Novel cross-correlation methods

Angus "Gus" Beane (UPenn)
with: Adam Lidz (UPenn), Paco Villaescusa-Navarro (CCA)

University of Pennsylvania

HERA publishes a 21cm power spectrum at $z \sim 6$-7

How do we convince ourselves we aren't contaminated by residual foregrounds?

One option: cross-correlate with a galactic emission line
[C II], [O III], CO, Hα, etc.

Taking cross-spectra is really nice

Cross-correlations with IM of different lines is well-studied, and with current data sets best way to make measurements

[C II] x BOSS quasars (z~2.6)

Pullen, A. et al. 2018 MNRAS 478 1911
arXiv:1707.06172

21cm x DEEP2 galaxies (z~1)

Chang, T.-C. et al. 2010 Nature 466 463

Lyα x BOSS quasars (z~3)

Croft, R. et al. 2016 MNRAS 457 3541
arXiv:1504.04088

For full review, see
Kovetz et al. (2017)

$$P_{21,\text{C II}} = r_{21,\text{C II}} \sqrt{P_{21,21} P_{\text{C II},\text{C II}}}$$

what we're after

also challenging to measure (e.g. interlopers)

What if we had three fields?

$$P_{21,\mathrm{C\,II}} = r_{21,\mathrm{C\,II}}\sqrt{P_{21,21}P_{\mathrm{C\,II},\mathrm{C\,II}}}$$

$$P_{21,\mathrm{O\,III}} = r_{21,\mathrm{O\,III}}\sqrt{P_{21,21}P_{\mathrm{O\,III}}}$$

$$P_{\mathrm{C\,II},\mathrm{O\,III}} = r_{\mathrm{C\,II},\mathrm{O\,III}}\sqrt{P_{\mathrm{C\,II},\mathrm{C\,II}}P_{\mathrm{O\,III},\mathrm{O\,III}}}$$

$$\downarrow$$

only cross-spectra enter!

$$\frac{P_{21,\mathrm{C\,II}}P_{21,\mathrm{O\,III}}}{P_{\mathrm{C\,II},\mathrm{O\,III}}} = \frac{r_{21,\mathrm{C\,II}}r_{21,\mathrm{O\,III}}}{r_{\mathrm{C\,II},\mathrm{O\,III}}}P_{21,21}$$

$$\frac{P_{21,\mathrm{C\ II}} P_{21,\mathrm{O\ III}}}{P_{\mathrm{C\ II},\mathrm{O\ III}}} = \frac{r_{21,\mathrm{C\ II}} r_{21,\mathrm{O\ III}}}{r_{\mathrm{C\ II},\mathrm{O\ III}}} P_{21,21}$$

Test whether this is ~ 1 in simulation:

1.) 21cm, halo field from old 186 Mpc sims

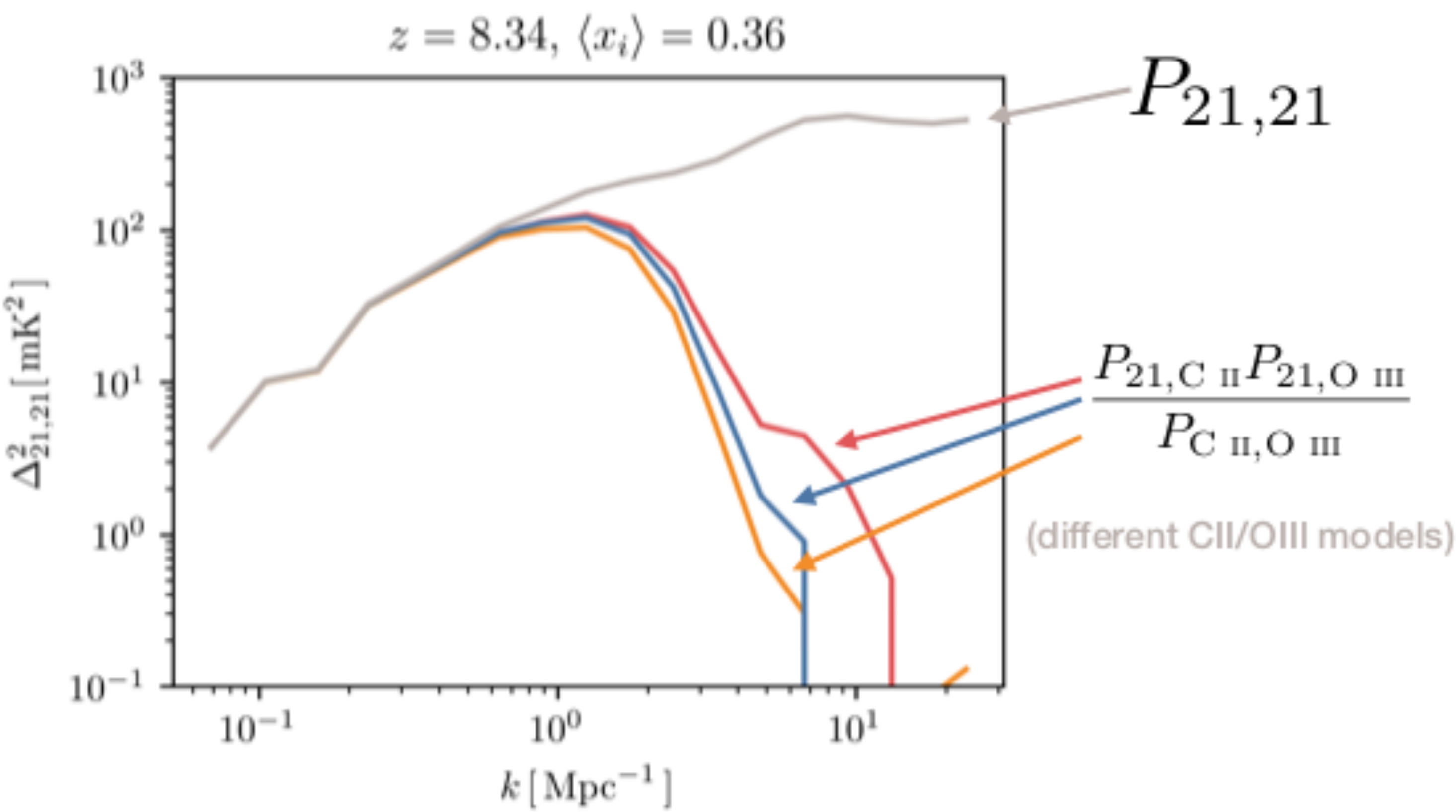
McQuinn et al. (2007) and Lidz et al. (2008)

