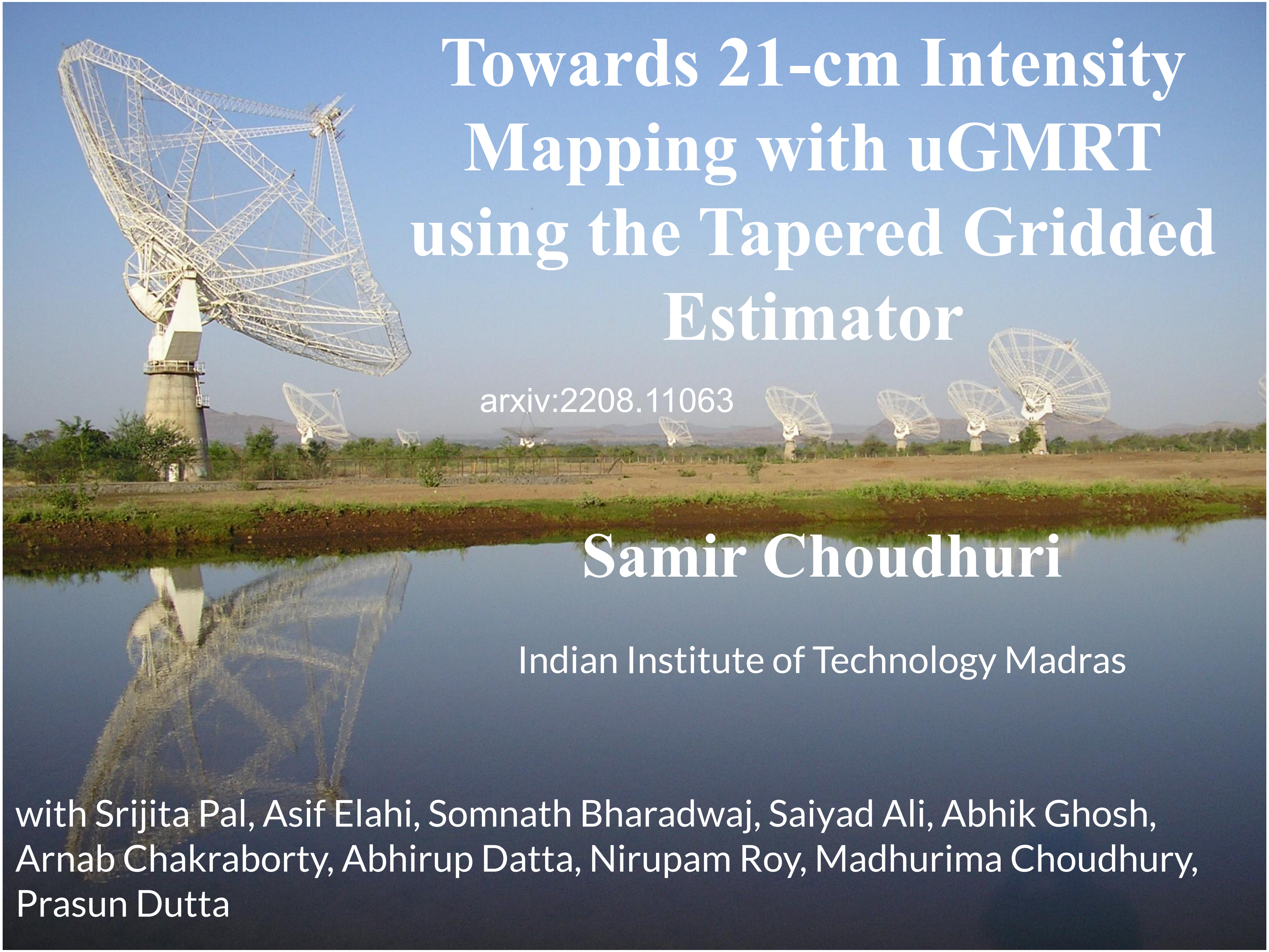


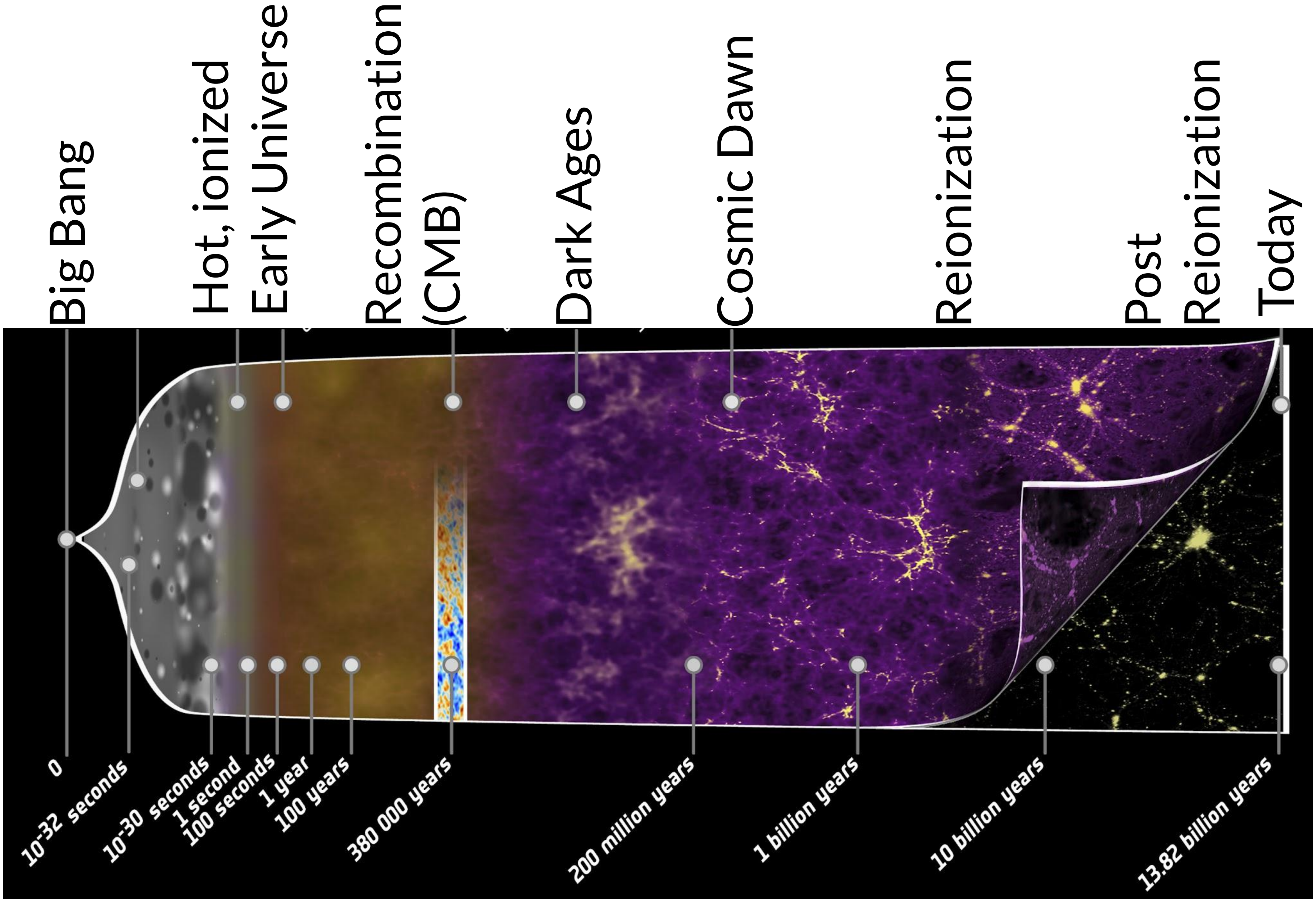
# Towards 21-cm Intensity Mapping with uGMRT using the Tapered Gridded Estimator

arxiv:2208.11063


**Samir Choudhuri**

Indian Institute of Technology Madras

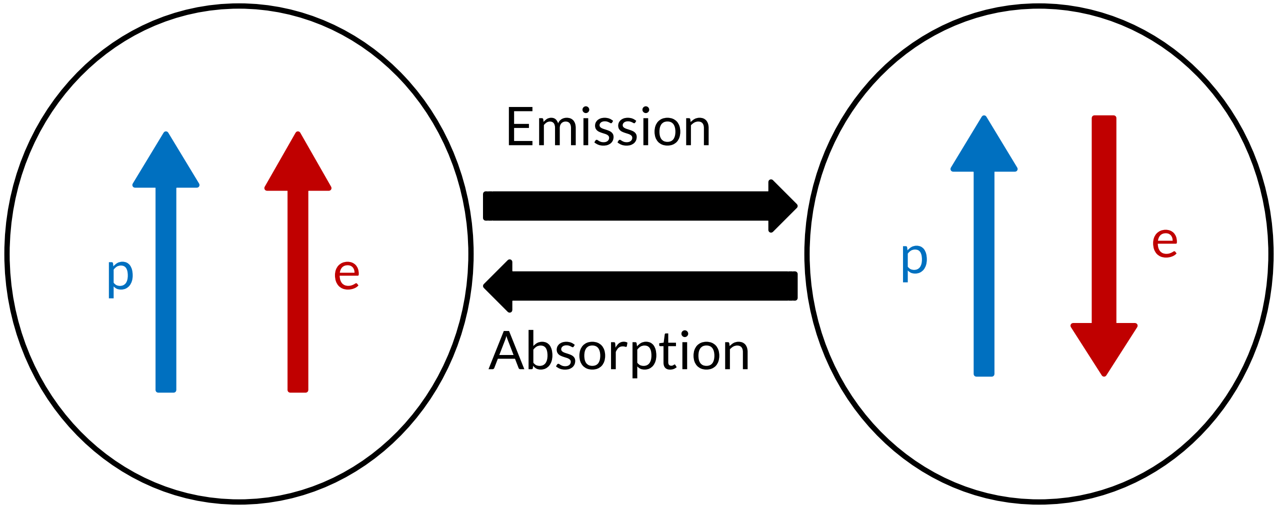
with Srijita Pal, Asif Elahi, Somnath Bharadwaj, Saiyad Ali, Abhik Ghosh, Arnab Chakraborty, Abhirup Datta, Nirupam Roy, Madhurima Choudhury, Prasun Dutta




No observational evidence

# 21-cm Line

21 cm / 1420 MHz



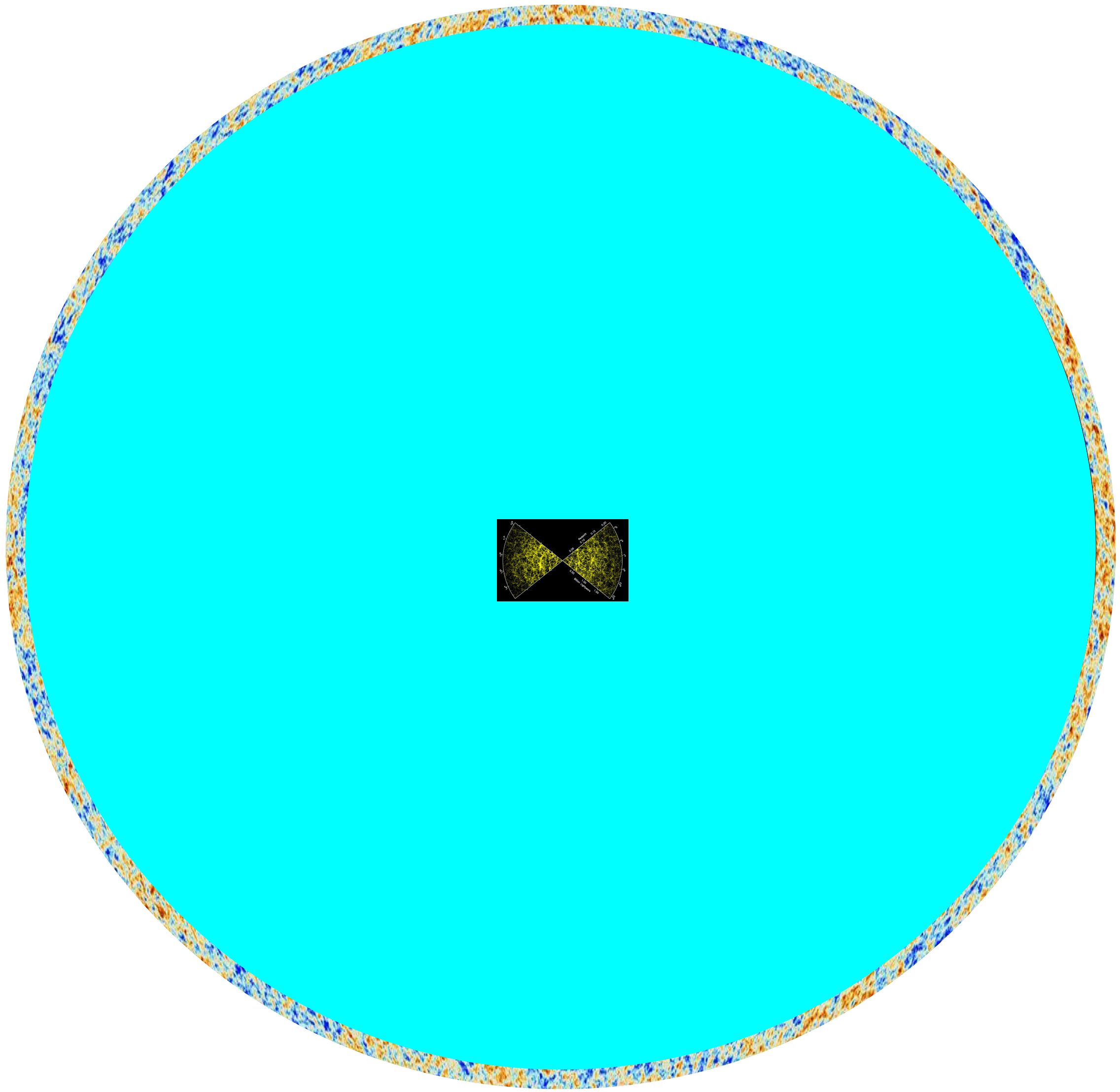

Hydrogen is the most abundant component of the Universe and can be traced through 21-cm radiation.

