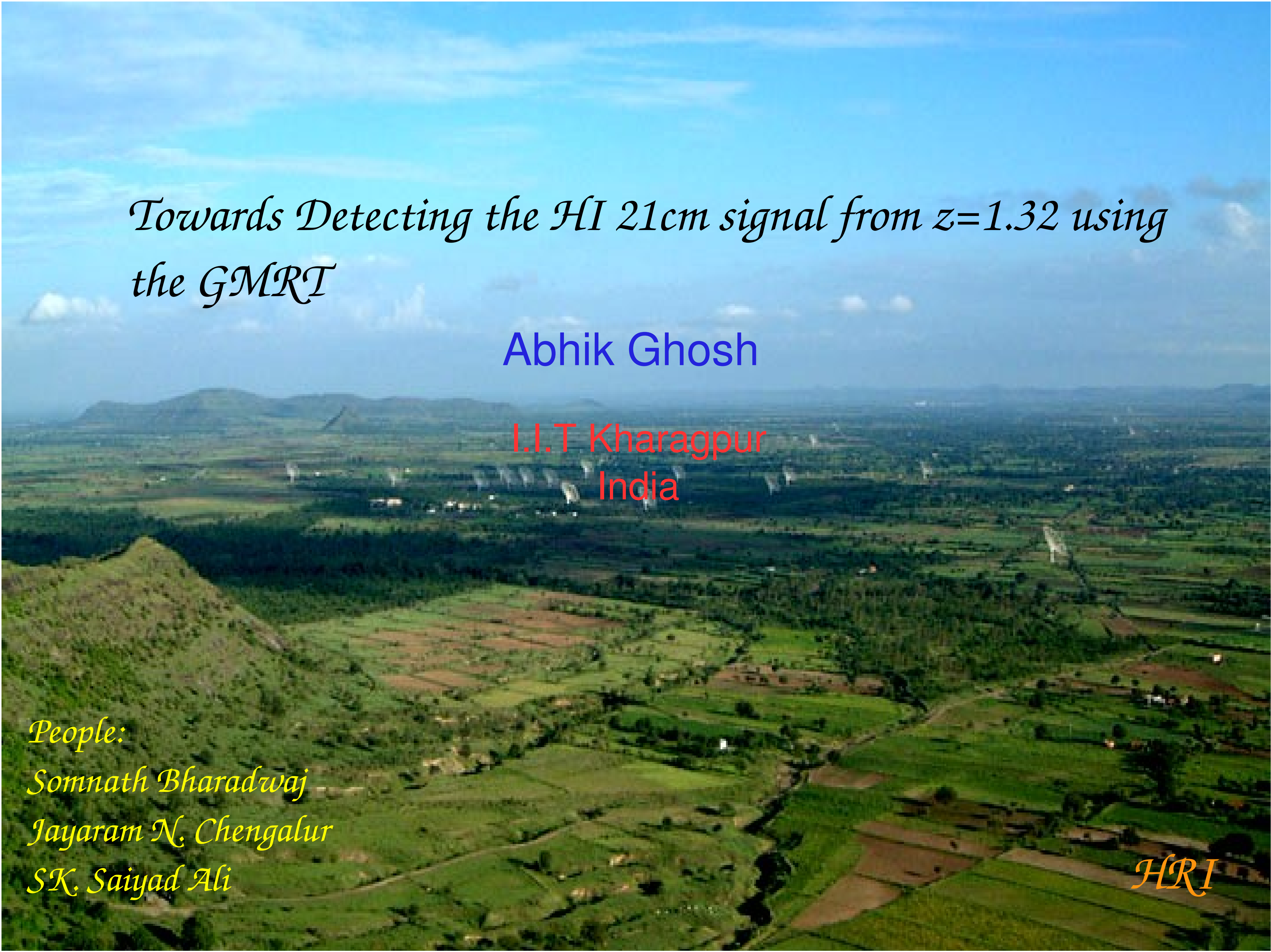

Towards Detecting the HI 21cm signal from z=1.32 using the GMRT

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Brief Outline :

what will the HI Signal tell us ?

GMRT Observations

Foregrounds

- Model Prediction
- Subtraction

Conclusion

Why HI :

- *By mapping red-shifted 21 cm radiation it can, in principle, provide a very precise picture of the matter power spectrum in the period after recombination all the way from Dark ages to the current epoch.*
- *Each measurement presents its own set of technical, theoretical, and observational challenges.*

- *The anisotropic power spectrum from HI is three- dimensional since the signal is a spectral line (as opposed to the two-dimensional CMB arising from continuum emission).*

Contd ……

- Reionization [$6 < z < 30$, $203 > \nu > 46$ MHz] Redshifted 21 cm signal offer us crucial information into the evolution of the IGM during the crucial times associated with the formation of the first stars, galaxies, and quasars. Measurements of both the mean (global) red-shifted 21 cm brightness temperature and the fluctuation power spectrum should yield the spin and kinetic temperature histories of the IGM and the re-ionization history.

- Post-Reionization [$0 < z < 6$, $1420 > \nu > 203$ MHz] Localized clumps of HI if detected gives us the opportunity for studying the galaxy evolution. In addition, $\Omega_{HI}(z)$ should be well constrained.

GMRT Observation:

610 MHz ~ z = 1.32

Giant Metrewave Radio Telescope, near Pune. 30 fixed antennas each of diameter 45 m.

$$\alpha_{2000} = 12^h 36^m 49^s,\ \delta_{2000} = 62^\circ 17' 57''$$

$$l = 125.87^o, b = 54.74^o$$

Total 30 Hrs including calibration

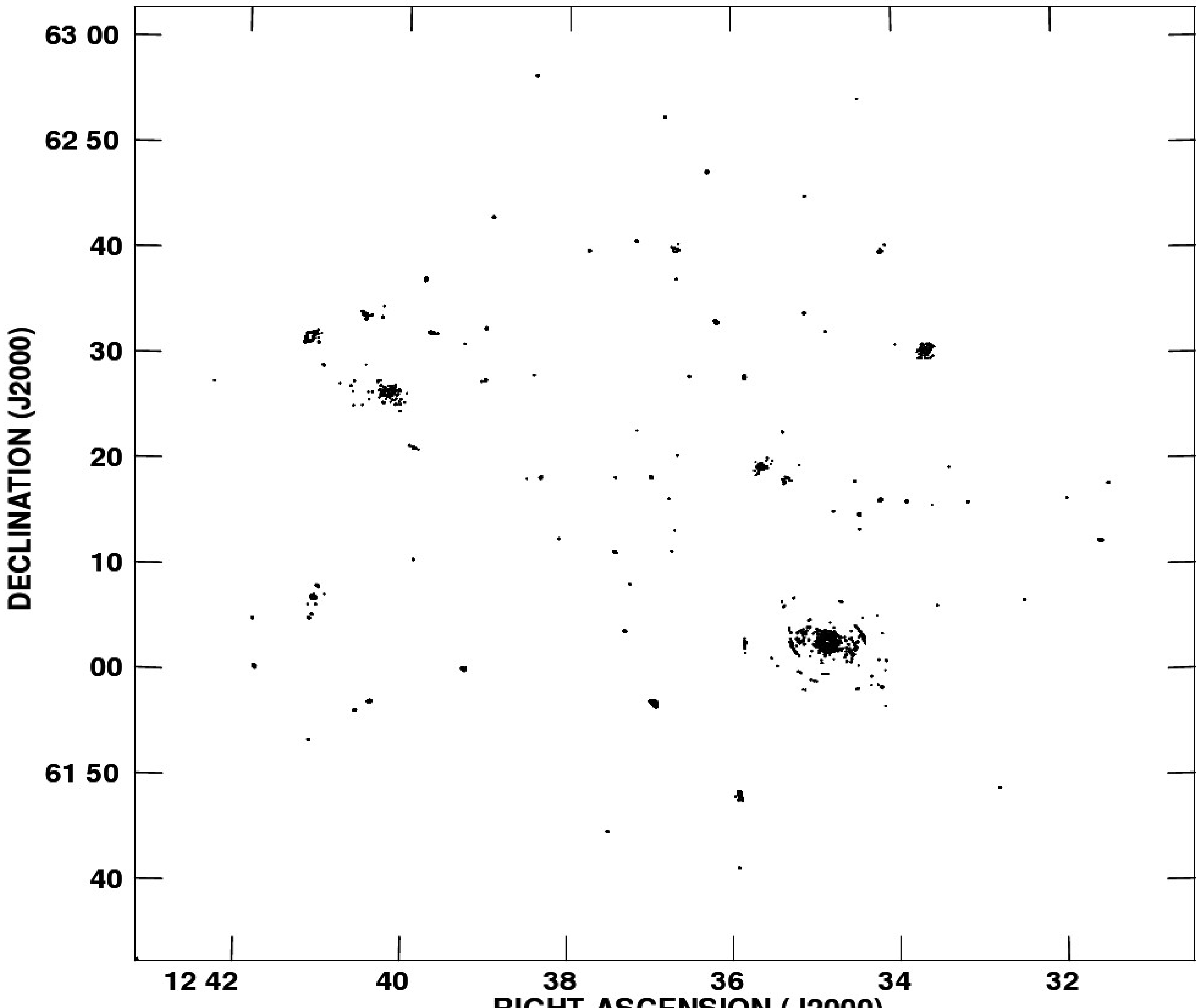
Sky Temp. - 20 k in 408 MHz Haslam Map

Bandwidth – 32 MHz ,

Channels - 128

Frequency resolution – 125 KHz

FoV ~ 0.61 degree



Cont peak flux = 5.9677E-02 JY/BEAM
Levs = 6.000E-05 * (-11, -9, -7, 7, 9, 11)

