Power Spectrum Measurements from drift scan observations: Results from MWA

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Collaborators

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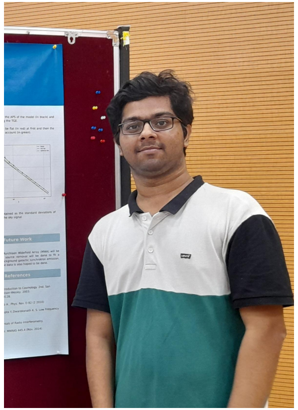
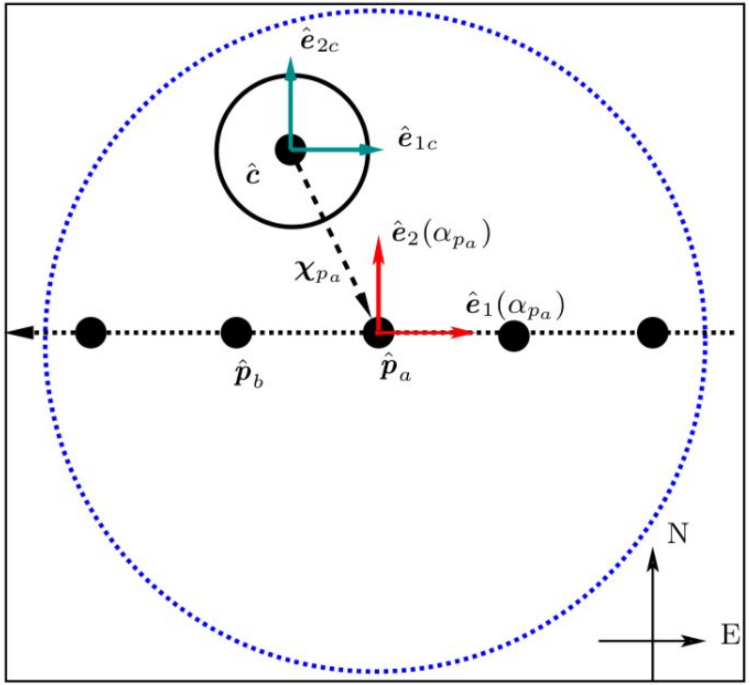


Shouvik Sarkar

Asif Elahi

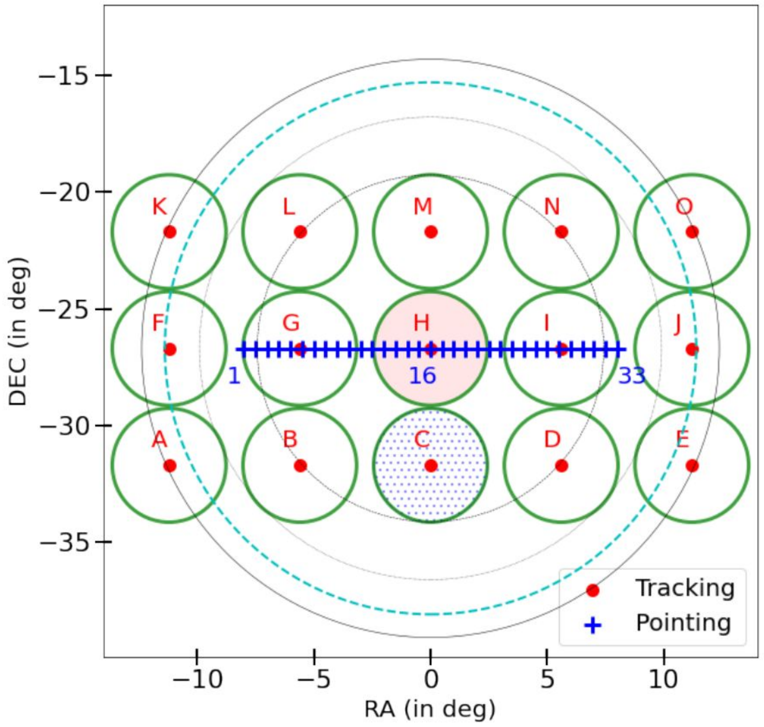
Suman Chatterjee

Drift scan



$\hat{e}_{2c}$
$\hat{e}_{1c}$
$\hat{c}$
$\hat{e}_2(\alpha_{p_a})$
χ_{p_a}
$\hat{e}_1(\alpha_{p_a})$
$\hat{p}_b$
$\hat{p}_a$
N
E

Drift scan



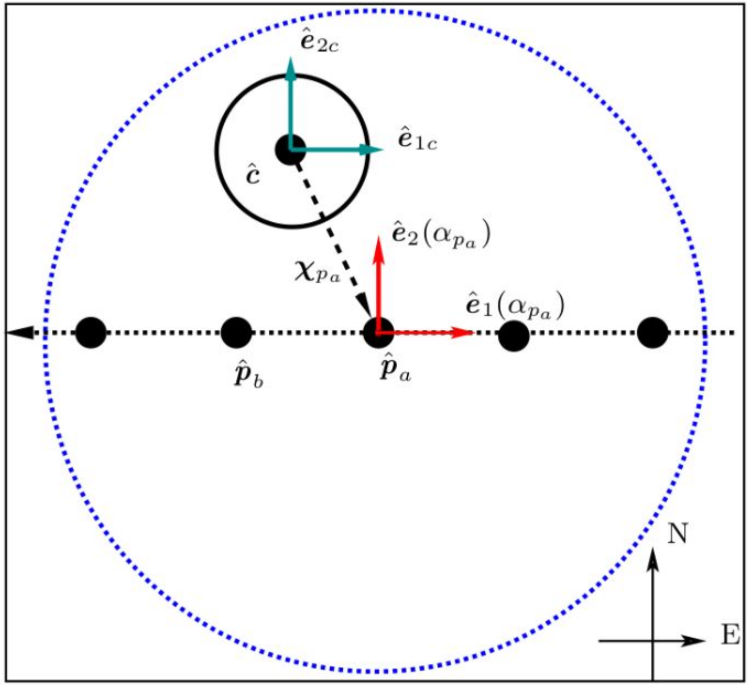
K
L
M
N
O
F
G
H
I
J
A
B
C
D
E
1
16
33
Tracking
Pointing
−15
−20
−25
−30
−35
DEC (in deg)
−10
−5
0
5
10
RA (in deg)

Aim

Develop an estimator for Drift scan observation which will increase SNR by combining different pointing and tracking centres to increase the SNR

-Tracking Tapered Gridded Estimator (TTGE)

Drift scan

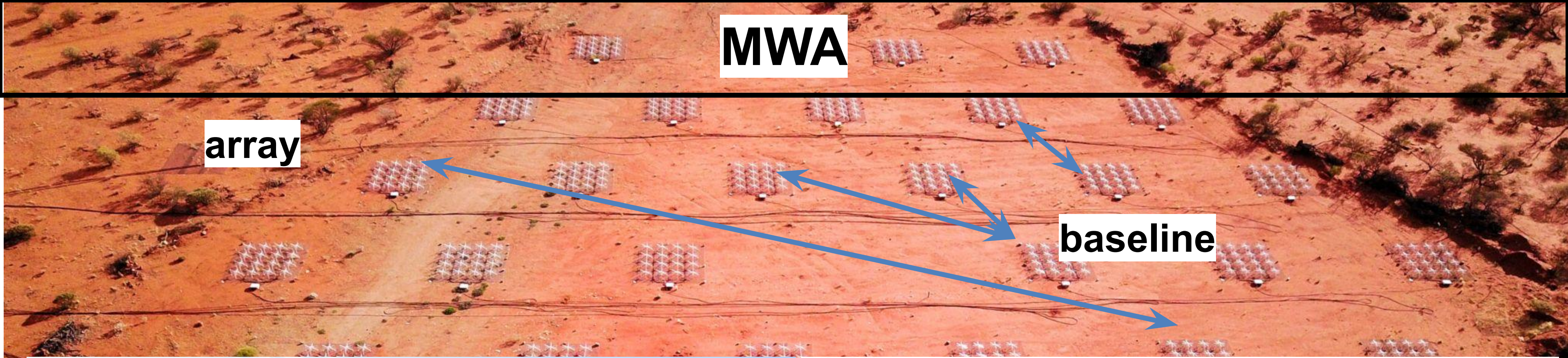


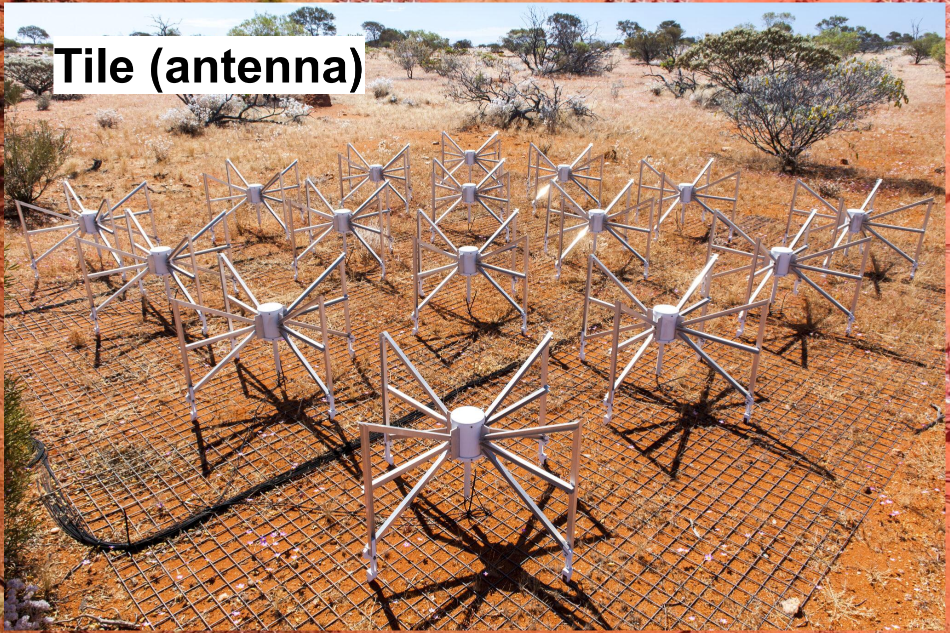
$$\mathcal{V}_{cg}(\nu) = \sum_p s_p \sum_n \tilde{w}(\boldsymbol{U}_g - \boldsymbol{U}_n) e^{2\pi i \boldsymbol{U}_n \cdot \boldsymbol{\chi}_p} \mathcal{V}(\alpha_p, \boldsymbol{U}_n, \nu)$$

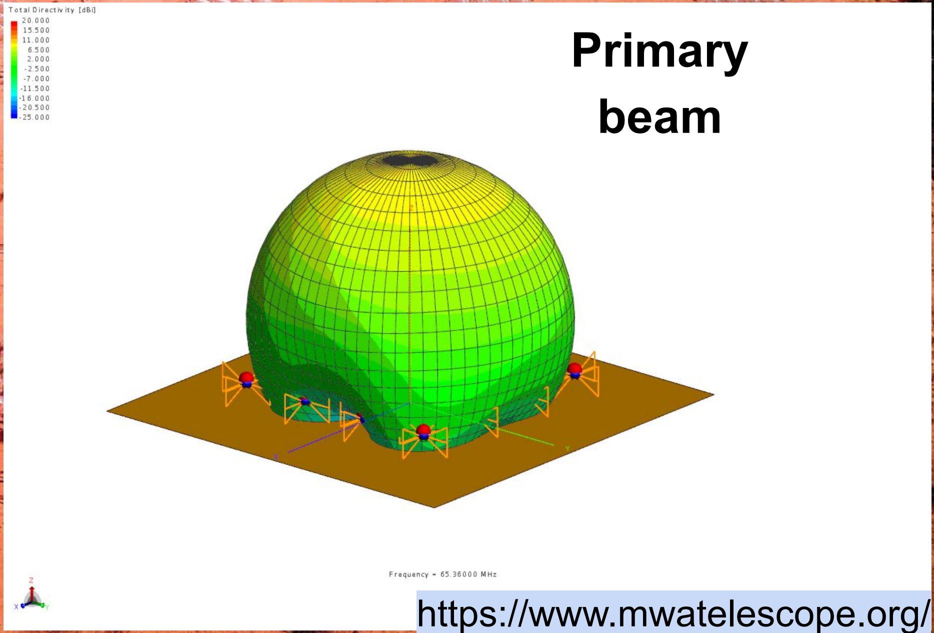
Estimator

$$\hat{E}_g(\nu_a, \nu_b) = M_g^{-1}(\nu_a, \nu_b) \mathcal{R}e \left[\mathcal{V}_{cg}(\nu_a) \mathcal{V}^*_{cg}(\nu_b) - \delta_{a,b} \sum_{p,n} \mid s_p \tilde{w}(\boldsymbol{U}_g - \boldsymbol{U}_n) \mid^2 \mid \mathcal{V}(\alpha_p, \boldsymbol{U}_n, \nu_a) \mid^2 \right].$$


