Foreground Removal and Angular Power Spectrum Estimation of 21cm Signal using Harmonic Space ILC

Albin Joseph
Arizona State University

based on arXiv:2405.02806 with Rajib Saha

PPC 2024

October 15, 2024

Why measure large-scale structure (LSS)?

Cosmic expansion history

standard rulers in clustering

Early universe

clustering statistics

LSS

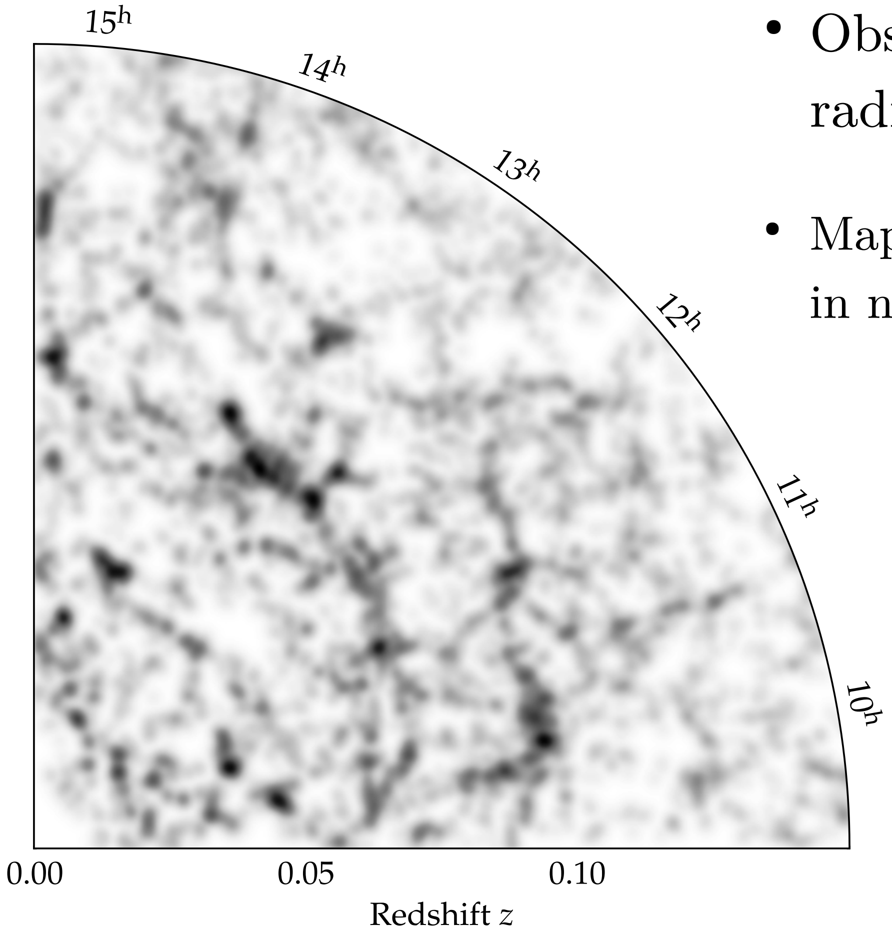
Nature of dark matter

small-scale structures

Nature of gravity

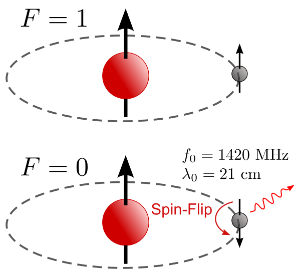
growth of structure

Large-scale structure with 21cm intensity mapping



- Observe the sky at *low resolution* in the radio ($\nu_{obs} < 1420.4$ MHz)

