Exploring 21 cm-Lyα Emitter Synergies for SKA

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Received 2016 September 18; revised 2016 December 13; accepted 2017 January 10; published 2017 February 17

Abstract

We study the signatures of reionization and ionizing properties of early galaxies in the cross-correlations between the 21 cm emission from the spin-flip transition of neutral hydrogen (H I) and the underlying galaxy population. In particular, we focus on a sub-population of galaxies visible as Lyα Emitters (LAEs). With both observables simultaneously derived from a z ≈ 6.6 hydrodynamical simulation (GADGET-2) snapshot post-processed with a radiative transfer code (pCRASH) and a dust model, we perform a parameter study and aim to constrain both the average intergalactic medium (IGM) ionization state (1 − ⟨X_H I⟩) and the reionization topology (outside-in versus inside-out). We find that, in our model, LAEs occupy the densest and most-ionized regions resulting in a very strong anti-correlation between the LAEs and the 21 cm emission. A 1000 hr Square Kilometer Array (SKA)-LOW1—Subaru Hyper Suprime-Cam experiment can provide constraints on ⟨X_H I⟩, allowing us to distinguish between IGM ionization levels of 50%, 25%, 10%, and fully ionized at scales r ≲ 10 comoving Mpc (assuming foreground avoidance for SKA). Our results support the inside-out reionization scenario where the densest knots (under-dense voids) are ionized first (last) for ⟨X_H I⟩ ≳ 0.1. Further, 1000 hr SKA-Low1 observations should be able to confirm the inside-out scenario by detecting a lower 21 cm brightness temperature (by about 2–10 mK) in the densest regions (≳2 arcmin scales) hosting LAEs, compared to lower-density regions devoid of them.

Key words: dark ages, reionization, first stars – galaxies: high-redshift – intergalactic medium – dust, extinction – methods: numerical – radiative transfer

1. Introduction

The epoch of reionization (EoR) marks the second, and last, major change in the ionization state of the universe. The first stars and galaxies emit hydrogen ionizing photons that permeate and gradually ionize the vast majority of the initially neutral hydrogen (H I) in the intergalactic medium (IGM), marking the end of the EoR by z ≈ 6 (Fan et al. 2006; Ouchi et al. 2010; McGreer et al. 2011, 2015). However, the growth of ionized regions (the reionization topology) in the cosmic web and their dependence on the IGM over-density (whether reionization proceeded from over-to under-dense regions or vice versa) remain open questions to date. This is because both the progress and topology of reionization depend on a number of poorly understood parameters, such as the abundance and spectral shapes of early galaxies, the IGM gas density distribution, and the fraction of ionizing photons produced by such sources that are able to escape galactic environment and contribute to reionization.

Given that the key sources of ionizing radiation are located in high-density peaks, ionization fronts might be expected to originate in over-dense regions before percolating into under-densities. This scenario, referred to as “inside-out” reionization, is supported by the majority of numerical and semi-numerical simulations (e.g., Iliev et al. 2006, 2012; Trac & Cen 2007; Battaglia et al. 2013; Bauer et al. 2015). However, recombinations can outweigh ionization events in the densest regions of the IGM, such that the outer parts of halos and filaments can become self-shielded and remain at least partially neutral. The existence of such self-shielded Lyman limit systems (LLSs; sinks of Lyα photons), indicates that reionization may have an additional outside-in component (Miralda-Escudé et al. 2000; Bolton & Haehnelt 2007; Choudhury et al. 2009; Bolton & Haehnelt 2013; Kakiichi et al. 2016), in which case ionizing photons might escape through low-density tunnels into under-dense voids and ionize the over-dense filaments last (Finlator et al. 2009). However, as these authors caution, a late reionization of filaments could also arise as a result of a highly biased emissivity field.

Furthermore, the nature of the key reionization sources, i.e., galaxies versus active galactic nuclei (AGNs), has recently come under discussion again. Over the past decade, a picture emerged wherein star-forming galaxies were considered to be the main drivers of reionization (e.g., Shapiro & Giroux 1987; Sokasian et al. 2003, 2004; Wyithe & Loeb 2003; Choudhury & Ferrara 2007), with AGN contributing a negligible fraction to the total reionization photon budget (Fan et al. 2001; Dijkstra et al. 2004; Meiksin 2005; Salvaterra et al. 2005, 2007; Bolton & Haehnelt 2007; Srbinovský & Wyithe 2007; McQuinn 2012). However, with deep (−22.5 ≲ M1480 ≲ −18.5) observations of z ≳ 4 − 6.5 AGN, Giallongo et al. (2015) found the faintest end of the luminosity function to extend to two to four magnitudes fainter luminosities than had been derived from previous surveys. The persistence of such high number densities of faint AGN to higher redshifts could imply AGN to be the main reionization drivers, with little or no contribution from galaxies (Madau & Haardt 2015). Indeed, these authors show that an AGN-driven reionization scenario is quite capable of producing photoionization rates and an electron scattering optical depth in agreement with observations (of the Lyα forest and Cosmic Microwave Background (CMB) polarization) and yields a reasonable reionization redshift of z ≃ 5.7. However, the observations of Giallongo et al. (2015) remain disputed, as
another analysis of the same field yields no convincing AGN candidates (Weigel et al. 2015). Additionally, an AGN-driven reionization scenario is disfavored by the measured metal absorber abundances (Finlator et al. 2016) and Lyα forest measurements of the IGM temperature (D’Aloisio et al. 2016).

Finally, the escape fraction of ionizing photons (fesc) from galactic environments (the interstellar medium; ISM) into the IGM remains a debated quantity, with theoretical estimates ranging from a few percent up to unity (e.g., Ferrara & Loeb 2013; Mitra et al. 2013; Kimm & Cen 2014). Depending on the exact model used, its value either shows an increase (Greif et al. 2008; Wise & Cen 2009) or decrease (Razoumov & Sommer-Larsen 2010; Ferrara & Loeb 2013; Wise et al. 2014; Paardekooper et al. 2015) with halo mass, or solely depends on redshift (Khaire et al. 2016, and references within). In addition, (infrared) observations provide only weak constraints that are limited to galaxies at z ≈ 3 − 4 (Cooke et al. 2014; Vanzella et al. 2015).

Over the past few years, high-z Lyα Emitters (LAEs), detected through their Lyα emission (at 1216 Å in the rest-frame of the galaxy), have become popular probes of reionization. Given the sensitivity of Lyα photons to even trace abundances (≈10^{-5}) of IGM HI, a drop in the Lyα luminosity function (Lyα LF) accompanied by an increased clustering at z ≥ 6.5 has been interpreted to indicate an increase in the HI fraction (Kashikawa et al. 2006, 2011; McQuinn et al. 2007; Ouchi et al. 2010; Jensen et al. 2013; Choudhury et al. 2015; Mesinger et al. 2015; Castellano et al. 2016). However, it must be noted that there are two additional effects that determine the “observed” Lyα luminosity: first, the intrinsic luminosity produced depends on the fraction of HI ionizing photons absorbed in the ISM (1 − fesc) that give rise to recombination lines, including the Lyα. Second, in addition to IGM attenuation, a fraction of the Lyα photons produced are absorbed by dust in the ISM (Dayal et al. 2008, 2011; Forero-Romero et al. 2010). Hutter et al. (2014, 2015) have shown that the effects of reionization, the ionizing photon escape fraction and dust, are degenerate on the Lyα LF. Indeed, clustering information is required in order to be able to put additional constraints on the neutral fraction χ_HI, because the decrease in the amplitude of the angular correlation function (ACF) is hard to attribute to anything other than reionization (e.g., McQuinn et al. 2007; Jensen et al. 2013; Hutter et al. 2015). However, it must be noted that, even combining all the available data sets (LFS+ACFs), LAEs can only shed light on the “global” average IGM ionization state at any redshift.

Radio interferometers, including the forthcoming Hydrogen Epoch of Reionization Array (HERA, Dillon & Parsons 2016) and the future Square Kilometer Array (SKA) aim to directly map out the reionization tomography by detecting the 21 cm emission from the spin-flip transition of H I. However, confirming the high-z nature of the 21 cm emission and interpreting the nature of reionization (inside-out versus outside-in) will require cross-correlating 21 cm data with an unrelated data set (e.g., high-z galaxies, Furlanetto & Lidz 2007). The precise redshifts afforded by LAEs, in conjunction with the increasing number from new observations, renders them particularly attractive as one such data set. The 21 cm-LAE cross-correlation has already been explored by a few works: using a combination of N-body and radiative transfer (RT) simulations, Vrbaneč et al. (2016) claim LOFAR should be able to detect an anti-correlation in the 21 cm-LAE cross-correlation power spectrum on scales larger than 60 h^{-1} Mpc. However, the signal is dominated by LOFAR’s system noise at smaller scales. Furthermore, using the 21CMFAST code (Mesinger et al. 2011) to model reionization on cosmological scales, Sobacchi et al. (2016) show that 1000 hr observations with LOFAR should be able to distinguish, at more than 1σ, a fully ionized IGM from one that is half ionized at scales of about 3–10 Mpc. These authors find that the SKA phase 1 array will even be capable of distinguishing a fully ionized IGM from one than is a quarter ionized. However, both these models assume the emergent Lyα luminosity to effectively scale with the host halo mass.

