Towards 21 cm Intensity Mapping with uGMRT – Foreground removal

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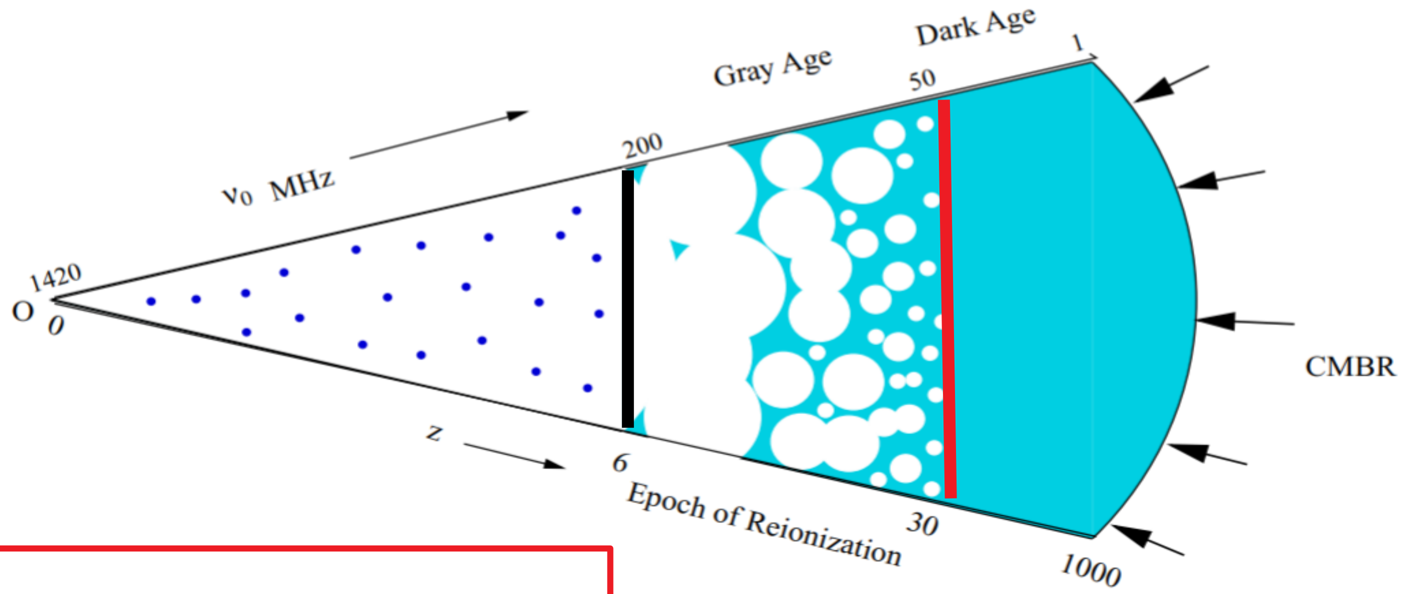
Post-reionization 21 cm intensity mapping

Redshifted HI 21 cm line can trace the evolution history of the Universe

Post-reionization
⇒ IGM is ionized,
⇒ HI inside the galaxies



Goal:

To measure the integrated emission 21 cm signal from the HI distribution

Image: Bharadwaj and Ali 2004

Post-reionization 21 cm intensity mapping

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

- **Measuring BAO ⇒ Constrain Dark Energy EoS, parameters**
  (e.g. Wyithe et al. 2008; Chang et al. 2008)

- **Cosmological parameter estimation**
  (e.g. Bharadwaj et al. 2009; Visbal et al. 2009)

- **Quantify non-Gaussianity**
  (e.g. Saiyad Ali et al. 2006; Hazra & Guha Sarkar 2012)

- **Constrain EoR models**
  (e.g. Long et al. 2022)

Post-reionization 21 cm intensity mapping

Synchrotron emission

4-5 orders of magnitude brighter

Continuum emission

How to remove them?

