ONE LAST THING

I am graduating this year.

Currently on the job market.

Would love to get a **postdoc** opportunity!

A First Detection of Neutral Hydrogen Intensity Mapping on Mpc Scales

Zhaoting Chen, on behalf of
Sourabh Paul, Mario Santos and Laura Wolz

SKA Cosmology SWG Meeting 2023

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Outline

- How to use interferometric radio data to do HI intensity mapping
- Why is it very **difficult**
- Analysis of the MeerKAT DEEP2 data
- HI Science from the data

Outline

- How to use interferometric radio data to do HI intensity mapping

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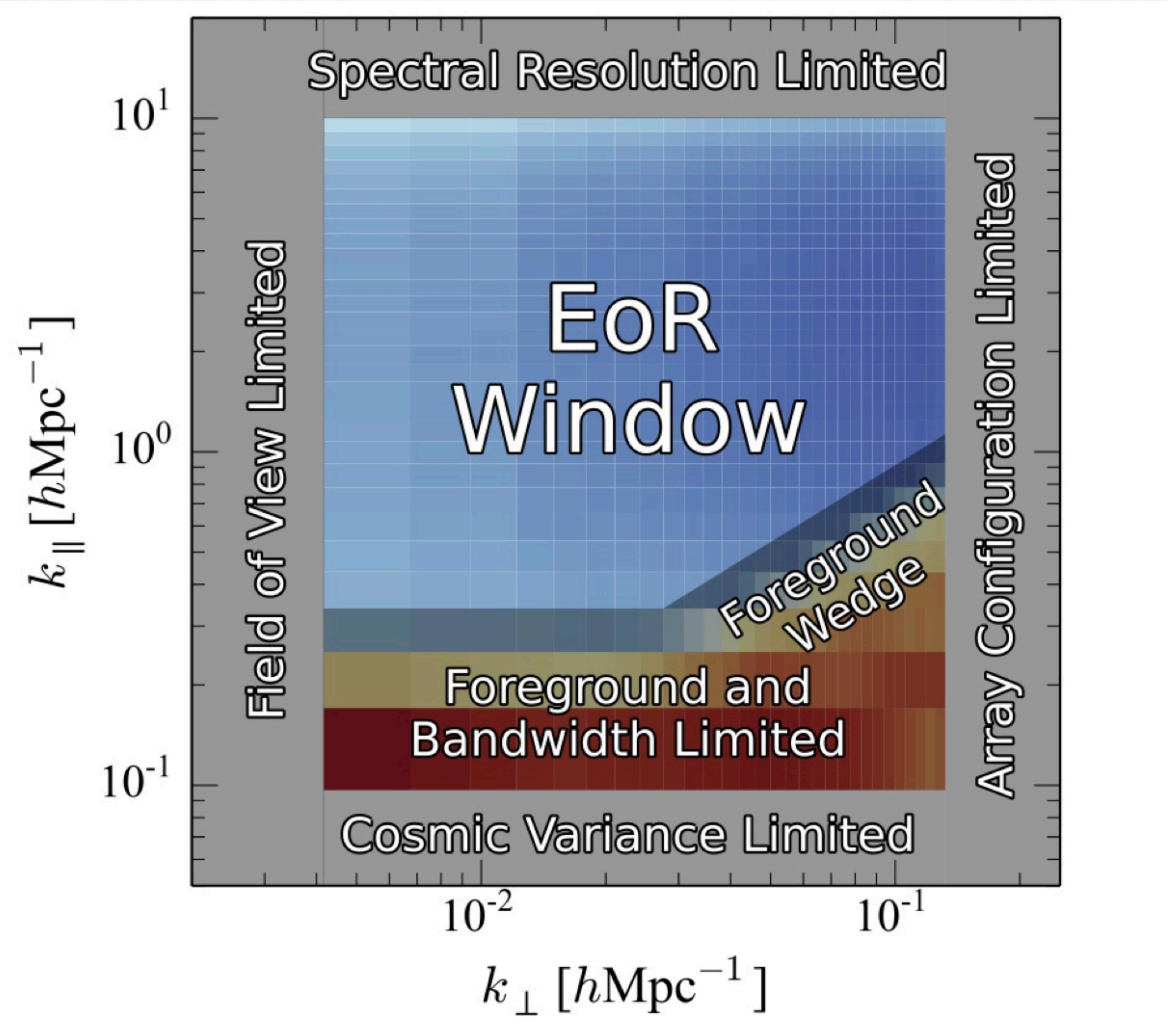
Foreground Avoidance

- We can measure the HI power spectrum outside the “wedge”



Liu, Parsons, and Trott 1404.2596

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The Uphill Battle

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    - Faint HI signal demands extreme field depth

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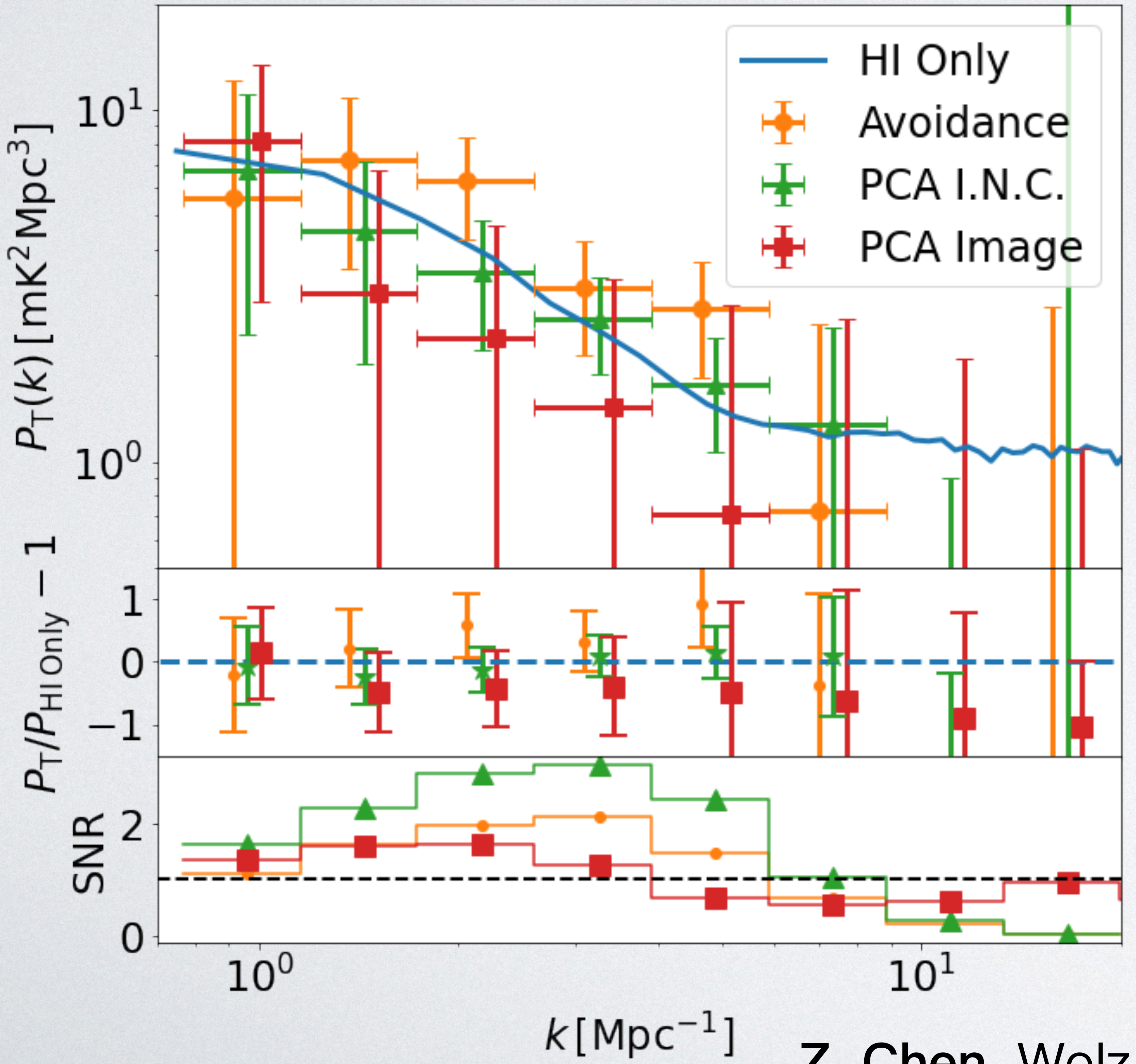
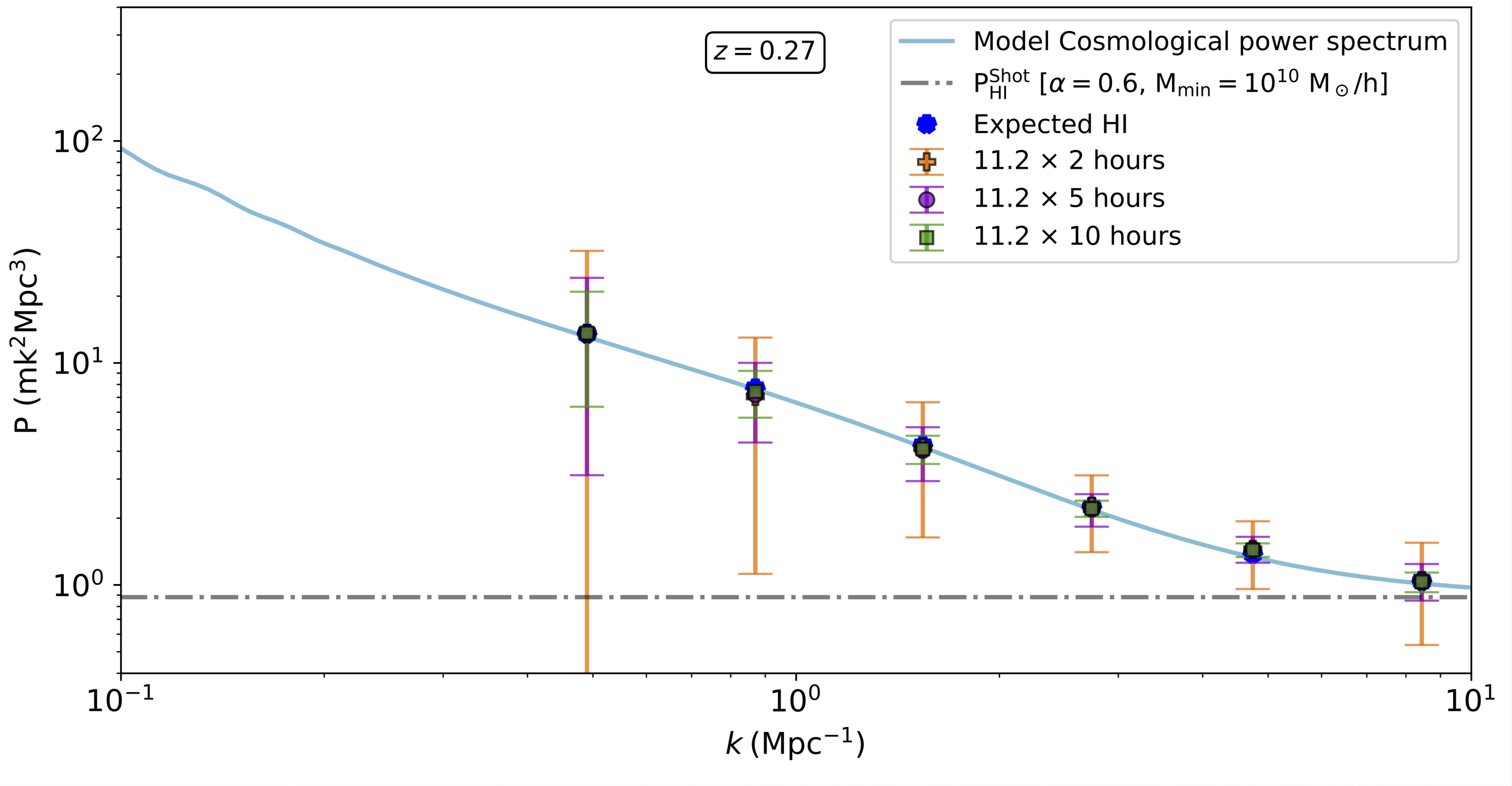


