Detectability of CMB Weak Lensing and HI Cross Correlation and constraints on cosmological parameters

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ABSTRACT
Neutral hydrogen (H\textsubscript{i}) intensity mapping is capable of measuring redshift evolution of H\textsubscript{i} density parameter \(\Omega\textsubscript{HI}\), which is an important parameter to understand structure formation in the post-reionization epoch. Future H\textsubscript{i} observation with Square Kilometre Array (SKA) can significantly improve constraints on the parameter. However, the observation of H\textsubscript{i} suffers from the contamination from extremely bright foreground emissions, and it is necessary to consider a signal validation method complementary to the measurement of H\textsubscript{i} auto power spectrum. In this work, we propose to take a cross correlation between 21cm line intensity map and convergence map reconstructed from Planck observation and forecast a constraint on the \(\Omega\textsubscript{HI}\). We find that the SKA-Mid operated as single-dish mode has a sufficient capability to detect the cross correlation and constrain \(\Omega\textsubscript{HI}\) with 10–20% precision at wide range of redshifts \(0.5 < z < 3\), when combined with the Planck constraints on the cosmological parameters.

Key words: cosmology: theory – cosmological: cosmological parameters – radio lines: general

1 INTRODUCTION

Recent remarkable progress of cosmological observations has tightly constrained cosmological parameters. In order to further improve the precision, one direction to go is to measure the dark matter distribution precisely across large cosmological volume. In the post-reionization epoch \((z<6)\), almost all of the hydrogen in the intergalactic medium (IGM) is ionized, and small amount of neutral gases remains within a high density region, typically inside galaxies (Zwaan et al. 1997, 2005; Briggs 1990). Therefore, 21 cm line from the neutral hydrogen (H\textsubscript{i}) can trace the dark matter distribution. Thus, the measurement of the 21 cm signal is one of the key sciences of an upcoming radio observation such as the square kilometer array (SKA) (Santos et al. 2015). The fine resolution and wide coverage of frequency of the SKA allow us to measure the three dimensional distribution of the matter across the wide range of redshifts.

The 21 cm signal from highly distant galaxies is faint, and the direct detection has not been achieved yet. Furthermore, foreground emission from our Galaxy contaminates

the cosmological 21 cm signal and therefore the foreground removal is a serious challenge to be solved (Wolz et al. 2015). Alternatively, the cross correlation of 21 cm line with other cosmological probes can be expected to avoid the foreground contamination. For example, Chang et al. (2010) has measured the cross-correlation power spectrum between the cumulative 21 cm line from the Green Bank Telescope and the distribution of 10,000 galaxies at \(z < 1\) which are measured using DEEP2 optical galaxy redshift survey (Mariononi et al. 2002). This has obtained the positive correlation and showed the statistical detection of 21 cm signal at the 4 \(\sigma\) level.

The amount of H\textsubscript{i} mass density \(\Omega\textsubscript{HI}\), is an important quantity to understand the property and evolution of galaxies at the post-reionization epoch. For example, spectrum of high-z quasars is absorbed by damped Lyman-\(\alpha\) system, and the absorption gives insights on the amount of H\textsubscript{i}. Since the quasars is measured over a wide range of redshift, \(\Omega\textsubscript{HI}\) is constraints at various redshifts. Moreover, the cross correlation between 21 cm line and galaxy has constrained \(\Omega\textsubscript{HI}\) at lower redshift \((z < 3.5)\) (Padmanabhan et al. 2015; Chang et al. 2010). However, the constraints on \(\Omega\textsubscript{HI}\) are not strict compared to standard cosmological parameters.

The cross correlation between the convergence field of
cosmic microwave background (CMB) lensing and 21 cm signal has been first formulated by Sarkar (2010). The CMB photon is deflected by the gravitational potentials of large-scale structure which reproduces the secondary CMB anisotropy. The CMB lensing is sensitive to the structure at \( z < 3 \) and thus well correlated with the 21 cm signal from post-reionization epoch. The convergence field of CMB can be reconstructed from temperature field fluctuation with high angular resolution. Furthermore, the B-mode polarization fluctuation can also be used as an alternative way to reconstruct convergence field. Recent CMB experiments tend to have a better sensitivity to small scale fluctuation and polarization, which can be suitable for the 21 cm cross correlation studies.

Sarkar (2010) has found that the 21 cm-CMB lensing cross power spectrum (CPS) will be a promising measure for detecting the 21 cm signals; however, the thermal noise, which in practice dominates the error budget after securely removing the foreground emission, has not been considered in the forecast.

