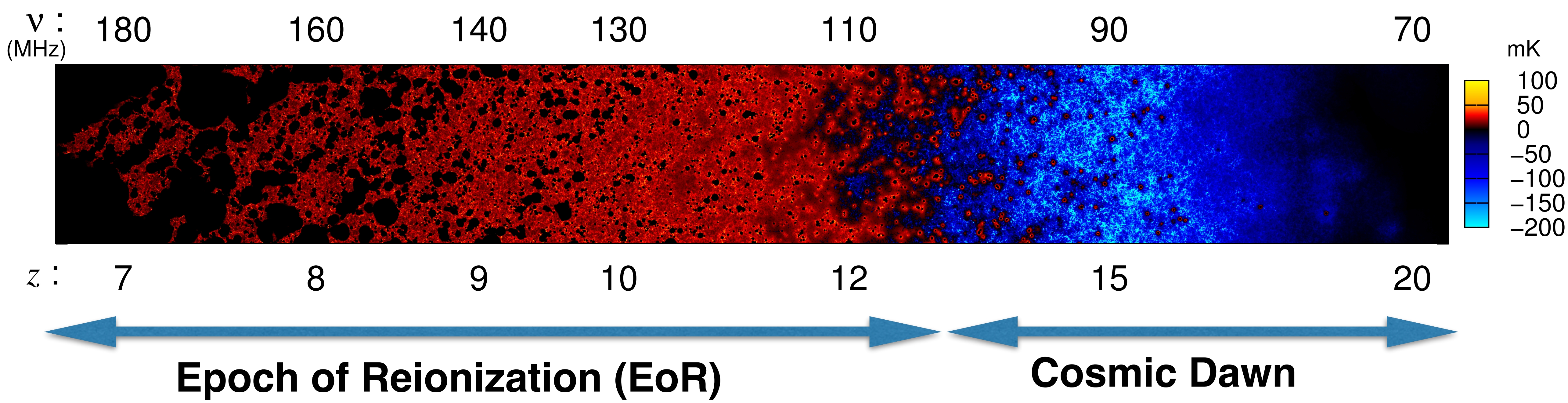
Towards simulating and quantifying the light-cone EoR/CD 21-cm signal

Kanan K. Datta
Presidency University, Kolkata, India
email: datta.kanan@gmail.com

Collaborators

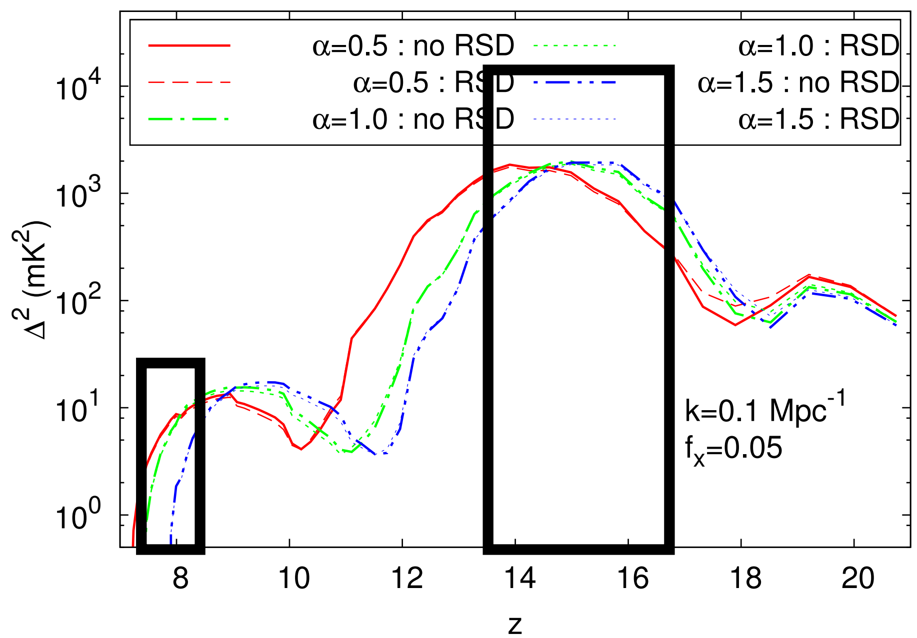
- Garrelt Mellema
- Hannes Jensen
- Suman Majumdar
- Ilian T. Iliev
- Raghunath Ghara
- Tirthankar Roy Choudhury
- Rajesh Mondal
- Somnath Bharadwaj

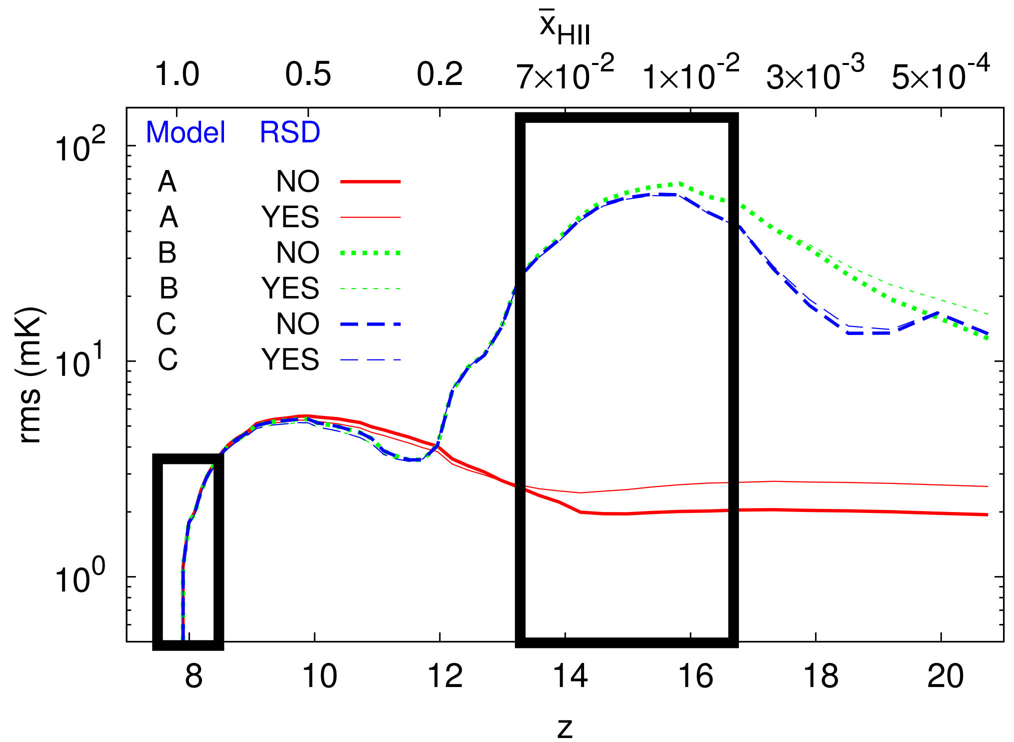
Light cone effect on 21-cm signal from EoR and Cosmic Dawn



