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Foreground Leakage from Calibration Errors in Interferometric MeerKAT 21cm Observations

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Porto, Jan. 16th

Detection of HI power spectrum using MeerKAT DEEP2 data

Paul, Santos, **Z Chen** & Wolz, 2301.11943

- A first detection using 96h of DEEP2 data from early MeerKAT observations.

  Mauch et al., 1912.06212

- Calibrated using the standard processmeerkat pipeline
- Coherent averaging and power spectrum estimation pipeline
- Cross-correlation of two independent datasets
- Systematics flagging and validation

Detection of HI power spectrum using MeerKAT DEEP2 data

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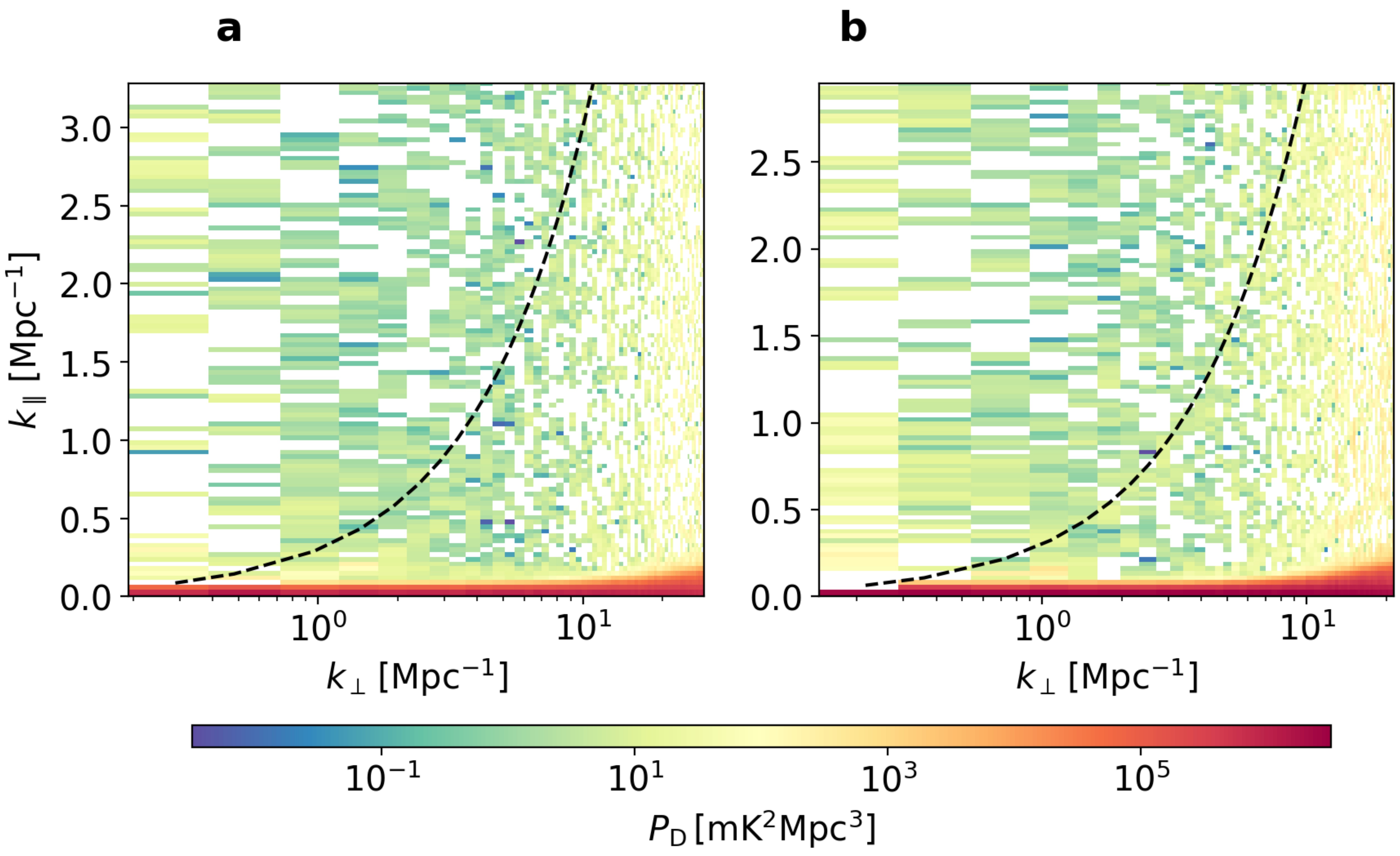
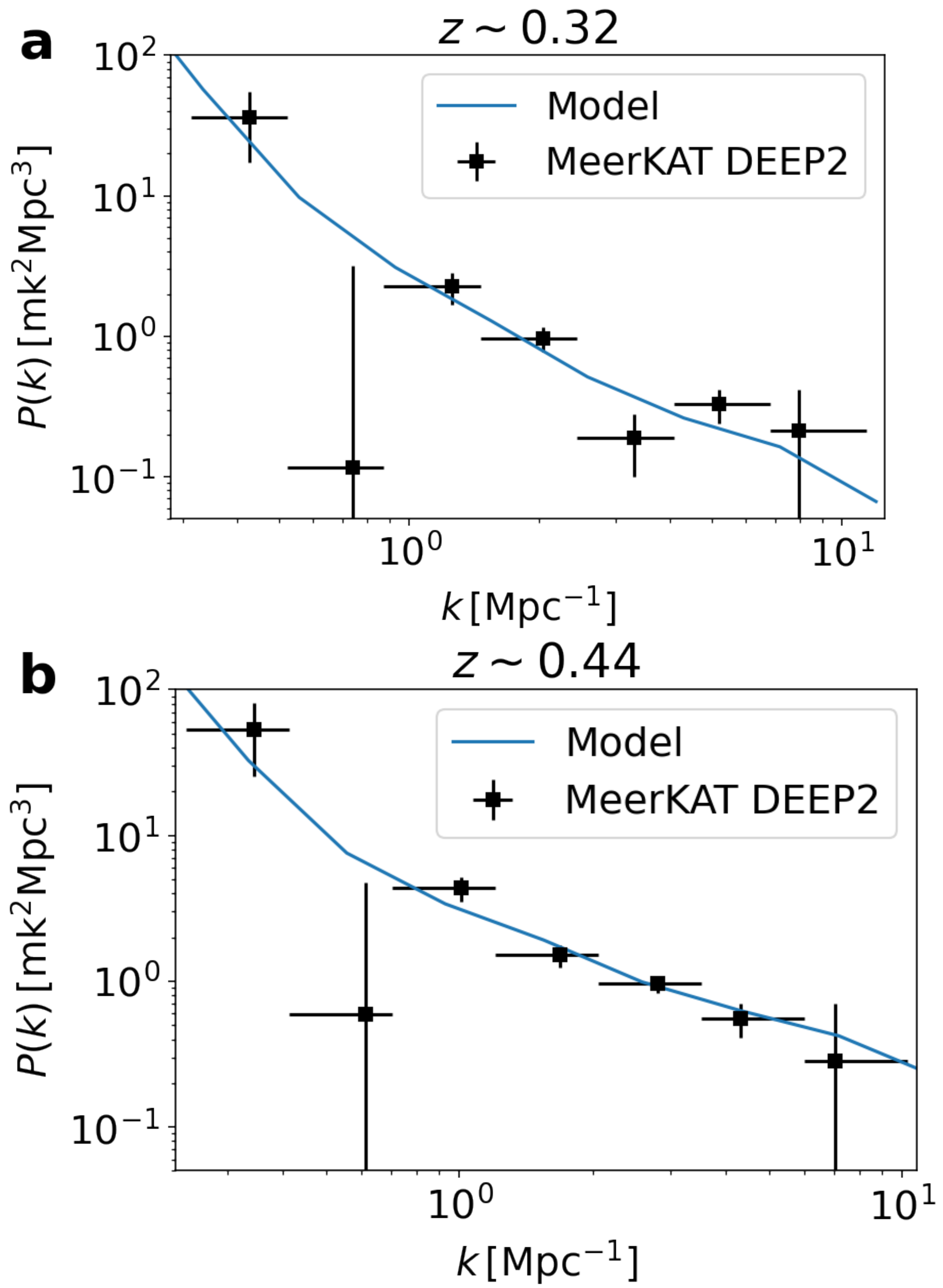
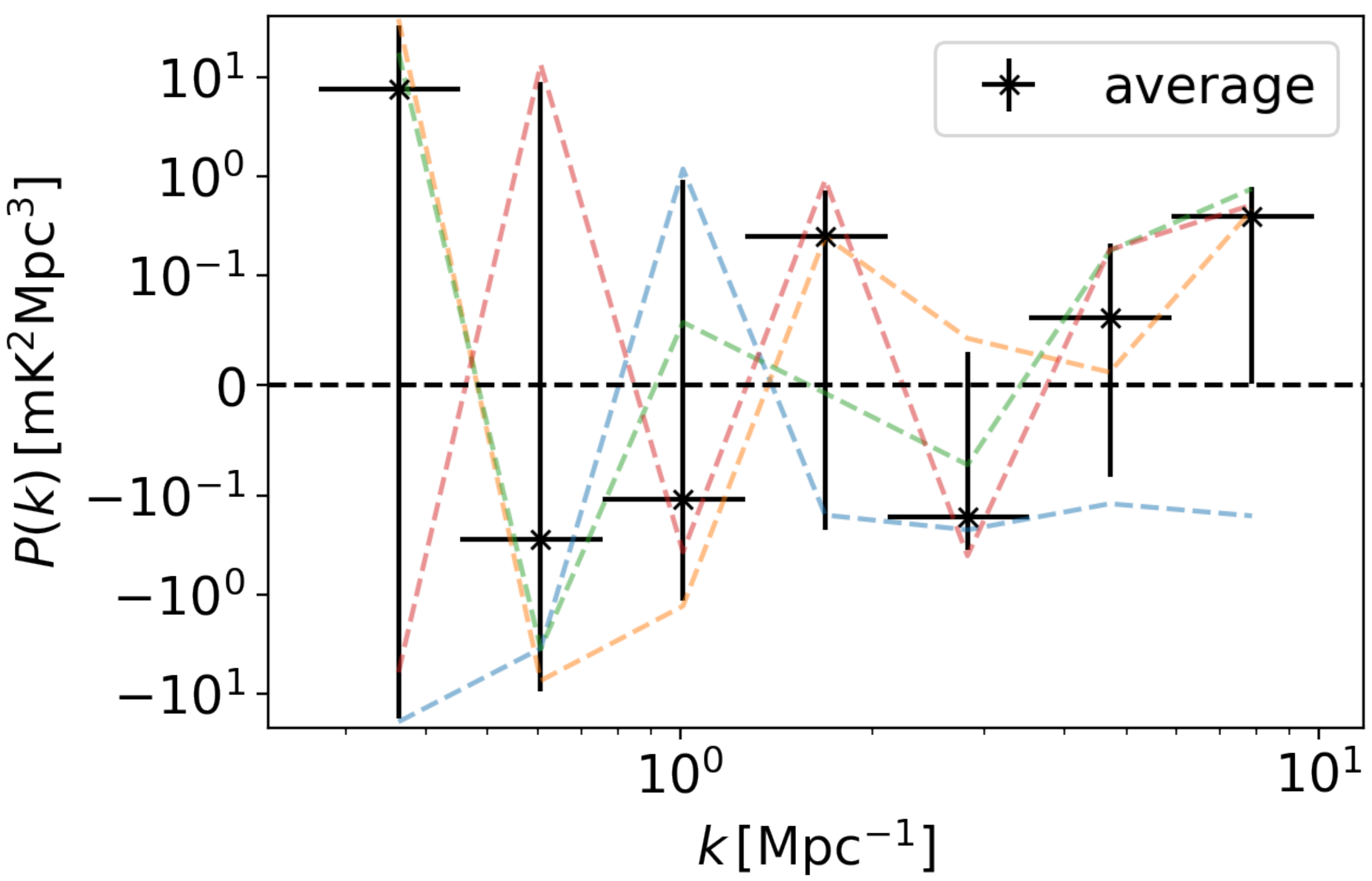


