HI intensity mapping with MeerKAT and the SKA

Mário G. Santos, University of the Western Cape

DSU, Kigali

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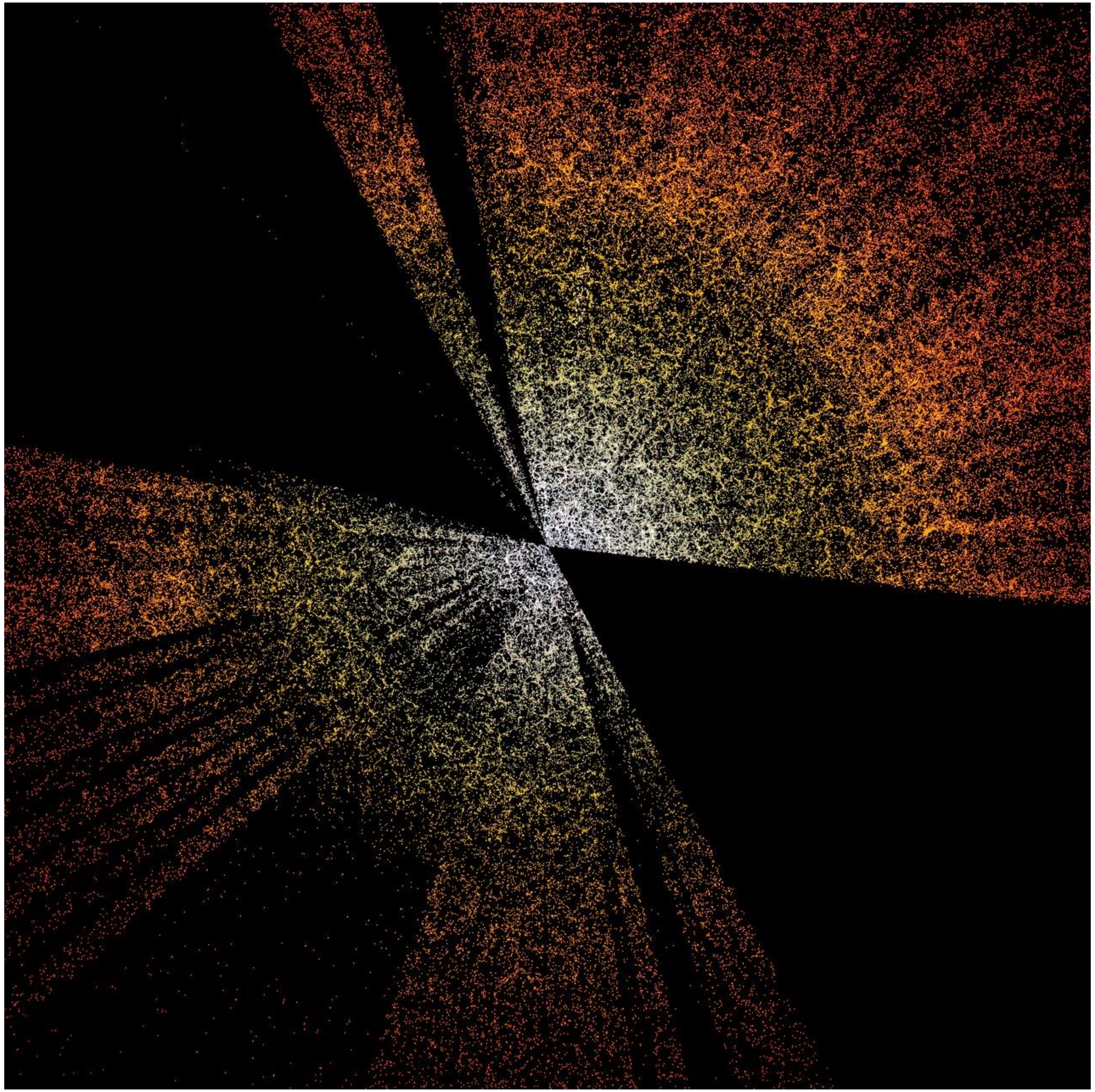
CRC
UNIVERSITY of the WESTERN CAPE
UWC ASTROPHYSICS
NRF National Research Foundation
SARAO South African Radio Astronomy Observatory

The future is 4D!

- Current questions: dark energy? dark matter? modified gravity? Primordial fluctuations?
- We need 3D measurements of large scale structure across time to probe fundamental questions in Cosmology
- Usually this is done through galaxy redshift surveys: Euclid, DESI, Roman/WFIRST…
- For the radio: HI 21cm line from each galaxy
- Very “expensive”!

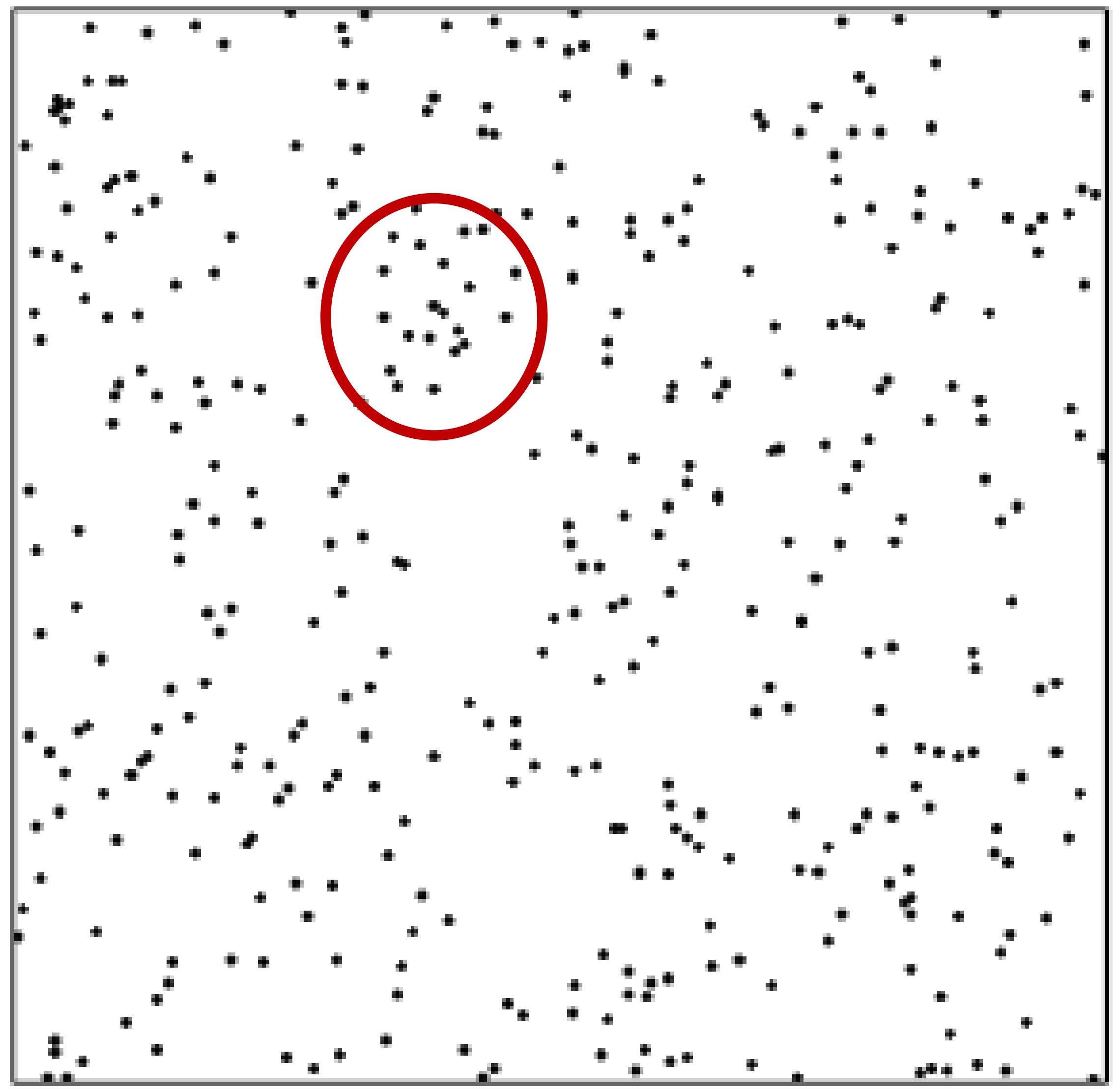


(SDSS/DESI)

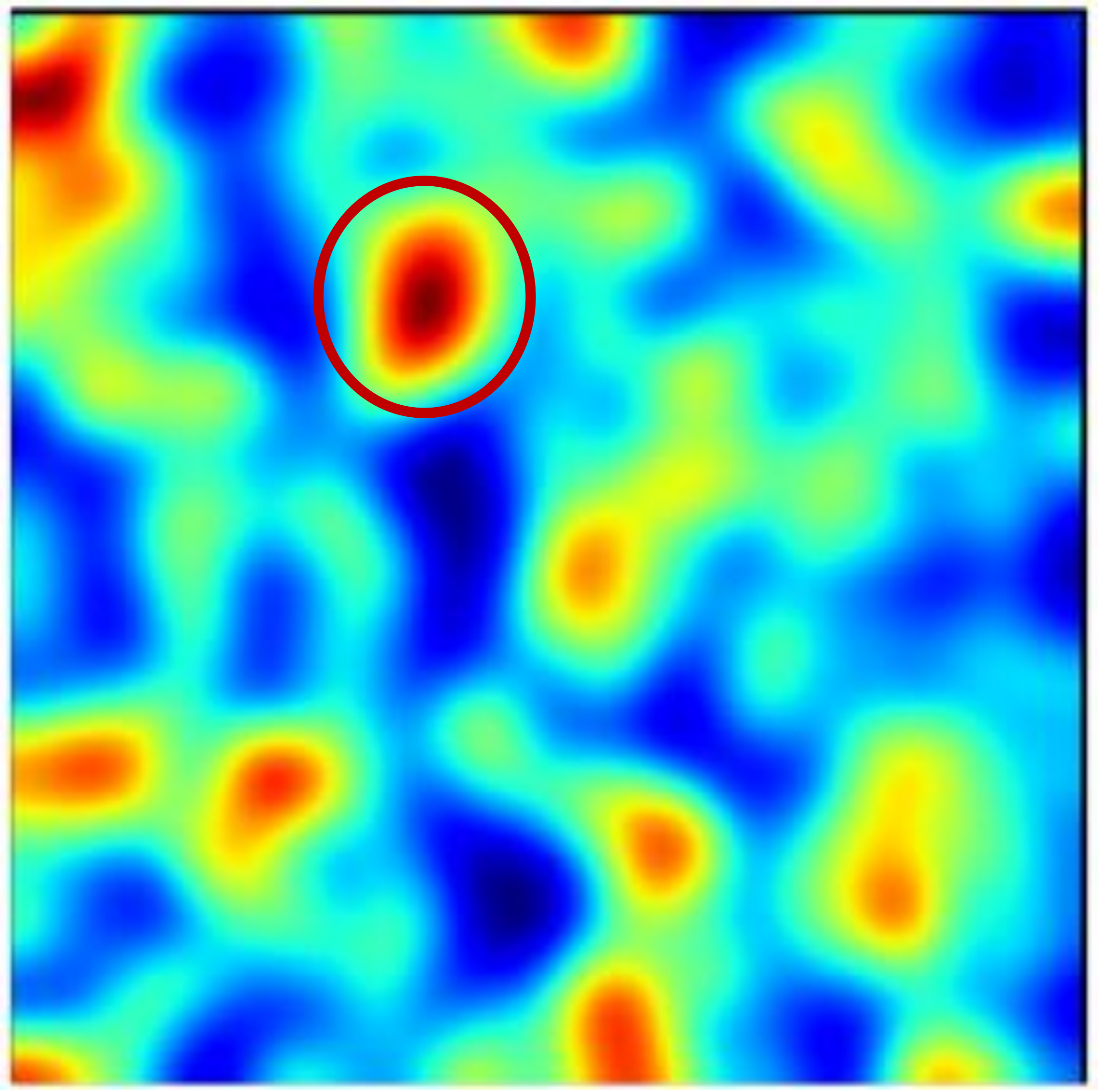
Probing LSS with intensity mapping

- For Cosmology, scales of interest are well beyond galaxy scales (Baryon Acoustic Oscillations ~ 150 Mpc)
- Intensity mapping is very fast → no threshold cutoff
- Provides high frequency/redshift resolution (in the radio…)
- Pixel will have joint emission from multiple galaxies
- Signal ~ 200 uK at z~1

Note: only way to probe the IGM HI

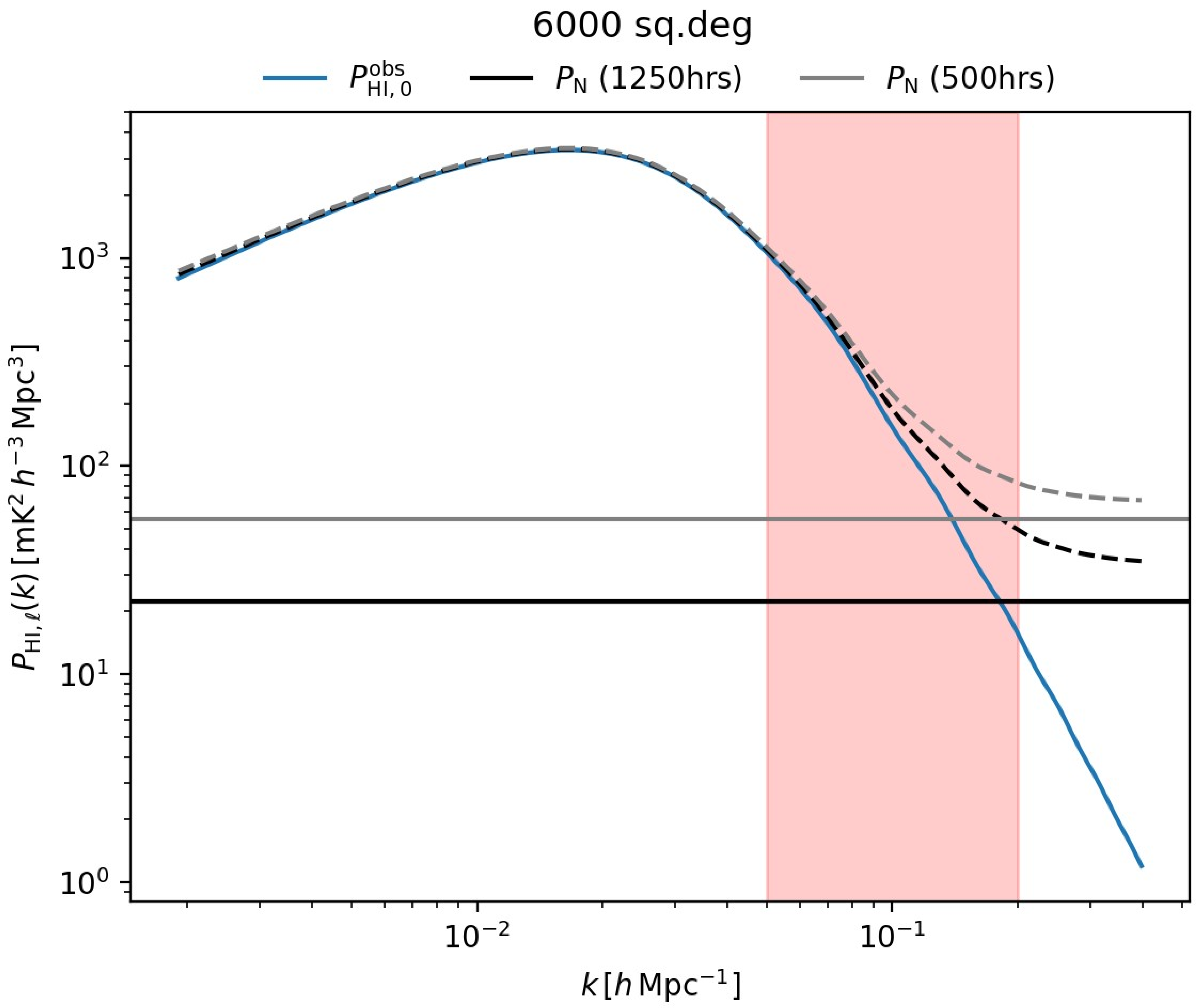


galaxies



Intensity map

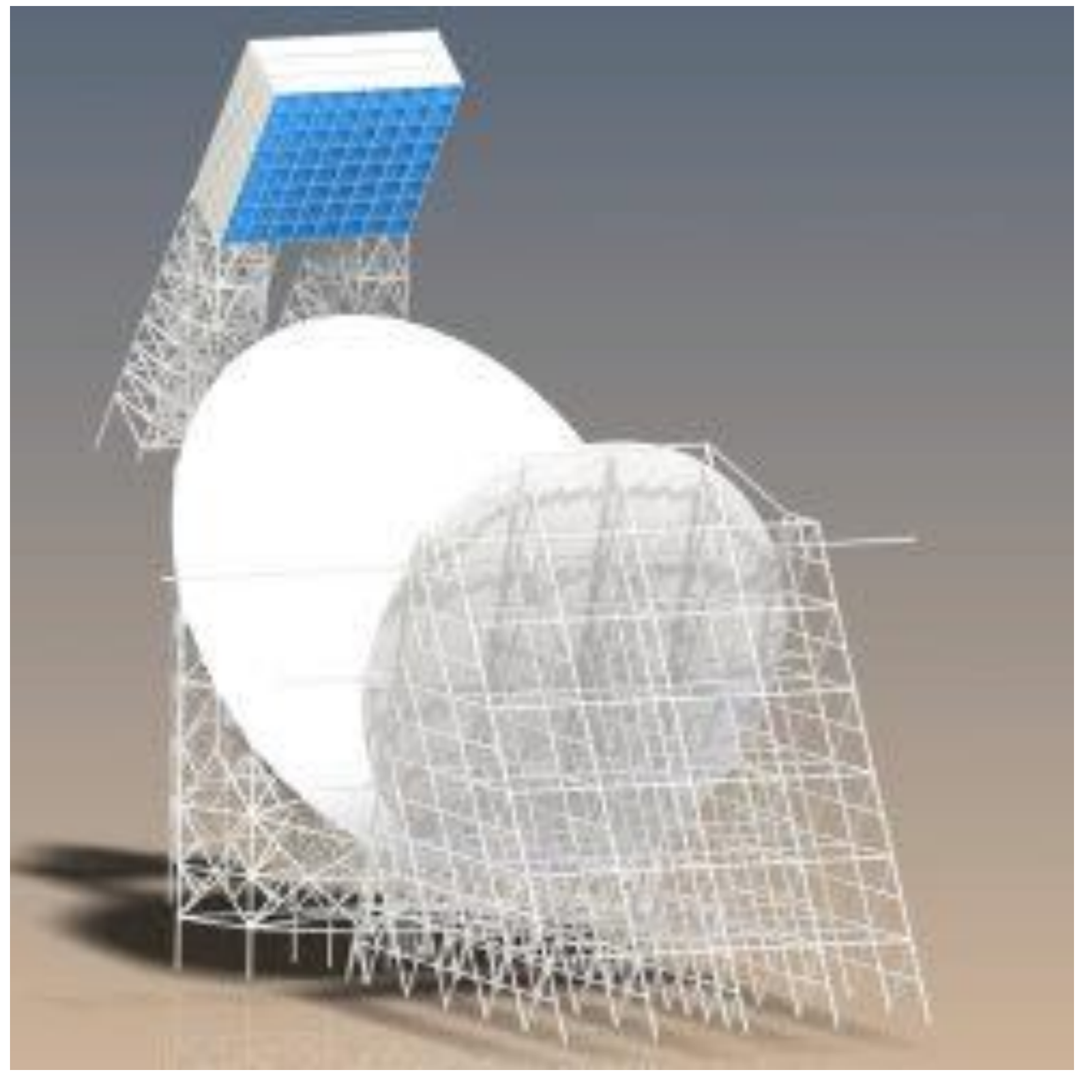
HI IM makes it “easy” to probe the power spectrum



- An example with the MeerKAT telescope: 500 hours is enough to detect the baryon acoustic oscillations. Noise is well below the signal on large scales

Dedicated experiments…

- HIRAX (South Africa)



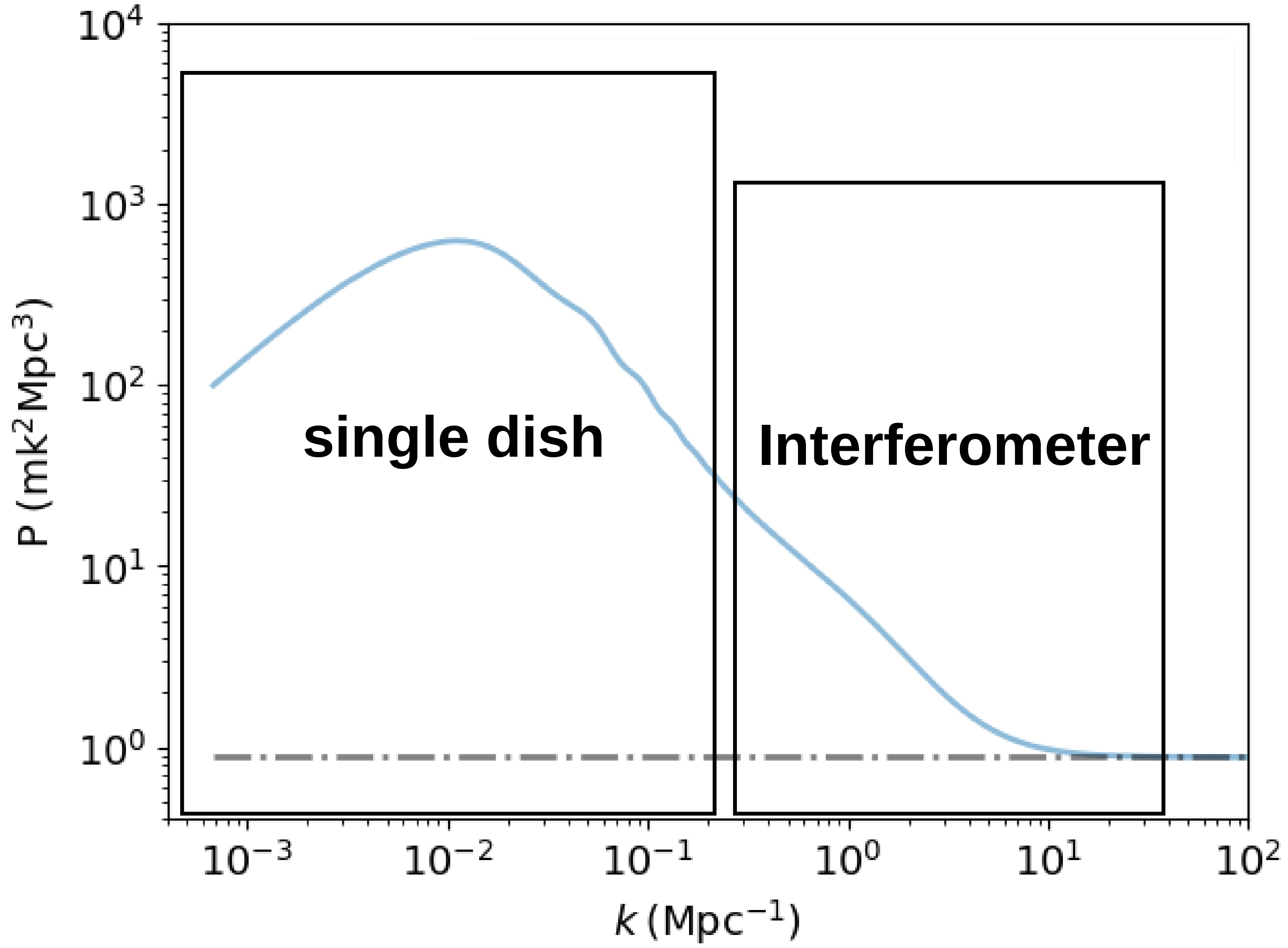
- BINGO? (Brazil)

