21-cm LIM with MWA:
The case of the missing channels

Khandakar Md Asif Elahi

Postdoctoral Researcher, IIT Madras, India

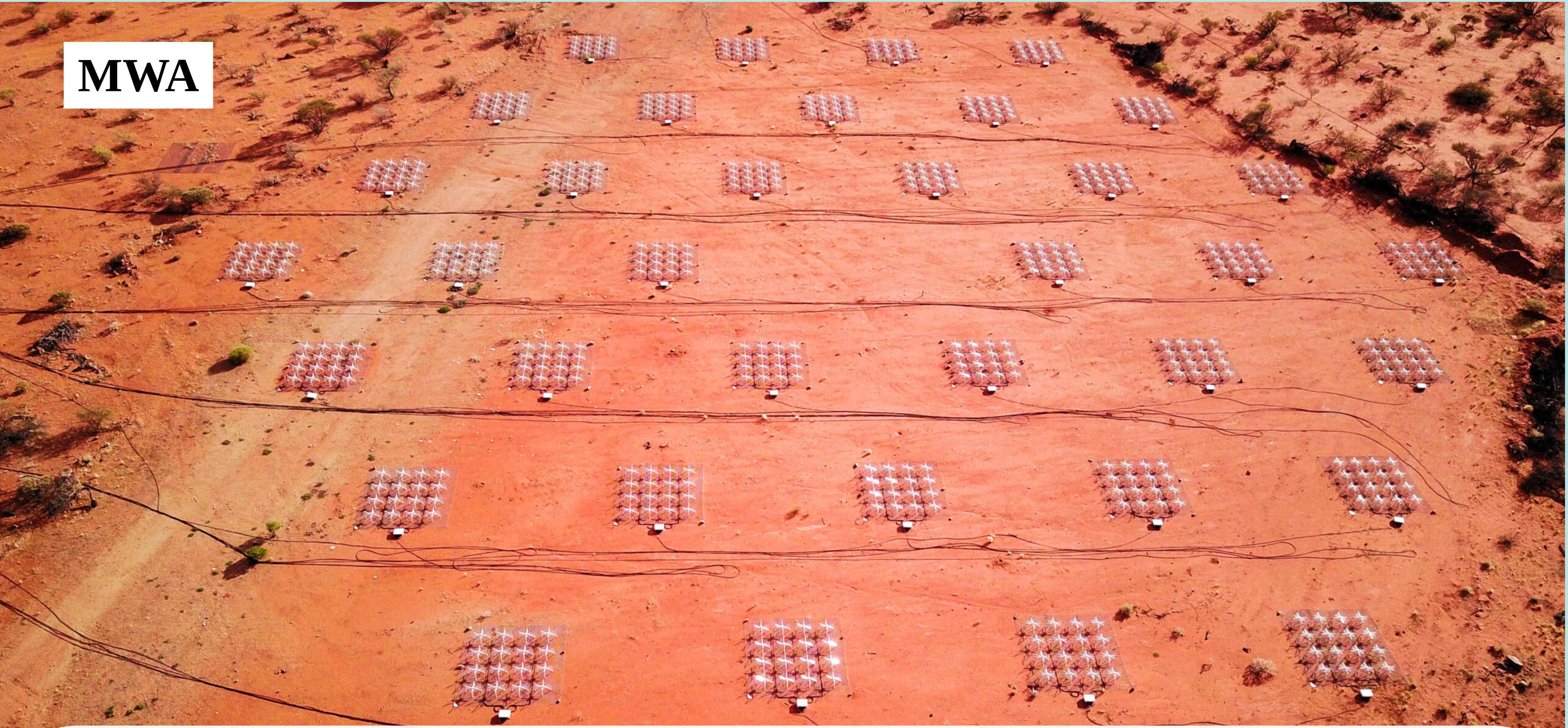
JOURNAL ARTICLE ACCEPTED MANUSCRIPT

The Tracking Tapered Gridded Estimator for the 21-cm power spectrum from MWA drift scan observations II: The Missing Frequency Channels

Khandakar Md Asif Elahi ✉ , Somnath Bharadwaj ✉ , Suman Chatterjee , Shouvik Sarkar , Samir Choudhuri , Shiv Sethi , Akash Kumar Patwa

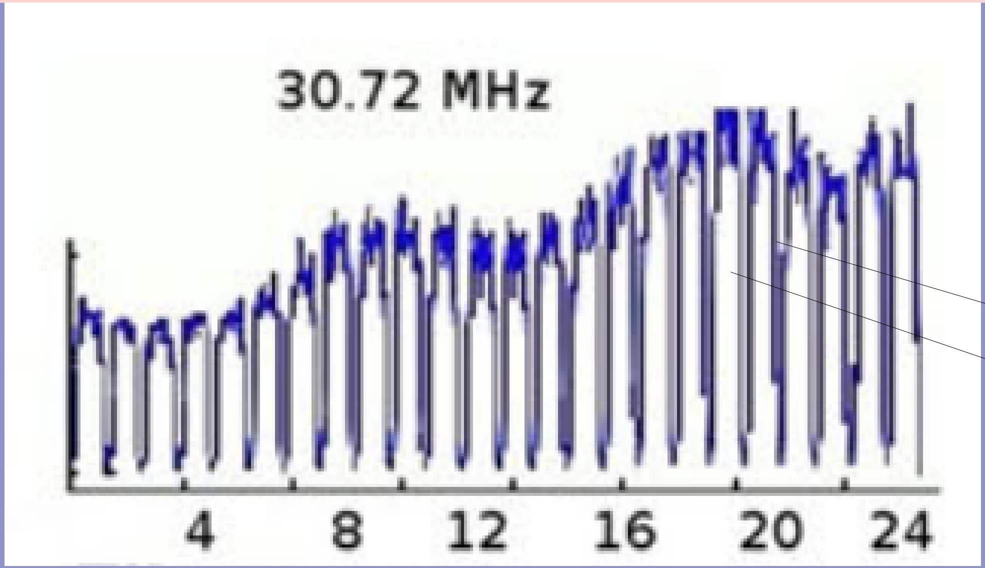
Monthly Notices of the Royal Astronomical Society, staf896,
https://doi.org/10.1093/mnras/staf896
Published: 31 May 2025

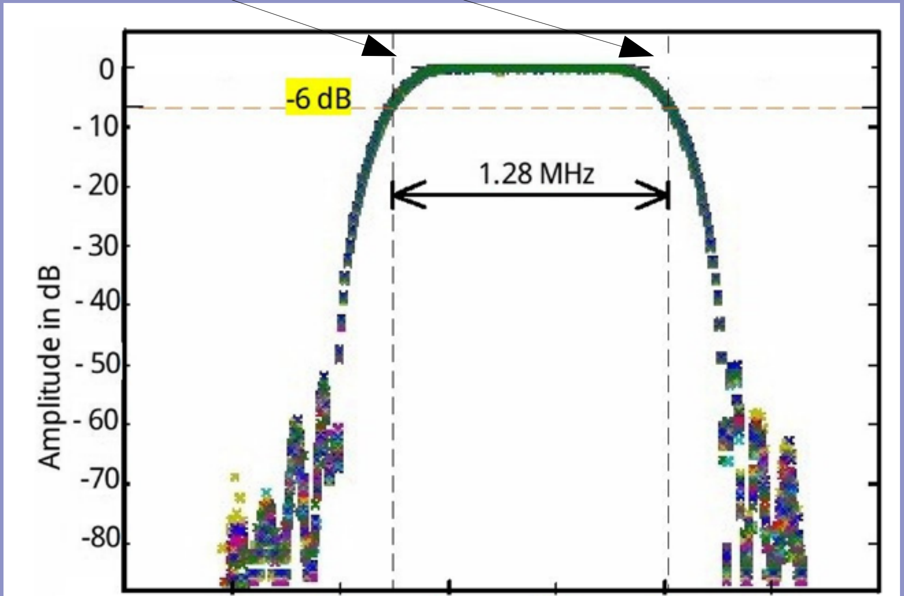
arXiv > astro-ph > arXiv:2410.11380



MWA is a powerful radio-interferometer capable of measuring the EoR 21-cm power spectrum - SKA Low precursor

