The University of Manchester
Jodrell Bank Centre for Astrophysics

Interferometric Intensity Mapping in Low-Redshift Universe

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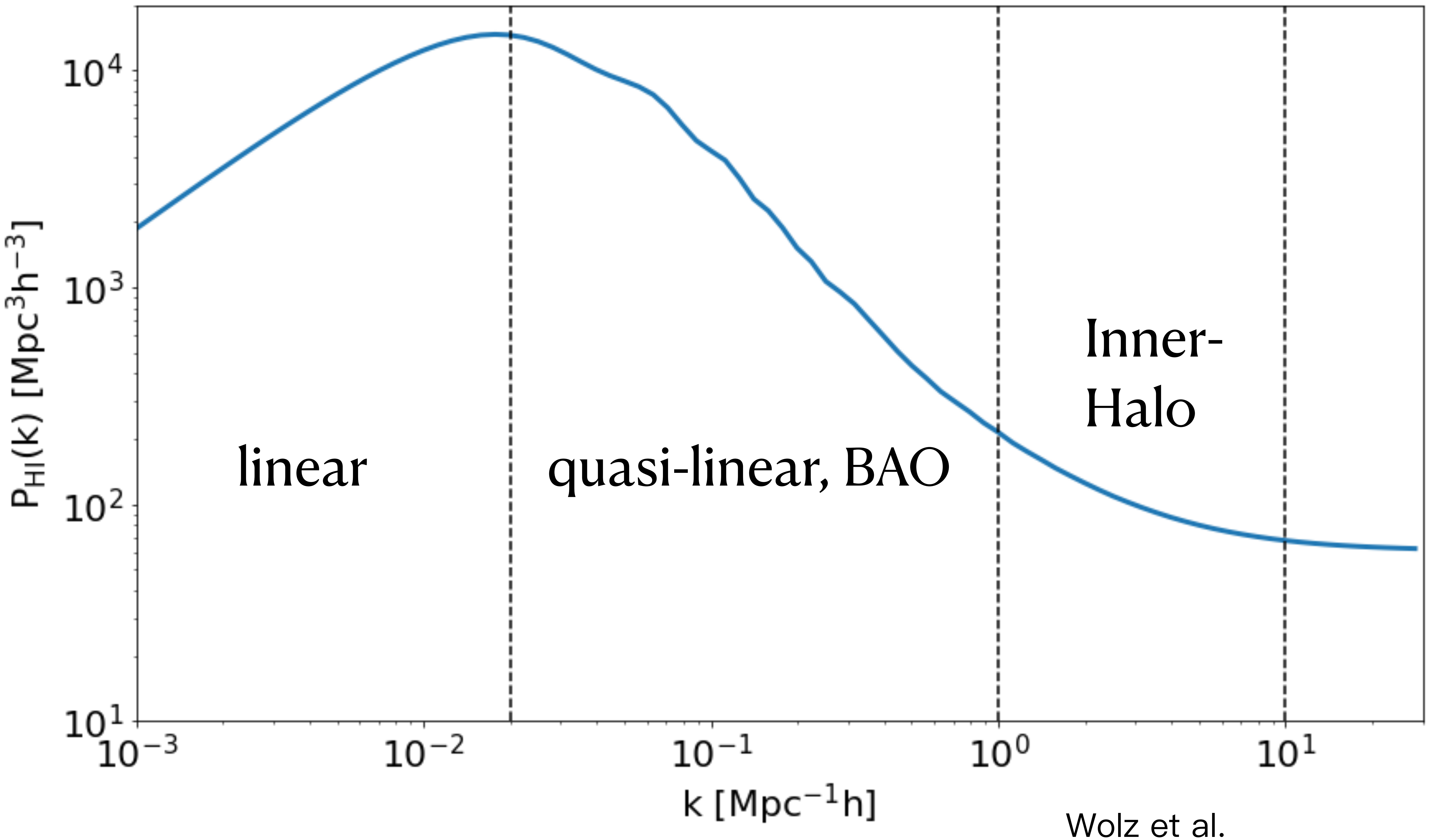
with Laura Wolz and Richard Battye

HITS 2022

Interferometer at z<2: Astrophysical Scales



Shot
Noise

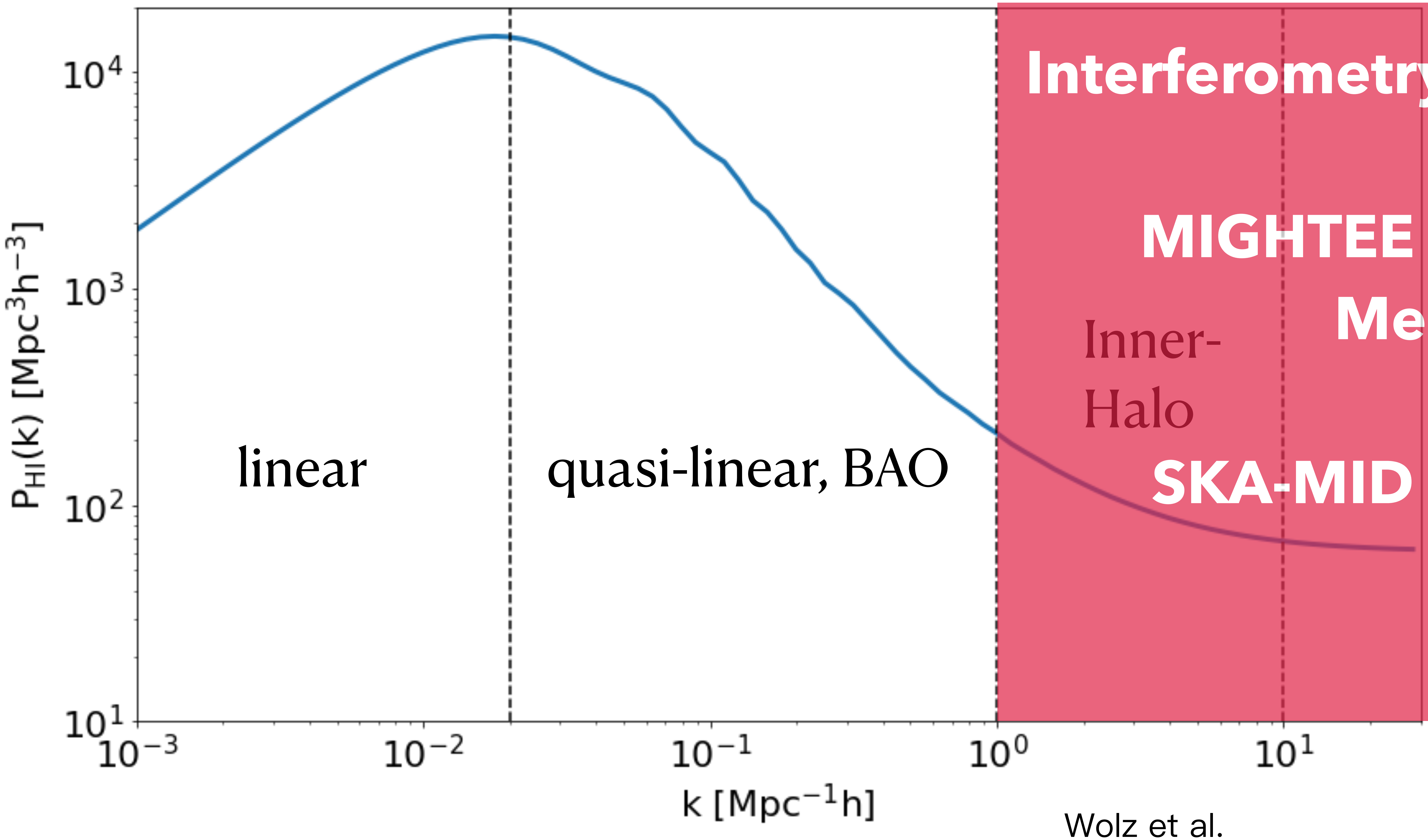
Wolz et al.
1703.08268

Soares et al.
2008.12102

Obuljen et al.
1610.05768

Wolz et al.
1803.02477
Chen et al.
2010.07985

Interferometer at z<2: Astrophysical Scales



Interferometry at low redshifts

MIGHTEE survey using MeerKAT

SKA-MID in the future

Wolz et al.
1703.08268

Soares et al.
2008.12102

Obuljen et al.
1610.05768

Wolz et al.
1803.02477
Chen et al.
2010.07985

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Outline

- 1. A case study of HI IM with MIGHTEE. (Astrophysical interpretation of HI power spectrum)

- 2. Some ongoing/future work

Interferometry

- For an instrument with primary beam response A(l,m,f), baseline (u,v,w) at frequency f sees the sky I(l,m,f) with the visibility:

$$V(u,v,w,f) = \int \frac{\mathrm{d}l\,\mathrm{d}m}{\sqrt{1-l^2-m^2}} I(l,m,f)A(l,m,f)\exp\left[-2\pi i\left(lu+mv+(1-n)w\right)\right],$$

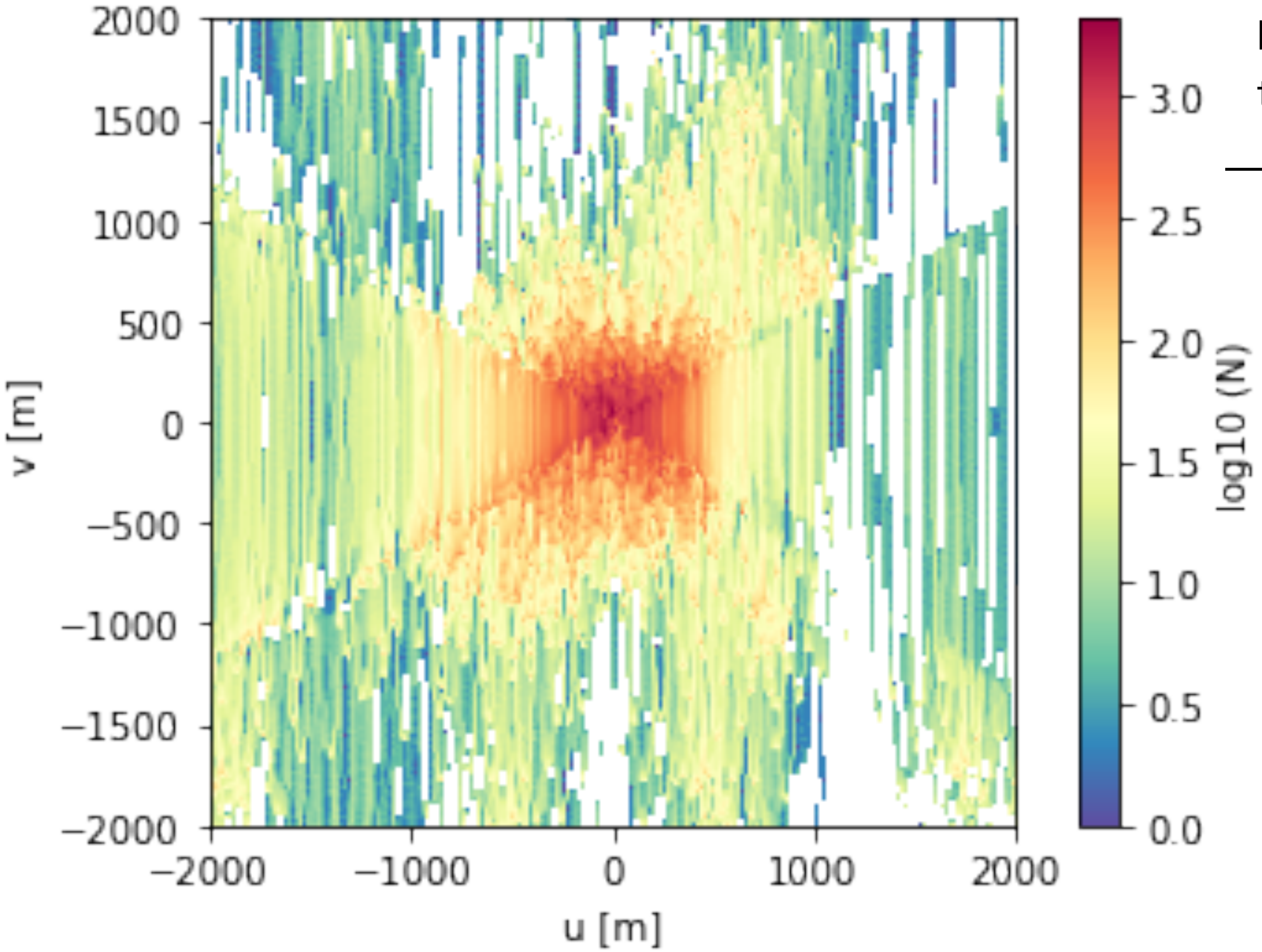
- Fourier-Transform along the frequency axis (and coordinate transformation):

$$\tilde{V}(u,v,\eta) \approx \frac{1}{X^2Y}\int \mathrm{d}r_x\mathrm{d}r_y\mathrm{d}r_z\; I(l,m,f)A(l,m,f)\exp\left[-2\pi i\left(lu+mv+f\eta\right)\right]),$$

$$\tilde{V}(u,v,\eta) \approx \left[\tilde{I}*\tilde{A}\right](k_x=\frac{2\pi u}{X}, k_y=\frac{2\pi v}{X}, k_{\parallel}=\frac{2\pi\eta}{Y})$$

