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UK Research and Innovation

Power spectrum multipoles and clustering wedges during EoR

ZC & Pourtsidou
2405.05414

See also ZC, to appear in Moriond 2024 proceedings

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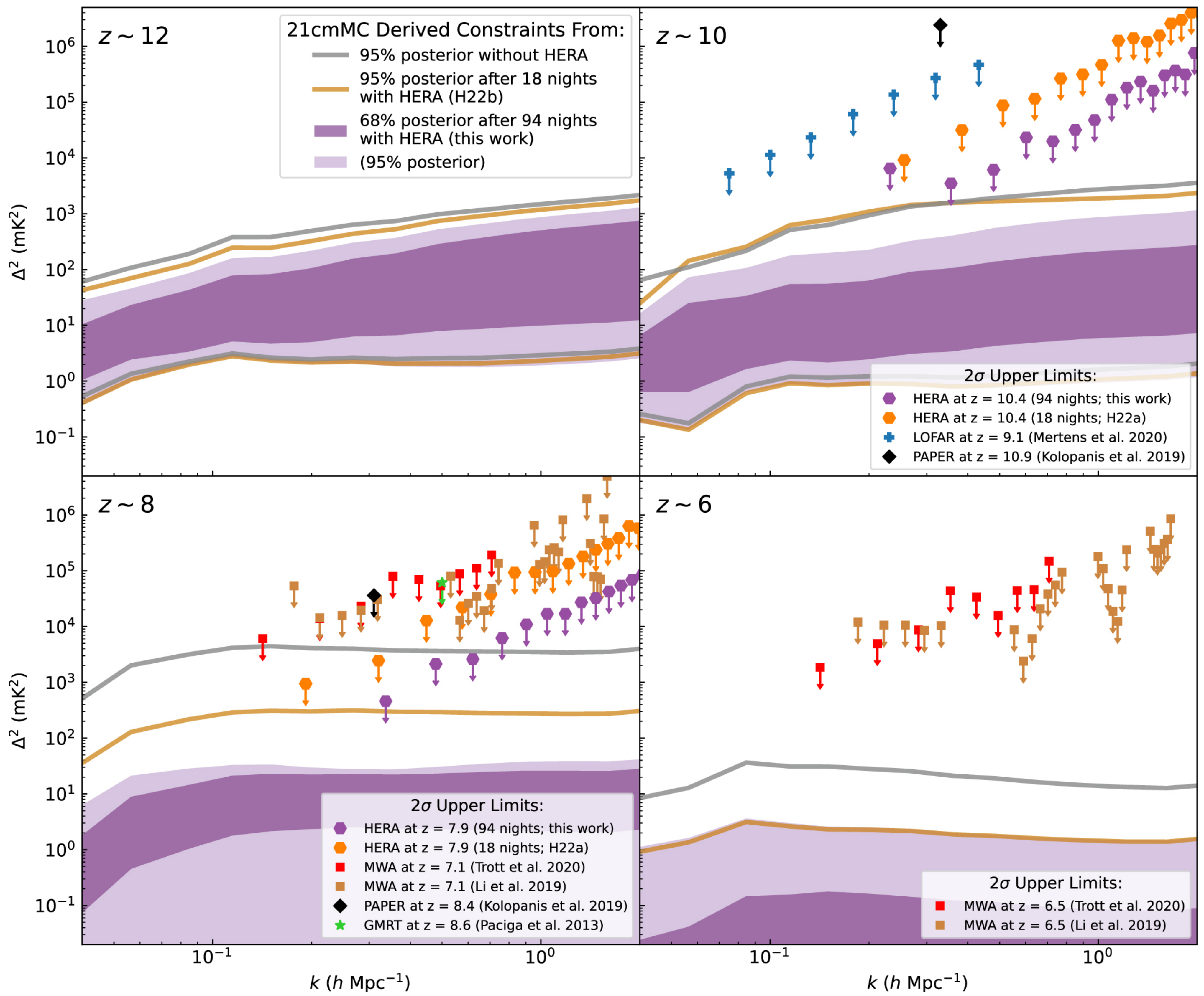
Measuring the 21cm tomography during EoR

- **Upper limits** from HERA, PAPER, LOFAR and MWA



HERA collaboration
2210.04912

- SKA-Low promises **high SNR detection**

Dreaming of the future with SKA-Low

- **High-fidelity** images

- Relatively fine redshift bin **probing throughout the reionization history**

- Coverage of **various physical scales**

Playing Devil's advocate…

For the first science product of SKA-Low EoR:

- No **high-fidelity** images?

— Continuum sky model needs to be **extremely deep and accurate**

— **Direction-dependent** calibration

— Wide field imaging

— Foreground subtraction highly non-trivial

— …

Playing Devil's advocate...

For the first science product for SKA-Low EoR:

- No tomographic image

ZC et al. 1812.10333 Diao, **ZC**, X. Chen & Mao 2406.20058

— **No morphology (e.g. Minkowski Functionals) or map-level inference.**

Power spectrum only.

Zhao et al. 2105.03344

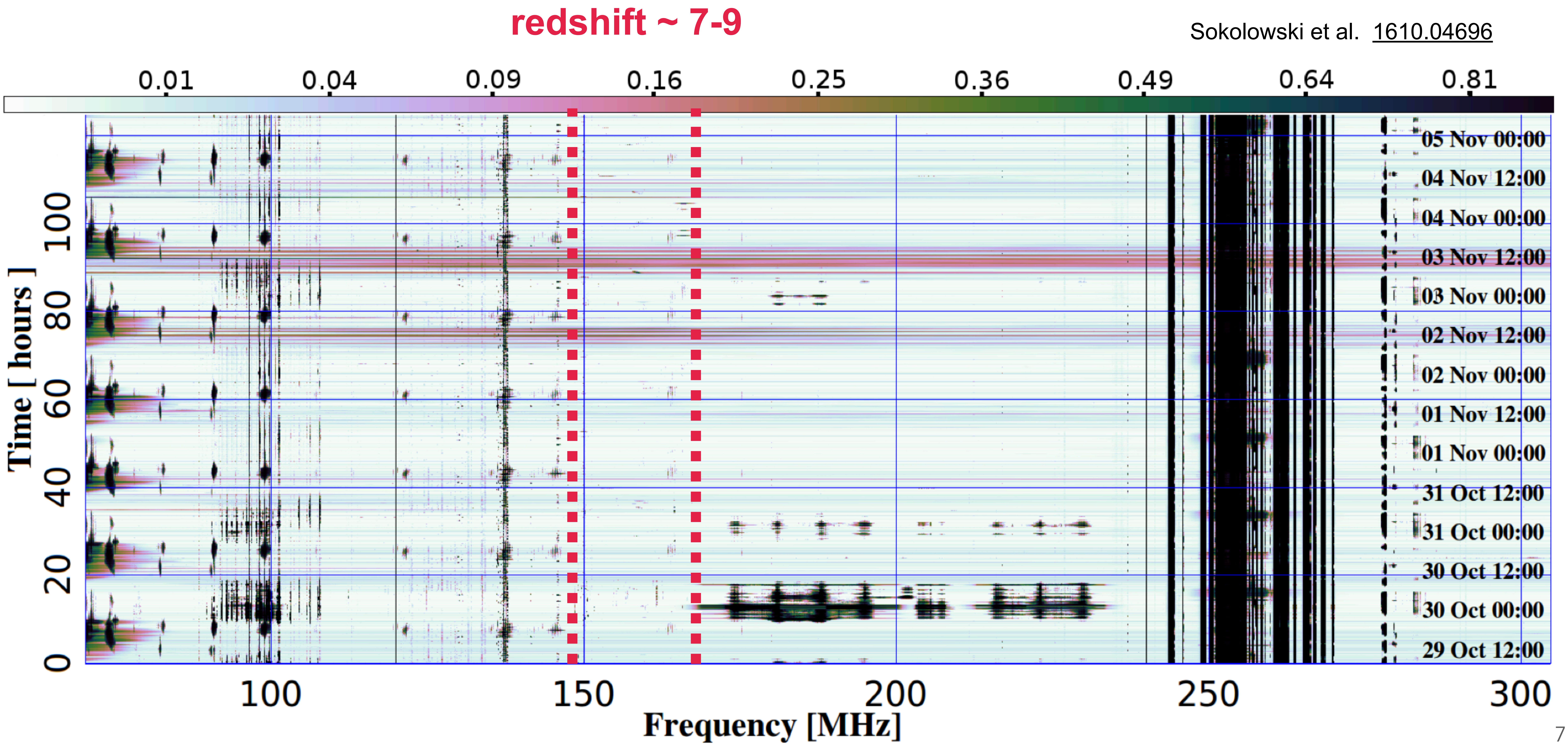
Playing Devil's advocate…

For the first science product for SKA-Low EoR:

- No tomographic image

- Fine redshift resolution?

What may be the first science product for SKA-Low EoR?



What may be the first science product for SKA-Low EoR?

- Moderate signal-to-noise ratio over a large redshift bin

— **Subject to large anisotropic effects due to RSD and lightcone evolution**

Mao et al. 1104.2094

Datta et al. 1109.1284
1402.0508

Highly anisotropic, non-Gaussian

"Trivial"

$$\delta T_b \approx 27\mathrm{mK}\, x_{\mathrm{HI}}(1+\delta_m)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{\Omega_m}{0.27}\right)^{\frac{1}{2}} \times\left(\frac{\Omega_b h}{0.44\times 0.7}\right)\left(1+\frac{\mathrm{d}v_{\parallel}/\mathrm{d}r}{H}\right)^{-1},$$

"Trivial"

What may be the first science product for SKA-Low EoR?