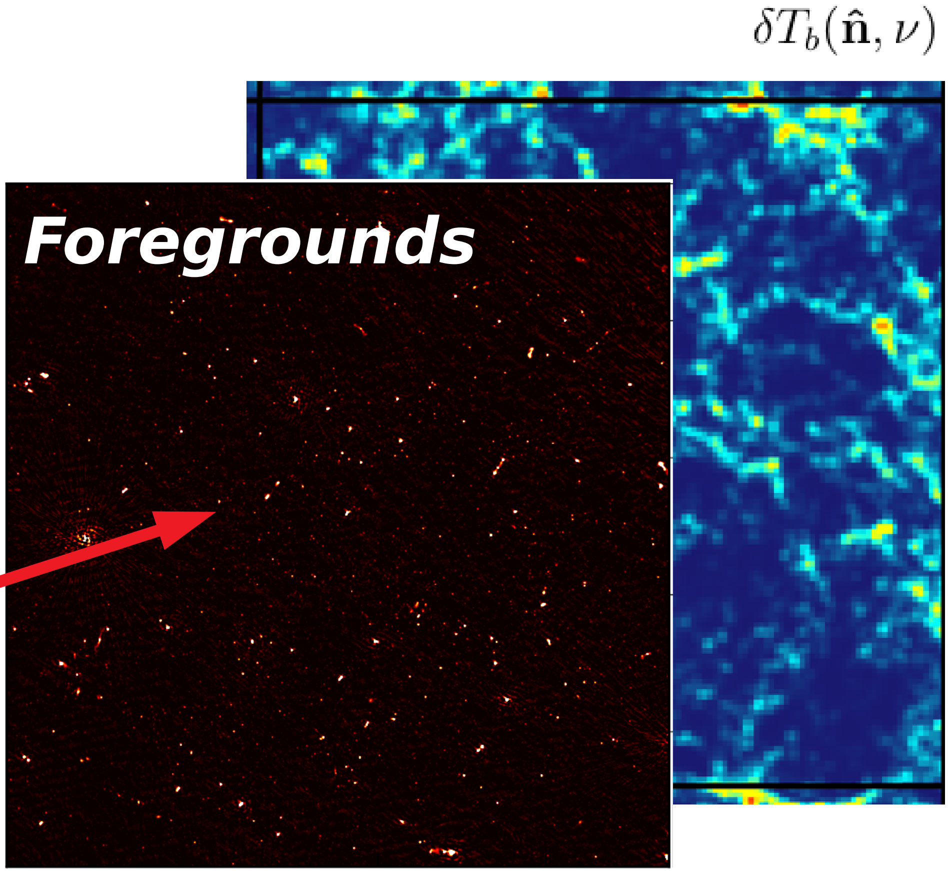


Image: Chakraborty et al., 2019

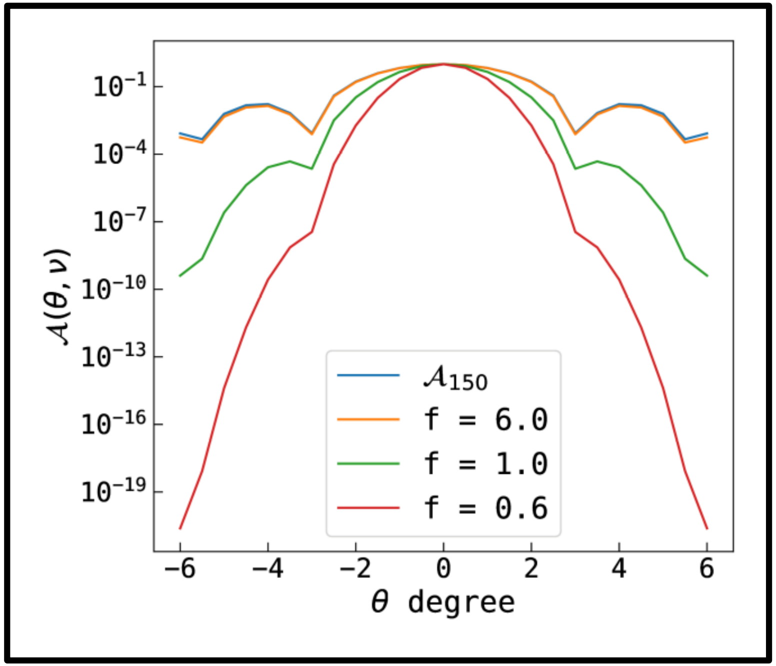
21 cm intensity mapping (statistics)

Multifrequency Angular Power Spectrum (MAPS) 2nd order statistics

$$\delta T_{\mathrm{b}}(\hat{\mathbf{n}},\, \nu) = \sum_{\ell,m} a_{\ell \mathrm{m}}(\nu)\, Y_{\ell}^{\mathrm{m}}(\hat{\mathbf{n}})$$

$$C_{\ell}(\nu_a, \nu_b) = \left\langle a_{\ell \mathrm{m}}(\nu_a)\, a^{*}_{\ell \mathrm{m}}(\nu_b) \right\rangle$$

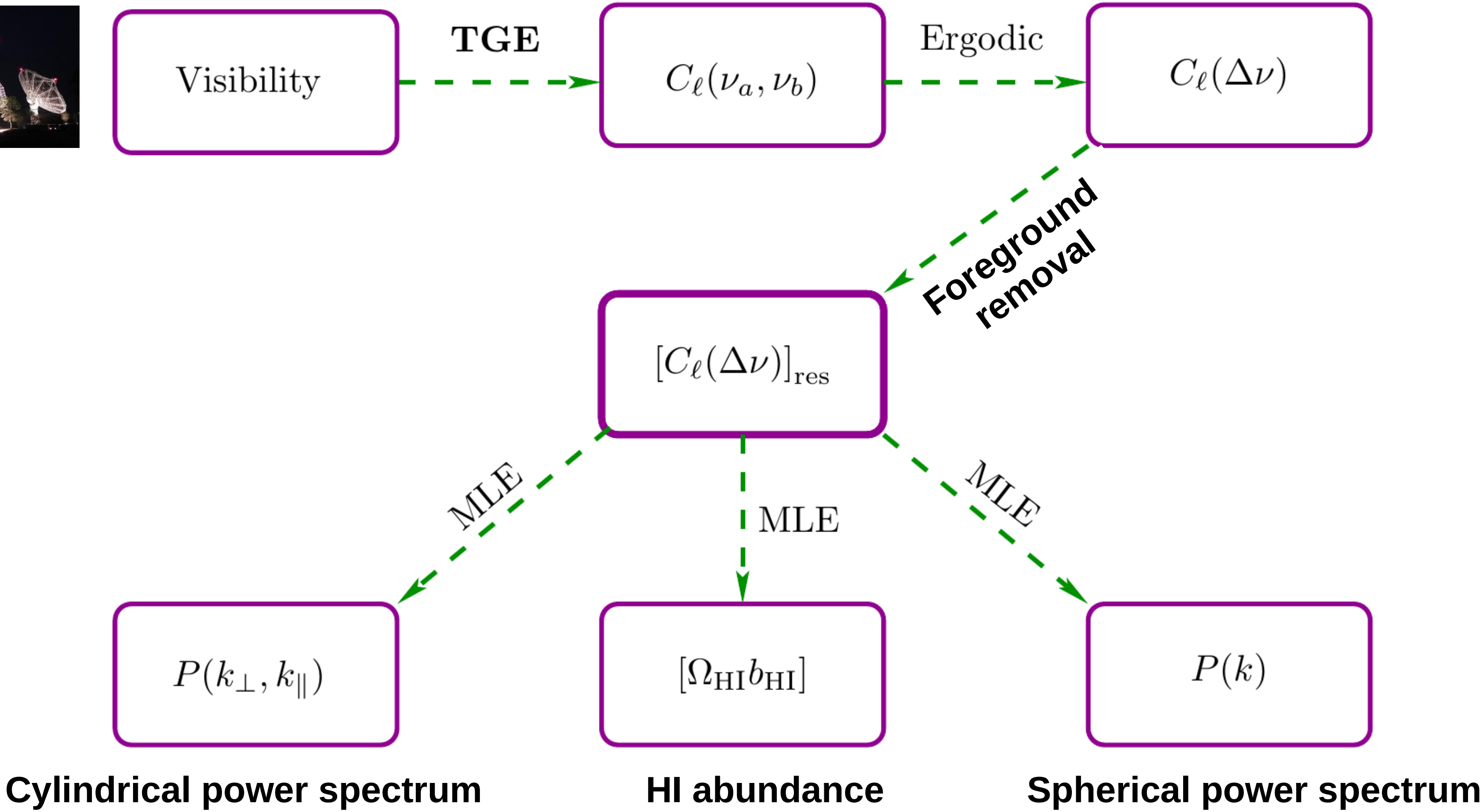
$$C_{\ell}(\nu_a, \nu_b) = C_{\ell}(\Delta\nu) \text{ where } \Delta\nu = \mid \nu_b - \nu_a \mid$$



Tapered Gridded Estimator (TGE)

- correlates visibilities to estimate the **MAPS**
- suppresses the sidelobes of the primary beam to ***reduce foreground contamination***
- unbiased estimator (noise-bias estimate / **cross-polarization**)