MWA Bandpass – The Missing Channels

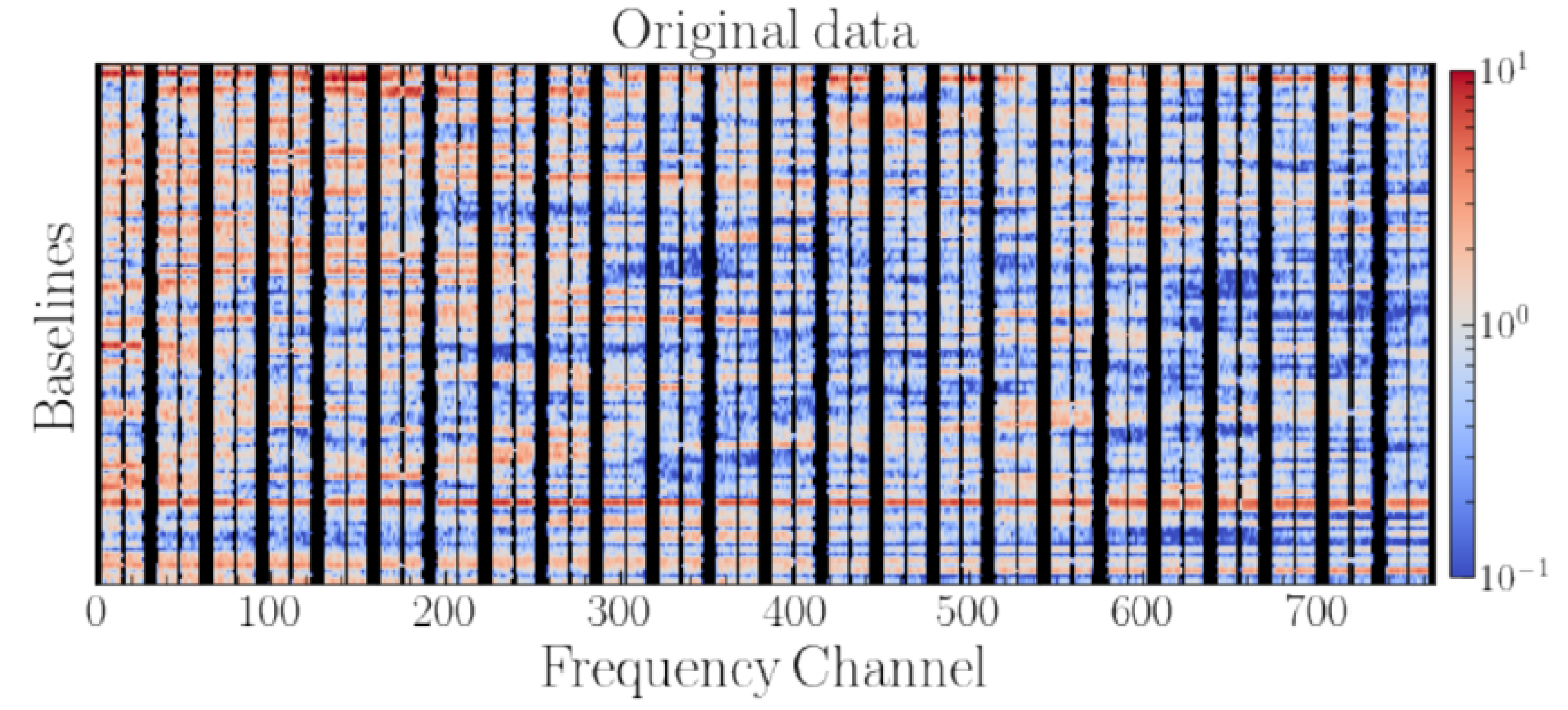




Prabu+ 2015

For computational efficiency

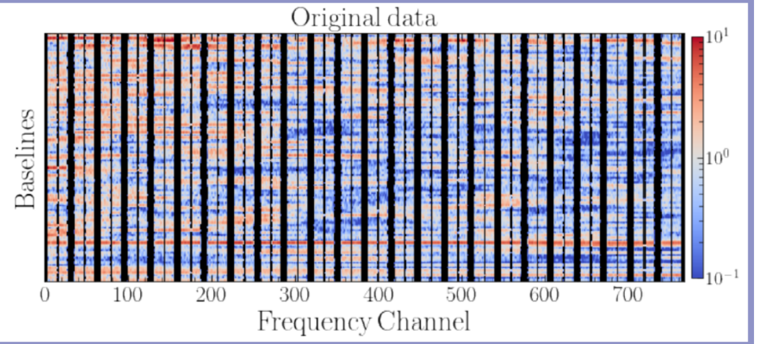
MWA Bandpass – The Missing Channels

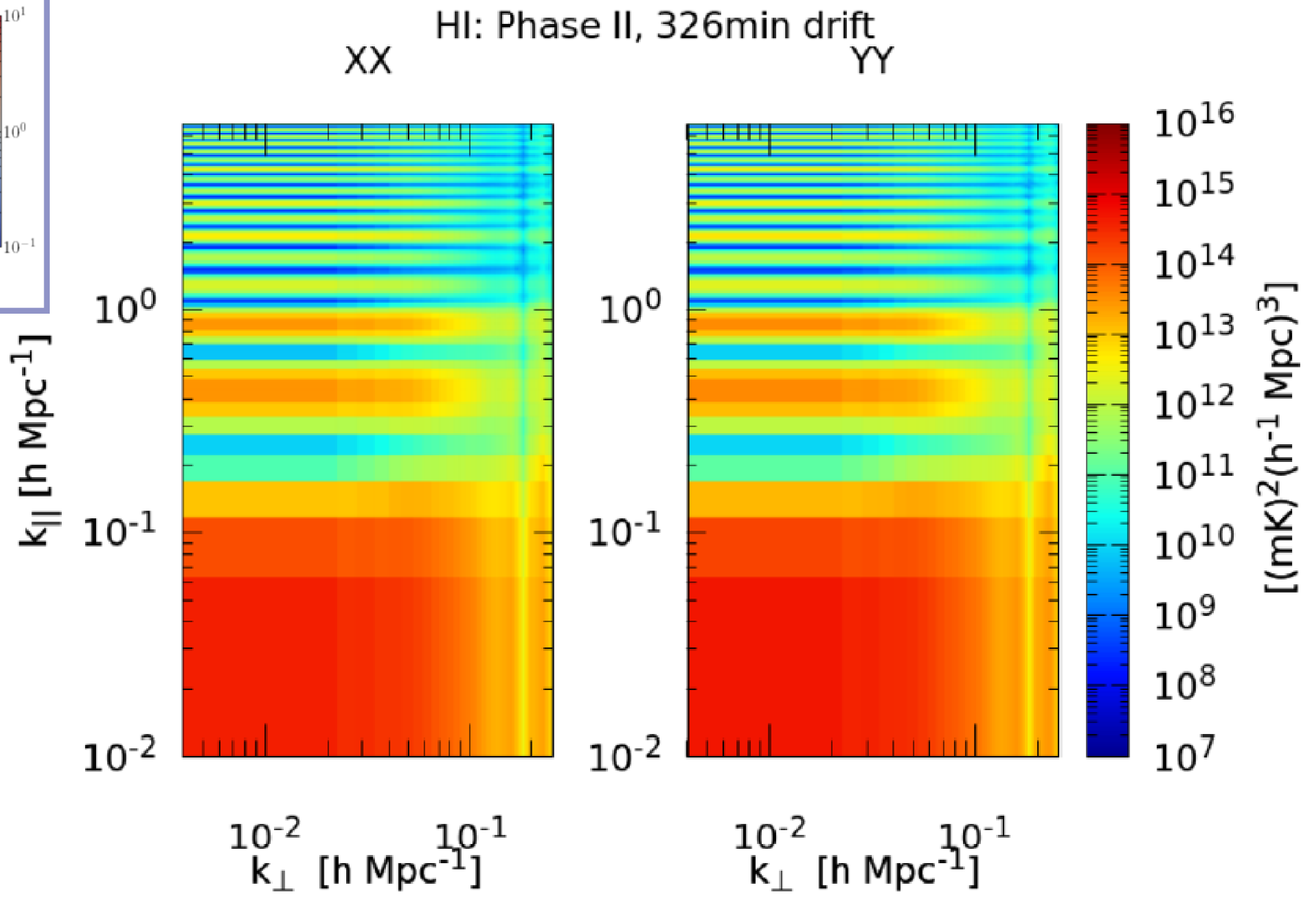


Actual observation @ 154 MHz (z = 8.2)

– Patwa+ 2021

The Missing Channels – "**coarse band harmonics**"

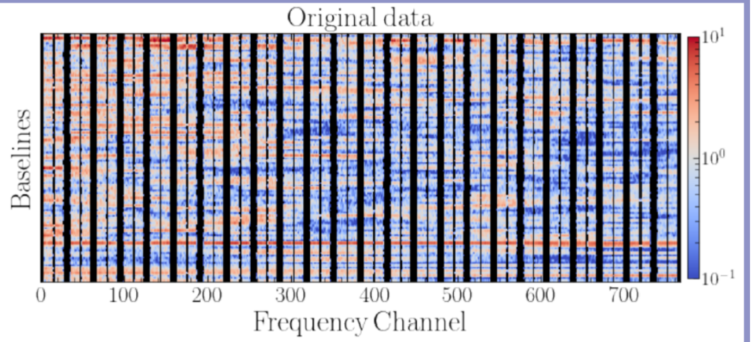


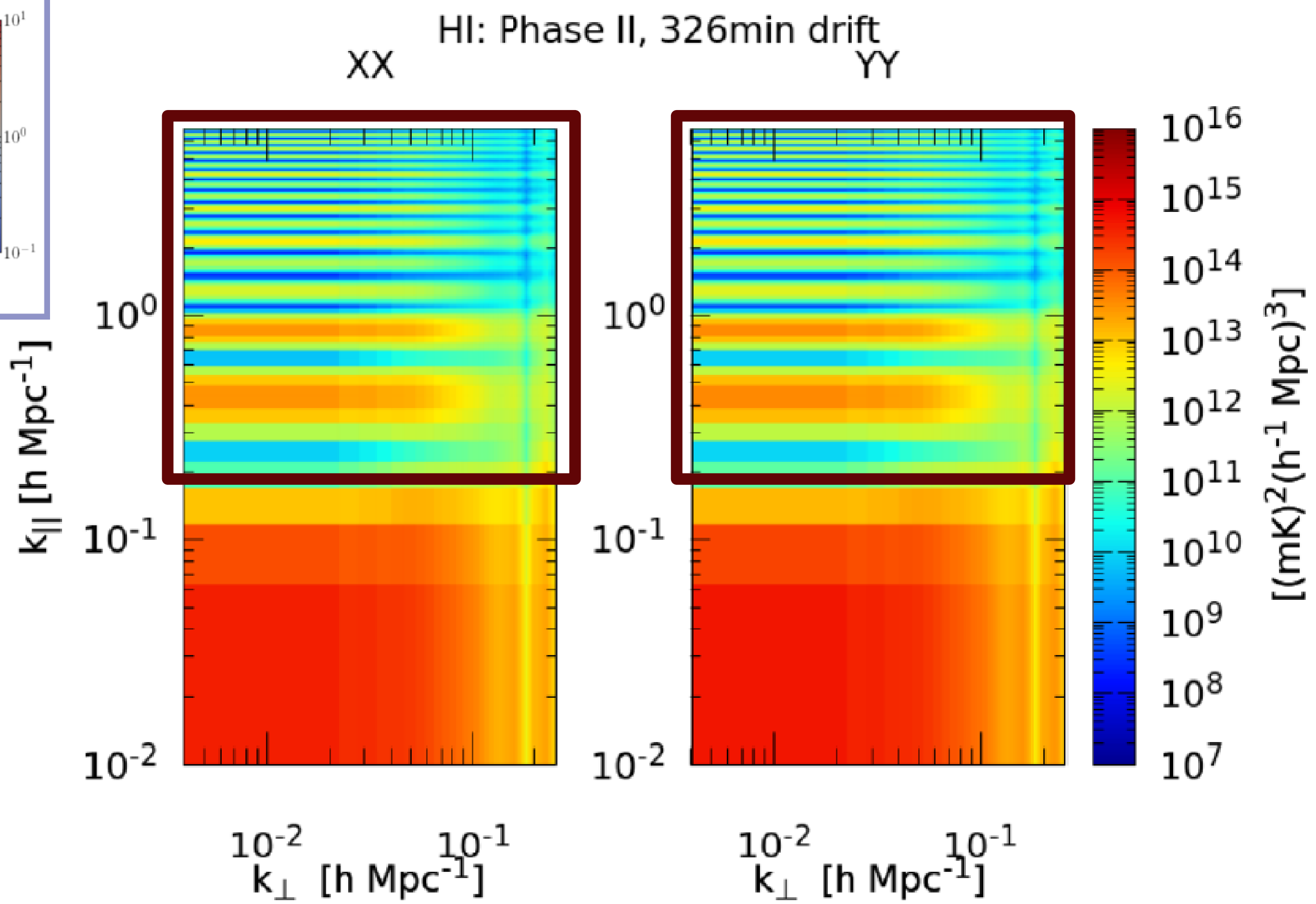


Same/similar pattern in

Li+ 2019
Trott+ 2020
.
.
.

The Missing Channels – “**coarse band harmonics**”





Same/similar pattern in

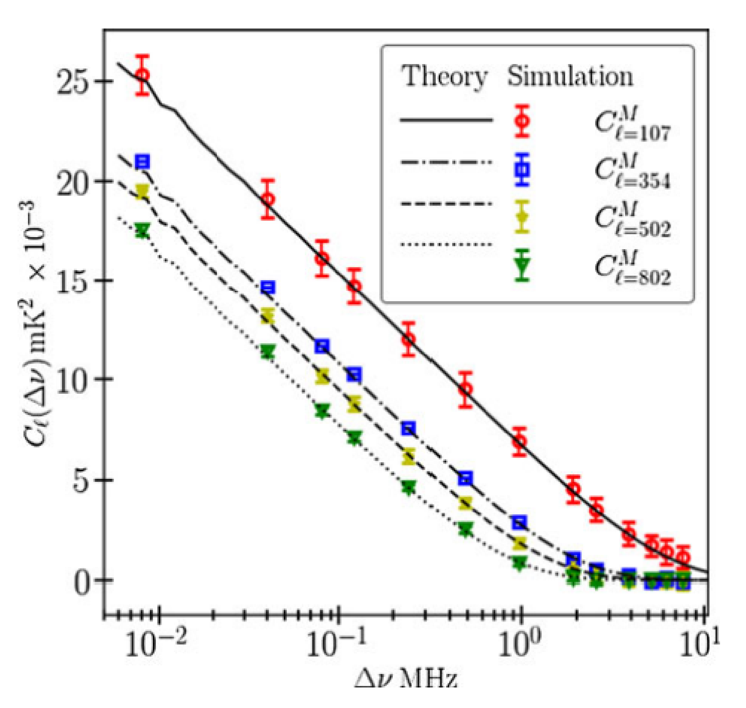
Li+ 2019
Trott+ 2020
.
.
.

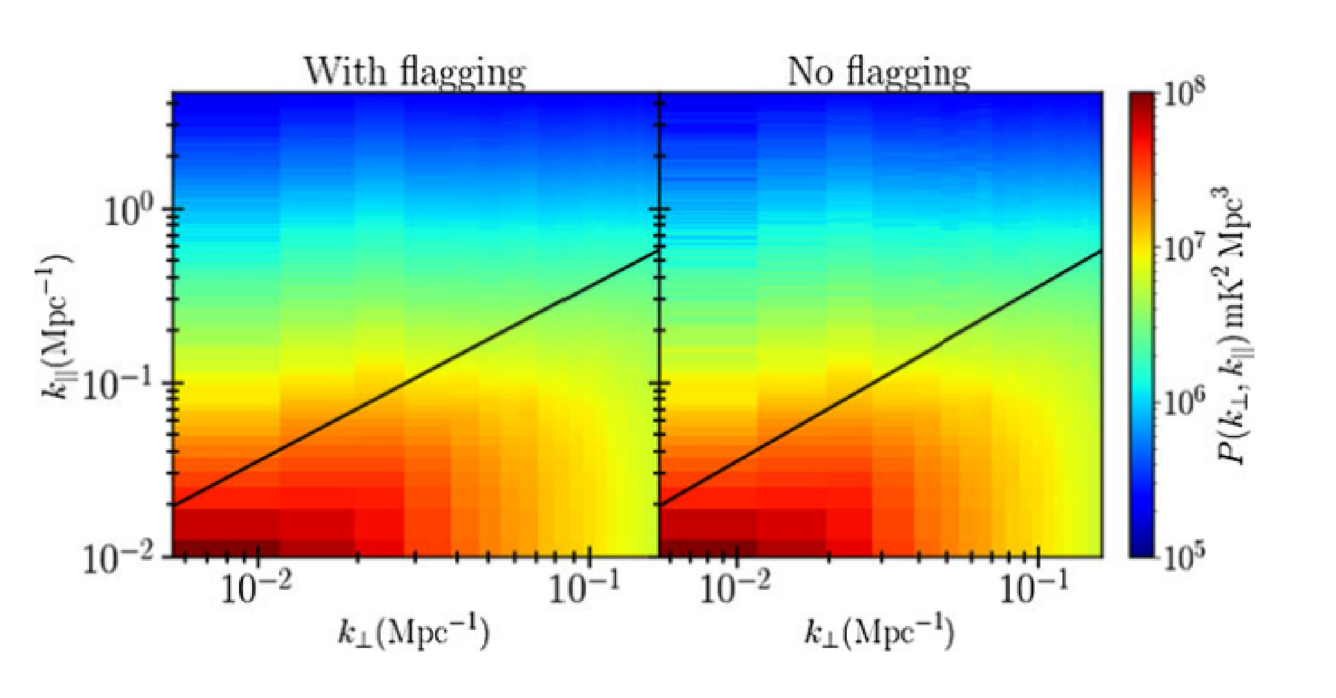
An alternative approach – first **estimate** the MAPS

$$P(k_\perp, k_\parallel) = r^2 r' \int_{-\infty}^{\infty} d(\Delta\nu)\, e^{-i k_\parallel r' \Delta\nu} C_\ell(\Delta\nu)$$