What we measure :

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

Measured Visibility

Signal

Foregrounds

Noise

At least 3 to 4 order of magnitude higher than the HI Signal

At Low Frequencies Foregrounds has to be known precisely in order to extract the Signal

Statistical Approach :

The statistical properties of the visibility can be quantified through the two visibility correlation

$$V_2(\mathbf{U}_1, \nu_1; \mathbf{U}_2, \nu_2) = \langle V(\mathbf{U}_1, \nu_1) V^*(\mathbf{U}_2, \nu_2) \rangle$$

and

$$V_2 = S_2 + F_2 + N_2$$

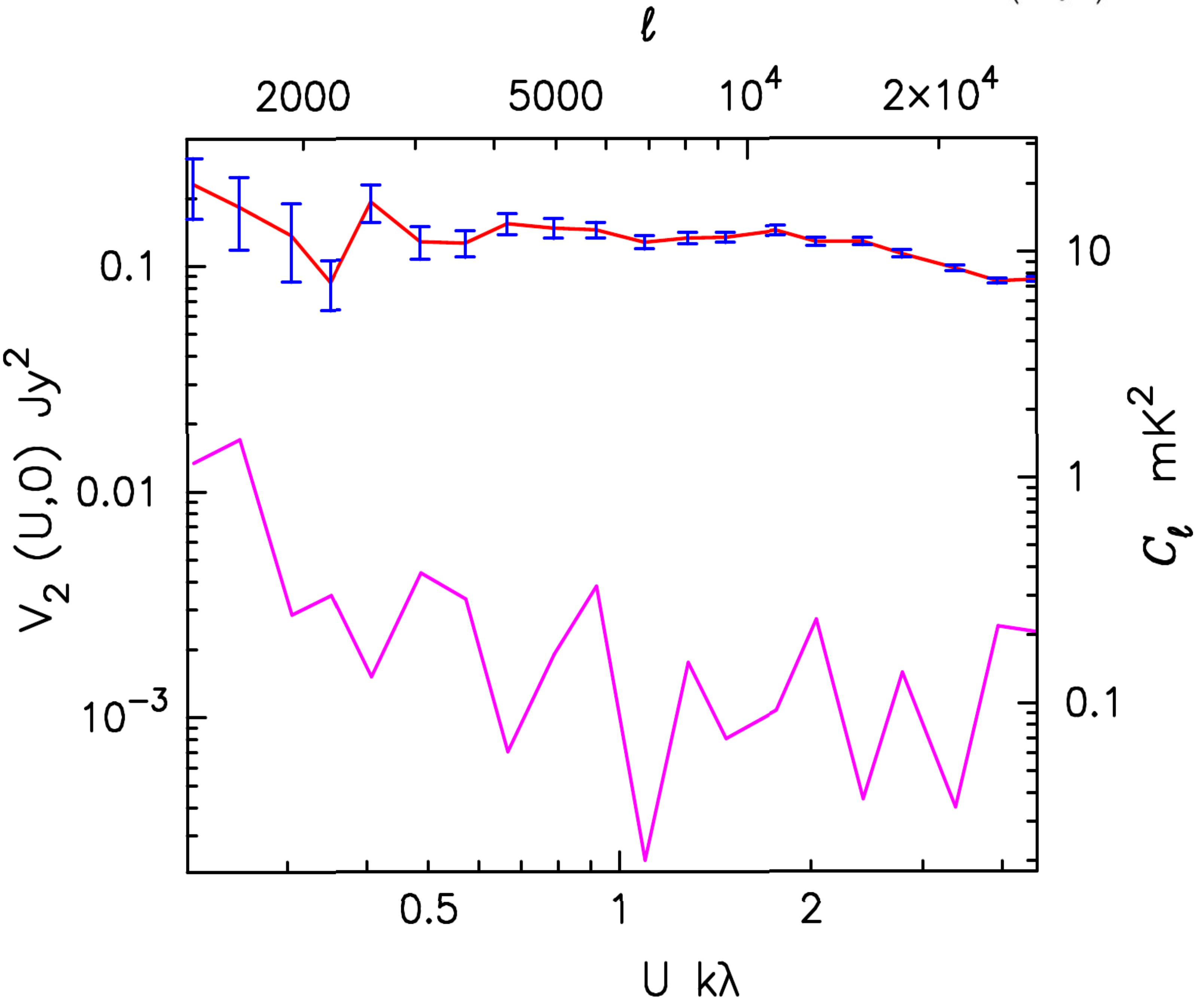
Relation between Two Visibility correlation (V_2) *& MAPS* $C_\ell(\Delta\nu)$

$$V_2(\mathbf{U}, \Delta\nu) = \frac{\pi\theta_0^2}{2} \left(\frac{\partial B}{\partial T}\right)^2 C_{\ell=2\pi U}(\Delta\nu)\, Q(\Delta\nu)$$

Ali, S.S. et. al. , 2008 , MNRAS, 385, 2166

MAPS of the Background Radiation:

$$C_{2\pi U}(\Delta\nu) = 87 \left(\frac{\mathrm{mK}}{\mathrm{Jy}}\right)^2 \times V_2(\mathbf{U}, \Delta\nu)$$



The contribution of HI Signal (S_2) is expected to be $C_\ell^{HI}(0) \sim 10^{-6}\ mk^2$ *at 610 MHz . This is negligible compared to the expected foreground and noise contributions in our observations.*

Foregrounds

- Point Sources
- Galactic Synchrotron emission
- Galactic & Extra-galactic free-free radiation

Foreground Model prediction

- *For each foreground component the MAPS can be modeled as:*

$$C_\ell(\Delta\nu) = A \left(\frac{1000}{\ell}\right)^\gamma \kappa_\ell(\Delta\nu)$$

Where,

$$A \propto \nu^{2\alpha}$$

$$\kappa_\ell(\Delta\nu) \sim 1$$

Continued:

Poisson part:

The contribution to the background below the flux cut S_{cut} due to sources with a Poisson distribution is given by:

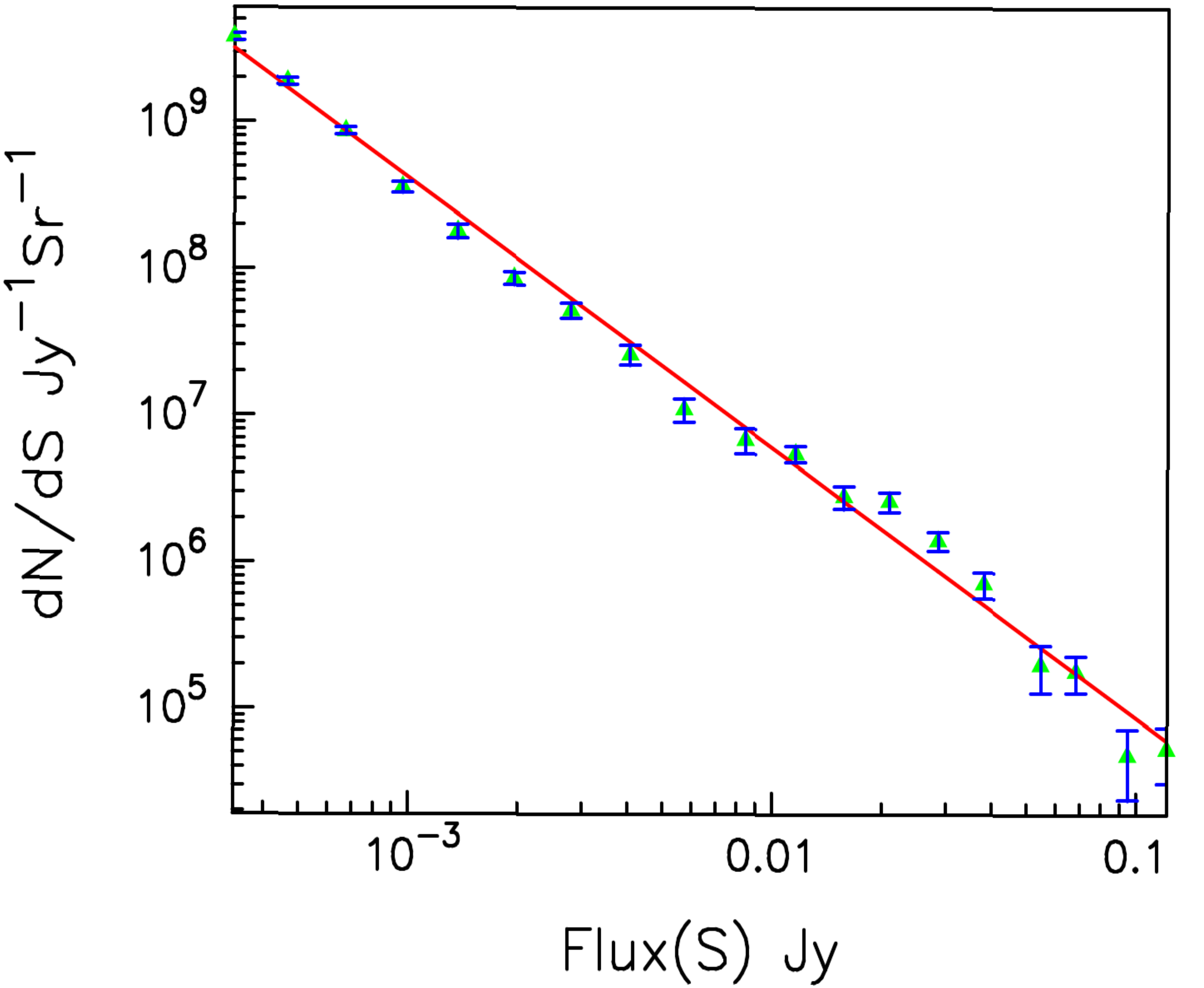
$$C_l^{Poisson} = \langle S^2 \rangle = \int_0^{S_{cut}} S^2 \frac{dN}{dS} dS$$

- *The differential source count is calculated from Garn, Green, Riley:*

$$\frac{dN}{dS} = \frac{1259}{Jy \cdot Sr} \cdot \left(\frac{S}{1Jy} \right)^{-1.84}$$

Model:

$$\frac{dN}{dS} = \frac{1259}{Jy \cdot Sr} \cdot \left(\frac{S}{1Jy}\right)^{-1.84}$$



Garn, T., Green, D. A., Riley, J. M., & Alexander, P. 2008, MNRAS, 387, 1037

Continued:

Clustered part:

The contribution due to clustered sources is quantified as:

$$C_l^{cluster} = w_l I^2$$

Where , $I = \int_0^{S_{cut}} S(dN/dS)dS$

w_ℓ is the Fourier transform of the angular correlation function $w(\theta) = (\theta/\theta_0)^{-\beta}$ (Scott & White 1999)

Here, we have taken $\beta = 1.1$ and $\theta_0 = 17.4$ arc-minute (Cress et. al. 1996)

Foreground Contribution at 610 MHz :

Foregrounds	$A(\mathrm{mK}^2)$	α	γ
Point source (Clustered part)	$20.03 \times \left(\frac{S_{cut}}{\mathrm{Jy}}\right)^{0.32}$	2.07	0.9
Point source (Poisson part)	$8.38 \times \left(\frac{S_{cut}}{\mathrm{Jy}}\right)^{1.16}$	2.07	0
Galactic synchrotron	0.122	2.80	2.4
Galactic free-free	1.14×10^{-4}	2.15	3.0
Extra Galactic free-free	2.11×10^{-5}	2.1	1.0

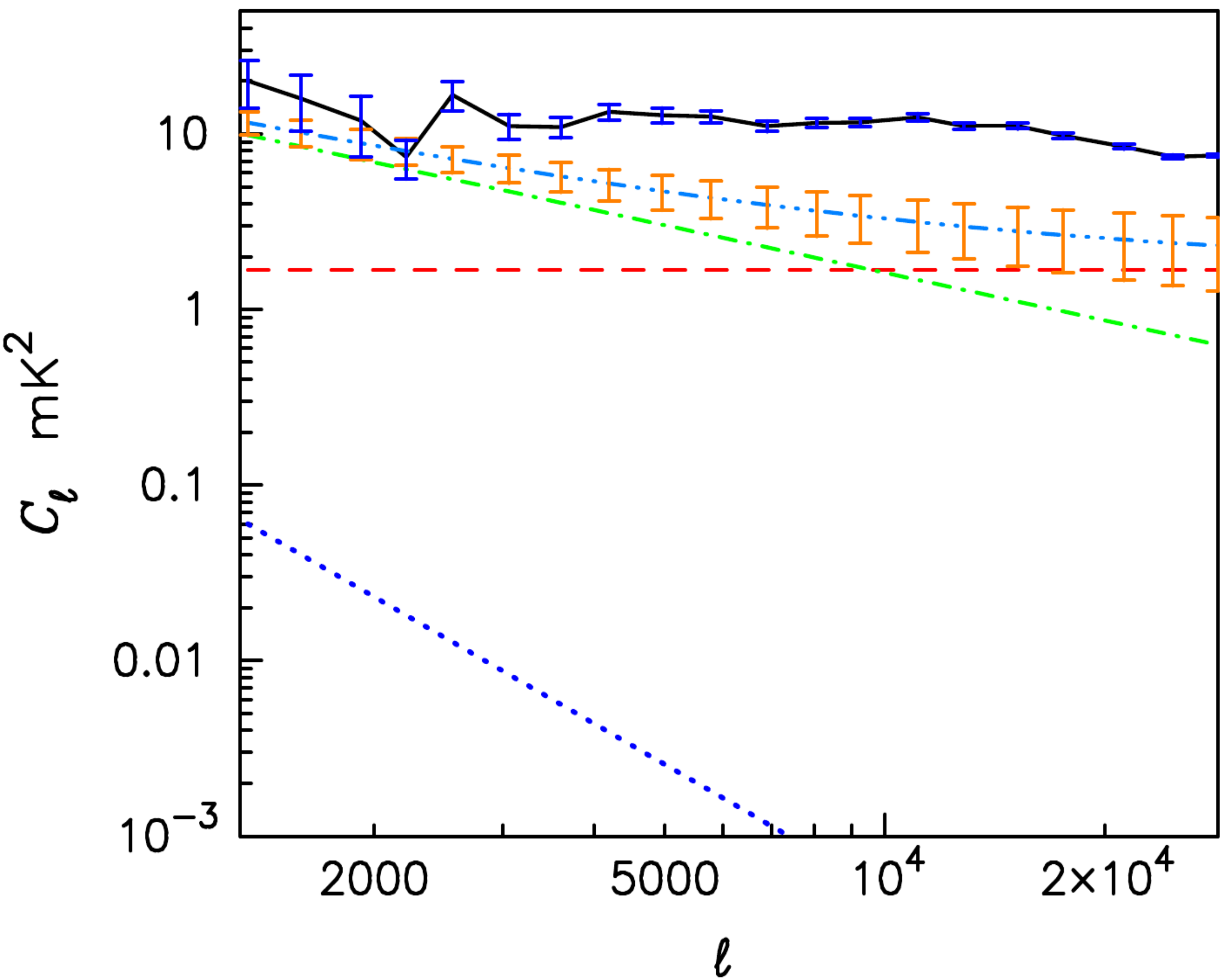
Gs, Gf & Egf are extrapolated from 130 MHz to 610 MHz