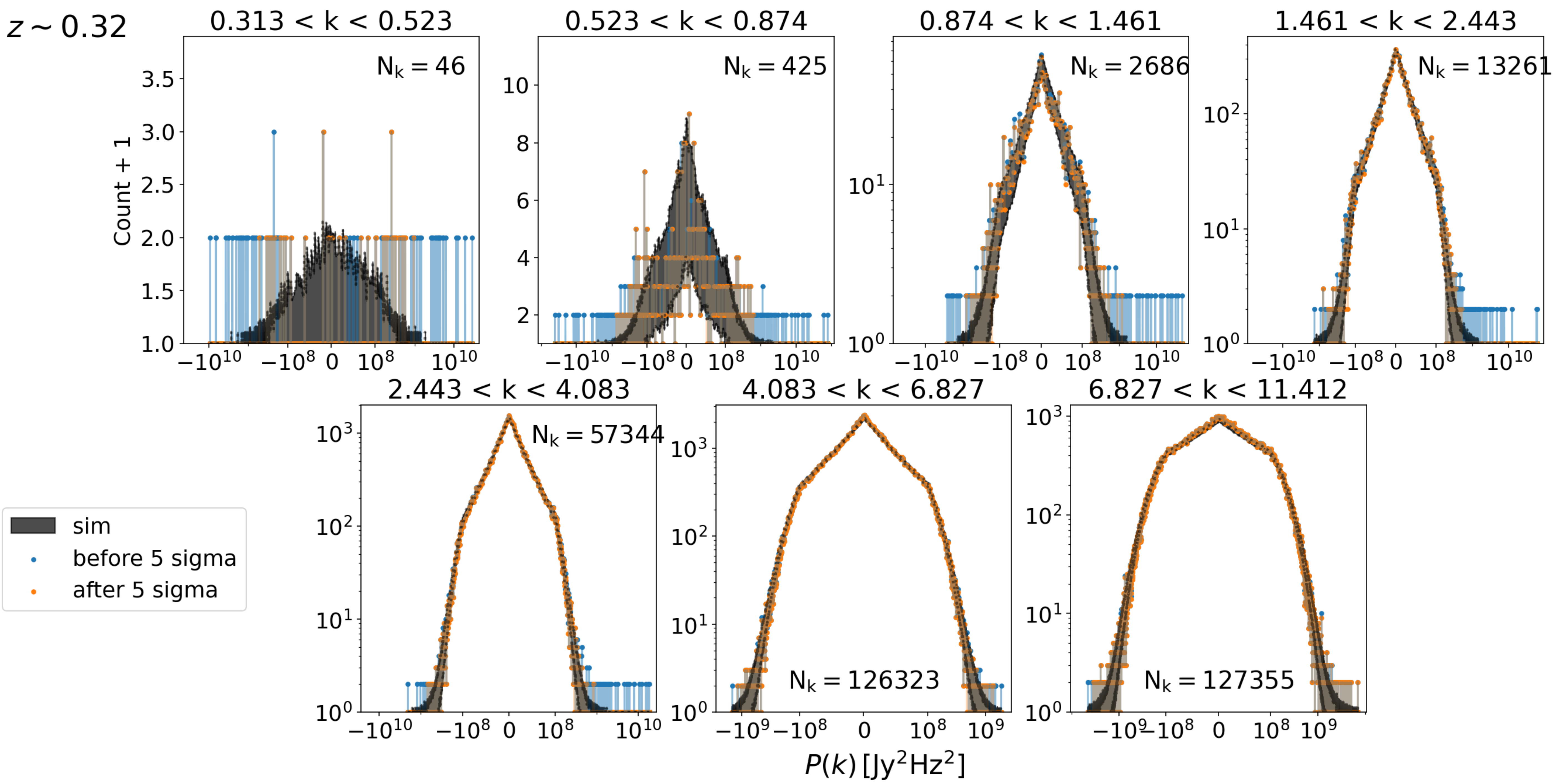


Validation Tests

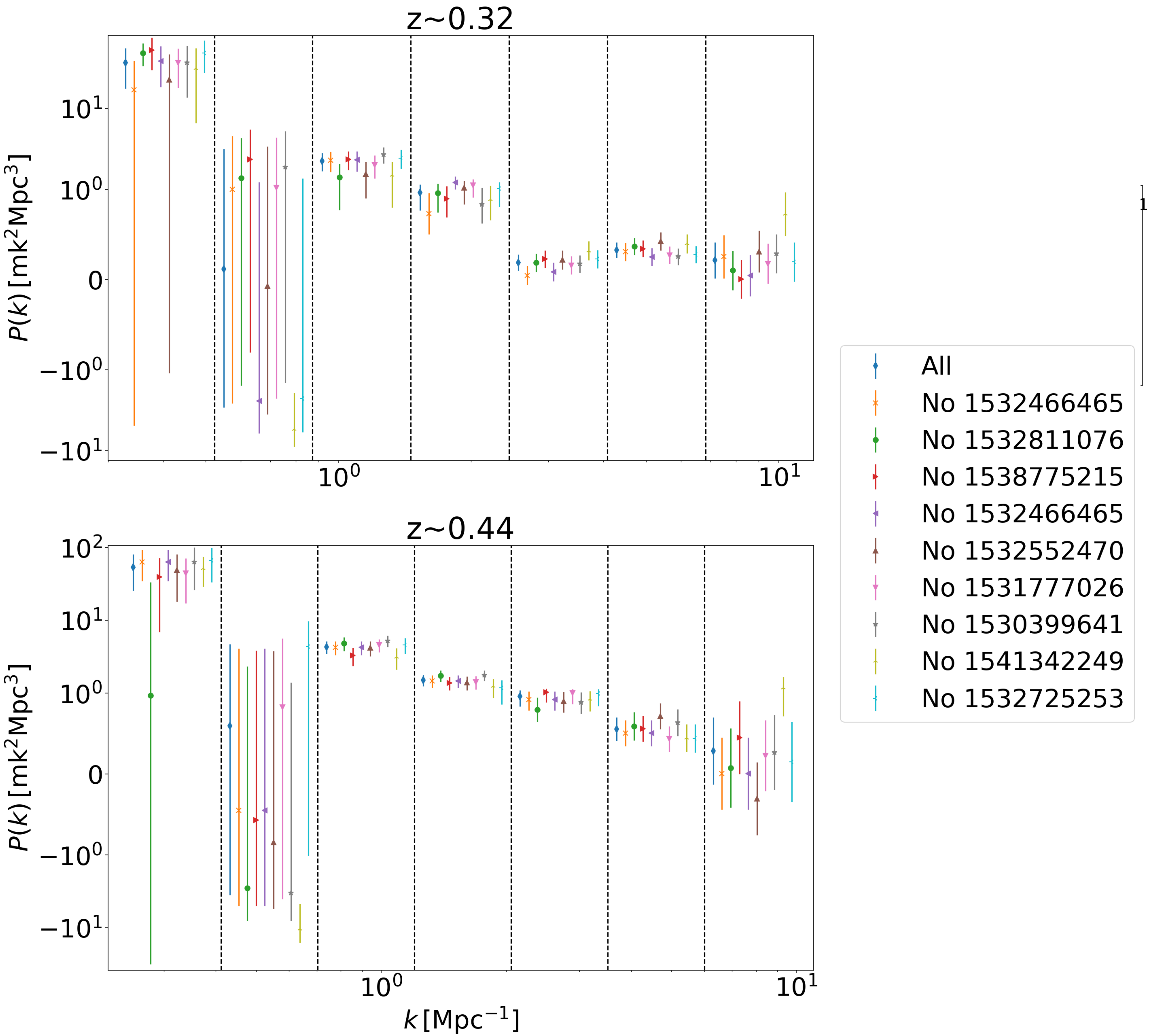
Null Test



Simulation Validation



Jackknife test



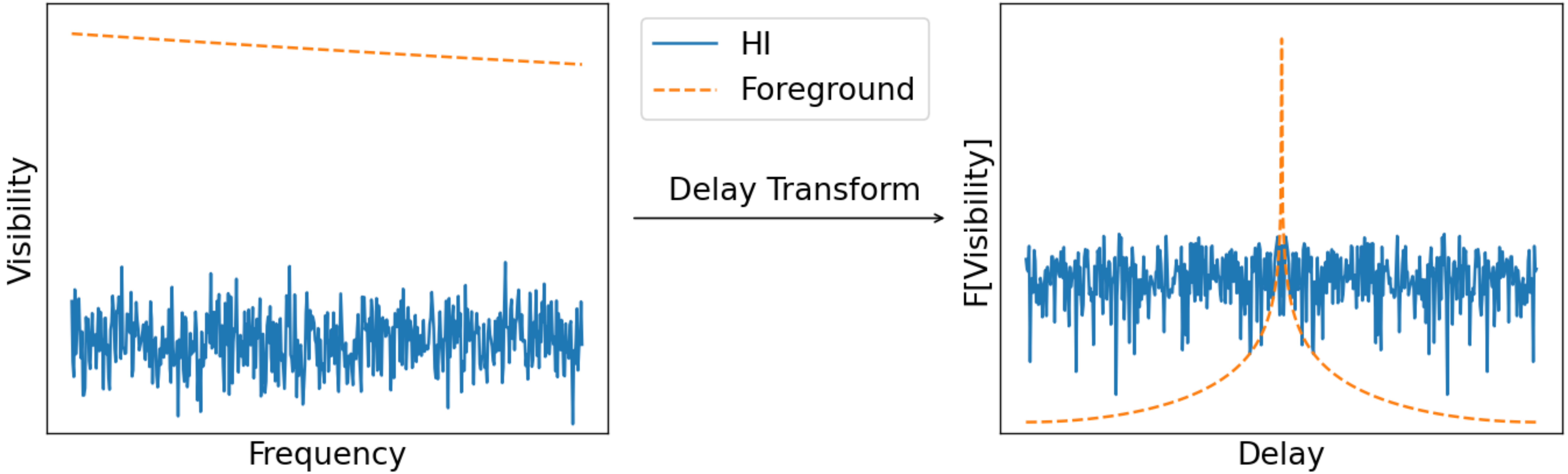
One validation in particular… calibration errors!

What makes 21cm observations work…

- Foregrounds are much brighter than the 21cm line signal from cosmic neutral hydrogen (HI). So why can we measure it?
- We **rely on** the spectral smoothness of the foregrounds.

Conventional method in interferometer:

Foreground avoidance



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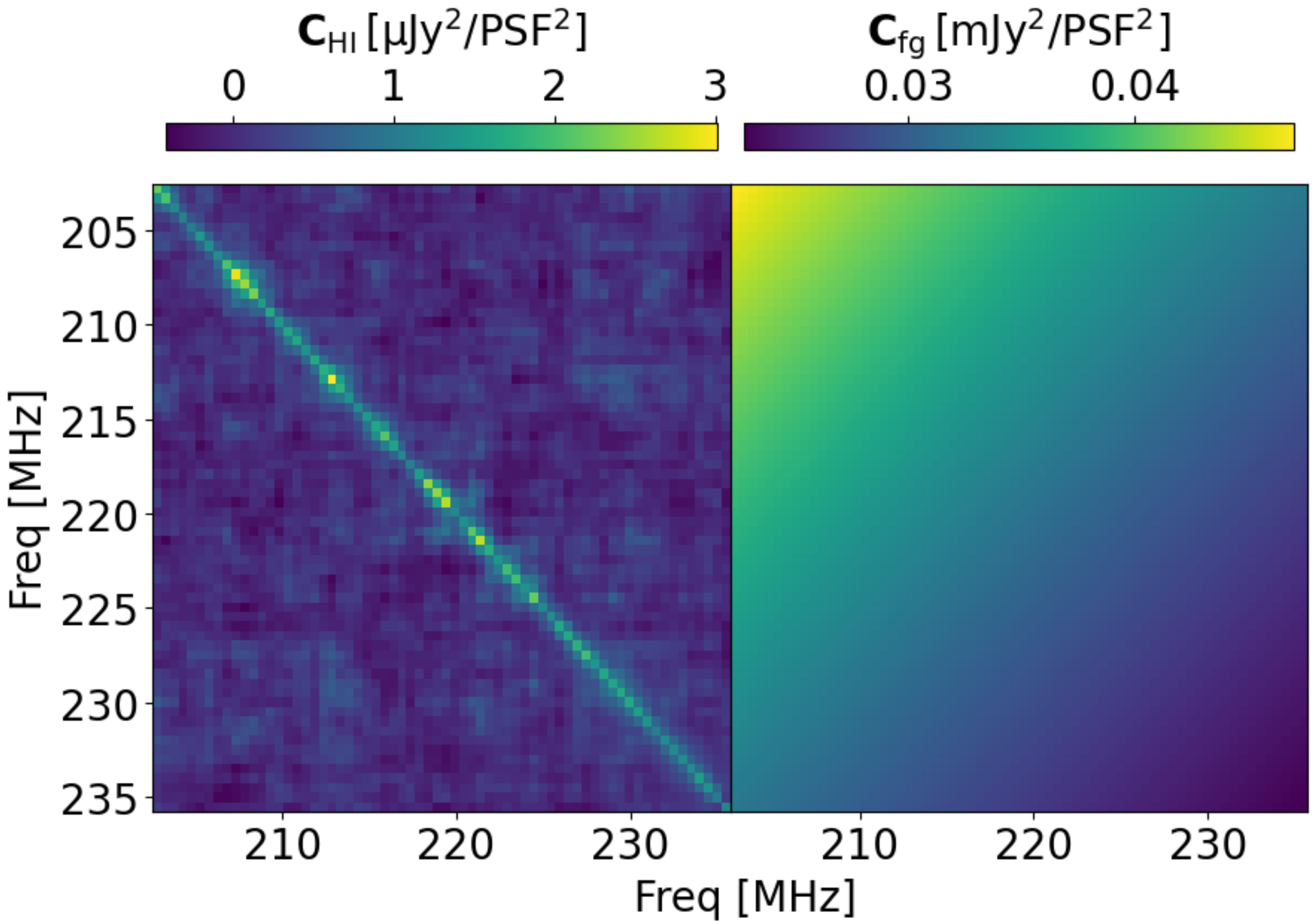
Z Chen et al., 2302.11504