- Moderate signal-to-noise ratio in a wide redshift bin

Mao et al. 1104.2094

Datta et al. 1109.1284
1402.0508

— **Subject to large anisotropic effects due to RSD and lightcone evolution**

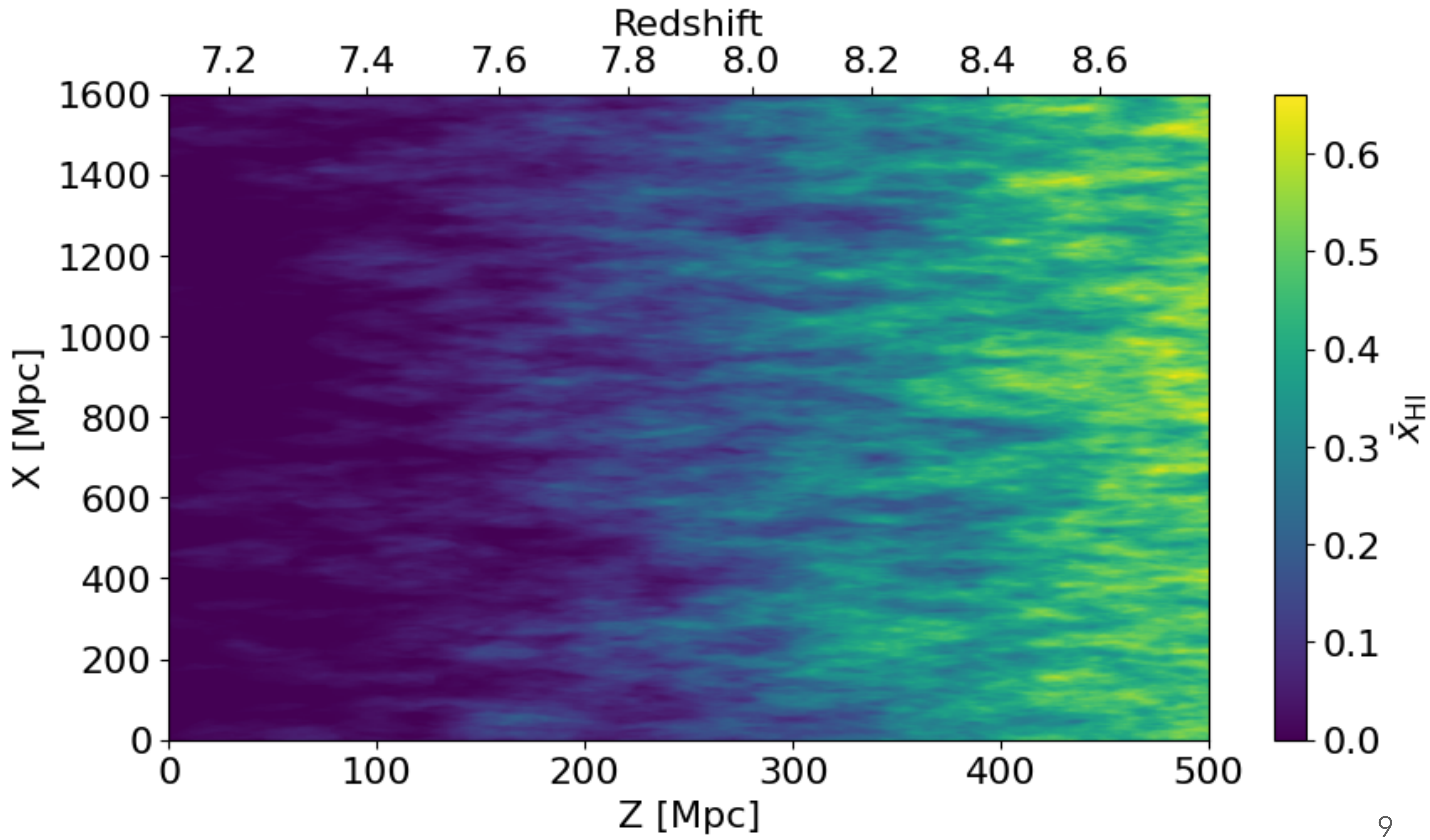
Murray et al. 2010.15121

21cmfast simulations with sub-grid RSD, inhomogeneous recombination, spin temperature fluctuation etc.

Fiducial model similar to the "**faint**" model.

Greig & Mesinger 1801.01592

$(\log_{10}[T_{vir}/K], \xi) = (4.7,65)$



Playing Devil's advocate...

For the first science product for SKA-Low EoR:

- No tomographic image

- Large light-cone effects

— **A representation of cylindrical PS is needed, for example multipoles.**

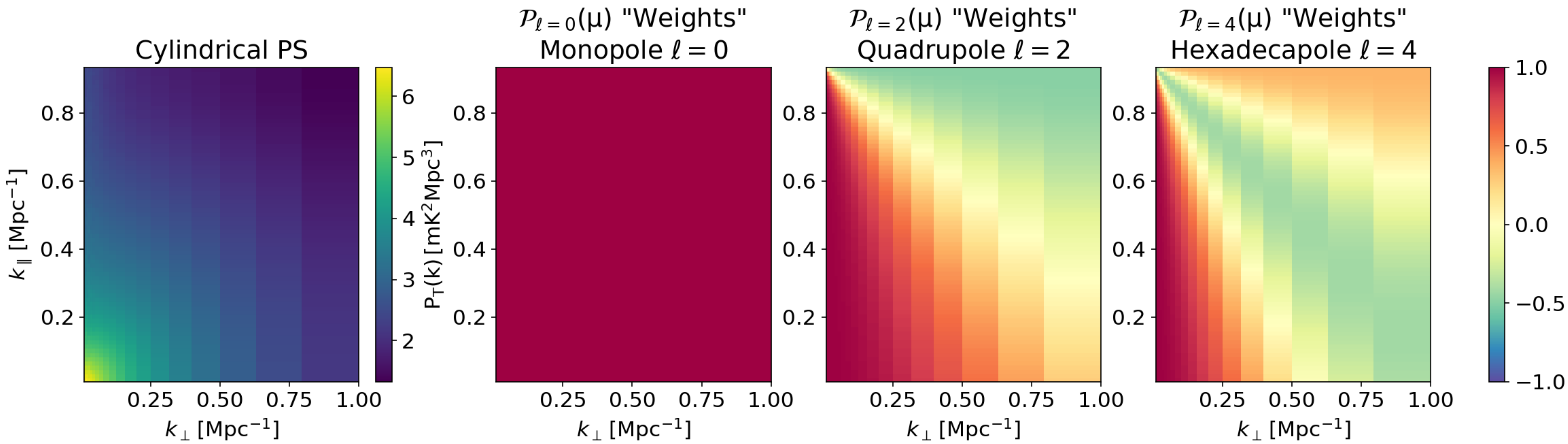
Greig et al. 2403.14060

Raut et al. 1708.02824

Flash course on multipoles

- Crudely speaking, multipoles are weighted averages of cylindrical PS

$$\mu = k_{\parallel}/k, P_{21}^{\ell}(k) = \frac{2\ell + 1}{\mu_1 - \mu_0} \int_{\mu_0}^{\mu_1} \mathrm{d}\mu \, \mathscr{P}_{\ell}(\mu) \, P_{21}(k, \mu)$$



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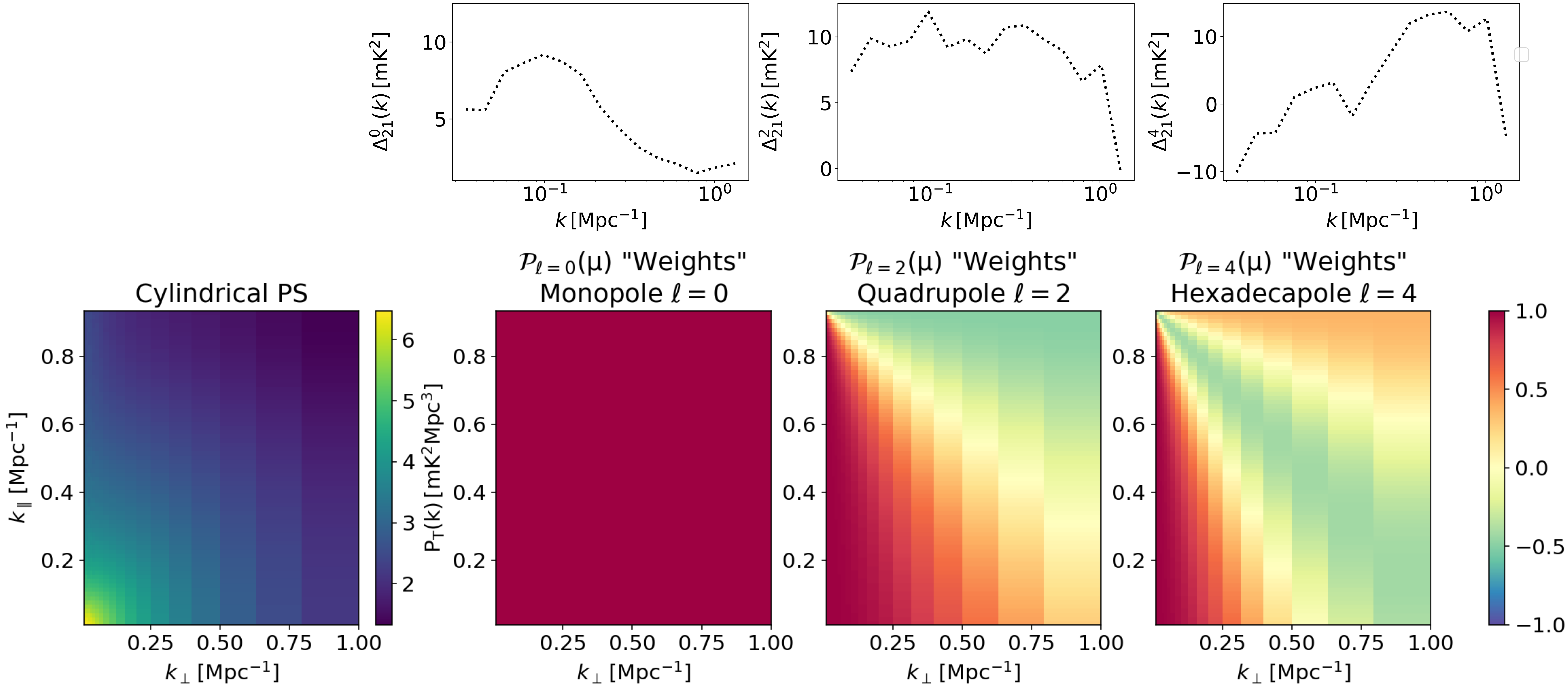
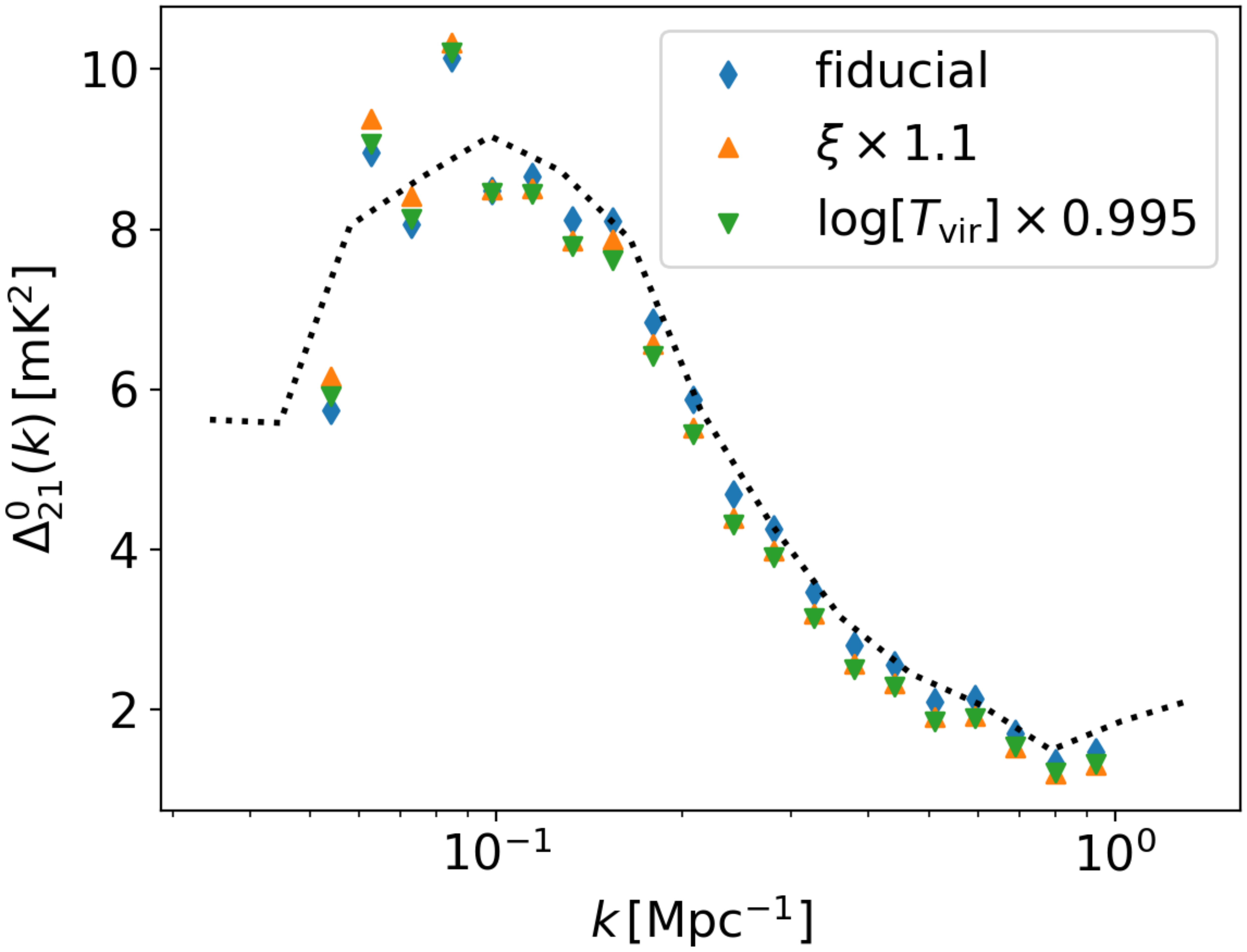