# 21-cm Line

$$\lambda_o = 21\,(1+z)\ \text{cm}$$

We can tune the receiver to observe the 21-cm signal from different distances.

# In principle, we can see the whole evolution using 21-cm radiation.



# 21-cm Intensity Mapping

Intensity mapping is an observational technique for surveying the large-scale structure of the universe by using the integrated radio emission from unresolved gas clouds.

# Using HI to Probe Large Scale Structures at z ∼ 3

Somnath Bharadwaj [1*], Biman B. Nath [2†] & Shiv K. Sethi [3‡]
[1] *Department of Physics and Meteorology & Center for Theoretical Studies, I.I.T. Kharagpur, 721 302, India*
[2] *Raman Research Institute, Bangalore 560 080, India*
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Received 2000 March 14; accepted 2000 October 21.

**Abstract.** The redshifted 1420 MHz emission from the HI in unresolved damped Lyman-$\alpha$ clouds at high z will appear as a background radiation in low frequency radio observations. This holds the possibility of a new tool for studying the universe at high-$z$, using the mean brightness temperature to probe the HI content and its fluctuations to probe the power spectrum. Existing estimates of the HI density at $z \sim 3$ imply a mean brightness temperature of 1 mK at 320 MHz. The cross-correlation between the temperature fluctuations across different frequencies and sight lines is predicted to vary from $10^{-7}\,\mathrm{K}^2$ to $10^{-8}\,\mathrm{K}^2$ over intervals corresponding to spatial scales from 10 Mpc to 40 Mpc for some of the currently favoured cosmological models. Comparing this with the expected sensitivity of the GMRT, we find that this can be detected with $\sim$ 10 hrs of integration, provided we can distinguish it from the galactic and extragalactic foregrounds which will swamp this signal. We discuss a strategy based on the very distinct spectral properties of the foregrounds as against the HI emission, possibly allowing the removal of the foregrounds from the observed maps.

*Key words*: Cosmology: theory, observations, large scale structures—diffuse radiation.

# HI Fluctuations at Large Redshifts: I–Visibility correlation

Somnath Bharadwaj[1] & Shiv K. Sethi[2*]
[1] *Department of Physics and Meteorology & Center for Theoretical Studies, I.I.T. Kharagpur, 721 302, India*
*email: somnath@phy.iitkgp.ernet.in*
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*email: sethi@rri.res.in*

Received 2002 March 15; accepted 2002 May 31

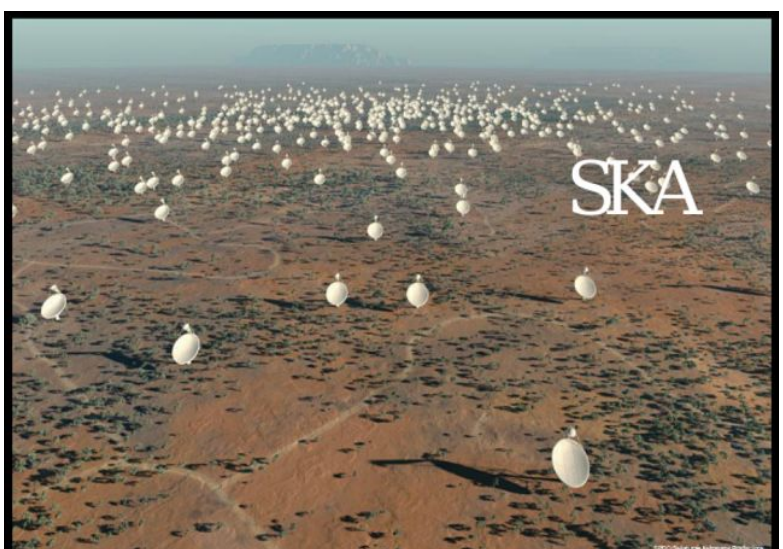
**Abstract.** We investigate the possibility of probing the large scale structure in the universe at large redshifts by studying fluctuations in the redshifted 1420 MHz emission from the neutral hydrogen (HI) at early epochs. The neutral hydrogen content of the universe is known from absorption studies for $z \lesssim 4.5$. The HI distribution is expected to be inhomogeneous in the gravitational instability picture and this inhomogeneity leads to anisotropy in the redshifted HI emission. The best hope of detecting this anisotropy is by using a large low-frequency interferometric instrument like the Giant Meter-Wave Radio Telescope (GMRT). We calculate the visibility correlation function $\langle V_{\nu}(\mathbf{U}) V_{\nu'}(\mathbf{U}) \rangle$ at two frequencies $\nu$ and $\nu'$ of the redshifted HI emission for an interferometric observation. In particular we give numerical results for the two GMRT channels centered around $\nu = 325$ MHz and $\nu = 610$ MHz from density inhomogeneity and peculiar velocity of the HI distribution. The visibility correlation is $\simeq 10^{-10}$–$10^{-9}$ Jy$^2$. We calculate the signal-to-noise for detecting the correlation signal in the presence of system noise and show that the GMRT might detect the signal for integration times $\simeq 100$ hrs. We argue that the measurement of visibility correlation allows optimal use of the uncorrelated nature of the system noise across baselines and frequency channels.

*Key words.* Cosmology: theory, observations, large scale structures — diffuse radiation.

# Radio Interferometer

**GMRT**

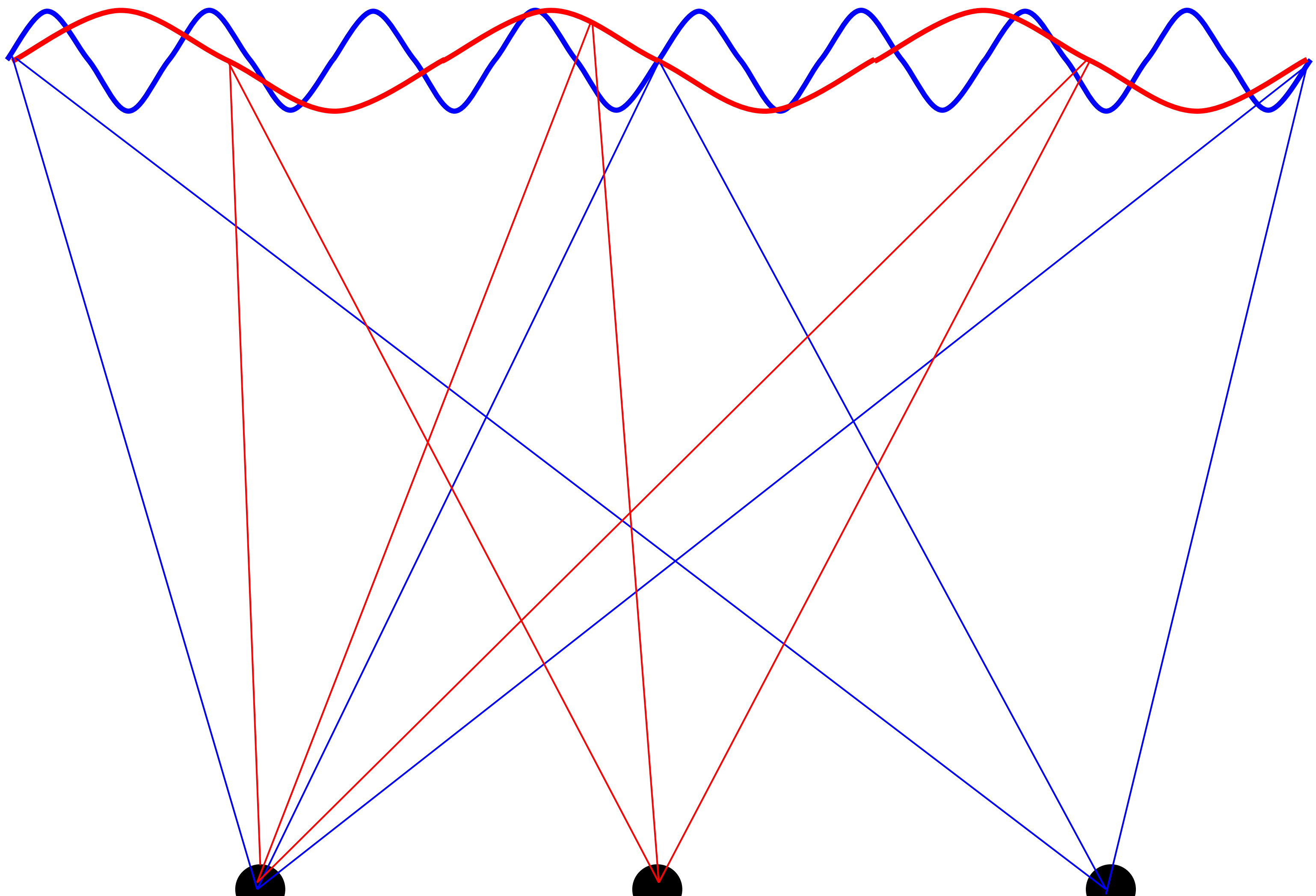
**SKA**




**OWFA**

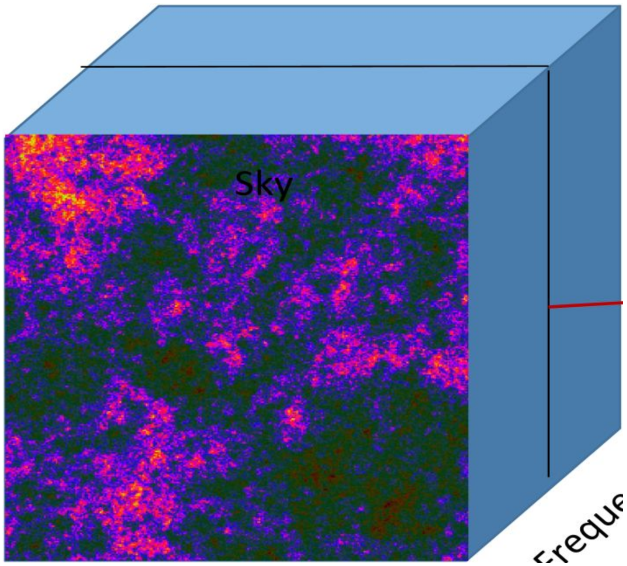
# Radio Interferometers measure the different Fourier modes of the sky.

