Towards 21-cm Intensity Mapping using the SKA pathfinder uGMRT

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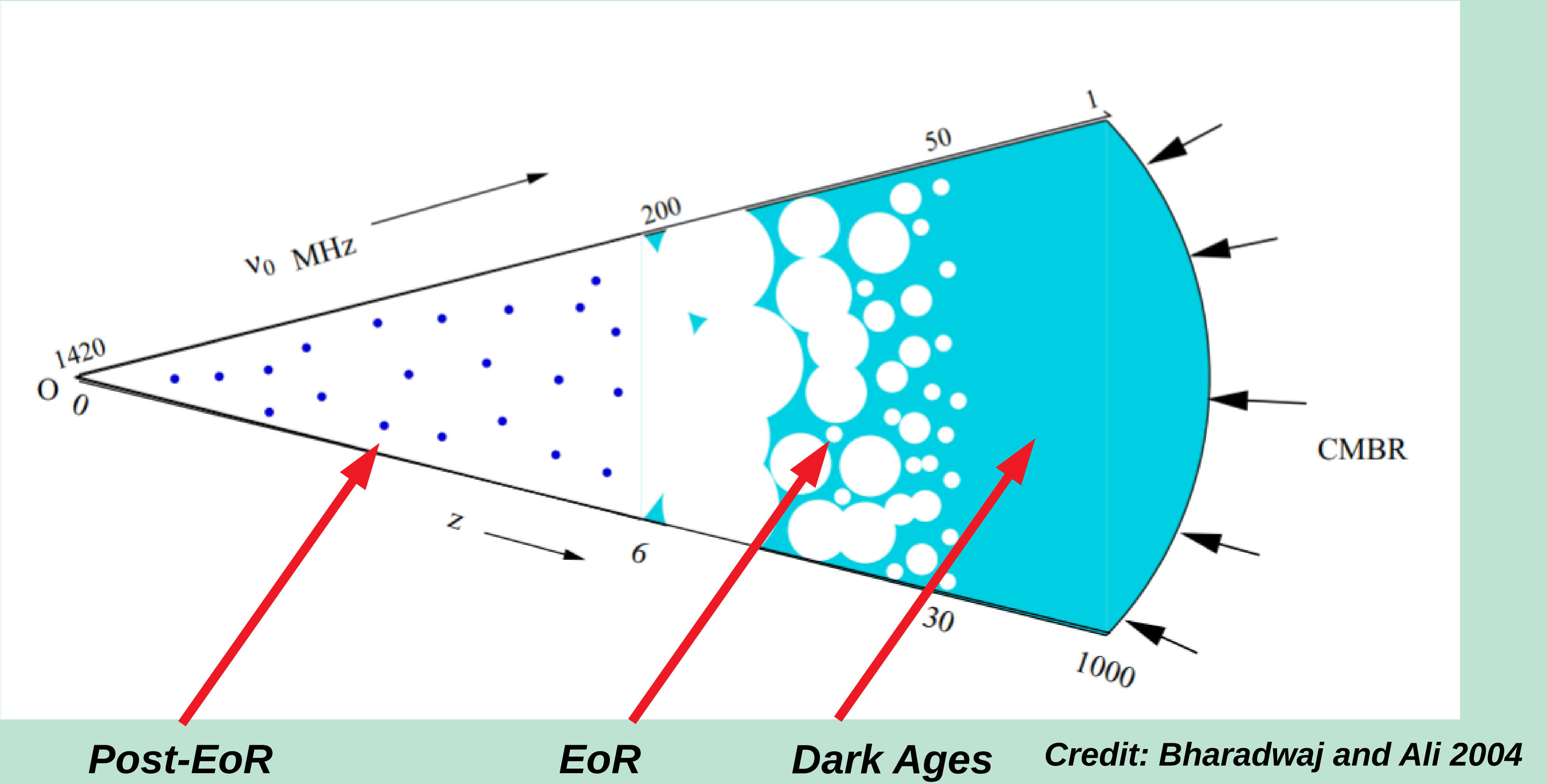
Based on: Pal + 2022, Elahi + 2023a, 2023b, 2024, MNRAS

SKA Cosmology SWG Meeting, November 2024

Evolution of Neutral Hydrogen (HI)



Credit: Bharadwaj and Ali 2004

21-cm intensity mapping

- **HI emits 21-cm signal**
- **The Universe expands ⇒ 21-cm signal gets redshifted**
- **Redshifted signal carries information from the z.**

Goal: Measuring the **intensity fluctuations** of the redshifted **21-cm** signal.

Cosmology with 21-cm IM at post-EoR ($z < 6$)

- **Probe large scale structures**
  (e.g. Bharadwaj, Nath & Sethi 2001)

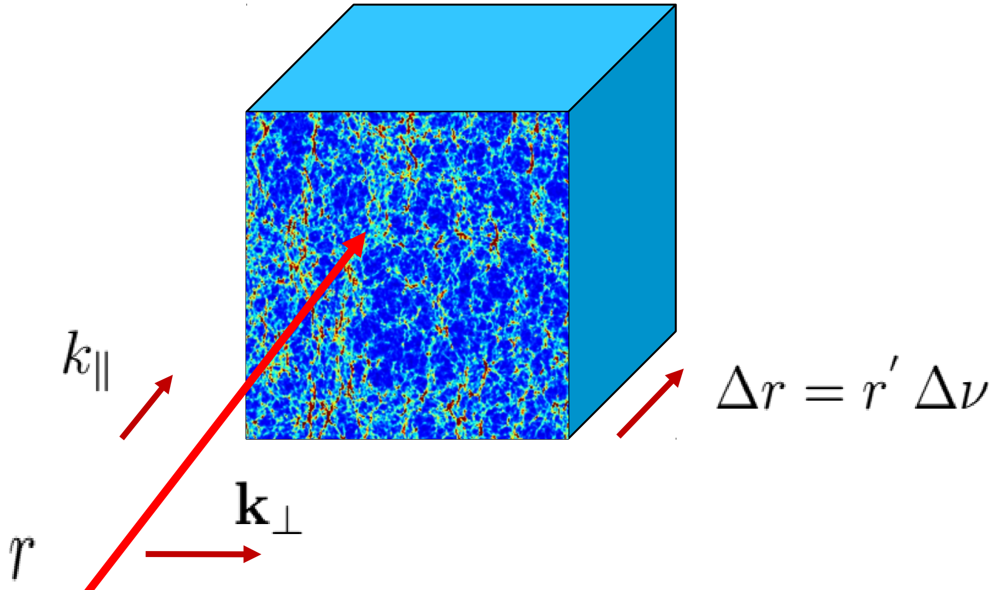
- **Measuring BAO $\Rightarrow$ Constrain Dark Energy**
  (e.g. Wyithe et al. 2008; Chang et al. 2008)

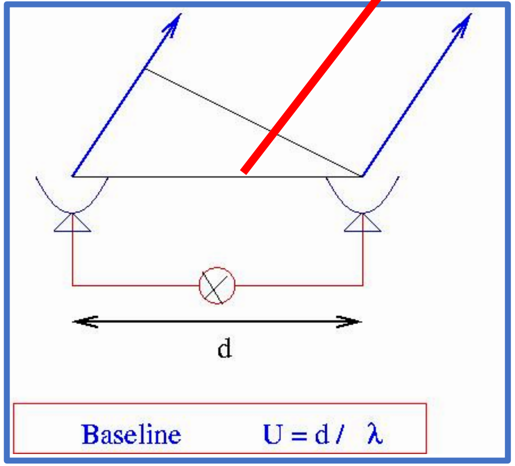
- **Cosmological parameter estimation**
  - ➔ **from BAO** (e.g. Wyithe et al. 2008)
  - ➔ **independent from BAO** (e.g. Visbal et al. 2009)

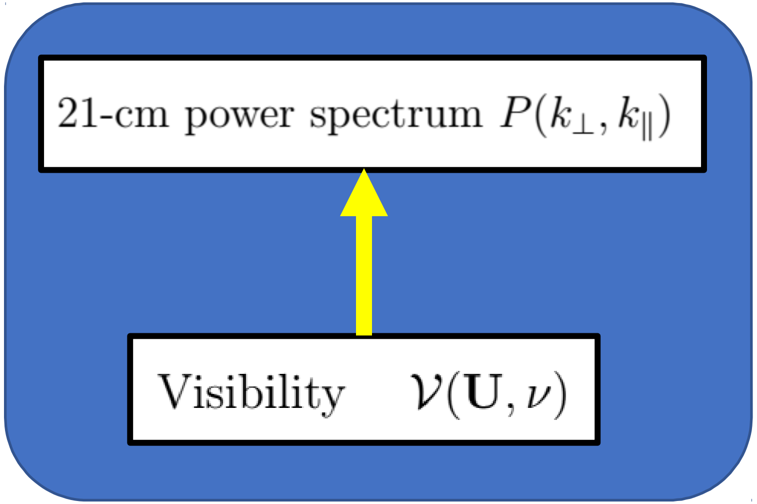
- **Quantify non-Gaussianity, constrain inflation, test Gravity on very large scales ...**

Our Aim

The IM Signal can be measured from the ground using radio telescopes







21-cm power spectrum from visibility-correlation

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

$Q = 2k_B/\lambda^2$

$$\left(\frac{\theta_0}{2}\right)^2 = \frac{1}{2\pi}\int d^2\theta \mid \mathcal{A}(\theta) \mid^2$$

