The role of galaxies and AGN in reionizing the IGM – I. Keck spectroscopy of $5 < z < 7$ galaxies in the QSO field J1148+5251


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ABSTRACT

We introduce a new method for determining the influence of galaxies and active galactic nuclei (AGN) on the intergalactic medium (IGM) at high redshift and illustrate its potential via a first application to the field of the $z = 6.42$ QSO J1148+5251. Correlating spatial positions Lyman break galaxies (LBGs) with the Lyman alpha forest seen in the spectrum of a background QSO, we provide a statistical measure of the typical escape fraction of Lyman continuum photons. Using Keck DEIMOS spectroscopy to locate seven colour-selected LBGs in the range $5.3 < z < 6.4$ we examine the spatial correlation between this sample and Ly$\alpha$/Ly$\beta$ transmission fluctuations in a Keck ESI spectrum of the QSO. Interpreting the statistical HI proximity effect as arising from faint galaxies clustered around the LBGs, we translate the observed mean Ly$\alpha$ transmitted flux into a constraint on the mean escape fraction $\langle f_{\text{esc}} \rangle \geq 0.08$ at $z \approx 6$. We also report individual transverse H$\alpha$ proximity effect for a $z = 6.177$ luminous LBG via a Ly$\beta$ transmission spike and two broad Ly$\alpha$ transmission spikes around the $z = 5.701$ AGN. We discuss the origin of such associations which suggest that while faint galaxies are primarily driving reionization, luminous galaxies and AGN may provide important contributions to the UV background or thermal fluctuations of the IGM at $z \approx 6$. Although a limited sample, our results demonstrate the potential of making progress using this method in resolving one of the most challenging aspects of the contribution of galaxies and AGN to cosmic reionization.

Key words: galaxies: formation – galaxies: high-redshift – intergalactic medium – quasars: absorption lines – cosmology: observations – dark ages, reionization, first stars.

1 INTRODUCTION

Understanding how and when cosmic reionization occurred represents one of the most important challenges in observational cosmology and galaxy formation. Of particular interest is the nature of sources responsible, which was first discussed over 50 yr ago (Gunn & Peterson 1965). Although reionization is commonly assumed to be driven by the abundant population of intrinsically faint star-forming galaxies (e.g. Robertson et al. 2013, 2015, for a review; see Stark 2016), a key assumption is that the average escape fraction of Lyman continuum (LyC) photons is $\sim 10$–20 per cent. Such high escape fractions are rarely encountered in lower redshift star-forming galaxies where direct measurements of the LyC leakage are possible (Mostardi et al. 2015; Naidu et al. 2017). On the other hand, recent observations of Ly$\alpha$ emission in the spectra of $z > 7$ galaxies (Oesch et al. 2015; Zitrin et al. 2015) might indicate that reionization is accelerated in the volumes around the most luminous galaxies (Stark et al. 2017), possibly as a result of their harbouring active galactic nuclei (AGN; Laporte et al. 2017). A significant contribution of ionizing photons from rare sources such as luminous galaxies and/or AGN (Giallongo et al. 2015, but see Parsa, Dunlop & McLure 2018) may also explain the significant scatter...
in the effective optical depth of Lyα absorption in the spectra of $z \gtrsim 5.5$ QSOs (Becker et al. 2015b; Chardin et al. 2015; Chardin, Puchwein & Haehnelt 2017; Bosman et al. 2018). However, both observationally and theoretically the relative ionizing contribution of galaxies and AGN is a subject of intense debate (Madau & Haardt 2015; D’Aloisio et al. 2017; Qin et al. 2017; Hassan et al. 2018; Mitra, Choudhury & Ferrara 2018).

A fundamental impasse to progress is the absence of a reliable technique to measure the escape fraction $f_{esc}$ of ionizing photons at high redshift where direct measures of the leaking LyC radiation become impractical due to foreground line-of-sight absorption. Indirect methods have been examined including absorption line measures of the covering fraction of low-ionization gas in the spectra of lensed galaxies (Jones et al. 2013; Leethochawalit et al. 2016) which suggest a modest increase in $f_{esc}$ to $z \simeq 4$, but the method assumes low-ionization gas is a faithful tracer, geometrically and kinematically, of neutral hydrogen (Reddy et al. 2016; Vasei et al. 2016). Other methods such as the analysis of recombination lines (Zackrisson, Inoue & Jensen 2013; Zackrisson et al. 2017), requires access to Balmer lines seen beyond 2 μm at high redshift and also necessitates an accurate knowledge of the nature of the stellar population.

In this paper, we propose a new method for estimating $f_{esc}$ at high redshift which is based on examining the cross-correlation between star-forming galaxies and the Lyα absorption spectrum of a background QSO probed in the same cosmic volume. Such an approach (Adelberger et al. 2003, 2005) has been productive at a background QSO probed in the same cosmic volume. Such an approach (Adelberger et al. 2003, 2005) has been productive at a background QSO probed in the same cosmic volume. Such an approach (Adelberger et al. 2003, 2005) has been productive at a background QSO probed in the same cosmic volume. Such an approach (Adelberger et al. 2003, 2005) has been productive at a background QSO probed in the same cosmic volume.

We illustrate the potential via an application to a cosmic volume in the series, we develop the method which exploits the statistical association between star-forming galaxies proximate to the QSO sightline and fluctuations in the Lyα forest which gives us the mean Lyα transmitted flux around galaxies. In Section 4, we discuss the physical origin of the observed Lyα transmitted flux around LBGs and introduce our methodology which takes into account the associated but fainter galaxies which are undetected in our imaging survey thereby deriving a mean escape fraction of LyC photons at $z \simeq 6$. The result is presented in Section 5. In Section 6, we examine two specific cases where sources can be directly associated with features in the Lyα forest which provides insight into the possible contribution of rarer, luminous sources including AGN. In Section 7, we discuss the promise and challenges of our new method and the prospects with further data.

Throughout this paper we adopt the Planck 2015 cosmology ($Ω_m$, $Ω_\Lambda$, $h$, $σ_8$, $n_s$) = (0.3089, 0.6911, 0.04860, 0.6774, 0.8159, 0.9667) (Planck Collaboration XIII 2016). We use pkpc and pMpc (ckpc and cMpc) to indicate distances in proper (comoving) units. All magnitudes in this paper are quoted in the AB system (Oke & Gunn 1983).

## 2 Observations

Our choice of the SDSS QSO J1148+5251 at $z = 6.4189$ (RA = 11h48m16.7s +52deg51m50.39s, J2000) for the illustration of our new method was based on the availability of its EHI high signal-to-noise spectrum and deep ground and space-based imaging from which we can photometrically select galaxies in the relevant redshift range. For this QSO the uncontaminated Lyα forest spans the redshift range $5.26 < z < 6.42$. Archival data from the Spitzer and Chandra Space Telescopes provides additional information on the stellar mass and AGN activity of selected sources in the QSO field (e.g. Jiang et al. 2006; Gallerani et al. 2017).

### 2.1 Imaging Data and Photometric Catalogue

Deep archival Large Binocular Telescope (LBT) images of the Q1148 field in the SDSS r-, i-, and z-band filters taken by the Large Binocular Camera (LBC) were used to construct a photometric catalogue of r- and i-dropout candidates for Keck spectroscopic follow-up. LBC pipeline-reduced images reported by Morselli et al. (2014) (PI: R. Gilli) were downloaded from the LBT archive The exposure times were $\sim$3 hrs in r and $\sim$1.5 hrs in i and z. This panoramic data

1. [http://www.oabo.inaf.it/ LBTz6/](http://www.oabo.inaf.it/ LBTz6/)
set covers a field of 23 × 25 arcmin (≈39.5 × 42.5 h⁻¹ cMpc at z = 6) which covers a substantial fraction of the expected mean free path of ionizing photons at this epoch, $\lambda_{\text{mfp}} \approx 6.0 (1 + z)^{5.4}$ pMpc (Worseck et al. 2014) or 17 arcmin. From the processed data, we constructed our own photometric source catalogue using Sextractor (Bertin & Arnouts 1996). The limiting magnitudes in each bandpass were estimated by randomly placing fixed 2 arcsec apertures in blank regions. We derived 5σ limiting magnitudes of $r = 26.3$, $i = 25.9$, and $z = 25.0$ (and at $2\sigma$, $r = 27.3$, $i = 26.9$, and $z = 26.0$) in agreement with the values reported by Morselli et al. (2014).

