Constraining the evolution of CII intensity through the end stages of reionization

Hamsa Padmanabhan*

Institute for Particle Physics and Astrophysics, ETH Zurich, Wolfgang-Pauli-Straße 27, CH-8093 Zürich, Switzerland

ABSTRACT
We combine available constraints on the local CII 158 μm line luminosity function from galaxy observations (Hemmati et al. 2017), with the evolution of the star-formation rate density and the recent CII intensity mapping measurement in Pullen et al. (2018, assuming detection), to derive the evolution of the CII luminosity - halo mass relation over z ≈ 0 − 6. We develop convenient fitting forms for the evolution of the CII luminosity - halo mass relation, and forecast constraints on the CII intensity mapping power spectrum and its associated uncertainty across redshifts. We predict the sensitivities to detect the power spectrum for upcoming PIXIE-, STARFIRE-, EXCLAIM-, CONCERTO-, TIME- and CCAT-p-like surveys, as well as possible future intensity mapping observations with the ALMA facility.

Key words: cosmology:observations – radio lines:galaxies – cosmology:theory

1 INTRODUCTION
Intensity mapping of atomic and molecular lines has emerged as a novel approach towards the study of large scale structure. Having been widely used for studying neutral hydrogen (e.g., Chang et al. 2010; Masui et al. 2013; Switzer et al. 2013; Anderson et al. 2018), it has now emerged as an exciting potential probe of various species of ionized and molecular gas in the post-reionization universe and recently, also the epoch of reionization (e.g., Gong et al. 2012; Lidz & Taylor 2016; Mashian et al. 2015; Dumitru et al. 2018). Since intensity mapping is sensitive to the total emission from all galaxies, it does not suffer from the magnitude cuts which are imposed on galaxy luminosity functions, and may thus offer a powerful tracer of the faintest galaxies thought to be responsible for reionization. Allowing for the low luminosity end of the galaxy population to be mapped effectively also makes this a complementary technique to galaxy surveys. In addition, cross-correlating various intensity mapping datasets provides a possible way of probing the large scale structure (e.g., Gong et al. 2012).

The fine structure line of ionized carbon (CII), with a rest wavelength 157.7 μm is thought to be an important tracer of the interstellar medium at the late stages of reionization (e.g., Gong et al. 2012; Serra et al. 2016; Li et al. 2016; Crites et al. 2017) due to its close association with star forming galaxies. This line arises due to a hyperfine transition between the 2P_1/2 and 2P_3/2 states of singly ionized carbon. CII is the dominant coolant in the interstellar medium, and with an ionization potential of 11.6 eV, the emission line is associated both with neutral and ionized hydrogen regions. The continuum foregrounds associated with CII emission are also smaller than for other emission lines. Above redshifts of about 0.6, the CII line becomes the brightest in the far-infrared and sub-millimetre part of galaxy spectra. It is known that the CII emission is closely connected to the star formation rate by a power law relation (De Looze et al. 2014) and thus offers constraints on the sources responsible for reionization. CII intensity mapping surveys also have the potential to constrain cosmology and models of inflation through measurements of primordial non-Gaussiansities (e.g., Fonseca et al. 2018; Moradinezhad Dizgah & Keating 2018).

There are several planned experiments that aim to place constraints on the integrated intensity of CII over the epoch of reionization, including (i) the Cerro Chajnantor Atacama Telescope (CCAT-prime; Parsley et al. 2018) 1 which plans to trace CII over z ∼ 5 − 8, probing the late stages of reionization, (ii) the Tomographic Intensity Mapping Experiment (TIME; e.g., Crites et al. 2014, 2017) and (iii) the CarbON CII line in post-reionization and Reionization TiOn (CONCERTO; Serra et al. 2016; Lagache 2018) experiment 2 which plans to observe the evolution of CII over z ∼ 4.5 − 8.5. Above z ∼ 4, the CII line redshifts into the millimetre wavelengths, where the Atacama Large Millimetre Array (ALMA) facility can make observations in the single dish mode; the ALMA bands 7 and 8 enable CII emission observations from z ∼ 2.8 − 5.

Much of the present data available in the context of CII observations at the epoch of reionization relies on individual galaxies, imaged e.g. with the ALMA telescope (Capak et al. 2015; Smit et al. 2018; Pentericci et al. 2016). On the other hand, local galaxies have been used to compute the CII luminosity function at z ∼ 0 (Hemmati et al. 2017). At redshifts z ∼ 2, observations of CII of-