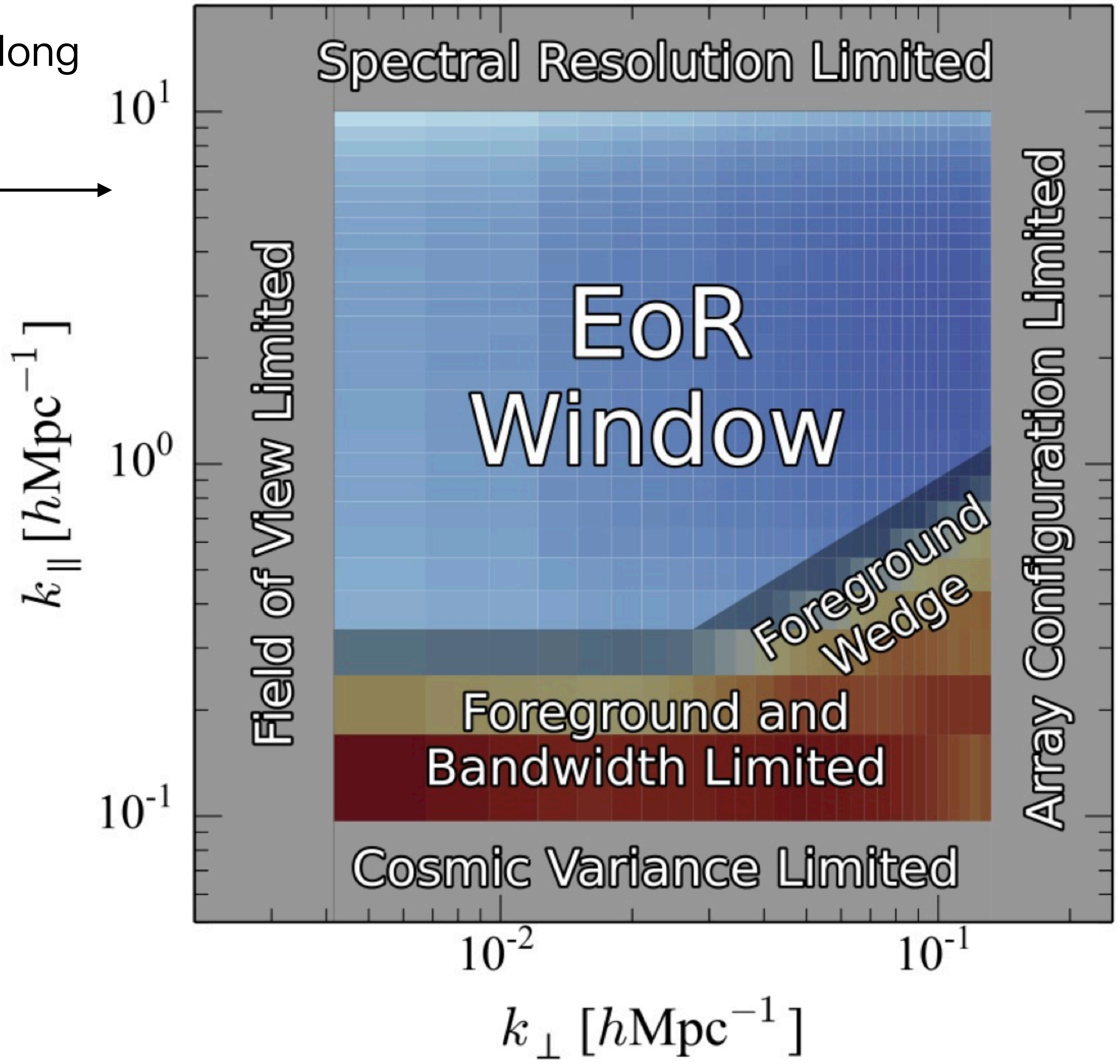
The Old Folklore

Visibility ~ 2–D Fourier modes of HI density



Delay Transform along the frequency axis

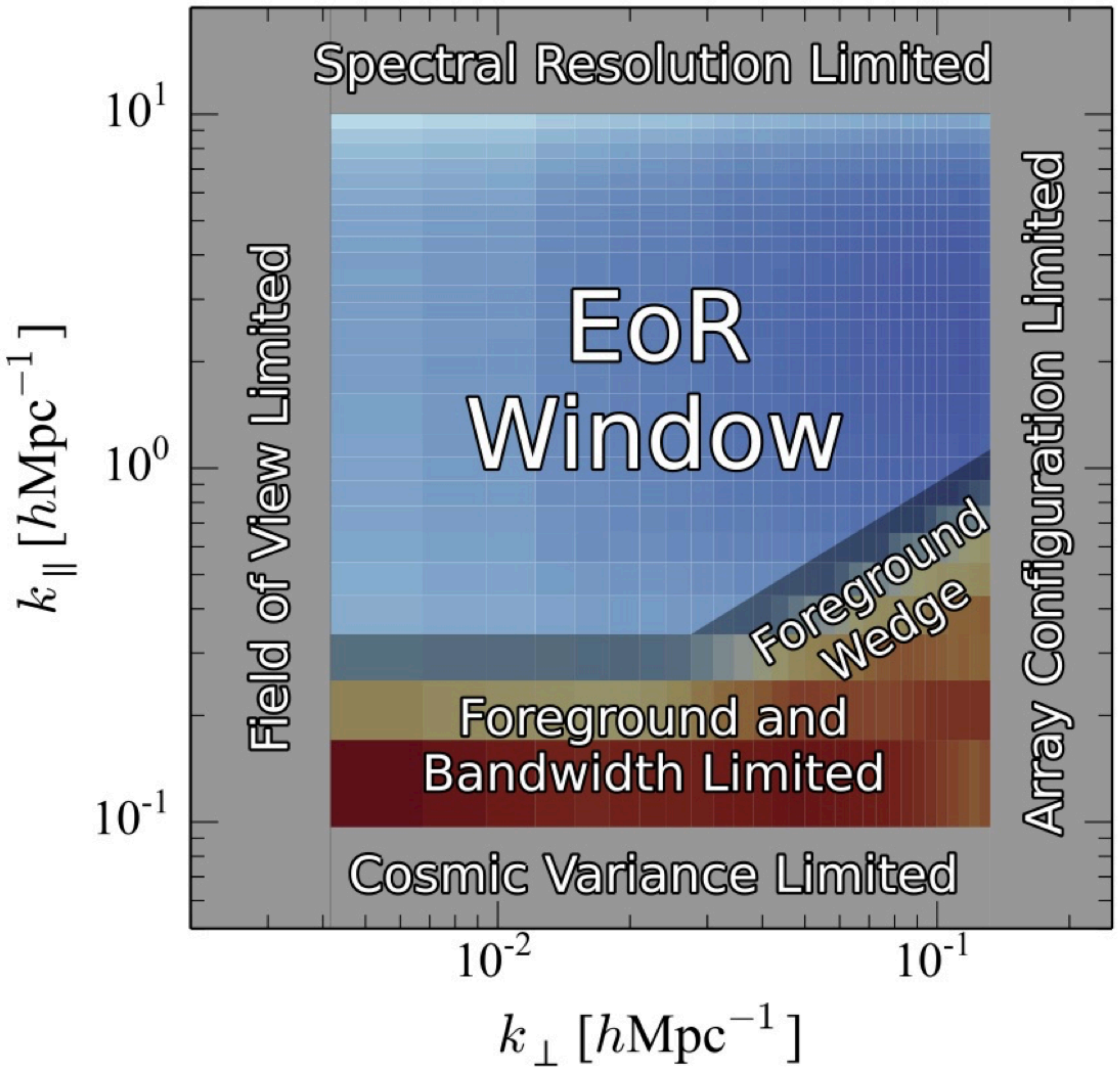
3–D cylindrical power spectrum



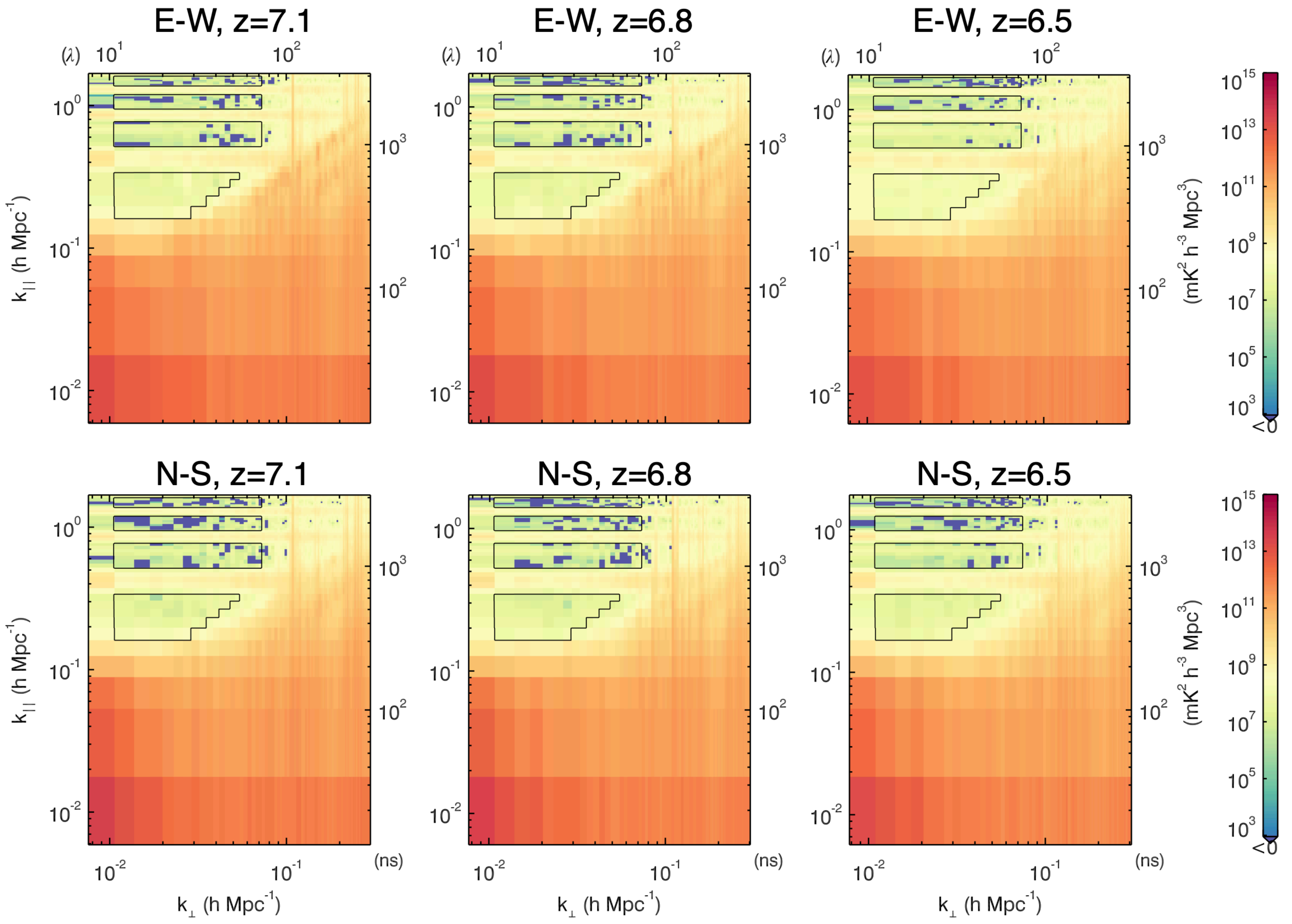
Liu, Parsons, and Trott 1404.2596

What's New (for low redshift)?

- 1. Is there an observational window? How large is it?



Liu, Parsons, and Trott 1404.2596

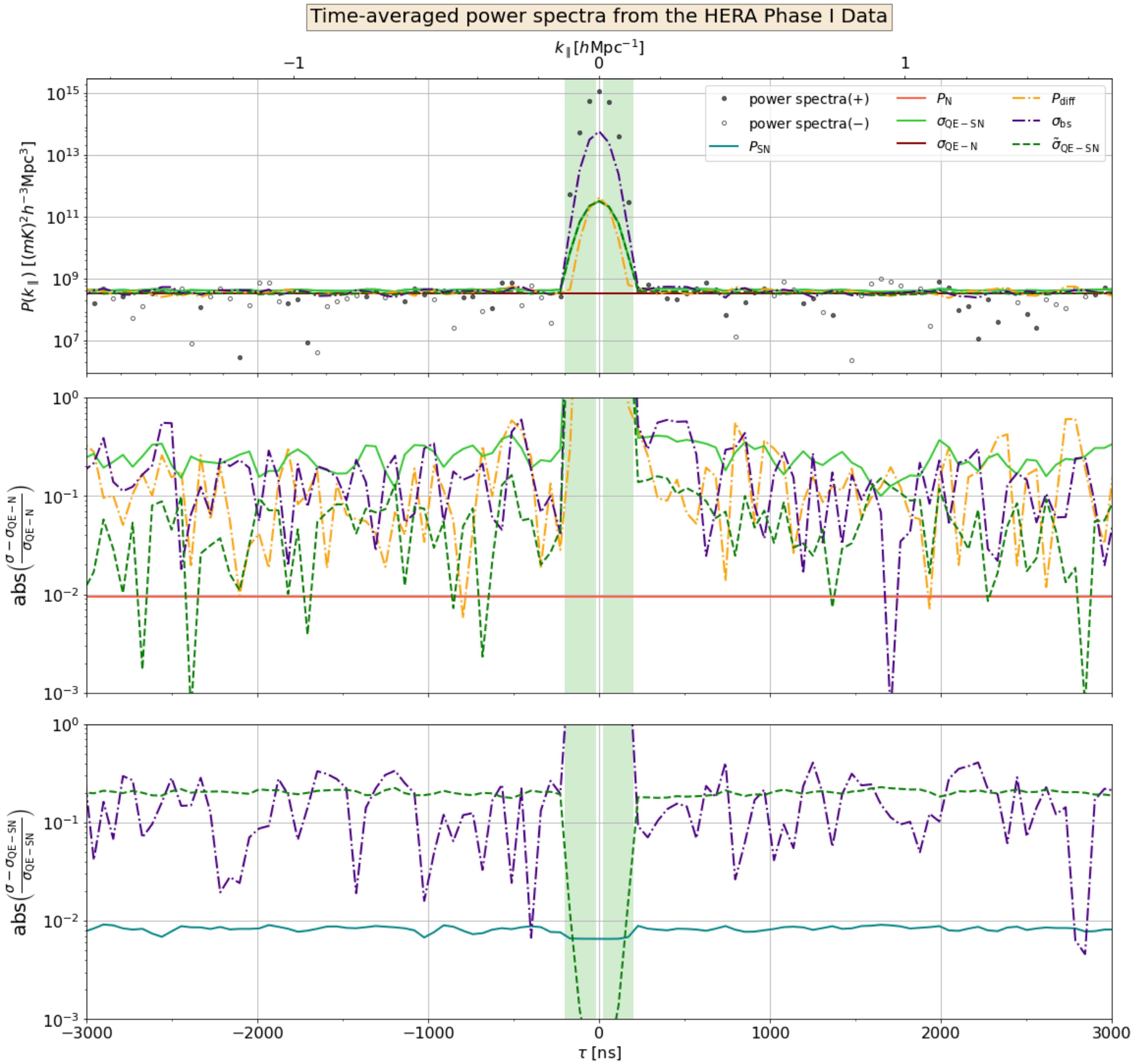


Beardsley et al. 1608.06281

What's New (for low redshift)?

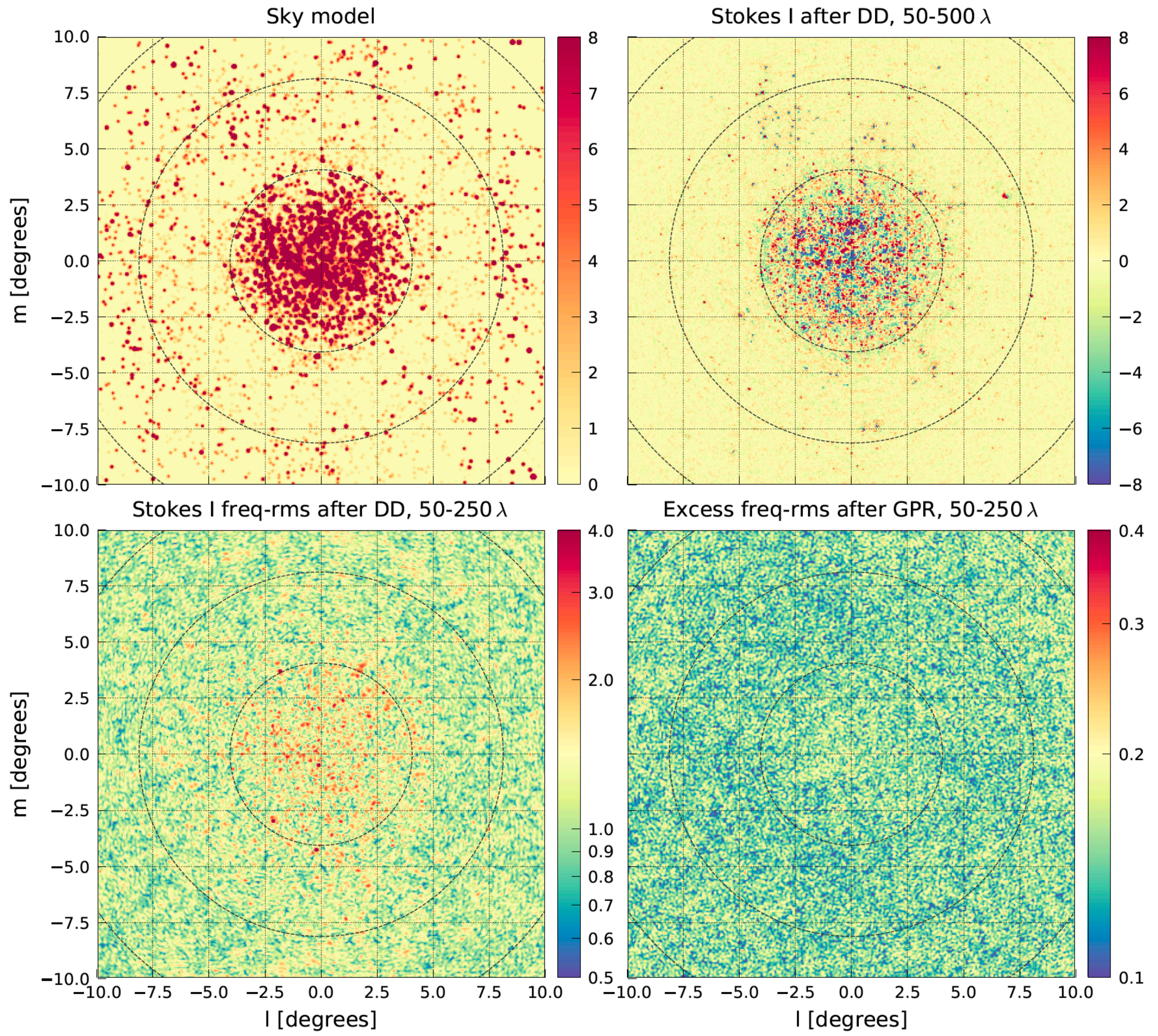
- 2. Power Spectrum from visibility? or image?

METHODS OF ERROR ESTIMATION FOR 21 CM DELAY POWER SPECTRA 19



Tan et al. 2103.09941

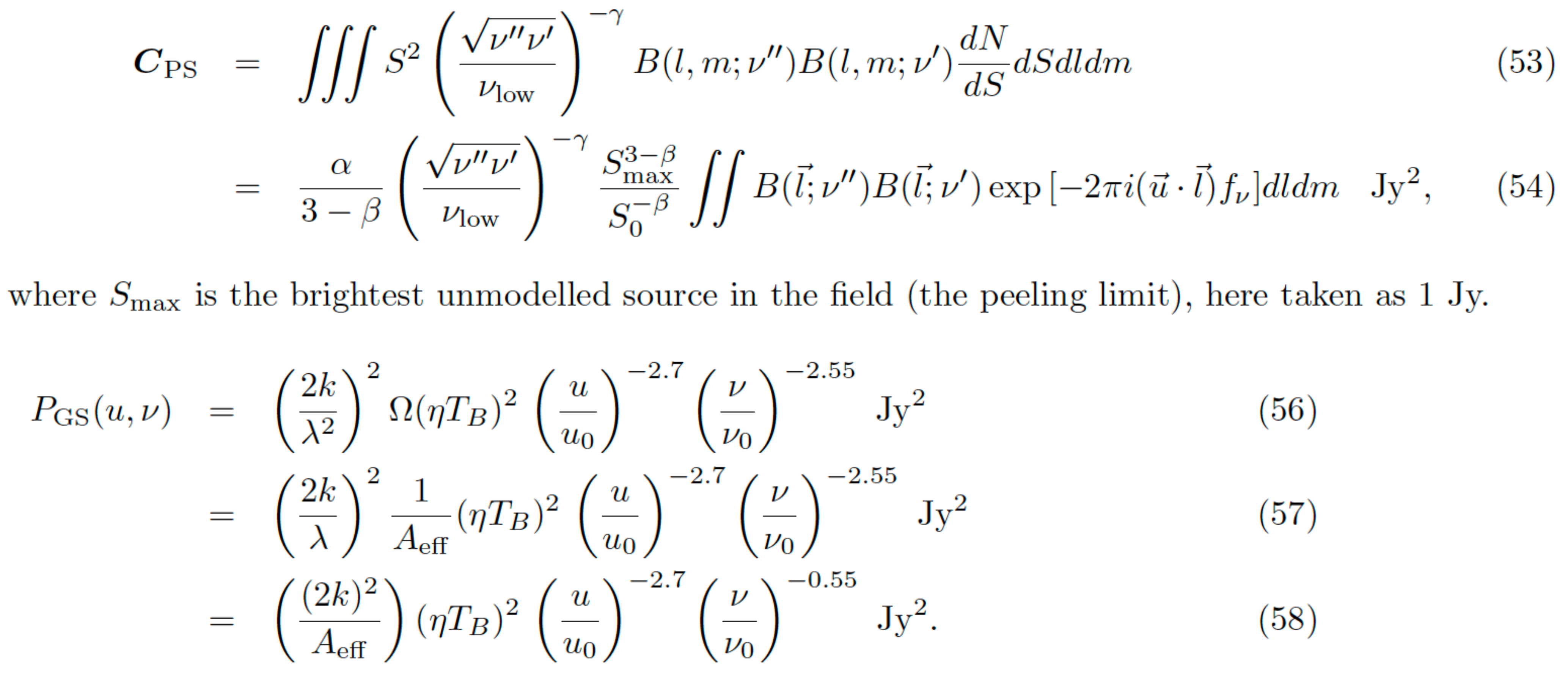
LOFAR-EoR 21-cm power spectrum upper limit 21



Mertens et al. 2002.07196

What's New (for low redshift)?

- 3. Avoidance? Foreground Mitigation?



$$C_{\mathrm{PS}} = \iiint S^2 \left(\frac{\sqrt{\nu''\nu'}}{\nu_{\mathrm{low}}}\right)^{-\gamma} B(l,m;\nu'')B(l,m;\nu')\frac{dN}{dS}\,dS\,dl\,dm \qquad (53)$$

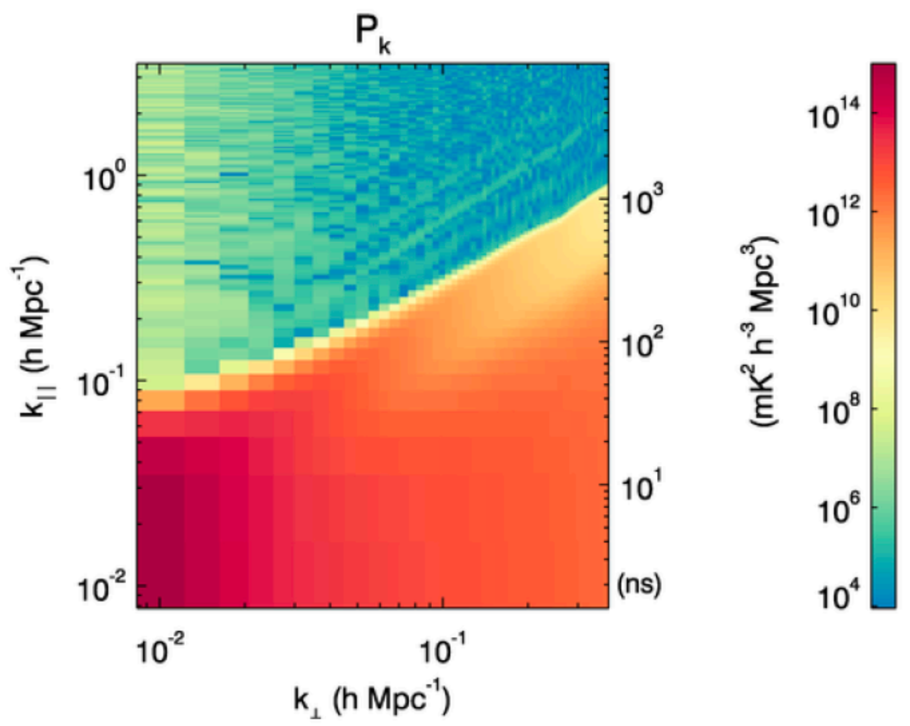
$$= \frac{\alpha}{3-\beta}\left(\frac{\sqrt{\nu''\nu'}}{\nu_{\mathrm{low}}}\right)^{-\gamma}\frac{S_{\mathrm{max}}^{3-\beta}}{S_0^{-\beta}}\iint B(\vec{l};\nu'')B(\vec{l};\nu')\exp\left[-2\pi i(\vec{u}\cdot\vec{l})f_\nu\right]dl\,dm \quad \mathrm{Jy}^2, \qquad (54)$$

where S_{max} is the brightest unmodelled source in the field (the peeling limit), here taken as 1 Jy.

$$P_{\mathrm{GS}}(u,\nu) = \left(\frac{2k}{\lambda^2}\right)^2 \Omega(\eta T_B)^2 \left(\frac{u}{u_0}\right)^{-2.7}\left(\frac{\nu}{\nu_0}\right)^{-2.55} \mathrm{Jy}^2 \qquad (56)$$

$$= \left(\frac{2k}{\lambda}\right)^2 \frac{1}{A_{\mathrm{eff}}}(\eta T_B)^2 \left(\frac{u}{u_0}\right)^{-2.7}\left(\frac{\nu}{\nu_0}\right)^{-2.55} \mathrm{Jy}^2 \qquad (57)$$

$$= \left(\frac{(2k)^2}{A_{\mathrm{eff}}}\right)(\eta T_B)^2 \left(\frac{u}{u_0}\right)^{-2.7}\left(\frac{\nu}{\nu_0}\right)^{-0.55} \mathrm{Jy}^2. \qquad (58)$$



(b) Foreground model.

