Predictions and sensitivity forecasts for reionization-era [C II] line intensity mapping

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ABSTRACT

Observations of the high-redshift Universe using the 21 cm line of neutral hydrogen and complimentary emission lines from the first galaxies promise to open a new door for our understanding of the epoch of reionization. We present predictions for the [C II] 158 µm line and H i 21 cm emission from redshifts \( z = 6–9 \) using high-dynamic-range cosmological simulations combined with semi-analytical models. We find that the CONCERTO experiment should be able to detect the large scale power spectrum of [C II] emission to redshifts of up to \( z = 8 \) (signal-to-noise ratio \( \geq 1 \) at \( k = 0.2 \ h/\text{Mpc} \) with 1500 hr of integration). A Stage II experiment similar to CCAT-p should be able to detect [C II] from even higher redshifts to high significance for similar integration times (signal-to-noise ratio of \( \sim 70 \) at \( k = 0.2 \ h/\text{Mpc} \) at \( z = 6–9 \)). We study the possibility of combining such future [C II] measurements with 21 cm measurements using LOFAR and SKA to measure the [C II]-21cm cross power spectra, and find that a Stage II experiment should be able to measure the cross-power spectrum for \( k \lesssim 1 \ h/\text{Mpc} \) to signal-to-noise ratio of better than 10. We discuss the capability of such measurements to constrain astrophysical parameters relevant to reionization and show that a measurement of the [C II]-21cm cross power spectrum helps break the degeneracy between the mass and brightness of ionizing sources.

Key words: dark ages, reionization, first stars – galaxies: active – galaxies: high-redshift – galaxies: quasars – intergalactic medium

1 INTRODUCTION

Atomic and molecular emission lines with wavelength redward of hydrogen Lyman-\( \alpha \) have the desirable property of remaining visible deep into the epoch of hydrogen reionization (redshift \( z = 6–10 \)), where the Ly\( \alpha \) line is difficult to observe due to saturated absorption. These emission lines, which depend on the cold gas content, the ionising radiation field, or the metallicity, uniquely probe the formation of the very first stars and galaxies. They should be a good tracer of the cosmic density structure.

Intensity mapping of such emission lines (e.g., \( \text{O I} \), \( \text{O III} \), \( \text{C II} \), \( \text{CO} \), \( \text{H I} \), \( \text{H}_2 \)) is an attractive tool to study the high-redshift Universe (Sugino et al. 1999; Vishal & Loeb 2010; Carilli 2011; Gong et al. 2011; Lidz et al. 2011; Gong et al. 2012, 2013; Silva et al. 2015; Yue et al. 2015; Serra et al. 2016; Fonseca et al. 2017). By measuring large-scale variations in line emission from many individual unresolved galaxies, intensity mapping provides a statistical measurement that encodes cosmological and astrophysical information. This capacity of intensity mapping experiments is particularly important at redshifts corresponding to the epoch of reionization, which is a key period in the history of the Universe, when the earliest galaxies and quasars form and ionize the surrounding neutral hydrogen. Constraints from the evolution in the Ly\( \alpha \) opacity of the intergalactic medium (IGM; e.g., Fan et al. 2006; Ota et al. 2017) and the temperature and polarization anisotropy in the cosmic microwave background (CMB; Planck Collaboration 2016) suggest that reionization occurs at redshifts \( z \sim 6–15 \). However, the nature of the sources of reionization remains uncertain. Measurements of the escape fraction of Lyman-continuum photons necessary for reionization from high-redshift galaxies are still elusive. Although galaxies down to rest-frame UV magnitudes of \( M_{\text{UV}} = -12.5 \) (\( L \sim 10^{-3} L^* \)) at redshift \( z = 6 \) (Livermore et al. 2017) and redshifts as high as \( z = 11.1 \)

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(Oesch et al. 2016) have been observed, the escape fraction of Lyman-continuum photons has been measured in only a handful of bright ($L > 0.5L^*$) and low-redshift ($z < 4$) galaxies. In these galaxies, the escape fraction is typically found to be 2–20% (Vanzella et al. 2010; Boutsia et al. 2011; Siana et al. 2013; Mostardi et al. 2015; Grazian et al. 2016; Japelj et al. 2017; Micheva et al. 2017) but reionization requires escape fractions of about 20% in galaxies down to $M^*_L = -13$ (Finkelstein 2016; Robertson et al. 2015; Khaire et al. 2016). There is tentative evidence for a dominant contribution to reionization from quasars from the suggestion of a rather steep faint end of the QSO luminosity function at high redshift by Giallongo et al. (2015), and large Lyα opacity fluctuations at very large scales in QSO absorption spectra (Becker et al. 2015; Chardin et al. 2015; Davies & Furlanetto 2016). But it may be difficult to reconcile this with measurements of the He II Lyα opacity and measurements of the IGM temperature at $z \sim 3$ (Puchwein et al. 2018; D’Aloisio et al. 2017; Madau & Haardt 2015), and also with measurements of the incidence rate of metal-line systems (Finlator et al. 2016).

Intensity mapping of atomic and molecular lines emission from galaxies in the epoch of reionization has the potential to unambiguously reveal the properties of the sources of reionization. The radiative transfer of emission in these lines in galaxies is very different from that of the Lyman-continuum emission. As a result, intensity mapping yields a view of high-redshift galaxies that is unbiased by their Lyman-continuum escape fraction. Cross-correlating this measurement with a measurement of the ionization state of the large-scale IGM, such as of the 21 cm emission or absorption from the IGM, can then result in constraints on reionizing sources.

Several experiments are currently in deployment to measure the large-scale clustering in the 21 cm signal from the IGM during the epoch of reionization, such as Murchison Widefield Array (MWA; Bowman et al. 2013; Tingay et al. 2013), Low Frequency Array (LOFAR; van Haarlem et al. 2013; Pober et al. 2014), Hydrogen Epoch of Reionization Array (HERA; Pober et al. 2014; DeBoer et al. 2016), and Square Kilometre Array (SKA; astronomers.skatelescope.org). However, 21 cm power spectrum observations alone are limited in their capability of constraining reionization parameters. This is due to the degeneracy between the Lyman-continuum escape fraction (sometimes also parameterised as the ionization efficiency) and the mass of ionizing sources: a wide range in the host halo mass of ionizing sources can produce very similar large-scale 21 cm power for a variety of escape fraction values (Greig & Mesinger 2015). Cross-correlations with other line intensity maps can potentially solve this problem by breaking the degeneracy. Our aim in this paper is to investigate this possibility.