Conventional method in single dish:
Component separation

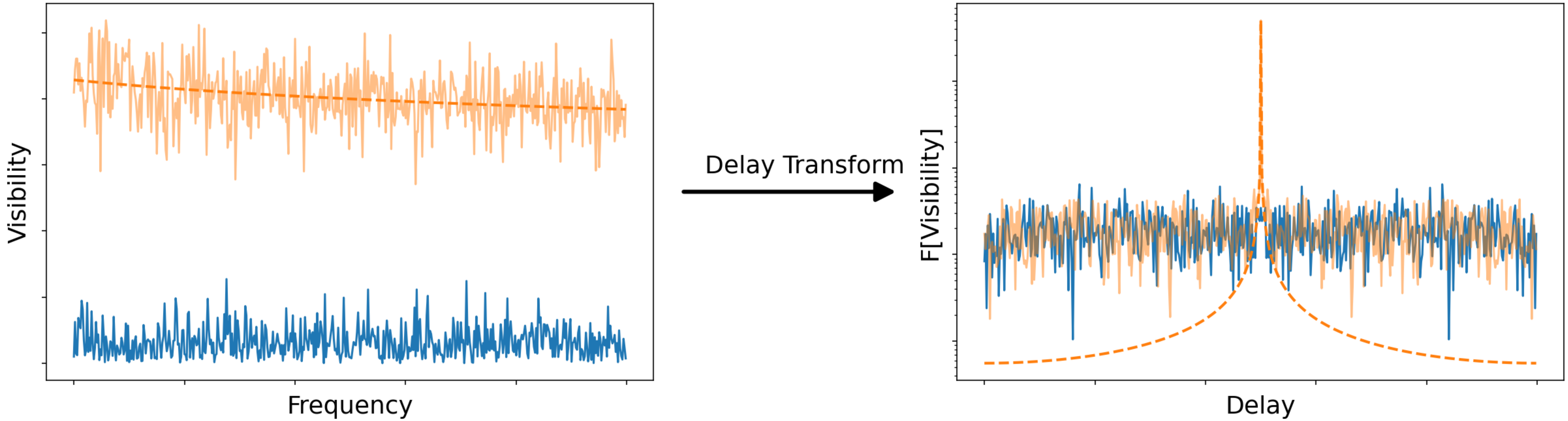
PCA, GPR …



...also breaks it completely

- We **rely on** the spectral smoothness of the foregrounds.
- But real observations have systematics that break the smoothness of the foregrounds.

Frequency-dependant calibration errors



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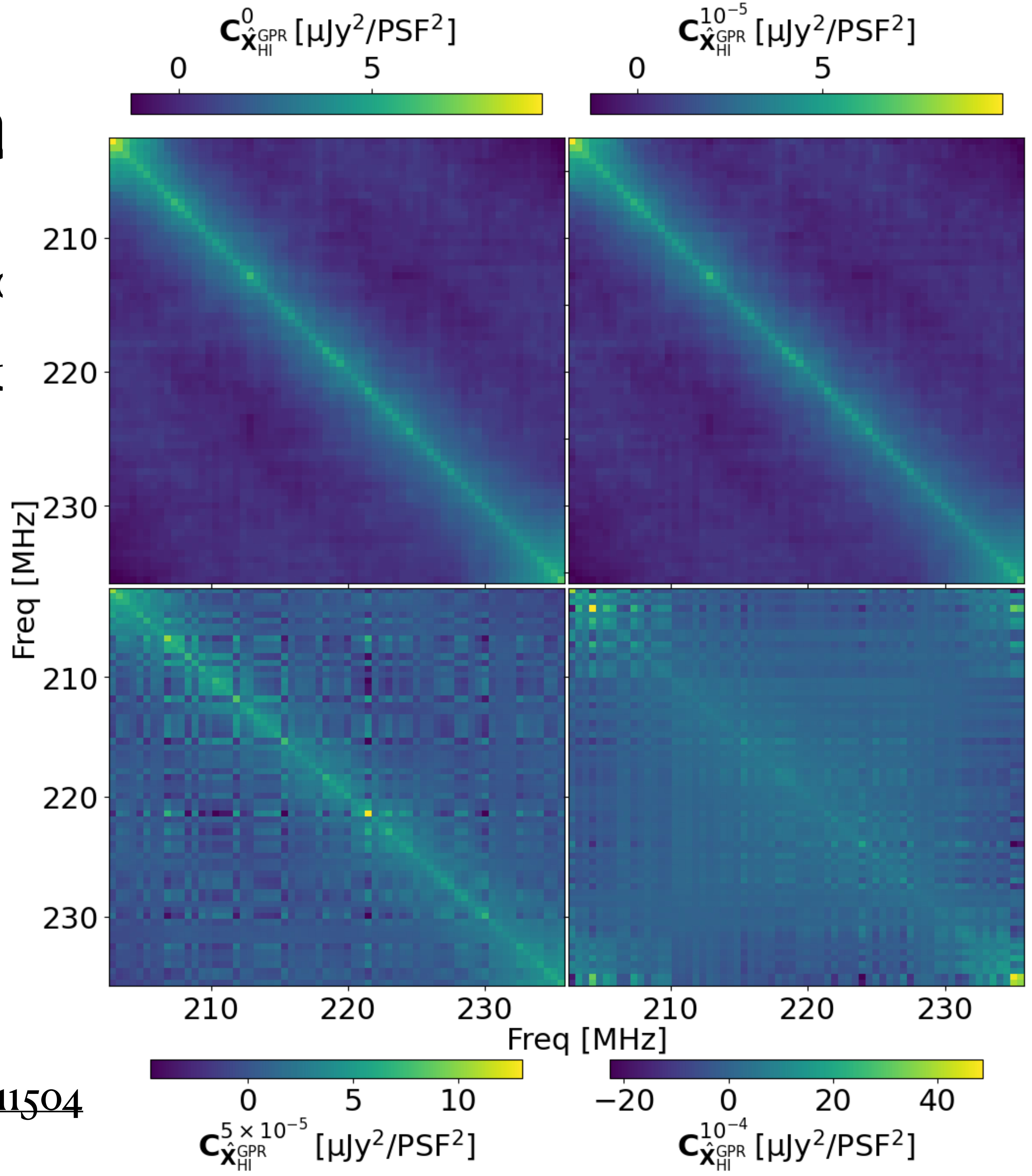

Z Chen et al., 2302.11504

What breaks 21cm observations

- Frequency-dependant calibration errors need to be <10^-4. Barry et al., 1603.00607

- Chromatic sampling rate along the frequency direction also leaks foregrounds.
Wilensky et al., 2110.08167

- Various instrumental effects create contamination that is unsmooth in frequency, such as cable reflection and cross-coupling.
Kern et al., 2110.08167

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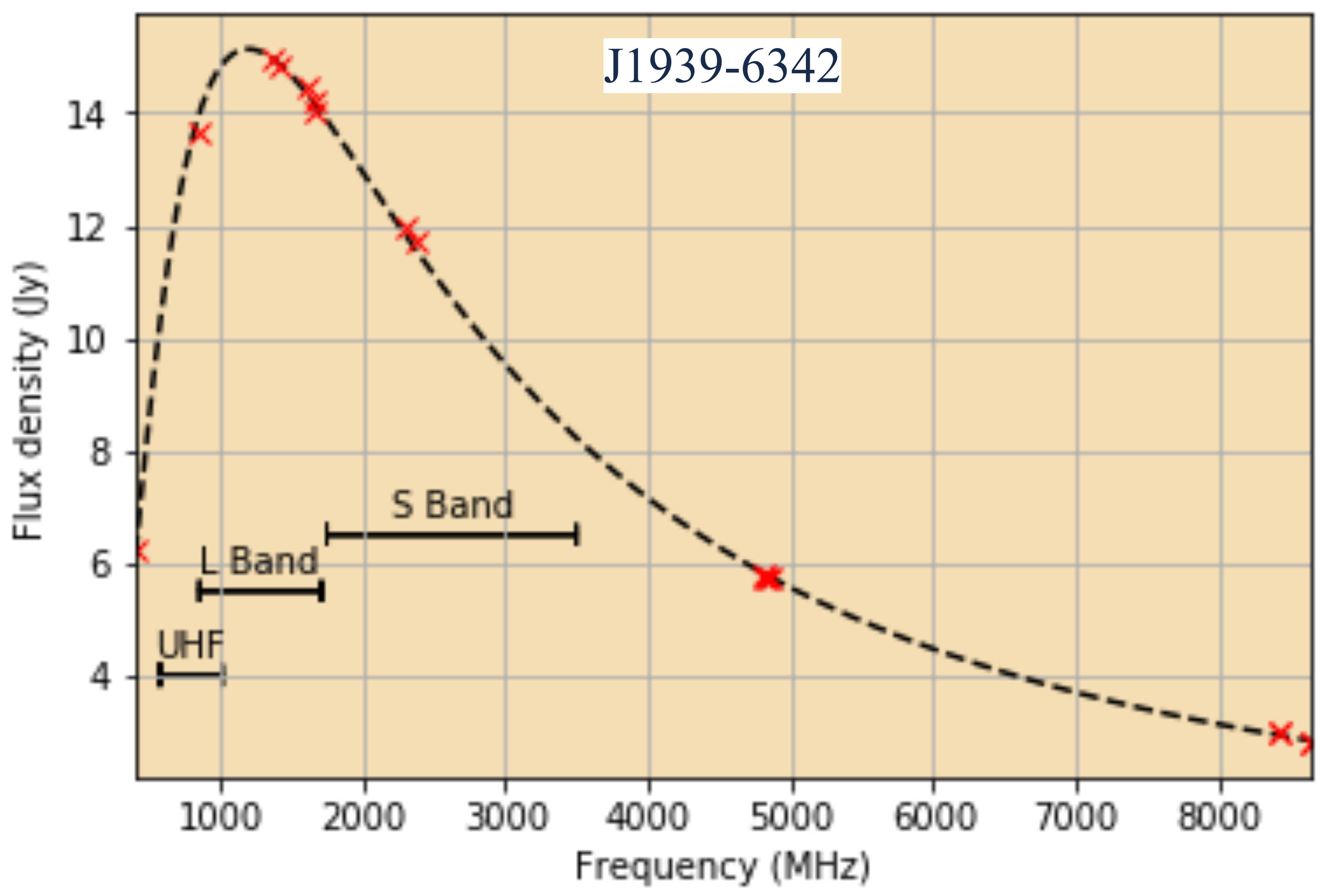
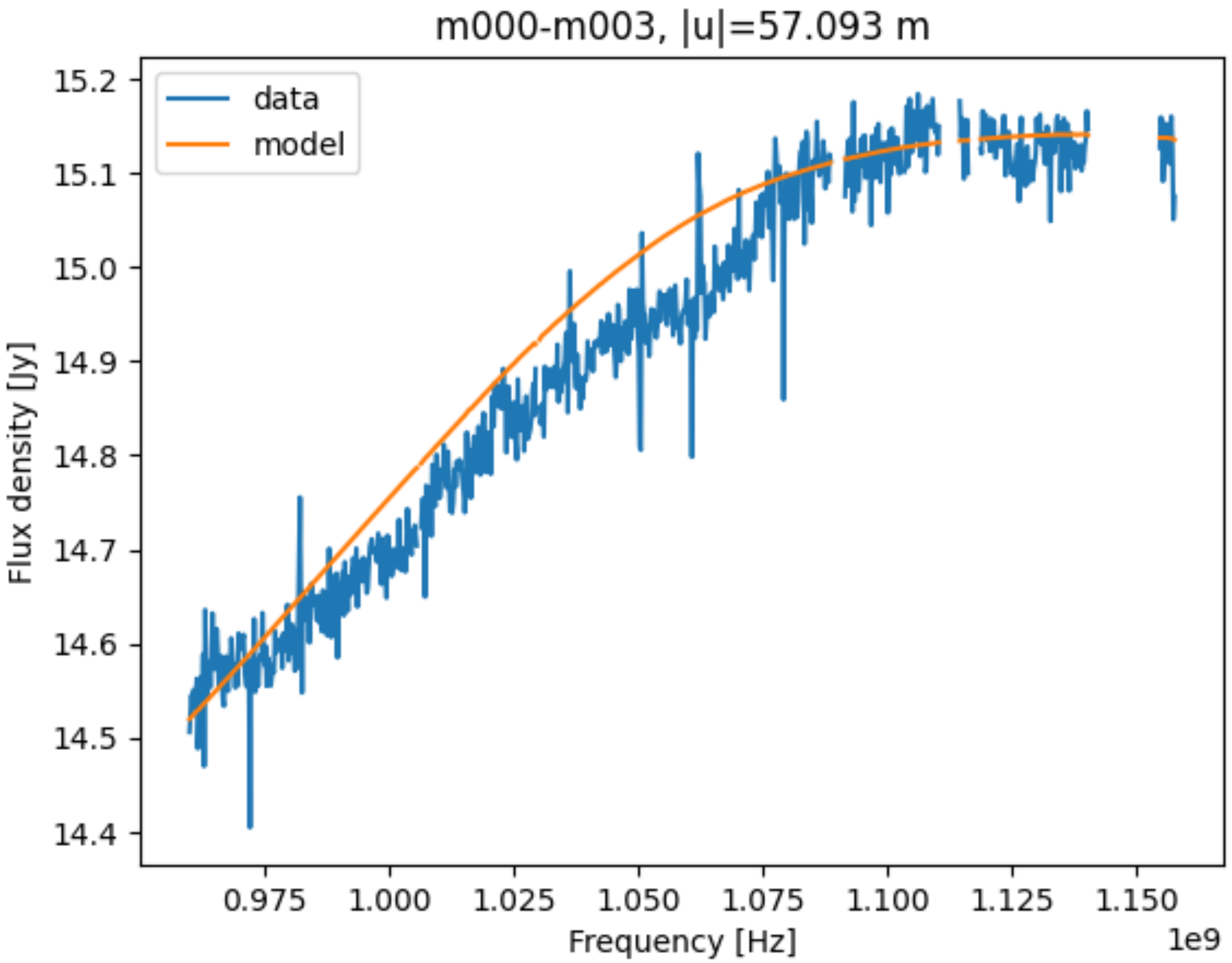
A crude view of calibration