Murchison Widefield Array
https://www.mwatelescope.org/

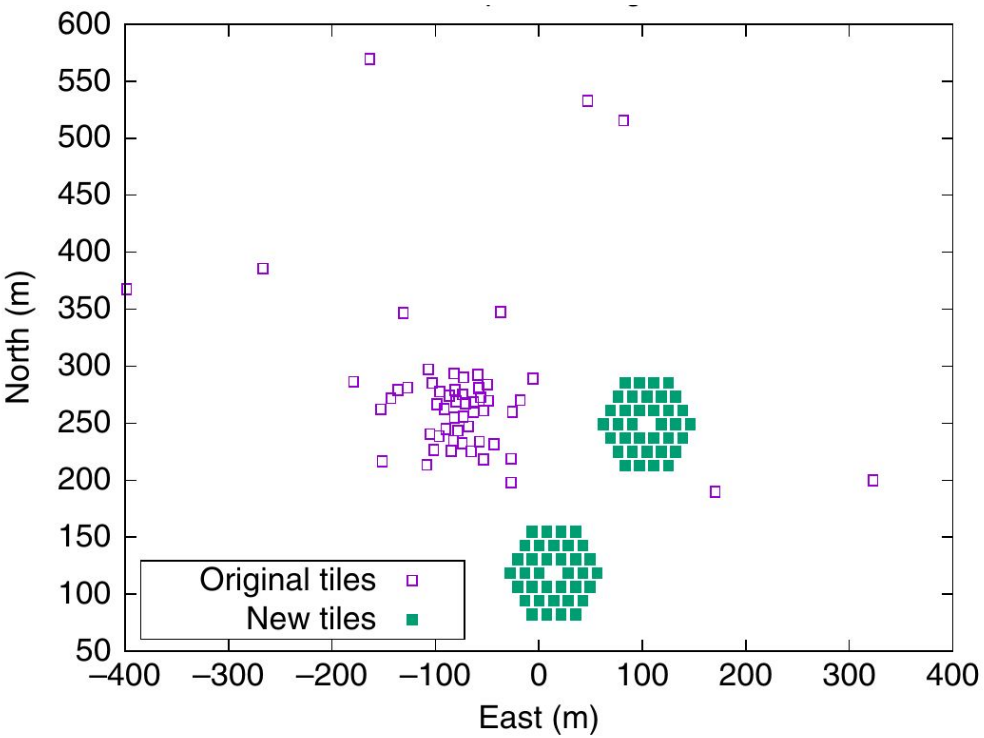


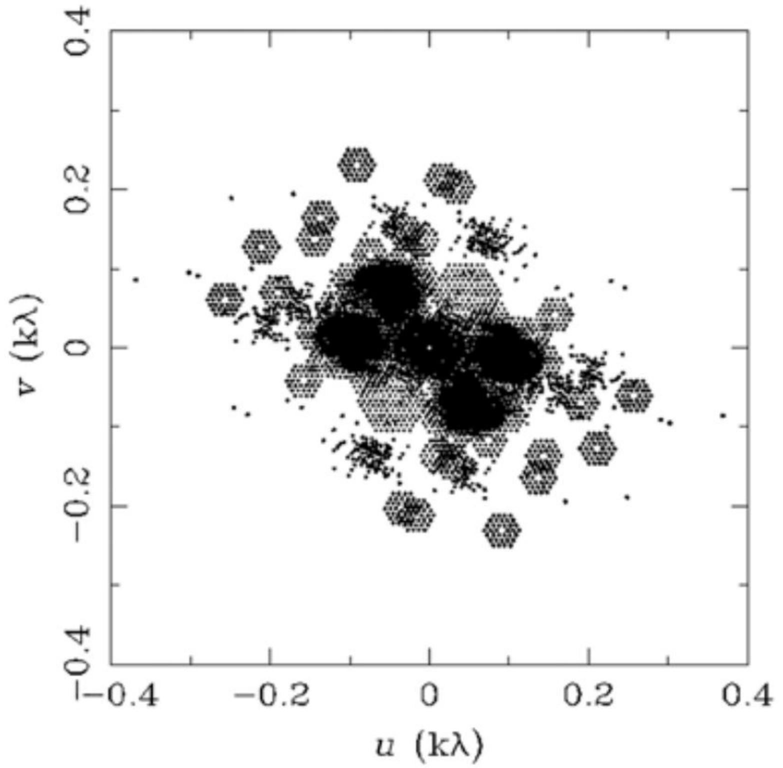




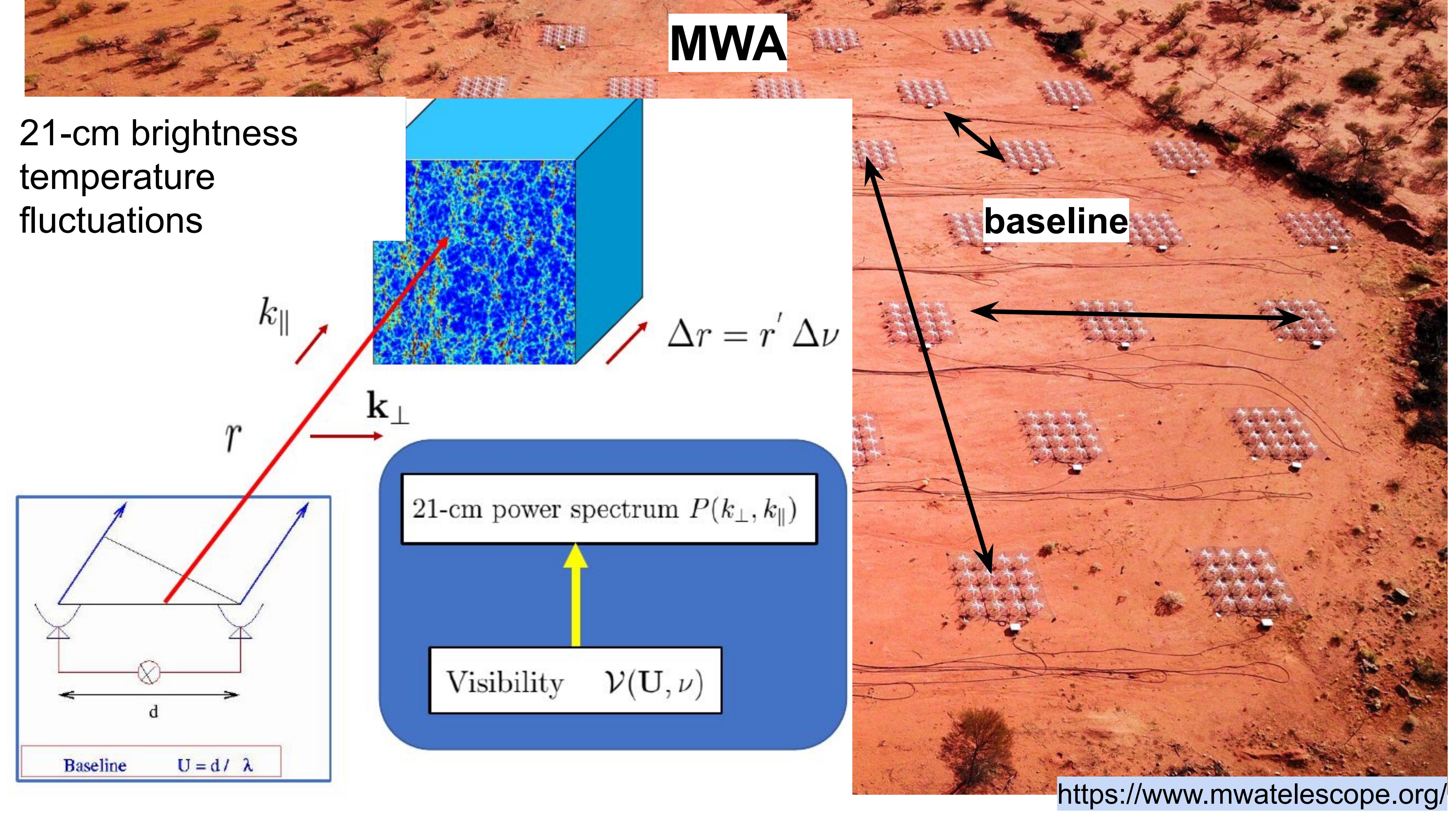
https://www.mwatelescope.org/

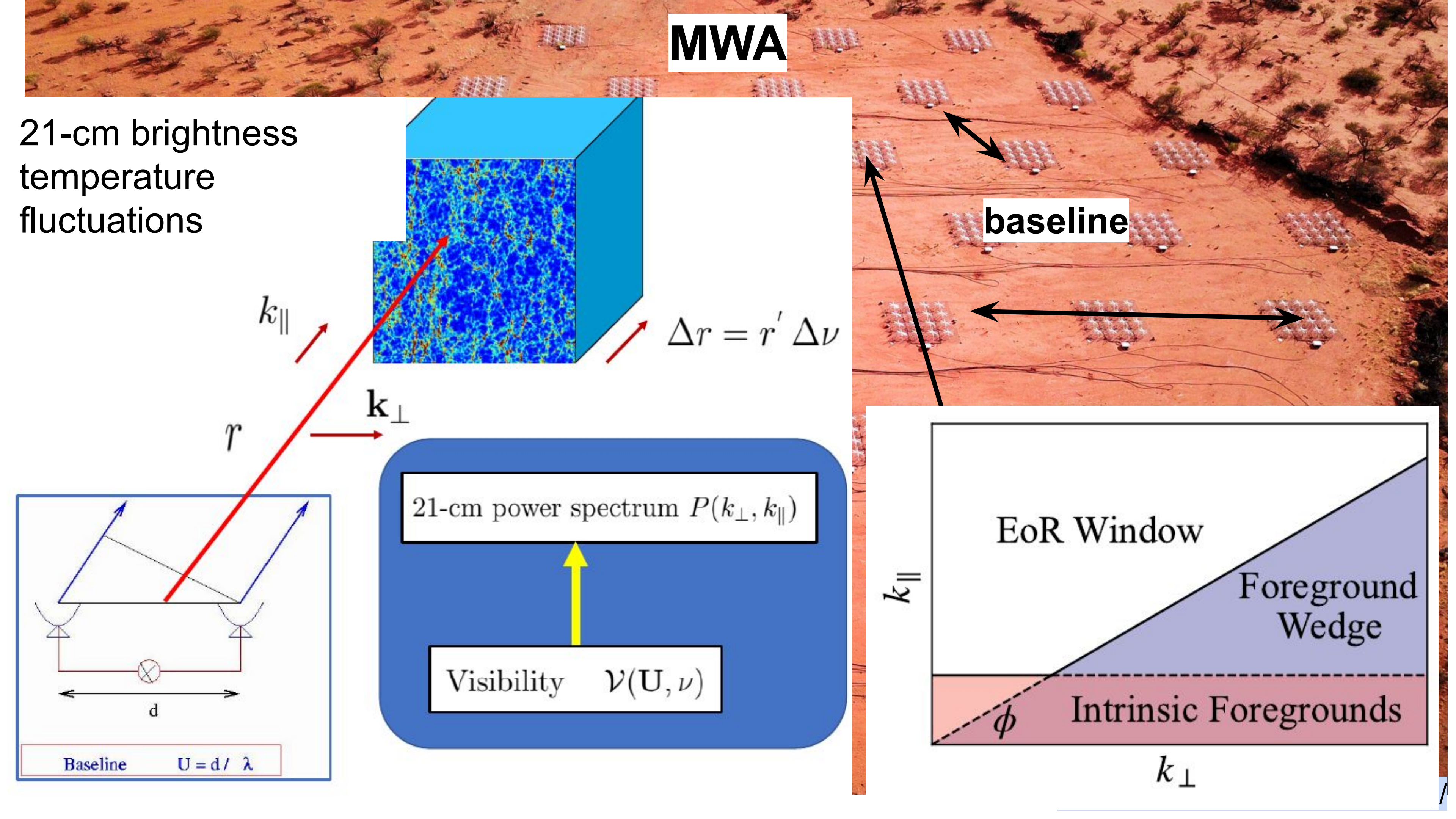
MWA Phase II compact configuration





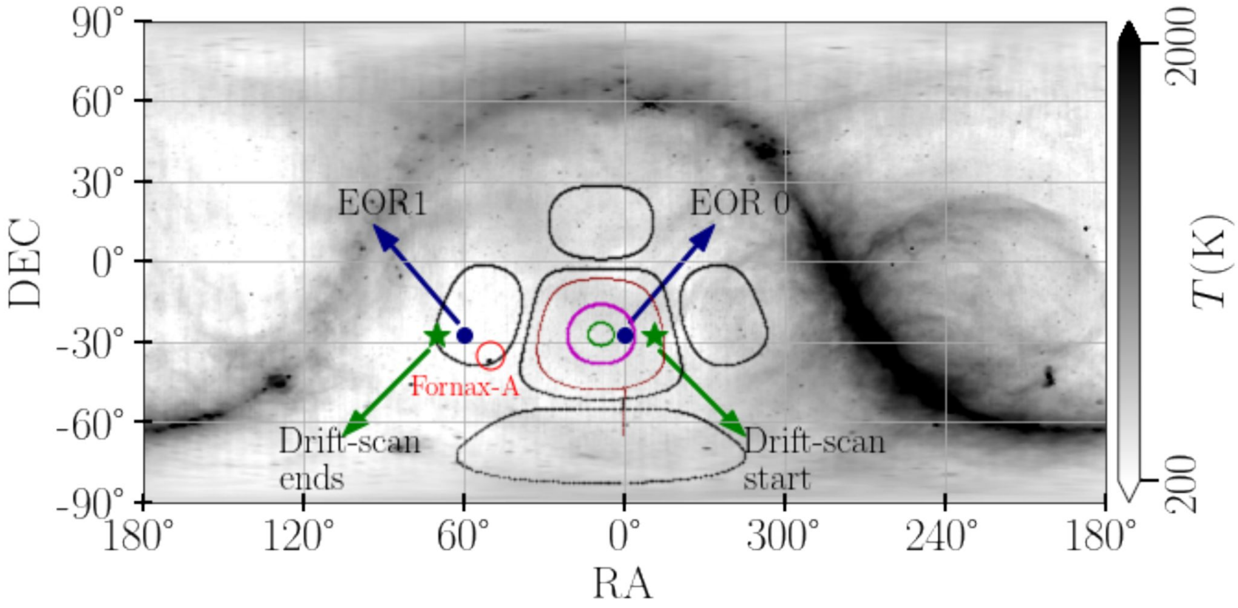
Wyath+ 2018


MWA
21-cm brightness temperature fluctuations
baseline
$k_{\parallel}$
$\Delta r = r' \Delta\nu$
$\mathbf{k}_{\perp}$
r
21-cm power spectrum $P(k_{\perp}, k_{\parallel})$
Visibility $\mathcal{V}(\mathbf{U}, \nu)$
d
Baseline U = d / λ
https://www.mwatelescope.org/



MWA
21-cm brightness temperature fluctuations
baseline
$k_{\|}$
$\Delta r = r' \Delta\nu$
$\mathbf{k}_{\perp}$
r
21-cm power spectrum $P(k_{\perp}, k_{\|})$
Visibility $\mathcal{V}(\mathbf{U}, \nu)$
d
Baseline $U = d/\lambda$
EoR Window
Foreground Wedge
Intrinsic Foregrounds
ϕ
$k_{\|}$
$k_{\perp}$

Phase II MWA Observation



RA - 349◦ to 70.3◦, 162 different pointing centers, 0.5◦ interval along RA

Time duration of 5 hr 24 min, 10 nights (project ID G0031)

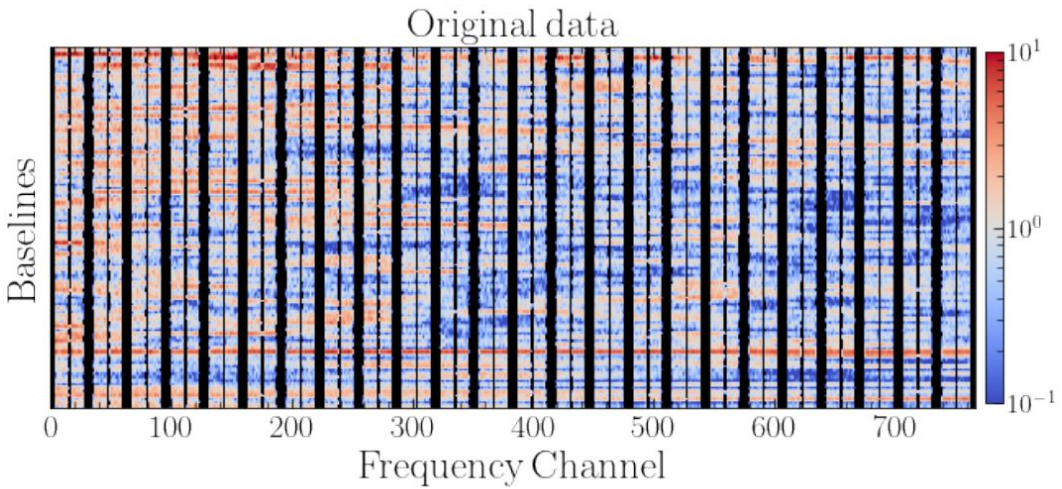
Phase II MWA Observation

Central frequency = 154.2 MHz (z = 8.2)

Nc = 768 channels, resolution = 40 kHz (BW = 30.72 MHz)

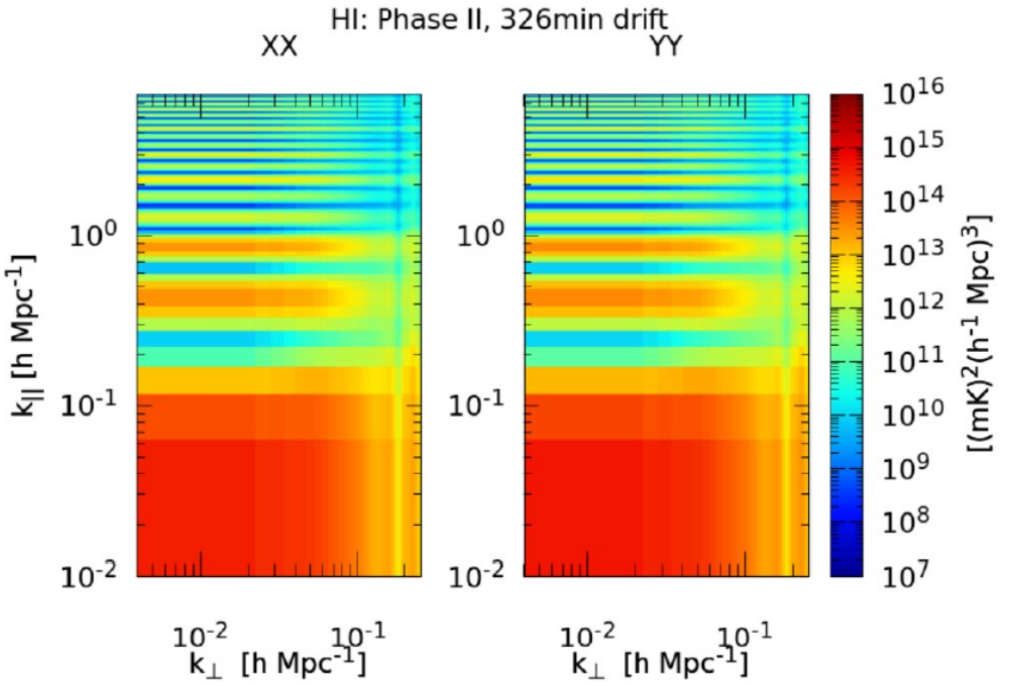
further divided into 24 coarse bands, containing 32 channels or 1.28 MHz

time resolution 0.5 sec



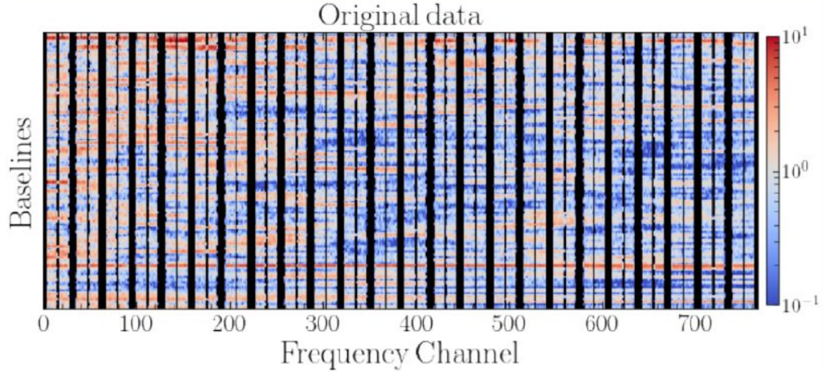
Data Analysis given in Patwa, Sethi, Dwarkanath 2021, MNRAS

The infamous "**coarse band harmonics**"



The power spectrum from a typical MWA data shows* a periodic pattern along $k_{\|}$

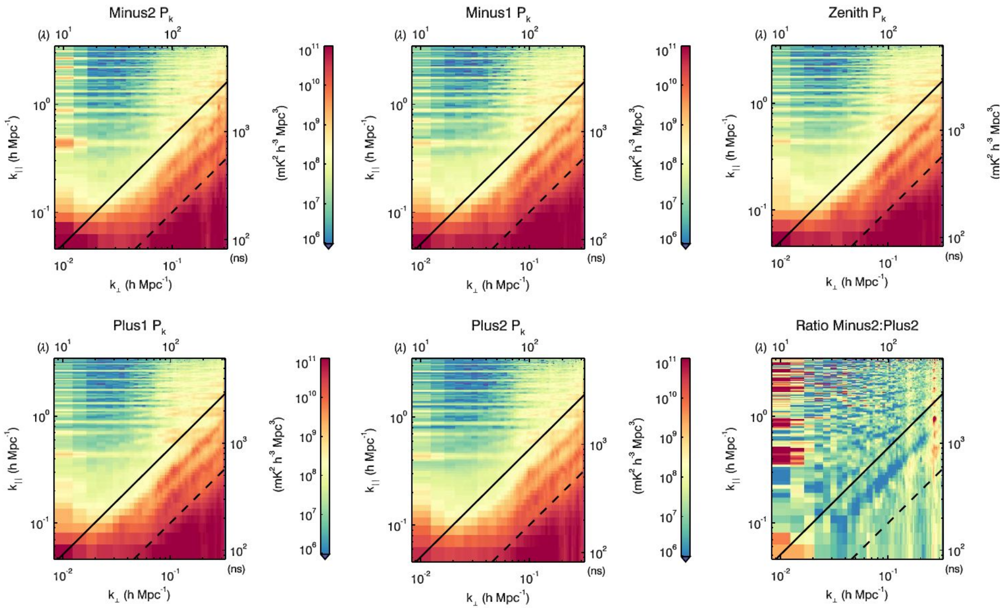
*in delay spectrum approach

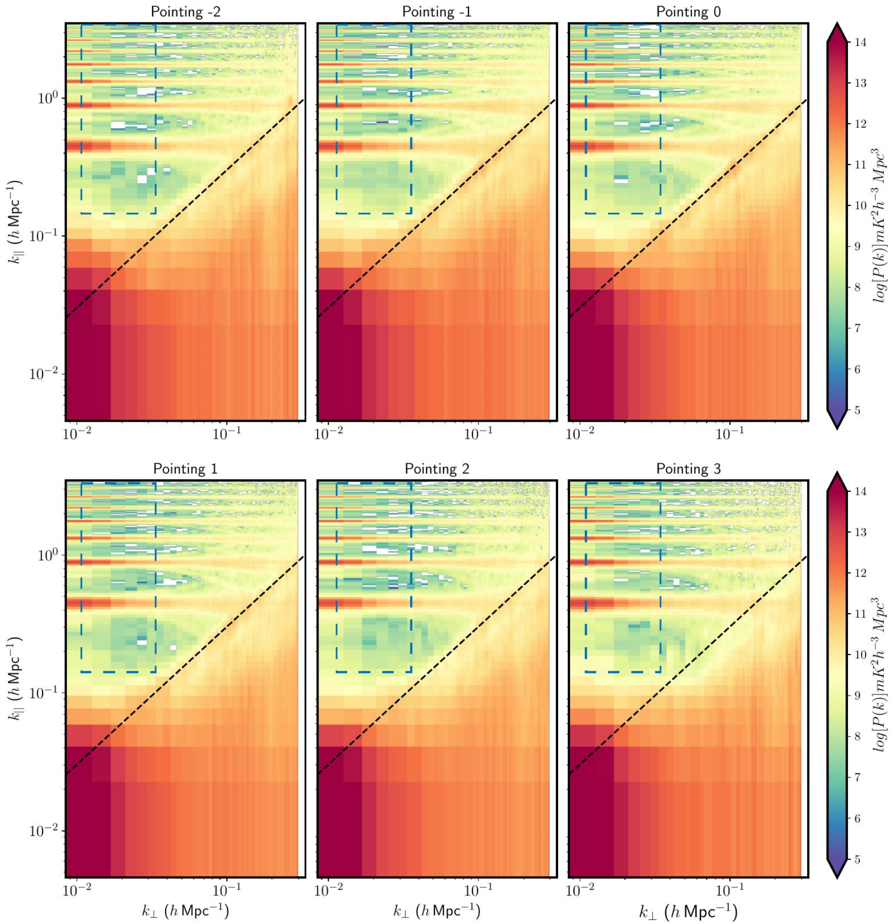


Actual observation at 154 MHz (z = 8.2)
Patwa et al. 2021

The "missing frequency channels" – The visibility data has a periodic pattern of flagging