Problem of degeneracy with 1D monopole

- The spherically averaged power spectrum monopole does not probe anisotropy, leading to loss of information and parameter degeneracy:



Problem of degeneracy with 1D monopole

- At smaller scales, including the multipoles can help resolve the degeneracy and retrieve more information

Playing Devil's advocate...

For the first science product for SKA-Low EoR:

- No tomographic image

Diao, **ZC**, X. Chen & Mao 2406.20058

— **No morphology (e.g. Minkowski Functionals) or map-level inference.**
Power spectrum only.

ZC et al. 1812.10333

Zhao et al. 2105.03344

- Large light-cone effects

— **A representation of cylindrical PS is needed, for example multipoles.**

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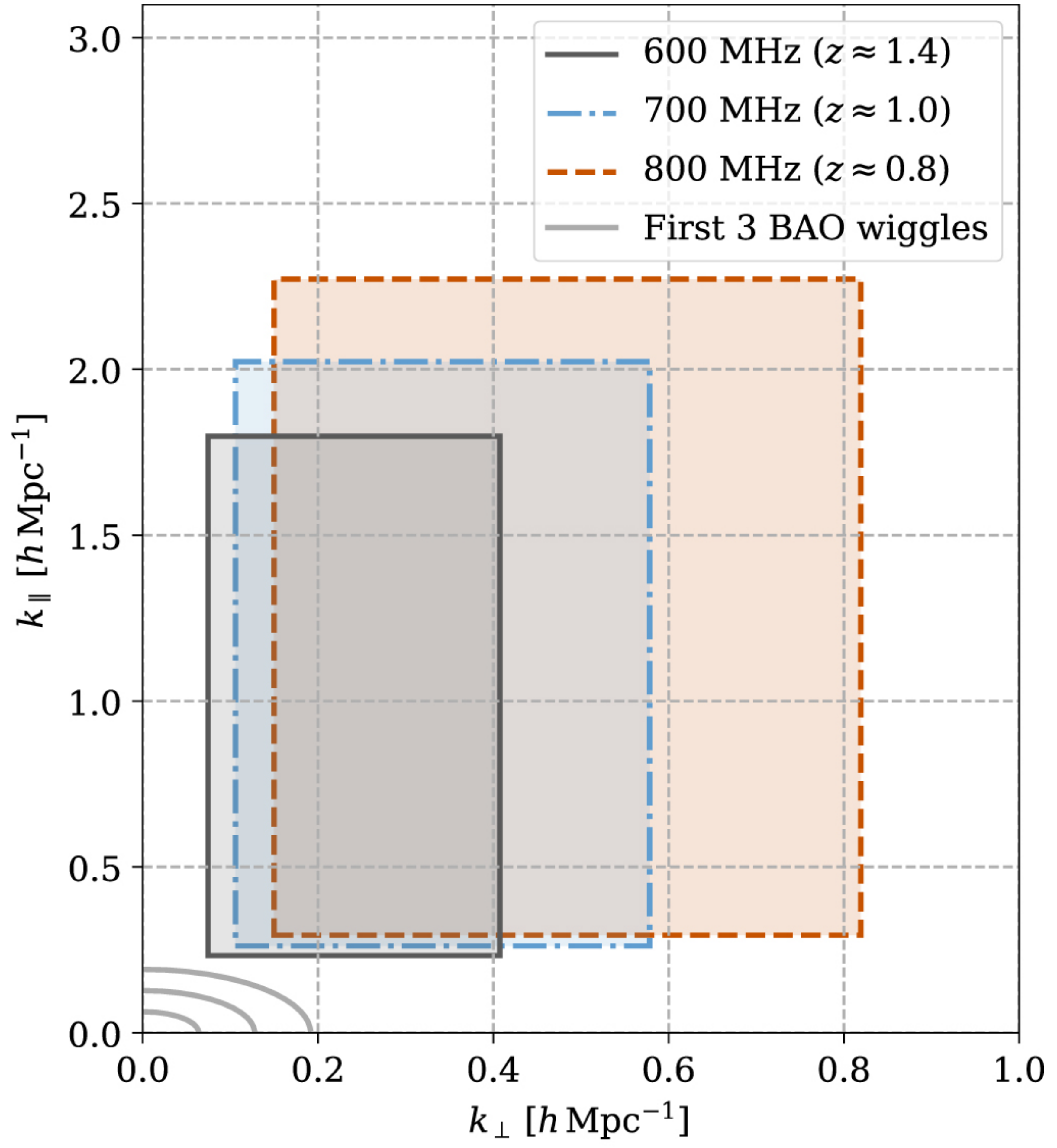
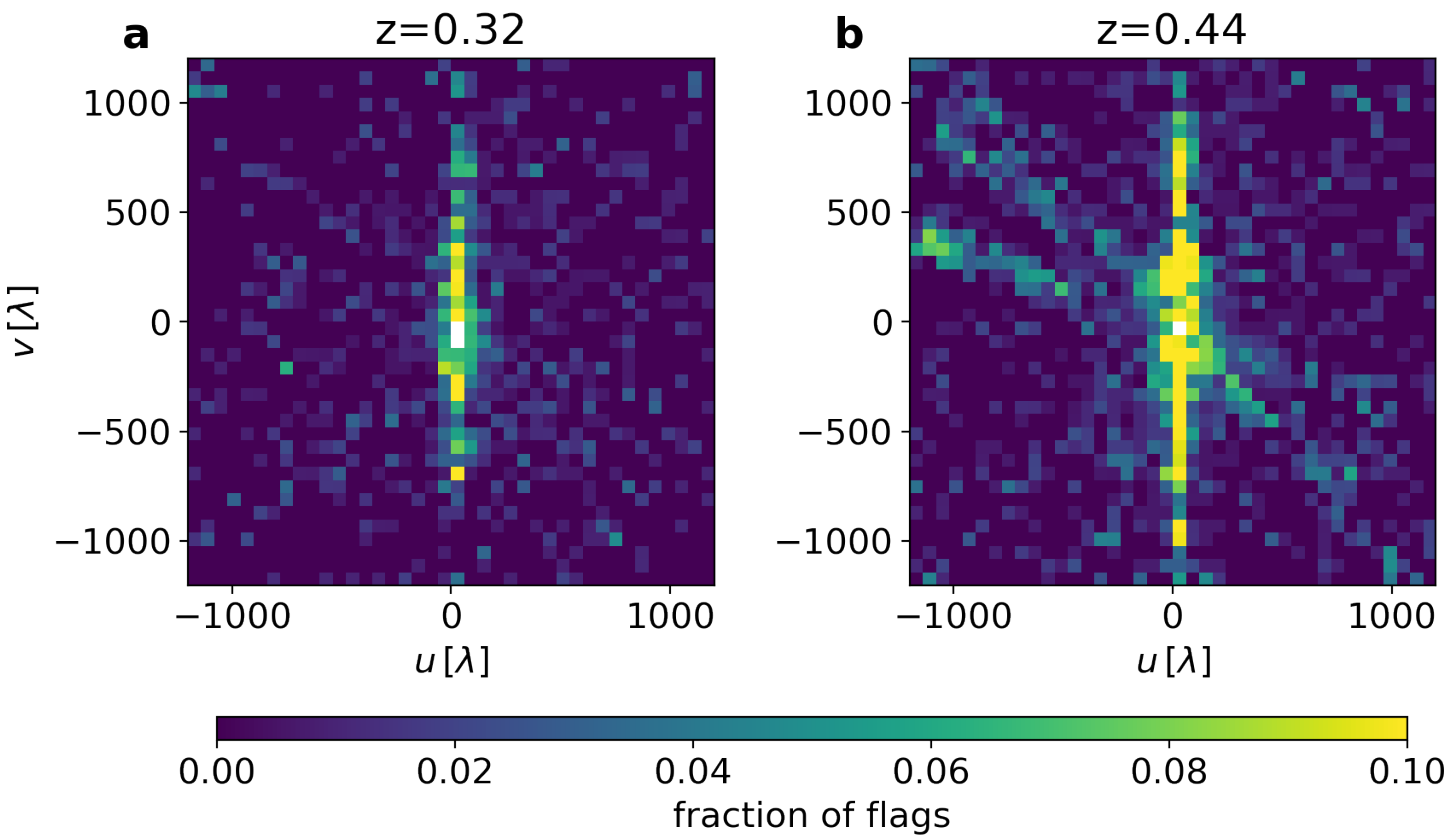
- Access to various scales?

Large angular scales are more contaminated

CHIME 2202.01242



MeerKAT DEEP2
Paul, Santos, **ZC** & Wolz
2301.11943



- Short baselines, i.e. large scales, may be contaminated by systematics.