- We want to know: how the receivers respond to the incoming signal $V_{ab} = g_a g_b V_{ab}^{sky}$
- Solution: point the telescope to a known source (for bandpass calibration)

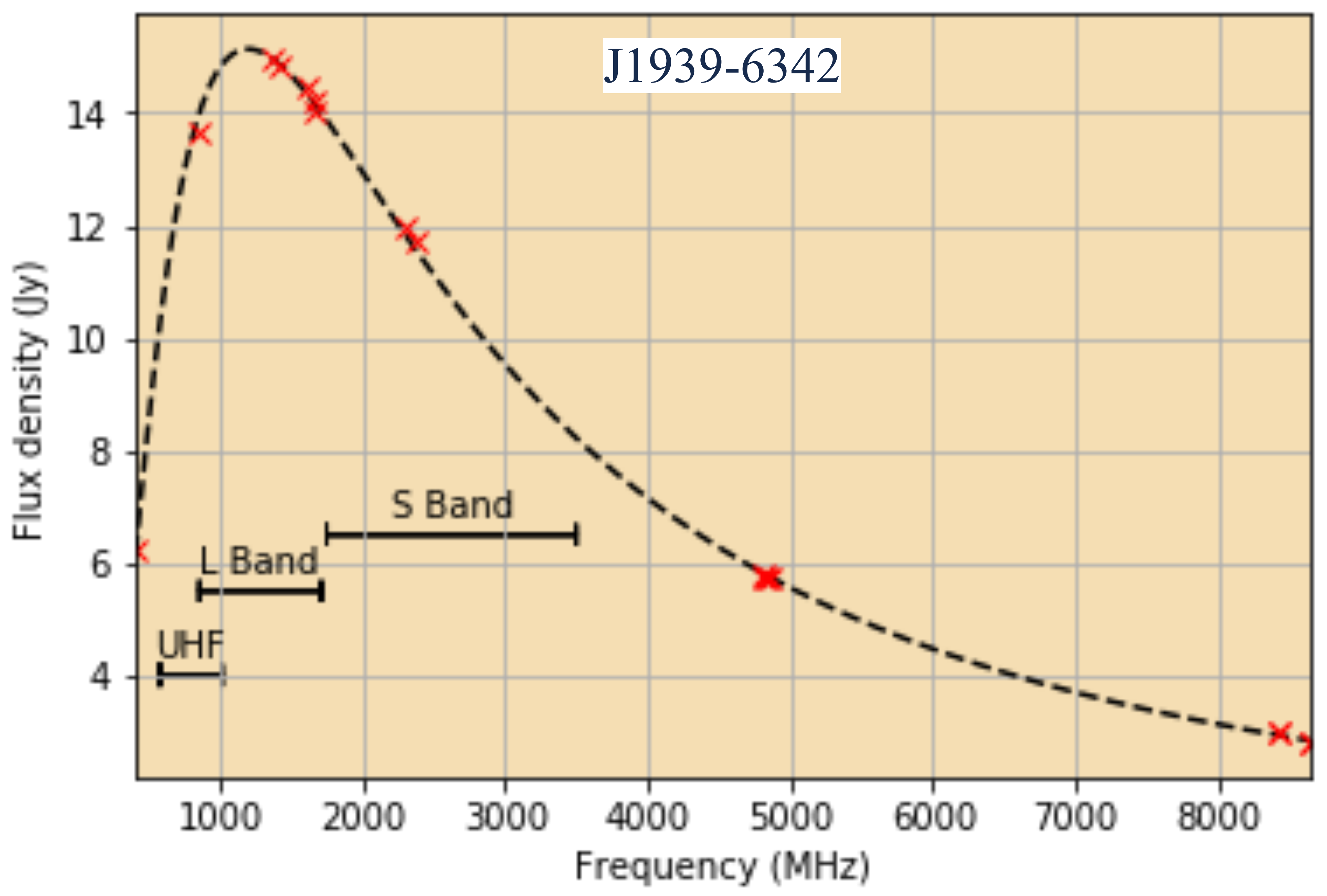


Reynolds 1994, Partidge et al., 1506.02892



A crude view of calibration

- Due to the extreme requirement on calibration precision e<10^-4, having **the correct model** is very important.



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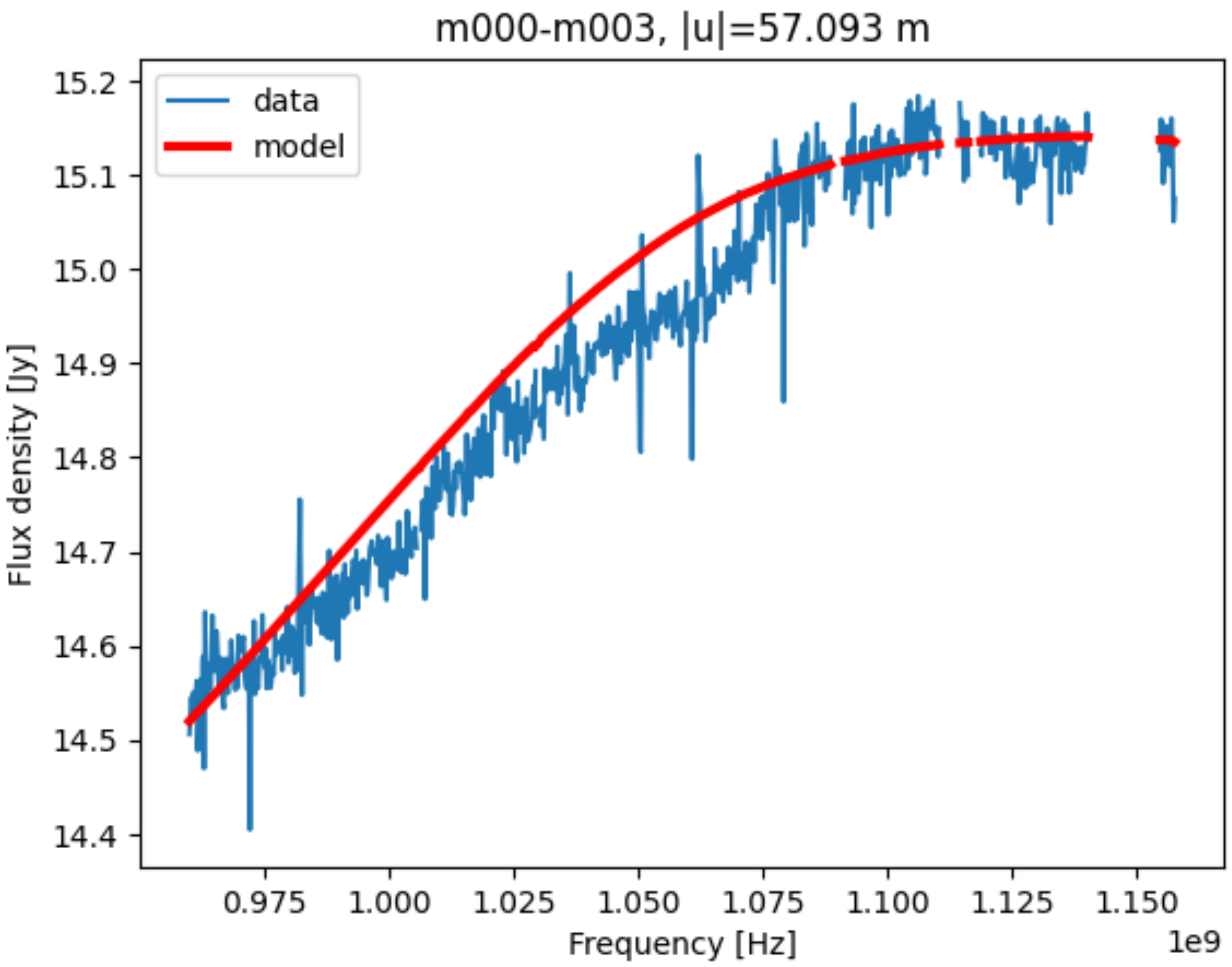
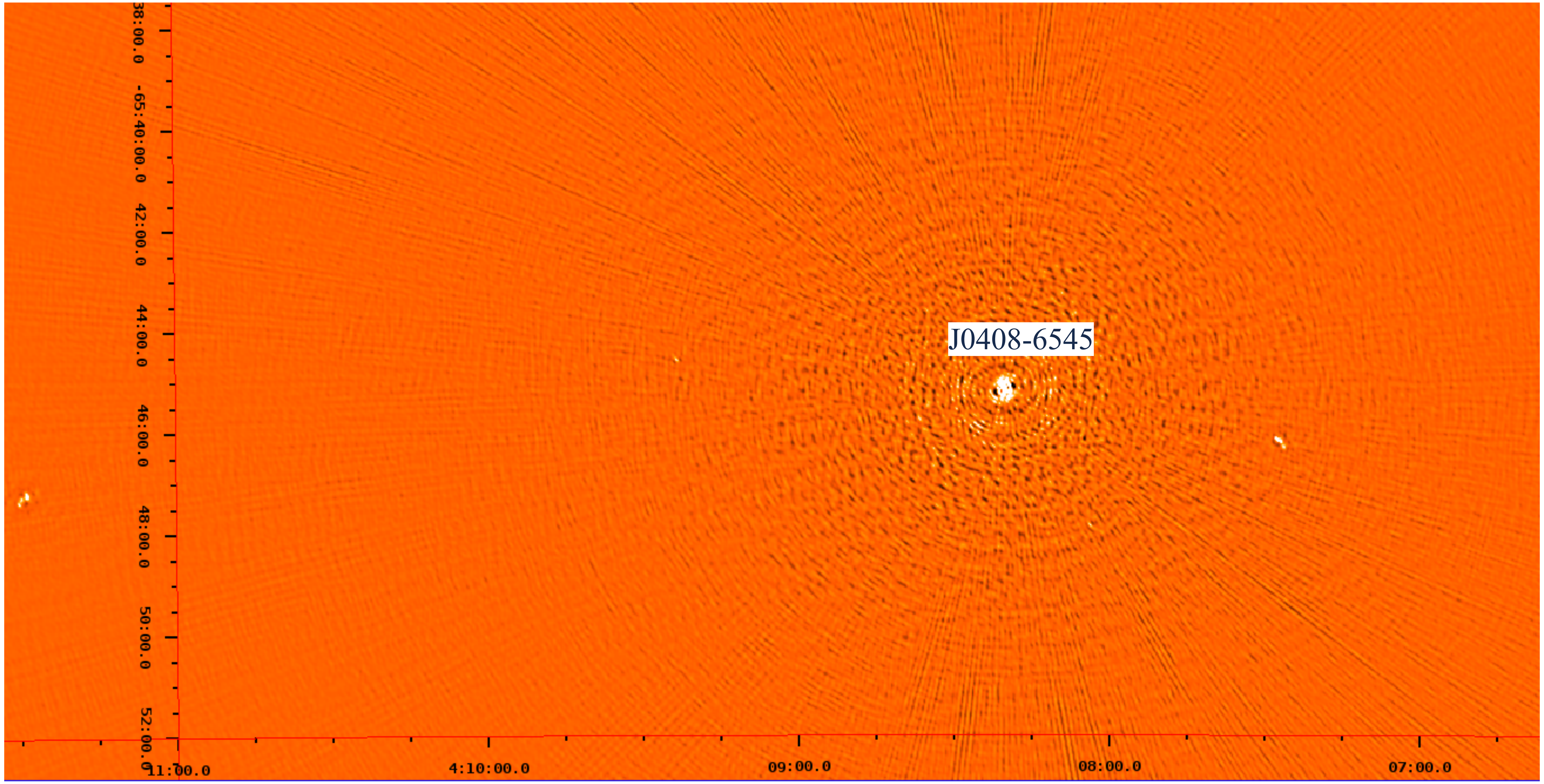


Importance of field sources

- When you point at a calibrator source, many other sources in your field-of-view also contributes. Traditionally this is ignored.

