Prospects of observing reionization MAPS using SKA-Low

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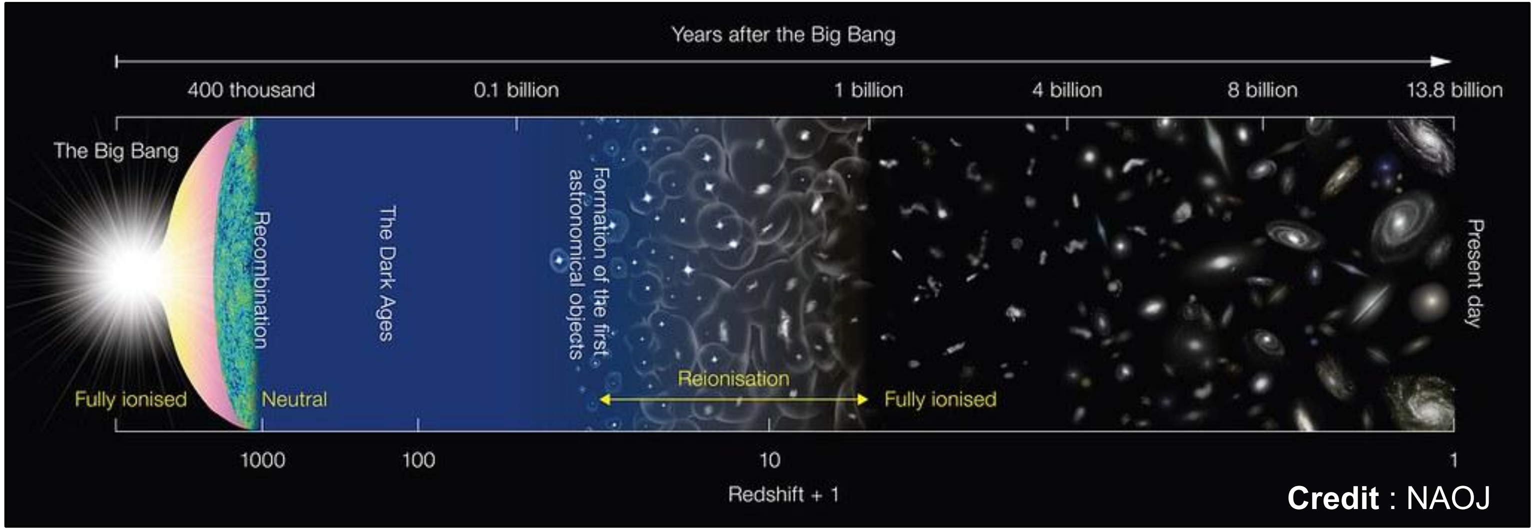
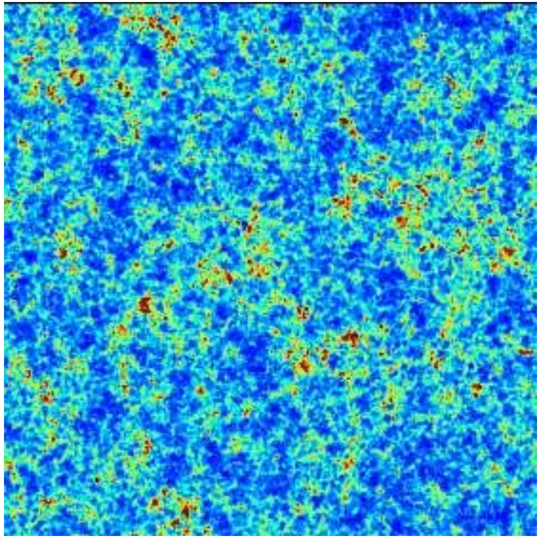
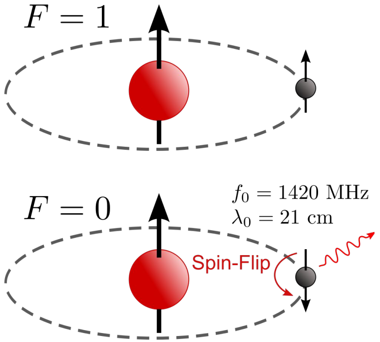
Cosmic history



- Epoch of Reionization (EoR) is a window when the universe changes its phase from completely neutral to completely ionized.
- Indirect observations (high-z QSOs, CMB Thomson scattering optical depth, UV-LF of high-z galaxies etc.) suggest the window is in the range $6 \leq z \leq 12$.