MAPS

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

$$\ell = 2\pi \mid \mathbf{U} \mid$$

$$\mathbf{k}_\perp = \frac{2\pi \mathbf{U}}{r}$$

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

PS

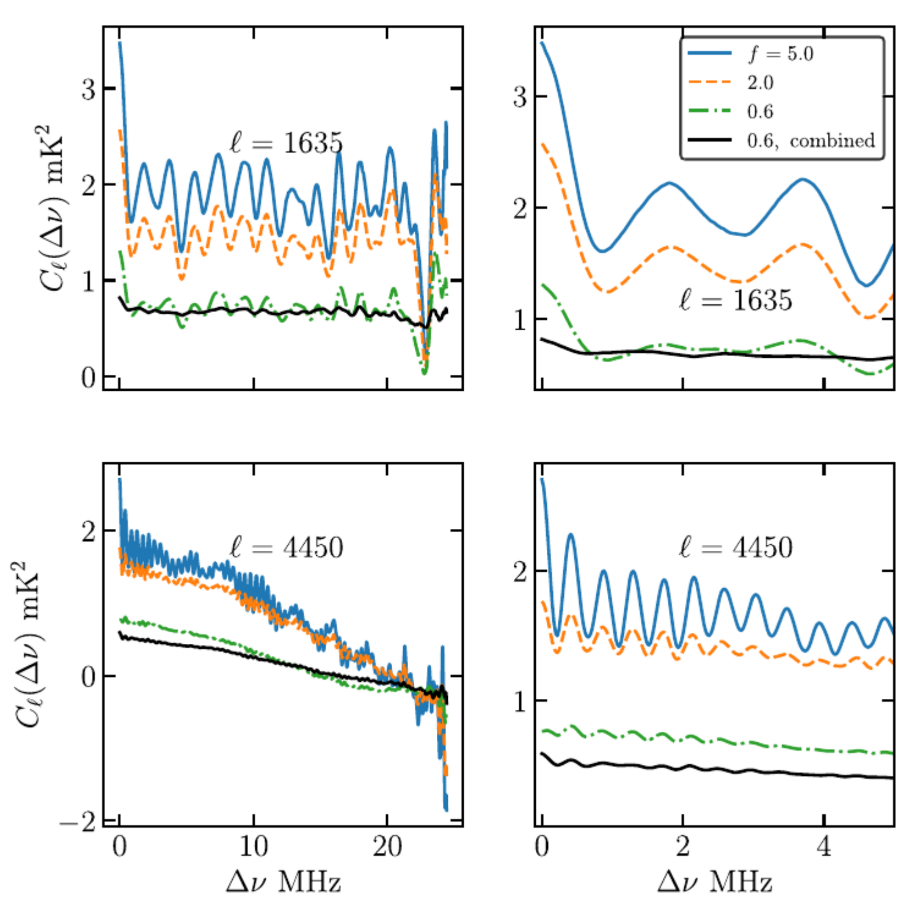
From:
Bharadwaj & Sethi 2001
Bharadwaj & Ali 2005

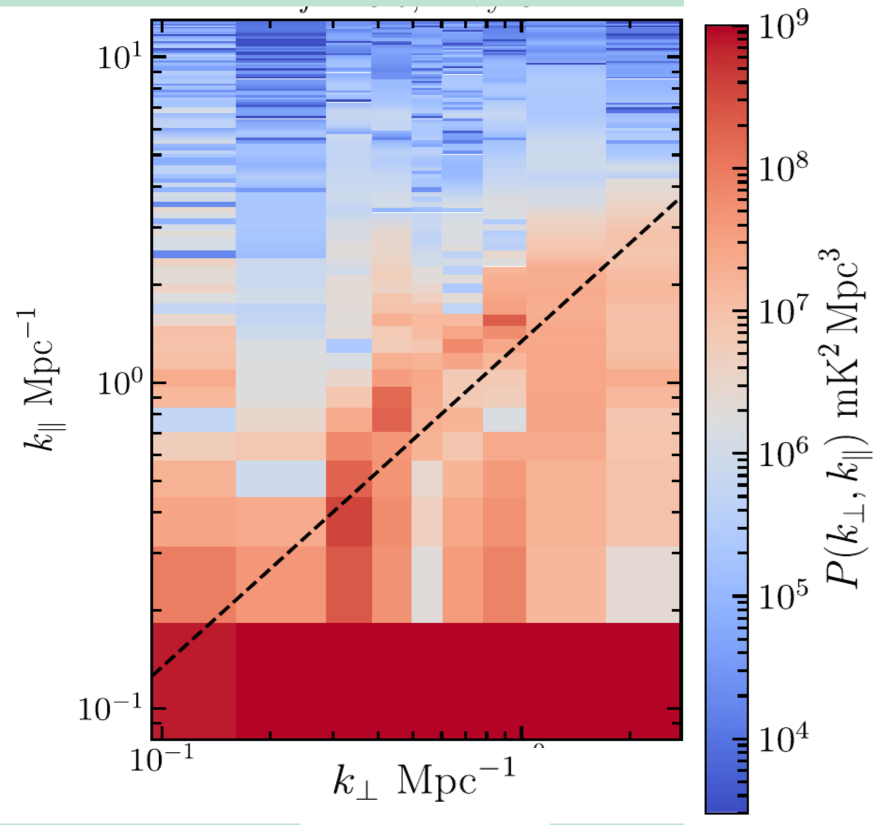
Oscillations in MAPS, **Wedge** in PS

$$C_\ell(\Delta\nu) \propto \cos(\ell\theta\Delta\nu/\nu_c)$$

$$\boldsymbol{k_\perp = \ell/r}$$

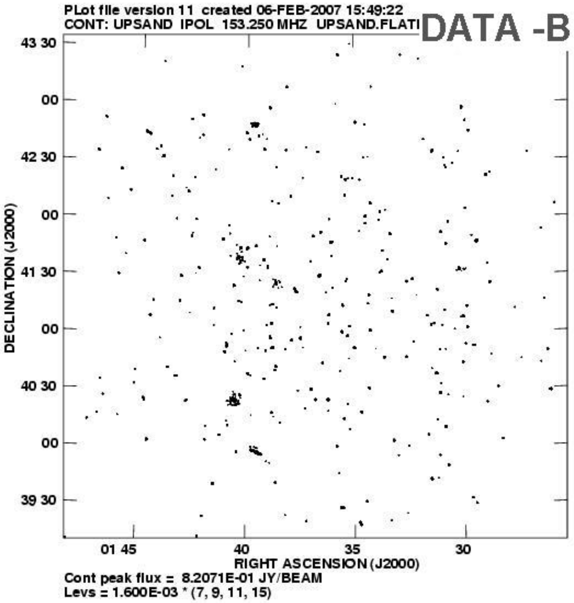
$$k_\parallel = \left[\frac{r\,\sin(\theta)}{r'\nu_c}\right]\, k_\perp$$



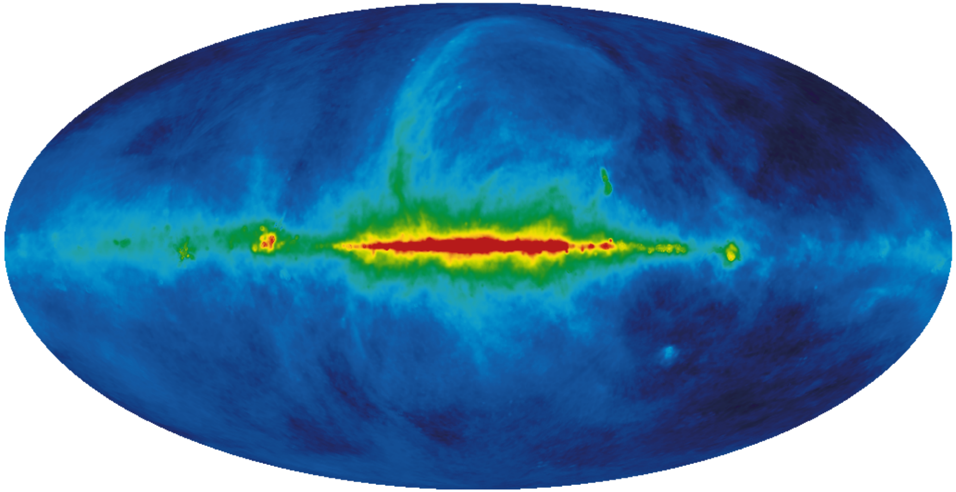


Pal, AE, Bharadwaj + 2022, MNRAS
(Earlier Ghosh et al 2011, 12)

Foregrounds



Extragalactic Point Sources

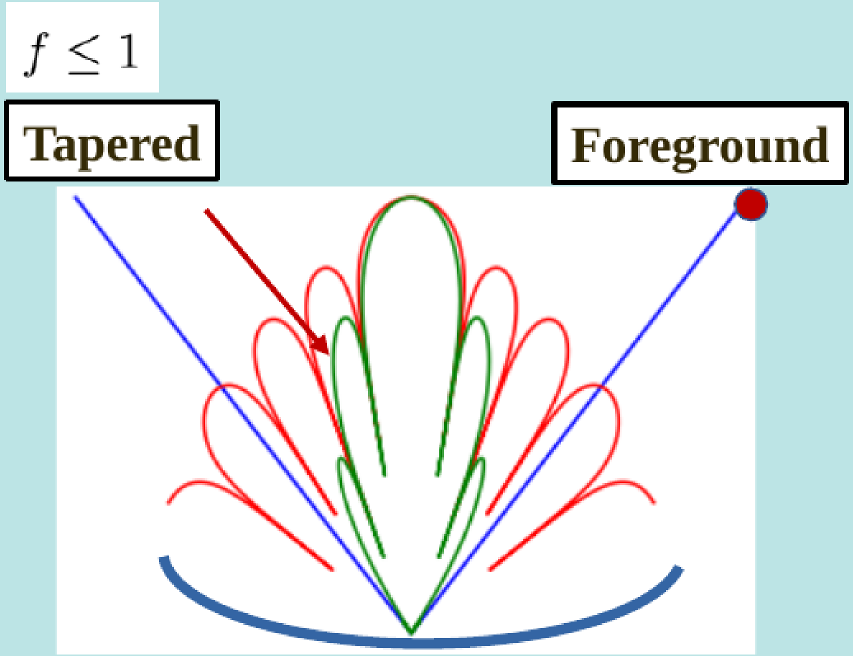


Diffuse Galactic Synchrotron Radiation

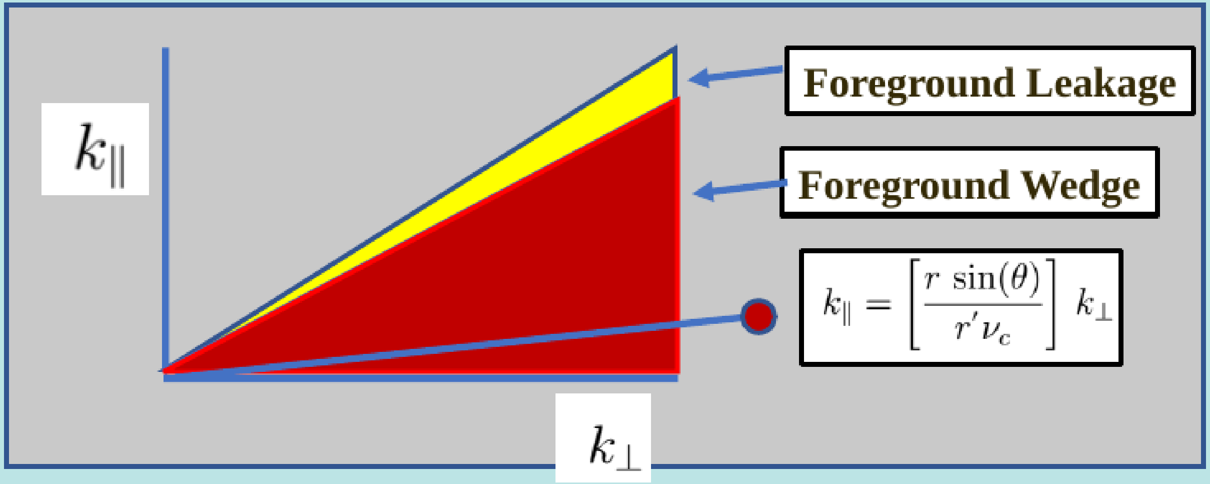
4 to 5 orders of magnitude larger than the 21-cm signal
Biggest Challenge