Large angular scales are more contaminated

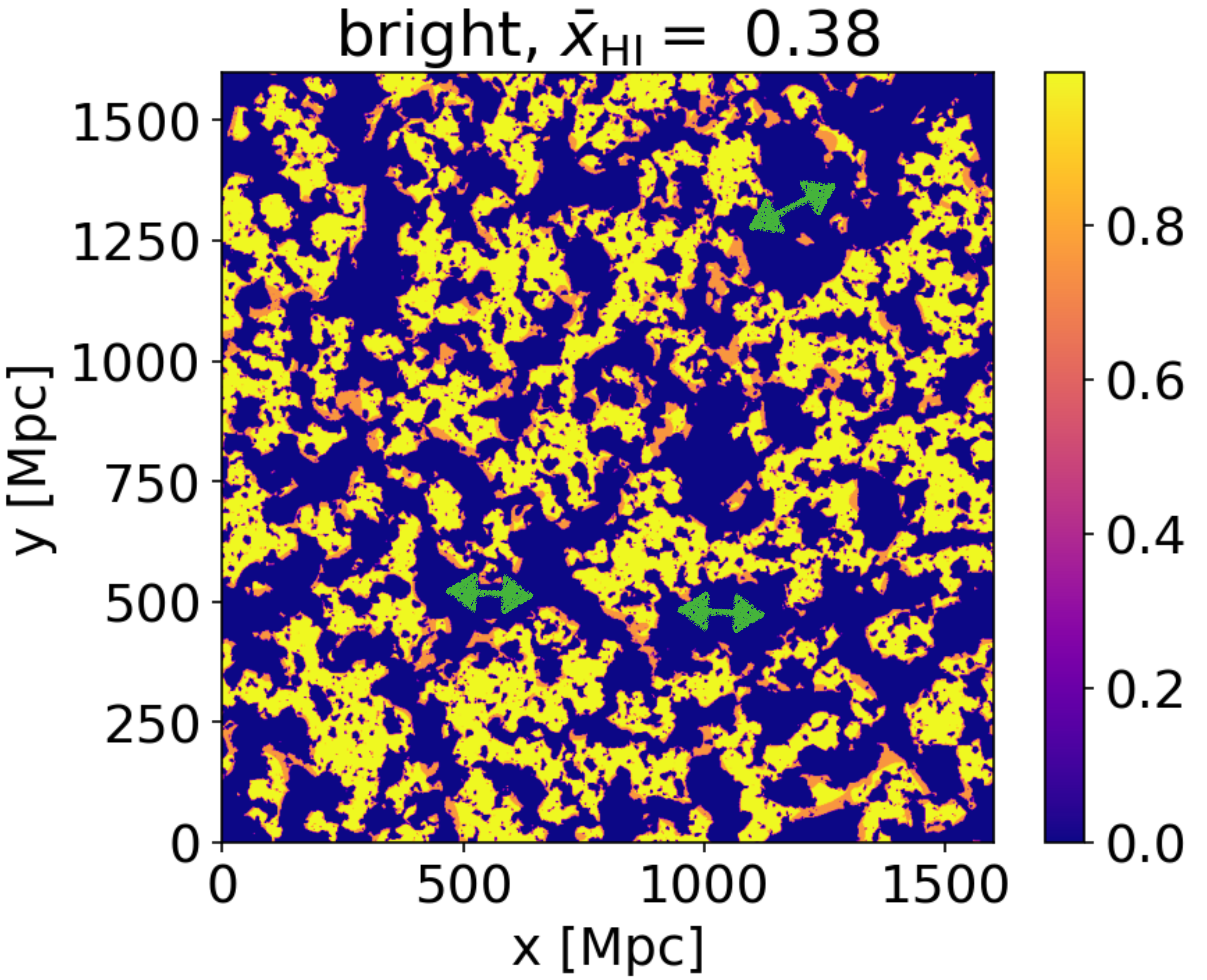
- Short baselines, i.e. large scales, may be contaminated by systematics.

— **Inference with only small scales. Focusing on EoR physics.**

1D monopole does not probe into the bubbles

"One-bubble" term of the 21cm PS will be completely correlated. Therefore, inner-bubble scales are almost entirely correlated.

Inner-bubble scale



Zero inside the bubble

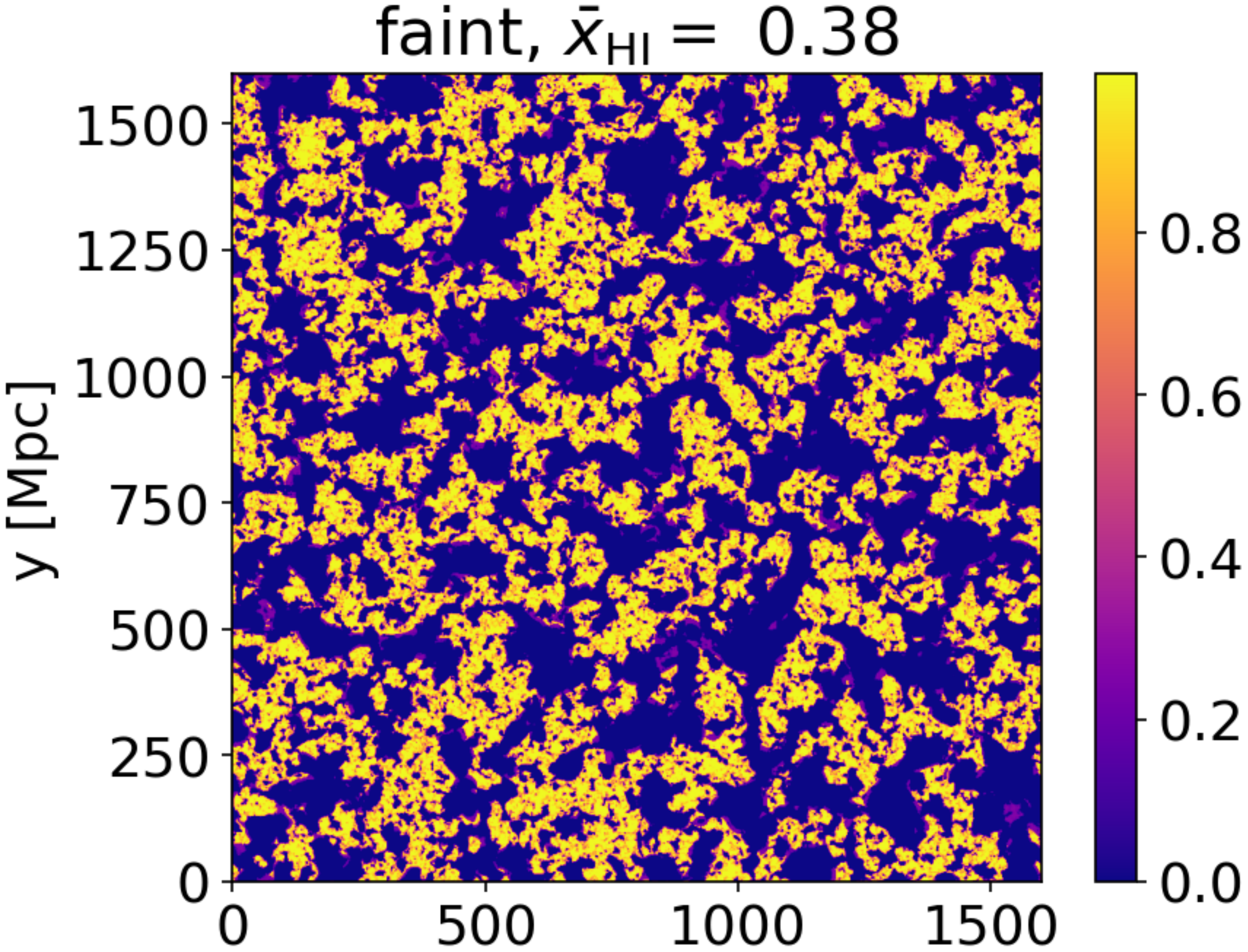
$$\delta T_b \approx 27\text{mK}\, x_{\rm HI}(1+\delta_m)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{\Omega_m}{0.27}\right)^{\frac{1}{2}} \times\left(\frac{\Omega_b h}{0.44\times 0.7}\right)\left(1+\frac{\mathrm{d}v_{\|}/\mathrm{d}r}{H}\right)^{-1},$$

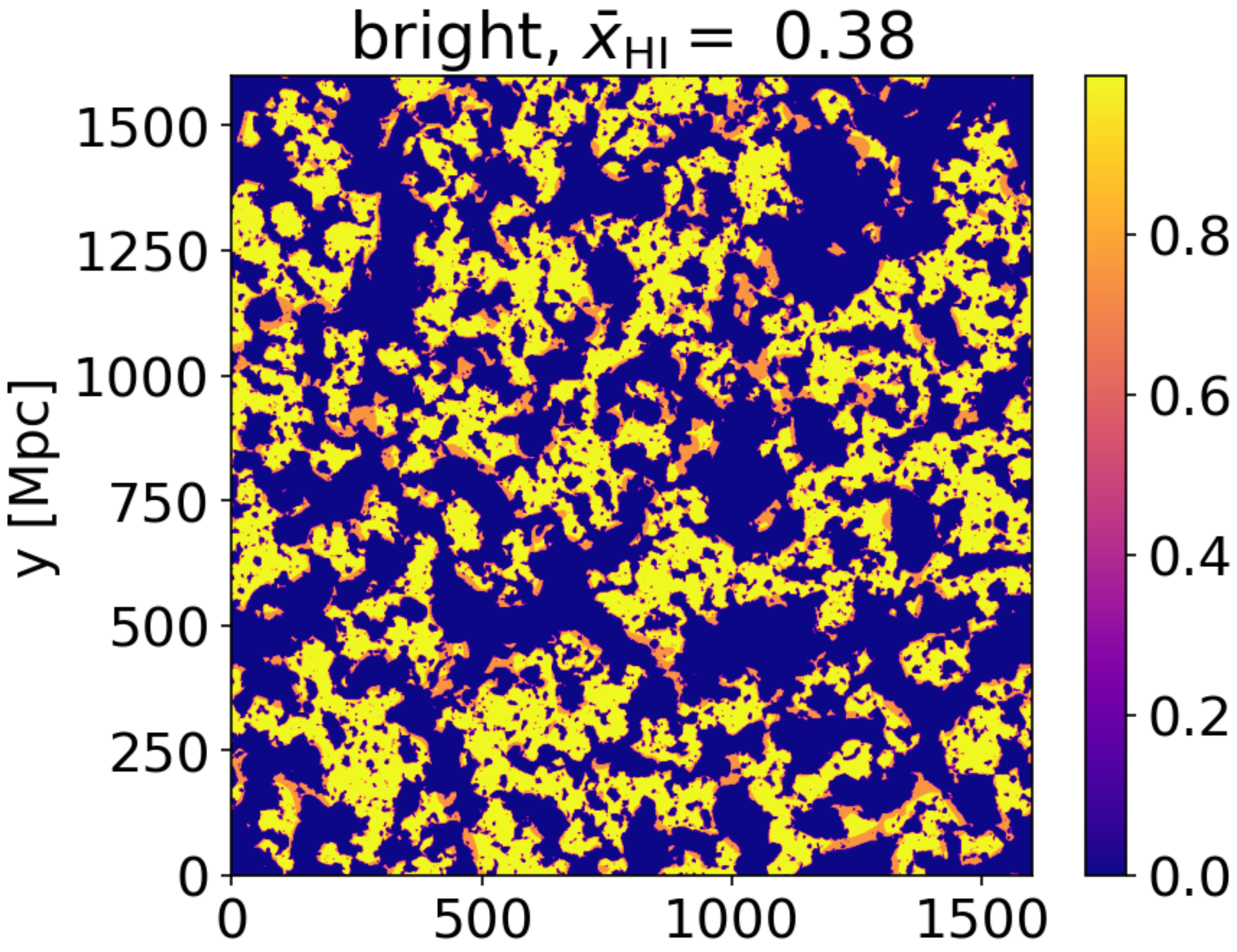
1D monopole does not probe into the bubbles