- Tianlai (China)

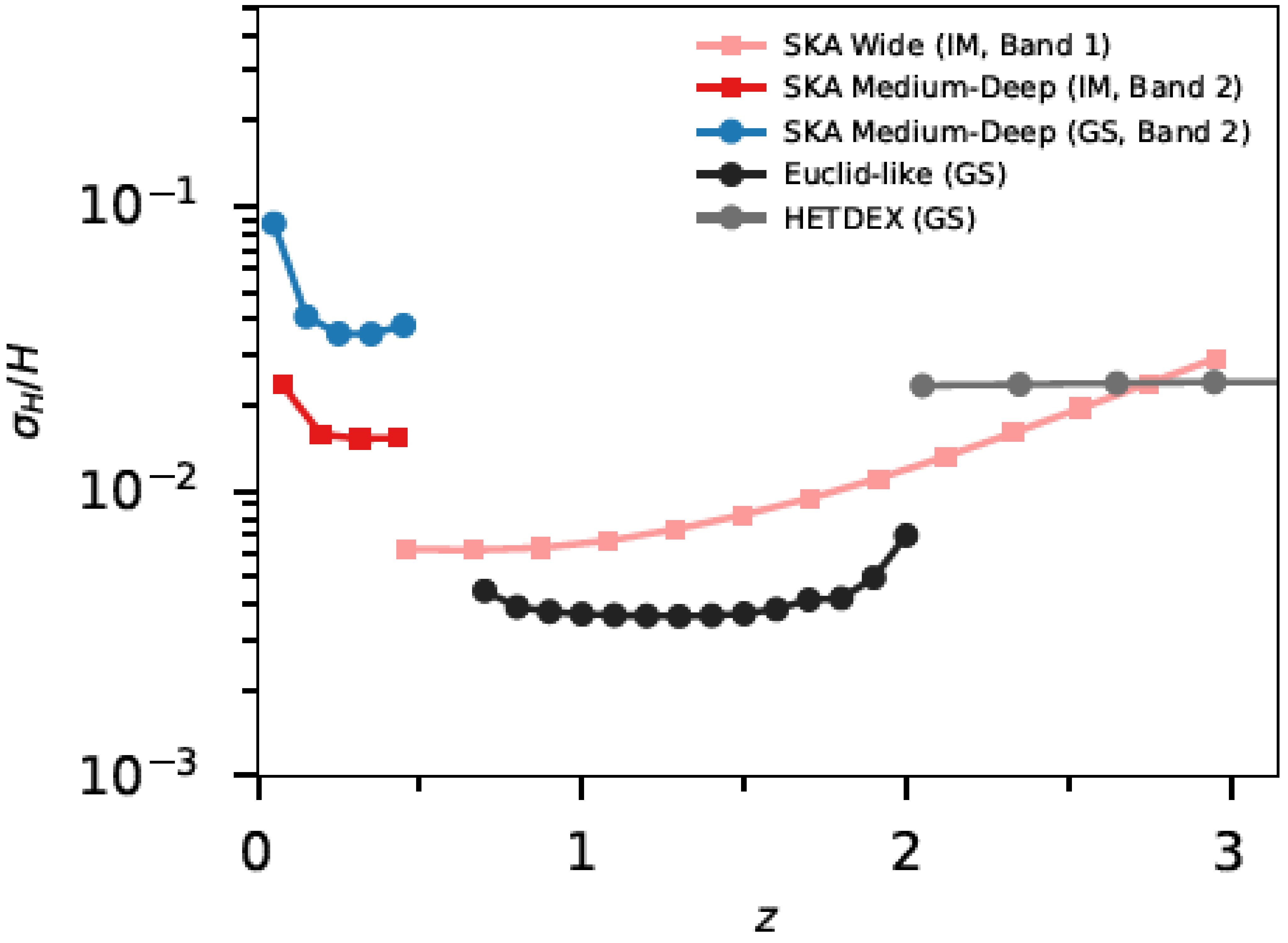
- CHIME (Canada)

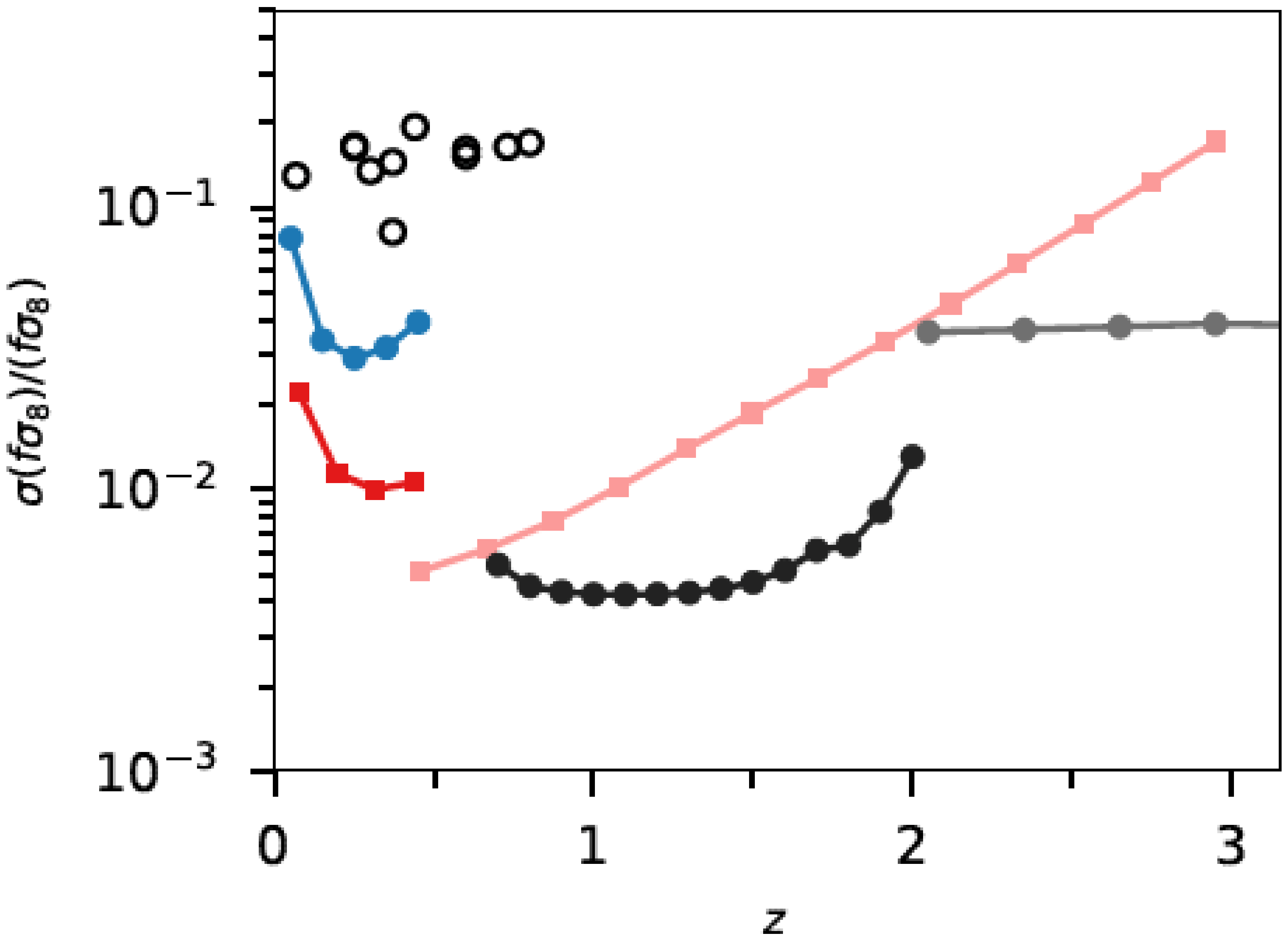
SKA1?

- Need SKA1-MID for z < 3 but baselines not small enough to probe BAO scales and above…
- Plan: use the array in "single dish mode"
- SKA1-MID single dish HI intensity mapping survey will turn SKA into a state of the art cosmology machine
- Only way to really go after the unexplored very large scales
- See: arXiv:1305.6928, arXiv:1405.1452, arXiv:1501.03989, arXiv: 1509.07562, arXiv:1811.02743



"Standard" Cosmology with SKA1-MID

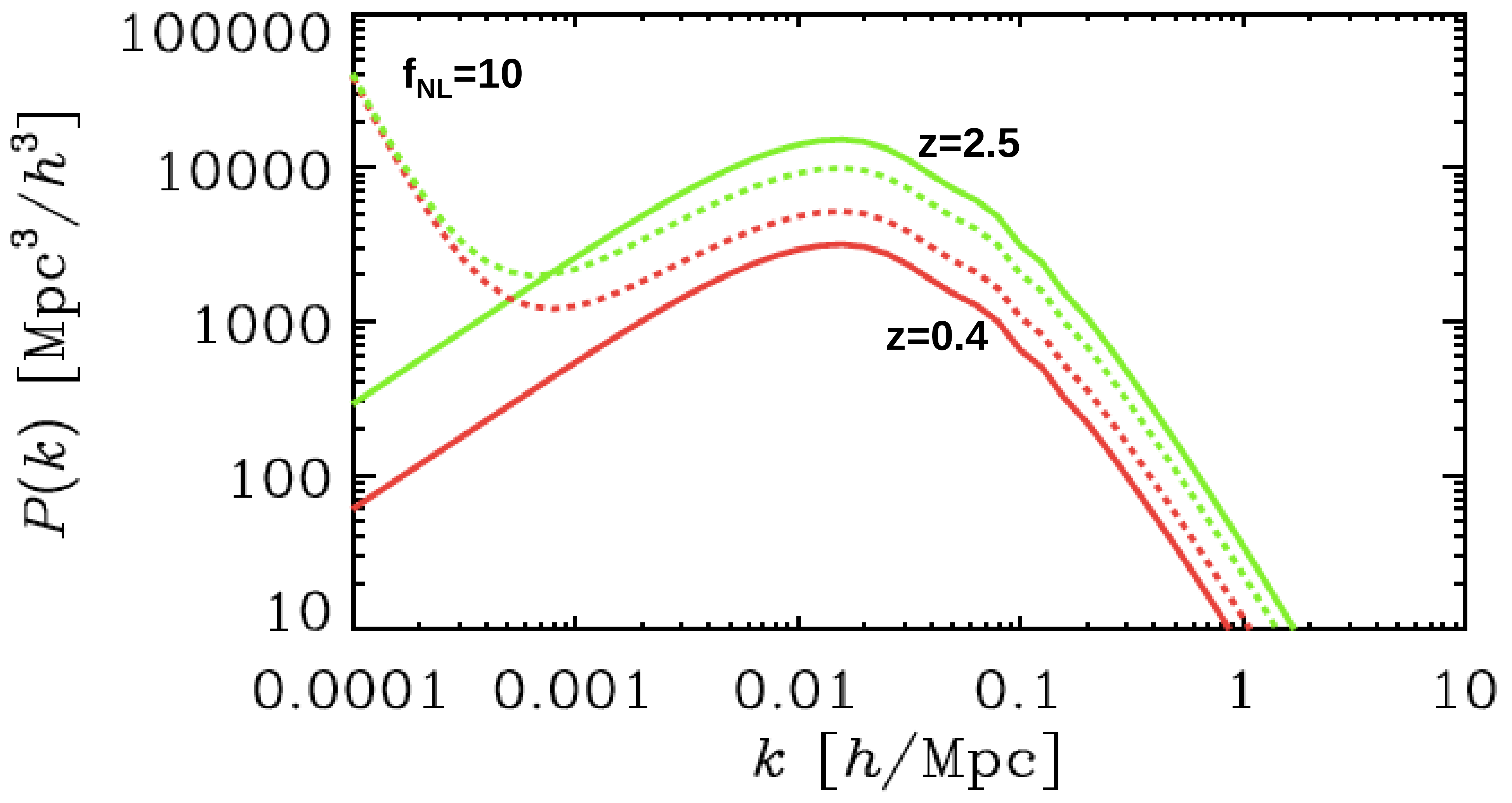




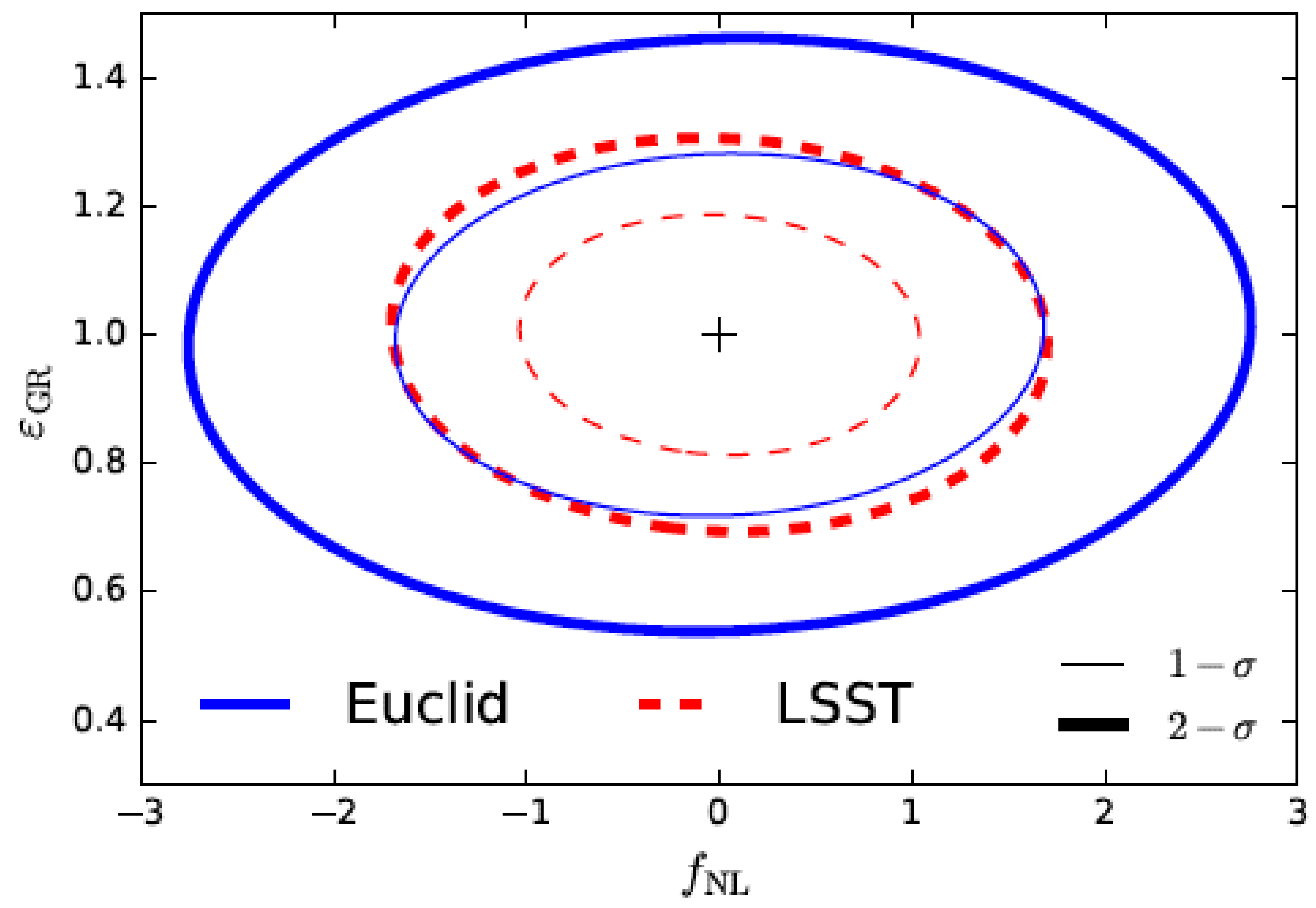
- Error forecast for the Hubble rate
- Error forecast for the growth rate

- SKA1 Cosmology "red book": arXiv:1811.02743

Constraints on large scale effects with SKA1-MID and multi-tracers



Camera et al., PRL, 2013



SKA1 Cosmology “red book”: arXiv:1811.02743

- The information is in the bias with respect to the dark matter field -> use multi-tracers to beat cosmic variance
- Combining an HI intensity mapping survey using SKA1-MID Band 1 with LSST will detect fNL ~ 1 as well as GR corrections
- A nice way to “fight” systematics
- See also: Alonso and Ferreira, PRD, 2015; Alonso et al. ApJ 2015; Fonseca et al., ApJ Letters, 2015; A Witzemann, et al., MNRAS, 2019; Matarrese and Verde, Astrophys.J. 2008; Dalal et al., PRD 2008; Squarotti et al., arXiv:2307.00058v1; Karagiannis et al., arXiv:2305.04028v1; Jolicoeur, arXiv:2301.02406v3…

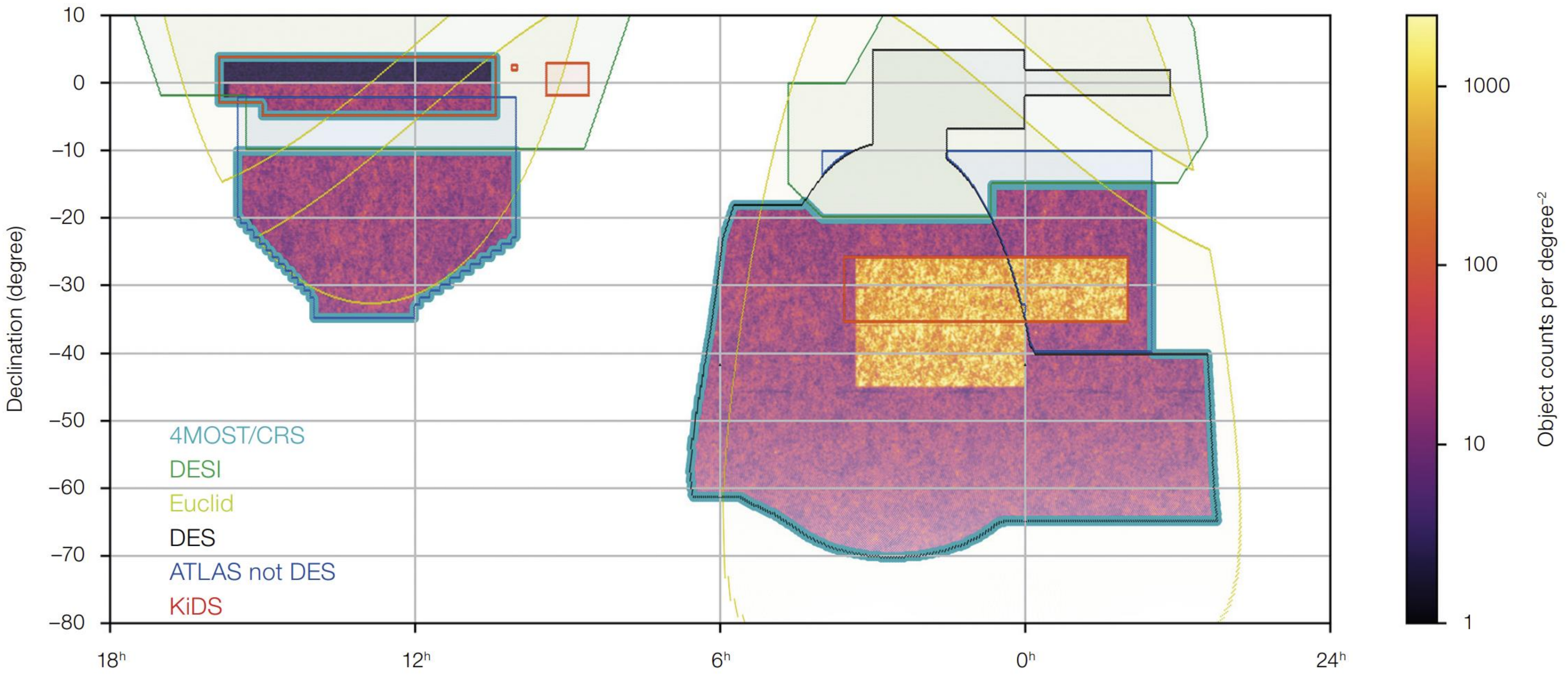
MeerKAT?