The coarse band harmonics



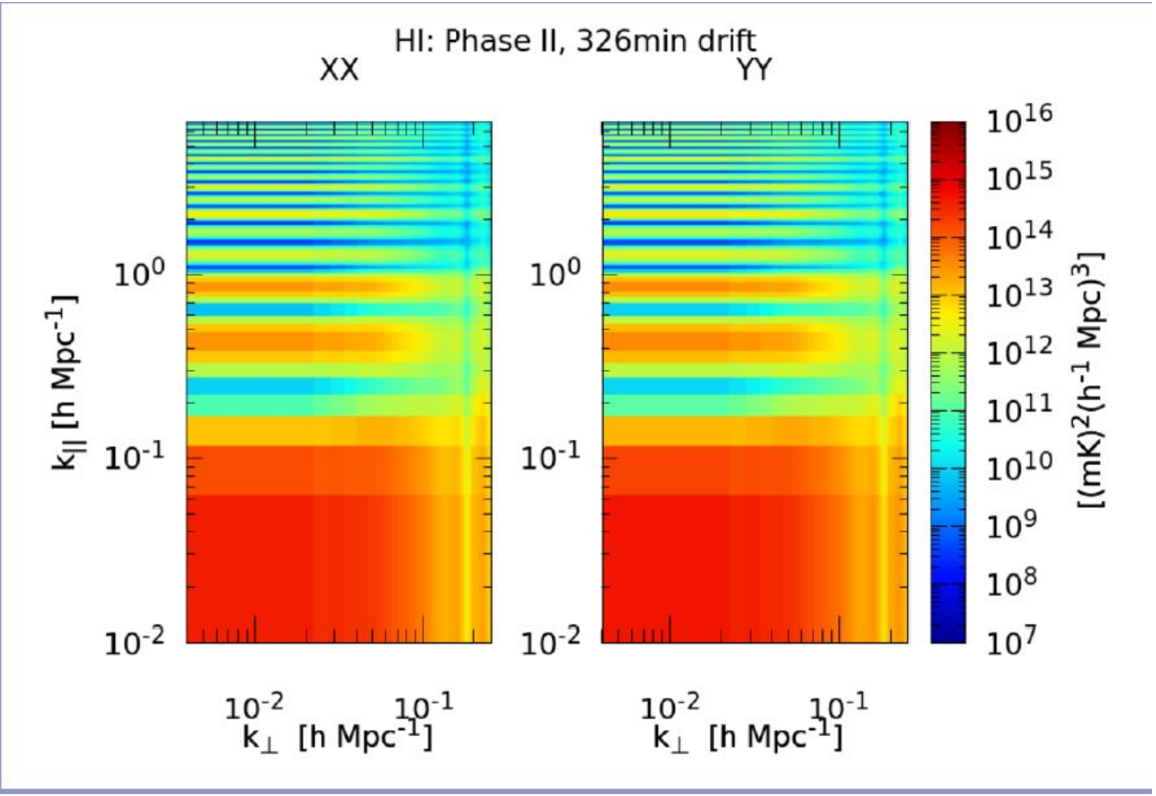


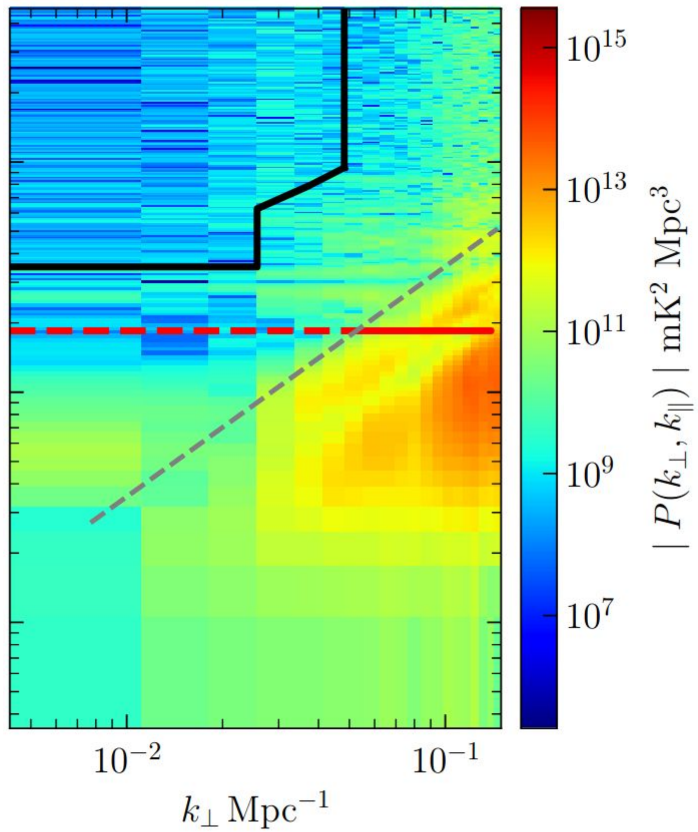
Trott + 2020

Nunhokee + 2024

Patwa et al. 21

Our results - 17 min

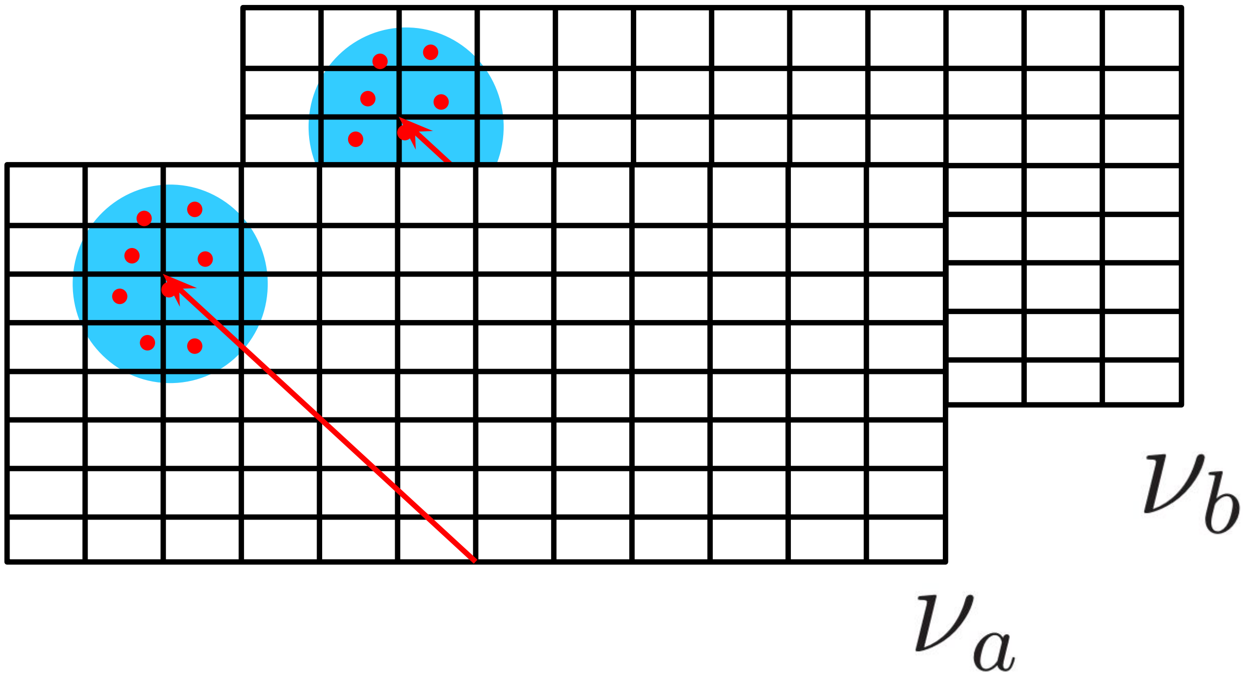




Same data

Elahi et al 2025

TGE: MAPS and the Power-Spectrum



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

MAPS

Tapered Gridded Estimator (TGE)

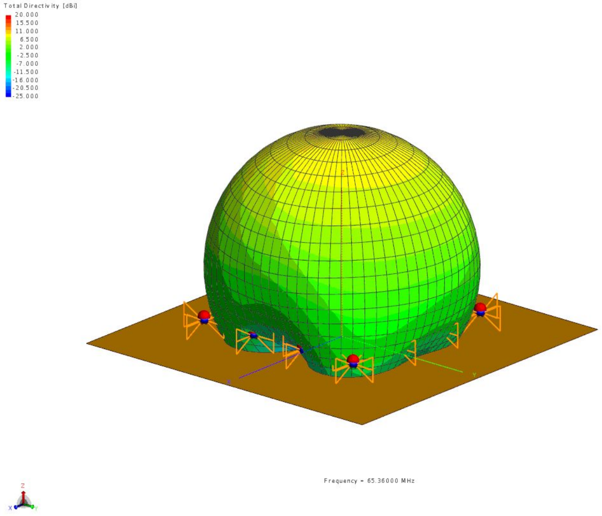
$$\langle \mathcal{V}(\mathbf{U}, \nu_a) \mathcal{V}(\mathbf{U}, \nu_b) \rangle = \left[\frac{\pi Q^2 \theta_0^2}{2} \right]_{\nu_c} C_\ell(\nu_a, \nu_b)$$

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

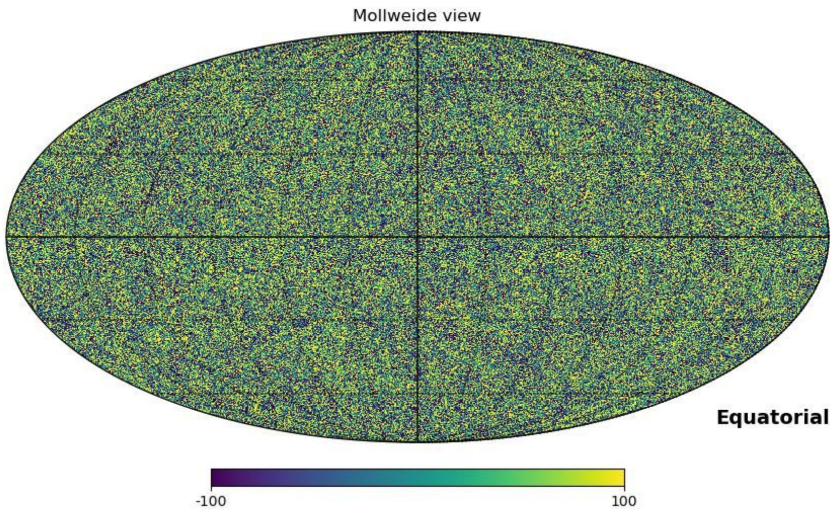
Visibility data → MAPS → Power Spectrum

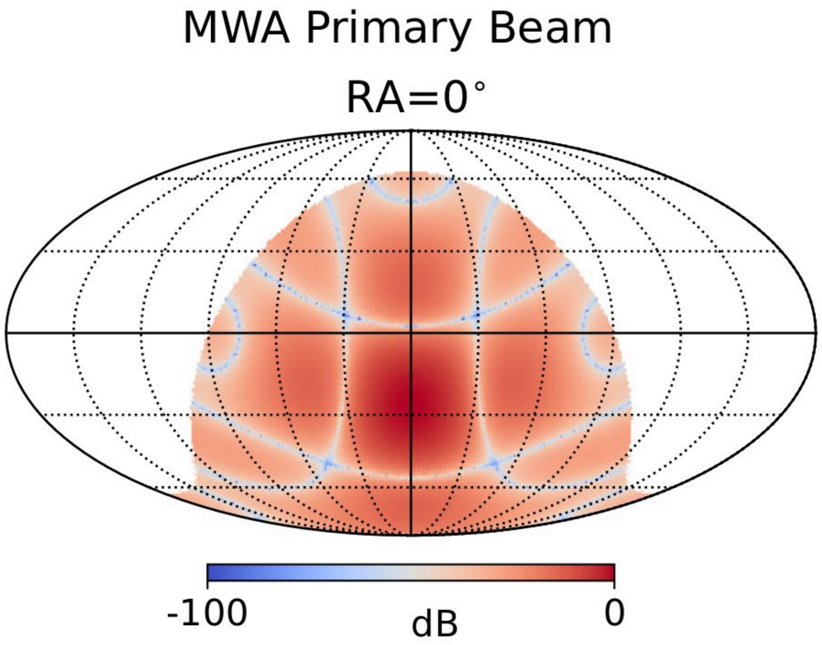
$$C_\ell(\Delta\nu) \equiv C_\ell(|\nu_a - \nu_b|) = C_\ell(\nu_a, \nu_b)$$

1. Sidelobe suppression
2. **Immune to missing frequency channels**
3. Fast
4. Unbiased



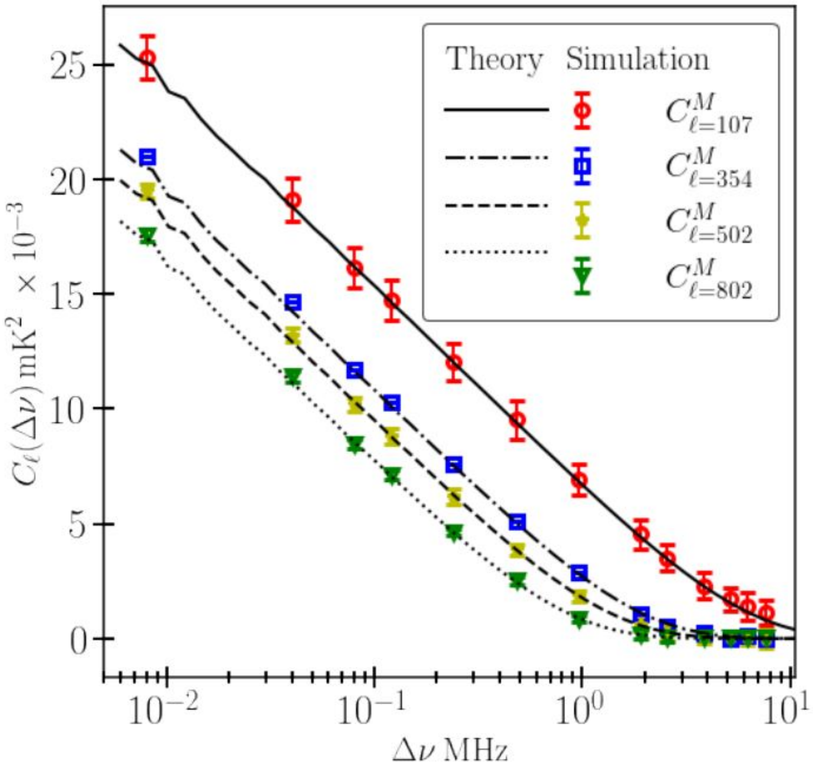
Validation

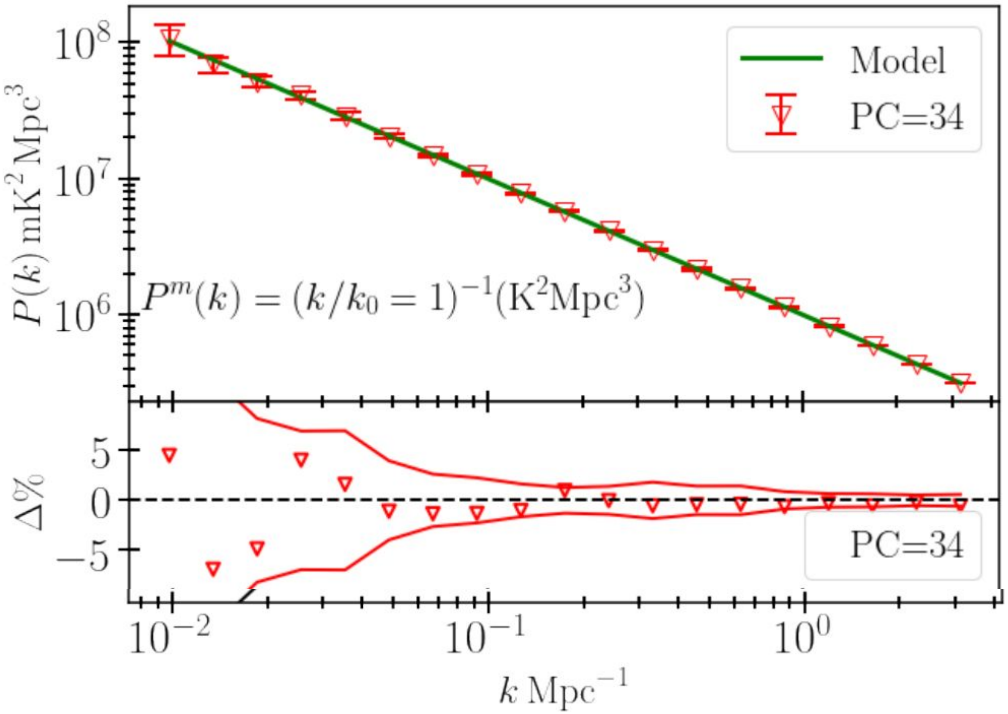




$$A(\Delta\boldsymbol{n}, \nu) = \mathrm{sinc}^2\left(\frac{\pi b \nu\, \Delta\boldsymbol{n} \cdot \hat{\boldsymbol{e}}_1(\alpha_p)}{c}\right) \mathrm{sinc}^2\left(\frac{\pi b \nu\, \Delta\boldsymbol{n} \cdot \hat{\boldsymbol{e}}_2(\alpha_p)}{c}\right)$$