Ali + 2008

Tapered Gridded Estimator



Choudhuri + 2014, 2016
Bharadwaj + 2018
Pal + 2020



Visibility = F.T. (sky-intensity x beam)

$$\mathcal{W}(\theta) = e^{-\theta^2/[f\,\theta_0]^2}$$

$$\mathcal{V}^x_{cg}(\nu_a) = \sum_i \tilde{w}\left(\mathbf{U}_g - \mathbf{U}_i\right) \mathcal{V}^x_i(\nu_a)\, F^x_i(\nu_a)$$

$$\hat{E}_g(\nu_a, \nu_b) = M_g^{-1}(\nu_a, \nu_b) \mathcal{R}e\Big[\mathcal{V}_{cg}(\nu_a)\mathcal{V}^*_{cg}(\nu_b) - \sum_i F_i(\nu_a)F_i(\nu_b) \mid \tilde{w}(\mathbf{U}_g - \mathbf{U}_i) \mid^2 \mathcal{V}_i(\nu_a)\mathcal{V}^*_i(\nu_b)\Big]$$

uGMRT Observation

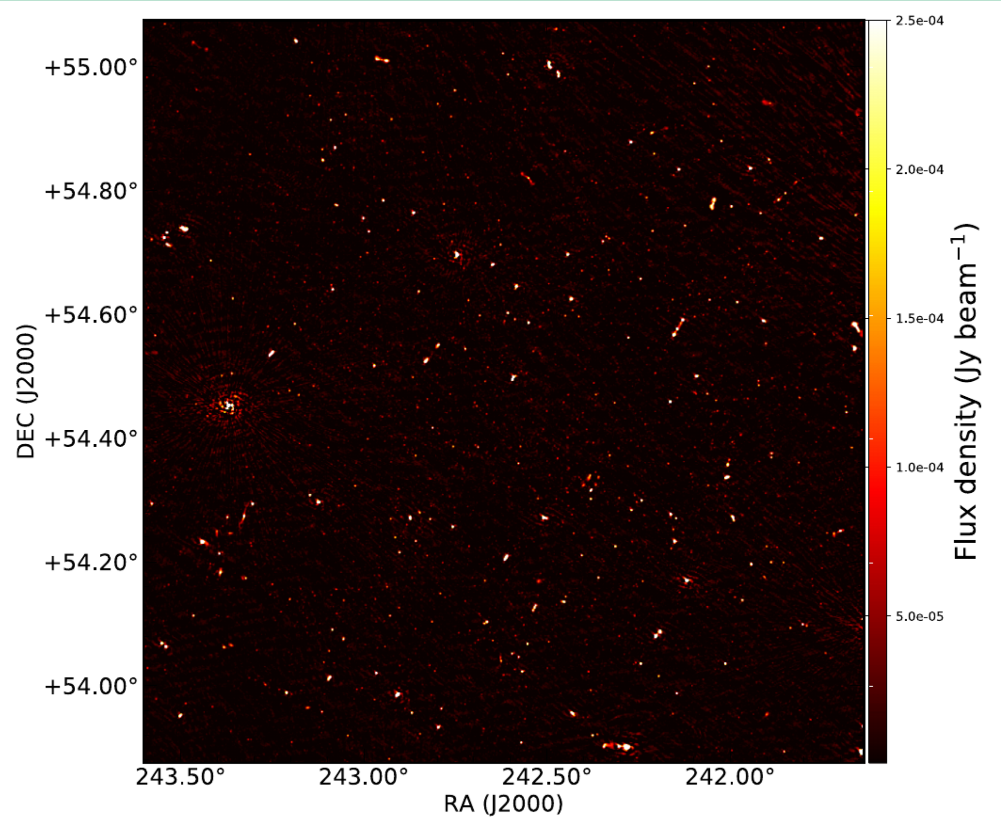
1.9 < z < 2.6
394 – 494 MHz

Table 3.1: Observation summary

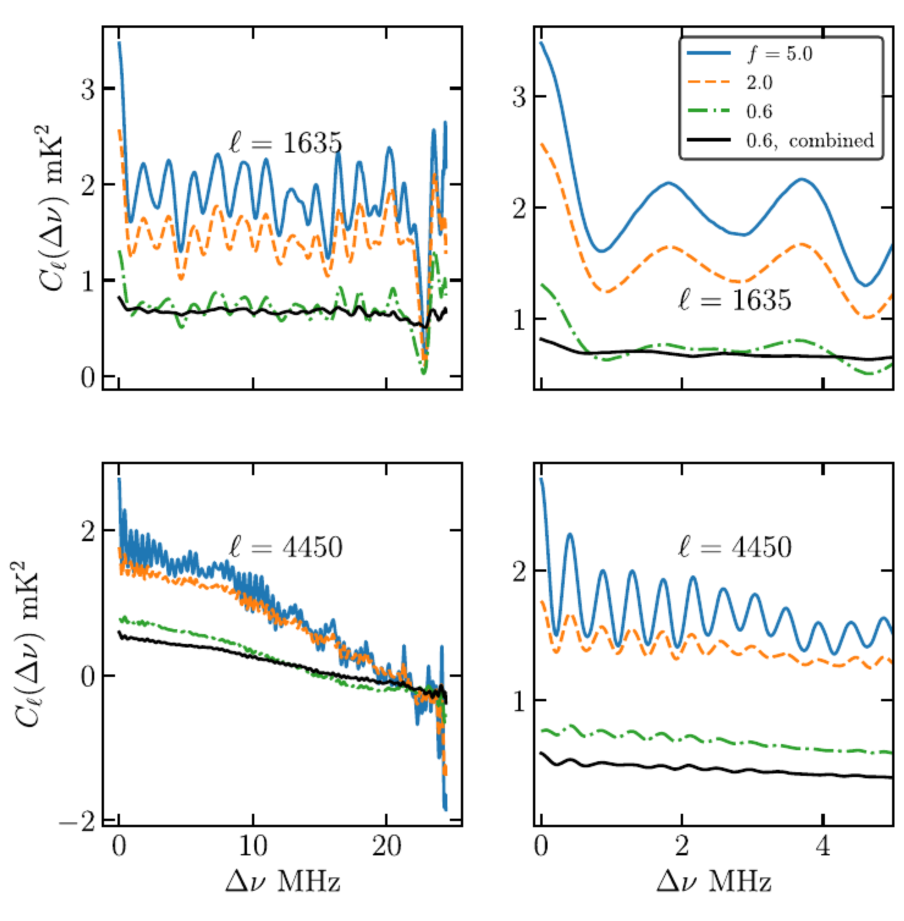
ELAIS-N1

Working antennas	28
Central Frequency	400 MHz
Number of Channels	8192
Channel width	24.4 kHz
Bandwidth	200 MHz
Total observation time	25 h
On-source observation time	13 h