In order to select our candidate LBGs in the desired redshift range, we imposed a 5σ detection limit of $z = 25.0$ for our primary selection with fainter secondary candidates at the 3σ limit of $z = 25.6$. We selected candidate LBGs in the sought-after redshift range $5.26 \lesssim z \lesssim 6.42$ according to the following criteria:

$$r - i > 1.0 \quad \text{and} \quad i - z < 1.0$$

(1)

for $r$-dropouts and

$$i - z > 1.0 \quad \text{and} \quad [r > 2\sigma \text{ or } r - z > 1.75]$$

(2)

for $i$-dropouts.

We can visualize the $i$-dropout criteria by considering template spectra for target LBGs and AGN in Fig. 1. Here, a strong $\lambda$ emission line could produce bluer $i - z$ colours and thus a traditional $i - z > 1.3$ colour cut (e.g. Bouwens et al. 2006, 2007) would miss a substantial fraction of objects at $5.3 < z < 5.7$ and $\sim 20–30$ per cent at $z > 5.7$ (Malhotra et al. 2005; Díaz et al. 2011). Likewise Type II QSOs could have a very blue $i - z < 0$ colour at $z > 5.3$ due to the strong Lyα emission line (Meiksin 2006b; Díaz et al. 2011). In Fig. 1, we consider both $r$- and $i$-dropout criteria in the context of the locus of a BPASS galaxy model (version 2.0, Stanway, Eldridge & Becker 2016; Eldridge et al. 2017) with continuous star formation at 100 Myr. $Z = 0.20 Z_\odot$, metallicity, and Lyα equivalent width $W_{\lambda_{Ly\alpha}} = 50$ Å, and that of a mean QSO template (Telfer et al. 2002) from redshift 5.3 to 6.4 at 0.1 redshift interval in the context of LBT filters. The IGM transmission is computed using IGMTRANSMISSION code (Harrison, Meiksin & Stock 2011) based on the transmission curves of Meiksin (2006a). The adopted selection criteria, equations (1) and (2), are marked. After applying these criteria, two authors (KK and NL) visually inspected all candidates removing sources contaminated with artefacts, diffraction spikes of nearby stars and sources close to the boundaries of the detector mosaic. There are 124 objects in the final photometric catalogue of $r$- and $i$-drop candidates.

### Figure 1

Colour–colour diagram for $r$- (left) and $i$-dropouts (right). The locii of LBGs with $W_{\lambda_{Ly\alpha}} = 50$ Å(red star symbols) and a QSO (filled blue symbols) template spectrum from $z = 5.2, \ldots, 5.7$ (left) and $5.8, \ldots, 6.4$ (right) by 0.1 interval are shown. The magenta points are the spectroscopically confirmed $r$, $i$-dropouts in the Q1148 field. The small black points represent candidates from the photometric catalogue identified by Sextractor. Typical colours for $0 < z < 3$ interlopers (open blue squares) from VUDS-DR1 samples in COSMOS field (Le Fèvre et al. 2015; Tasca et al. 2017) and for Galactic stars (open green triangles) (Gunn & Stryker 1983) are overlaid. Our adopted selection criteria for dropout candidates are indicated by dotted lines.

### 2.2 Galaxy spectroscopy

The photometric candidates were spectroscopically observed through an ongoing survey undertaken with the DEIMOS at the Nasmyth focus of the 10-m Keck II telescope (Faber et al. 2003) on 2013 March 26–27 (PI: Zitrin). Conditions were clear and seeing was typically between 0.9–1.5 arcsec on 26th and 0.7–1.0 arcsec on 27th. We placed one slitmask of 16.7 × 5.0 arcmin² field of view so as to maximize the number of dropout targets from the LBT photometric catalogue and encompassing a large volume within the mean free path of ionizing photons at this epoch (Fig. 2). In selecting targets for the mask, greater priority was given to $i$-dropouts to increase the likelihood of detecting Lyα emission in redshift range sampled by the Lyα forest, yielding 45 dropout targets in the mask. A 1.0 arcsec slitwidth was used with the 600 line mm⁻¹ grating (600ZD) providing spectroscopic coverage between 4950 Å and 10 000 Å with a spectral resolution of 3.5 Å . The mask was observed for 4.3 h. All data were reduced using the Spec2d IDL pipeline (Cooper et al. 2012; Newman et al. 2013). The wavelength calibration was done using the Haarlem ARCAmp lamp. The final reduction provides two-dimensional (2D) spectra and variance arrays. The spectra were visually inspected for emission lines independently by the four of the authors (KK, RSE, NL, and AZ). Two authors (RSE and NL) were blinded from the locations of transmission features in the QSO spectrum (see below) to avoid unconscious biases.

2The filter bandpasses were derived from http://abell.as.arizona.edu/lbsci/Instruments/LBC/lbc.html
In total we secured spectroscopic redshifts for 16 sources including a previously identified AGN (Mahabal et al. 2005), corresponding to a $\geq 35$ per cent success rate of spectroscopic confirmation. All emission lines in each 2D spectrum coincide with the expected location of the dropout target on the slit. The overall redshift distribution of the spectroscopic sample is shown in Fig. 3. However, due the limited three bands photometry for the Q1148 field, the photometric redshifts were fairly approximate. Within the $5.3 < z < 6.4$ redshift range which overlaps the volume where the IGM transmission can be traced in the absorption line spectrum of SDSS J1148+5251, we have a sample of six spectroscopically confirmed LBGs plus the AGN (excluding one LBG at $z_{\text{Ly} \alpha} = 6.415$ lying in the proximity zone of the Q1148). Thus, the final success rate of finding galaxies in the Ly$\alpha$ forest region was $\sim 13$ per cent. Spectra of the LBGs and AGN are shown in Figs 4 and 5. The properties of the sources in the relevant redshift range for this study are listed in Table 1.

2.3 QSO spectroscopy and Ly$\alpha$ transmission features

To examine the structure in the Ly$\alpha$ forest of SDSS J1148+5251 QSO (Fan et al. 2003), we used a spectrum taken with the Echellette Spectrograph and Imager (ESI) at the Keck II telescope from a large sample of QSOs uniformly reduced by Eilers et al. (2017) (Fig. 6). The systemic redshift of J1148+5251 is taken from the CO redshift presented in Carilli et al. (2010). The spectral resolution is $R \approx 5000$ sampled with $\sim 5$ pixels ($\sim 10$ km s$^{-1}$ per pixel) within one resolution element.

To estimate the wavelength-dependent continuum level, we use a principal component analysis (PCA) as described by Eilers et al. (2017). This PCA-based continuum estimate $C_\lambda$ is used to calculate the Ly$\alpha$ transmitted flux $F_\alpha = e^{-\tau_\alpha}$,

$$F_\alpha = f_\lambda / C_\lambda + n_\lambda / C_\lambda,$$

(3)

where $f_\lambda$ is the observed flux and $n_\lambda$ is the noise in the Q1148 ESI spectrum.

To estimate the uncertainty, we also employed an empirical technique based on $HST$/COS spectra of $z \lesssim 1$ UV-bright AGN (Danforth et al. 2016). The continuum level was then estimated for the subset of 17 $HST$/COS continuum spectra classified as type ‘QSO’. We compared the continuum redward of the Ly$\alpha$ emission line of the $HST$/COS spectra with the Q1148 ESI spectrum and derived the best-fitting continuum by minimizing the chi-square for $\lambda > 1270$ Å.