Trott et al. 1601.02073

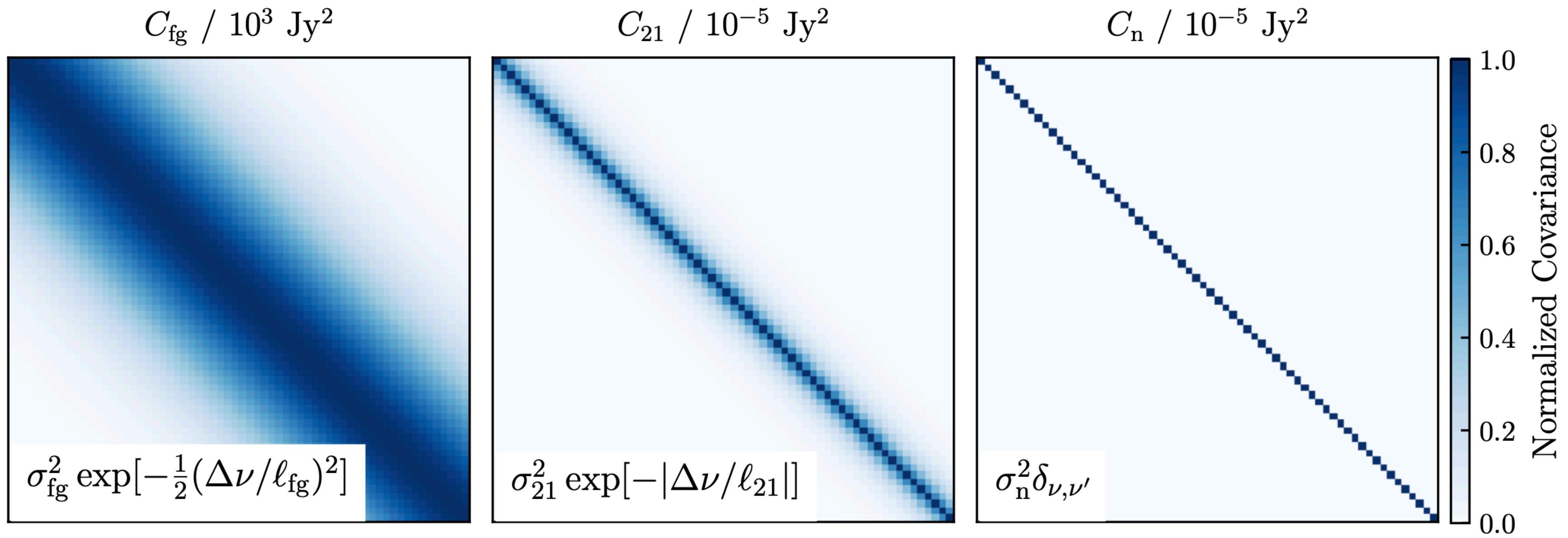
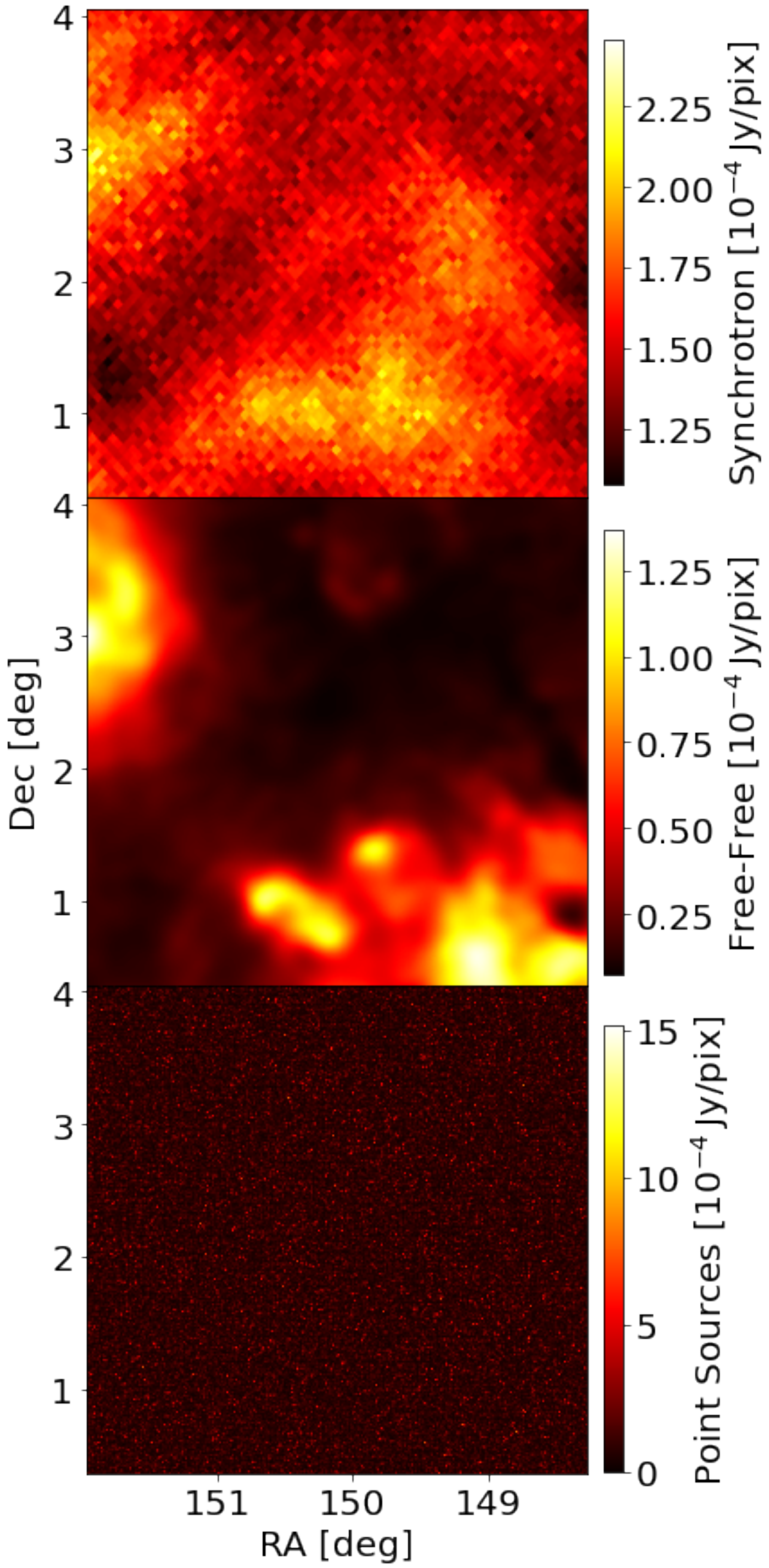


Figure 1. The covariance of the foregrounds, EoR, and noise components of our analytic data simulations in section 3. Parameters for the foreground covariance ($\sigma_{\mathrm{fg}}^2 = 10^2$ Jy^2, $\ell_{\mathrm{fg}} = 4$ MHz) are selected to be roughly characteristic of HERA data. The EoR covariance parameters ($\sigma_{21}^2 = 10^{-5}$ Jy^2, $\ell_{\mathrm{fg}} = 0.75$ MHz) are selected to be roughly in line with fiducial theoretical expectations (Mertens et al. 2018), and the noise is artificially selected depending on the amount of integration assumed for the data.

Kern & Liu 2010.15892

Simulation Pipeline

Chen, Wolz & Battye,
2205.07776



- MeerKAT configuration, 220 frequency channels at z~0.25-0.30.

- 1. Foreground simulation following the statistics of MIGHTEE Deep2 field (Matthews et al. 2101.07827) and other components.

Simulation Pipeline

- 2. Log-normal HI galaxy simulation with lightcone.

Wolz et al. 1803.02477

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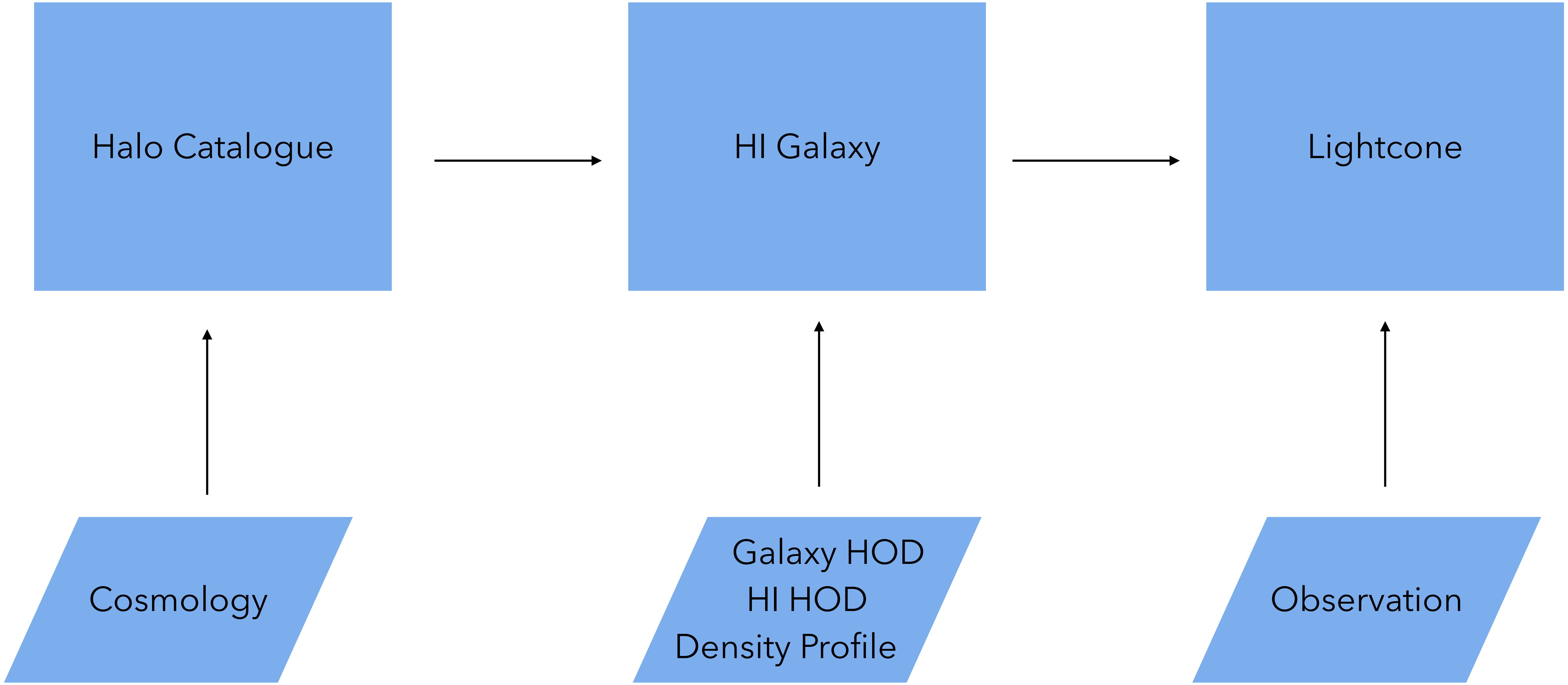
Simulation Pipeline

- 2. Log-normal HI galaxy simulation with lightcone.

Wolz et al. 1803.02477



Halo Catalogue

HI Galaxy

Lightcone

Cosmology

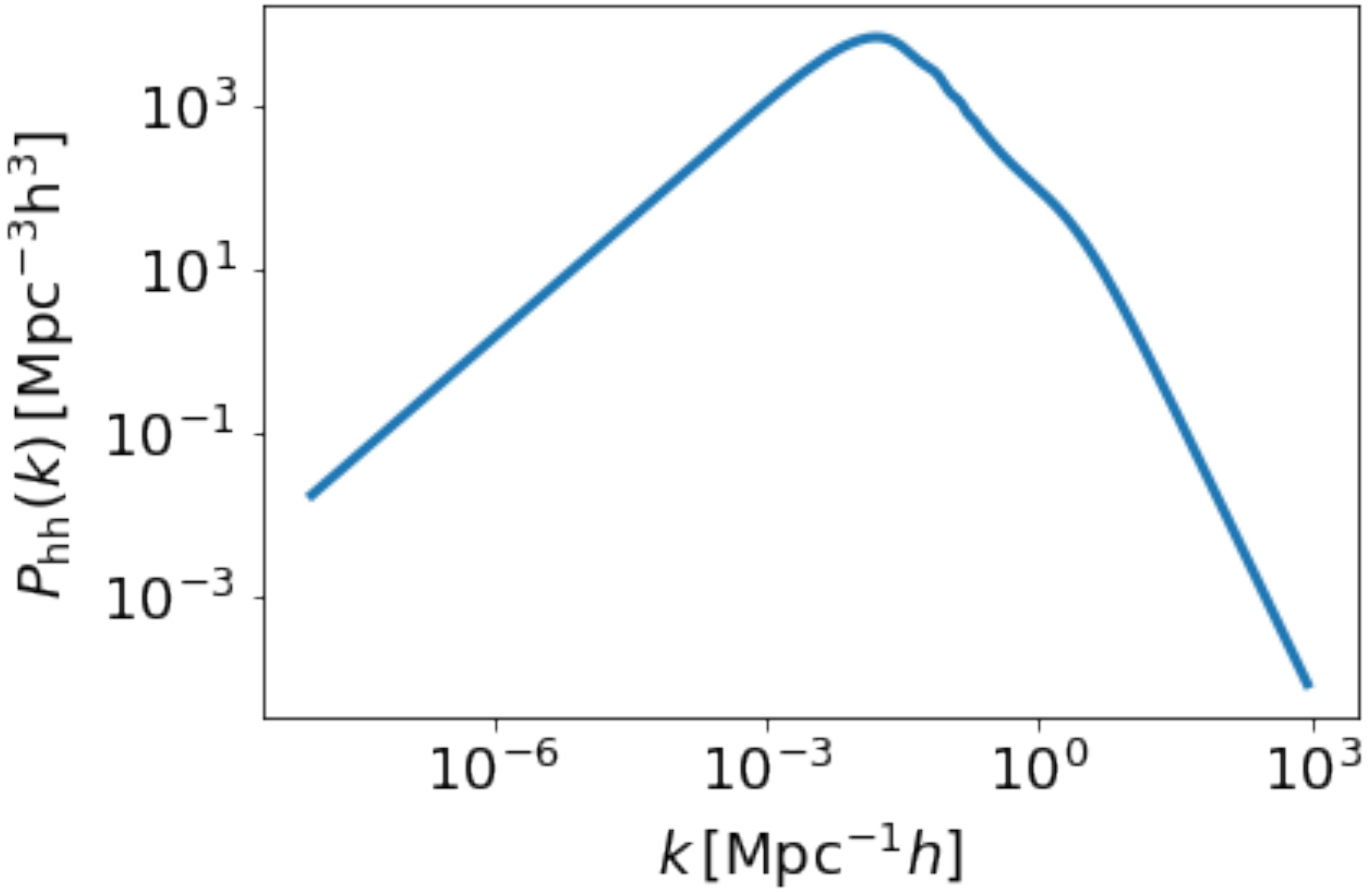
Galaxy HOD
HI HOD
Density Profile

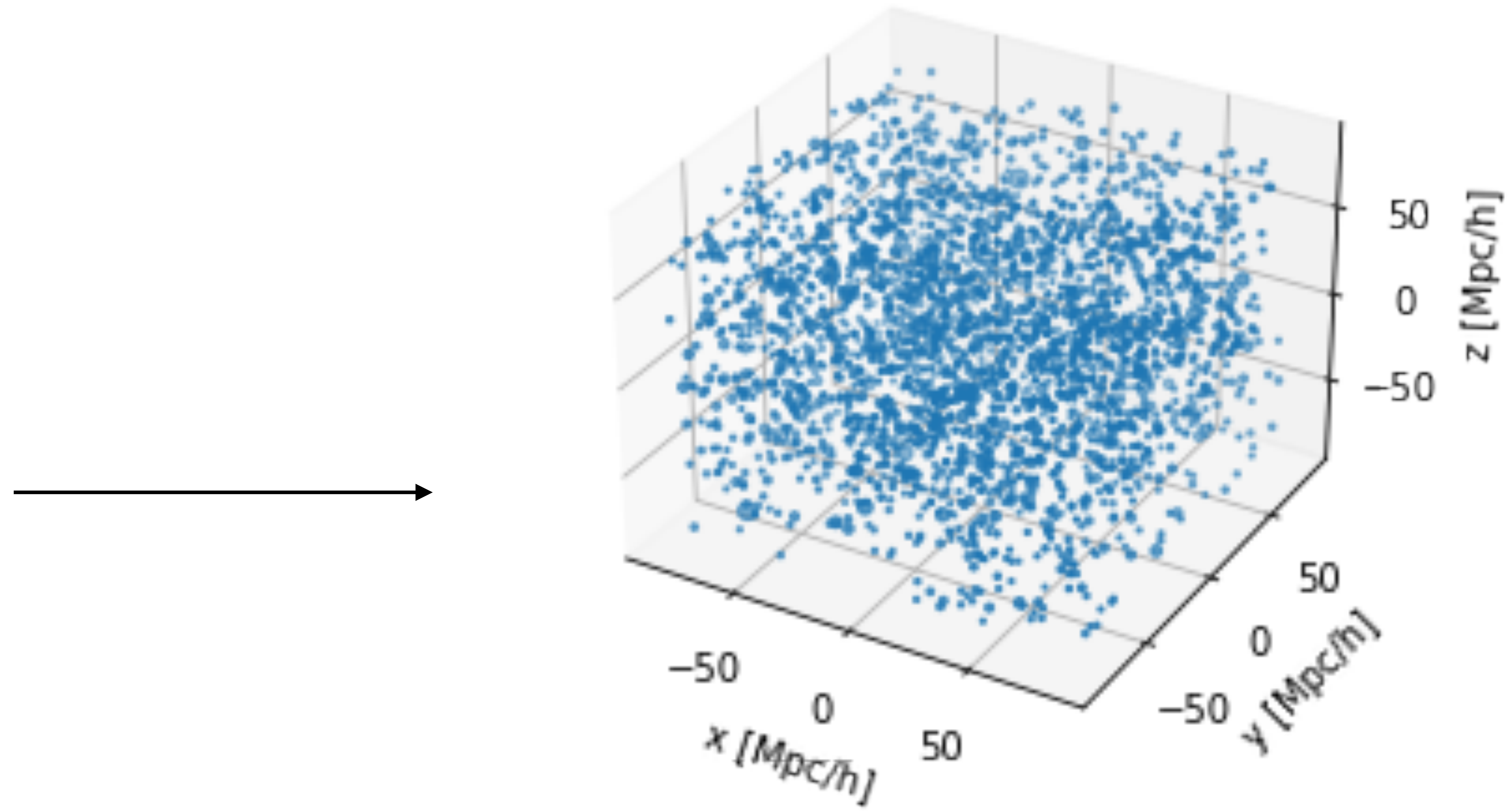
Observation

Simulation Pipeline

- Construct a halo catalogue:
- 1. Find the halo position using the halo centre power spectrum (assuming halo mass function and halo bias)

