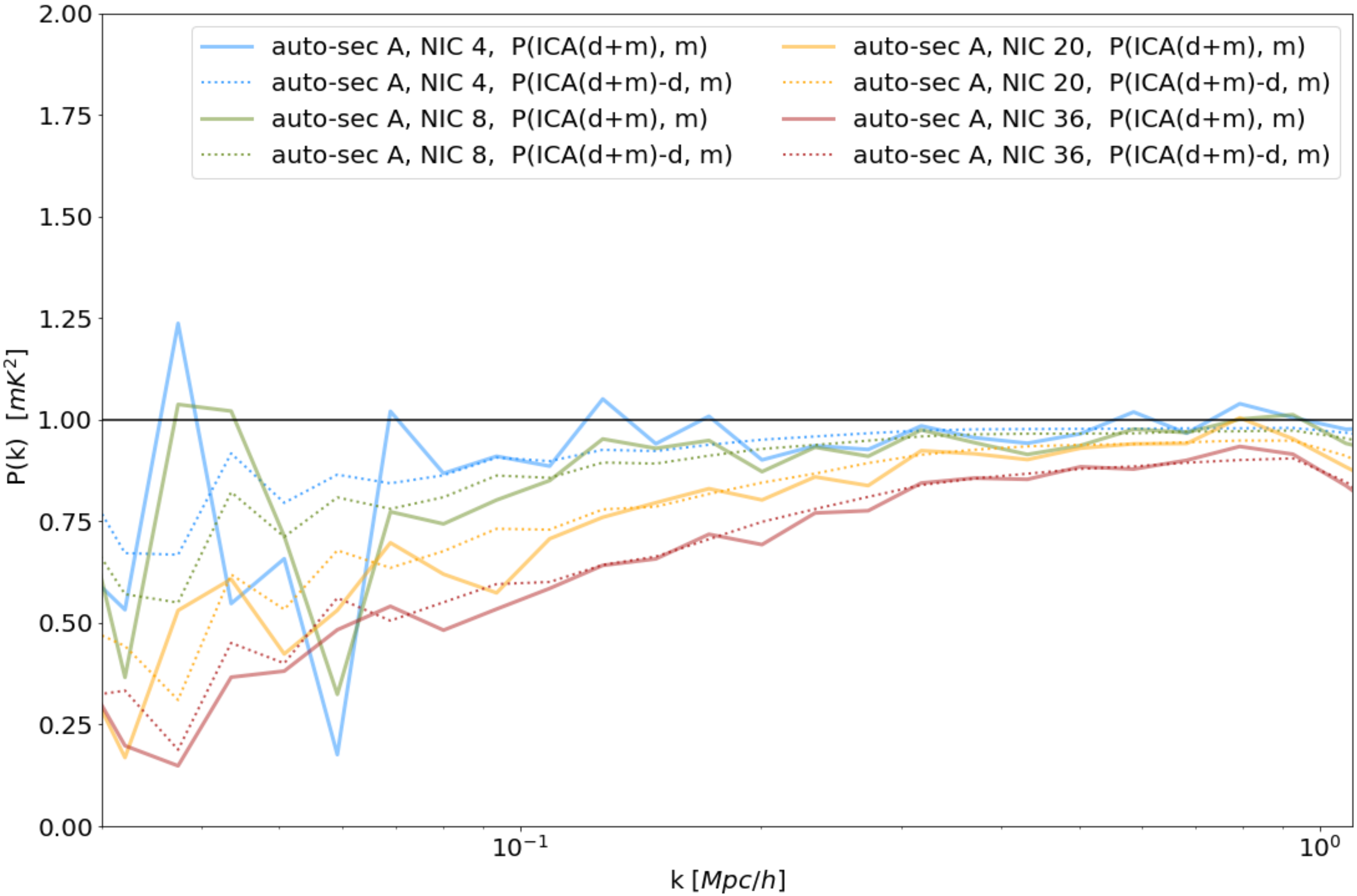

Cleaned
0
25
50
75
100
125
150
175
200
0
50
100
0.02
0.01
0.00
−0.01
−0.02
−0.03

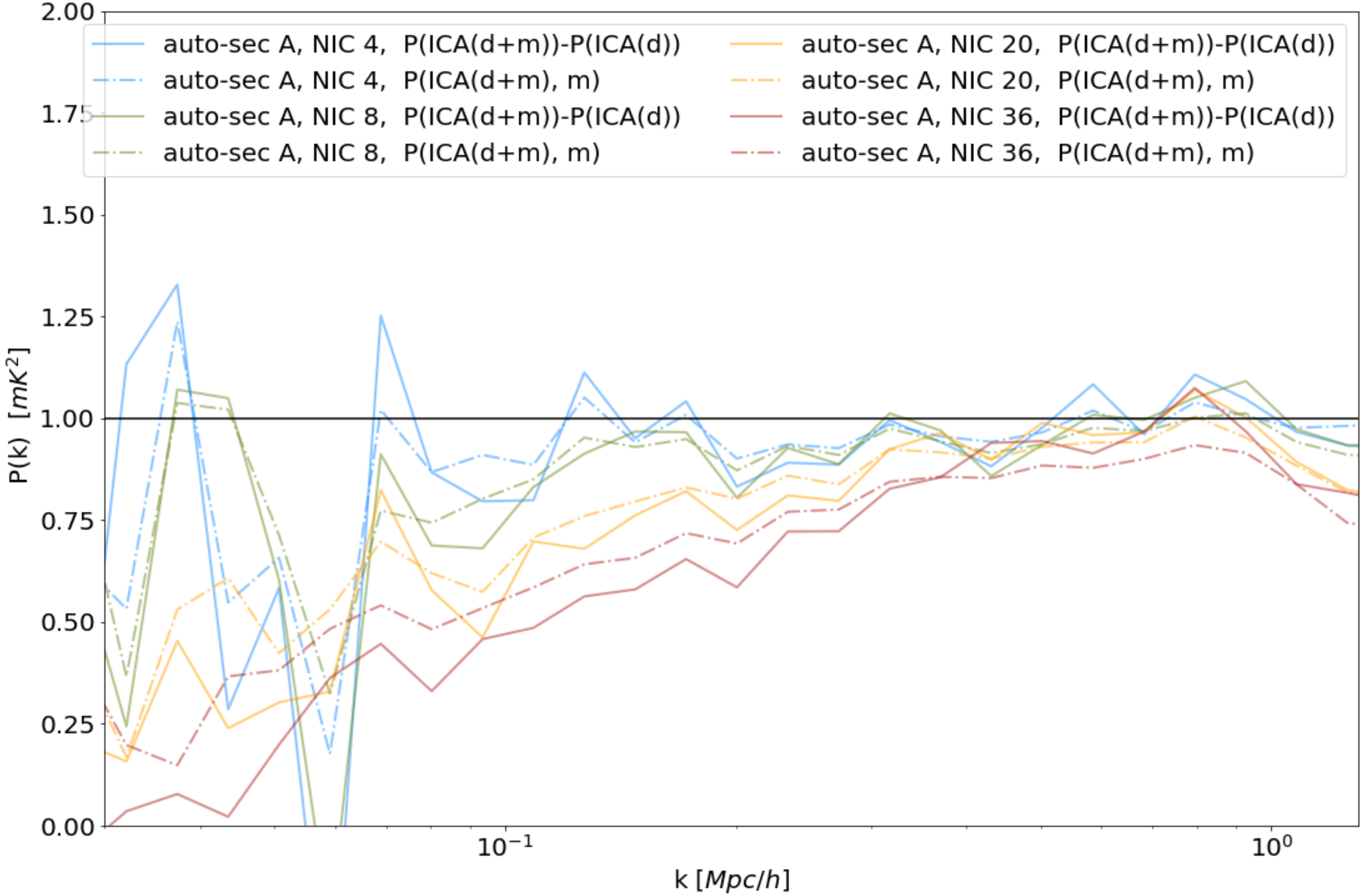
fastICA transfer function

- Lognormal simulations populated with HI in underlying haloes
- 100 mock realisations with flat survey geometry at med redshift
- Grid according to IM data and convolve with beam
- Apply fastICA to (data + mock) for each dataset, realisation and NIC, *subtract original data* and compute power spectra P
- Transfer function for each sub season determined through
  T_cross = P(ICA(d+m) , m) / P(m)
  T_auto = P(ICA(d+m) - P(ICA(d)) /P(m)
- Correct for signal loss via P(ICA(d)) / T
- Some discussion remaining to finalise transfer function (later)