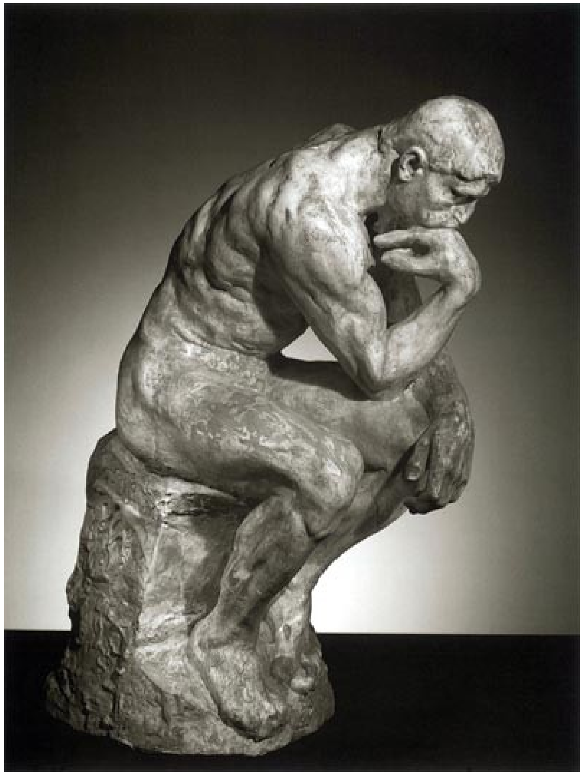
Santos, M.G. et. al. , 2005 , ApJ, 625, 575

FOREGROUND Contributions :

Theoretical prediction

$$C_\ell^{HI}(0) \sim 10^{-6} \quad mk^2$$



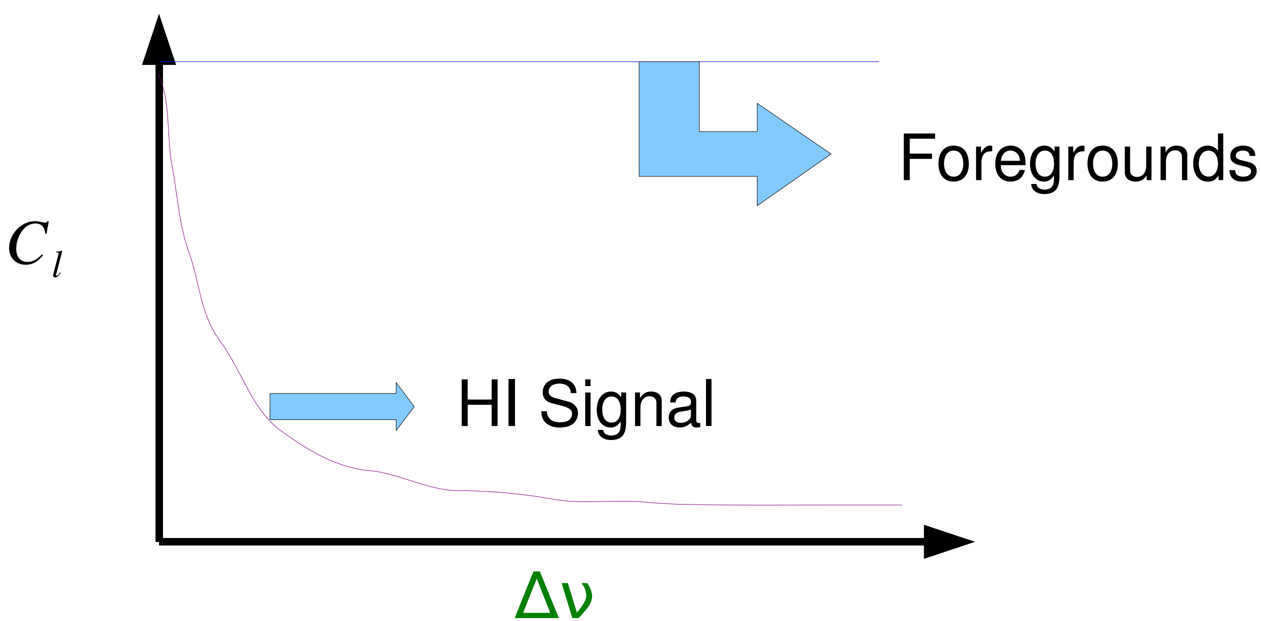


What's the solution

Foreground Subtraction:

***Assumption*:**

The foregrounds are expected to have a continuum spectra and the contribution *at two different frequencies* are expected to be highly correlated . The HI signal is expected to be uncorrelated at such a frequency separation and thereby we can separate the signal from the foregrounds.



Possible line of approaches:

a) ***Image plane subtraction***:

Subtract out the slowly varying frequency dependent component directly from the Image Cube. (Jelic et al. 2008, Bowman et al. 2009, Liu, Tegmark & Zaldarriaga 2009)

Problems:

i) Liu et al. 2009 have showed that this method fails at *large baselines* if the uv sampling is sparse.

ii) We find that this method fails to remove point sources efficiently, several *imaging artifacts remain* in the vicinity of bright sources. (Ali, Bharadwaj & Chengalur 2008)

b) ***uv plane subtraction***:

Liu et al. 2009 proposed to subtract out the frequency dependence directly from the *visibility data* with fitted polynomials .

Problem:

i) This visibility based technique requires the data to be gridded in the uv plane which will introduce a *positive noise bias* in the measured $C_\ell(\Delta\nu)$

Our Technique:

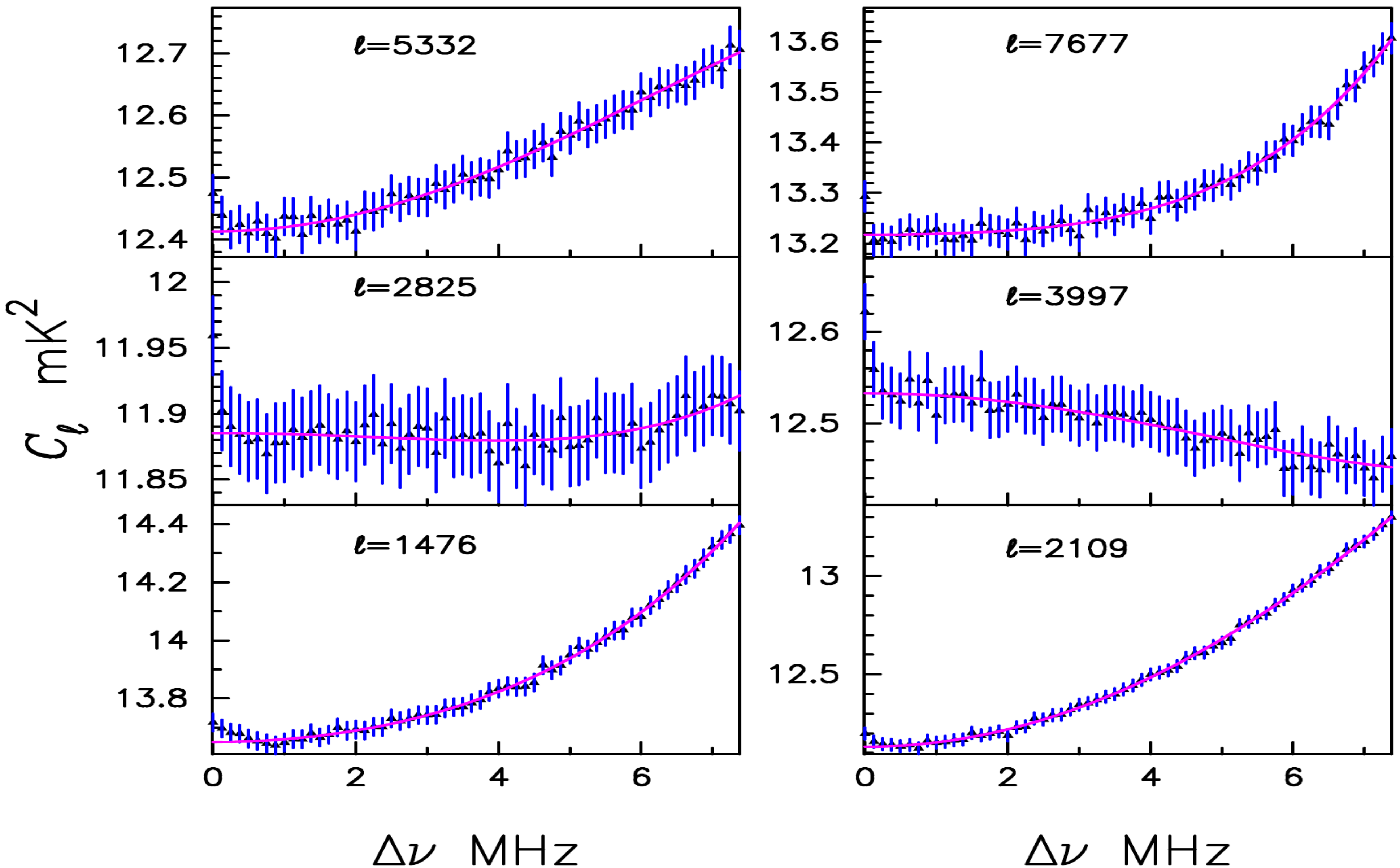
- *All earlier foreground subtraction techniques have tried to remove the foregrounds* ***before*** *determining the angular power spectrum. In our method the foregrounds are subtracted* ***after*** *determining the angular power spectrum .*