- 64, 13.5 m dishes – 2018
- Maximum baseline: 8 Km - soon ~ 20Km
- Frequencies: 580 MHz – 3500 MHz ($0 < z < 1.5$)
- It's in the South!
- Part of SKA1-MID in the future

The present: an SKA cosmology survey precursor with MeerKAT

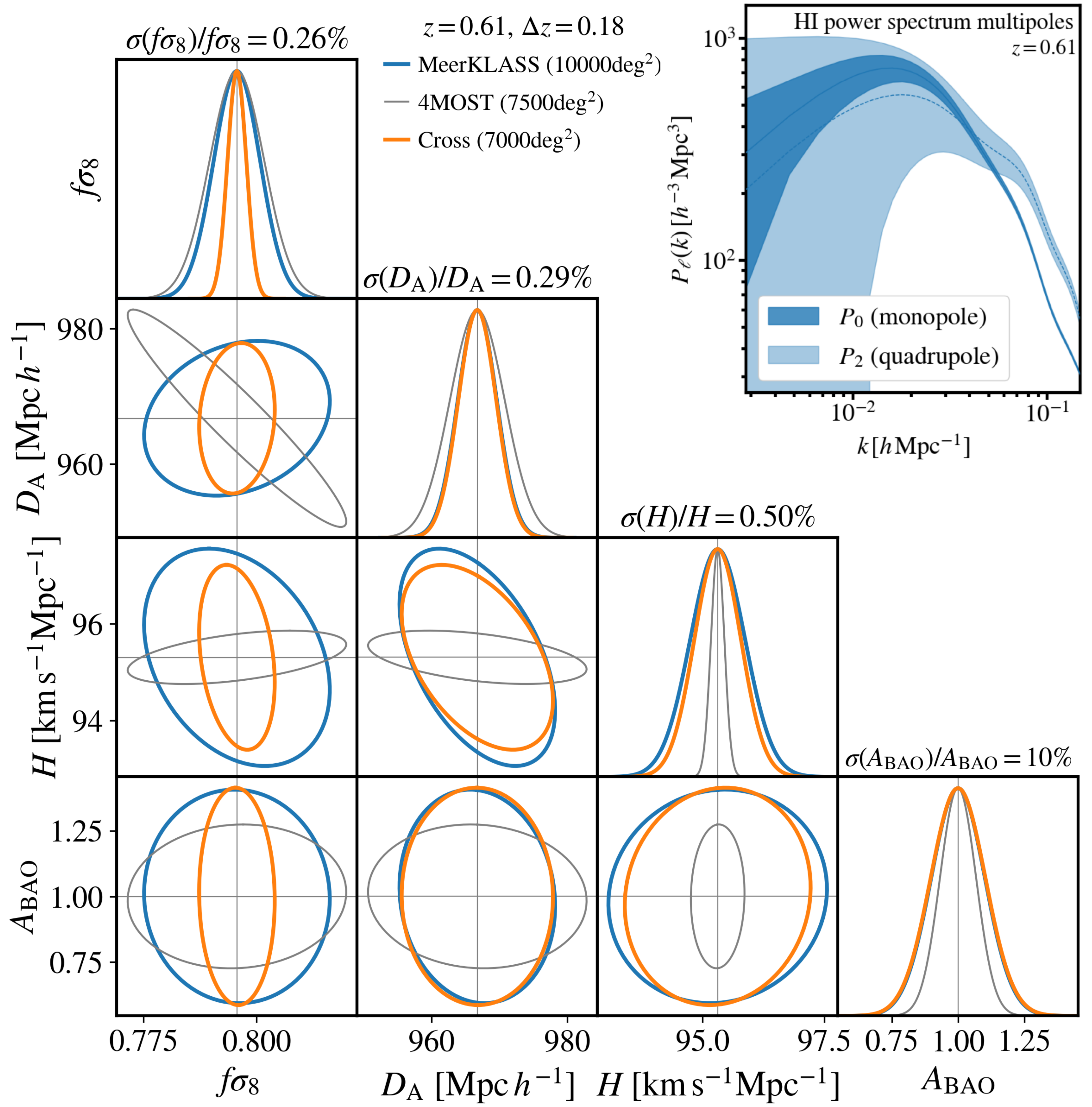
- ***MeerKLASS: MeerKAT Large Area Synoptic Survey:*** http://arxiv.org/abs/1709.06099
- Aim: Cosmology (HI intensity mapping) but commensal with lots of other science (continuum survey)
- Focus on sky patches with multi-wavelength data for cross-correlation (DESI, 4MOST, Euclid, Rubi/LSST, DES)

- L-band: 900-1670 MHz (z<0.58) ~ 100 hours observed
- **UHF band:**
  - 580 MHz-1015 MHz (0.40 < z < 1.45)
  - ~ 120 hours observed
  - Goal: 2,500 hours over 10,000 deg^2 (25 uJy rms in continuum) within next 5 years



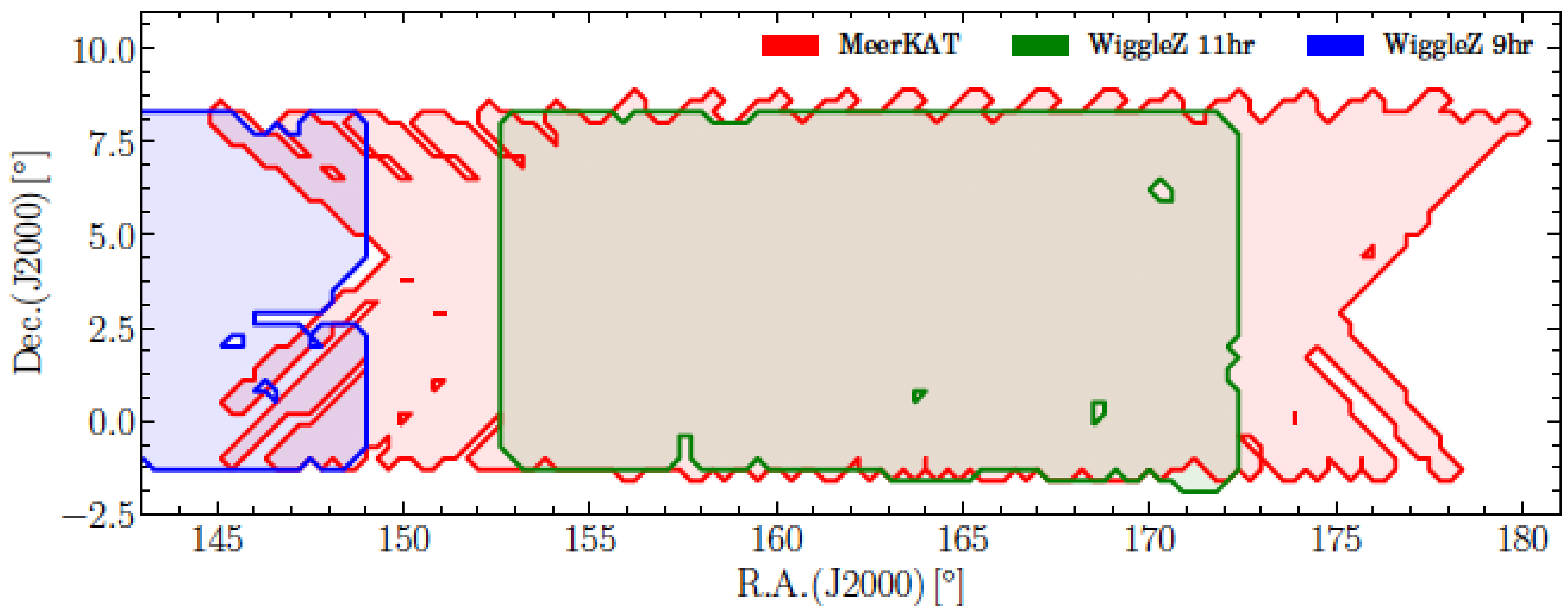
MeerKLASS: Cosmology

- Measurement of Baryon Acoustic Oscillations (BAO), Hubble rate and redshift space distortions
- Measure the HI content of the Universe at 0.4 < z < 1.4 (UHF-band)
- Cross-correlations with galaxy surveys
- Constraints of primordial non-Gaussianity (f_{NL}) by measuring large scale correlations and multi-tracers (Fonseca et al., arXiv1611.01322)
  - xDESI ~ 4.3
  - x4MOST ~ 3.5
  - xEuclid ~ 1.5
  - xDES ~ 3.5
  - xRuby/LSST ~ 1.8
  - (compare to CMB ~ 5 and eBOSS ~ 20)

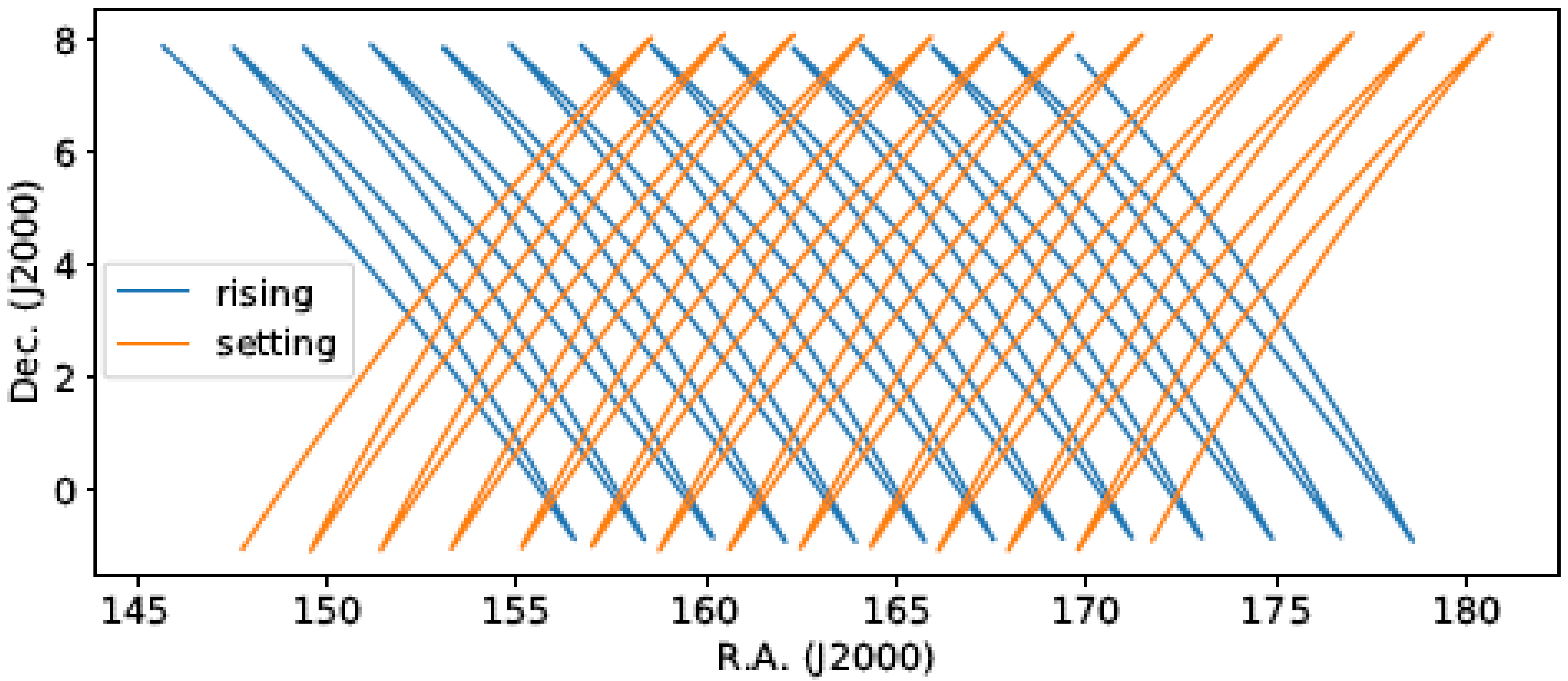


MeerKAT: 1,300 hours. 60 dishes

First results with a MeerKAT single dish pilot survey
(Wang et al., MNRAS, arxiv:2011.13789)



Footprint

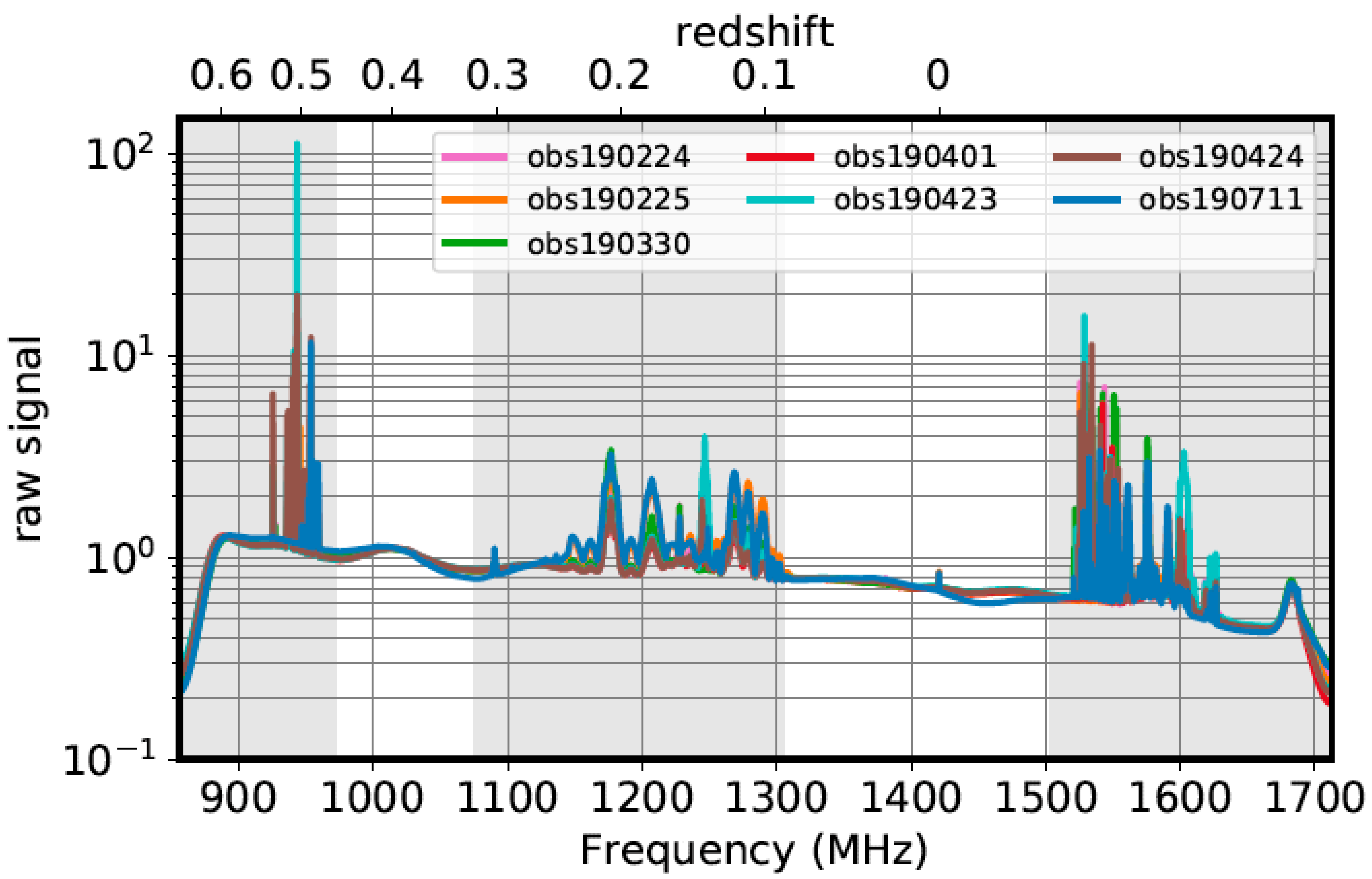


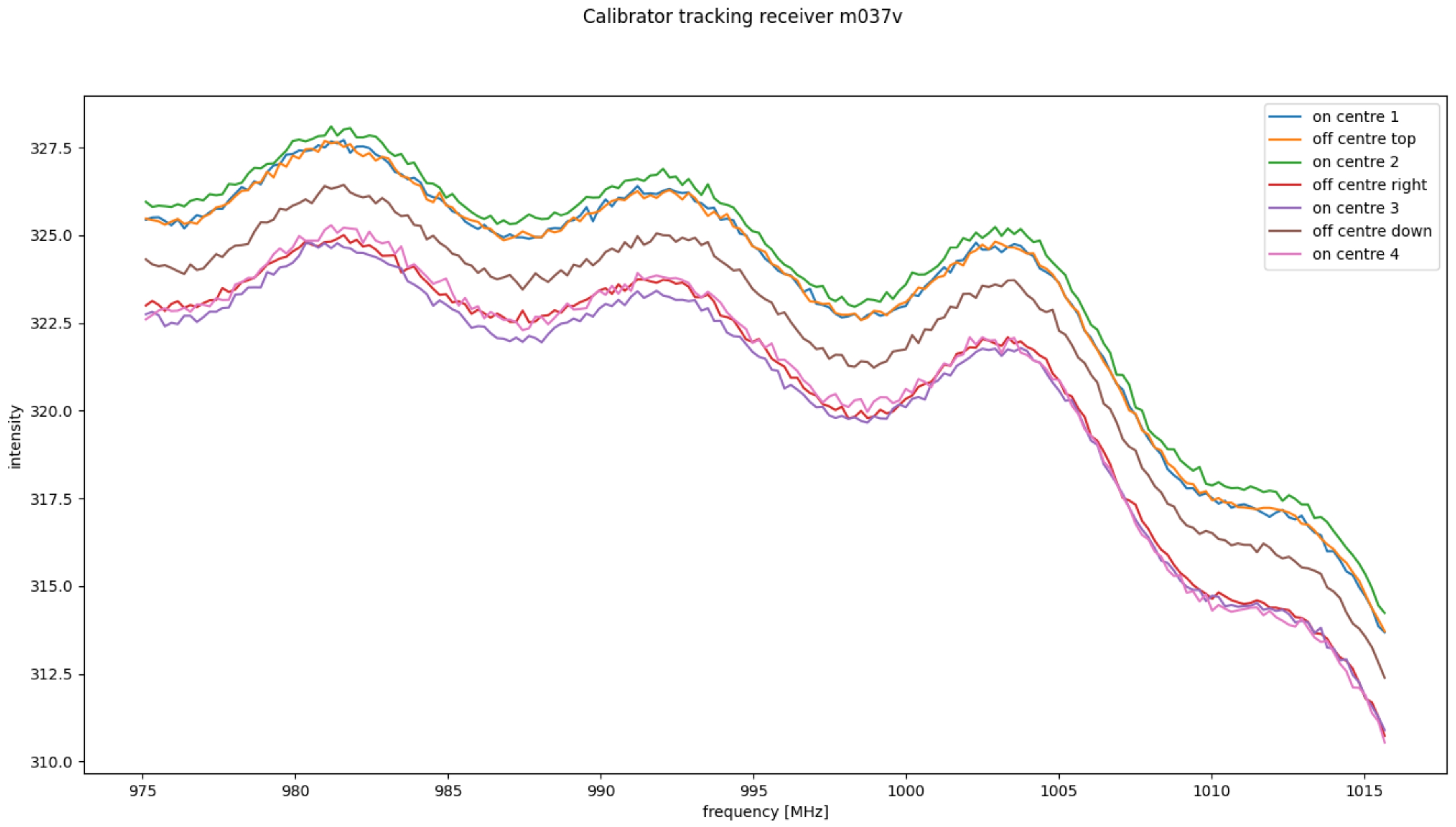
Scanning pattern

- ~ 15 hours
- ~ 60 dishes used (~ 600 hours combined)
- ~ 200 deg^2 over the WiggleZ 11h field
- L-Band: 900 MHz - 1700 MHz ($z < 0.5$)

- Resolution: 2 sec/0.2 MHz
- Scans at constant elevation (> 40 deg)
- Speed: 5 arcmin/sec
- ~ 200 sec per scan line, 1.5 hours per block

Contamination (sky foregrounds+ground+RFI+instrumental)