- 3D imaging of universe with 21-cm observations
- The mean and statistical properties of HI 21-cm signal change with redshift.
- This effect, known as the ‘light-cone’ (LC) effect.
- LC effect has a significant impact on 3D power spectrum etc.

Light cone effect on 21-cm signal: An example





16 MHz frequency bandwidth covers redshift range

~7.5<z<8.5 (at z=8)

~13.4<z<16.6 (at z=15)

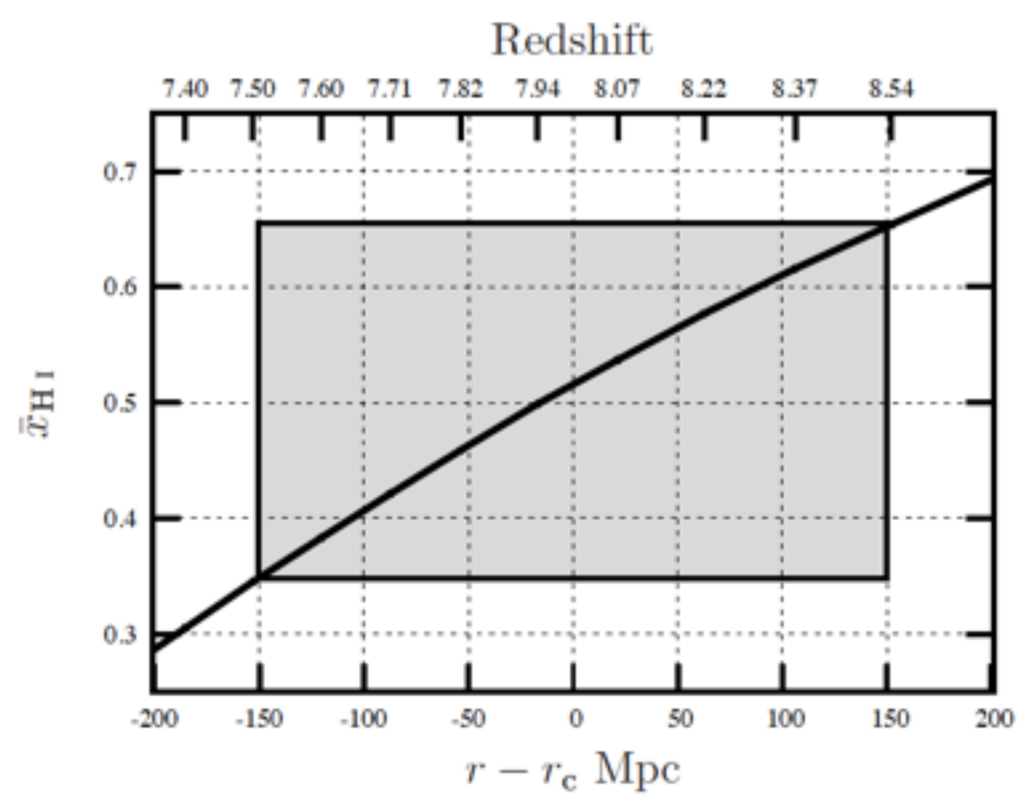
Ghara, Datta, Choudhury MNRAS, 2015

Two important issues

- How to simulate Light Cone 21-cm signal?
- How to quantify the Light Cone signal ?