2.) [C II], [O III] fields from simple model:

$$\langle L_i \rangle (M) = L_{i,0} \left[\frac{M}{M_0} \right]^{\alpha_i} \qquad \alpha_i = 2/3, 1, 4/3$$

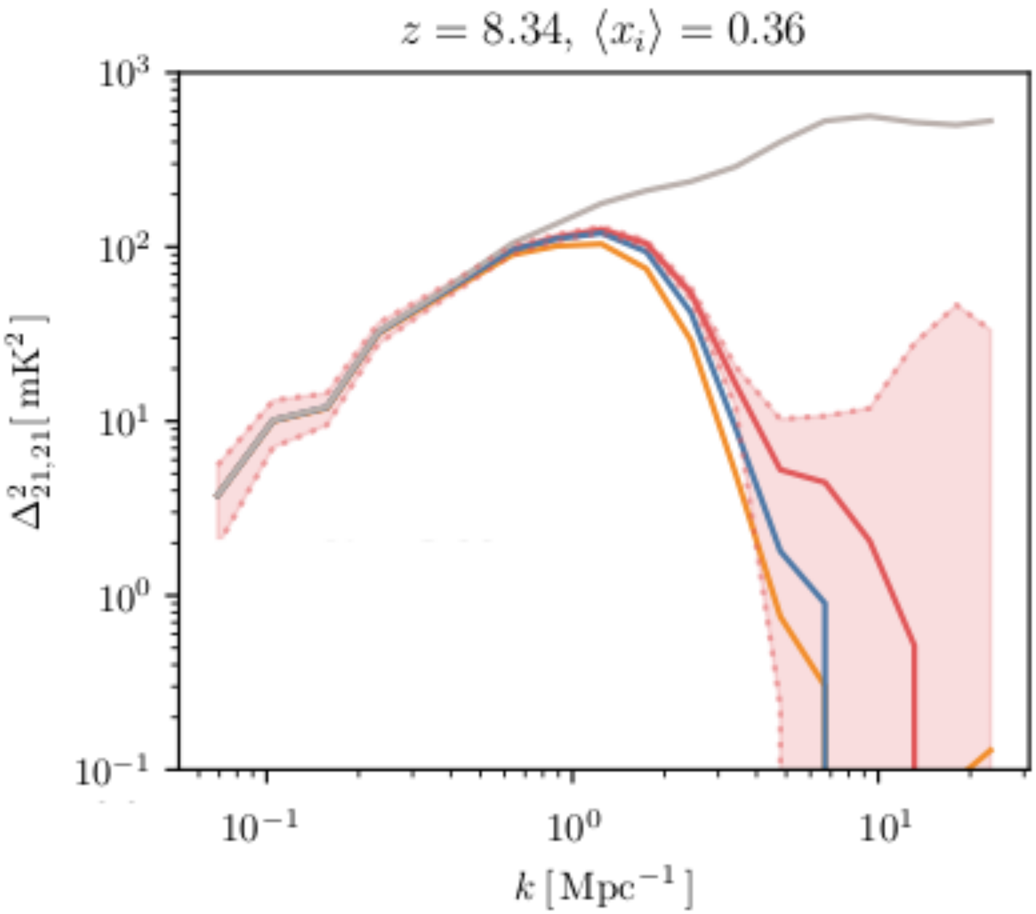
Does it work?

$$\frac{P_{21,\mathrm{C\,II}}P_{21,\mathrm{O\,III}}}{P_{\mathrm{C\,II},\mathrm{O\,III}}} = \frac{r_{21,\mathrm{C\,II}}r_{21,\mathrm{O\,III}}}{r_{\mathrm{C\,II},\mathrm{O\,III}}}P_{21,21}$$