---

1 http://www.ccatobservatory.org/docs/ccat-technical-memos/ccatp_m_v2.pdf
2 https://people.lam.fr/lagache.guilaine/CONCERTO.html
fer interesting prospects towards constraining the peak of the star formation rate density of the universe, however, these wavelengths are not accessible from the ground. Nevertheless, there are interesting prospects for balloon-based observations of CII at intermediate redshifts, $z \sim 1 - 1.5$ (Uzgil et al. 2014) as well as from upcoming studies of CMB spectral distortions (e.g., Kogut et al. 2011; Hernández-Monteagudo et al. 2017). Recently, the first tentative detection of the integrated CII intensity at $z \sim 2.6$ was reported in Pullen et al. (2018) using Planck intensity maps cross-correlated with BOSS quasars and CMASS galaxies from SDSS-III. The main observable in a CII intensity mapping survey is the power spectrum of intensity fluctuations, $P_{\text{CII}}(k,z)$ as a function of scale and redshift. The astrophysical component of the power spectrum is encoded by the relation between the CII luminosity (which is used in computing the integrated emission intensity), and the underlying halo mass. Several theoretical and simulation approaches have been used to place constraints on this relation and the power spectrum of CII fluctuations up to the mid- to the end stages of reionization (e.g., Gong et al. 2012; Yue et al. 2015; Serra et al. 2016; Silva & Kulkarni 2017; Padmanabhan et al. 2017) and the evolution of the CII luminosity - halo mass relation (e.g., Hemmati et al. 2017). We combine this information with the recent high-redshift constraints on the CII intensity (Pullen et al. 2018, assuming the CII detection) at $z \sim 2.6$ to model the evolution of this relation at higher redshifts, and find the predictions to be consistent with the currently available observational limits from galaxy data at $z \sim 4 - 6$ (Matsumura et al. 2015; Swinbank et al. 2012; Aravena et al. 2016). We use the CII luminosity - halo mass relation thus derived to calculate the power spectrum of intensity fluctuations across $z \sim 0 - 6$, and forecast its measurement sensitivity by future intensity mapping experiments.

The plan of the paper is as follows: In Sec. 2, we describe the current CII data used for constraining the model parameters and their evolution. We also describe the abundance matching procedure and the parameter constraints with their associated uncertainties. In the following section (Sec. 3), we use the resultant CII luminosity - halo mass relation to predict the power spectra of intensity fluctuations, both at low and high redshifts (up to $z \sim 6$). In Sec. 4, we use the results of the model with the parameters of several planned or upcoming CII intensity mapping experiments to place sensitivity forecasts on the expected CII auto-correlation signal. We summarize our results and discuss future prospects in Sec. 5. Throughout this work, we adopt a $\Lambda$CDM cosmology with the following parameters: $h = 0.71$, $\Omega_b = 0.046$, $\Omega_m = 0.281$, $\sigma_8 = 0.8$, $\Omega_{\Lambda} = 0.719$, $n_s = 0.963$.

## 2 MODELLING THE OCCUPATION OF CII

The main observable in CII intensity mapping is the power spectrum of fluctuations, denoted by $P_{\text{CII}}(k,z)$. This quantity is related to the intensity of the observed emission, given by:

$$I_{\nu,\text{CII}} = \frac{c}{4\pi} \int_0^\infty dz' \frac{\epsilon [\nu_{\text{obs}}(1+z')] D(H(z')(1+z'))^4}{H(z')(1+z')}$$

where the emissivity, $\epsilon(\nu)$ is given by:

$$\epsilon(\nu,z) = \delta_D(\nu - \nu_{\text{CII}})(1+z)^3 \int_{M_{\text{min,CII}}}^\infty dM \frac{dn}{dM} L_{\text{CII}}(M,z)$$

where $L_{\text{CII}}$ represents the luminosity of CII-emitting galaxies as a function of their halo mass $M$ and redshift $z$, and $M_{\text{min,CII}}$ stands for the minimum halo mass associated with CII-emitting galaxies. Thus the intensity of emission becomes:

$$I_{\nu,\text{CII}} = \frac{c}{4\pi} \frac{1}{\nu_{\text{CII}} H(z_{CII})} \int_{M_{\text{min,CII}}}^\infty dM \frac{dn}{dM} L_{\text{CII}}(M,z)$$

The above expression thus depends on the relation between the CII luminosity and halo mass at different redshifts. Various approaches in the literature have been used to constrain this relation from hydrodynamical simulations and semi-analytical techniques. Here, we develop a data-driven, halo model framework for modelling this relation, following similar approaches for stellar-halo mass relations (e.g., Behroozi et al. 2013; Moster et al. 2013), the HI - halo mass relation (e.g., Padmanabhan & Regfiger 2017; Padmanabhan & Kulkarni 2017; Padmanabhan et al. 2017) and the evolution of the CO luminosity - halo mass relation (e.g., Padmanabhan 2018).

The method outlined here relies on the technique of abundance matching, in which the relative abundances of CII-luminous galaxies and their associated host haloes are assumed to follow a one-to-one correspondence. In other words, the brightest CII emitting galaxies are assumed to populate the most massive dark matter haloes. The equivalence to the assumption that:

$$\int_{M(L_{\text{CII}})}^{\infty} \frac{dn}{d\log_{10} M} \frac{d\log_{10} M'}{d\log_{10} L_{\text{CII}}} = \int_{L_{\text{CII}}}^{\infty} \phi(L_{\text{CII}}) \frac{d\log_{10} L_{\text{CII}}}{L_{\text{CII}}}$$

where $dn/d\log_{10} M$ is the number density of dark matter haloes with logarithmic masses between $\log_{10} M$ and $\log_{10}(M + dM)$, and $\phi(L_{\text{CII}})$ is the corresponding number density of CII-luminous galaxies in logarithmic luminosity bins.
CII intensity mapping

At redshift zero, we use the recent available constraints on the local CII luminosity function observed with the Herschel PACS observations of the Luminous Infrared Galaxies in the Great Observatories All-sky LIRG Survey (Hemmati et al. 2017) to constrain the local CII luminosity - halo mass relation. Motivated by approaches to model the atomic hydrogen gas, in e.g., Padmanabhan et al. (2017), we use an $L_{\text{CII}} - M$ relation at $z \sim 0$ having a power law form with an exponential cutoff:

$$L_{\text{CII}}(M,z=0) = \left( \frac{M}{M_1} \right)^\beta \exp(-N_1/M)$$

with the three free parameters, $M_1$, $\beta$ and $N_1$ for the two characteristic mass scales and the slope of the relation.