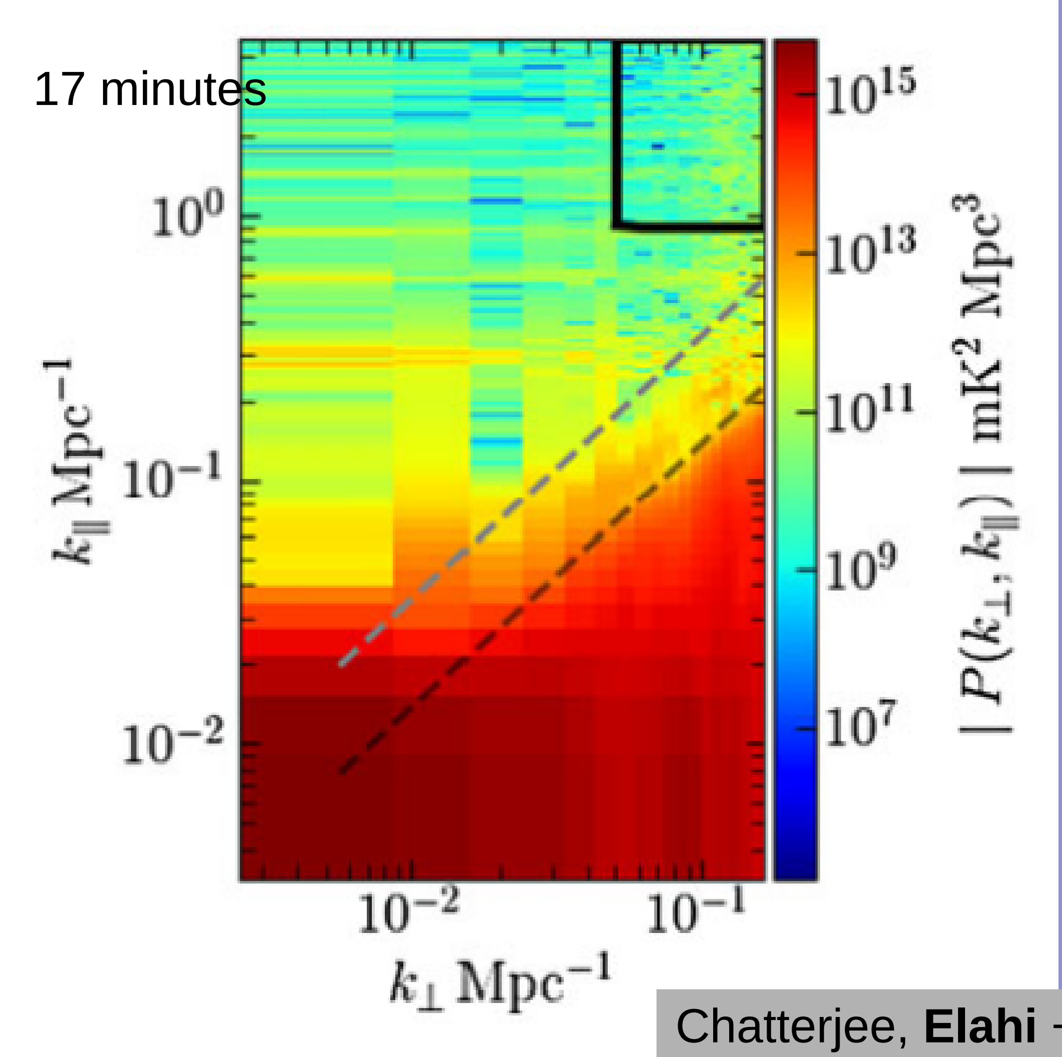
No missing Δν

Multi-frequency angular power spectrum - MAPS

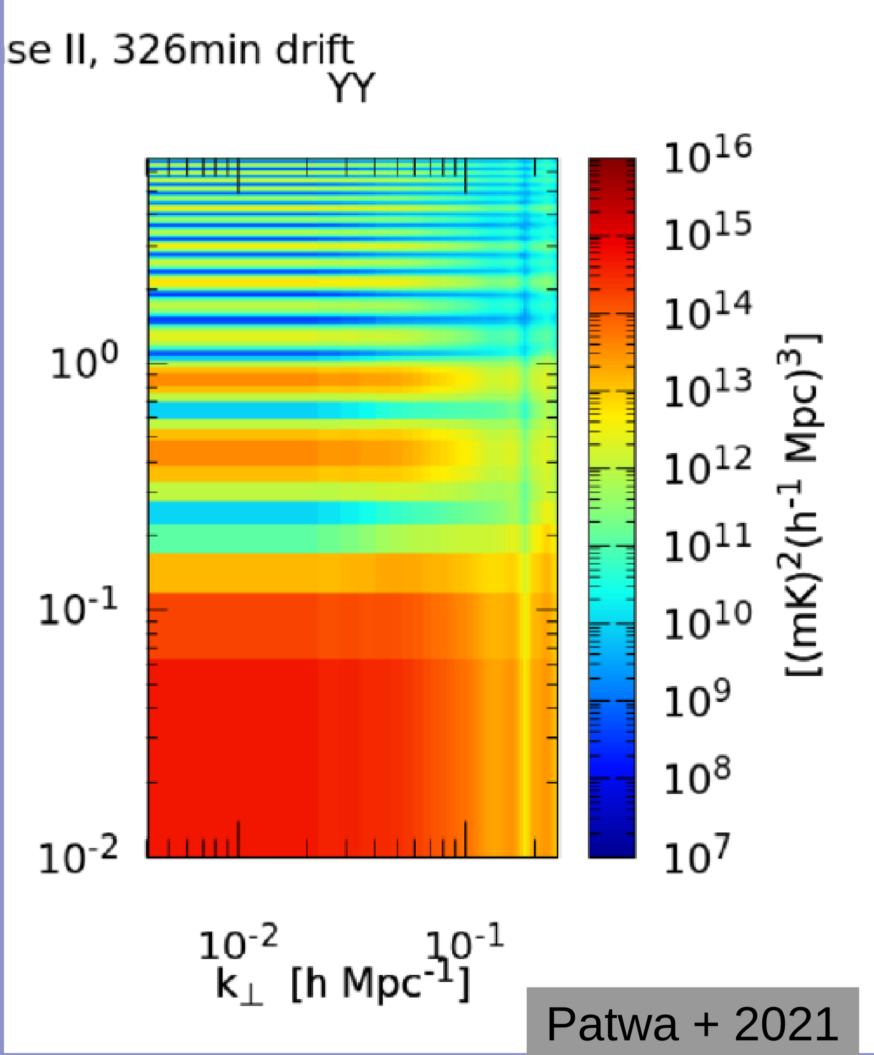




Actual MWA data – the same observation

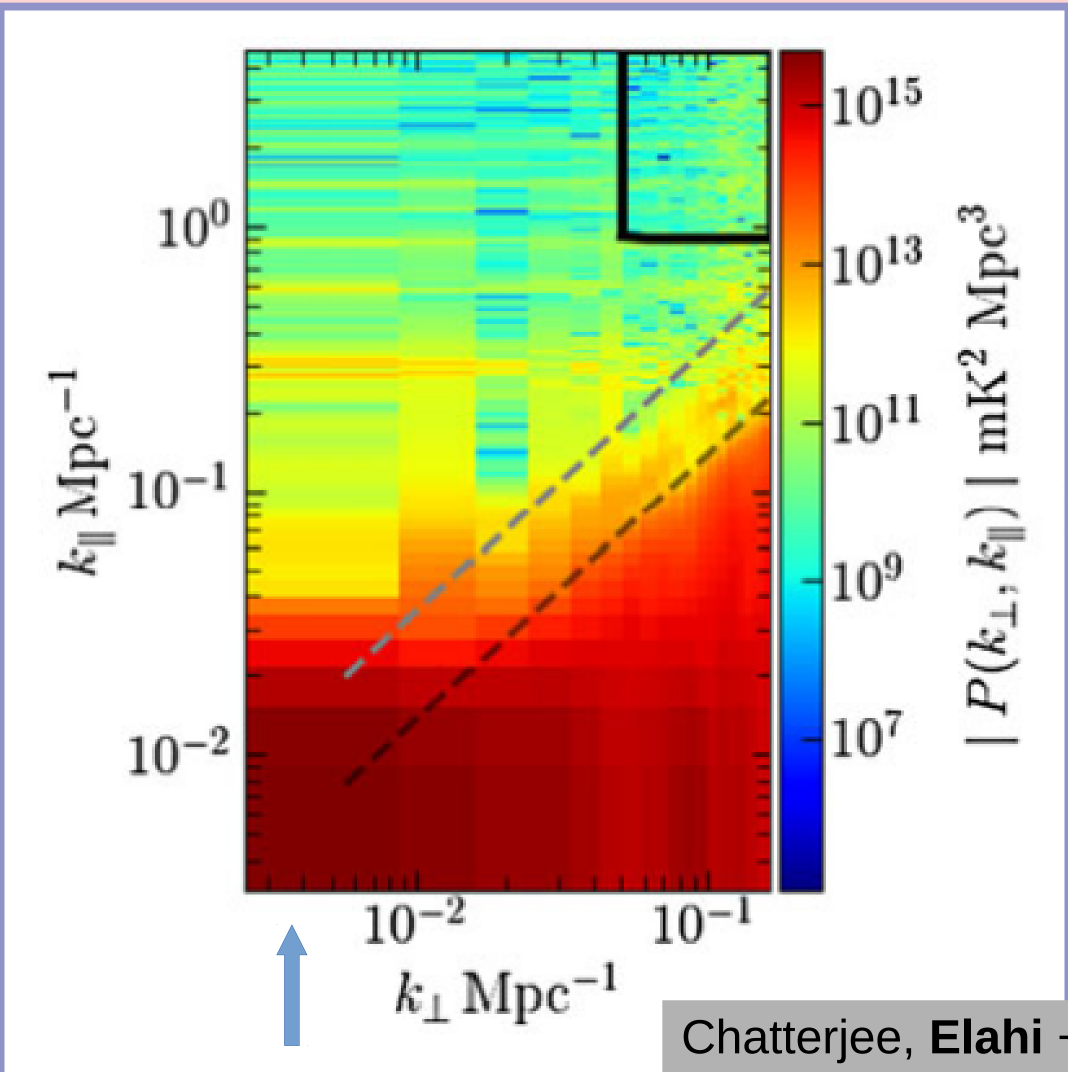


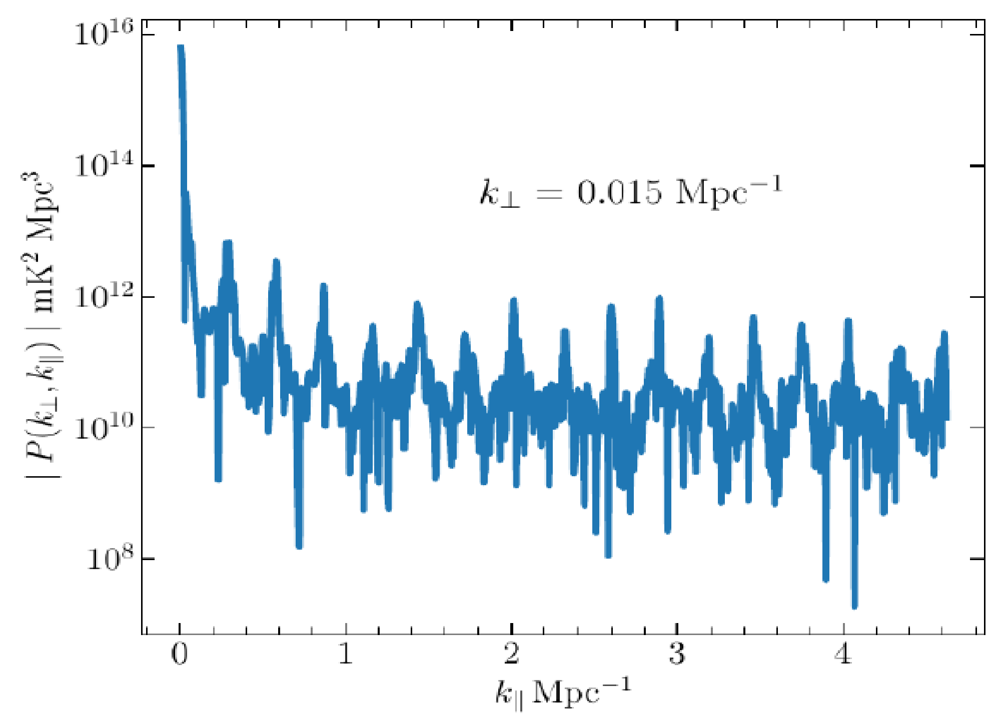
Chatterjee, **Elahi** + 2024



Patwa + 2021

But ..

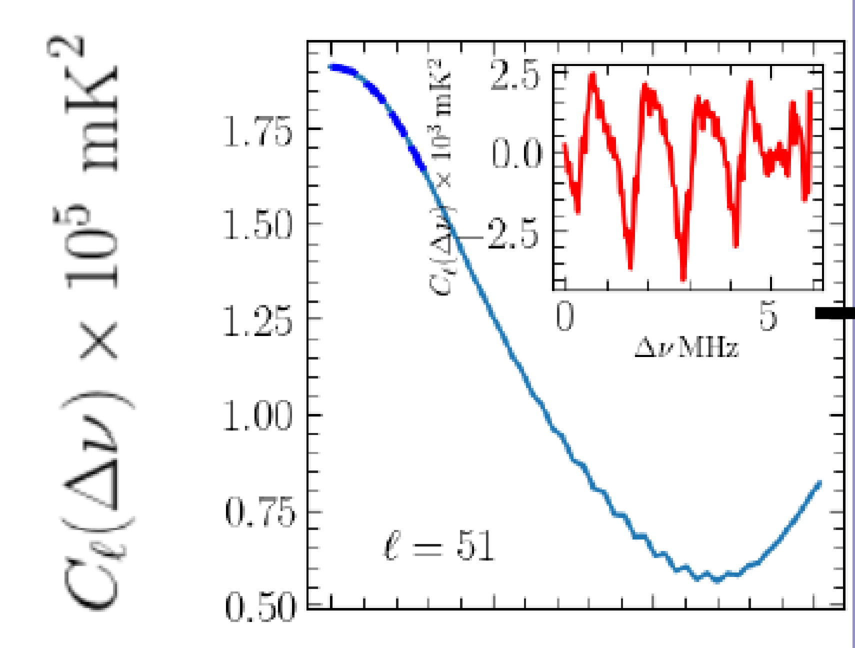


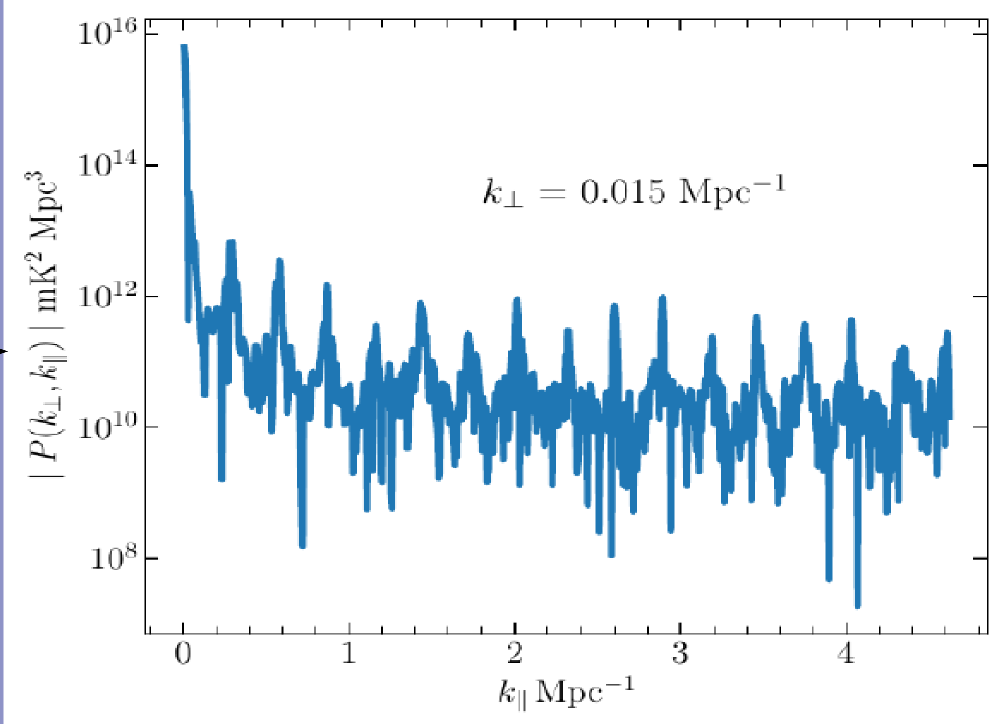


Chatterjee, **Elahi** + 2024

Why do we see these small ripples?