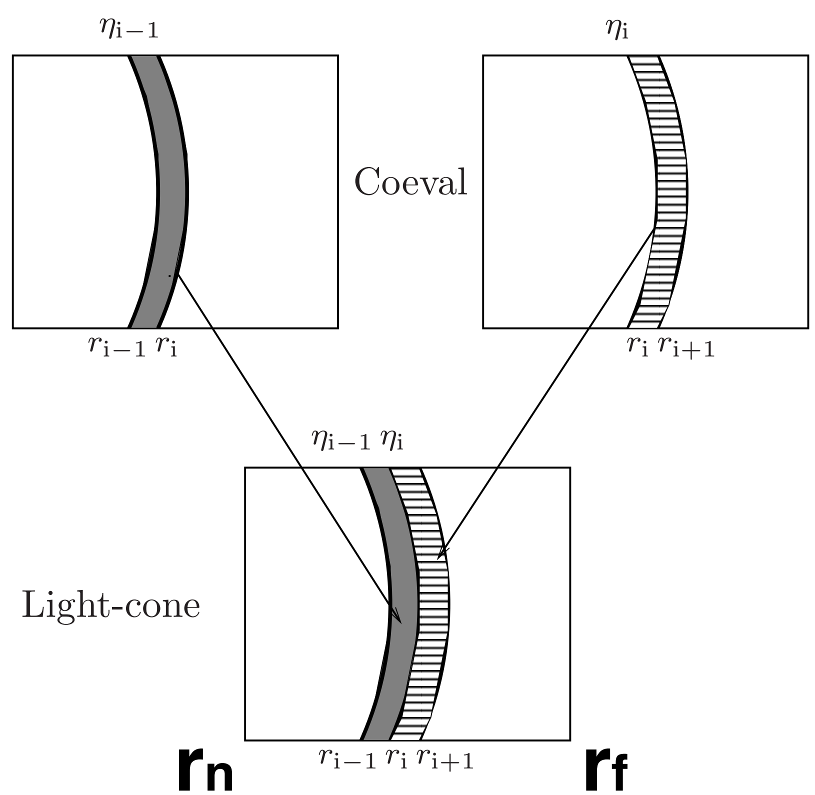
Generating the coeval cubes

- Used semi-numerical simulations (Choudhury et al (2009), Majumdar et al(2012), Mondal et al (2016)
- Box size L = 300.16 Mpc
- 4288^3 particles, grids of spacing 0.07Mpc
- Mass resolution of ~10^8 M⊙
- Identify collapsed halos using FoF
- generated the coeval cubes in the range r_n = 9001.45 Mpc (nearest) to r_f = 9301.61 Mpc (farthest) (7.51<z<8.53).
- The change in the mass-averaged HI fraction $\bar{x}_{HI}$ is $\bar{x}_{HI} \approx 0.65 - 0.35 = 0.30$
- 25 different coeval simulations.
- The LC box is centred at redshift 8
- co-moving distance r_c = 9151.53 Mpc, frequency ν_c = 157.78 MHz and $\bar{x}_{HI} \approx 0.51$.



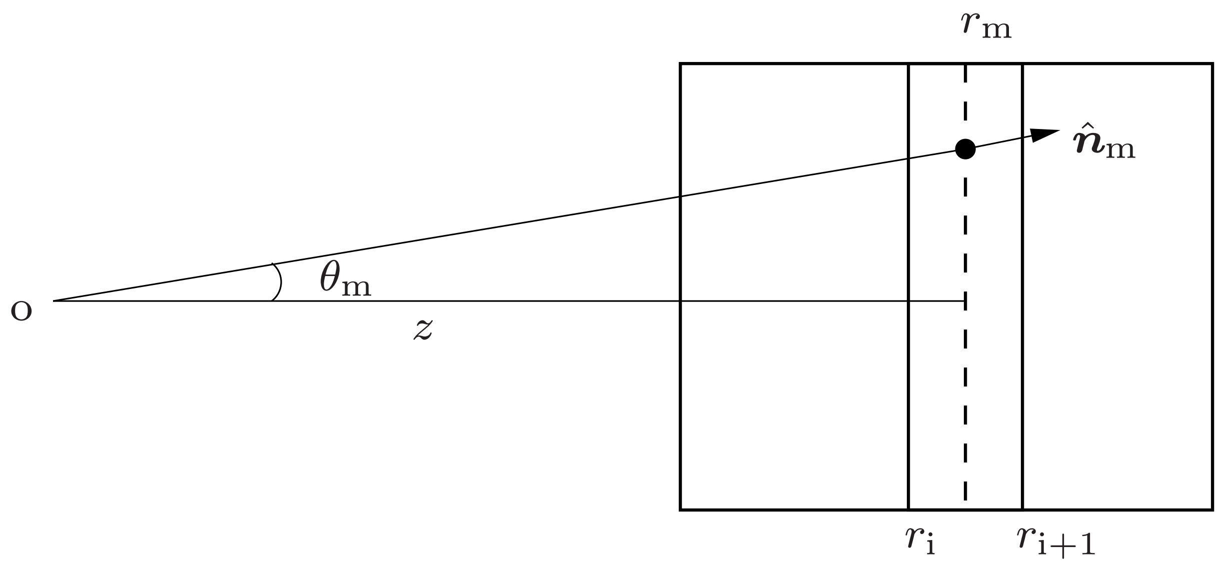
Simulating Light Cone 21-cm signal -A particle based method

- We consider a simulation that span the comoving distance range **r_n** (nearest) to **r_f** (farthest).



- The HI distribution is represented by particles
- HI masses vary with position
- For each slice we have filled the region r_i to r_{i+1} with the HI particles from the corresponding region in the coeval box

Flat sky approximation
Mapping to angle (theta) -frequency coordinates



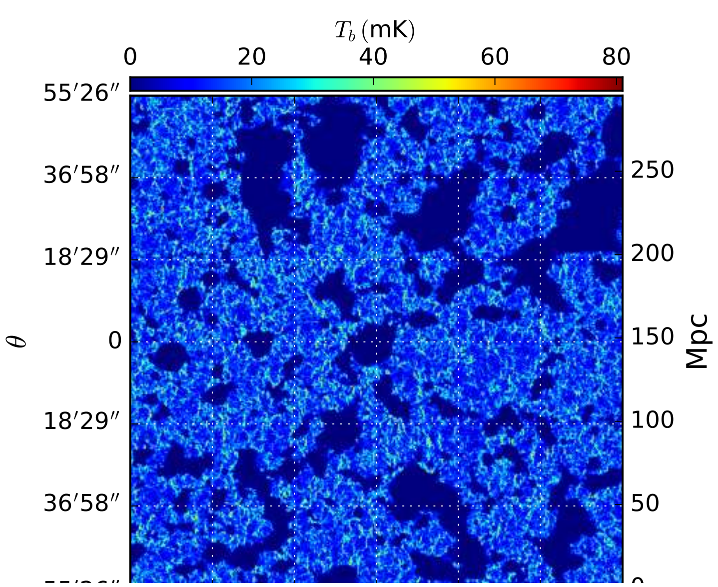
$$\hat{\boldsymbol{n}} = \hat{\boldsymbol{k}} + \boldsymbol{\theta}$$

$\theta_x = x/r_c,\ \theta_y = y/r_c$ **eq. 1**

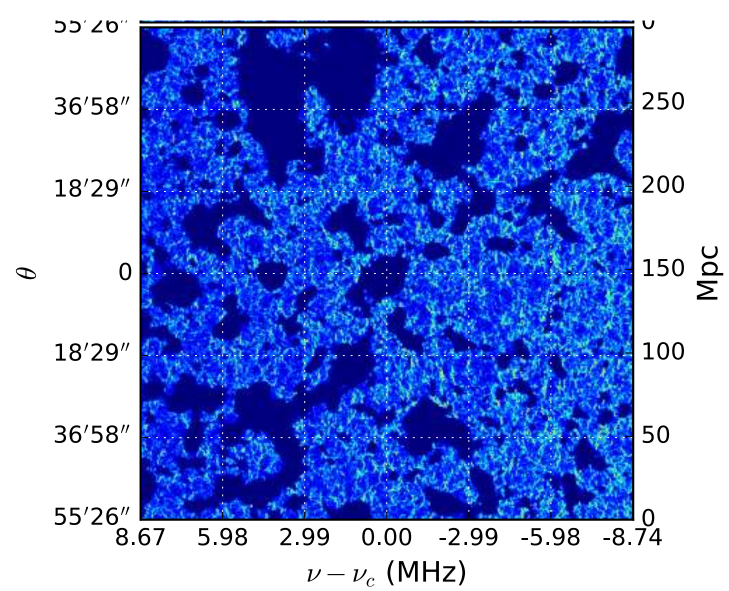
$$\nu_{\rm m} = \nu_{\rm i}\left[1 - \frac{a_{\rm i} H_{\rm i}(r_{\rm m} - r_{\rm i}) + \hat{\boldsymbol{n}}_{\rm m}\cdot\boldsymbol{v}_{\rm m}}{c}\right]$$ **eq. 2**