AB, Villaescusa-Navarro, F and Lidz, A
arXiv:1811.10609

Can we detect?



futuristic survey:

[C II] and [O III] surveys of $100\,\mathrm{deg}^2$

$$N_{21} = P_{21,21}$$
$$N_{\mathrm{C\,II}} = P_{\mathrm{C\,II,C\,II}} \quad \text{at } k = 0.1\,\mathrm{Mpc}^{-1}$$
$$N_{\mathrm{O\,III}} = P_{\mathrm{O\,III,O\,III}}$$

$N_{\mathrm{C\,II}} \sim 3 \times 10^9$ if $\langle I_{\mathrm{C\,II}} \rangle = 500$

$N_{\mathrm{C\,II}} \sim 1 \times 10^8\,(\mathrm{Jy/sr})^2\,\mathrm{Mpc}^3$ if $\langle I_{\mathrm{C\,II}} \rangle = 100\,\mathrm{Jy/sr}$

$N_{\mathrm{C\,II}} \sim 4 \times 10^6$ if $\langle I_{\mathrm{C\,II}} \rangle = 20$

AB, Villaescusa-Navarro, F and Lidz, A
arXiv:1811.10609

Side-Stepping Line Confusion

Foregrounds aren't as bad as EoR 21cm case, but line confusion is a serious problem

Simple extension of our results gives another way to sidestep line confusion

SPHEREx should measure Hα, Hβ, and [O III] at $0.5 < z < 2$

What if we used three-point statistics?

$$B_{21,\mathrm{C\,II},\mathrm{C\,II}}(k_1, k_2, k_3) \equiv \langle T_{21}(k_1) I_{\mathrm{C\,II}}(k_2) I_{\mathrm{C\,II}}(k_3) \rangle$$

"reduced cross-bispectrum"

$$Q_{21,\mathrm{C\,II},\mathrm{C\,II}} \equiv \frac{B_{21,\mathrm{C\,II},\mathrm{C\,II}} + 2 \text{ perm.}}{P_{21,\mathrm{C\,II}}(k_1) P_{21,\mathrm{C\,II}}(k_2) + 2 \text{ perm.}}$$

$$\Big\downarrow$$

$$Q_{21,\mathrm{C\,II},\mathrm{C\,II}} = \frac{Q_{\delta,\delta,\delta}}{\langle T_{21} \rangle b_{21}} + C_{21,\mathrm{C\,II},\mathrm{C\,II}}$$

perturbation theory

$$Q_{21,\text{C II},\text{C II}} = \frac{Q_{\delta,\delta,\delta}}{\langle T_{21}\rangle b_{21}} + C_{21,\text{C II},\text{C II}}$$

perturbation theory

functions of k_1, k_2, θ_{12}

$$Q_{21,\mathrm{C\,II},\mathrm{C\,II}} = \frac{Q_{\delta,\delta,\delta}}{\langle T_{21}\rangle b_{21}} + C_{21,\mathrm{C\,II},\mathrm{C\,II}}$$

perturbation theory

functions of k_1, k_2, θ_{12}

$$Q_{21,\text{C II},\text{C II}} = \frac{Q_{\delta,\delta,\delta}}{\langle T_{21}\rangle b_{21}} + C_{21,\text{C II},\text{C II}}$$