$$P(k_\perp, k_\parallel) = r^2 r' \int_{-\infty}^{\infty} d(\Delta\nu)\, e^{-i k_\parallel r' \Delta\nu} C_\ell(\Delta\nu)$$



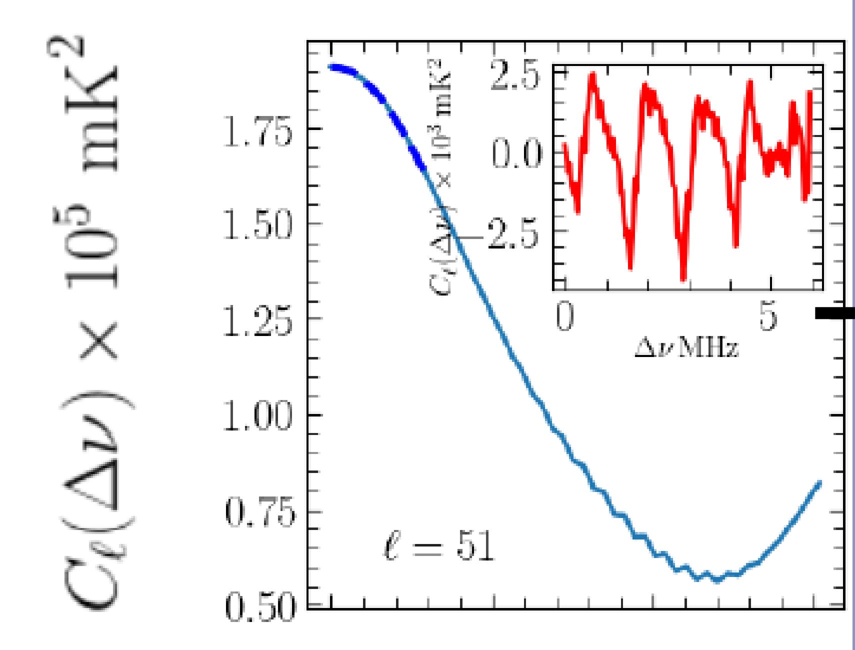


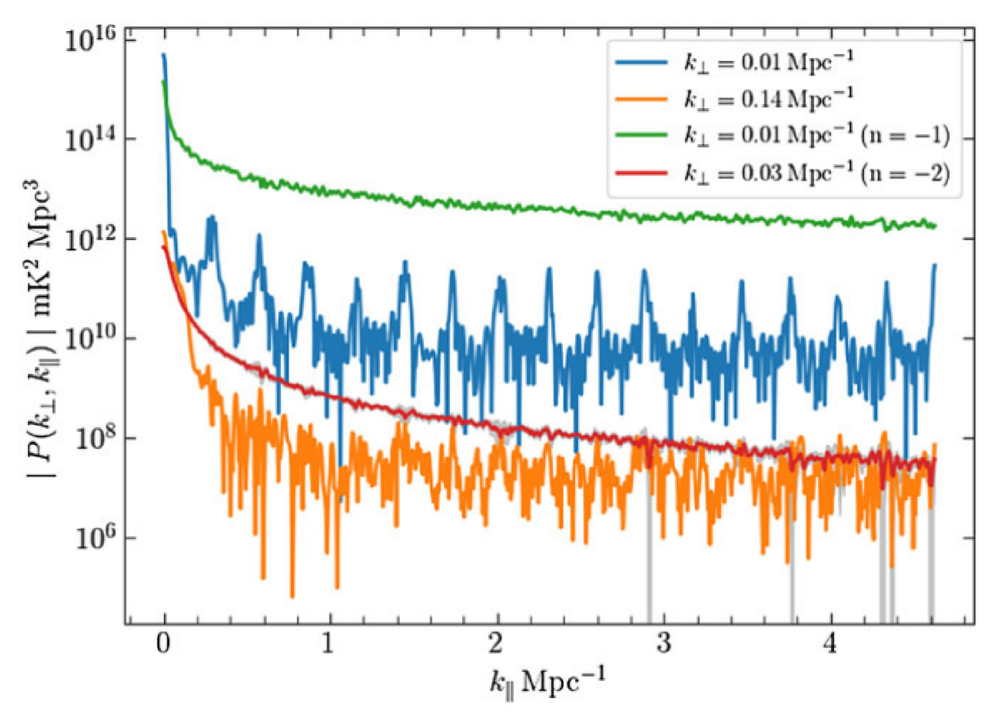
Chatterjee, **Elahi** + 2024

Why do we see these small ripples?

$$P(k_\perp, k_\parallel) = r^2 r' \int_{-\infty}^{\infty} d(\Delta\nu)\, e^{-i k_\parallel r' \Delta\nu} C_\ell(\Delta\nu)$$

$$P^m(k) = (k/k_0)^s \, \mathrm{K}^2 \, \mathrm{Mpc}^3$$





Chatterjee, **Elahi** + 2024

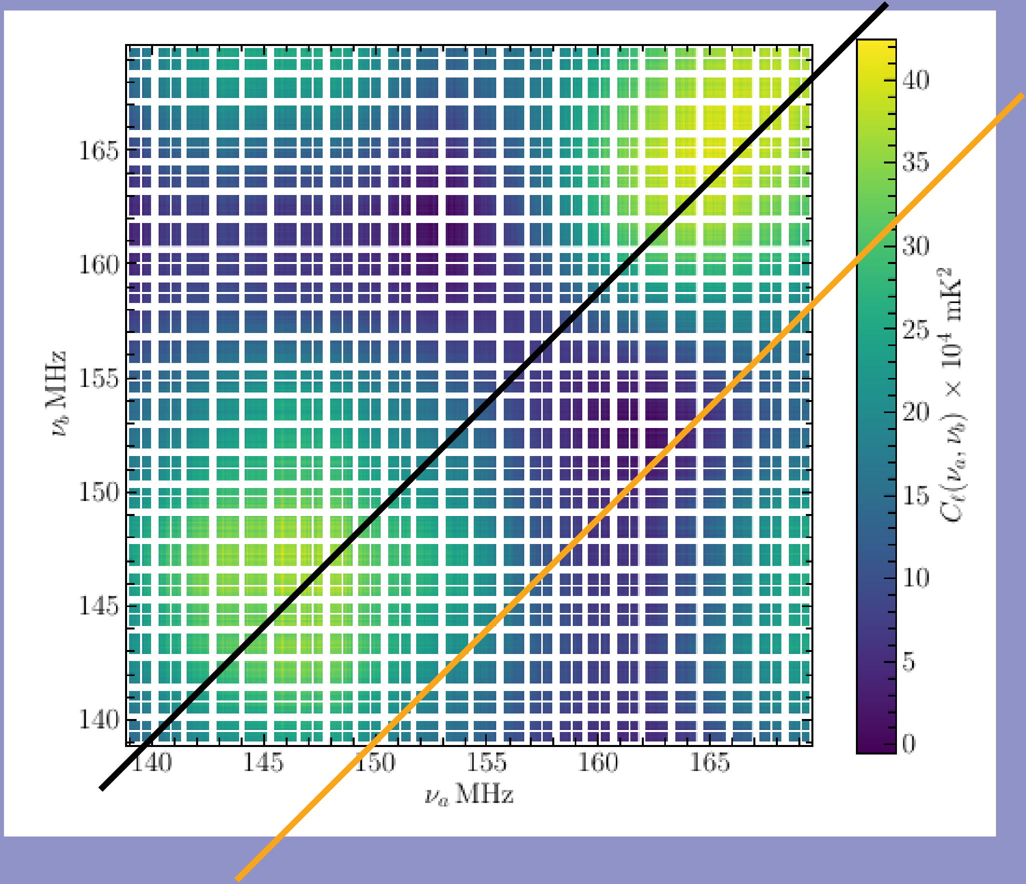
(absent in simulated data)

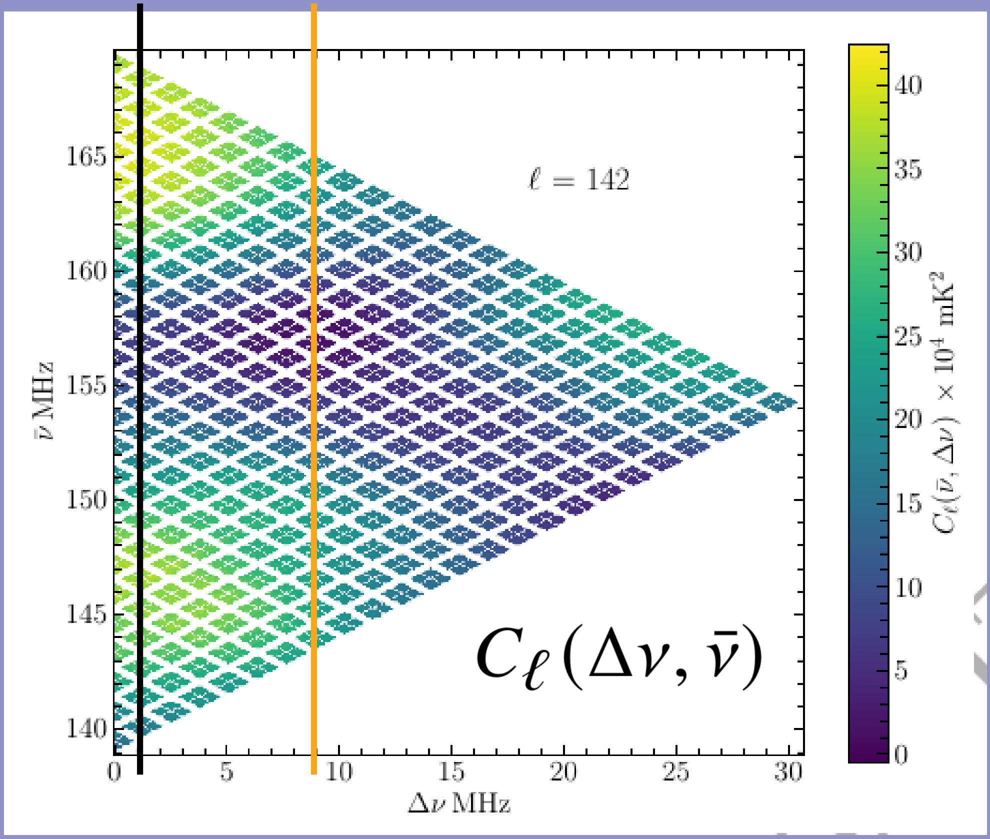
$$C_\ell(\nu_a, \nu_b) = \left[\frac{2}{\pi Q^2 \theta_0^2}\right]_{\nu_c} \langle \mathcal{V}(\mathbf{U}, \nu_a)\mathcal{V}(\mathbf{U}, \nu_b)\rangle$$

Tapered Gridded Estimator

Bharadwaj & Sethi 2001

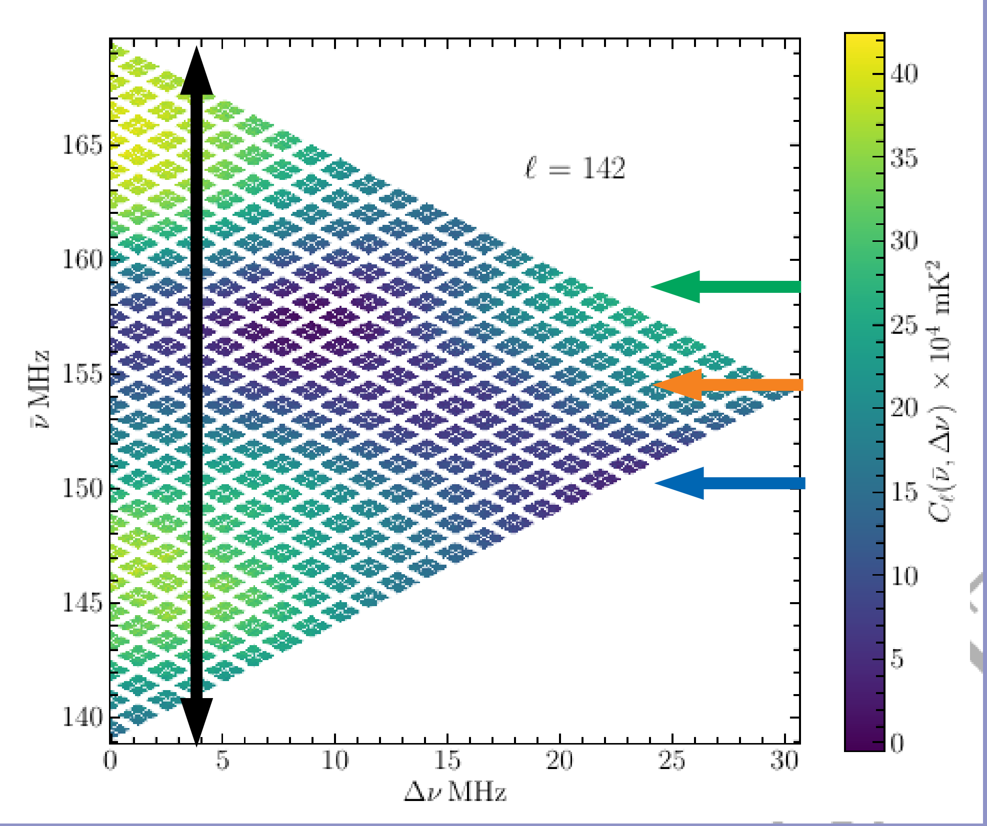
Choudhuri+ 2016, Bharadwaj+ 19, **Elahi**+ 2025