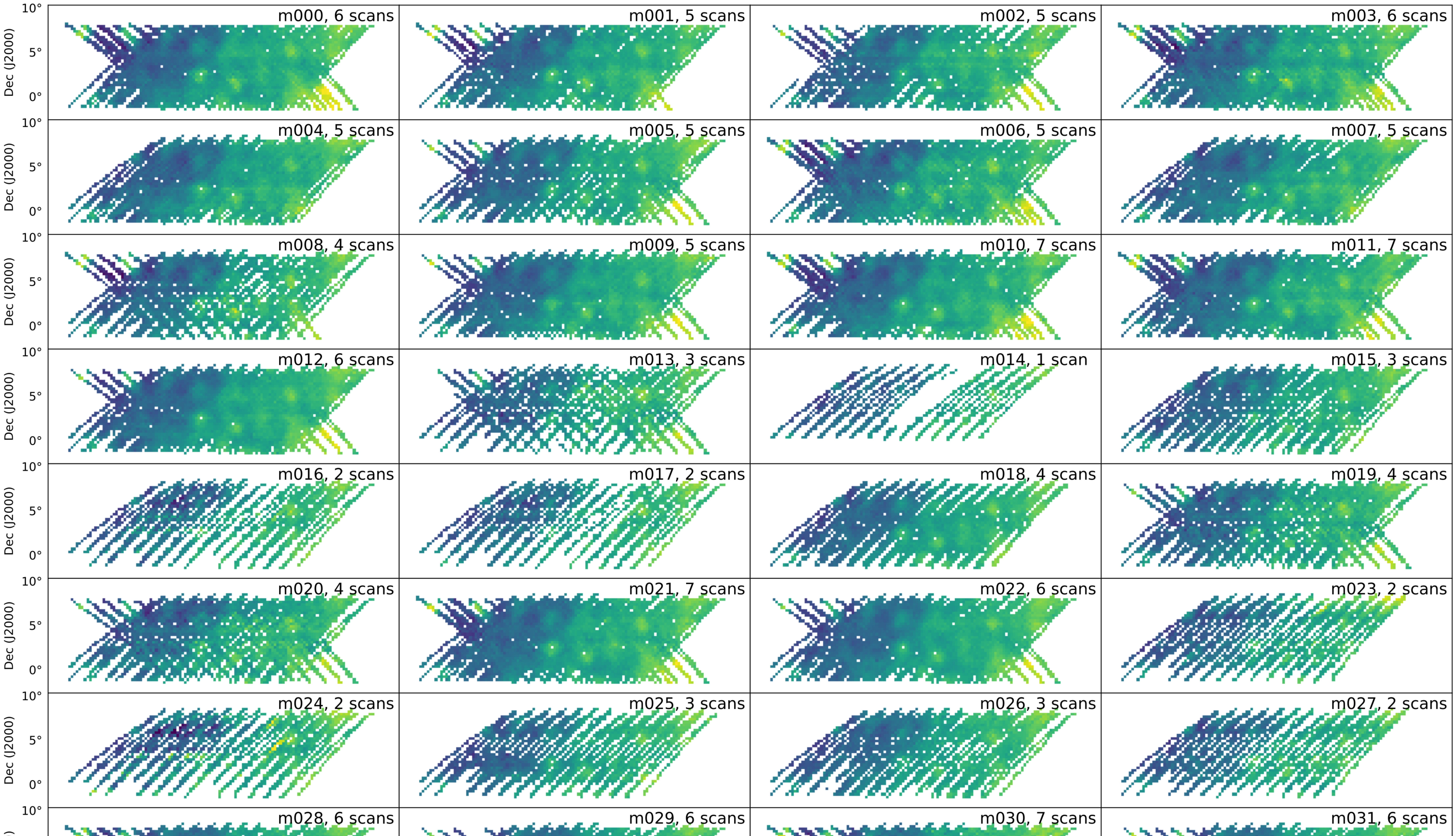




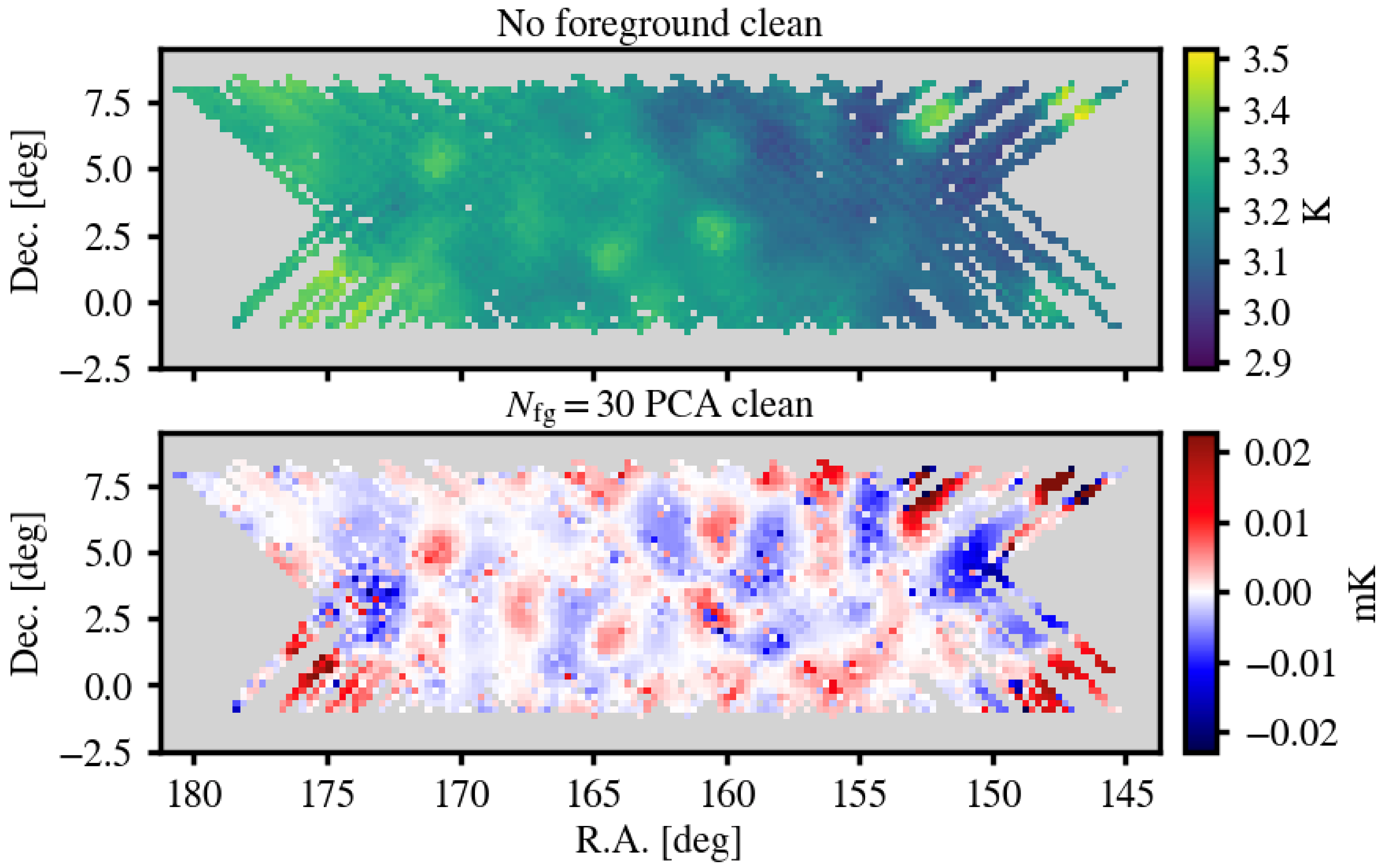
Looking for fluctuations ~ 1/10^5

- Satellites are a big concern, in particular with single dish data and in particular from the beam sidelobes
- RFI free regions in L band: **0.32 < z < 0.46**
- Calibration/modelling is crucial
- Methods for foreground cleaning are crucial (PCA, GMCA, Gaussian Processes,Machine Learning…)
- Also important to improve signal extraction methods (power spectrum)

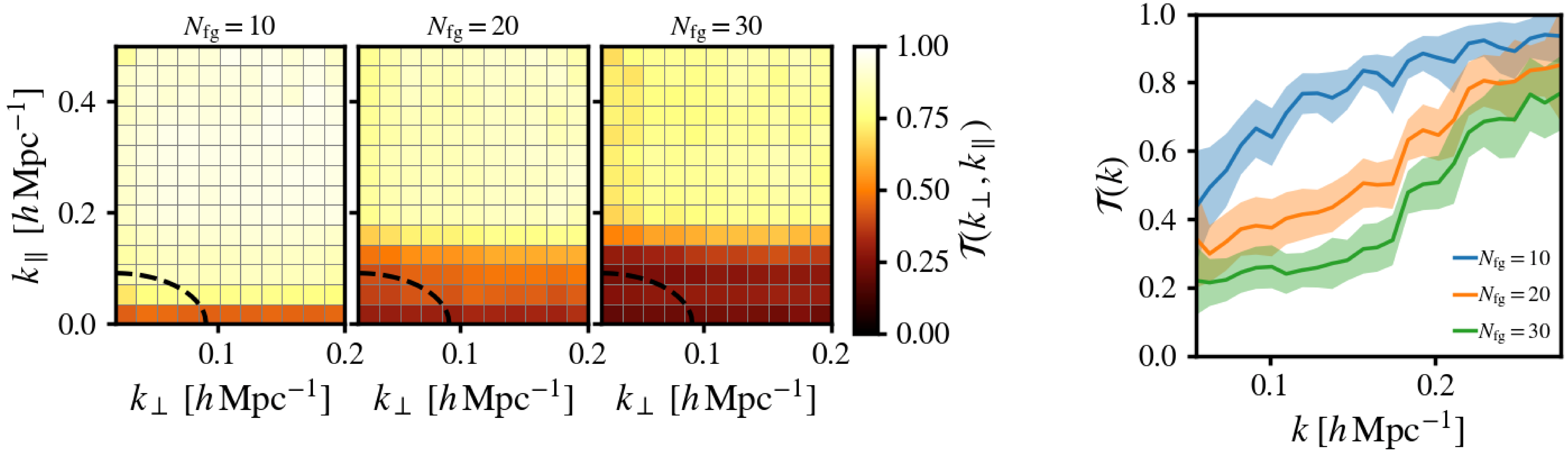
Temperature maps at 1023 MHz – we can cross-correlate between dishes!



Foreground cleaned maps



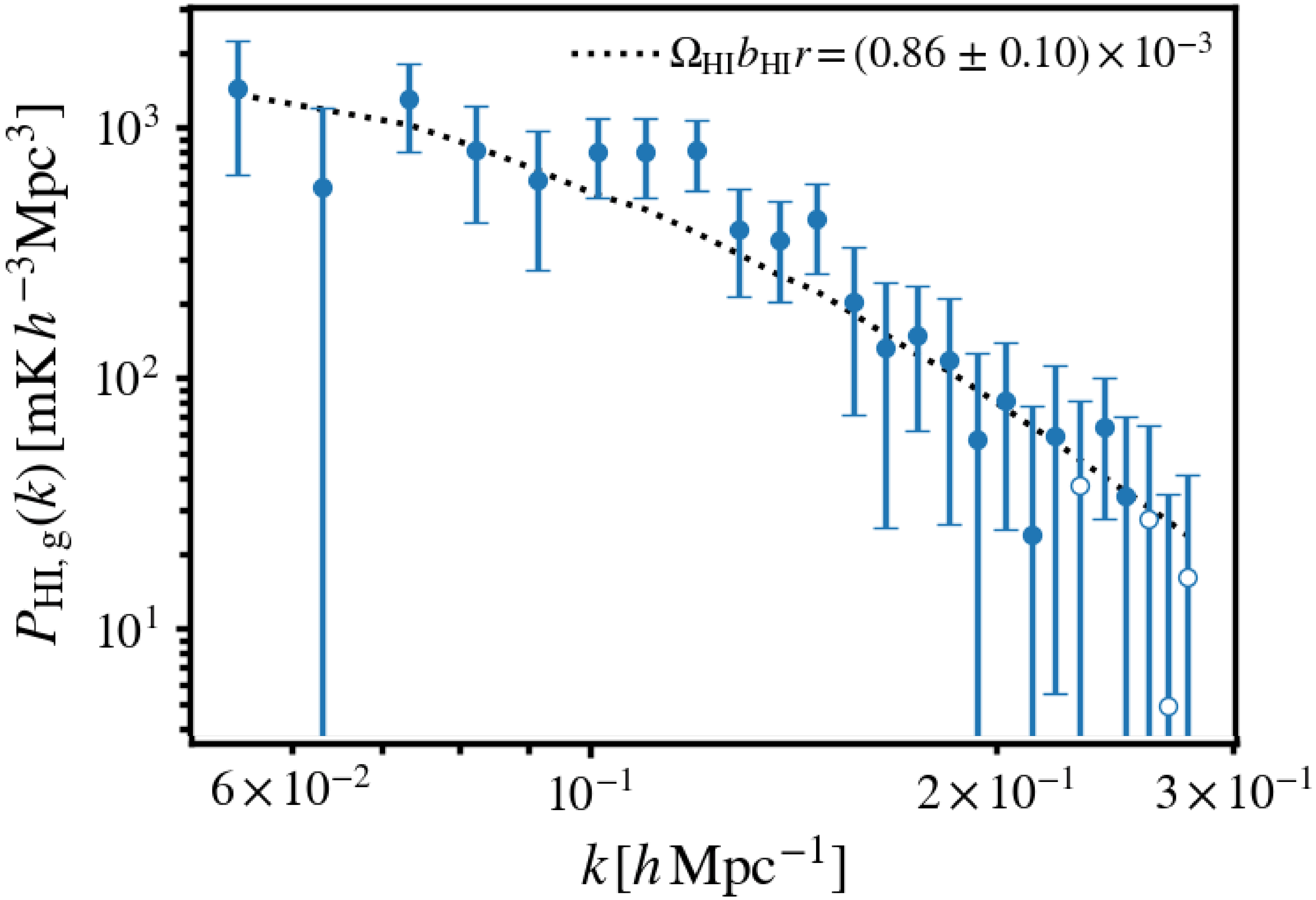
Transfer function / signal loss



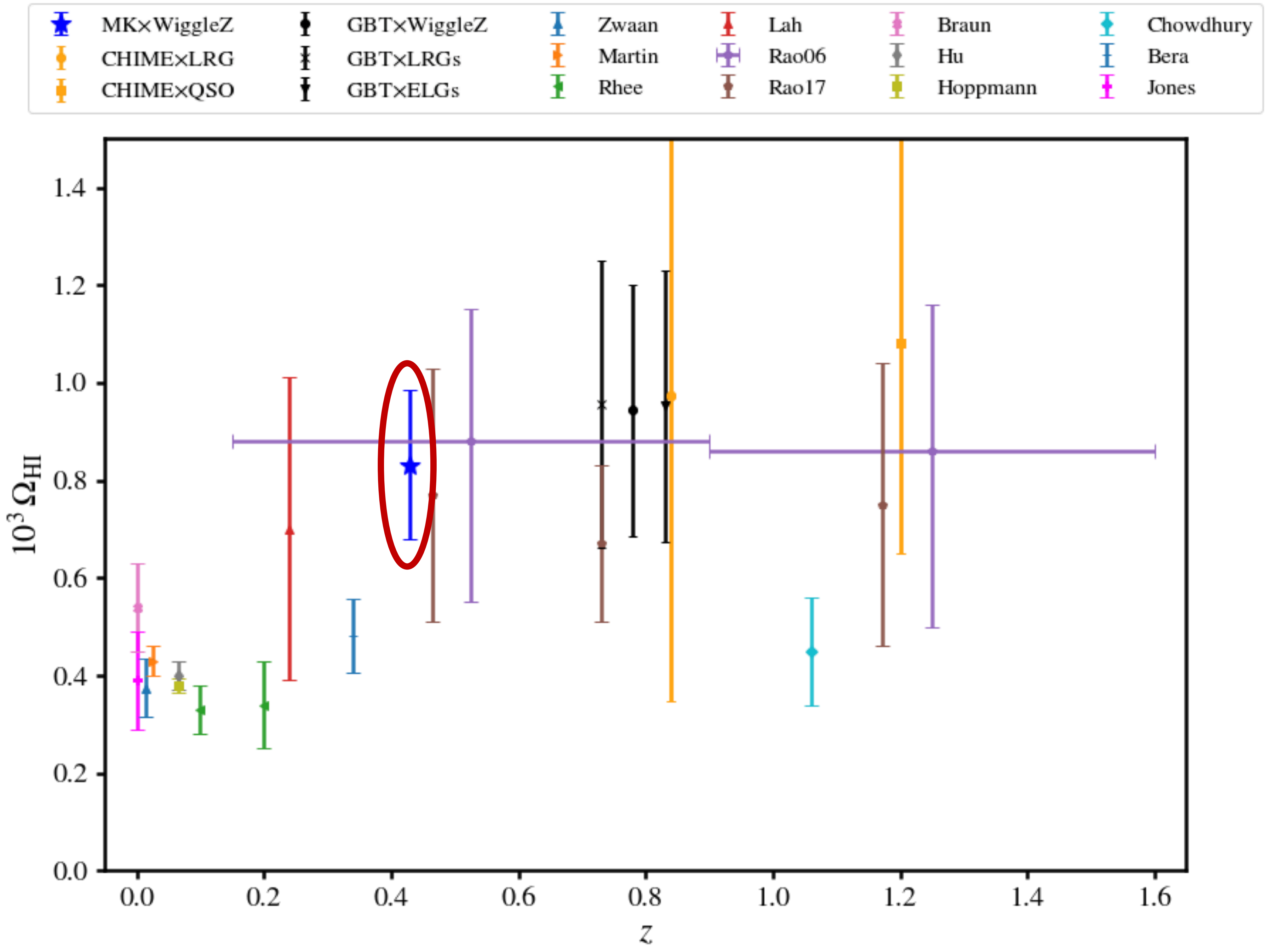
- Signal loss due to foreground cleaning affects all scales but mostly small k_par
- Transfer function crucial to unbias the power spectrum estimator
- Calculated through signal injection
- Need to improve calibration to reduce foreground cleaning!

See Cunnington, et al., MNRAS, arXiv:2302.02683

First cosmological results with MeerKAT: Detection of the cross-correlation power spectrum with WiggleZ galaxies



0.400 < z < 0.459

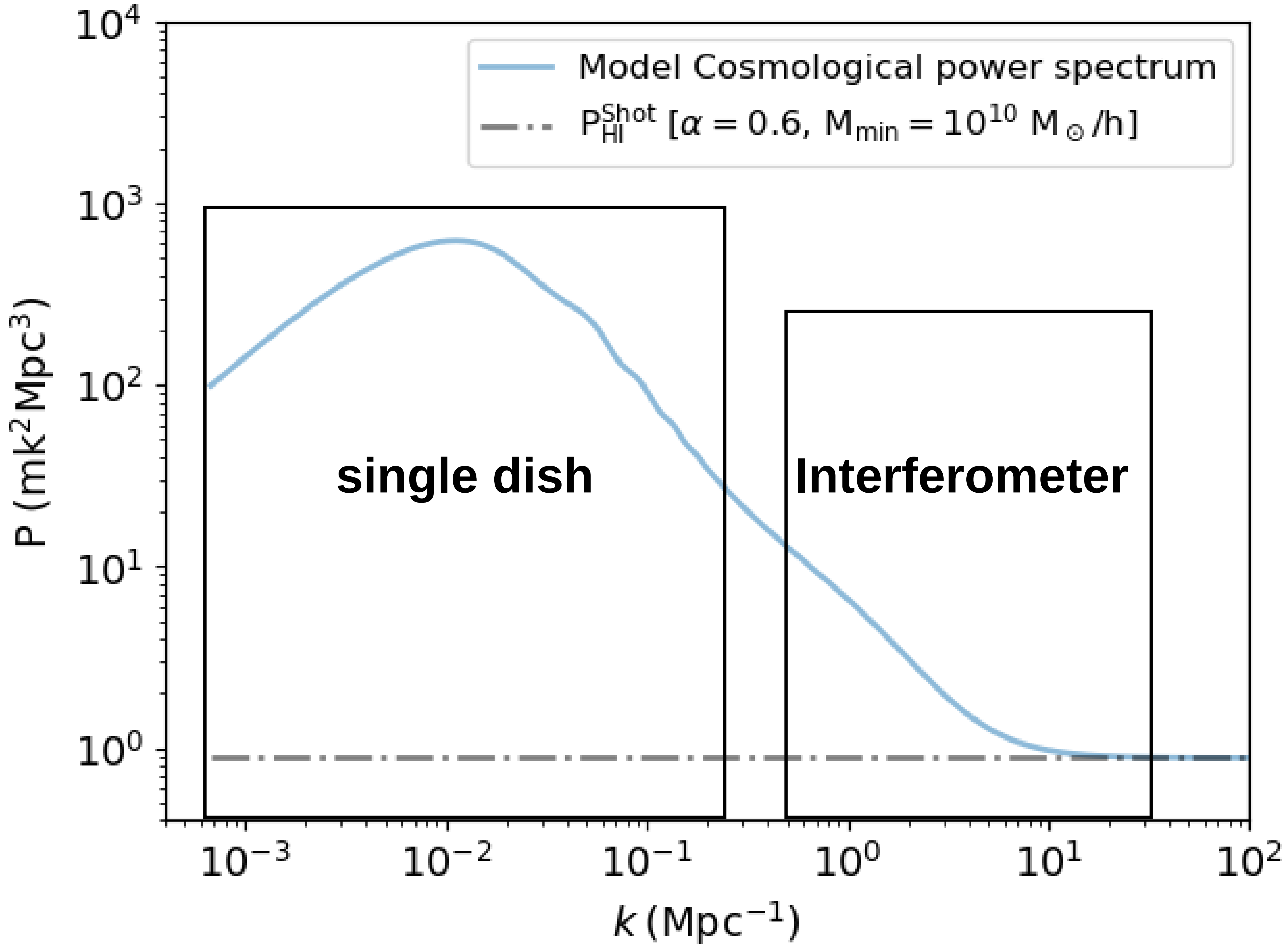


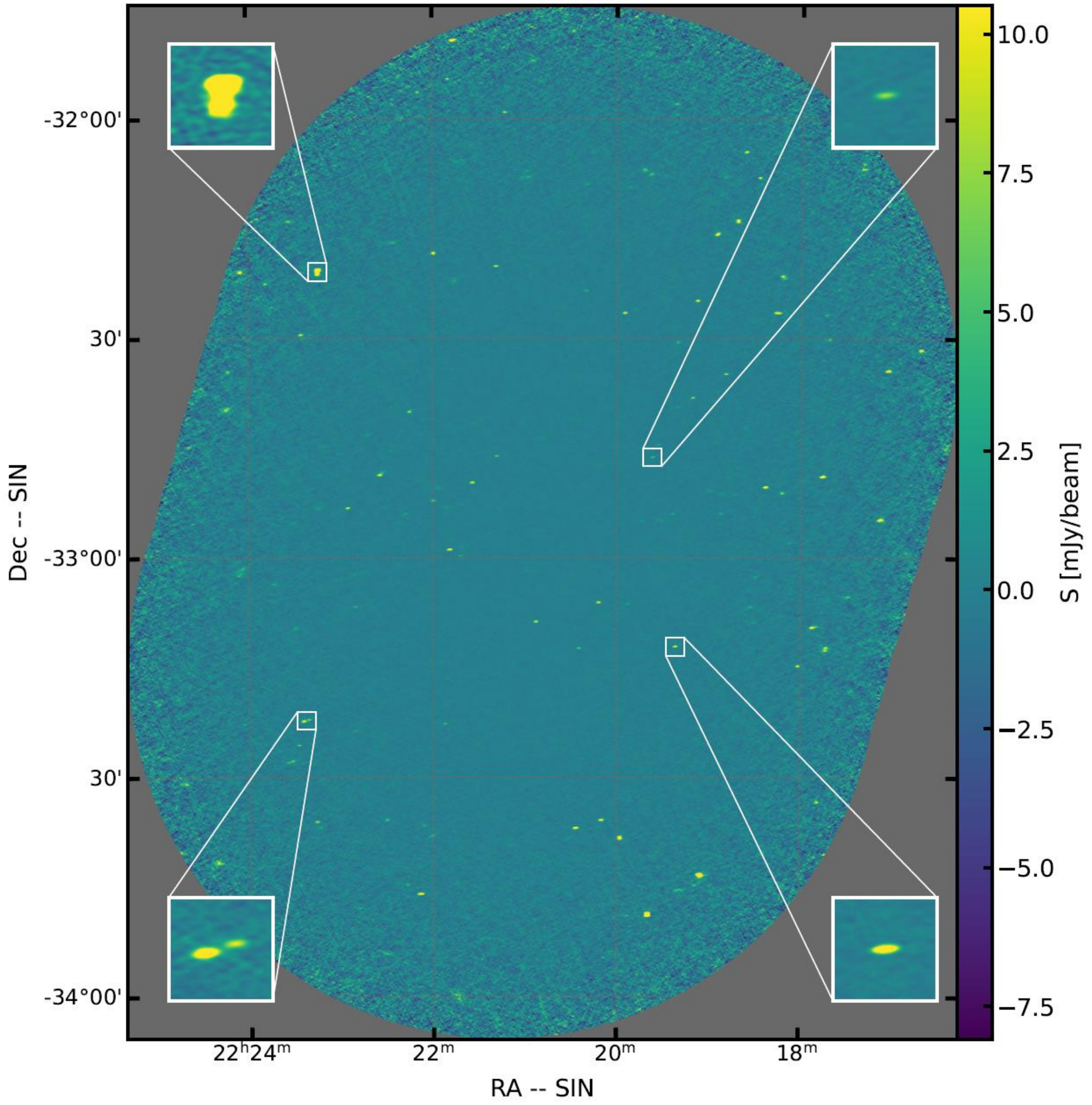
Cunnington, Li, Santos, et al., MNRAS 2023

What about the interferometer data?