constant

perturbation theory

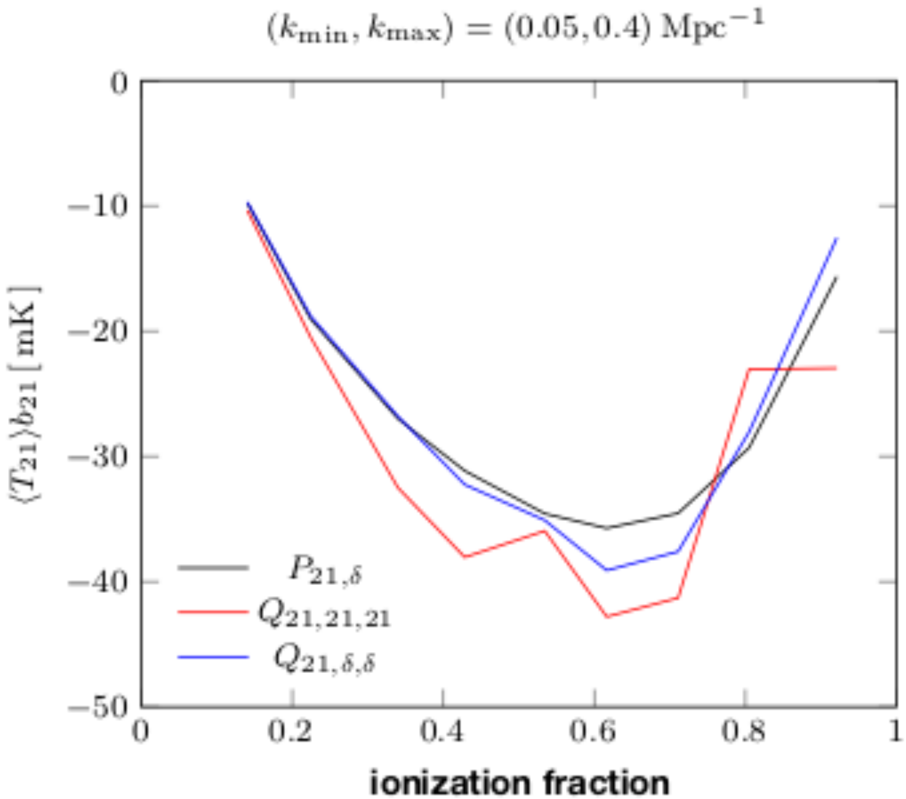
simulate this

$$Q_{21,\text{C II},\text{C II}} = \frac{Q_{\delta,\delta,\delta}}{\langle T_{21} \rangle b_{21}} + C_{21,\text{C II},\text{C II}}$$

measure this

fit these

Does it work?

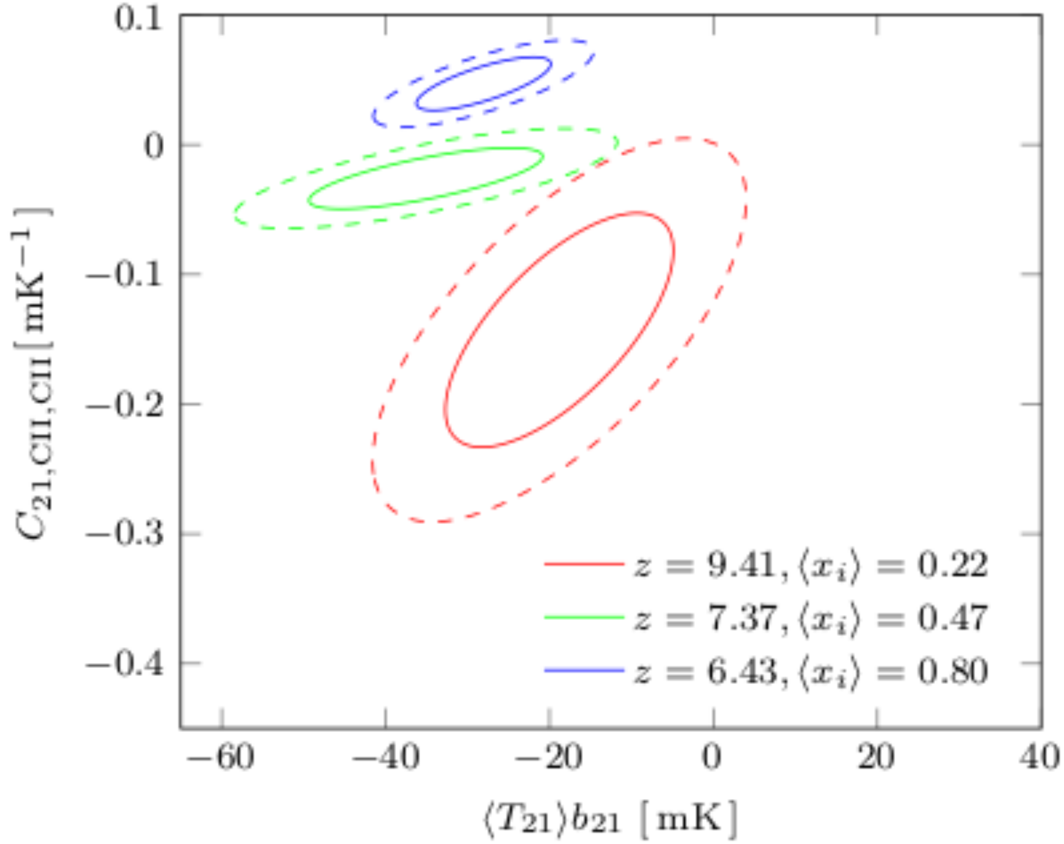


Only uses large triangles

Simulations are noisy

AB and Lidz, A 2018 ApJ 867 26
arXiv:1806.02796

Can we detect?



futuristic survey:

[C II] survey of $50\,\mathrm{deg}^2$

$$N_{21} = P_{21,21}$$
$$N_{\mathrm{C\,II}} = P_{\mathrm{C\,II},\mathrm{C\,II}} \quad \text{at } k = 0.1\,\mathrm{Mpc}^{-1}$$