Signal loss comparison

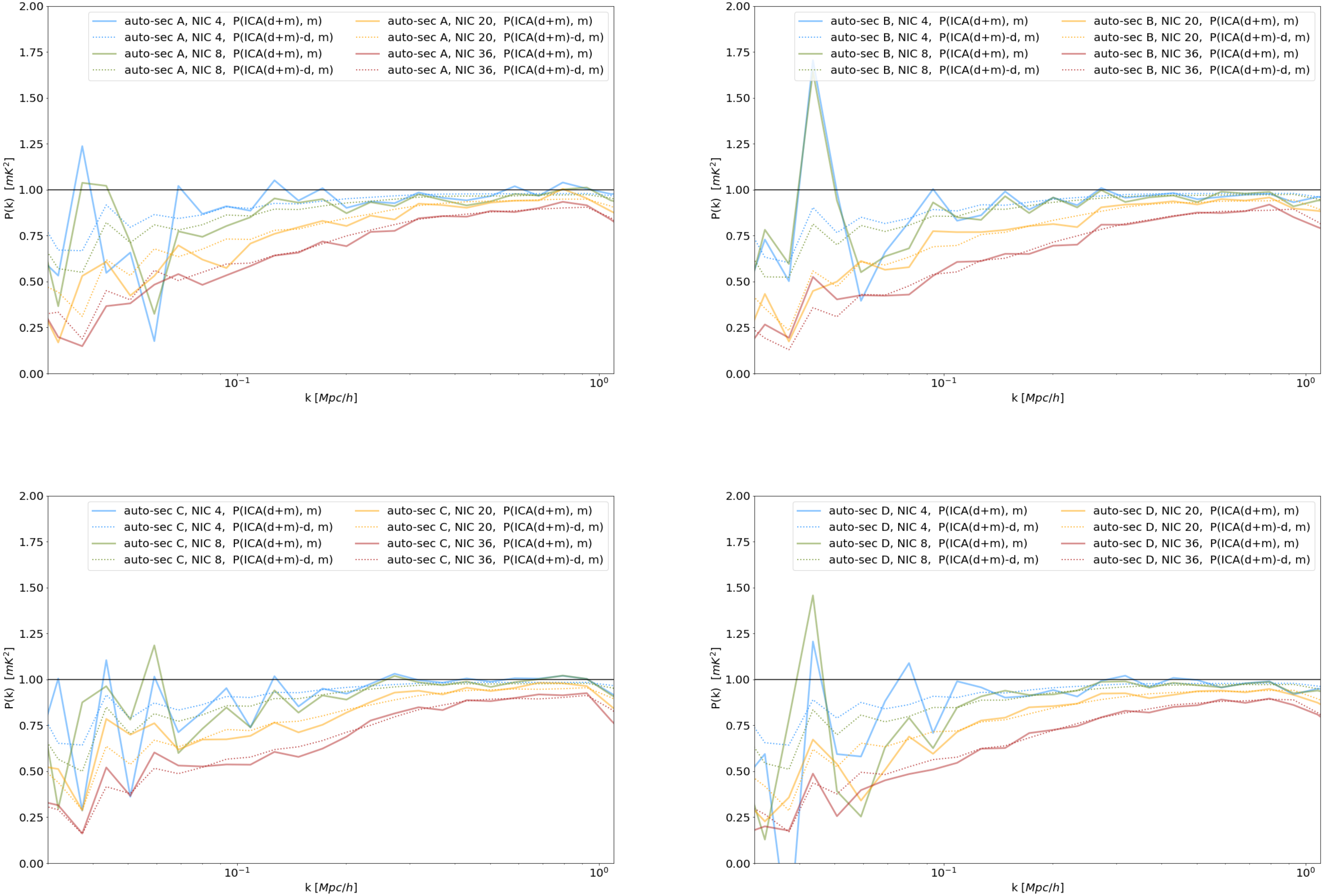
100 mock realisations; Sub data set A



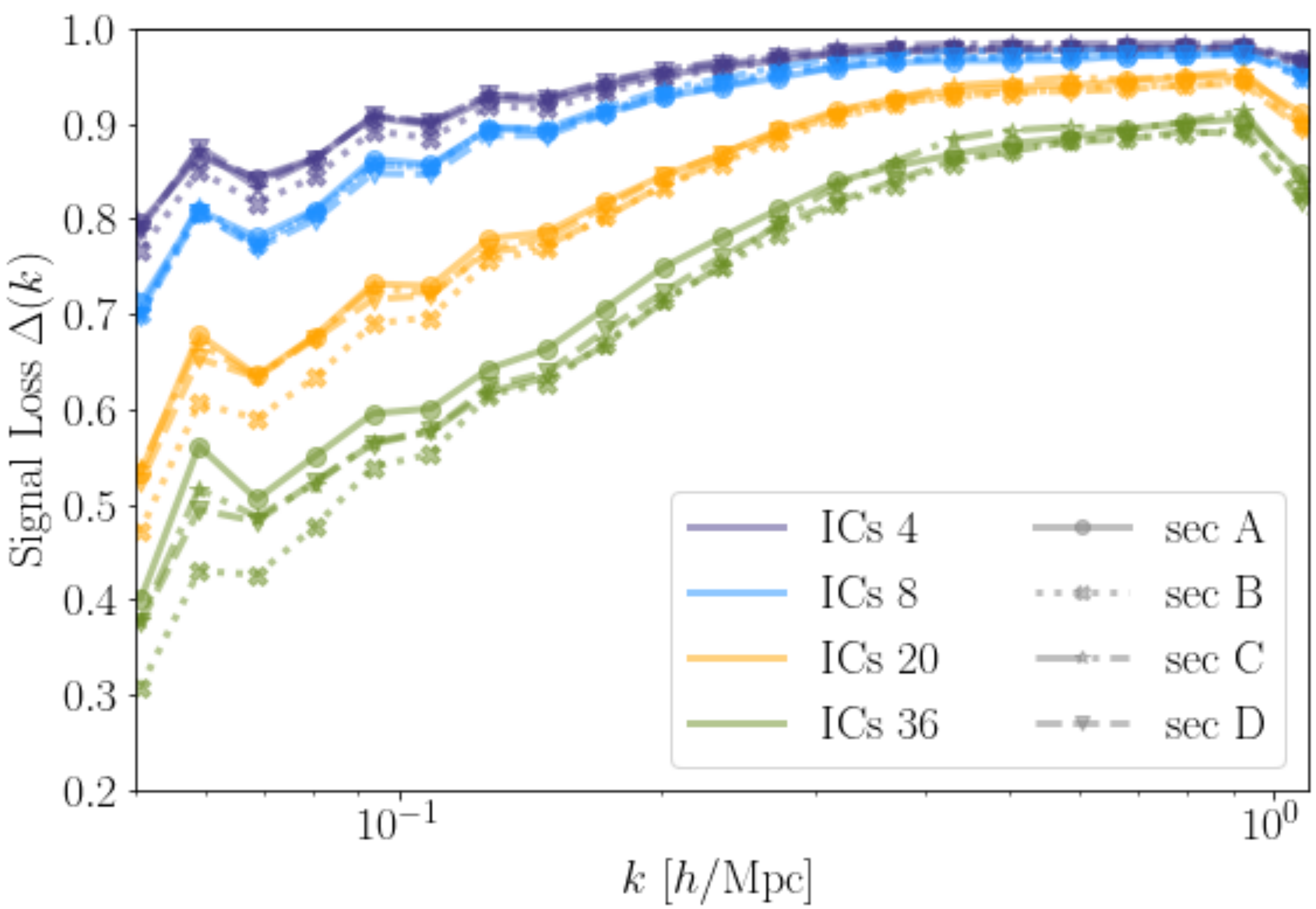


auto-sec A, NIC 4, P(ICA(d+m))-P(ICA(d))
auto-sec A, NIC 4, P(ICA(d+m), m)
auto-sec A, NIC 8, P(ICA(d+m))-P(ICA(d))
auto-sec A, NIC 8, P(ICA(d+m), m)
auto-sec A, NIC 20, P(ICA(d+m))-P(ICA(d))
auto-sec A, NIC 20, P(ICA(d+m), m)
auto-sec A, NIC 36, P(ICA(d+m))-P(ICA(d))
auto-sec A, NIC 36, P(ICA(d+m), m)
P(k) [mK^2]
k [Mpc/h]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10^{-1}
10^{0}