$$\rho'_{\rm H\,I} = (\Delta\Omega\,\Delta\nu)^{-1}\left(\frac{H_0\nu_{\rm c}}{c}\right)\sum_m \frac{[M_{\rm H\,I}]_{\rm m}}{r_{\rm n}^2}$$ **eq. 3**

$$T_{\rm b}(\hat{\boldsymbol{n}},\nu) = \bar{T}_0\,\frac{\rho'_{\rm H\,I}}{\bar{\rho}_{\rm H}}$$ **eq. 4**



Coeval



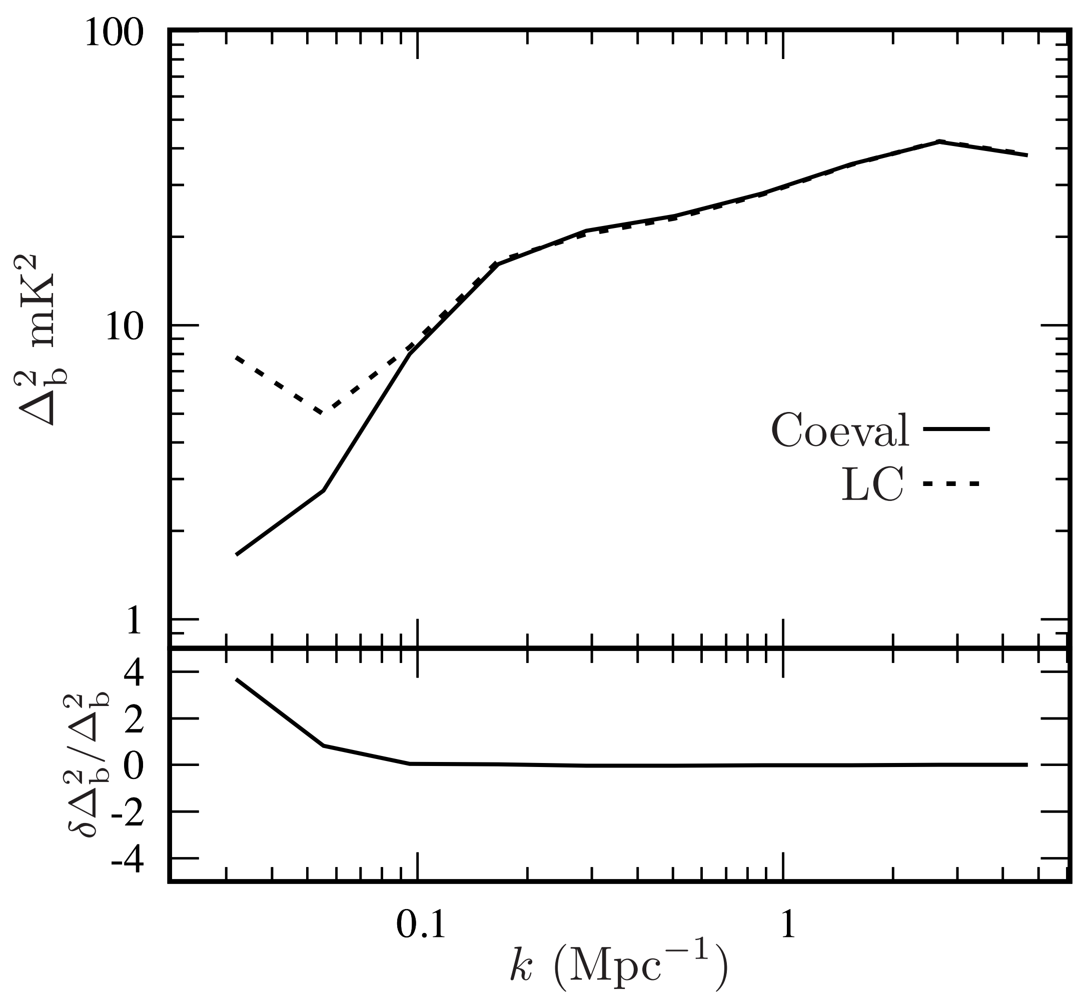
Light cone

LC effect has been implemented before the peculiar velocity effect- **very important!!!**