EoR 21-cm Signal



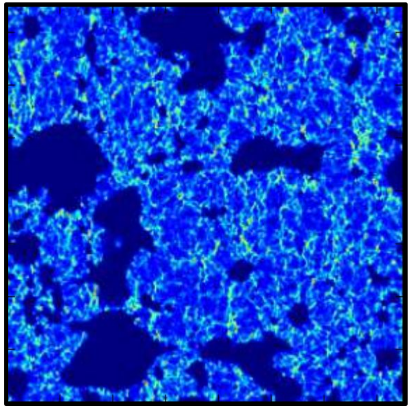


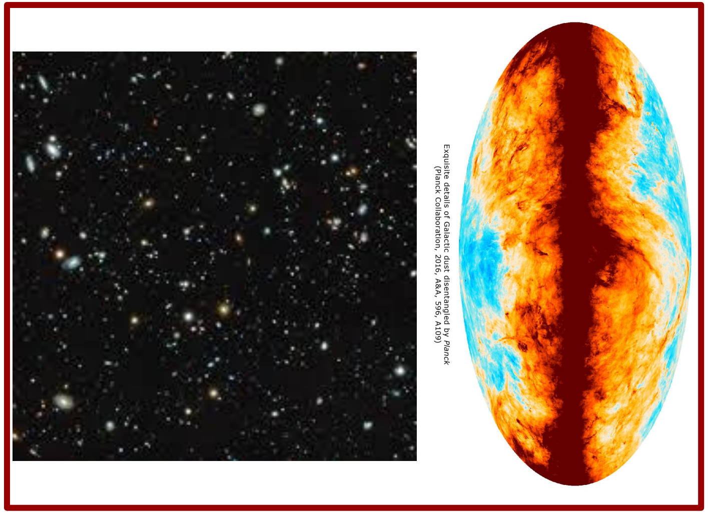
- Redshifted 21-cm radiation from HI in the IGM is most promising probe to this epoch.
- Radio interferometers aim to map the brightness temperature distribution of the EoR 21-cm radiation.

$$\begin{aligned} \delta T_{\rm b}(\nu) &= \frac{T_{\rm S} - T_{\gamma}}{1+z}\left(1 - {\rm e}^{-\tau_{\nu_0}}\right) \\ &\approx \boxed{27 x_{\rm H\,I}(1+\delta_{\rm nl})\left(\frac{H}{{\rm d}v_{\rm r}/{\rm d}r + H}\right)}\left(1 - \frac{T_{\gamma}}{T_{\rm S}}\right) \\ &\quad \times \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_{\rm m}h^2}\right)^{1/2}\left(\frac{\Omega_{\rm b}h^2}{0.023}\right)\ {\rm mK}, \end{aligned}$$

The brightness temperature of 21-cm radiation is a proxy for the neutral hydrogen distribution which has potential to tell us about the astrophysical process and the sources during EoR.

Challenges





- Strong foregrounds (10^4-10^5 times), system noise, RFI etc. keeps us at bay from direct mapping.
- First detection through statistical estimator (e.g. **power spectrum**, variance, bispectrum)

Measurement of the spherically averaged 3D power spectrum is a major goal of the EoR observations.

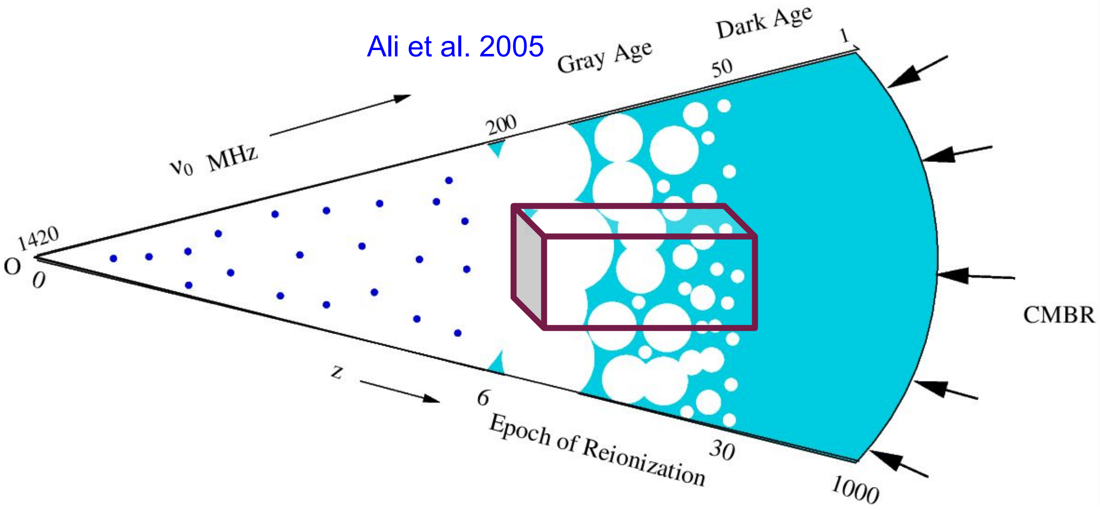
Light Cone Effect

- The EoR signal evolves significantly within the observed volume along the LoS direction as the light speed is finite. This is called Light-cone effect.

- The LC effect makes the signal non-homogeneous and aperiodic along the LoS axis of the box.