We use the observed CII luminosity function [the raw data points in Hemmati et al. (2017)] abundance-matched to the Sheth-Tormen (Sheth & Tormen 2002) halo mass function in order to derive constraints on the parameters of the $L_{\text{CII}} - M$ relation from Equation (4). This gives the following best-fitting and error values for the free parameters:

$$M_1 = (2.39 \pm 1.86) \times 10^{-5}; \; N_1 = (4.19 \pm 3.27) \times 10^{11};$$
$$\beta = 0.49 \pm 0.38$$

Fig. 1 shows the luminosity function at $z \sim 0$ obtained from the best-fitting $L_{\text{CII}} - M$ relation thus obtained, and its associated uncertainty. Also shown are the data points from Hemmati et al. (2017) used in deriving this relation.

At high redshifts, the following datasets are available from candidate CII galaxies and blind searches:

(i) At $z \sim 4.4$, Swinbank et al. (2012) provide lower limits on the cumulative CII luminosity function based on observations of two ALMA candidate sub-millimetre galaxies (SMGs).

(ii) Matsuda et al. (2015) obtain upper limits on the cumulative CII luminosity function at $z \sim 4.5$, based on a blind search using ALMA archival data.

(iii) Aravena et al. (2016) obtain upper limits on the cumulative CII luminosity function at $z \sim 6$ from candidate CII-emitters.

The first constraints on the integrated CII emission, $I_{\nu,\text{CII}}$ at $z \sim 2.6$ have been placed by Pullen et al. (2018) using cross-power spectra between high-frequency Planck intensity maps, spectroscopic quasars from BOSS-DR12 and CMASS galaxies from SDSS-III, finding a tentative CII intensity measurement of $I_{\nu,\text{CII}} = 6.6^{+5.0}_{-4.9} \times 10^4 \text{ Jy sr}$ at 95% confidence.

To propagate the empirically derived $L_{\text{CII}} - M$ relation to higher redshifts, we use the observed evolution of the star formation rate density (SFRD; Madau & Dickinson 2014). This is consistent with the results of Hemmati et al. (2017), who find the observed CII luminosity function to evolve following that of the SFR (Behroozi et al. 2013), and Lagache et al. (2018) whose simulations do not find evidence for significant evolution in the $L_{\text{CII}}$ - SFR relation. The results of Pentericci et al. (2016) and Aravena et al. (2016) also find that the observations in the late stages of reionization closely follow the SFR-CII scaling, expressed in a power law form as $L_{\text{CII}} = SFR^\alpha$. Hence, the high-$z$ CII-halo mass relation can be expressed as:

$$L_{\text{CII}}(M,z) = \left( \frac{M}{M_1} \right)^\beta \exp(-N_1/M) \left( \frac{(1+z)^{2.7}}{1 + [(1+z)/2.9]^{5.6}} \right)^\alpha$$

The value of $\alpha$ is constrained by fitting the intensity mapping measurement of Pullen et al. (2018) at $z \sim 2.6$ using Eq. (3). This leads to $\alpha = 1.79 \pm 0.30$; the intensity mapping data may favor values consistent with (though slightly higher than) those predicted by the simulations of Lagache et al. (2018). The present data do not constrain a mass-dependent redshift evolution of the $L_{\text{CII}} - M$ relation, but only the component arising from the evolution of the star formation rate density. The data also do not constrain the redshift evolution of the parameter $\alpha$ itself, though several studies report the values for different galaxy samples across redshifts (e.g., De Looze et al. 2011). Such a redshift dependence may also be suggested by the results of simulations (Lagache et al. 2018).

The predicted evolution of the mean intensity of CII emission, $I_{\nu,\text{CII}}$ across redshifts is shown in Fig. 2 along with the data point at $z \sim 2.6$ from Pullen et al. (2018). The resultant $L_{\text{CII}} - M$ relation is also found to be consistent with the limits from the observations (Matsuda et al. 2015; Swinbank et al. 2012; Aravena et al. 2016) at higher redshifts $z \sim 4 - 6$, as shown in Fig. 3. Also shown are the results form the semi-analytical modelling of Popping et al. (2018) at $z \sim 4$ and $z \sim 6$, which uses a sub-grid treatment of SFR and ISM physics across redshifts.

---

$^3$ This measurement is also sensitive to the minimum halo mass $M_{\text{min,CII}}$ used in the calculation of $I_{\nu,\text{CII}}$. Throughout this work, we use $M_{\text{min,CII}} = 10^{10} h^{-1} M_\odot$ for consistency, which also gives a good fit to the intensity mapping data for sensible values of the evolution parameter $\alpha$.