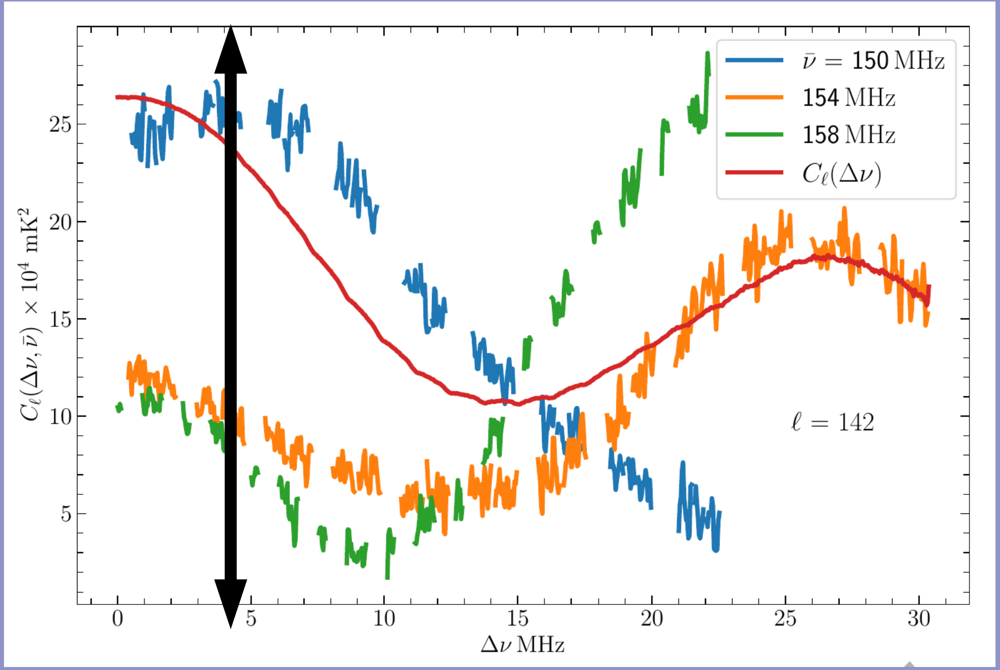




$$C_\ell(\Delta\nu, \bar{\nu}) \rightarrow C_\ell(\Delta\nu)$$

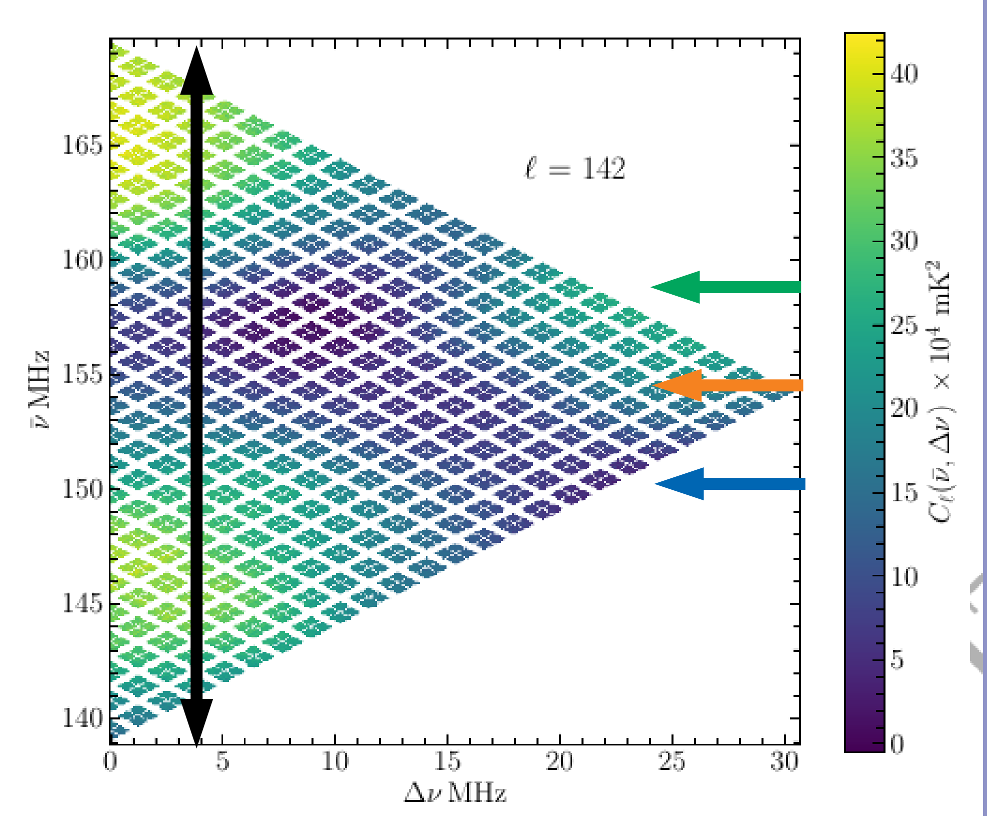
21-cm signal ergodic along the LoS



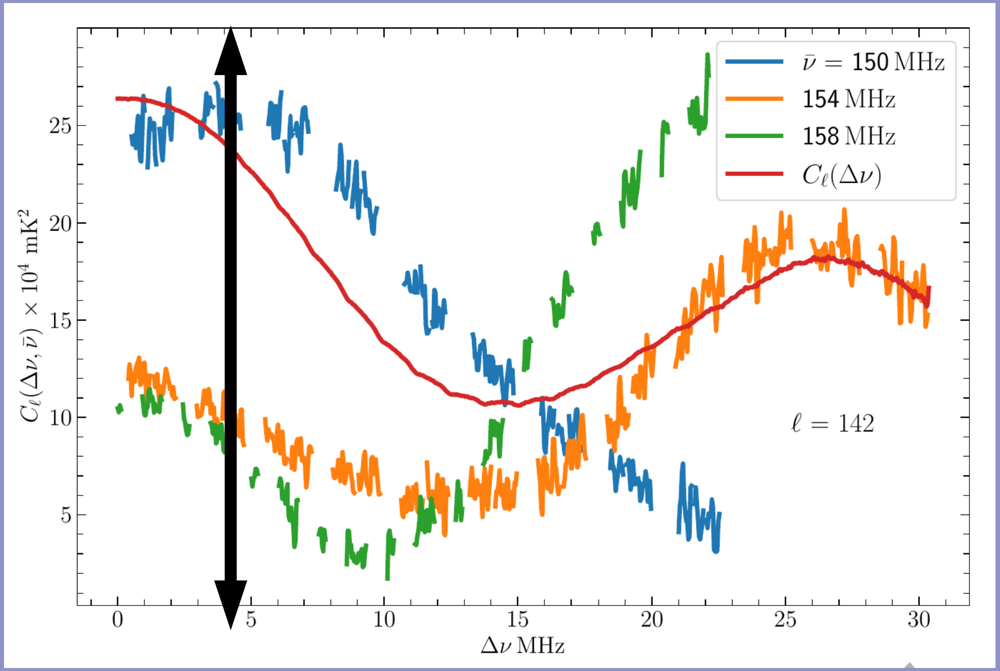


Elahi+ 2025

$C_\ell(\Delta\nu, \bar{\nu})$ → $C_\ell(\Delta\nu)$

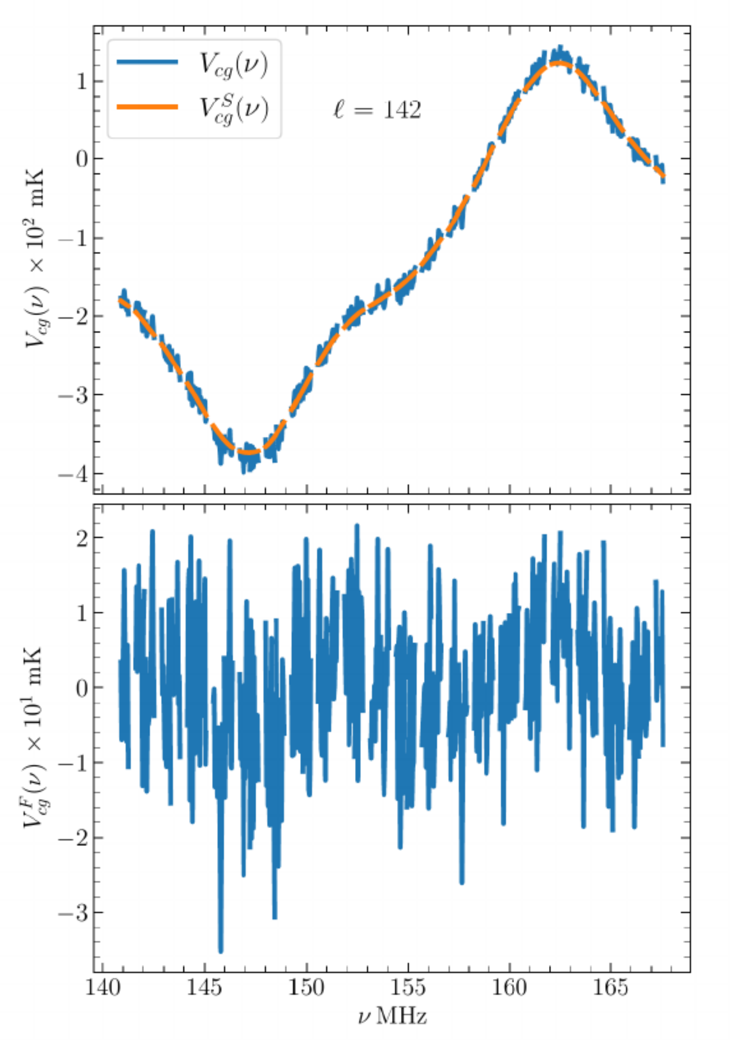


21-cm signal ergodic along the LoS



Foregrounds have spectral feature – it matters **from which frequency we sample** it

Smooth Component Filtering (SCF)



Idea – remove the strong spectral feature

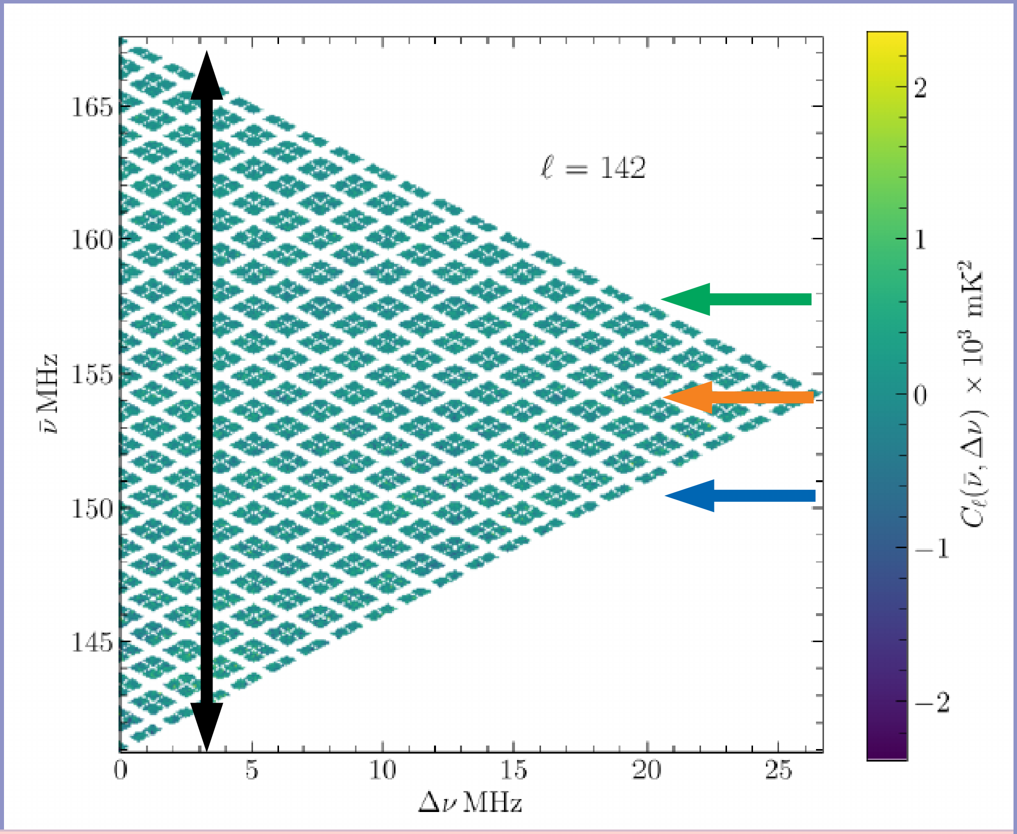
$$H(n) = \frac{1}{4N}\left[1 + \cos\left(2\pi \frac{n}{2N}\right)\right], \quad -N \le n \le N$$

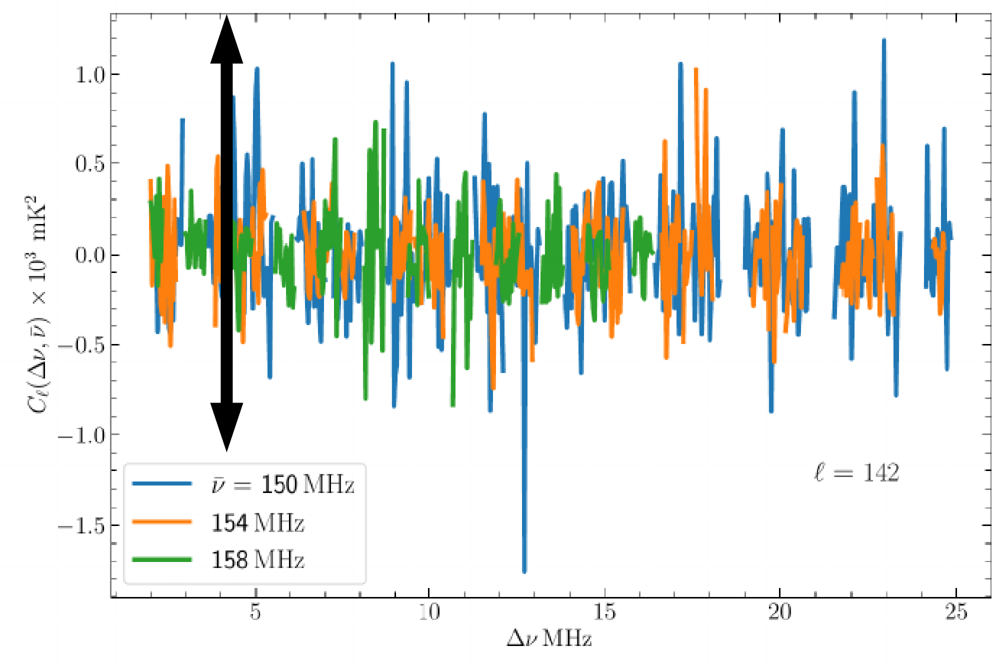
$$\mathcal{V}^S_{cg}(\nu_n) = (\mathcal{V}_{cg} * H)(\nu_n) = \sum_{m=-N}^{N} \mathcal{V}_{cg}(\nu_m) H(n-m)$$