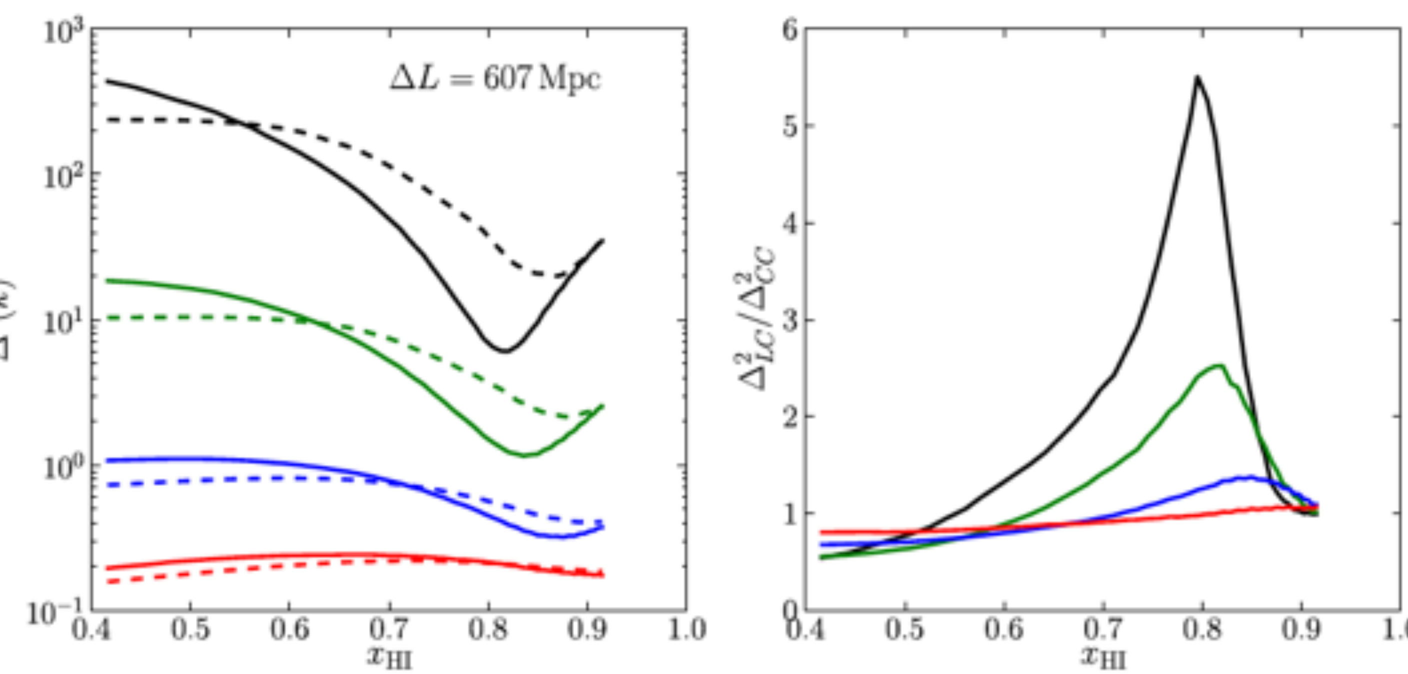
Effects on EoR 3D power spectrum

Reverse mapping of EoR 21-cm brightness temperature fluctuations to spatial comoving coordinates **$\delta T_b(\theta_x, \theta_y, \nu) \rightarrow \delta T_b(x, y, z)$**

$$(x, y, z) = [r_c\, \theta_x,\ r_c\theta_y,\ z_c + r_c' (\nu - \nu_c)]$$



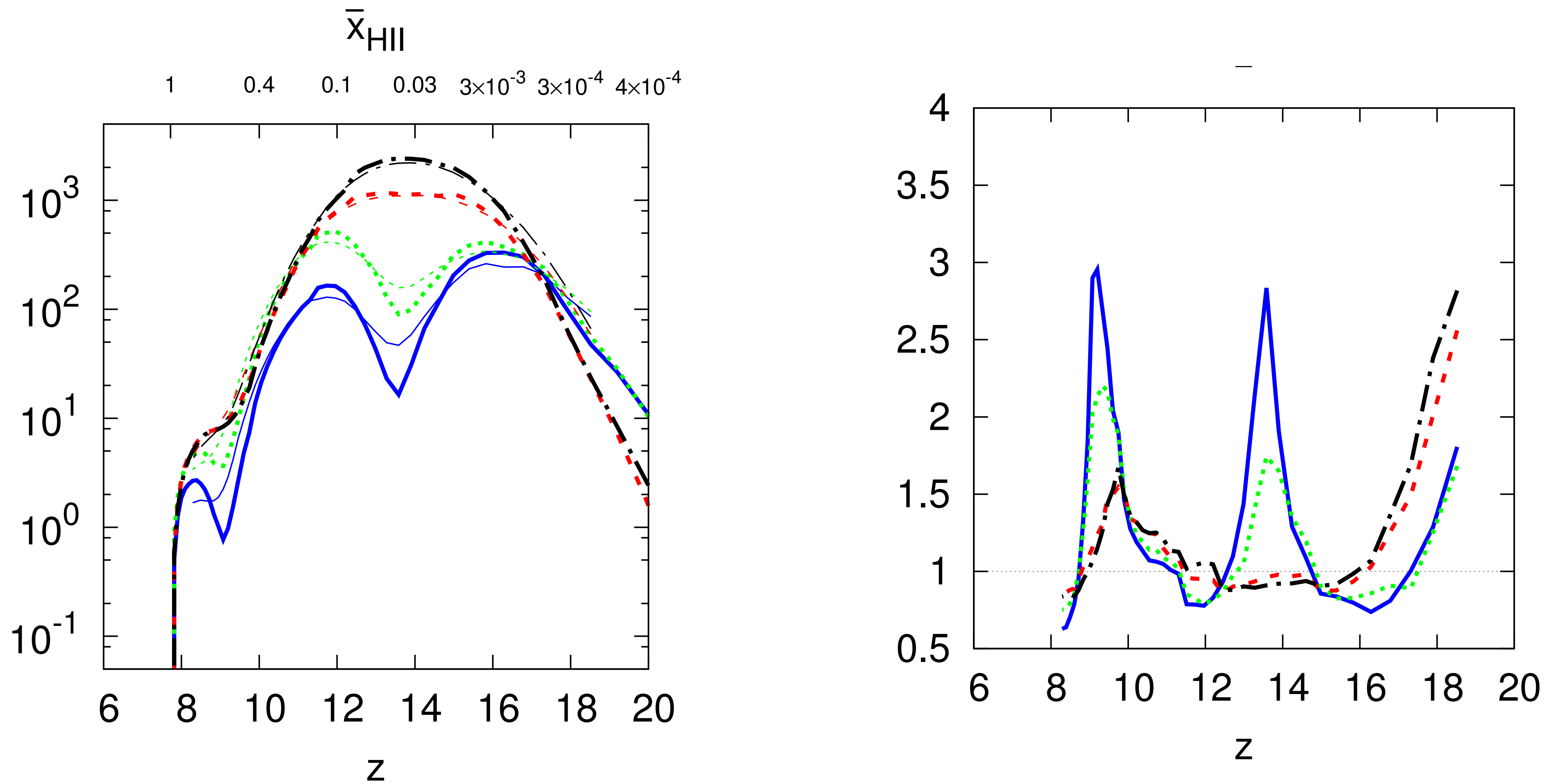
Mondal, Bharadwaj, Datta, 2017



The LC effect is stronger at large scales.