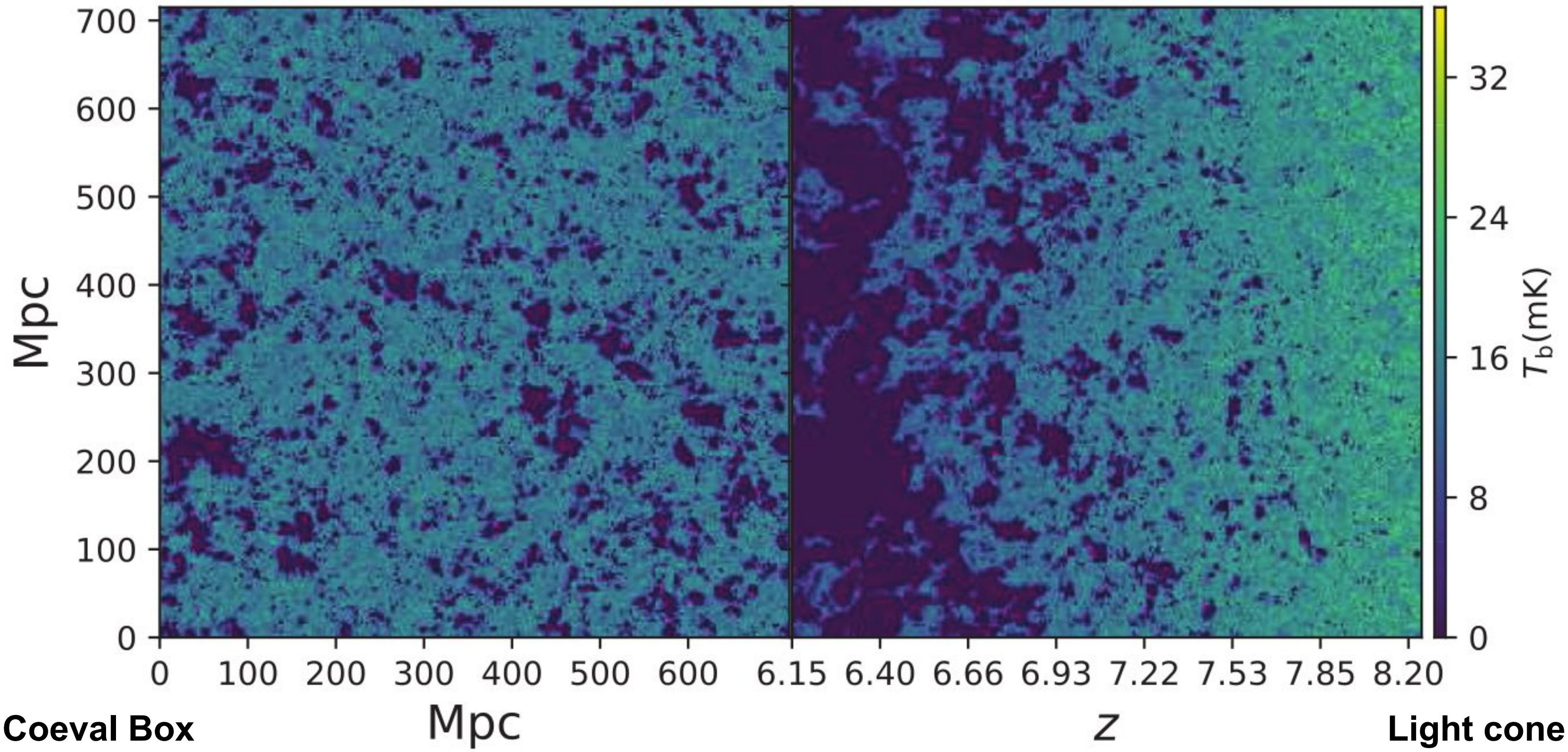
- This makes Fourier basis an inappropriate choice for the signal along LoS, and thus the spherically averaged PS becomes a biased statistic.

Ali et al. 2005



- The light-cone effect is severe for the EoR 21-cm signal due to rapid evolution of neutral fraction (x_{HI}) of the IGM that modulates the signal.

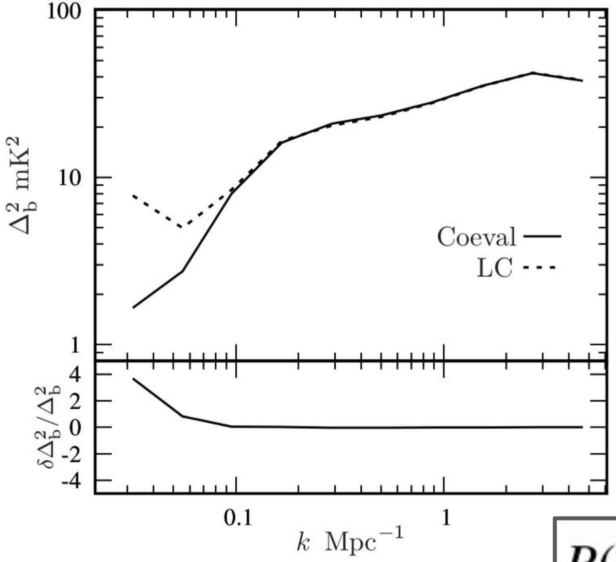
Visual Illustration



Coeval Box

Light cone Box

Impact on 3D Power spectrum



Centered at x_{HI}~0.5

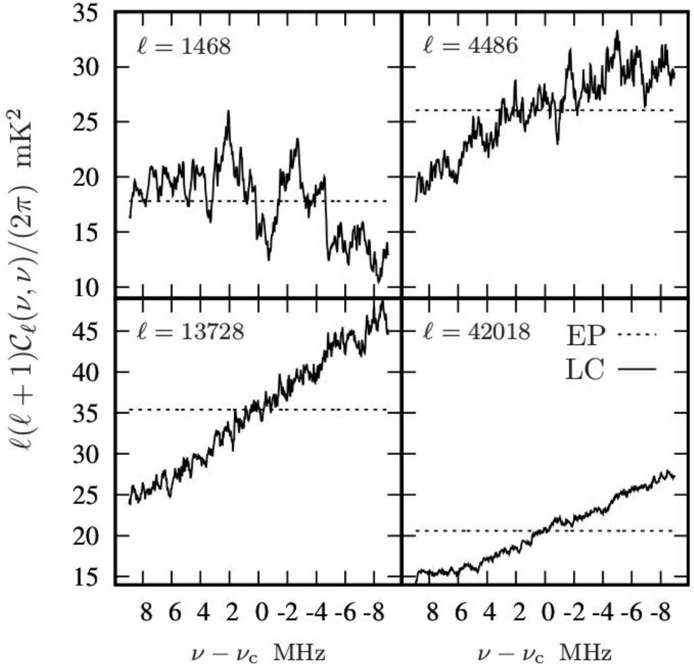
V is the volume.