## longer wavelength ~ short baselines

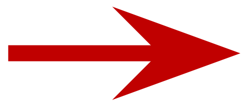


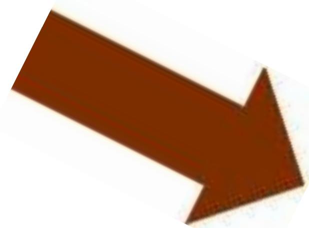
# Statistical Detection

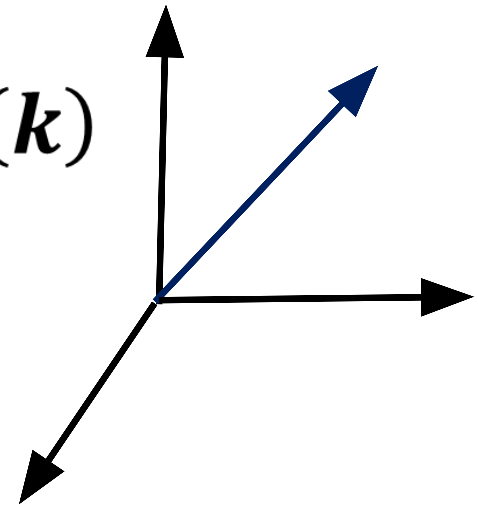
# Power Spectrum

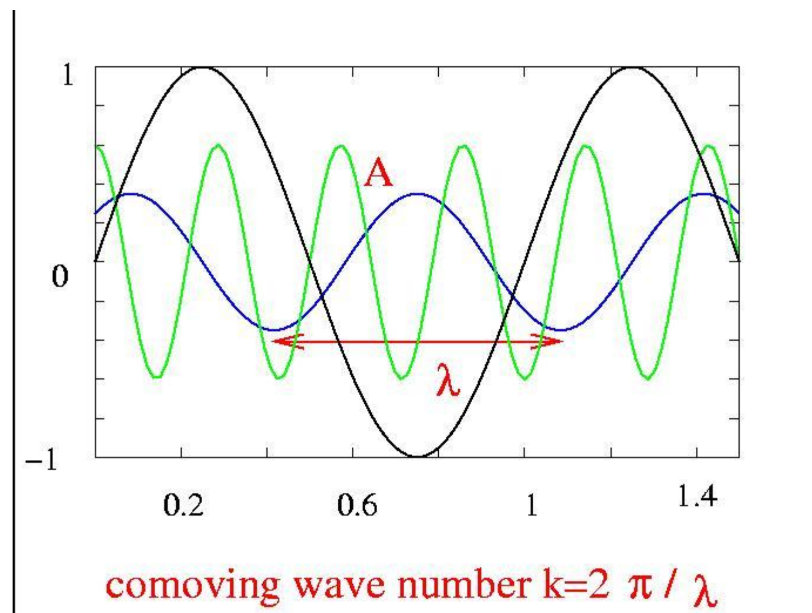



Fourier Transform $\Delta(\boldsymbol{k})$










Power Spectrum

$$P(k) = \frac{\Delta(k)\Delta^*(k)}{V}$$

# How are they related?

$$\mathcal{V}(\mathbf{U},\nu) = \mathcal{S}(\mathbf{U},\nu) + \mathcal{N}(\mathbf{U},\nu)$$

**Entire Sky Signal**

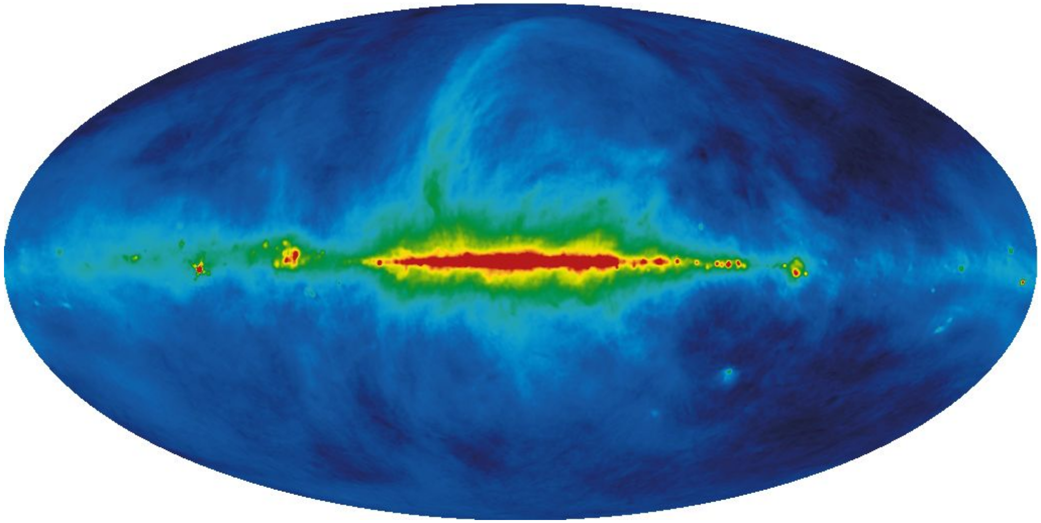
Two Visibility Correlation:

$$V_{2ij} \equiv \langle \mathcal{V}_i \mathcal{V}_j^* \rangle = V_0 \, e^{-|\Delta \mathbf{U}_{ij}|^2/\sigma_0^2} \, C_{\ell_i} + \delta_{ij} 2\sigma_n^2$$

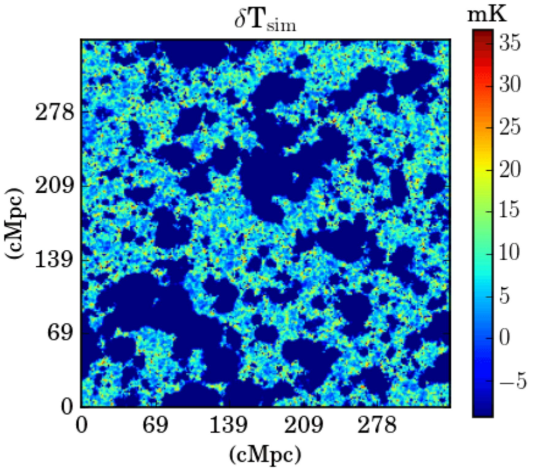
$$S_2(\mathbf{U}, \mathbf{U} + \Delta\mathbf{U}) = \frac{\pi\theta_0^2}{2} \left(\frac{\partial B}{\partial T}\right)^2 \exp\left[-\left(\frac{\Delta U}{\sigma_0}\right)^2\right] C_\ell$$

$$V_0 = \frac{\pi\theta_0^2}{2} \left(\frac{\partial B}{\partial T}\right)^2 \quad \mathcal{A}_{\rm G}(\boldsymbol{\theta}, \nu) = \exp\left[-\theta^2/\theta_0^2\right]$$

# Challenges: Foregrounds



~ $10^{10}$ mK$^2$

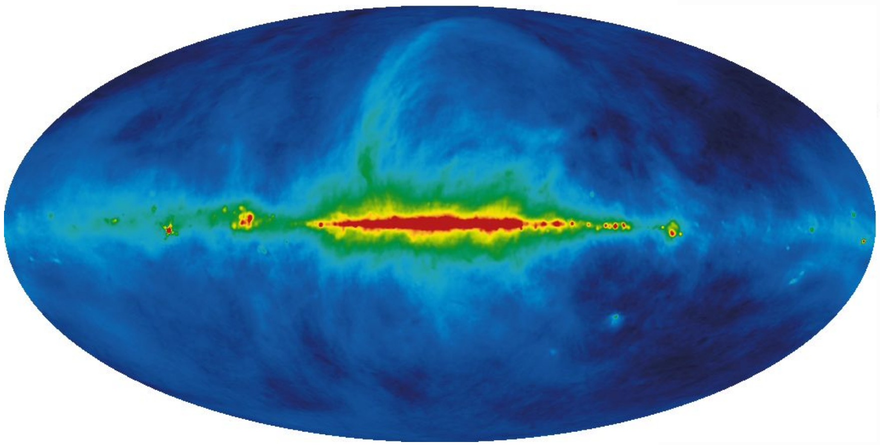



~ 10 mK$^2$

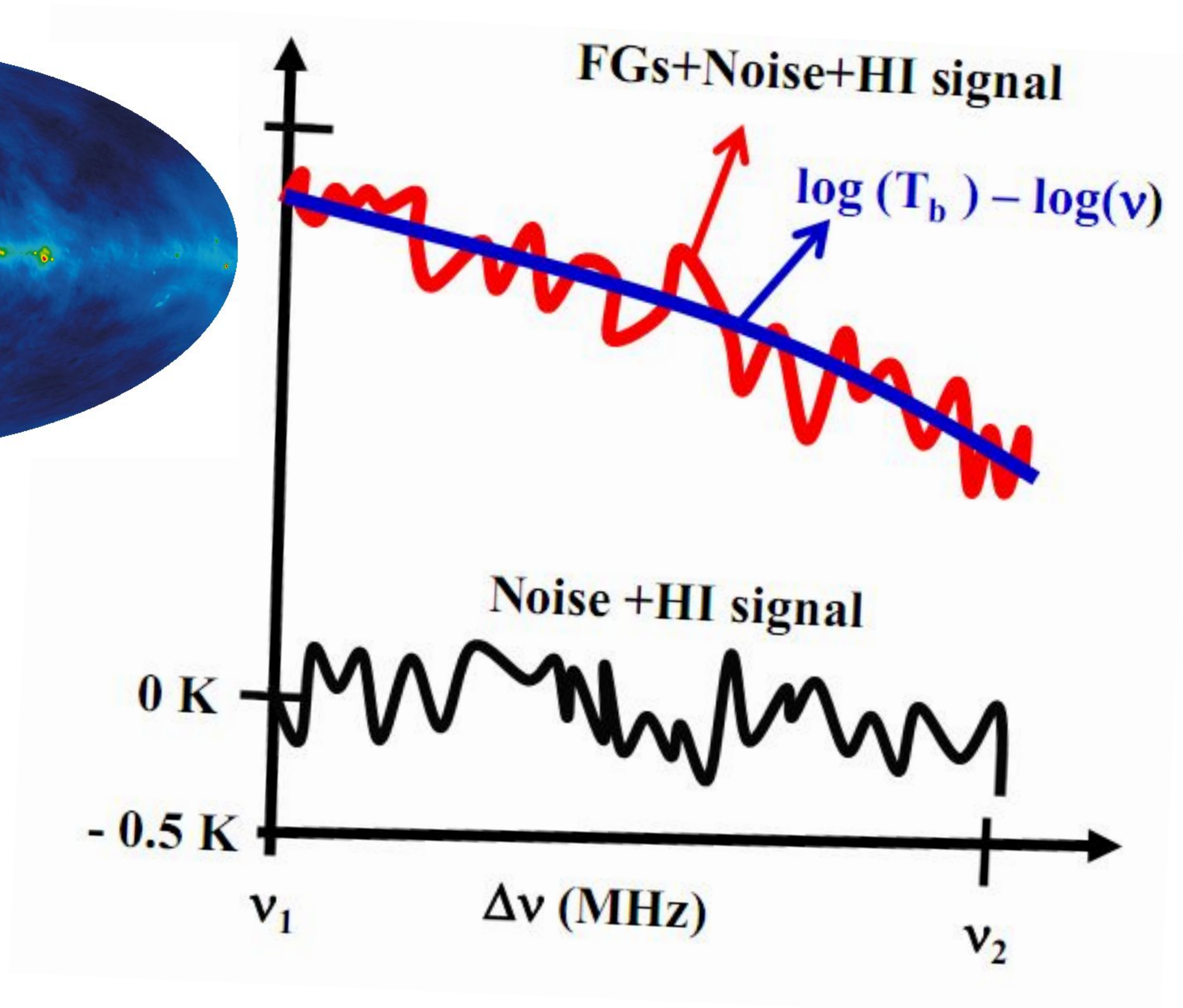
Image credit: NASA / LAMBDA Archive Team