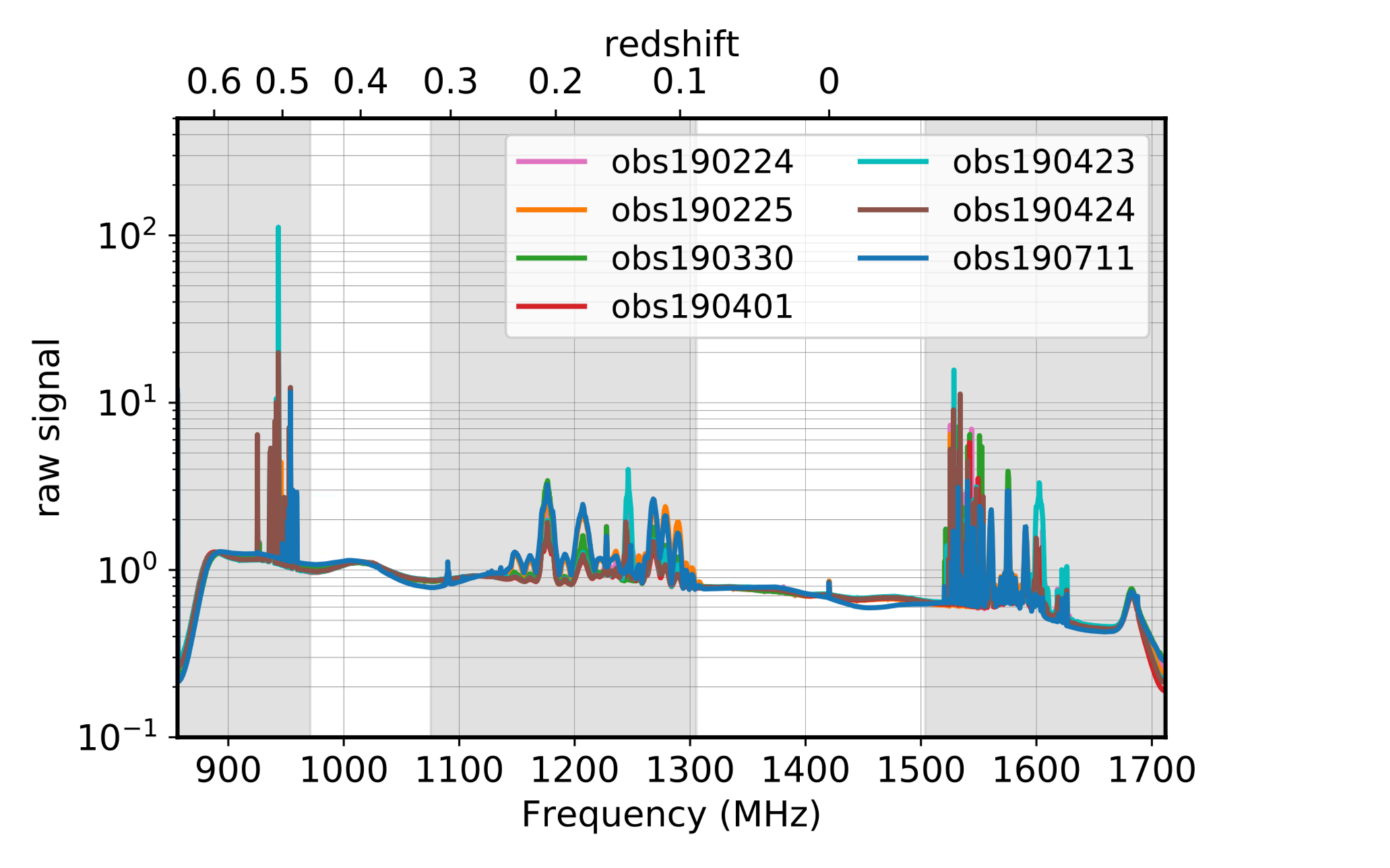
Z. Chen, Wolz and Battye 2205.07776



Paul, Santos et al. 2009.13550

The Uphill Battle

- Why is it very **difficult**
  - Systematic issues such as RFI



Wang et al. 2011.13789

The Uphill Battle

- Why is it very **difficult**
    - **EXTREME** requirements for instrument stability and calibration precision

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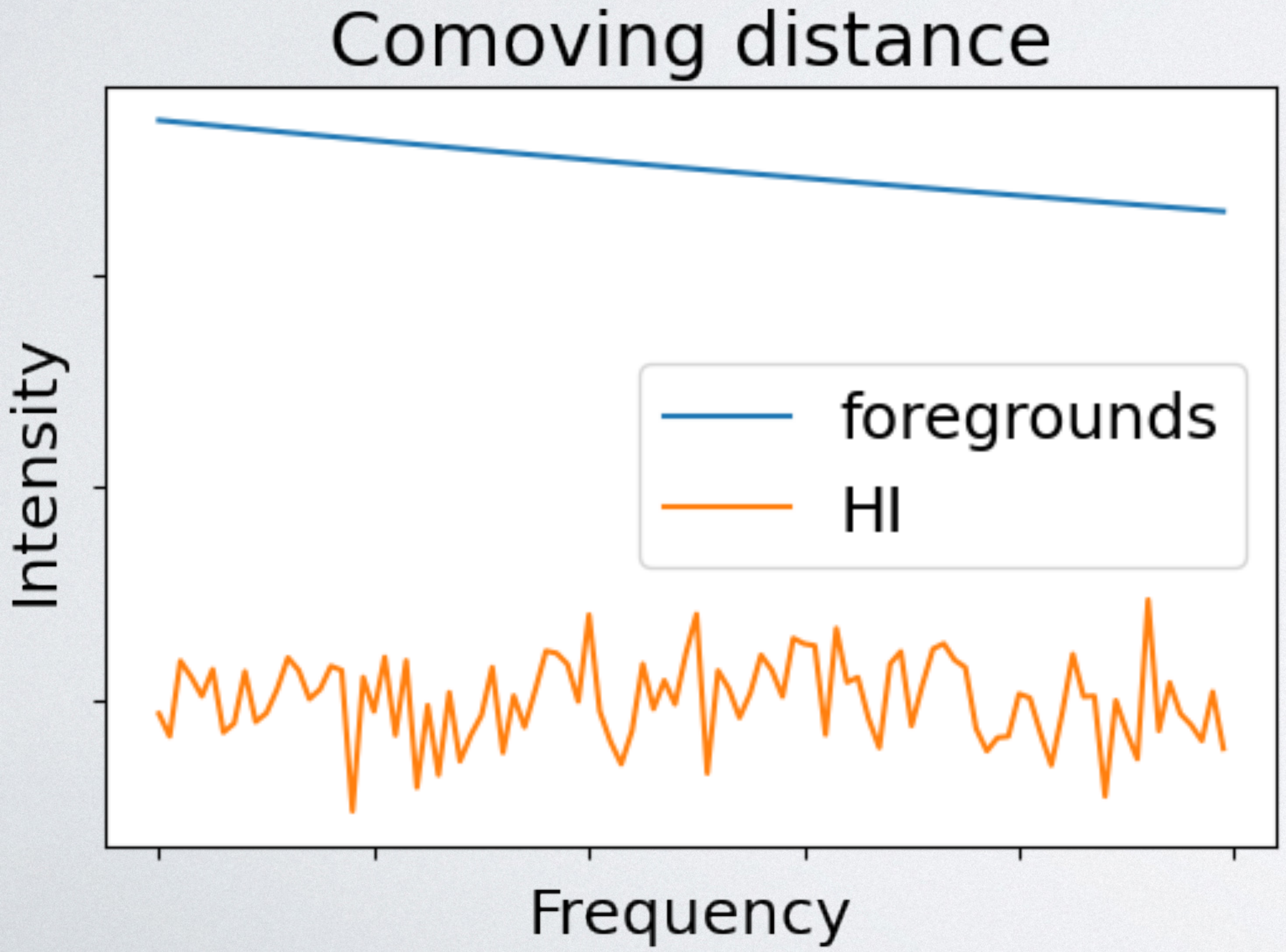
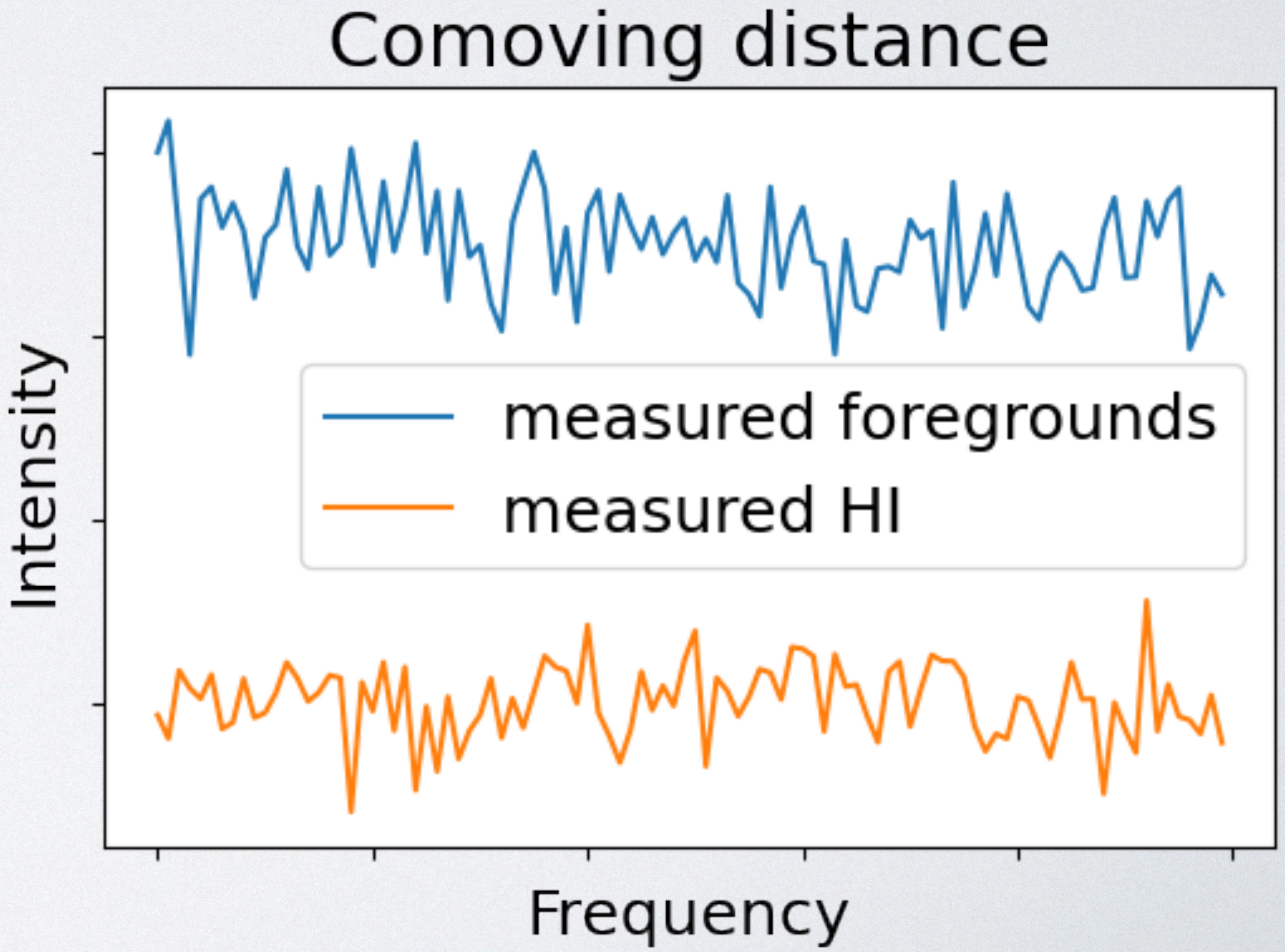