AB and Lidz, A 2018 ApJ 867 26
arXiv:1806.02796

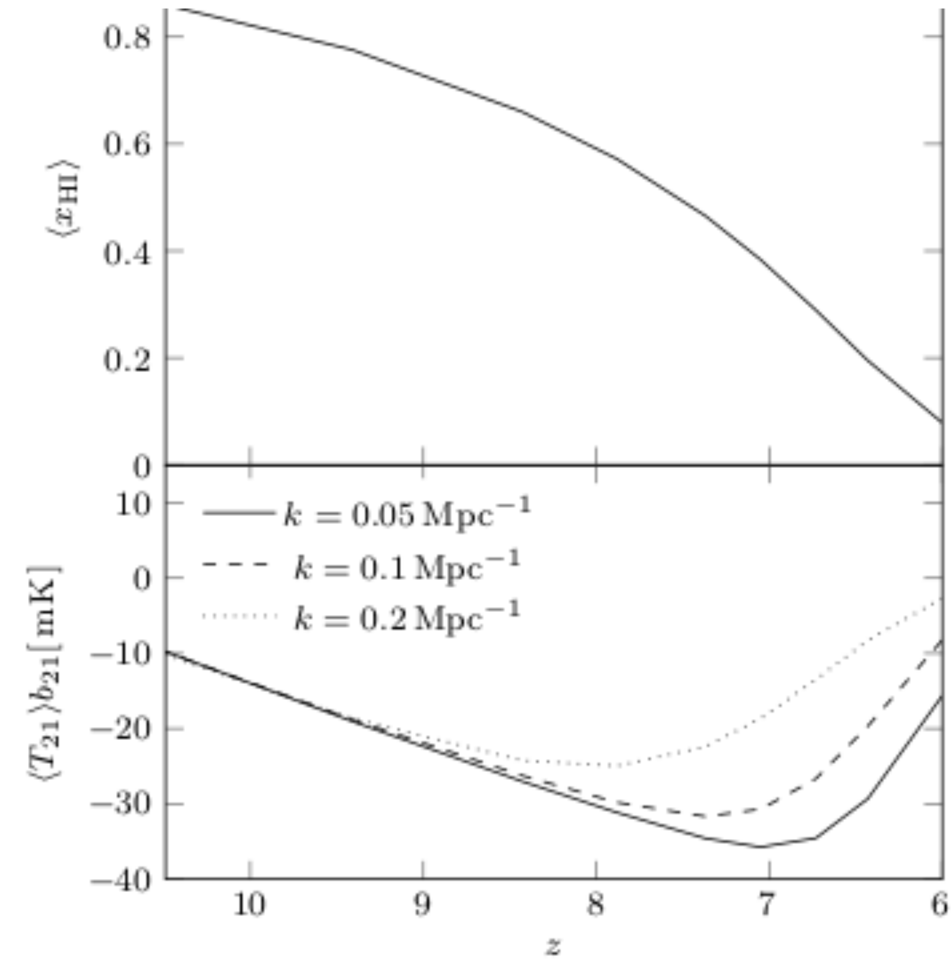
Summary

- Want to **confirm** our 21cm power spectrum measurement
  - Have to make sure we aren't biased by residual foregrounds
  - Can directly estimate 21cm power spectrum <u>on large scales</u> with: a.) three field approach, b.) cross-bispectrum
  - Measurements may be in reach of next generation surveys

- Question: If you have measurements of multiple fields which are biased tracers of the underlying density field, what is the optimal way to extract information on the density field?