# Foreground: Solutions

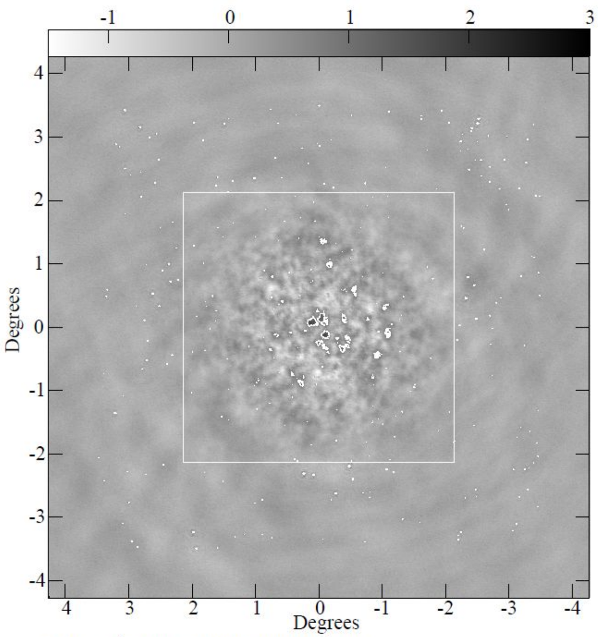
**Foreground Removal:**



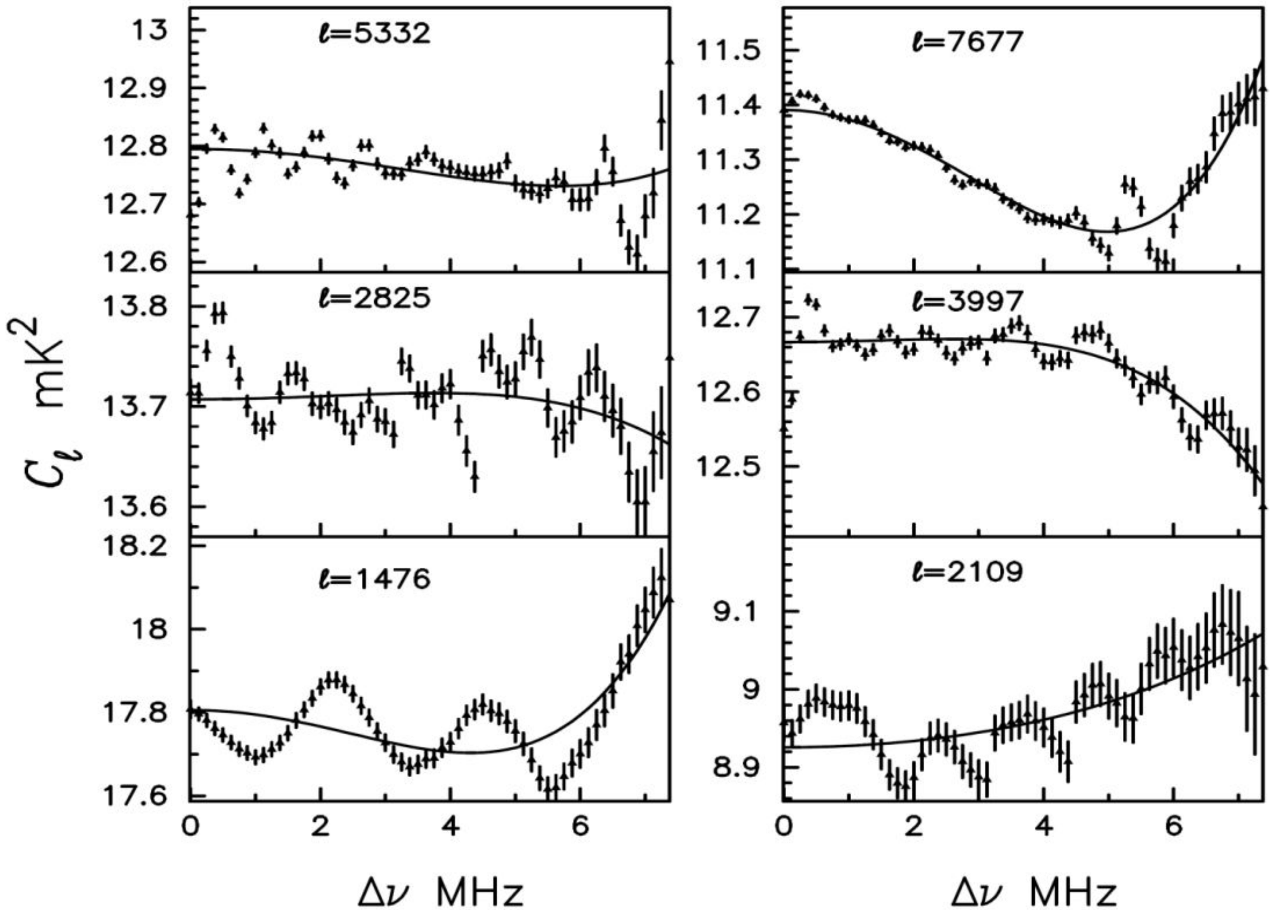
~ $10^{10}$ $mK^2$



# Challenge: Wide-field Foregrounds




Grey scale range: -1.5 to 3.0 mJy/beam
Peak flux: 44.9 mJy/beam; Contour: 6 x 150 microJy

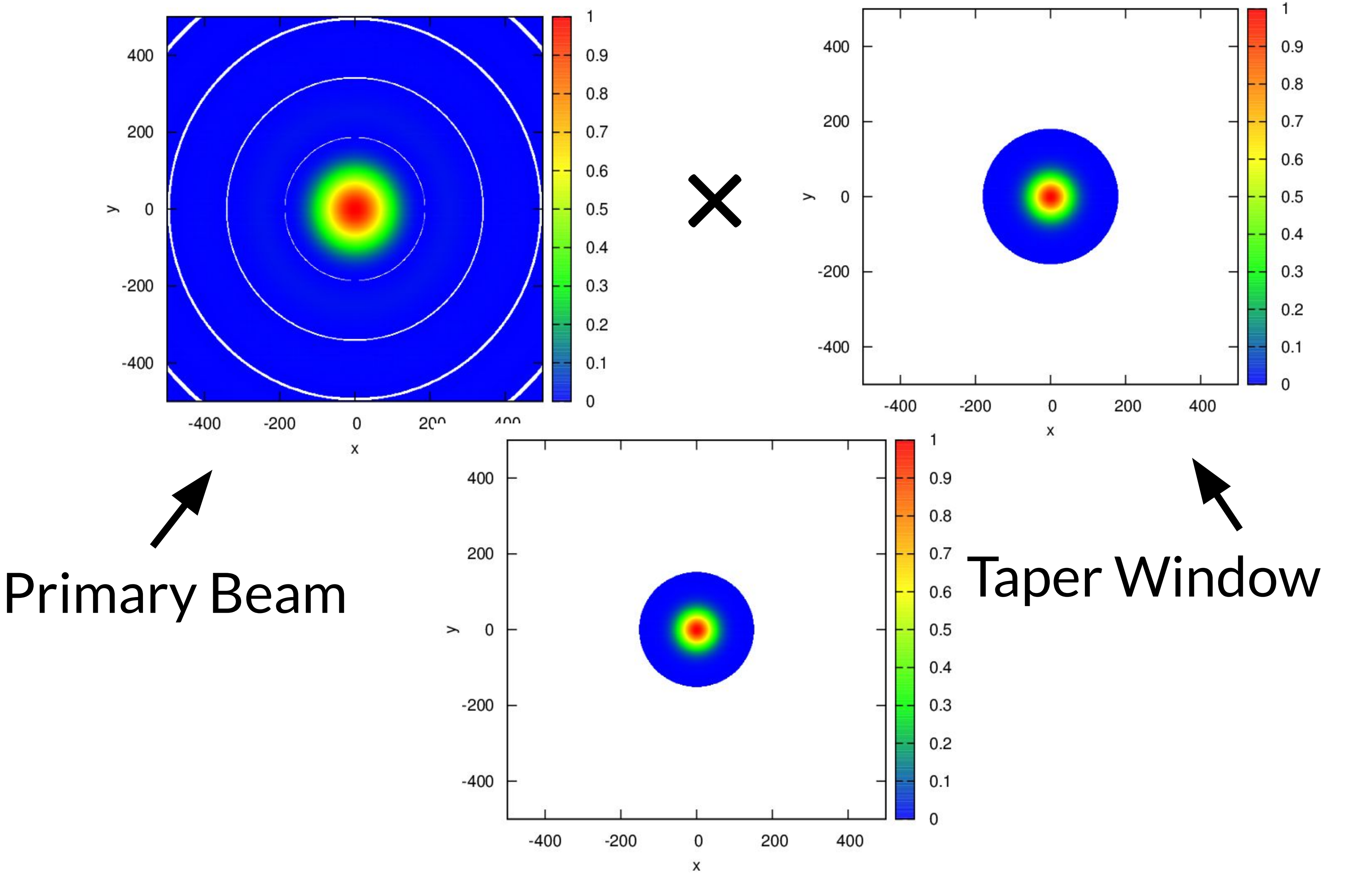



Choudhuri S. et al 2017b, New Astronomy, 57, 94

Ghosh et al 2011,MNRAS

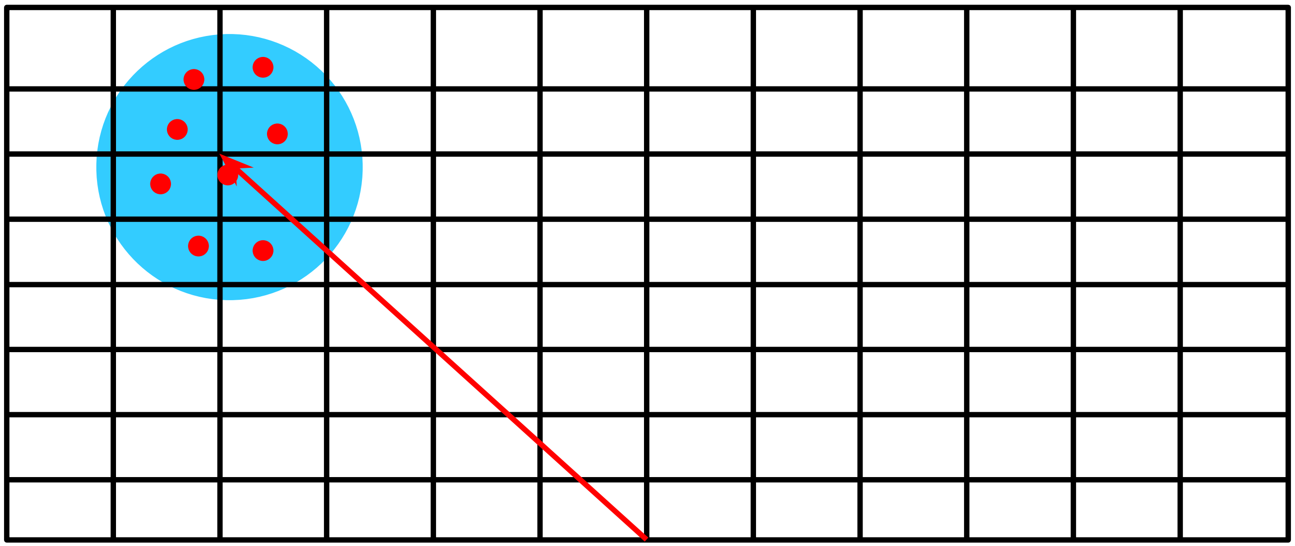
# Tapered Gridded Estimator

# Tapered Gridded Estimator



# Tapering and Gridding

Visibility-based :



$$\mathcal{V}_{cg} = \sum_i \tilde{w}(\mathbf{U}_g - \mathbf{U}_i)\,\mathcal{V}_i$$

# Tapered Gridded Estimator

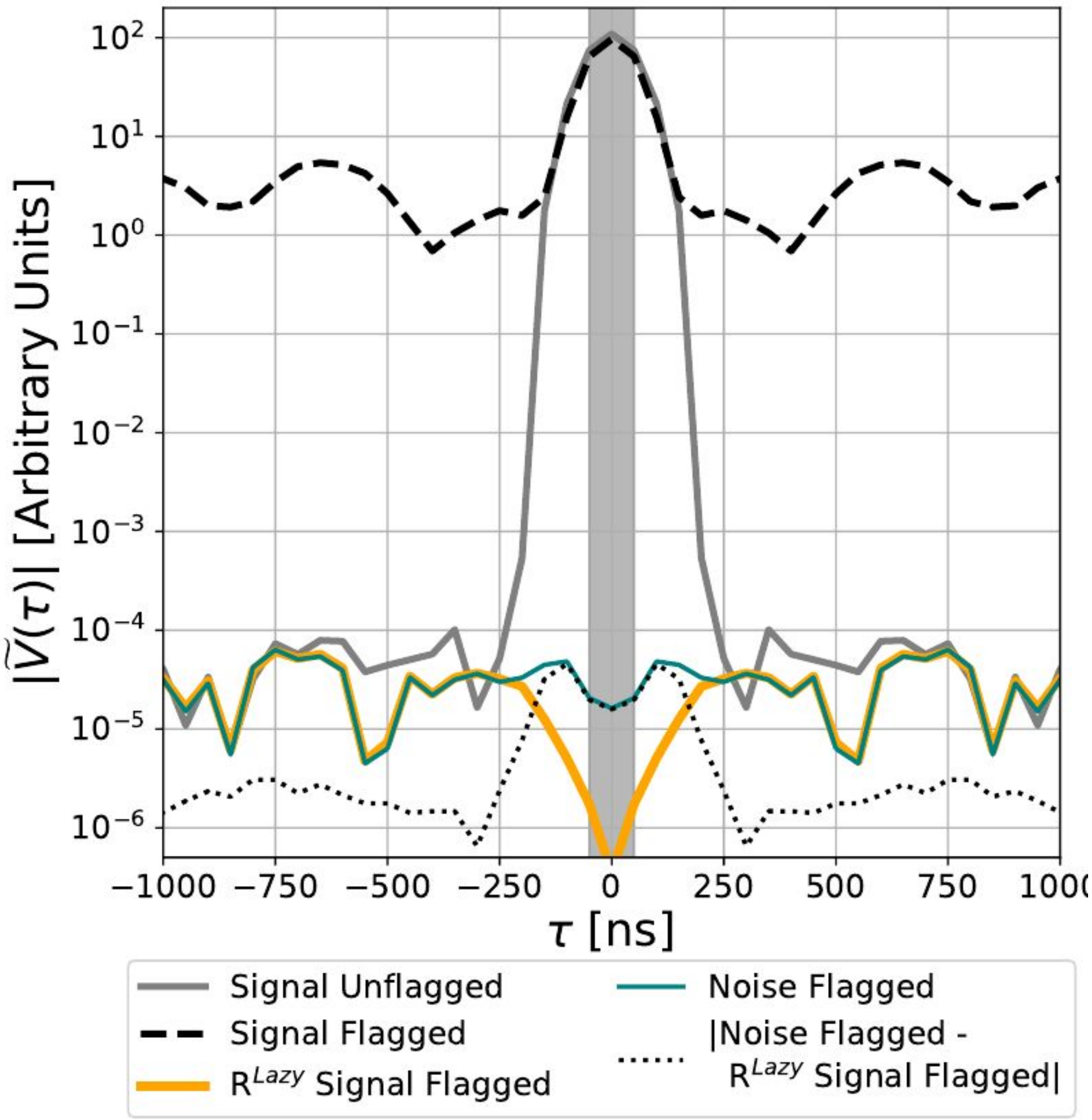
1. Gridded Estimator
2. Suppress Side-lobe Response
3. Remove Noise Bias