Although Q1148 has a weak Ly$\alpha$ emission line, unlike those in the set of the 17 $HST$/COS spectra, this only affects the derived Ly$\alpha$ absorption properties in the vicinity of the QSO, which is not used in the subsequent analysis. Comparing the Ly$\alpha$ transmitted flux between the PCA-based and $HST$/COS-based methods, the difference in the continuum level is $\sim 20$ per cent at median over the redshift range $5.5 < z_{\text{Ly} \alpha} < 6.3$. This is sufficiently small not to affect the subsequent analysis and results in this paper.

We identify Ly$\alpha$ and Ly$\beta$ transmission spikes using an automated wavelet-based algorithm. We correlate (i.e. wavelet transform) the continuum-normalized Ly$\alpha$ forest spectrum with a ‘Mexican hat’ wavelet $\psi_\sigma(x) \propto \sigma^{-1/2}(1 - (x/\sigma)^2)\exp(-x^2/2\sigma^2)$ (normalized with

3Publicly available online: https://archive.stsci.edu/prepds/igm/
What reionized the Universe?

Table 1. DEIMOS spectroscopic catalogue.

<table>
<thead>
<tr>
<th>ID</th>
<th>$z_{Ly\alpha}$</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>$r$ (mag)</th>
<th>$i$ (mag)</th>
<th>$z$ (mag)</th>
<th>$M_{1V}$</th>
<th>Note</th>
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<tr>
<td>002</td>
<td>5.701</td>
<td>11h48m16.20s</td>
<td>52d53m39.55s</td>
<td>$&gt;27.3$</td>
<td>24.63 ± 0.06</td>
<td>23.55 ± 0.04</td>
<td>−23.11 ± 0.04</td>
<td>AGN (Ly$\alpha$+N V)</td>
</tr>
<tr>
<td>004</td>
<td>6.177</td>
<td>11h48m37.80s</td>
<td>52d50m39.60s</td>
<td>$&gt;27.3$</td>
<td>26.9 ± 0.06</td>
<td>25.01 ± 0.14</td>
<td>−21.78 ± 0.14</td>
<td>LBG (Ly$\alpha$)</td>
</tr>
<tr>
<td>008</td>
<td>5.597</td>
<td>11h48m28.98s</td>
<td>52d54m04.50s</td>
<td>$&gt;27.3$</td>
<td>26.9 ± 0.06</td>
<td>25.53 ± 0.13</td>
<td>−21.10 ± 0.13</td>
<td>LBG (Ly$\alpha$)</td>
</tr>
<tr>
<td>009</td>
<td>6.415</td>
<td>11h48m16.32s</td>
<td>52d55m22.94s</td>
<td>$&gt;27.3$</td>
<td>26.9 ± 0.06</td>
<td>24.90 ± 0.12</td>
<td>−21.95 ± 0.12</td>
<td>LBG (near Q1148)</td>
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<td>015</td>
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<td>52d49m51.97s</td>
<td>26.76 ± 0.69</td>
<td>25.36 ± 0.39</td>
<td>24.46 ± 0.31</td>
<td>−22.24 ± 0.31</td>
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<td>5.748</td>
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<td>52d54m28.56s</td>
<td>$&gt;27.3$</td>
<td>26.9 ± 0.06</td>
<td>25.37 ± 0.15</td>
<td>−21.30 ± 0.15</td>
<td>LBG (Ly$\alpha$)</td>
</tr>
<tr>
<td>043</td>
<td>5.758</td>
<td>11h47m48.72s</td>
<td>52d56m37.98s</td>
<td>$&gt;27.3$</td>
<td>26.9 ± 0.06</td>
<td>25.58 ± 0.16</td>
<td>−21.10 ± 0.16</td>
<td>LBG (Ly$\alpha$)</td>
</tr>
</tbody>
</table>

$^a$ By interpreting the peak of the line as Ly$\alpha$ redshift (measured in this work).

$^b$ Based on the apparent $z$ magnitude, assuming the $k$-correlation $2.5(\alpha - 1)\log_{10}(1 + z_{Ly\alpha})$ with a spectral slope $\alpha = 2$.

\[
\int \psi_\sigma(x)dx = 0,
\]

\[
w_\sigma(\lambda) = \int F_\lambda(\lambda)\psi_\sigma(\lambda - \lambda')d\lambda'.
\]

The width of the wavelet was varies according to $\sigma = 10, \ldots, 250$ km s$^{-1}$ with 10 km s$^{-1}$ interval. At each wavelength pixel, we record the maximum wavelet coefficient $w_{\sigma\text{max}}(\lambda) = \max_{\sigma} w_\sigma(\lambda)$ for all width choice. Robust transmission spikes are chosen as the local maxima of the wavelet coefficients, $w_{\sigma\text{max}}(\lambda)$, whose signal-to-noise ratio at a peak pixel is larger than 5$\sigma$. The wavelet-based estimate of the widths of the transmission spikes are recorded as the width at which gives the local maxima of the wavelet coefficients. The method successfully identifies the previous known Ly$\alpha$ transmission spike at $z = 6.083$ (White et al. 2003, 2005; Oh & Furlanetto 2005). The list of the identified Ly$\alpha$ and Ly$\beta$ transmission spikes is tabulated in Table 2.

Figure 5. Same as Fig. 4, but for spectroscopically confirmed $z > 5.3$ LBGs in the Q1148 field.
We now introduce the observed correlation between galaxies and Lyα transmission features in the J1148 QSO field. We focus initially on the 3D mapping of galaxies as it relates to identifiable Lyα transmission spikes and absorption troughs. We then examine the statistical correlation between spectroscopically confirmed galaxies and the Lyα transmitted flux. Later, in Section 4 we discuss the physical basis of this cross-correlation signal and develop a methodology in order to derive a constraint on the mean LyC escape fraction at z ~ 6 in Section 5.

3.1 The observed distribution of galaxies around Lyα transmission spikes and absorption troughs

In Fig. 7, we show the spatial distribution of spectroscopically confirmed galaxies from our DEIMOS survey in the context of Lyα forest transmission spikes and absorption troughs in the ESI spectrum of QSO J1148+5251. The continuum normalized QSO spectrum of the transmitted Lyα flux, e^{-τα}, is shown with the Lyα redshifts zLyα and the physical separation r∥ of the galaxies relative to the QSO sightline. This 3D mapping of galaxies around the varying Lyα transmission gives us our first glimpse of how galaxies influence the physical state of the IGM at the end of reionization. Three out of our 6 LBGs (at zLyα = 5.597, 5.845, 6.177) lie close to the vicinity of Lyα and/or Lyβ transmission spikes in the QSO spectrum, while 2 LBGs at zLyα = 5.748, 5.758 are located close to deep absorption troughs. One of our LBGs at zLyα = 6.415 resides within the proximity zone of the J1148+5251 QSO (indicated by the blue shaded region). The source at zLyα = 5.701 is a previously known AGN (Mahabal et al. 2005) and its location is bracketed by two broad Lyα transmission spikes (Gallerani et al. 2008).

It is noteworthy that ~40 per cent of our spectroscopic sample is found close to Lyα transmission spikes, particularly since the redshift distribution of r∥-dropout selection is quite broad (Vanzella et al. 2009; Stark et al. 2010). However, there may well be selection effects biasing the visibility of Lyα emission in the galaxy sample, e.g. in wavelength regions unaffected by strong skylines. In order to quantify the relative spatial distribution of LBGs and Lyα absorption more rigorously, it is necessary to adopt a statistical approach.