Signal loss comparison

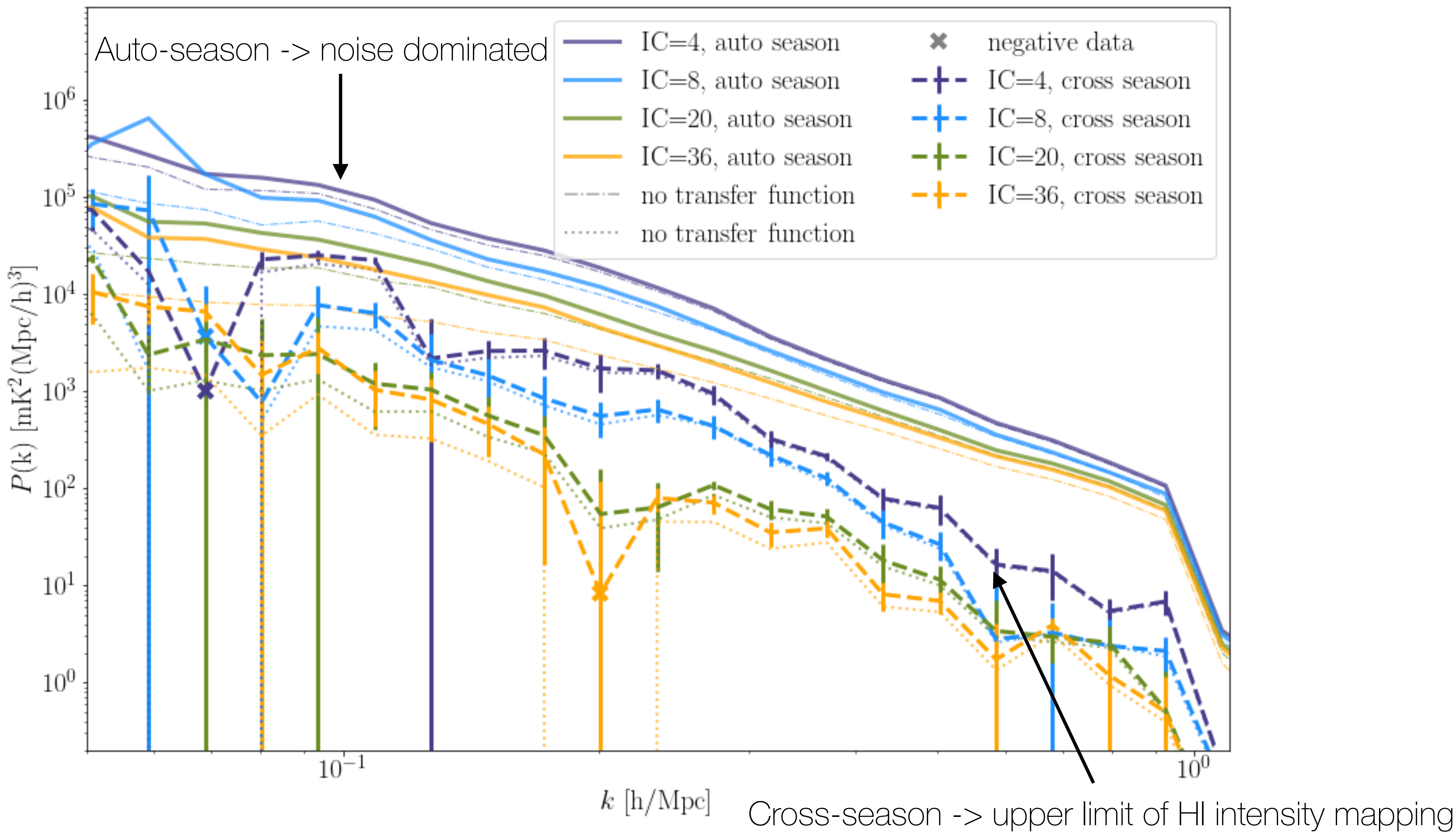


Foreground Subtraction Transfer Function to correct for HI signal loss

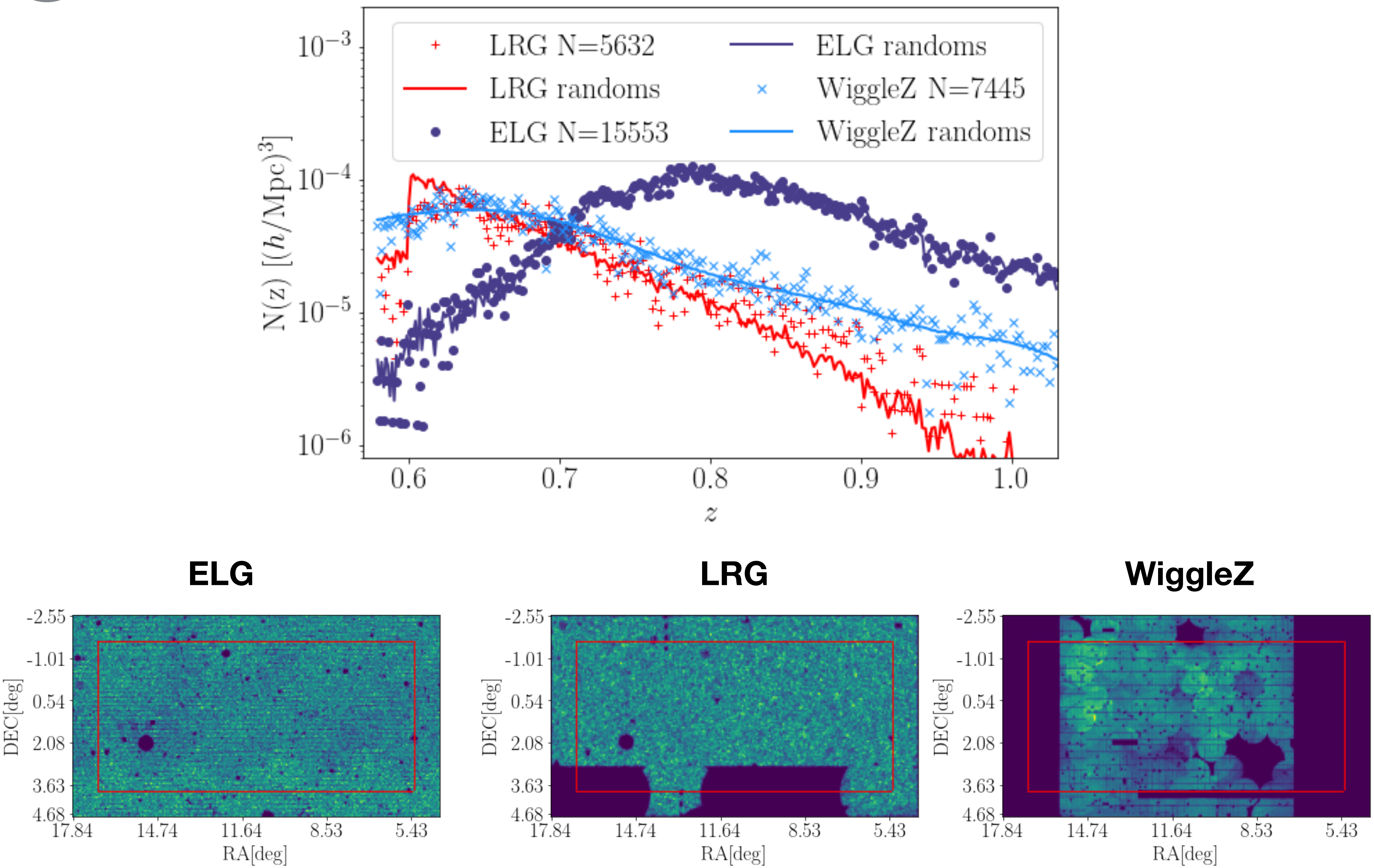


Based 100 mock realisations added to the data pre-fastICA and run through our analysis pipeline

GBT HI intensity mapping power spectrum



Galaxy samples: data and mock


LRG N=5632
LRG randoms
ELG N=15553
ELG randoms
WiggleZ N=7445
WiggleZ randoms
N(z) [(h/Mpc)^3]
z
ELG
LRG
WiggleZ
DEC[deg]
RA[deg]

- Semi-analytic simulation, light cone with data geometry based on Millennium N-body, galaxy formation Dark SAGE; Galaxies with log10(M*)>8.5M_sun

- Redshift Space Distortions included

- Spectral energy distribution following Conroy 2009, Filters for SDSS ugriz, Galex FUV/NUV and Spitzer IRAC1

- Mock galaxy samples based on eBOSS target selections

LRG

eBOSS targets galaxies that are fainter than BOSS. Targets are restricted to the following flux limits:

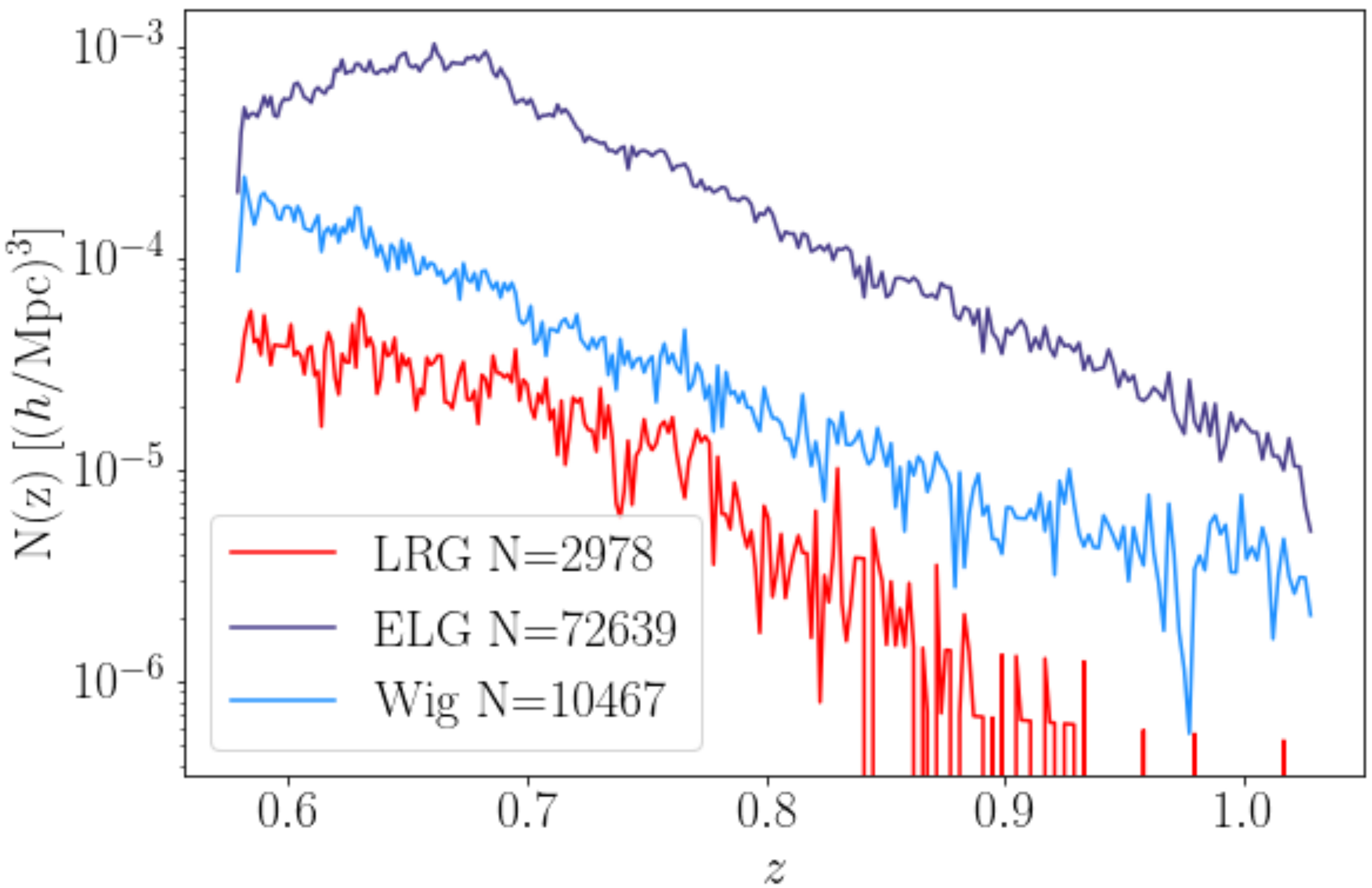
- $19.9 \leq i \leq 21.8$
- $z \leq 19.95$
- $W1 \leq 20.299$

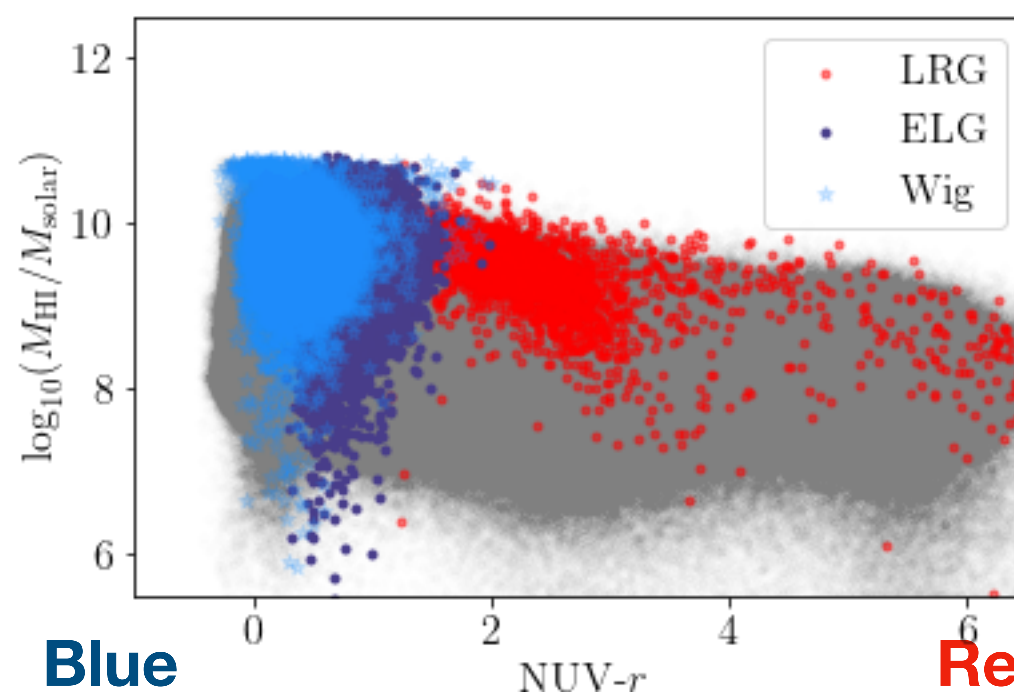
The selection cuts are as follows:

1. $r - i > 0.98$
2. $r - W1 > 2.0 \times (r - i)$
3. $i - z > 0.625$

ELG

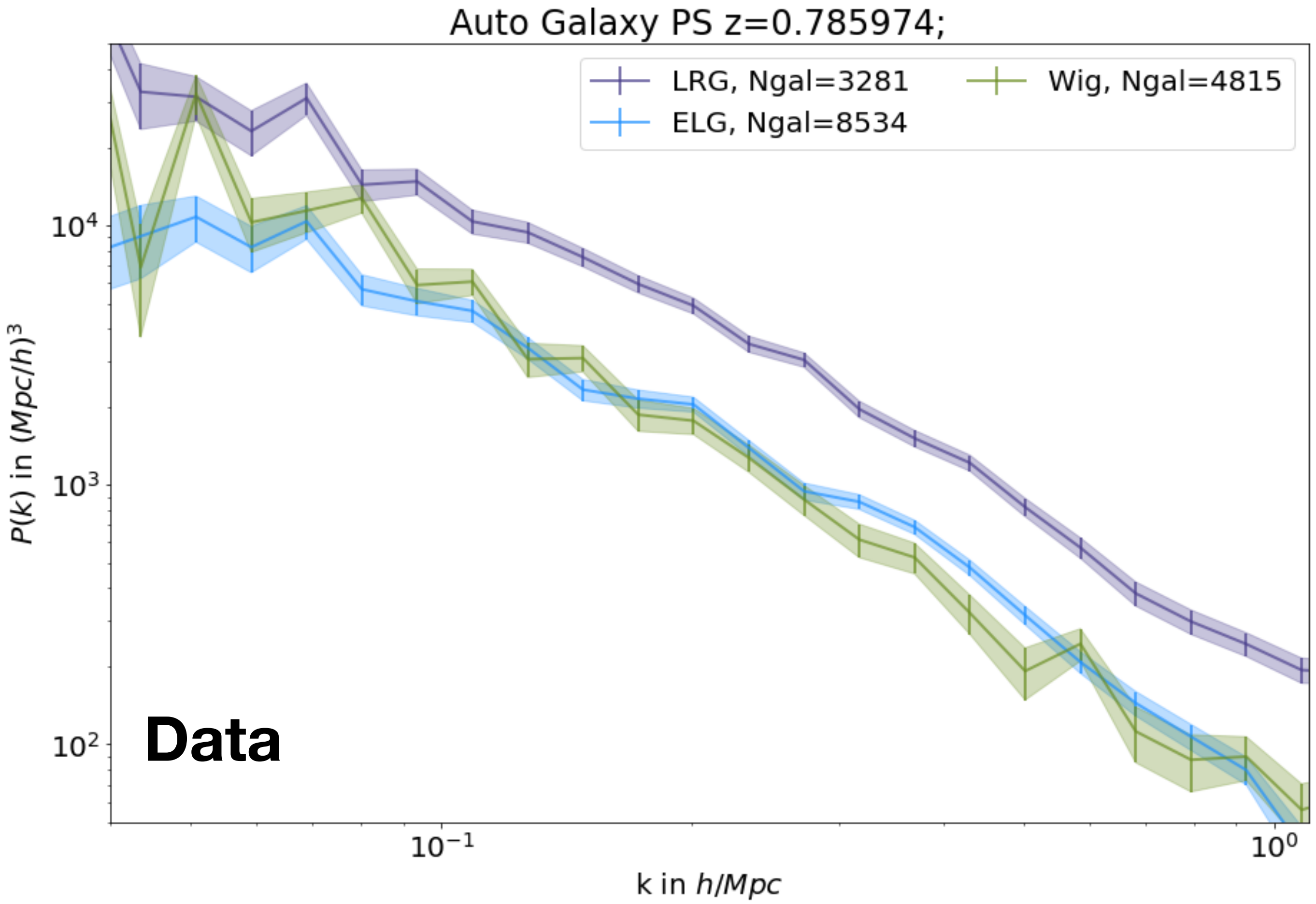
Criterion	eBOSS/ELG SGC [240 deg^{-2}]	eBOSS/ELG NGC [200 deg^{-2}]
Clean photometry	SDSS bright object mask[9] and 0 mag $< V <$ 11.5 mag Tycho2 stars mask; BRICK_PRIMARY and decam_anymask[grz]=0 and tycho2inblob==False	SDSS bright object mask[9] and 0 mag $< V <$ 11.5 mag Tycho2 stars mask; BRICK_PRIMARY and decam_anymask[grz]=0 and tycho2inblob==False; Custom mask† [chunk eboss23 only]
[OII] emitters	$21.825 < g < 22.825$	$21.825 < g < 22.9$
Redshift range	$-0.068 \times (r - z) + 0.457 < g - r < 0.112 \times (r - z) + 0.773$; $0.218 \times (g - r) + 0.571 < r - z < -0.555 \times (g - r) + 1.901$	$-0.068 \times (r - z) + 0.457 < g - r < 0.112 \times (r - z) + 0.773$; $0.637 \times (g - r) + 0.399 < r - z < -0.555 \times (g - r) + 1.901$



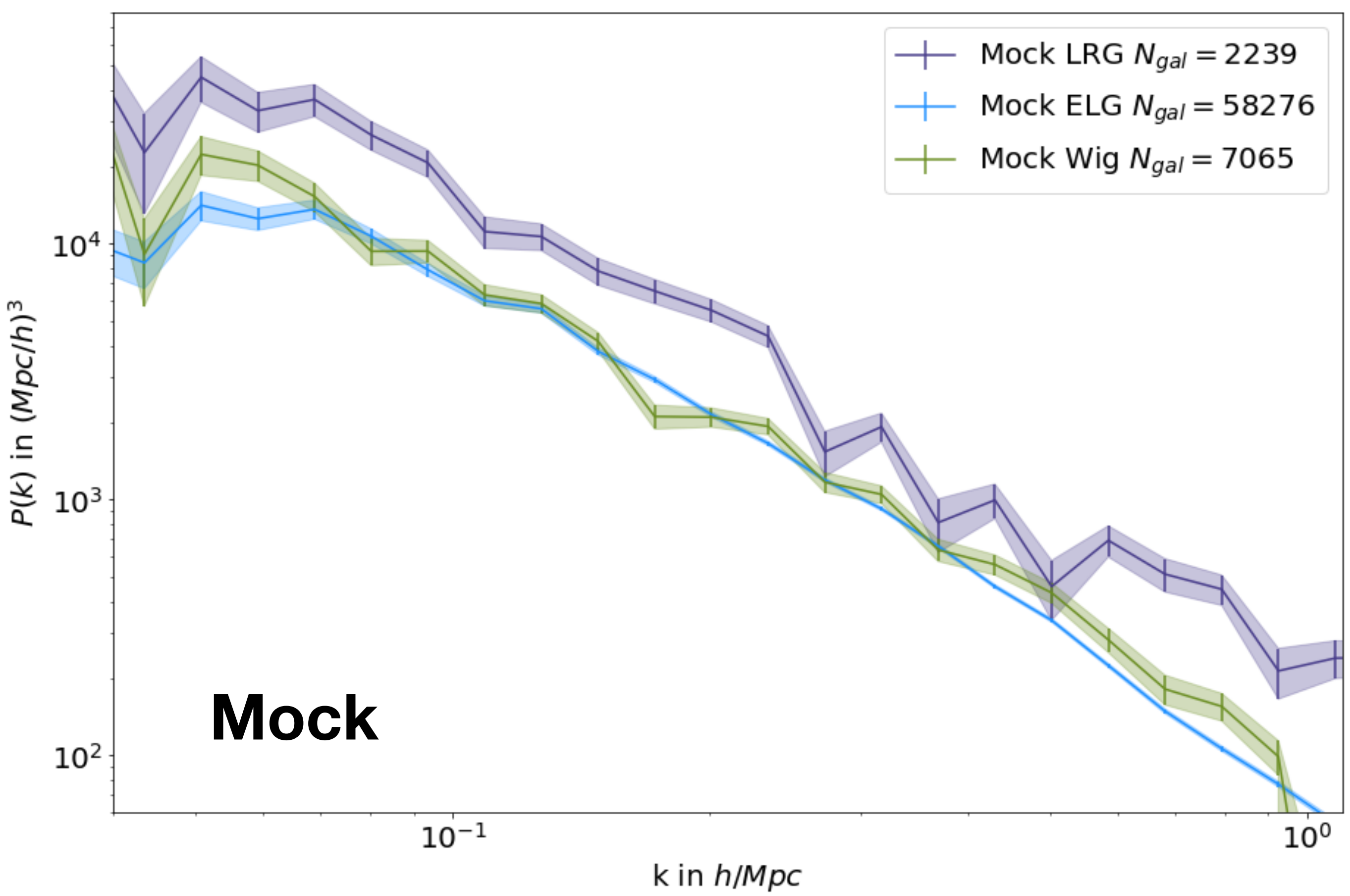


Blue **Red**

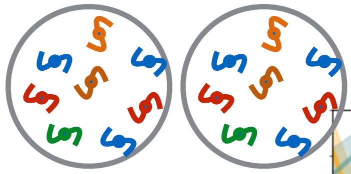
Galaxy Colour

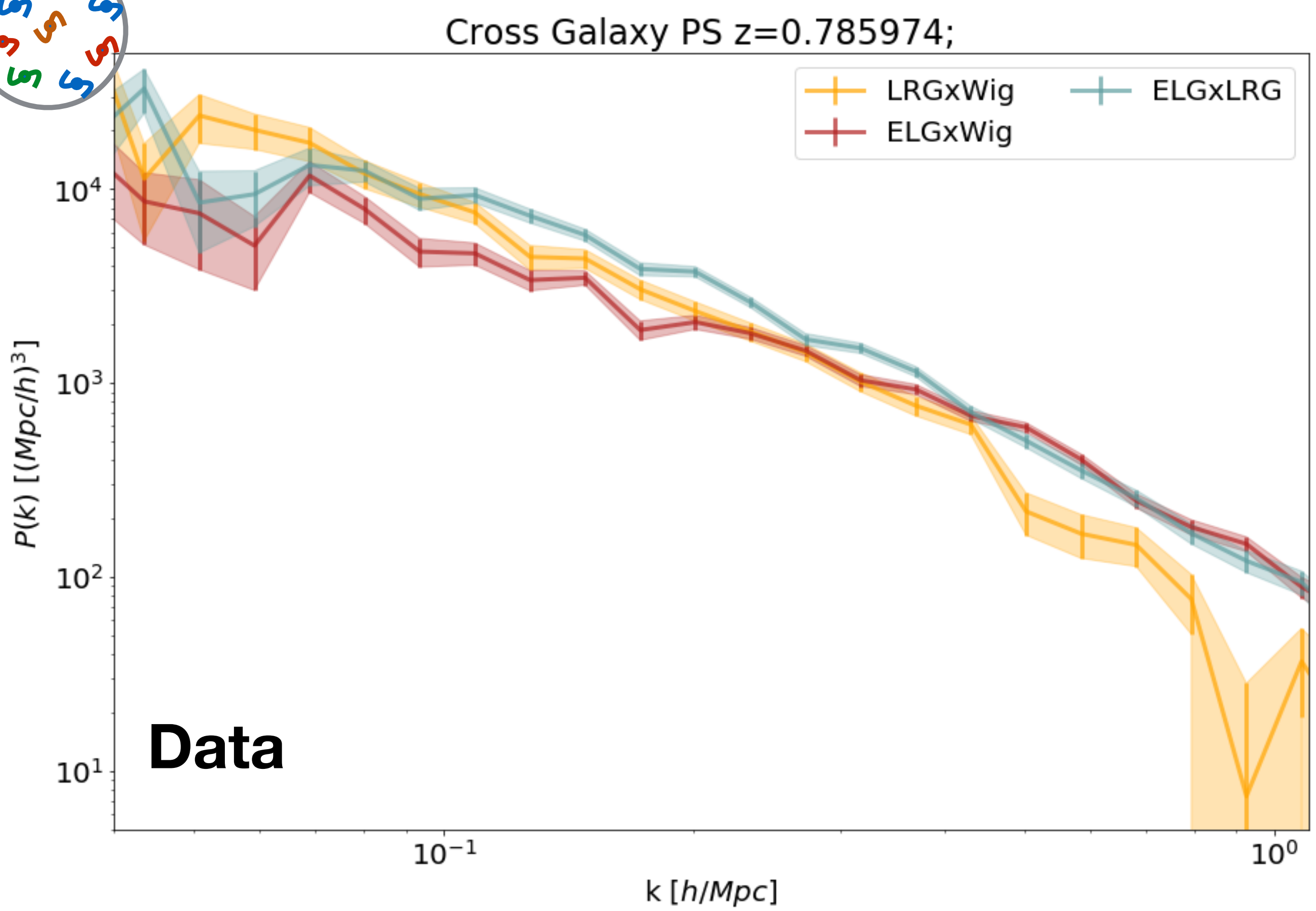


Auto Galaxy PS z=0.785974;
LRG, Ngal=3281
ELG, Ngal=8534
Wig, Ngal=4815
10^4
10^3
10^2
P(k) in (Mpc/h)^3
Data
10^{-1}
10^0
k in h/Mpc