$$\hat{E}_g = M_g^{-1} \left( \mid \mathcal{V}_{cg} \mid^2 - \sum_i \mid \tilde{w}(\mathbf{U}_g - \mathbf{U}_i) \mid^2 \mid \mathcal{V}_i \mid^2 \right)$$

Choudhuri S et al 2016a, MNRAS, 463, 4093

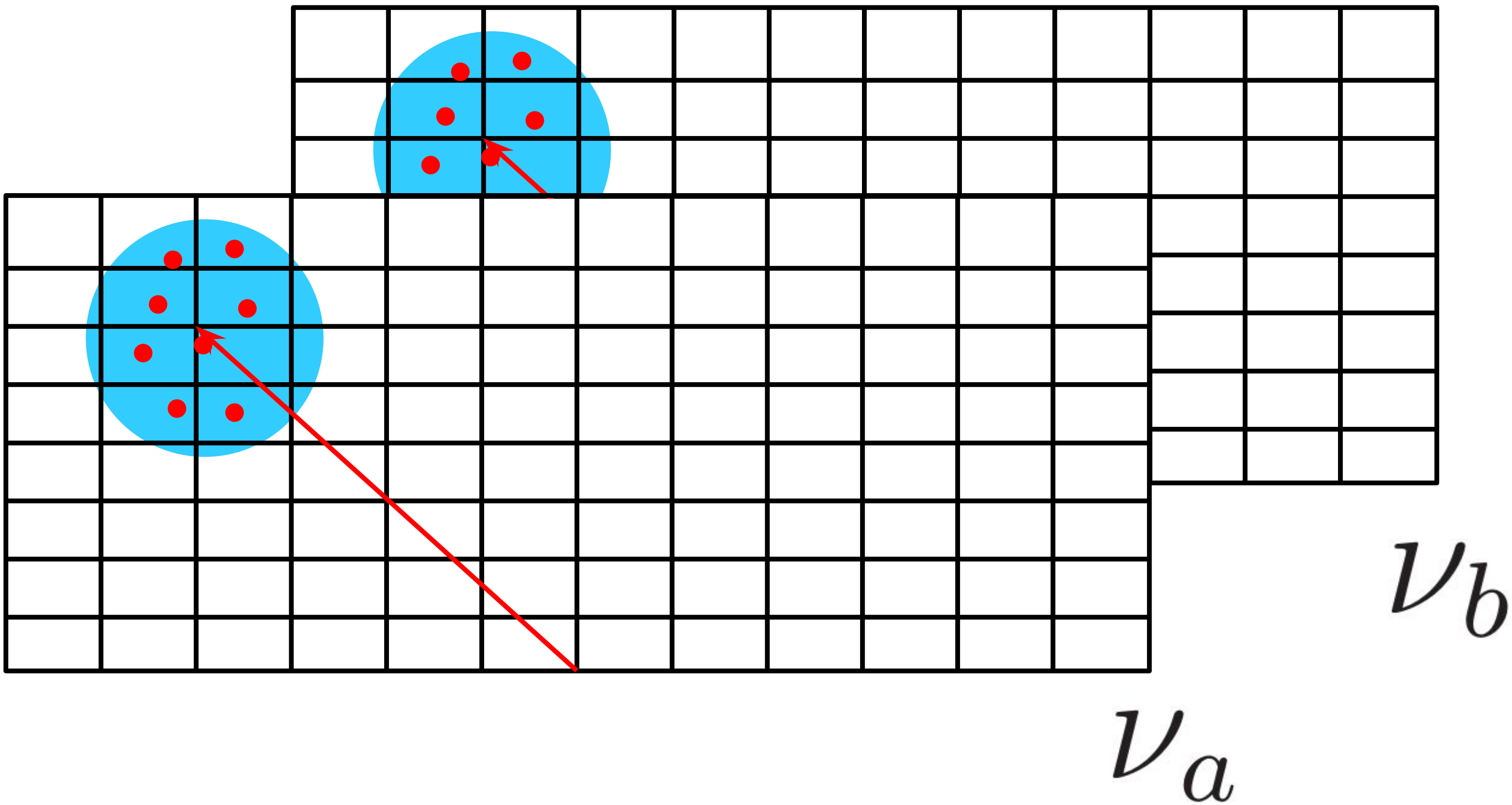
https://github.com/samirchoudhuri/TGE

# Channel Flagging




Ewall-Wice, A et al 2020, MNRAS

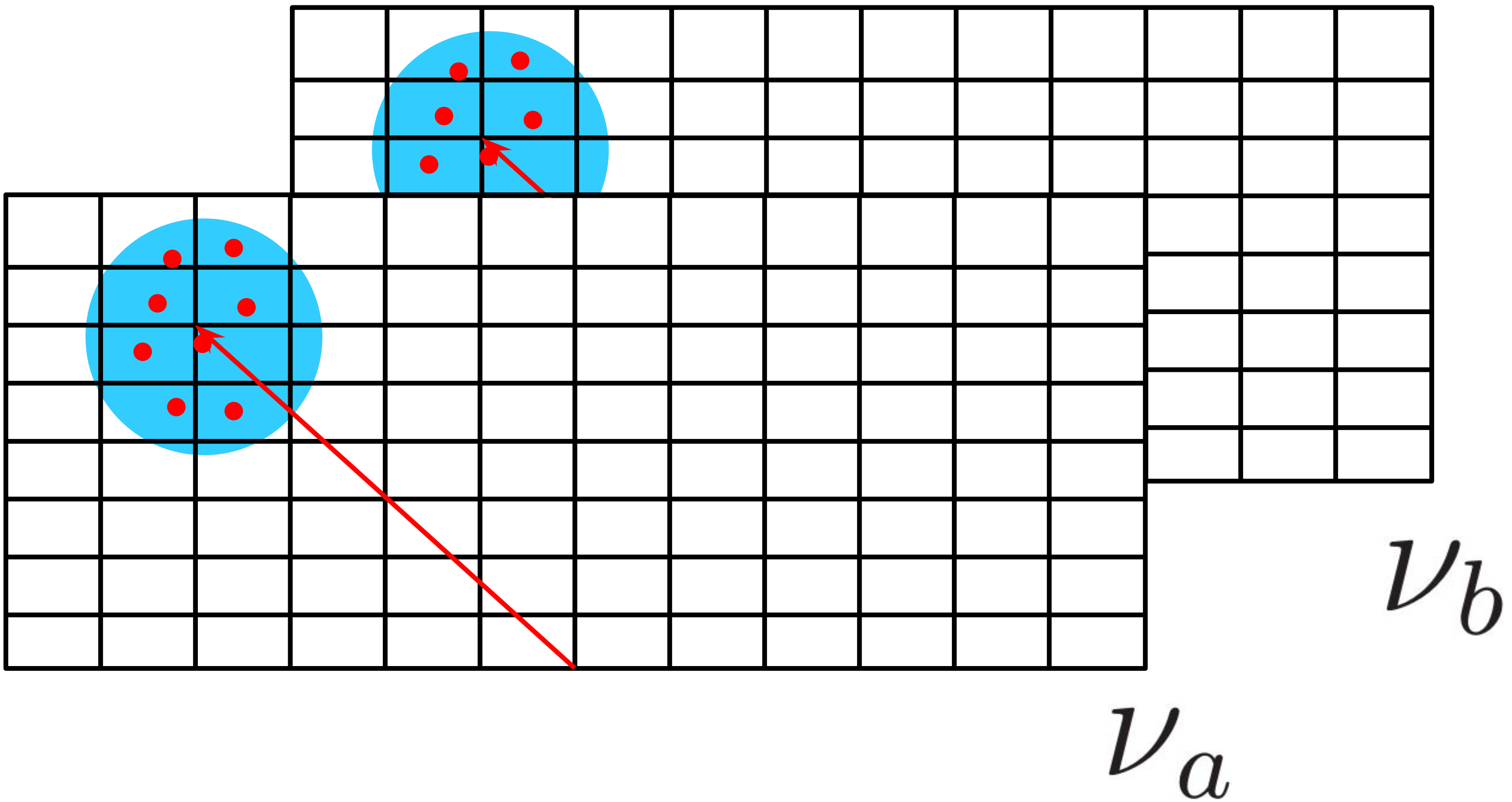
# TGE: the MAPS and the Power-Spectrum




Multi-frequency angular power spectrum (MAPS)