$^4$ Note that this makes the implicit assumption that the SFRD is separable, i.e. SFR $(M,z) = f(M)g(z)$. Although this separability may not be strictly true in general, this functional form is found to provide a good fit to the available CII data (and is also supported by the fact that the CII luminosity functions thus derived closely resemble those from semi-analytic models involving more detailed sub-grid treatments of SFR and ISM physics across redshifts, e.g., in Fig. 3.
3 RESULTANT CII-HALO MASS RELATION AND POWER SPECTRUM

The CII luminosity-halo mass relation from the present data can thus be described by the functional form in Eq. (7), with the best-fitting parameters:

\[ M_1 = (2.39 \pm 1.86) \times 10^{-5}, \quad N_1 = (4.19 \pm 3.27) \times 10^{11}, \quad \beta = 0.49 \pm 0.38; \quad \alpha = 1.79 \pm 0.30 \]  

(8)

The relation for redshifts 0.5, 1.5, 5 and 6 is plotted on the panels of Fig. 4 along with the estimated uncertainty (shown by the grey bands). These can now be used to derive the predicted CII power spectrum of intensity fluctuations using the relations:

\[ P_{\text{shot}}(z) = \left( \frac{\int_{M_{\text{min},\text{CII}}}^{\infty} dM (dn/dM) L_{\text{CII}}(M, z)^2}{\int_{M_{\text{min},\text{CII}}}^{\infty} dM (dn/dM) L_{\text{CII}}(M, z)^2} \right)^2 \]  

(9)

representing the shot noise component, and

\[ b_{\text{CII}}(z) = \frac{\int_{M_{\text{min},\text{CII}}}^{\infty} dM (dn/dM) L_{\text{CII}}(M, z) b(M, z)}{\int_{M_{\text{min},\text{CII}}}^{\infty} dM (dn/dM) L_{\text{CII}}(M, z)} \]  

(10)

representing the clustering. In the above expression, \( b(M, z) \) denotes the dark matter halo bias following Scoccimarro et al. (2001). These can be combined to obtain the full power spectrum:

\[ P_{\text{CII}}(k, z) = I_{v,\text{CII}}(z)^2 [b_{\text{CII}}(z)^2 P_{\text{lin}}(k, z) + P_{\text{shot}}(z)] \]  

(11)

The power spectra of intensity fluctuations thus derived are plotted for \( z = \{0.5, 1.5, 5, 6\} \) in the panels of Figs. 5 and 6, in units of \((\text{Jy/sr})^2\). The associated uncertainty in each case is indicated by the grey band.

Also plotted for the higher redshift panels are the semi-empirical and simulation estimates for the same redshifts obtained in the literature:

\begin{itemize}
  \item (i) Vishal & Loeb (2010) present an analytical formalism to calculate the cross-correlation power spectra for different emission lines including OI, OII, OIII, NII and CO transitions.
  \item (ii) Gong et al. (2012) obtain the CII line intensity fluctuations over \( z \sim 6 - 8 \) by modelling the various radiative processes in the ISM both analytically and numerically.
  \item (iii) Silva et al. (2015) use four different models, m1, m2, m3 and m4 corresponding to different parameterizations of the CII luminosity to SFR relation coupled to results from simulations.
  \item (iv) Serra et al. (2016) present a framework based on measurements of the cosmic infrared background (CIB) to compute the intensity mapping power spectra of multiple far infra-red cooling lines in the ISM, including CII, NII, OI and the CO transitions.
\end{itemize}

Although there is considerable variation in the power spectra values in the literature, we note that the predicted values are also sensitive to the choice of the parameter \( M_{\text{min,\text{CII}}} \) as discussed in the previous section. Nevertheless, these plots provide an estimate of the effect of the intensity mapping measurement, if confirmed, on the sensitivities of future CII measurements at post-reionization epochs. We explore this more fully in the following section.

4 SENSITIVITY FORECASTS

In this section, we use the predicted evolution of the power spectra of CII intensity fluctuations to place constraints on the SNR expected from current and future experiments targeting CII over post-reionization epochs. We consider configurations resembling the following CII experiments in this work, with parameters as provided in Table 1:

\begin{itemize}
  \item (i) A Primordial Inflation Explorer (PIXIE: Kogut et al. 2011, 2014)-like mission which aims to measure spectral distortions of...
the CMB over a broad range of frequencies. This experiment will be able to detect CII intensity fluctuations at \( z \sim 0.05 \) – 11.7, and is suitable for wide field intensity mapping surveys, including in cross-correlation with galaxy data (e.g., Uzgil et al. 2014; Switzer 2017; Pullen et al. 2018). This survey can be assumed to cover the full sky area (E. Switzer, private communication); we restrict to \( 2\pi \) sr, corresponding to about 20000 deg\(^2\) in order to avoid the Galactic plane.

(ii) An upcoming Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE; Aguirre 2015; Hailey-Dunsheath et al. 2018\(^5\))-like experiment, a balloon-borne, far-infrared spectroscopic array with tomographic sensitivity to CII over \( z \sim 0.5 \) – 1.6, planned to be hosted on a 2.5 m aperture telescope.

(iii) An EXperiment for Cryogenic Large-Aperture Intensity Mapping (EXCLAIM)-like configuration (E. Switzer and A. Pullen, private communication) for CO and CII at redshifts \( z \sim 3 \), to be hosted on a 0.74 m aperture telescope.