21 cm intensity mapping pipeline



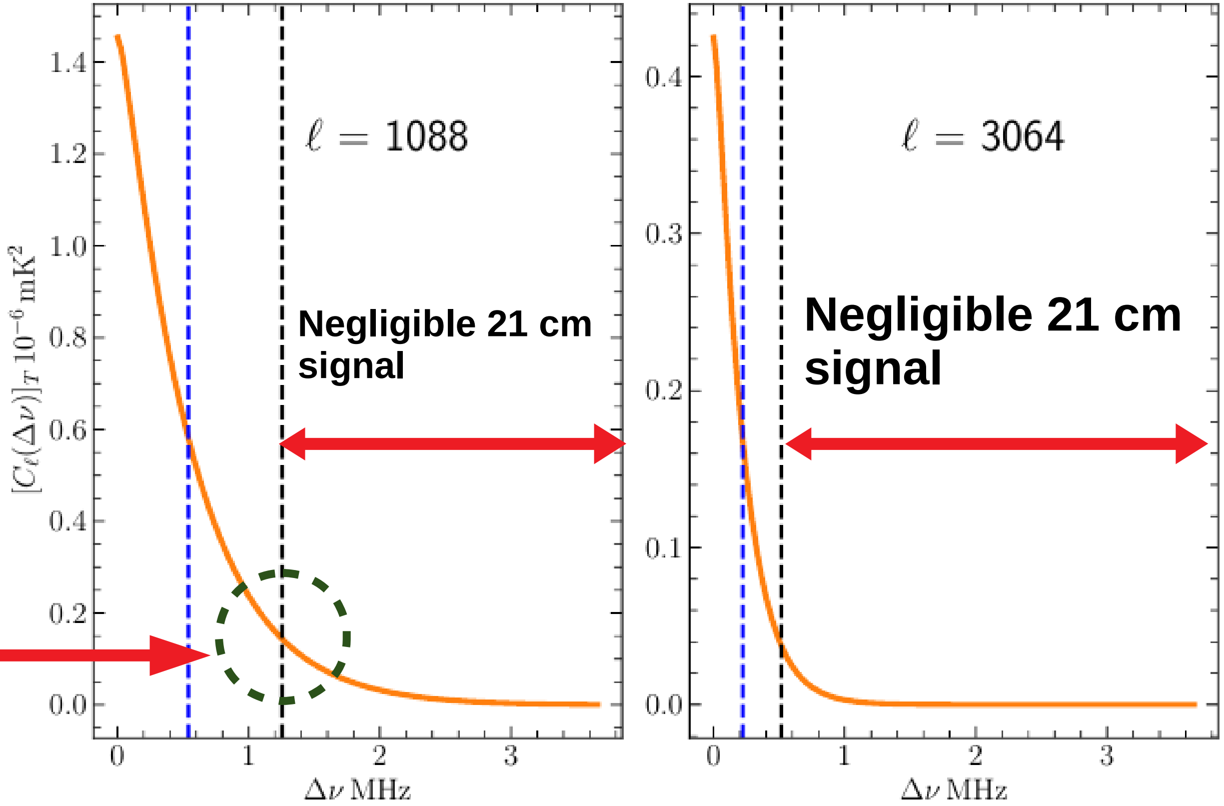
predicted 21 cm signal

21 cm signal behaves differently from the foregrounds

$$\left[C_{\ell_a}(\Delta\nu_n)\right]_T = [\Omega_{\rm H\,I} b_{\rm H\,I}]^2 \frac{\bar{T}^2}{\pi r^2} \int_0^\infty {\rm d}k_\parallel \cos(k_\parallel r' \Delta\nu_n) \times {\rm sinc}^2\left(k_\parallel r' \Delta\nu_c/2\right) P_m\left(k_{\perp a}, k_\parallel\right)$$

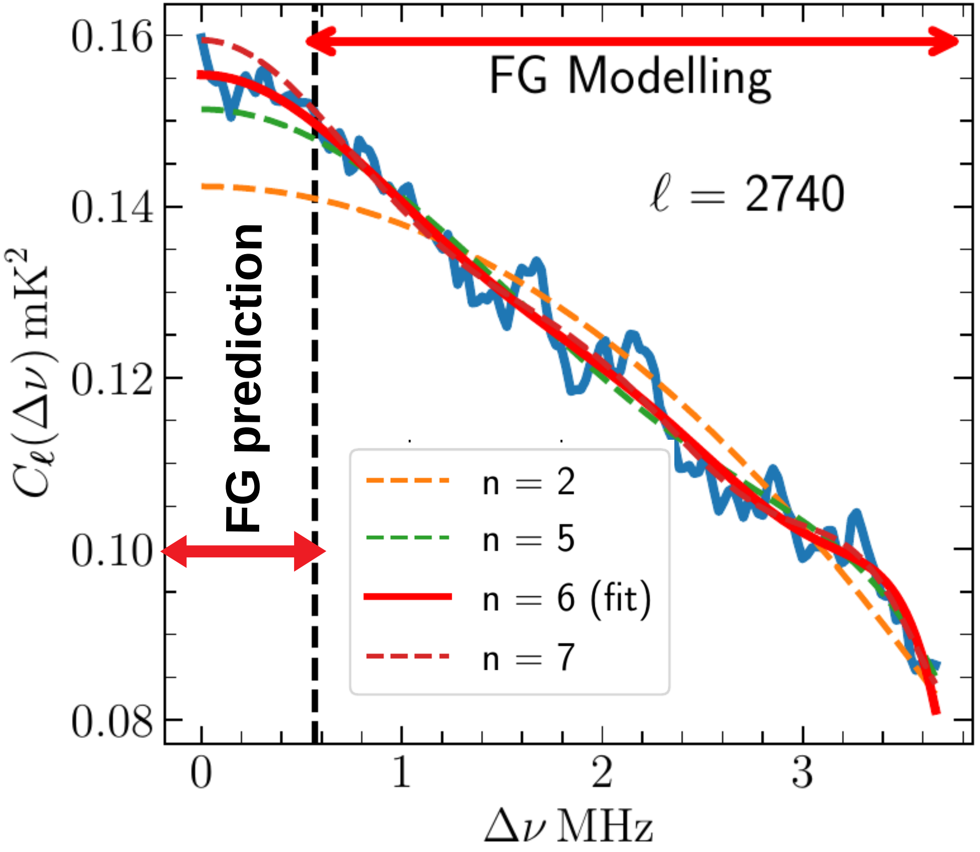
line emission ⇒ decorrelates rapidly

localized in a small $\Delta\nu$ range



Signal's amplitude is 10% of its initial value

Foreground modelling and prediction



continuum emission ⇒ decorrelates slowly

correlated over a large $\Delta\nu$ range

$$C_\ell(\Delta\nu) = [C_\ell(\Delta\nu)]_{FG} + [\text{Noise}]$$

Polynomial fitting (PF)

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

Gaussian Process regression (GPR)

$$[C_\ell(\Delta\nu)]_{\mathrm{FG}} \sim \mathcal{GP}\left[0,\,(\Delta\nu_m\,\Delta\nu_n + b)^P\right]$$

Data

Field	ELAIS-N1

uGMRT Band 3 (300-500 MHz)