Datta et al 2007, MNRAS

# TGE: the 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

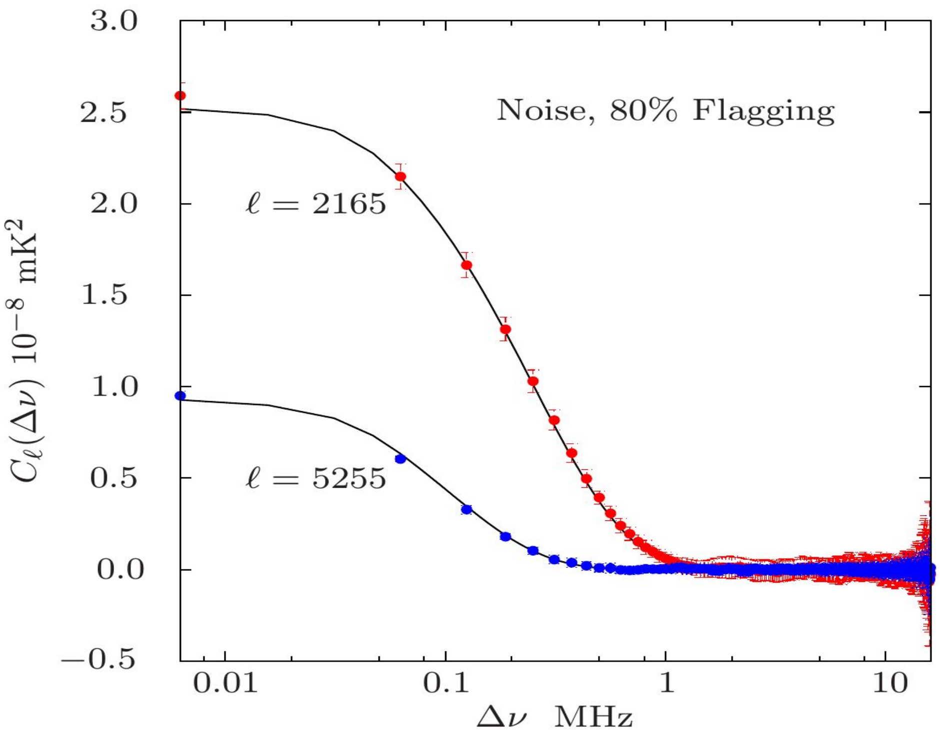
# Mathematical formalism

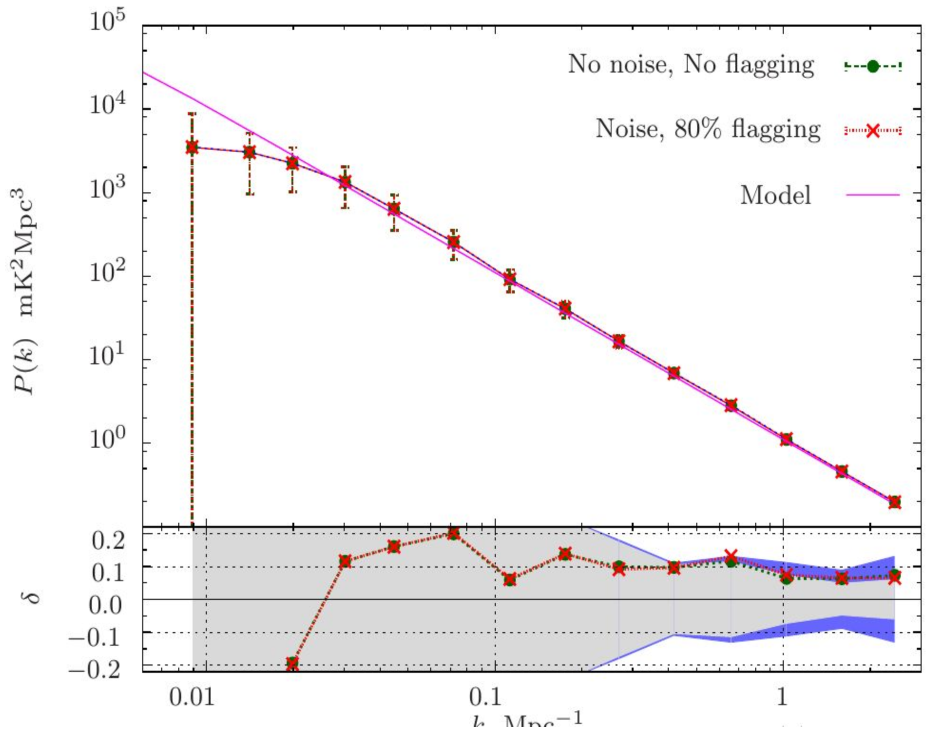
$$\hat{E}_g(\nu_a,\nu_b) = M_g^{-1}(\nu_a,\nu_b)\mathcal{R}e\Big[\mathcal{V}_{cg}(\nu_a)\mathcal{V}_{cg}^{*}(\nu_b) - \sum_i F_i(\nu_a)F_i(\nu_b) \mid \tilde{w}(\mathbf{U}_g - \mathbf{U}_i) \mid^2 \mathcal{V}_i(\nu_a)\mathcal{V}_i^{*}(\nu_b)\Big] \quad (6)$$

$$P(k_\perp, k_\parallel) = r^2 r' \int_{-\infty}^{\infty} d(\Delta\nu)\, e^{-ik_\parallel r' \Delta\nu}\, C_\ell(\Delta\nu) \quad (9)$$

Pal et al 2022, MNRAS

# TGE: the MAPS and the Power-Spectrum




Bharadwaj, Pal, Choudhuri et al 2019, MNRAS

# GMRT Observations

**Table 1.** Observation summary

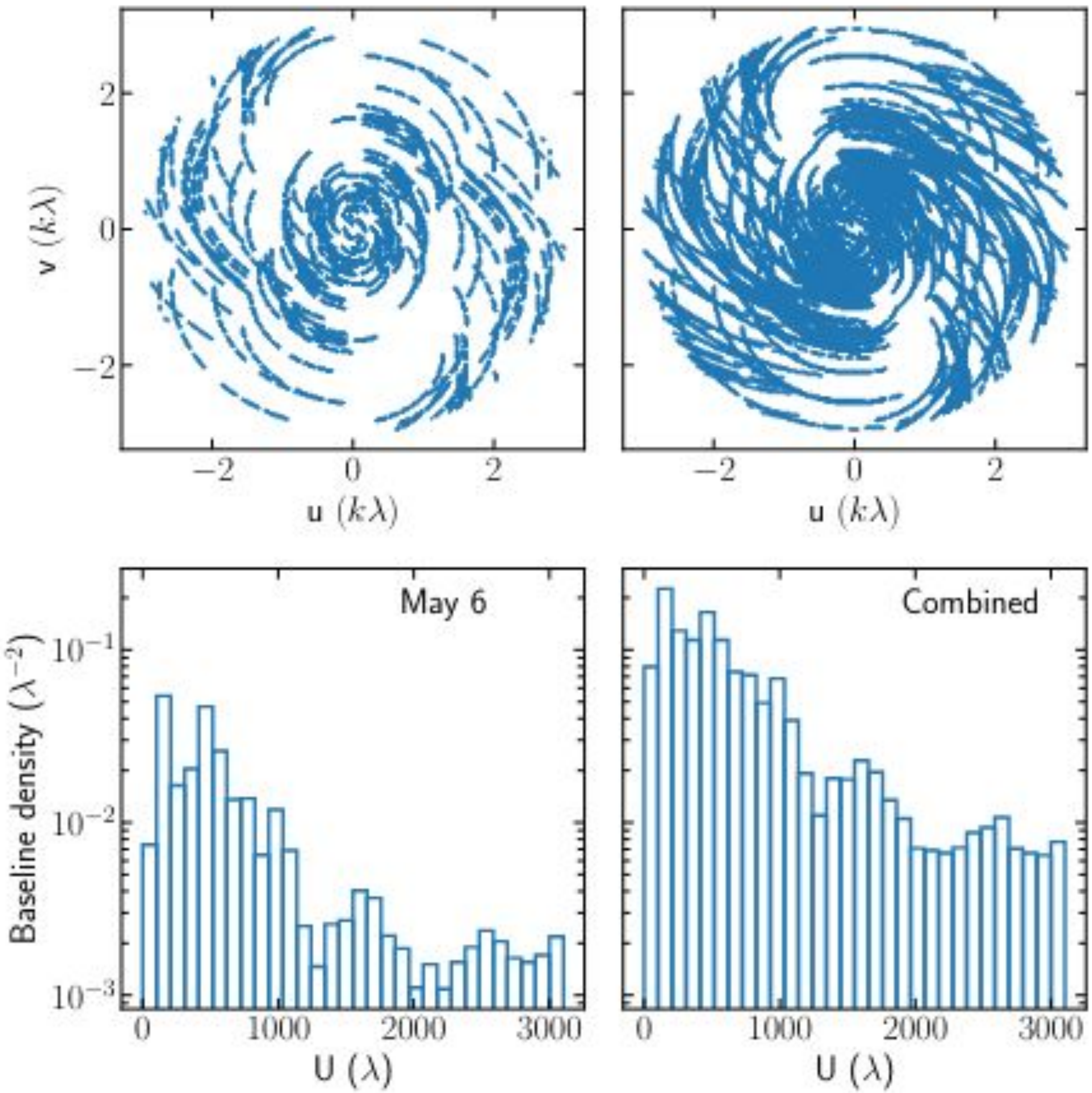
| | |
|---|---|
| Working antennas | 28 |
| Central Frequency | 400 MHz |
| Number of Channels | 8192 |
| Channel width | 24.4 kHz |
| Bandwidth | 200 MHz |
| Total observation time | 25 h |
| Integration time | 2 s |
| Target field $(\alpha, \delta)_{2000}$ | $(16^h 10^m 1^s$, $+54^\circ 30' 36'')$ |
| Galactic coordinates $(l, b)$ | $86.95^\circ$, $+44.48^\circ$ |

**Table 2.** Detail of Calibrators of this observation

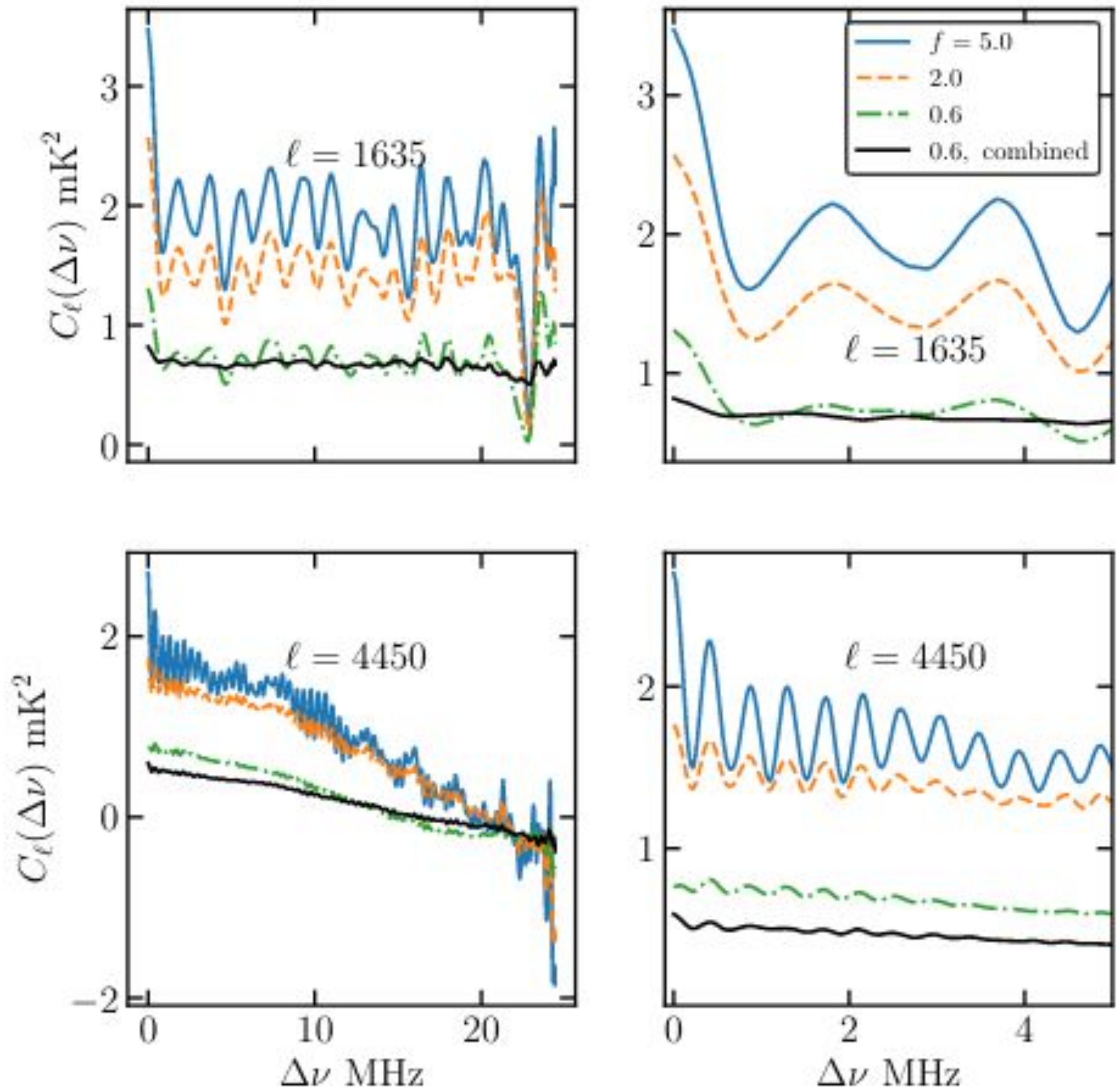
| | |
|---|---|
| Flux Calibrator | |
| Source | 3C286 |
| Flux Density | 23 Jy |
| Source | 3C48 |
| Flux Density | 42Jy |
| Scale | Scaife-Heald |
| Phase Calibrator | |
| Source | J1549+506 |
| Flux Density | 0.3 Jy |
| Target Field | |
| Source | ELAIS N1 |
| time | 14 hours |