- Maps contain *21cm line emission* from spin flips in neutral hydrogen



- Observing frequency ⟶ redshift

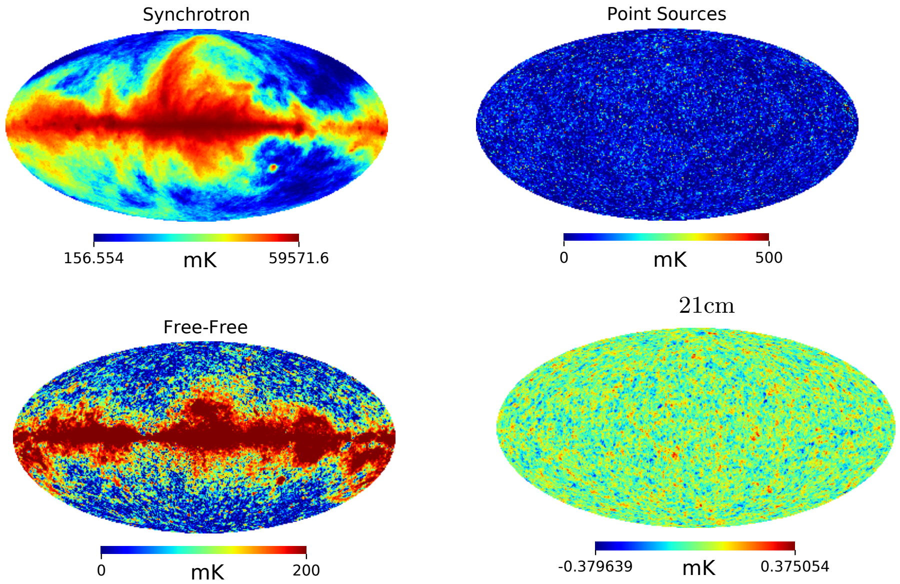
$$z = \frac{1420.4\text{MHz}}{\nu_{obs}} - 1$$

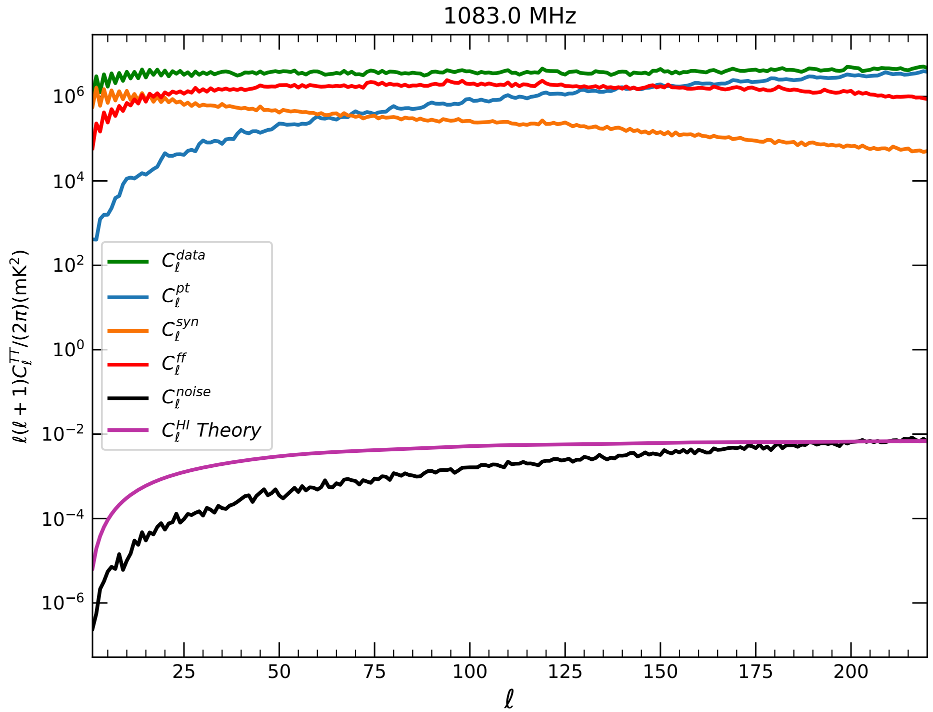
(figure: Richard Shaw)

Challenges in 21cm Detection

Foregrounds

- Synchrotron, extragalatic point sources and free-free emissions
- $10^4 - 10^5$ times brighter than 21cm signal





The angular power spectra of various astrophysical sources of contamination and thermal noise in comparison with the theoretical 21cm power spectrum.