3.2 Statistical H I proximity effect: the mean Lyα transmitted flux around galaxies

To examine the cross-correlation between the location of spectroscopically confirmed galaxies and Lyα forest absorption features, we compute the mean Lyα transmitted flux, \langle \exp(-\tauα(r)) \rangle, around the spectroscopically confirmed LBGs as a function of physical distance r from a galaxy to Lyα forest pixels,

\[ \langle \exp(-\tauα(r)) \rangle = \frac{\sum wi F_{α,i}}{\sum wi}, \]

where \( F_{α,i} = e^{-\tauα,i} \) is the Lyα transmitted flux at a physical distance \( r_i \) from a galaxy of interest, \( w_i \) is the weight for galaxy–Lyα forest pixels, with which we down-weight noisy pixels as \( wi = 1/\sigma_{N,i}^2 \). For a given galaxy–Lyα forest pixel, we did not divide the Lyα transmitted flux \( F_i \) in each pixel by the mean absolute flux.

4We take a Lyα redshift as a galaxy redshift, zLyα = zLBG. The velocity offsets of Lyα redshifts relative to the systemic galaxy redshifts vary by ~0–500 km s^{-1} (e.g. Mainali et al. 2017, and references therein). At a typical velocity offset \( \pm 200 \) km s^{-1} the systematic error in distance is \( \pm 300 \) kpc at \( z \approx 5.8 \). While for small-scale applications this involves a correction (Steidel et al. 2010; Turner et al. 2014), this has a negligible effect on the large-scale cross-correlation presented in this paper.

Figure 6. ESI spectrum and estimated continuum level for the SDSS J1148+5251 z = 6.4189 QSO (black). The latter is based on the PCA spectrum (blue) and HST/COS spectrum (red: continuum of SDSS J0929+4644 z = 0.24 QSO). The dotted lines indicate a power-law continuum with α = −0.5.

Table 2. Transmission features at z > 5.5 in the Lyα and Lyβ forest regions in the Q1148 ESI spectrum.

<table>
<thead>
<tr>
<th>z</th>
<th>S/N</th>
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<th>S/N</th>
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<td>5.527</td>
<td>6.1</td>
<td>5.641</td>
<td>20.0</td>
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3.3 Statistical H I proximity effect: the mean Lyα transmitted flux around galaxies

To examine the cross-correlation between the location of spectroscopically confirmed galaxies and Lyα forest absorption features, we compute the mean Lyα transmitted flux, \( \langle \exp(-\tauα(r)) \rangle \), around the spectroscopically confirmed LBGs as a function of physical distance \( r \) from a galaxy to Lyα forest pixels,
Lyα transmission $e^{-\tau_{\alpha}(z)}$ (to subtract the mean redshift evolution of the IGM, $\tau_{\alpha}(z)$ (e.g. Fan et al. 2006; Becker et al. 2013) because, at $z \geq 5.75$, the observed Lyα transmitted flux is below the noise level. While equation (5) gives more weight to the Lyα transmission around lower redshift LBGs, it provides the most direct statistical measurement independent of external constraints. A further advantage of this statistical measure is that we need not apply uncertain completeness corrections to our spectroscopic samples. Our procedure provides a measure of the mean H I gas density around detected galaxies. This galaxy-centric view contrasts with Lyα forest-centric statistical measures, e.g. the number of galaxies around Lyα transmission spikes, for which completeness corrections in the galaxy sample would be critical.

In Fig. 8, we show the observed mean Lyα transmitted flux around spectroscopically confirmed LBGs with $5.3 < z < 6.3$ as a function of proper distance in the Q1148 field. We consider $\langle z \rangle \approx 5.8 \pm 0.2$ as the representative redshift based on the mean redshift of the LBG sample. The maximum distance (6 pMpc) is governed by the typical mean free path of ionizing photons at $z \approx 6$ (Worseck et al. 2014).

The error is estimated using the Jackknife resampling based on three sub-samples removing one galaxy at a time. As the two innermost bins at $r < 1$ pMpc are based on only one source, we exclude them from the statistical analysis. Although a modest sample, the data presents tentative, intriguing evidence for an increasing Lyα forest transmission closer to the LBGs. This indicates the presence of statistical HI proximity effect at $z \approx 5.8$. The Spearman rank correlation coefficient is $r_s = -0.47$ which corresponds to a ‘moderate’ correlation at a $\approx 80$–90 per cent confidence level (Wall & Jenkins 2012). The correlation is somewhat weaker if the AGN sample is included, degrading the coefficient to $r_s = -0.30$.

Our sample probes only one sightline, thus any interpretation of the positive signal is affected by both potential systematic errors and small number statistics. The apparent hump at $r \approx 4$ pMpc is caused by repeatedly selecting the same prominent Lyα transmission spike at $z \approx 5.7$. We have tested this by artificially masking between $z = 5.64$ and 5.74, where Lyα forest is likely affected by the proximity $z = 5.701$ AGN, and find that the hump is removed. The Jackknife method likely underestimates the error discussed above as the removal of one source near $z \approx 5.7$ contributes little to the variance. At this stage we consider the positive correlation between LBGs and Lyα transmission spikes tentative, but sufficient to demonstrate the potential of our method. Although an increased sample size is clearly required, Fig. 8 demonstrates it is possible to probe the gaseous environment of galaxies at the end of reionization by a spectroscopic survey in $z > 6$ QSO fields.

4 INTERPRETING THE GALAXY–LYα FOREST CROSS-CORRELATIONS

The HI proximity effect is normally thought to arise due to the enhanced UV background around ionizing sources. In this section, we discuss the physical interpretation of the statistical HI proximity effect seen in the mean Lyα transmitted flux around LBGs in J1148 QSO field. The basis of our method will be to assume that this statistical HI proximity effect arises not only from the detected LBGs but also from undetected fainter galaxies which cluster around them. By balancing the ionizing output of this combined population of luminous and fainter galaxies and the UV background via the statistical HI proximity effect, we can constrain the population-averaged LyC escape fraction at $z \approx 6$. Although the fainter sources cannot be detected in our observing campaign, we will use our spectroscopically detected luminous LBGs effectively as signposts, indicating their likely presence as predicted both by deeper imaging observations and expectations of hierarchical clustering in $\Lambda$CDM cosmology.

4.1 Methodology

In order to interpret our data, we have developed a simple radiative transfer model to examine the influence of galaxies on the IGM. Later we use the model to fit the observed mean Lyα transmitted flux around LBGs to derive a constraint on LyC escape fraction. Although more approximate than one based on numerical radiative transfer or radiation hydrodynamic simulations, it has the benefit of illustrating explicitly how various physical processes influence the interaction between galaxies and Lyα forest transmission features.

4.1.1 Model: the mean Lyα transmitted flux around galaxies

The Lyα optical depth around galaxies depends on the density, ionization, and thermal state of the IGM. Using the fluctuating
Figure 8. Comparison of the observed mean Lyα transmitted flux around LBGs (black) with the theoretical model at \(z = 5.8\). The model shows the contribution to the photoionization rate from sub-luminous galaxies clustered around the LBGs for different values of (left-hand panel) the mean LyC escape fraction and (right-hand panel) the minimum UV luminosity of ionizing galaxies. In the left (right) panel the value of \(M_{\text{lim}}^{\text{UV}} = -15\) (\(f_{\text{esc}} = 0.10\)) is fixed. The local contribution from a bright LBG alone is indicated as the dotted line. The average photoionization rate and mean Lyα transmitted flux around LBGs are shown in the top and bottom panels.

The model embraces a number of physical factors – density fluctuations, UV background, and thermal state of the IGM – important for the mean Lyα transmitted flux around LBGs. We discuss each physical process in the following section.