Measured with radio interferometer



The Uphill Battle

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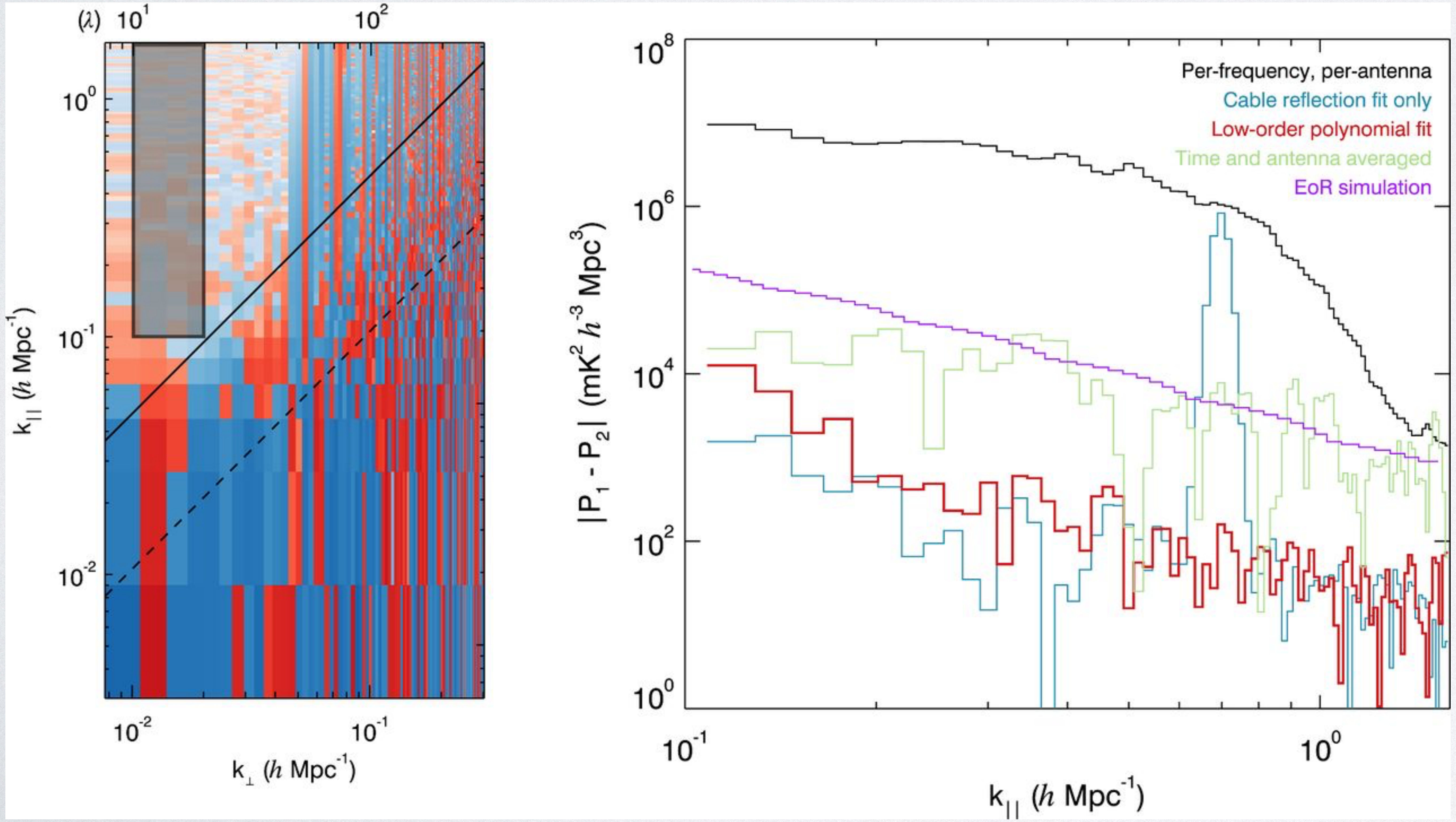
The Uphill Battle

- Why is it very **difficult**
  - **EXTREME** requirements for instrument stability and calibration precision. **e<10^-4** is needed for enabling the measurements.



Barry et al. 1603.00607

The Uphill Battle

- Why is it very **difficult**
  - Accurate understanding of the sensitivity of the instrument to remove the noise bias.

3.2.3 Noise statistics and weight estimates

Several noise metrics are computed to analyse the noise statistics in the data. In general, the noise can be estimated with reasonable accuracy from the Stokes V image cube (circularly polarized sky), the sky being only weakly circularly polarized. Ten second time-difference visibilities, $\delta_t V(u, v, \nu)$, are obtained from taking the difference between the odd and even gridded visibilities sets, yielding a good estimate of the thermal noise (at this time resolution, the foregrounds and ionospheric errors cancel out almost perfectly).

Another noise estimate can be derived from the visibility difference between sub-bands, $\delta_\nu V(u, v, \nu)$, which should better reflect the spectrally-uncorrelated noise in the data. Compared to the time difference noise spectrum (in baseline-frequency space), we find that the sub-band difference noise variance is on average higher by a factor ≈ 1.35 for Stokes V and ≈ 2 for Stokes I (sixth and seventh columns of Table 1, respectively) with a small night-to-night variation. We also

Mertens et al. 2002.07196

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The Uphill Battle

- Why is it very **difficult**
  - Leakage from bright sources in side-lobes shows up in high delay
  - Mode-mixing from the primary beam
  - ………

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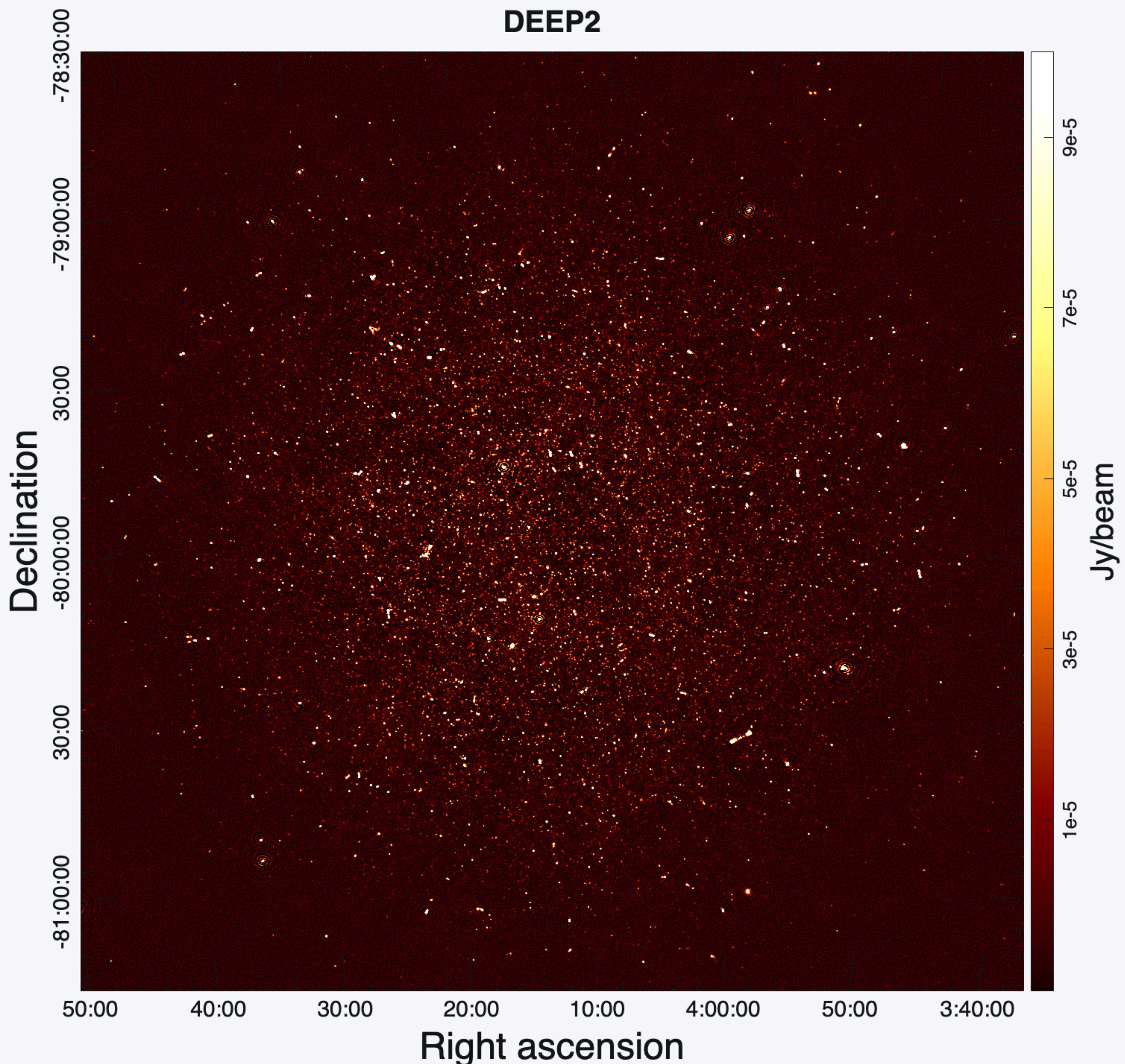
MeerKAT DEEP2 data

Integration Time✓
Avoid Bright Sources✓

- Pointing at the DEEP2 field. 96 hrs in total, 9 observing sessions.



Mauch et al. 1912.06212

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MeerKAT DEEP2 data

- Pointing at the DEEP2 field. 96 hrs in total, 9 observing sessions in L-band.
- Well-tested, established calibration pipeline using **processMeerKAT** (Collier et al.).
- Our own data processing pipeline after calibration.

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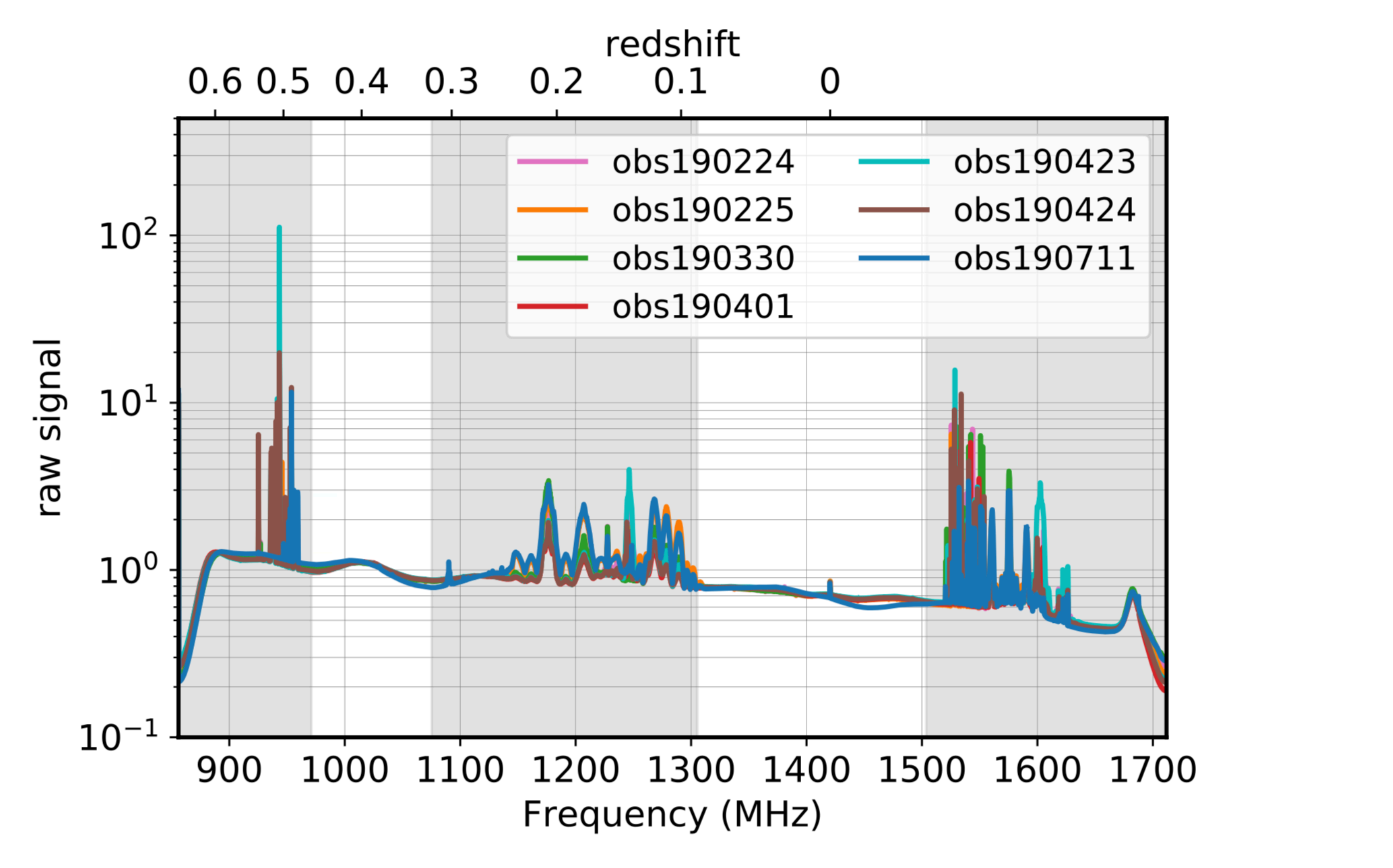
Less RFI✓

MeerKAT DEEP2 data

- Two sub-bands, each with a width of 46MHz centred around 986 and 1077.5 MHz.