Simulations

Foregrounds

- Synchrotron emission
- Free-free emission
- Extra galactic pointsources

Thermal Noise

- Single-dish telescope

Baryon acoustic oscillations In Neutral Gas Observations (BINGO)

Parameters	
Redshift range $[z_{min}, z_{max}]$	[0.13, 0.48]
Bandwidth $[\nu_{min}, \nu_{max}]$(MHz)	[960, 1260]
Number of feed horns n_f	80
Observation time t_{obs} (yrs)	1
System temperature T_{sys} (K)	50
Beamwidth θ_{FWHM} (arcmin)	$40'$ (0.12 rad)

Table 1: Instrumental parameters for a single-dish simulation.

Methodology: Harmonic space ILC with PCA

- The **sky observations** $d_\nu(p)$ at a frequency ν and pixel p,

$$\mathrm{d}_\nu(p) = s_\nu(p) + f_\nu(p) + n_\nu(p)\,.$$

- The spherical harmonic coefficients,

$$a^{\nu}_{\ell m} = a^{s(\nu)}_{\ell m} + a^{f(\nu)}_{\ell m} + a^{n(\nu)}_{\ell m}\,.$$

Obtain the $n_{ch} \times n_{ch}$ covariance matrix,

$$\widehat{\mathbf{R}}(\ell) = \widehat{\mathbf{R}}_{21\,\mathrm{cm}}(\ell) + \widehat{\mathbf{R}}_n(\ell) + \widehat{\mathbf{R}}_f(\ell)$$

$$\widehat{\mathbf{R}}(\ell) = \widehat{\mathbf{R}}_s(\ell) + \widehat{\mathbf{R}}_f(\ell)\,.$$

- If 'm' defines the subspace dominated by foregrounds, we can write the 21cm signal as a superposition of '(n_{ch} - m)' independent templates $\mathbf{t}$,

$$\mathrm{s}_{\ell m} = \mathbf{S}(\ell)\mathbf{t}_{\ell m},$$

Mixing matrix $n_{ch} \times (n_{ch} - m)$

$(n_{ch} - m)$

Methodology: Harmonic space ILC with PCA

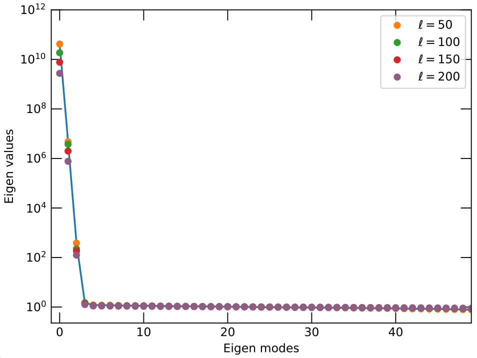
- We use *Principal Component Analysis (PCA)*, to determine the mixing matrix.

- To estimate the mixing matrix, we first normalize the empirical covariance matrix by:

$$\mathbf{R}_{\rm s}^{-1/2}(\ell)\widehat{\mathbf{R}}(\ell)\mathbf{R}_{\rm s}^{-1/2}(\ell),$$

where $\mathbf{R}_{\rm s}$ is the sum of the theoretical 21 cm and the noise covariance matrices.

$$\begin{aligned}\mathbf{R}_{\rm s}^{-1/2}(\ell)\widehat{\mathbf{R}}(\ell)\mathbf{R}_{\rm s}^{-1/2}(\ell) &= \mathbf{R}_{\rm s}^{-1/2}(\ell)\widehat{\mathbf{R}}_f(\ell)\mathbf{R}_{\rm s}^{-1/2}(\ell) + \mathbf{R}_{\rm s}^{-1/2}(\ell)\widehat{\mathbf{R}}_s(\ell)\mathbf{R}_{\rm s}^{-1/2}(\ell)\,, \\ &= \mathbf{R}_{\rm s}^{-1/2}(\ell)\widehat{\mathbf{R}}_f(\ell)\mathbf{R}_{\rm s}^{-1/2}(\ell) + \tilde{\mathbf{I}}(\ell)\,.\end{aligned}$$