4.1.2 Balancing the galaxy abundance with the photoionization rate required by statistical H\(\text{I}\) proximity effect

To derive a constraint on the LyC escape fraction from the statistical H\(\text{I}\) proximity effect, we balance the observed galaxy number density with the photoionization rate required from the Lyα transmitted flux. We formulate this cosmological radiative transfer problem using a statistical argument; the full treatment is presented in AppendixA for an interested reader. Here, we focus on the physics essential for understanding the workflow of the methodology. Each star-forming galaxy emits LyC photons at the ionizing photon production rate (Robertson et al. 2013),

\[
\dot{N}_{\text{ion}} = f_{\text{esc}} \xi_{\text{ion}} L_{\text{UV}},
\]

where \(f_{\text{esc}}\) is the LyC escape fraction, the LyC photon production efficiency \(\xi_{\text{ion}}\) is the ratio of ionizing and non-ionizing UV photons, and \(L_{\text{UV}}\) is the non-ionizing UV (1500 Å) luminosity (in units of ergs s\(^{-1}\) Hz\(^{-1}\)). The total ionizing photon production rate density (in units of photons s\(^{-1}\) cm\(^{-3}\)) is supplied by all star-forming galaxies

\[
\tau_a \simeq 11 \Delta_b^2 \left( \frac{\Gamma_{\text{H}}}{10^{12} \text{ s}^{-1}} \right)^{-1} \left( \frac{T}{10^4 \text{ K}} \right)^{0.72} \left( \frac{1 + z}{7} \right)^{9/2},
\]

where \(\Delta_b\) is the baryon overdensity, \(\Gamma_{\text{H}}\) is the H\(\text{I}\) photoionization rate, \(T\) is the temperature of the IGM. For the H\(\text{I}\) proximity effect, the primarily quantity of interest is the typical H\(\text{I}\) photoionization rate around a galaxy, \(\langle \Gamma_{\text{H}}(r) \rangle\), which is enhanced relative to the mean value in the IGM, \(\bar{\Gamma}_{\text{H}}\). By averaging over many sightlines (ensemble averaging over density fluctuations), the mean Lyα transmitted flux around galaxies is given by

\[
\langle \exp(-\tau_a(r)) \rangle = \int \text{d} \Delta_b P_V(\Delta_b) \exp \left[ -\bar{\tau}_a(\bar{\Gamma}_{\text{H}}(r)) \Delta_b^2 \left( \frac{\bar{\Gamma}_{\text{H}}(r)}{\bar{\Gamma}_{\text{H}}} \right)^{-1} \right],
\]

where \(\bar{\tau}_a(\bar{\Gamma}_{\text{H}}, T) \simeq 11 \left( \frac{\bar{\Gamma}_{\text{H}}}{10^{12} \text{ s}^{-1}} \right)^{-1} \left( \frac{T}{10^4 \text{ K}} \right)^{0.72} \left( \frac{1 + z}{7} \right)^{9/2}\) is the optical depth at mean and \(P_V(\Delta_b)\) is the volume-weighted density probability distribution function (Miralda-Escudé, Haehnelt & Rees 2000), for which we use the Pawlik, Schaye & van Scherpenzeel (2009) fitting formula based on the cosmological hydrodynamical simulations. We assume a uniform temperature of \(T = 10^4\) K as a fiducial value unless otherwise stated, but examine the impact of the IGM temperature later in the paper.
above a certain minimum UV luminosity $L_{UV}^{\text{min}}$, 
\[ \hat{n}_{\text{ion}}(> L_{UV}^{\text{min}}) = \left( f_{\text{esc}} \xi_{\text{ion}} \right) \int_{L_{UV}^{\text{min}}}^{\infty} L_{UV} \Phi(L_{UV}) dL_{UV}, \]  
(9)
where $\left( f_{\text{esc}} \xi_{\text{ion}} \right)$ is the population average of the product of the LyC escape fraction and LyC photon production efficiency and $\Phi(L_{UV})$ is the UV luminosity function. $\langle \cdot \rangle$ means the ensemble-averaged quantity.

The UV luminosity function at $z \sim 6$ is now well constrained by both Hubble Ultra Deep Field and Frontier Field data (we adopt the UV luminosity function of Bouwens et al. (2015)). Thus, the primary unknowns are $\left( f_{\text{esc}} \xi_{\text{ion}} \right)$ and $L_{UV}^{\text{min}}$. Although the unknown parameter always comes in the product, $\left( f_{\text{esc}} \xi_{\text{ion}} \right)$, $\xi_{\text{ion}}$ can be derived from SED fitting (Bouwens et al. 2016) or UV metal line ratios (Stark et al. 2015, 2017; Matthee et al. 2017; Harikane et al. 2018a).

The independent measure of the ionizing photon production rate density comes from the mean transmitted flux in the Ly$\alpha$ forest, which provides a measure of the H$\text{I}$-photoionization rate of the IGM, $\Gamma_{\text{HI}}$, (e.g. Faucher-Giguère et al. 2008; Becker & Bolton 2013), whence:
\[ \hat{\Gamma}_{\text{HI}} = \int_{0}^{\infty} \sigma_{\text{HI}}(\nu) \frac{4\pi}{\lambda_{\text{HI}}} d\nu \simeq \frac{4\alpha_{g}}{\alpha_{g} + 3} \sigma_{912} \lambda_{\text{ad}} \hat{n}_{\text{ion}}(> L_{UV}^{\text{min}}), \]  
(10)
where $\sigma_{912} = 6.35 \times 10^{-18}$ cm$^2$ is the H$\text{I}$ photoionization cross-section at the Lyman limit and $\alpha_{g}$ is EUV (>13.6 eV) spectral slope of galaxies. Both the EUV spectral slope $\alpha_{g}$ and the LyC photon production efficiency $\xi_{\text{ion}}$ characterize the hardness of the galaxy spectra; for a given population synthesis model (e.g. Bruzual & Charlot 2003; Eldridge et al. 2017) the best-fitting SED fixes both $\alpha_{g}$ and $\xi_{\text{ion}}$. We use the mean free path of ionizing photons provided by Worseck et al. (2014), $\lambda_{\text{ad}} \approx 6.0(1 + z)/7$ $10^{13}$ km s$^{-1}$.

In previous work, Becker & Bolton (2013) (see also Inoue, Iwata & Deharveng 2006; Kuhlen & Faucher-Giguère 2012) have used the global mean of the photoionization rate from Ly$\alpha$ forest at $2 < z < 5$ and the observed UV luminosity function of galaxies to derive $\left( f_{\text{esc}} \xi_{\text{ion}} \right)$ at a given $L_{UV}^{\text{min}}$. Applying this global mean method, however, becomes difficult at $z > 5$ because of the large spectral fluctuations in the intergalactic opacity of the IGM (Becker et al. 2015b; Bosman et al. 2018). The local UV background may differ from the global mean, therefore hindering any balance between the mean galaxy number density and the global mean of the UV background.