(iv) The CONCERTO experiment aims to map CII evolution over \( z \sim 4.5 \) – 8.5 using the 12-m APEX telescope at Chajnantor in Chile (Lagache et al. 2018; Serra et al. 2016). Parameters for this work,

\[ z = 0.5 \]

\[ z = 1.5 \]

\[ z = 5.0 \]

\[ z = 6.0 \]
a CONCERTO-like configuration are based largely on the recent analysis of Dumitru et al. (2018).

(v) A Tomographic Intensity Mapping Experiment (TIME; Crites et al. 2017)-like configuration which aims to measure the CII line intensity emission over the redshift range $5 < z < 9$. We consider a survey area of 78' by 0.5' with a 12-m aperture telescope, and other parameters of the TIME-Pilot experiment following the discussions in Crites et al. (2014).

(vi) The Cerro Chajnantor Atacama Telescope (CCAT)-prime experiment (Parshley et al. 2018) with the Prime-Cam instrument (Vavagiakis et al. 2018) and P-Spec imaging spectrometer, plans to probe the late stages of reionization using CII line emission over $z \sim 5 - 8$. The parameters adopted for a CCAT-p-like configuration are based on the discussions in the document, https://www.ccatobservatory.org/docs/pdfs/DraftCCAT-p.prospectus.170809.pdf.

(vii) Finally, we consider a CII intensity mapping survey with the ALMA telescope (e.g. Carilli et al. 2018) based on the ALMA MACAL experiment (e.g., Klitsch et al. 2018) targeting CII line emission over $z \sim 5 - 9$. Such surveys have been discussed, e.g., in the context of the ALMA Spectroscopic Survey in the Hubble Deep Field (ASPECS; Walter et al. 2014; Carilli et al. 2016). The parameters used here correspond to a survey using the ALMA array over 1000 hours of observation targeting 5 arcmin$^2$.

For each experiment, we calculate the noise power spectrum using the following equations (Silva et al. 2015; Serra et al. 2016; Dumitru et al. 2018):

$$P_N = V_{\text{pix}} \sigma_N^2 t_{\text{pix}}$$

(12)

We now consider the terms in the RHS of the above Eq. (12) one by one. The time per observing pixel, $t_{\text{pix}}$, is given by:

$$t_{\text{pix}} = t_{\text{obs}} N_{\text{spec,eff}} \Omega_{\text{beam}} / A_{\text{survey}}$$

(13)

In the above expression, $t_{\text{obs}}$ is the total observing time, $A_{\text{survey}}$ is the survey area, $\Omega_{\text{beam}} = 2 \pi \sigma_{\text{beam}}^2$, with $\sigma_{\text{beam}} = \theta_{\text{beam}}/(2.355)$ in terms of the beam angular size $\theta_{\text{beam}}$.

The beam FWHM is calculated using the diffraction formula $\theta_{\text{beam}} = 1.22 \lambda_{\text{obs}} / D_{\text{dish}}$, where $\lambda_{\text{obs}} = 158 \mu\text{m} (1 + z)$ for all the experiments except the PIXIE-like configuration. For PIXIE, we assume a FWHM of 1.65 deg due to the detectors being highly multi-moded (Switzer 2017, and E. Switzer, private communication). $N_{\text{spec,eff}}$ is the effective number of detectors which integrate in parallel on voxels on a given frequency.$^6$

The pixel volume, $V_{\text{pix}}$, is given by (Gong et al. 2012; Dumitru et al. 2018):

$$V_{\text{pix}} = 1.1 \times 10^3 (\text{cMpc}/h)^3 \left( \frac{\lambda}{158 \mu\text{m}} \right) \left( \frac{1 + z}{8} \right)^{1/2} \left( \frac{\theta_{\text{beam}}}{10'} \right)^2 \left( \frac{\Delta \nu}{400\text{MHz}} \right)$$

(14)

as a function of the rest wavelength $\lambda$ of the line transition, the redshift $z$ and the spectral resolution $\Delta \nu$.

The variance per pixel, $\sigma_N$ in Eq. (12) is given by:

$$\sigma_N = \frac{\text{NEFD}}{\Omega_{\text{beam}}}$$

(15)

$^6$ Note that the CONCERTO-like configuration used here assumes that 1500 detectors integrate on voxels at a given frequency.

where the NEFD (Noise Equivalent Flux Density), can be calculated on the sky for the instrument under consideration by using the expression:

$$\text{NEFD} = \frac{\text{NEI}}{\sqrt{N_{\text{detectors}}}}$$

(16)

where the NEI is the Noise Equivalent Intensity (in units of Jy $s^{-1}/\text{ster}$) and represents the intensity required to achieve a signal-to-noise ratio of unity at the detector, and $N_{\text{detectors}}$ is the number of detectors.$^7$

$^7$ For some experiments, the value of the Noise Equivalent Power (NEP) is quoted instead of the NEI; the NEI is then calculated by using NEI $\approx$
Table 1. Various experimental configurations considered in this work. †: A FWHM of 1.65 deg is used as a good approximation for the PIXIE-like configuration (Switzer 2017) instead of the usual diffraction formula, due to the detectors being highly multi-moded. For the PIXIE-like, STARFIRE-like, EXCLAIM-like and CCAT-p-like configurations, the value of $\sigma_N$ is directly quoted in units of Jy s$^{-1/2}$/sr; for all other experiments, the value of the NEFD is quoted in mJy s$^{1/2}$. For PIXIE, the $\sigma_N$ is calculated from Eq. (15) assuming the NEP value $0.7 \times 10^{-16}$ W$/\sqrt{Hz}$ and the etendu of 4 cm$^2$ sr from Kogut et al. (2011). For the STARFIRE-like experiment, the median value of $\sigma_N$ from the experiment description in https://asd.gsfc.nasa.gov/conferences/FIR/posters/Aguirre_STARFIRE.pdf is used. *For the ALMA intensity mapping survey considered here, we use an ALMACAL-like configuration targeting CII in Band 6. The NEFD is calculated from the rms sensitivity in a field, which is taken to be roughly $S_{\text{rms}} = 0.09$ mJy on combining 30 pointings.