In this work, we study the detectability of the 21 cm-CMB lensing CPS assuming a realistic SKA observation and the cross power spectrum will be a promising measure for detecting the 21 cm signals; however, the thermal noise, which in practice dominates the error budget after securely removing the foreground emission, has not been considered in the forecast.

This paper is organized as follows. Section 2 details the 21 cm-CMB lensing cross correlation, and briefly describes the error formulae and Fisher analysis. In Section 3, we give the main results on the detectability of the CPS and forecasts for parameter constraints. Finally, Section 4 is devoted to the summary. Throughout the paper, we assume $\Lambda$CDM model and adopt cosmological parameters consistent with (Planck Collaboration VI 2018) unless otherwise stated, $\Omega_{\text{HI}}, \Omega_b h^2, \Omega_c h^2, n_s, H_0 = (1.00, 0.0224, 0.119, 0.967, 67.7)$.

## 2 21 CM-CMB LENSING CROSS CORRELATION

### 2.1 auto and cross power spectra

The CMB lensing of CMB is quantified by the convergence field \( \kappa \) and can be written as,

\[
\kappa(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n}),
\]

and

\[
F(z) = \frac{dA(z)_{\text{LSS}} - \bar{z}dA(z)_{\text{D}}(z)}{dA(z)_{\text{LSS}} a(z)},
\]

where \( \Omega_{\text{m0}} \) is the matter density parameter, \( H_0 \) is the Hubble constant, \( z_{\text{LSS}} \) is the redshift at the last scattering surface, \( a(z) \) is the scale factor, \( dA \) is comoving angular diameter distance, \( \delta \) is a matter fluctuation today and \( D_a \) is the growth factor.

Since the convergence field is calculated as an integral of density fluctuation from the last scattering surface up to the present, we cannot measure the density fluctuations at a particular redshift. However, the cross correlation between the CMB lensing and the H I can extract the effect of CMB lensing at given redshift.

Following the Sarkar (2010), here we briefly revisit the formulation of 21 cm-CMB lensing CPS. Using spherical harmonics, the convergence field contributed from large scale structures can be expanded as,

\[
\kappa(\hat{n}) = \sum_{lm} a_{lm}^* Y_{lm}(\hat{n}),
\]

where \( Y_{lm}(\hat{n}) \) is the spherical harmonic function. Then, the coefficients \( a_{lm}^* \) is obtained as,

\[
a_{lm}^* = \int d\omega(\hat{n}) \kappa(\hat{n}) Y_{lm}^*(\hat{n}).
\]

where \( \omega(\hat{n}) \) is the solid angle. The coefficients can be described using Raleigh expansion as

\[
a_{lm}^* = 6\pi \Omega_{\text{m0}} \left( \frac{H_0}{c} \right)^2 (-i)^l \int \frac{d^3 k}{(2\pi)^3} \int_0^{z_{\text{LSS}}} dz F(z) \delta(k) j_l(kr) Y_{lm}^*(\hat{k}),
\]

where \( \delta(k) \) is the Fourier transform of \( \delta(r) \), and \( j_l(x) \) is the spherical Bessel function.

For the 21 cm observation, we measure the brightness temperature \( T \) which can be expressed as

\[
T(\nu, \hat{n}) = \bar{T}_{\text{HI}}(z)[1 + \delta_{\text{HI}}(z, \hat{n})] \left[ 1 - \frac{T_\gamma}{T_S} \right] \frac{1 - 1 + z}{\bar{T}_{\text{HI}}(z)} \frac{\partial v(z, \hat{n}_{\text{HI}})}{\partial r}.
\]

where \( T_\gamma \) and \( T_S \) are the CMB temperature and the spin temperature respectively. The mean brightness temperature and mean neutral hydrogen fraction are scaled as

\[
\bar{T}(z) = 4.0 \text{mK}(1 + z)^2 \left( \frac{\Omega_{\text{m0}}h^2}{0.02} \right) \left( \frac{70}{H_0 \text{km/s/Mpc}} \right)
\]

and

\[
\bar{\chi}_{\text{HI}} = 50 \Omega_{\text{HI}} h^2 \left( \frac{0.02}{\Omega_b h^2} \right).
\]

respectively. Now we see that the brightness temperature fluctuation can be generated both from density fluctuation and velocity gradient of the neutral hydrogen clouds. Working in the Fourier space makes things much simpler.