$T_b(\boldsymbol{k})$ is FT of signal

< > → Ensemble avg

$$P(k) = V^{-1}\langle \tilde{T}_b(\vec{k})\tilde{T}_b(-\vec{k})\rangle$$

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



Credit : Mondal et al. 2018

Solutions….?

1. Divide the obs. volume into thin slices along LoS direction where LC effect can be neglected safely. (e.g. **Shaw** et. al. 2019; Ewall-Wice et al. 2016; Pober et al. 2014)

2. Use **MAPS** statistic which need not assume homogeneity and ergodicity along LoS. (e.g. **Mondal** et. al. 2018; La Plante et al. 2014; Zawada et al.2014; Datta et al. 2012)

Multi-frequency Angular PS (MAPS)

Signal is ergodic and periodic on the plane of sky.

Assumption : Flat sky

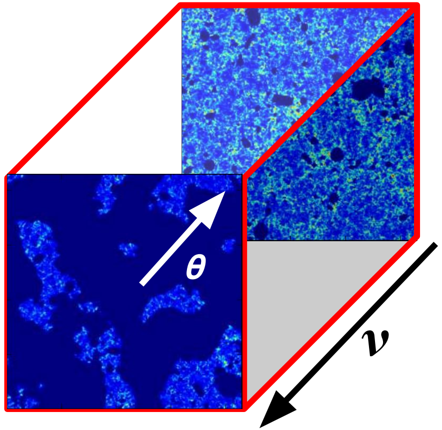
We can do 2D FT on the sky plane and correlate the transformed signal across the different frequency channels.

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

U is Fourier conjugate of 2D vector ***θ*** on the sky plane

Here also we have binned the **ℓ** plane into several anuuli and define **binned MAPS estimator**

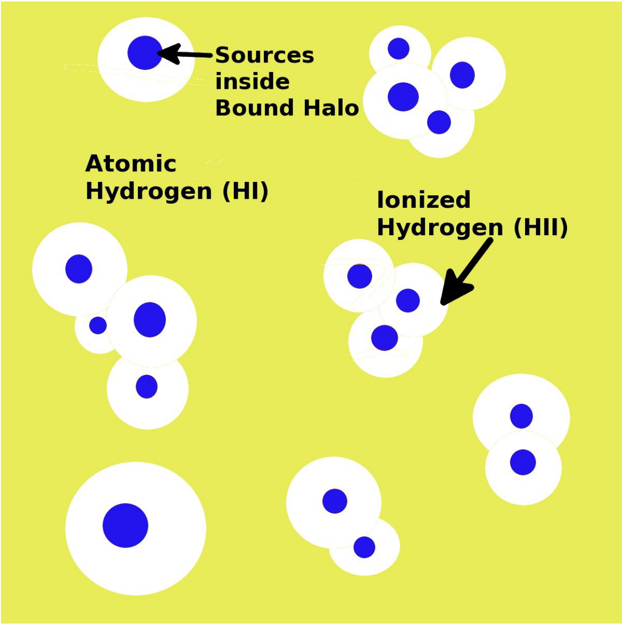
$$\hat{C}^{t}_{\ell_i}(\nu_1,\nu_2) = \frac{1}{2\Omega}\sum_{\boldsymbol{U}_{g_i}} w(\boldsymbol{U}_{g_i})\,[\tilde{T}^{t}_{b2}(\boldsymbol{U}_{g_i},\nu_1)\,\tilde{T}^{t}_{b2}(-\boldsymbol{U}_{g_i},\nu_2) + \tilde{T}^{t}_{b2}(\boldsymbol{U}_{g_i},\nu_2)\,\tilde{T}^{t}_{b2}(-\boldsymbol{U}_{g_i},\nu_1)]\,.$$



Reionization Model

- Inside-out reionization model.
- Assumptions :
    - Hydrogen follows underlying dark matter field.
    - Sources from within the collapsed DM halos.
    - Ionizing radiation rate, leaking out of a halo, is proportional to the halo mass above a certain lower cut-off.

$$\dot{N}_\gamma = g_\gamma \frac{M\Omega_\mathrm{b}}{\mu m_\mathrm{p}(10\,\mathrm{Myr})\Omega_0}$$



Parameters :

$$g_\gamma = f_* f_\mathrm{esc} N_\mathrm{i} \left(\frac{10\ \mathrm{Myr}}{t_\mathrm{s}}\right)$$

M_{min} =10^9 $M_\odot$ (Iliev et al. 2012)

We also include the atomically cooled mini-halos in our model.

Simulation details

1) Density field and halo catalogues from **PRACE4LOFAR** simulation within $[700 \text{ Mpc}]^3$ box (Giri et al. 2019)

2) Reionization process is simulated using the C^2-RAY code (Mellema et al. 2006) on $[300]^3$ grids.

3) The LC boxes are generated using coeval boxes from Dixon et al. 2016.