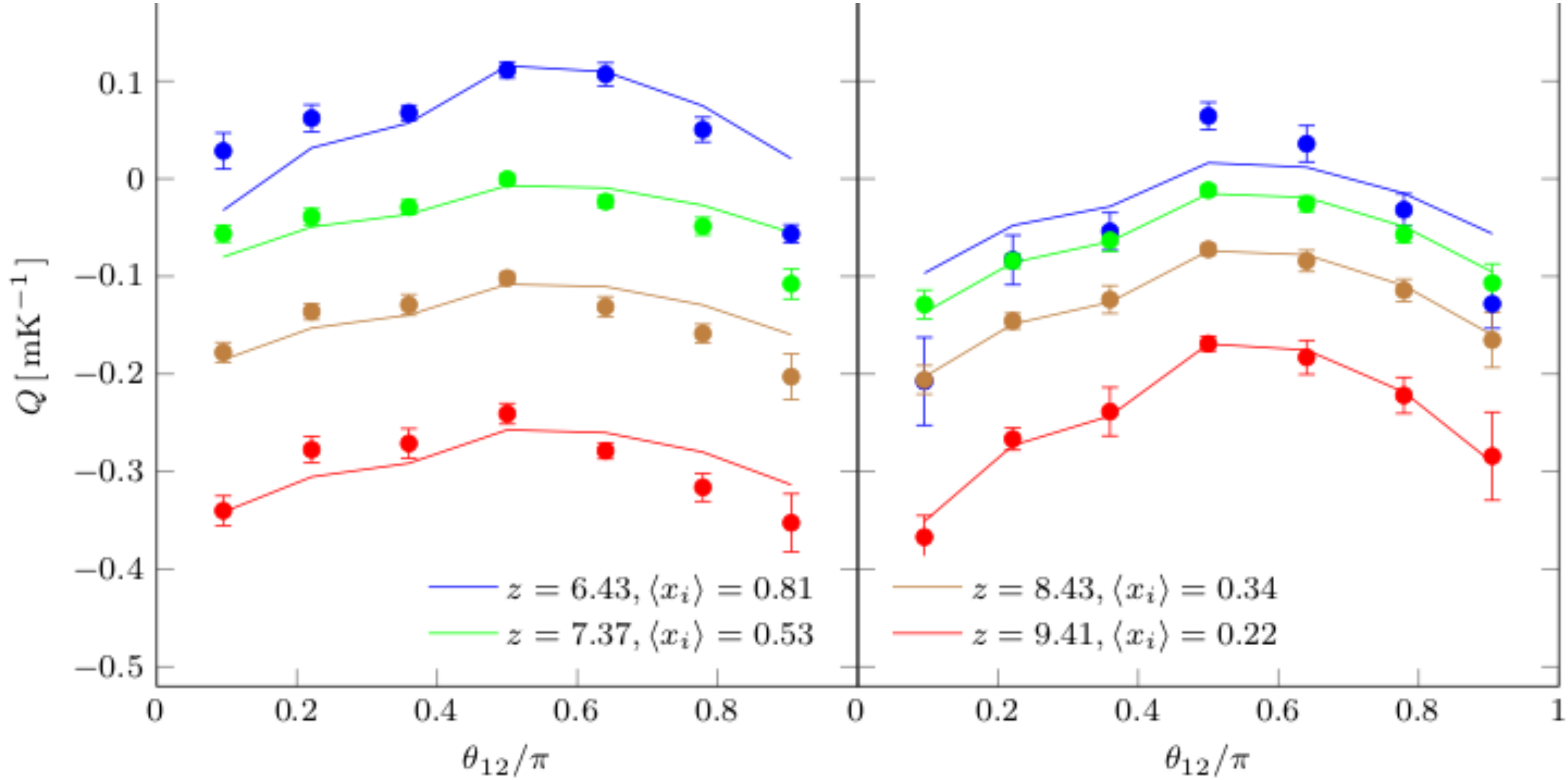
https://gusbeane.github.io

$$C_{21,\mathrm{C\,II},\mathrm{C\,II}} = \frac{1}{6}\frac{b_{21}^{(2)}}{b_{21}^{2}} + \frac{1}{3}\frac{b_{\mathrm{C\,II}}^{(2)}}{b_{21}b_{\mathrm{C\,II}}}$$



$\langle x_{\mathrm{HI}} \rangle$
0.8
0.6
0.4
0.2
0
10
0
−10
−20
−30
−40
$\langle T_{21} \rangle b_{21}$ [mK]
$k = 0.05\,\mathrm{Mpc}^{-1}$
$k = 0.1\,\mathrm{Mpc}^{-1}$
$k = 0.2\,\mathrm{Mpc}^{-1}$
10
9
8
7
6
z

$Q_{21,21,21}$
$Q_{21,\delta,\delta}$
0.2

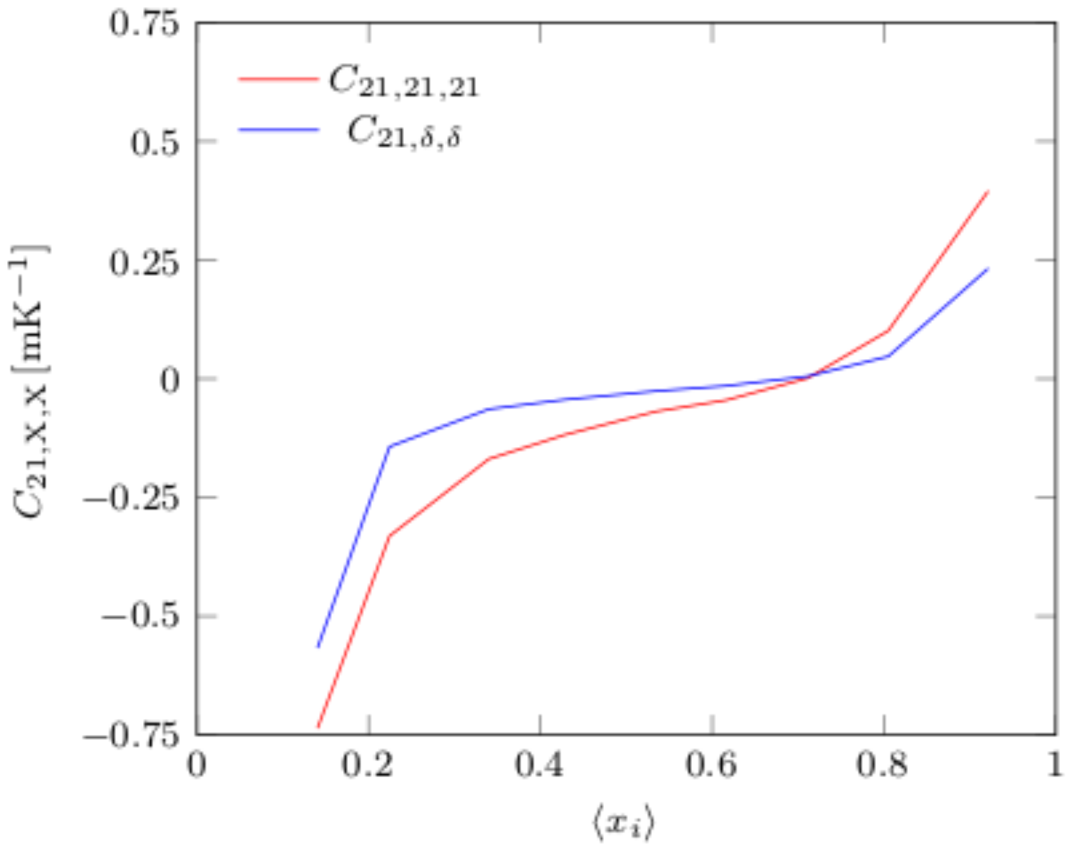

$Q\,[\mathrm{mK}^{-1}]$
θ_{12}/π
θ_{12}/π
$z = 6.43, \langle x_i \rangle = 0.81$
$z = 7.37, \langle x_i \rangle = 0.53$
$z = 8.43, \langle x_i \rangle = 0.34$
$z = 9.41, \langle x_i \rangle = 0.22$