$$\mathcal{V}^F_{cg}(\nu) = \mathcal{V}_{cg}(\nu) - \mathcal{V}^S_{cg}(\nu)$$

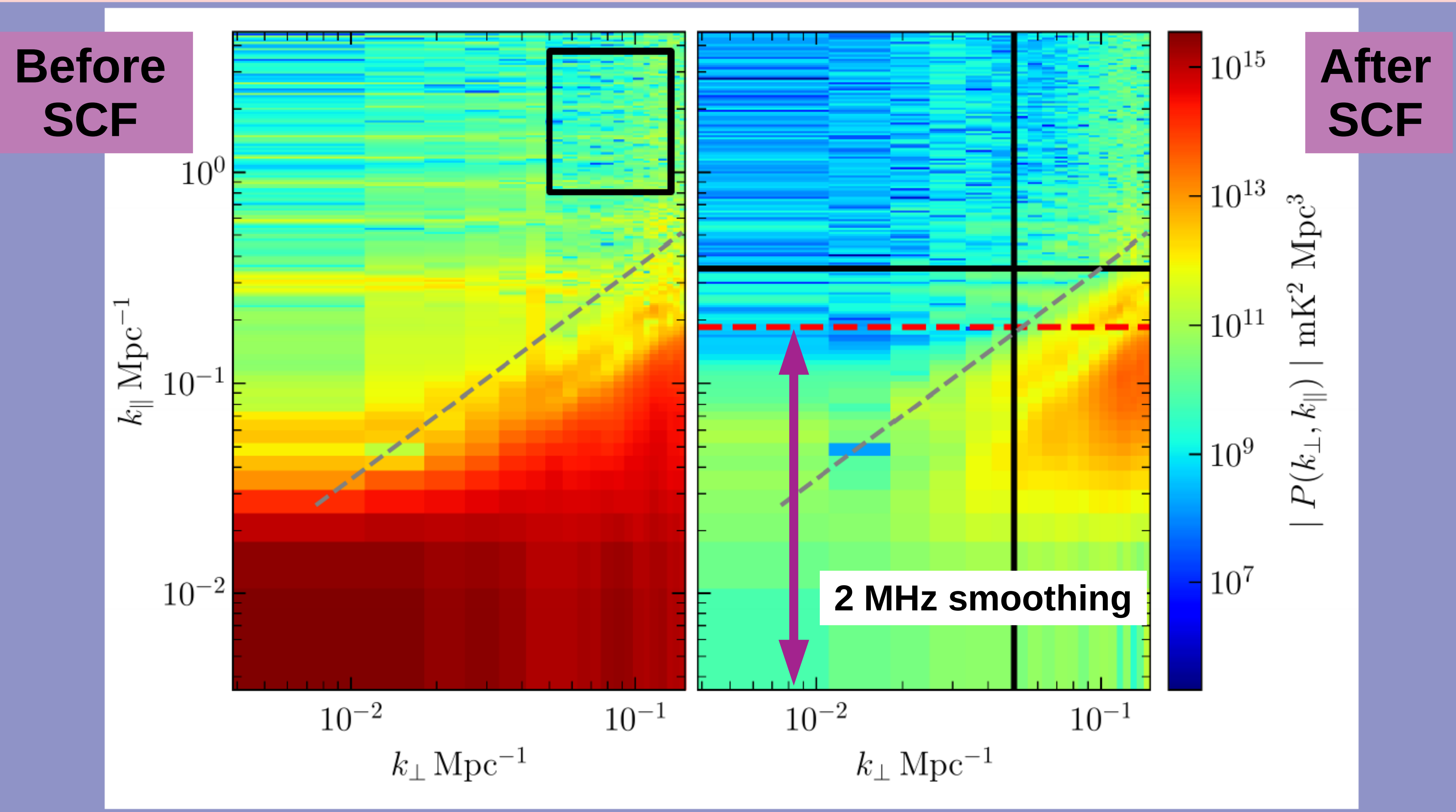
NO signal loss beyond the smoothing scale

The data becomes ***ergodic*** after SCF





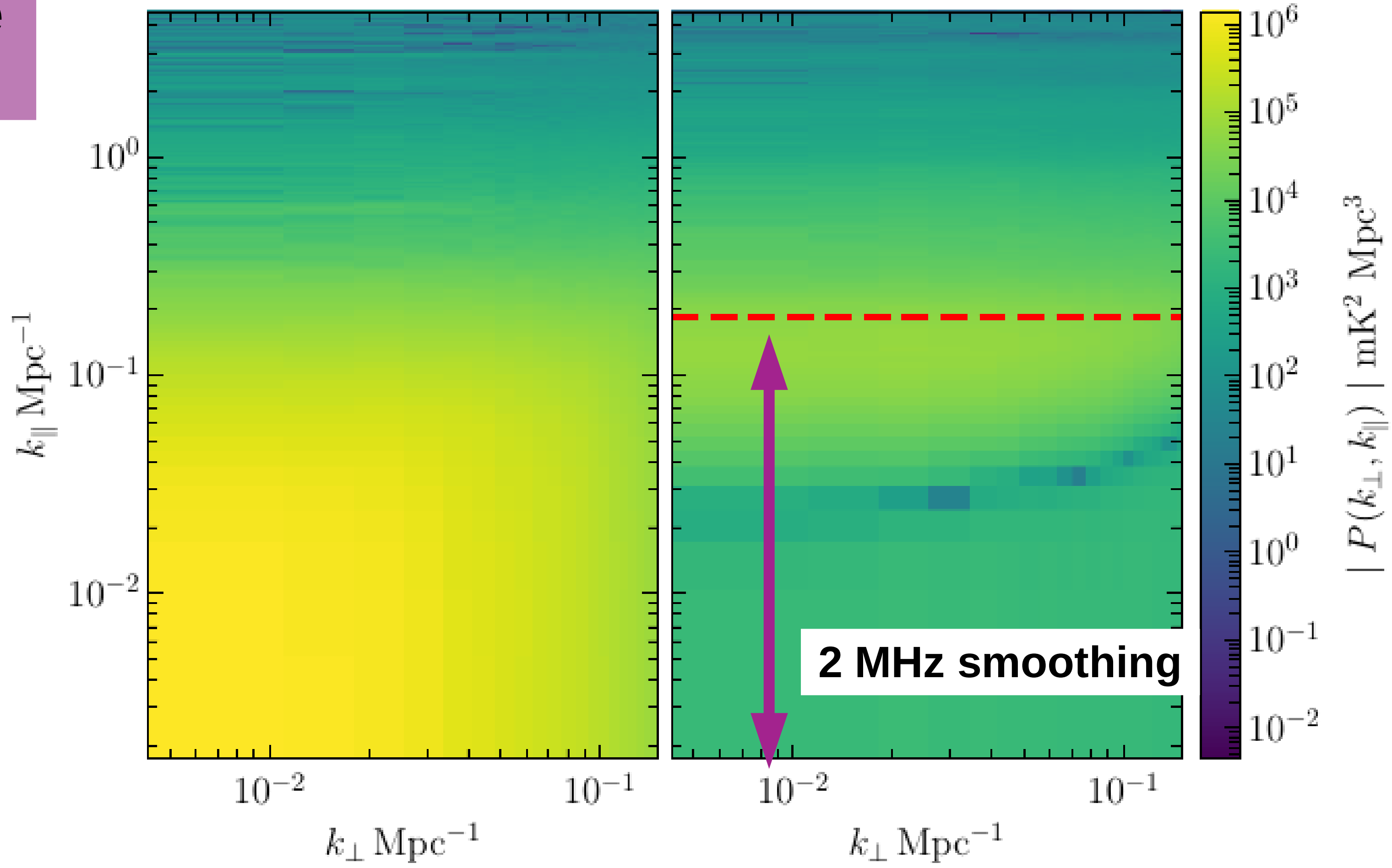
The missing channels have a minimal effects in the power spectrum



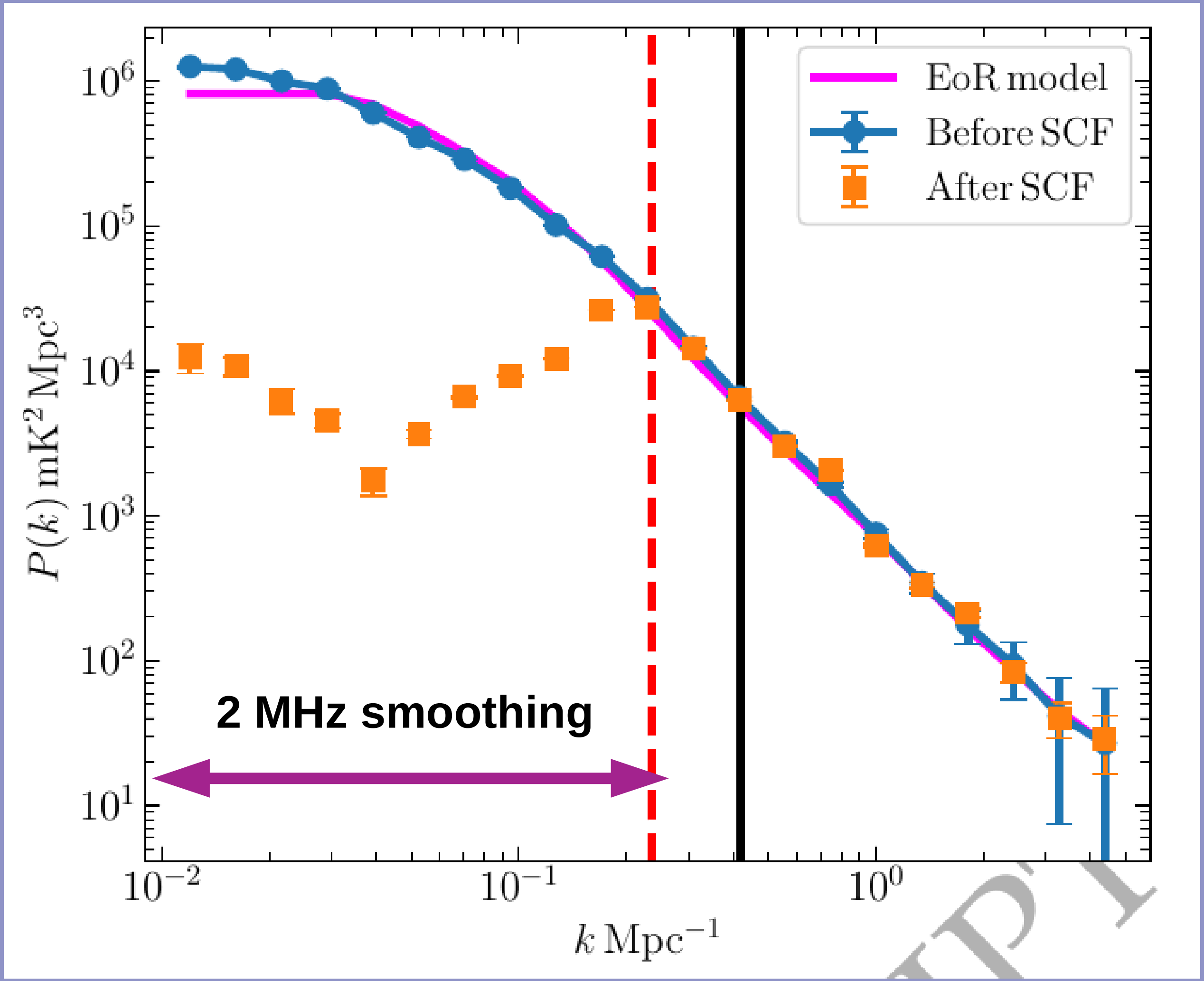
NO signal loss beyond the smoothing scale – simulated 21-cm signal