4) We have generated two LC boxes with the details as follows

LC1

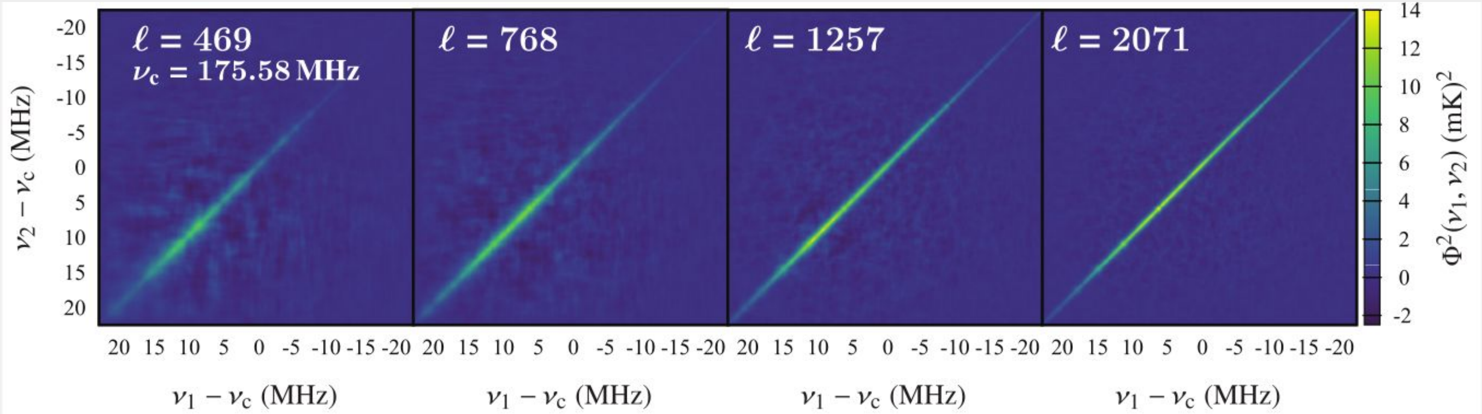
$$z_c = 7.09$$
$$\nu_c = 175.58 \text{ MHz}$$
$$\bar{x}_{\rm HI} \approx 0.50$$
$$\text{Range} : 6.15 \le z \le 8.25$$

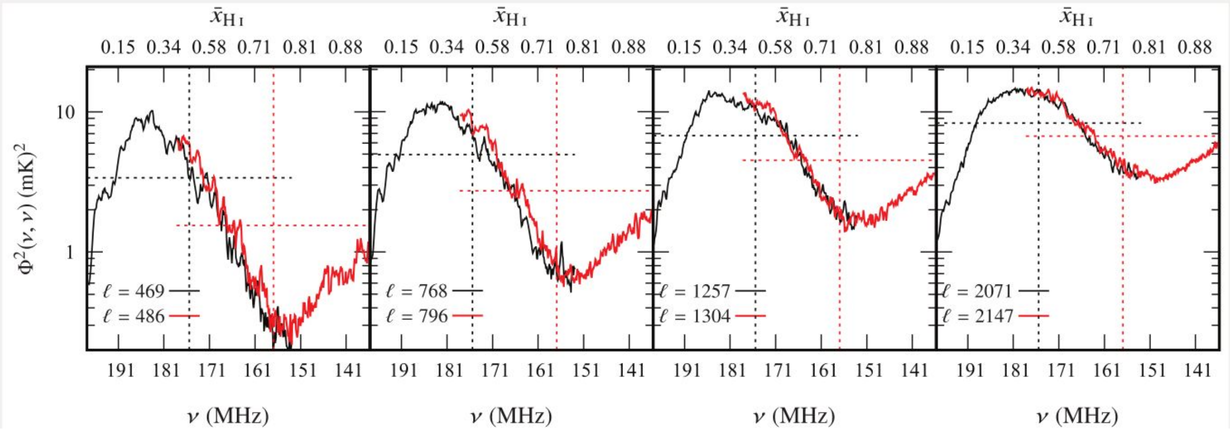
LC2

$$z_c = 8.04$$
$$\nu_c = 157.08 \text{ MHz}$$
$$\bar{x}_{\rm HI} \approx 0.75$$
$$\text{Range} : 6.92 \le z \le 9.40$$

**** I shall focus on LC1 results. LC2 results are qualitatively similar.

Signal MAPS





$$\Phi^2(\nu_1, \nu_2) = [\ell(\ell+1)\mathcal{C}_\ell(\nu_1, \nu_2)/2\pi]$$

We use semi-numerical simulations to generate the LC boxes of 21-cm signal based on inside out reionization model, and estimate its MAPS.

MAPS Error Variance

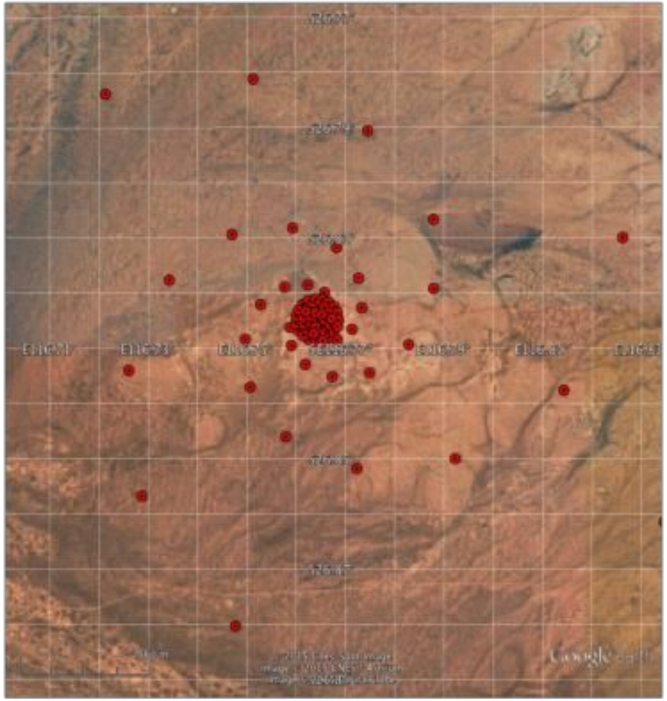
Considering system noise and assuming the Gaussian signal, we compute the error variance of the MAPS to be