In this work, we pursue another approach by post-processing a z ∼ 6.6 hydrodynamic simulation snapshot (GADGET-2) that yield realistic galaxy populations with a dust model and a 3D RT code (pCRASH) to simultaneously derive the reionization topology and the underlying LAE distribution at z ∼ 6.6. Then, cross-correlating the 21 cm signal with the LAE population for physical scenarios (fesc, IGM ionization states and dust), in accord with LAE data: (a) we show constraints that can be obtained on the IGM ionization state combining LAE and 21 cm data, from the next generation Subaru and SKA observations, respectively, and (b) we show how these data sets can be used to answer the question of whether reionization had an inside-out or outside-in topology.

This paper represents a parameter study to explore the signatures of properties of early galaxies on the ionization field, and on the 21 cm-galaxy cross-correlation in particular. In our model, we take the z ∼ 6.6 output of a hydrodynamical simulation as a starting point of the evolution of the reionization field for five values of the escape parameter. We are then able to (a) disentangle the effects of galactic properties on the 21 cm-galaxy cross-correlation from those entirely due to galaxy evolution, and (b) to evaluate the agreement of each physical scenario to LAE and 21 cm observations at z ∼ 6.6. The next step is an post-processing of all the evolution steps of our hydrodynamical simulation for one realistic parameter set that transfers the ionization fields over the whole redshift range of reionization. This is planned for a future paper.

We start by describing our model for high-z LAEs in Section 2. We demarcate the location of the entire underlying galaxy population, and the fraction visible as LAEs, as a function of the IGM density and ionization state in Section 3. We describe the characteristics of the 21 cm-galaxy and 21 cm-LAE cross-correlation in Section 4. We investigate the effects of reionization topology on the 21 cm brightness temperature in over-densities/voids, and provide estimates of the SKA-LOW1 detectability of the brightness temperature in regions with/without galaxies/LAEs in Section 5, before concluding in Section 6.

2. The Model

In this section, we describe our model for z ∼ 6.6 LAEs that combines a cosmological smoothed particle hydrodynamic (SPH) simulation run using GADGET-2 (Springel 2005) with the pCRASH RT code (Partl et al. 2011) and a model for ISM dust (Dayal et al. 2010). The interested reader is referred to Hutter et al. (2014, 2015) for a detailed description.

The hydrodynamical simulation used as the basis for our model is run with the TreePM-SPH code GADGET-2 with a box size of 80 h^{-1} comoving Mpc (cMpc). The simulation
follows a total of $2 \times 10^2$ dark matter (DM) and gas particles, resulting in a DM and gas particle mass resolution of $3.6 \times 10^7$ $h^{-1}$ M$_\odot$ and $6.3 \times 10^4$ $h^{-1}$ M$_\odot$, respectively. It includes physical prescriptions for star formation, metal production and feedback as described in Springel & Hernquist (2003), assuming a Salpeter (1955) initial mass function between 0.1 and 100 M$_\odot$. Bound structures with more than 20 particles are identified as galaxies using the Amiga Halo Finder (Knollmann & Knebe 2009). We only use “resolved” galaxies leading to a complete halo mass function, with at least 10 star particles (corresponding to a minimum of 160 gas particles) and a halo mass $M_h > 10^{12} M_\odot$. We obtain the total intrinsic spectrum for each galaxy summing over all its star particles using the stellar population synthesis code STAR-BURST99 (Leitherer et al. 1999); the intrinsic spectrum for each star particle naturally depends on its mass, age and metallicity. For each galaxy we compute the dust mass produced considering SN II to be the main dust factories in the first billion years; the corresponding UV attenuation is calculated using the dust model described in Dayal et al. (2010).

The observed ultra-violet (UV) luminosity ($L_{\text{UV}}^\text{obs}$) is then related to the intrinsic value ($L_{\text{UV}}^\text{int}$) as $L_{\text{UV}}^\text{obs} = f_\mu \times L_{\text{UV}}^\text{int}$, where $f_\mu$ is the fraction of UV continuum ($\sim$1500 Å) photons that escape the ISM unattenuated by dust. Further, the observed Ly$\alpha$ luminosity is calculated as $L_{\text{Ly}\alpha}^\text{obs} = L_{\text{Ly}\alpha}^\text{int} f_{\text{Ly}\alpha} T_\alpha$, where $f_{\text{Ly}\alpha}$ and $T_\alpha$ account for the Ly$\alpha$ attenuation by ISM dust and IGM H I, respectively. In accord with observational selection criteria, galaxies with an absolute UV magnitude $M_{\text{UV}} < -17$ are identified as Lyman break Galaxies (LBGs); galaxies with $L_{\text{Ly}\alpha}^\text{obs} \geq 10^{42}$ erg s$^{-1}$ and a Ly$\alpha$ equivalent width $EW = L_{\text{Ly}\alpha}^\text{obs} / f_{\text{Ly}\alpha} > 20$ Å are identified as LAEs. We note that LAEs are a subset of the underlying LBG population: while only a fraction of LBGs show Ly$\alpha$ emission fulfilling the observational criterion, depending on the IGM ionization state and dust clumping in the ISM, all LAEs are bright enough in the UV to be classified as LBGs (see e.g., Dayal & Ferrara 2012; Hutter et al. 2015).

In order to obtain $T_\alpha$, we post-process the $z \approx 6.6$ snapshot of our hydrodynamical simulation with the RT code pCRASH (Partl et al. 2011). pCRASH is a MPI$^5$ parallelized version of CRASH (Ciardi et al. 2001; Maselli et al. 2003, 2009) which is a 3D RT code capable of treating multiple source spectra, a spatially dependent clumping factor and evolving density fields. pCRASH naturally yields both the evolving ionization fields and the IGM temperature that are used to calculate the 21 cm H I emission, as explained in Section 3.2. Given the poor constraints on the escape fraction of ionizing photons $f_{\text{esc}}$ ($\lambda < 912$ Å), and its impact on both the IGM ionization state as well as the intrinsic Ly$\alpha$ luminosity, we explore a wide range of values such that $f_{\text{esc}} = 0.05, 0.25, 0.5, 0.75, 0.95$. Thus, we perform 5 RT simulations, whereas in each a different global $f_{\text{esc}}$ value is assumed for all galaxies. Starting from a completely neutral IGM, we run pCRASH until the IGM is fully ionized, reaching an average H I fraction of $\langle \xi_{\text{HI}} \rangle \approx 10^{-4}$, for each $f_{\text{esc}}$ value by following the ionizing radiation from 31855 “resolved” galaxies on a 128$^3$ grid. With pCRASH computing the evolution of the ionized regions, we obtain the ionization history, i.e., snapshots at different $\langle \xi_{\text{HI}} \rangle$, for each of our chosen $f_{\text{esc}}$ values. Assuming a Gaussian profile for the Ly$\alpha$

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$^5$ http://www.mpi-forum.org

3. Distribution of Galaxies and 21 cm in Over-dense and Ionized Regions

Now that the galaxy populations visible as LAEs and LBGs have been identified, we study the probability density distribution of all galaxies, and the subset visible as LAEs, as a function of over-density and the surrounding IGM ionization state in Section 3.1. We then discuss how the presence of galaxies in over-densities impacts the probability density distribution of the 21 cm brightness temperature in Section 3.2.