Chakraborty et al. , MNRAS, 2019

# Baseline distribution

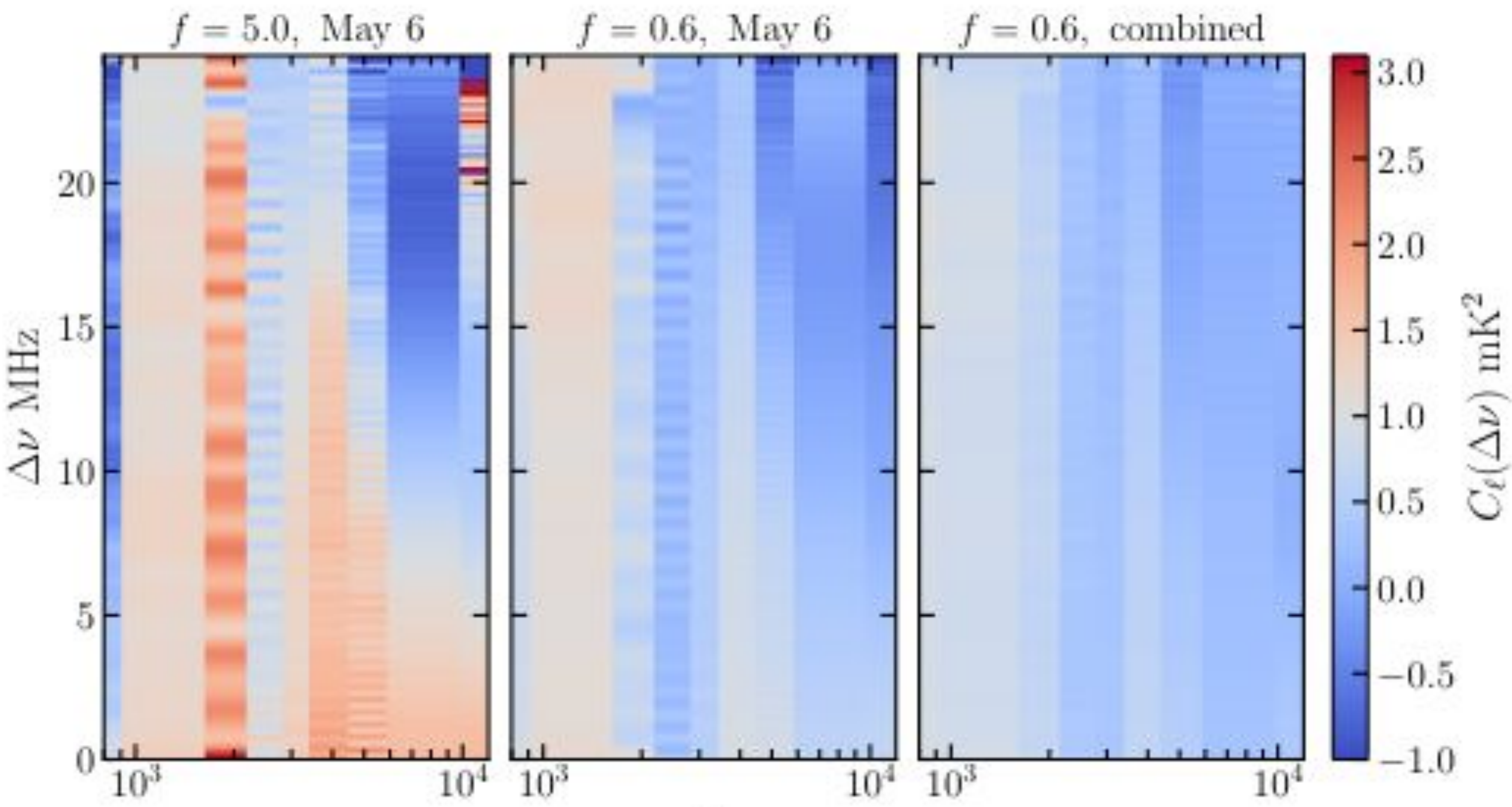


# TGE: the MAPS and the Power-Spectrum




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

# TGE: the MAPS and the Power-Spectrum



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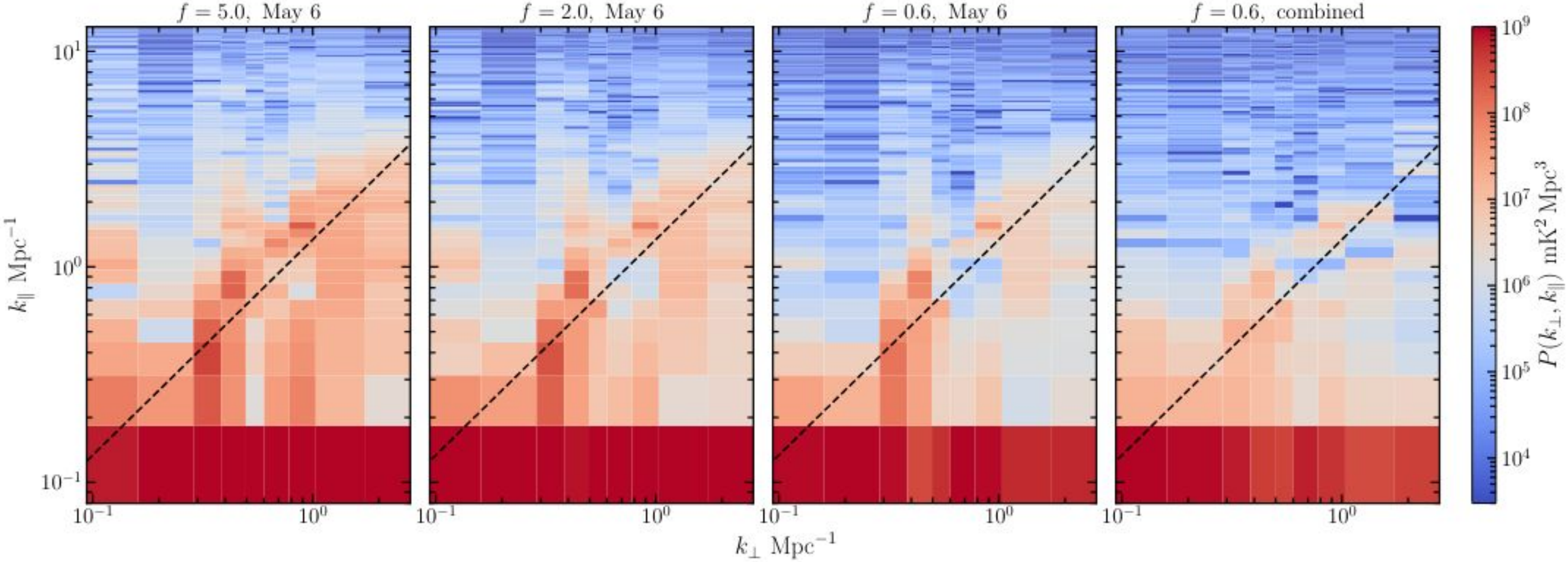
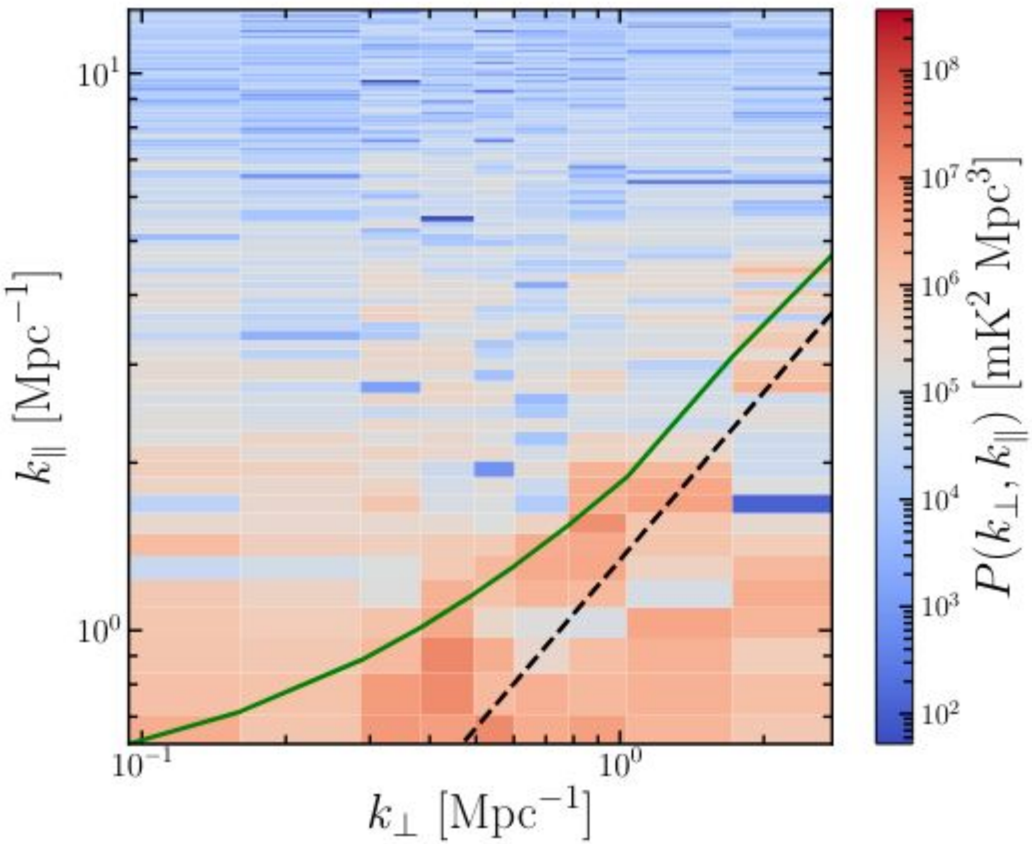
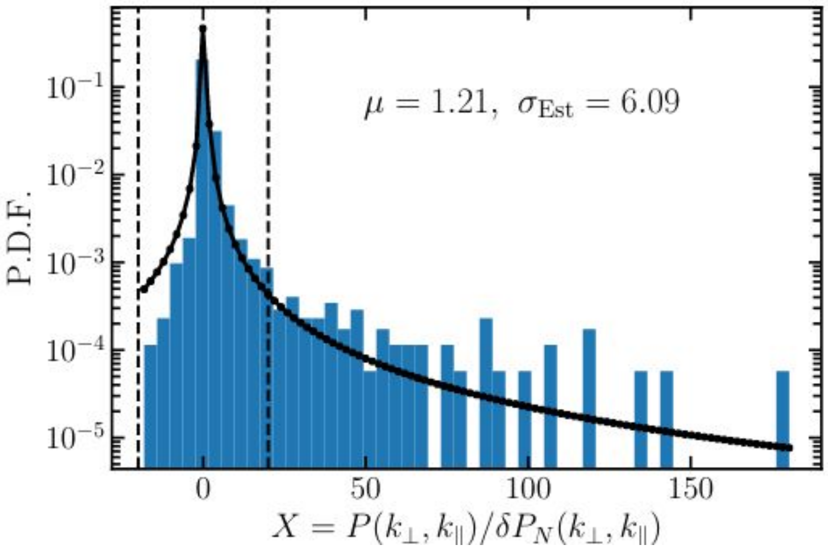
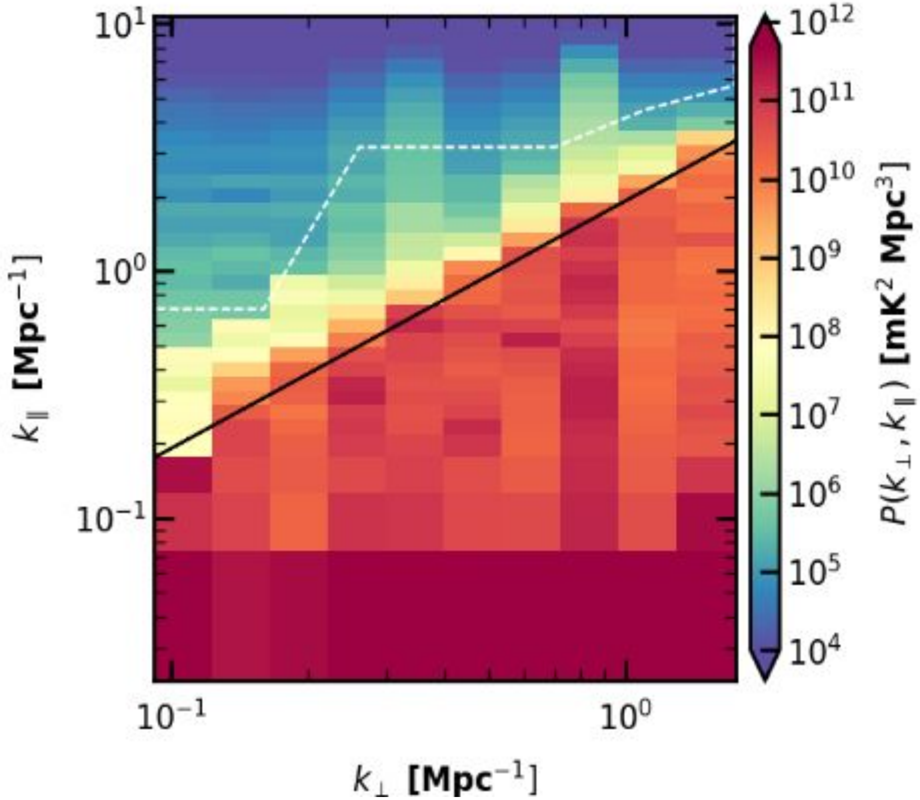