Before SCF

After SCF



NO signal loss beyond the smoothing scale – simulated 21-cm signal



17 minutes of data, a single pointing center

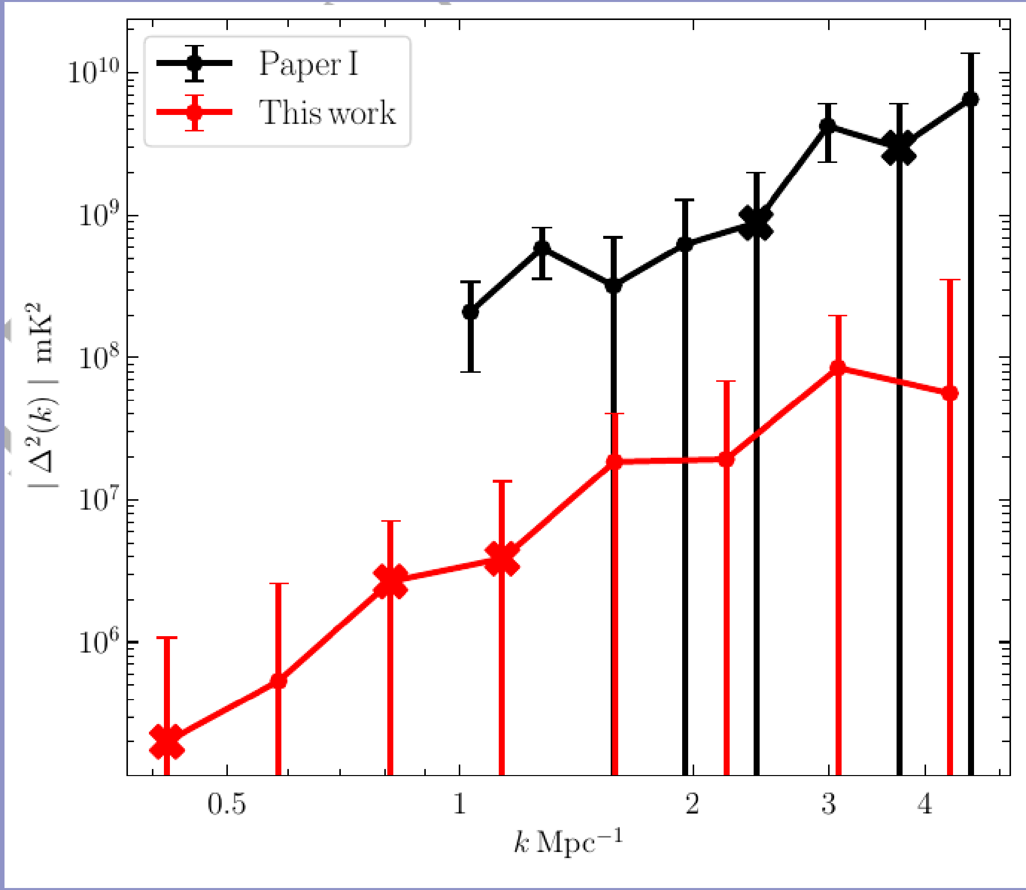


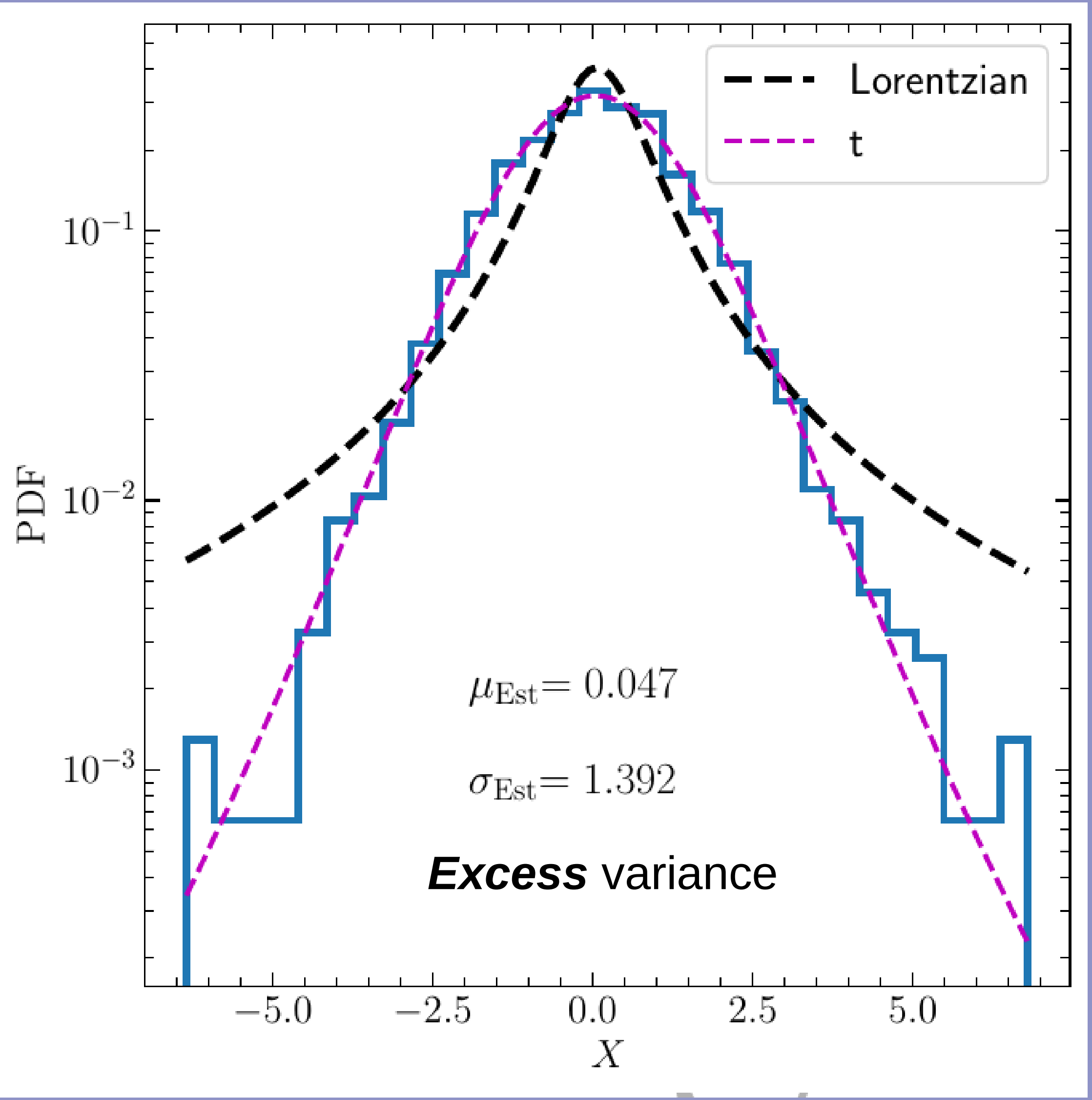
Table 1. The measured $\Delta^2(k)$, corresponding errors $\sigma(k)$, SNR $= \Delta^2(k)/\sigma(k)$, and the 2σ upper limits $\Delta^2_{\mathrm{UL}}(k)$.

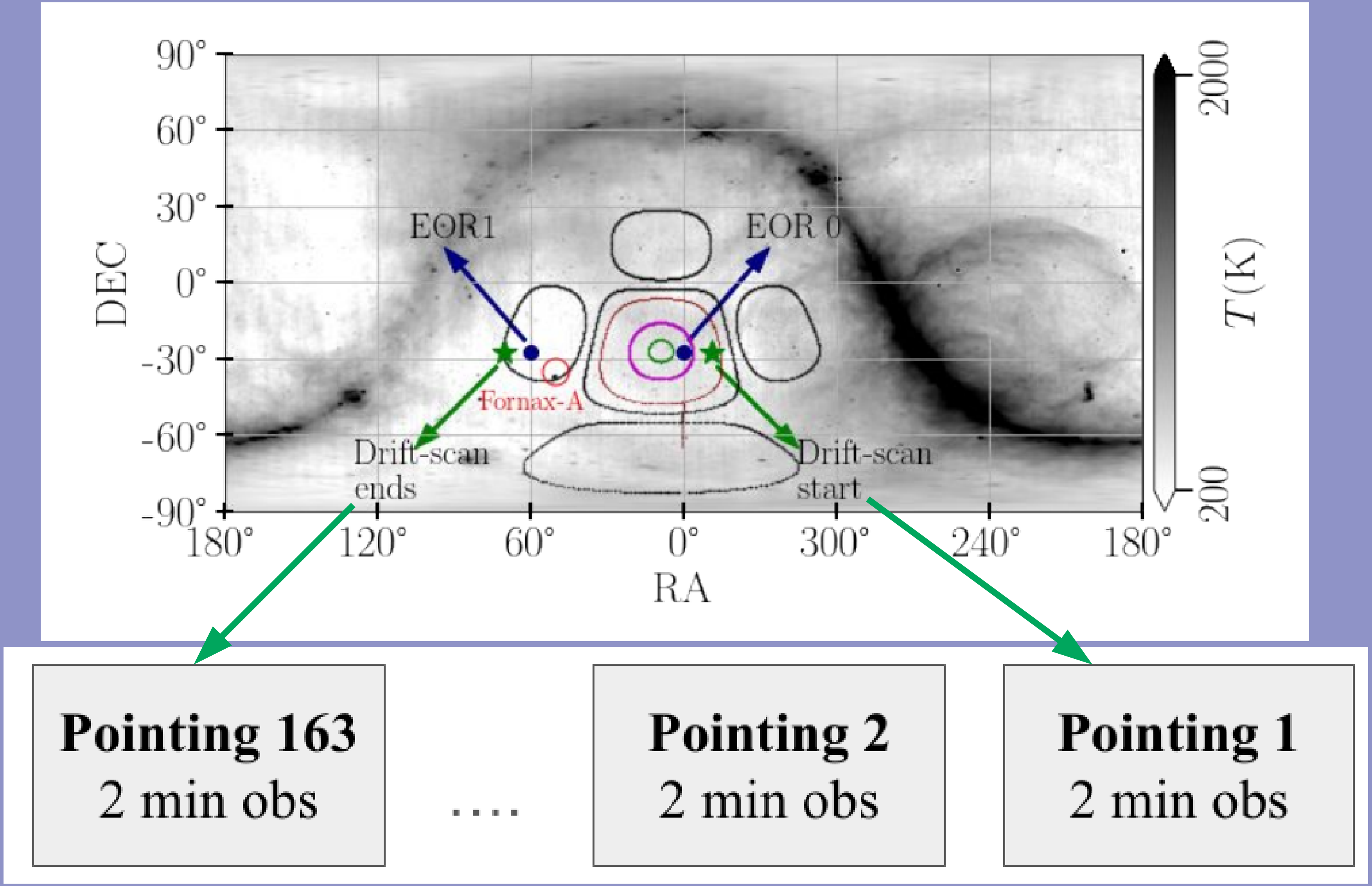
k Mpc^{-1}	$\Delta^2(k)$ mK^2	$\sigma(k)$ mK^2	SNR	$\Delta^2_{\mathrm{UL}}(k)$ mK^2
0.418	$-(447.46)^2$	$(660.86)^2$	−0.46	$(934.60)^2$
0.583	$(731.46)^2$	$(1009.24)^2$	0.53	$(1603.80)^2$
0.813	$-(1633.44)^2$	$(1499.97)^2$	−1.19	$(2121.28)^2$
1.135	$-(1966.73)^2$	$(2190.81)^2$	−0.81	$(3098.28)^2$
1.584	$(4304.10)^2$	$(3301.66)^2$	1.70	$(6350.37)^2$
2.210	$(4395.35)^2$	$(4941.38)^2$	0.79	$(8255.52)^2$
3.085	$(9203.94)^2$	$(7467.56)^2$	1.52	$(14008.62)^2$
4.305	$(7500.37)^2$	$(12154.35)^2$	0.38	$(18753.99)^2$

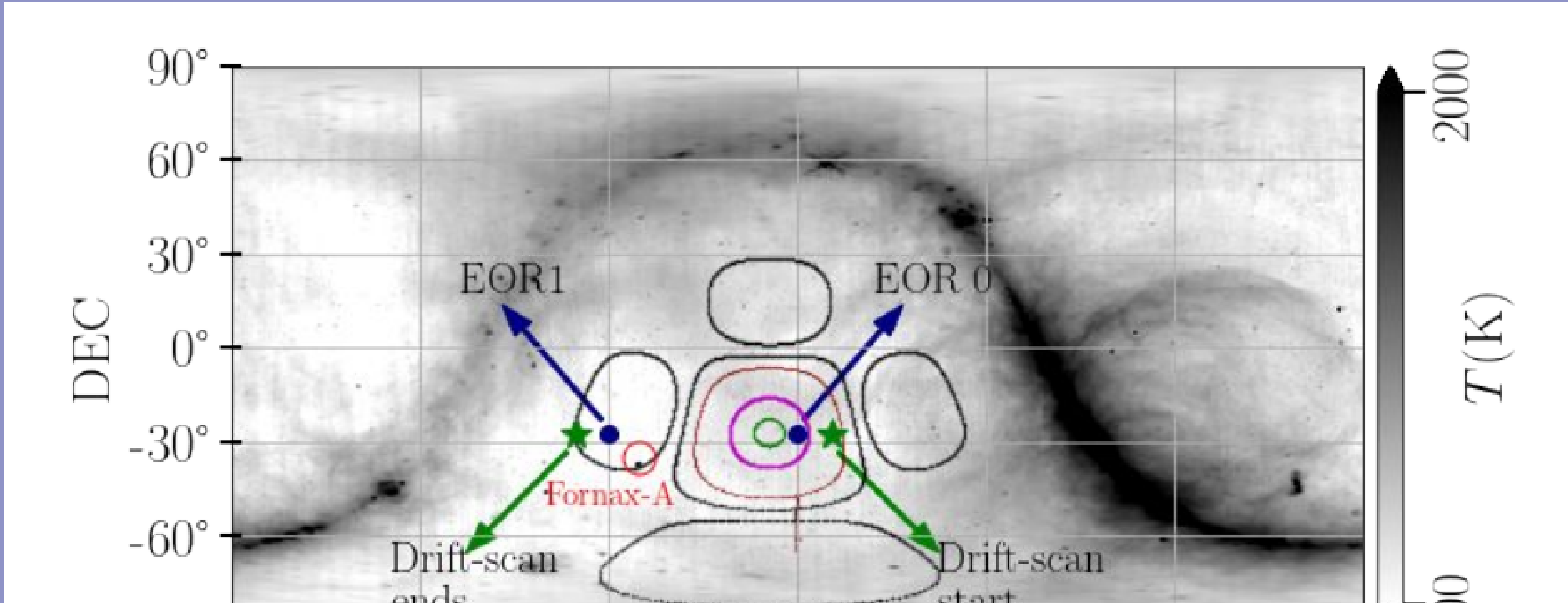
$$X = \frac{P(k_\perp, k_\parallel)}{\delta P_N(k_\perp, k_\parallel)}$$

Pal+ 2020
Elahi+ 2023a,b, 24, **25**

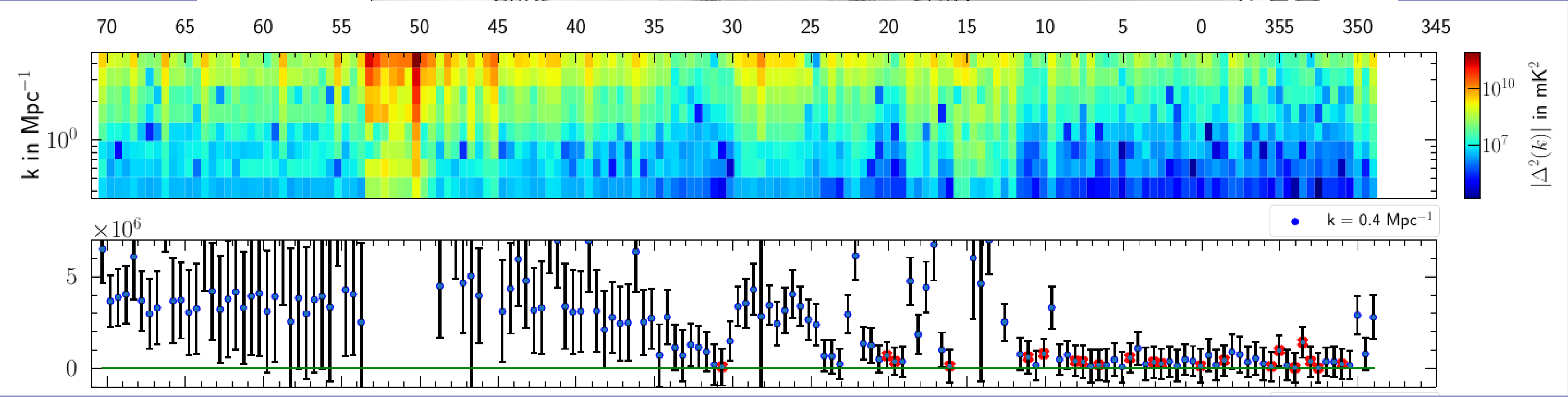
Noise-limited
95% confidence




90°
60°
30°
0°
-30°
-60°
-90°
DEC
EOR1
EOR 0
Fornax-A
Drift-scan
ends
Drift-scan
start
180°
120°
60°
0°
300°
240°
180°
RA
2000
200
T(K)
Pointing 163
2 min obs
....
Pointing 2
2 min obs
Pointing 1
2 min obs