3.1. Galaxies as Tracers of Ionized and Over-dense Regions

We use the $f_{\text{esc}}$ and $\langle \xi_{\text{HI}} \rangle$ combinations identified in Section 2 to analyze the relation between the IGM gas over-density/ionization state and the underlying galaxy population. We start by discussing the probability density distribution of the neutral hydrogen fraction $\langle \xi_{\text{HI}} \rangle$ with respect to the gas over-density $\left(1 + \delta \right)$ in the entire simulation box, and compare it to cells containing galaxies before studying how these differ in the subset of galaxies visible as LAEs. We explore all parameter $f_{\text{esc}}$, $f_{\text{Ly}\alpha}$ and $\langle \xi_{\text{HI}} \rangle$ combinations that are in accord with the observed LAE LF (see Hutter et al. 2014). We use each computing cell of the grid $\left(1 + \delta \right)$ $\langle \xi_{\text{HI}} \rangle$ in our RT calculations to derive the probability density distributions of the IGM gas in the entire simulation box, which are shown by means of the gray scale in Figure 1 for $f_{\text{esc}} = 0.05, 0.25, 0.5$ (rows), and $\langle \xi_{\text{HI}} \rangle \approx 0.9, 0.5, 10^{-4}$ (columns). With a size of 625 $h^{-1}$ ckpc, our simulated galaxies mostly lie within one computing cell. Due to this rather coarse resolution, we omitted subtracting galaxies from the gas density grid. Only a small fraction of cells contain galaxies and their circumgalactic medium; the majority of cells represent the IGM. For convenience, we refer always to the IGM in the following.

We expect the bulk of the cells to be completely neutral in the initial stages of reionization. The successive growth and overlap of ionized regions would lead to an increase in the local
photoionization rate, resulting in shifting the bulk of cells toward lower $\chi_{H_1}$ values. Finally, we expect very few cells to have a neutral fraction $\chi_{H_1} > 10^{-3}$ for a fully ionized universe. This is exactly the behavior shown by our results in Figure 1.

As expected, we find galaxies to lie in regions of over-density as seen from the red contours in Figure 1: the least massive galaxies lie in marginally over-dense regions ($1 + \delta \approx 1.5$), whereas the most massive galaxies lie in regions 10–15 times more over-dense than average. Although the over-density is fixed by the SPH simulation, the distribution of galaxies in the ionization field naturally evolves while reionization progresses. From the sharp ionization fronts of stellar sources, we expect a bimodal probability distribution in $\chi_{H_1}$ distinguishing the ionized ($\chi_{H_1} \lesssim 0.01$) from the neutral ($\chi_{H_1} = 1$) regions. Indeed, we see from Figure 1 that most cells are either ionized or neutral. However, we also find partially ionized cells ($0.01 \lesssim \chi_{H_1} < 1$), whose existence is a consequence of the finite resolution of our RT simulations. In this context, we can understand galaxies being located in neutral/partially ionized cells as sources that have not emitted enough photons to fully ionize their cell. Thus, given their large over-densities, most galaxies lie in neutral cells in the initial stages of reionization ($\langle \chi_{H_1} \rangle \approx 0.9$). As expected, the distribution of galaxies widens considerably for a half-ionized IGM: although some galaxies still occupy neutral regions ($\chi_{H_1} \approx 1$), others (possibly those in clustered regions) are embedded in a fully ionized IGM with $\chi_{H_1} \approx 10^{-4}$. Finally, the distribution of all galaxies shifts to lie at $\chi_{H_1} \lesssim 10^{-2}$ for a fully ionized IGM. At a given IGM state (columns in the same figure), differences in galaxy distributions naturally vary with $f_{esc}$ because the strength of the photoionization field created by any source scales with this parameter. It is interesting to note that, due to a combination of low IGM densities and photoionization rate contributions from multiple galaxies, many under-dense regions are as highly ionized as $\chi_{H_1} \approx 10^{-5}$, even for an average ionization state of $\langle \chi_{H_1} \rangle \approx 0.9$.

We find that the observed Ly$\alpha$ LF at $z \approx 6.6$ can only be reproduced for $\langle \chi_{H_1} \rangle \lesssim 0.5$; for $\langle \chi_{H_1} \rangle > 0.5$, the number of galaxies identified as LAEs drops significantly, because the IGM Ly$\alpha$ transmission decreases considerably for rising $\langle \chi_{H_1} \rangle$ values. We find that the subset of galaxies visible as LAEs (blue contours in Figure 1) are those that lie in the most over-dense (over-density between 2 and 15) and highly ionized regions ($\chi_{H_1} \lesssim 10^{-2}$). Although the galaxy population is not evolving in our scenario, we expect our findings to be robust, given the conditions required for galaxies to be visible as LAEs: first, galaxies must produce enough intrinsic Ly$\alpha$ luminosity; second, they must transmit enough of this luminosity through the IGM so as to result in $L_{\alpha, obs} \gtrsim 10^{12}$ erg s$^{-1}$. Given that the spatial scale imposed by the Gunn–Peterson damping wing on the size of the H II region corresponds to a redshift separation of $\Delta z \approx 4.4 \times 10^{-3}$, i.e., about 280 kpc (physical) at $z = 6$ (Miralda-Escudé 1998), $z \approx 6.6$ LAEs require a halo mass $\gtrsim 10^{10.5} M_\odot$ (Dayal & Ferrara 2012), with significantly larger ($10^{9}–10^{11} M_\odot$) stellar masses being inferred observationally (Pentericci et al. 2009). Naturally, as the high-mass end of the galaxy population, LAEs are expected to lie in the most over-dense and highly ionized regions.

### 3.2. 21 cm Emission from Over-dense Neutral Regions

The distribution of the neutral hydrogen in the IGM can be observed through its 21 cm brightness temperature, which measures the intensity of the emission (or absorption) of 21 cm radiation against the CMB. We now discuss how the 21 cm brightness temperature depends on the IGM density, and its dependence on the presence of galaxies, especially the subset visible as LAEs. We start by calculating the differential 21 cm brightness temperature ($\delta T_b$) in each of the $(128)^3$ pCRASH cells as (e.g., Iliev et al. 2012)\[ \delta T_b(x) = T_0 \langle \chi_{H_1} \rangle (1 + \delta(x)) (1 + \delta_H(x)), \] where\[ T_0 = 28.5 \text{ mK} \left( \frac{1 + z}{10} \right)^{1/2} \frac{\Omega_b}{0.042} h \left( \frac{\Omega_m}{0.24} \right)^{-1/2}. \]

Here, $\Omega_b$ and $\Omega_m$ represent the baryonic and matter densities, respectively, and $h$ is the Hubble parameter. Further, $1 + \delta(x) = \rho(x)/\rho_0$ represents the local gas density compared to the average global value, and $1 + \delta_H(x) = \chi_{H_1}(x)/\langle \chi_{H_1} \rangle$ represents the local HI density fraction compared to the average global value. Our computation of the differential 21 cm brightness temperature does not include fluctuations in the spin temperature and peculiar velocities of the gas. For $\langle \chi_{H_1} \rangle \lesssim 0.8$, spin temperature fluctuations become negligible, as the heating of the IGM by X-rays from the first sources leads to spin temperatures that exceed well the CMB temperature (Ghara et al. 2015). Spin temperature fluctuations may only become
important when the IGM is mostly neutral and has not been entirely preheated. Similarly, the effect of peculiar velocities is only imprinted in the 21 cm power spectrum as long as the 21 cm signal is not dominated by the H I fluctuations, e.g., at high \( \langle X_{HI} \rangle \) values (Ghara et al. 2015).

In Figure 2, we show the resulting probability density distribution in terms of the over-density and the differential 21 cm brightness temperature. As seen from Equation (1), \( \delta T_b \) depends both on the gas over-density as well as the neutral fraction that together determine the H I density in any cell. The fact that most over-dense cells contain H I, with only a few cells being ionized in the initial reionization stages (\( \langle X_{HI} \rangle \approx 0.9; \) Section 3.1 above), results in the average \( \delta T_b \) (orange line) increasing from about 4 to 250 mK as the density increases from \( 1 + \delta = 0.14 \) to 14 times the average density. As reionization progresses to a state where it is half-completed (\( \langle X_{HI} \rangle \approx 0.5 \)), the distribution of all cells shifts toward more ionized values, resulting in a drop in the average \( \delta T_b \) amplitude, ranging between 4 and 200 mK from the rarest to the densest regions. Finally, given that very few cells have \( X_{HI} \gtrsim 10^{-2.5} \) for a fully ionized IGM (\( \langle X_{HI} \rangle \approx 10^{-4} \)), the average \( \delta T_b \) signal changes both in shape and amplitude, although it still increases with the over-density, given that the H I density scales with this. Naturally, however, \( \delta T_b \) has much lower values, ranging between about \( 10^{-4.5} \) to 10 mK. For each of the \( \langle X_{HI} \rangle - f_{esc} \) combinations studied here, the drop in \( \delta T_b \) for \( 1 + \delta \gtrsim 14 \) values is essentially a statistical fluctuation driven by a few over-dense cells.