Various emission lines have been considered in the literature as candidates for high-redshift intensity mapping such as Lyα (Silva et al. 2013; Pullen et al. 2014), [O i] 63.2 μm and 145.5 μm (Visbal et al. 2011; Serra et al. 2016), CO(1–0) 2601 μm (Lidz et al. 2011; Gong et al. 2011), [N II] 121.9 μm and 205.2 μm (Serra et al. 2016) and [C ii] 157.6 μm (Gong et al. 2012; Silva et al. 2015; Serra et al. 2016). As these lines are a result of a reprocessing of stellar emission by the interstellar medium (Barkana & Loeb 2001; Carilli & Walter 2013), we generally expect an anti-correlation on large scales between their signal and that of the 21 cm line, which originates in the neutral regions far away from galaxies (Lidz et al. 2011).

The intensity mapping technique has been used at $z \sim 0.8$ using the 21 cm line (Chang et al. 2010), and at $z \sim 3$ using the [C ii] (Pullen et al. 2017) and CO (Keating et al. 2016) lines. Surveys suggested for future intensity mapping include CO Mapping Pathfinder (Li et al. 2016) for CO at redshifts $z \sim 2$–3; TIME (Crites et al. 2014) and CONCERTO (Lagache 2018; Serra et al. 2016) for [C ii] at redshifts $z = 5$–9; HETDEX (Hill et al. 2008) for Lyα at $z = 1.9$–3.5; SPHEREx for Lyα at redshift $z \sim 6$–8 and other lines at lower redshifts (Dorè et al. 2014, 2016), and CDIM (Cooray et al. 2016) for Hα, O III, and Lyα at $z = 0.2$–10. 

In this paper, we present predictions for [C ii] and 21 cm brightness power spectra and the [C ii]–21 cm cross-power spectra from the epoch of reionization ($z = 6$–10) using a high-dynamic-range cosmological hydrodynamical simulation of the Sherwood simulation suite (Bolton et al. 2017). We forecast the sensitivity to measure these statistical quantities for the CONCERTO experiment (Lagache 2018; Serra et al. 2016) as well as a Stage II successor experiment beyond TIME and CONCERTO for [C ii]. For H i, we use the experimental setups of LOFAR and SKA. Finally, we discuss the feasibility of such experiments to constrain key parameters by considering simple models of reionization. The paper is organized as follows. We first present our [C ii] emission line model and 21 cm line maps in Sections 2 and 3, and then compute the cross-correlation between the [C ii] and the 21 cm lines from the epoch of reionization in Section 4. We discuss the observability of the [C ii] and 21 cm power spectra and the [C ii]–21 cm cross power spectrum in Section 5. Finally, we illustrate in Section 6 how the cross-correlation can be used to probe the nature of ionizing sources, using in particular two quantities: the minimum halo mass corresponding to a non-zero Lyman-continuum photon escape fraction and the number of ionizing photons produced by a halo. We end by summarising our results in Section 7. Our ΛCDM cosmological model has $\Omega_m = 0.0482$, $\Omega_{\Lambda} = 0.308$, $\Omega_b = 0.692$, $h = 0.678$, $n_s = 0.961$, $\sigma_8 = 0.829$, and $Y_{He} = 0.24$ (Planck Collaboration 2014).

## 2 [C II] EMISSION FROM HIGH-REDSHIFT GALAXIES

Our predictions for the [C ii] and 21 cm emission lines from the epoch of reionization are based on a cosmological hydrodynamical simulation that is part of the Sherwood simulation suite (nottingham.ac.uk/astronomy/sherwood; Bolton et al. 2017). This simulation suite has been run using the energy- and entropy-conserving TreePM smoothed particle hydrodynamical (SPH) code p-gadget-3, which is an updated version of the gadget-2 code (Springel et al. 2001; Springel 2005). Our simulation was performed in a cubic box of length 160 $h^{-1}$Mpc on a side. Periodic boundary conditions were imposed. The number of gas and dark matter particles were both 2048$^3$. This corresponds to a dark matter particle mass of $M_{\text{DM}} = 3.44 \times 10^5$ $h^{-1}$M⊙ and gas particle mass of $M_{\text{gas}} = 6.38 \times 10^5$ $h^{-1}$M⊙. The soften-
ing length was set to $l_{\text{soft}} = 3.13 \, h^{-1}\text{ckpc}$. The simulation evolves the gas and dark matter density fields from $z = 99$ to $z = 4$, with snapshots saved at every 40 Myr interval. We use the QUICKLYALPHA implementation in p-gadget-3 in order to speed up the simulation: gas particles with temperature less than $10^5 \, \text{K}$ and overdensity of more than a thousand times the mean baryon density are converted to collisionless stars and removed from the hydrodynamical calculation (Viel et al. 2004).

In addition to the cosmological evolution of baryons and dark matter, the simulation follows photoionization and photoheating of baryons by calculating the equilibrium ionization balance of hydrogen and helium in a optically thin UV background based on the model of Haardt & Madau (2012), modified so that the resultant IGM temperature agrees with the measurements by Becker et al. (2011). Radiative cooling is implemented by taking into account cooling via two-body processes such as collisional excitation of H i, He i, and He ii, collisional ionization of H i, He i, and He ii, recombination, and Bremsstrahlung (Katz et al. 1996). Likewise, p-gadget-3 also includes inverse Compton cooling off the CMB (Ikeuchi & Ostriker 1986), which can be an important source of cooling at high redshifts. We ignore metal enrichment and its effect on cooling rates, which is a good approximation for the IGM. In the redshift range relevant to this paper, we use snapshots of the particle positions at $z = 6.3, 7.1, 8.2$ and 9. Dark matter haloes are identified using the friends-of-friends algorithm. To calculate power spectra, we project the relevant particle onto a grid to create a density field, using the cloud-in-cell (CIC) scheme that accounts for the SPH kernel. After calculating the power spectrum, we deconvolve the CIC kernel, ignoring small errors due to aliasing on the smallest scales (Cui et al. 2008).

If a source population at redshift $z$ is assumed to have a line emission comoving volume emissivity $\epsilon(\nu_{\text{obs}}, 1 + z)$, then the specific intensity of the observed emission can be determined by solving the cosmological radiative transfer equation. The angle-averaged solution at $z = 0$ can be written as

$$I(\nu_{\text{obs}}, z = 0) = \frac{1}{4\pi} \int_0^\infty dz' \frac{dI(\nu_{\text{obs}}(1 + z'))}{dz'} \epsilon(\nu_{\text{obs}}(1 + z')), \quad (1)$$

where $dI/dz = c/(1 + z)H(z)$ denotes the proper line element, and we have assumed that there is negligible absorption by the intervening intergalactic medium. Assuming an absence of contamination from other redshifts, we can model the frequency dependence by a $\delta$-function and write

$$I(\nu_{\text{obs}}, z = 0) = \epsilon \frac{1}{4\pi} \frac{1}{H(z)} \nu_{\text{em}}(z) \epsilon(\nu_{\text{obs}}(1 + z)), \quad (2)$$

where the $\nu_{\text{em}} = \nu_{\text{obs}}(1 + z)$ is the rest-frame emission frequency.