- *We have proposed and implemented a technique that uses polynomial fitting in $\Delta\nu$ to subtract out any smoothly varying component from the measured $C_\ell(\Delta\nu)$*

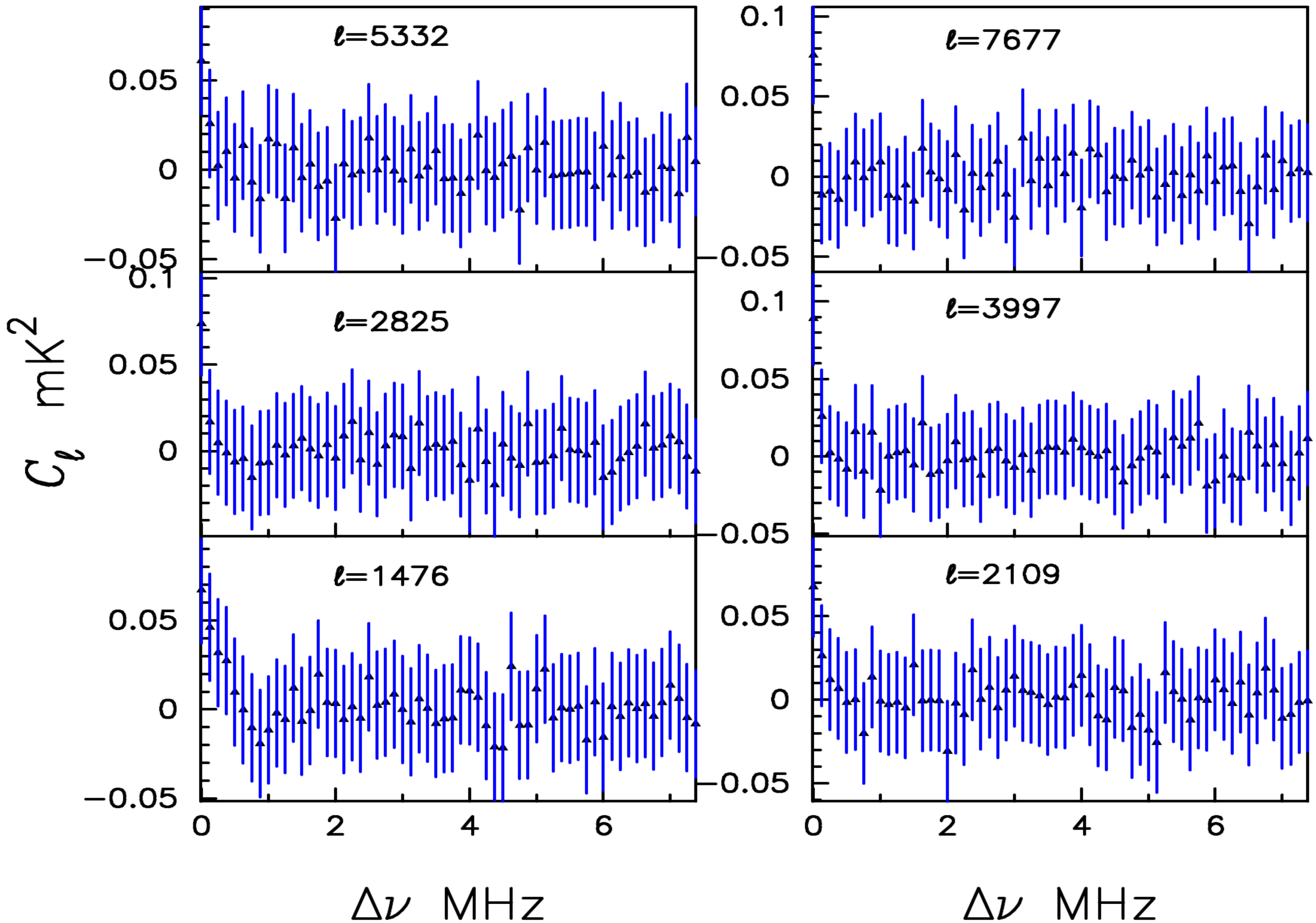
Efficacy of our technique on simulated data:

$0.5\ \mathrm{MHz} \leq \Delta\nu \leq\ 7.5\ \mathrm{MHz}$

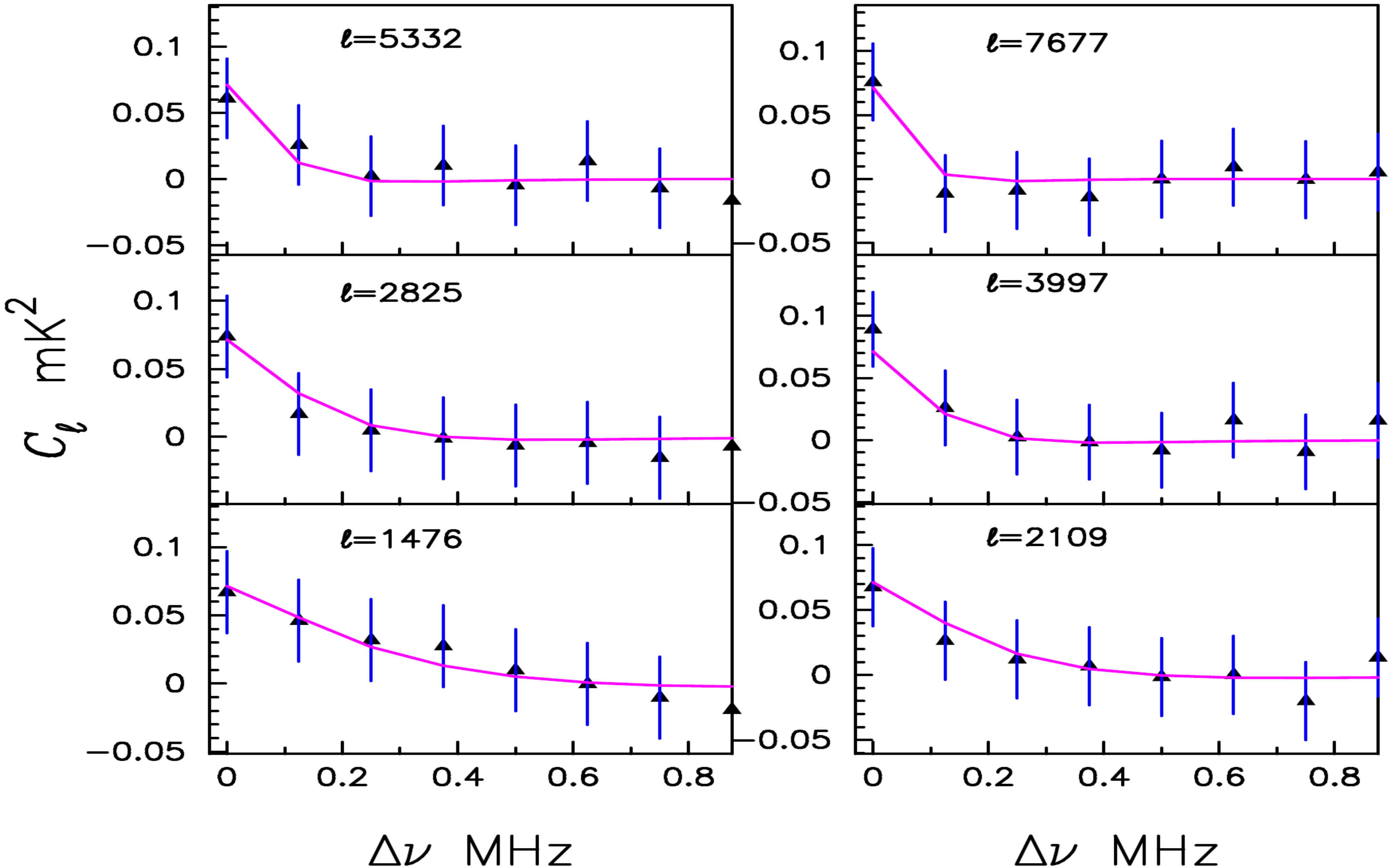
$$C_\ell(\Delta\nu) = \sum_n a_n\ (\Delta\nu)^n\ +\ \delta + \alpha\ C_\ell^{\mathrm{HI}}(\Delta\nu)$$