Given that galaxies are located in highly over-dense and neutral regions in the early stages of reionization, simulation cells hosting galaxies show a high \( \delta T_b \) signal (\( \gtrsim 4-150 \) mK). As reionization proceeds to being half-complete, the galaxy distribution widens considerably—although a fraction of galaxies occupy ionized regions with \( \delta T_b \approx 0.003 \) to 4 mK, field galaxies are embedded in partly neutral regions showing \( \delta T_b \approx 4 \) to 250 mK. Finally, the \( \delta T_b \) signal from cells hosting galaxies drops by about two orders of magnitude to 0.003 to a few mK once reionization is complete.

Given that only highly clustered sources in ionized regions are visible in the Ly\( \alpha \) in the initial reionization stages (McQuinn et al. 2007; Hutter et al. 2015), LAEs exhibit much lower average \( \delta T_b \) values (blue line in Figure 2) compared to cells without galaxies at the same over-density: e.g., LAE hosting cells show \( \delta T_b \approx 1 \) mK compared to \( \approx 10 \) mK shown for \( 1 + \delta \approx 3 \) for a half-ionized IGM; we remind the reader that no galaxies are visible as LAEs for \( \langle X_{HI} \rangle \approx 0.9 \). Finally, the signal from LAEs is quite similar to that from galaxies, ranging between 0.003 to a few mK once reionization is complete. However, given that they preferentially occupy ionized regions compared to the entire underlying galaxy population, LAE hosting cells show much less variation in the average \( \delta T_b \) compared to that averaged over all simulation/galaxy hosting cells.

### 4. Linking 21 cm Emission to the Underlying Galaxy Population

Differential 21 cm brightness temperature tomographic maps will be ideal indicators of the IGM ionization history. However, understanding the key reionization sources, and indeed, even verifying that the 21 cm signal originates at high-redshifts, will require correlating the 21 cm brightness temperature signal with the underlying galaxy population, especially the subset visible as LAEs, given their precise redshifts (e.g., Furlanetto & Lidz 2007; Wyithe & Loeb 2007; Lidz et al. 2009). In this section, we show the IGM ionization state constraints possible with the SKA by combining 21 cm-galaxy data (Section 4.1) and 21 cm-LAE data (Section 4.2).

#### 4.1. The 21 cm–Galaxy Cross-correlation

Taking \( \Delta_i \) and \( \Delta_j \) to represent the 21 cm brightness temperature and galaxy fields, respectively, their cross-correlation power spectrum can be calculated as (Park et al. 2014)

\[
P_{i,j}(k) = \langle \tilde{\Delta}_i(k) \tilde{\Delta}_j(-k) \rangle, \tag{3}
\]

\[
\tilde{\Delta}_i(k) = \frac{1}{V} \int \Delta_i(x) \exp(-ikx) \, dx \quad \text{for} \quad l = i, j. \tag{4}
\]

Computing the Fourier transformation of the cross-power spectrum \( P_{21 \, \text{cm-gal}}(k) \), we derive the cross-correlation function as

\[
\xi_{21 \, \text{cm-gal}}(r) = \frac{1}{(2\pi)^3} \int P_{21 \, \text{cm-gal}}(k) \frac{\sin(kr)}{kr} \, 4\pi k^2 \, dk. \tag{5}
\]

The integration along the \( k \)-axis is carried out numerically using the composite trapezoidal rule. The resulting cross-correlation functions are shown in Figure 3 for \( f_{esc} \) values...
ranging between 0.05 and 0.95 and the associated ionization states ranging from fully neutral to fully ionized. Throughout this paper, we compute the cross-correlation functions taking the entire simulation box volume into account. Our simulated volume is sufficient to trace the cross-correlations up to a scale of $\sim 10^{\frac{1}{h} \text{cMpc}}$. The finite box size poses a lower limit in $k$-space ($\leq k_{\text{lim}} \approx 0.2 h \text{cMpc}^{-1}$), which introduces uncertainties in the amplitude of our cross-correlation function. However, given the cross-power spectrum has the same sign at $k < k_{\text{lim}}$ than at $k_{\text{lim}}$, an extension of the integration in Equation (5) to lower $k_{\text{lim}}$ values would result in higher amplitudes in the cross-correlation function (indicating an even stronger correlation/anti-correlation for a positive/negative $P_{21 \text{ cm,gal}}(k)$).

In the early stages of reionization ($\langle \chi_{\text{H}I} \rangle \approx 0.9$, beginning of RT simulation), the 21 cm brightness temperature and galaxy distribution are positively correlated on small ($\lesssim 10 h^{-1} \text{cMpc}$) scales as seen in Figure 3. This behavior is driven by galaxies being embedded in over-dense and only partly ionized regions that therefore show 21 cm emission, as also seen from Figure 2. As expected, the strength of the correlation decreases with increasing scale, saturating to 0 at $\approx 20 h^{-1} \text{cMpc}$ where galaxy positions and 21 cm emission are uncorrelated. As the global neutral hydrogen fraction drops to $\langle \chi_{\text{H}I} \rangle \lesssim 0.75$, the correlation flips in sign and becomes anti-correlated at small-scales—this is driven by galaxies being embedded in mostly ionized regions. The strength of the anti-correlation is strongest for $\langle \chi_{\text{H}I} \rangle \approx 0.5$ and then decreases with decreasing $\langle \chi_{\text{H}I} \rangle$ as the H I content becomes lower, leading to the 21 cm emission approaching 0—this happens for $\langle \chi_{\text{H}I} \rangle \approx 0.01$, irrespective of the parameters used. We find that $\xi_{21 \text{ cm,gal}}$ shows significant small-scale fluctuations for $\langle \chi_{\text{H}I} \rangle \gtrsim 0.5$ where (low-mass, $M_* \lesssim 10^{9.5} M_\odot$) galaxies are embedded in partially ionized regions of varying sizes. Indeed, we find that the relative amplitude of the oscillations decreases as the IGM becomes more ionized, resulting in field/lower-mass galaxies being enclosed by increasingly ionized regions. Given that we use a single simulation snapshot, the underlying galaxy field is fixed in this work, and we note that the variations in $\xi_{21 \text{ cm,gal}}$ are solely introduced by an evolution of the ionization fields.

We find that these above results qualitatively hold true for all the $f_{\text{esc}}$ values explored in this work. We remind the reader that the average ionization fraction is a combination of the volume ionized and the degree of ionization: an increasing $f_{\text{esc}}$ leads to a higher degree of ionization for a given galaxy population, requiring smaller ionized volumes to result in a given $\langle \chi_{\text{H}I} \rangle$ (e.g., Hutter et al. 2014)—this results in the slight differences in $\xi_{21 \text{ cm,gal}}$ with varying $f_{\text{esc}}$ for a given $\langle \chi_{\text{H}I} \rangle$. We therefore find the strongest small-scale anti-correlation for $f_{\text{esc}} = 0.95$ where the H I is most highly ionized; the

![Figure 3](image-url)
correlation strength decreases with decreasing \( f_{\text{esc}} \) where galaxies reside in larger ionized regions for a given \( \langle \chi_{\text{H}} \rangle \).

We then calculate the ability of SKA1-Low to discriminate between models, by computing the 1\( \sigma \) uncertainties on the 21 cm-galaxy cross-correlation functions for an idealized 1000 hr SKA1-Low experiment. The thermal noise and sample variance includes the most recent array configuration V4A, with a filling factor that reduces substantially outside the core, yielding poorer brightness temperature sensitivity performance on small scales. The system temperature and effective collecting area as a function of frequency are matched to the 

$$\langle \chi_{\text{H}} \rangle = 0.50 \quad \langle \chi_{\text{H}} \rangle = 0.25 \quad \langle \chi_{\text{H}} \rangle = 0.10 \quad \langle \chi_{\text{H}} \rangle = 0.01 \quad \langle \chi_{\text{H}} \rangle = 10^{-4}$$

The cross-correlation function \( \xi_{21\text{-cm-LAE}} \) for the differential 21 cm brightness temperature and LAE distribution as a function of distance \( r \) from galaxies. In each panel, lines indicate \( \xi_{21\text{-cm-LAE}} \) for different IGM ionization states, ranging between \( \langle \chi_{\text{H}} \rangle = 0.9 \times 10^{-4} \); shaded regions show the uncertainties associated with idealized SKA1-Low and Subaru Hyper Suprime-Cam 1000 hr observations. As marked, panels show results for different \( f_{\text{esc}} \) values ranging between 0.05 and 0.95. As shown, these combined observations can provide exquisite constraints on the IGM ionization state, allowing us to differentiate between \( \langle \chi_{\text{H}} \rangle \sim 0.5, 0.25, 0.1, \) and 0.01 (see Section 4.2 for details).