Two sets of fiducial parameters similar to "**faint**" and "**bright**" model.

$$(\log_{10}[T_{vir}/K], \xi) = (4.7,65), (5.1,150)$$

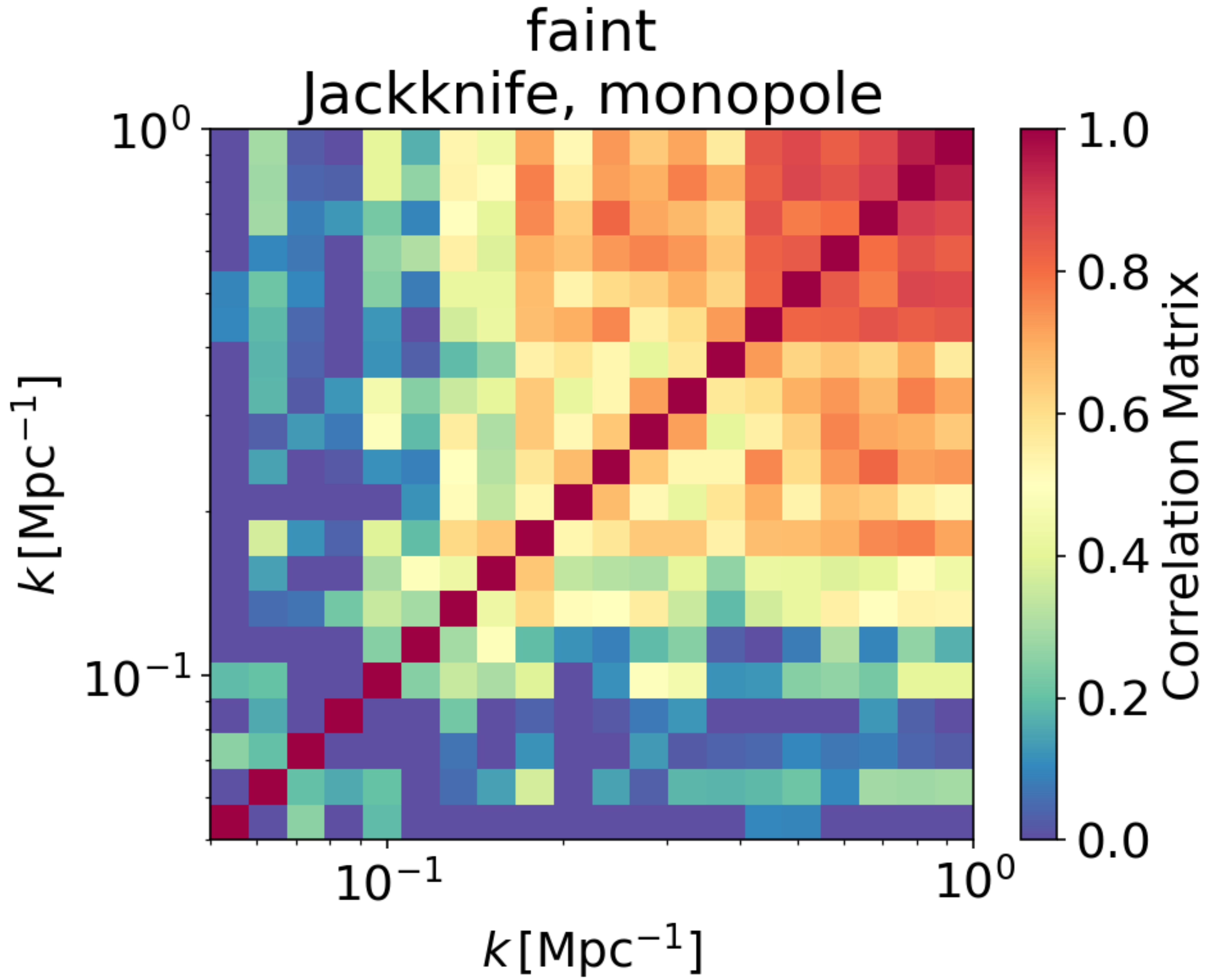
Greig & Mesinger 1801.01592

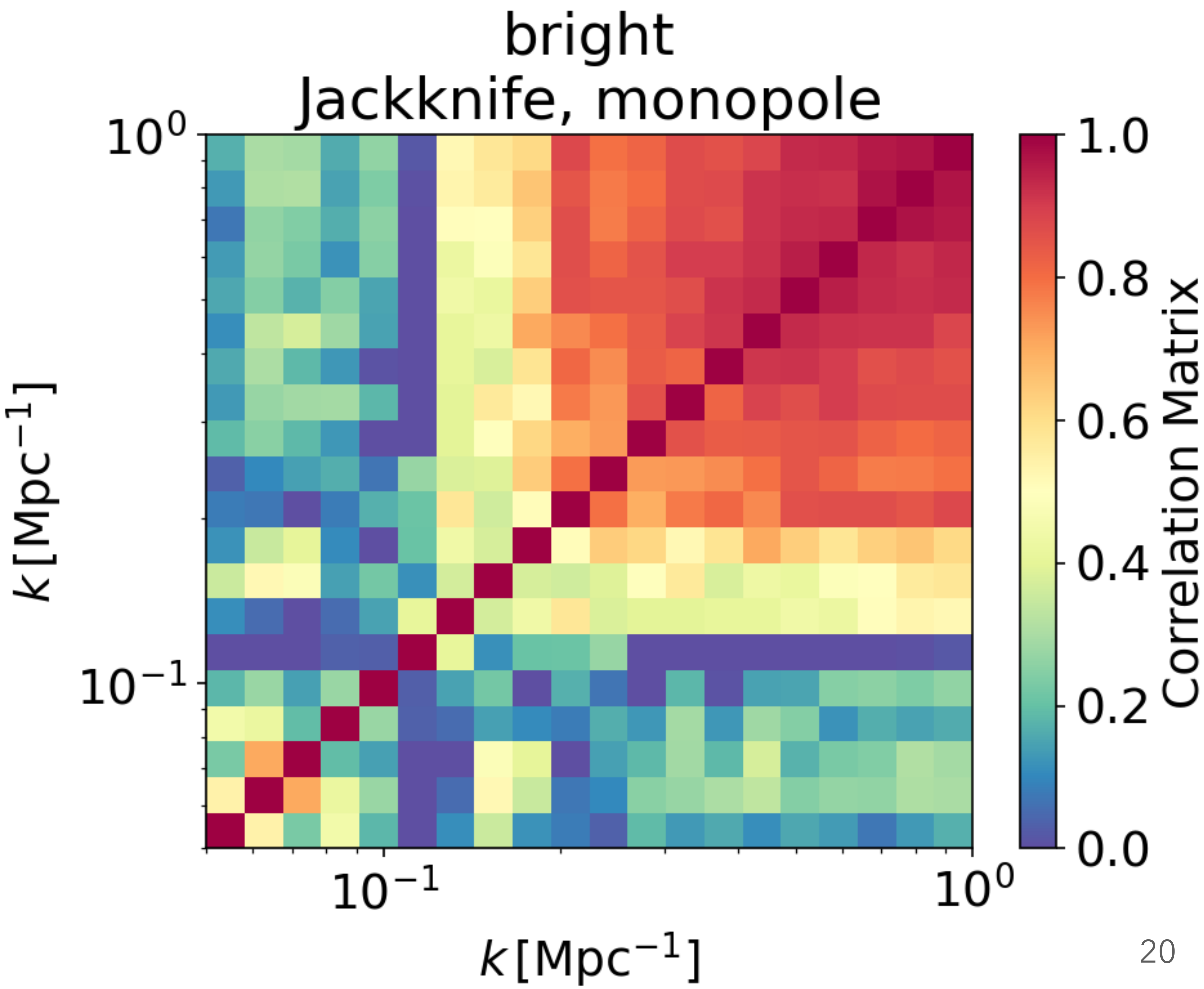




1D monopole does not probe into the bubbles

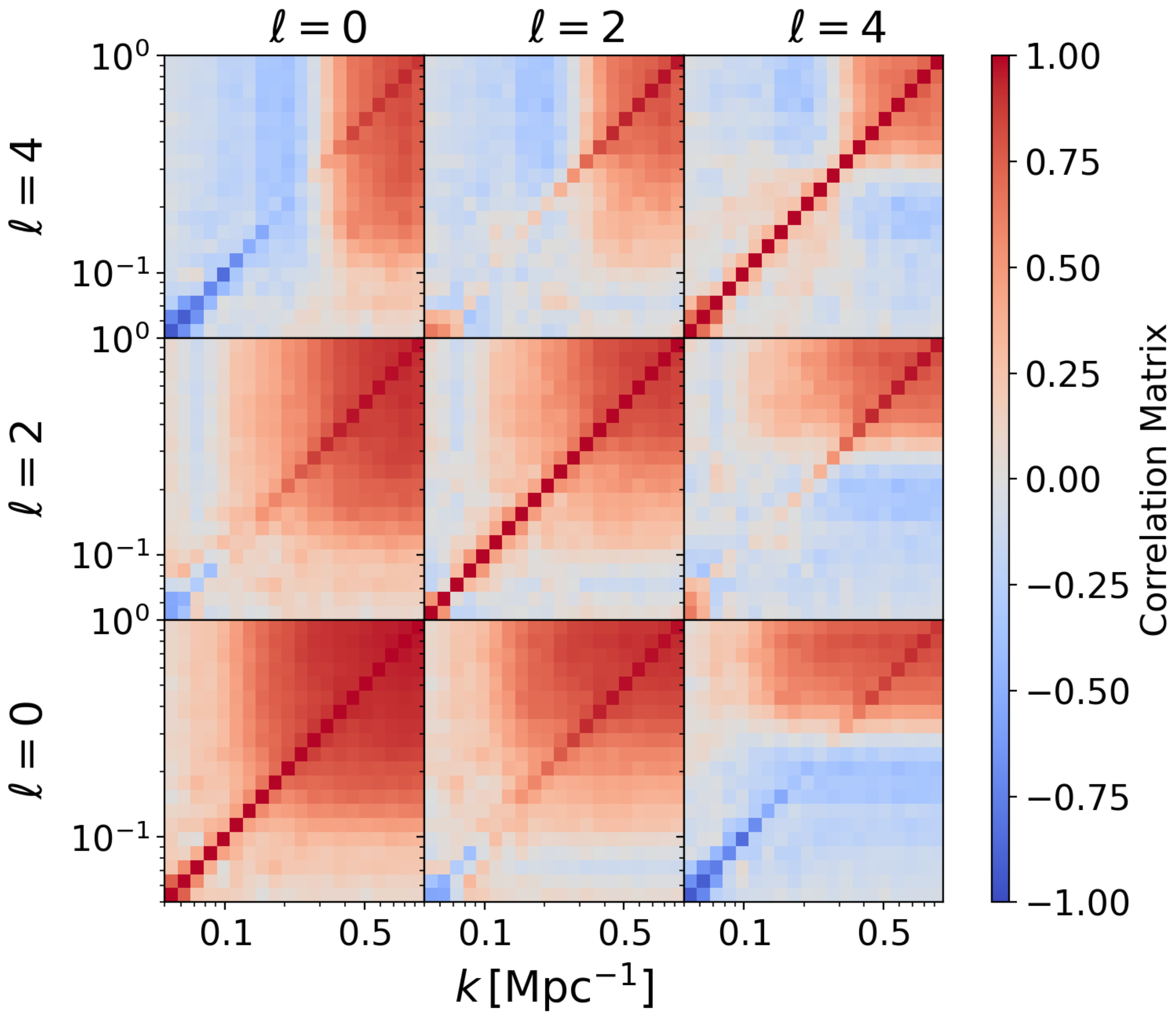
For a z~7-9 lightcone, depending on the reionization model, scales beyond 0.2 Mpc^-1 may be entirely correlated due to large sizes of the bubbles.