- One can then obtain mixing matrix,

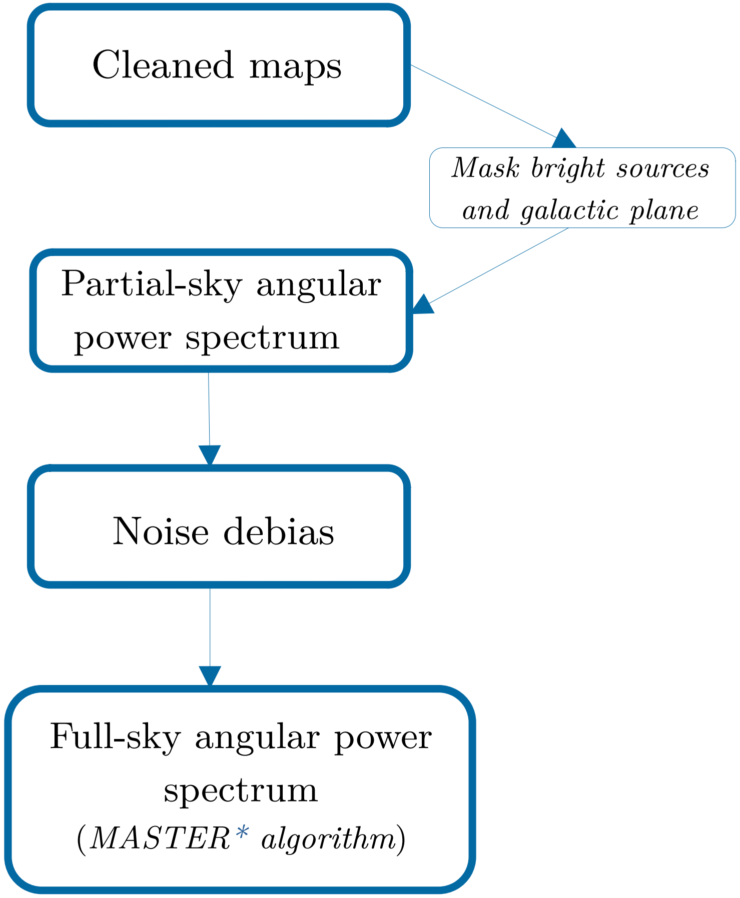
$$\mathbf{S}(\ell) = \mathbf{R}_{\rm s}^{1/2}(\ell)\mathbf{U}_s(\ell)\,.$$

- Now the cleaned 21cm harmonic modes can be obtained by performing **h-ILC***,

$$\mathrm{s}_{\ell m}^{i,\,\rm Clean} = \sum_{j=1}^{n_{ch}} w_\ell^{ij} a_{\ell m}^j\,, \qquad \text{with} \qquad \mathrm{W}(\ell) = \mathbf{S}(\ell)[\mathbf{S}^T(\ell)\widehat{\mathbf{R}}^{-1}(\ell)\mathbf{S}(\ell)]^{-1}\mathbf{S}^T(\ell)\widehat{\mathbf{R}}^{-1}(\ell)\,.$$

*(*Albin and Rajib 2024)*

Methodology: Harmonic space ILC with PCA



$$\mathbf{s}^i(p) = \sum_{\ell>0} \sum_{m=-\ell}^{\ell} s_{\ell m}^{i,\,\mathrm{Clean}} Y_{\ell m}(p)\,.$$

$$\tilde{C_\ell}^{i,\mathrm{Clean}} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \tilde{s}_{\ell m}^{i,\,\mathrm{Clean}} \tilde{s}_{\ell m}^{i,\,\mathrm{Clean}*}\,.$$