- HI intensity mapping can still measure quasi-linear cosmological scales (k ~ 1 Mpc^{-1} and above)
- Great for comparison to full HI simulations
- Can be used for other science (continuum…)

z ~ 0.3

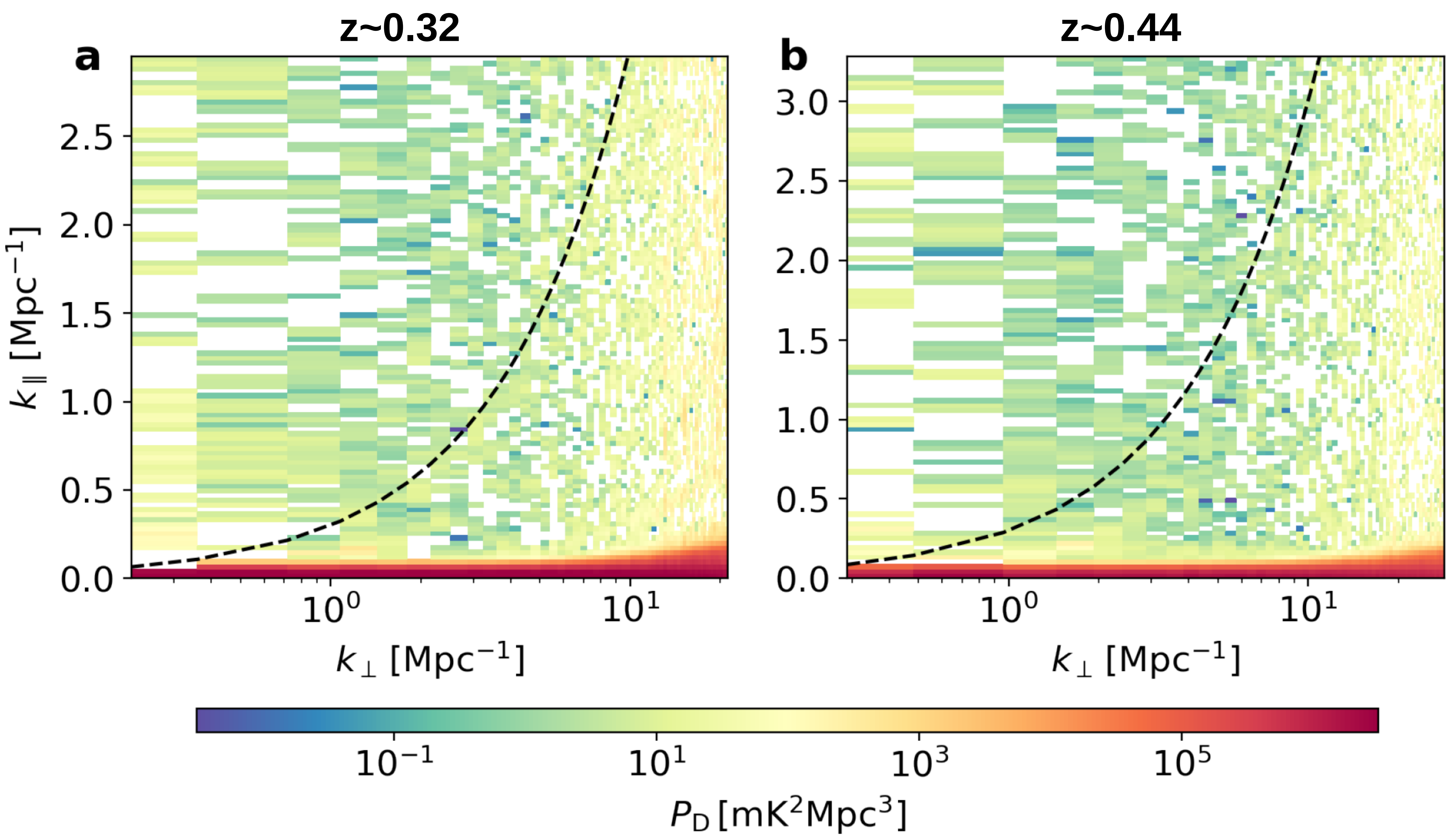




Kristof Rozgonyi

HI IM using the MeerKAT interferometer

- Field: ~ 2 deg^2, 96 hours
- 2d power spectrum (cross-correlate different times)
- Smooth components in frequency will be at low $k_{\parallel}$
- Pick a window with low continuum contamination ("foreground avoidance")
- Great way to test the halo model and compare to HI simulations!

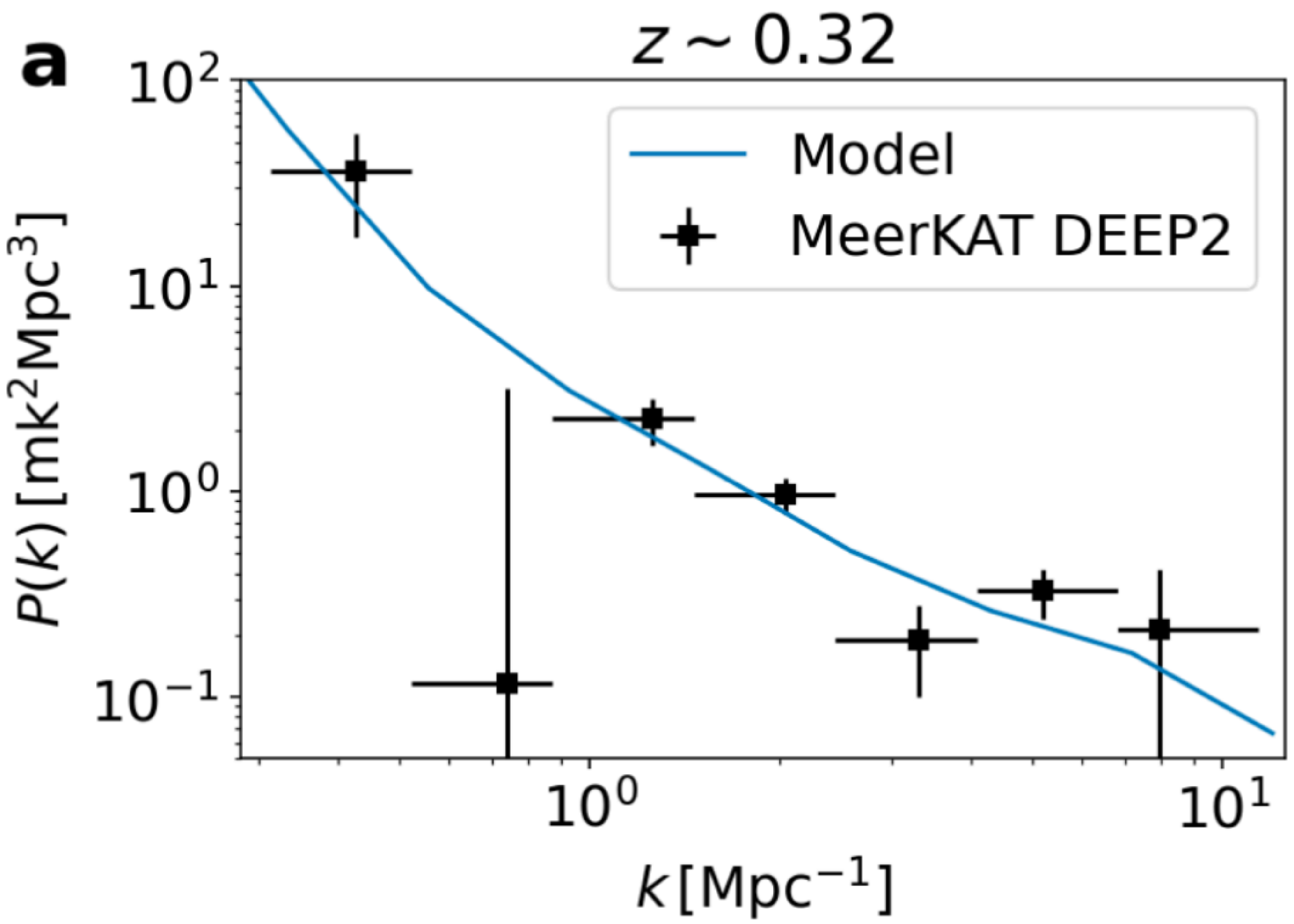


$$P_{\rm D}(k_\perp, k_\parallel) = P_{\rm 2h}(k_\perp, k_\parallel) + P_{\rm 1h}(k_\perp, k_\parallel) + P_{\rm SN}(k_\parallel)$$

$$P_{\rm SN}(k_\parallel) = \frac{P^0_{\rm SN}}{1 + (k_\parallel \sigma_p)^2/2}$$

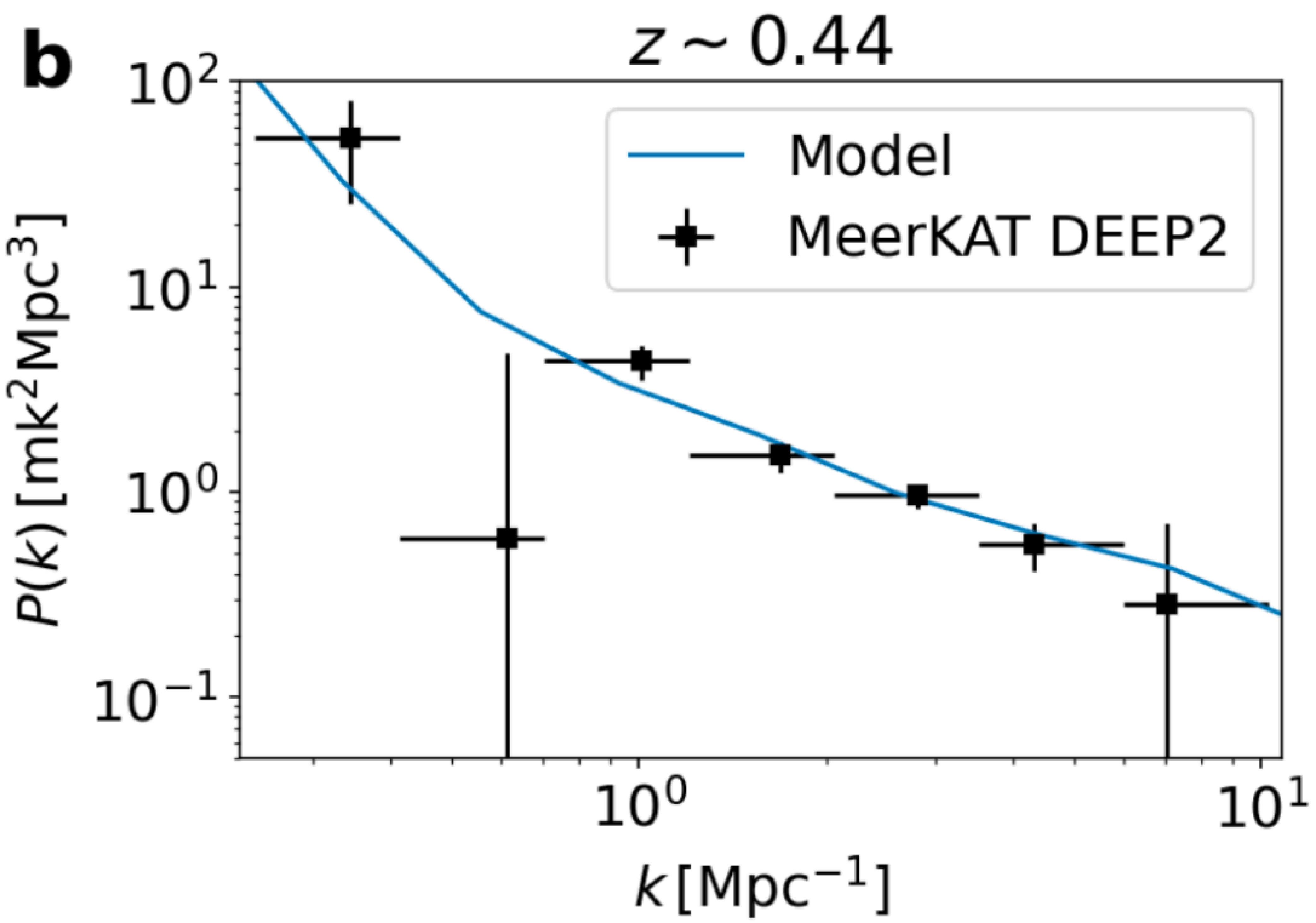
First direct detection of the HI power spectrum on Mpc scales

$\sigma_{\mathrm{HI}}\,(1\mathrm{Mpc}) = 0.44 \pm 0.04\ \mathrm{mK}$



8σ

$\sigma_{\mathrm{HI}}\,(1\mathrm{Mpc}) = 0.63 \pm 0.03\ \mathrm{mK}$



11.5σ

Sourabh Paul, Mario G. Santos ,Zhaoting Chen and Laura Wolz, https://arxiv.org/abs/2301.11943

Summary

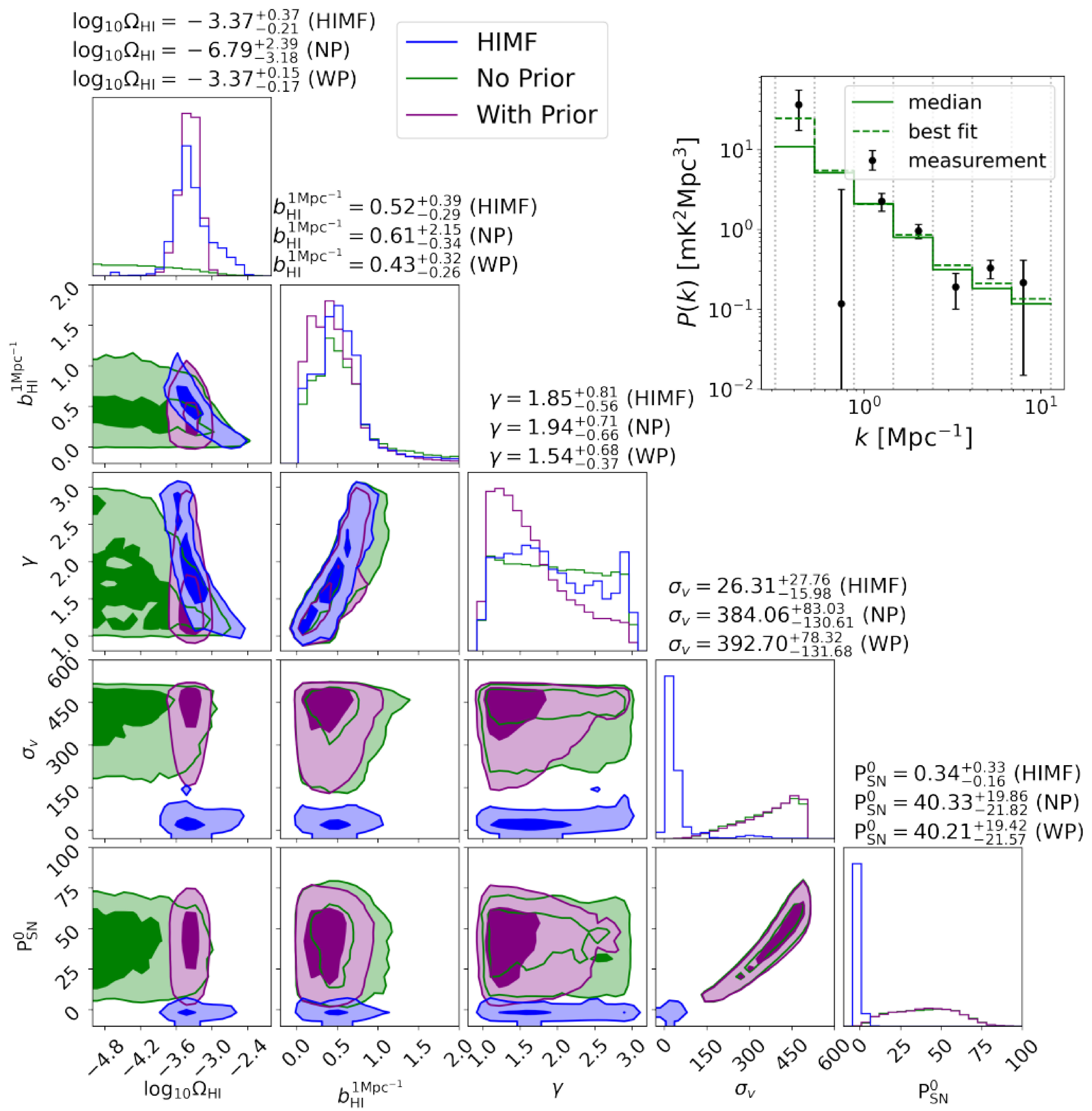
- HI intensity mapping with MeerKAT/SKA in single dish mode will deliver state of the art cosmological constraints: BAO in HI – dark energy, RSDs – modified gravity, primordial non-Gaussianity…
- Multi-wavelength cross correlations adds more than the sum of the parts
- MeerKAT interferometer data adds an exciting observational window to HI IM on small scales
- We have HI IM detections using the MeerKAT single dishes in cross with optical galaxies and auto detections with the interferometer – time to start fitting those theories!
- Dealing with low level systematics is the main challenge
- Ongoing observations and data processing with MeerKAT UHF single dish (BAO and past equality peak) – plan is to observe 2,500 hours over 10,000 deg^2 by 2028
- Ongoing data processing with MeerKAT interferometer data (small scales)
- Expect more results towards end of the year

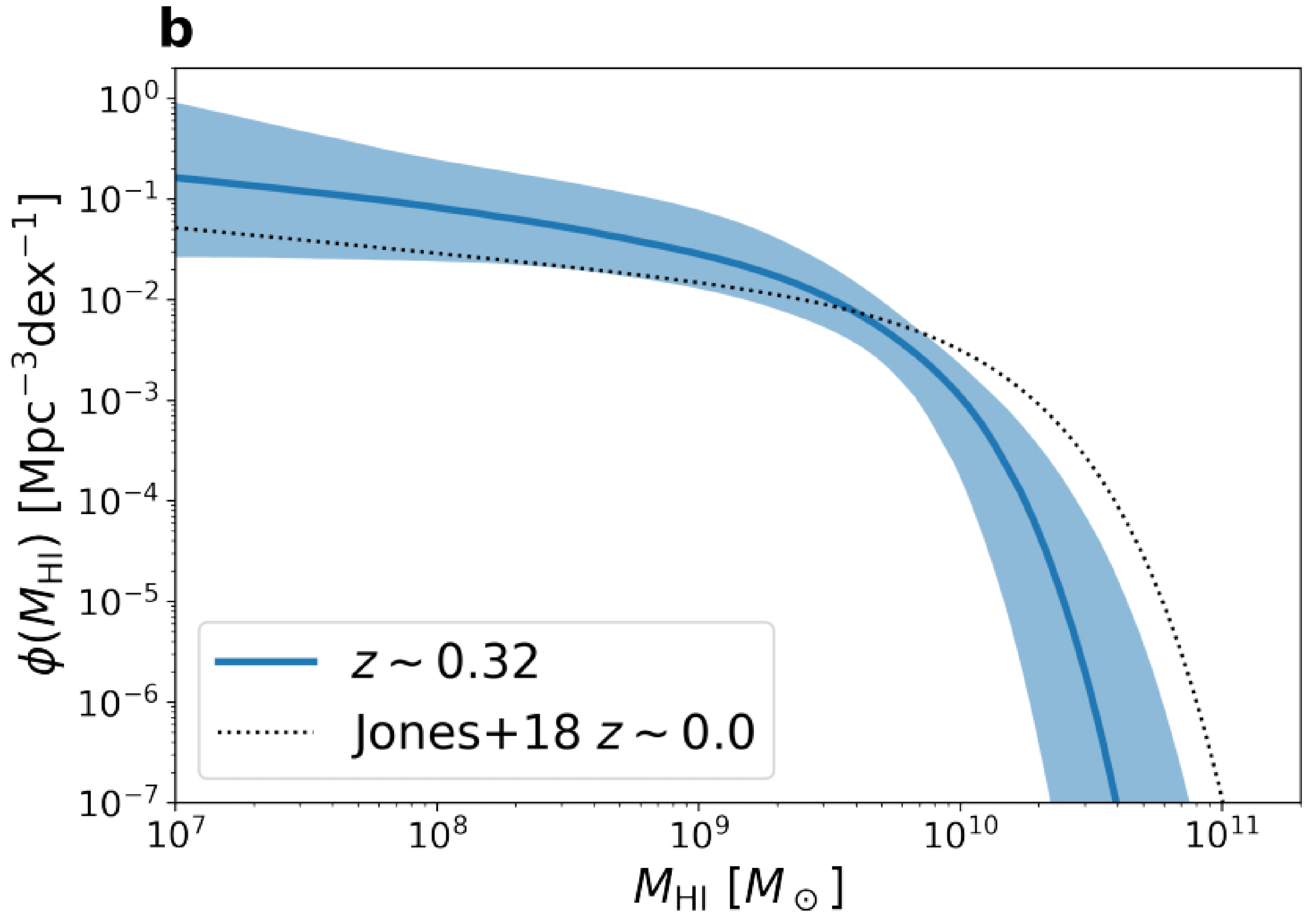
Bonus slides

Experiments

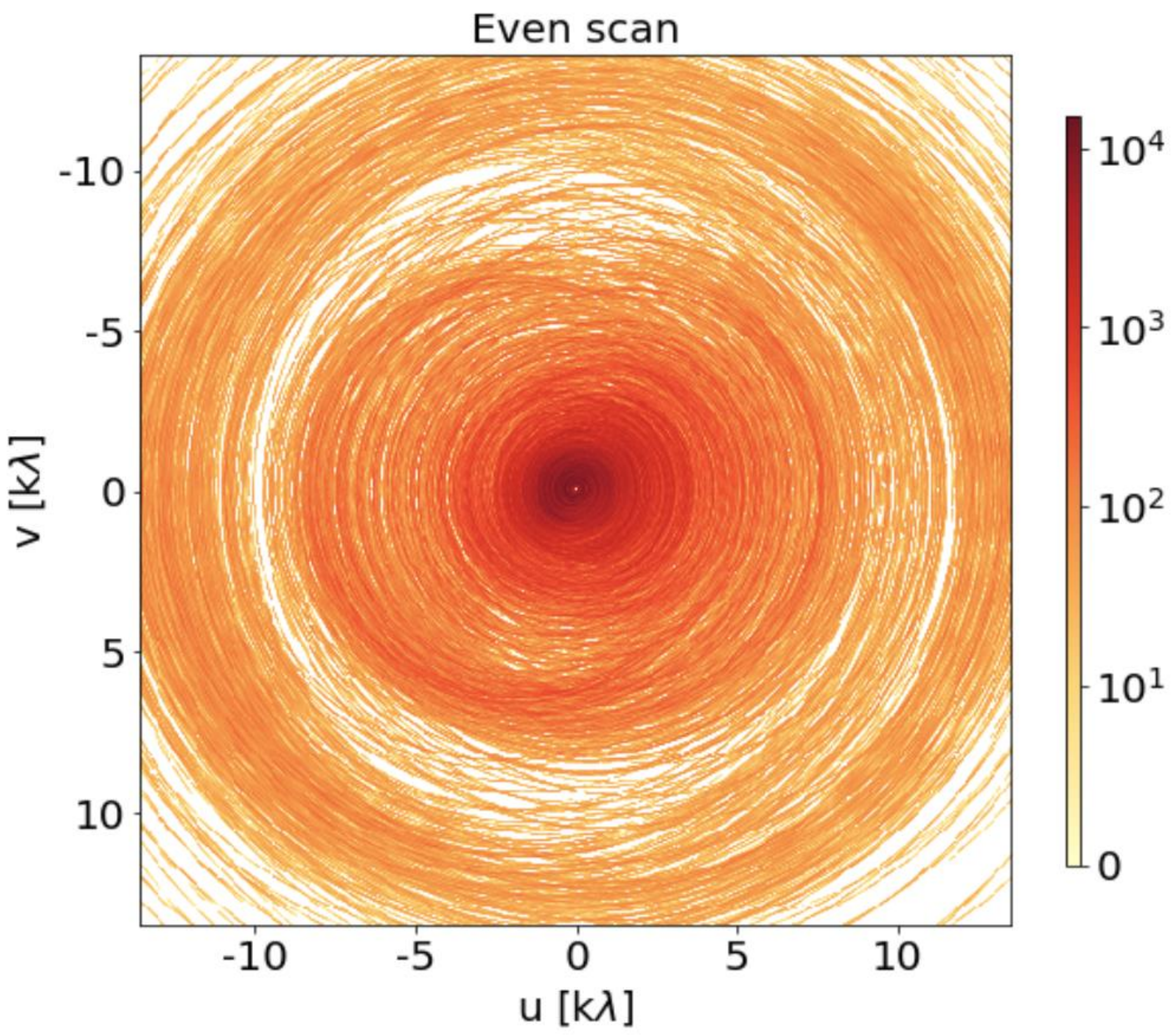
- “Tailored” interferometers: designed to have lots of measurements on the relevant angular scales (BAO scales). Highly redundant baselines
  - CHIME: Cylinder. Been taking data for a few years
  - HIRAX: ~ 1000 6m dishes placed in a close-packed redundant configuration (funding for 256 elements so far)
  - Tianlai: mix of dishes and cylinders. Been taking data for a few years
  - CHORD: 512 6m dishes + outrigger stations (seed funding?)
  - PUMA: 32,000 6m dishes in a packed array (not funded yet)
  - 2000-element Deep Synoptic Array (DSA-2000): More like an HI galaxy survey. 120 elements funded
- Tailored dishes:
  - BINGO: ~40m dish (primary) + ~ 35m (secondary), 28 feed horns (partially funded?)
- Multi-purpose instruments:
  - GBT
  - Parkes
  - FAST (in operation)
  - MeerKAT (both single dish and interferometer): 64, 13.5m dishes. Already taking data
  - SKA1-MID (both single dish and interferometer): MeerKAT + 133 15m dishes. Funded (I think). 2029?