The volume-averaged emissivity $\epsilon$ is related to the line luminosity $L$ of individual haloes by

$$\epsilon(z) = \int_{M_{\text{min}}}^\infty dM \frac{dn}{dM} L_{\epsilon}(M, z), \quad (3)$$

where $dn/dM$ is the halo mass function. $M_{\text{min}}$ is the minimum mass of haloes that can form stars and produce line emission. At $z = 7$, the minimum halo mass in our simulation is $2.3 \times 10^9 \, h^{-1}\text{M}_\odot$, which is close to the atomic hydrogen cooling limit. The maximum halo mass at this redshift

![Figure 1](image-url)

Figure 1. Top panel shows the star formation rate density evolution in our model (black curve) in comparison with various extinction-corrected observational measurements (coloured symbols). Bottom panel shows the resultant evolution of the average intensity of $[C \, \text{ii}]$ line emission.

is $3.1 \times 10^{12} \, h^{-1}\text{M}_\odot$. In order to model the emissivity $\epsilon(z)$, we now need to model the halo luminosities $L(M, z)$.

### 2.1 Star formation rate

Linking the halo luminosities $L(M, z)$ to the star formation rate (SFR) can be done either using observational data or theoretical models of the emission processes of the different lines. The mechanism of line emission is complex; it depends on, e.g., the morphology and structure of galaxies, their metallicity, radiation field and density. Line emission can be excited by starlight, dissipation of mechanical energy by turbulence and shocks, or by the active galactic nuclei. In the reionization epoch, CMB heating and attenuation can also be important (LAGACHE et al. 2017). Several empirical models have been proposed for the emission of different lines, e.g., CO (Obreschkow et al. 2009; Gong et al. 2011), Lyα (Silva et al. 2013; Pullen et al. 2014; Feng et al. 2017), C II (Gong et al. 2012; Serra et al. 2016), but all of them rely on sets of poorly known parameters that characterize the galaxies and their interstellar medium in the reionization era. For the C II line, while individual galaxies have been detected at $z > 6$ (e.g., Knudsen et al. 2016; Pentericci et al. 2016; Bradač et al. 2017; Carniani et al. 2017; Strandet et al. 2017), a complete understanding of the line excitation is still lacking.

Considering the large amount of uncertainties in the detailed modelling, we will continue our study using empirical relations from the literature that relate the halo luminosity to its star formation rate (SFR) as a power law,

$$L_{\epsilon} \propto \text{SFR}^\gamma, \quad (4)$$

where the exponent $\gamma$ encodes possible nonlinearities due to processes such as collisional excitation (LAGACHE et al. 2017).
We assume that the SFR of a halo of mass $M$ is proportional to the halo mass

$$SFR = f_\star(z)M_{\text{halo}},$$

(5)

where we obtain the redshift-dependent proportionality factor by assuming a linear evolution of $f_\star$ with redshift and calibrating it so that the resultant SFR density in the simulation box is consistent with observed data (Oesch et al. 2015).

Figure 1 shows the SFR density in our model in comparison with extinction-corrected observational measurements.

### 2.2 CII line emission

Once we have the star formation rate model, we assign [C ii] line luminosities $L_{\text{CII}}$ to each halo in our simulation box, by using the predicted $L_{\text{CII}}$–SFR relation from the model presented by Lagache et al. (2017),

$$\log \left( \frac{L_{\text{CII}}}{L_\odot} \right) = (1.4 - 0.07z) \times \log \left( \frac{\text{SFR}}{M_\odot \text{yr}^{-1}} \right) + 7.1 - 0.07z. \quad (6)$$

In this paper, the semi-analytical model (SAM) of galaxy formation G.A.S. described in Cousin et al. (2015, 2016) was used, after further modifications assuming an inertial turbulent cascade in the gas that generates a delay between the accretion of the gas and the star formation (Cousin and Guillard, submitted). It is assumed that the [C ii] emission in high-$z$ galaxies arises predominantly from photo-dominated regions (PDR). For each galaxy in the SAM, an equivalent PDR characterised by three parameters (the mean hydrogen density, gas metallicity, and interstellar radiation field) is defined. The [C ii] line emission is then computed using the CLOUDY photoionisation code (Ferland et al. 2017). This model allows computation of the [C ii] luminosity for a large number of galaxies (e.g., 28,000 at $z = 5$). It takes into account the effects of CMB heating and attenuation that are important at such high redshifts. The model is able to reproduce the $L_{\text{CII}}$–SFR relation observed for 50 star-forming galaxies at $z \geq 4$. We used here the mean relation given in Equation (6) although it is found that the $L_{\text{CII}}$–SFR relation is very dispersed (0.51 to 0.62 dex from $z = 7.6$ to $z = 4$). The large dispersion is due to the combined effect of different interstellar radiation fields, metallicities, and gas contents in the simulated high-redshift galaxies.

In order to calculate the three-dimensional distribution of the specific [C ii] line intensity, we created coeval emission maps by assigning to each halo in the simulation volume a line luminosity $L_{\text{CII}}(M)$ modelled as above. Using the information about their spatial positions, we then sum the volume emissivities in each cell of a uniform 512$^3$ grid to obtain three-dimensional emission maps representing co-moving regions of space of volume $(160 \, \text{cMpc}/h)^3$. Using Equation (2), the observed specific intensity corresponding to the cell is then given by

$$I_{\text{cell}} = \frac{c}{4\pi} \frac{1}{\nu_{\text{CII}}} \frac{L_{\text{CII,cell}}}{V_{\text{cell}}},$$

(7)

where $L_{\text{CII,cell}}$ is the luminosity of the cell, given by the sum of the luminosities of any haloes located in the cell. Figure 1 shows the evolution of the average line intensity. Figure 2 shows a light cone of the CII specific intensity created by interpolating between simulation snapshots spaced at 40 Myr intervals between $z = 6$ and 10. The simulation corresponds to a total survey area of about $1.5 \times 1.5 \, \text{deg}^2$, with each cell occupying an area of $0.2' \times 0.2'$. At redshift $z = 7$, a comoving distance of $160 \, \text{cMpc}/h$ along the observation axis corresponds to about $\Delta z = 0.5$.