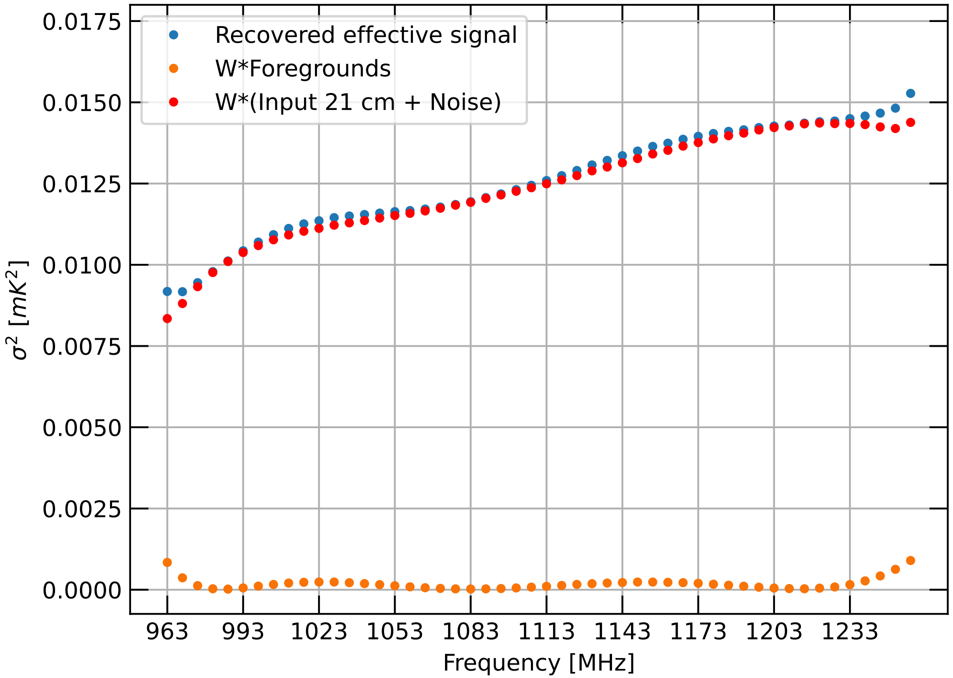
$$\tilde{C_\ell}^{i,\mathrm{Clean}'} = \tilde{C_\ell}^{i,\mathrm{Clean}} - \sum_{j=1}^{n_{ch}} w_\ell^{ij} \tilde{\sigma_\ell}^{jj} w_\ell^{ji}\,.$$

$$C_\ell^{i,\mathrm{Clean}} = M_{\ell\ell'}^{-1,i} \tilde{C_{\ell'}}^{i,\mathrm{Clean}}\,.$$

$$M_{\ell\ell'} = \frac{2\ell'+1}{4\pi} \sum_{\ell''} (2\ell''+1) C_{\ell''}^{M} \begin{pmatrix} \ell & \ell' & \ell'' \\ 0 & 0 & 0 \end{pmatrix}^2 .$$

(*Hivon et al. 2002)

Results: Effectiveness of Harmonic Space ILC

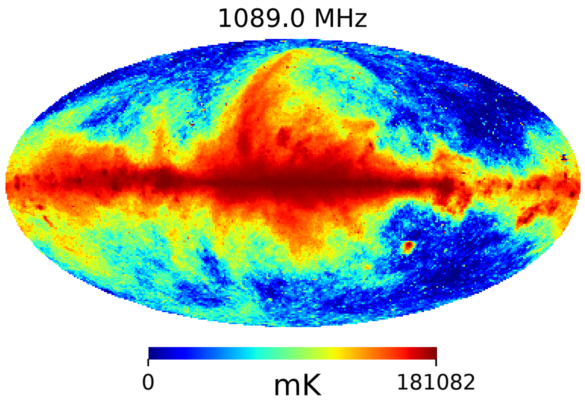


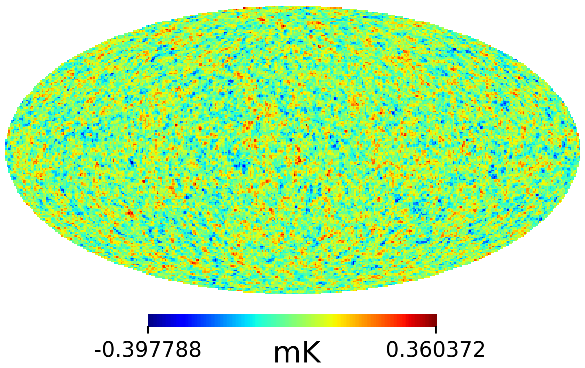
Variance Analysis Across Frequency Channels