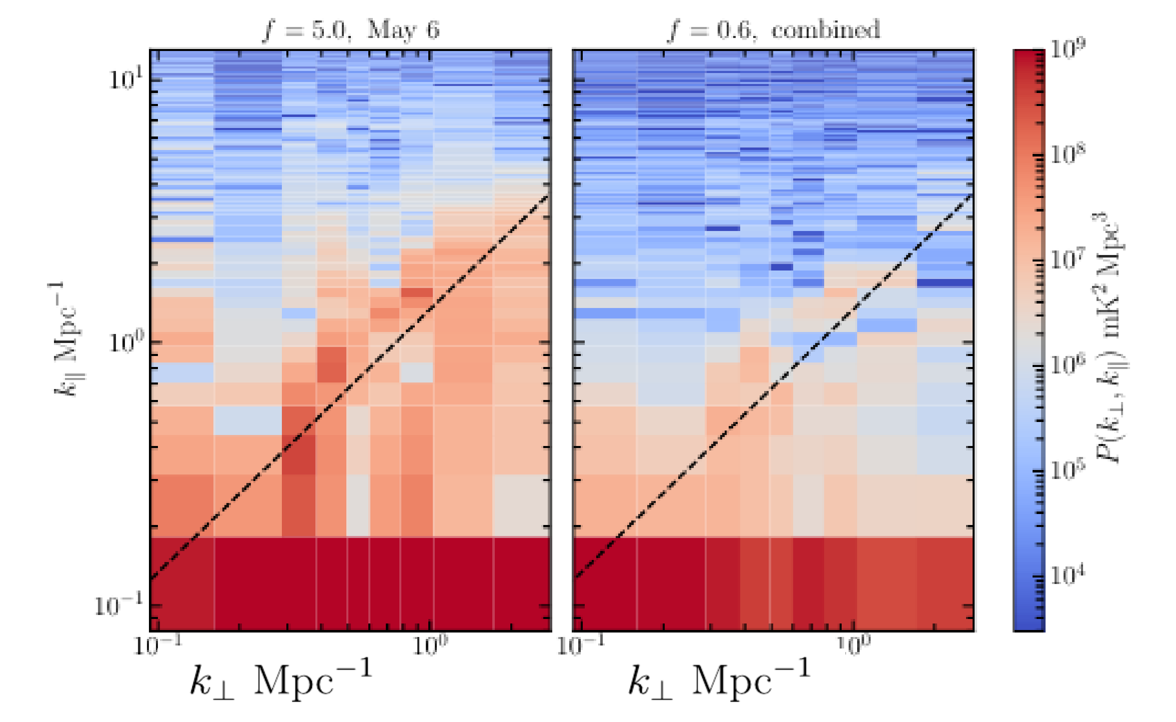
Chakraborty + 2019



TGE in action



Foreground suppression



Pal, AE, Bharadwaj + 2022, MNRAS

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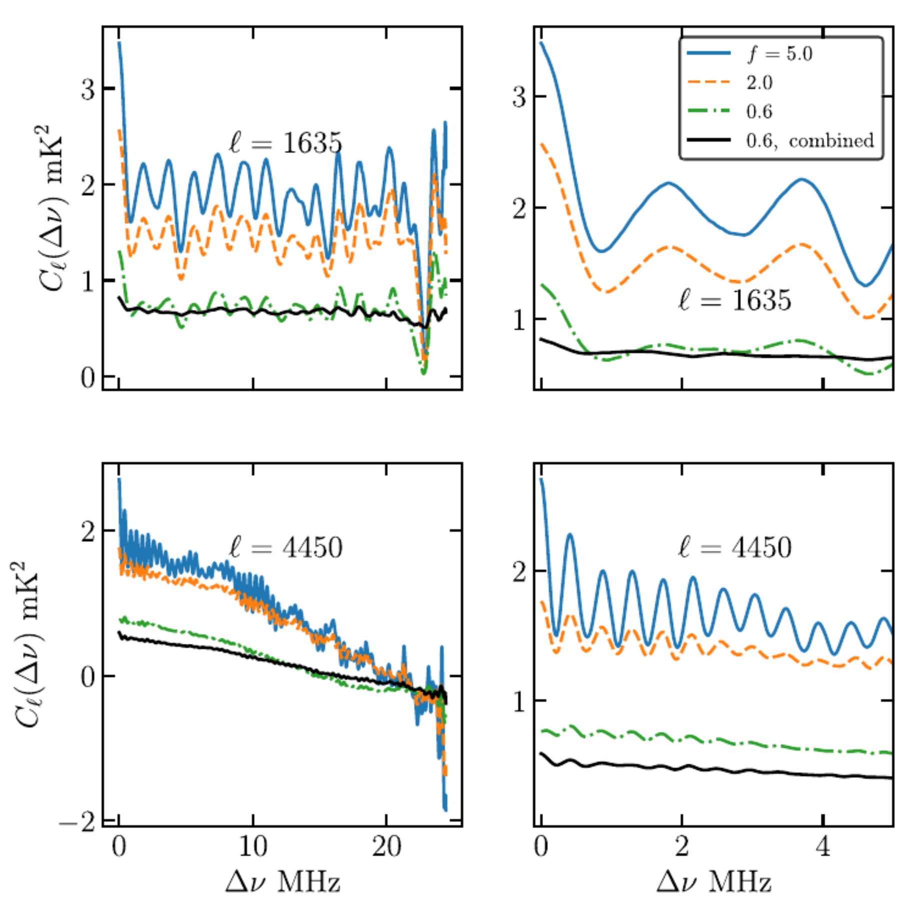

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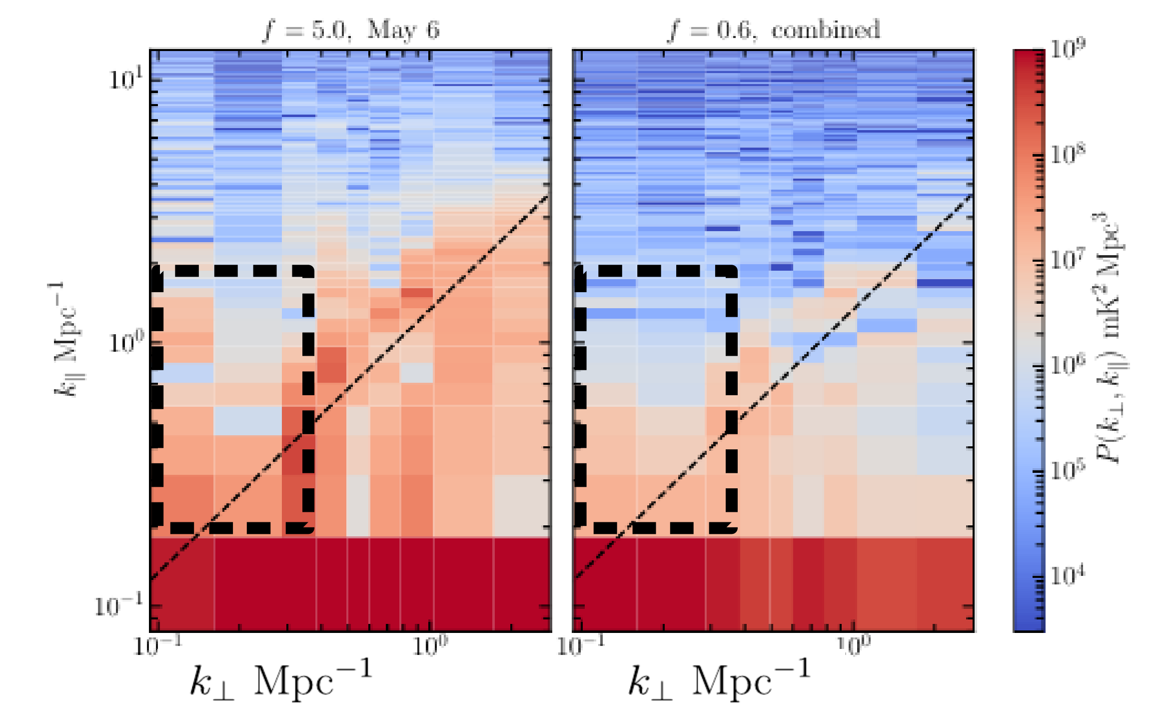

Pal, AE, Bharadwaj + 2022, MNRAS

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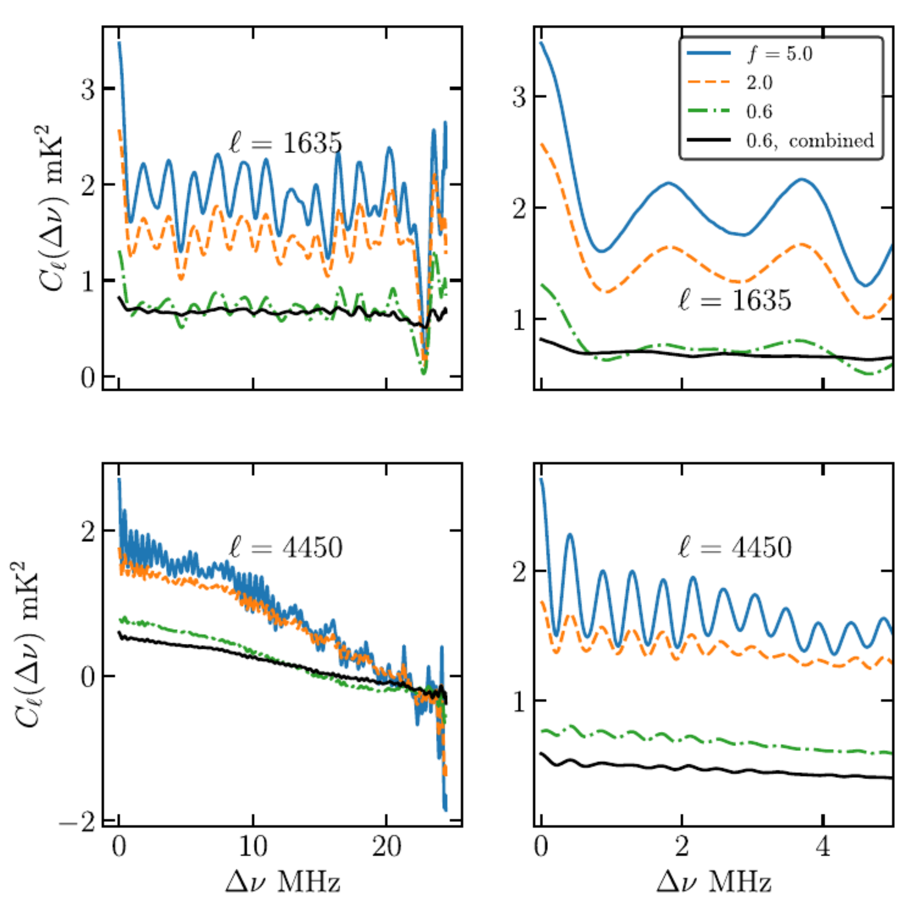

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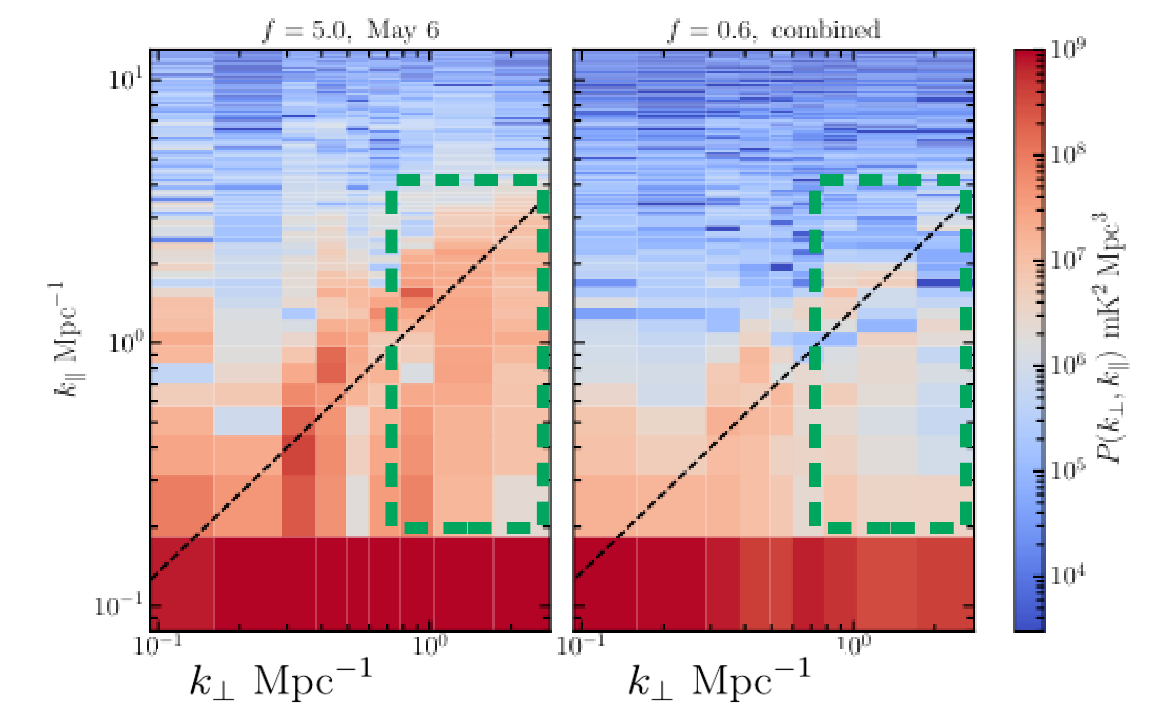