Flagging, calibration, imaging

Chakraborty et al., 2019
10.1093/mnras/stz2533; arXiv:1908.10380

Bandwidth	24.4 MHz
ν_c	432.8 MHz ***(z = 2.28)***
$\Delta\nu$	24.4 kHz
N_c	1000

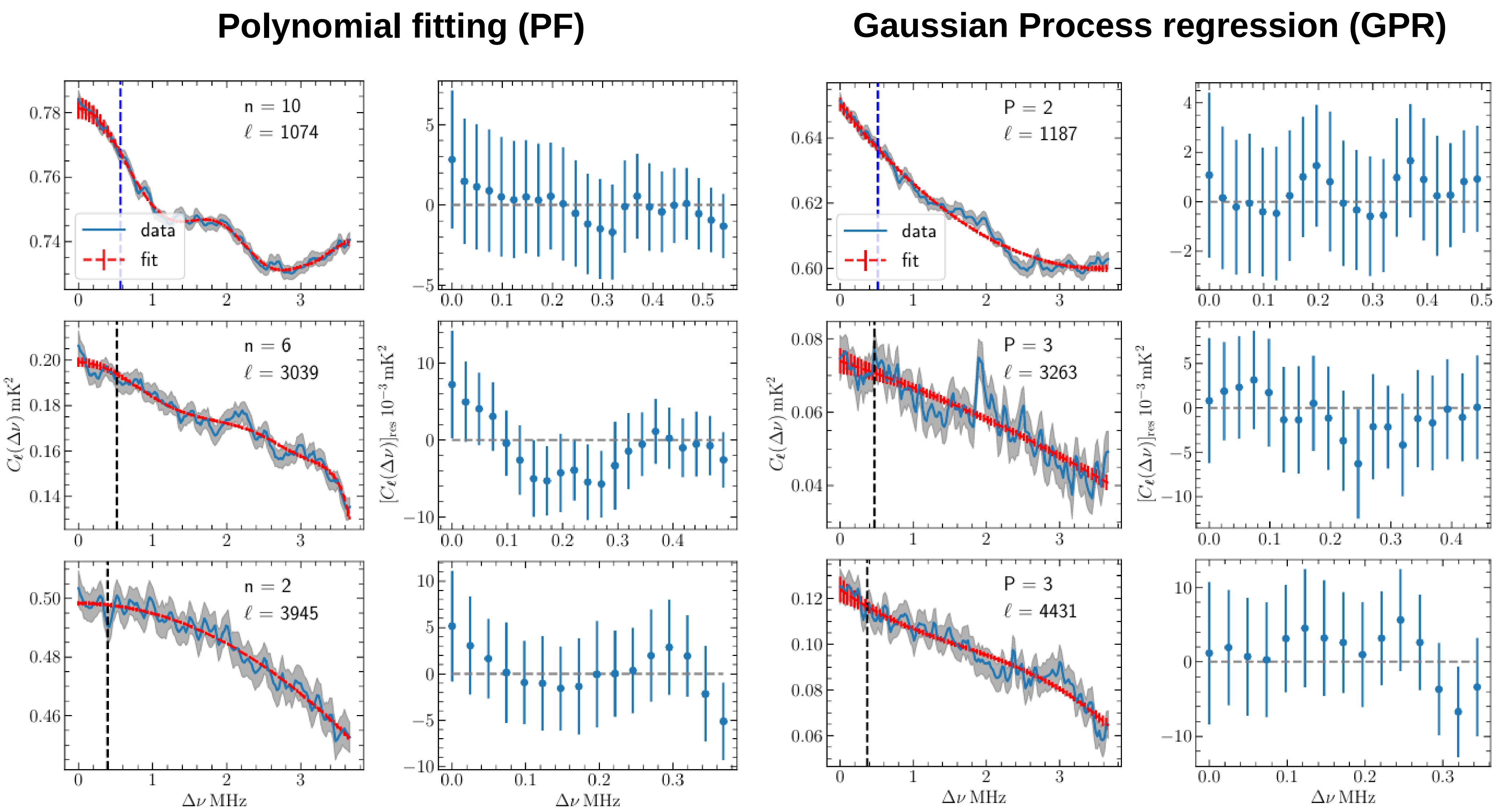
Foreground avoidance
Pal, **Elahi**, Bharadwaj + others, 2022

Cross-polarization power spectrum
Elahi, Bharadwaj, Ghosh + others 2023

Foreground removal
Elahi, Bharadwaj, Pal + others 2023

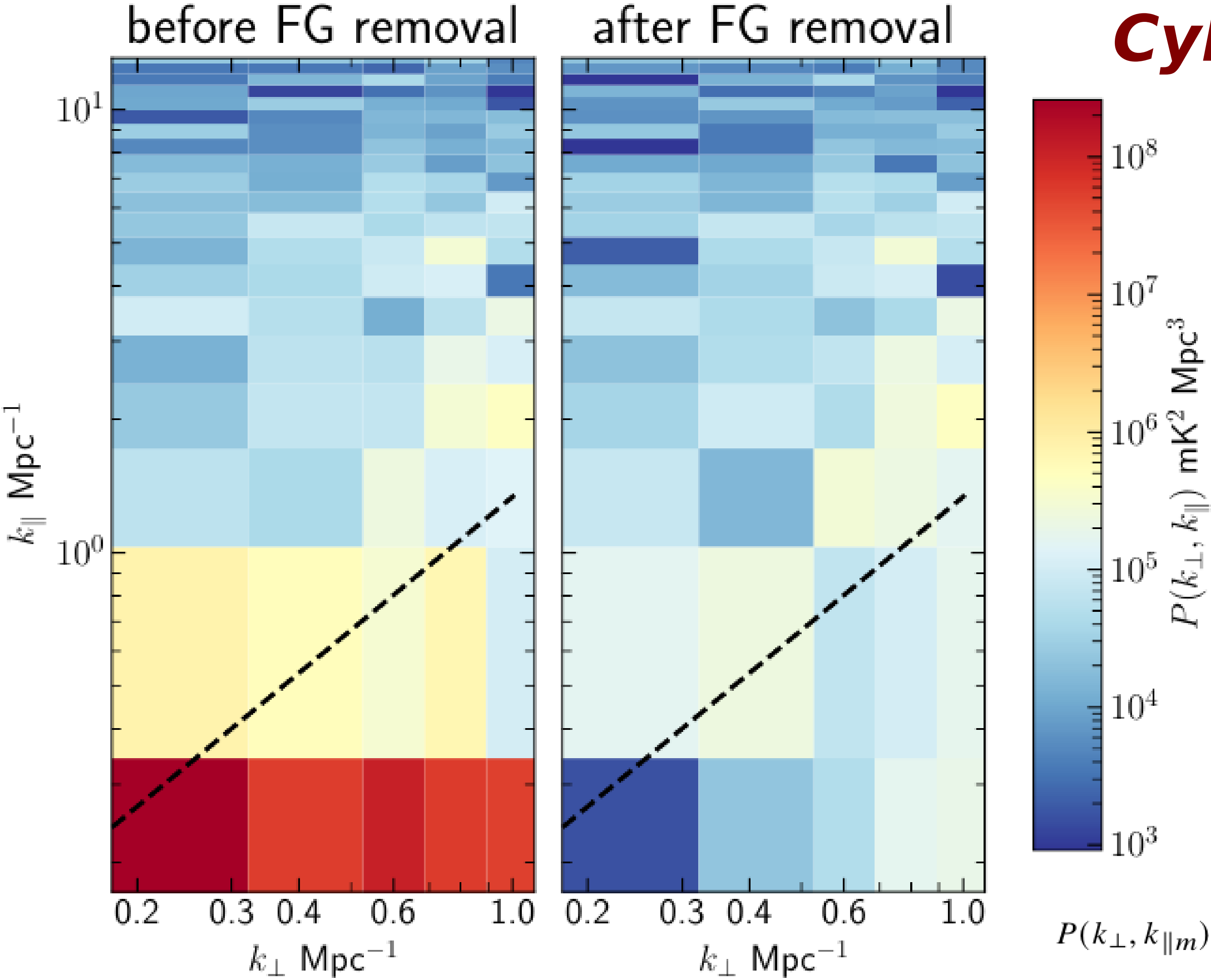
Bandwidth	100 MHz
ν	394-494 Mhz ***(z = 1.9-2.6)***
N_c	4096