Strong suppression of foreground residuals

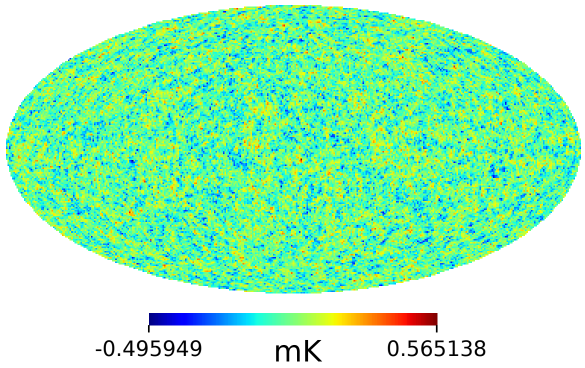
Results: Cleaned Maps

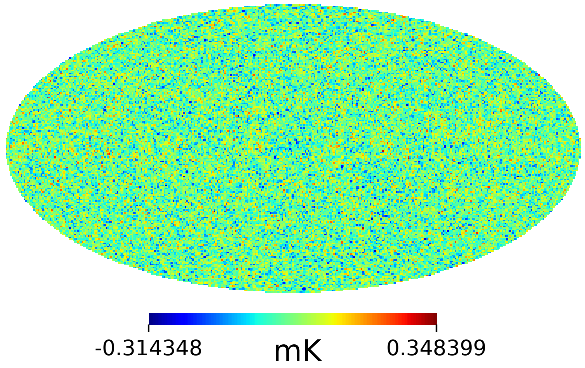
Input data and 21cm signal maps