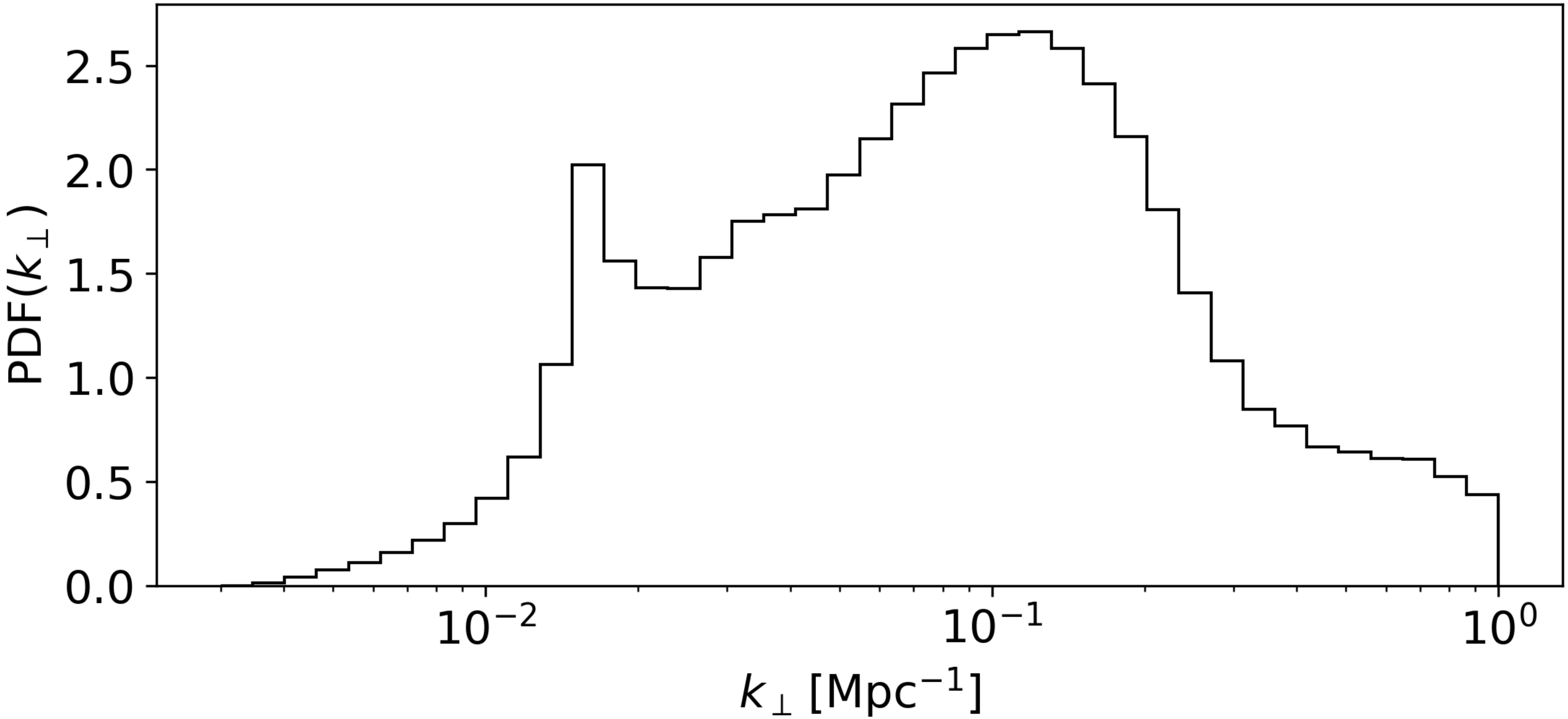
Information in anisotropy

Baseline distribution and corresponding sampling of k-space is explicitly propagated into the calculation



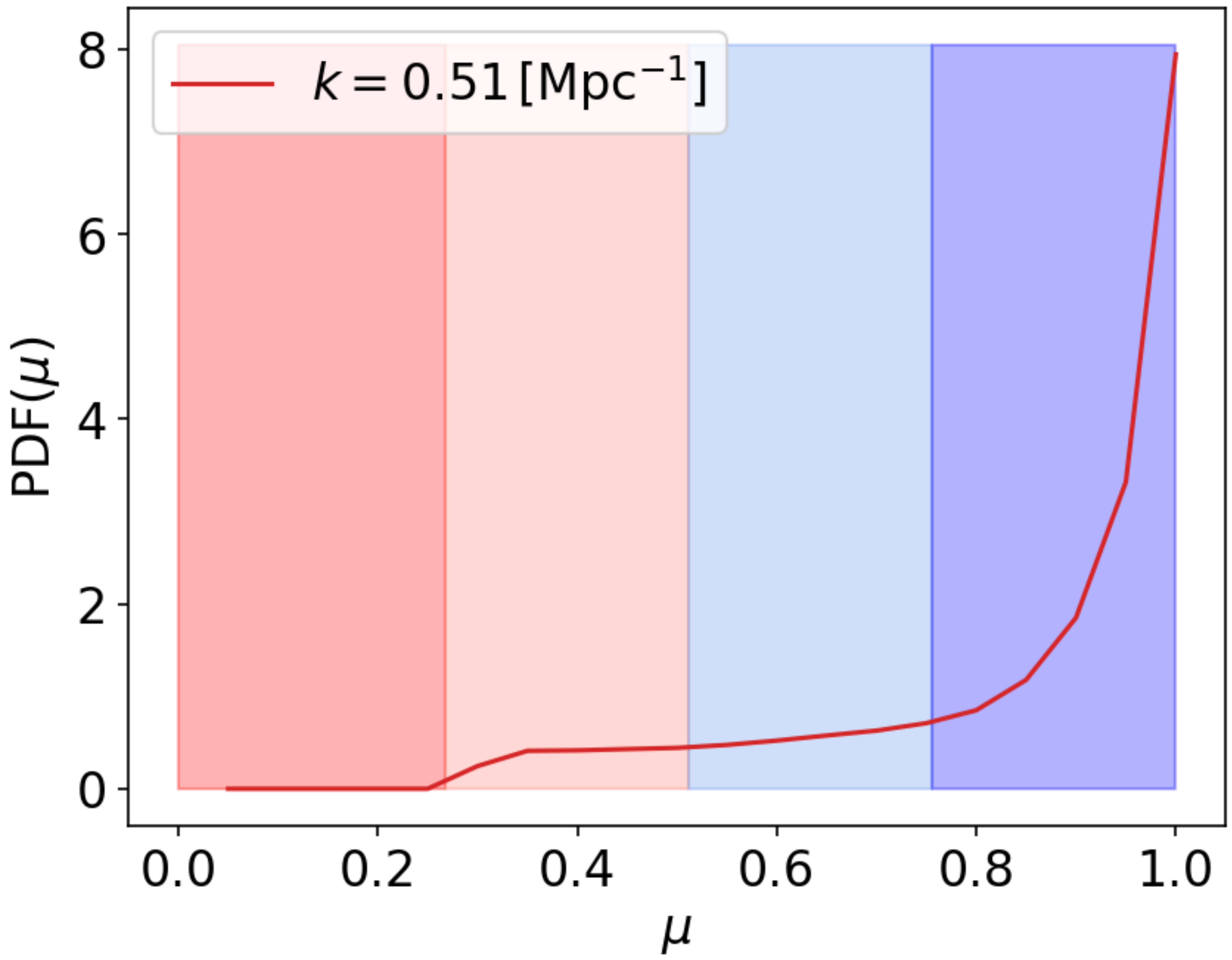
Small scales are not sampled properly

- Short baselines, i.e. large scales, may be contaminated by systematics.
- Sampling in k-space is highly skewed due to baseline distribution



What may be the first science product for SKA-Low EoR?

- On small scales, high k_para is massively oversampled.
- Split into clustering wedges to have relatively uniform sampling



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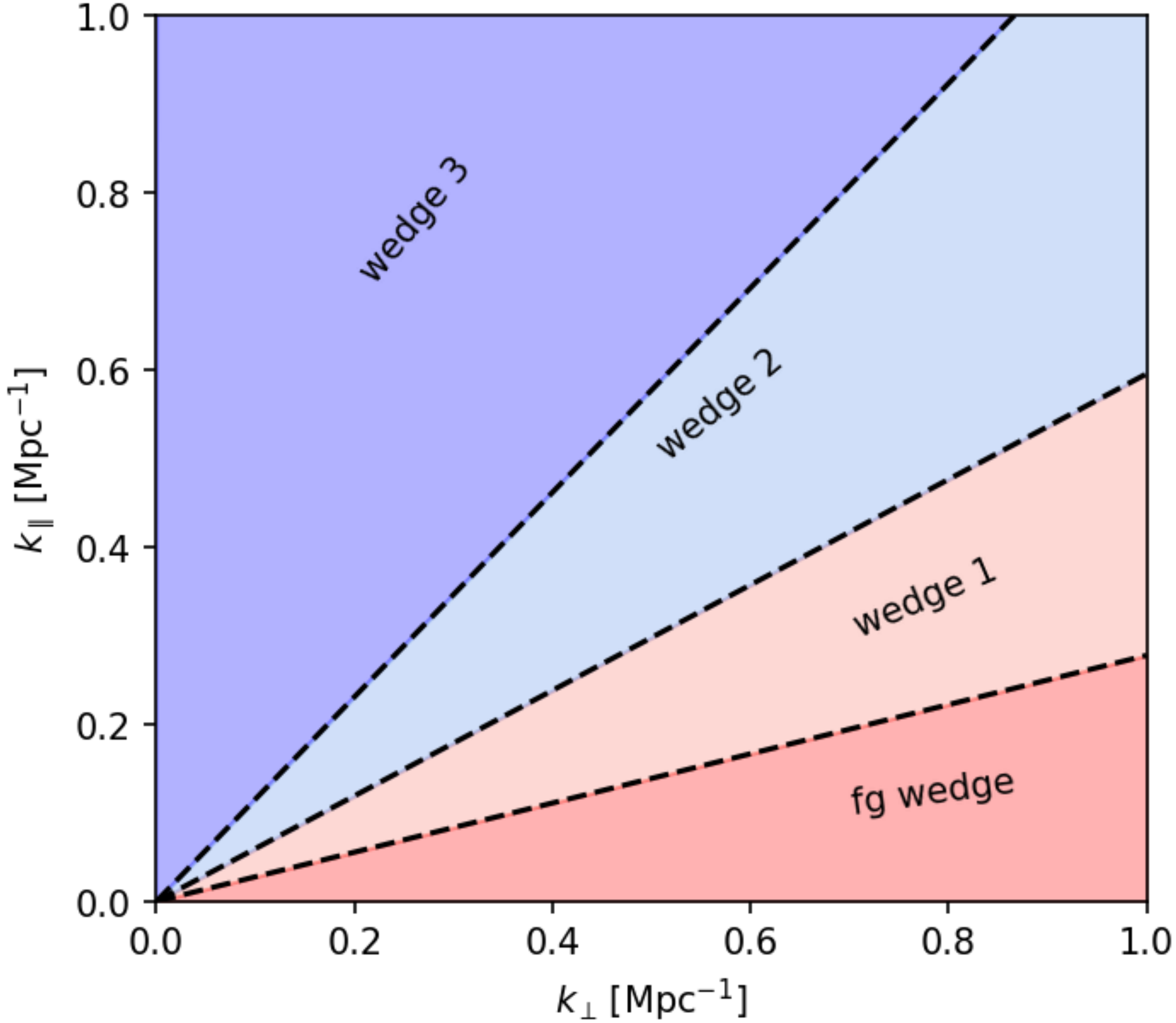