Results: Validation

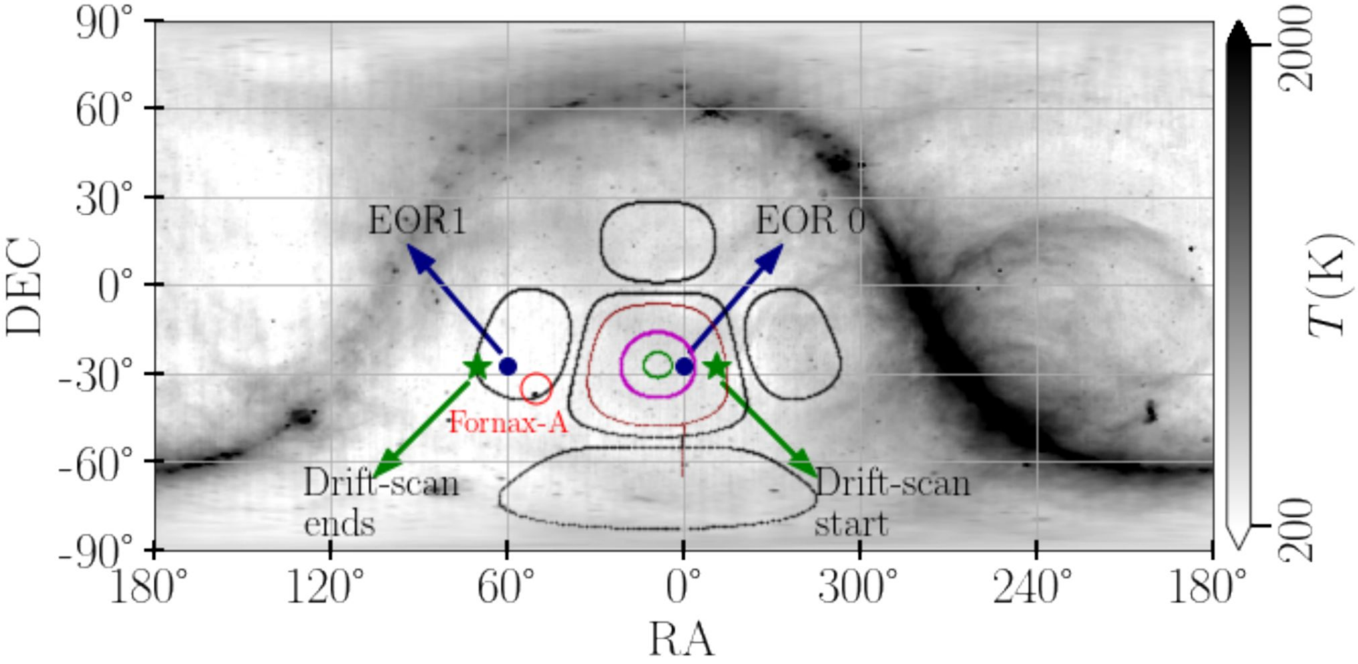




Chatterjee et al 2024, PASA

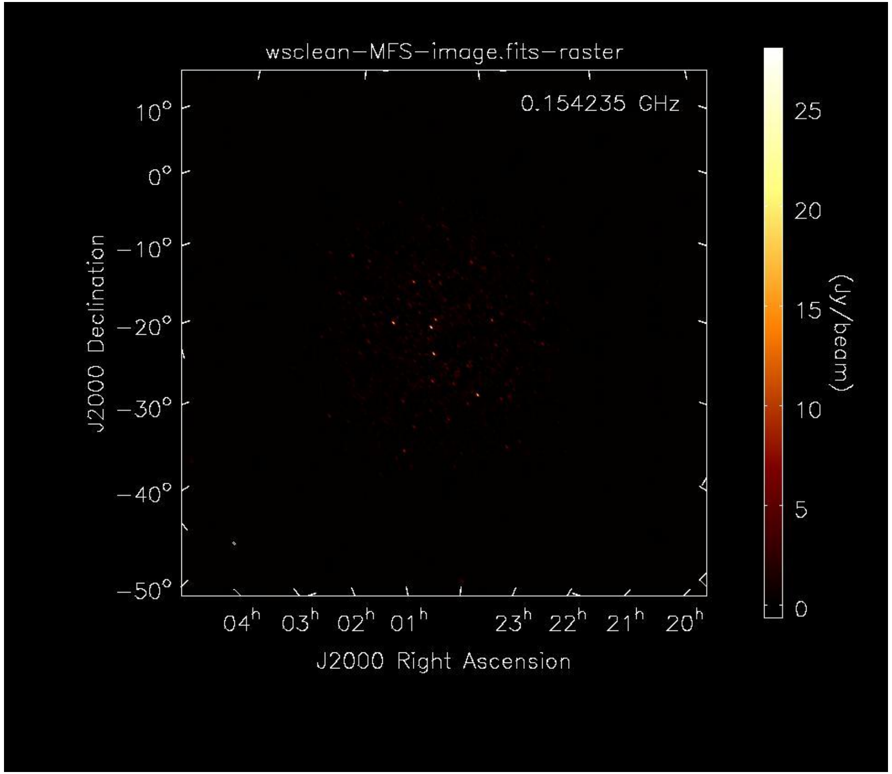
Results: Data for Single PC

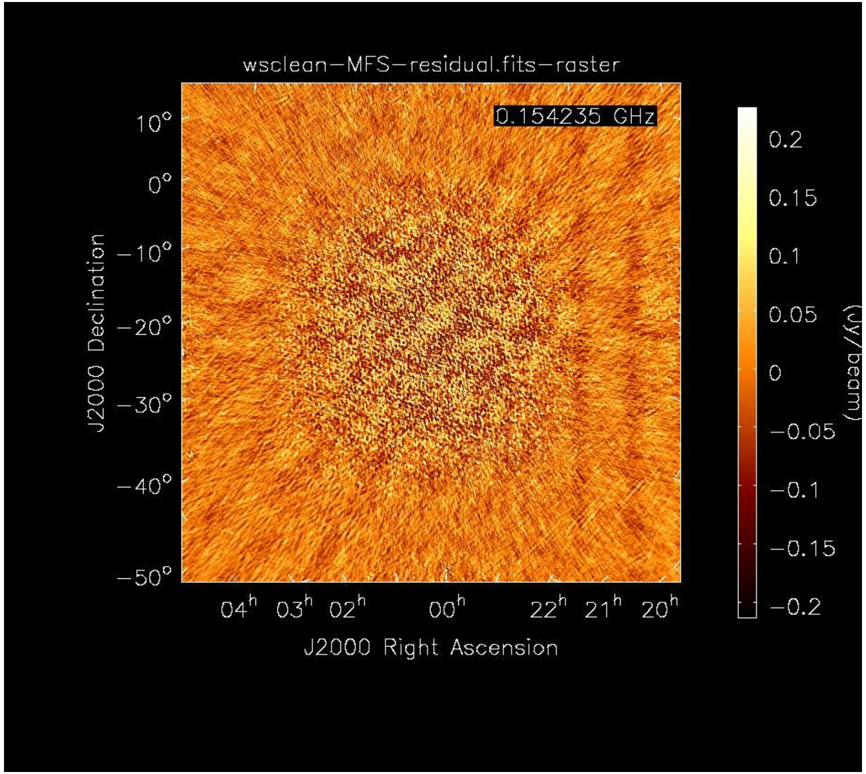
Results: Data



single pointing center at (RA, DEC) = (6.1◦, –26.7◦)

Results: Data



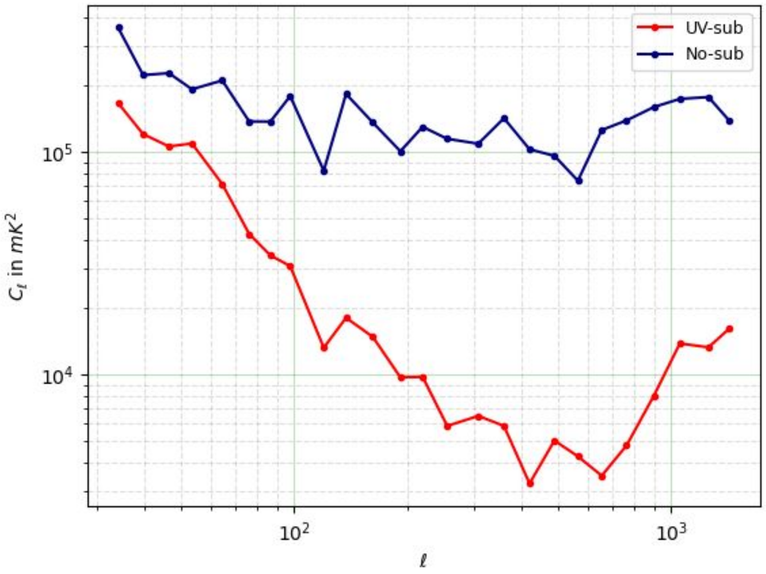


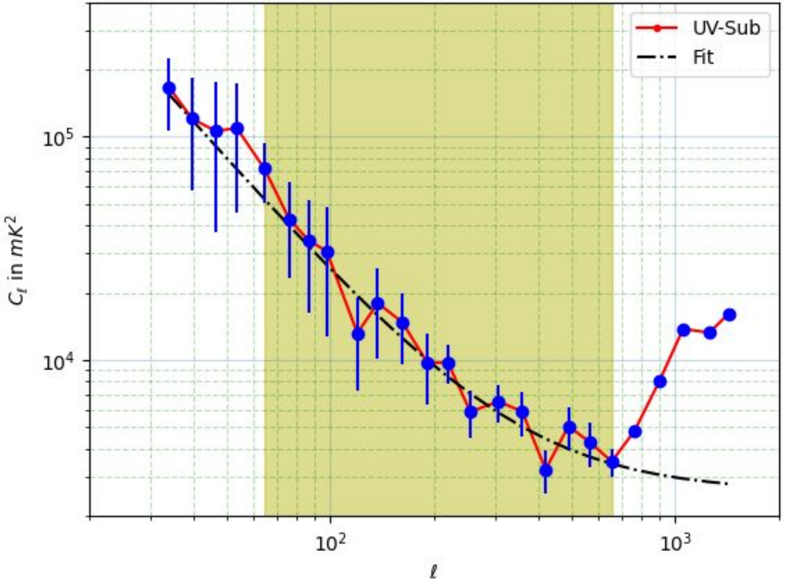
RMS - 140mJy

Sources removed above 3 sigma

Chatterjee, Sarkar et al, 2025 MNRAS

Results

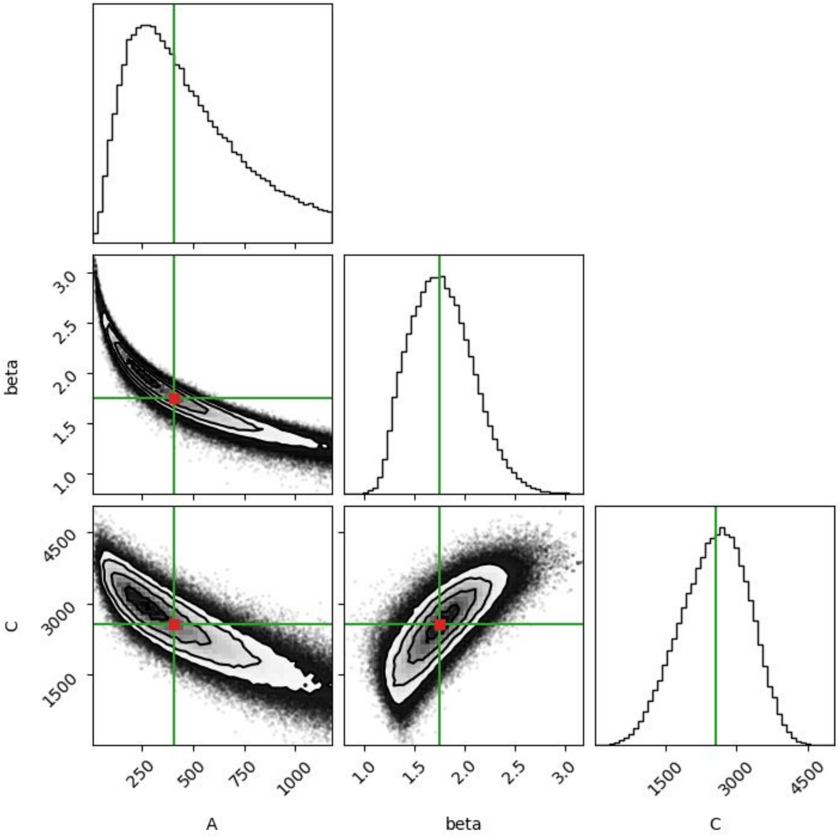




$$\mathcal{C}_\ell^M = A \times \left(\frac{1000}{\ell}\right)^\beta + C$$

Chatterjee, Sarkar et al, 2025 PASA

Results



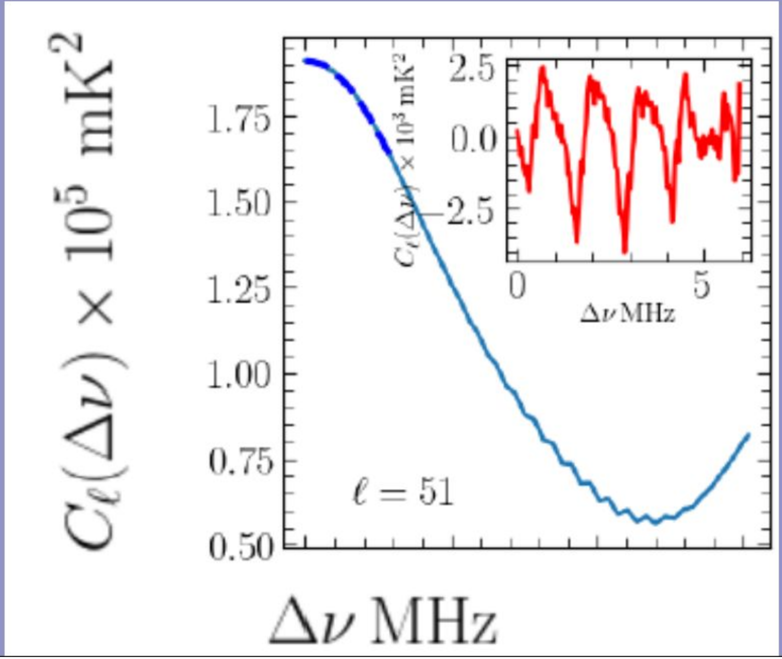
A (in mK^2)	β	C (in mK^2)
$407.7^{+353.7}_{-211.0}$	$1.7^{+0.3}_{-0.3}$	$2574.8^{+679.0}_{-777.0}$

Chatterjee, Sarkar et al, 2025 PASA

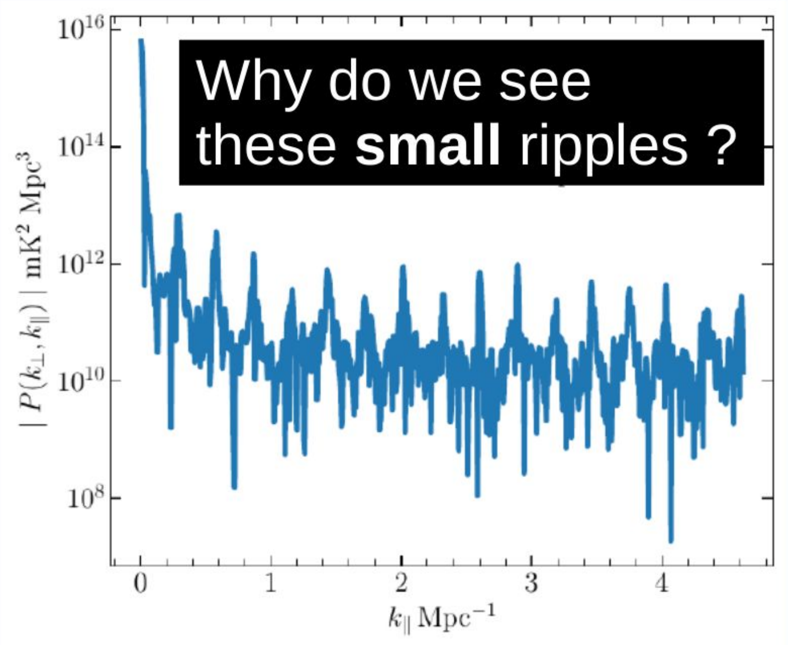
Actual data - periodic ripples the power spectrum