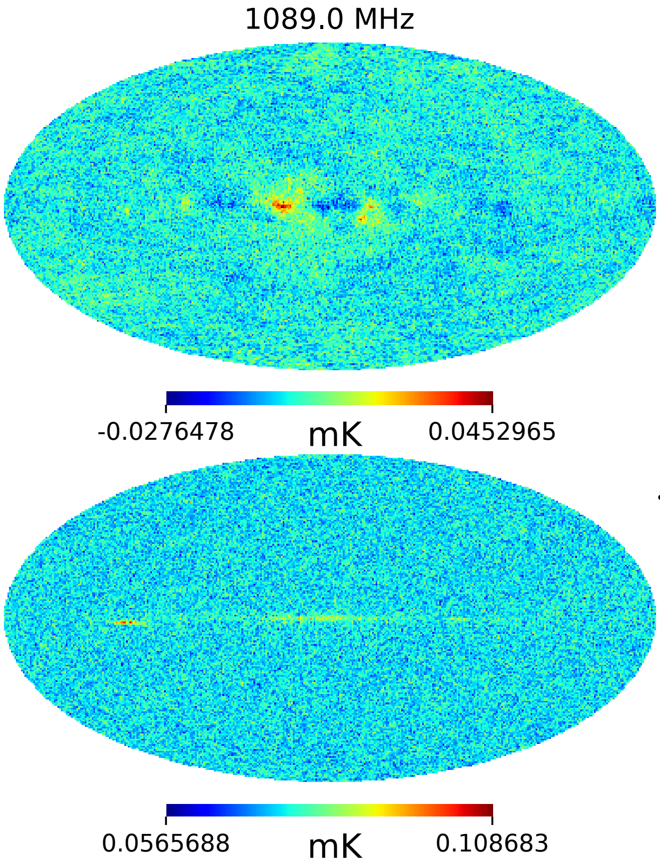


Recovered 21cm and difference maps

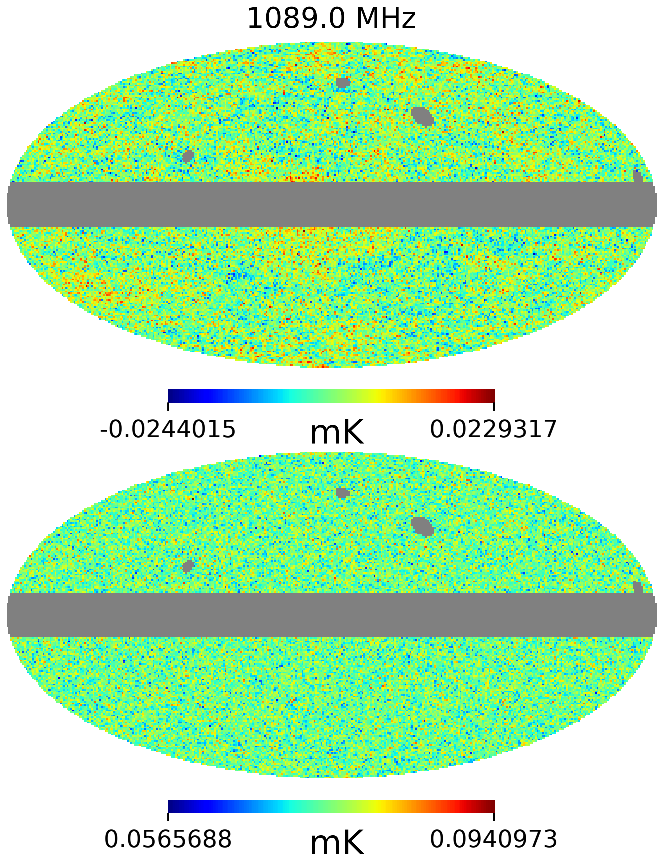




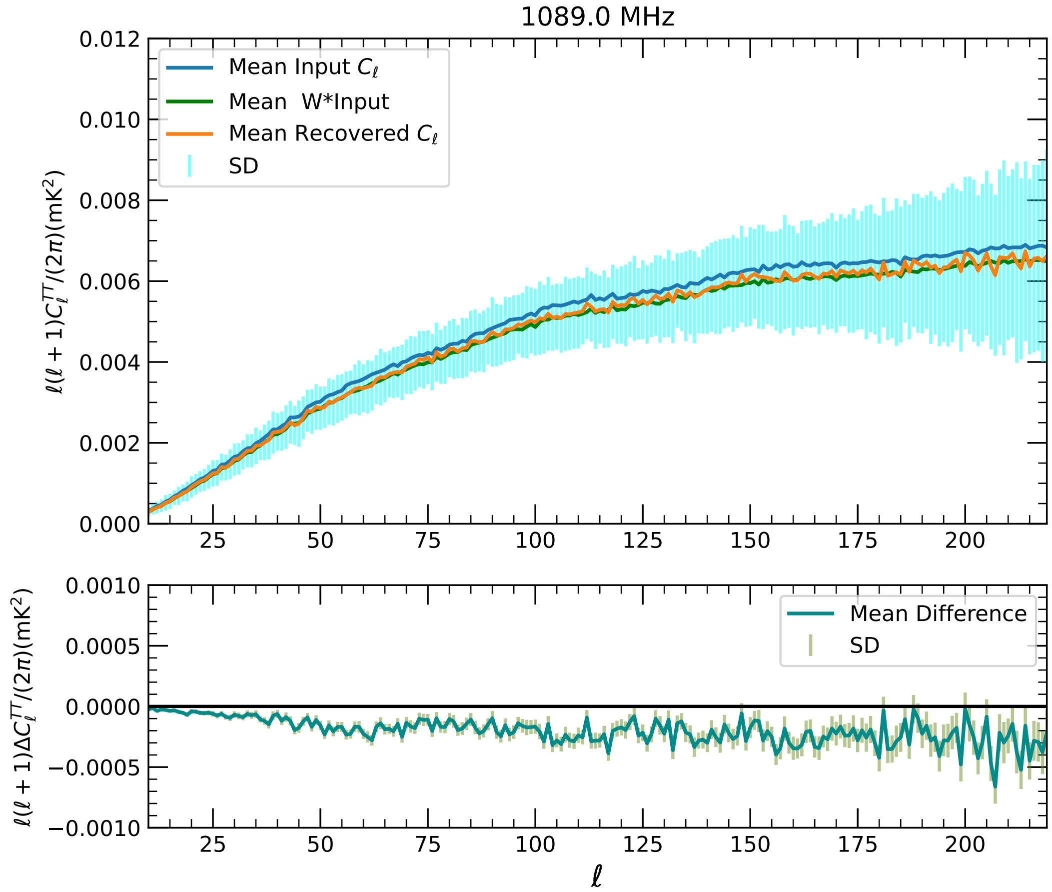
Results: Mean difference and Std. Dev. Maps