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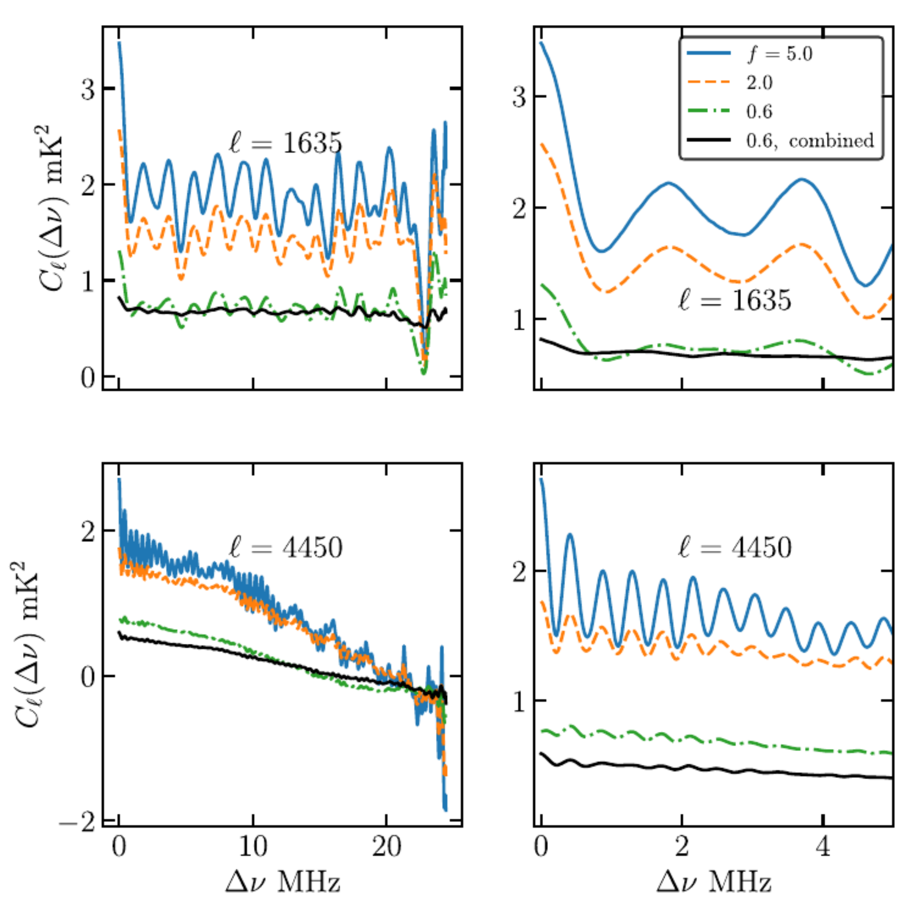

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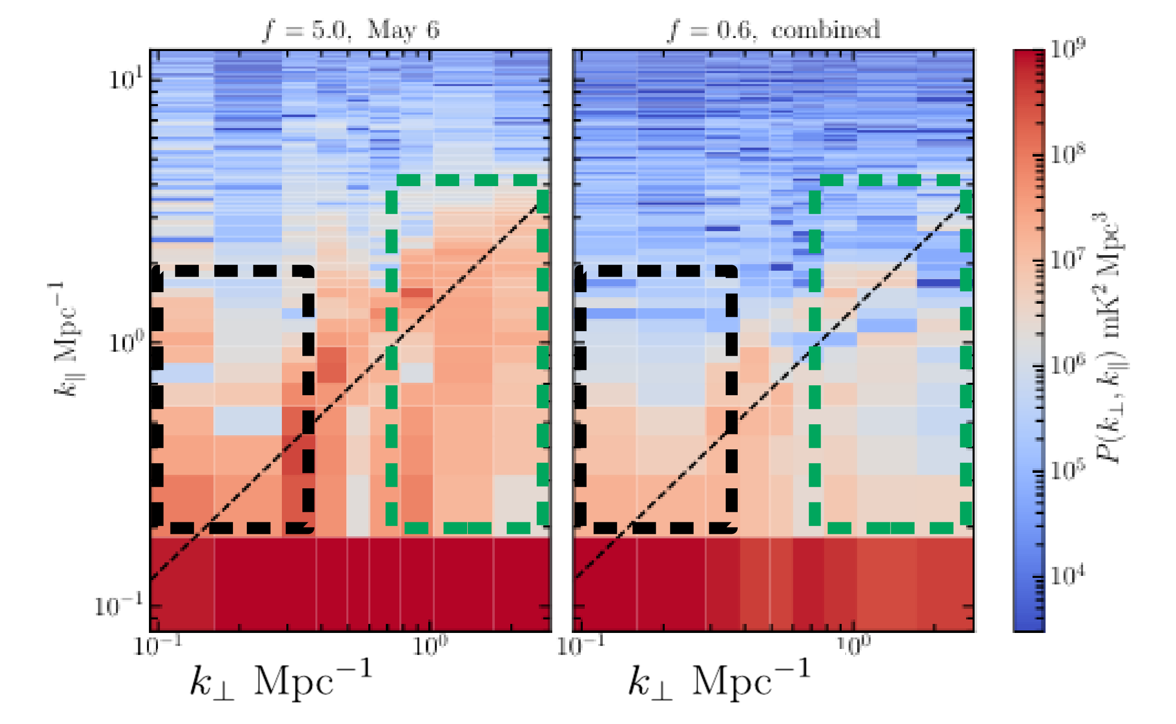

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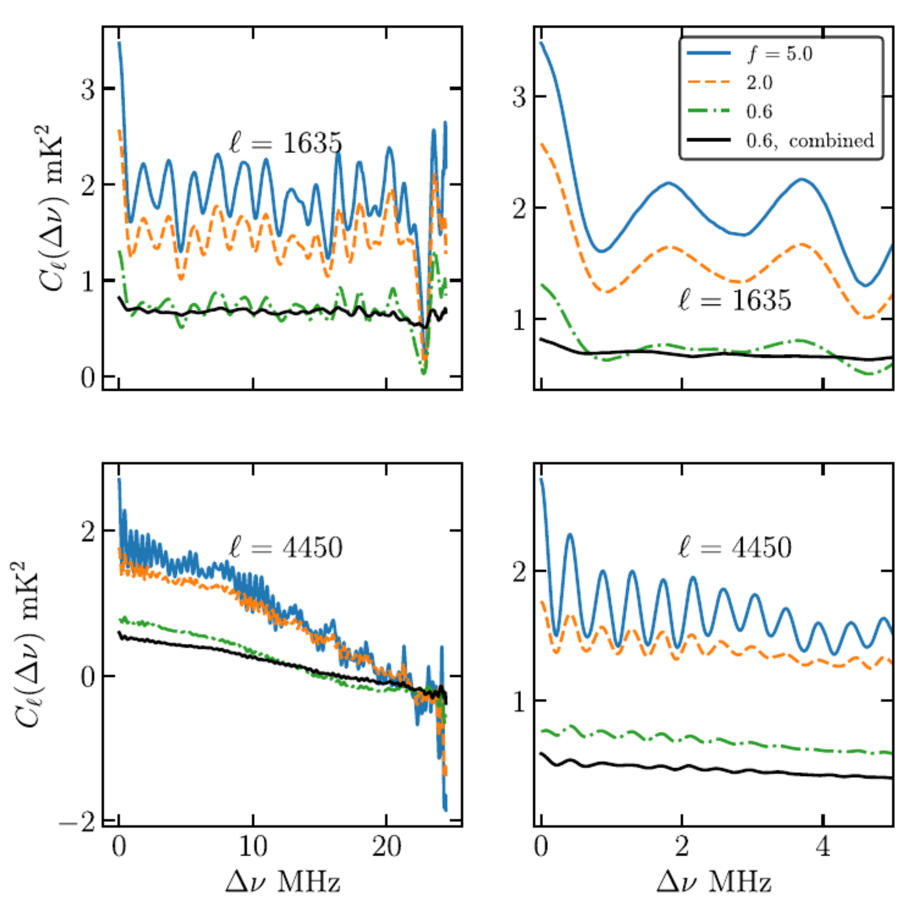
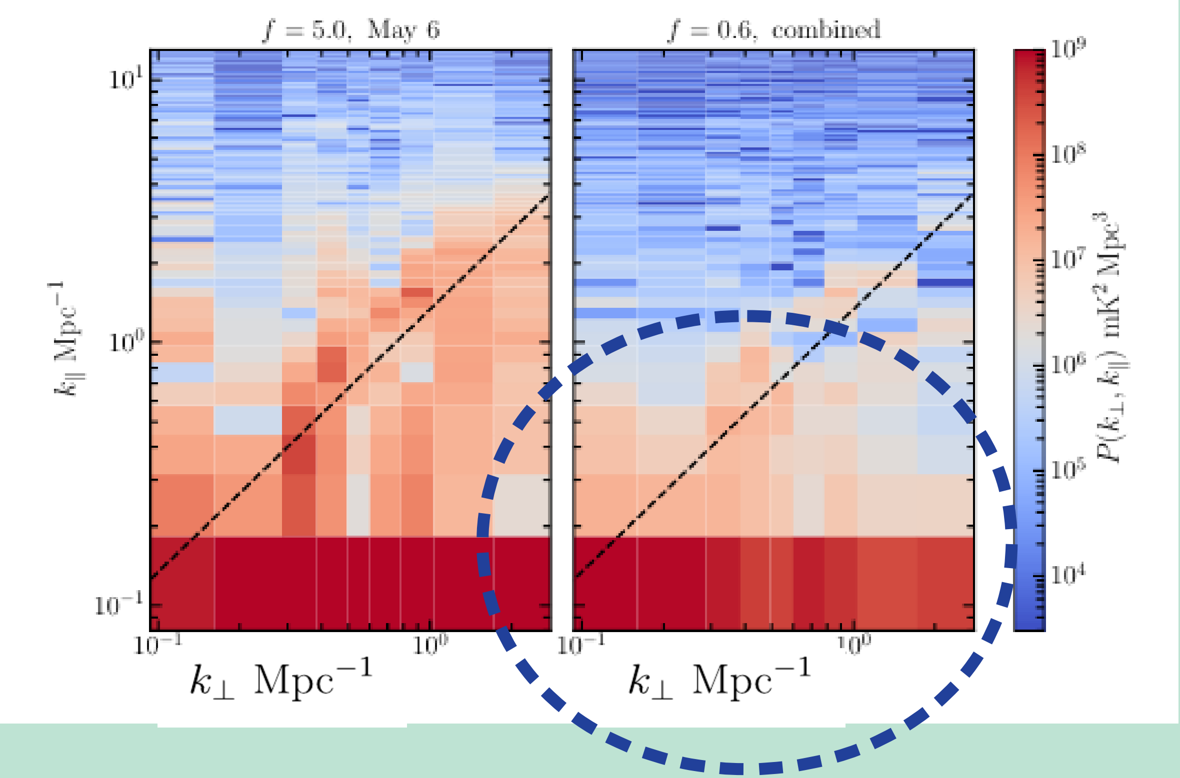