halomod, Murray et al. (including **ZC**) 2009.14066

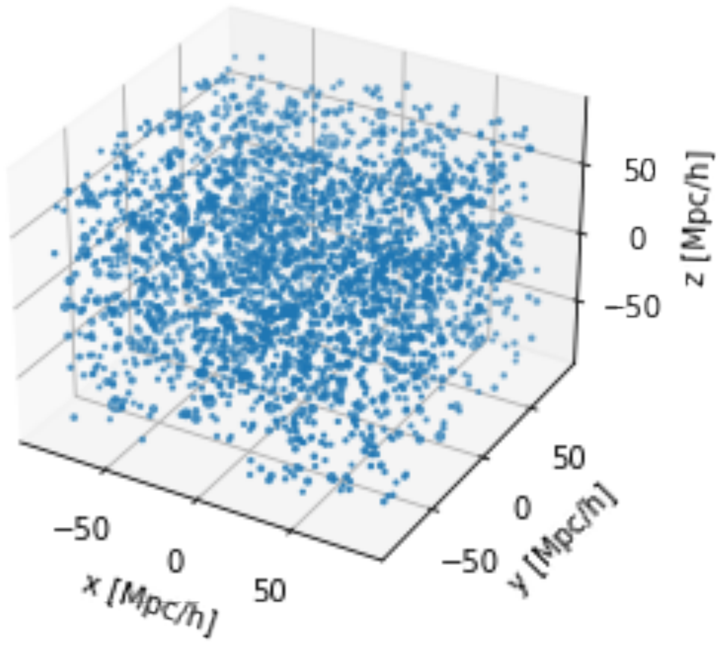


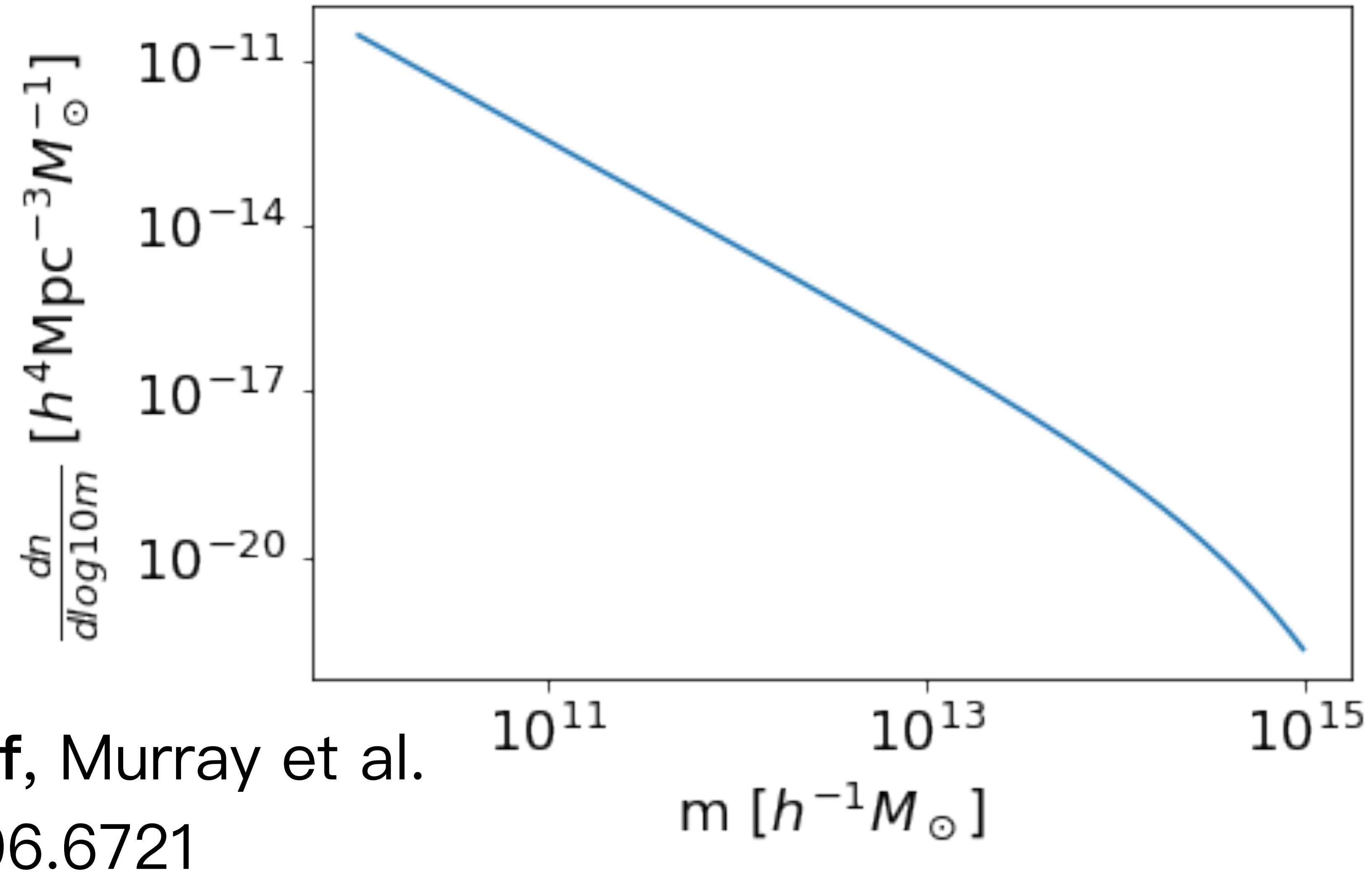


powerbox,
Murray
1809.05030

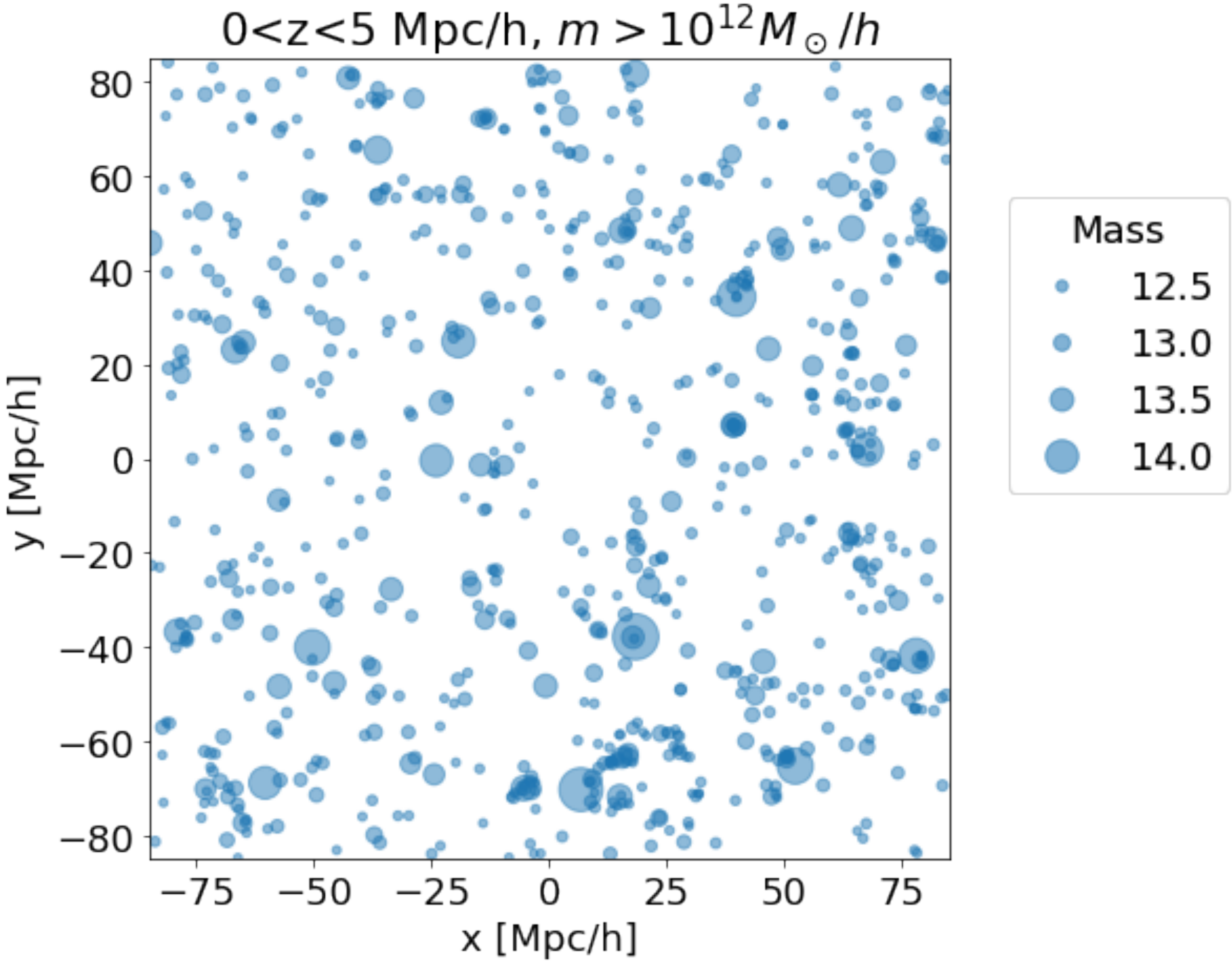
Simulation Pipeline

- Construct a halo catalogue:
- 2. Assign halo mass based on halo mass function





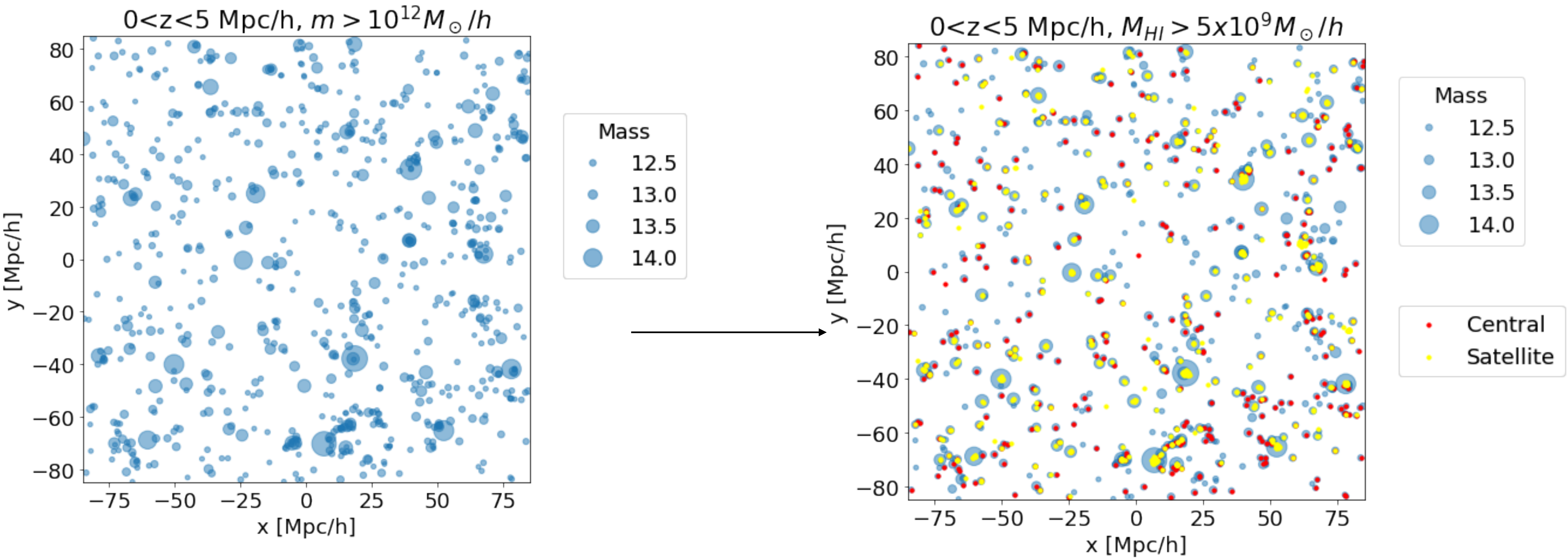
hmf, Murray et al. 1306.6721



Simulation Pipeline

What Intensity Mapping Probe

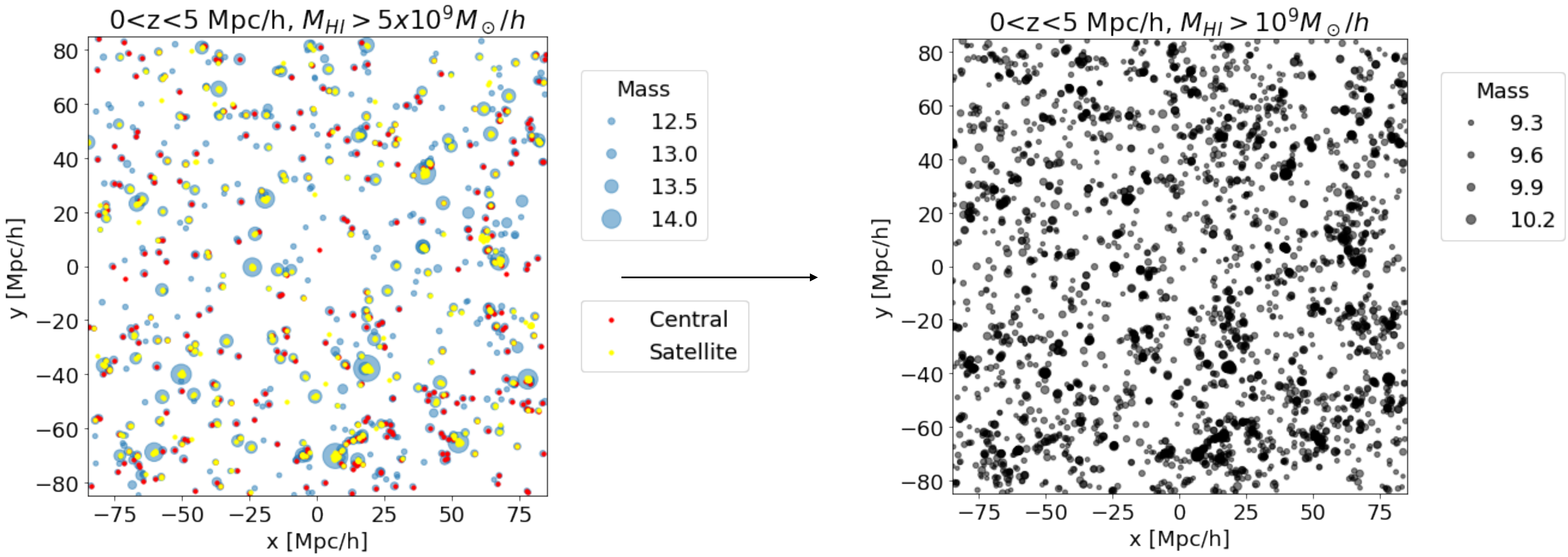
- Construct a HI galaxy catalogue:
- 3. Assign galaxy position based on galaxy HOD and density profile



Simulation Pipeline

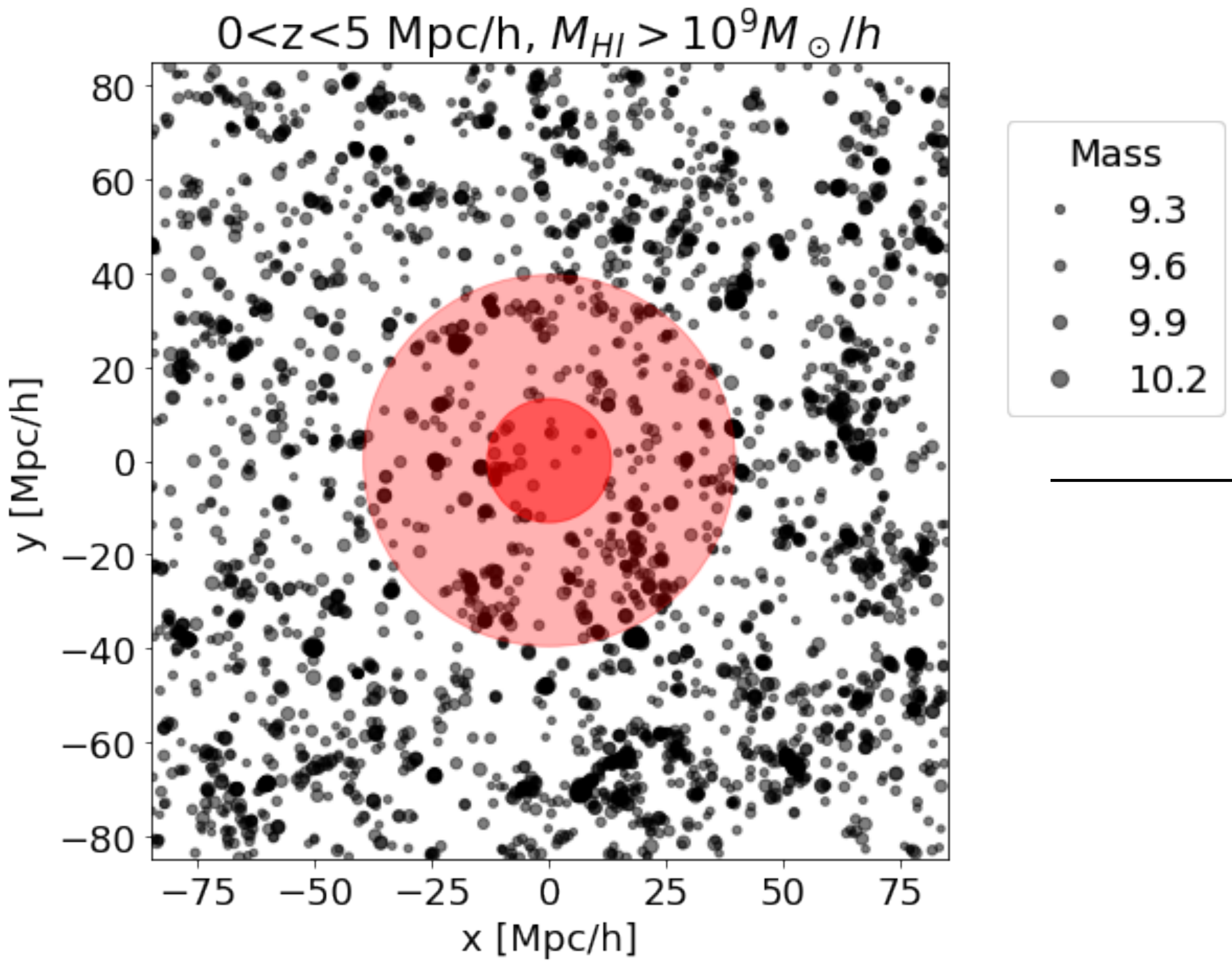
What Intensity Mapping Probe

- Construct a HI galaxy catalogue:
- 4. Assign HI mass to galaxies based on HI HOD



Simulation Pipeline

- Construct a lightcone:
- 5. Convert the HI galaxy catalogue to lightcone assuming point sources