### 2.3 Power spectra

We derive three-dimensional spherically-averaged power spectra of the [C ii] line emission in our model as

$$\Delta^2(k) = \frac{k^3}{2\pi^2} \frac{\langle \tilde{I}^2(k) \rangle}{V_{\text{box}}},$$

(8)

where $\tilde{I}$ is the Fourier transform of the specific intensity defined in Equation (2), and $V_{\text{box}}$ is the box volume, $(160 \, \text{cMpc}/h)^3$. We ignore the anisotropies arising from redshift-space distortions and the redshift evolution across the box. Left column of Figure 3 shows the resultant power spectra for the [C ii] emission for redshifts from $z = 6$ to 9. The shot noise contribution to the [C ii] power spectrum is included. The shot noise is given by

$$\Delta^2_{\text{shot}}(k, z) = \frac{k^3}{2\pi^2} \left( \frac{c}{4\pi \nu_{\text{CII}} H(z)} \right)^2 \sum_i \frac{L_{\text{CII}}(M_i, z)^2}{V_{\text{box}}},$$

(9)

where $L_{\text{CII}}(M_i, z)$ is the C II luminosity (in erg s$^{-1}$) of halo $i$ with mass $M_i$ and the summation is over all haloes. The frequency $\nu_{\text{CII}}$ is the rest-frame frequency of the C II line. Shot noise dominates the power spectrum at $k \gtrsim 0.5 \, h/\text{cMpc}$ (Serra et al. 2016), but is irrelevant in the [C ii]-21cm cross power spectrum discussed in this paper, as the 21 cm emission comes from the extended IGM. Also shown in Figure 3 are the sensitivities corresponding to experimental configurations, which we discuss below.

The line emission power spectra trace the halo power spectrum, with a constant bias factor as the emission amplitude is simply proportional to the halo mass. The amplitude of the [C ii] power spectrum decreases from redshift $z = 6$ to 9 by a factor of 100. Our values are consistent with those from other models in the literature (Serra et al. 2016; Silva et al. 2015; Gong et al. 2012). The signal is dominated by shot noise at $k \gtrsim 0.3–0.7 \, h/\text{cMpc}$.

### 3 21 CM LINE MAPS

The redshifted 21 cm signal originates in the neutral intergalactic regions. We model the brightness temperature at location $x$ in our simulations as

$$T_b(x) = T_{b, x_{\text{HI}}} (x) \Delta (x),$$

(10)

where the mean temperature $T_b \approx 22 \, \text{mK}[(1 + z)/7]^{1/2}$ (Choudhury et al. 2009), $x_{\text{HI}}$ is the neutral hydrogen fraction in a cell, and $\Delta$ is the gas density in units of the average density in the simulation. The above relation neglects the impact of redshift space distortions due to peculiar velocities, and possible fluctuations in the spin temperature, i.e., it implicitly assumes that the spin temperature is much greater than the CMB temperature and that the Ly$\alpha$ coupling is sufficiently complete throughout the IGM. This is a good approximation in the redshift range considered here, when the global ionized fraction is greater than a few per
cent (Pritchard & Loeb 2012; Majumdar et al. 2014; Ghara et al. 2015). We derive the ionization field $x_{\text{HI}}$ in our simulation by placing sources of Lyman-continuum radiation in dark matter haloes and using the well-known excursion set method (Furlanetto et al. 2004; Choudhury et al. 2009; Mesinger et al. 2011). The total number of ionizing photons $N_\gamma$ produced by a halo is assumed proportional to the halo mass (Kulkarni et al. 2016)

$$N_\gamma(M) = N_{\text{LyC}} M,$$

where the proportionality factor $N_{\text{LyC}}$ includes the Lyman-continuum escape fraction. A grid cell at position $x$ is ionized if the condition

$$\zeta_{\text{eff}} f(x, R) \geq 1$$

(12)

is satisfied in a spherical region centred on the cell for some radius $R$. Here,

$$f \propto \rho_{\text{m}}(R)^{-1} \int_{M_{\text{min}}}^{\infty} dM \left. \frac{dN}{dM} \right|_R N_\gamma(M),$$

(13)

where $\rho_{\text{m}}(R)$ is the average matter density, $dN/dM|_R$ is the halo mass function in the sphere of radius $R$ and $M_{\text{min}}$ is the minimum mass of halos that emit Lyman continuum photons. The quantity $f$ is proportional to the collapsed fraction $f_{\text{coll}}$ into haloes of mass $M > M_{\text{min}}$ if $N_\gamma(M) \propto M$. The parameter $\zeta_{\text{eff}}$ here is the effective ionizing efficiency, which corresponds to the number of photons in the IGM per hydrogen atom in stars, compensated for the number of hydrogen recombinations in the IGM. It is the only parameter that determines the large scale ionization field in this approach. Cells that do not satisfy the criterion in Equation (12) are neutral. We denote the ionized volume fraction in a cell $i$
as $Q_i$. The total volume-weighted ionized fraction is then $Q_V \equiv \sum_i Q_i/n_{\text{cell}}$, where $n_{\text{cell}}$ is the total number of grid cells.

We consider two reionization models in this paper. The evolution of the ionized fraction $Q_V$ is identical in both models, and follows the evolution in the Late/Default model of Kulkarni et al. (2016). The simulation box is completely ionized, i.e., $Q_V = 1$, at $z = 6$. This evolution of the ionized fraction is consistent with the constraint from the CMB measurement of the electron scattering optical depth. The two models differ however in the range of halo masses that contribute to reionizing photons. In one of the models, we set the value of the minimum halo mass in Equation (13) to be $M_{\text{min}} = 2.3 \times 10^8 \, M_\odot$, which is approximately the mass of the smallest halo resolved in our simulation at $z = 7$. This model should represent reionization dominated by star-forming galaxies reasonably well. In our second reionization model, we assume $M_{\text{min}} = 10^{11} \, M_\odot$. Only high-mass haloes contribute to reionization in this model. This model represents a quasar-dominated reionization process (Kulkarni et al. 2017).

The bottom two panels of Figure 2 show the evolution of

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.pdf}
\caption{The [C\textsc{ii}] power spectrum (including the shot noise contribution), 21 cm power spectrum, and [C\textsc{ii}]-21cm cross power spectrum at redshifts $z = 6-9$ for the galaxies-dominated reionization model. Error bars on the [C\textsc{ii}] power spectra show the 1σ sensitivities for CONCERTO for $\Delta z = 0.5$ at $z = 7$. Two sets of shaded regions show errors corresponding to LOFAR and SKA1-LOW. On the cross power spectra on the right panels, orange (yellow) lines are for negative (positive) cross-correlation coefficients.}
\end{figure}
21 cm brightness in our two reionization models. These light cones are analogous to those obtained for the [C ii] emission, shown in the top two panels of this figure. Although the average ionized hydrogen fraction is the same in the two reionization models, the distribution of the 21 cm signal is quite different. The quasar-dominated reionization model has large and more clustered ionized regions with low 21 cm brightness. More importantly, in the galaxies-dominated reionization model, every source of [C ii] emission is also a source of hydrogen-ionizing photons. As a result, the distribution of the 21 cm signal is anti-correlated with that of the [C ii] signal: every [C ii] source is located in regions with low 21 cm brightness. In the quasar-dominated reionization model, on the other hand, [C ii] emitters in haloes with masses less than $M_{\text{min}} = 10^{11} \, M_{\odot}$ do not contribute any hydrogen-ionizing photons. As a result, these low-mass [C ii]-emitters are located in neutral regions, which are bright in 21 cm. This has an important effect on the [C ii]-21 cm correlation.