What r … ow EoR?

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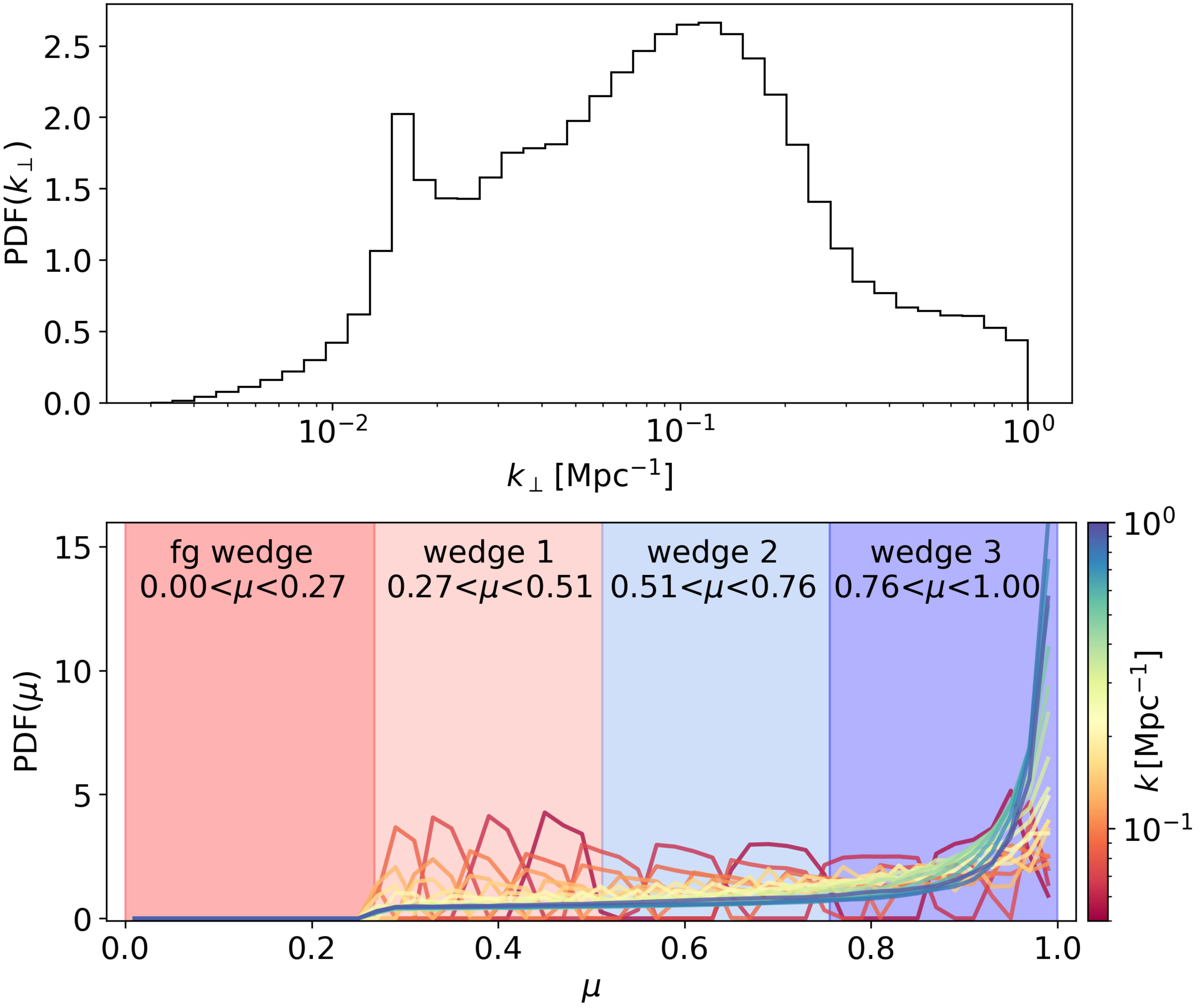
- Samplin
- On smal



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Power spectrum only.

- Large light-cone effects

— **A representation of cylindrical PS is needed, for example multipoles.**

Greig et al. 2403.14060

Raut et al. 1708.02824

- Small scales only

— **Clustering wedges to fully utilise anisotropy to decouple small scales**

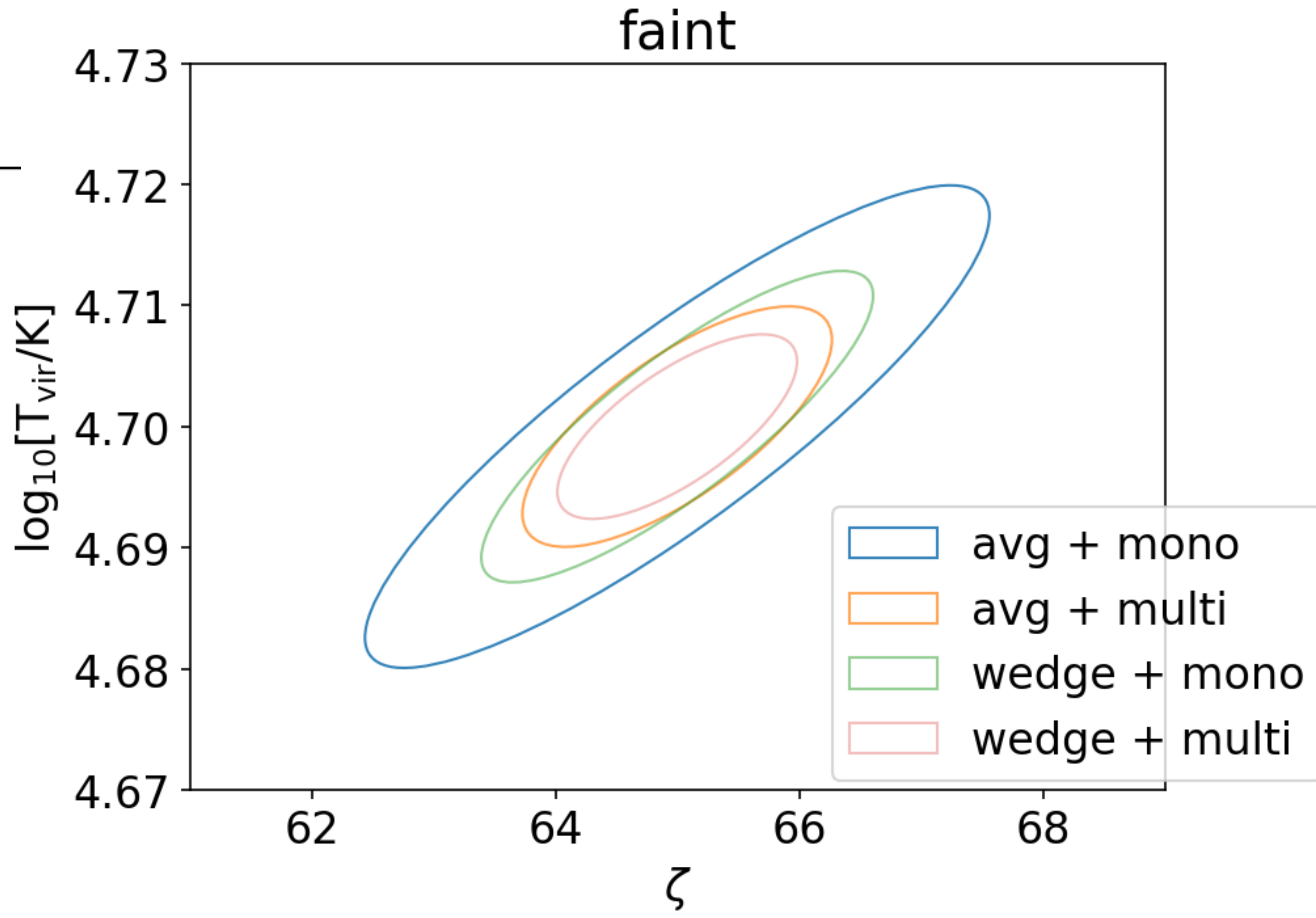
Dissecting into clustering wedges

Extra information can be extracted out of the multipoles by splitting the k-space into clustering wedges:

Information content of multipoles in wedges

Fisher information shows large improvements in the constraining power from including the multipoles. There is also slight improvement in the degeneracy between the parameters.

model		faint			
parameter	fid	mono+avg	multi+avg	mono+wedge	multi+wedge
ζ	65	5.124	2.540	3.215	1.967
$\log_{10}[T_{\rm vir}/{\rm K}]$	4.7	0.040	0.020	0.026	0.015
$\rho_{\zeta \log T_{\rm vir}}$		0.875	0.723	0.841	0.708
$\det[\mathcal{F}]$		102.169	824.186	499.218	2231.363