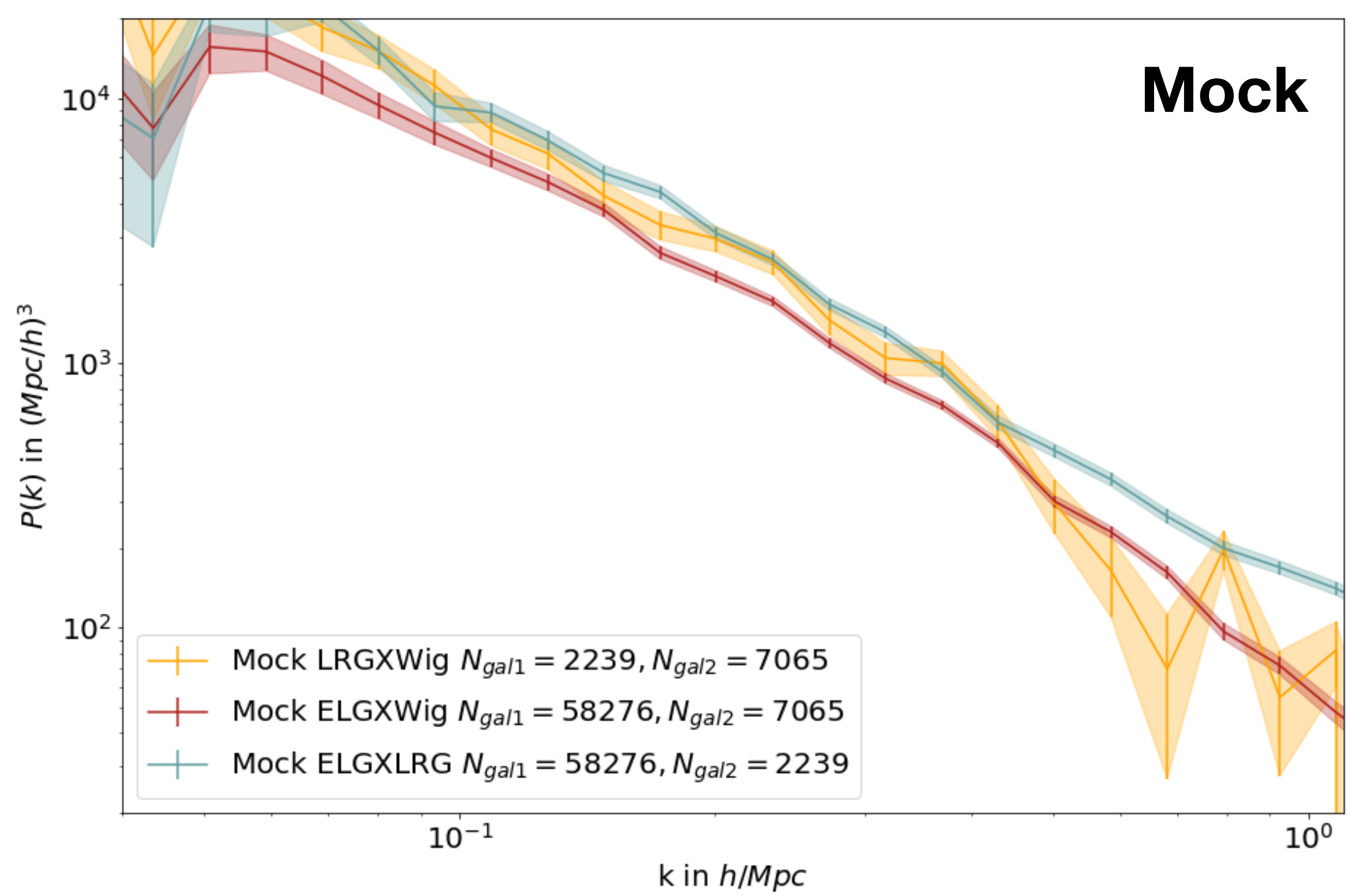


Mock LRG $N_{gal} = 2239$
Mock ELG $N_{gal} = 58276$
Mock Wig $N_{gal} = 7065$
10^4
10^3
10^2
P(k) in (Mpc/h)^3
Mock
10^{-1}
10^0
k in h/Mpc





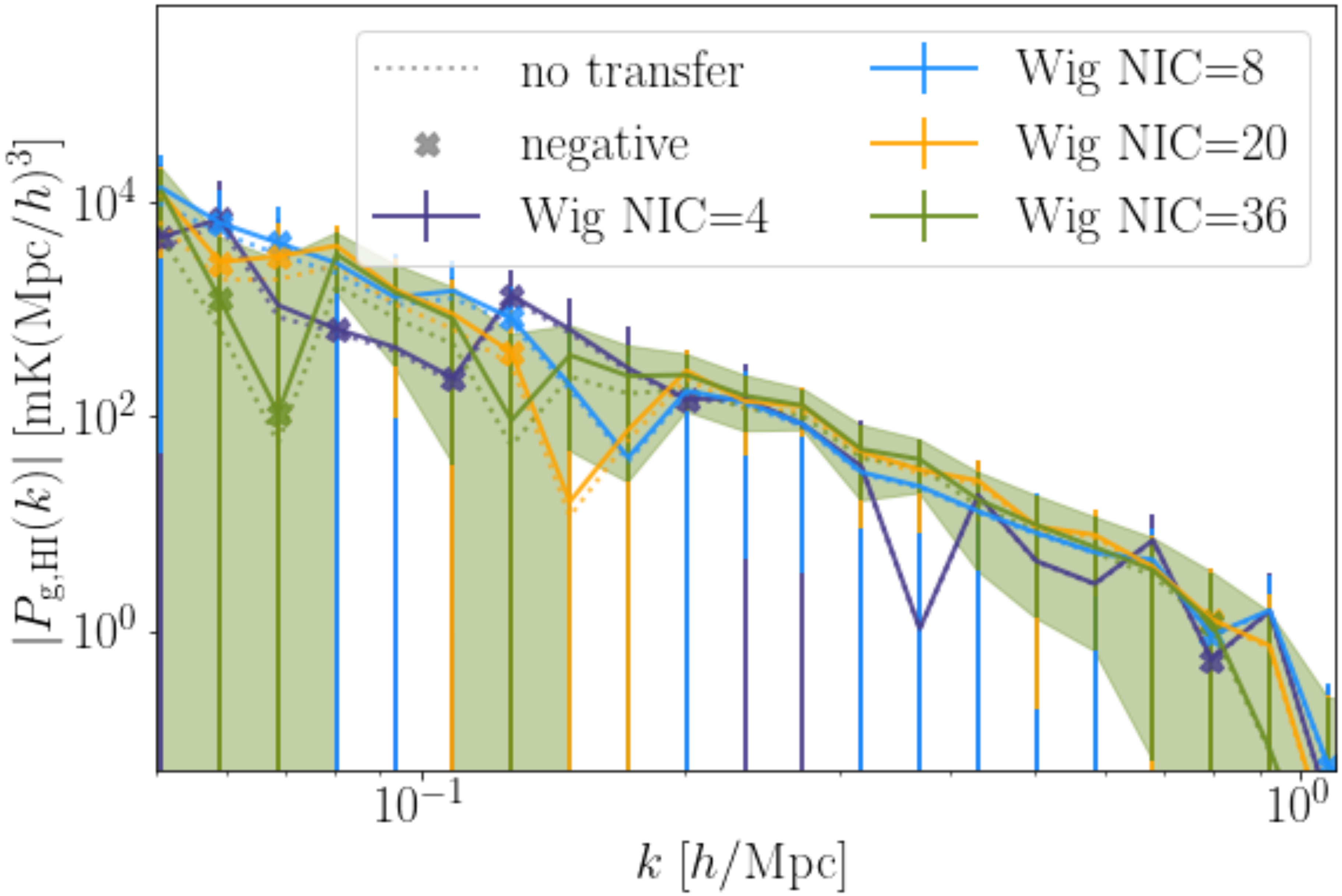
Cross Galaxy PS z=0.785974;
LRGxWig
ELGxWig
ELGxLRG
$P(k)$ $[(Mpc/h)^3]$
k $[h/Mpc]$
Data



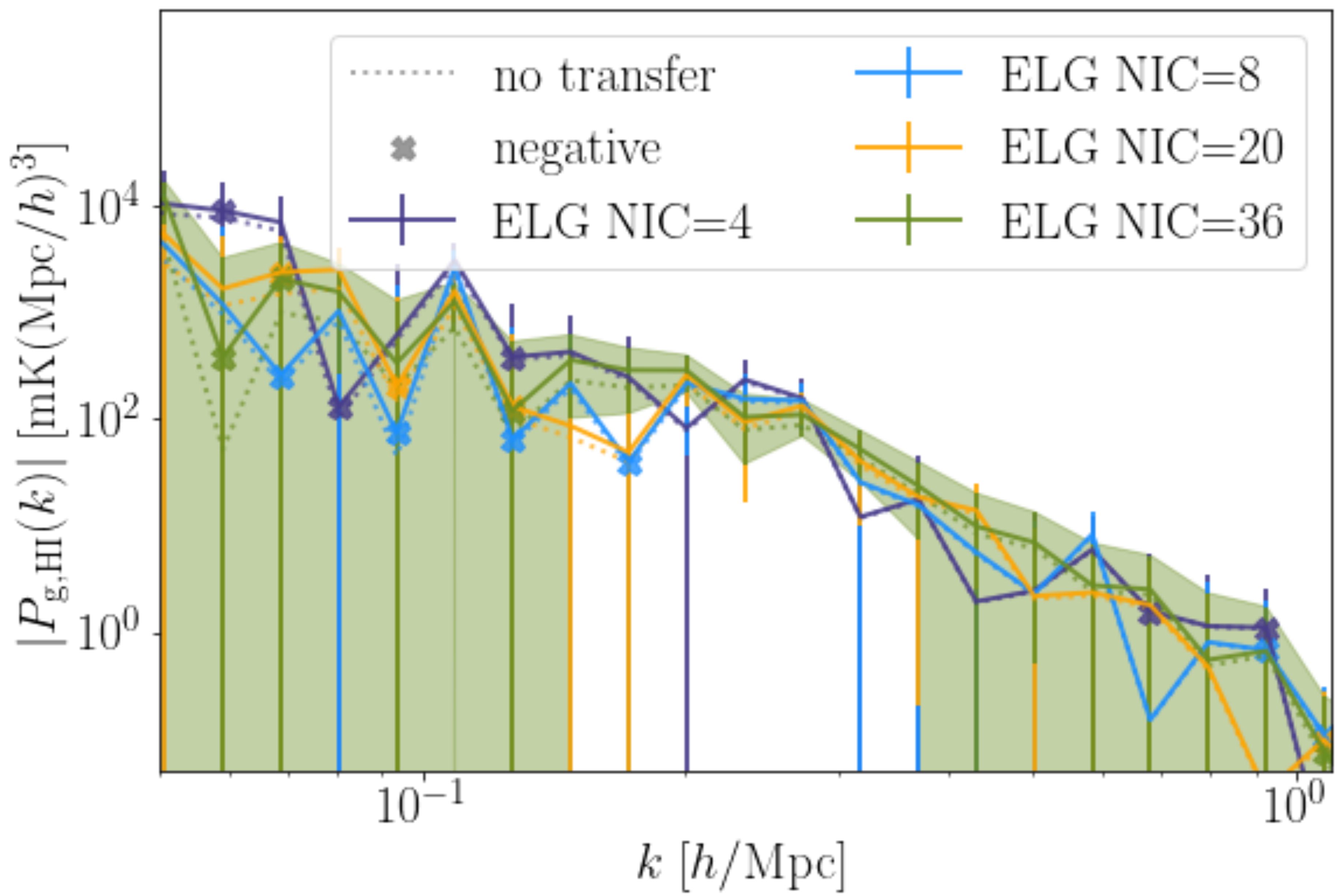
Mock
Mock LRGXWig $N_{gal1} = 2239, N_{gal2} = 7065$
Mock ELGXWig $N_{gal1} = 58276, N_{gal2} = 7065$
Mock ELGXLRG $N_{gal1} = 58276, N_{gal2} = 2239$
$P(k)$ in $(Mpc/h)^3$
k in h/Mpc