The middle columns of Figures 3 and 4 show the predicted 21 cm power spectra in our simulation in the galaxies-dominated and quasar-dominated reionization models, respectively. The power spectrum has a familiar shape: at small scales it is dominated by the matter power spectrum, and at large scales by a prominent “bump” due to ionized bubbles. At $k = 0.1 \, h/\text{cMpc}$ the amplitude of the 21 cm power spectrum evolves from $\Delta^2(k) \sim 2 \, \text{mK}^2$ at $z = 9$. 

Figure 4. As Figure 3 but for the quasar-dominated reionization model. The [C ii] power spectra are identical to those in Figure 3. The 21 cm power spectra and the [C ii]-21 cm cross power spectra from Figure 3 are shown in dashed black for comparison.
to 10 mK$^2$ at $z = 7.1$ in the galaxies-dominated reionization model. In the quasar-dominated case, the large-scale amplitude of the 21 cm power spectrum is higher, with $\Delta^2(k) \sim 35$ mK$^2$ at $z = 9$ to 30 mK$^2$ at $z = 7.1$, due to the higher clustering of ionized regions (Kulkarni et al. 2017). Note that our power spectrum amplitudes are somewhat higher than those in the quasar-dominated model considered by Kulkarni et al. (2017) because we ignore 21 cm emission from self-shielded regions within ionized regions. Figures 3 and 4 also show the sensitivity of experiments aiming to detect the 21 cm signal. We discuss this in Section 5 below.

4 THE [C II]-21CM CROSS POWER SPECTRUM

An exciting prospect for high-redshift [C II] intensity mapping is to combine it with observations of the coeval redshifted 21 cm line signal from the epoch of reionization. A detection of the [C II]-21cm cross power spectrum will assist in foreground decontamination and complement the [C II] and 21 cm power spectra as a probe of the epoch of reionization (Visbal & Loeb 2010; Lidz et al. 2011). Furthermore, the [C II]-21cm cross power spectrum may act as a direct tracer of the growth of ionizing bubbles during reionization (Gong et al. 2012).

As discussed above, Figure 2 shows light cones of the [C II] and 21 cm intensity. Typically, on large scales, we expect the [C II] emission from halos and the 21 cm signal from the IGM to be anti-correlated, because fully neutral regions do not contain emitting galaxies, while the halo rich regions are depleted of neutral hydrogen. On scales smaller than the ionized bubbles, however, there is positive correlation between the two fields. This behaviour is visually apparent in Figure 2, particularly at redshift $z \sim 7$, where the ionized regions are sufficiently large.

In order to study this cross-correlation quantitatively, we define the cross power spectrum of the [C II] and 21 cm intensity maps as

$$\Delta^2(k) = \frac{k^3}{2\pi^2} \frac{1}{V_{\text{box}}} \langle \tilde{I}_1(k) \tilde{I}_2(k) + \tilde{I}_1(k) \tilde{I}_2^*(k) \rangle,$$

(14)

where $I_1$ and $I_2$ denote the intensities of [C II] and 21 cm, respectively. The result is shown in the right column of Figures 3 and 4 for our galaxies-dominated and quasar-dominated reionization models, respectively. On large scales the cross-correlation is negative, as expected. In both models, at $k = 0.1$ h$/c$Mpc, the value of the cross power spectrum is $\sim 10^2$ mK Jy/Hz at redshift $z \sim 9$. This increases to close to $5 \times 10^2$ mK Jy/Hz at $z \sim 6$. (Figures 3 and 4 also show the experimental sensitivities for measuring the cross power spectra; we discuss this in the next section.)

The scale at which the cross power spectrum transitions from positive to negative values is quite different in the two reionization models. In the galaxies-dominated model, this scale is at $k_{\text{transition}} = 3-5$ h$/c$Mpc, while it is close to $k_{\text{transition}} = 0.3$ h$/c$Mpc in the quasar-dominated model. This is consistent with the picture that the transition scale measures the average size of ionized regions. As seen in Figure 2, the ionized regions are larger in the quasar-dominated model, which is reflected in the value of the transition scale of the cross power spectrum. Figure 5 shows the evolution of the transition scale in the two models. The blue curve in this figure shows the evolution of the average bubble size $k_{\text{bubble-size}}$ in the simulation, as measured by the cube root of the ionized volume. The evolution of the cross power spectrum transition scale in the galaxy dominated model follows that of $k_{\text{bubble-size}}$, whereas the evolution in the transition scale for the quasar-dominated model has a qualitatively different trend. This is because in the galaxies-dominated reionization model, each [C II] source is also a source of hydrogen ionizing photons. Therefore, every [C II] source is in an ionized region, and there is perfect anti-correlation between the [C II] and 21 cm fields at scales larger than the bubble size. This is not the case in the quasar-dominated reionization model, where most [C II] sources lie in neutral regions.

5 INTENSITY MAPPING EXPERIMENTS

To estimate the feasibility of [C II] intensity mapping, we consider the the CONCERTO experiment (Lagache 2018; Serra et al. 2016). We also consider a successor Stage II experiment beyond CONCERTO. The specifications for these two experiments are summarised in Table 1. Our choice of
the Stage II experiment parameters is inspired by the CCAT-p telescope\footnote{www.ccatobservatory.org/docs/pdfs/Draft_CCAT-p.prospectus.170809.pdf}. For the 21 cm signal from the same redshifts, we consider measurements using LOFAR and SKA.

5.1 [C II] experimental sensitivities

We estimate the sensitivity of experiments to measure the [C II] power spectrum by computing the uncertainty on the power spectrum following Lidz et al. (2011); Gong et al. (2012) and Serra et al. (2016):

$$\text{var}[P_{\text{CII}}(k)] = \frac{[P_{\text{CII}}(k) + P_{\text{N,CII}}(k)]^2}{N_m(k, z)},$$  \hspace{1cm} (15)

where $P_{\text{CII}}(k)$ is the model power spectrum, $N_m$ is the number of modes in the survey volume with wavenumber $k$ at redshift $z$, and $P_{\text{N,CII}}$ is the noise power spectrum. The noise power spectrum is given by

$$P_{\text{N,CII}} = V_{\text{pix}} \frac{\sigma_{\text{pix}}^2}{t_{\text{pix}}},$$  \hspace{1cm} (16)
where $V_{\text{pix}}$ is the volume surveyed by a single pixel, $t_{\text{pix}}$ is the observing time per pixel, and $\sigma^2_{\text{pix}}$ is the noise variance per spectral element. The observing time per pixel is given by

$$t_{\text{pix}} = t_{\text{survey}}N_{\text{pix}} \frac{\Omega_{\text{beam}}}{A}.$$  (17)

Here, $t_{\text{survey}}$ is the survey duration, which we take to be 1500 hr. The beam area $\Omega_{\text{beam}}$ is given by $\Omega_{\text{beam}} = 2\pi (\theta_{\text{beam}}/2.355)^2$, where $\theta_{\text{beam}} = 1.22A_{\text{beam}}/D$ and $D = 12\text{ m}$ for CONCERTO. We assume a survey area of $A = 2\text{ deg}^2$.