Wang et al. 2011.13789

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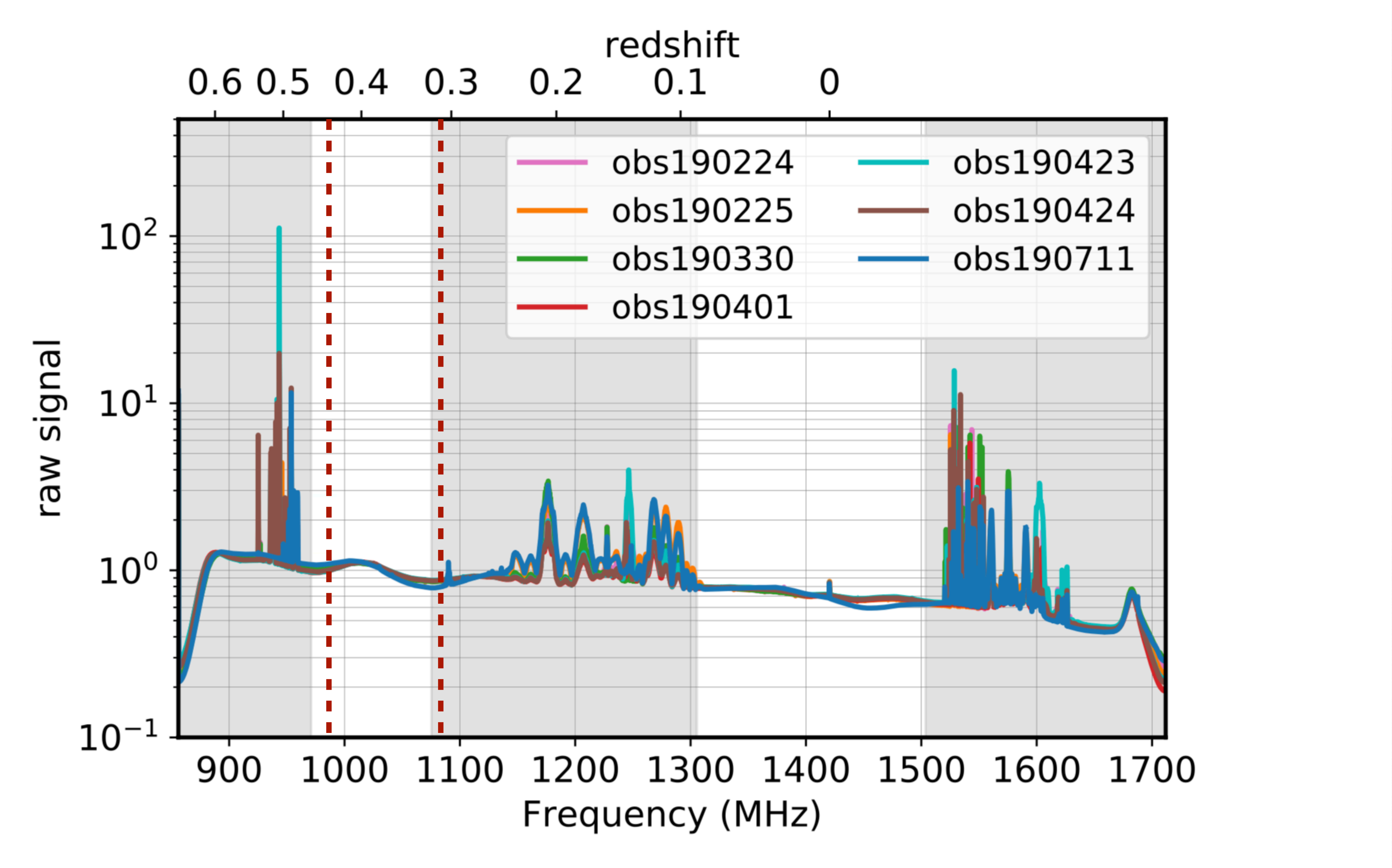


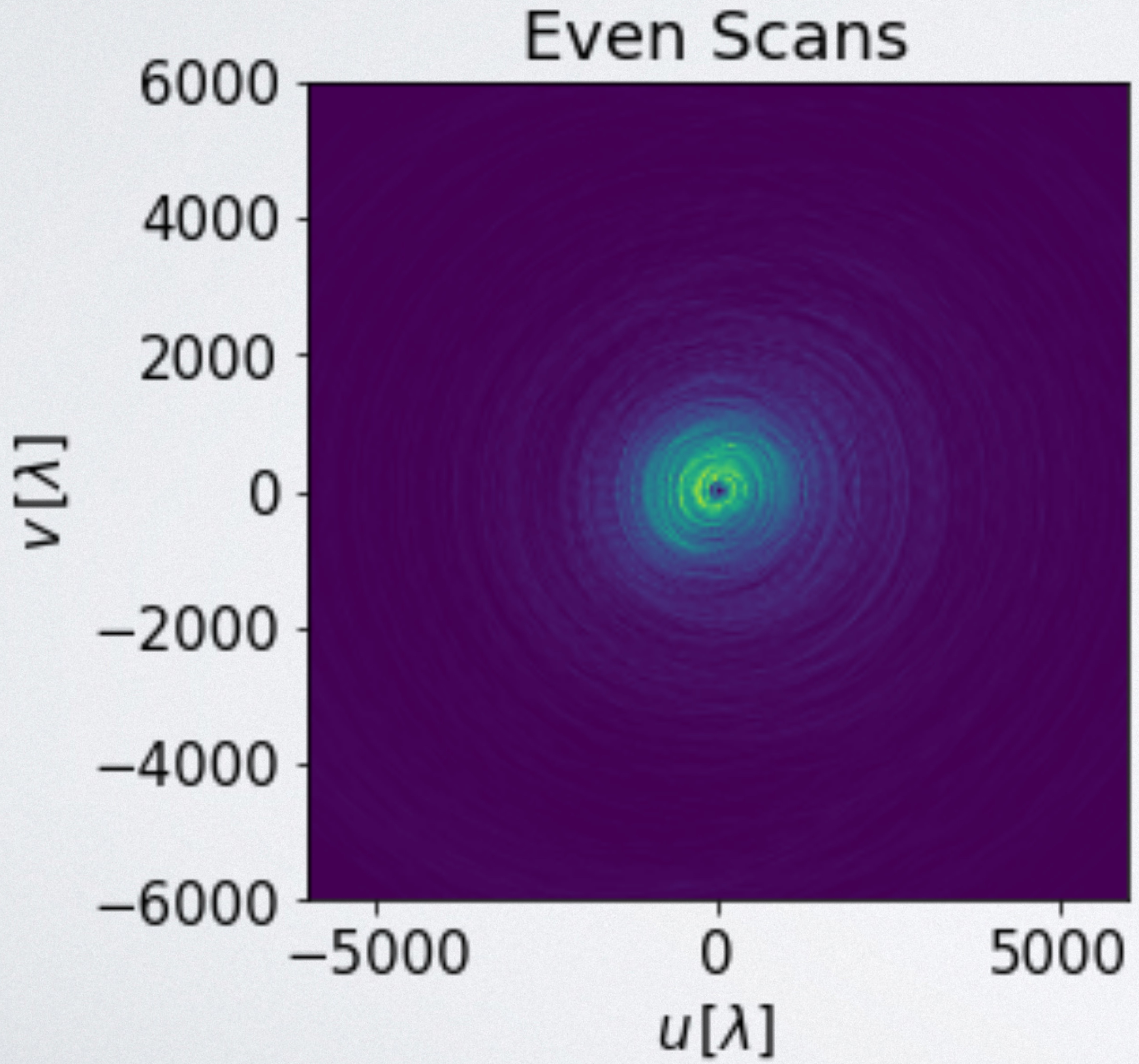
Wang et al. 2011.13789

MeerKAT DEEP2 data

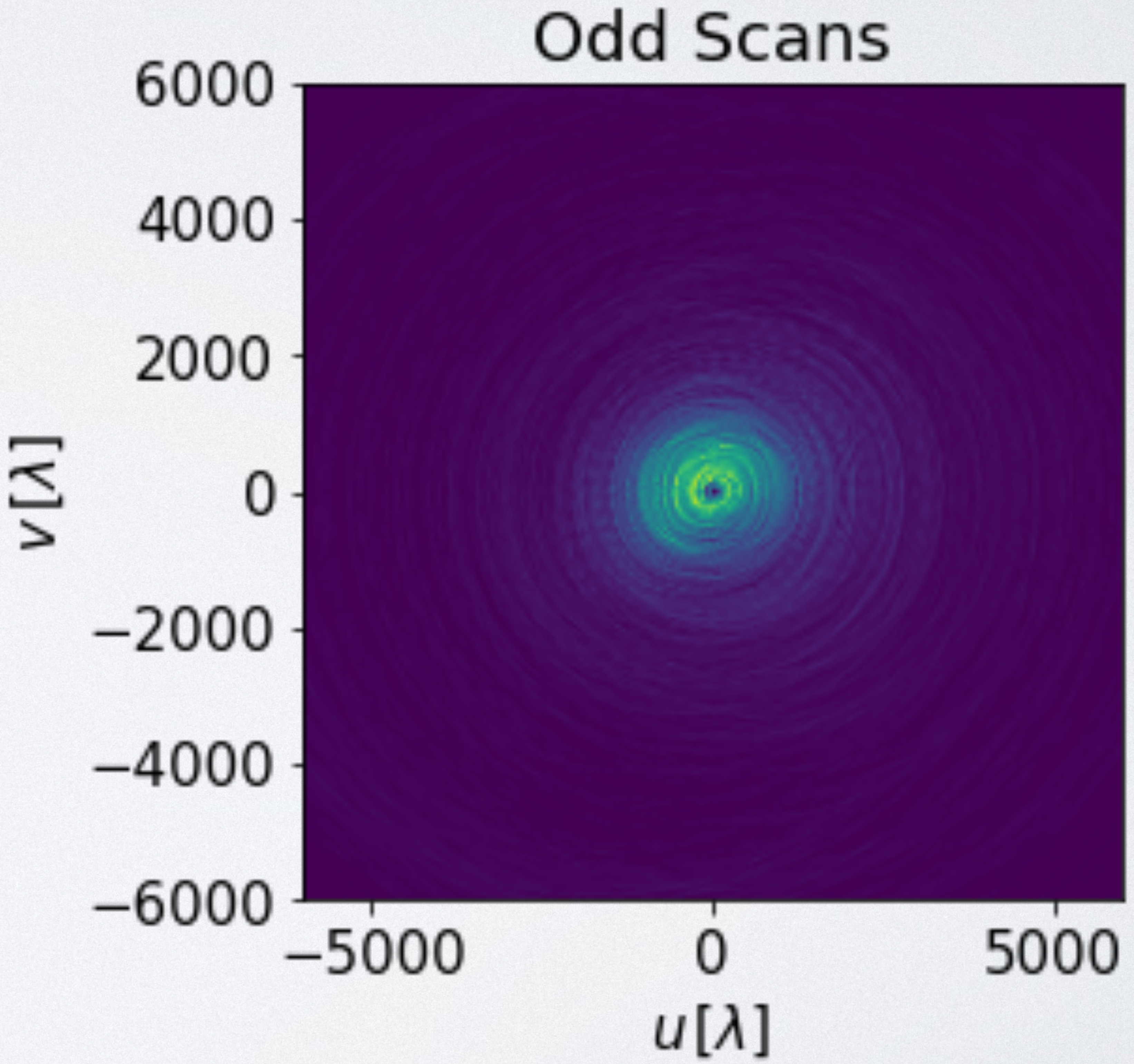
- Flux+bandpass cal on the primary calibrator, secondary phase cal, selfcal. 10^-3 errors for each solution interval, overall <10^-4.