| Configuration       | $D_{\text{dish}}$ (m) | $\Delta \nu$ (MHz) | $N_{\text{spec, eff}}$ | $S_{\text{A}}$ (sq. deg.) | NEFD (mJy s$^{1/2}$/sr) | $\sigma_N$ (Jy s$^{1/2}$/sr) | $B_0$ (GHz) | $t_{\text{surv}}$ (h) |
|---------------------|-----------------------|--------------------|-------------------------|---------------------------|----------------------|-----------------------------|-------------|---------------------|
| PIXIE-like          | 0.55†                 | 15000              | 4                       | 20000                     | 5.83 $\times 10^6$†  | 120                         | 1500        |
| STARFIRE-like       | 2.5                   | 1700               | 100                     | 1                         | 2.6 $\times 10^6$†   | 15                          | 450         |
| EXCLAIM-like        | 0.74                  | 1000               | 6                       | 400                       | 6 $\times 10^6$†     | 120                         | 8           |
| CONCERTO-like       | 12                    | 1500               | 1500                    | 1.4                       | 155                  | 40                          | 1200        |
| TIME-like           | 12                    | 400                | 32                      | 0.01                      | 65                   | 40                          | 1000        |
| CCAT-p-like         | 6                     | 400                | 200                     | 16                        | 2.5 $\times 10^6$†   | 40                          | 4000        |
| ALMACAL-like *      | 12                    | 15                 | 3000                    | 0.0014                    | 2.85*                | 8                           | 1000        |

For the ALMACAL-like configuration, the survey considered targets CII in Band 6 using four 2 GHz windows. The NEFD = $S_{\text{rms}}^{1/2}$ is calculated from the integration time $t_{\text{int}} = 1000$ hours and the the rms sensitivity $S_{\text{rms}}$ in a field, which is taken to be roughly $S_{\text{rms}} = 0.09$ mJy on combining 30 pointings for this survey. $^8$ The $N_{\text{spec, eff}}$ here corresponds to the number of spatial resolution elements, which is close to 3000 for the full survey area (R. Dutta and T. Mroczkowski, private communication).

Once the noise power is known, the variance of the CII observation is calculated as:

$$\text{var}_\text{CII} = \left(\frac{P_{\text{CII}} + P_N}{N_{\text{modes}}}\right)^2$$  \hspace{1cm} (17)

with the number of modes given by:

$$N_{\text{modes}} = 2\pi k^2 \Delta k \frac{V_{\text{surv}}}{(2\pi)^2}$$  \hspace{1cm} (18)

with $\Delta k$ denoting the bin width in $k$-space (for all the experiments considered here, we use logarithmically eqiupaced $k$-bins with $\Delta \ln k = 0.05$), and the survey volume (Gong et al. 2012; Dumitru et al. 2018) given by:

$$V_{\text{surv}} = 3.7 \times 10^7 \left(\text{cMpc}/h\right)^3 \left(\frac{\lambda}{158 \mu m}\right)^2 \frac{1 + z}{8}^{1/2} \left(\frac{A_{\text{survey}}}{16\text{deg}^2}\right) \left(\frac{B_0}{20\text{GHz}}\right)^{-2}$$  \hspace{1cm} (19)

Finally, the SNR is calculated from Eq. (17) as:

$$\text{SNR} = \frac{P_{\text{CII}}}{(\text{var}_\text{CII})^{1/2}}$$  \hspace{1cm} (20)

for each experiment under consideration.

The SNRs for surveys with the seven experiments described above in Table 1 are plotted in the panels of Figs. 7, 8 and 9 respectively. As the sensitivity depends on the assumed $k$-bin size ($\Delta k$) through the number of modes (Eq. (18)), the SNRs for each experimental configuration are plotted as stair steps in $k$-space. The associated signal uncertainties are indicated by the thinner steps in each case. Note that the SNRs derived here may be somewhat optimistic since the derivation above does not take into account the beam and spectral width transfer functions. Specifically, SNR estimates beyond $k \sim 1$ Mpc$^{-1}$ may be subject to caveats coming from beam size in some configurations.

5 CONCLUSIONS

We have developed a data-driven, halo model based framework towards interpreting future intensity mapping experiments involving the ionized carbon (CII) emission with rest-wavelength 158 $\mu$m. Combining data from low redshift galaxy survey constraints (Hemmati et al. 2017) on the CII luminosity function, the empirical evolution of the star-formation rate density (Madau & Dickinson 2014).
and the high-redshift constraints from the recent intensity mapping experiment at \( z \sim 2.6 \) (Pullen et al. 2018, assuming the CII detection), we develop fitting forms for the local CII luminosity - halo mass relation and its predicted evolution with redshift. Although the current data at higher redshifts mainly provide upper or lower limits to the CII luminosity function, the predicted evolution is fully consistent with these constraints. This formalism is used to predict the power spectra of CII intensity fluctuations both at intermediate redshifts as well as towards the end stages of reionization. The best-fitting model and the parametrization are summarized in Table 2.