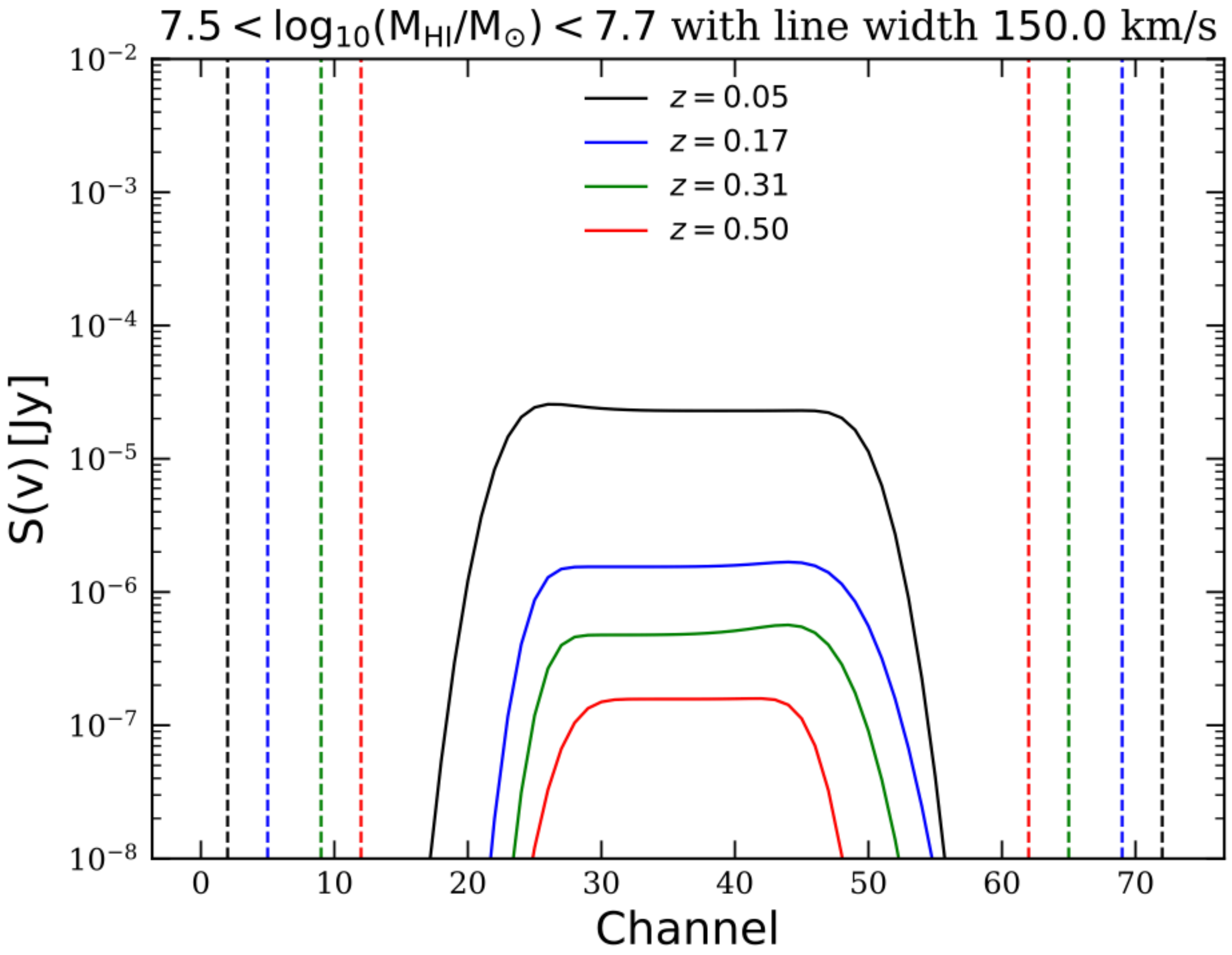


- Convert to sky coordinates
- Assign flux intensity based on HI mass assuming narrow emission line profile.

$$I_i = \frac{2k_{\mathrm{B}}}{\lambda_i^2}\frac{C^i_{\mathrm{HI}}M^i_{\mathrm{HI}}}{X^2\Delta X}\,.$$

Emission Line Profile

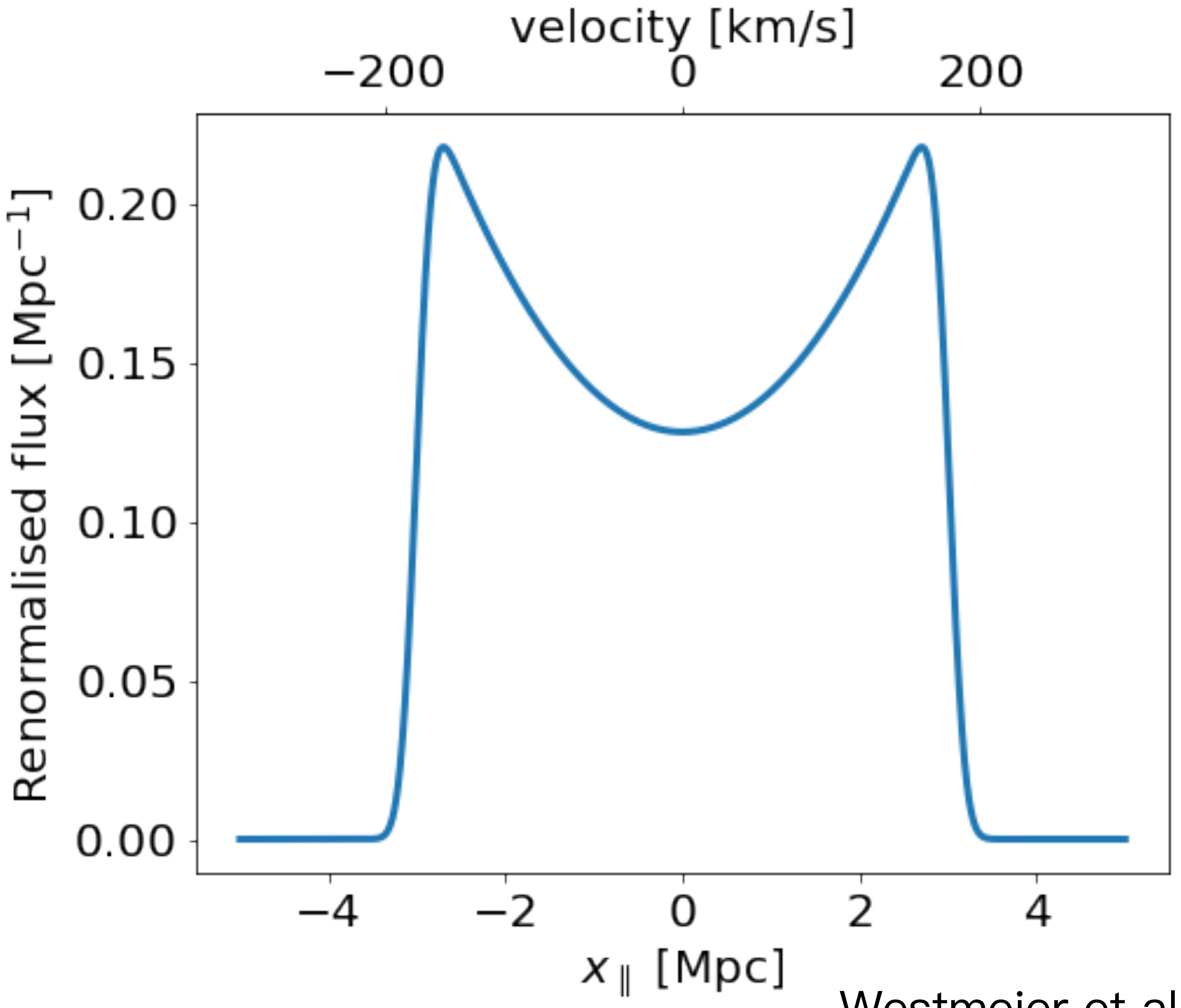
- We always assume the profile width is smaller than the frequency resolution (which is wildly untrue).



Pan et al.
1907.10404

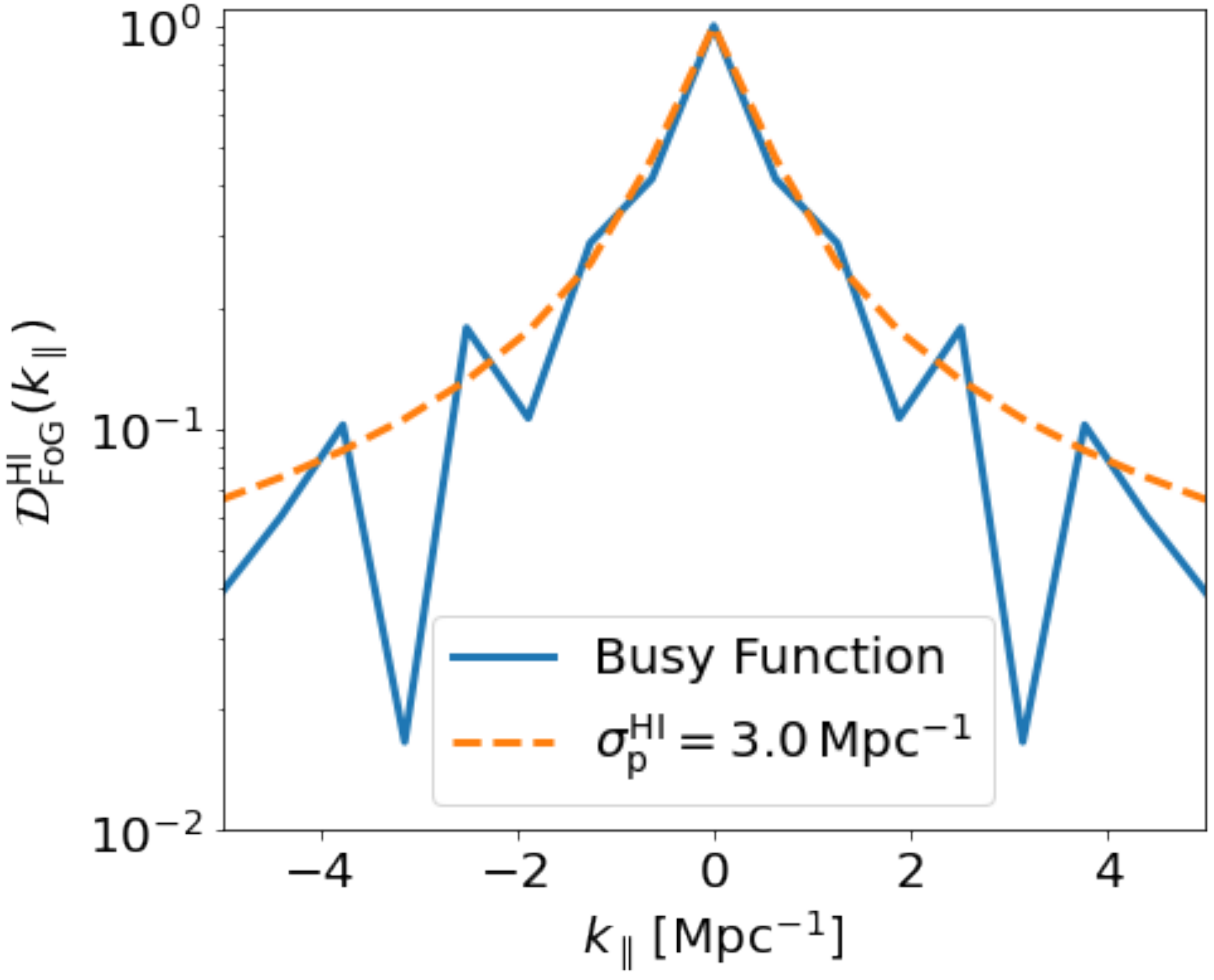
Emission Line Profile

- The profile actually acts as the non-linear FoG effect term in the power spectrum.



Westmeier et al. 1311.5308

Chen, Battye, Cunnington & Wolz in prep.



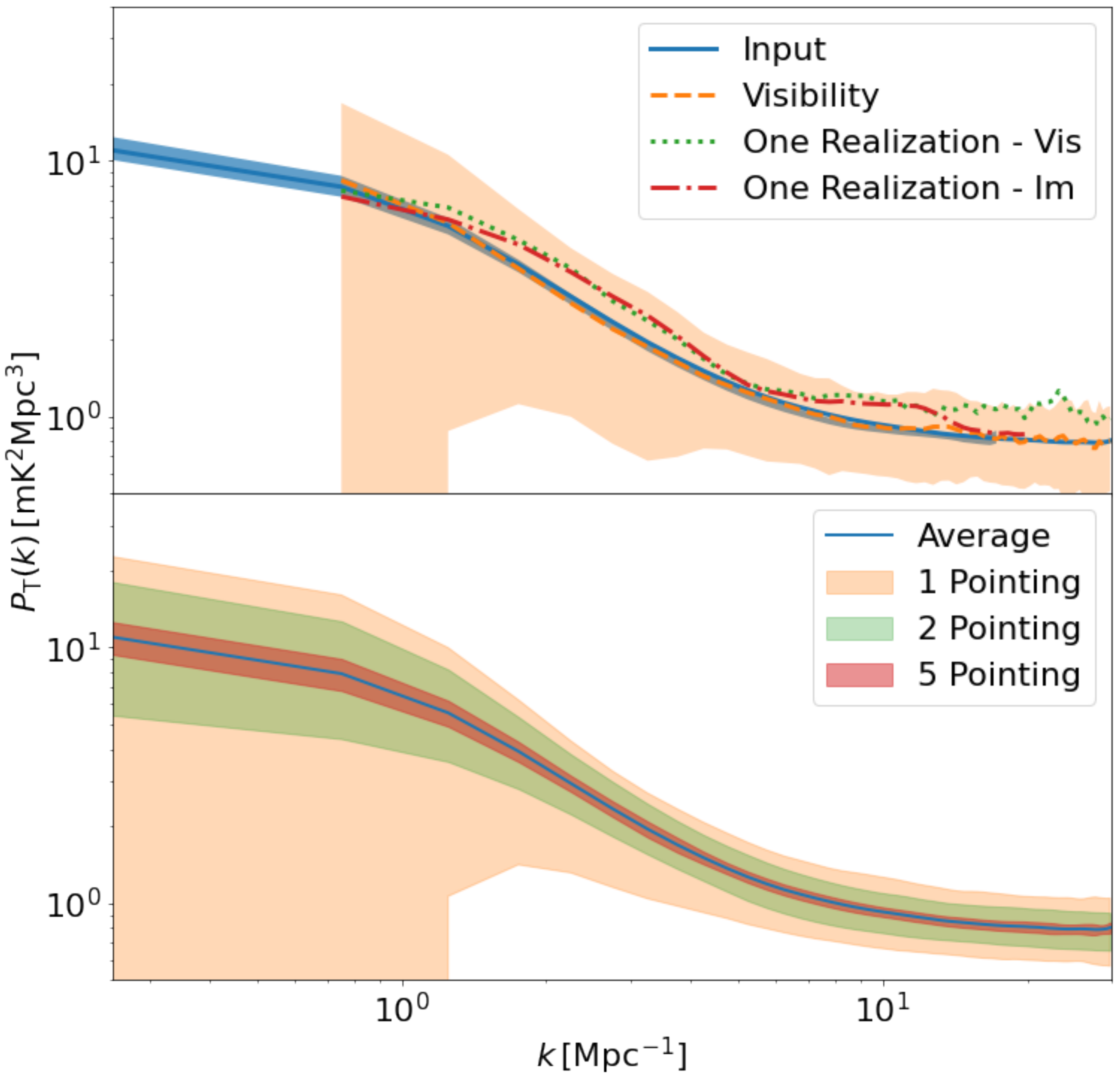
Emission Line Profile

- We always assume the profile width is smaller than the frequency resolution (which is wildly untrue).
- The profile actually acts as the non-linear FoG effect term in the power spectrum.
- Therefore, intensity mapping (especially shot noise) directly tells you what the emission line profile looks like (velocity dispersion).
- We are keen to simulate this properly in future work!

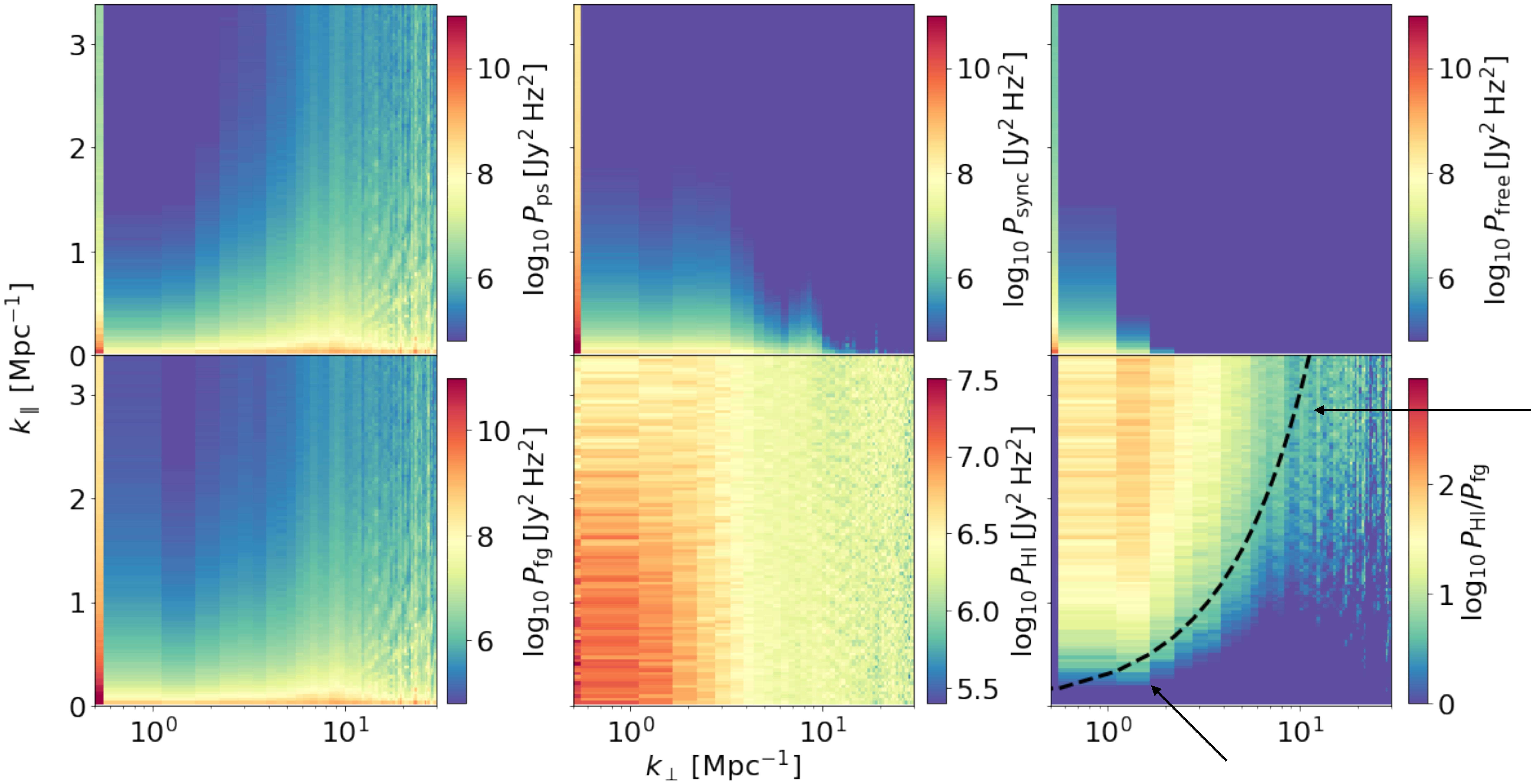
Simulation Pipeline

- Pass the sky model to OSKAR and then the output visibility to power spectrum estimation. The observational strategy follows the MIGHTEE specification (Paul et al. 2021), which is an 11.2-hour tracking for COSMOS field.