The volume surveyed by one pixel is given by (Gong et al. 2012)

$$V_{\text{pixel}}(z) = 1.1 \times 10^8 (\text{cMpc}/h)^3 \left[ \frac{\lambda}{158 \text{ m}\mu\text{m}} \right]$$

$$\times \left( \frac{1 + z}{8} \right)^{1/2} \left( \theta_{\text{beam}}/10 \text{ arcmin} \right)^2 \left( 400 \text{ MHz} \right).$$  (18)

The noise variance $\sigma^2_{\text{pix}}$ in Equation (16) is given by

$$\sigma^2_{\text{pix}} = \frac{\text{NEI}}{N_{\text{pix}}}$$  (19)

where the noise equivalent power input from diffuse emission, defined as the power from diffuse emission absorbed that produces a signal-to-noise ratio of unity at detector output, is (in MJy sr$^{-1}$ s$^{1/2}$)

$$\text{NEI} = \frac{10^{-9}}{\Omega_{\text{beam}}}.$$  (20)

For CONCERTO, $\text{NEI} / \sqrt{N_{\text{pix}}}=155$ mJy s$^{1/2}$ (see Table 3 of Serra et al. 2016), assuming an overall transmission of the system $T = 0.3$, a spectral resolution $\delta \nu = 1.5$ GHz, a number of pixel (and thus of spectrometer) $N_{\text{pix}}=1500$, a precipitable water vapor of 2 mm, an elevation of 60 degrees, and assuming the sensitivity already achieved by the NIKA2 KIDS detectors on sky (Adam et al. 2018).

The number of Fourier modes $N_m$ in Equation (15) is given by

$$N_m(k, z) = 2\pi k^2 \Delta k V_{\text{survey}}(2\pi)^3.$$  (21)

Here, $\Delta k$ is the bin size assumed in $k$-space, and the survey volume is given by

$$V_{\text{survey}}(z) = 3.7 \times 10^7 (\text{cMpc}/h)^3 \left[ \frac{\lambda}{158 \text{ m}\mu\text{m}} \right]$$

$$\times \left( \frac{1 + z}{8} \right)^{1/2} \left( \frac{A}{16 \text{ deg}^2} \right)^2 \left( \frac{B_\nu}{20 \text{ GHz}} \right).$$  (22)

This allows us to estimate $\text{var}[P_{21}(k)]$ using Equation (15). Table 1 summarises all the properties of the CONCERTO experiment.

The left columns in Figures 3 and 4 show the uncertainties in the [C II] power spectrum for the CONCERTO experiment from $z \sim 6$ to $z \sim 9$. We find that the CONCERTO should be able to measure the large scale power spectrum of [C II] emission to redshifts of up to $z = 8$ (with a signal-to-noise ratio of $\gtrsim 1$ at $k = 0.2\text{ h}/\text{cMpc}$ with 1500 hr of integration). Our predictions thus agree with the “pessimistic” case discussed by Lagache (2018).

For the Stage II experiment, we consider a noise variance per pixel $\sigma^2_{\text{pix}}$ that is five times better than CONCERTO. We assume an aperture size of $D = 6\text{ m}$, and a spectral resolution of $\delta \nu = 400$ MHz. The survey duration is assumed to be $t_{\text{survey}} = 1000$ hr, while the survey area is set to $A = 10\text{ deg}^2$. These parameters are also summarised in Table 1. The left columns in Figure 6 shows the uncertainties in the [C II] power spectrum for the Stage II experiment from $z \sim 6$–9. The signal-to-noise ratio is now enhanced by a factor of $\sim 70$ relative to CONCERTO at $k = 0.2\text{ h}/\text{cMpc}$, which makes the power spectrum detectable even at $z \sim 9$ with a signal-to-noise ratio of $\sim 70$ at $k = 0.2\text{ h}/\text{cMpc}$.

### 5.2 21 cm experimental sensitivities

We study here the detectability of the 21 cm power spectrum for Low Frequency Array (LOFAR; van Haarlem et al. 2013, and the low frequency instrument from Phase 1 of the Square Kilometre Array (SKA1-LOW; http://astronomers.skatelescope.org). These are listed in Table 2. Similar to Equation (15), the variance of the power spectrum at mode $k$ and redshift $z$ is given by

$$\text{var}[P_{21}(k)] = \frac{\left[ P_{21}(k) + P_{21}^\dagger(k) \right]^2}{N_m(k, z)}.$$  (23)

The noise power spectrum $P_{21}^\dagger(k)$ is now estimated as follows. Following Thompson et al. (2007), we assume a system temperature of

$$T_{\text{sys}} = 60 \text{ K} \left( \frac{300 \text{ MHz}}{\nu_c} \right)^{2.25},$$  (24)

and calculate the thermal noise power for an integration over 180 days, assuming a bandwidth of 6 MHz, an observing time of 6 hr per day, and a mid-latitude location.

We follow Parsons et al. (2012) for calculating experimental sensitivities, which we briefly summarize below. The $uv$ coverage of an interferometric array, obtained by accounting for a rotation synthesis of array baselines, is binned in $uv$ pixels. Each pixel then corresponds to an independent sampling of a transverse $k_\parallel$ mode of the cosmological 21 cm signal. For each such sampling, the array measures a range of line-of-sight $k_\perp$ modes depending on the bandwidth and frequency resolution. The thermal noise power for each mode is given by

$$P_{21}^N(k) \approx X^2 Y \frac{\Omega_{\text{sys}}}{2\ell} T_{\text{sys}}^2.$$  (25)

where $k = (k_\parallel^2 + k_\perp^2)^{1/2}$, $\Omega$ is the field of view of an element of the array, and $\ell$ is the total integration time for this $k$-mode (McQuinn et al. 2006; Parsons et al. 2012). The field of view is given by $\lambda^2/A_{\text{eff}}$ where $\lambda = 21\text{ cm}(1 + z)$ and $A_{\text{eff}}$ is the effective area of an interferometric element.