Figure 4. The cross-correlation function \( \xi_{21\text{-cm-LAE}} \) for the differential 21 cm brightness temperature and LAE distribution as a function of distance \( r \) from galaxies. In each panel, lines indicate \( \xi_{21\text{-cm-LAE}} \) for different IGM ionization states, ranging between \( \langle \chi_{\text{H}} \rangle = 0.9 \times 10^{-4} \); shaded regions show the uncertainties associated with idealized SKA1-Low and Subaru Hyper Suprime-Cam 1000 hr observations. As marked, panels show results for different \( f_{\text{esc}} \) values ranging between 0.05 and 0.95. As shown, these combined observations can provide exquisite constraints on the IGM ionization state, allowing us to differentiate between \( \langle \chi_{\text{H}} \rangle \sim 0.5, 0.25, 0.1, \) and 0.01 (see Section 4.2 for details).

4.2. The 21 cm–LAE Cross-correlation

In Figure 4, we investigate the cross-correlation between the 21 cm signal and the subset of galaxies visible as LAEs. Unlike the entire galaxy population used in the previous section, the
visibility of galaxies as LAEs sensitively depends on $f_{\text{esc}}$ and $\langle \chi_{\text{H}} \rangle$—both the 21 cm and LAE fields therefore evolve with these two parameters. We now show the 21 cm-LAE cross-correlation function $\xi_{21 \text{ cm-LAE}}$ for all $f_{\text{esc}}$ and $\langle \chi_{\text{H}} \rangle$ values in agreement with the observed Ly$\alpha$ LFs.

First, we find that there is no correlation ($\xi_{21 \text{ cm-LAE}} = 0$) for $\langle \chi_{\text{H}} \rangle \lesssim 0.01$, for all $f_{\text{esc}}$ ranging between 5% and 50%, due to the lack of any 21 cm emission. For higher $\langle \chi_{\text{H}} \rangle$ values, $\xi_{21 \text{ cm-LAE}}$ shows a clear anti-correlation on small ($\lesssim 20 h^{-1}$ cMpc) scales with an amplitude that decreases (i.e., anti-correlation weakens) from $-0.25$ to $-0.05$ as the IGM decreases from being 50% to 10% neutral. This trend is essentially driven by a decrease in the amplitude of the 21 cm power spectrum as the IGM becomes progressively ionized. This anti-correlation is much more pronounced than that seen for the 21 cm signal and the entire underlying galaxy population, as shown in Section 4.1 above. This is because only galaxies in predominantly clustered regions, hosting the most luminous galaxies with stellar masses $\gtrsim 10^{9.5} M_\odot$ (see e.g., Hutter et al. 2015), lie in sufficiently large ionized regions to transmit enough Ly$\alpha$ luminosity to be visible as LAEs. As a result of their large masses, and therefore ionizing photon output, LAEs comprise the galaxy subset that reside in the most ionized (and over-dense) regions of the simulation (see Figure 1) where all the H I is ionized. As expected, the 21 cm and LAE distribution are uncorrelated at scales larger than $20 h^{-1}$ Mpc.

Further, we find that although $\xi_{21 \text{ cm-LAE}}$ shows similar qualitative trends for all the three $f_{\text{esc}}$ values, its value becomes more negative, showing a stronger anti-correlation, as $f_{\text{esc}}$ increases from 5% to 50%. This is because an increasing $f_{\text{esc}}$ value results in a higher emissivity, and hence a lower H I content, resulting in a lower 21 cm emission near LAEs.

We then calculate the joint SKA1-Low-Subaru Hyper Suprime-Cam (HSC) detectability of the 21 cm-LAE correlation. The 1$\sigma$ error bars displayed in Figure 4 are computed for an idealized Subaru HSC and a 1000 hr SKA1-Low experiment. The errors include thermal noise for a 1000 hr SKA experiment and sample variance for both optical and radio measurements. We assume the same SKA1-Low configuration and system specifications as in the previous Section. However, because the field-of-view (FOV) of Subaru is smaller than for SKA, we assume the observation volume to be limited by Subaru. This reduces the number of independent samples within the volume, and the sample variance increases relative to an SKA-only experiment. The Subaru Suprime camera specifications are assumed, with a FOV of 34 arcmin $\times$ 27 arcmin. Again, we match the bandwidth to each distance, $r$, in the two-point cross-correlation function, with a minimum resolution of $1.9 h^{-1}$ Mpc. We assume that the Subaru narrowband filter can resolve scales of this size, although, in practice, the NB921 filter has an intrinsic resolution of $\sim 7 h^{-1}$ Mpc at $z = 6.6$. Convolution of the simulated cube with this narrowband filter (i.e., taking the narrowband resulting redshift uncertainties into account) would suppress small-scale power, but this is not considered in this work. The corresponding decrease in the cross-correlation amplitude will be approximately the ratio between the effective spectral depth for a given separation $r$ and the Subaru spectral resolution. However, the increasing number of spectroscopically followed-up LAEs will allow us to exploit more precise redshift measurements of LAEs. Under these assumptions, the synergistic SKA1-Low-HSC experiment would be able to yield constraints on the IGM ionization state. Indeed, as shown in the Figure 3, we find that the SKA1-Low-HSC experiment would be able to distinguish between $\langle \chi_{\text{H}} \rangle$ of 10%, 25%, and 50%, in addition to being able to differentiate a 10% neutral IGM from one that was fully ionized, irrespective of the parameter space ($f_{\text{esc}}, f_{\alpha}, f_{\text{f}}$) being explored.

Including an evolution of the galaxy population and density contrast should not have a considerable impact on the 21 cm-LAE cross-correlation function on scales $< 10 h^{-1}$ Mpc considered here. First, the propagation speed of the ionization fronts is about 1 Mpc in $\Delta z \approx 0.4$ for the mean galaxy, and even higher for LAEs; thus, the photoionization rate in the vicinity of galaxies is largely determined by the present source. Second, LAEs are luminous galaxies residing in clustered regions (most overdense and ionized); due to their similar properties, the photoionization and thus ionization field in their vicinity should be comparable and the amplitude of the anti-correlation should remain similar for same $\langle \chi_{\text{H}} \rangle$ values. The same rationale applies to observed galaxies. However, an evolving galaxy population introduces continuously partially ionized cells, and a growing density contrast keeps the gas density imprinted in the residual H I: both lead to a rather constant amplitude of the oscillations in the 21 cm-galaxy cross-correlation functions.

Increasing the spatial resolution of our simulations would allow us to resolve LLSs, which will damp the emitted Ly$\alpha$ luminosities from adjacent galaxies, particularly luminous galaxies (Kakiichi et al. 2016). Their impact on the 21 cm-LAE cross-correlation functions depends on their H I volume and content; although an increasing H I volume leads to an overall boost of the 21 cm brightness temperature on small scales of the cross-correlation, a rising H I content can damp the Ly$\alpha$ emission of adjacent galaxies just enough that they cannot be seen as LAEs anymore and do not contribute to the 21 cm-LAE cross-correlations. An analysis which of those two effects dominates is subject for future work.

5. The Topology of Reionization

The reionization topology remains a much-studied topic with theoretical approaches ranging from relating the mass to the volume averaged ionization fraction (Iliev et al. 2005) to using Minkowski functionals (Gleser et al. 2006; Lee et al. 2008; Friedrich et al. 2011) to computing cross-correlations of density and ionization redshift fields (Battaglia et al. 2013). These have yielded results ranging from the popular “inside-out” scenario where densest regions close to sources are ionized first, with under-dense filaments being ionized last (Iliev et al. 2006, 2007; Trac & Cen 2007; Dayal et al. 2011; Battaglia et al. 2013; Bauer et al. 2015), to the “outside-in” topologies that predict the opposite (Miralda-Escudé et al. 2000). We start by determining the reionization topologies in the different cosmic web components (knots, filaments, sheets, and voids) in Section 5.1. We then build on the analytic approach proposed by Wyithe & Loeb (2007) to examine the signatures of 21 cm emission in over-densities (hosting galaxies) and voids in Section 5.2, to shed light on whether reionization proceeded “inside-out,” or vice-versa.