The statistical H$\text{I}$ proximity effect provides a natural way forward by providing a measure of the local photoionization rate $\left( \Gamma_{\text{HI}}(r) \right)$ in the same cosmic volume. The average H$\text{I}$-photoionization rate around a LBG depends on the Ly$\alpha$ photons both from a central luminous (detected) LBG and fainter (undetected) galaxies around the central system: 
\[ \left( \Gamma_{\text{HI}}(r) \right) = \left( \Gamma_{\text{LBG}}(r) \right) + \left( \Gamma_{\text{HI}}^{\text{cl}}(r) \right). \]  
(11)
The local ionizing effect caused by a spectroscopically detected luminous LBG is 
\[ \left( \Gamma_{\text{LBG}}(r) \right) = \frac{\alpha_{g} \sigma_{912}}{\alpha_{g} + 3} \frac{\lambda_{\text{LBG}}}{4\pi r^2} \left( f_{\text{esc}} \xi_{\text{ion}} \right) e^{-r}/\lambda_{\text{ad}}, \]  
(12)
where $\left( N_{\text{LBG}}^{\text{cl}} \right) = \left( f_{\text{esc}} \xi_{\text{ion}} \right) L_{UV}$ is the mean ionizing production rate for which the average UV luminosity is given directly from the observed UV magnitudes. Furthermore, the collective LyC photon flux from the fainter undetected galaxies depends on the luminosity-weighted galaxy correlation function $\langle \xi_{g}(r) \rangle_L$ (or power spectrum $P_g(k)$) between the luminous LBGs and fainter galaxies above a certain minimum UV luminosity $L_{UV}^{\text{min}}$ (see Appendix A),
\[ \left( \Gamma_{\text{HI}}^{\text{cl}}(r) \right) = \int_{\infty}^{r} \frac{\alpha_{g} \sigma_{912}}{\alpha_{g} + 3} \frac{\lambda_{\text{LBG}}}{4\pi r^2} \left( f_{\text{esc}} \xi_{\text{ion}} \right) L_{UV} \Phi(L_{UV}) dL_{UV}, \]  
(13)
where $P_g(k)$ is the Fourier transform of the galaxy correlation function from the HST+Subaru/Hyper Suprime-Cam samples (Harikane et al. 2016). Note that the Ly$\alpha$ escape fraction enters as a conditional luminosity function (CLF) approach to populate dark matter haloes with galaxies (Yang, Mo & van den Bosch 2003; van den Bosch et al. 2013) described fully in Appendix A. The CLF model is constrained by simultaneously fitting the UV luminosity function of $z \sim 6$ LBGs from Hubble Legacy Fields (Bouwens et al. 2015) and the LBG angular correlation function from the HST+Subaru/Hyper Suprime-Cam samples (Harikane et al. 2016). To see the parameter dependence, it is informative to schematically write:
\[ \left( \Gamma_{\text{HI}}(r) \right) \propto \left( f_{\text{esc}} \xi_{\text{ion}} \right) e^{-r}/\lambda_{\text{ad}} \left( 1 + (1 + z)/7 \right)^{-4} \times \left[ \text{Galaxy abundance:} \frac{L_{\text{UV}}}{L_{\text{LBG}} + \text{galaxy clustering } P_g(k)} \right], \]  
(14)
where we assumed $f_{\text{esc}}$ and $\xi_{\text{ion}}$ are statistically independent. This highlights how a measure of $\left( \Gamma_{\text{HI}}(r) \right)$ from the statistical H$\text{I}$ proximity effect is balanced with the galaxy abundance estimate from the luminosity function and angular clustering measurements, leading to a constraint on the product of Ly$\alpha$ escape fraction and ionizing photon production efficiency.

Noting the spectral hardness of ionizing sources enters as a combination of the EUV slope and ionizing production efficiency, we define an effective spectral hardness parameter $\xi_{\text{ion}}^{\text{eff}}$ and assume a fiducial value, 
\[ \log(\xi_{\text{ion}}^{\text{eff}})/(\text{erg}^{-1}\text{Hz}) = \log \left( \frac{\alpha_{g} \sigma_{912}}{\alpha_{g} + 3} \right) = 24.8 \text{ (fiducial)}. \]  
(15)
We have adopted a canonical value for the ionizing photon production efficiency, $\log \xi_{\text{ion}}^{\text{eff}}/(\text{erg}^{-1}\text{Hz}) = 25.2$ (Robertson et al. 2013) consistent with LBG observations at intermediate redshift (Bouwens et al. 2016; Shibaei et al. 2018). The EUV slope varies from $\alpha_{g} = 1$ to 3 (Kuhlen & Faucher-Giguère 2012; Becker & Bolton 2013) depending on metallicity and age (Eldridge et al. 2017). For simplicity, we adopt a fiducial value of $\alpha_{g} = 2$. However, adopting $\alpha_{g} = 1 - 3$ only changes the value of $\xi_{\text{ion}}^{\text{eff}}$ by 0.2 dex, comparable to the typical uncertainty.

In this radiative transfer model, the nominal free parameters of interest are the product of the Ly$\alpha$ escape fraction and LyC photon production efficiency, $\left( f_{\text{esc}} \xi_{\text{ion}} \right)$, and the minimum UV luminosity of galaxies that contribute to reionization, $L_{UV}^{\text{min}}$. We vary both parameters when fitting the model to the observed mean Ly$\alpha$ transmitted flux around LBGs, thereby deriving a constraint on the LyC escape fraction. Before presenting the derived constraint on the LyC...
escape fraction from the statistical H I proximity effect, we first discuss the impacts of individual physical processes on the mean Lyα transmitted flux around galaxies.

4.2 Physical processes governing the mean Lyα transmitted flux around galaxies

The spatial relationship between galaxies and Lyα forest features carries a wealth of information about the physics of early galaxy formation and reionization.

4.2.1 UV background

Although the UV background includes a contribution from those luminous LBGs detected in our DEIMOS survey, such central LBGs have little impact on the large-scale (>1 pMpc) mean Lyα transmitted flux around the LBGs. Their average UV luminosity is \( L_{\text{UV}}^{\text{LBG}} = 1.9 \pm 0.86 \times 10^{39} \) erg s\(^{-1}\) Hz\(^{-1}\) where the error indicates the 1σ scatter of luminosities. The local ionizing effect is then

\[
\langle \Gamma_{\text{HI}}^{\text{LBG}}(r) \rangle \approx 6.4 \times 10^{-15} r_{\text{pMpc}}^{-2} \left( \frac{\langle f_{\text{esc}} \rangle \times (\xi_{\text{eff}})^{-1}}{0.1 \times 10^{24.8} \text{erg}^{-1} \text{Hz}^{-1}} \right) \text{s}^{-1},
\]

(17)

for \( r \ll \lambda_{\text{LyC}} \) and \( r_{\text{pMpc}} = r/(1 \text{ pMpc}) \) is a distance from the central LBG in proper Mpc. This is more than one order of magnitude lower than the \( z \approx 6 \) mean photoionization rate measurement from the mean Lyα transmitted flux of the IGM \( \Gamma_{\text{HI}} = 1.8^{+1.8}_{-0.9} \times 10^{-13} \) s\(^{-1}\) (Wyithe & Bolton 2011). The same would be true even if the ionizing radiation were harder \( \log_{10} \xi_{\text{eff}}(\text{erg}^{-1} \text{Hz}^{-1}) = 25.6 \) (e.g. Stark et al. 2017) or if we assume a LyC escape fraction of unity. This demonstrates that fainter galaxies, undetected in our survey, are needed to explain the large-scale statistical H I proximity effect. In Fig. 8 the contribution of these fainter galaxies is shown for different values of the mean LyC escape fraction \( f_{\text{esc}} \) and the minimum UV luminosity \( L_{\text{UV}}^{\text{LBG}} \) (or \( M_{\text{UV}}^{\text{LBG}} \)) assuming the observed \( z \approx 6 \) UV luminosity function (Bouwens et al. 2015) and angular clustering (Harikane et al. 2016) brighter than \( M_{\text{UV}}^{\text{LBG}} \) (see Appendix A). A higher escape fraction increases the average photoionization rate, enhancing the strength of the statistical H I proximity effect. Integrating to a fainter \( M_{\text{UV}}^{\text{LBG}} \) clearly has a similar effect.

The radial dependence of the Lyα transmitted flux, however, provides additional information on the clustering bias of ionizing sources, which, in principle, offers a means to break the degeneracy between \( f_{\text{esc}} \) and \( M_{\text{UV}}^{\text{LBG}} \) Fig. 8 (right) shows that if only bright galaxies reionize the IGM, they will be clustered more strongly, producing a somewhat steeper slope of the average photoionization rate and mean Lyα transmitted flux. However, if faint galaxies dominate reionization (extending below the current Hubble UV magnitude limit \( \approx -15 \), e.g. Bouwens et al. 2017), their weaker clustering will produce a flatter slope. The luminosity-weighted bias can easily be modelled: on the large scale \( \langle P_s(b) \rangle_L \approx b_{\text{LBG}}(b_L)P_m(k) \) we have

\[
\langle \Gamma_{\text{HI}}^\text{CL}(r) \rangle \approx \Gamma_{\text{HI}} \left[ 1 + b_{\text{LBG}}(b_L) \int_0^\infty \frac{k^2 dk}{2\pi^2} R(k\lambda_{\text{LyC}})P_m(k) \frac{\sin kr}{kr} \right],
\]

(18)

where \( \langle b_L \rangle_L \) is the luminosity-weighted bias factor\(^5\) of ionizing galaxies above \( L_{\text{UV}}^{\text{min}} \).

\[
\langle b_L \rangle_L = \frac{\int_{L_{\text{UV}}^{\text{min}}}^{L_{\text{UV}}} L_{\text{UV}} b_L(L_{\text{UV}})\Phi(L_{\text{UV}})dL_{\text{UV}}}{\int_{L_{\text{UV}}^{\text{min}}}^{L_{\text{UV}}} L_{\text{UV}}\Phi(L_{\text{UV}})dL_{\text{UV}}},
\]

(19)

and \( b_{\text{LBG}} \) is the bias factor of LBGs \( (M_{\text{UV}} < -21) \) and \( b_f(L_{\text{UV}}) \) is the bias factor of galaxies with luminosity \( L_{\text{UV}} \). The constraint on \( \langle b_L \rangle_L \) from the observed mean Lyα transmitted flux around LBGs can thus be translated to a measure of the minimum UV luminosity once combined with the galaxy luminosity function \( \Phi(L_{\text{UV}}) \) and angular correlation function measurements (i.e. \( b_f(L_{\text{UV}}) \)).