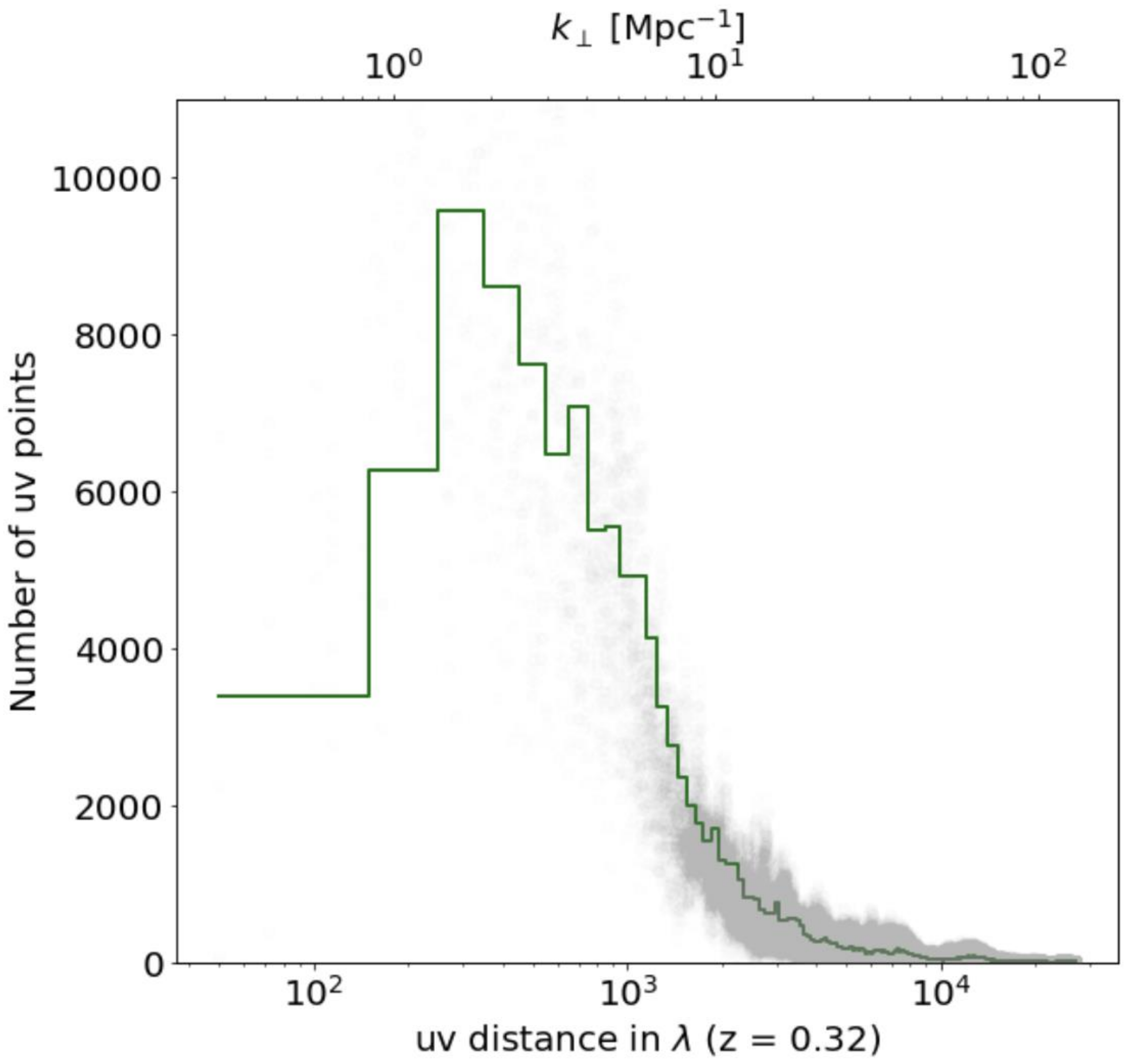
The halo model and HI mass function at z~0.32





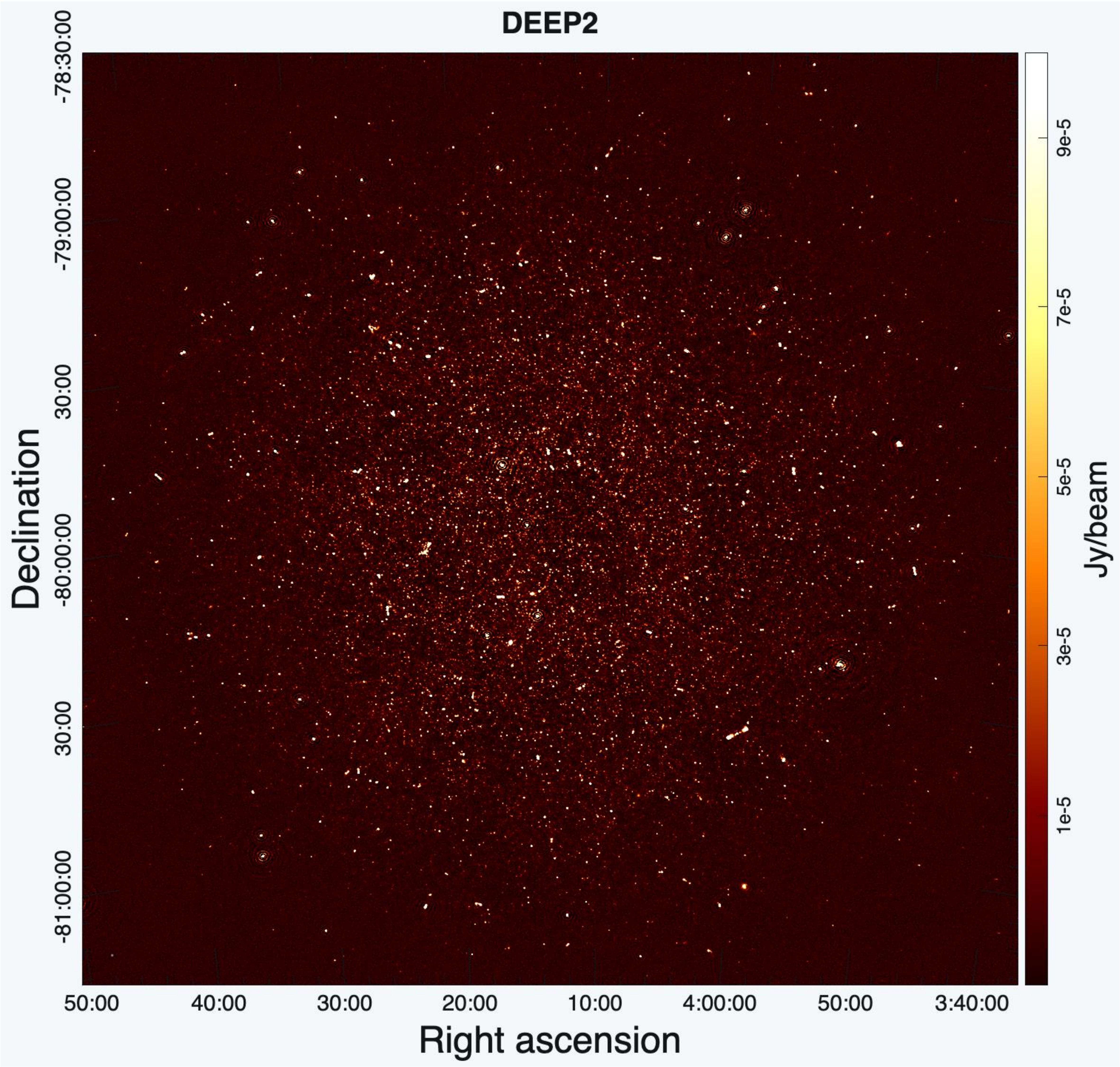
MeerKAT UV coverage





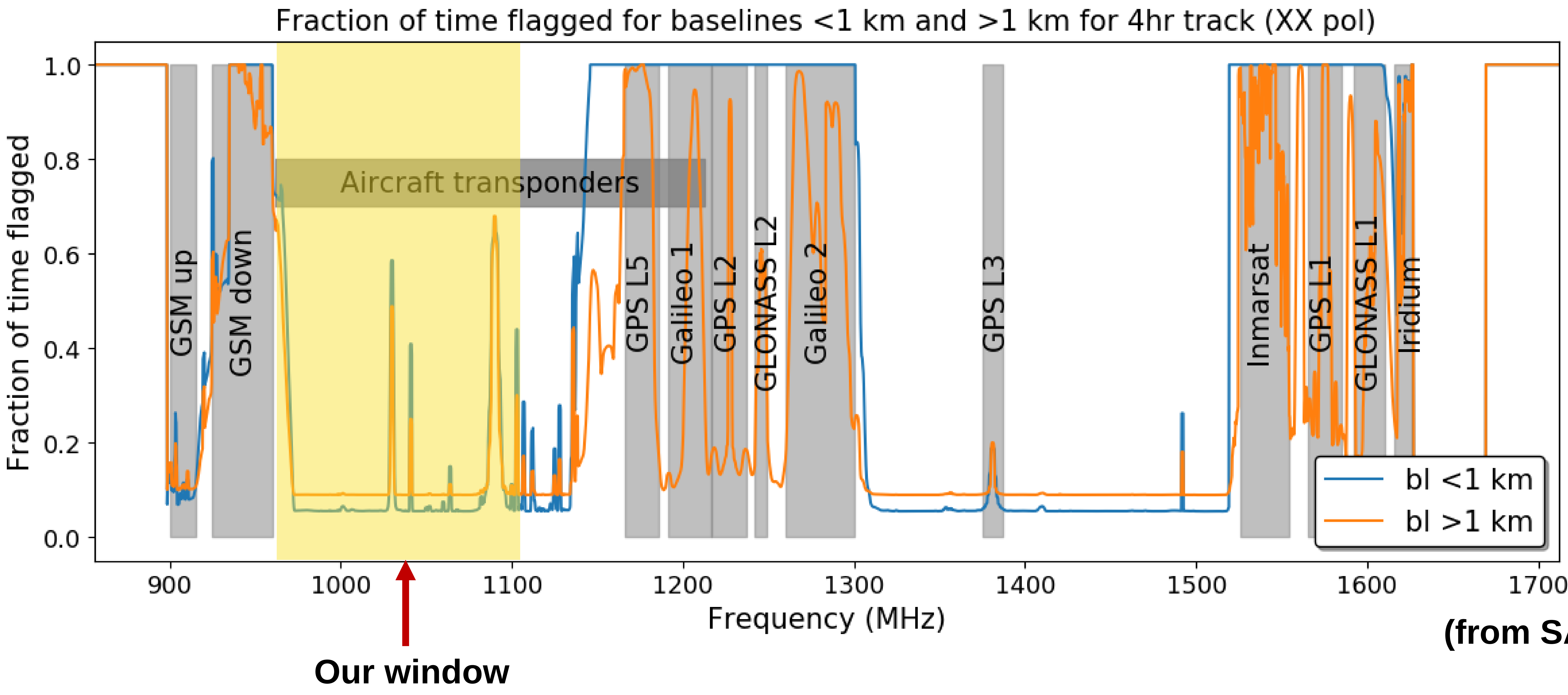
“Deep 2” field

- Deepest (~ 100 hours) MeerKAT pointing until recently (public commissioning data from 2018)
- α = 04h13m26.4s, δ = −80°0′0″
- Very clean field (no strong point sources)
- 0.21 MHz and 8s resolution
- Used to calculate continuum source counts using P(D) analysis down to 0.25 uJy (arXiv:1912.06212, arXiv:2101.07827)



RMS: 3 µJy/beam

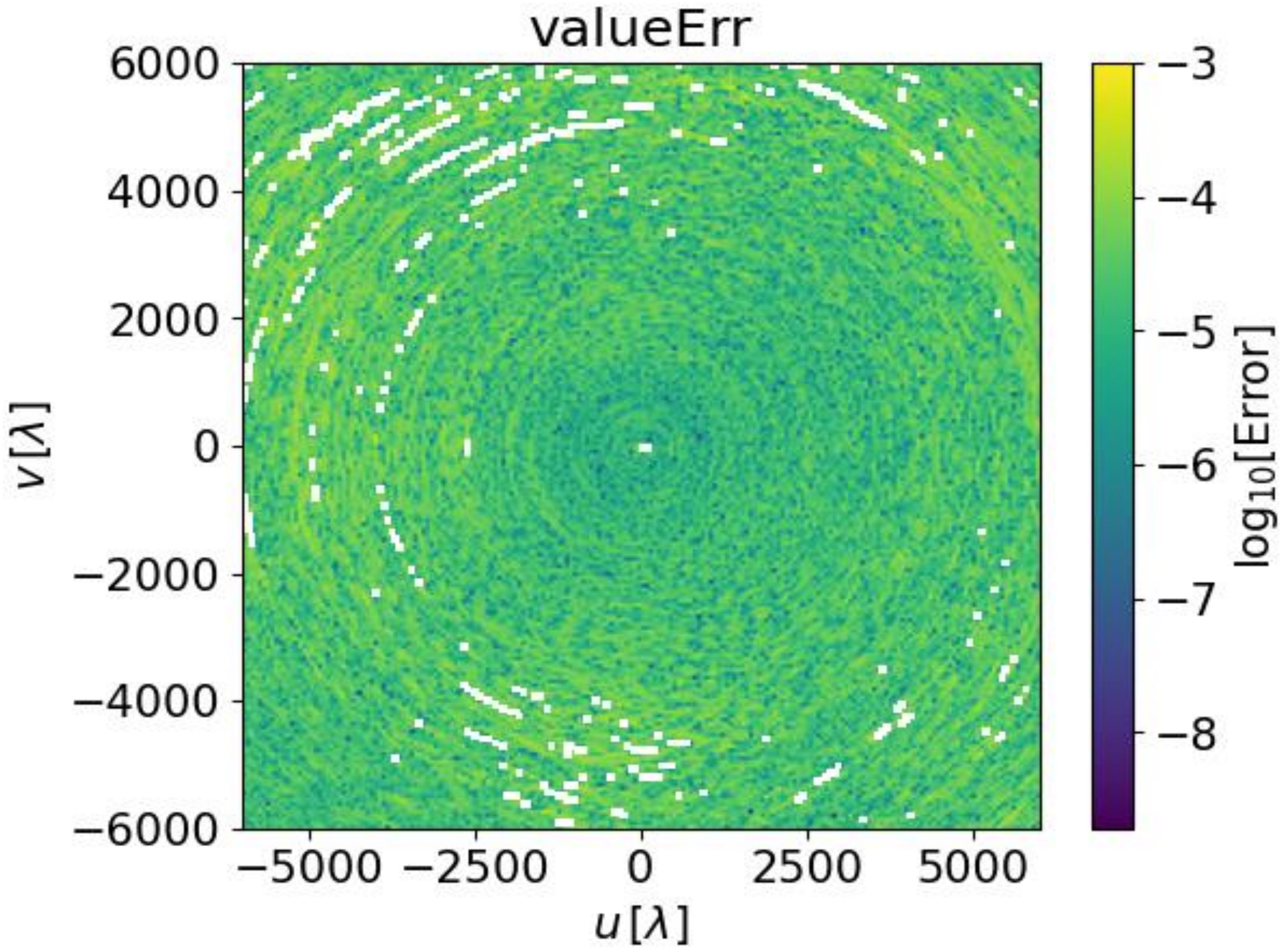
RFI for MeerKAT/SKA-MID…



(from SARAO)

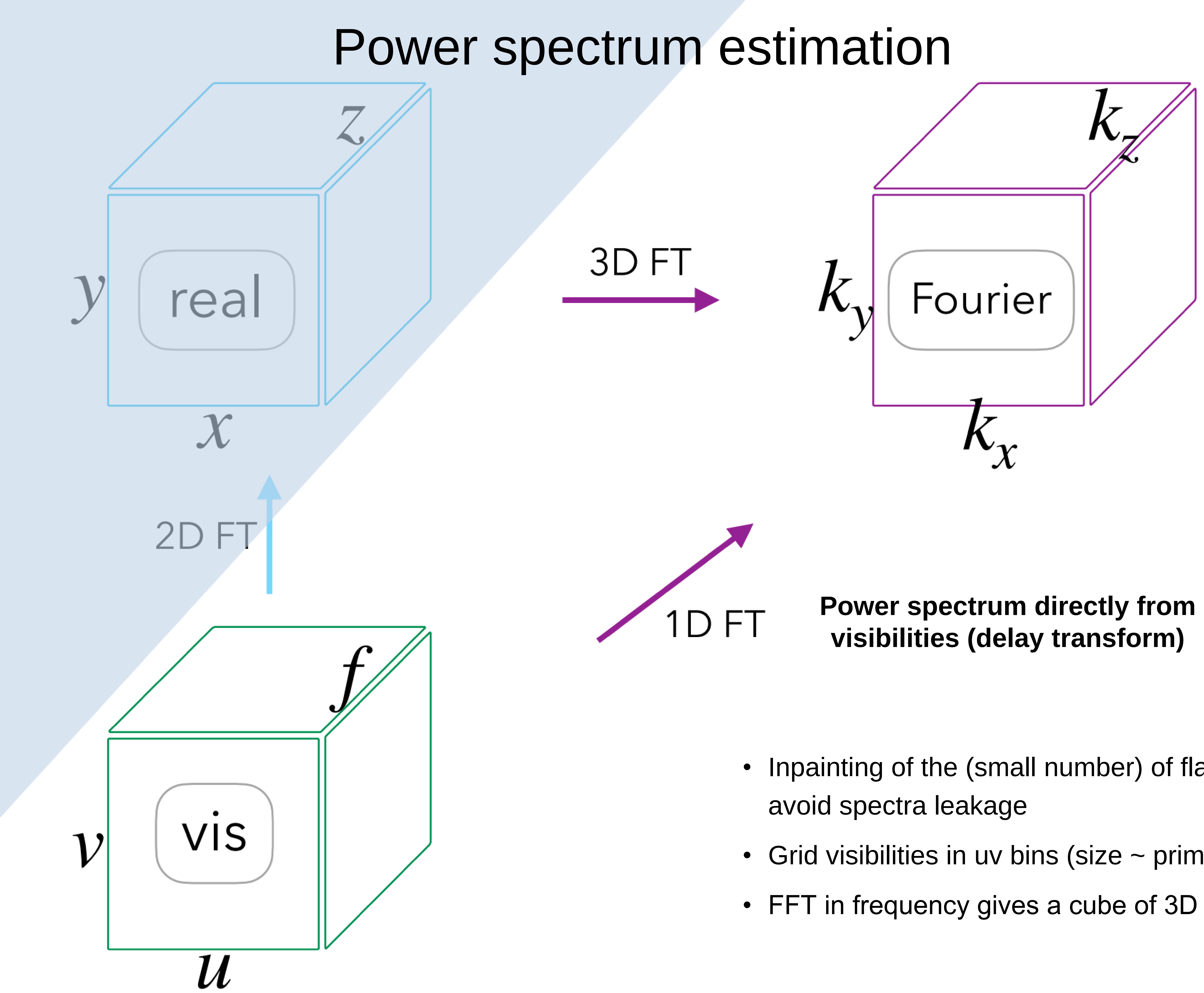
Calibration

- 96 hrs of data spanned through 9 separate observing sessions (data blocks)
- RFI flagging and calibration done using the **processMeerKAT** (Collier et al. 2021) software
- Primary calibrator PKS B1934-638 is observed for 10 minutes every 3 hours for flux and bandpass calibration (main source of error)
- Secondary calibrator is PKS J0252-7104 is observed for 2 minutes every 15 minutes for phase calibration.
- For each data block, an iterative self-calibration is performed for further phase corrections.
- Model visibilities produced from ***clean*** process (our point source/foreground model)
- Full stokes data produced