As indicated in Pullen et al. (2018), a confirmation of this initial CII intensity mapping measurement would provide exciting insights for galaxy evolution and the metallicity of the ISM. From the results of the present work, we find that it can also be used to investigate how the CII - SFRD relation evolves with redshift during and after the peak of star formation in the universe. An assumption implicit in the present model is that the CII-SFRD connection continues to hold up to \( z \sim 6 \) representing the end stages of reionization. This is supported by the recent findings of Smit et al. (2018) who find no evidence for a deviation in the mean CII luminosity - SFR relation at \( z \sim 6.8 \) (compared to \( z \sim 0 \) and \( z \sim 5.5 \) galaxies) from ALMA observations of OII - selected galaxies; however, at higher redshifts (\( z \sim 7 \)), other results (Pentericci et al. 2016) suggest a deficit in the CII luminosity compared to the lower redshift CII - SFR relation in Ly-\( \alpha \) selected CII galaxies. Clearly, further constraints on this dependency would be possible with the present model in conjunction with future CII surveys in the late stages of the reionization phase of the universe. Larger, homogeneous CII galaxy detections would also help place independent constraints on the evolution of the slope of the CII - SFRD relation, thus helping confirm the robustness of the intensity mapping measurements. Extrapolating this dependence to even higher redshifts would be possible with the data from blind or dedicated surveys with the JWST/ALMA.

The present work does not examine the effects of foregrounds, which would presumably be the limiting systematic in CII surveys at reionization epochs. The most dominant interloper lines arise from the CO (3-2) and (4-3) emission from \( z \sim 0 - 2 \), with an additional component coming from the cosmic infrared background (CIB). Efficient removal techniques (cleaning/masking) have been developed to mitigate line foregrounds (e.g., Bregman et al. 2015; Cheng et al. 2016; Visbal & Loeb 2010; Lidz & Taylor 2016; Sun et al. 2018). At lower redshifts, the main contaminants are expected to be Galactic and extragalactic thermal dust emissions and their associated instrument response. However, at these frequencies, the results of simulations indicate excellent prospects for the robust recovery of the CII signal by using linear combination cleaning techniques (e.g., Switzer 2017).

It is of interest to explore cross-correlation possibilities with CII intensity mapping and large galaxy photometric/spectroscopic redshift surveys to be undertaken in the future, which would provide valuable information about the stellar and gas properties of dark matter haloes. Such cross-correlation studies in the context of CO (e.g., Cheng et al. 2018) may promise good constraints on the astrophysical parameters of the CO luminosity - halo mass relation and would offer interesting complementary information in the case of CII, especially in the context of planned surveys with several future programs, e.g. the forthcoming ALPINE survey which aims to measure CII properties in a sample of galaxies between \( 4 < z < 6 \). Cross-correlations of galaxy survey data with CII intensity maps can also be used to shed light into various processes of galaxy formation and the metal enrichment of the ISM. Through the mid to end stages of reionization, synergies with HI and other surveys can offer exciting prospects into constraints on cosmology and astrophysics, including the baryon cycle and star formation rate, as well as the predicted sizes of ionization bubbles from the turnover of the cross-correlation coefficient (Visbal & Loeb 2010; Gong et al. 2012; Dumitru et al. 2018).
Table 2. Summary of the best-fitting $L_{\text{CII}} - M$ relation, and the free parameters involved. The $L_{\text{CII}}$ is in units of $L_\odot$ and all masses are in units of $M_\odot$.

| $L_{\text{CII}}(M,z)$ | $F(z) = [(1+z)^eta (1+[(1+z)/2.9]^{5.6})]^{\alpha}$ | $M_1 = (2.39 \pm 1.86) \times 10^{-5}$ | $N_1 = (4.19 \pm 3.27) \times 10^{11} M_\odot$ | $\alpha = 1.79 \pm 0.30$ | $\beta = 0.49 \pm 0.38$ |
|------------------------|------------------------------------------------|------------------|-----------------|------------------|------------------|

**ACKNOWLEDGEMENTS**

I thank Marco Viero, Girish Kulkarni, Dongwoo Chung, Guochao Sun, Marta Silva and Guilaine Lagache for helpful initial conversations and discussions related to CII intensity mapping. I thank Martin Zwaan, Gergö Popping, Fabian Walter, Celine Peroux, Rajeshwari Dutta and Tony Mroczkowski for useful discussions especially regarding possible ALMA intensity mapping surveys, and the ESO, Garching and the MPIA, Heidelberg for hospitality during my visits. I thank Simon Foreman, Anthony Pullen, Christos Karoumpis and José Fonseca for detailed comments on the manuscript. I am grateful to Marta Silva, Sebastian Dumitrut and Gergö Popping for sharing data from their simulations. It is a pleasure to thank Dongwoo Chung for a very careful reading of the manuscript, several useful comments and for sharing a draft version of his work in preparation. I also thank Guilaine Lagache, Eric Switzer, Celine Peroux and Tony Mroczkowski for helpful inputs regarding the various instrumental and survey designs used. My research is supported by the Tomalla Foundation.