MeerKAT DEEP2 data

- Cross-correlating even and odd scans to remove noise bias, avoiding the effects of wrongly estimated noise amplitude.

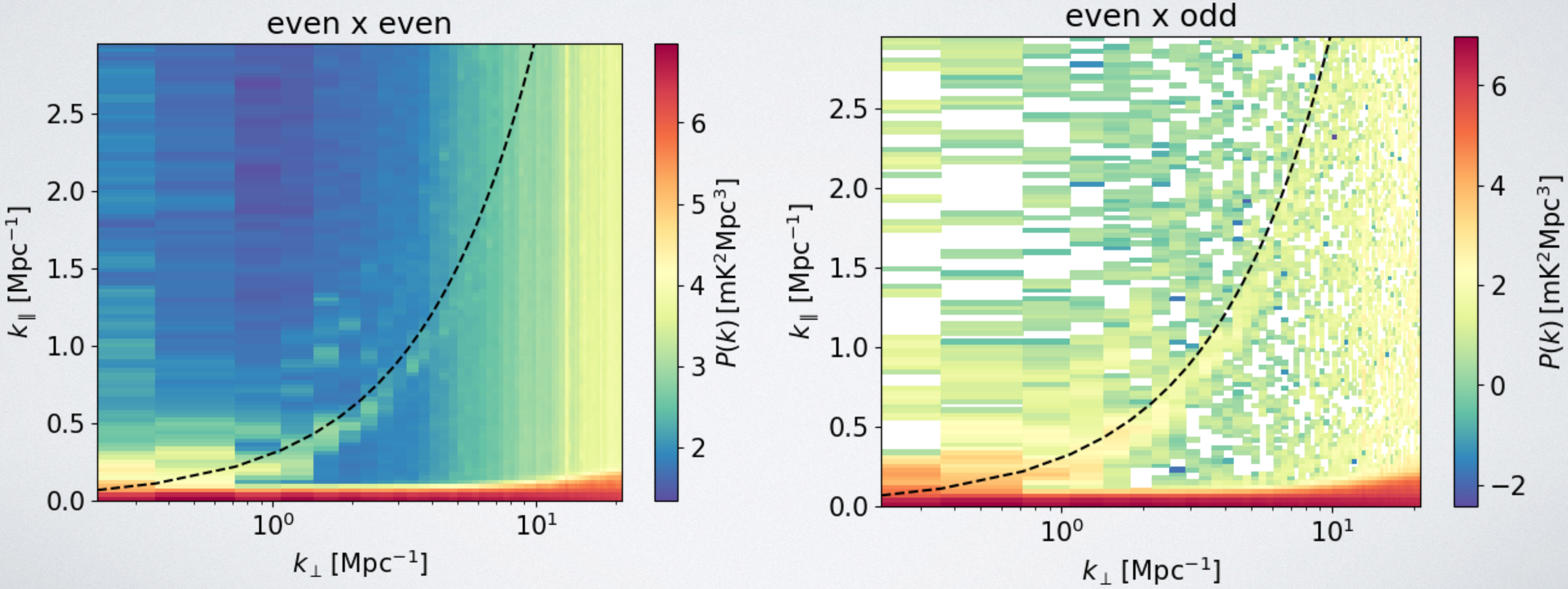


x



Residual RFI

- A clear structure of contamination in the cylindrical power spectrum



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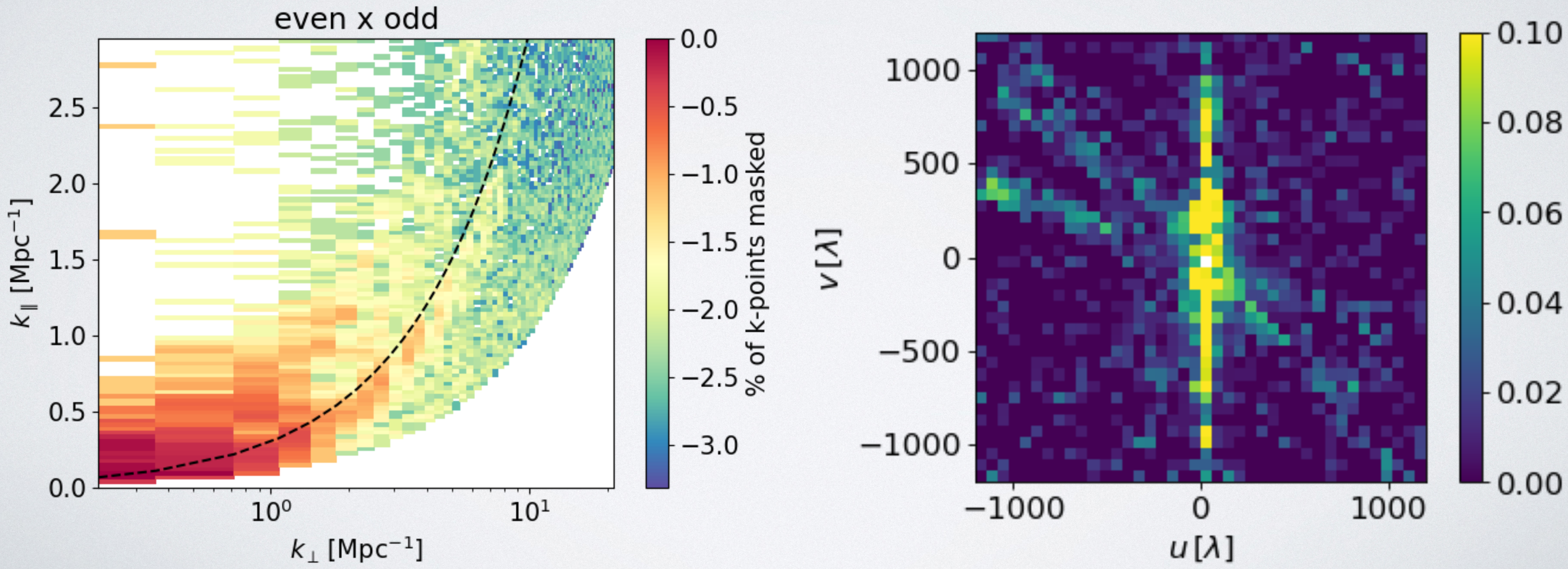
Noise✓