Wideband analysis (394 – 494 MHz)
Elahi, Bharadwaj, Pal + others 2023
MNRAS (under revision)



Polynomial fitting (PF)
Gaussian Process regression (GPR)
n = 10
ℓ = 1074
n = 6
ℓ = 3039
n = 2
ℓ = 3945
P = 2
ℓ = 1187
P = 3
ℓ = 3263
P = 3
ℓ = 4431
data
fit
$C_\ell(\Delta\nu)$ mK^2
$[C_\ell(\Delta\nu)]_{\rm res}$ 10^{-3} mK^2
$\Delta\nu$ MHz

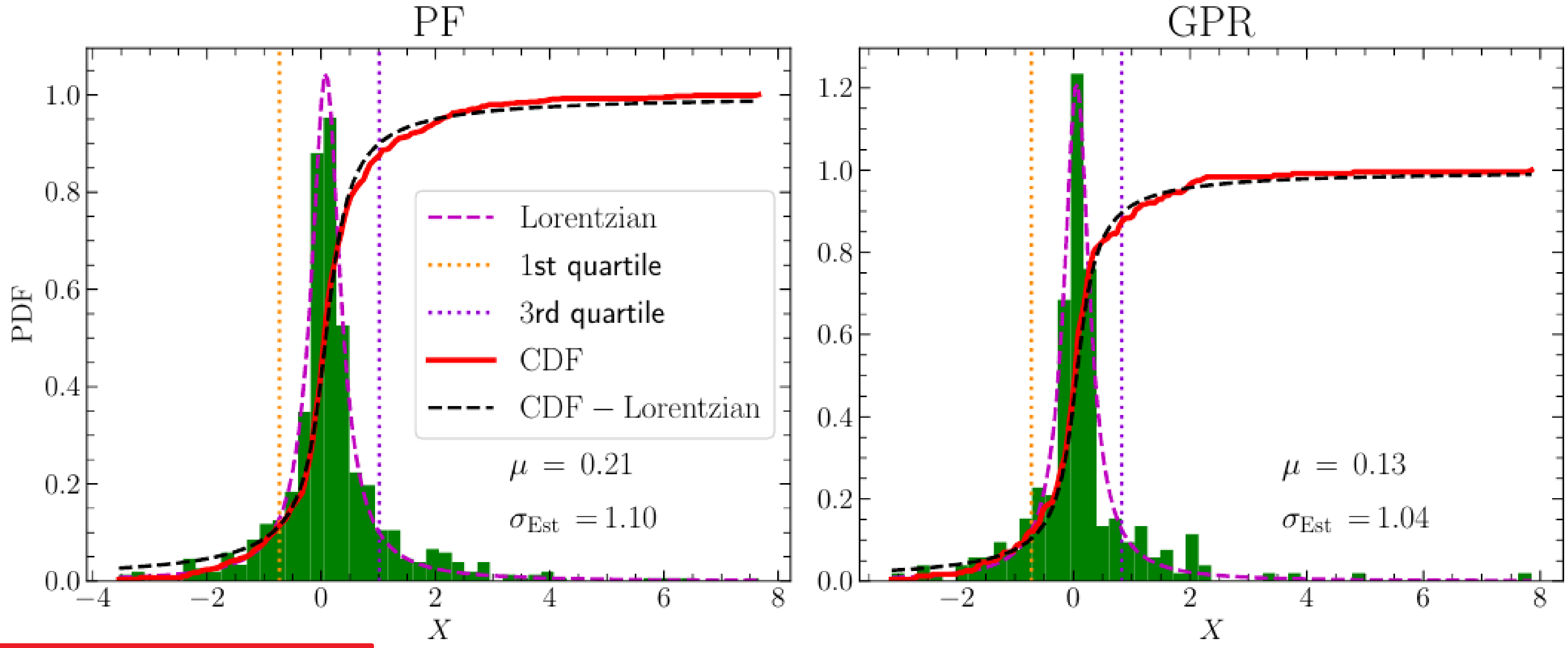
Cylindrical Power Spectrum



Maximum likelihood estimator

$$P(k_\perp, k_{\parallel m}) = \sum_n \left[\left(\mathbf{A}^\dagger \mathbf{N}^{-1} \mathbf{A} \right)^{-1} \mathbf{A}^\dagger \mathbf{N}^{-1} \right]_{mn} C_\ell(\Delta\nu_n)$$