The cosmological quantities $X$ and $Y$ convert from angles and frequencies to comoving distance, respectively, and are given by (Parsons et al. 2012)

$$X \approx 1.9 \frac{h^{-1}\text{cMpc}}{\text{arcmin}} \left( \frac{1 + z}{10} \right)^{0.2},$$  (26)

and

$$Y \approx 11.5 \frac{h^{-1}\text{cMpc}}{\text{MHz}} \left( \frac{1 + z}{10} \right)^{0.5} \left( \frac{\Omega_m h^2}{0.15} \right)^{-0.5}.$$  (27)

The factor of two in Equation (25) assumes measurement of two orthogonal polarizations. To obtain the total thermal noise power, the power from individual modes, given
by Equation (25), is in quadrature. We assume that every baseline can contribute to the measurement of each $k$-mode, i.e., that the range of $k_j$ is broad enough. When multiple non-instantaneously redundant measurements are made, measurements of a $k$-mode can be added up in quadrature thereby reducing the uncertainty in power by the square root of number of measurements. On the other hand, multiple instantaneously redundant measurements of a $k$-mode are equivalent to coherent integration of the temperature measurement. This reduces the uncertainty in power with increasing number of measurements. In this work, we add all sampling in quadrature. This is this a worst case noise estimate.

We combine redundant measurements in each $k$-bin in which the power spectrum is measured. For logarithmic bins of width $\Delta \ln k$, this modifies the thermal noise power of Equation (25) so that

$$P_{21}^N(k) \approx X^2 Y^{k-1/2} \frac{1}{2\pi^2} \left( \frac{1}{B} \right)^{1/2} \left( \frac{1}{\Delta \ln k} \right)^{1/2} \frac{\Omega}{\Delta t_{\text{sys}}^2} \sqrt{N},$$

where $B$ is the bandwidth of the observation, which decides the total number of $k$-modes observed for a given resolution. In this paper, we assume $B = 6$ MHz for both LOFAR and SKA1-LOW.

A second combination is performed over measurements of the same $k$-mode by different baselines as they are moved into suitable $uv$-pixels by Earth’s rotation. We assume that $N_{\text{ant}}$ antennas are distributed uniformly up to a maximum baseline $b_{\text{max}}$. Thus all redundant measurements are added in quadrature and instantaneously redundant measurements are ignored. Since we assume that each mode can be observed by every baseline, that introduces a term $\propto 1/\sqrt{N}$, where $N$ is number of baselines. Following Parsons et al. (2012), we first sum the sensitivity over rings of $uv$-pixels and then sum over all such rings. This results in a power spectrum given by

$$P_{21}^N(k) \approx X^2 Y^{k-1/2} \frac{1}{2\pi^2} \left( \frac{1}{B} \right)^{1/2} \left( \frac{1}{\Delta \ln k} \right)^{1/2} \frac{\Omega}{\Delta t_{\text{sys}}^2} \sqrt{N_{\text{ant}}} \frac{1}{\Omega_{\text{per-day}}^2},$$

where $N_{\text{ant}}$ is the maximum baseline $b_{\text{max}}$ in wavelength units. We assume $t_{\text{per-day}} = 6$ hr for 120 days.

The thermal noise power spectrum calculated using Equation (29) determines the power spectrum sensitivity of 21 cm experiments. The middle columns of Figures 3 and 4, show the resultant uncertainties in the 21 cm power spectrum for LOFAR (yellow) and SKA (brown). These experiments are only sensitive to large scales due to limited baselines. Neither of the experiments are sensitive to 21 cm power for $k \lesssim 1$ cMpc$^{-1}$. SKA1-LOW has much greater sensitivity than LOFAR primarily due to large number of antenna elements. The signal to noise ratio is about 100 for these two experiments $k \sim 0.1$ cMpc$^{-1}$. LOFAR has sensitivity for scales corresponding to $k \lesssim 0.2$ cMpc$^{-1}$. At $k \sim 0.1$ cMpc$^{-1}$, the signal to noise ratio for LOFAR is $\sim 10$.

### 5.3 CII-21cm cross power spectrum sensitivity

We calculate the uncertainty on the cross power spectrum of [C II] with 21 cm following Gong et al. (2012),

$$\text{var}[P_{CII, 21}(k, z)] = \frac{1}{2} \left[ \frac{P_{21, CII}^2 + P_{21, CII}^{\text{total}}(k, z) P_{\text{total}}}{N_{\text{sys}}(k, z)} \right],$$

where

$$P_{21}^{\text{total}}(k, z) = P_{21}(k, z) + P_{21}^N(k, z),$$

and

$$P_{CII}^{\text{total}}(k, z) = P_{CII}(k, z) + P_{CII}^N(k, z).$$

The right-hand-side columns in Figures 3 and 4 show the errors on the cross power spectra for CONCERTO-LOFAR (cyan) and CONCERTO-SKA (blue) combinations. In both cases, a high signal-to-noise detection of the cross power spectrum is possible only for scales larger than $k \sim 0.1$ cMpc$^{-1}$. These scales evolve moderately up to $z = 10$. In the galaxies-dominated reionization model, the transition scale at which the cross power spectrum changes sign is at $k \sim 5$ cMpc$^{-1}$, which is out of the experimental reach. However, as discussed in the previous section, the transition scale is much larger, $k \sim 0.3$ cMpc$^{-1}$, in the case of the quasar-dominated reionization. This allows a detection of this scale, at least at redshifts $z = 6$ and 7. Figure 6 shows errors on the cross power spectra for LOFAR (cyan) and SKA (blue) combined with our Stage II [C II] experiment. As expected the sensitivities are enhanced now to scales $k \sim 5$ cMpc$^{-1}$ for LOFAR and $k > 6$ cMpc$^{-1}$ for SKA at $z = 7$. Note that as the 21 cm signal originates in the extended IGM, the shot noise contribution to the 21 cm power spectrum and the [C II]-21cm cross power spectrum is subdominant (Kulkarni et al. 2016) and is not computed here.

### 6 FORECASTS FOR CONSTRAINTS

We now consider the constraints that can be obtained for astrophysical parameters related to reionization from measurements of (a) the 21 cm power spectrum alone, and (b) the 21 cm power spectrum and the [C II]-21cm cross power spectrum. A variety of astrophysical parameters determine the [C II] and 21 cm emission from the high-redshift universe. As such [C II] and 21 cm experiments can potentially constrain all of these. However, for simplicity, we consider only two parameters. We consider a scenario in which haloes down to the mass corresponding to the atomic hydrogen cooling limit $T_{\text{vir}} = 10^4$ K produce [C II] emission, but only haloes with mass $M > M_{\text{esc}}$ have a non-zero Lyman-continuum photon escape fraction. Our simulation resolves haloes close to the atomic hydrogen cooling limit. Thus, this scenario assumes that all haloes in our simulation are able to produce [C II] emission, but only massive haloes with mass $M > M_{\text{esc}}$ participate in reionization of the IGM. The second parameter of our model is $N_{\text{esc}}^{\text{LyC}}$, which appears in Equation (11) and sets number $N_{\gamma}$ of ionizing photons produced by a halo. Our two parameters, $M_{\text{esc}}$ and $N_{\gamma}^{\text{LyC}}$ thus set the minimum mass of haloes that produce ionizing photons and their Lyman-continuum brightness, respectively. The dependence of the Lyman-continuum photon escape fraction on the halo mass...
is not well understood. Our choice of these parameters is therefore a simple proof of concept. Nonetheless, some simple radiative transfer models in the literature do suggest that Lyman-continuum photons are able to escape from a narrow range of halo masses (Ferrara & Loeb 2013). Our parameterisation describes this possibility.