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

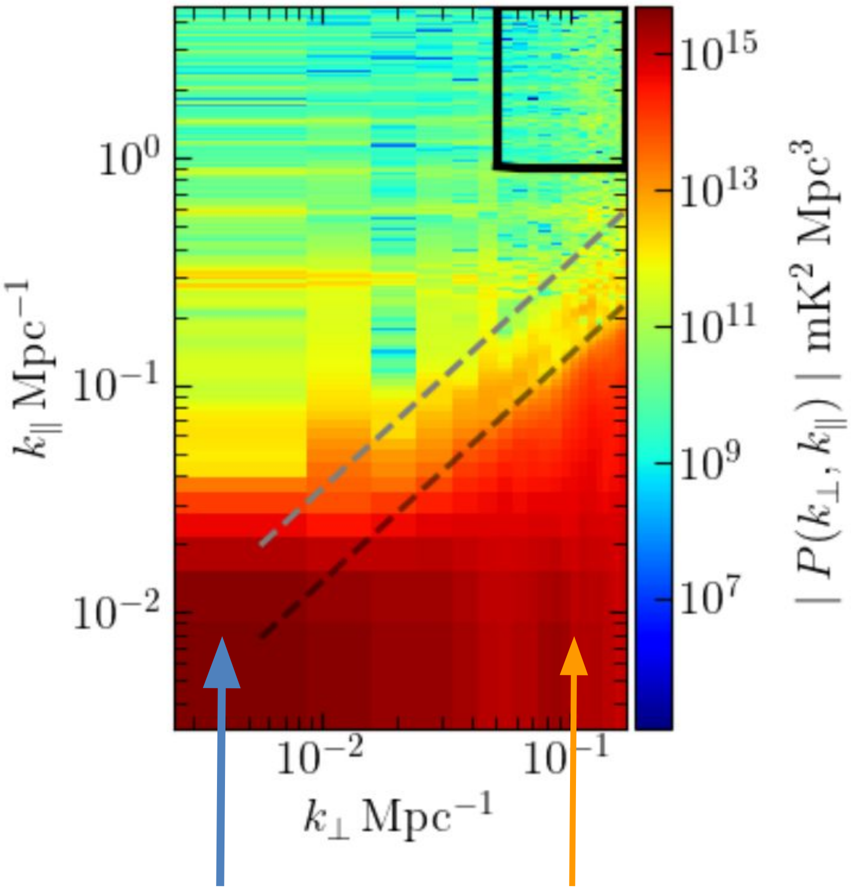
No missing Δν

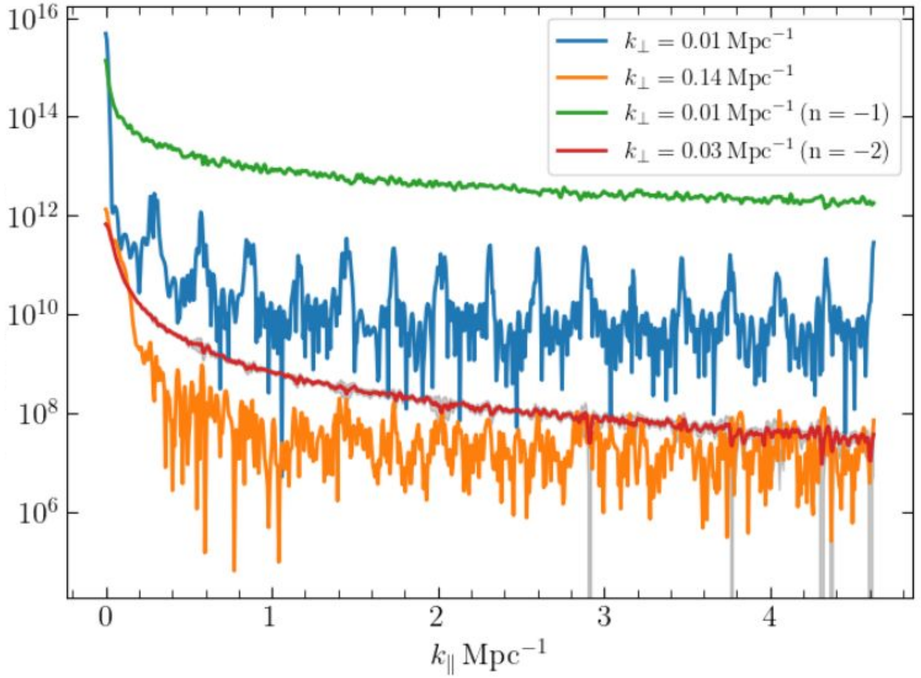


FT



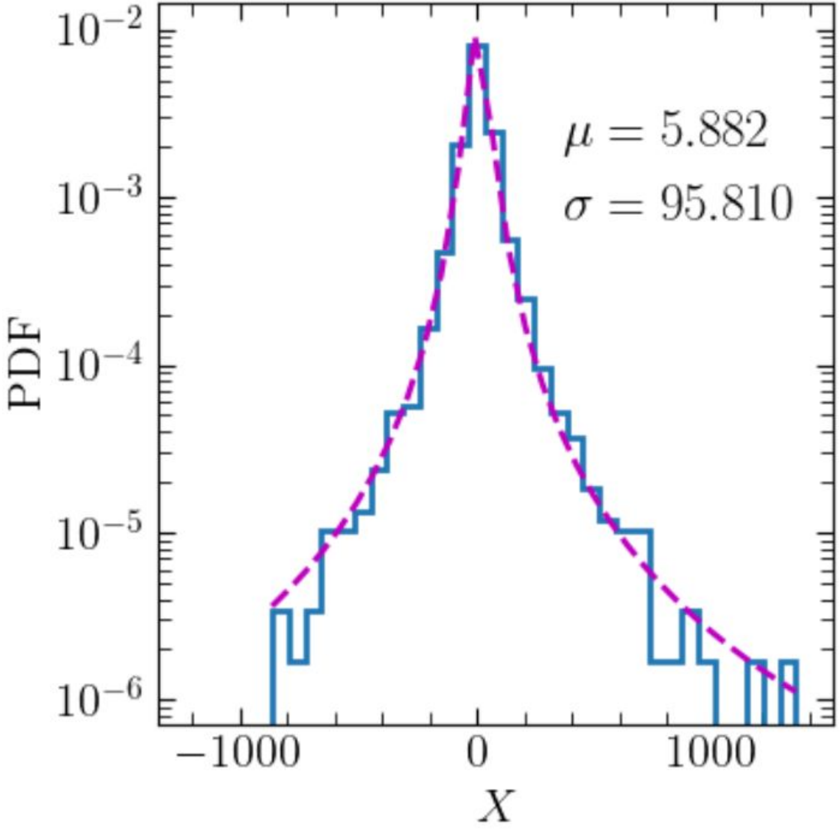
The coarse band harmonics



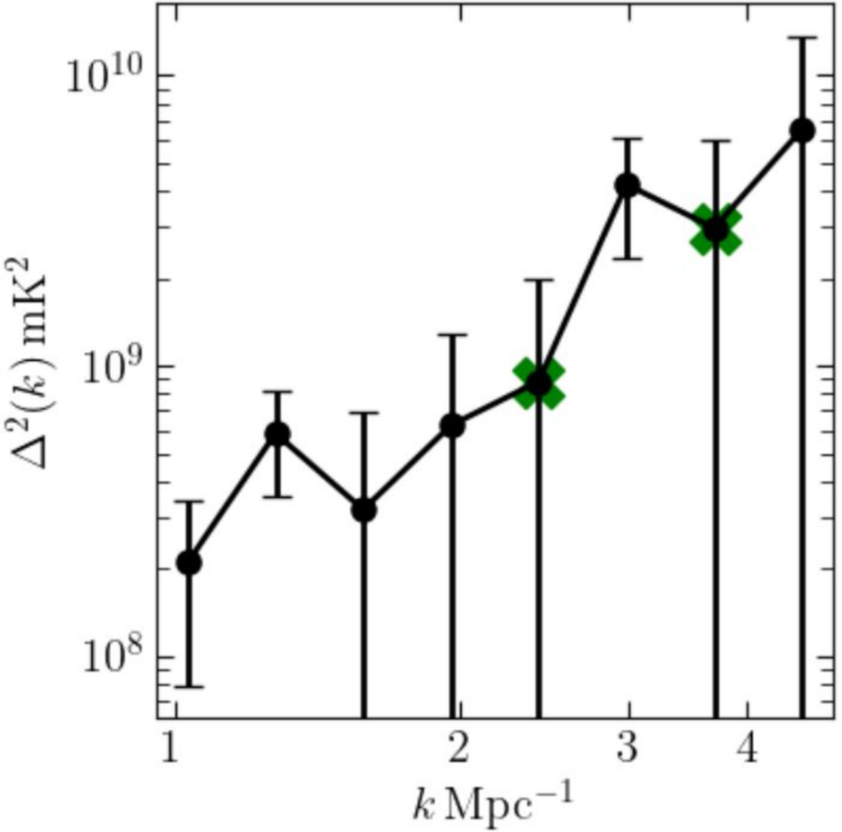


Chatterjee, **Elahi** + 2024

Results



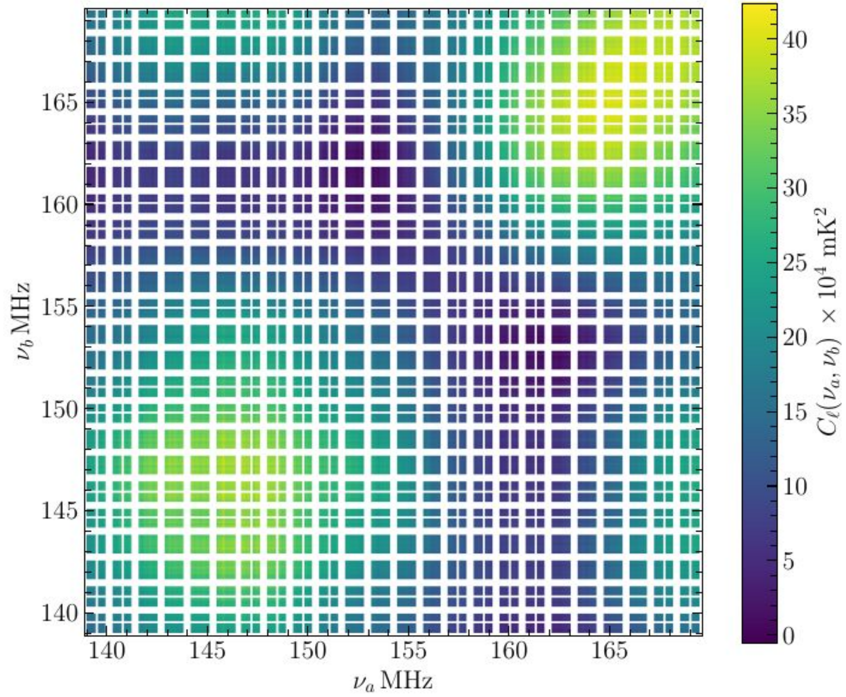
Chatterjee et al 2024, PASA

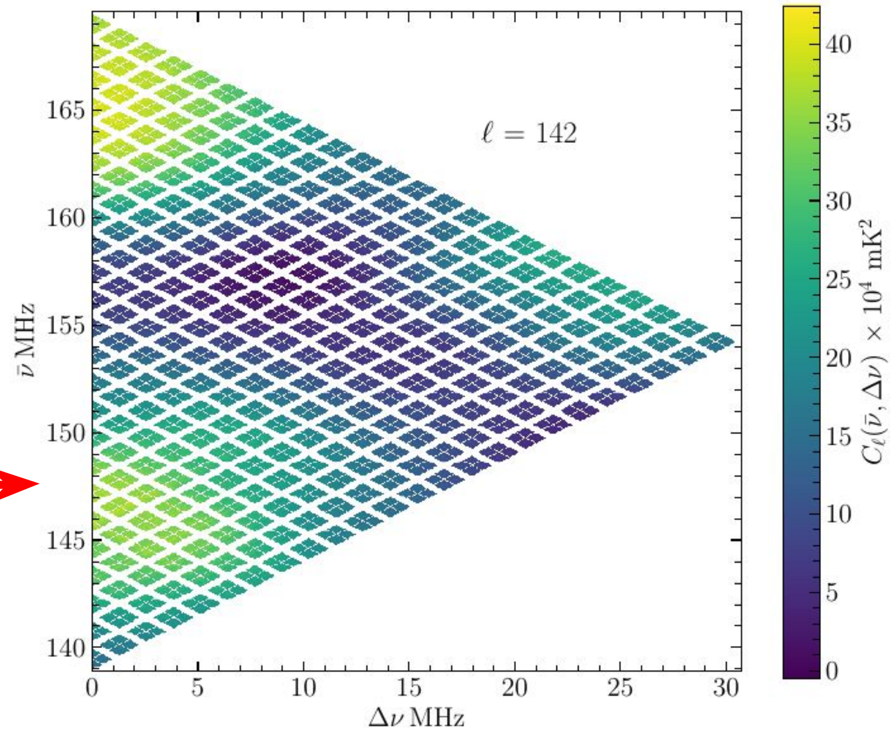


$\Delta^{\hat{2}}(\hat{k}) < (1.85 \times 10^4)^2\ \mathrm{mK}^2 \qquad k = 1\ \mathrm{Mpc}^{-1}$

The missing frequency channels

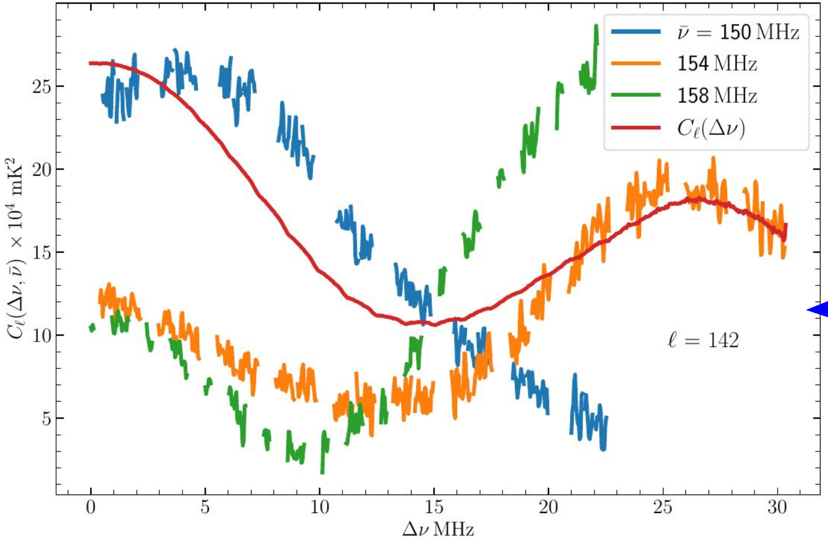
$$C_\ell(\nu_a, \nu_b) \xrightarrow[\Delta\nu = \nu_a - \nu_b]{\bar{\nu} = (\nu_a + \nu_b)/2} C_\ell(\Delta\nu, \bar{\nu})$$

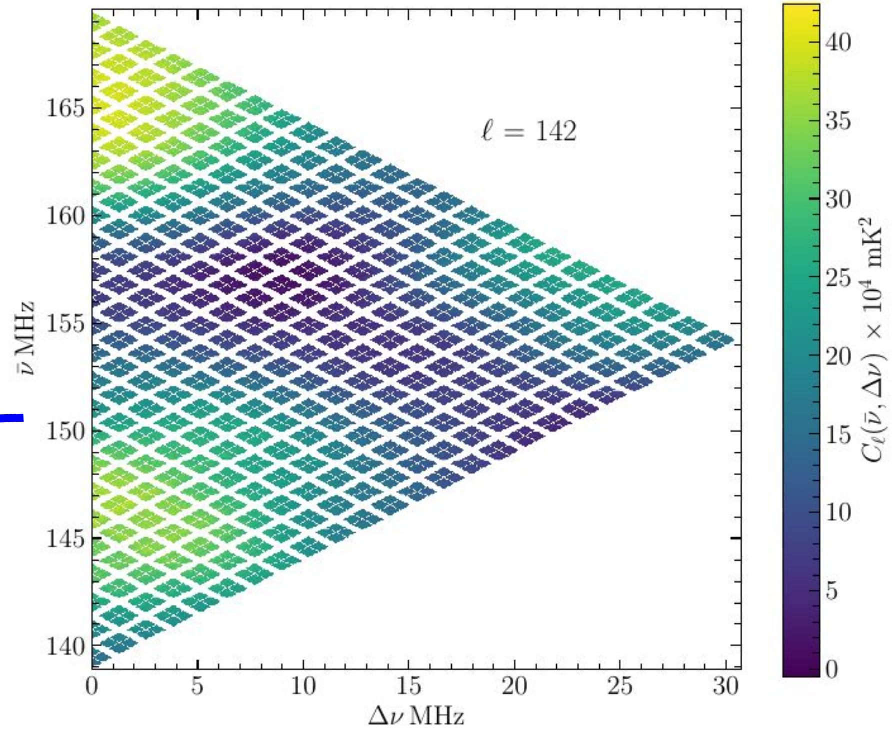




The missing frequency channels

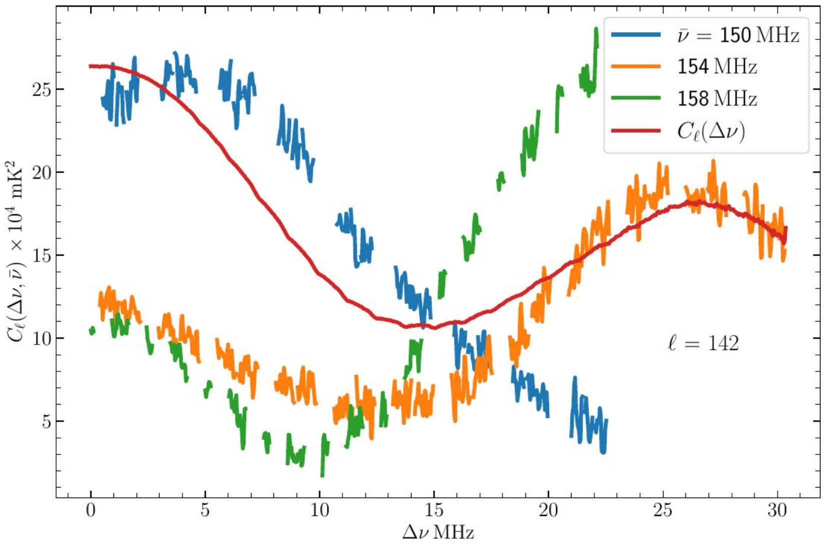
$$C_\ell(\Delta\nu) \longleftarrow C_\ell(\Delta\nu, \bar{\nu})$$

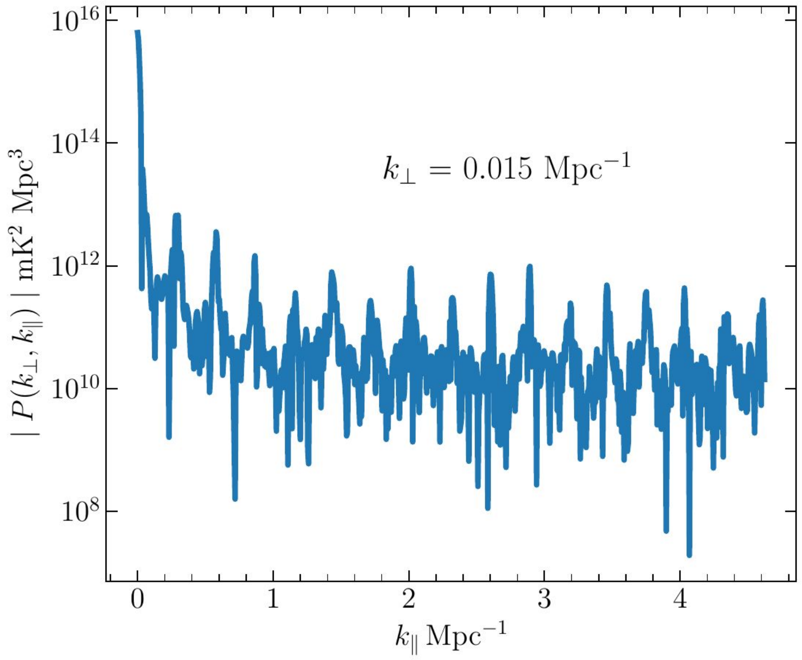




The missing frequency channels

$$C_\ell(\Delta\nu) \longrightarrow P(k_\perp, k_\parallel)$$





What is there in the data? - Check with simulations

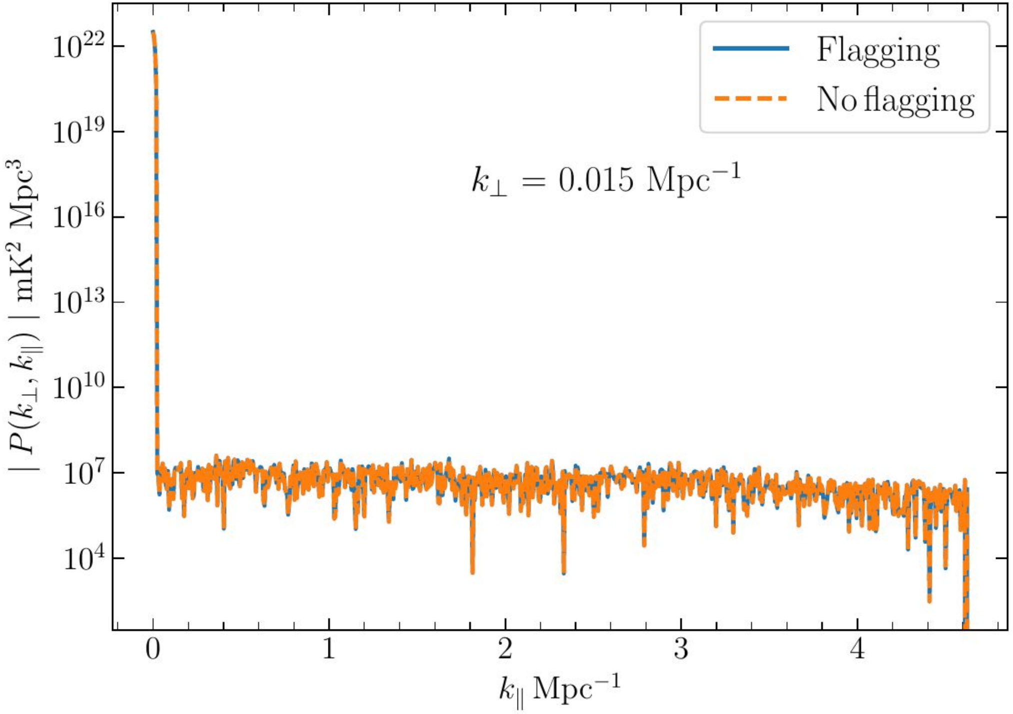
The missing frequency channels

No periodic pattern

simulations

Monochromatic signal

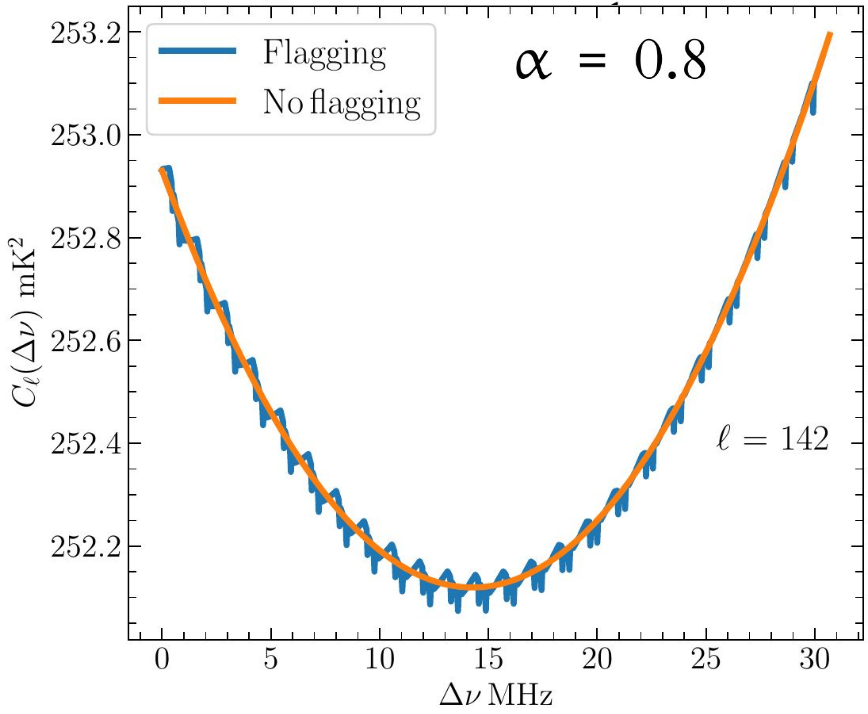
i.e., MAPS is constant.