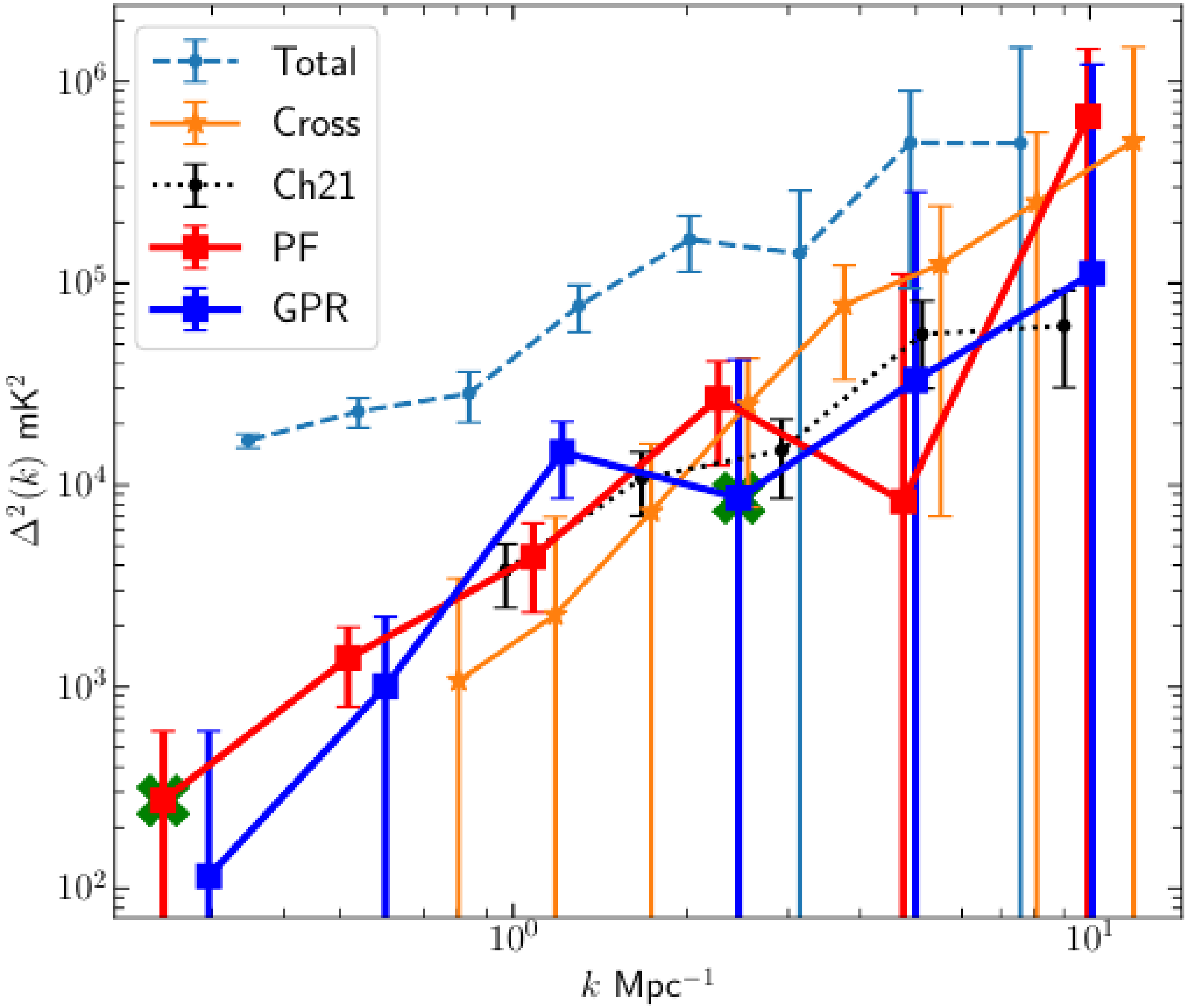
Power spectrum statistics



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

- X is symmetric, mean ~ 0, standard deviation ~ 4-5
- No Negative systematics
- Very few outliers

Spherical Power Spectrum



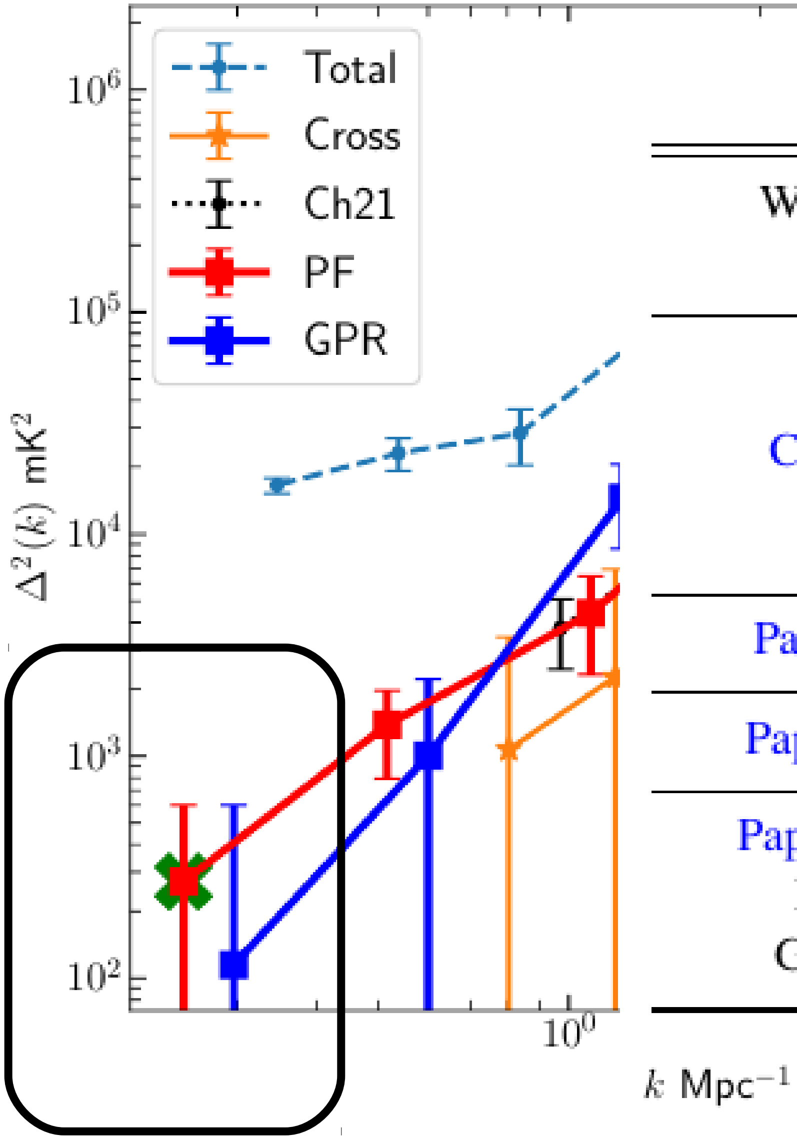
Maximum likelihood estimator

$$[C_\ell(\Delta\nu)]_{\text{res}} = [C_\ell(\Delta\nu)]_T + [C_\ell(\Delta\nu)]_R$$

$$[C_{\ell_a}(\Delta\nu_n)]_T = \sum_i B_i(a,n)\,[P(k_i)]_T$$

$$B_i(a,n) = \textstyle\sum_m A_{nm}$$

Upper limits



Works	z	k Mpc^{-1}	$\Delta^2_{\mathrm{UL}}(k)$ mK^2	$[\Omega_{\mathrm{H\,I}} b_{\mathrm{H\,I}}]_{\mathrm{UL}}$
Ch21	1.96	0.99	$(58.57)^2$	0.09
	2.19	0.97	$(61.49)^2$	0.11
	2.62	0.95	$(60.89)^2$	0.12
	3.58	0.99	$(105.85)^2$	0.24
Paper I	2.28	0.35	$(133.97)^2$	0.23
Paper II	2.28	0.80	$(58.67)^2$	0.072
Paper III				
PF	2.28	0.25	$(18.07)^2$	0.036
GPR		0.30	$(24.54)^2$	0.045

Wideband intensity mapping

Bandwidth	100 MHz
ν	394-494 Mhz *(z = 1.9-2.6)*
N_c	4096

Wideband TGE

- Baseline migration
- Frequency dependent primary beam

Median Absolute Deviation (MAD)