Credit: MeerKAT wiki



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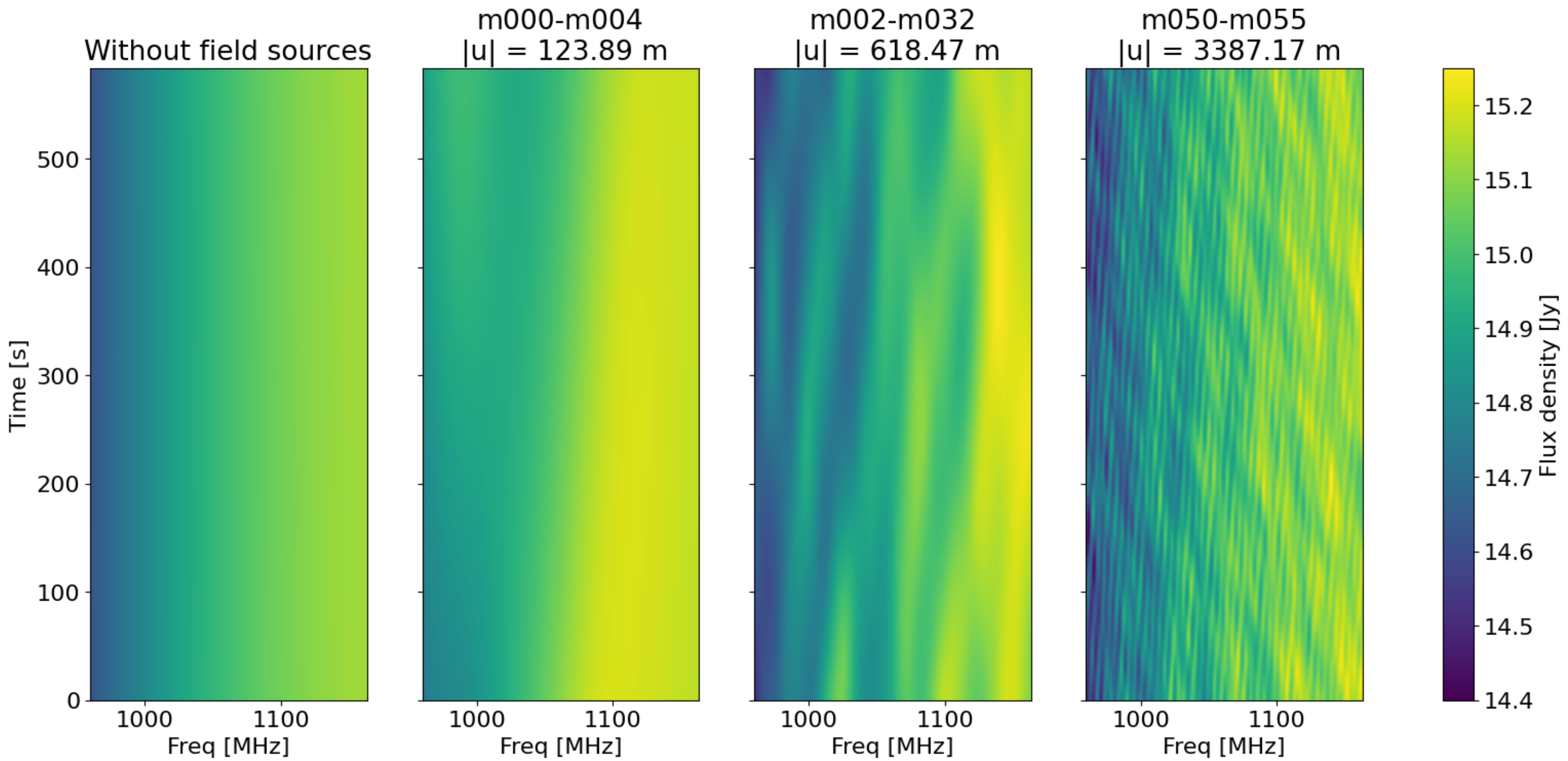
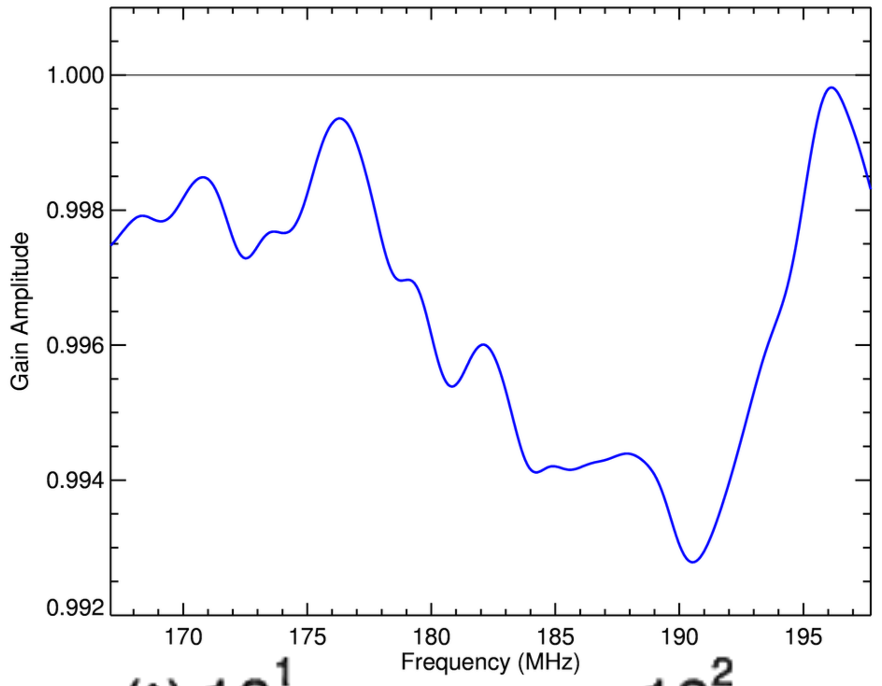


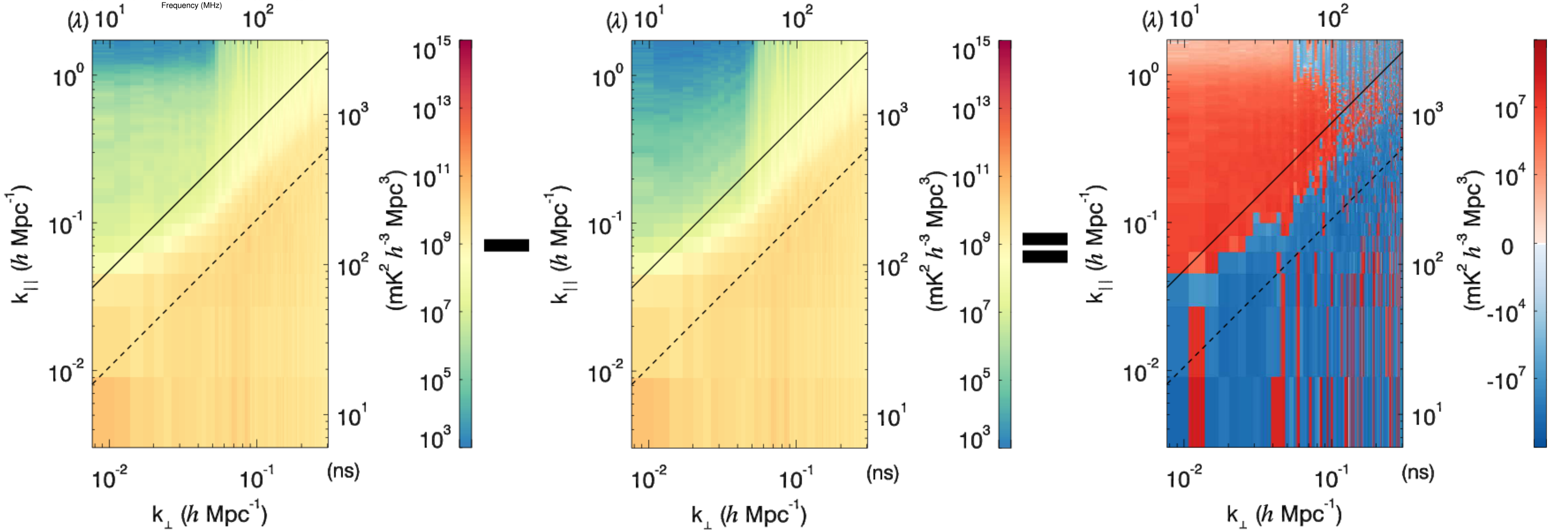
Importance of field sources

- Insufficient modelling of the sources lead to calibration errors that induce foreground contamination. calibration errors need to be <10^-4



Byrne et al., 1811.01378

Barry et al., 1603.00607



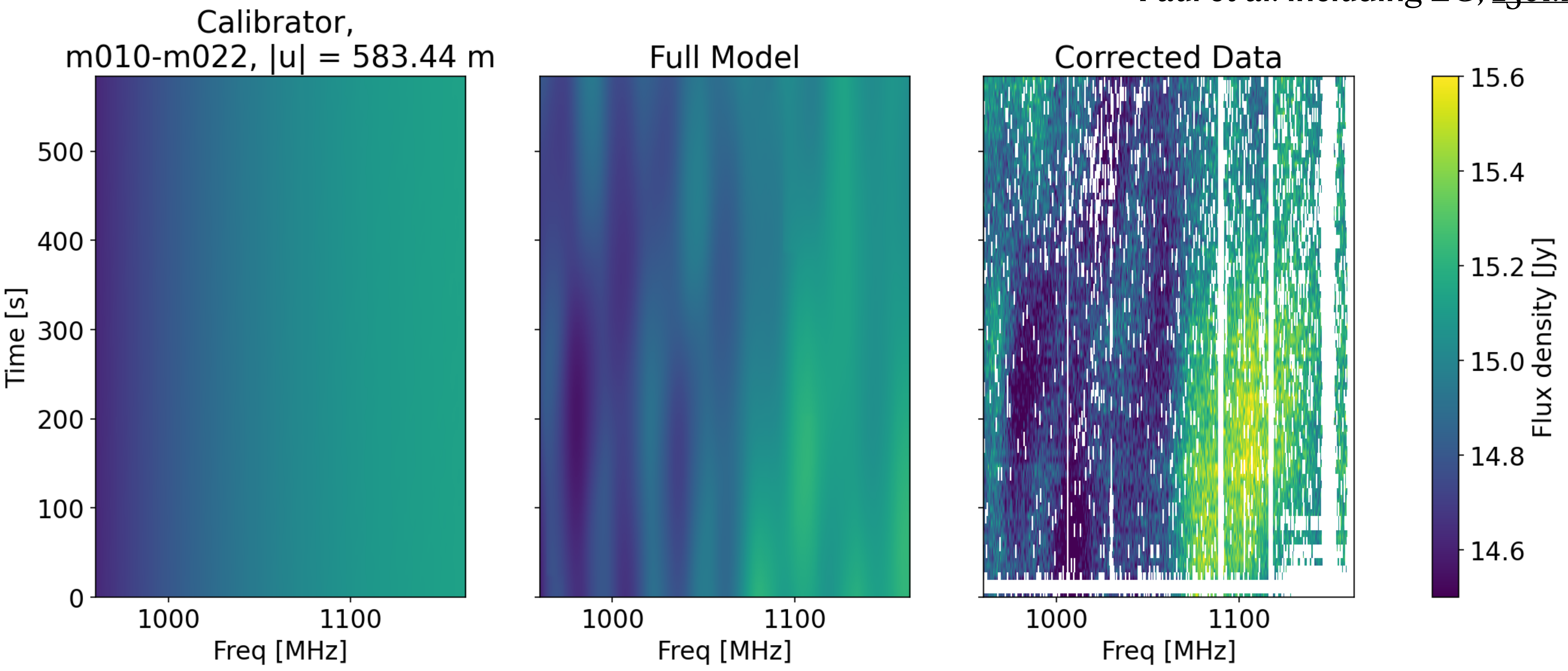
Updating the calibration pipeline for MeerKAT