\[
\frac{\partial v(z, \hat{n}_{\text{HI}})}{\partial r} \rightarrow \frac{k^2}{k_\parallel^2} D_a(z) \delta(k) \rightarrow \frac{k^2}{k_\parallel^2} D_a(z) \delta(k)
\]

where \( f = \text{dln} D_a/\text{dln} a = D_a(z)/(D_a(z)H(z)) \gtrless \Omega_{\text{m0}} h^2, \mu \) stands for the cosine of angle between the line of sight direction \( \hat{n} \) and the wave vector(\( \mu = \hat{k} \cdot \hat{n} \)). As we focus on the post reionization epoch, spin temperature is much higher than that of CMB, i.e. \( T_\gamma \ll T_S \). With the assumptions of constant bias of \( H_1 \), \( \delta_{\text{HI}} = b \delta, \) and no velocity bias, we obtain

\[
a_{lm}^* = 4\pi \bar{T}(z) (-i)^l \int \frac{d^3 k}{(2\pi)^3} \delta(k, z) j_l(kr) Y_{lm}^*(\hat{k}),
\]

where \( J_l \) is defined

\[
J_l(x) \equiv \left( b - f \frac{d^2}{dx^2} \right) j_l(x).
\]

Using Eq. (5), Eq. (10) and the Limber approximation
for large $l$ in Fourier space, we can describe the CPS as,

$$C_{l}^{\text{HI}-\kappa} \approx \frac{\pi}{2} \Lambda_{\text{HI}}(b) \frac{F(\text{HI})}{d_{A}^{2}(\text{HI})} \left(\frac{l}{\Lambda_{\text{HI}}}\right), \quad (12)$$

$$A(z) = \frac{3}{\pi} \Omega_{m0} \left(\frac{H_{0}}{c}\right)^{2} T(z) D_{+}(z), \quad (13)$$

where $\Lambda_{\text{HI}}$ is a comoving distance at a redshift $z_{\text{HI}}$ and $P(k)$ is the present day dark matter linear power spectrum. We use CAMB (Lewis et al. 2000; Lewis, & Challinor 2011) for theoretical prediction of $P(k)$. We assume a constant linear bias $b = 2$ at all redshifts. Since the CMB lensing has broad kernel along the line of sight, these modes parallel to the line of sight are cancelled out and thus we can always set $\mu = 0$. For the latter convenience, we describe the auto power spectra for CMB lensing and 21 cm fluctuation. The convergence power spectrum for large $l$ is approximately given by,

$$C_{l}^{\kappa} \approx \frac{9}{4} \Omega_{m0}^{2} \left(\frac{H_{0}}{c}\right)^{4} \int dl C_{l}^{2}(z) \frac{l}{dA(z)}.$$  \quad (14)

The angular power spectrum of 21 cm signal, $C_{l}^{\text{HI}}(z_{\text{HI}})$, is a direct observational estimator of the H I fluctuation at redshift $z_{\text{HI}}$. The $C_{l}^{\text{HI}}(z_{\text{HI}})$ with the flat sky approximation (Datta et al. 2007) for $l > 10$ is given by

$$C_{l}^{\text{HI}}(z_{\text{HI}}) = \frac{t^{2}}{\pi^{2} z_{\text{HI}}^{4}} D_{+}^{2} \int_{0}^{\infty} dk ||b + f \mu||^{2} P(k), \quad (15)$$

where $z_{\text{HI}}$ denotes the comoving distance to redshift $z_{\text{HI}}$, and the wave-number vector $k$ has magnitude $k = \sqrt{k_{||}^{2} + f^{2} k_{\perp}^{2}}$. For the SKA-mid (SD) observation, the noise term is written as (Bull et al. 2015),

$$N_{l,\text{SD}}^{\text{HI}} = \frac{A_{\text{eff}}^{2} T_{\text{sys}}^{2} S_{\text{sky}}}{B_{\text{tot}} \theta_{B}^{2}}.$$  \quad (17)
and varies with frequency. The interferometer observation is required if we measure smaller scale fluctuations. Thus, the available multipole modes depend both on the configuration of the observation and redshift, which is summarised in Table 1. We only use \(8 \leq l \leq 2000\), where the smallest multipole is limited by the sky fraction observed by Planck and assumed \(f_{\text{sky}}\) for SKA. Although the SKA can measure modes at \(l > 2000\), error on convergence map are large at the small scales. Therefore we do not consider these small scales.

While foregrounds do not contribute to the CPS measurement itself because they do not correlate statistically with the convergence map, they do contribute to the error estimation of the CPS. The foreground can be removed as it is spectrally smooth, while it is hard to remove it perfectly and residuals still contribute to the error (Wolz et al. 2015). The foreground removal is one of the most important and challenging issue for the 21 cm data analysis; however, the foreground removal studies are yet to be well matured, and it is unpredictable how much residuals remains. For that reason, and for the purpose of simplicity, we ignore the contribution of residuals to the error budget in this paper.