Galaxy-intensity mapping cross-correlation

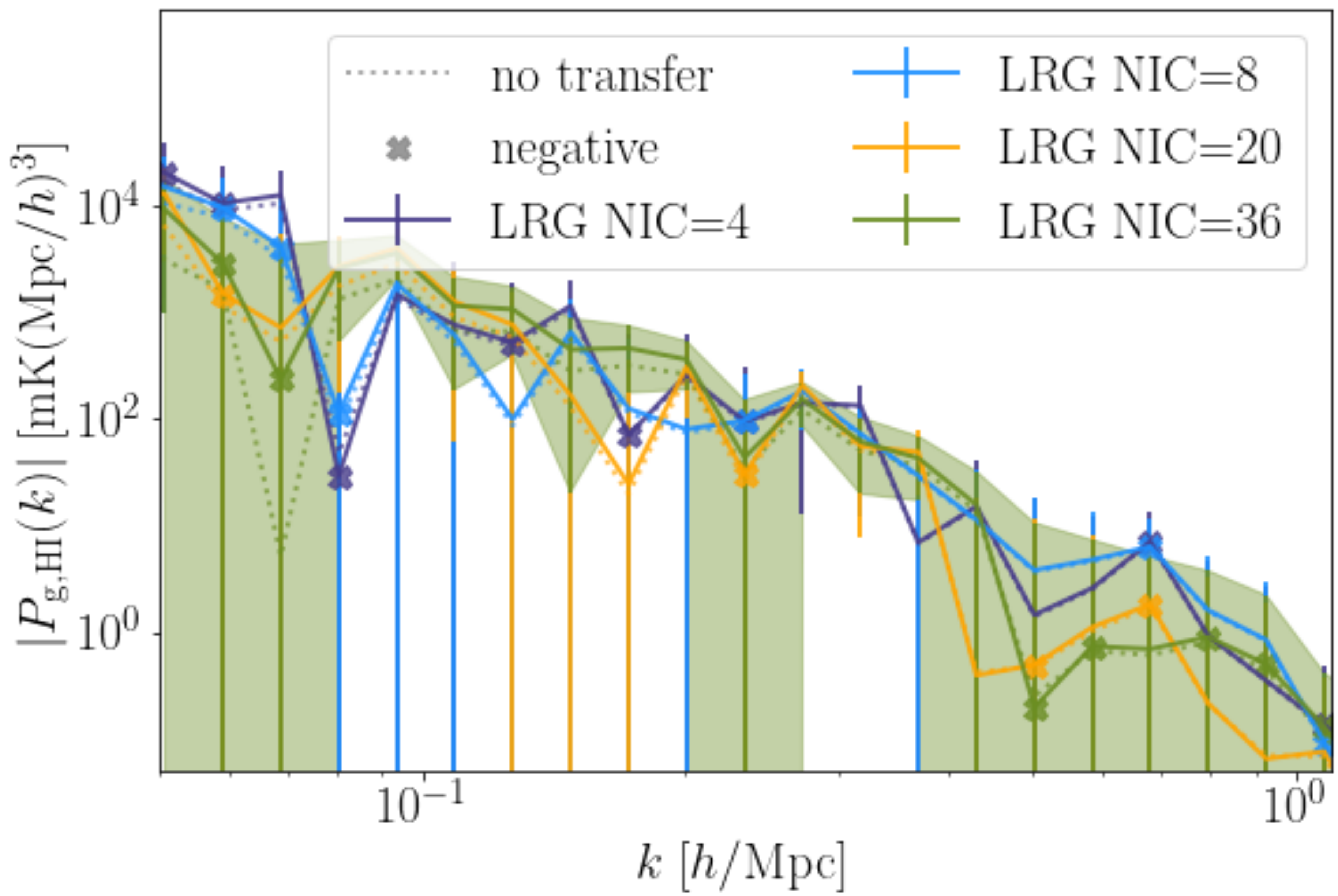
GBT-WiggleZ cross-power spectrum



GBT-ELG cross-power spectrum



GBT-LRG cross-power spectrum



Model choice for HI constraints

The empirical model we use includes CAMB-HALOFIT matter power spectrum, Kaiser dark matter RSDs, and the galaxy bias and HI factors:

$$P_{\mathrm{HIg}}(k) = T_{\mathrm{HI}} b_{\mathrm{HI}} b_{\mathrm{g}} r P_{\delta\delta}(k)$$

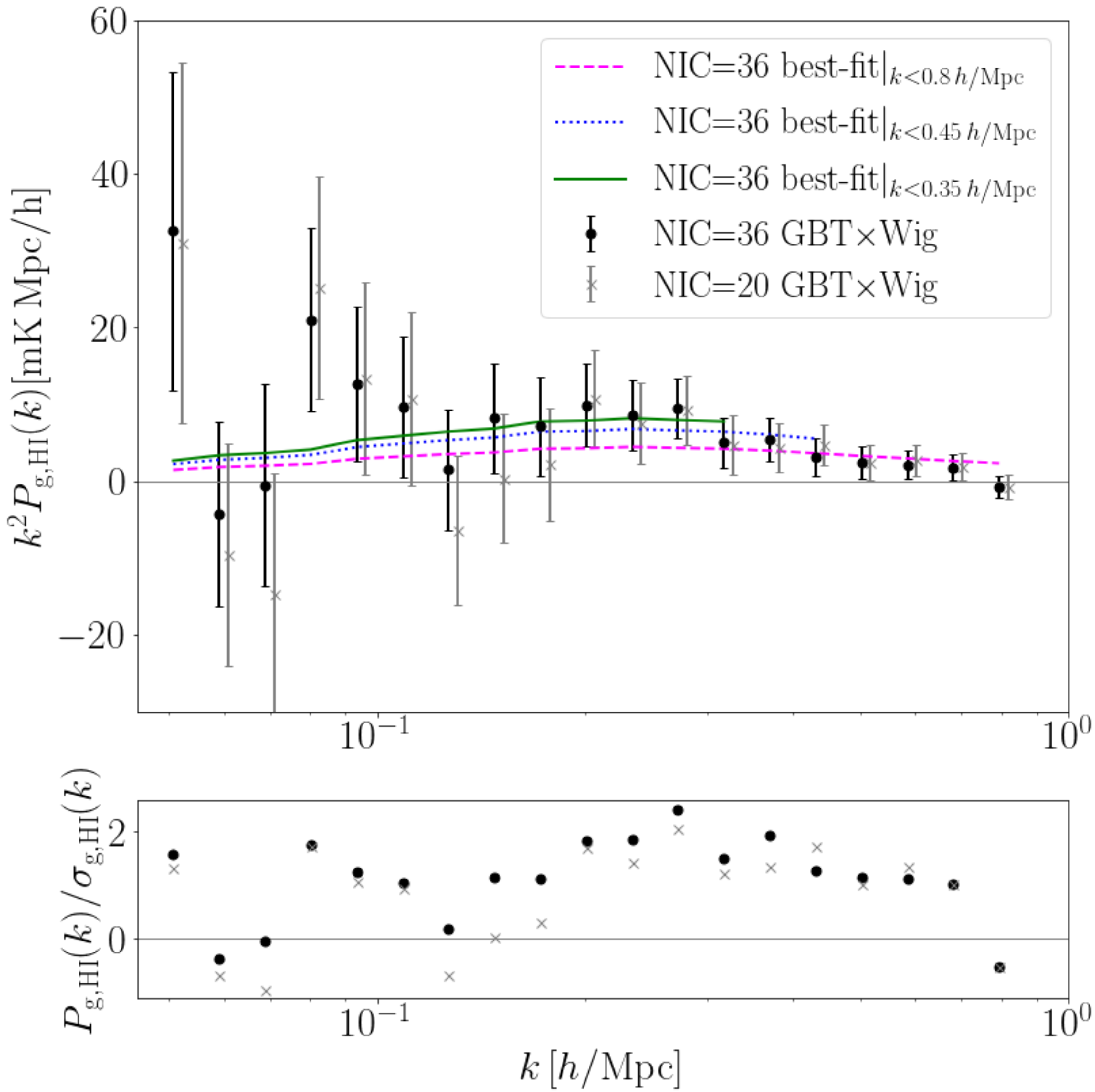
$$T_{\mathrm{HI}} \propto \Omega_{\mathrm{HI}}$$

$$T_b = 0.29 \frac{\Omega_{\mathrm{HI}}}{10^{-3}} \left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.37} \right)^{-\frac{1}{2}} \left(\frac{1+z}{1.8} \right)^{\frac{1}{2}} \mathrm{mK}$$