$$C_{21,21,21} = \frac{1}{2}\frac{b_{21}^{(2)}}{\langle T_{21}\rangle b_{21}^2},$$

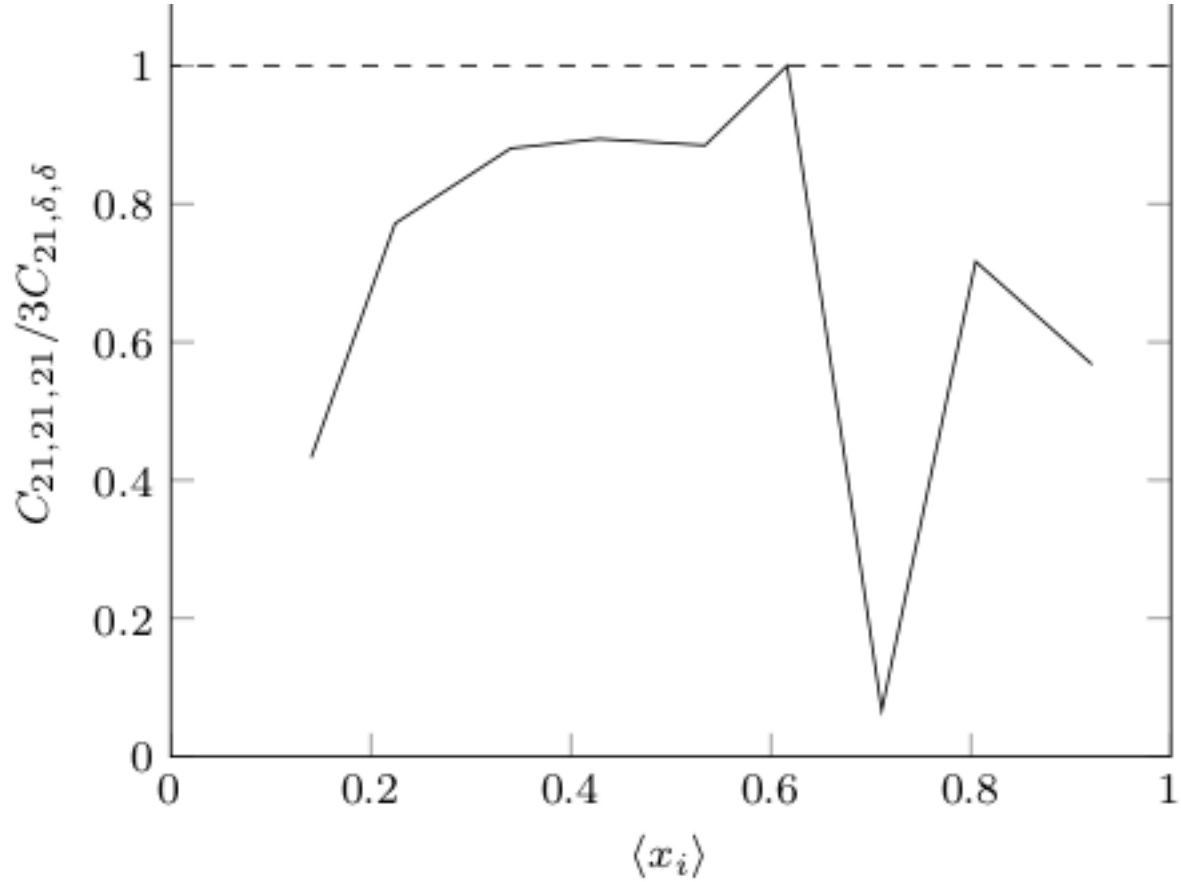
$$C_{21,\delta,\delta} = \frac{1}{6}\frac{b_{21}^{(2)}}{\langle T_{21}\rangle b_{21}^2},$$

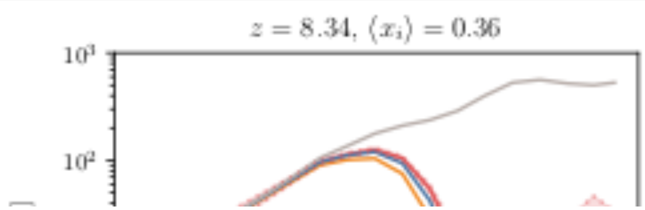
$$C_{21,\mathrm{CII},\mathrm{CII}} = \frac{1}{6}\frac{b_{21}^{(2)}}{\langle T_{21}\rangle b_{21}^2} + \frac{1}{3}\frac{b_{\mathrm{CII}}^{(2)}}{\langle T_{21}\rangle b_{21} b_{\mathrm{CII}}}.$$