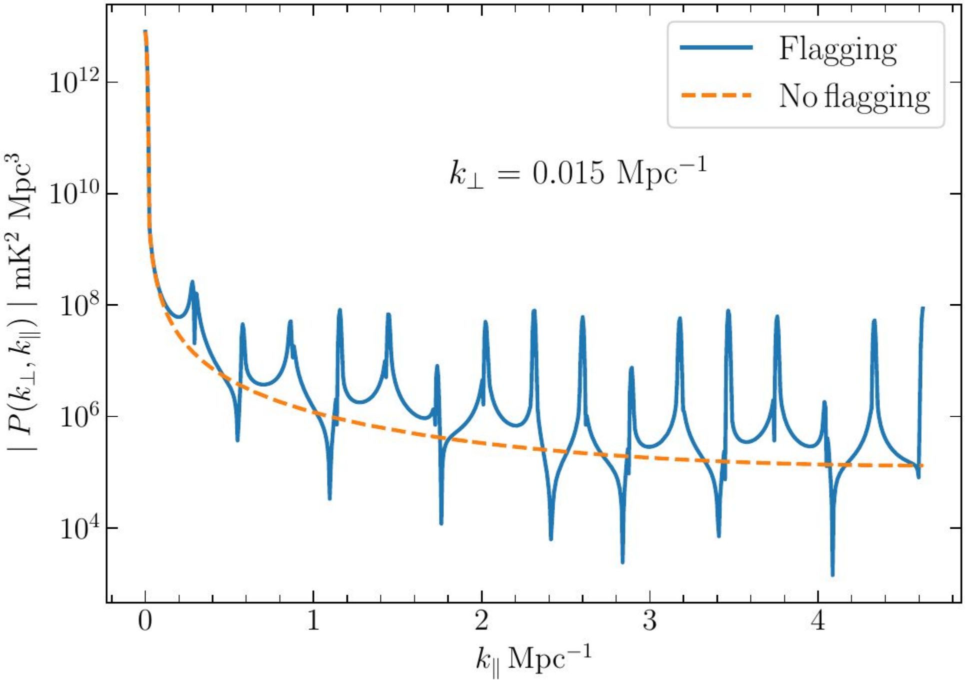


The non-ergodic signal - foregrounds

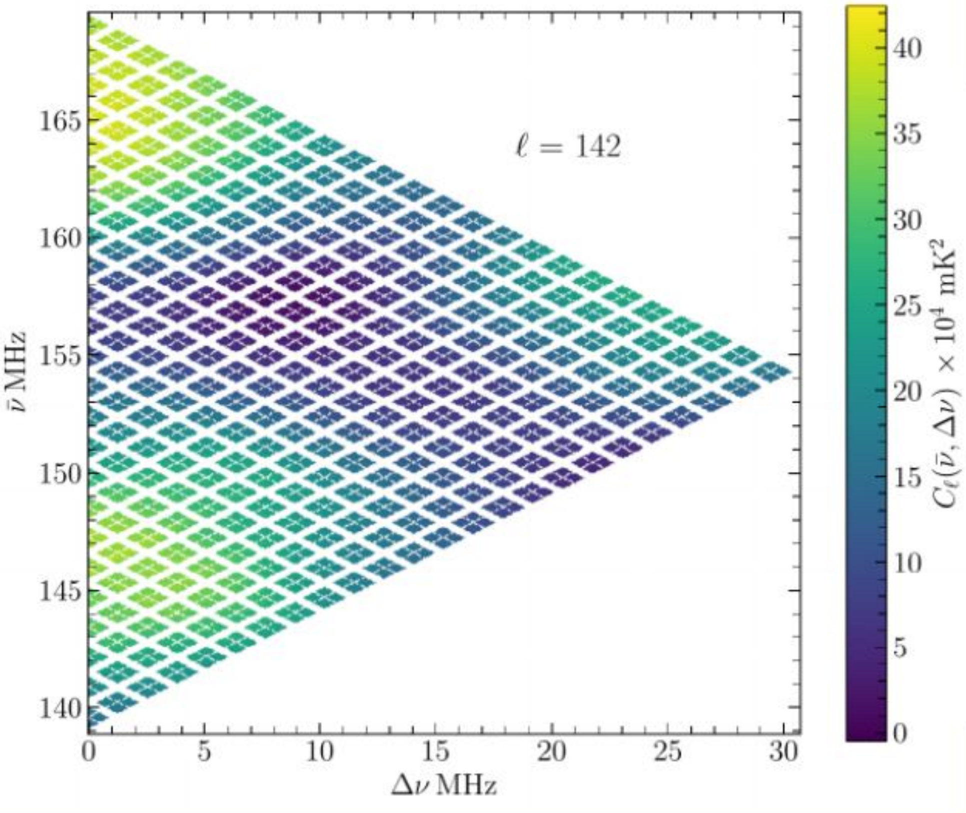
simulations

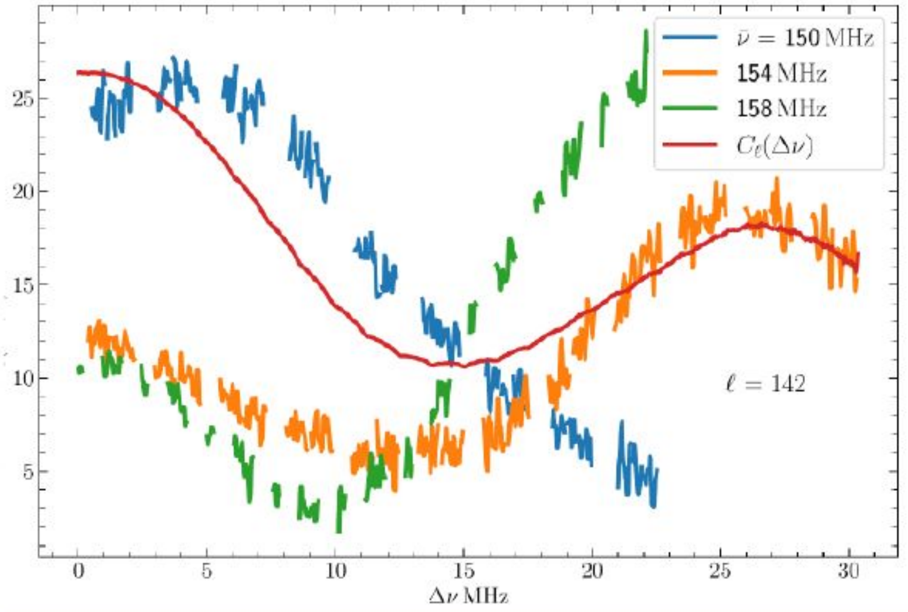
$$\mathcal{V}_{cg}(\nu) \propto (\nu/\nu_c)^{-\alpha}$$



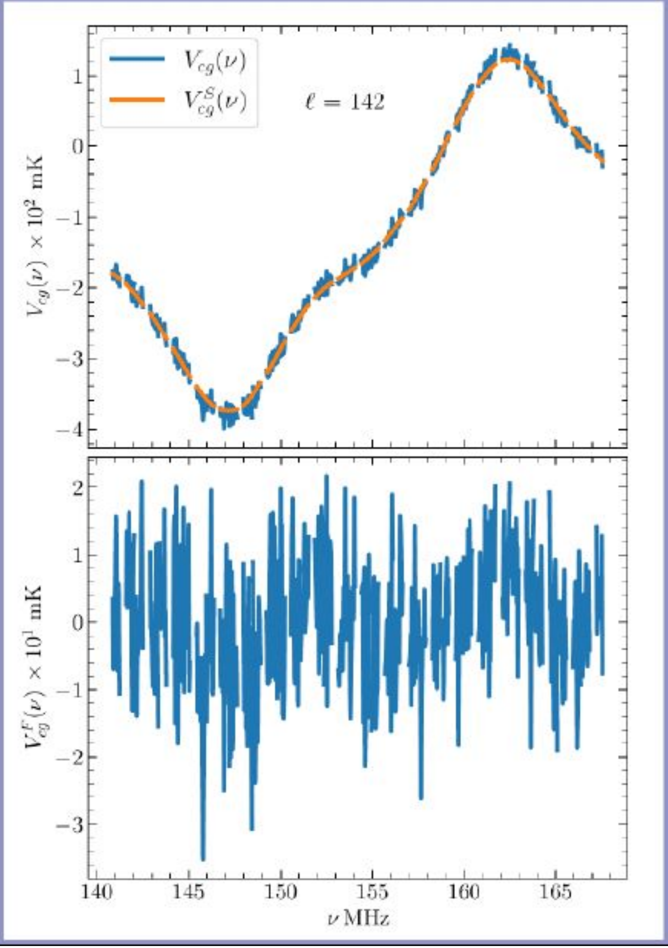


The foregrounds are NOT ergodic - it matters from which frequency you sample the foregrounds





Smooth Component Filtering (SCF)



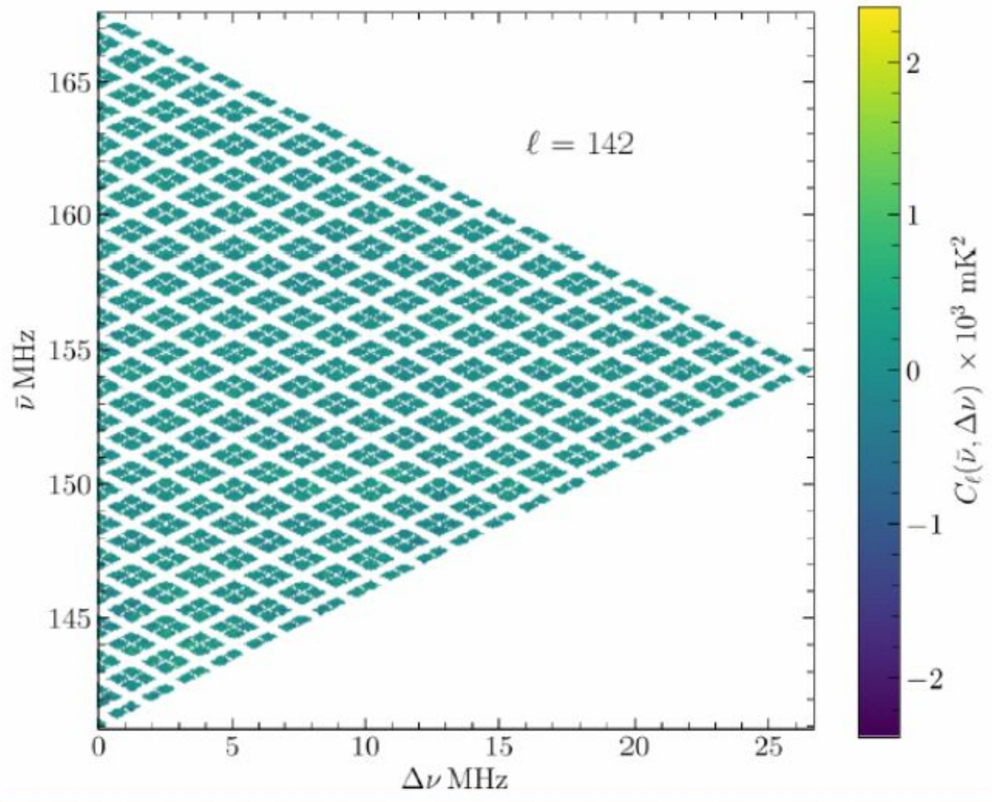
Idea – remove the strong spectral feature

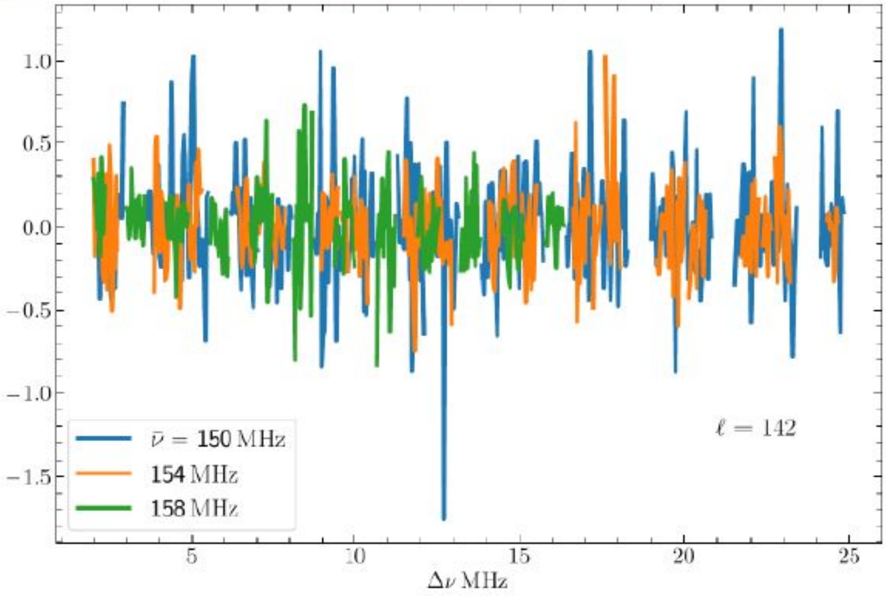
We remove smooth component of the data which only affects from the small $k_{\parallel}$ modes which **we do NOT use to constrain the 21-cm signal**

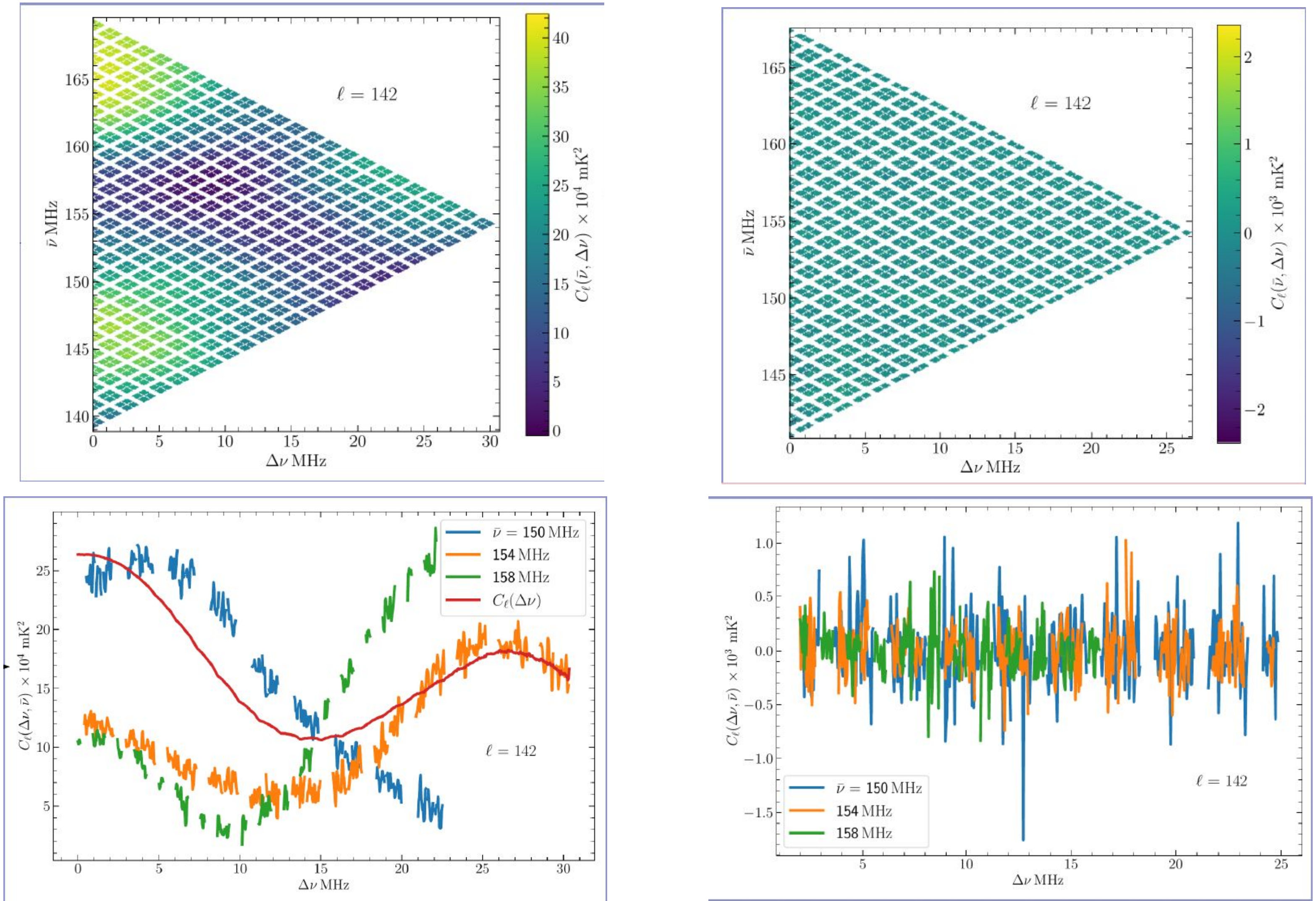
This is a hybrid approach of foreground removal and avoidance