$$
\begin{aligned}
X^{\ell_i}_{12,12} &= \left[\sigma^{\ell_i}_{12}\right]^2 = \left\langle \left[\delta \mathcal{C}^{t}_{\ell_i}(\nu_1,\nu_2)\right]^2 \right\rangle \\
&= \frac{1}{2}\sum_{U_{gi}} w^2_{gi}\left[\mathcal{C}^{t}_{\ell_{gi}}(\nu_1,\nu_1)\mathcal{C}^{t}_{\ell_{gi}}(\nu_2,\nu_2) + \left\{\mathcal{C}^{t}_{\ell_{gi}}(\nu_1,\nu_2)\right\}^2\right] \\
&= \frac{1}{2}\sum_{U_{gi}} w^2_{gi}\left[\left\{\mathcal{C}_{\ell_{gi}}(\nu_1,\nu_1) + \mathcal{C}^{N}_{\ell_{gi}}(\nu_1,\nu_1)\right\}\right. \\
&\quad \times \left\{\mathcal{C}_{\ell_{gi}}(\nu_2,\nu_2) + \mathcal{C}^{N}_{\ell_{gi}}(\nu_2,\nu_2)\right\} \\
&\quad \left. + \left\{\mathcal{C}_{\ell_{gi}}(\nu_1,\nu_2) + \delta^{K}_{\nu_1\nu_2}\,\mathcal{C}^{N}_{\ell_{gi}}(\nu_1,\nu_2)\right\}^2\right],
\end{aligned}
$$

Where the weight which extremizes SNR is

$$
\begin{aligned}
\tilde{w}_g = \Big[&\left\{\mathcal{C}_{\ell_{gi}}(\nu_1,\nu_1) + \mathcal{C}^{N}_{\ell_{gi}}(\nu_1,\nu_1)\right\}\left\{\mathcal{C}_{\ell_{gi}}(\nu_2,\nu_2) + \mathcal{C}^{N}_{\ell_{gi}}(\nu_2,\nu_2)\right\} \\
&+ \left\{\bar{\mathcal{C}}_{\ell_g}(\nu_1,\nu_2) + \delta^{K}_{\nu_1\nu_2}\,\mathcal{C}^{N}_{\ell_g}(\nu_1,\nu_2)\right\}^2\Big]^{-1}.
\end{aligned}
$$

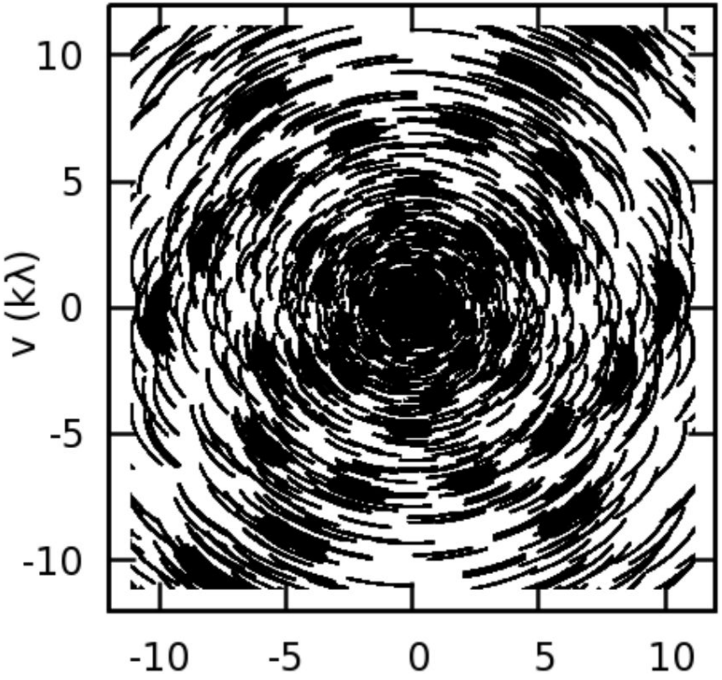
Mock Observation (SKA-Low)



Planned in Australia

512 stations

Rotation synthesis



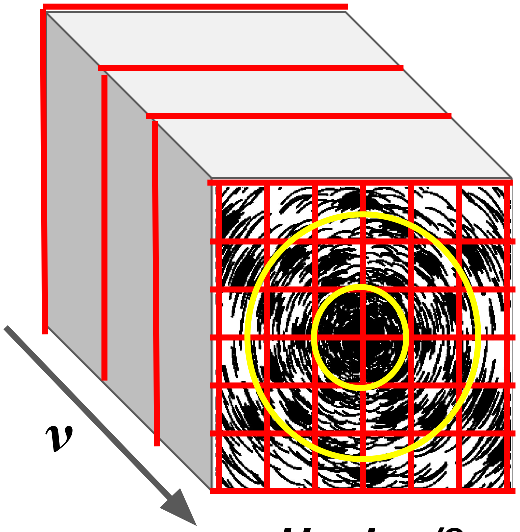
50 - 350 MHz

8 hrs/ night

DEC = -30°

System Noise

- Considering observations with SKA-Low (8 hrs/night) we generate the respective baselines distribution.
- Fill every frequency channel with the uv distribution
- Grid the ($\boldsymbol{U}$,ν) space and count the baselines contributing to each grid.
- Estimate the noise MAPS at the $\boldsymbol{U}$ grids and at the same frequency channel.