To assess the capability of observations to constrain the parameters $M_{\text{esc}}$ and $N_{\gamma}^{\text{LyC}}$, we create mock power spectra with experimental uncertainties and derive posterior probability distributions for these parameters using MCMC. This approach is similar to that considered, for instance, for 21 cm experiments by Greig & Mesinger (2015). Our mock data sets for 21 cm and [C ii] in the galaxies-dominated reionization model are those shown in Figure 3. These have $M_{\text{esc}} = 5.56 \times 10^8 \, M_\odot$ and $N_{\gamma}^{\text{LyC}} = 3.5$. The associated errors are also those shown in Figure 3. For the quasar-dominated reionization model, the mock data and associated errors are taken from Figure 4. This model has $M_{\text{esc}} = 10^{11} \, M_\odot$ and $N_{\gamma}^{\text{LyC}} = 14$.

We infer the posterior distributions for $M_{\text{esc}}$ and $N_{\gamma}^{\text{LyC}}$ by writing a Gaussian likelihood for the data as

$$L(\Delta^2 | M_{\text{esc}}, N_{\gamma}^{\text{LyC}}) \propto -2 \sum_i \text{var}(k_i)$$

$$-2 \sum_i \frac{\left( \Delta_{\text{mock}}^2(k_i) - \Delta_{\text{model}}^2(k_i, M_{\text{esc}}, N_{\gamma}^{\text{LyC}}) \right)^2}{\text{var}(k_i)}, \quad (33)$$

where $\Delta^2$ denotes the power spectrum or the cross-power spectrum, as the case may be, the index $i$ runs over the $k$-bins, and var is the error on the mock observation. We then use a modified version of the 21 cm inference code 21CMMC (Greig & Mesinger 2015) to derive posterior distribution for the parameters $M_{\text{esc}}$ and $N_{\gamma}^{\text{LyC}}$ assuming wide, uniform priors.

The resultant posterior joint probability distributions are shown in Figure 7. Panels in the top row describe the galaxies-dominated reionization scenario, and those in the bottom row describe the quasar-dominated reionization scenario. The two panels in each case refer to the use of LOFAR and SKA for the 21 cm power spectrum measurement. The dashed lines show the location of the “true” values of the parameters, which were used to produce the mock data. The yellow contours show the 1σ and 2σ constraints when only 21 cm power spectrum data is used. In this case, there is a strong degeneracy in the two parameters in the galaxies-dominated reionization scenario. This degeneracy persists in the quasar-dominated case, although its magnitude is considerably reduced. Constraints in the quasar-dominated case are good even with the 21 cm data alone, as the power spectrum has an enhanced amplitude in this case, which allows for a high signal-to-noise measurement. Contours in other colours in Figure 7 show constraints obtained when the [C ii]-21 cm cross power spectrum data is added to the analysis. We find that this considerably improves the constraints for the Stage II [C ii] experiment. With data from 1000 hr and 5000 hr of the Stage II experiment, the improvement in 1σ constraints on $M_{\text{esc}}$ relative to 21 cm measurements is by factors of 3 and 10 respectively. The improvement is of a comparable magnitude in the quasar-dominated case. The constraints also show a modest improvement when SKA measurements are considered instead of LOFAR. Due to low signal-to-noise, 1500 hr data from CONCERTO do not result in a significant improvement in the constraints.

### Table 1. Specifications for [C ii] experiments considered in this paper.

| Parameter | LOFAR | SKA1-LOW |
|-----------|-------|----------|
| Number of antennae ($N_{\text{ant}}$) | 48 | 512 |
| Effective collecting area ($A_{\text{eff}}$) | 526.0 m² | 962.0 m² |
| Maximum baseline ($b_{\text{max}}$) | 3475.6 m | 40286.8 m |
| Minimum baseline ($b_{\text{min}}$) | 22.92 m | 16.8 m |
| Survey duration per day ($t_{\text{per-day}}$) | 6 hr | 6 hr |
| Survey number of days | 120 | 120 |
| System temperature ($T_{\text{sys}}$) | Equation (24) | Equation (24) |

### Table 2. Specifications for 21 cm experiments considered in this paper. We use SKA parameters obtained by Ghara et al. (2016) which broadly agrees with the baseline distribution given in the latest SKA1-LOW configuration document (Document number SKA-SCI-LOW-001; date 2015-10-28; http://astronomers.skatelescope.org/documents/).
7 CONCLUSIONS

We have outlined the prospects of intensity mapping the epoch of reionization using the redshifted 21 cm line and the [C II] emission line from high-redshift galaxies. We have modelled the galaxy line emissions using a semi-analytical model. Using a high dynamic range cosmological simulation, we found that on large scales of $\gtrsim 60 \, c\, \text{Mpc}/h$ at redshift $z = 6$ the spherically averaged power spectrum of the [C II] line emission have values of $\Delta^2 \sim 10^5 \, (\text{Jy}/\text{sr})^2$ at $k \sim 0.2 \, h/c\, \text{Mpc}$. This value reduces to about $10^3 \, (\text{Jy}/\text{sr})^2$ at $z \sim 9$.

We find that the [C II] power spectrum predicted in our model should be detectable with the CONCERTO experiment up to $z \sim 8$ with a signal-to-noise ratio of $\gtrsim 1$ at $k = 0.2 \, h/c\, \text{Mpc}$. A Stage-II experiment with five times better sensitivity than CONCERTO should be able to detect the [C II] power spectrum at even higher redshifts. The cross power spectrum of the [C II] and coeval 21 cm signal from the epoch of reionization would be valuable in many ways. The scale at which this cross power spectrum changes sign can constrain the average size of ionized regions, at least when the sources of reionization coincide with the galaxies that produce the [C II] signal. A detection of this cross power spectrum could help in the removal of low-redshift foregrounds.
from the 21 cm data. The cross power spectrum will also provide constraints on important astrophysical parameters. We have investigated the capability by analysing mock 21 cm power spectrum data and [C ii]–21cm cross power spectrum data in a Bayesian way to derive constraints under various experimental assumptions. We find that [C ii]–21cm correlation measurements can improve constraints on the mass of reionization sources by factors of 3–10 beyond constraints from 21 cm experiments alone.

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