5.1. Ionization History of the Cosmic Web

We start by classifying the cosmic web into knots, filaments, sheets, and voids, following a slightly modified approach to the
tidal field tensor method proposed by Hahn et al. (2007). We first calculate the tidal field tensor
\[ T_{ij} = \frac{\partial F}{\partial x_i \partial x_j}, \]
and compute the three eigenvalues \( \lambda_i \), which quantify the curvature of the gravitational potential \( \Phi \). Hahn et al. (2007) propose classifying structures collapsing \( (\lambda_i > 0) \) along three, two, and one spatial dimensions as knots, filaments, and sheets, respectively; structures showing no collapse in any dimension \( (\lambda_i < 0) \) are classified as voids. However, Forero-Romero et al. (2009) have pointed out that such a scheme results in a very low volume filling fraction for voids. This is because (infinitesimally) small positive eigenvalues represent a scenario wherein the collapse will occur in the distant future; inspection at the present time would therefore not classify these regions as collapsing. To correct for this, we classify structures according to the number of eigenvalues \( \langle N_i \rangle \) above a threshold \( (\gamma) \)-cells with \( N_i = 3, 2, 1, 0 \) are identified as knots, filaments, sheets, and voids, respectively. In our calculations, we use a threshold of \( \gamma = 0.3 \), resulting in 60% of the volume being identified as voids. The cosmic web and its classification on the threshold \( (\gamma) \) from our simulated volume are shown in Appendix A.

In Figure 5, we show the average \( H I \) fractions for the four cosmic web components: voids \( \langle \chi_{HI,v} \rangle \), sheets \( \langle \chi_{HI,s} \rangle \), filaments \( \langle \chi_{HI,f} \rangle \), and knots \( \langle \chi_{HI,k} \rangle \) for all the \( f_{esc} \) and reionization states values used in this work. The gray dotted line marks \( \langle \chi_{HI} \rangle \), i.e., ionization values lying above and below this line imply structures that are less and more ionized than the average IGM ionization state, respectively.

For an IGM more neutral than \( \langle \chi_{HI} \rangle \geq 0.1 \), we find the \( H I \) fraction to be the lowest in knots, followed by filaments, sheets, and voids in that order, i.e., \( \langle \chi_{HI,k} \rangle < \langle \chi_{HI,f} \rangle < \langle \chi_{HI,s} \rangle < \langle \chi_{HI,v} \rangle \). This increase in the \( H I \) fraction from over-dense to under-dense regions shows that reionization follows the “inside-out scenario” where ionization fronts propagate from (galaxies in) the densest regions, reaching the most under-dense voids last. Further, the continual output of ionizing photons ensures the densest regions remain ionized, at least in the initial reionization stages, given the long recombination timescales. The situation reverses (undergoes an “inversion”) in the end stages of reionization, when \( \langle \chi_{HI} \rangle \lesssim 10^{-2} \), such that voids are now the most ionized, followed by sheets, filaments, and knots, respectively. This arises as a result of the larger gas densities pushing up the average \( \chi_{HI} \) values in the most over-dense knots; ionization fronts from multiple sources and lower gas-densities ensure a lower neutral fraction in under-dense voids. Naturally, such a behavior is expected to arise only at the end stages of reionization when ionized regions around galaxies essentially percolate throughout the IGM, leading to a more homogeneous photoionization rate.

As for \( f_{esc} \), this parameter affects both the volume ionized by a source as well as the ionization fraction within it. As noted, a degeneracy exists between these two quantities such that, for a given \( \langle \chi_{HI} \rangle \), galaxies build smaller ionized volumes containing larger ionized fractions over smaller timescales for an increasing \( f_{esc} \). This naturally leads to a shift in the ionization fraction of the cosmic web components—as \( f_{esc} \) increases from 0.25 to 0.95, the inversion occurs at successively lower \( \langle \chi_{HI} \rangle \) values. As expected, given that the photoionization rate drops with the square of the distance from the source, the strongest effect of \( f_{esc} \) is felt by over-dense knots. Finally, \( f_{esc} = 0.05 \) represents a special case because the long timescales of about 1 Gyr required to reionize the IGM in this case result in recombinations becoming important, especially in the densest regions. Finally, we have carried out these calculations for various values of the Eigenvalue threshold \( (\gamma) \) ranging between 0 and 0.7, to ensure that our qualitative results are independent of the precise value used.

Our results, therefore, support a scenario where reionization proceeds from over-dense to under-dense regions, in agreement with most other works (e.g., Trac & Cen 2007; Iliev et al. 2012; Battaglia et al. 2013; Bauer et al. 2015). However, our results are in tension with Finlator et al. (2009), who find filaments to be ionized last. One possible reason for this disagreement is that, although our RT resolution is lower than theirs, we properly account for the local clumping factor for each cell, down to the resolution of the SPH simulation. Another possible reason is that we find the emissivity bias for galaxies with the youngest stellar populations to be lower than that found by Finlator et al. (2009), where the ionizing emissivity scales with halo mass as \( M_\bullet \).

5.2. 21 cm Emission from Regions with and without Galaxies

As shown in Section 3.1, galaxies and in particular LAEs, reside in over-dense and highly ionized regions, thereby exhibiting a lower 21 cm brightness temperature as compared to similarly over-dense regions devoid of galaxies. As the universe approaches complete ionization, the ionizing emissivity (and hence \( \langle \chi_{HI} \rangle \)) becomes more homogeneous and causes the \( H I \) distribution to follow the underlying spatial density distribution; the 21 cm brightness temperature in under-dense regions then drops below that in over-dense regions. We now investigate the detectability of the reionization topology by combining 21 cm emission information with galaxy surveys (see also Wyithe & Loeb 2007). We start by dividing the 21 cm differential brightness temperature calculated in Equations (1) and (2) into cells that contain galaxies as
\[ T_{gal} = T_0 \langle \chi_{HI} \rangle \langle 1 + \delta_{HI}(x) \rangle \langle 1 + \delta(x) \rangle_{x \in V_{gal}}, \]
whereas \( T_0 \) is defined as the temperature in cells not containing galaxies:
\[ T_{nogal} = T_0 \langle \chi_{HI} \rangle \langle 1 + \delta_{HI}(x) \rangle \langle 1 + \delta(x) \rangle_{x \in V_{nogal}}. \]
To imitate the observational angular resolution of any imaging (e.g., \( \theta \)) we convolve these temperatures with a top-hat filter of width \( \Delta s = 1.8 h^{-1} \) cMpc (\( \theta/\text{arcmin} \)^{-1}, corresponding to the comoving distance of two points separated by an angular distance \( \theta \) on the sky at \( z \approx 6.6 \). From the convolved temperature fields, we derive the variances for \( T_{gal} \) and \( T_{nogal} \), whereas the corresponding variances depend on \( \theta \). In an experiment where \( N \) independent fields of an angular size \( \theta \) and corresponding vector \( \pi(\Delta s)^2/6 \) are measured, the variance reduces by \( N^{-1/2} \). For \( N = 10 \), the corresponding average values along with the 1σ errors are shown in Figure 6 for two representative cases of \( f_{esc} = 0.05 \) and 0.5. In order to compare to observations, we calculate the SKA1 imaging sensitivity using the same SKA1-Low array configuration (V4A configuration) as was used in Section 4, comprising a
densely-packed core and outer stations configured in a spiral-like configuration. The computation considers two polarizations, a 1000 hr observation, and a 1 MHz bandwidth. We propose to conduct a 1000 hr SKA1 observation of such angular size that 10 non-overlapping fields with angular size $\theta$ containing (not containing) galaxies can be extracted.

A comparison of the 21 cm brightness temperature $T_D$ in regions with and those without galaxies then provides an estimate of the reionization topology, allowing constraints on whether reionization had progressed faster in over-dense regions (hosting galaxies) or under-dense regions (devoid of galaxies):

$$\Delta T = T_{\text{nogal}} - T_{\text{gal}}.$$  

In the initial reionization stages ($\langle \chi_{\text{HI}} \rangle \approx 0.9$), a number of low-mass ($M_* \lesssim 10^{9.5} M_\odot$) field galaxies are embedded in only partially ionized regions at scales $\lesssim 1$ arcmin ($\sim 2.5$ cMpc)—this, combined with the high gas densities around galaxies, results in brightness temperatures as high as $T_{\text{gal}} \gtrsim 40$ mK, as seen from panel (a) of Figure 6, where $f_{\text{esc}} = 0.05$. The progress of reionization leads to a drop in the $\text{HI}$ content even around low-mass field galaxies, resulting in a drop in $T_{\text{gal}} \sim 16$ mK for $\langle \chi_{\text{HI}} \rangle \approx 0.25$ at these scales. Finally, $T_{\text{gal}}$ drops to about 0 mK once the IGM is more ionized than 99%, or $\langle \chi_{\text{HI}} \rangle \lesssim 0.01$. At increasing angular scales, $T_{\text{gal}}$ drops due to a decrease in the gas density—this is mostly driven by the lower gas density in voids that cover roughly 60% of the simulation volume. In this case too, $T_{\text{gal}}$ scales with the average IGM ionization state, dropping from $\sim 22$ mK to $\sim 2$ mK as $\langle \chi_{\text{HI}} \rangle$ decreases from 0.9 to 0.1 for $\theta \approx 4$ arcmin ($\approx 10.2$ cMpc); as expected $T_{\text{gal}} \sim 0$ mK once $\langle \chi_{\text{HI}} \rangle$ drops below 0.01.