$(k_{\min}, k_{\max}) = (0.05, 0.4)\,\mathrm{Mpc}^{-1}$

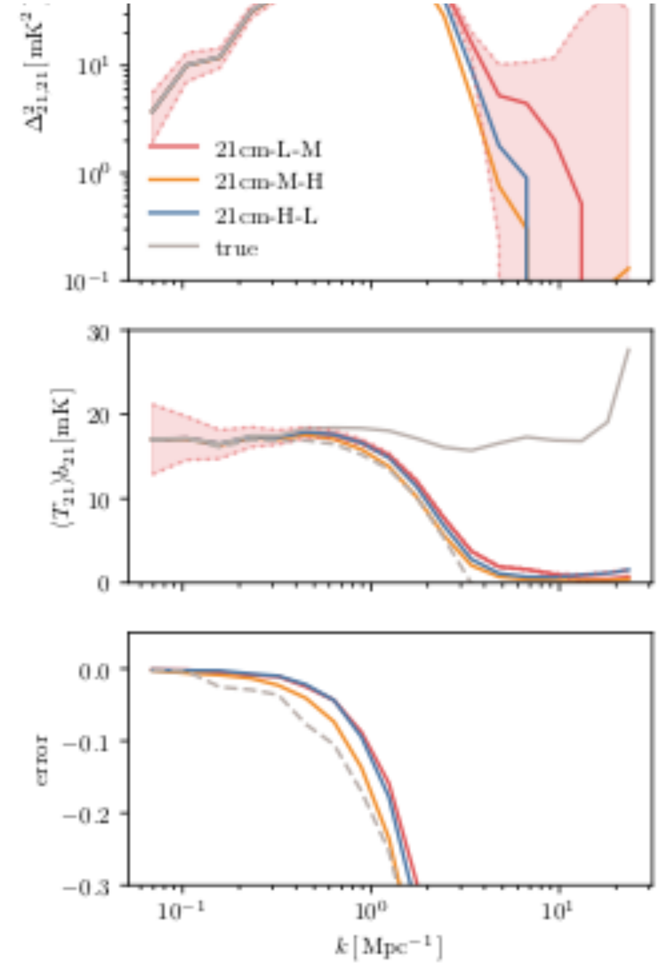

0.75
0.5
0.25
0
−0.25
−0.5
−0.75
0
0.2
0.4
0.6
0.8
1
$C_{21,21,21}$
$C_{21,\delta,\delta}$
$C_{21,\mathrm{x},\mathrm{x}}\,[\mathrm{mK}^{-1}]$
$\langle x_i \rangle$


1.2

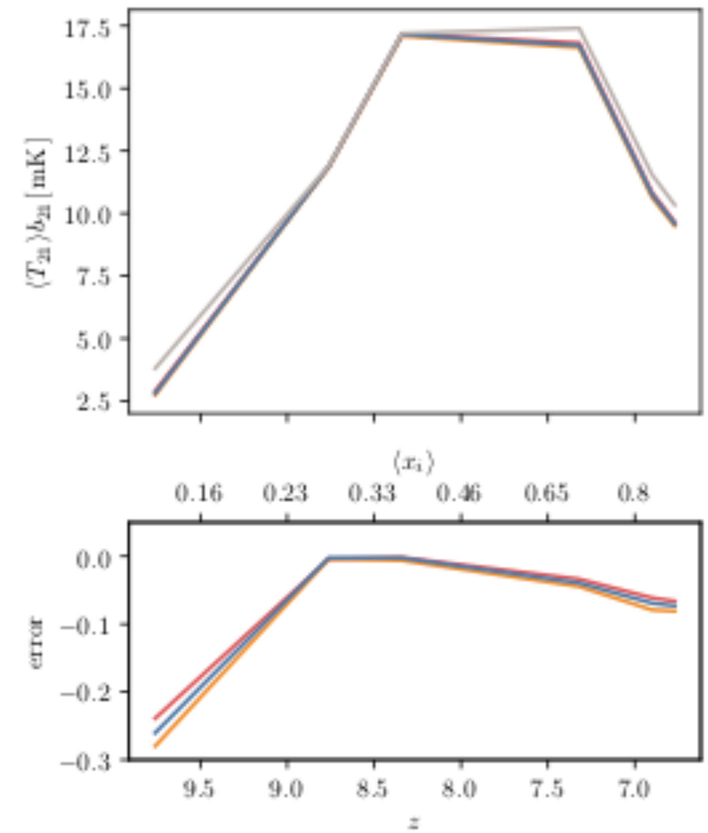




$k = 0.10\,\mathrm{Mpc}^{-1}$



$\Delta^2_{21,21}$ [mK^2
21cm-L-M
21cm-M-H
21cm-H-L
true
$\langle T_{21}\rangle b_{21}$ [mK]
error
k [Mpc^{-1}]



$\langle T_{21}\rangle b_{21}$ [mK]
$\langle x_i \rangle$
error
z