Thermal Noise

- Use Stokes V data to estimate and simulate thermal noise

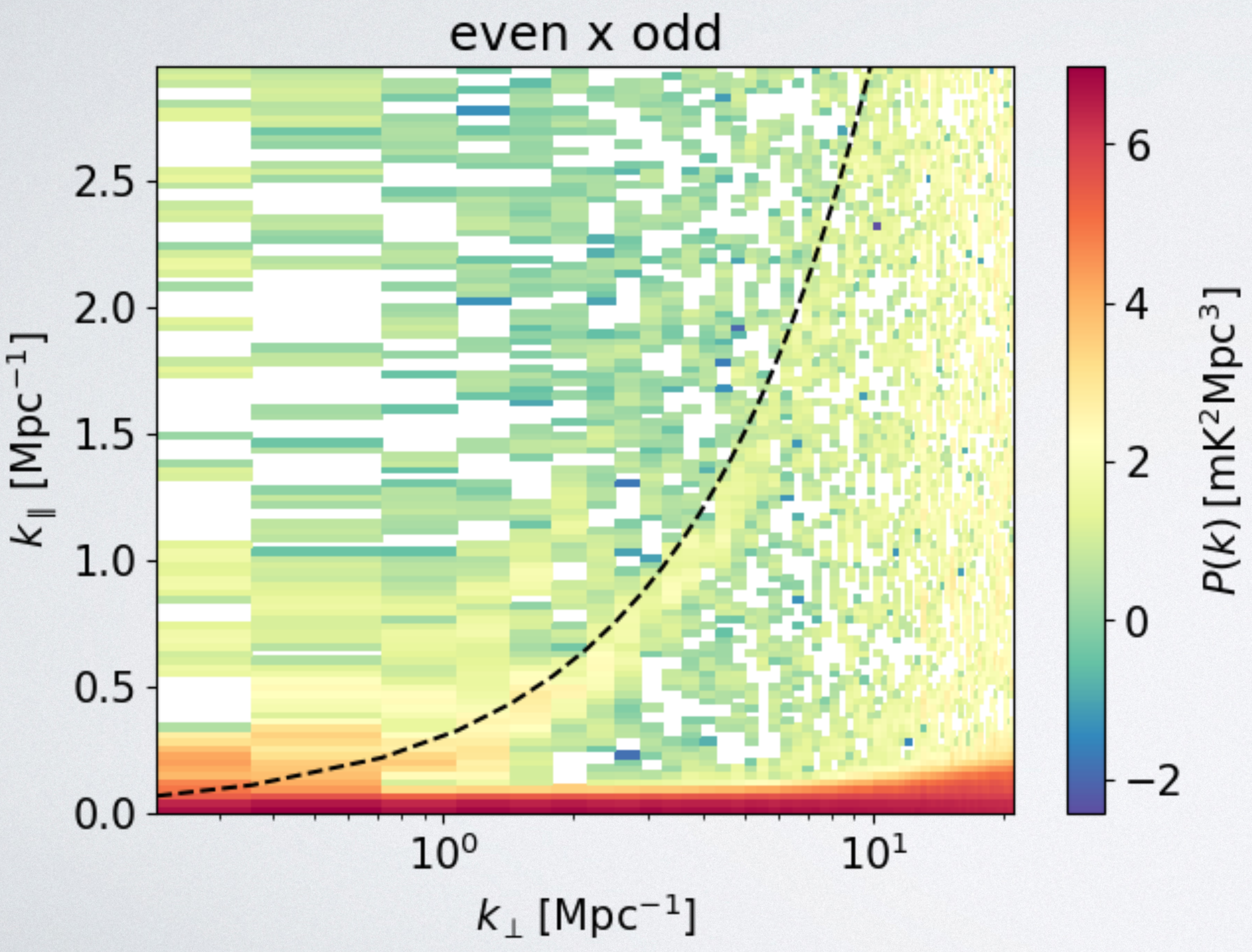
Masking Residual RFI

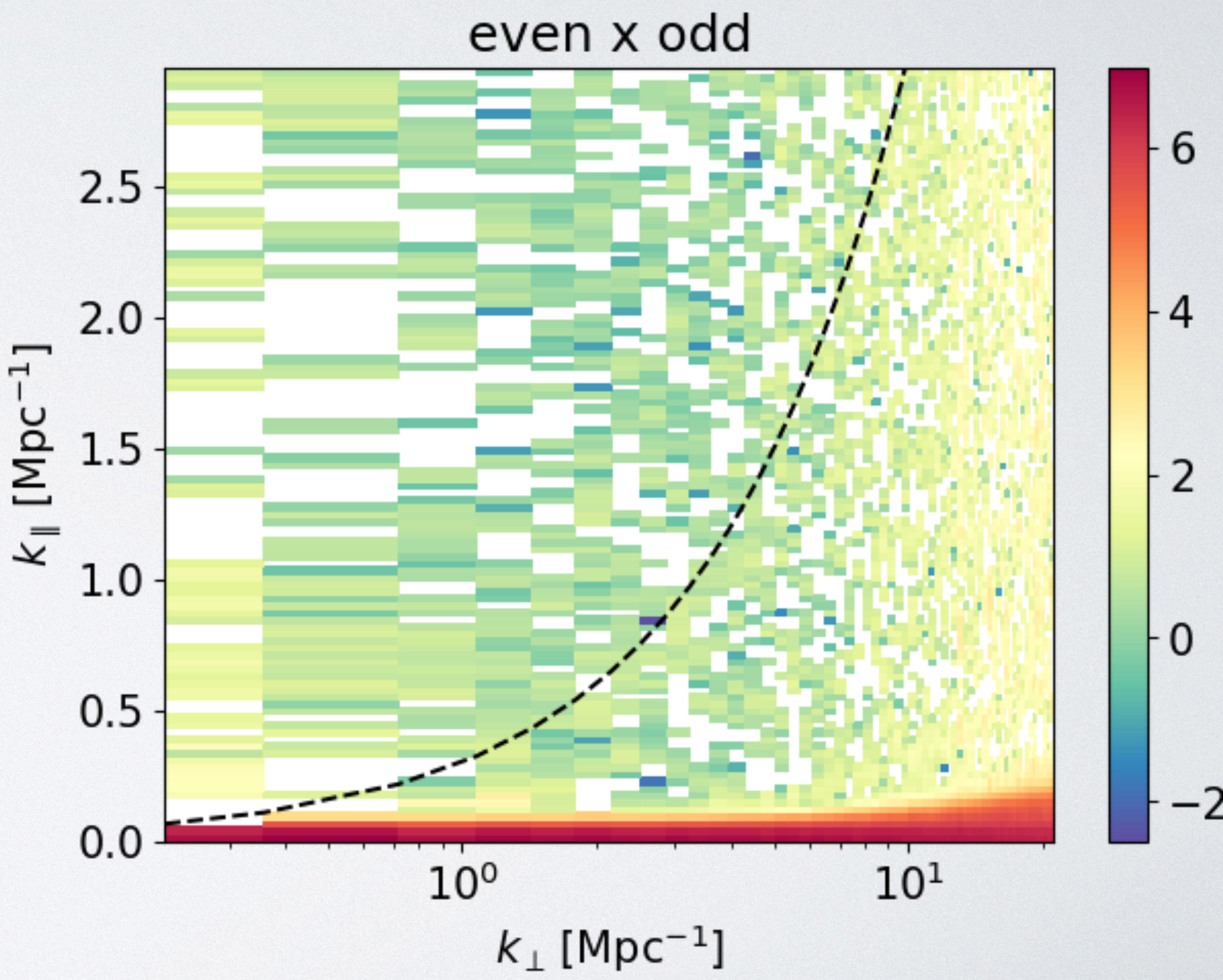
- The simulations are then used to mask the excess power with 5-sigma cuts.



Masking Residual RFI

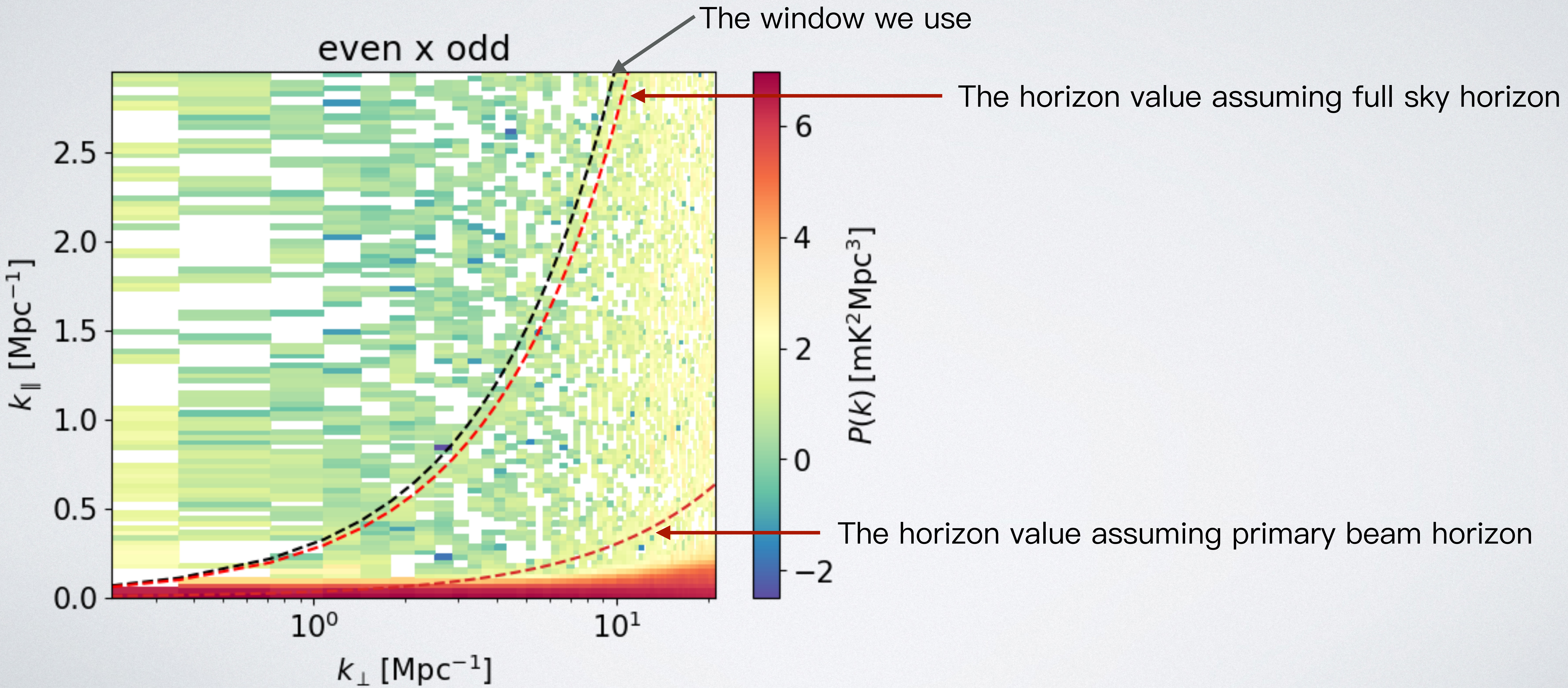
- We are able to mitigate the RFI structure from the masking





Foreground Avoidance

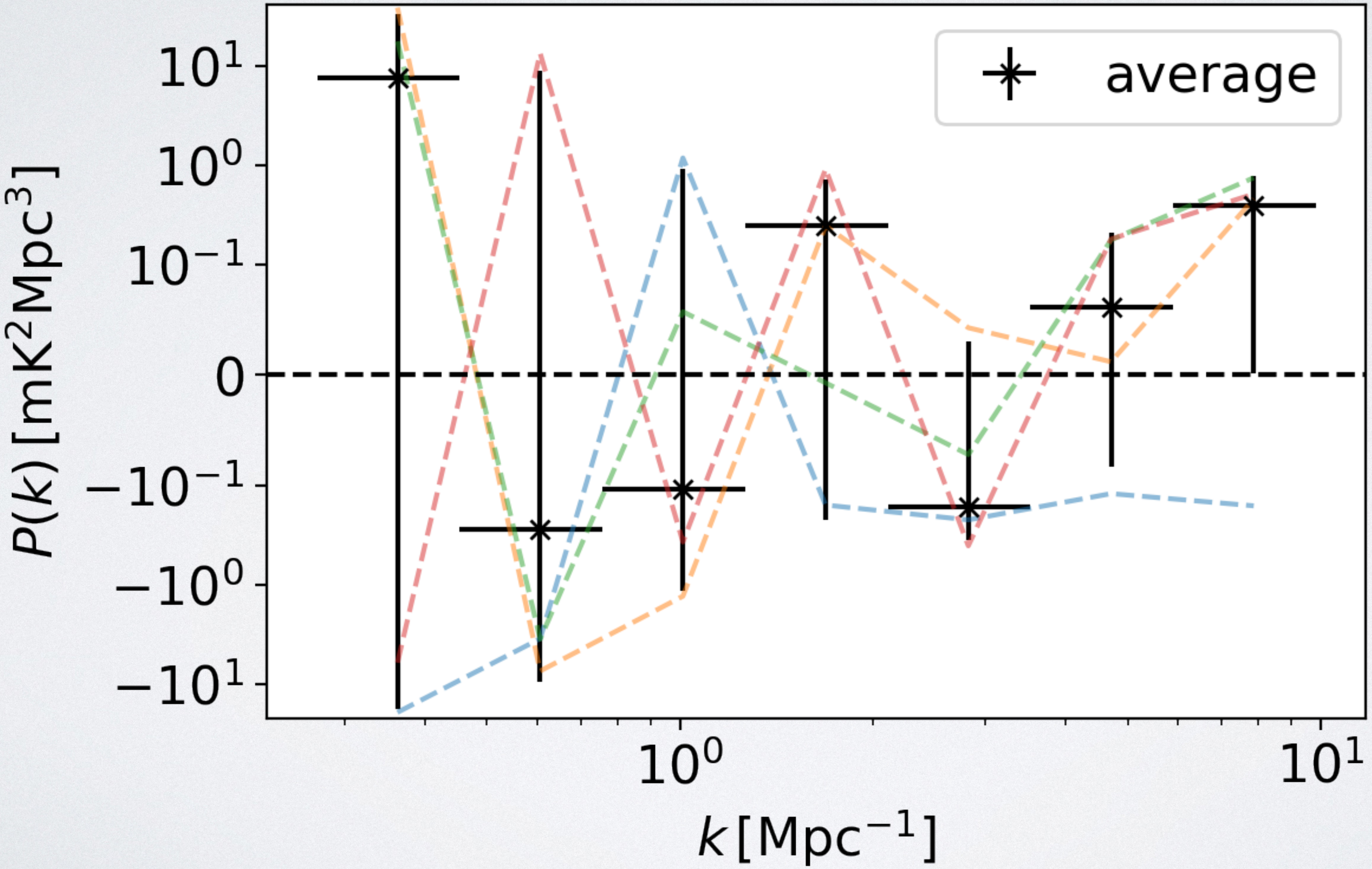
- We choose a window above the horizon value. Liu, Parsons, and Trott 1404.2596



No Sizeable Leakage✓

Null Test

- Cross-correlating visibility data from different sub-bands

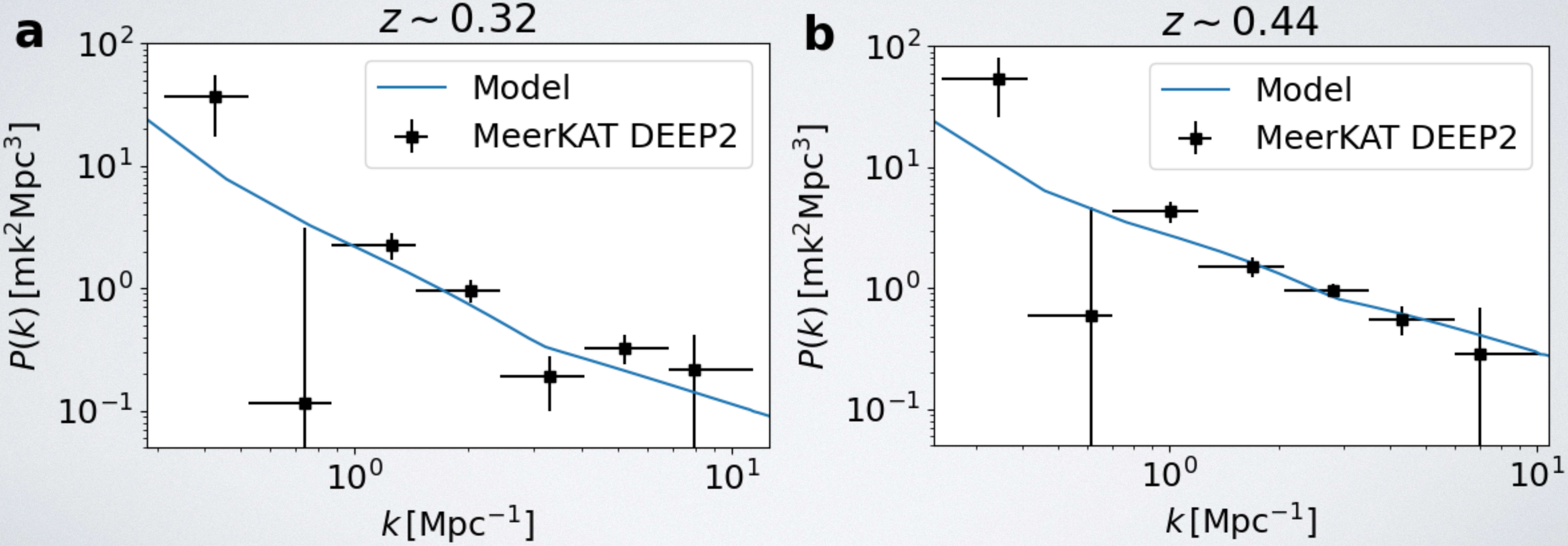


The Measurement

- The 3-D k-points are binned to 1-D k-bins.