4^{th} Order Residuals:

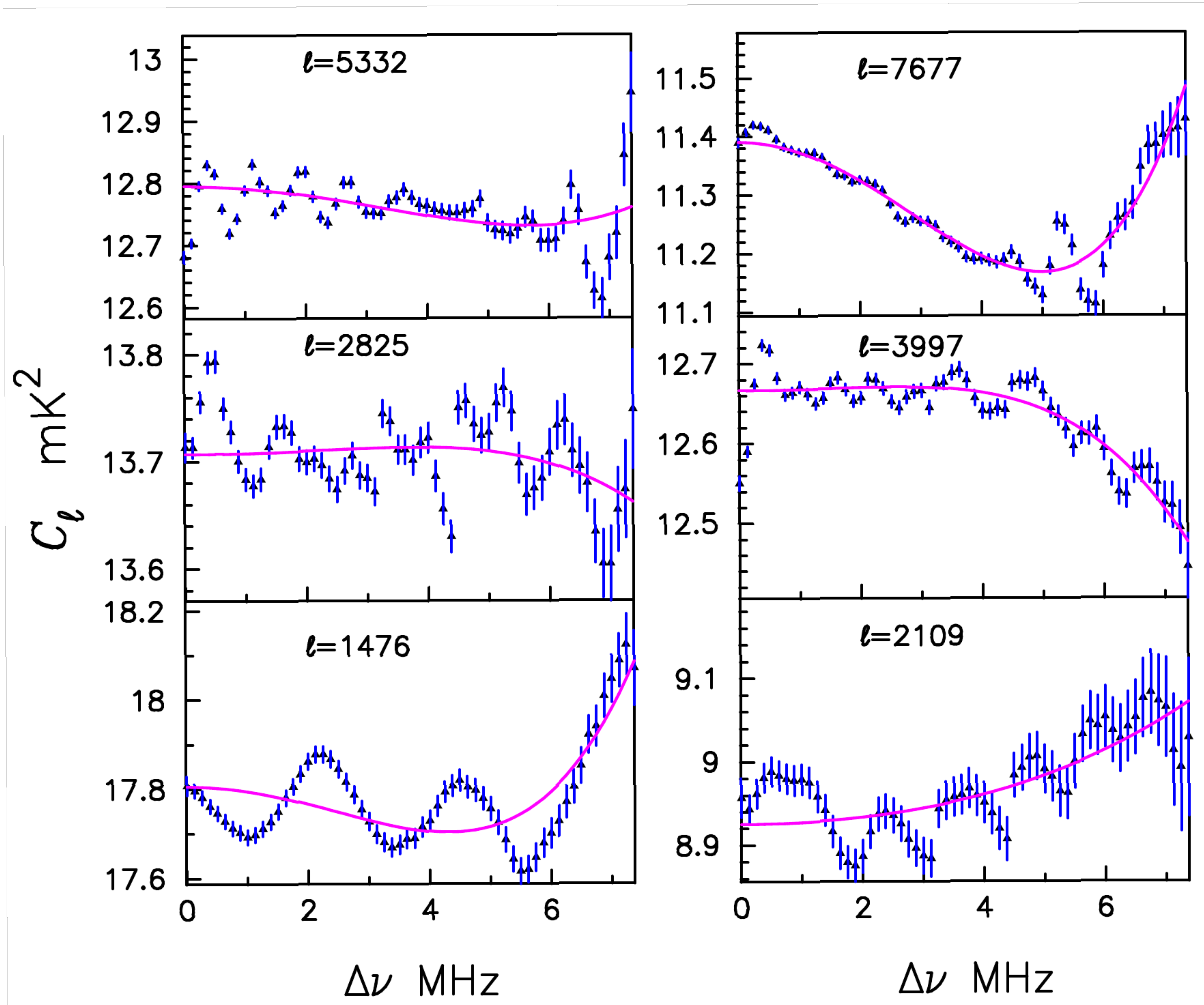


Residuals (Δν < 1 MHz)



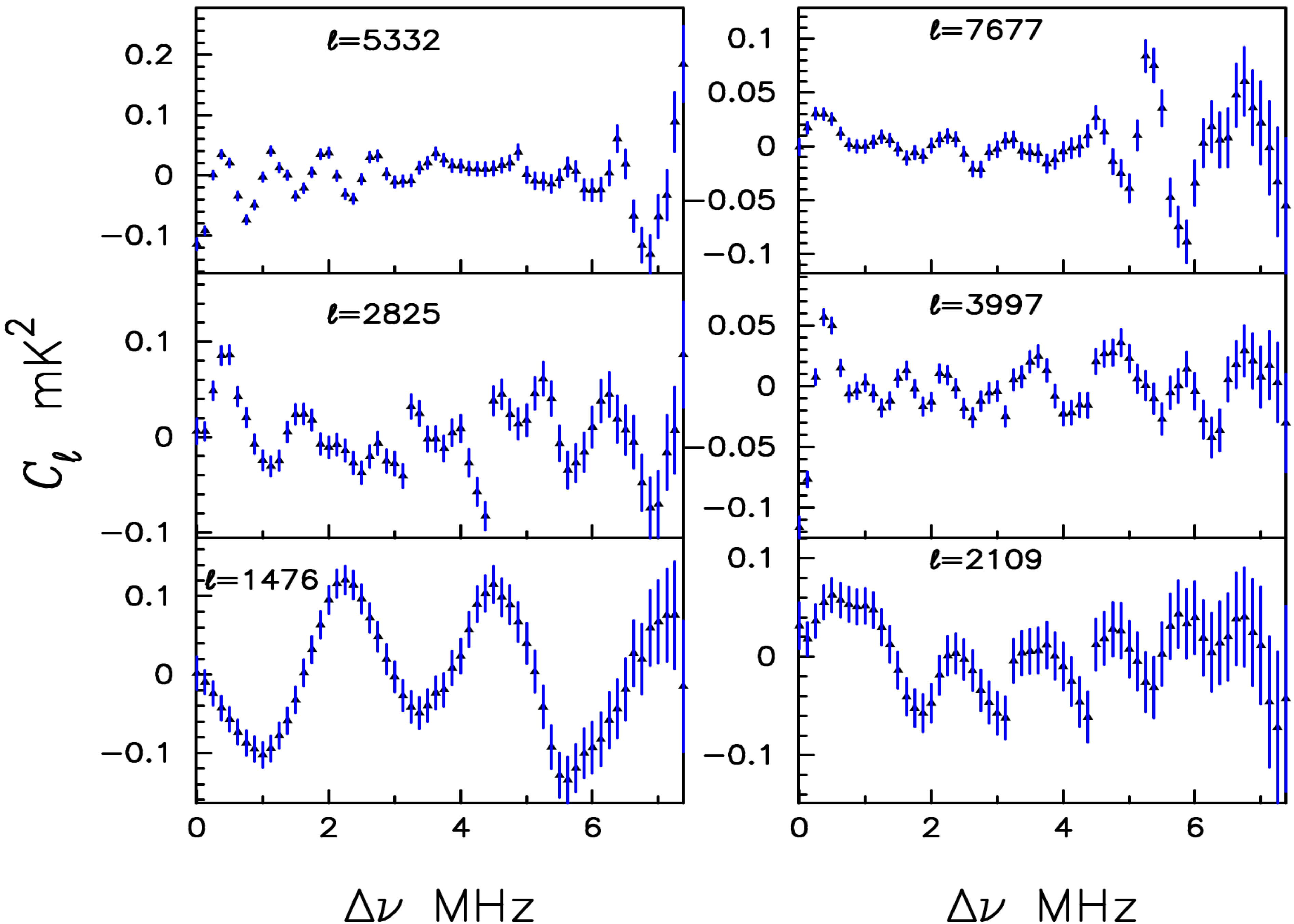
We find that our foreground subtraction technique successfully extracts the HI signal, despite its being buried in foregrounds which are ~ 200 times larger !!

Our Technique on Measured C_l $(\Delta\nu)$



4 th order Residues:

- The oscillatory pattern persists !!



How to remove this oscillatory pattern from the residues?