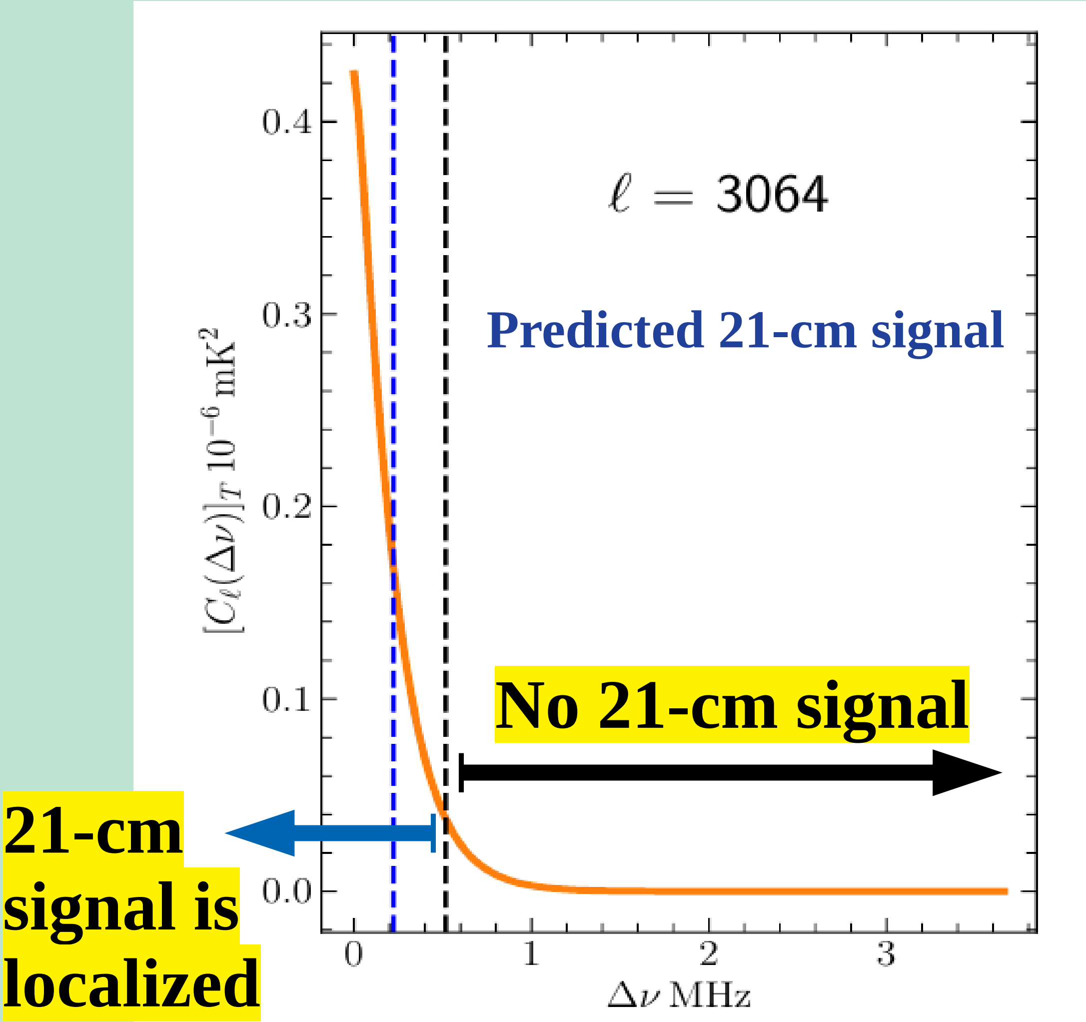
Foreground removal

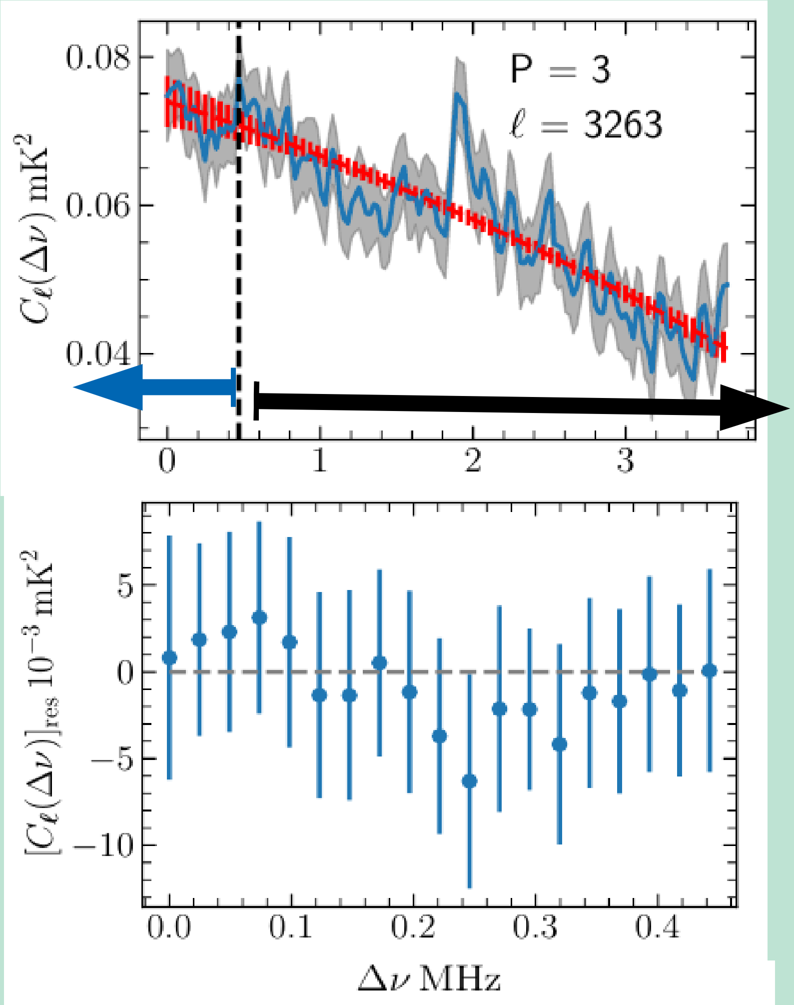


Pal, AE, Bharadwaj + 2022, MNRAS

Foreground removal

Elahi et al 2023; MNRAS



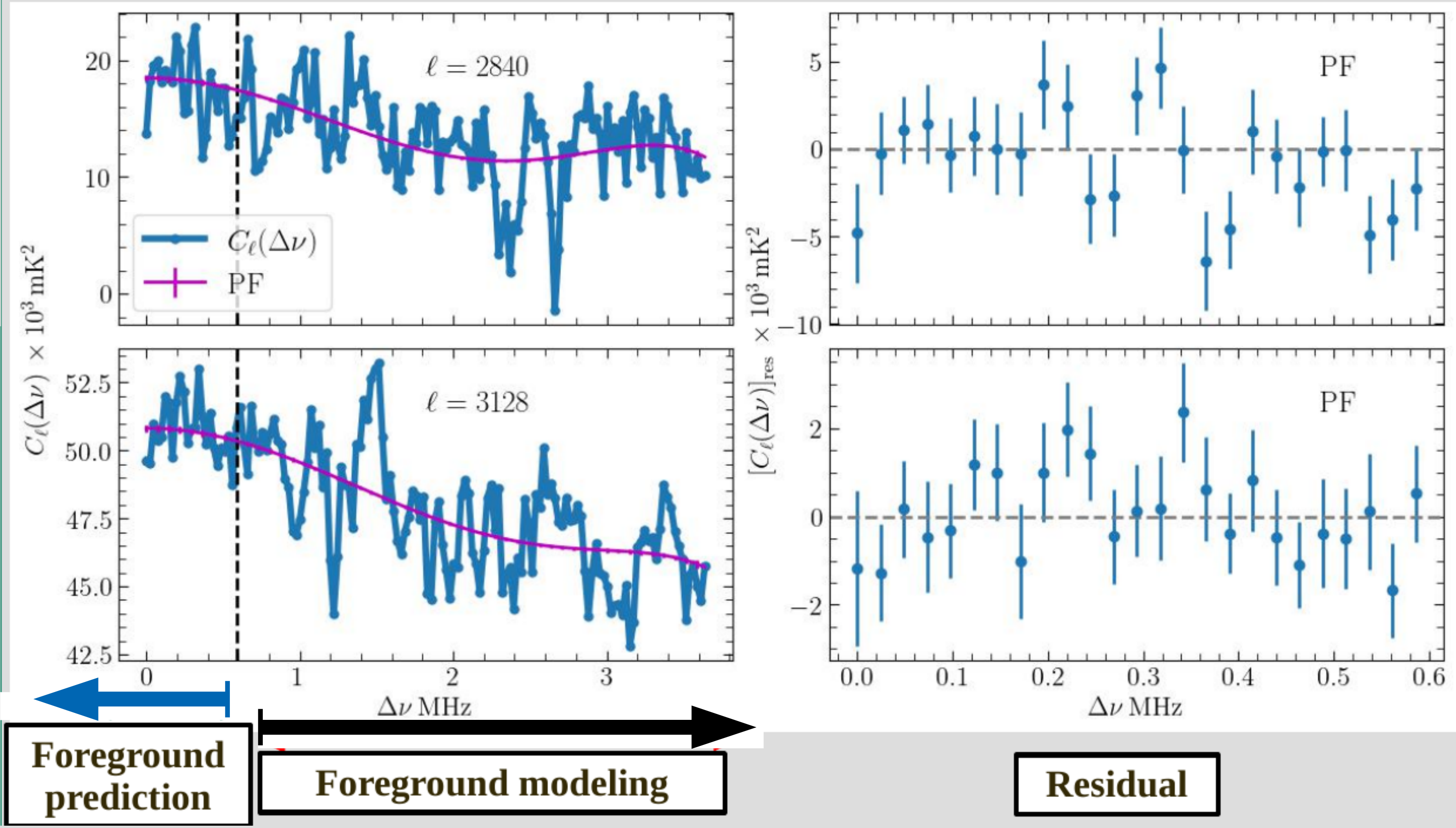


Foreground removal from MAPS - PF

21-cm signal is localized within $\Delta\nu < [\Delta\nu] \Rightarrow$ minimal signal loss

Polynomial Fitting (PF)

$$[C_\ell(\Delta\nu)]_{\mathrm{FG}} = \sum_{m=0}^{n} a_{2m} \, (\Delta\nu)^{2m}$$



Elahi et al 2023; MNRAS

Foreground removal from MAPS - GPR

Gaussian Process Regression (GPR)

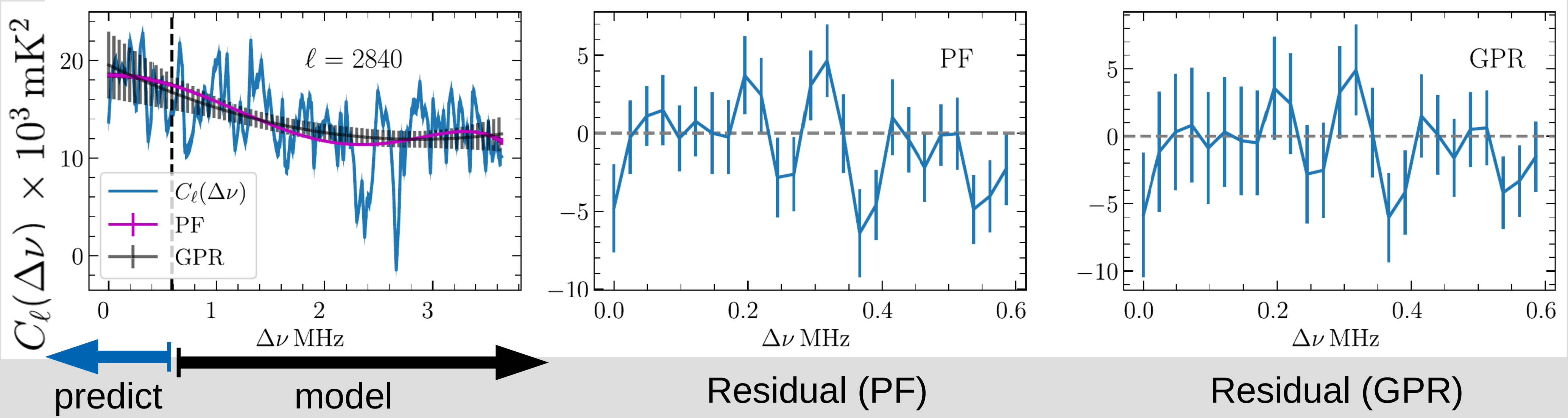
$$[C_\ell(\Delta\nu)]_{\rm FG} \sim \mathcal{GP}\,[0,\ k_{\rm FG}(\Delta\nu_m, \Delta\nu_n)]$$

$$k_{\rm FG}(\Delta\nu_m, \Delta\nu_n) = c_1\,(\Delta\nu_m \cdot \Delta\nu_n + b)^P$$

Polynomial kernel

Idea: 21-cm signal decorrelates faster than foreground
21-cm signal is localized within $\Delta\nu \leq [\Delta\nu]$

- **Step 1**: Model the foregrounds from the range $\Delta\nu > [\Delta\nu]$
  $C_\ell(\Delta\nu) = [C_\ell(\Delta\nu)]_{\rm FG} + [\rm Noise]$
- **Step 2**: Predict the foreground in the range $\Delta\nu \leq [\Delta\nu]$
- **Step 3**: Subtract the foreground prediction
  $[C_\ell(\Delta\nu)]_{\rm res} = C_\ell(\Delta\nu) - [C_\ell(\Delta\nu)]_{\rm FG}$