NO signal loss beyond the smoothing scale

The data becomes ergodic after SCF

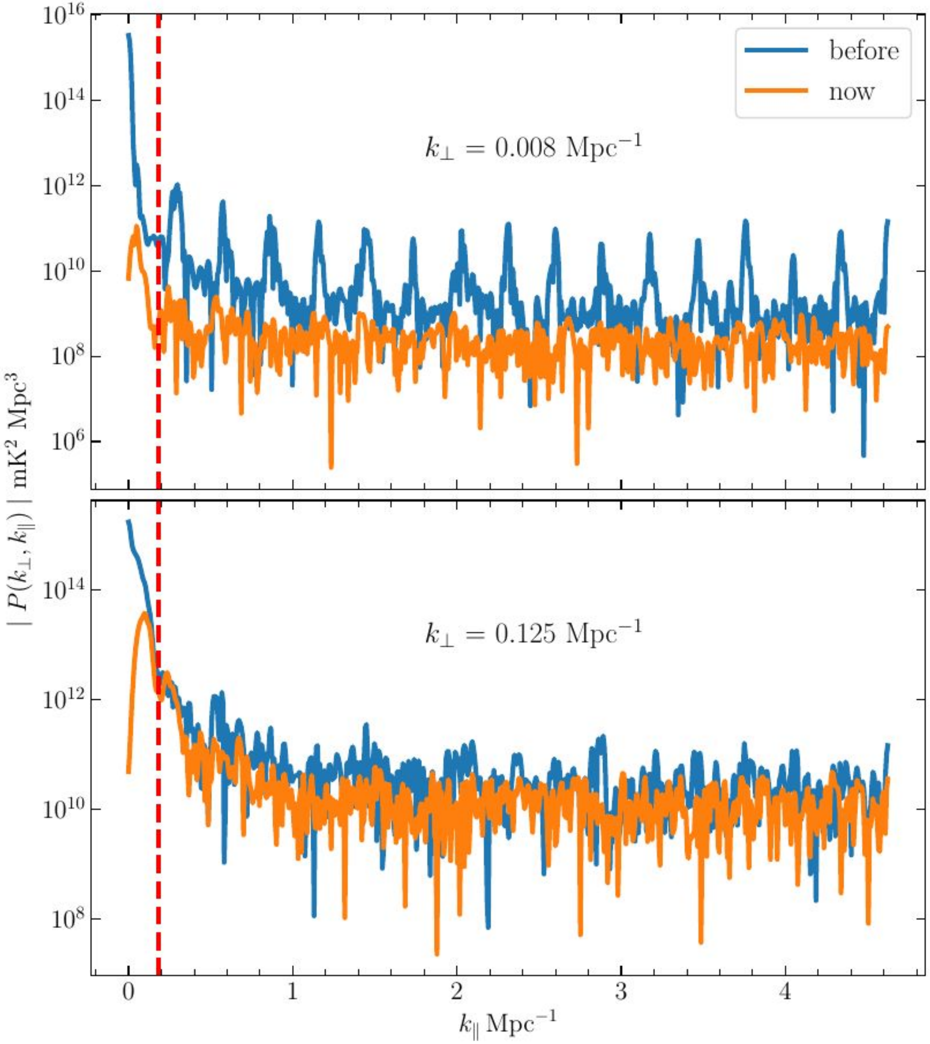






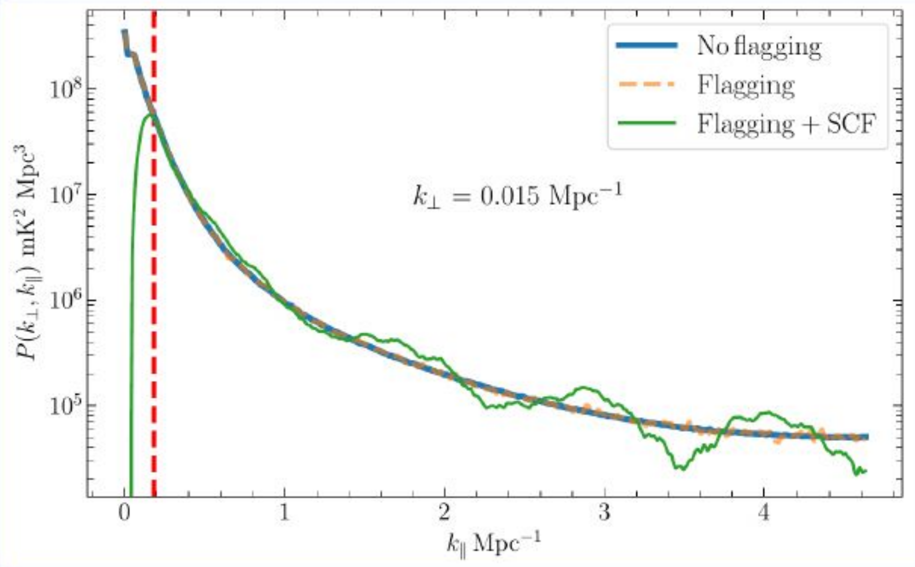
ℓ = 142
Δν MHz
ν̄ MHz
C_ℓ(ν̄, Δν) × 10^4 mK^2
ℓ = 142
Δν MHz
ν̄ MHz
C_ℓ(ν̄, Δν) × 10^3 mK^2
ν̄ = 150 MHz
154 MHz
158 MHz
C_ℓ(Δν)
ℓ = 142
C_ℓ(Δν, ν̄) × 10^4 mK^2
Δν MHz
C_ℓ(Δν, ν̄) × 10^3 mK^2
ν̄ = 150 MHz
154 MHz
158 MHz
ℓ = 142
Δν MHz

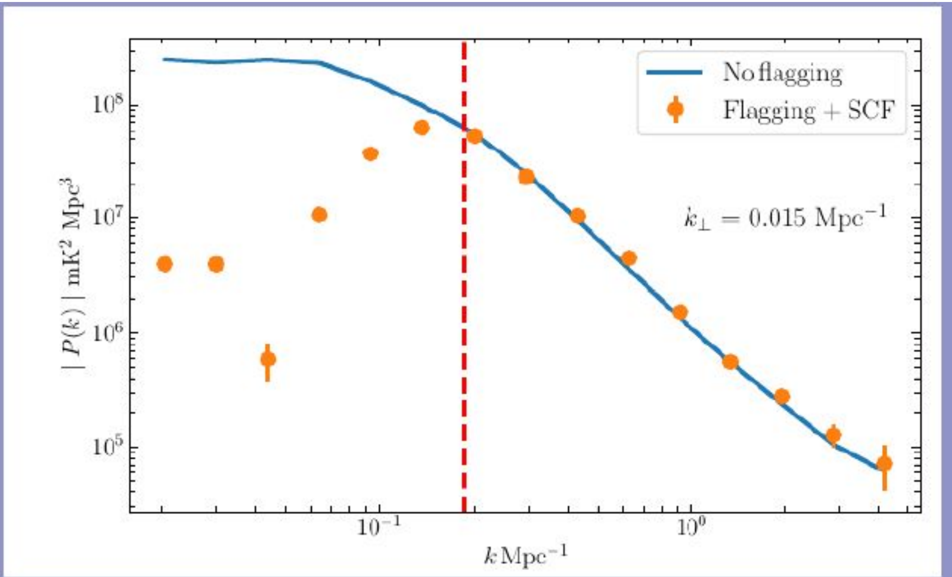
The missing frequency channels do not affect the power spectrum



Signal Loss?

$$\mathcal{V}_{cg}(\nu) = \int \frac{dk_{||}}{2\pi}\sqrt{\frac{P^m(k_\perp, k_{||})}{2r^2}}e^{i\,k_{||}r'(\nu-\nu_c)}[x(k_{||}) + iy(k_{||})]$$

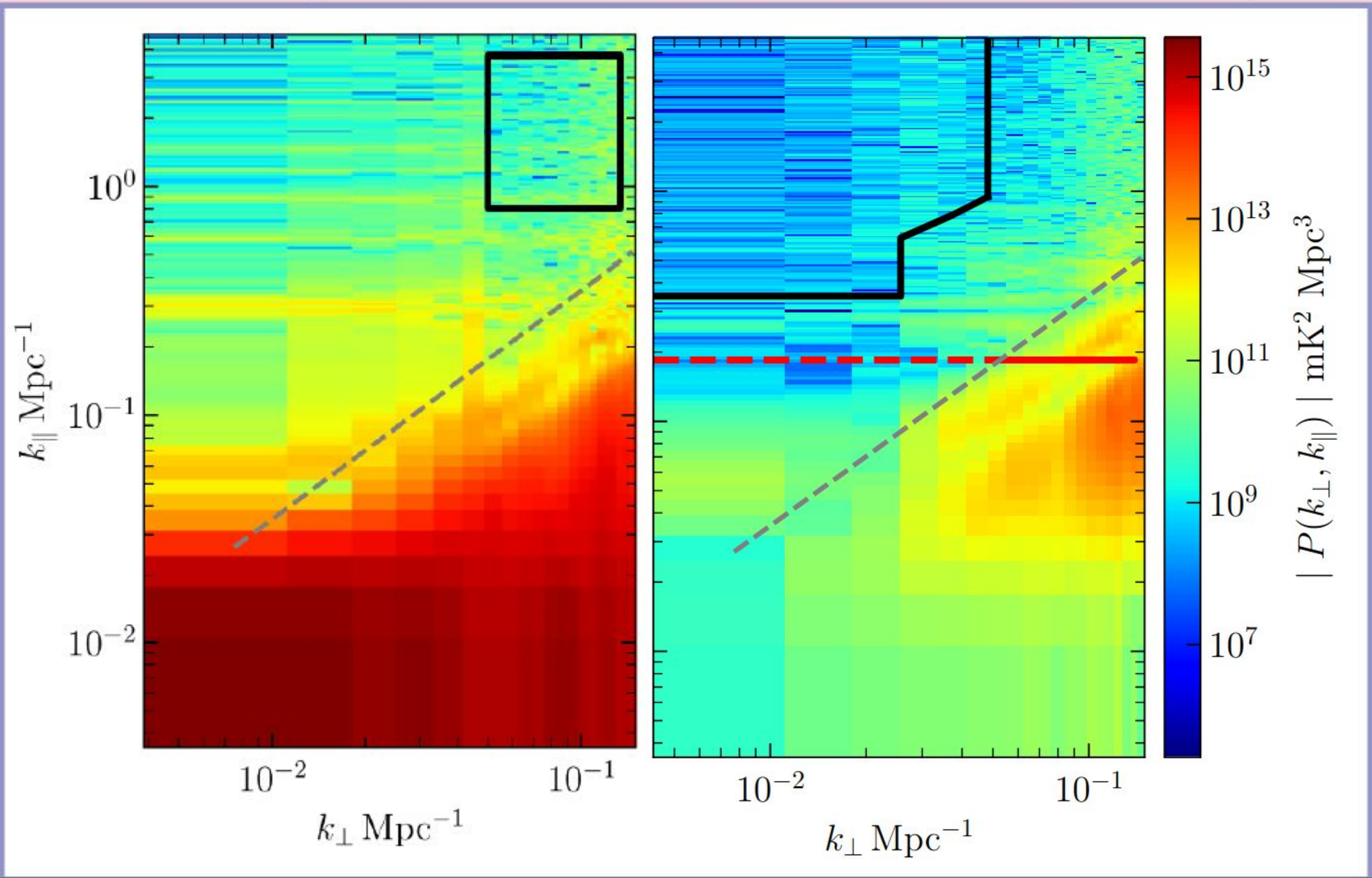


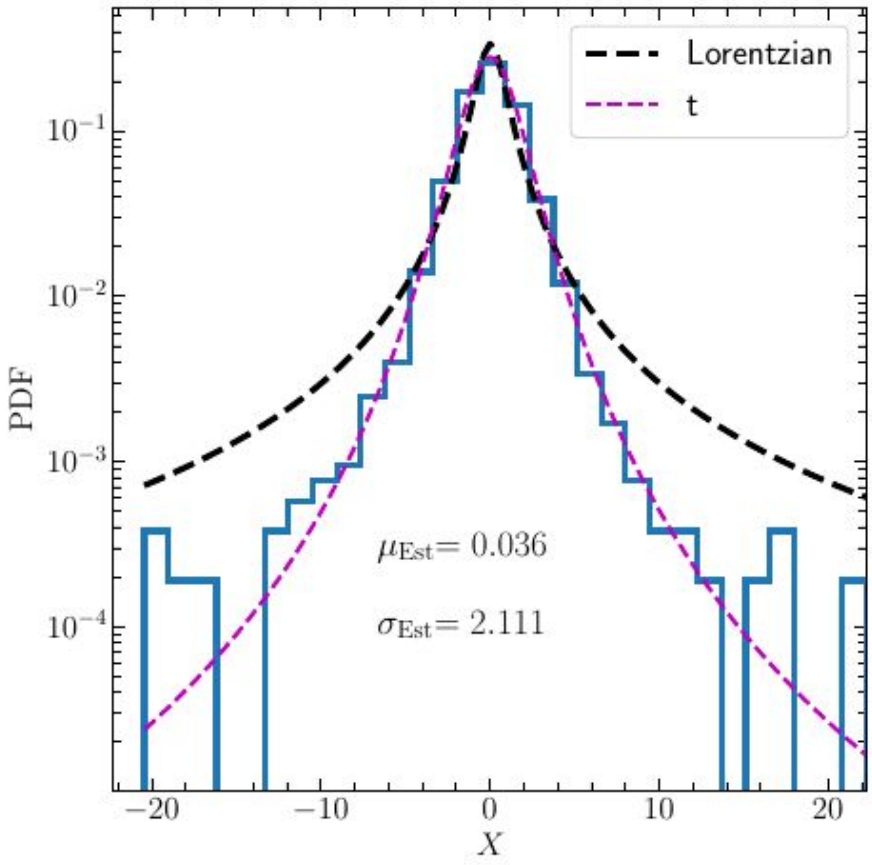


The two plots above shows simulated EoR 21-cm power spectrum

There are no signal loss beyond k > 0.2 Mpc $^{-1}$

The missing channels have no effects in the power spectrum





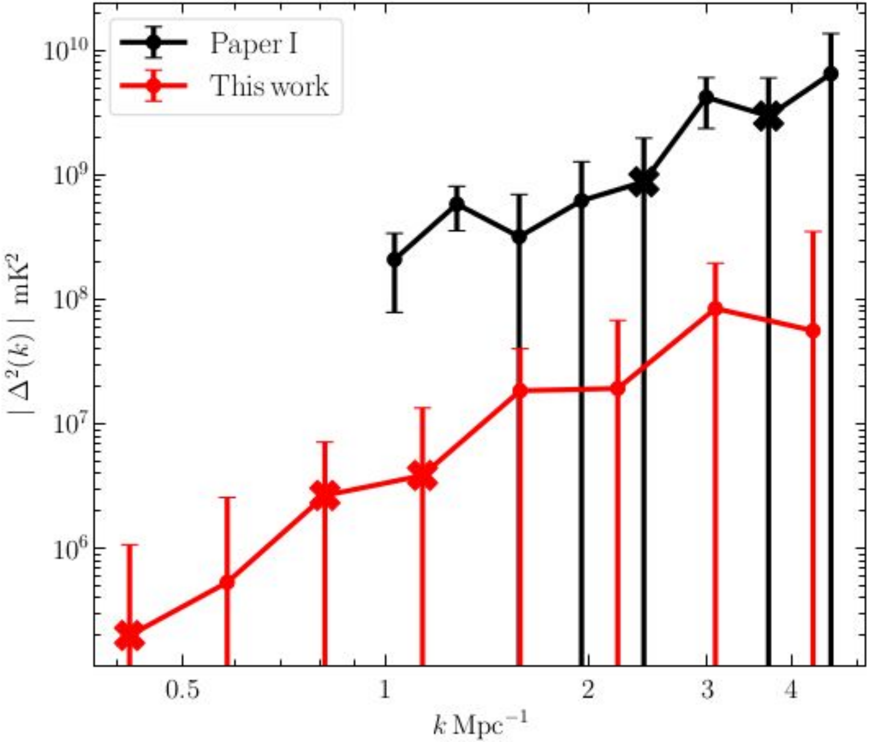
$$X = \frac{P(k_\perp, k_\parallel)}{\delta P_N(k_\perp, k_\parallel)}$$

If noise, X should be

1. Symmetric
2. **Mean** zero
3. **Variance** 1 iff our noise prediction is 'correct'

Pal+ 2021

17 mins of data, Single PC



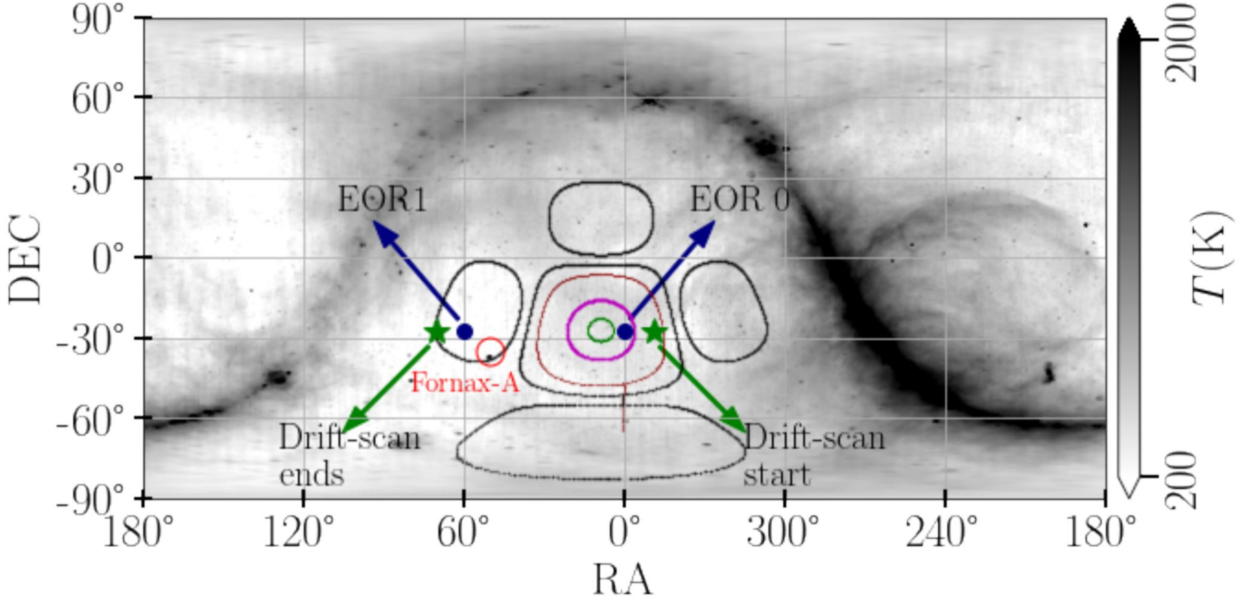
400 improvement on our earlier results

$$\Delta^2_{\mathrm{UL}}(k) = (918.17)^2 \,\mathrm{mK}^2 \qquad k = 0.404\ \mathrm{Mpc}^{-1}$$