Datta, Jensen, Mellema et al 2014

Effects on Cosmic dawn 21-cm power spectrum



- The LC effect becomes when power spectrum takes a turn.
- Peaks and dips are smoothed out due to the LC effect

Ghara, Datta, Choudhury, 2015

But

Can the 3D power spectrum describe light-cone 21-cm signal completely?

Mondal, Bharadwaj, Datta, 2017

Light Cone effect breaks the statistical homogeneity

and

makes the signal non-ergodic

along the LoS.

In addition

Light Cone effect breaks periodicity of the signal along LOS

Information theory

- The Fourier modes form orthogonal Eigen basis only for a statistically homogeneous or ergodic signal
- The second order statistics is completely quantified by the 3D power spectrum P(k).
- 3D P(k) assumes that the signal is ergodic (E) and periodic (P) along the LoS direction. Both are not valid for Light cone 21-cm signal
- For light cone signal which is non-ergodic, **different Fourier modes along the LoS is correlated** and **P(k) does not retain the entire information of the 21-cm signal.**

The multi-frequency angular power spectrum (MAPS) $\mathcal{C}_\ell(\nu_1,\, \nu_2)$

Datta, Choudhury, Bharadwaj, 2007

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

$$\mathcal{C}_\ell(\nu_1, \nu_2) = \langle a_{\ell \rm m}(\nu_1)\, a^*_{\ell \rm m}(\nu_2) \rangle$$

In the flat-sky approximation

$$\mathcal{C}_\ell(\nu_1,\, \nu_2) = \mathcal{C}_{2\pi \rm U}(\nu_1,\, \nu_2) = \Omega^{-1} \langle \tilde{T}_{\rm b2}(\boldsymbol{U},\, \nu_1)\, \tilde{T}_{\rm b2}(-\boldsymbol{U},\, \nu_2) \rangle$$

$\tilde{T}_{\rm b2}(\boldsymbol{U}, \nu)$ is the 2D Fourier transform of $\delta T_{\rm b}(\boldsymbol{\theta}, \nu)$

By imposing the conditions (i) $\mathcal{C}_\ell^{\rm EP}(\nu_1, \nu_2) = \mathcal{C}_\ell^{\rm EP}(\Delta\nu)$ (ergodic)

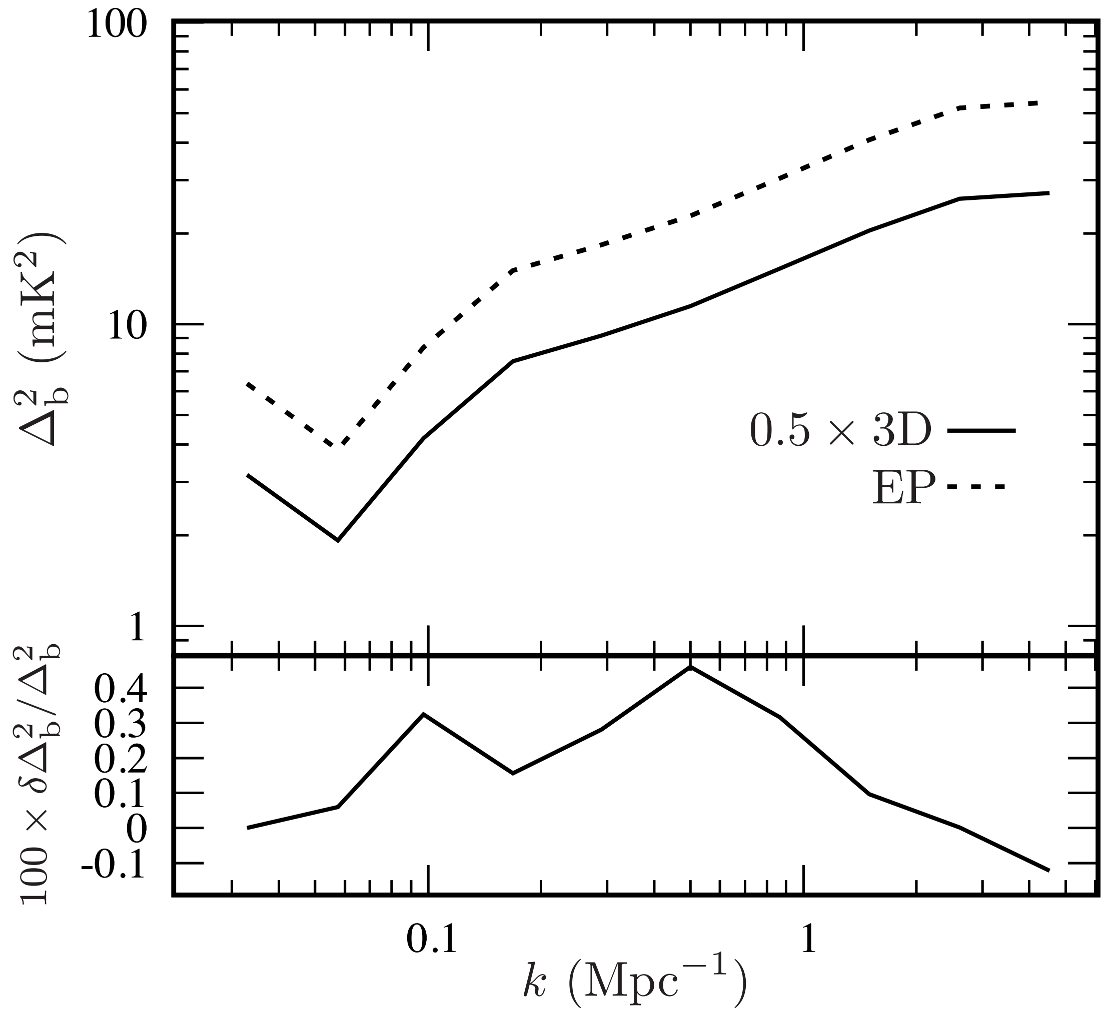
(ii) $\mathcal{C}_\ell^{\rm EP}(\Delta\nu) = \mathcal{C}_\ell^{\rm EP}(B - \Delta\nu)$ (periodic)

We show

$$P(k_\perp,\, k_\parallel) = r_{\rm c}^2\, r'_{\rm c} \int d(\Delta\nu)\, e^{-ik_\parallel r'_{\rm c} \Delta\nu}\, \mathcal{C}_\ell^{\rm EP}(\Delta\nu)$$

If ergodicity and periodicity are imposed, 3D power spectrum is exactly recovered from MAPS.