$T_{\text{nogal}}$ shows lower temperatures as a result of the lower gas-densities in regions devoid of galaxies. This trend may seem counterintuitive; however, we remind the reader that $T_{\text{gal}}$ is strongly driven by the high gas densities that galaxies reside in, particularly those galaxies in partially ionized cells. $T_{\text{nogal}}$ still scales with the IGM ionization state, decreasing from $\sim 22$ mK to $\sim 2$ mK as $\langle \chi_{\text{HI}} \rangle$ drops from 0.9 to 0.1 at 1 arcmin scales.

Figure 5. Evolution of the mean neutral hydrogen fraction $\langle \chi_{\text{HI}} \rangle$ in the cosmic web components—voids (green squares), sheets (light blue circles), filaments (dark blue upside triangles), and knots (magenta downside triangles)—as a function of the overall mean neutral hydrogen fraction $\langle \chi_{\text{HI}} \rangle$ for the $f_{\text{esc}}$ value marked in each panel. The gray dotted line indicates $\langle \chi_{\text{HI}} \rangle = \langle \chi_{\text{HI}} \rangle$. The $1 - \sigma$ standard deviations for knots and voids are indicated by correspondingly colored areas.
Given that $T_{\text{nogal}}$ probes lower gas-density contrasts in regions devoid of galaxies, its scale variation is less than that seen for $T_{\text{gal}}$: $T_{\text{nogal}}$ varies by $\sim 6$ mK from scales ranging between 0.1 and 5 arcmin, compared to $T_{\text{gal}}$ that can vary by as much as 20 mK ($\langle \chi_{\text{HI}} \rangle \gtrsim 0.5$) on the same scales. Finally, we note that $T_{\text{nogal}} \sim 0$ mK on all scales once $\langle \chi_{\text{HI}} \rangle$ drops below 0.01.

As expected from the above discussion, the temperature difference between regions without and with galaxies ($\Delta T$) is negative at scales less than about 0.8 arcmin, where $T_{\text{gal}}$ is enhanced as a result of (low-mass field) galaxies being embedded in high-density, partially ionized regions. Naturally, $\Delta T$ flips in sign, becoming slightly positive ($\sim 2$–$4$ mK) at larger scales for $\langle \chi_{\text{HI}} \rangle \lesssim 0.5$; as expected, $\Delta T \sim 0$ mK for an IGM more ionized than 99%. These trends remain the same even if the ionizing photon escape fraction increases by an order of magnitude to $f_{\text{esc}} = 0.5$, as shown in the lower three panels of Figure 6.

Figure 6. Differential 21 cm brightness temperature in regions containing galaxies (left column), in regions not containing galaxies (central column), and their difference $\Delta T = T_{\text{nogal}} - T_{\text{gal}}$ (right column) as a function of the smoothing scale $\theta$. The upper and lower panels show the results for $f_{\text{esc}} = 0.05$ and 0.5, respectively. In each panel, we show the differential brightness temperature at different stages of reionization ($\langle \chi_{\text{HI}} \rangle = 0.9$–$10^{-4}$); the solid black line shows the SKA imaging sensitivity limits for a 1000 hr observation.

In each panel, we show the differential brightness temperature at different stages of reionization ($\langle \chi_{\text{HI}} \rangle = 0.9$–$10^{-4}$); the solid black line shows the SKA imaging sensitivity limits for a 1000 hr observation.

5.3. 21 cm Emission from Regions with and without LAEs

In the next step, we calculate the 21 cm differential brightness temperature in cells that contain LAEs as

$$T_{\text{LAE}} = T_0 \langle \chi_{\text{HI}} \rangle \langle (1 + \delta_{\text{HI}}(x))(1 + \delta(x)) \rangle_{x \in \text{V_{LAE}}},$$

whereas $\delta T_{\text{nolAE}}$ for cells not containing LAEs is calculated as

$$T_{\text{nolAE}} = T_0 \langle \chi_{\text{HI}} \rangle \langle (1 + \delta_{\text{HI}}(x))(1 + \delta(x)) \rangle_{x \in \text{V_{nolAE}}},$$

Finally, the difference in the 21 cm brightness temperature in regions with/without LAEs can be expressed as

$$\Delta T_{\text{LAE}} = T_{\text{nolAE}} - T_{\text{LAE}}.$$
results for which are shown in Figure 7. We note that $T_{\text{noLAE}}$ may contain non-\text{Ly}$\alpha$ emitting galaxies.

We start by noting that we only match the observed LAE LFs for $c \approx 0.5$H I, which marks the upper limit for both $T_{\text{LAE}}$ and $T_{\text{noLAE}}$. Given that LAEs represent the subset of galaxies located in the most over-dense and ionized regions (see Section 3.1), we find $T_{\text{LAE}} \sim 0$ mK at all scales, for both $f_{\text{esc}} = 0.05$ and 0.5, for $\langle \chi_{\text{H}I} \rangle \lesssim 0.5$ as shown in Figure 7. For $\langle \chi_{\text{H}I} \rangle \simeq 0.5$, on the other hand, $T_{\text{LAE}}$ shows a slight increase in temperature from 0 to $\sim 5$ mK, with increasing scale (from 0.1 to 5 arcmin), because we effectively sample the brightness temperatures of voids at such large scales. We remind the reader that an average IGM ionization state of $\langle \chi_{\text{H}I} \rangle \simeq 0.5$ is obtained due to a higher ionized fraction inside smaller ionized volumes, as $f_{\text{esc}}$ increases from 0.05 to 0.5. Naturally, the smaller total ionized volume results in a larger neutral fraction, boosting $T_{\text{noLAE}}$ to about 12 mK at the largest scales for $f_{\text{esc}} = 0.5$.

Given that LAEs occupy the largest halos in the most ionized regions, $T_{\text{noLAE}}$ is generically higher than $T_{\text{regal}}$ and shows a steady decrease as the IGM becomes increasingly ionized: $T_{\text{noLAE}}$ falls from $\sim 12$ to 2.5 mK as $\langle \chi_{\text{H}I} \rangle$ decreases from 0.5 to 0.1 at $\sim 0.1$ arcmin scales; again, $T_{\text{noLAE}} \sim 0$ mK, if the IGM is more ionized than 99%. Finally, given that voids are more neutral in the initial reionization stages (see Section 5.1), $T_{\text{noLAE}}$ increases by about 2 mK as $\theta$ increases from 0.1 to 5 arcmin. Finally, we note that $T_{\text{noLAE}} > T_{\text{LAE}}$ results in a positive value of $\Delta T_{\text{LAE}}$ at all scales for $\langle \chi_{\text{H}I} \rangle > 0.01$; $\Delta T_{\text{LAE}} \simeq 0$ mK for a more ionized IGM.

In terms of SKA observations, we find that SKA1 should be able to detect $T_{\text{LAE}} \sim 2 - 4$ mK values at scales greater than three arcmin. With its larger values, SKA-LOW1 provides a much cleaner probe: SKA1 should be able to distinguish between $\langle \chi_{\text{H}I} \rangle \approx 0.1$ and 0.5 at scales larger than two arcmin, irrespective of $f_{\text{esc}}$: this naturally implies $\Delta T_{\text{LAE}}$ can also be used to differentiate between an IGM that is 10% neutral to one that is 50% ionized at these scales. The fact that $\Delta T_{\text{LAE}} > 0$ mK and $T_{\text{LAE}} \simeq 0$ mK, therefore, support the inside-out scenario, where ionized regions percolate from over- to under-dense regions in the IGM, characterized by a lower differential 21 cm brightness temperature in regions around LAEs compared to regions not containing galaxies. This provides a promising experiment for combining future LAE Subaru and 21 cm SKA observations (see also Wyithe & Loeb 2007).
Including an evolution of the galaxy population and the gas density increases not only the 21 cm brightness temperature in neutral regions, but also leads to a decrease in the density contrast toward higher redshifts (rising $\langle \chi_{H I} \rangle$ values). Although the first effect will be dominant in underdense regions, the latter may balance the first in overdense regions, i.e., $T_{\text{gal}}$ remains similar for small $\theta$, but can be larger at higher $\theta$. However, given the reduced optical depth as indicated by Planck, reionization progressed later and faster than anticipated, making the mentioned effects secondary.