The mean free path \( \lambda_{\text{LyC}} \) of ionizing photons also impacts the radial dependence of the Lyα transmitted flux by setting the maximum distance for influencing the IGM. It is controlled by the number density of H I absorbers, primarily Lyman-limit systems. Our assumed value at \( z \approx 6 \) is based on an extrapolation of the trend within \( 2.3 < z < 5.5 \) (Worseck et al. 2014). However, hydrodynamical simulations predict \( \lambda_{\text{LyC}} \) falls markedly at the end of reionization (Gnedin & Fan 2006; Rahmati & Schaye 2018). A further uncertainty may arise if Lyman-limit systems are clustered around galaxies; Rudie et al. (2013) find that inclusion of the CGM of galaxies reduces \( \lambda_{\text{LyC}} \) by 20 per cent. Ultimately, this galaxy-Lyα forest cross-correlation analysis of many QSO sightlines should be interpreted with detailed hydrodynamical simulations. In this analysis, we quantify this modelling uncertainty by lowering \( \lambda_{\text{LyC}} \) by 20 per cent (i.e. \( \lambda_{\text{LyC}} = 4.8 \) pMpc) for a comparison.

4.2.2 Gas density fluctuations

The inhomogeneous gas distribution in the IGM has the effect of rendering individual associations between galaxies and Lyα transmission spikes stochastic. The Lyα optical depth at the end of reionization, e.g. at \( z = 5.8 \), is large:

\[
\tau_a \approx 48 \Delta_b^2 \left( \frac{\Gamma_{\text{HI}}}{2 \times 10^{-13} \text{s}^{-1}} \right)^{-1}. \]

(20)

The level of photoionization rate required by the statistical H I proximity effect is \( \langle \Gamma_{\text{HI}}(r) \rangle \approx 3.1\times10^{-13} \text{s}^{-1} \) at radius \( r = 1\text{ pMpc} \) (see Fig. 8), corresponding to the Lyα optical depth value \( \tau_a \approx 32–61 \). Thus, observable Lyα transmission spikes only occur within IGM underdensities \( \Delta_b < 1 \) even if the UV background is enhanced. The required gas underdensity for producing a Lyα transmission spike larger than \( \Gamma_{\text{HI}}^\text{th} \) is

\[
\Delta_b < \Delta_b^\text{th} = 0.25 \left( \frac{\tau_a}{3} \right)^{1/2} \left( \frac{\Gamma_{\text{HI}}}{2 \times 10^{-13} \text{s}^{-1}} \right)^{1/2}, \]

(21)

where \( \tau_a^\text{th} \) is the corresponding pixel optical depth threshold. For a typical identifiable Lyα transmission spike in the Q1148 spectrum (i.e. \( \tau_a^\text{th} = 3 \) corresponding to a height \( F_a \approx 0.05 \)), using the density fluctuations from cosmological simulations (Pawlik et al. 2009), the expected occurrence probability of Lyα transmission spike is found as

\[
P(< \Delta_b) = \int_0^{\Delta_b^\text{th}} P_b(\Delta_b)d\Delta_b \approx 8.7 \text{ per cent} \]

(22)

\(^5\)Note that the luminosity-weighted bias factor is typically much larger than the normal bias factor (Croft et al. 2016), contributing to a large spatial cross-correlation.
at \( r = 1 \) pMpc at an enhanced UV background of \( \langle \Gamma_{\text{H}_1} \rangle \approx 3.1 \times 10^{-13} \) s\(^{-1}\) decreasing to \( \approx 1.5 \) per cent at large distance (for \( f_{\text{esc}} = 0.1 \) and \( M_{\text{lim}}^{\text{UV}} = -15 \)). The remaining \( \approx 90 \) per cent of the IGM produces opaque Gunn–Peterson troughs even with an enhanced UV background. Thus, this provides a natural interpretation for the non-exact alignment (see Fig. 7) between a LBG redshift and the nearest Ly\( \alpha \) transmission spike. While the enhanced UV background increases the probability that the Ly\( \alpha \) transmission spikes occur at the IGM around LBGs, but the exact location prefers an underdense IGM.

At smaller radii \( \lesssim 1 \) pMpc approaching the CGM regime, the gaseous overdensity increases. This counteracts with the UV background as \( \tau_\alpha \propto \Delta T_{\text{HI}}^{-1} \) introducing more absorption and eventually a negative signal in the cross-correlation.\(^6\) In the intermediate redshift range \( z \approx 2-3 \), overdensity around LBGs dominates the small-scale mean Ly\( \alpha \) transmitted flux (Adelberger et al. 2003, 2005; Crighton et al. 2011; Rakic et al. 2012; Rudie et al. 2012; Tummuangpak et al. 2014; Turner et al. 2014; Bielby et al. 2017), consistent with a wide range of cosmological hydrodynamical simulations (Meiksin, Bolton & Tittley 2015; Rahmati et al. 2015; Meiksin, Bolton & Puchwein 2017; Turner et al. 2017; Sorini et al. 2018). However, the scale where this downturn occurs is \( r \lesssim 1 \) pMpc (Turner et al. 2014; Bielby et al. 2017), i.e. several times the commonly defined CGM scale (\( \approx 300 \) pkpc). In Appendix B, using the linear theory model we show that the effect of galaxy-gas density correlation is below 10–20 per cent level at \( r \approx 1 \) pMpc. Given the range we can measure in the Q1148 field, we therefore expect such small-scale effects to be unimportant.

4.2.3 Thermal state of the IGM

Thermal fluctuations of the IGM will introduce further modulation of the Ly\( \alpha \) optical depth as \( \tau_\alpha \propto \Delta T_{\text{HI}}^{-1} T^{-0.72} \), causing the IGM to be more transparent at higher gas temperature. The thermal state of the IGM is primarily controlled by the balance between photoionization heating and the cooling by adiabatic expansion and Compton scattering off CMB photons; it produces a tight asymptotic power-law relation (Hui & Gnedin 1997; McQuinn & Upton Sanderbeck 2016)

\[
T = T_0 \Delta^{-1}. \tag{23}
\]

For \( T_0 = 10^4 \) K and assuming \( \gamma = 1.3 \), the Ly\( \alpha \) transmitted flux is lower than for the fiducial \( \gamma = 1 \). This is because the temperature of the underdense IGM which gives rise to Ly\( \alpha \) transmission spikes is lower (e.g. \( \log_{10} \Delta/ T = 3.82 \) at \( \Delta_0 = 0.25 \)). Cosmological radiative transfer simulations find a large scatter around \( \gamma = 1 \) in the temperature–density relation just after the IGM is reionized (Tittley & Meiksin 2007; Trac, Cen & Loeb 2008; Kakiihi et al. 2017; Keating, Puchwein & Hachnelt 2018), which is not captured by the single power-law relation. Thus, we adopt a uniform temperature for simplicity for a fiducial analysis, but also repeat the analysis with \( T = T_0 \Delta^{-1} \) assuming \( T_0 = 10^4 \) K and \( \gamma = 1.3 \). The increased opacity arising from temperature fluctuations requires more ionizing photons to match the statistical H\( \text{I}\) proximity effect and hence a higher Ly\( \alpha \) escape fraction.