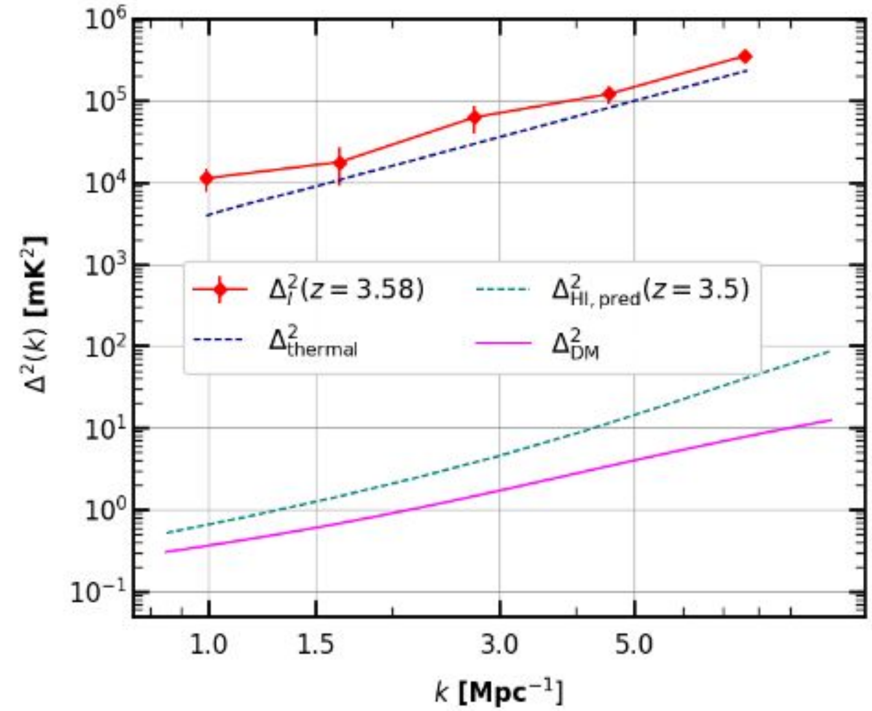

Pal et al 2022,MNRAS

# TGE: the MAPS and the Power-Spectrum

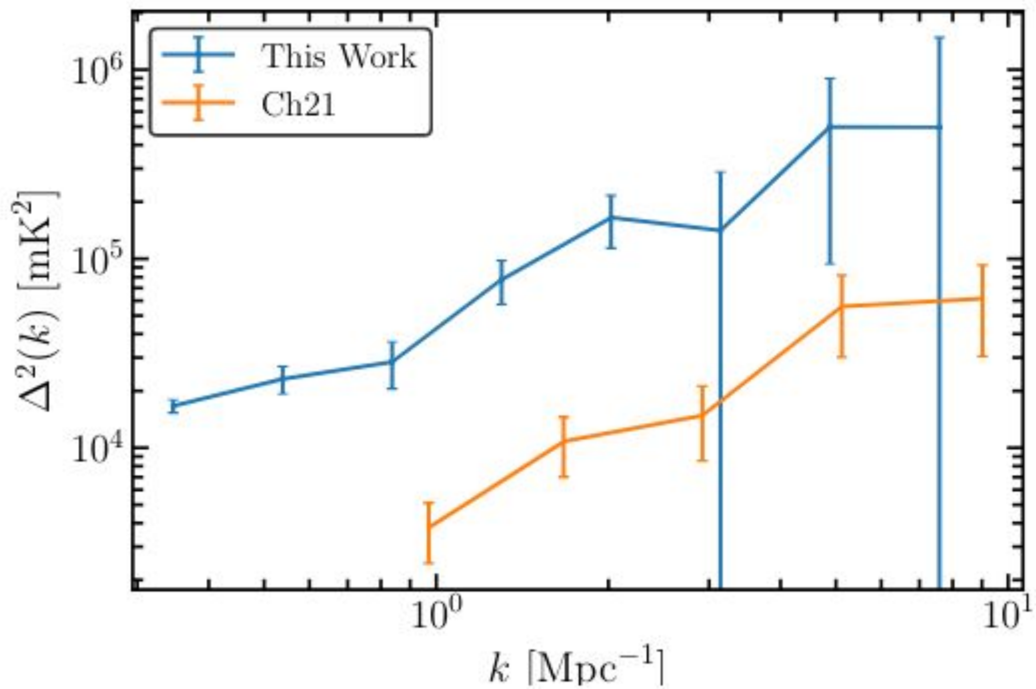





Chakraborty et al. , ApJL, 2021



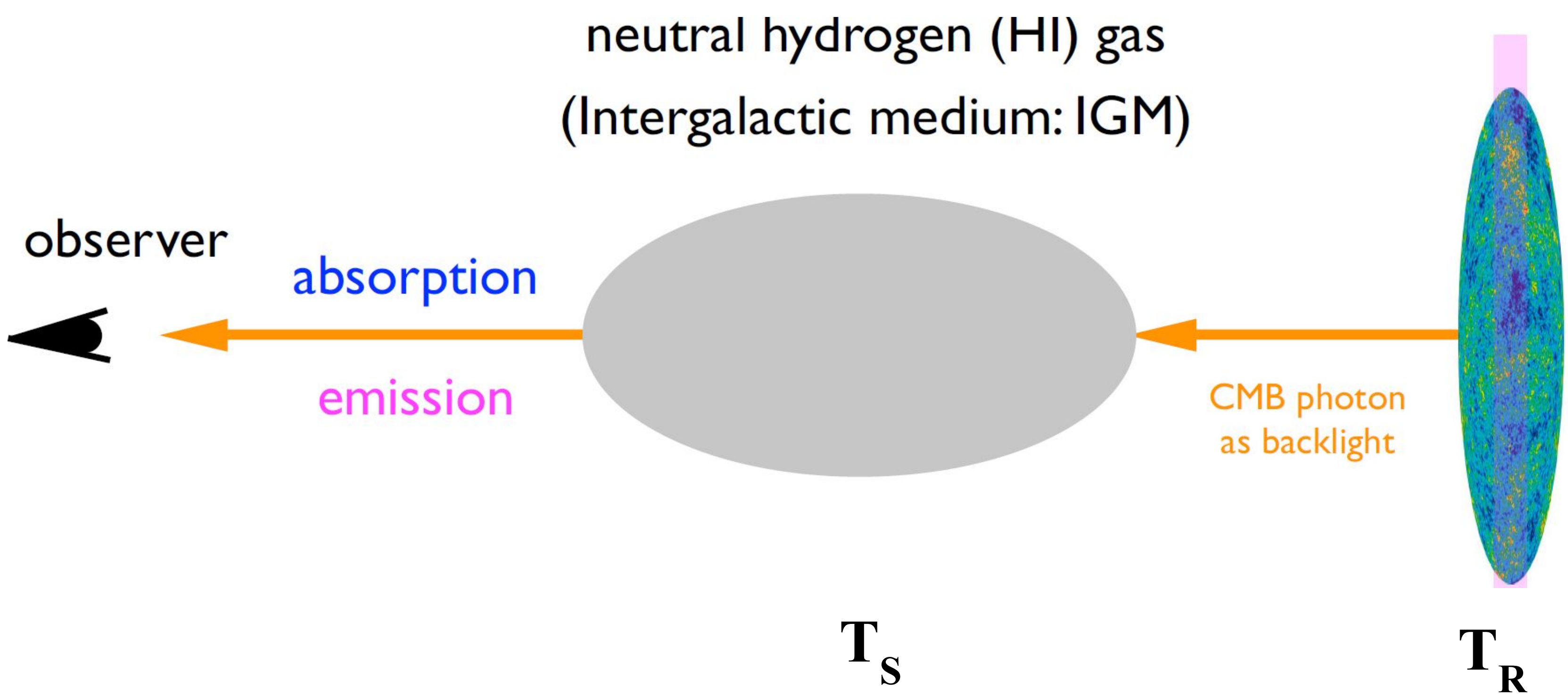

$$[\Omega_{\rm H\,I}\, b_{\rm H\,I}] \leq 0.11 \text{ at } k = 1\,{\rm Mpc}^{-1}.$$

# Summary

- 21-cm radiation is an important tool to study the evolution of the Universe.
- 21-cm cosmology is a growing research field in radio astronomy.
- We have developed a novel estimator TGE for the detection of the 21-cm signal.
- We have used GMRT 432 MHz (z=2.28) observation to constrain $[\Omega_{\rm H\,I}\, b_{\rm H\,I}]$

***Thank You***

# 21cm Brightness Temperature



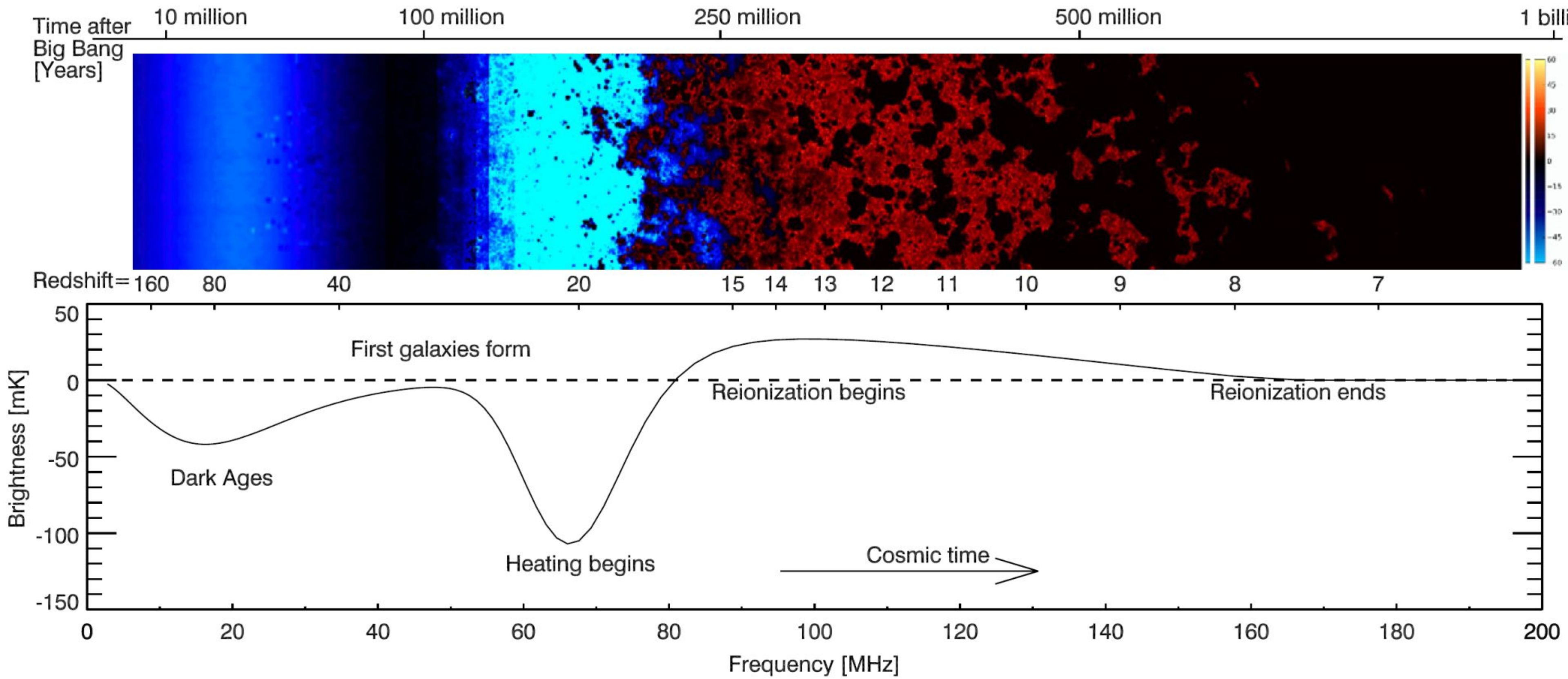

$$\delta T_b \approx 27 x_{\rm HI} (1+\delta_b) \left(\frac{\Omega_b h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_R}{T_S}\right) \mathrm{mK}$$

$T_S > T_R$ : Emission

$T_S < T_R$ : Absorption

Pritchard and Loeb 2012

# 21cm Brightness Temperature




Pritchard and Loeb 2012