**REFERENCES**

Aguirre J., 2015, The Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE): a Next-Generation Experiment for Galaxy Evolution Studies, NASA APRA Proposal.

Anderson C. J., et al., 2018, MNRAS, 476, 3382

Aravena M., et al., 2016, ApJ, 833, 71

Behroozi P. S., Wechsler R. H., Conroy C., 2013, ApJ, 770, 57

Breysse P. C., Kovetz E. D., Kamionkowski M., 2018, MNRAS, 475, 492

Carilli C. L., Murphy E. J., Ferrara A., Dayal P., 2018, preprint, (arXiv:1810.02850)

Chang T.-C., Pen U.-L., Bandura K., Peterson J. B., 2010, Nature, 466, 463

Chung D. T., 2018, preprint, (arXiv:1809.04550)

Crites A. T., et al., 2014, in Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII, p. 91531W, doi:10.1117/12.2057207

Crites A., et al., 2017, in American Astronomical Society Meeting Abstracts #229, p. 125.01

De Looze I., Baes M., Bendo G. J., Cortese L., Fritz J., 2011, MNRAS, 416, 2712

De Looze I., et al., 2014, A&A, 568, A62

Dumitrut S., Kulkarni G., Lagache G., Haehnelt M. G., 2018, preprint, (arXiv:1802.04804)

Fonseca J., Maartens R., Santos M. G., 2018, MNRAS, 479, 3490

Gong Y., Cooray A., Silva M., Santos M. G., Bock J., Bradford C. M., Zemcov M., 2012, ApJ, 745, 49

Hailey-Dunsheath S., et al., 2018, Journal of Low Temperature Physics, 174, 107

Hernandez-Monteagudo C., Maio U., Ciardi B., Sunyaev R. A., 2017, preprint, (arXiv:1707.01910)

Klitsch A., Péroux C., Zwaan M. A., Smail I., Oteo I., Biggs A. D., Popping G., Swinbank A. M., 2018, MNRAS, 475, 492

Kogut A., et al., 2011, J. Cosmology Astropart. Phys., 7, 025

Kogut A., et al., 2014, in Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave. p. 91431E, doi:10.1117/12.206840

Lagache G., 2018, in Jelic V., van der Hulst T., eds, IAU Symposium Vol. 333, Peering towards Cosmic Dawn. pp 228–233 (arXiv:1801.08054), doi:10.1117/12.21800058

Lagache G., Cousin M., Chatzikos M., 2018, A&A, 609, A130

Li T. Y., Wechsler R. H., Devarar K., Church S. E., 2016, ApJ, 817, 169

Lidz A., Taylor J., 2016, ApJ, 825, 143

Madau P., Dickinson M., 2014, ARA&A, 52, 415

Masini N., Sternberg A., Loeb A., 2015, J. Cosmology Astropart. Phys., 11, 028

Masui K. W., et al., 2013, ApJ, 763, L20

Matsuda Y., Nagao T., Iono D., Hikage K., Koyama K., Yamaguchi Y., Shimozi I., 2015, MNRAS, 451, 1141

Moradinezhad Dizgah A., Keating G. K., 2018, preprint, (arXiv:1810.02850)

Moster B. P., Naab T., White S. D. M., 2013, MNRAS, 428, 3121

Padmanabhan H., 2018, MNRAS, 475, 1477

Padmanabhan H., Kulkarni G., 2017, MNRAS, 470, 340

Padmanabhan H., Refregier A., 2017, MNRAS, 464, 4008

Padmanabhan H., Refregier A., Amara A., 2017, MNRAS, 469, 2323

Parshley S. C., et al., 2018, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 107005X (arXiv:1807.06675), doi:10.1117/12.2314046

Pentericci L., et al., 2016, ApJ, 829, L11

Popping G., Narayanan D., Somerville R. S., Faissat A. L., Krumholz M. R., 2018, preprint, (arXiv:1805.11093)

Pullen A. R., Serra P., Chang T.-C., Doré O., Ho S., 2018, MNRAS, 478, 1911

Scozziccario R., Sheth R. K., Hui L., Jain B., 2001, ApJ, 546, 20

Serra P., Doré O., Lagache G., 2016, ApJ, 833, 153

Sheth R. K., Tormen G., 2002, MNRAS, 329, 61

Silva M., Santos M. G., Cooray A., Gong Y., 2015, ApJ, 806, 209

Smit R., et al., 2018, Nature, 553, 178

Sun G., et al., 2018, ApJ, 856, 107

Swinbank M., et al., 2012, The Messenger, 149, 40

Switzer E. R., 2017, ApJ, 838, 82

Switzer E. R., et al., 2013, MNRAS, 434, L46

Uzgil B. D., Aguirre J. E., Bradford C. M., Lidz A., 2014, ApJ, 793, 116

Vavagiakis E. M., et al., 2018, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. p. 107081U, doi:10.1117/12.2313868

Vishal E., Loeb A., 2010, J. Cosmology Astropart. Phys., 11, 016

Walter F., et al., 2014, ApJ, 782, 79

Yue B., Ferrara A., Pallottini A., Gallerani S., Vallini L., 2015, MNRAS, 450, 3829

**CII intensity mapping**

2712