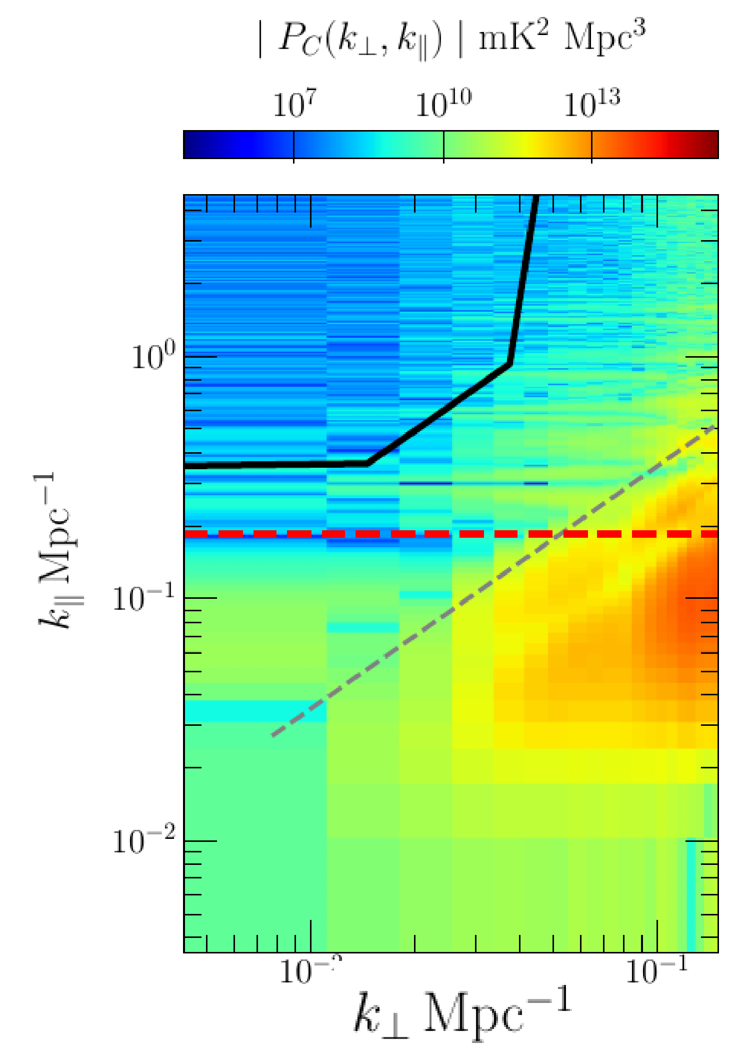


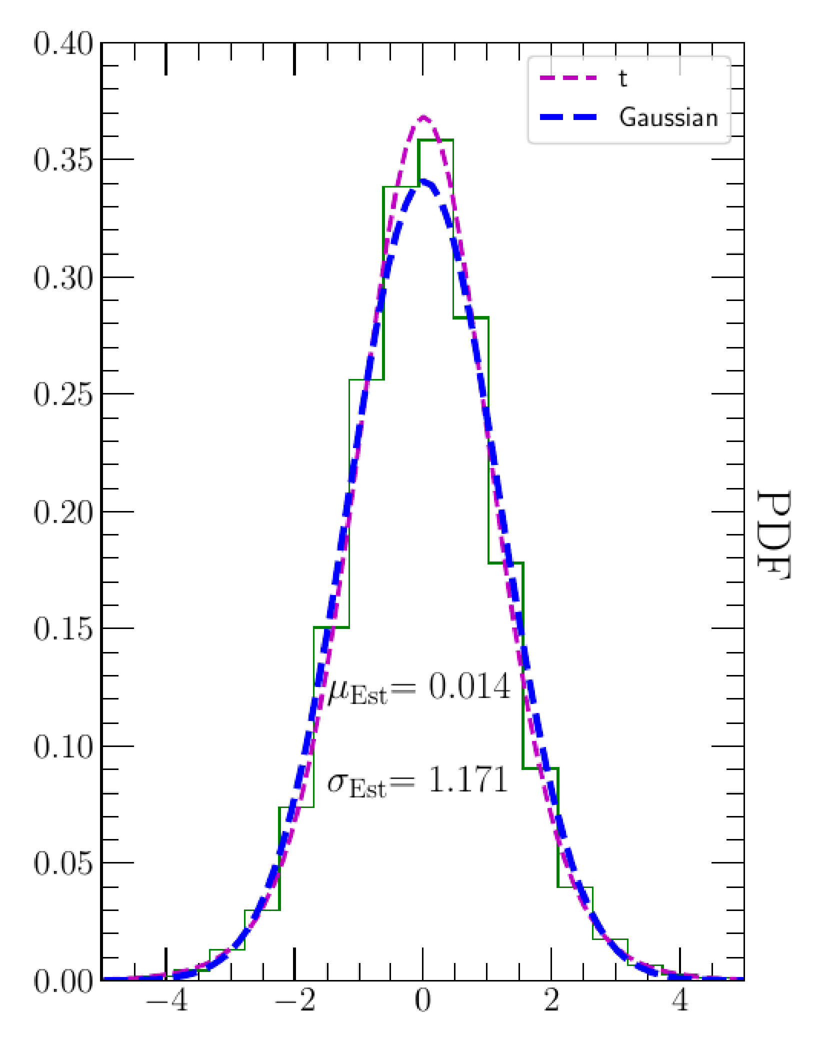
90°
60°
30°
0°
-30°
-60°
DEC
EOR1
EOR 0
Fornax-A
Drift-scan
Drift-scan
2000
T(K)

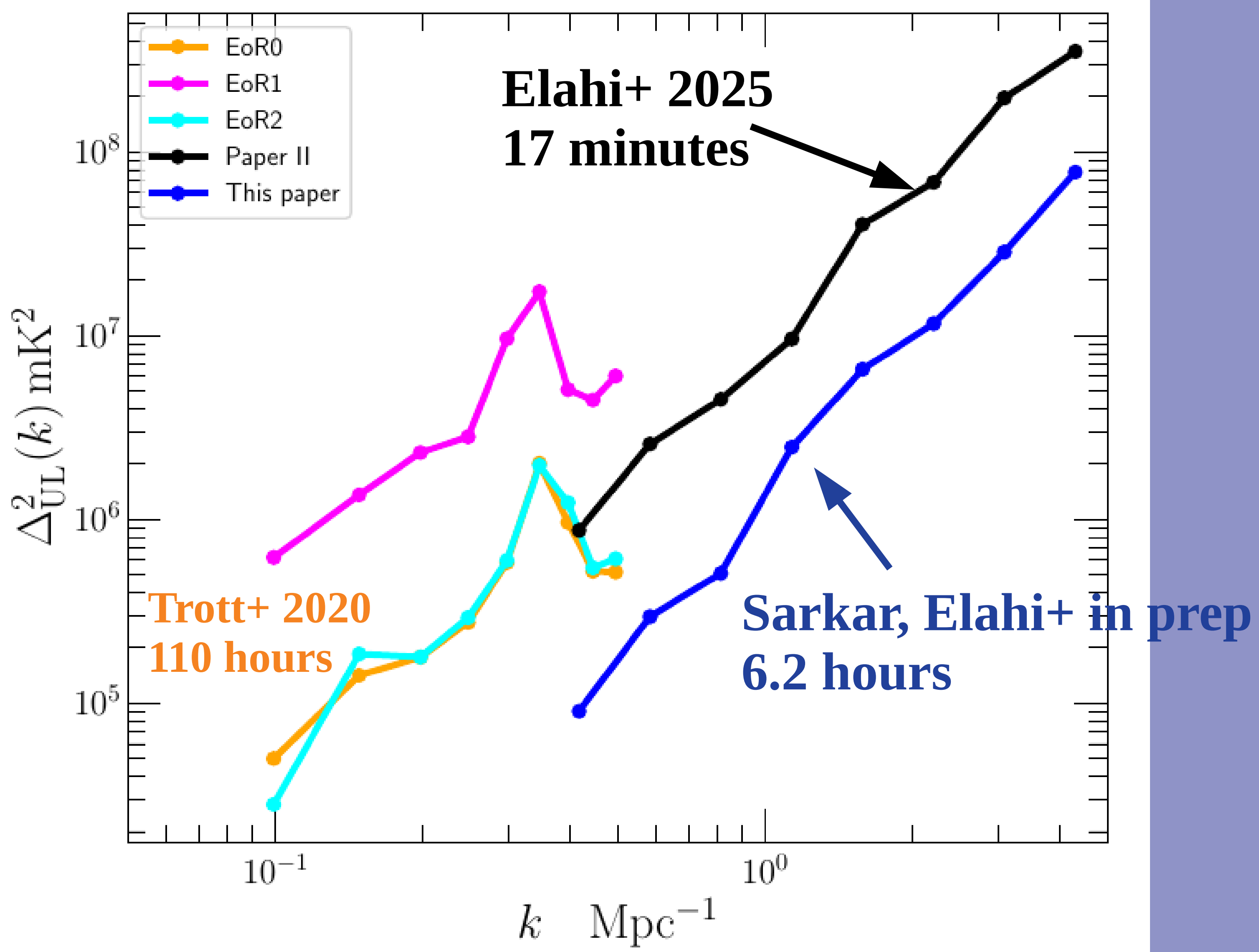


70 65 60 55 50 45 40 35 30 25 20 15 10 5 0 355 350 345
k in Mpc^{-1}
10^0
10^{10}
10^7
$|\Delta^2(k)|$ in mK^2
$\times 10^6$
k = 0.4 Mpc^{-1}
5
0

Incoherent addition







EoR0
EoR1
EoR2
Paper II
This paper
Elahi+ 2025
17 minutes
Trott+ 2020
110 hours
Sarkar, Elahi+ in prep
6.2 hours
10^{8}
10^{7}
10^{6}
10^{5}
$\Delta^2_{\mathrm{UL}}(k)\,\mathrm{mK}^2$
10^{-1}
10^{0}
$k\quad \mathrm{Mpc}^{-1}$

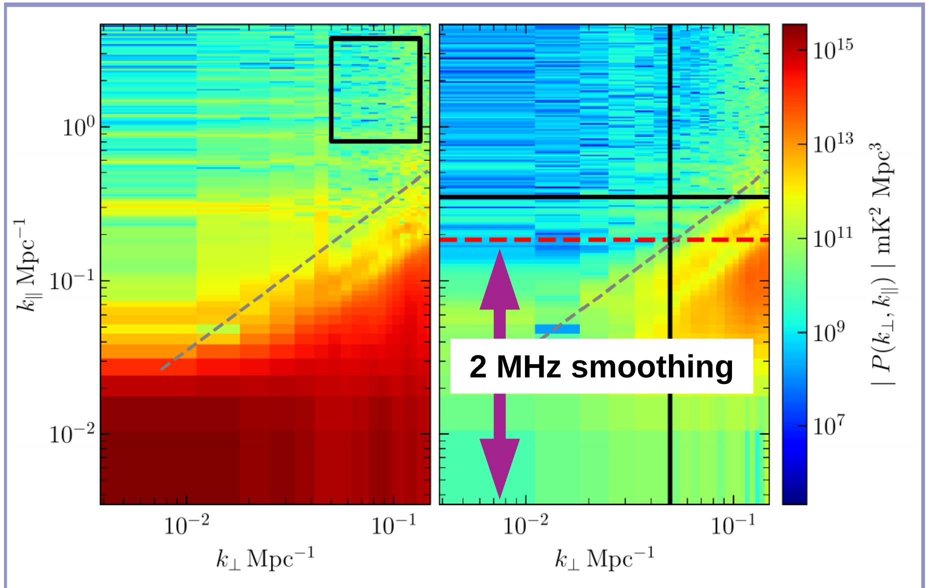
Summary

1. MWA bandpass has a priodic gap – leads to **a periodic pattern of missing channels**
2. Direct FFT of the visibilities – **a periodic spike in the power spectrum**
3. Instead, **estimate MAPS** then do a FFT

$$P(k_{\perp}, k_{\|}) = r^2 r' \int_{-\infty}^{\infty} d(\Delta\nu)\, e^{-i k_{\|} r' \Delta\nu} C_{\ell}(\Delta\nu)$$

4. **Still tiny ripples – due to strong spectral features in the data**
5. **SCF** – filter out the smooth component first
6. **No signal loss** beyond the smoothing scale
7. Tight constraints from only **17 minutes** of data

8. *(preliminary)* **10 times improved** once **incoherently** combine **6.2 hours** the drift scan.



Thank You

>> The Polyphase Filter Bank (PFB) technique divides the bandwidth of 30.72 MHz into 24 coarse bands, each of 1.28 MHz.

This is right. The *PFB does* the spectral decomposition (divides) the observed band (up to 330 MHz) into equal-width (1.28 MHz) subbands. Out of 256 such subbands, 24 coarse channels are selected and recorded for observation.

>> Is this division required for a faster processing of the signal?

The division is necessary to efficiently distribute data chunks to different backend computers, each processing one or more subbands. First, the subbands are divided into 10 kHz channels, and then they are correlated between all possible baselines. This is a compute-intensive task.

>> Next, the PFB response is not uniform over a coarse band

Normally, getting strictly uniform band shapes for a filter is a little hard. It concerns the length of the PFB filter used, coefficient choice (filter shape considered for the base filter), weightage and the PFB architecture choices.

>> For some reason, the response falls near the edges (just like a bandpass filter). Is this the reason for flagging four channels from each end of a course band?

This is due to a choice made for the filter coefficients; there was a complex tradeoff taken in the initial day, considering maximal flatness of the band, reasonable sideband attenuation and reducing the leakages from the neighbouring channels. We are flagging and not using the edge channels, where there will be some amount of leakages of signal information from the adjacent frequency channels. Calibrating and using those channels is a little tricky and hard.