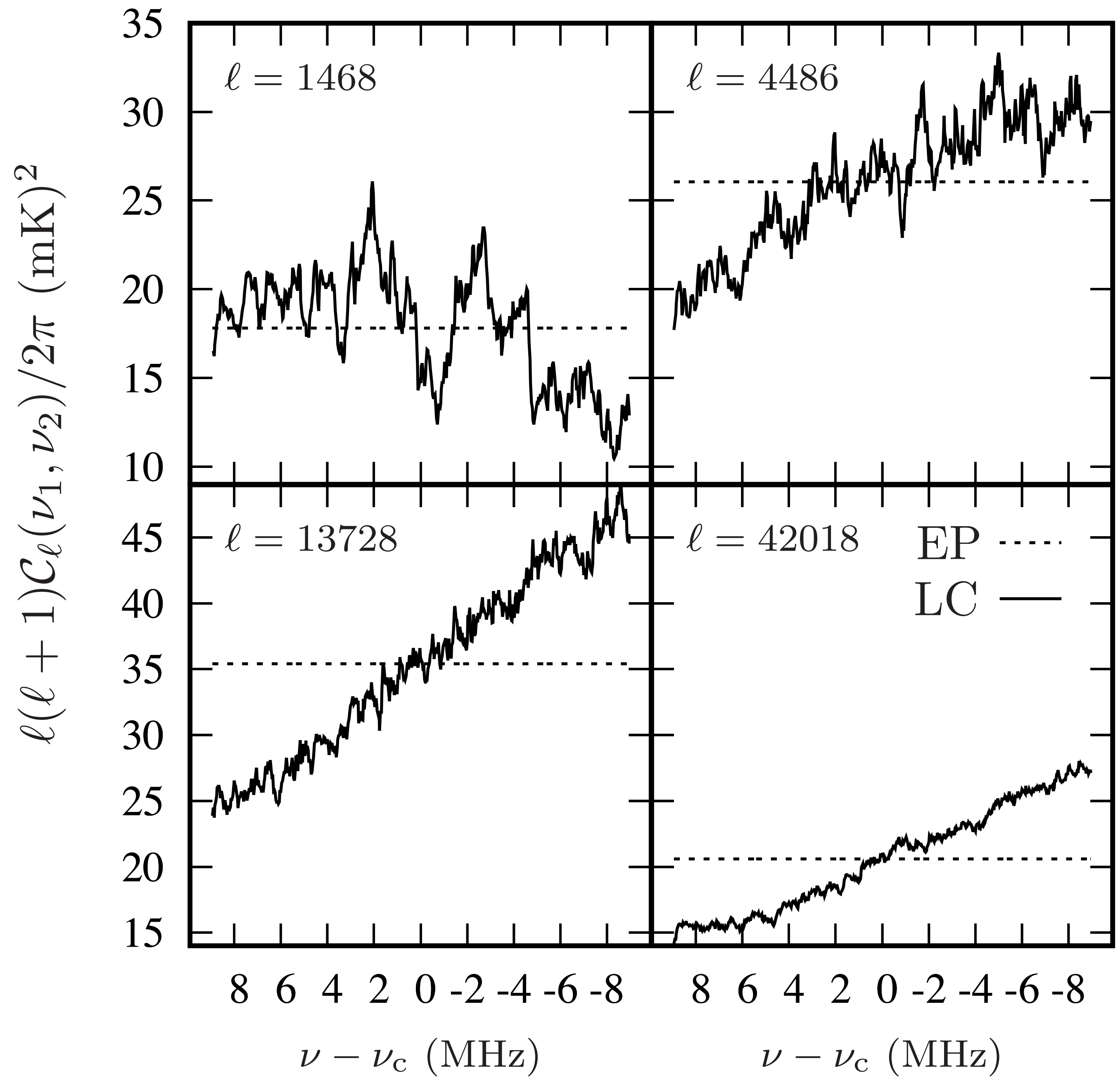
$$P(k_\perp,\, k_\parallel) = r_c^2\, r_c' \int d(\Delta\nu)\, e^{-ik_\parallel r_c' \Delta\nu}\, \mathcal{C}_\ell^{\rm EP}(\Delta\nu)$$



This implies that MAPS contains much more information than P(k) and a better statistics to quantify light cone EoR 21-cm signal.