Calibration error ~ 10^{-5}

Power spectrum estimation



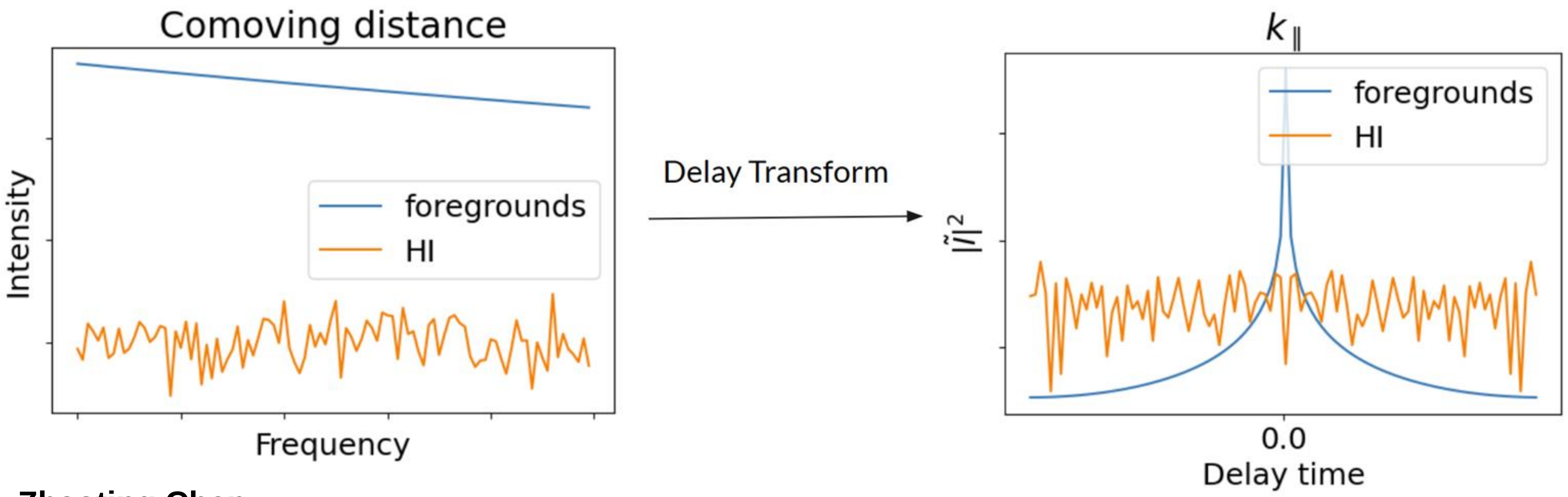
Power spectrum directly from visibilities (delay transform)

- Inpainting of the (small number) of flagged channels to avoid spectra leakage
- Grid visibilities in uv bins (size ~ primary beam)
- FFT in frequency gives a cube of 3D power spectra…

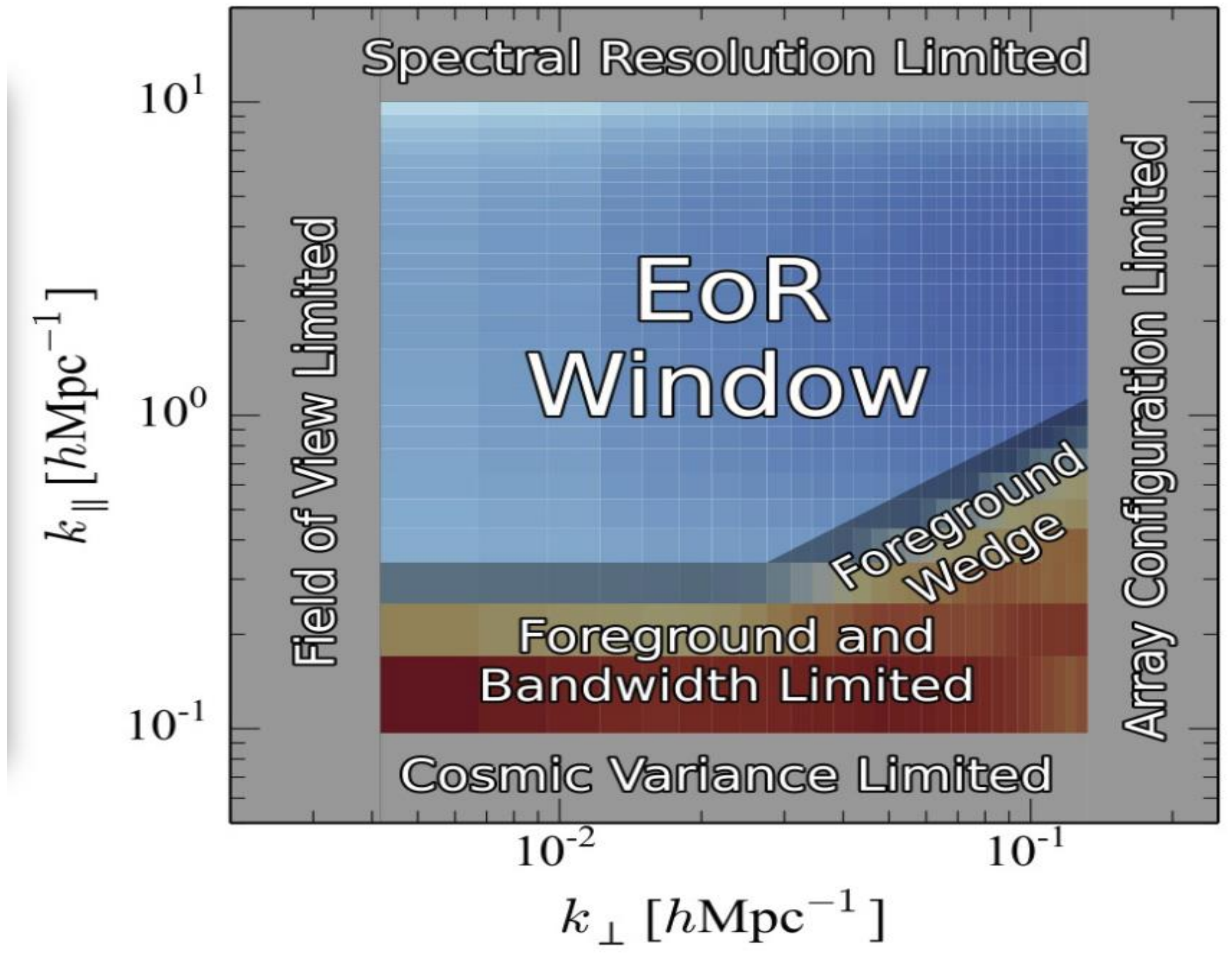
(Sourabh Paul)

Foreground avoidance

- Radio foregrounds are orders of magnitude brighter than HI signal
- Pick a region that is “foreground free”



Zhaoting Chen

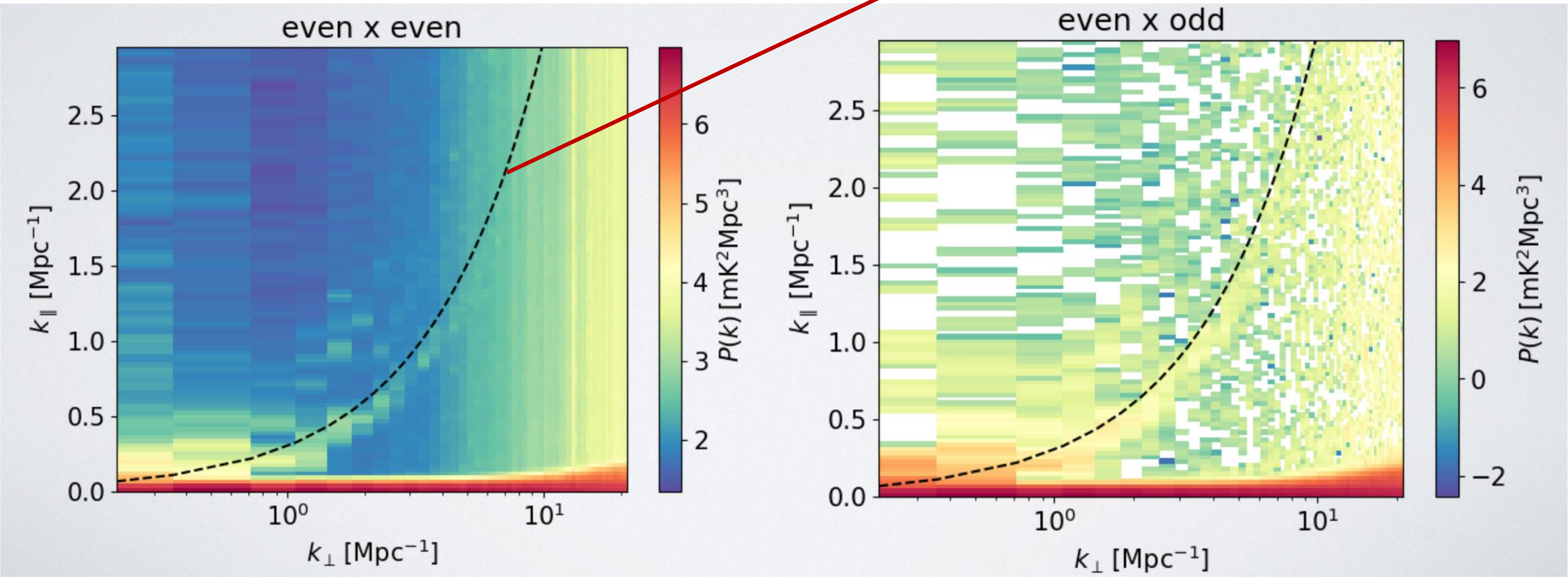


Liu, Parsons & Trott, 1404.2596

2d Power Spectra

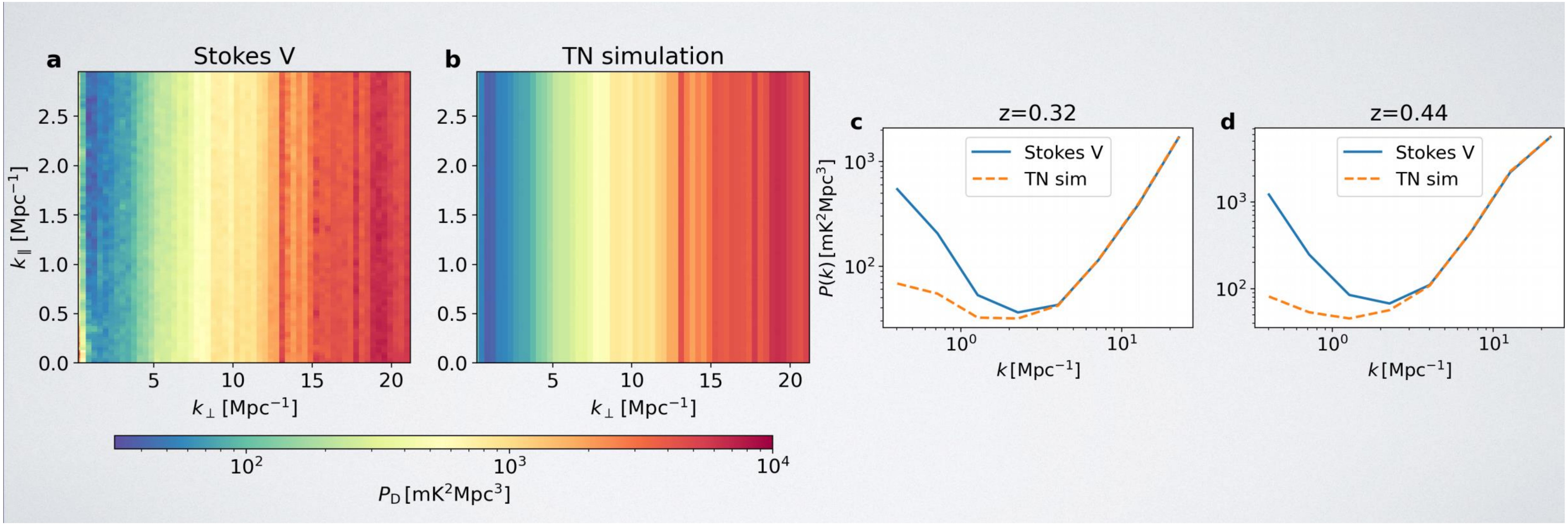
- A clear structure of contamination in the cylindrical power spectrum
- How to remove it?

Foreground wedge (horizon)

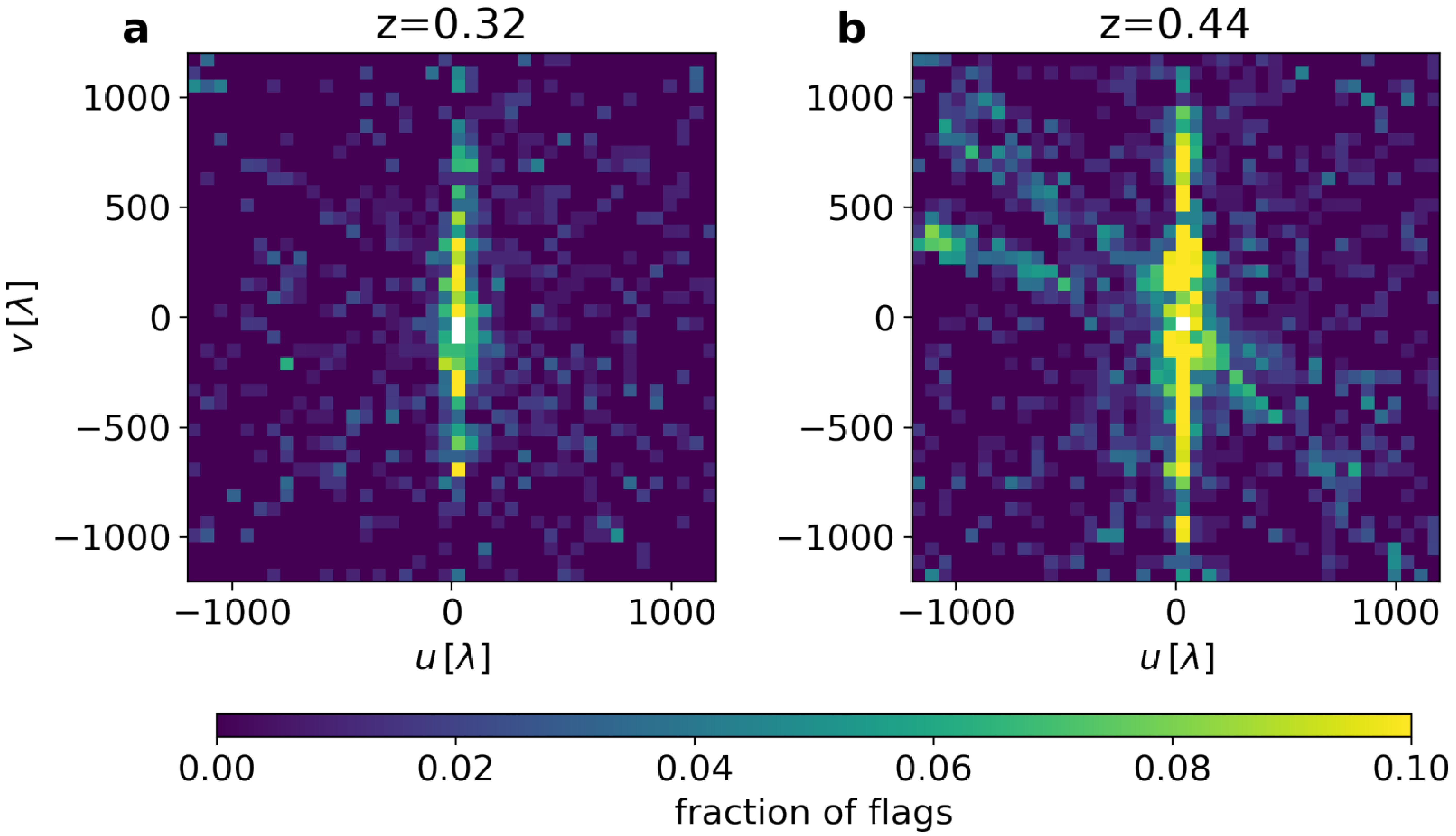


Thermal noise

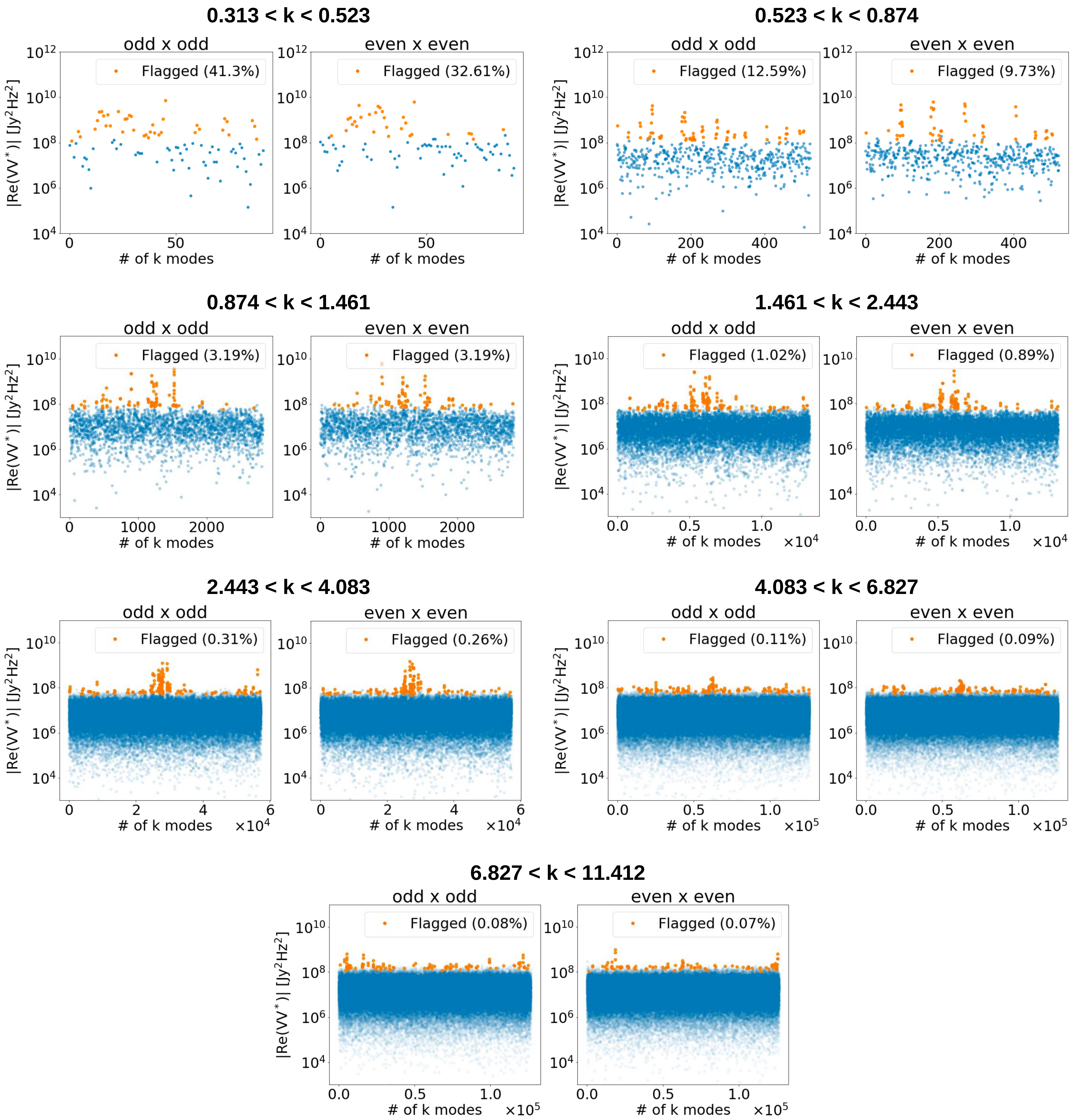
- Use Stokes V data to estimate and simulate thermal noise (end to end simulations developed in Paul et al. https://arxiv.org/abs/2009.13550)
- Flag strong deviations from thermal noise (5 sigma cut) – tested with simulations



Fraction of k_{par} pixels flagged



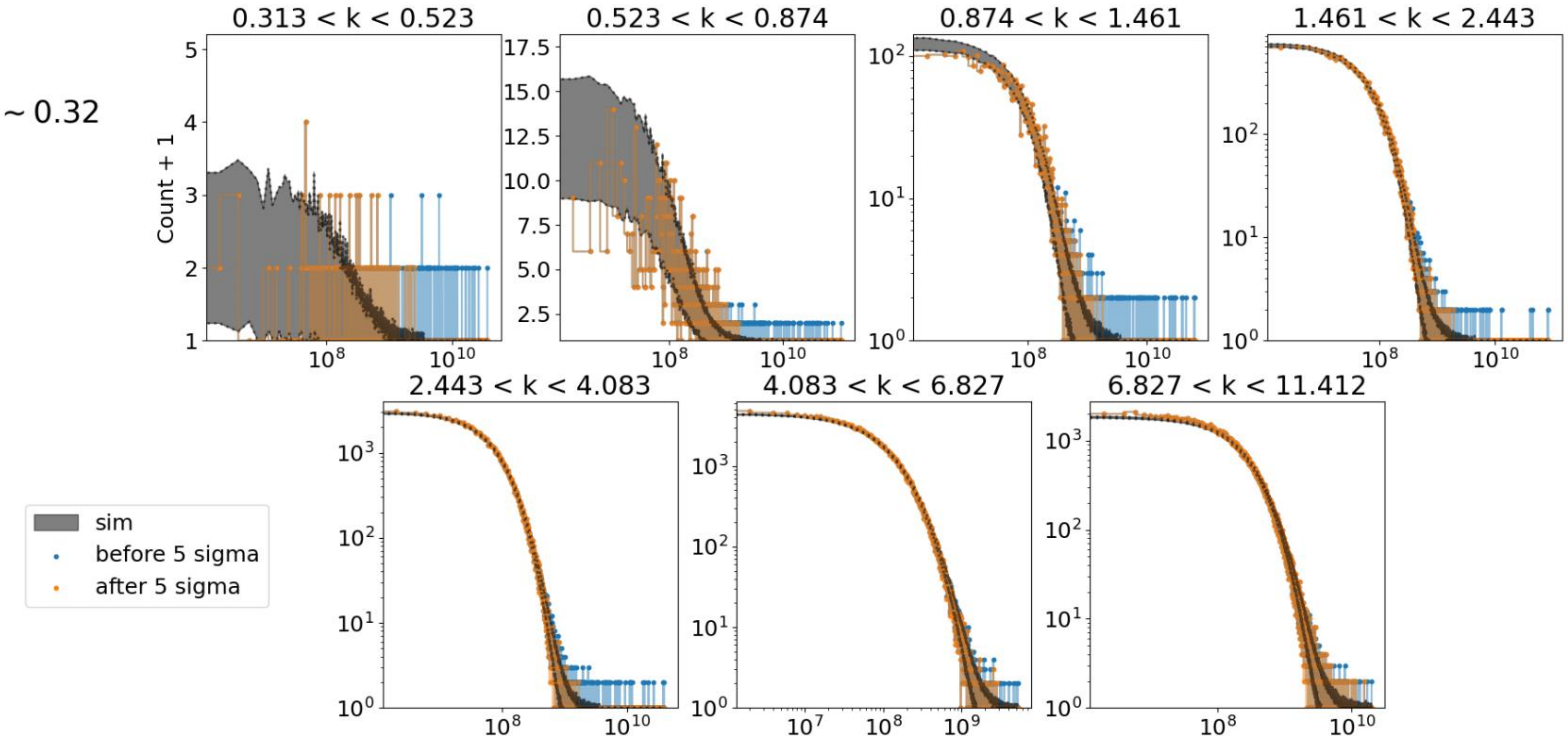
Using thermal noise simulations, we can identify the k-pixels that are outliers and flag them. Tracing these k-pixels, we find that the excess power comes from a weak wide-band RFI which shows up at u=0.