Conclusion

Using power spectrum multipoles as summary statistics

- **Reduce correlation** at small scales

- Probe into the evolution of ionisation field along the light cone

- Information can be further extracted by partitioning the k-space into wedges

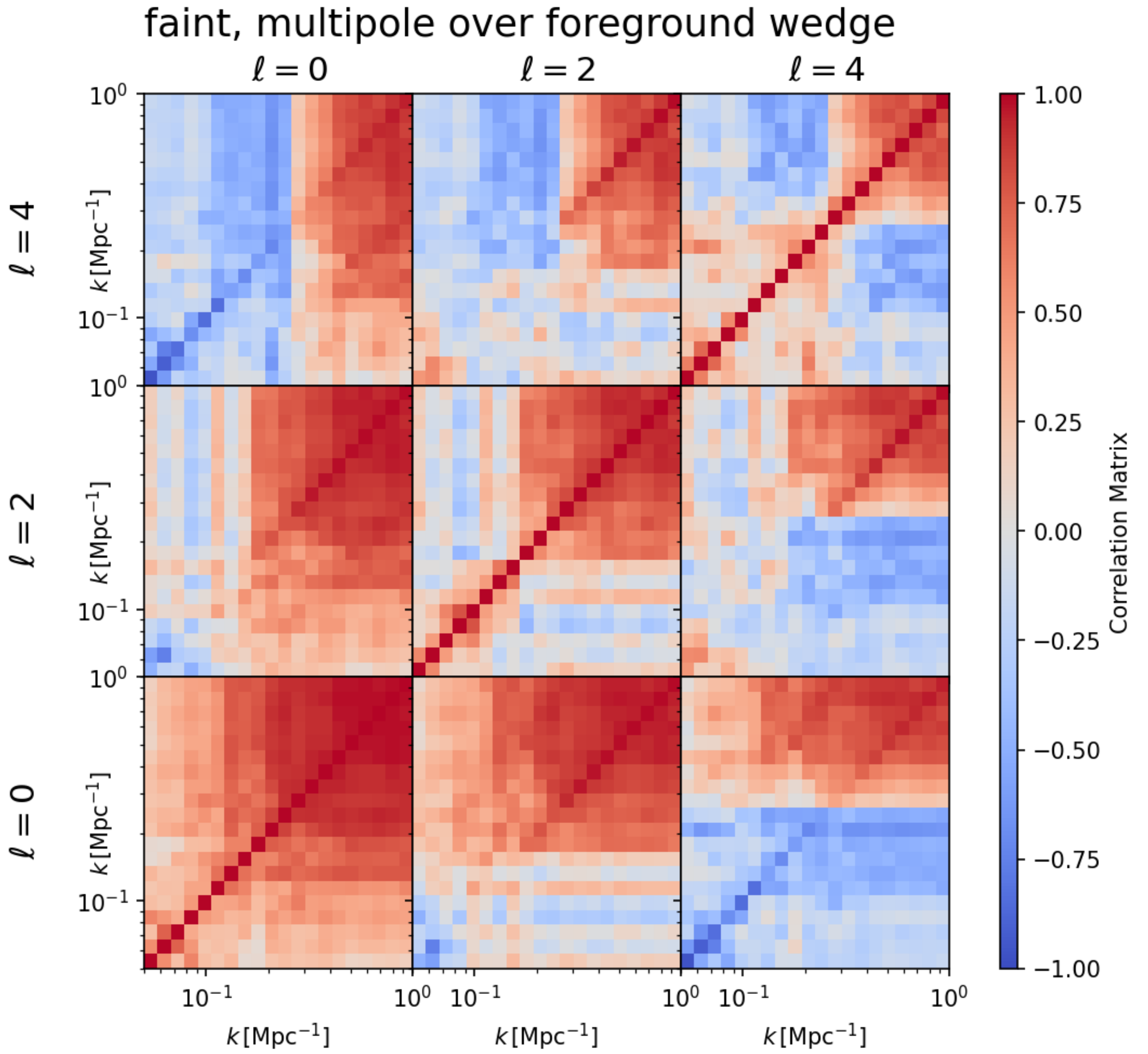
- For SKA-Low with integration time of ~100h, **per-cent level constraints** on reionization history can be achieved.

- Comparing to spherically averaged monopole, multipoles in clustering wedges yield **a factor of ~2.5 improvement**.

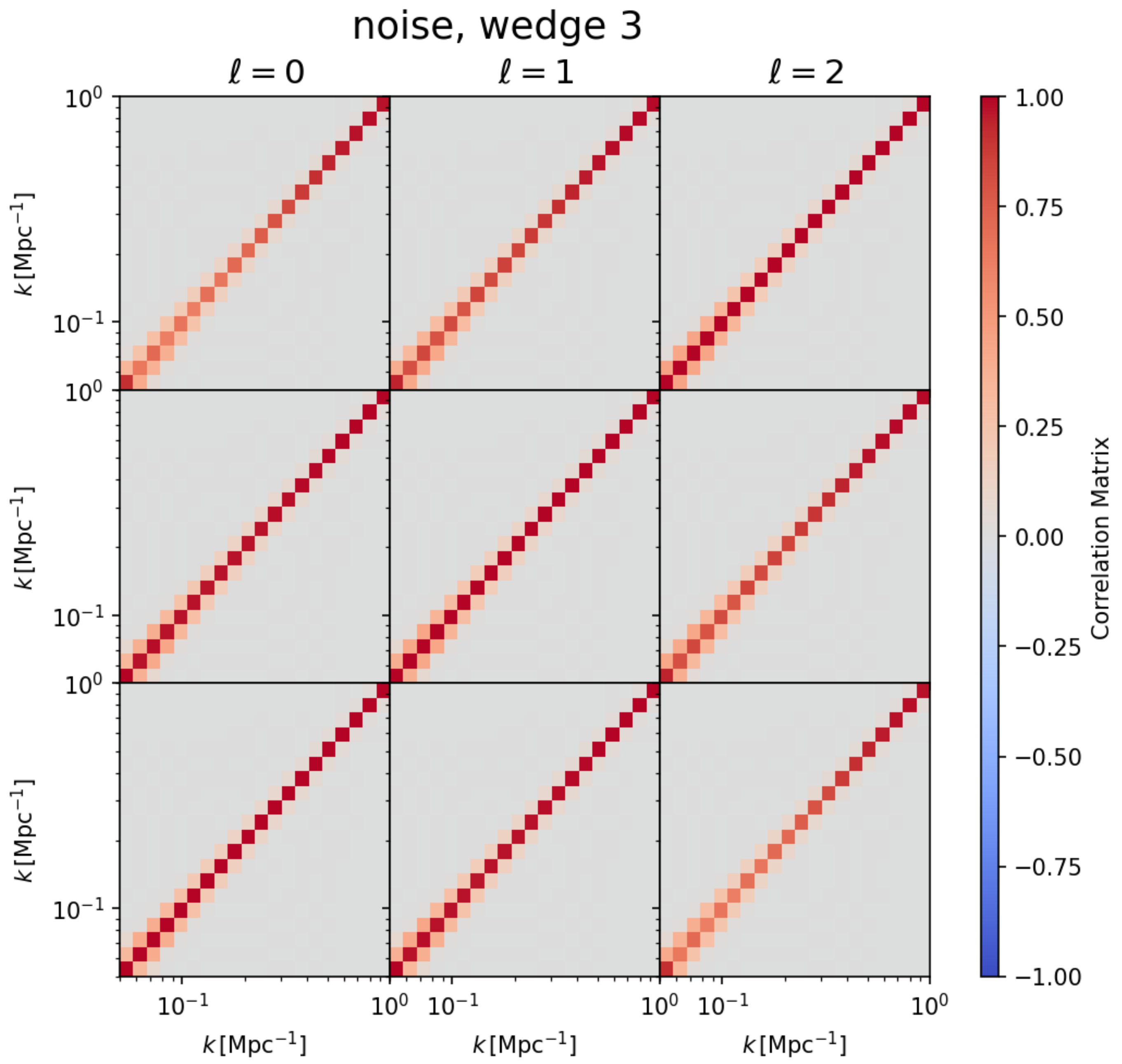
Thanks

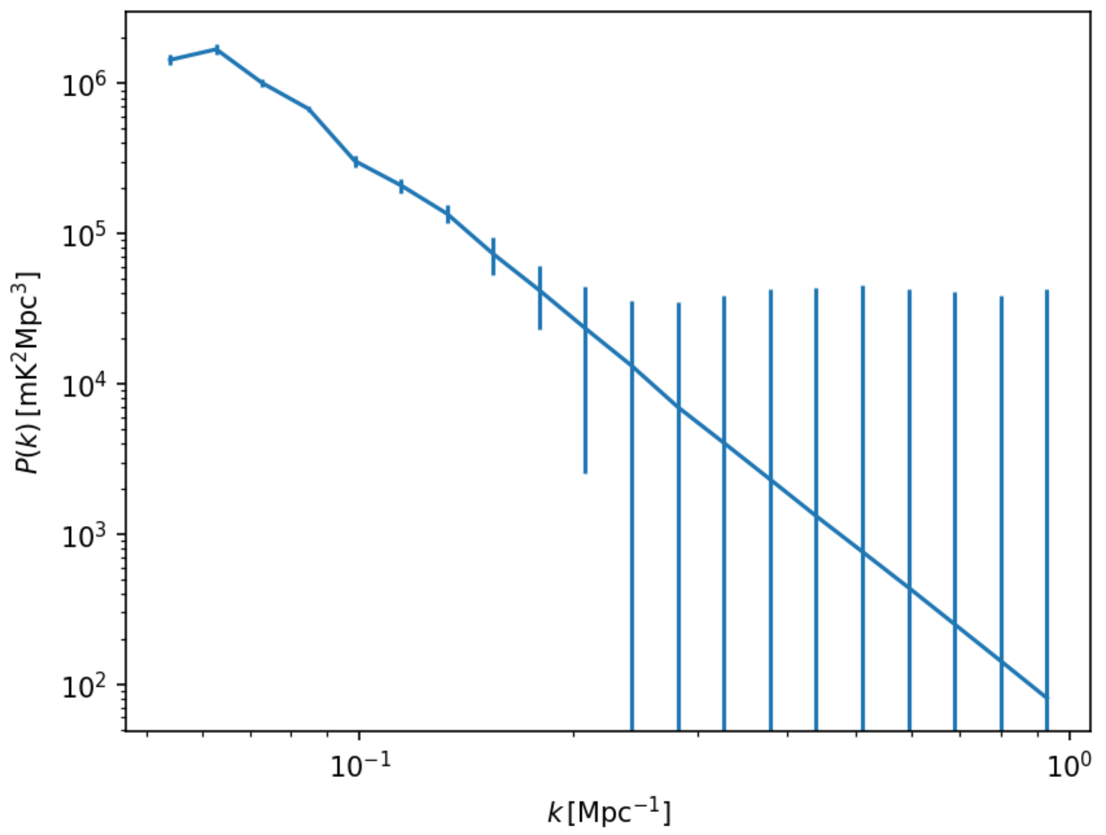
Fisher Matrix forecasts

Signal covariance through jackknife of simulation lightcones



Noise covariance through baseline distribution and quadratic estmators





Multipoles in wedges

Data covariance

Vary parameters, average over different ICs

$$F_{\alpha\beta} = \frac{1}{2}\mathrm{tr}[\frac{\partial C}{\partial\theta_\alpha}C^{-1}\frac{\partial C}{\partial\theta_\beta}C^{-1}] + \frac{\partial u^T}{\partial\theta_\alpha}C^{-1}\frac{\partial u}{\partial\theta_\beta}$$