The Measurement

- For each sub-band, we have a >10 sigma detection



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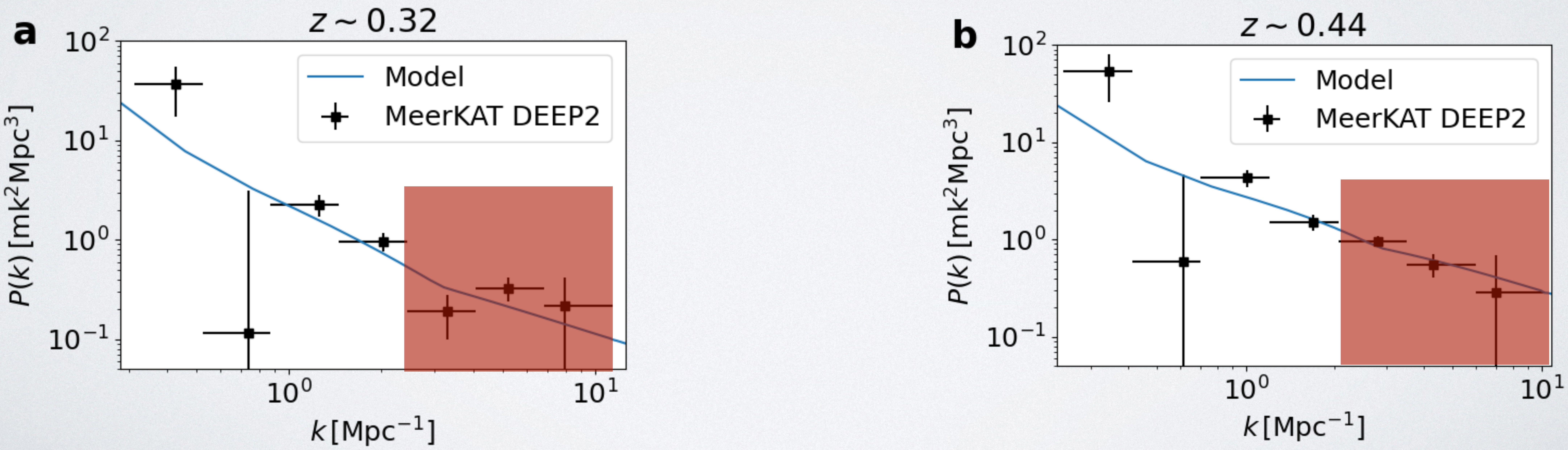
Modelling the Power Spectrum

- The power spectrum measured at these scales are dominated by the velocity dispersion and the shot noise.

$$P_{\rm D}(k_\perp, k_\parallel) = P_{\rm 2h}(k_\perp, k_\parallel) + P_{\rm 1h}(k_\perp, k_\parallel) + \frac{P_{\rm SN}}{1 + (\sigma_p k_\parallel)^2/2}, \quad \sigma_p = \sigma_v (1+z)/(Hf)$$



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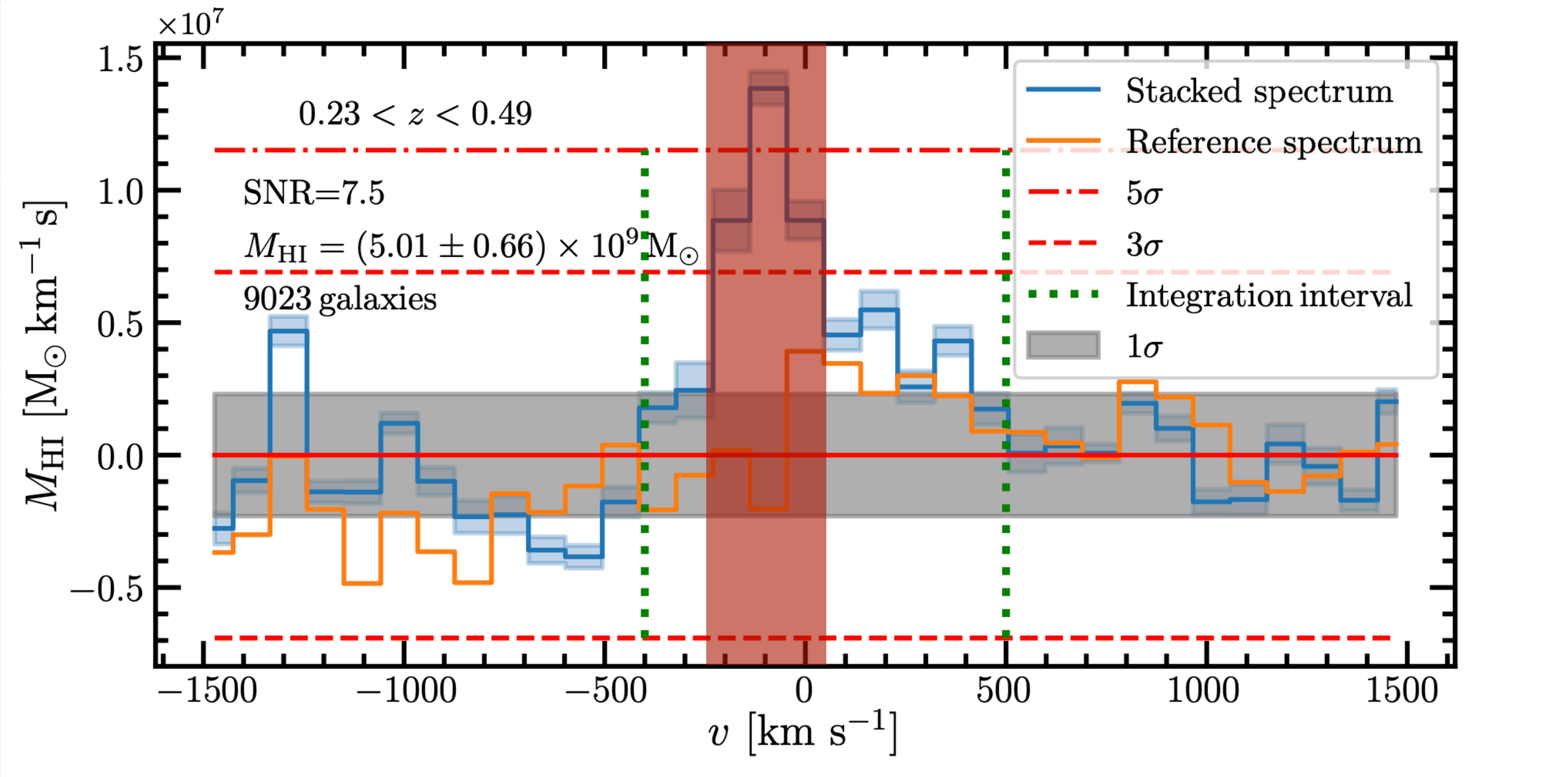


$$\sigma_v \propto W_{50}$$

Sinigaglia et al. 2208.01121

Parameter Fitting

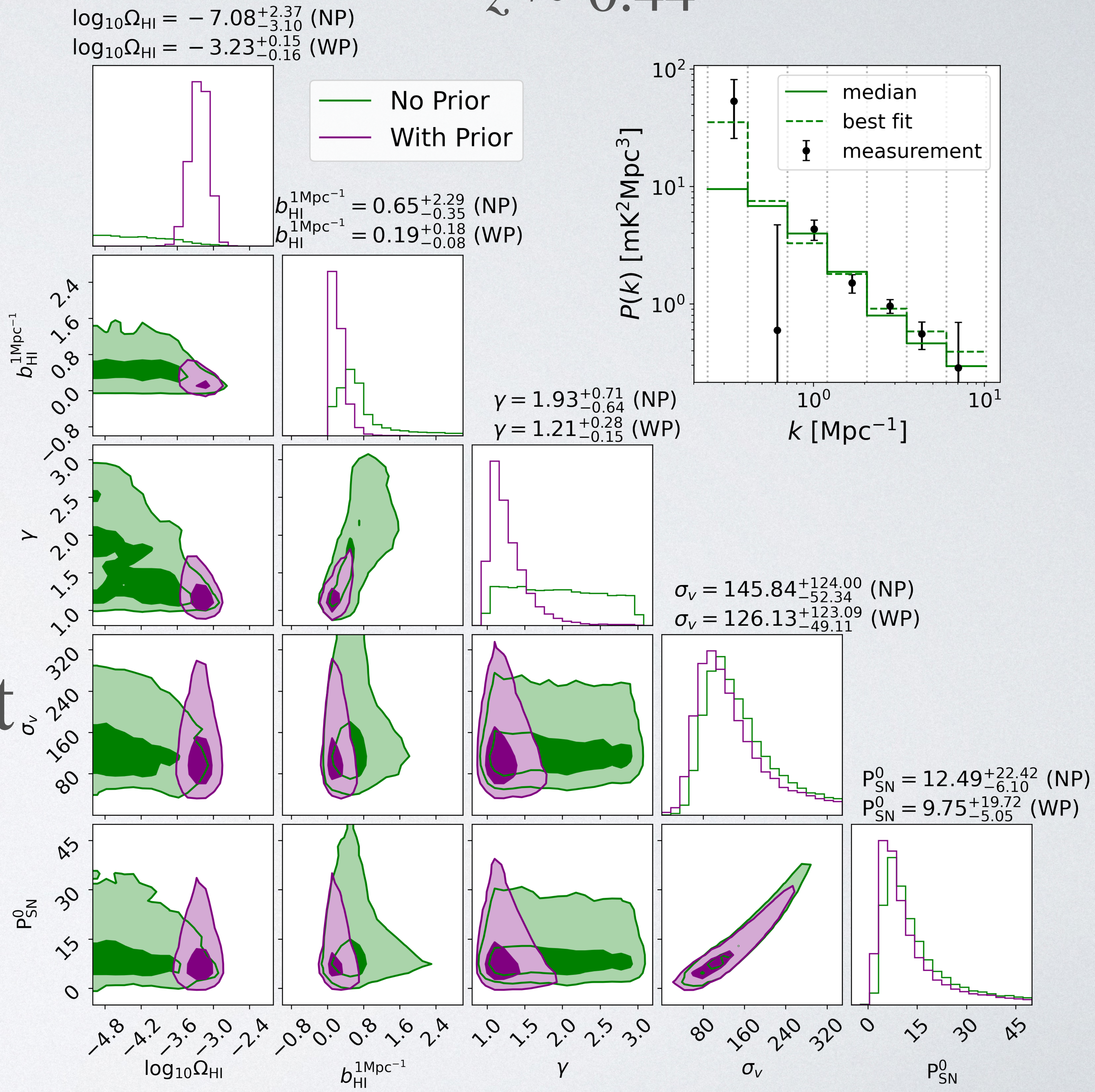
- We put in a basic 3-parameter halo model and perform MCMC fitting.

Z. Chen et al. 2010.07985 Murray, Diemer, **Z. Chen** et al. 2009.14066

- We don't have constraining power of the overall amplitude.

- Degeneracy between velocity and shot noise due to 1-D binning.