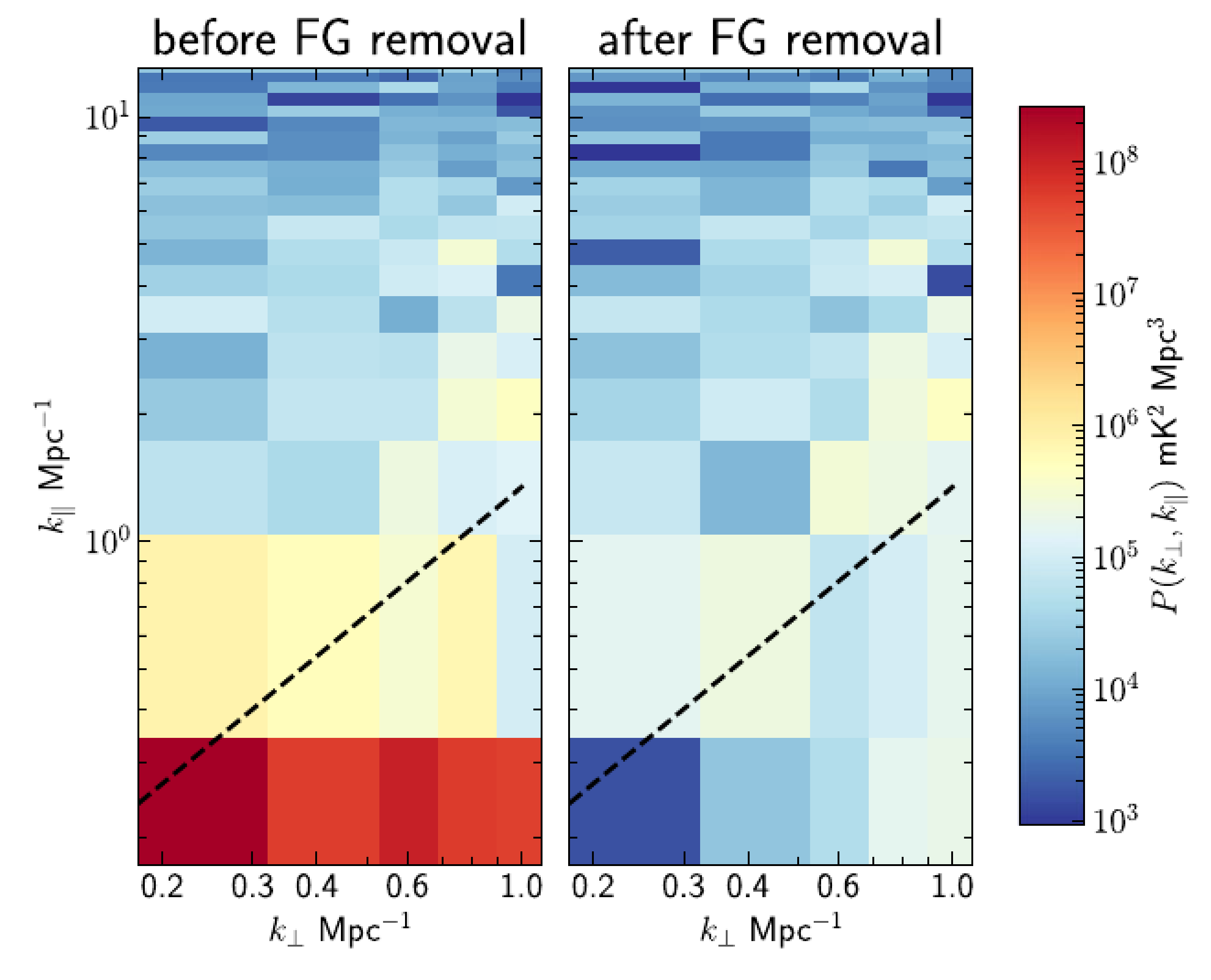


uGMRT

24.4 MHz Bandwidth

At 432.8 MHz

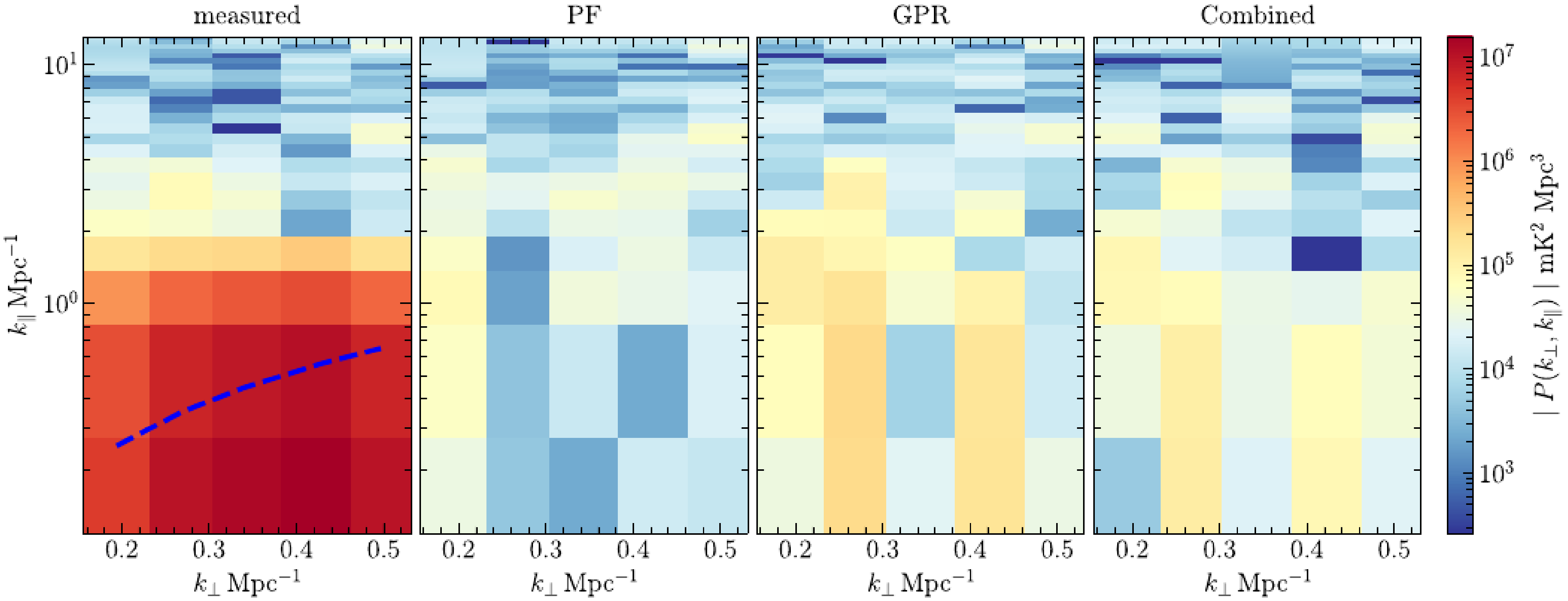
z = 2.28



Elahi et al 2023; MNRAS

uGMRT

100 MHz Bandwidth, 394 - 494 MHz, 1.9 < z < 2.6



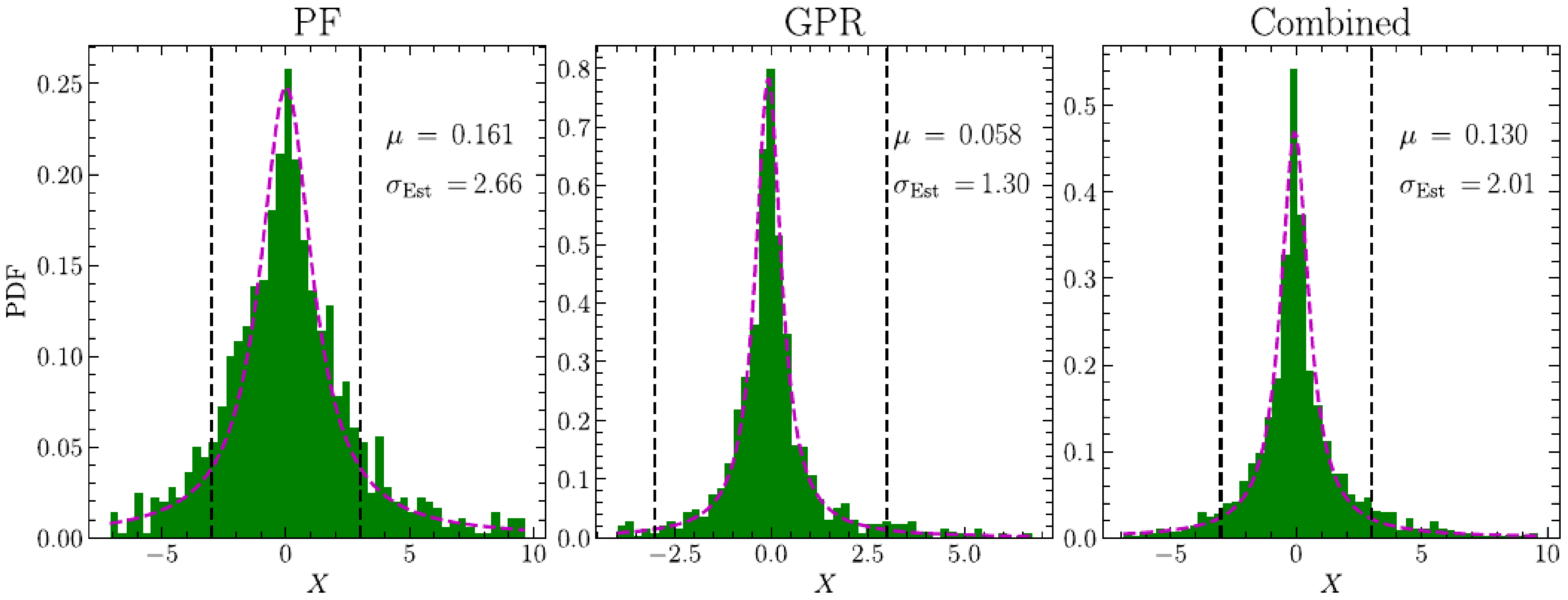
Wideband Analysis (Elahi et al 2024; MNRAS)

Consistent with noise?

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

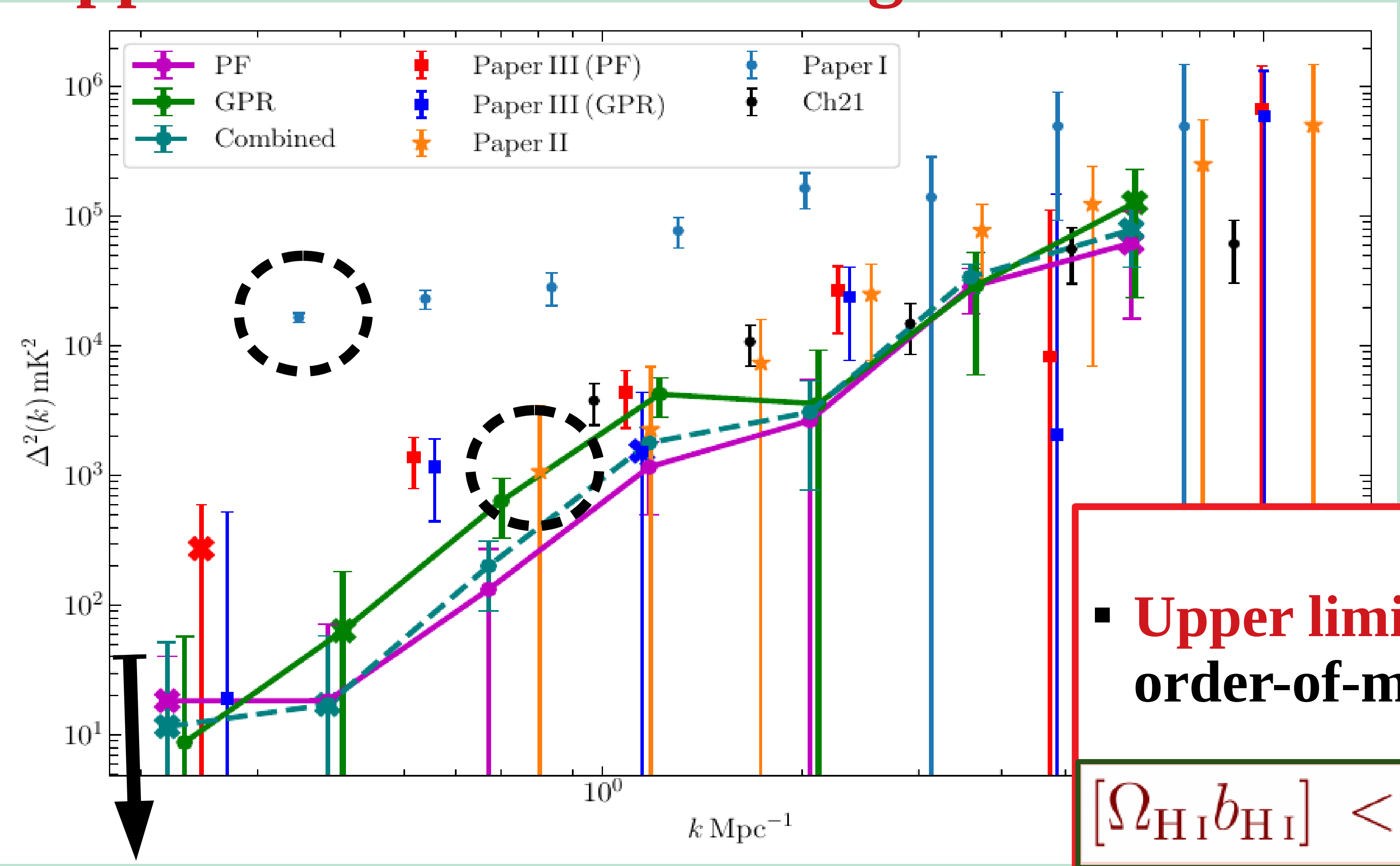
Consistent with noise

95% confindence



Wideband Analysis (Elahi et al 2024; MNRAS)

Upper limit on the 21-cm signal



- **Upper limit is within an order-of-magnitude.**

$$[\Omega_{\rm H\,I} b_{\rm H\,I}] < 1.01 \times 10^{-2}$$

Highlights

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TGE	Visibility-based (i.e., directly from the observed data) **mitigates foregrounds**, unbiased, immune to missing frequency channels, **wideband**
Foreground removal	Removes foregrounds from **MAPS**, 21-cm signal is **localized**, PF and GPR
Power Spectrum	Consistent with noise
Upper limit	Observation 25 hours $[\Omega_{\rm H\,I} b_{\rm H\,I}] < 1.01 \times 10^{-2}$
Future	✔ Longer Observation (obtained 50h, 2σ detection $k < 0.4$ Mpc^{-1}) ✔ Other telescope (MeerKAT, **SKA**) ✔ Other frequencies (e.g. EoR using MWA/**SKA-low**)