For each baseline, polarization,

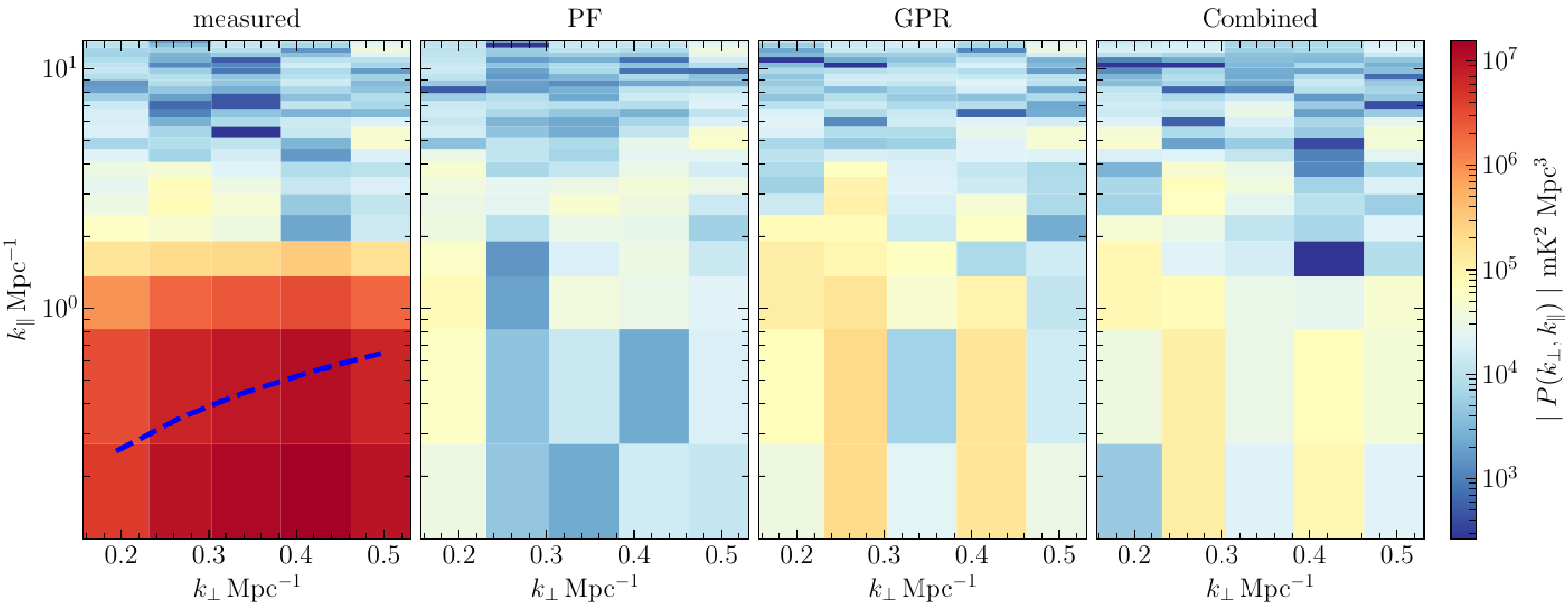
σ = median (| x – median(x) |)