- Including the field sources in calibration

https://github.com/ska-sa/katsdpcal/tree/master/katsdpcal/conf/sky_models

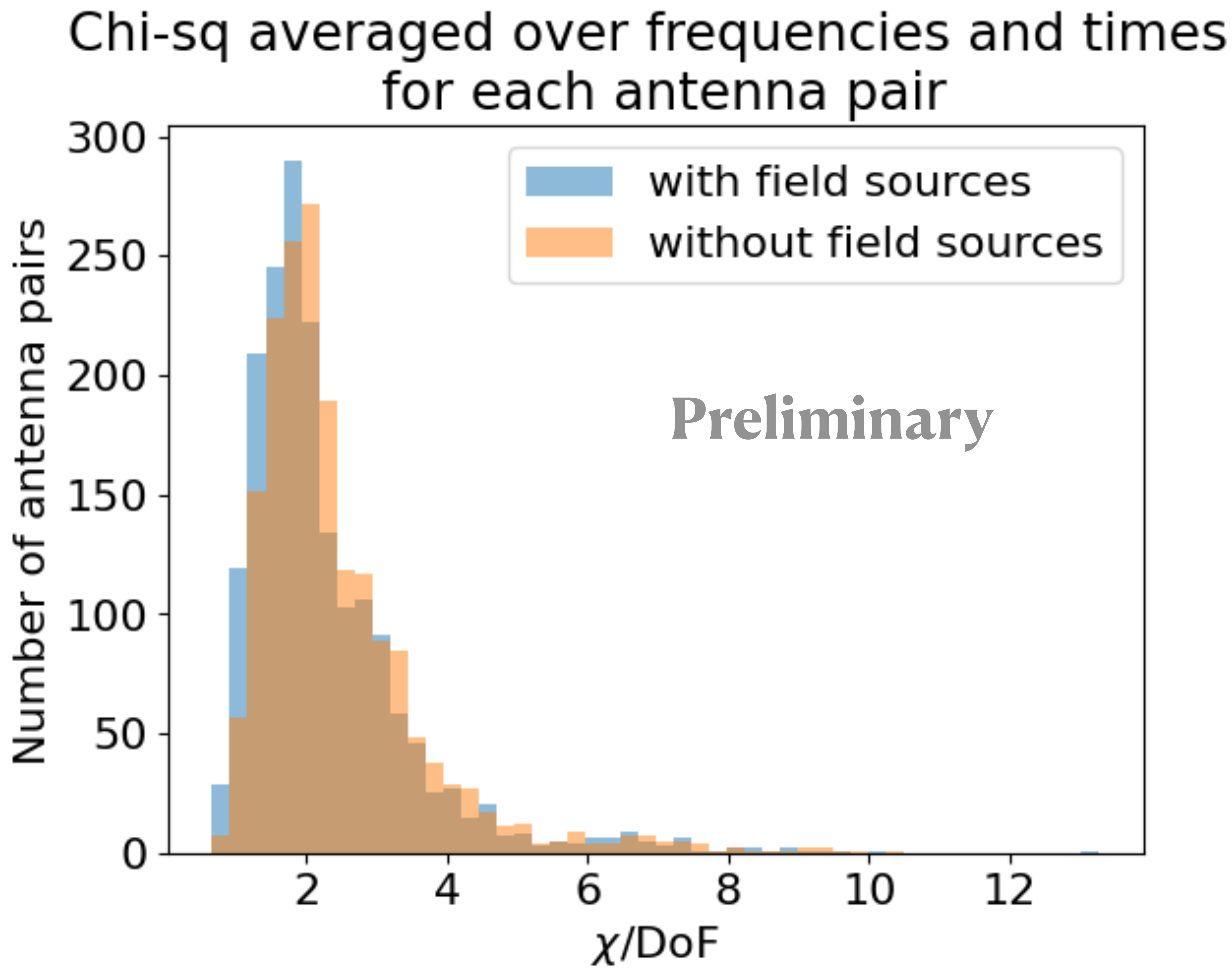
- Rerun calibration process for one block of the DEEP2 detection data

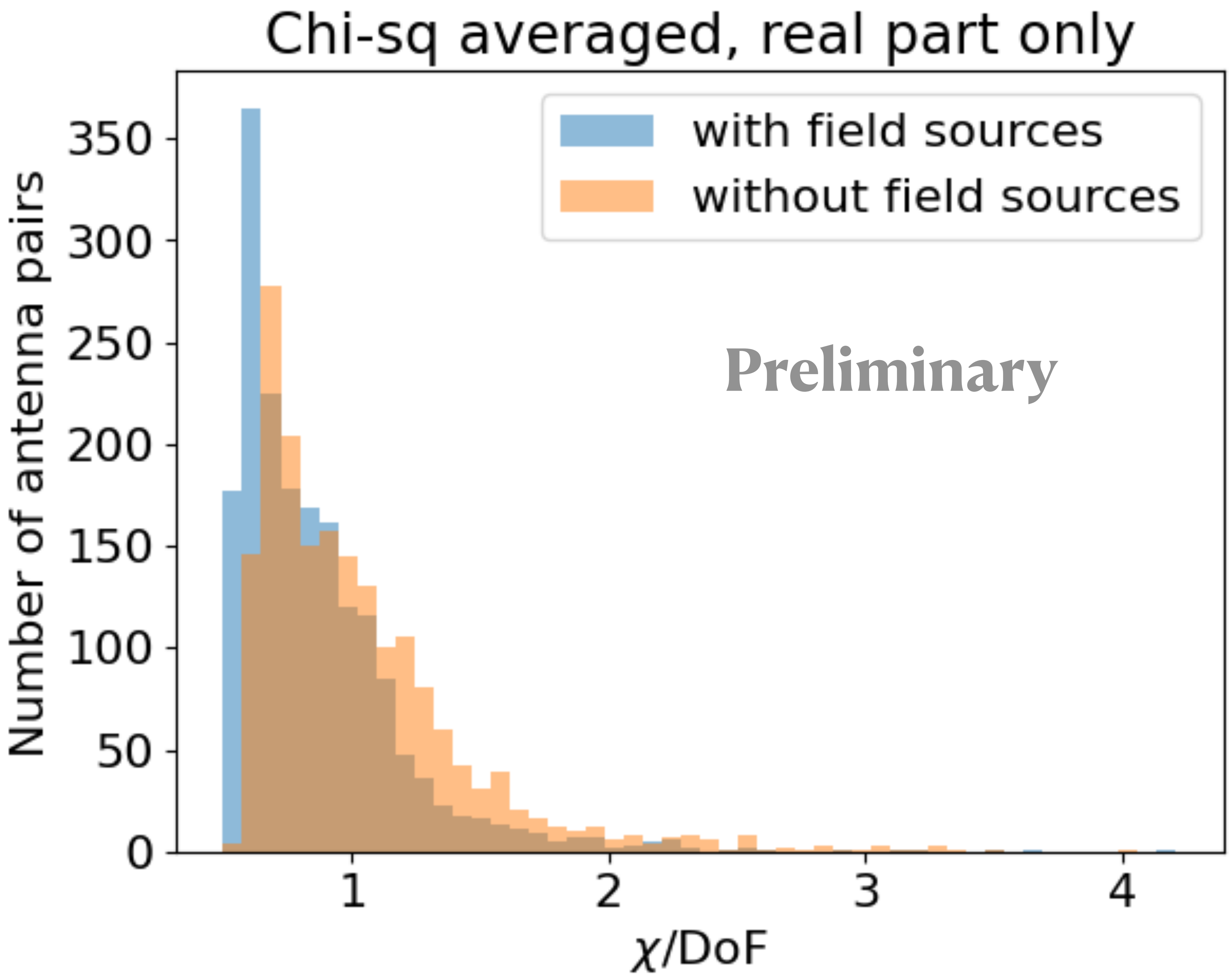
Paul et al. including ZC, 2301.11943



Updating the calibration pipeline for MeerKAT

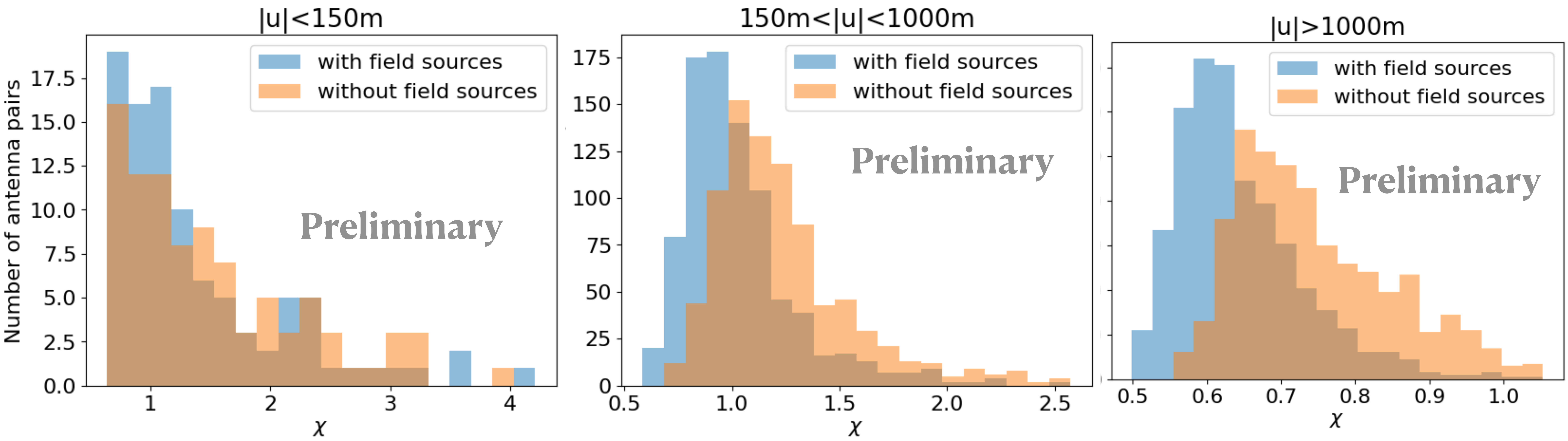
- Clear improvement in calibration quality:





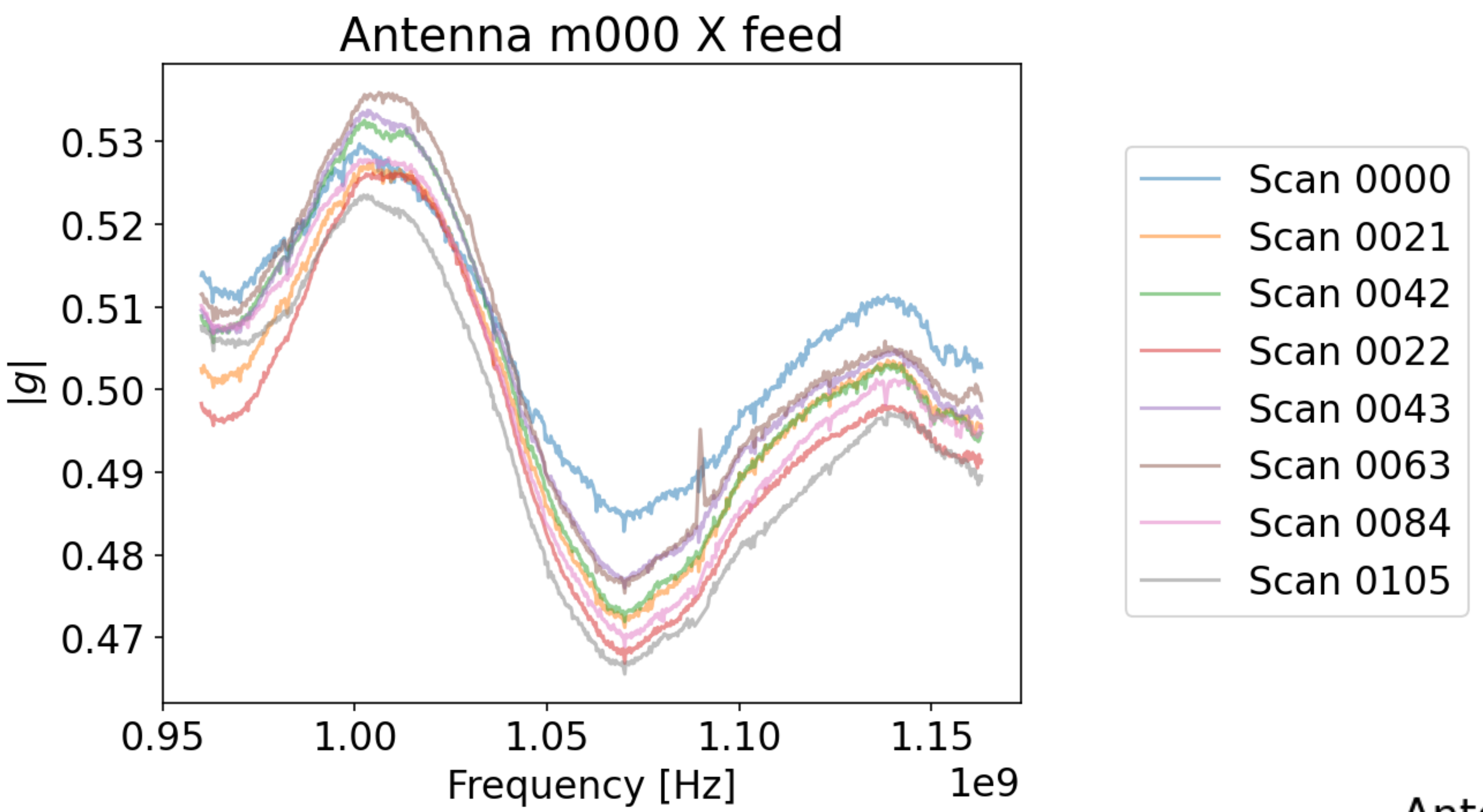
Updating the calibration pipeline for MeerKAT

- The improvement is significant across angular scales:



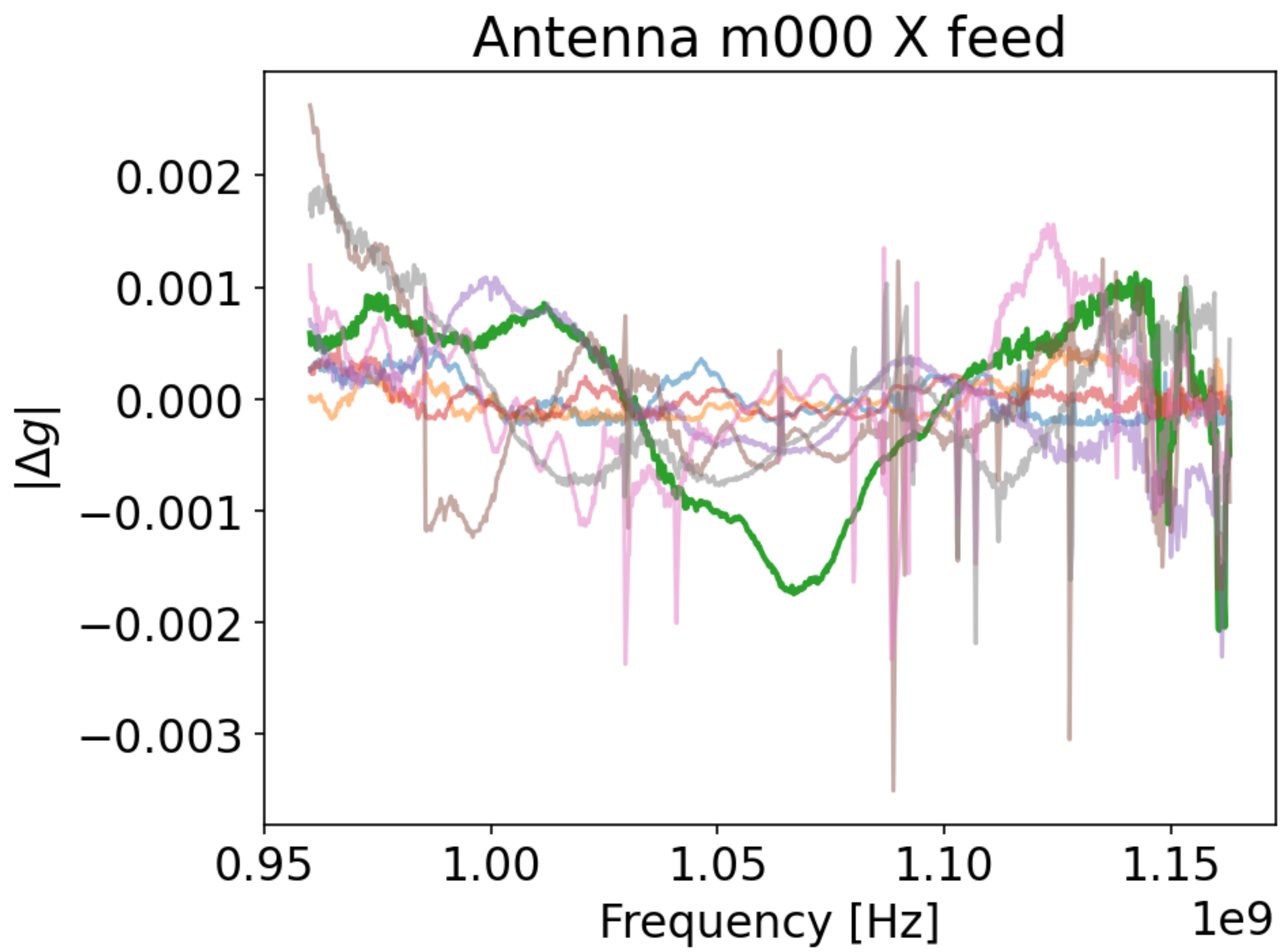
Calibration errors in the DEEP2 data

- The calibration errors can then be quantified by comparing the calibration solutions.

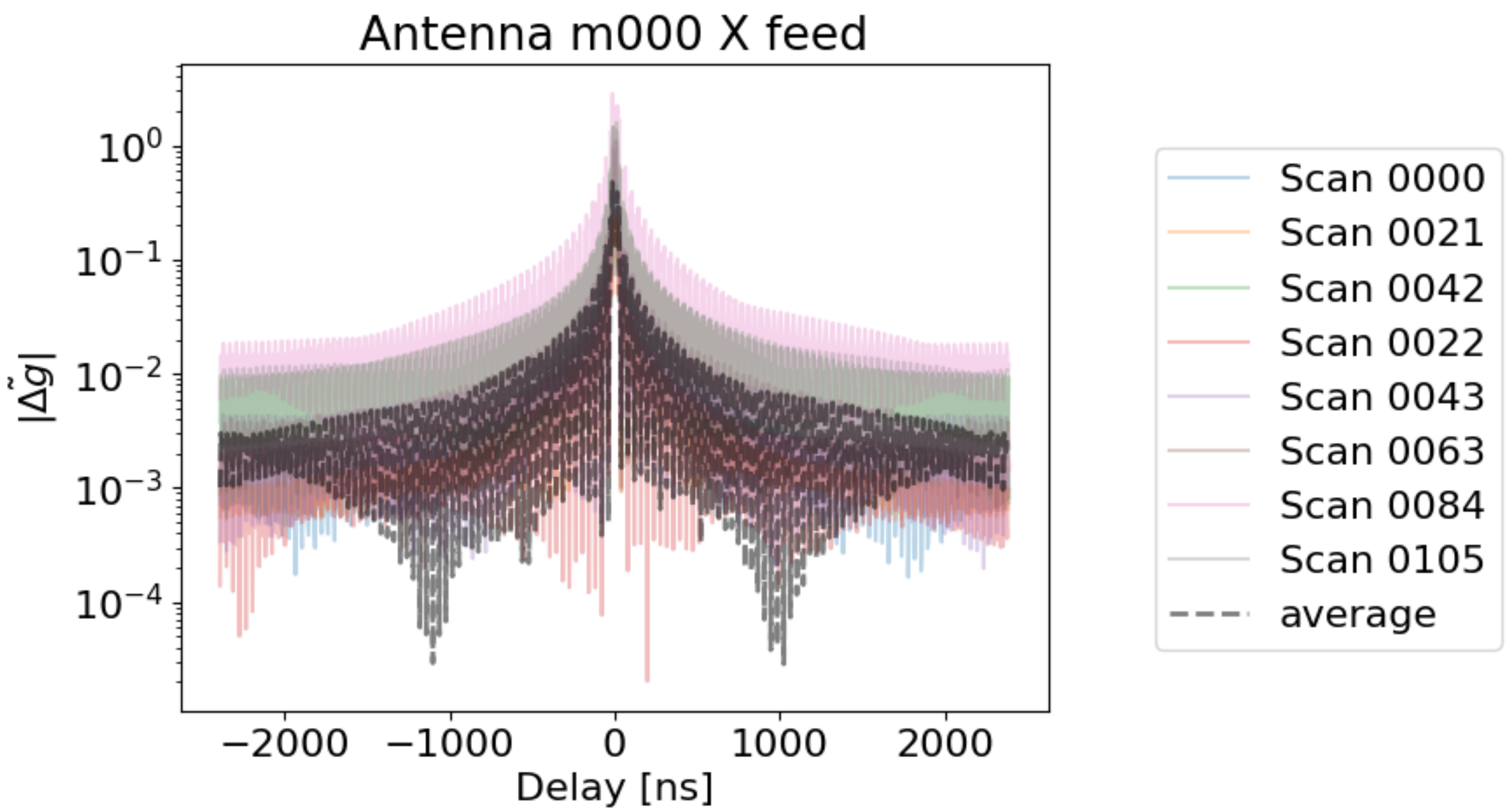


Take the difference

between calibrations with & w/o field source models

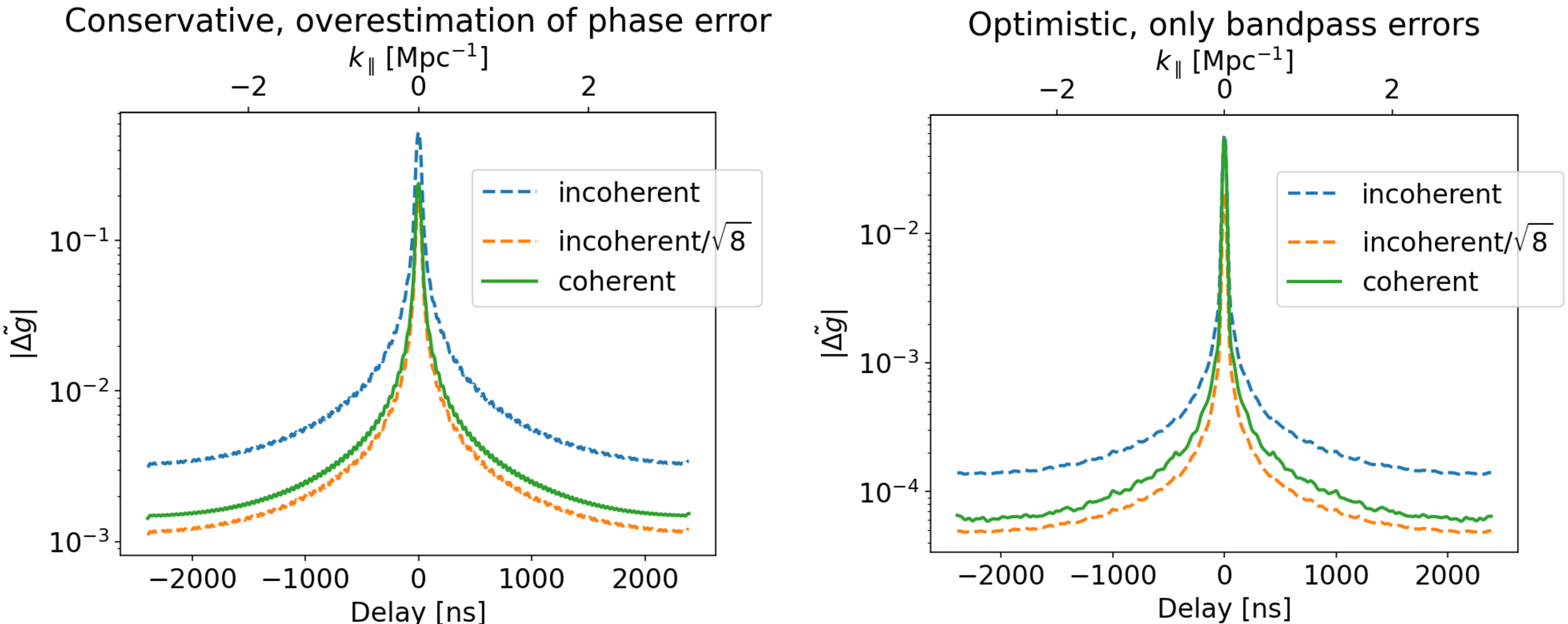


Delay Transform



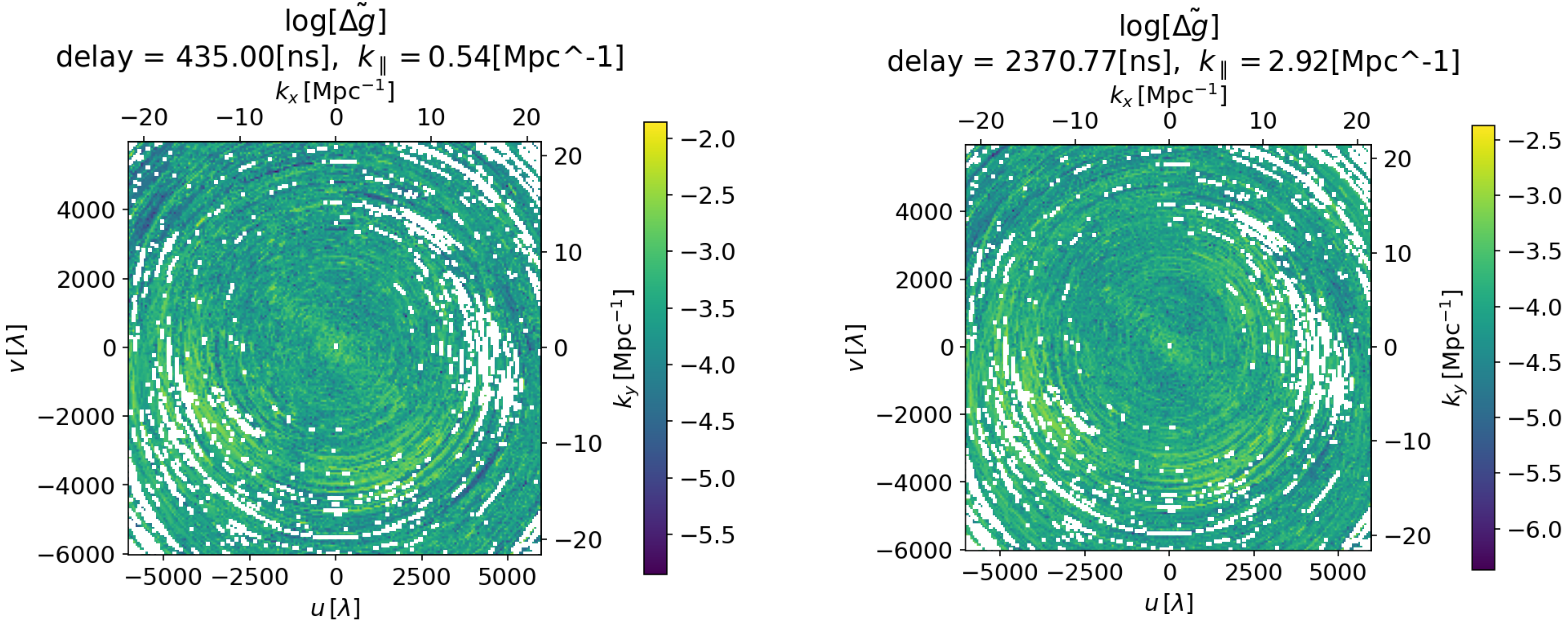
Calibration errors in the DEEP2 data

- Averaging across all antennas for both polarisation feeds, we can approximately estimate the amplitude of calibration errors
- The calibration errors are noise-like, and for each antenna at ~10^-3 level for each solution interval.