Simulation Pipeline



Forecast for MIGHTEE: Foreground Window



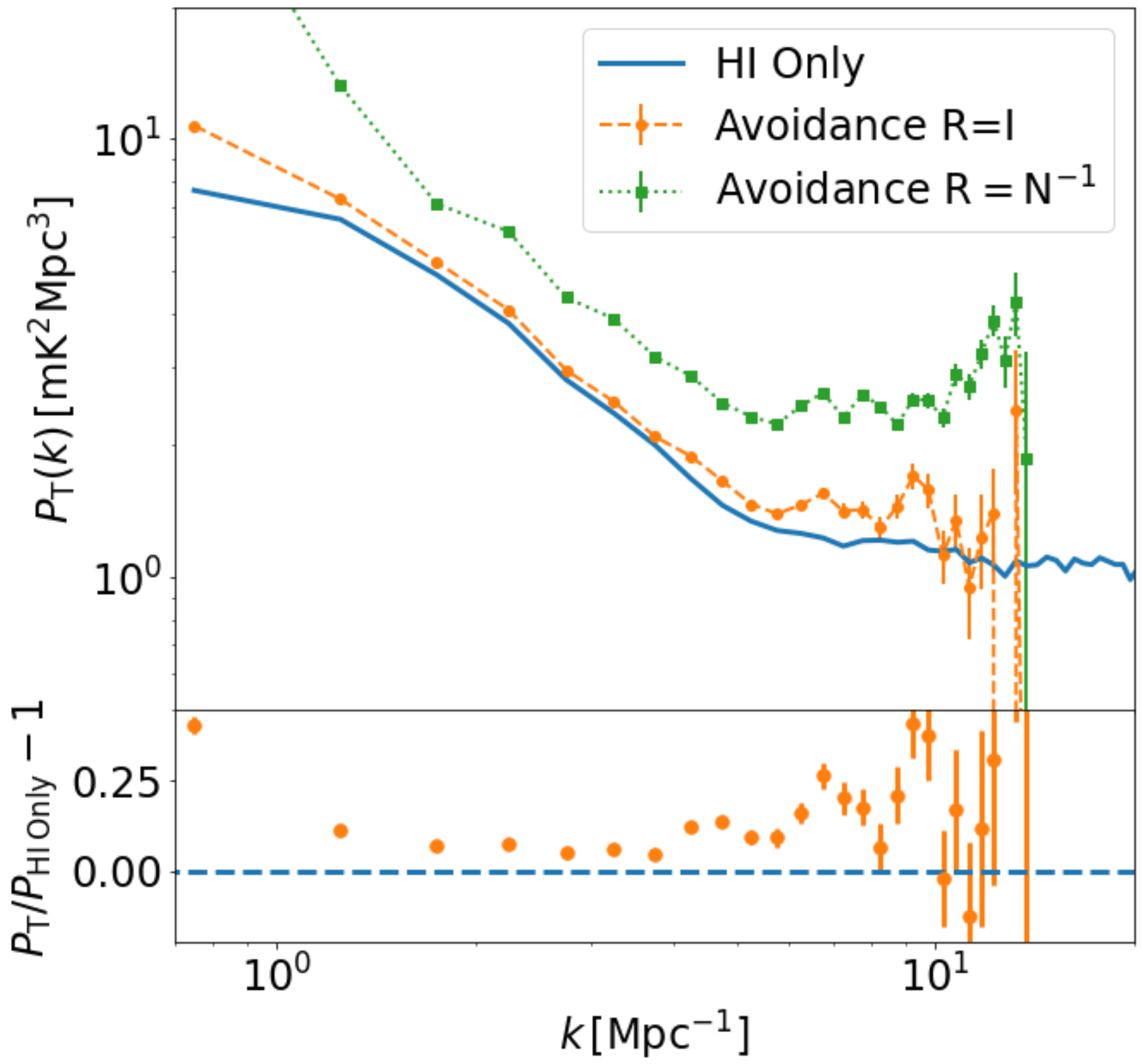
$k_\parallel > 0.3 k_\perp$

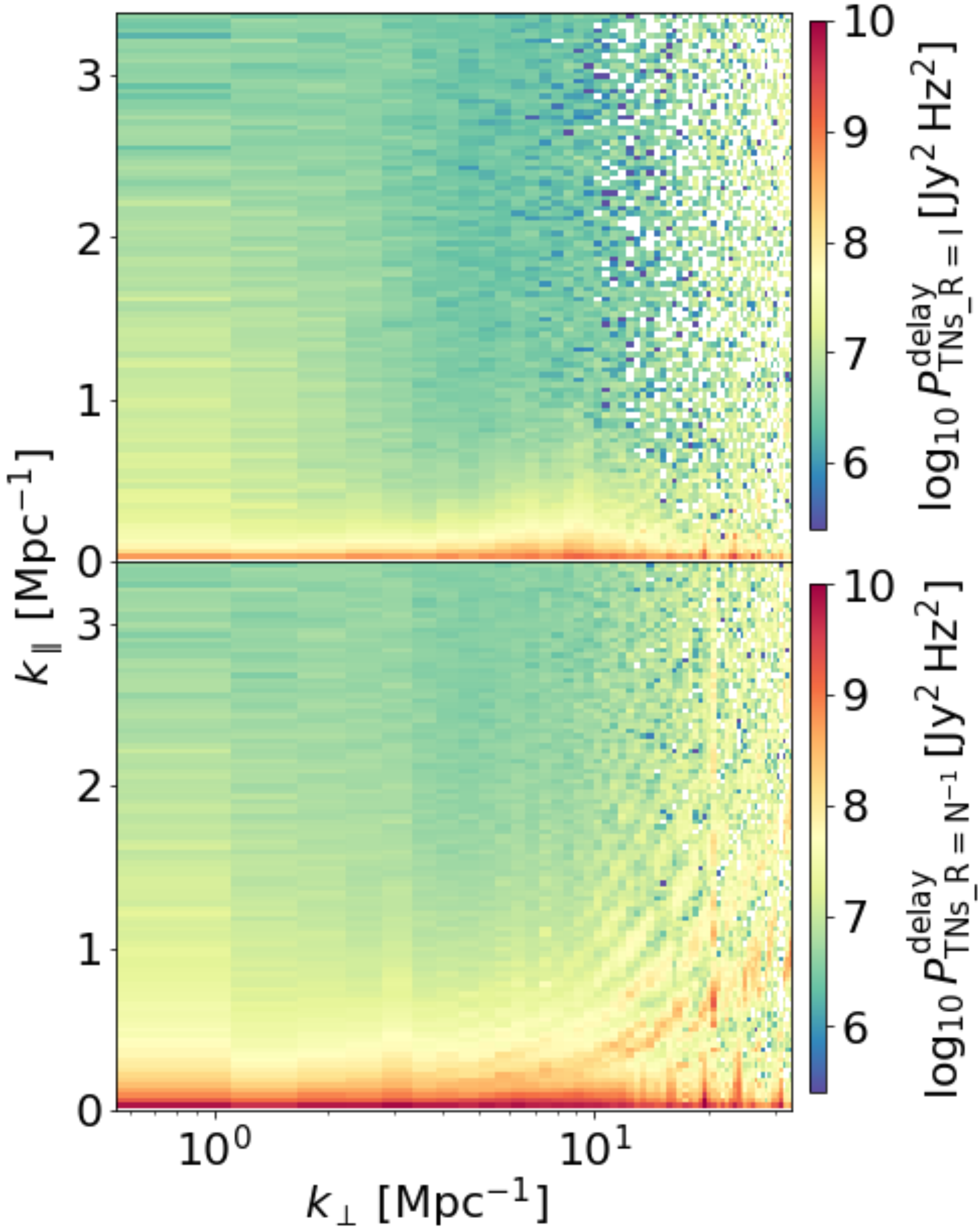
Smaller RSD FoG smoothing here!

Huge loss of information

Avoidance

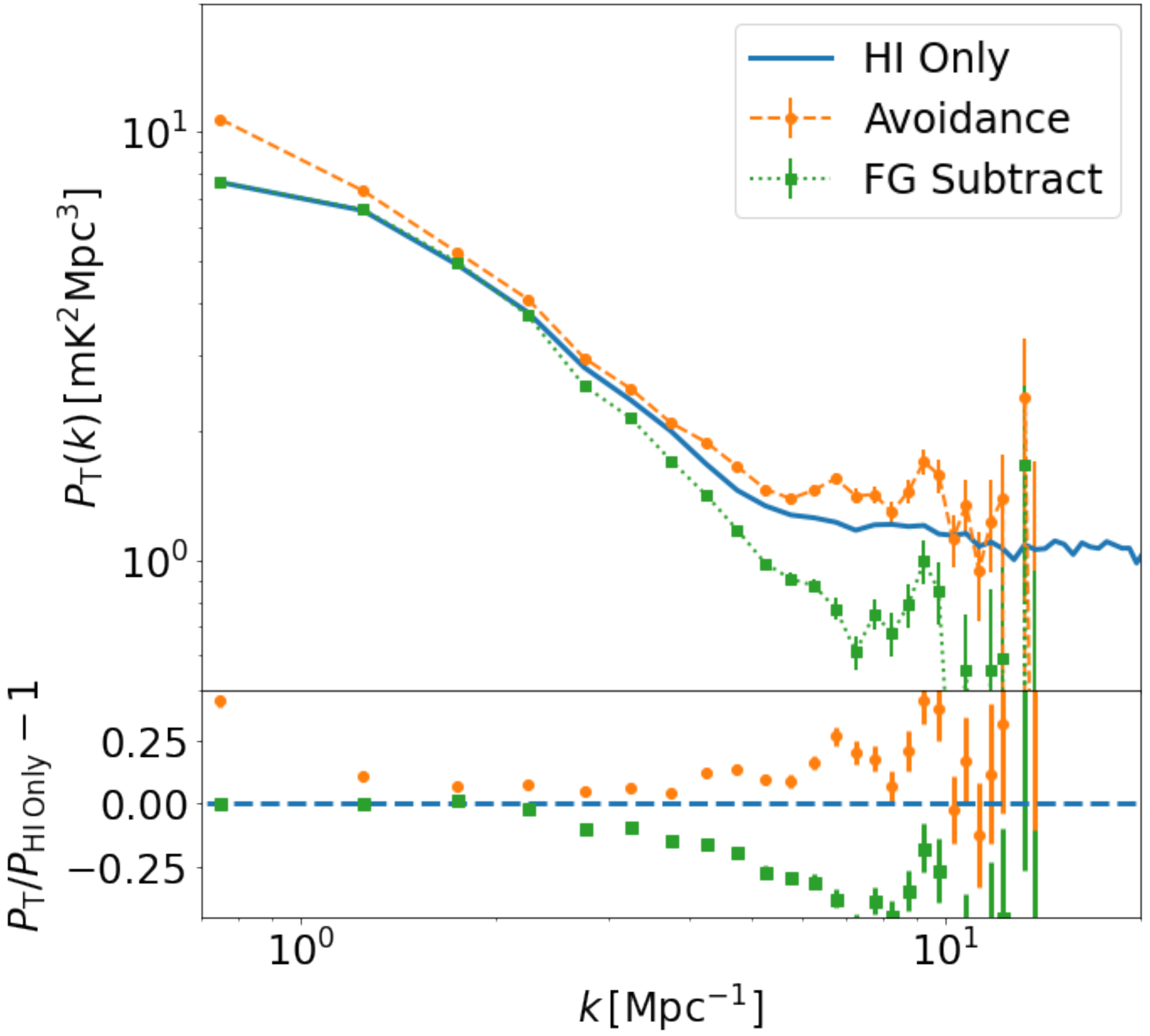
- Over-estimation. Mode mixing along the frequency axis will further contaminate the signal (can be resolved by frequency tapering, but renomalization will further bias the esimation).

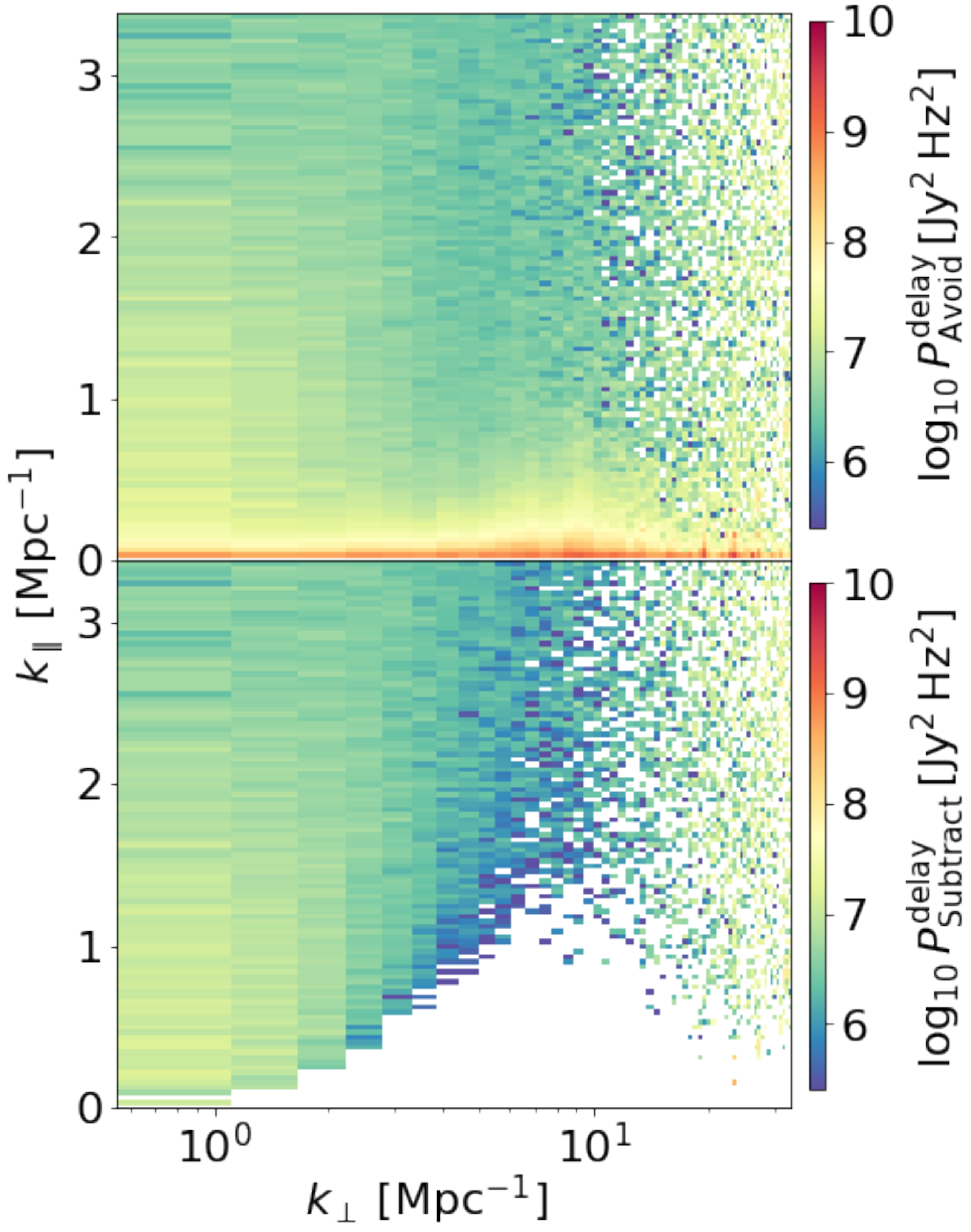


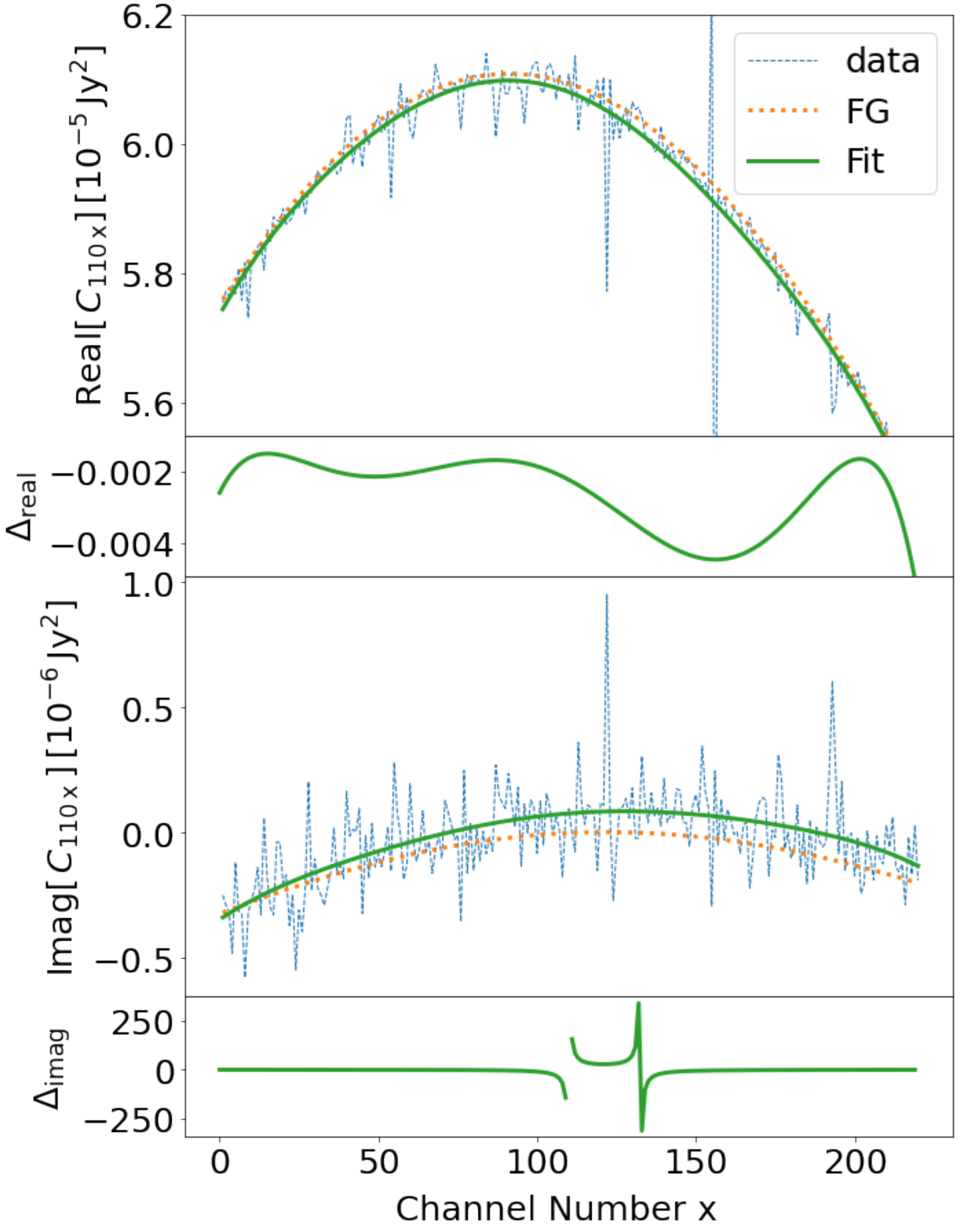


Polynomial Fitting

- Over-cleaning. The bias correction with wrong estimation of foreground covariance typically ends up with signal loss. Cheng+ 1810.05175