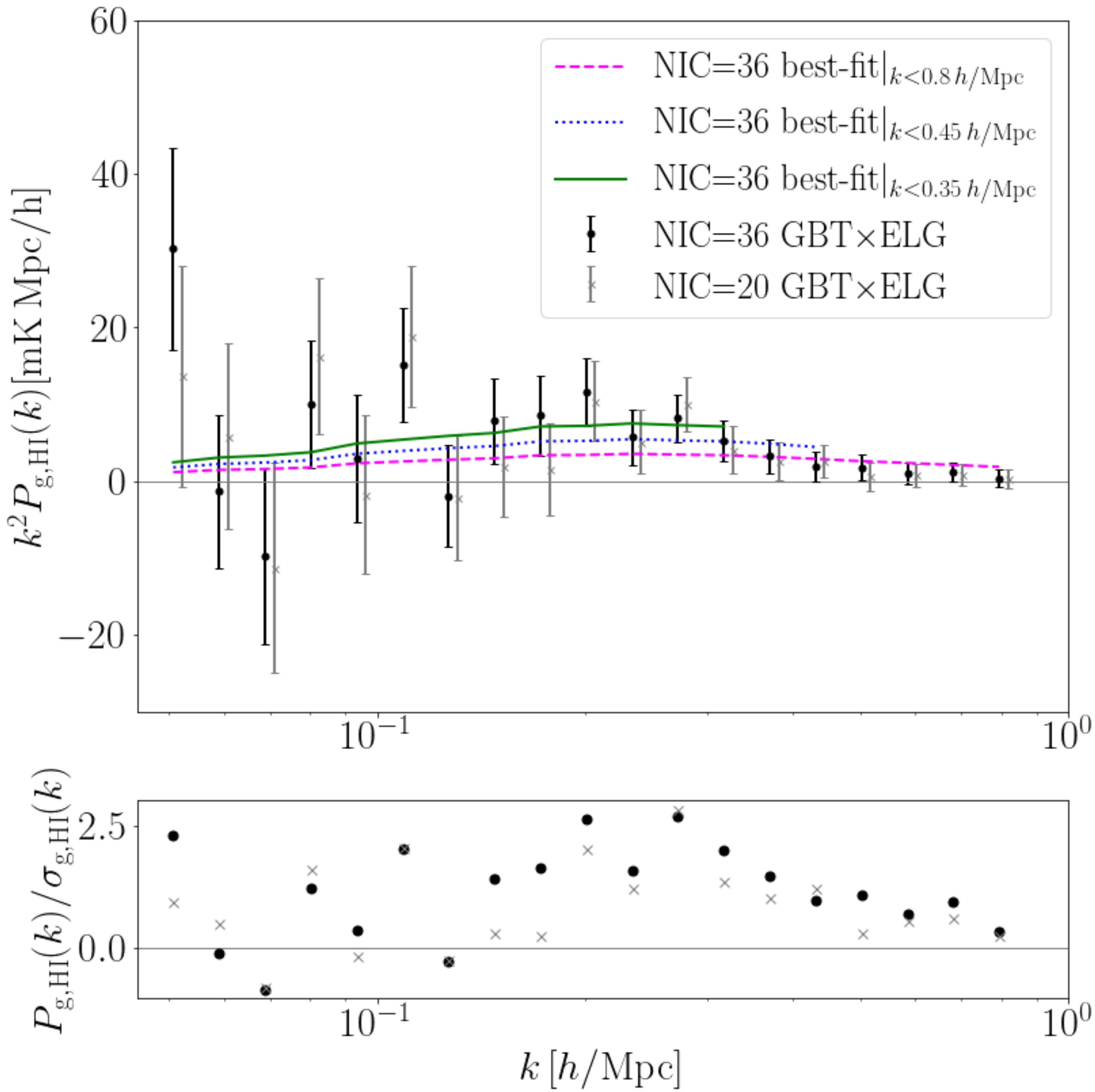
The model is weighted and convolved with the beam, i.e. it goes through the same pipeline as the data.

Our goal is to constrain: $\Omega_{\mathrm{HI}} b_{\mathrm{HI}} r$

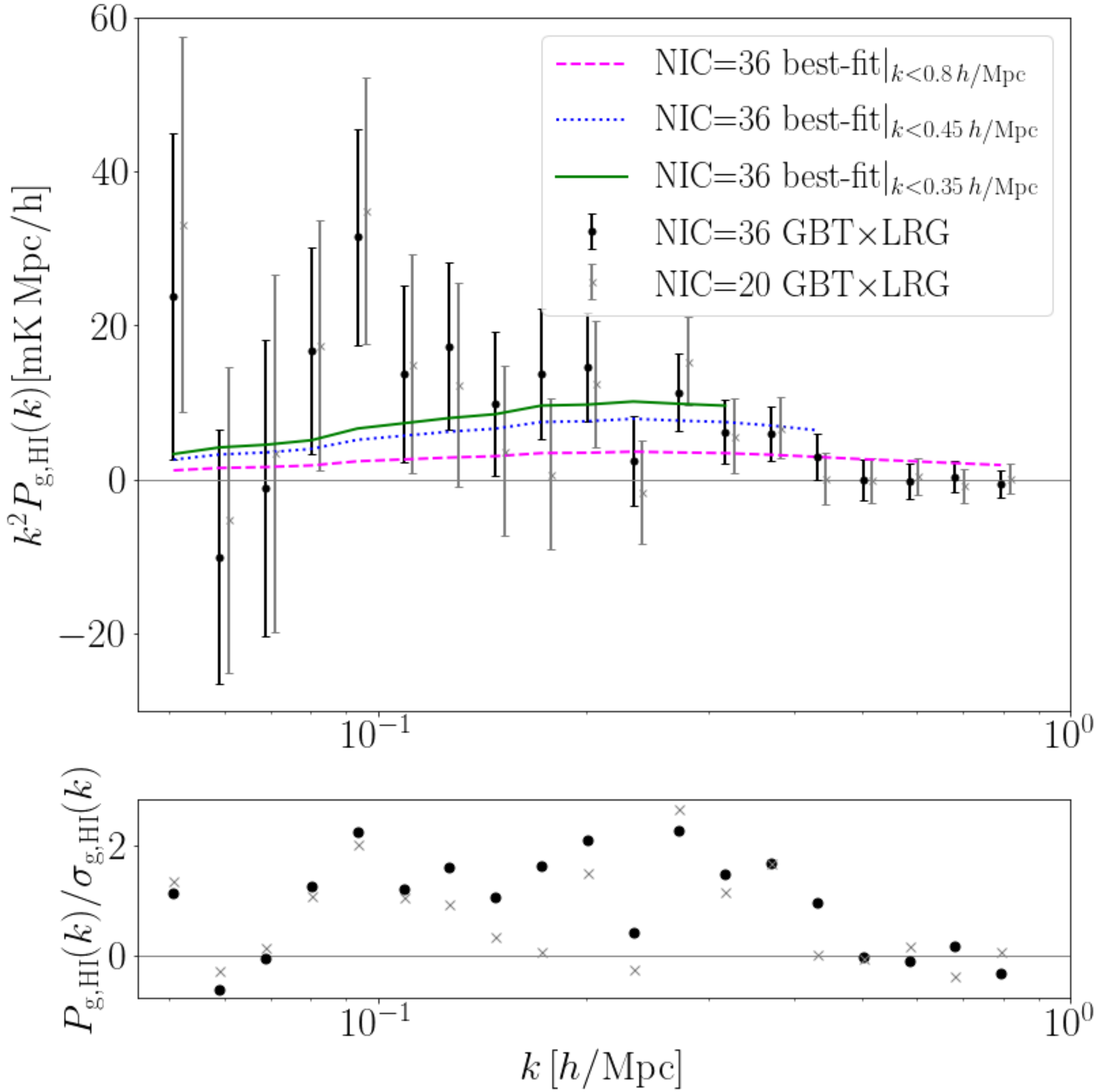
Power spectra and detection significance



Power spectra and detection significance



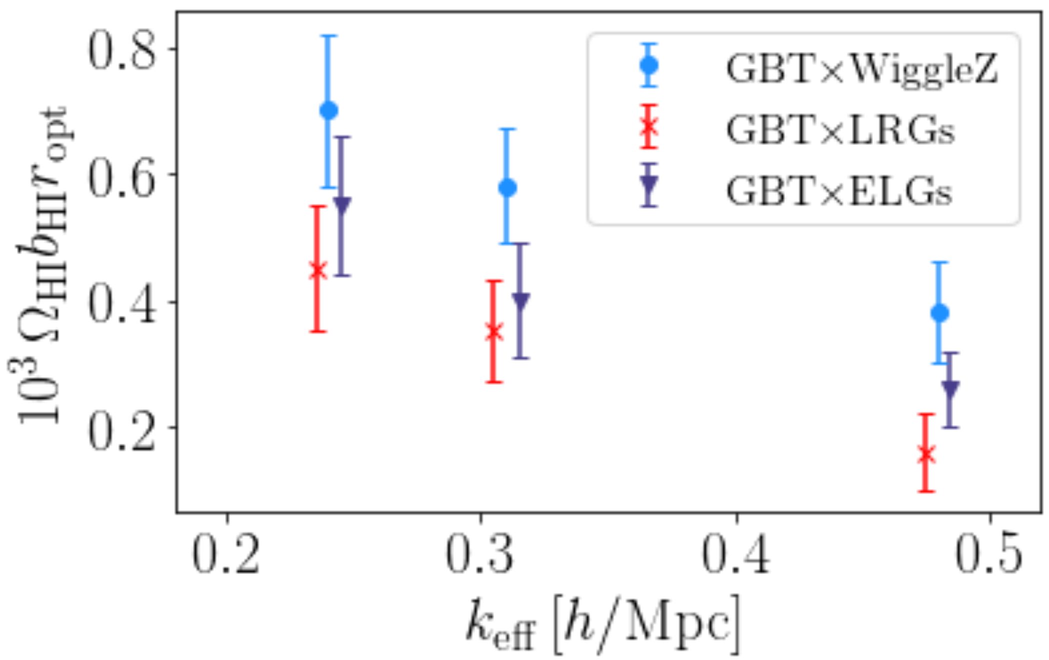
Power spectra and detection significance