masking bright radio sources and galactic plane

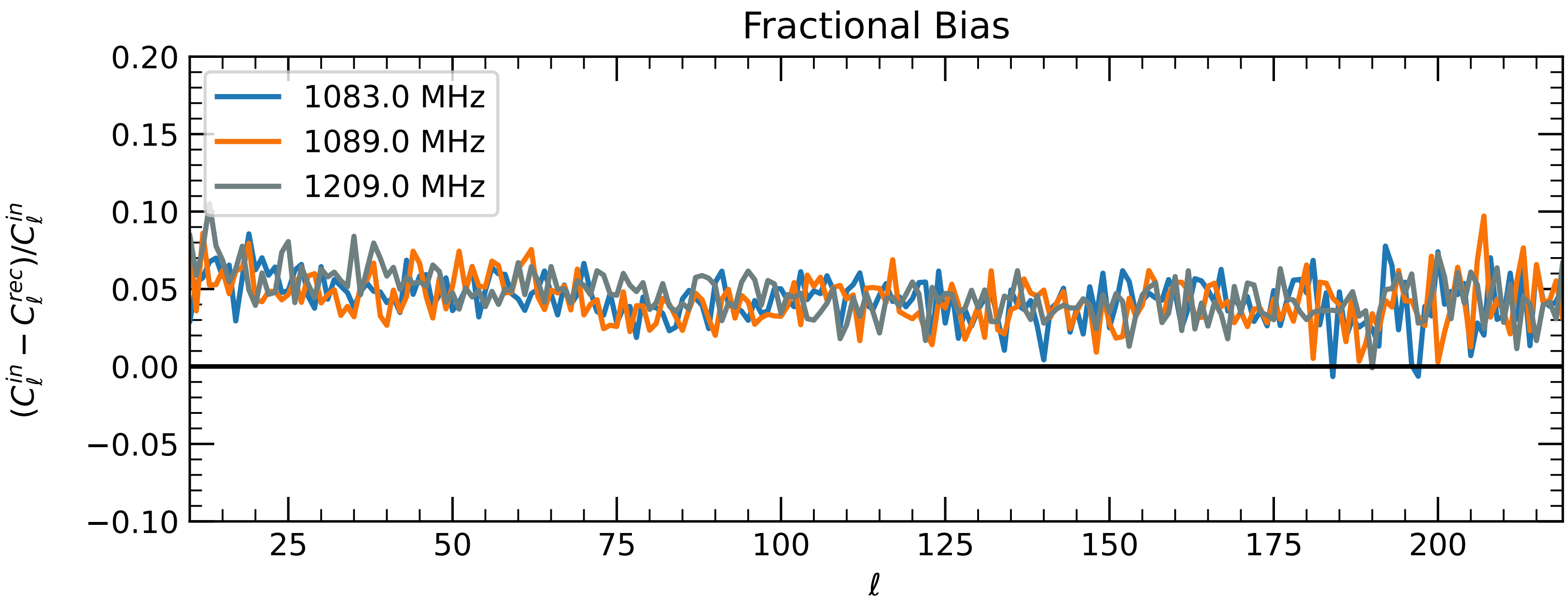


Results: Recovered full-sky angular power spectrum



Recovered mean angular power spectrum.

Results: Fractional Bias



Signal loss is $\sim$ 6%

Summary

- We propose a novel, foreground model-independent method using harmonic space Internal Linear Combination (ILC) to extract the 21 cm signal from simulated radio observations.
- The method effectively removes foreground contamination that is several orders of magnitude stronger than the 21 cm signal, without requiring explicit foreground modeling.
- The method reconstructs the 21 cm angular power spectrum with less than 6% bias for most multipoles, demonstrating its effectiveness in preserving the cosmological signal.
- The technique is computationally efficient

Thank You