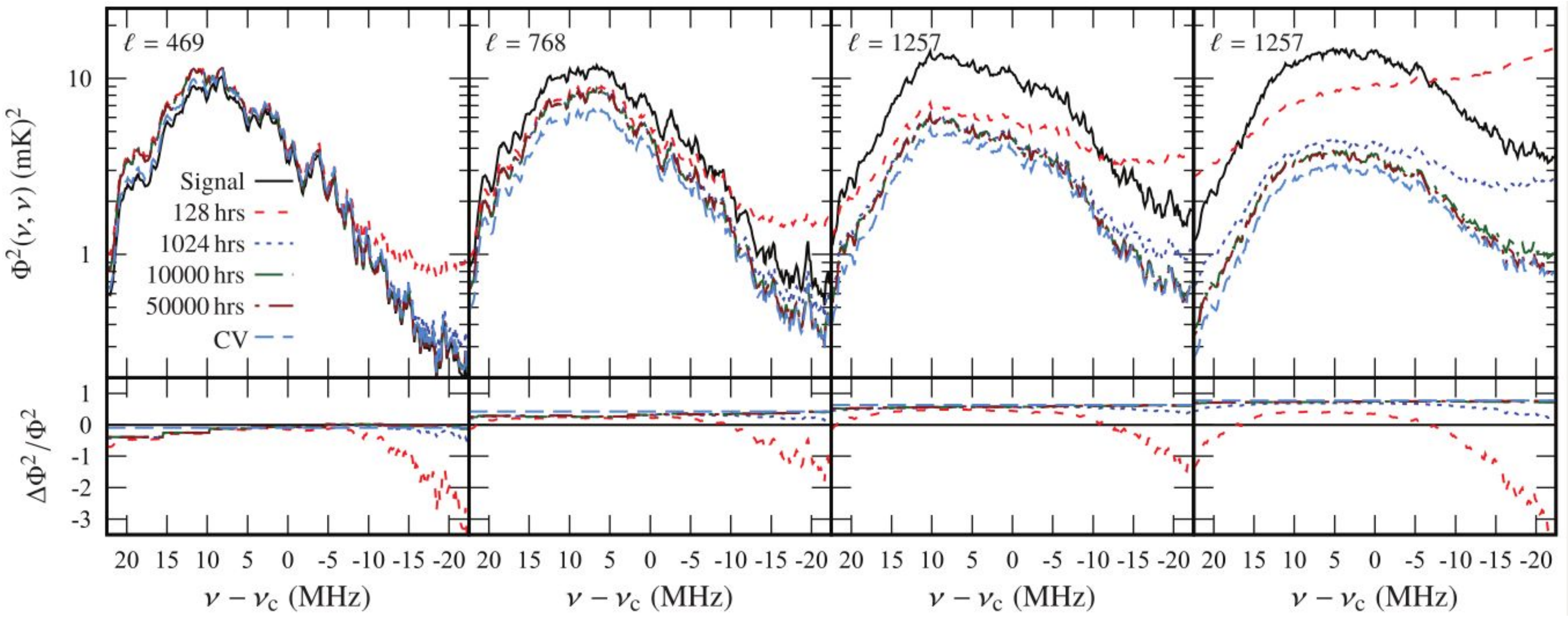


$$\mathcal{C}^{\mathrm{N}}_{\ell_g}(\nu,\nu) = \frac{T^2_{\mathrm{sys}}\,\lambda^4}{N_{\mathrm{p}}\,N_{\mathrm{t}}\,\Delta t\,\Delta\nu\,a^2\,\tau(\boldsymbol{U}_{\mathrm{g}})} \times \frac{1}{\int d\boldsymbol{U}'\,\mid \tilde{A}(\boldsymbol{U}-\boldsymbol{U}')\mid^2}$$

$T_{sys} = T_{sky} + T_{rec}$ $\quad$ $T_{\mathrm{sky}} = 60\lambda^{2.55}\,\mathrm{K}$ (Fixsen et al. 2011)

Noise PS decreases for large t_{obs} and denser baseline sampling.