The oscillatory residual pattern is quite distinct from the expected HI signal and also from random noise, and in principle it should be possible to distinguish between these by considering the Fourier transform

$$\tilde{C}_\ell(\tau_m) = \sum_n e^{i2\pi\,\tau_m\,\Delta\nu_n}\; C_\ell(\Delta\nu_n)$$

Note:

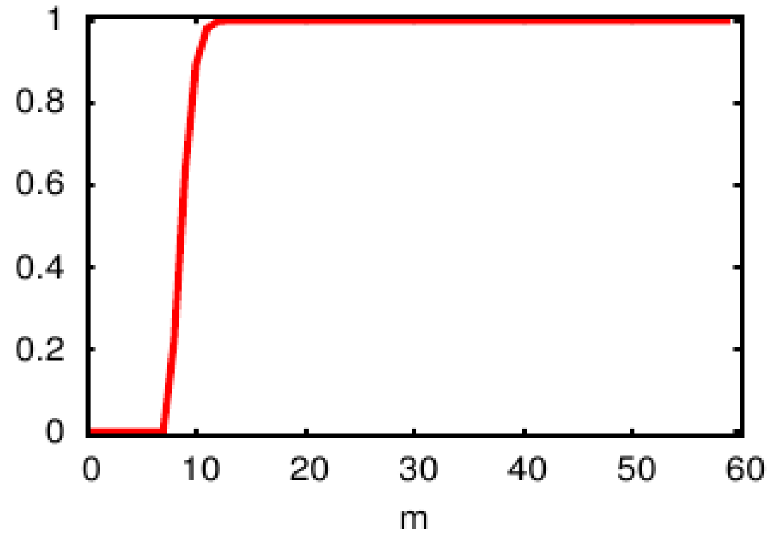
The oscillatory pattern manifest itself as a localized feature in $\tilde{C}_\ell(\tau_m)$

and it should be possible to remove the oscillatory feature by applying a suitable filter

to $\tilde{C}_\ell(\tau_m)$

★ Filter:

$\tilde{F}(\tau_m)$



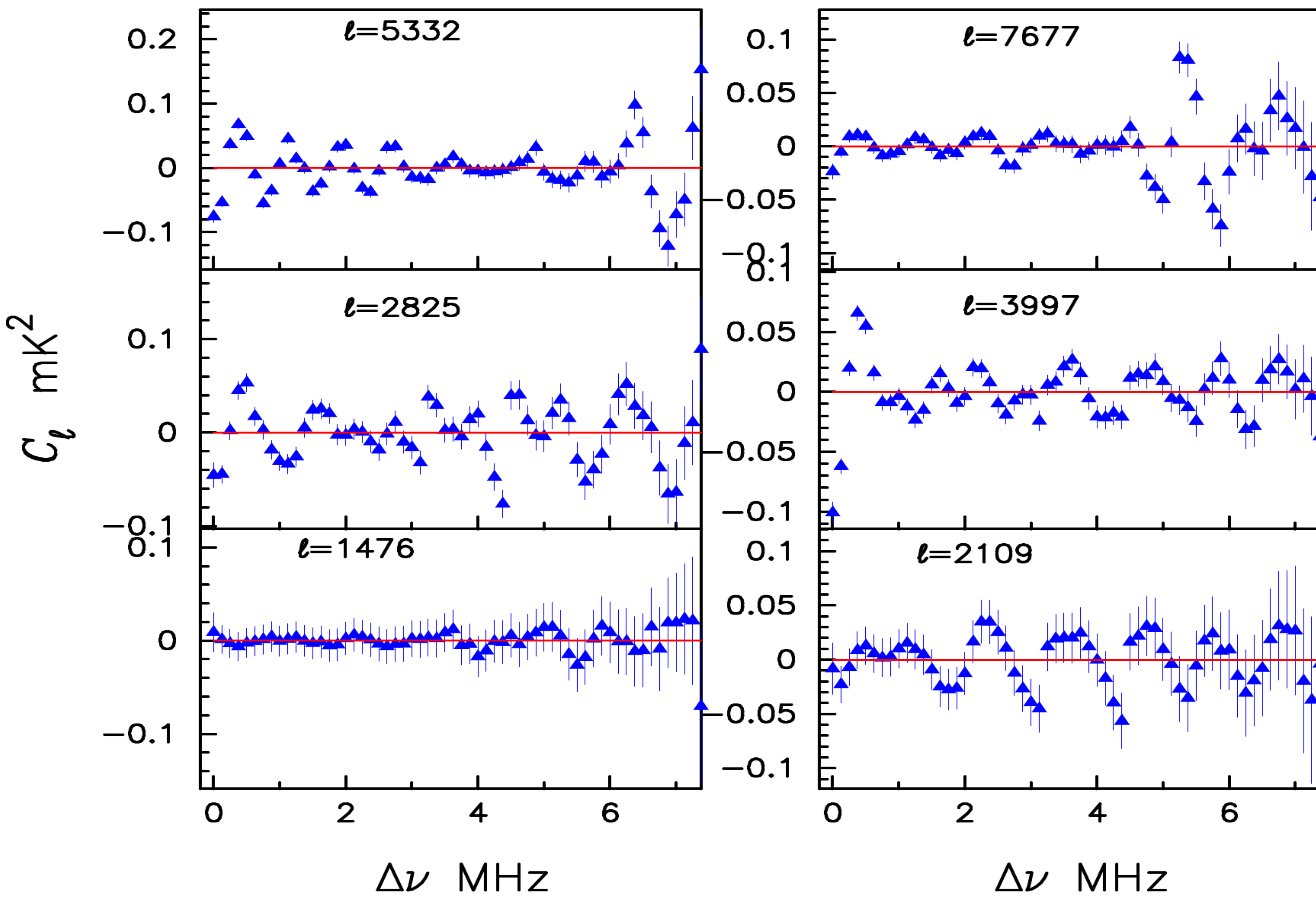
$$\tilde{F}(\tau_m) = 0 \qquad |\, m \,| \leq m_c$$
$$= 1.0 - e^{-(|m|-m_c)^2/2} \qquad |\, m \,| > m_c$$

such that $\tilde{F}(\tau_m)\tilde{C}_\ell(\tau_m)$ *removes the Fourier components within*

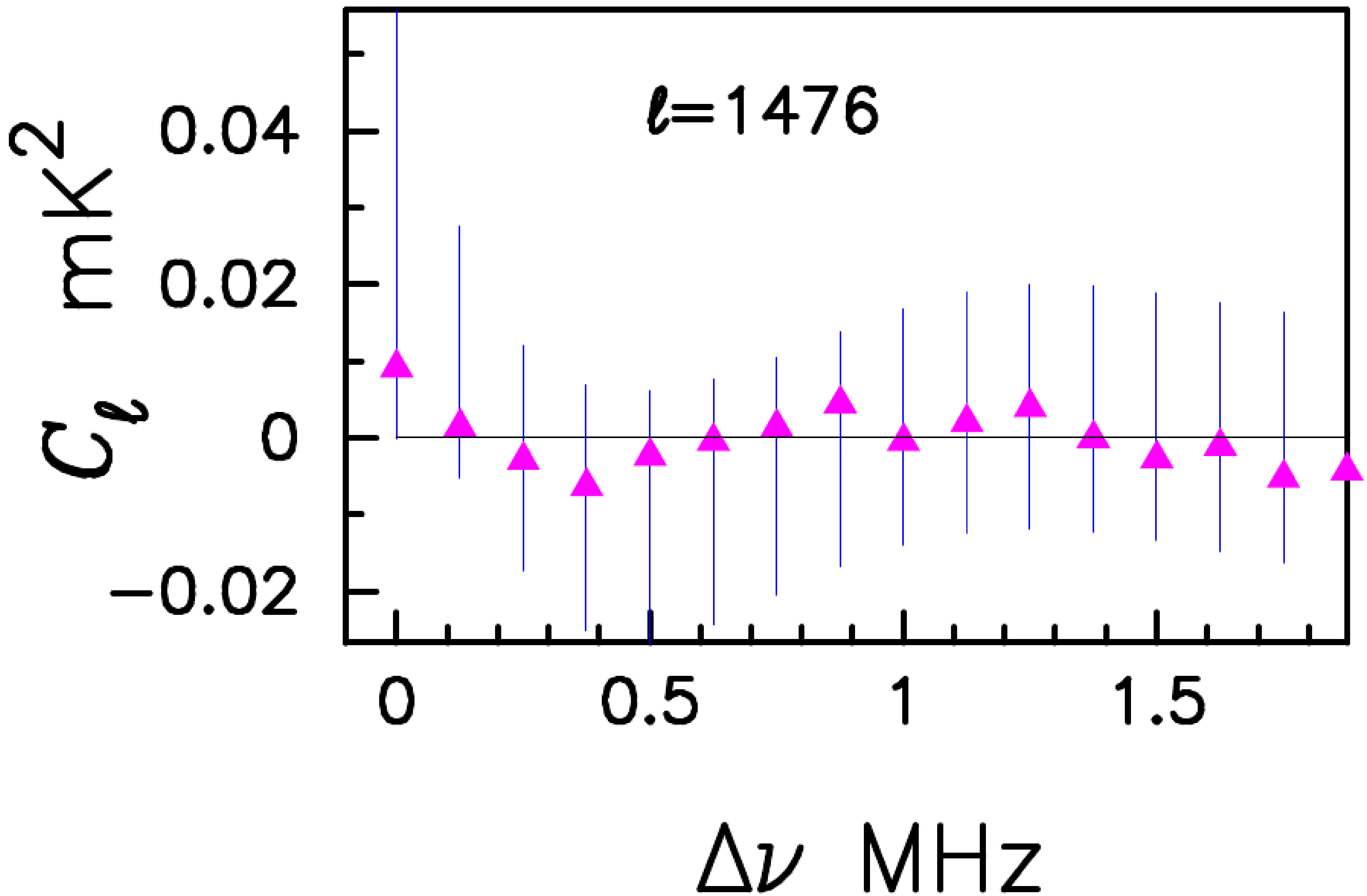
$|\, m \,| \leq mc$ *from the residual* $\tilde{C}_\ell(\tau_m)$