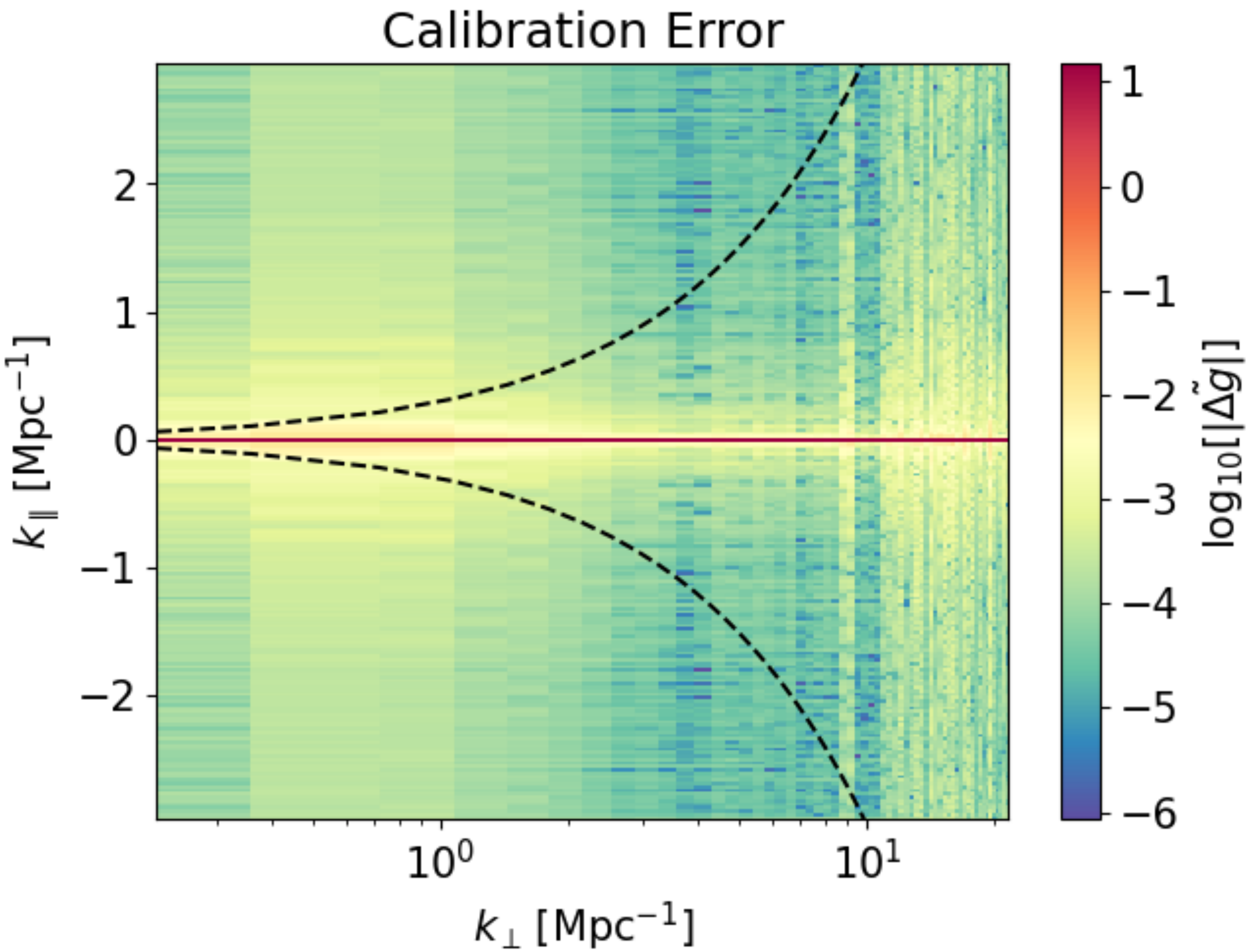
Calibration errors in the DEEP2 data

- We then propagate the per-antenna, per-frequency, per-solution errors into each visibility data and perform the rest of the data process pipeline.
- Find ~10^-4 gain errors across the k-range of our interests.



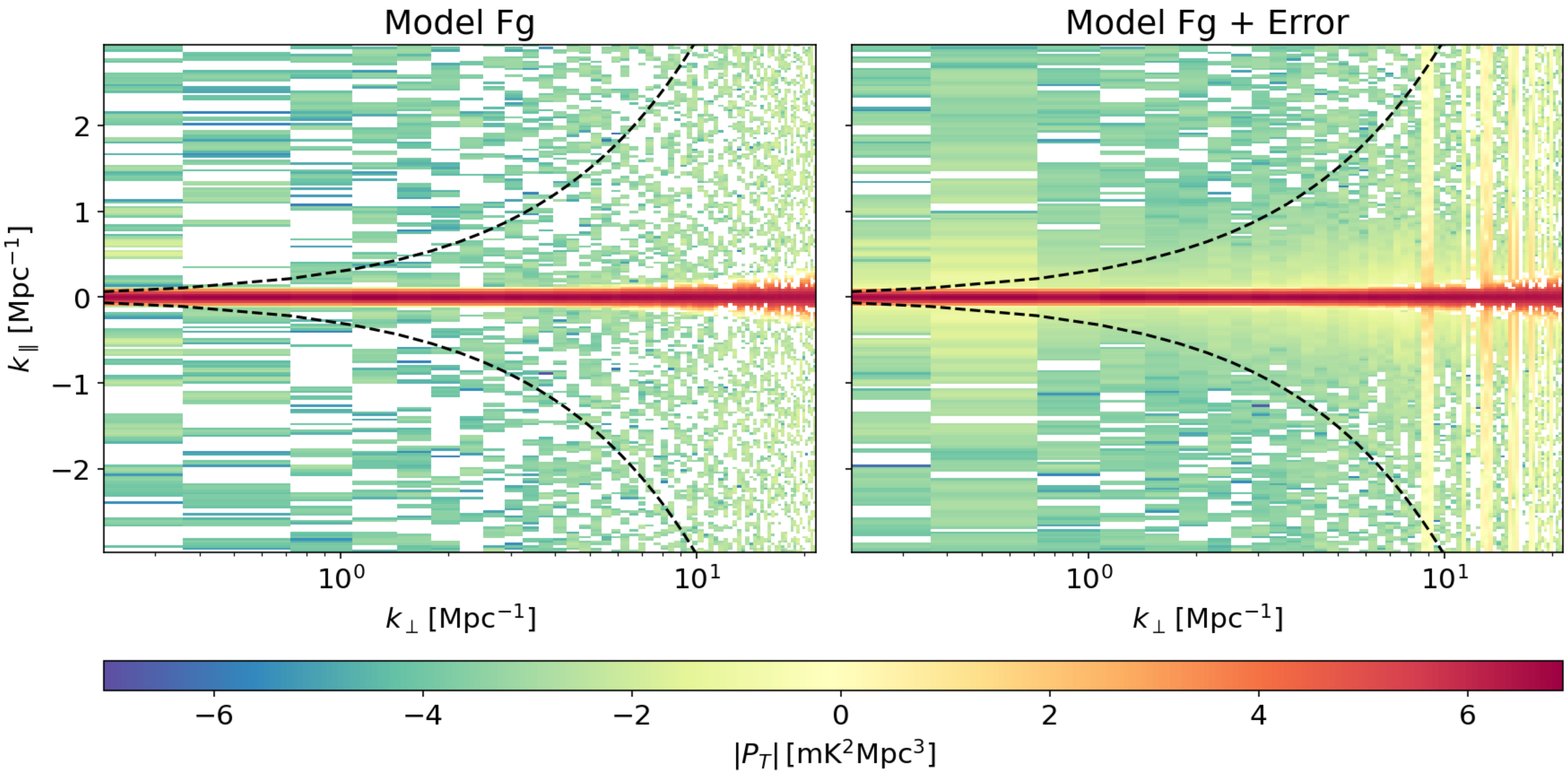
Calibration errors in the DEEP2 data

- As expected, shorter baselines have larger calibration errors, consistent with previous work Ian Heywood, 2004.00454



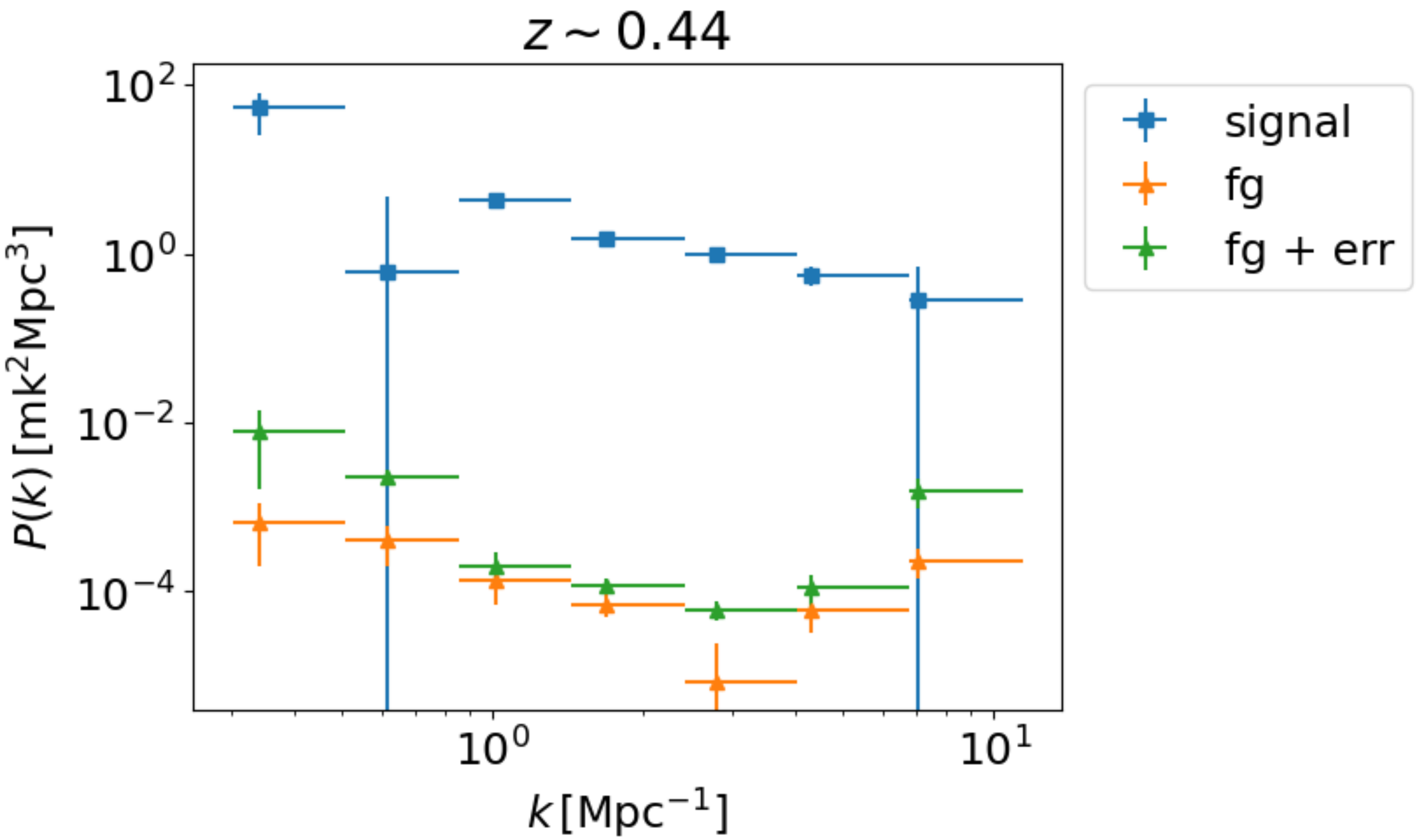
Calibration errors in the DEEP2 data

- Applying the estimated calibration error to model foregrounds, we find a visible but not severe scatter of foreground power.



Calibration errors in the DEEP2 data

- Applying the estimated calibration error to model foregrounds, we find a visible but not severe scatter of foreground power.
- Note that the errors shown are for 1 out of 9 blocks. The full DEEP2 data is likely to have smaller foreground scatter.



Conclusion

- We update the calibration pipeline for interferometric MeerKAT intensity mapping observations. Hope to make it public soon.

- Using the updated pipeline, we can estimate the calibration errors due to insufficient modelling of the reference sky.

- We find that even though field sources are completely ignored for reference calibration, the calibration errors induced are ~10^-4

- For DEEP2 field with 9 blocks and faint foregrounds, the scatter is negligible.

- In the future, MIGHTEE fields with only one block per field and stronger foregrounds will require higher precision in calibration to maintain the pristineness of the window.