An increase of the spatial resolution of our simulations could reveal more details about the environment of galaxies; the signatures of overdense LLS could be studied, in particular. Assuming LLS are located in filaments, we would find $T_{\text{gal}}$—especially close to galaxies—to rise as the $H I$ content in LLS increases. LLS will affect $T_{\text{gal}}$ (and $T_{\text{negal}}$ on small scales); however, it remains an open question how much $T_{\text{LAE}}$ will be affected, given the balance between a low enough $H I$ content for a sufficient Ly$\alpha$ transmission and a high enough $H I$ volume to make a significant difference in the 21 cm signal.

### 6. Conclusions and Discussion

We post-process a GADGET-2 simulation snapshot at $z \approx 6.6$ with a dust model and an RT code (pCRASH), which provide our framework for high-$z$ galaxies, and especially the subset visible as LAEs. We perform five RT simulations with pCRASH, each adopting a different $f_{\text{esc}}$ value (for all galaxies) between 0.05 and 0.95. Starting from a neutral IGM ($\langle \chi_{H I} \rangle = 1$), we run pCRASH until the universe is completely ionized in each case. From the resulting ionization fields, we derive the associated 21 cm brightness temperature maps, and compute the 21 cm–galaxy and 21 cm–LAE cross-correlations, the results of which are now summarized:

1. Although galaxies are located in the most over-dense regions ($1 + \delta \sim 1.5 - 15$), the subset visible as LAEs preferentially occupy the densest ($1 + \delta \sim 2 - 15$) and most ionized regions ($\langle \chi_{H I} \rangle \approx 10^{-2}$). This naturally results in 21 cm brightness temperatures an order of magnitude lower ($\sim$1 mK) in regions hosting LAEs, as compared to similarly over-dense regions ($1 + \delta \sim 3$) devoid of them.

2. The 21 cm–LAE anti-correlation (which increases with the increasing $\langle \chi_{H I} \rangle$) at small ($\lesssim 10$ cMpc) scales will provide an exquisite probe of the average ionization state at high-$z$ within errors, a 1000 hr joint SKA-Low/Subaru HSC experiment will be able to distinguish between an IGM that was fully ionized and one that was 10%, 25%, or 50% neutral, irrespective of the parameter space ($f_{\text{esc}}$, $f_{\gamma}$) explored.

3. Even conducting a 1000 hr survey of 10 fields around regions with galaxies, SKA1 should be able to distinguish between IGM ionization states of $\langle \chi_{H I} \rangle_{\text{gal}} \approx 0.25$, 0.5, 0.75, and 0.9 at scales greater than 1 arcmin. However, given their larger masses, the 21 cm temperature around LAEs effectively tends to 0 at almost all scales.

4. In terms of the reionization topology, for an IGM more neutral than $\langle \chi_{H I} \rangle \gtrsim 0.1$, we find the $H I$ fraction to be the lowest in knots, followed by filaments, sheets, and voids in that order supporting the "inside-out scenario." If fields devoid of LAEs can be identified, an SKA1 1000 hr survey of 10 fields around regions with and without LAEs can be used as a probe of the reionization topology.

A positive differential 21 cm brightness temperature in voids that tends to zero in regions hosting LAE at scales larger than two arcmin will provide strong support for the inside-out reionization scenario.

We end by summarizing the major caveats in this work. As a natural consequence of simulating cosmological volumes, we do not resolve LLSs. Including LLS can decrease the Ly$\alpha$ transmission along those LOS that traverse such systems, affecting the visibility of bright galaxies as LAEs (Kakiichi et al. 2016). Second, the prevalence of LLS in large numbers at early cosmic epochs could, in principle, lead to knots/filaments being ionized last, resulting in an inside-out-middle reionization (c.f. Finlator et al. 2009).

In our error estimate of the 21 cm–LAE cross-correlation in a combined Subaru HSC and 1000 hr SKA experiment, we have assumed that the location of LAEs in the IGM can be measured with a maximum uncertainty of 1.9 $h^{-1}$ Mpc, whereas the redshift uncertainty from Subaru HSC filters will be about 7 $h^{-1}$ Mpc. This may lead to increased uncertainties and a weaker anti-correlation signal in the 21 cm–LAE cross-correlations at scales <7 $h^{-1}$ Mpc. Furthermore, narrowband selected LAEs resemble more a 2D distribution, and the resulting projection effect may weaken the cross-correlation signal. However, we have chosen to (a) employ the full three-dimensional information to investigate trends of changing galactic properties and (b) provide a rough estimate on the detectability with focus on SKA.

We also note that, due to poor constraints on its mass dependence, we assume the same escape fraction of ionizing photons for each galaxy. An evolution in $f_{\text{esc}}$ with mass and/or redshift could have implications for the progress and sources of reionization that might be reflected in the 21 cm-galaxy/LAE correlations. Forthcoming observations with the James Webb Space Telescope will be invaluable on shedding light on this parameter to identify the sources of reionization.

The authors would like to thank Marco Castellano, Dijana Vrbacek, Benedetta Ciardi, Darren Croton, and Manodeep Sinha for useful discussions and comments. The authors acknowledge Peter Creasey for permission to use his Python library as a basis for the computation of the power spectra, and Benedetta Ciardi for a collaboration in developing pCRASH. A.H. is supported under the Australian Research Council’s Discovery Project funding scheme (project number DP150102987). P.D. acknowledges support from the European Commission’s CO-FUND Rosalind Franklin program. C.M.T. is supported under the Australian Research Council’s Discovery Early Career Researcher funding scheme (project number DE140100316) and the Centre for All-sky Astrophysics (an Australian Research Council Centre of Excellence funded by grant CE110001020). Finally, this research was supported by the Munich Institute for Astro- and Particle Physics (MIAPP) of the DFG cluster of excellence “Origin and Structure of the Universe.”

### Appendix A

#### Cosmic Web

In Figure 8, we show how the threshold $\gamma$ determines the classification of the cosmic web. An increase in the $\gamma$ (which can be thought of as an increase in the collapse time) results in an increase in both the mass- and volume-weighted fraction of
voids, accompanied by a decrease in the values for knots, filaments, and sheets. Given the mass concentration in knots, filaments, and sheets—and the lack thereof in voids—we find that the mass-weighted fraction of collapsed structures is always higher than the volume-weighted fraction.

In this paper, we use a threshold that corresponds to a volume-weighted fraction of 60% for voids; this threshold is found at \( \gamma = 0.3 \). The corresponding classification of the cosmic web is shown for a slice through the middle of the simulation in Figure 9.

Appendix B

Results for a Double Peak Ly\( \alpha \) Line Profile

We compute the Ly\( \alpha \) transmission \( T_\alpha \) for a double peak line profile using a Gaussian-minus-a-Gaussian (GmG) line shape with a width that depends on the halo mass as described Jensen et al. (2013). Their employed fitting function (Equations (6)–(8) in Jensen et al. 2013) was obtained by fitting the emergent Ly\( \alpha \) line profiles of a high-resolution galaxy sample spanning a range of stellar masses. Assuming GmG line shapes, we find the Ly\( \alpha \) transmissions \( T_\alpha \) of our simulated galaxies boosted by \( \sim 0.1 \) in comparison with \( T_\alpha \) of Gaussian line shapes; the attenuation of Ly\( \alpha \) radiation aside the resonance is the strongest, causing a larger fraction of the emergent Ly\( \alpha \) radiation to be attenuated for a Gaussian line profile. The boosted Ly\( \alpha \) transmission can be compensated by a lower ratio between the escape fractions of Ly\( \alpha \) and UV continuum photons (\( f_{\alpha}/f_{\text{UV}} \)). We find that the population of galaxies visible as LAEs hardly changes, and thus the 21 cm-LAE cross-correlations do not change. In fact, they look identical to the results in Figure 4.

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Figure 8. Volume (left panel) and mass (right panel) weighted fractions of voids, sheets, filaments, and knots vs. the threshold \( \gamma \) (Nuza et al. 2014). The vertical line at \( \gamma = 0.3 \) represents the threshold for which 60% of the volume is identified as voids and corresponds to the limit used in this work.

Figure 9. A slice through the 80 h\(^{-1}\) cMpc simulation box, showing the large-scale cosmic web. The different colors indicate the different cosmic web components: voids (white), sheets (orange), filaments (brown), and knots (black).