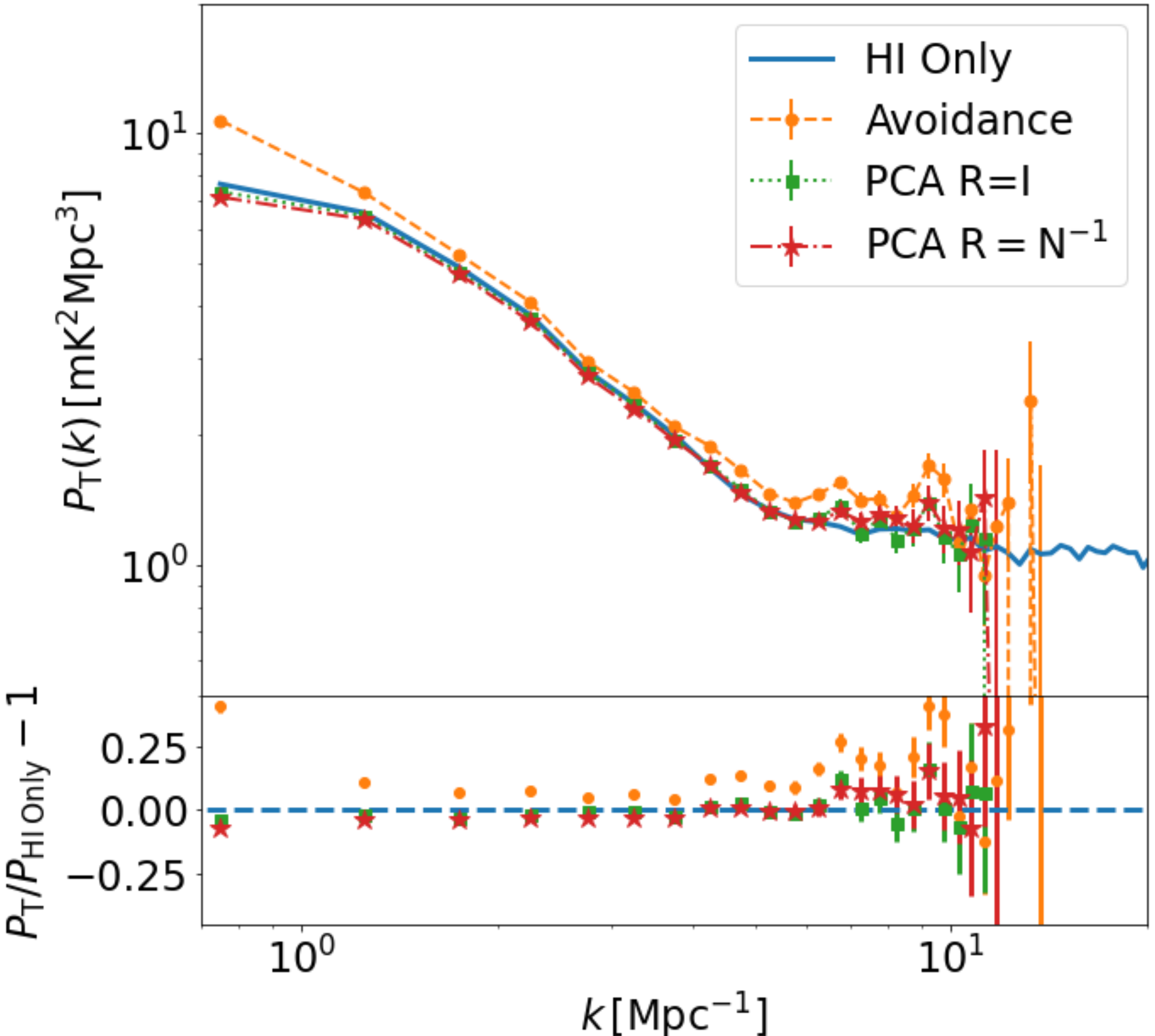


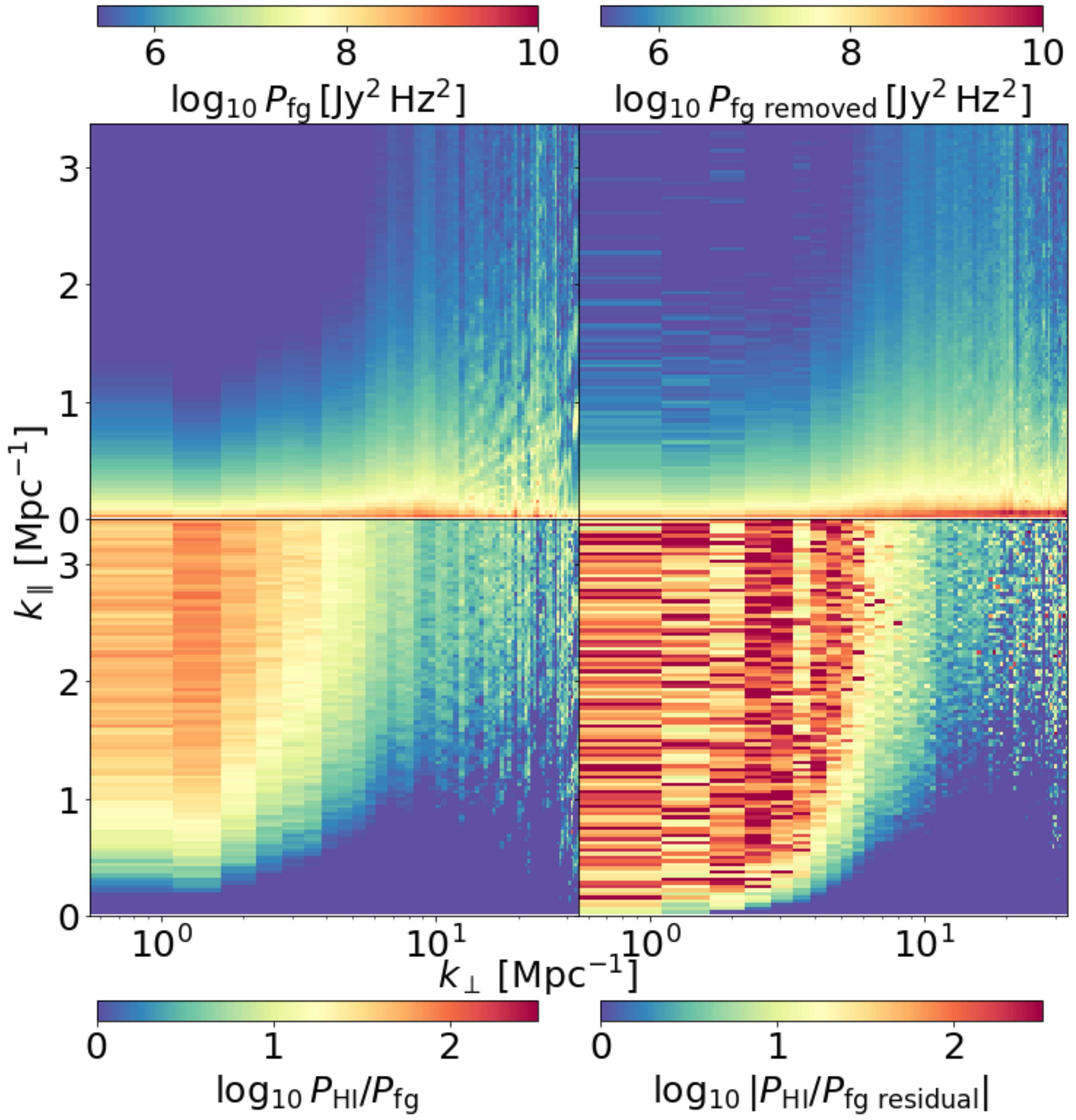




PCA

- Corrects the amplitude. Allows inverse covariance weighting.
- Conservative cleaning. Only nfg=2.
- A much larger window. Accessing lower k_\parallel.

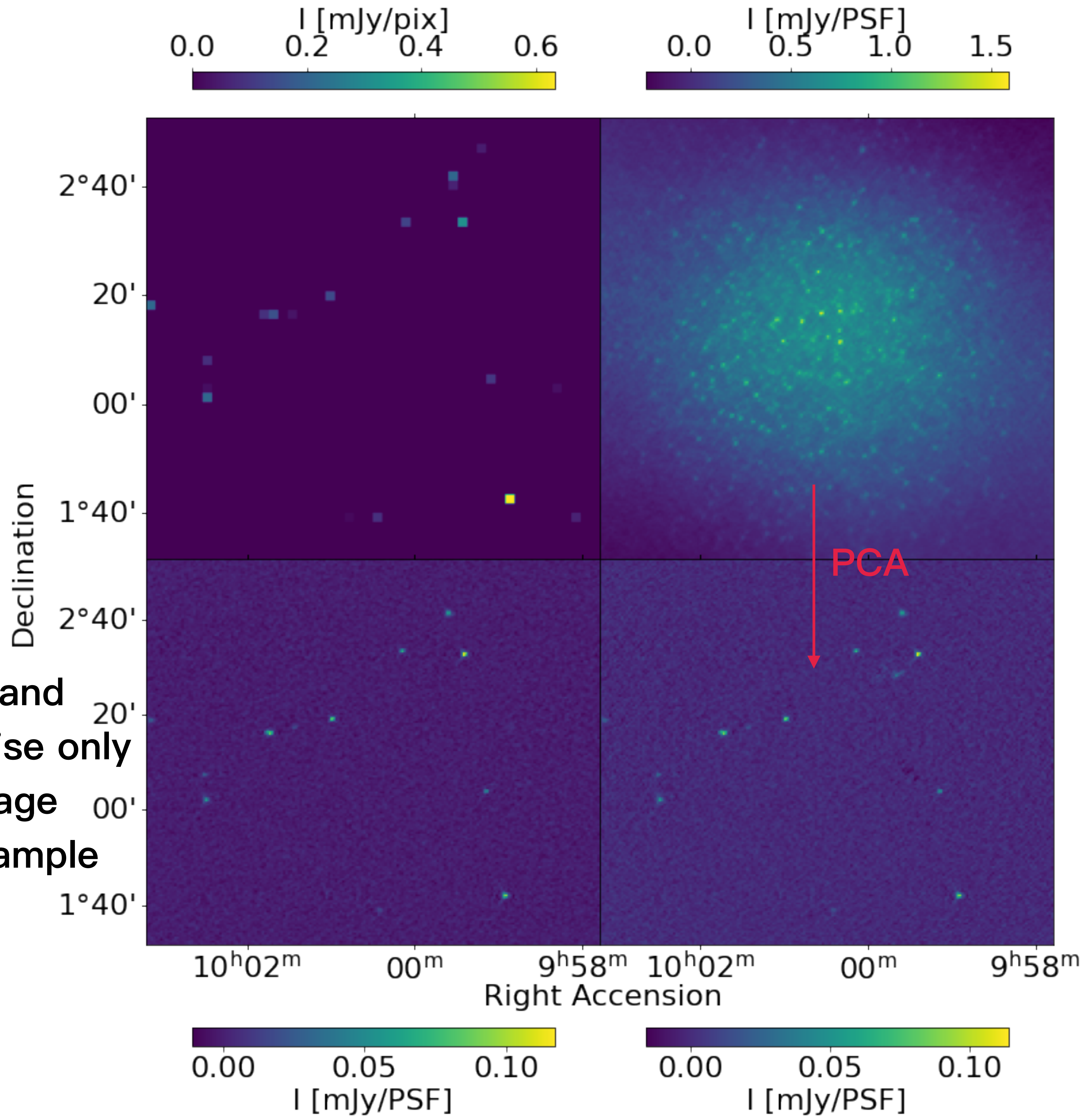




Visibility PCA Is GOOD!

How About Image?

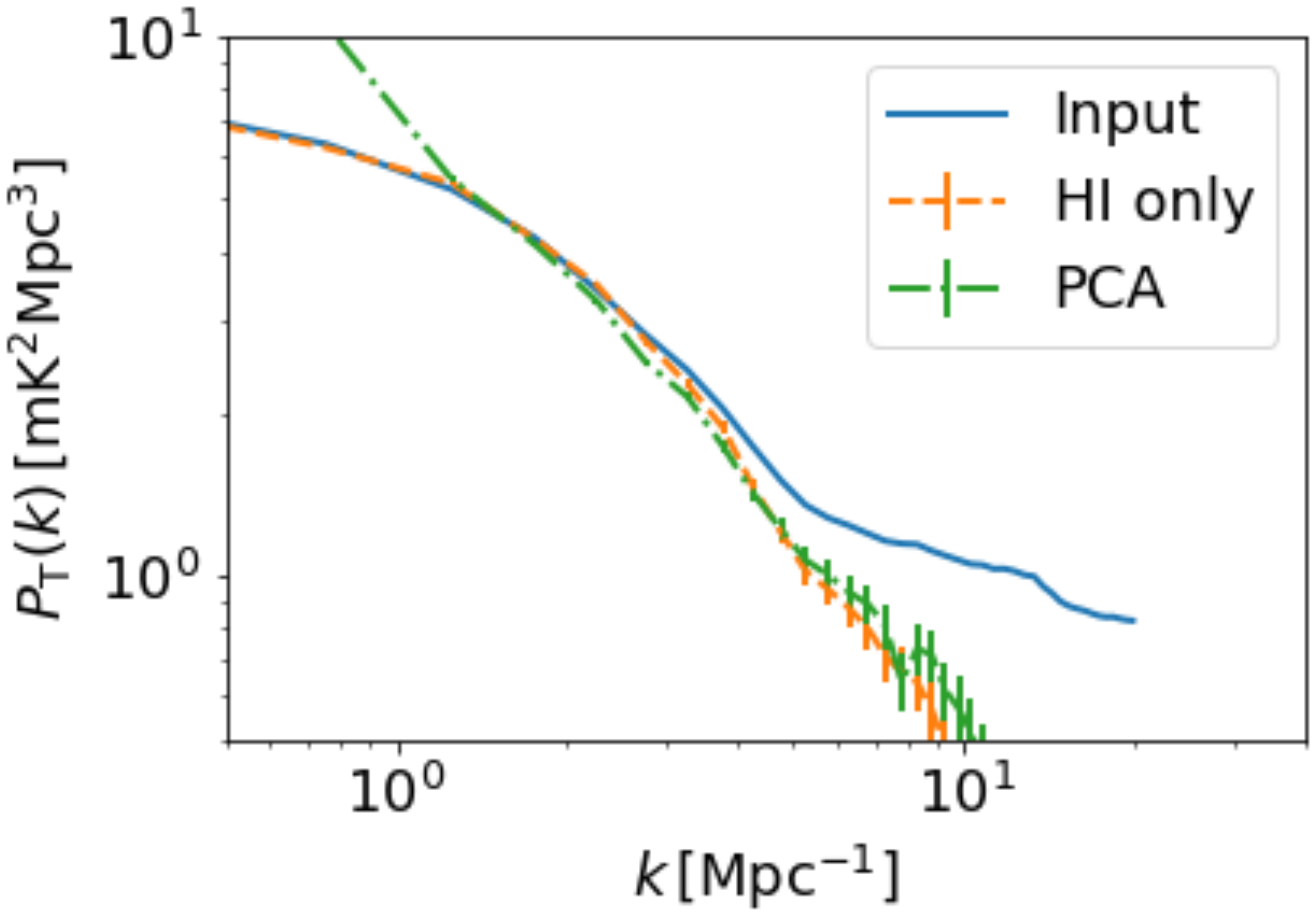
- Not bad but not so good either. (Disclaimer: Just a naive look)



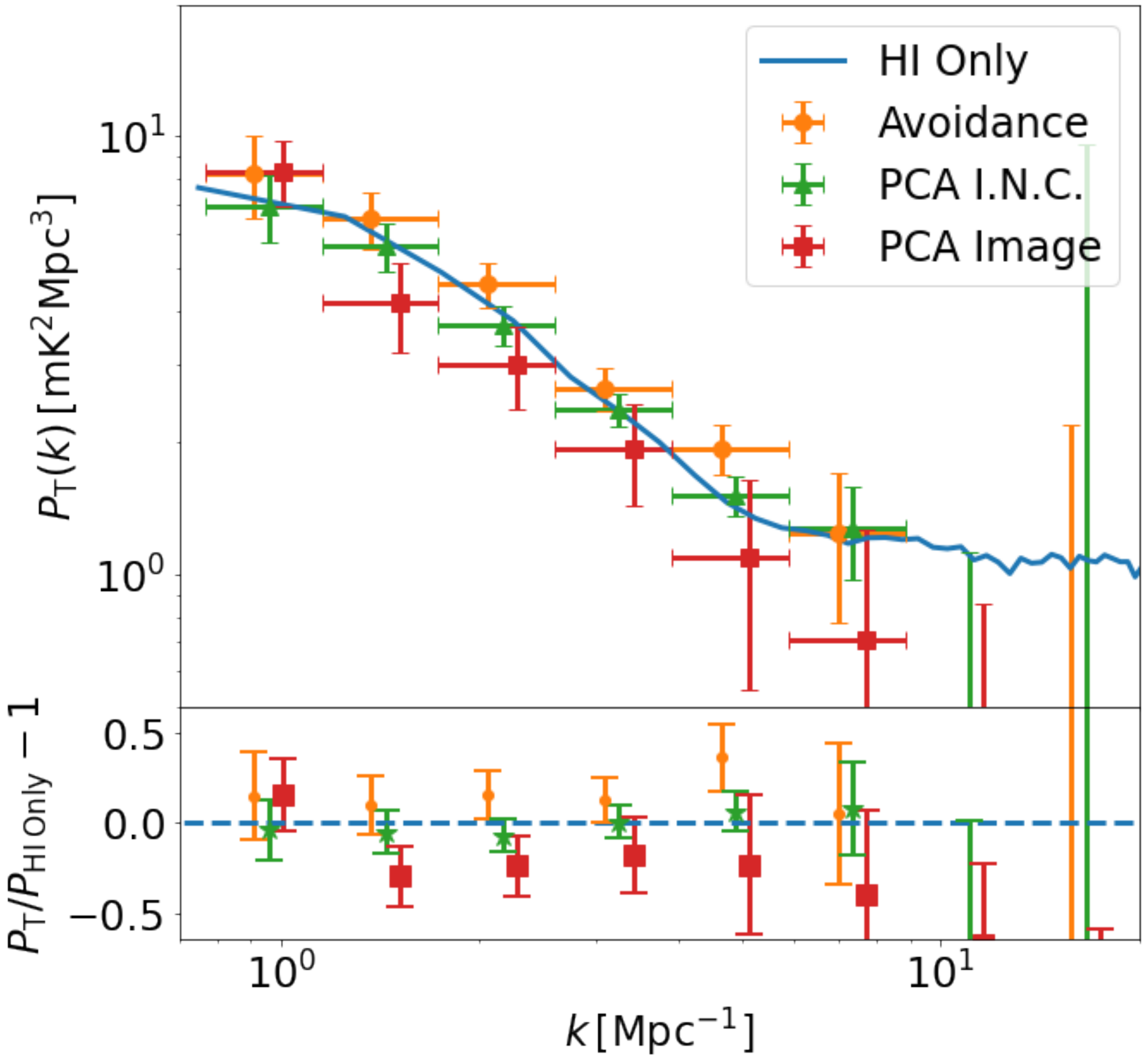
output image example

HI and noise only image example

image after PCA



In Real World (of Noise Level)



- For the entire MIGHTEE survey, HI power spectrum can be measured with high accuracy in multiple narrow redshift bins.
- PCA in visibility is closest to truth with smallest error bars.
- Huge potential in constraining HI halo model and velocity dispersion

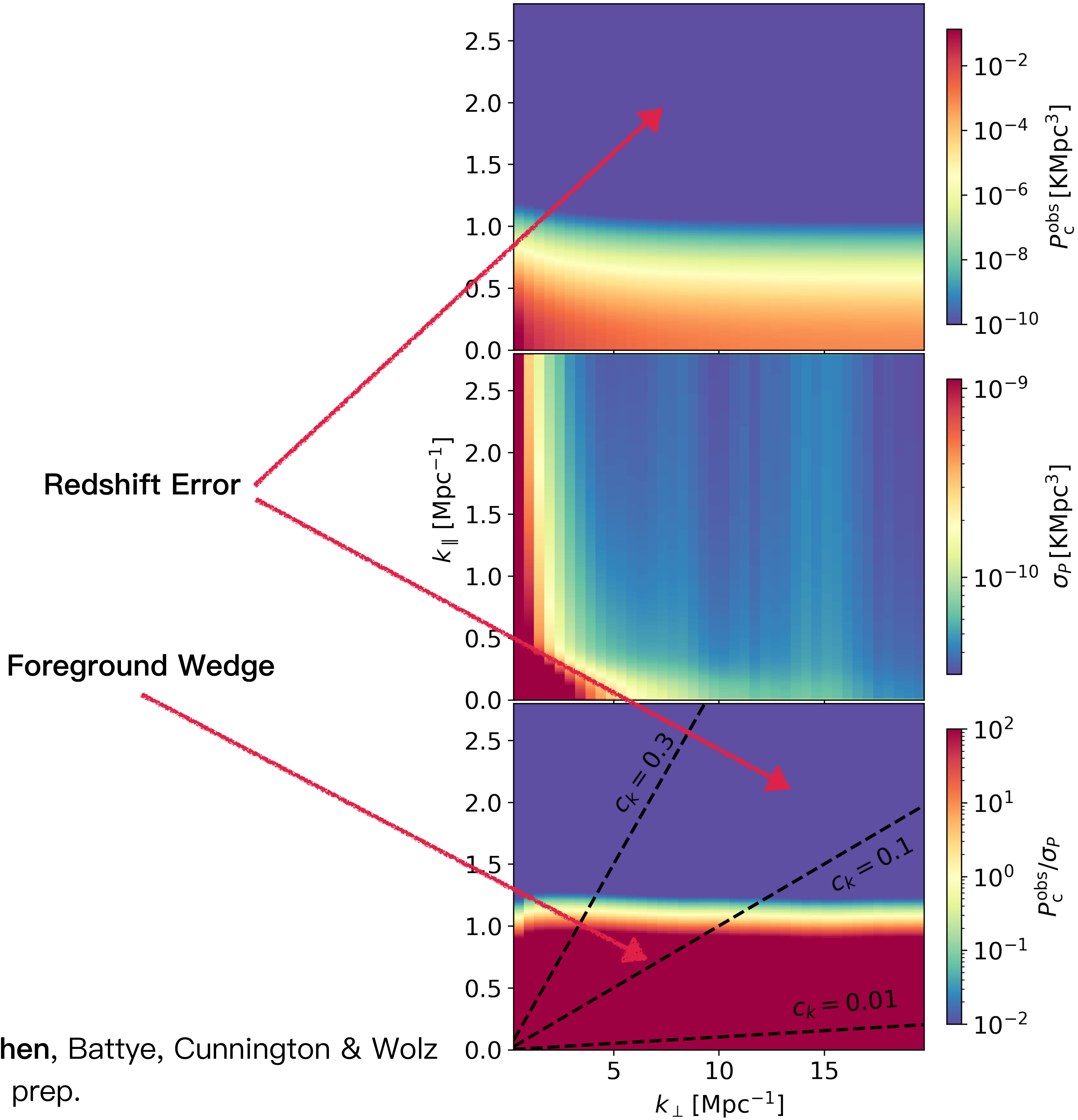
Cross-Correlation with Optical Galaxy?