$z \sim 0.44$



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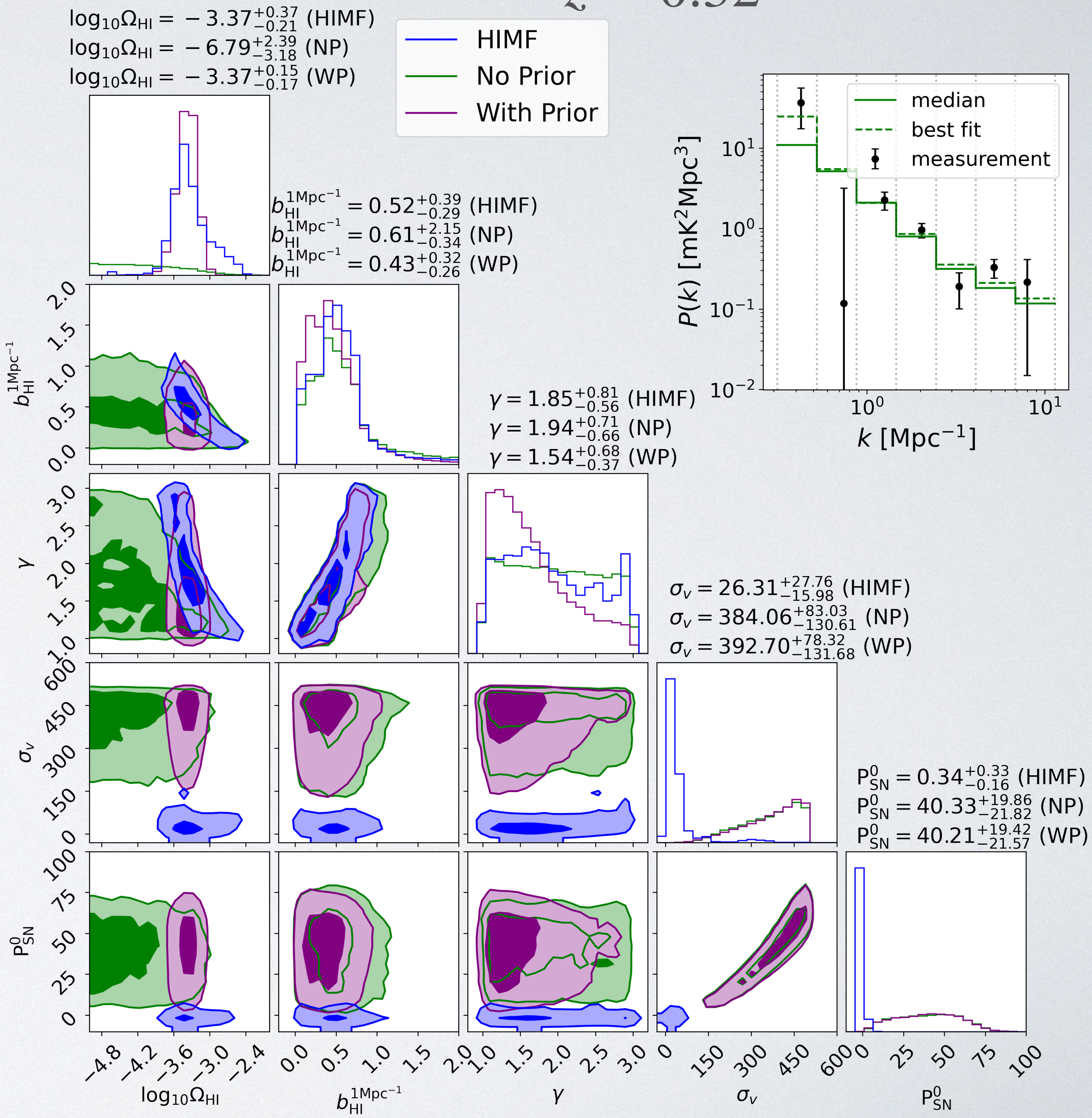
Utilising the HIMF

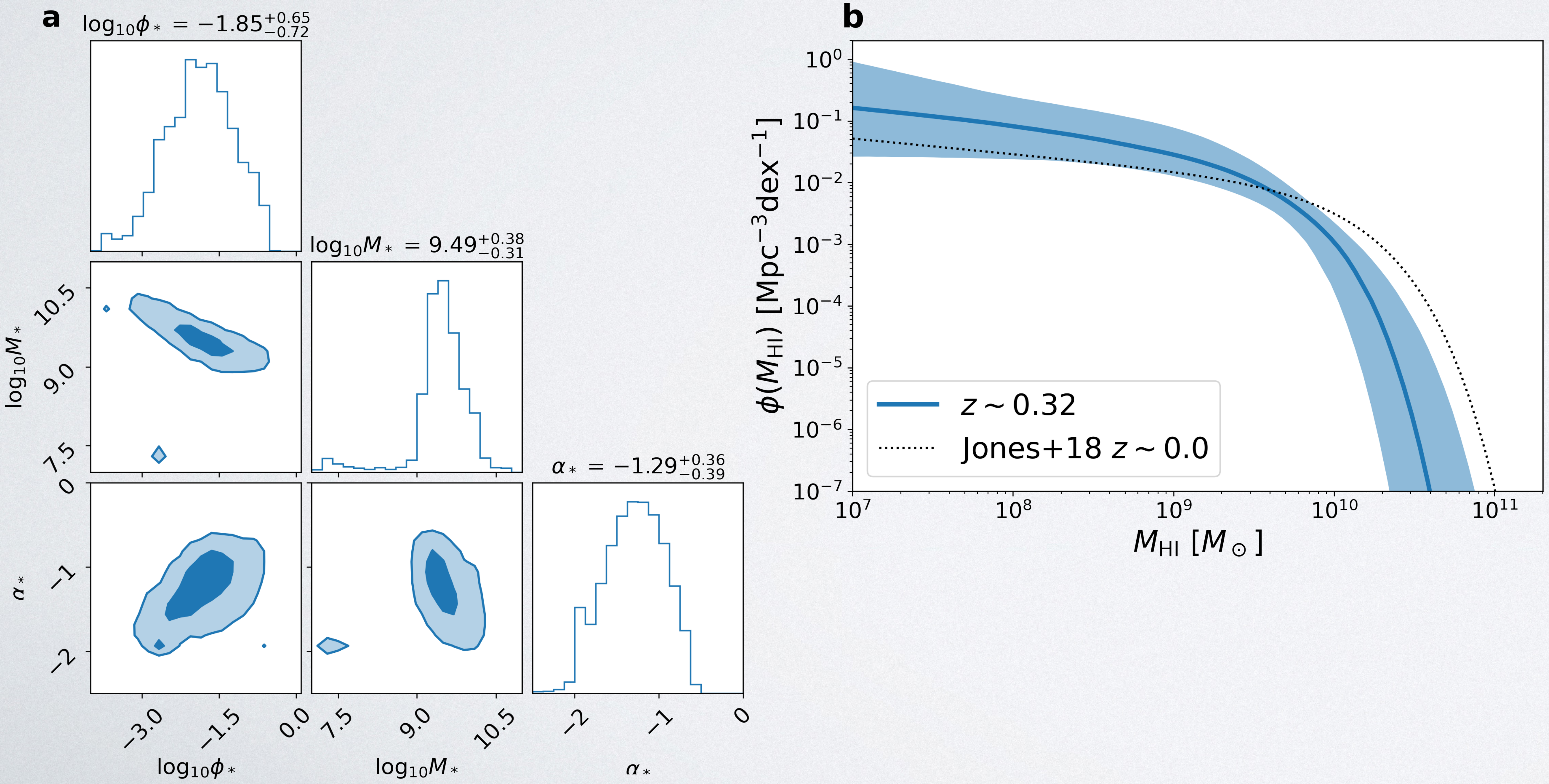
$z \sim 0.32$

- Using HIMF to calculate the shot noise and check with HI density from halo model.
- Need additional input from stacking. Ree et al. 1709.07596
- A proof-of-concept for the z=0.32 bin

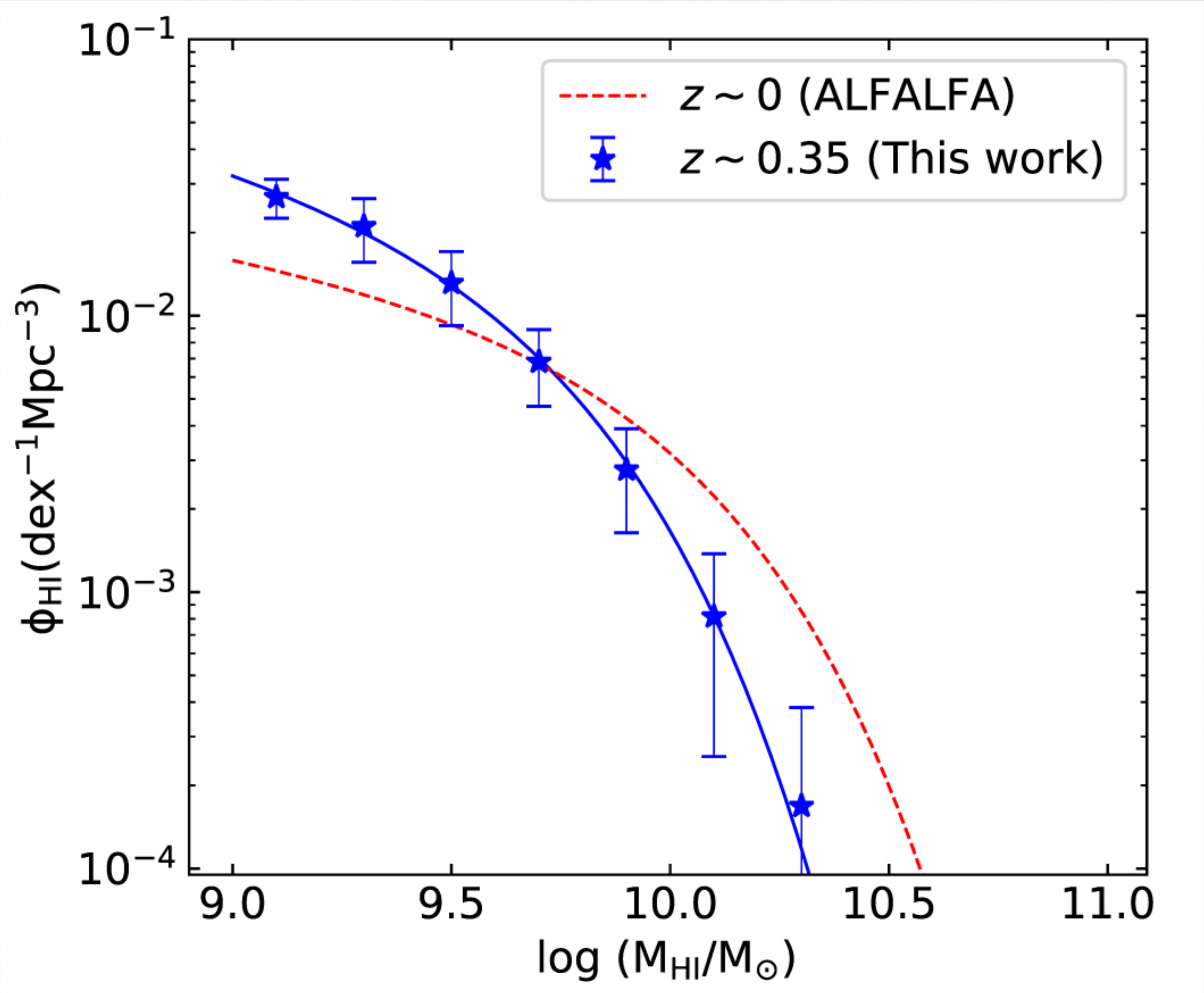


Constraining the HIMF

- Using HIMF to calculate the shot noise and check with HI density from halo model. Consistent with GMRT results as well as MIGHTEE-HI.



Bera et al. 2210.17018



Conclusion

- We report the **first-ever** detection of the HI auto-power spectrum using intensity mapping.

- The detection is possible due to sufficient RFI mitigation, precise calibration and large signal-to-noise ratio.

- Milestone in 21cm cosmology!

- The inner-halo scales inform us about the density profile, the velocity widths of the HI galaxies, and the HIMF.