5σ Error Estimates

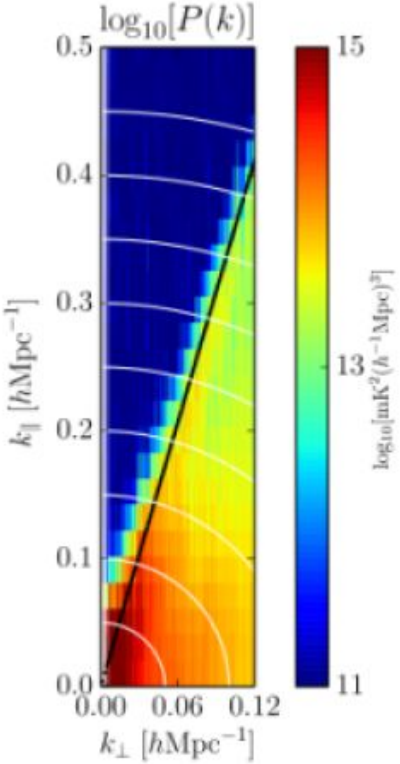


*** These results are free from any Foreground contamination.

Foreground Avoidance

Foregrounds are typically restricted within a wedge shaped region in ($\boldsymbol{k}_\perp$, $k_{//}$) plane whose boundary is given by, (Morales et al. 2012)

$$k_{||} = \left[\frac{r_c \ \sin(\theta_{\rm L})}{r_c' \ \nu_c} \right] \times k_\perp$$



Foreground scenarios :

1) Optimistic (no foregrounds, i.e. θ_L=0°)
2) Mild (significant foregrounds within θ_L= 3 x FWHM/2)
3) Moderate (significant foregrounds within θ_L= 9 x FWHM/2)
4) Pessimistic (foregrounds from all sky i.e. θ_L=90°)

Foreground Avoidance

Here also we avoid foregrounds in ($\boldsymbol{k}_{\perp}$,$k_{\parallel}$) plane.

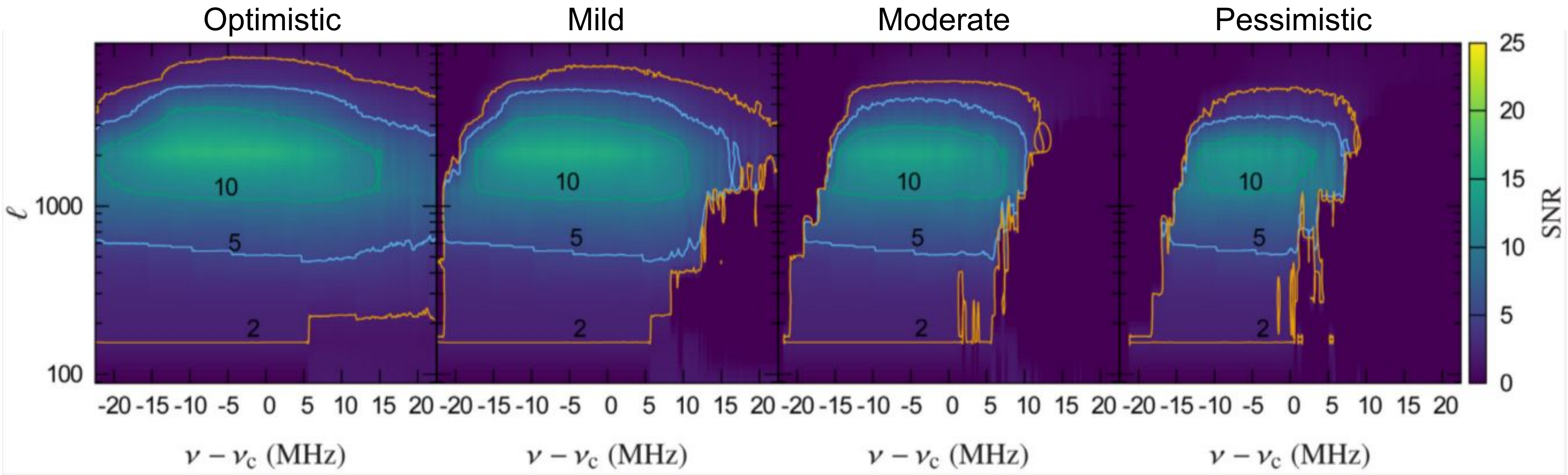
We estimate the MAPS corresponding to the avoided wedge spherically averaged power spectrum and subtract it from our complete MAPS estimates.

This basically assumes the ergodicity along the LoS direction.

$$\mathcal{C}_{\ell}^{\mathrm{EP}}(\Delta\nu) = \frac{1}{\pi r_{\mathrm{c}}^2} \int_0^{\infty} \mathrm{d}k_{\parallel} \cos\left(k_{\parallel} r_{\mathrm{c}}' \Delta\nu\right) P(k_{\perp}, k_{\parallel})$$

$$\mathcal{C}_{\ell}^{\mathrm{FA}}(\nu_1, \nu_2) = \mathcal{C}_{\ell}(\nu_1, \nu_2) - \mathcal{C}_{\ell}^{\mathrm{EP}}(\Delta\nu)$$

SNR Plots



t_{obs}=1024 hours

Summary

- Light cone effects are severe for the EoR 21-cm signal which shows rapid evolution with time (along LoS direction).
- LC effects breaks the ergodicity and periodicity along LoS direction which make spherically averaged PS a biased statistic of the signal.
- MAPS provides the complete information of the EoR 21-cm signal incorporating the signature variation in signal. It can potentially tell us about time evolution of the properties of the ionizing source.
- SKA-Low is able to detect the 21-cm MAPS at $> 5\sigma$ with 1000 hrs of observations in the intermediate ℓ values (~1300) across the full 44 MHz bandwidth. However this decreases at larger ℓ values.
- Incorporating foregrounds decreases the MAPS signal and hence reduces the bandwidth accessible for $> 5\sigma$ detection gradually from Optimistic to Mild, Moderate and finally Pessimistic scenario where the bandwidth reduces to ~ 20 MHz.

Thank You...