Results -MAPS

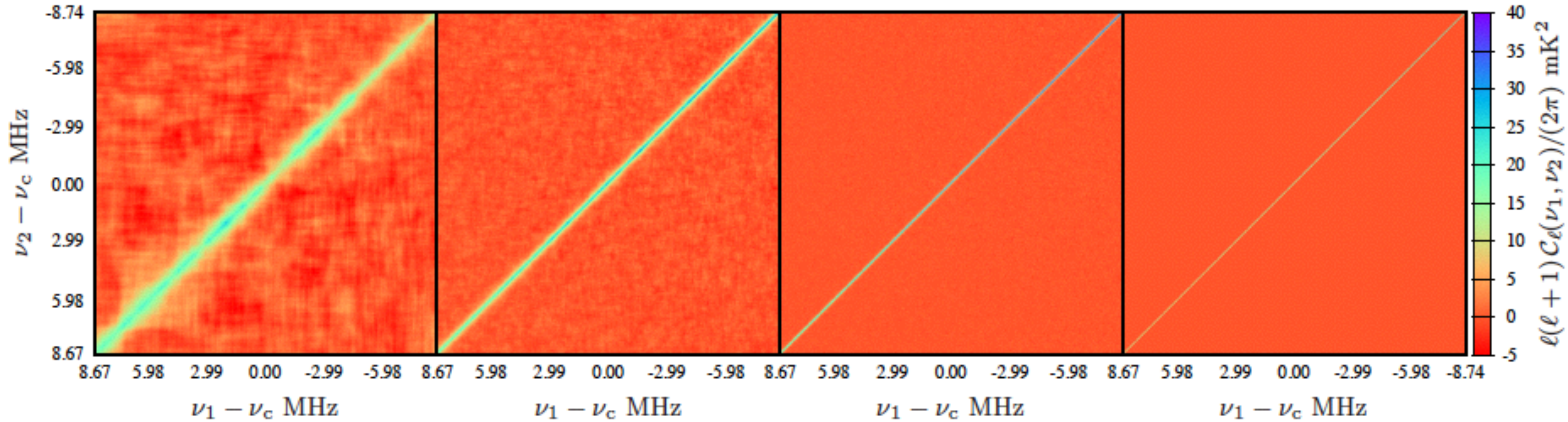
From Light cone and coeval simulations

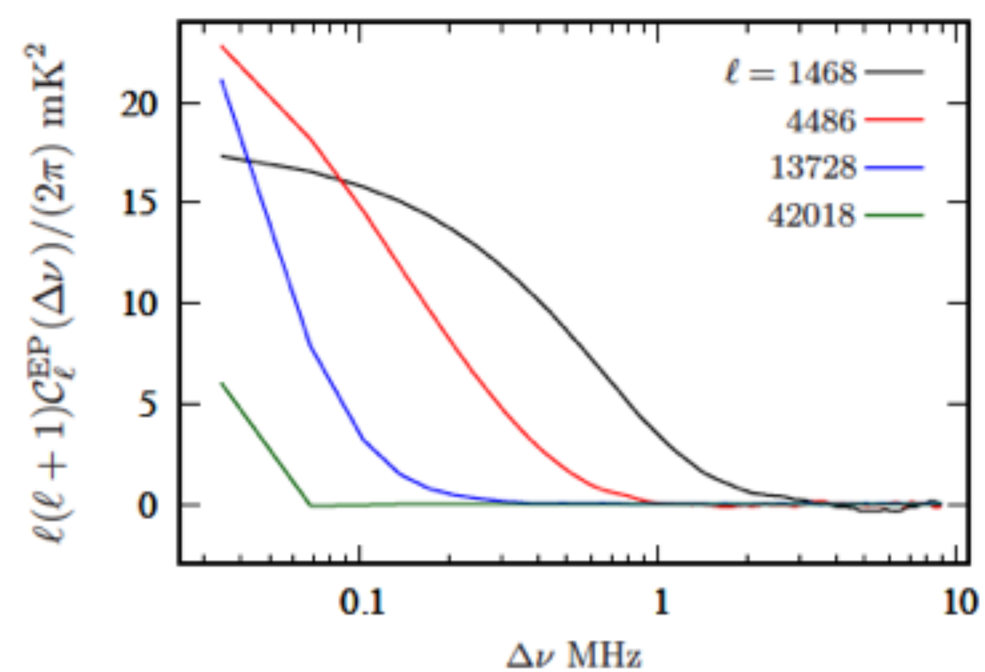


Results -MAPS

From Light cone simulations

l=1468 **l=4486** **l=13728** **l=42018**

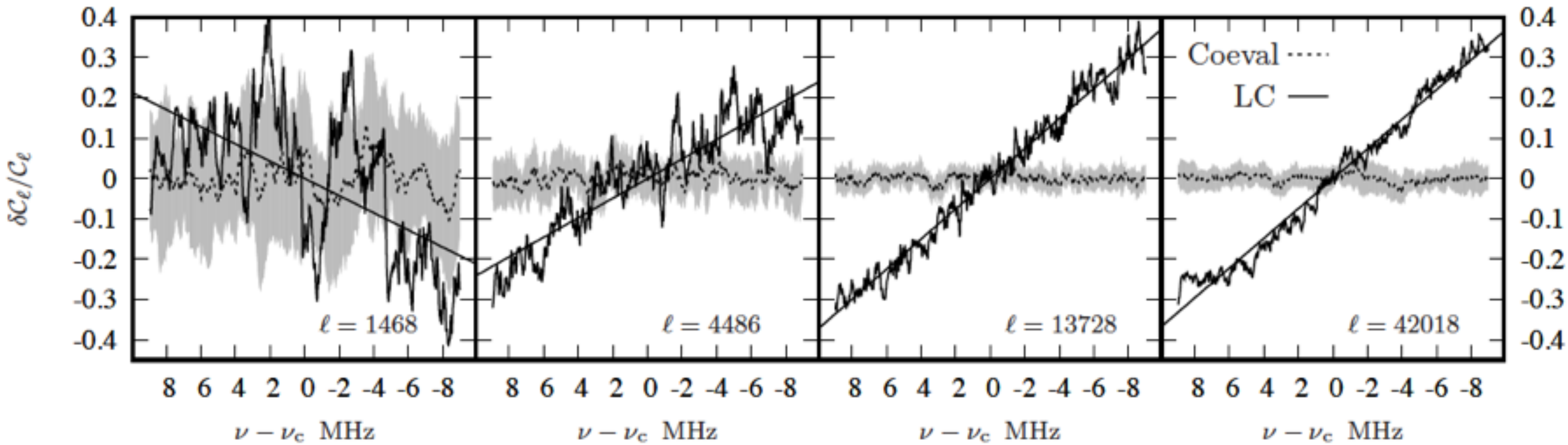




Assuming periodicity and ergodicity

Results -MAPS

From Light cone and coeval simulations



Summary

- The light cone effect is found to be an important effect and should be considered in the statistical analysis of EoR 21-cm signal.

- It is important that the LC effect should be implemented before correcting for the peculiar velocity effect.

- The LC effect makes the signal non-ergodic and non-periodic along the los.

- 3D power spectrum or spherically averaged power spectrum of HI 21-cm signal can not retain full information of the light cone EoR/CD signal.

- Multi-frequency angular power spectrum (MAPS) retains the entire information of the second order statistics of the signal and therefore a better statistical estimator of the signal. The 3D power spectrum can be recovered from the MAPS assuming the signal to be ergodic and periodic along the los.

Thank you