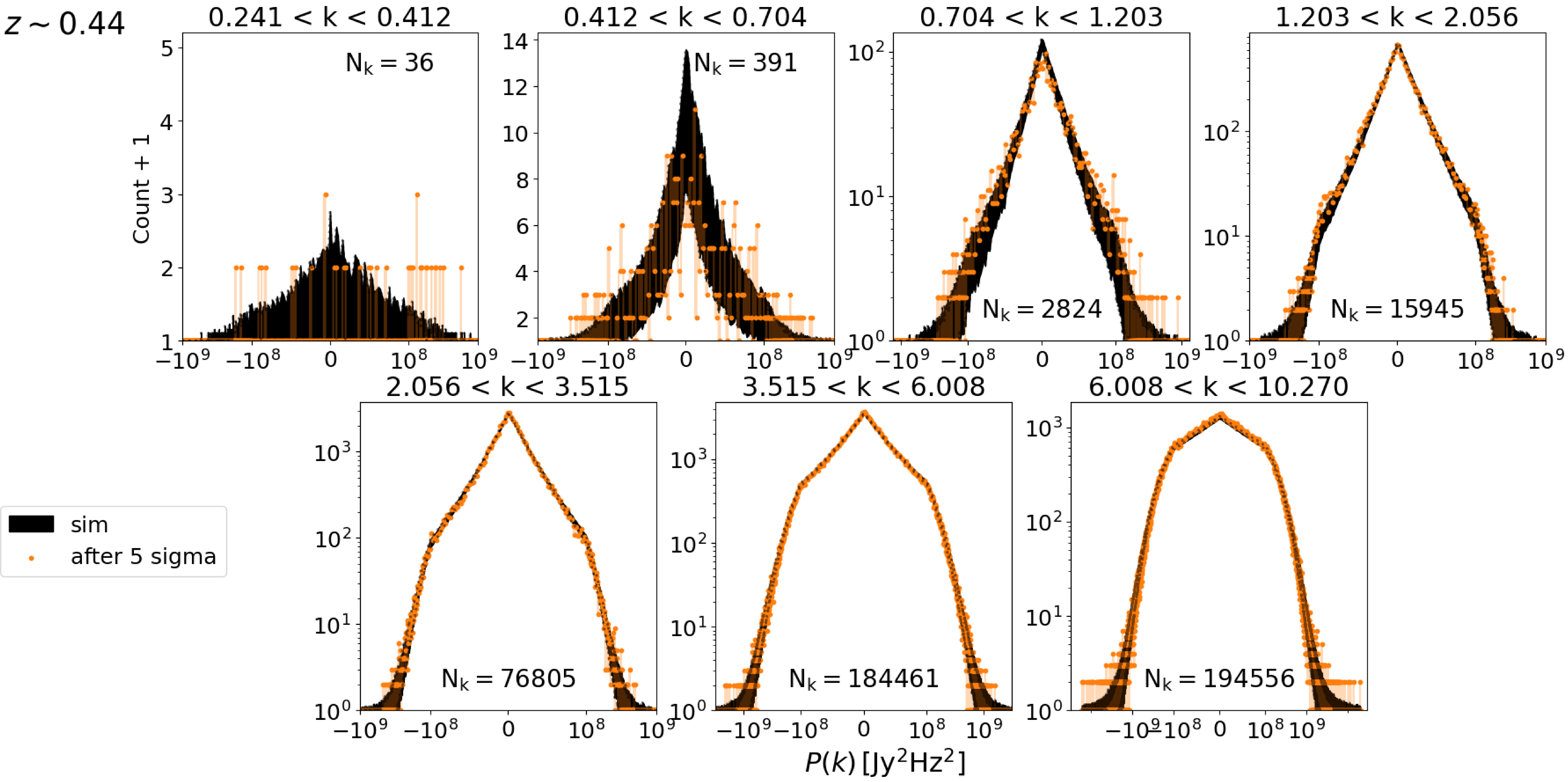


0.313 < k < 0.523
odd x odd
Flagged (41.3%)
even x even
Flagged (32.61%)
0.523 < k < 0.874
odd x odd
Flagged (12.59%)
even x even
Flagged (9.73%)
0.874 < k < 1.461
odd x odd
Flagged (3.19%)
even x even
Flagged (3.19%)
1.461 < k < 2.443
odd x odd
Flagged (1.02%)
even x even
Flagged (0.89%)
2.443 < k < 4.083
odd x odd
Flagged (0.31%)
even x even
Flagged (0.26%)
4.083 < k < 6.827
odd x odd
Flagged (0.11%)
even x even
Flagged (0.09%)
6.827 < k < 11.412
odd x odd
Flagged (0.08%)
even x even
Flagged (0.07%)
|Re(VV*)| [Jy²Hz²]
# of k modes

Flagging in the auto Pk

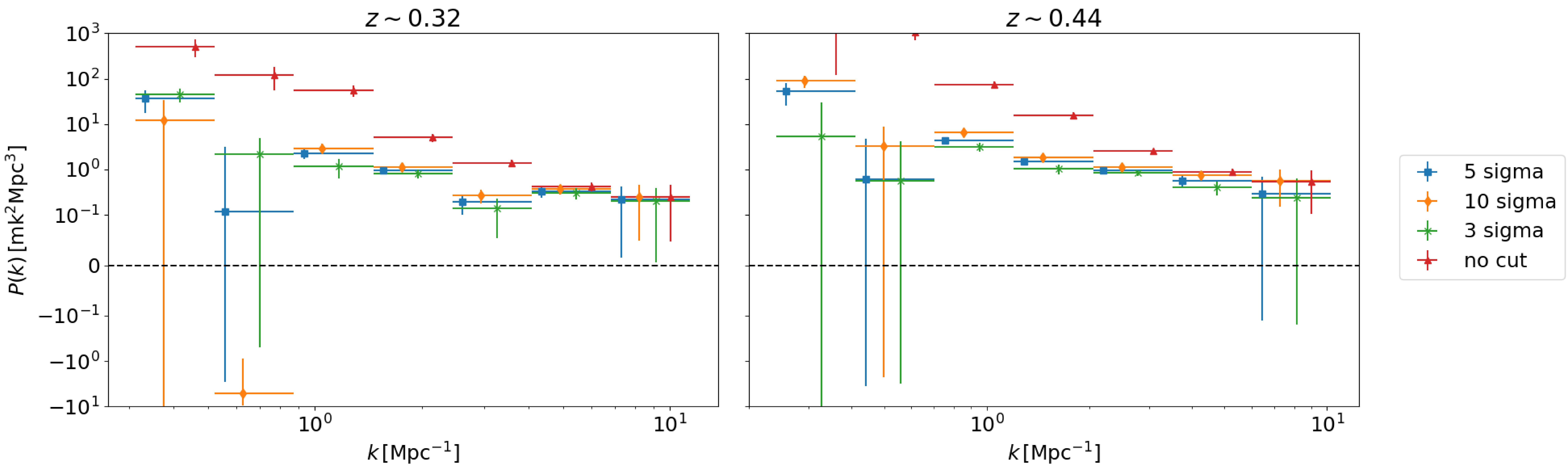
$z \sim 0.32$





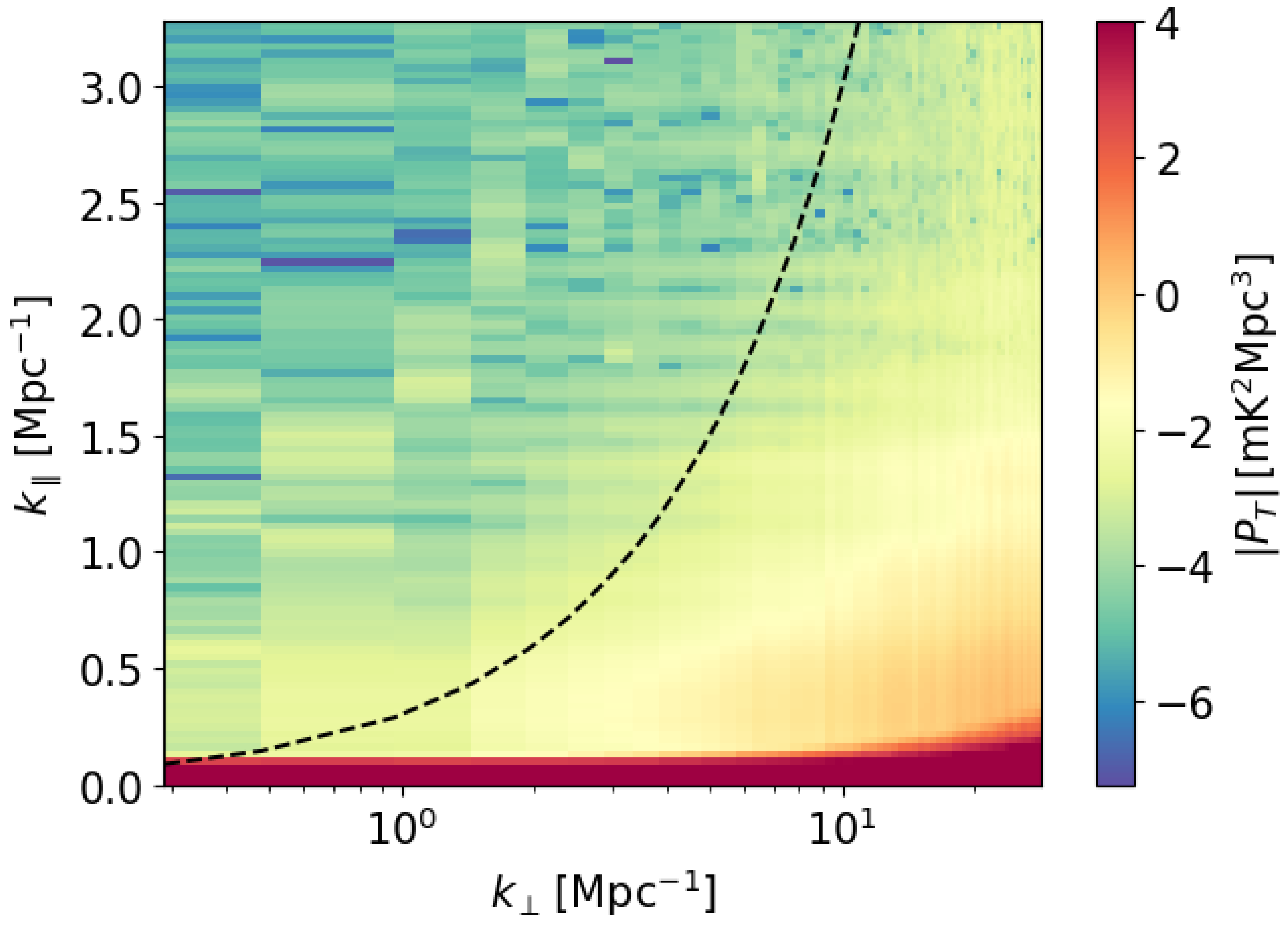
z ~ 0.44
0.241 < k < 0.412
N_k = 36
0.412 < k < 0.704
N_k = 391
0.704 < k < 1.203
N_k = 2824
1.203 < k < 2.056
N_k = 15945
2.056 < k < 3.515
N_k = 76805
3.515 < k < 6.008
N_k = 184461
6.008 < k < 10.270
N_k = 194556
Count + 1
P(k) [Jy²Hz²]
sim
after 5 sigma

Effect of 5 sigma cut

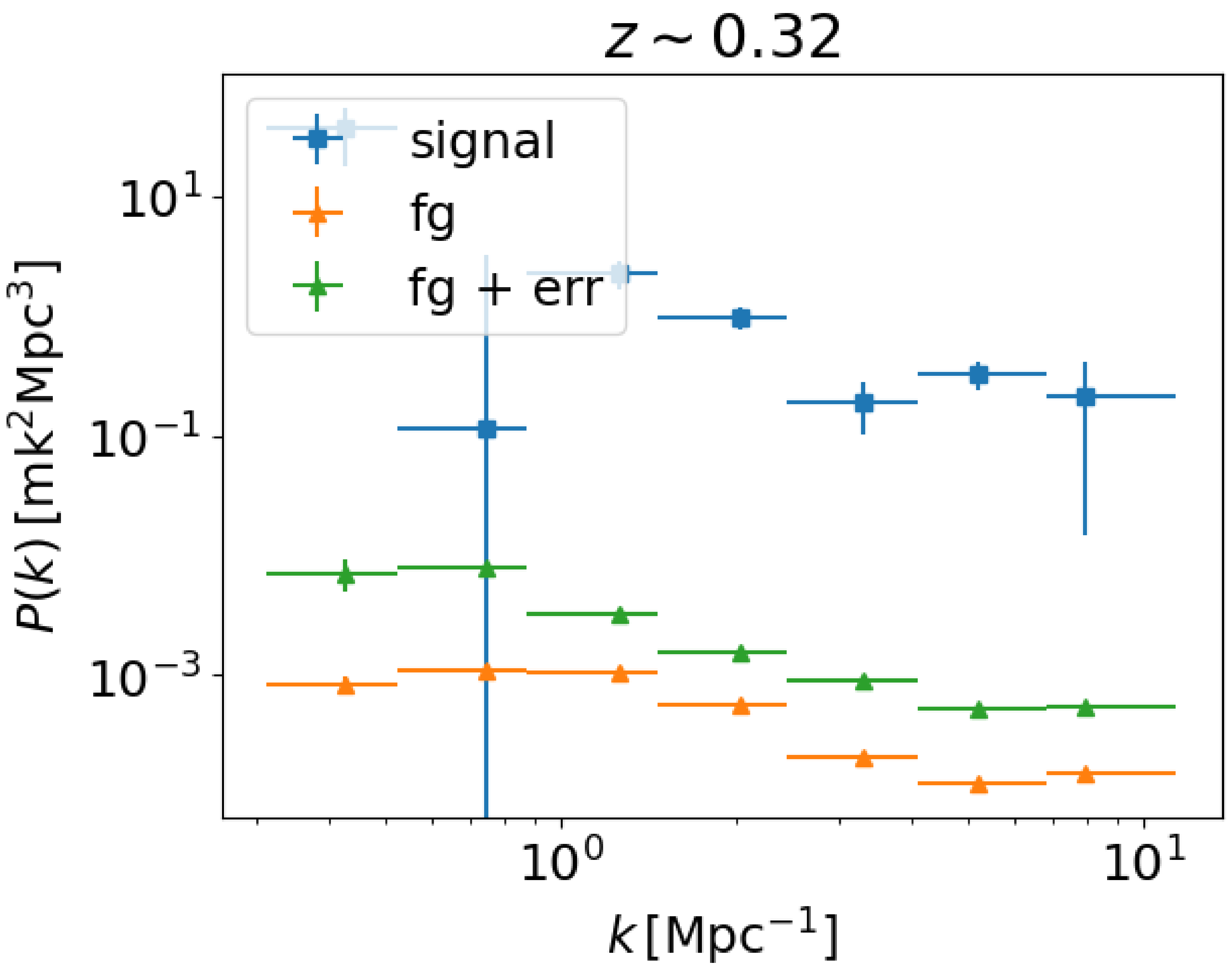


Foreground leakage?

The foreground power, with leakage from inpainting, RFI flagging, calibration error, is still insignificant compared to the measured signal -> no need for point source subtraction

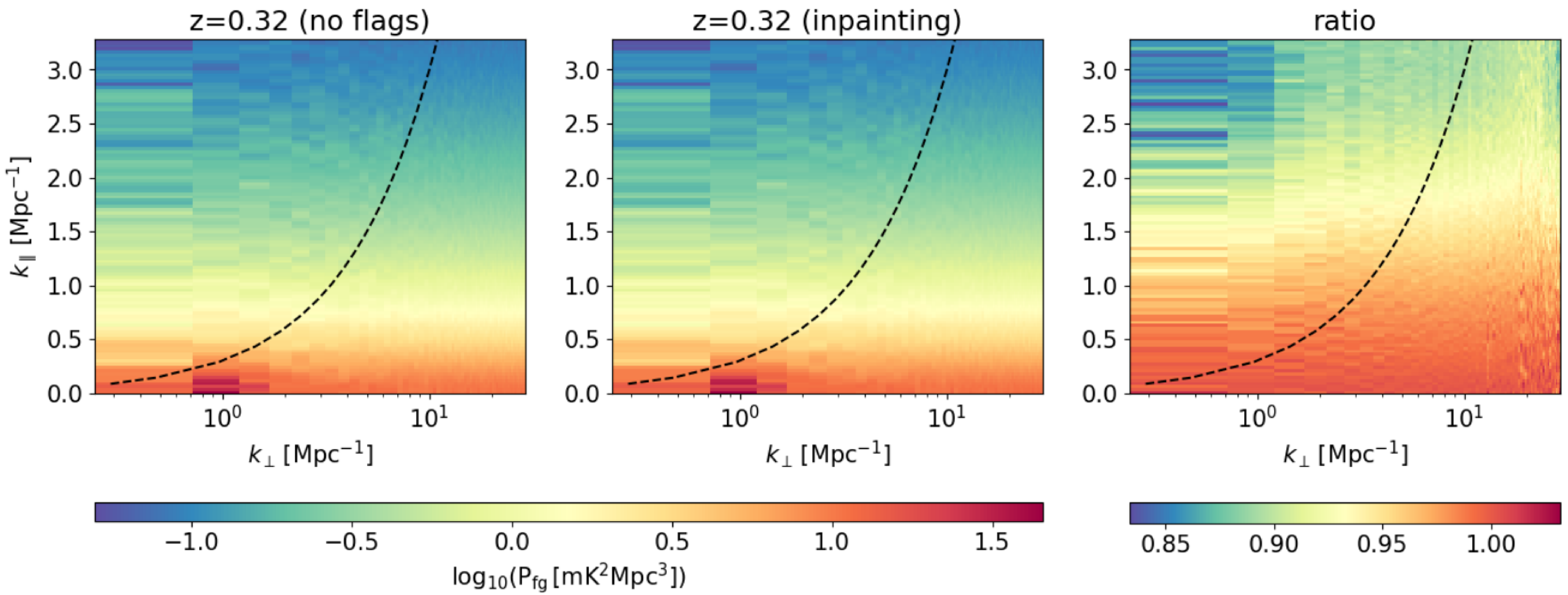


Foregrounds using point source model from Clean (color scale saturated)

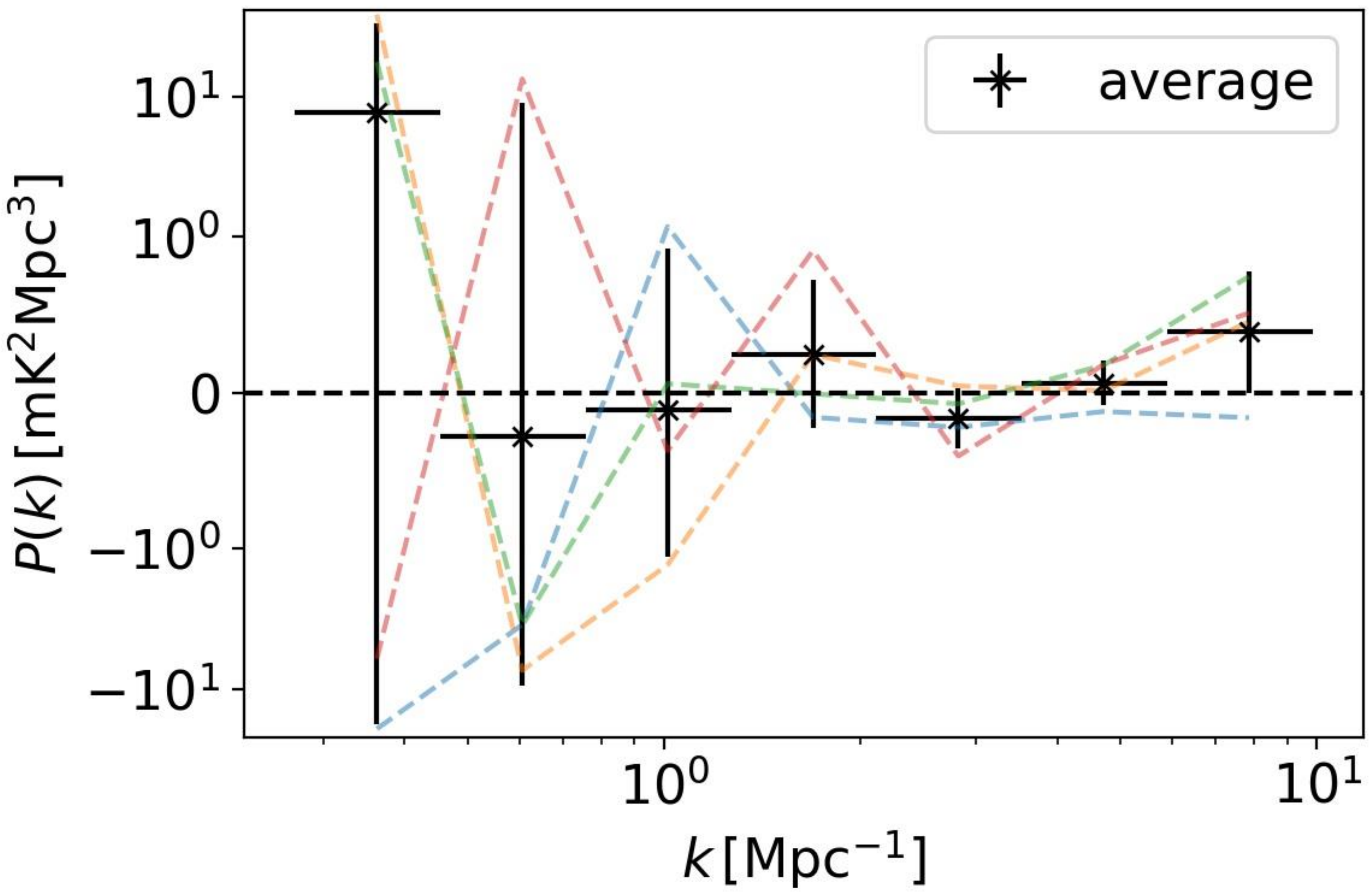


Foreground power spectrum

Effect of flagging and inpainting on the HI signal



Null test: cross-correlate visibility data between the two redshifts



No evidence of excess power

Jackknife of different data blocks