### 2.3 Fisher analysis

We perform the Fisher analysis to estimate future constrains on \(\Omega_{\text{HI}}\) and other cosmological parameters. The Fisher matrix on parameter \(p_i\) and \(p_j\) is calculated as (Tegmark et al. 1997; Coe 2009)

\[
F_{ij} = \frac{1}{2} \left[ \frac{\partial^2 \ln \mathcal{L}}{\partial p_i \partial p_j} \right]_{p = p_{\text{fid}}},
\]

(20)

where the log likelihood is given by,

\[
\ln \mathcal{L}(p) = \sum_{l_{\min}}^{l_{\max}} \frac{C_{\text{H}i}^{-1}(\mathbf{p}) - C_{\text{H}i}^{-1}(p_{\text{fid}})}{\Delta C_{\text{H}i}^{-1}(p_{\text{fid}})} + \ln |F^{-1}|_{ii},
\]

(21)

where we choose the parameters as \(p = (\Omega_{\text{HI}}, \Omega_c, h^2, n_s, H_0)\) and \(p_{\text{fid}}\) represents our fiducial parameter set. The error on the parameters are evaluated using covariance matrix, which corresponds to the inverse matrix of Fisher matrix,

\[
\sigma(p_i) = \sqrt{|F^{-1}|_{ii}}.
\]

In this work, we focus on \(\Omega_{\text{HI}}\) and three cosmological parameters (\(\Omega_c, h^2, n_s, H_0\)). Note that the cosmological parameters are much better constrained (Planck Collaboration VI 2018) compared with \(\Omega_{\text{HI}}\). Therefore we can set a strong constraint on \(\Omega_{\text{HI}}\) using the results in Planck Collaboration VI (2018) as the prior. We note that \(\sigma_p\) completely degenerates with \(\Omega_{\text{HI}}\) in the cross power spectrum, and therefore we assume \(\sigma_p\) has been constrained by other observations and we do not consider it as a free parameter in our Fisher analysis. We mention that the \(\sigma_\theta\) is precisely constrained by the Planck.

### 3 RESULTS & DISCUSSION

In this section, we present our main results. Fig. 1 shows the auto power spectrum of the convergence calculated using Eq. (14) and the minimum variance reconstruction approximate noise spectrum for the Planck CMB observation from the temperature fluctuation and the polarization map. The signal is less than the noise at any \(l\), and the noise is two orders of magnitude larger than the signal on small scales. Therefore, the error on the cross power spectrum on small scales is dominated by the noise of the convergence and makes the detection difficult even if the sensitivity of SKA-mid (IF) is sufficient to measure the 21cm line signal.

Fig. 2 represents the H\(_1\) auto power spectrum and the thermal noise of the SKA-mid. The thermal noise is much smaller than the expected signal at \(z = 0.5\) and 1.5, and therefore the significant detection of the H\(_1\) signal using SKA-mid is relatively easy in the absence of foregrounds. However, the noise is comparable to the signal at \(z = 2.5\), and thus the thermal noise of 21cm line observation limits the detection of the cross power spectrum.

The correlation coefficient, defined as

\[
\rho = \frac{C^{\text{H}i}}{\sqrt{C^{\text{H}i} C^{\text{H}i}}},
\]

(23)

is plotted in Fig. 2.
has a broad peak at $l \sim 50$ and is typically 0.05. This indicates that the factor $\sqrt{N_s^{\text{sky}}}$ in Eq. (19) must be larger than O(10) for a significant detection even if the instrumental noise terms ($N_s^C, N_s^{HI}$) are negligible.

Fig. 4 shows signal to noise ratio for individual multipole mode and accumulated over $l$, assuming the SKA-mid (SD). The accumulated S/N reaches 10 for $z = 0.5$ and 1.5 and it only reaches to 5 for $z = 2.5$. They are saturated at $l \sim 200$. SKA-mid (IF) does not contribute to the cumulative S/N so much. The gain from the interferometer mode is only (S/N)~ 0.4. This results indicates that the detection of $C_l^{\text{HI} - \kappa}$ can be achieved with only the SKA-mid (SD) for the current survey parameters.

Fig. 5 shows 68.5 % confidence regions on two parameters obtained by marginalizing over the other two parameters. If we compare the power of constraints among different redshifts, it is slightly stronger at lower redshifts than those for high redshift because lower redshifts have higher S/N. In the case we simultaneously fit all the parameters we consider, the constraints are rather weak and we cannot exclude $\Omega_{HI} = 0$.