if | x - σ | > 3xσ, flag the frequency channel

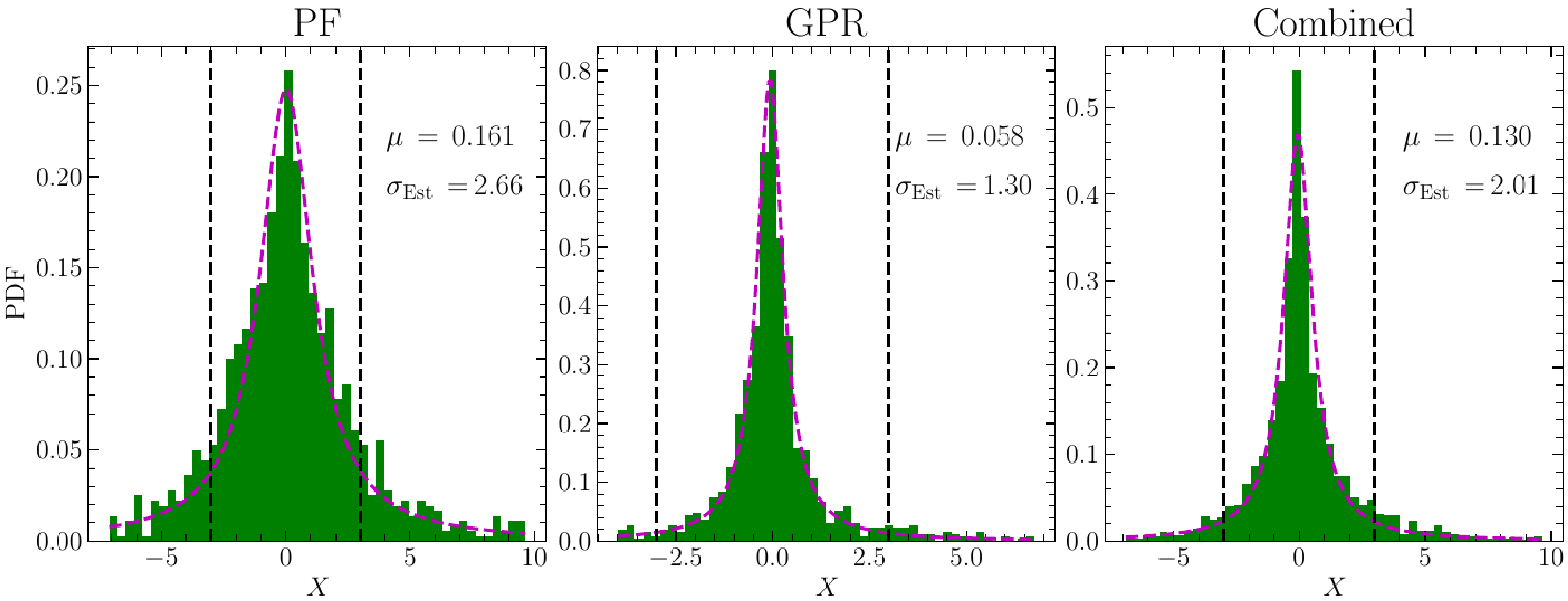
U < 500 λ

	Before MAD	After MAD
Flagging percentage	64	79
r.m.s. (mJy)	0.54	**0.33**

Wideband intensity mapping

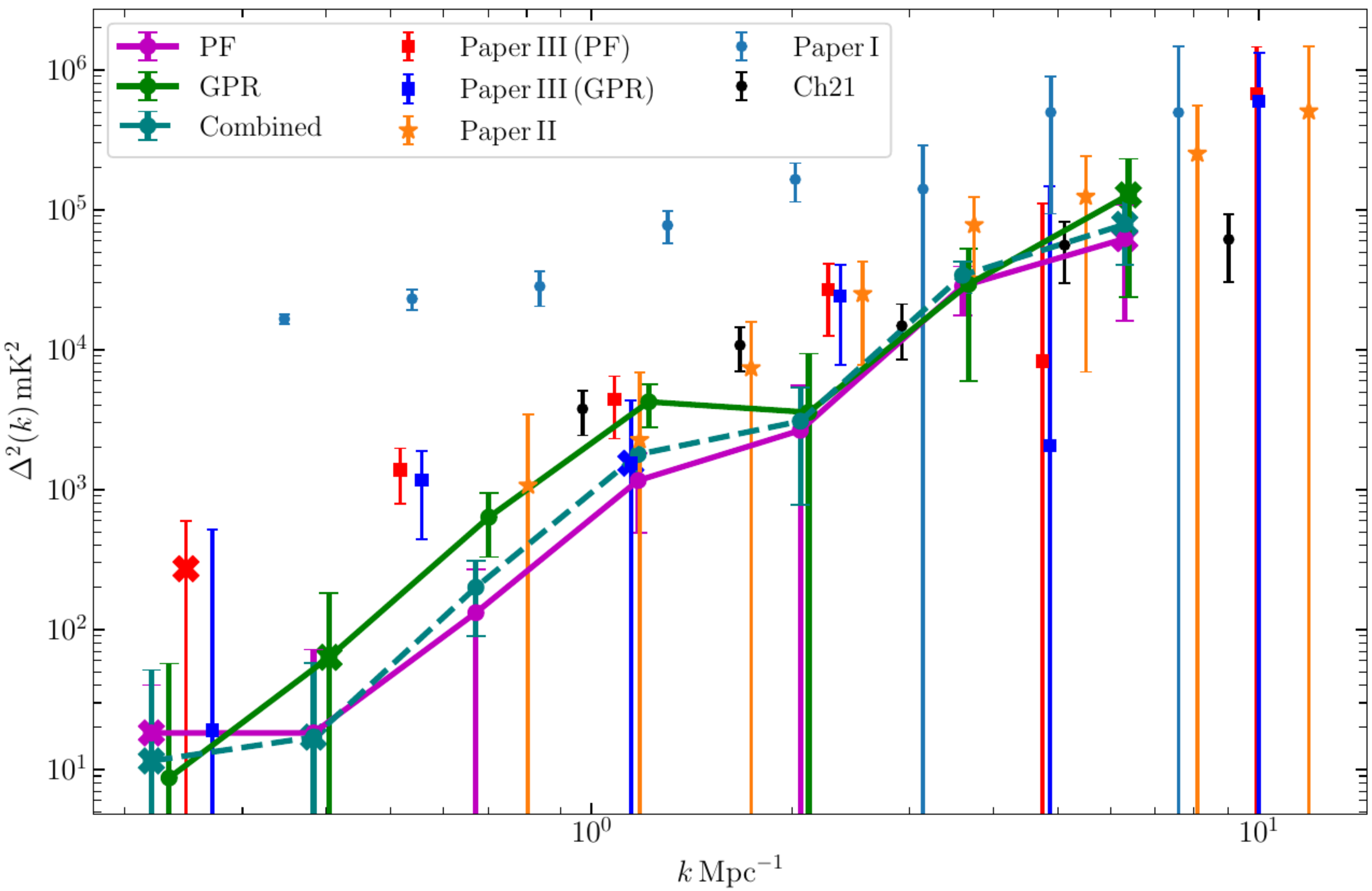


Wideband intensity mapping

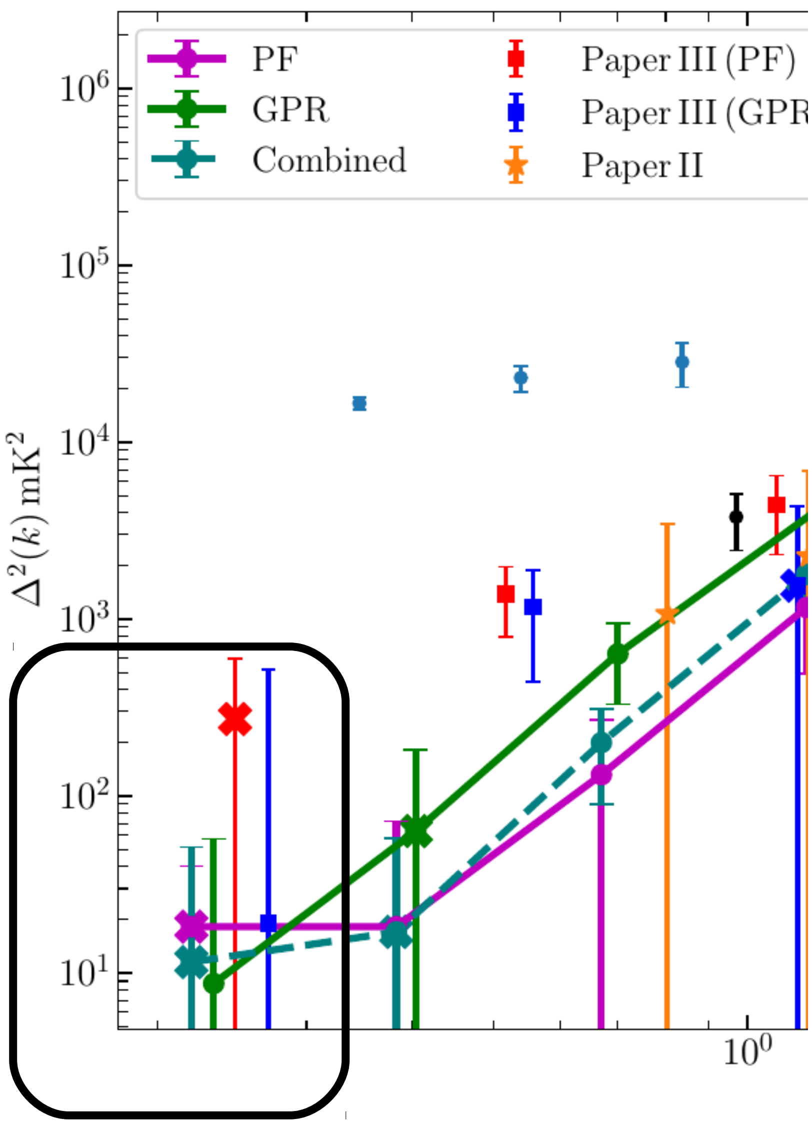


$$X = \frac{P(\boldsymbol{k}_\perp, k_\parallel)}{\delta P_N(\boldsymbol{k}_\perp, k_\parallel)}$$

- X is symmetric, mean ~ 0, standard deviation ~ 2-3
- No Negative systematics
- Very few outliers



Wideband intensity mapping



Works	z	k Mpc^{-1}	$\Delta^2_{\rm UL}(k)$ mK^2	$[\Omega_{\rm HI} b_{\rm HI}]_{\rm UL}$
Ch21	1.96	0.99	$(58.57)^2$	0.09
	2.19	0.97	$(61.49)^2$	0.11
	2.62	0.95	$(60.89)^2$	0.12
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Paper III PF	2.28	0.25	$(18.07)^2$	0.036
Paper III GPR		0.30	$(24.54)^2$	0.045
Present work				
PF	1.9 – 2.6	**0.22**	$\mathbf{(4.68)^2}$	**0.010**
		0.38	$(8.48)^2$	0.014
GPR		0.22	$(7.56)^2$	0.016
		0.40	$(10.90)^2$	0.018
Combined		0.22	$(6.32)^2$	0.014
		0.38	$\mathbf{(6.38)^2}$	**0.011**

How far (close) are we?

$$0.5 \times 10^{-3} \lesssim \Omega_{\rm H\,I} \lesssim 0.9 \times 10^{-3} \text{ for } z \sim 1.9 - 2.6$$

Prochaska et al. 2009
Noterdaeme et al. 2009, 2012
Zafar et al. 2013
Bird et al. 2017

The upper limit is 0.01 ⇒ 10 times smaller than the actual signal

For detection,
we need 10^2 = 100 times improvement in the power spectrum amplitude
⇒ 10 times improvement required in visibility r.m.s.
⇒ 100 times more observation (400 days)

For a “cleaner” band ⇒ 50 times more observation (200 days)

Summary

Post-reionization 21 cm intensity mapping

⇒ a promising probe to the large scale structure, BAO, Cosmological parameters

⇒ foregrounds are the biggest challenge

Foreground removal

⇒ removes the foregrounds from the measured MAPS

⇒ **polynomial fitting** and **Gaussian Process Regression (GPR)**

Wideband TGE

⇒ Incorporates baseline migration and frequency-dependent beam pattern in TGE

⇒ tight upper limit

⇒ more observation / cleaner band / better calibration / other telescope / ??