Elahi, A, et al 2025, MNRAS

Results: Data for Multiple PCs

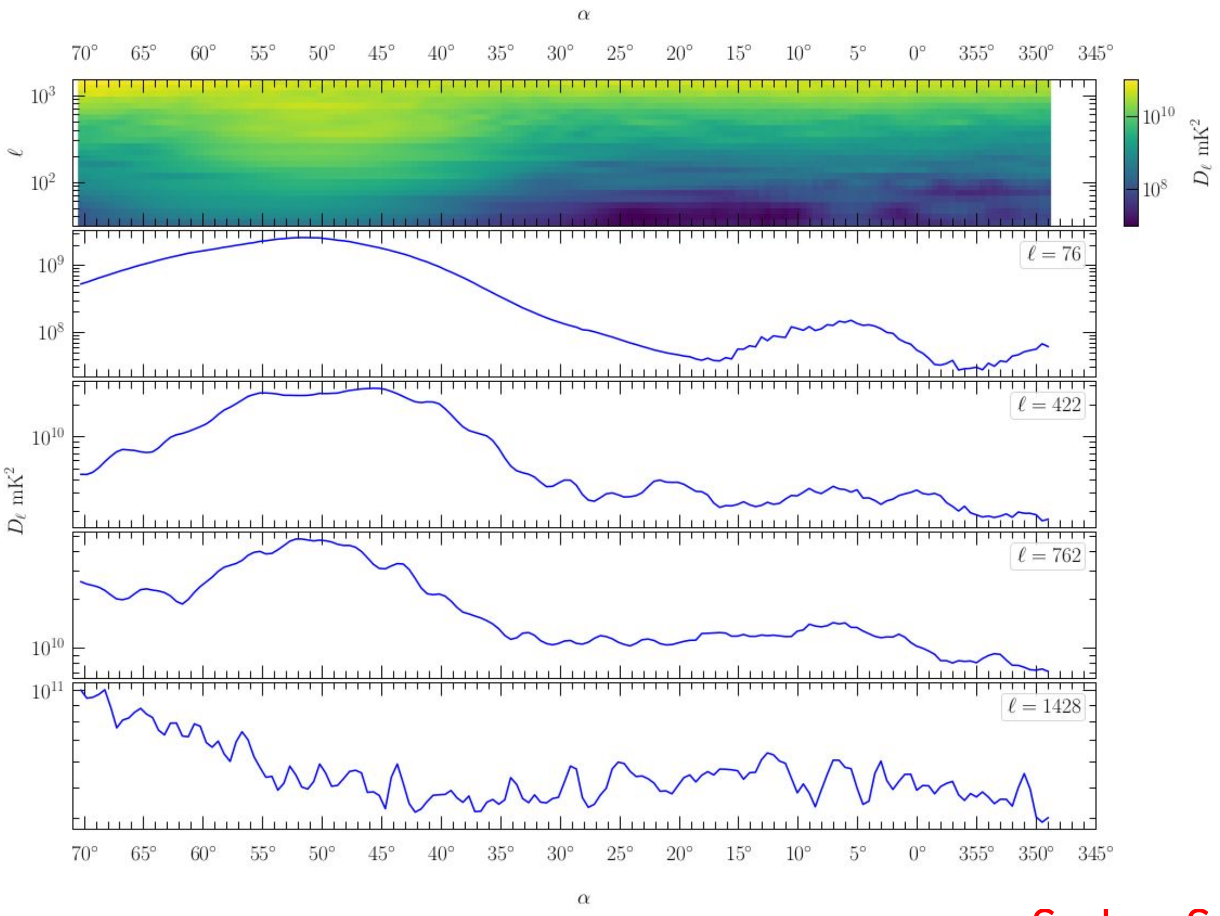
MWA Observation



Time duration of 5 hr 24 min, 10 days, total ~55 Hrs

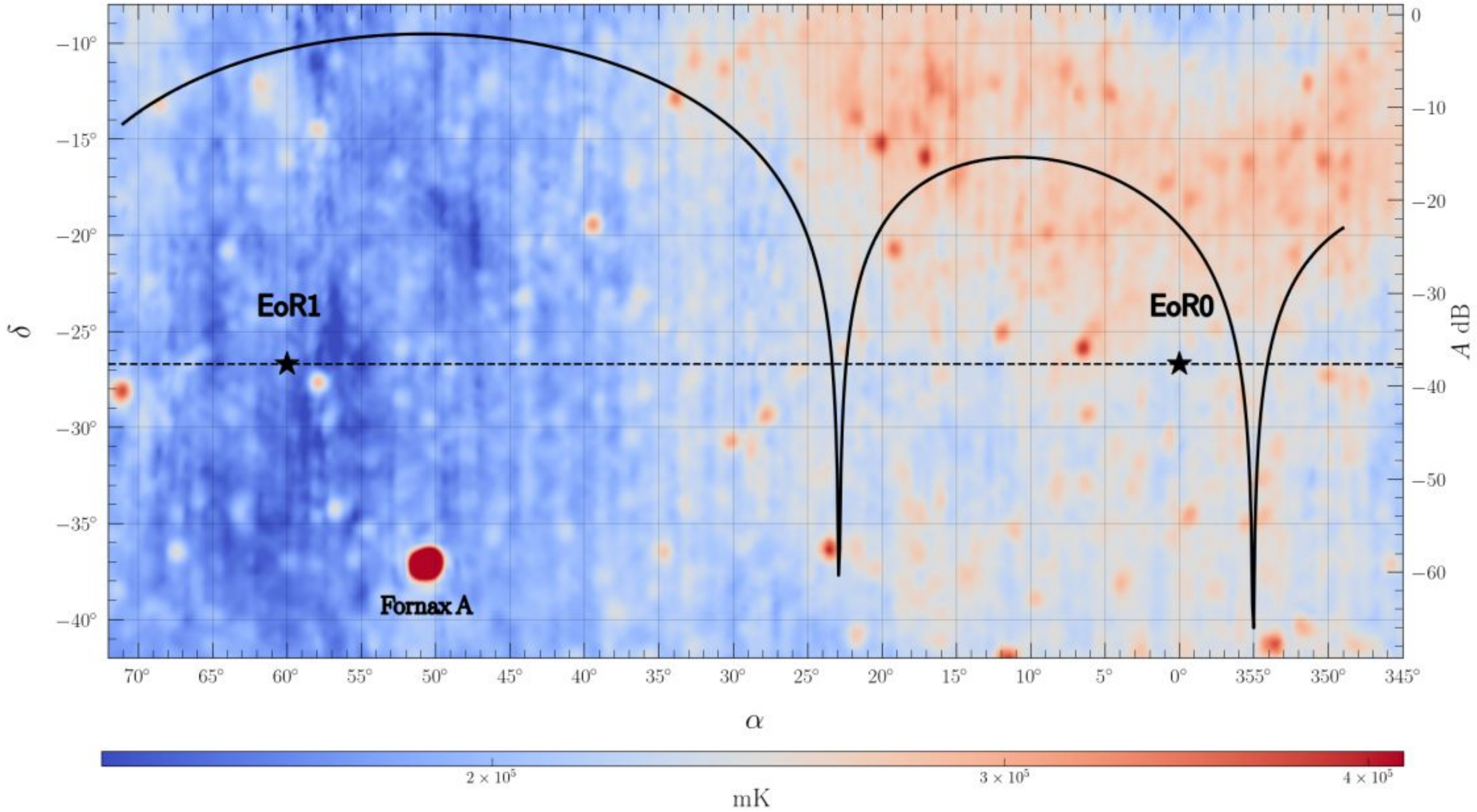
RA - 349◦ to 70.3◦, 162 different pointing centers

Angular Power Spectrum vs RA



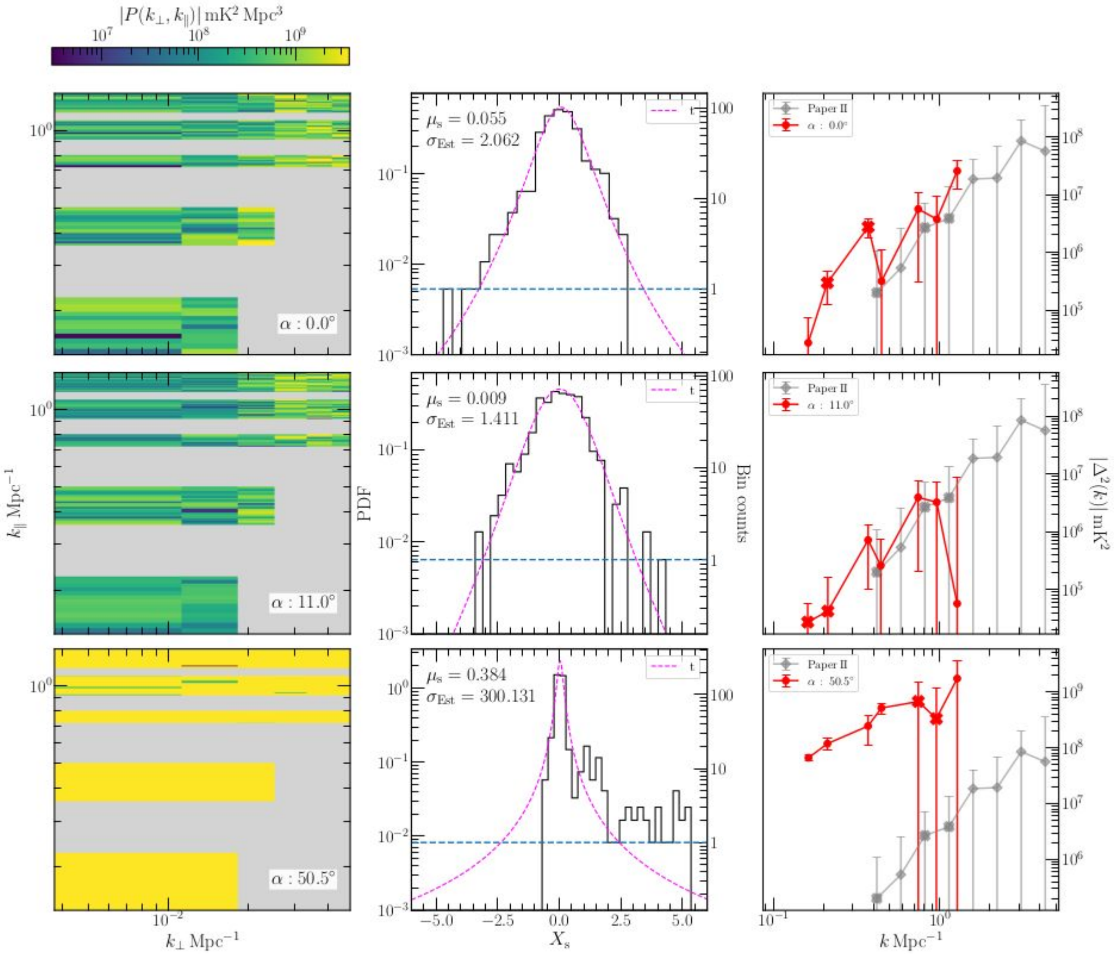
Sarkar, S, et al 2026, submitted

Angular Power Spectrum vs RA

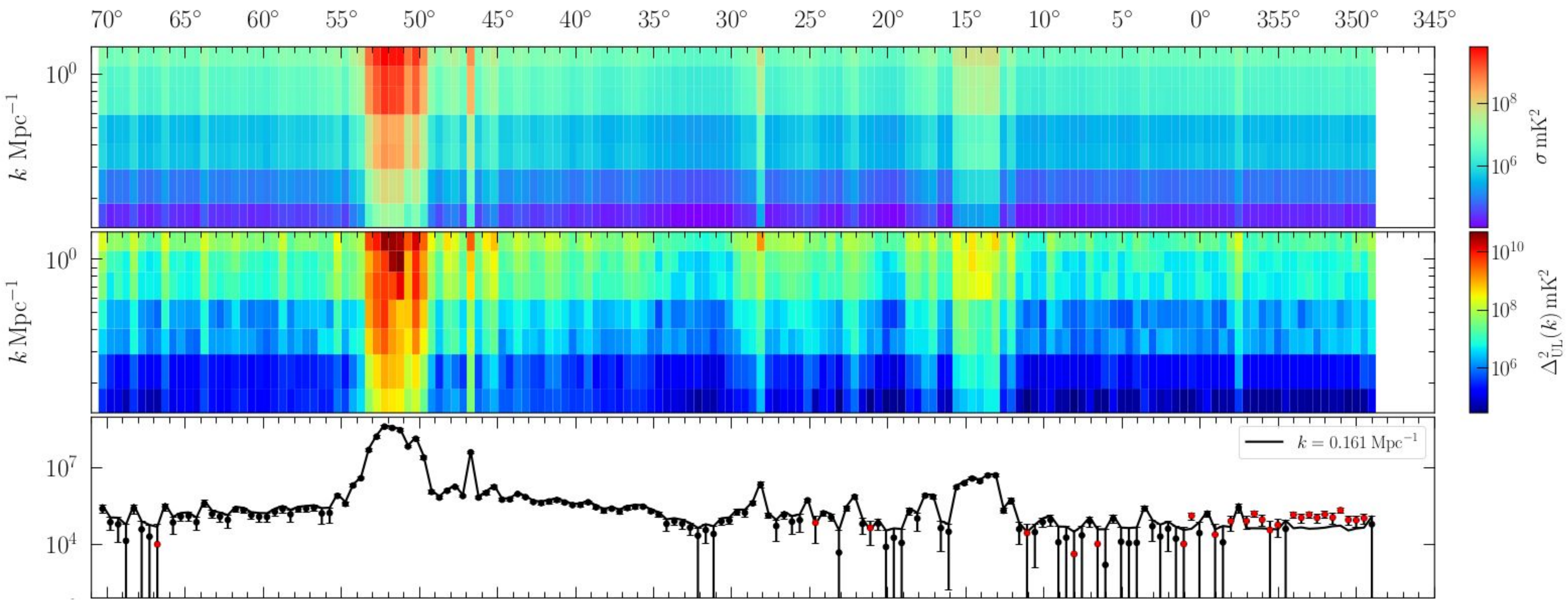


Sarkar, S, et al 2026, in prep.

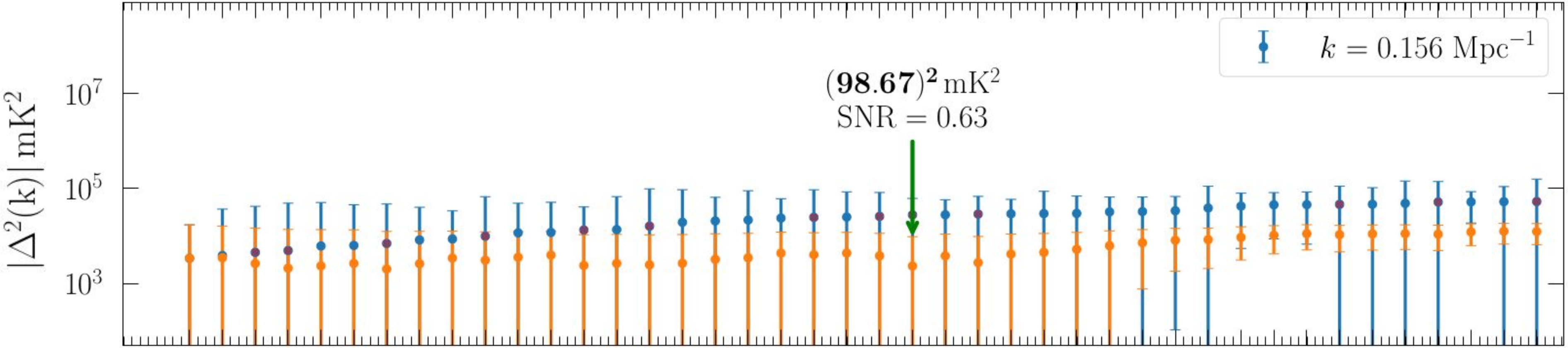
Power Spectrum: Multiple PCs



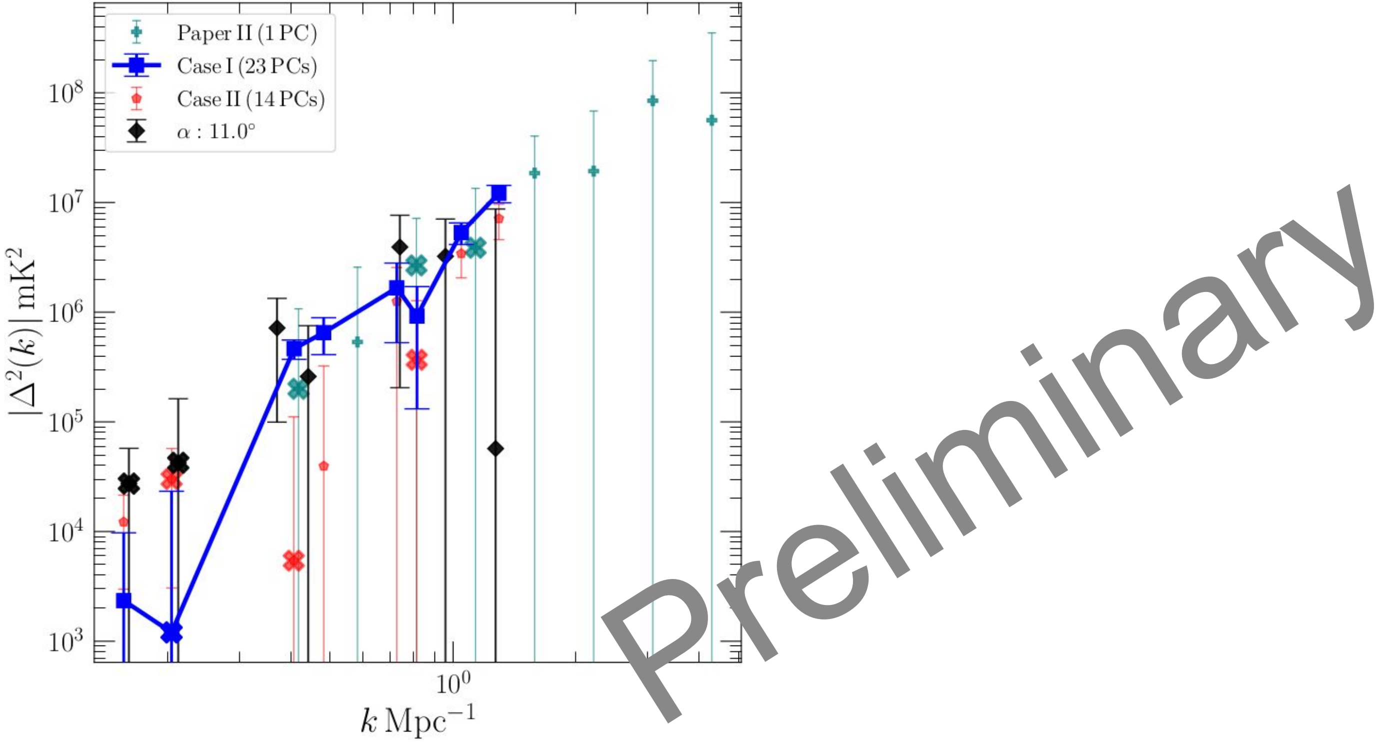
Power Spectrum vs RA



RA Selection



Incoherent Averaging



23 pointing combined

best 2σ upper limit of $(98.67)^2\ \mathrm{mK}^2$ at $k = 0.156\ \mathrm{Mpc}^{-1}$ at $z = 8.2$, almost 90 times lower than before incoherent averaging.

Sarkar Shouvik, et al, submitted

Summary

- We have developed a novel estimator tracking TGE for the drift scan radio observation in presence of channel flagging.

- We combined different pointing centres to increase the SNR.

- We validated using simulation with real flagging pattern.

- We applied in MWA drift scan data set to get an improved upper limit.

Thank You