Among our parameters, the standard cosmological parameters, $\Omega_c, h^2, H_0$ and $n_s$, have already been determined precisely by other observations with typical errors less than 1% and we can use them as priors. We demonstrate the combined constraints on $\Omega_{HI} b$ by simply removing cosmological parameters from Fisher matrix, rather than marginalizing or putting priors on them. This treatment gives a reasonable estimate of an expected constraint because the precision of the cosmological parameters is much better than expected from the CPS. In Fig. 6, we show constraints on $\Omega_{HI} b$ and $n_s$ obtained by fixing $\Omega_c h^2$ and $H_0$. The constraints are remarkably improved and the expected error on $\Omega_{HI} b$ is about 20% ($z = 0.5$ and 1.5) and 65% ($z = 2.5$).

Further, fixing $n_s$ as well, the constraints on $\Omega_{HI} b$ become even better. Fig. 7 compares the current constraints on $\Omega_{HI}$ and the expected constraints from the CPS. Here, we assume the value of the bias is known from other probes. We find that the constraints from the CPS are typically 10% and comparable or better than the previous ones at these $z = 0.5, 1.5$ and 2.5.

The detection of the CPS at small scales with the SKA-mid (IF) is not likely and this is due to the sensitivity of Planck at small scales. Other instruments with a high angular resolution such as ACTPol (Niemack et al. 2010; Thornton et al. 2016) will reduce significantly the noise at small scales and allows us to constrain cosmological parameters even more precisely. In addition, recently, Subaru Hyper Supreme-Cam has made a wide field optical weak lensing map (Oguri et al. 2018). Although the measured area is small, the data should be suitable for the cross correlation with the SKA-mid (IF) at only low-z.

As we can see in Fig. 2, $C_l^{HI}$ can dominate over the noise due to the auto power spectra and also the cross correlation contributions to the error is one order of magnitude smaller than those from auto power spectra, which can be seen in Fig. 3. Therefore, with a fixed observation time, we can further reduce the error effectively with a survey with wider sky coverage with shorter exposure time per visit.

In addition to the observational challenges, there is an uncertainty on the bias between the cold dark matter and H I gas. In this work, we assumed a constant linear bias model, which is appropriate on large scales. The non-linear scale and redshift dependent bias model has been studied using numerical simulation in the literature Sarkar et al. (2016); Villaseca-Navarro et al. (2018); Ando et al. (2019). Thus, detection of the 21 cm-CMB lensing CPS at various scales and redshifts can provide us with a lot of insights into the bias model.

4 SUMMARY

In this work, we have studied the detectability of the 21 cm-CMB lensing CPS using a practical model of instrumental noise. For the observation of the 21 cm signal, we assumed the SKA-mid operating as single dish mode and interferometer mode. For the modeling of the noise of convergence map, we referred to the recent Planck result. We found that the CPS can be detected at large scales by combining the Planck and SKA-mid (SD). However, the detection on small scales is pessimistic due to the less sensitivity on the convergence field.

We also performed Fisher analysis to estimate expected constraints on cosmological parameters, especially $\Omega_{HI} b$. A-
though the constraints from the CPS alone is rather weak, priors on well-determined parameters \( \Omega_c h^2, n_s, H_0 \) make it possible to constrain \( \Omega_{\text{HI}} b \) with a precision of \( \sim 10\% \) at \( z = 0.5, 1.5 \) and 2.5.

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-8 -6 -4 -2 0 2 4 6
\( \Omega_{\text{HI}} b [10^{-3}] \)

Figure 5. Expected constraints on cosmological parameters from 21 cm-CMB lensing CPS for SKA-mid (SD) observation. Correlation between \( \Omega_{\text{HI}} \) and \( \Omega_{\text{HI}} h^2, n_s, H_0 \) are shown.

Figure 6. The constraint on \( \Omega_{\text{HI}} \) and \( n_s \) fixing the other two cosmological parameters.

Figure 7. The comparison of constraints on \( \Omega_{\text{HI}} \) from previous study and our result. Current constraints on \( \Omega_{\text{HI}} \) is obtained in Lah et al. (2007); Khandai et al. (2011); Rao et al. (2006). For our prediction, the results of 1D Fisher analysis on \( \Omega_{\text{HI}} b \) are plotted assuming the value of the bias is known.

Figure 8. The cumulative S/N reaches 0.22, 0.34 and 0.19 for \( z = 0.5, 1.5 \) and 2.5, respectively, if the sky fraction is 1000 times larger than the primary field of view with reduced observation time per pointing by a factor of 1000.
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