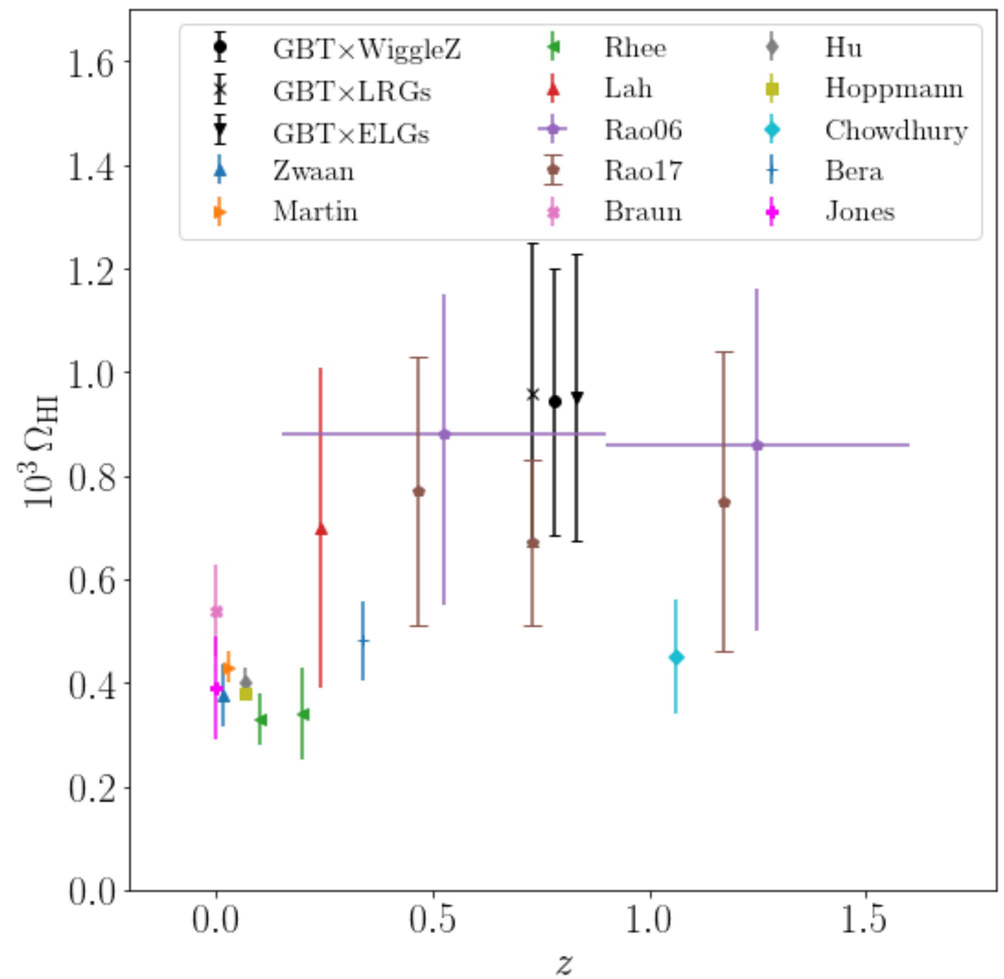


Constrain HI density via $\Omega_{\rm HI} b_{\rm HI} r_{\rm HI-gal}$

	GBTxWiggleZ	GBTxELGs	GBTxLRGs	$k_{\rm eff}\,[h/{\rm Mpc}]$
Case I $[k < 0.8\,h/{\rm Mpc}]$				
NIC=20:	0.35 ± 0.09	0.20 ± 0.06	0.12 ± 0.06	-
NIC=36:	0.38 ± 0.08 (4.4σ)	0.26 ± 0.06 (4.5σ)	0.16 ± 0.06 (2.9σ)	0.48
Case II $[k < 0.45\,h/{\rm Mpc}]$				
NIC=20:	0.53 ± 0.12	0.36 ± 0.09	0.28 ± 0.09	-
NIC=36:	0.58 ± 0.09 (4.8σ)	0.40 ± 0.09 (4.9σ)	0.35 ± 0.08 (4.4σ)	0.31
Case III $[k < 0.35\,h/{\rm Mpc}]$				
NIC=20:	0.58 ± 0.17	0.48 ± 0.12	0.38 ± 0.12	-
NIC=36:	0.70 ± 0.12 (4.4σ)	0.55 ± 0.11 (5σ)	0.45 ± 0.10 (4.2σ)	0.24

HI energy density constraints





Further Assumptions:

$b_{\rm HI} = 0.825$

Cross-correlation factor for WiggleZ $r_{\rm HI,Wig} = 0.9$

Use this as benchmark and derive ELG and LRG r from our simulations

$r_{\rm HI,ELG} = 0.7$ and $r_{\rm HI,LRG} = 0.6$

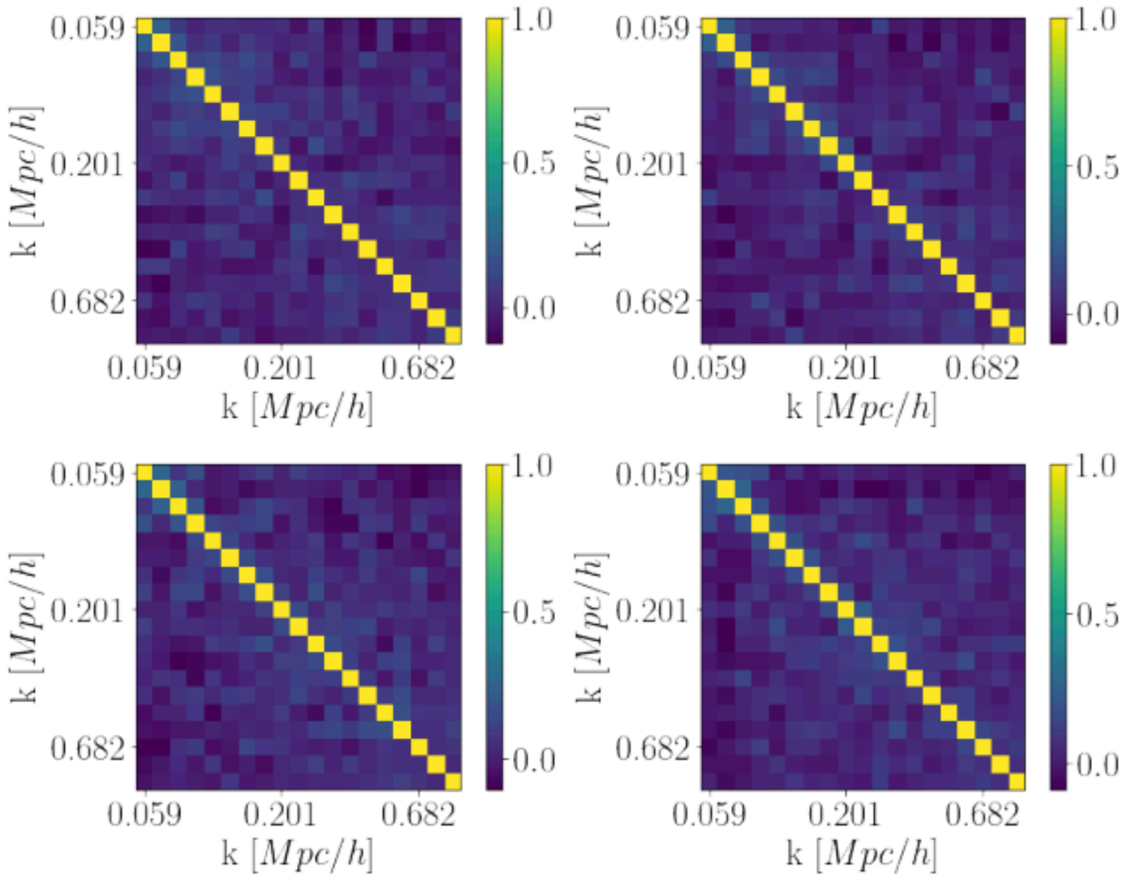


Figure B1. The covariance matrix computed from the power spectrum of the foreground removed lognormal realisations with the original lognormals, as described in subsection 3.2 with clockwise increasing numbers of ICs $N_{\rm IC}$. *Upper left panel*: $N_{\rm IC}$ = 4; *Upper right panel*: $N_{\rm IC}$ = 8; *Lower left panel*: $N_{\rm IC}$ = 20; *Lower right panel*: $N_{\rm IC}$ = 36. For illustrative purposes the diagonals of the covariance matrices have been normalised to unity; i.e. the correlation matrix is pictured.

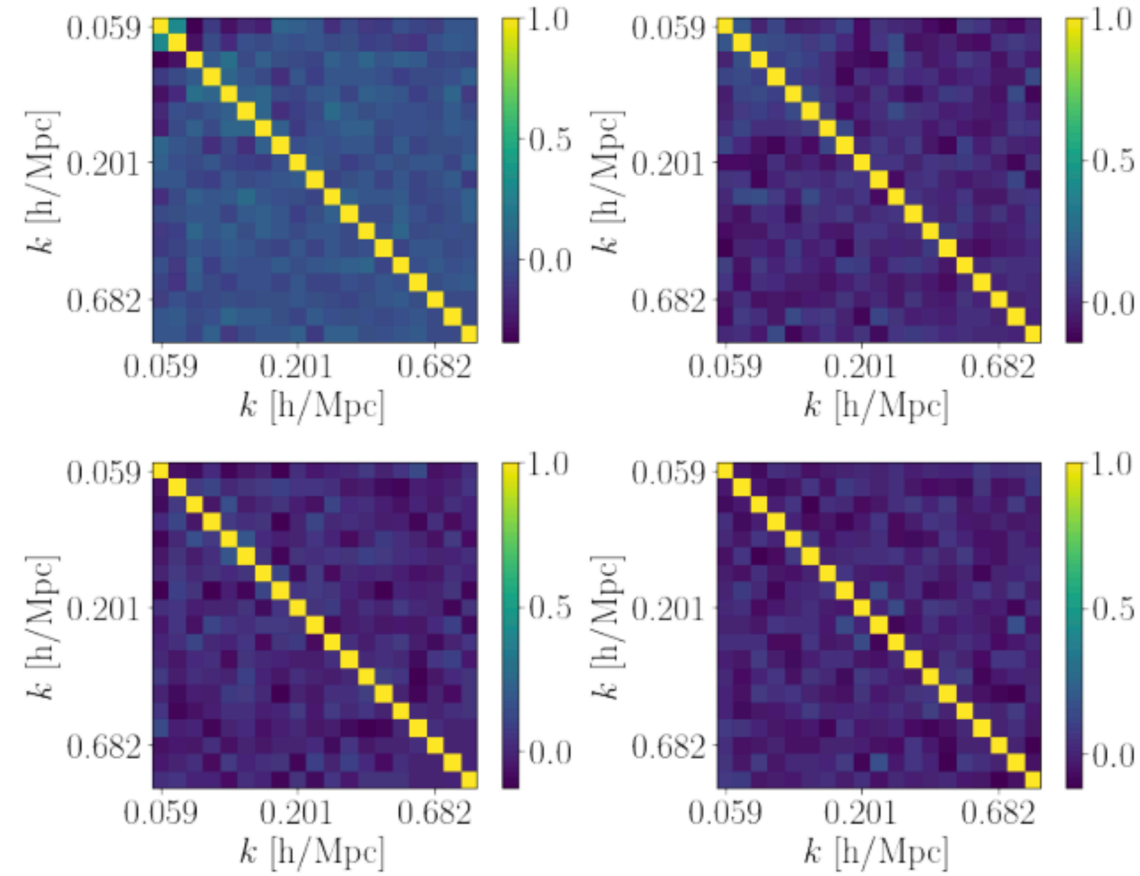


Figure B2. The covariance matrix computed from the cross-correlation of the foreground removed GBT data with WiggleZ random catalogues, as described in subsection 4.5 with clockwise increasing numbers of ICs $N_{\rm IC}$. *Upper left panel*: $N_{\rm IC}$ = 4; *Upper right panel*: $N_{\rm IC}$ = 8; *Lower left panel*: $N_{\rm IC}$ = 20; *Lower right panel*: $N_{\rm IC}$ = 36. For illustrative purposes the diagonals of the covariance matrices have been normalised to unity; i.e. the correlation matrix is pictured.