- The redshift kernel of optical galaxy kills small line-of-sight scales. Foreground in HI kills the large los scales (Modi+ 2102.08116). Very difficult to do!

Chen, Battye, Cunnington & Wolz
in prep.

- It can **only** be done if you understand the clustering redshift of your optical galaxy samples very well. At the same time, foreground needs to sufficiently cleaned to enlarge the observation window.

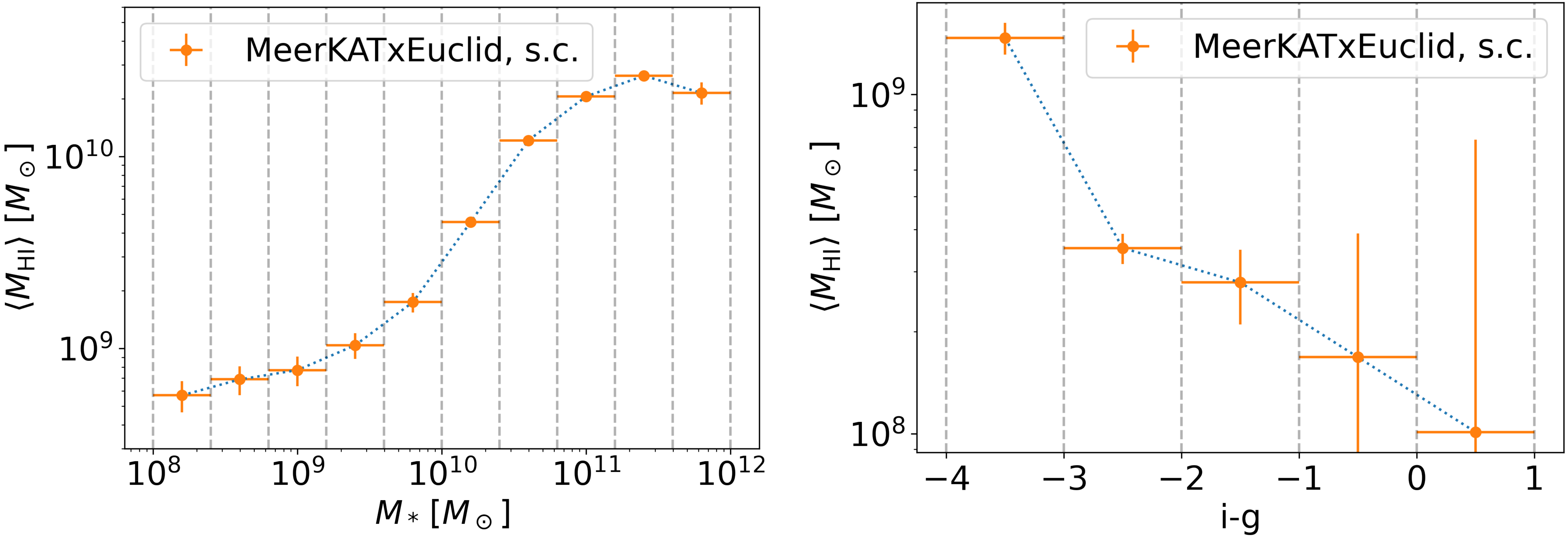
- We find that $\sigma_z \lesssim 0.1\,\%$ and $c_k \lesssim 0.1$ are needed for meaningful measurements.



Chen, Battye, Cunnington & Wolz in prep.

Cross-Correlation with Optical Galaxy?

- If it can be done, it can be used to constrain star-forming properties of galaxies (Wolz+ 1703.08268)

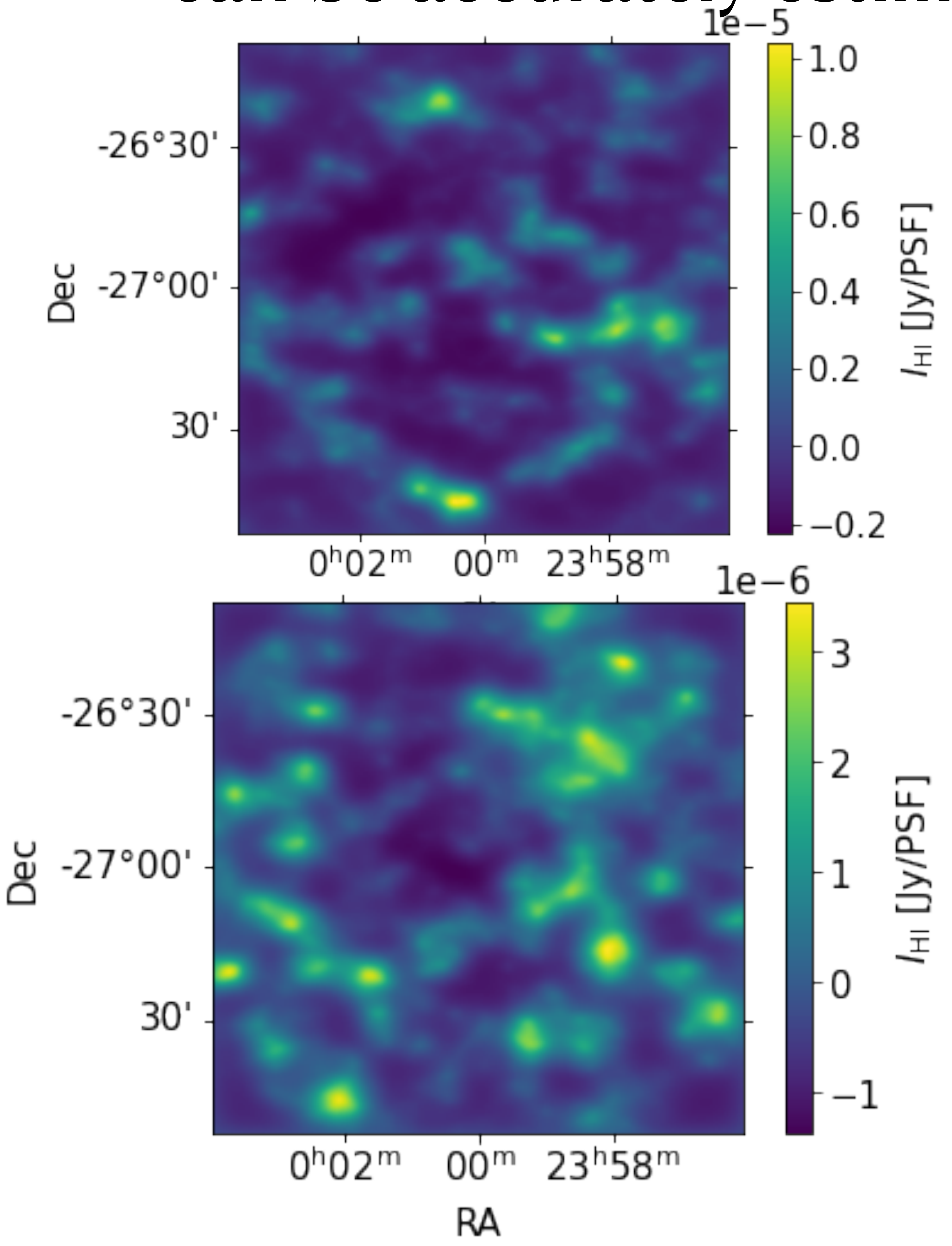


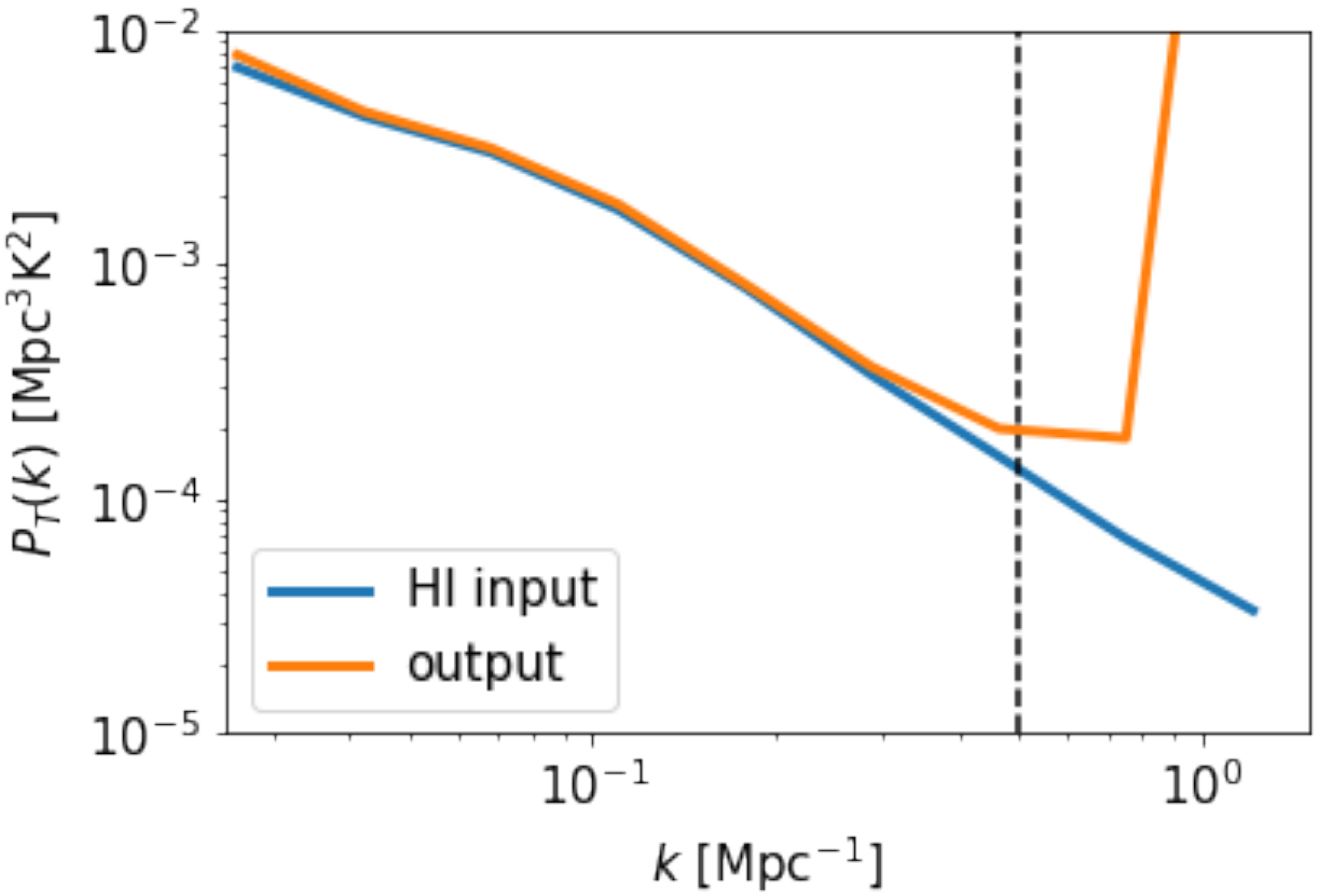
Chen, Battye, Cunnington & Wolz
in prep.

Higher Redshifts with SKA-low

Chen, Chapman & Wolz
in prep.

- Within the primary beam FoV and sufficient continuum subtraction, HI power spectrum can be accurately estimated from image cubes.

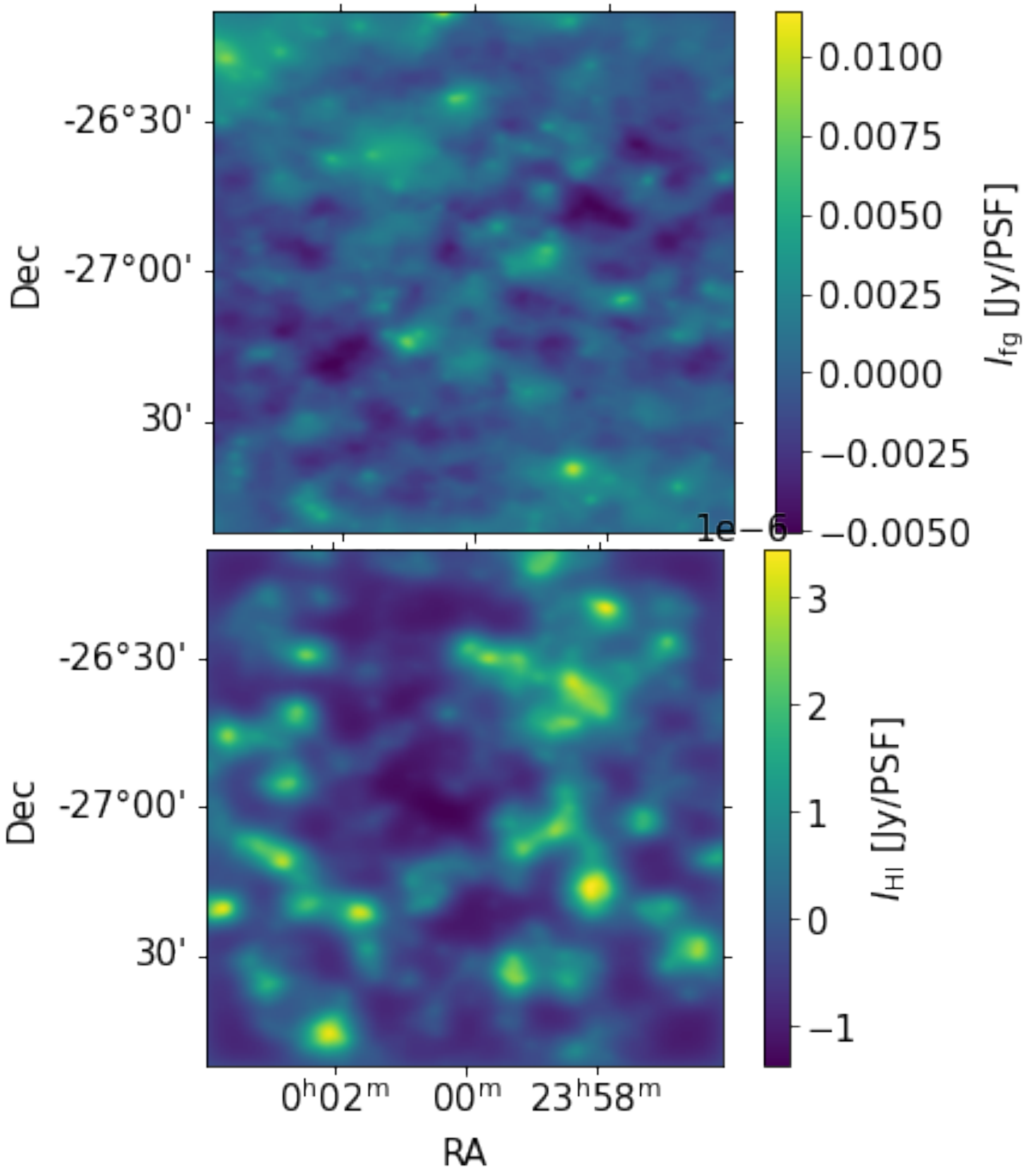




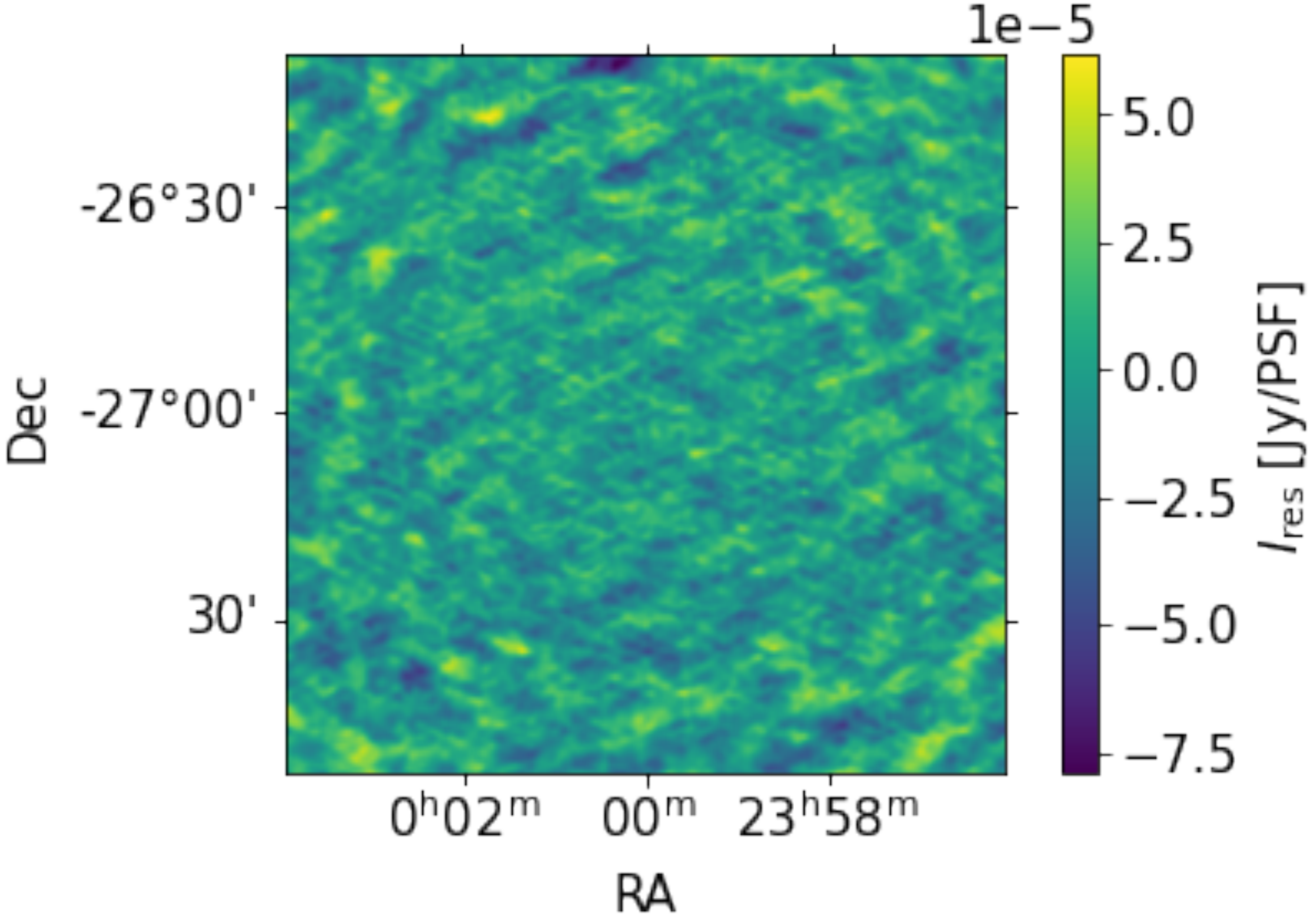
Higher Redshifts with SKA-low

Chen, Chapman & Wolz
in prep.

- However, foreground contamination is coupled with beam and other instrument chromaticity, making foreground removal much harder.



PCA



Higher Redshifts with SKA-low

Chen, Chapman & Wolz
in prep.

- To remove foreground, more careful treatment of image cube including PSF and foreground separation is needed.

- To make it useful for cosmology, wide-field imaging and mosaicking are needed which will make things more difficult.

Conclusion

- Interferometric HI intensity mapping has huge potential of probing HI galaxies and their star forming properties at low-redshift.

- There are many challenges, both from observation and from theory/simulation.

Thanks