- *We have chosen* $m_c = 7$

Residuals After Filtering :



★ Foreground *removed* Successfully : The residuals are consistent with zero at 3σ level at the smallest ℓ value, But at larger ℓ values the Oscillatory pattern persists!!



- *Synchrotron radiation contribution with 1σ noise for different values of l :*

ℓ	Synchrotron radiation (mK^2)	1σ (mK^2)
1476	4.79×10^{-2}	7.03×10^{-3}
2109	2.03×10^{-2}	7.82×10^{-3}
2825	1.01×10^{-2}	4.43×10^{-3}
3997	4.39×10^{-3}	2.93×10^{-3}
5332	2.19×10^{-3}	3.13×10^{-3}
7677	9.16×10^{-4}	2.4×10^{-3}

Note : For first Four l values the 1σ noise is less than the expected Synchrotron radiation contribution .

Upper limit on $\bar{x}_{\rm HI}\, b$

$C_\ell(\Delta\nu)$ at $\ell = 1476$ *used to place an upper limit on HI signal .*

- *Considering* $\bar{x}_{\rm HI}\, b$ *an unknown parameter the expected HI signal can be expressed as*

$$C_\ell^{\rm HI}[\bar{x}_{\rm HI} b](\Delta\nu) = \left[\frac{\bar{x}_{\rm HI} b}{2.45 \times 10^{-2}}\right]^2 C_\ell^{\rm HI}(\Delta\nu)$$

- *The HI signal would be detectable in our observation at a 3σ level if*

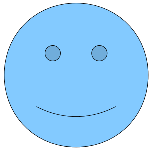
$$C_\ell^{\rm HI}[\bar{x}_{\rm HI} b](\Delta\nu) > 3\sqrt{\{C_\ell^{\rm HI}[\bar{x}_{\rm HI} b](\Delta\nu)\}^2/N_E + \{\Delta C_\ell(\Delta\nu)\}^2_{sys}}$$

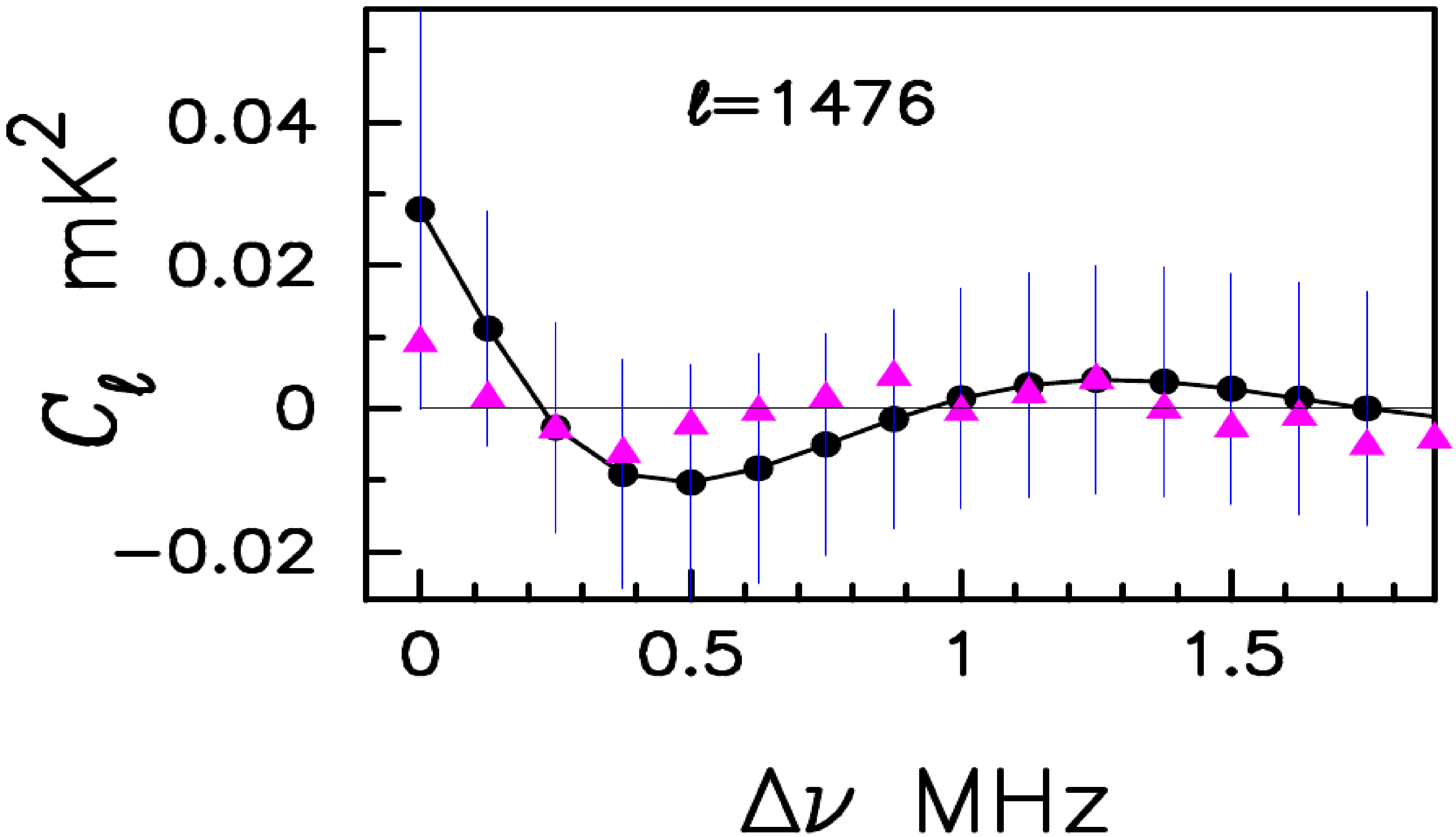
.... (A)

Signal & the Residuals:

After applying the same filter to $C_\ell^{\rm HI}[\bar{x}_{\rm HI} b](\Delta\nu)$ & using Eq. A

We obtain the 3σ upper limit $\bar{x}_{\rm HI} b > 7.95$





Result & Conclusions :

- *The statistical properties of the back ground radiation has been measured across an angular scale of 20" to 10' using the Multi-frequency angular Power spectrum* $C_\ell(\Delta\nu)$.

- *The foreground model prediction are found to be consistent with the Observed* $C_\ell(\Delta\nu)$ *below* $\ell \leq 2200$ *, equivalent to* $\theta > 0.08^o$.

Contd.....

- *We have seen our proposed polynomial fitting technique successfully removes foreground at the smallest l value (l = 1476) from the measured* $C_\ell(\Delta\nu)$ *at 3σ level. Also, for the first Four l values the 1σ system noise is less than the Synchrotron radiation contribution at these l values.*

- *Based on Our analyzed data we found an upper limit on* $\bar{x}_{\rm HI} b > 7.95$*, which is around 330 times larger than the value expected from quasar absorption spectra which imply* $\bar{x}_{\rm HI} = 2.45 \times 10^{-2}$ *with b=1 .*

The HI signal should in principle be detectable in observations that are few hundred times more sensitive than the one analyzed here.


THANK YOU