Large-scale thermal fluctuations may also be caused by environmental effects in the reionization process. In ‘inside-out’ reionization, highly biased regions around luminous galaxies are thought to have ionized earlier, allowing more time for the gas to cool by adiabatic expansion and CMB Compton cooling. This causes the low-density IGM near luminous galaxies to be preferentially cooler (D’Aloisio, McQuinn & Trac 2015), reducing the mean Ly\( \alpha \) transmitted flux around LBGs at inner radii (Davies, Becker & Furlanetto 2017). The extent of this effect is debated (e.g. Keating et al. 2018). For the low-density IGM close to luminous galaxies, the temperature asymptotically relaxes to the value set by the balance between the adiabatic expansion and instantaneous photoinization rate. On the other hand, the IGM away from the galaxies that has been engulfed by a H\( \text{II}\) I-front raises the temperature to about \( 10^4 \) K. The large-scale thermal fluctuations vary from \( \approx 5000 \) K to \( T \approx 1.0 - 1.5 \times 10^4 \) K which contributes to the negative correlation of the mean Ly\( \alpha \) transmitted flux around LBGs. As the temperature has a weaker dependence on the optical depth \( \tau_\alpha \propto \Delta T_{\text{HI}}^{-1} T^{-0.72} \), this can easily be compensated by only moderate enhancement of the UV background. Although both UV background and thermal fluctuations co-exist, because of the steeper dependence on the photoinization rate it is likely that the UV background variation dominates creating a positive correlation, with secondary modulation by thermal fluctuations weakening it (Davies et al. 2017, private communication).

5 Constraining the mean escape fraction

We now utilize the foregoing to analyse the balance between inferred galaxy abundance in the Q1148 field with the observed mean Ly\( \alpha \) transmitted flux in terms of a statistically averaged Ly\( \alpha \) escape fraction \( f_{\text{esc}} \). To accomplish this we fit the model to the observed mean Ly\( \alpha \) transmitted flux data using a Markov Chain Monte Carlo (MCMC) method (Foreman-Mackey et al. 2013) varying \( f_{\text{esc}} \) and \( M_{\text{lim}}^{\text{UV}} \). We assume a Gaussian likelihood and place a flat prior in the range of \( -2 < \log_{10} f_{\text{esc}} < 0 \) and \( -18 < M_{\text{lim}}^{\text{UV}} < -10 \). We have tested the result against an enlarged prior range (\( -20 < M_{\text{lim}}^{\text{UV}} < -8 \)) and find a consistent result. For the covariance matrix we only use diagonal elements from the Jackknife error estimate.

In Fig. 9 we show the derived constraint on \( f_{\text{esc}} - M_{\text{lim}}^{\text{UV}} \) plane. The inferred mean Ly\( \alpha \) escape fraction at \( z \approx 6 \) is found to be

\[
(f_{\text{esc}}) = 0.083^{+0.037}_{-0.016} \left( \frac{\langle \Delta M \rangle}{10^{20} \text{ erg Hz}} \right)^{-1}, \tag{24}
\]

for \( M_{\text{lim}}^{\text{UV}} = -14.53^{+2.57}_{-3.16} \) for the fiducial analysis.\(^8\) This constraint is dependent upon the assumed mean free path and IGM temperature. None the less, as discussed in the previous section, a lower mean free path and thermal fluctuations would mean a larger (\( > 10 \) per cent) mean Ly\( \alpha \) escape fraction to compensate the increased opacity. These uncertainties on radiative transfer can be included in the MCMC analysis once a larger data set becomes available.

Although our sample is modest, our result suggests that \( f_{\text{esc}} = 0.06 - 0.16 \) for star-forming galaxies above \( M_{\text{lim}}^{\text{UV}} = -14.53^{+2.57}_{-3.16} \) including modelling systematic error. In Fig. 10 we

\(^6\)As the probability distribution function \( P_\text{d} ( \Delta_0 ) \) adopted here is measured from the entire simulation box (Pawlik et al. 2009), the effect of a gaseous overdensity around galaxies is ignored in the model.

\(^7\)At scales less than \( \approx 100 \) pkpc, galactic feedback and hydrodynamic processes complicate the distribution of cold gas.

\(^8\)Note that for fiducial analysis we have ignored the three radial bins at 3.5–4.5 pMpc as they are likely affected by systematics. Their inclusion would give a 12 per cent larger \( f_{\text{esc}} \) with two possible best-fitting values of \( M_{\text{lim}}^{\text{UV}} \) due to the poor constraint on the shape.
by the recently revised synthesis model of the cosmic UV background (Puchwein et al. 2018) and the minimal reionization model of Haardt & Madau (2012). This means that faint galaxies deposit sufficient ionizing radiation into the IGM for driving the reionization process (see also Faisst 2016). Since the inclusion of temperature fluctuations would require more ionizing photons to match the observed positive correlation of the mean Ly transmitted flux around LBGs, our fiducial analysis provides a fairly conservative lower limit to the mean LyC escape fraction.

6 THE IMPACT OF LUMINOUS SYSTEMS

Finally, we turn our attention to two individual cases of a LBG and AGN for which we can identify associated transmission spikes in the Q1148 spectrum. We investigate both as examples of spatial fluctuations in the IGM environment induced by luminous sources. We discuss how they might contribute to spatial fluctuations of the ionization and thermal states of the IGM and the possible role of rare, luminous sources on the reionization process.

6.1 $z = 6.177$ LBG J1148+5250 and Ly$\beta$ transmission spike

LBG J1148+5250 is a newly discovered Ly$\alpha$ emitting galaxy in our DEIMOS sample. It is a luminous ($M_{UV} = -21.8$) galaxy with a secure asymmetric Ly$\alpha$ line at $z_{Ly\alpha} = 6.177$. Interestingly, the LBG redshift coincides with that of a Ly$\beta$ transmission spike at $z = 6.185$. This is the first case of a possible individual transverse proximity effect around a $z > 6$ LBG (Table 3). The Ly$\beta$ transmission spike is separated by $d_{spike} = 1.9$ pMpc (9.4 $h^{-1}$ cMpc) from the LBG.

The detection of a Ly$\beta$ transmission spike and the high optical depth in the Ly$\beta$ forest region (see Fig. 11) places a bound on the Ly$\beta$ transmission spike above $z = 5.26$ equivalent, $\tau_{Ly\beta} = 2.68$. Because the high-redshift ($z > 6$) Ly$\beta$ forest overlaps with its lower redshift ($z < 5.26$) Ly$\alpha$ equivalent, this translates into an upper limit on the $z = 6.185$ Ly$\beta$ optical depth $\tau_{Ly\beta} < \tau_{Ly\alpha}$ and, using the ratio between the Ly$\beta$ and Ly$\alpha$ optical depths $\tau_{Ly\beta}/\tau_{Ly\alpha} = f_{Ly\beta}/f_{Ly\alpha} = 0.16$ predicted by atomic physics, a range of 4.2 (3$\sigma$) $< \tau_{Ly\beta} < 16.7$ ± 0.6. (25) consistent with the absence of a clear Ly$\alpha$ transmission spike above the 3$\sigma$ noise in the QSO spectrum.

Compared to the Gunn–Peterson optical depth at $z = 6.185$, $\tau_{GP} \simeq 1.8 \times 10^{3} \Delta_{6}$, this upper limit on $\tau_{Ly\beta}$ is quite low, suggesting that

---

Table 3. Summary of the IGM environment of the $z = 6.177$ luminous Ly$\alpha$ emitting LBG. The associated Ly$\beta$ transmission spike is the evidence of highly ionized intergalactic gas around the LBG, which is maintained likely by the faint galaxy overdensity (indicated by the excess OI absorbers).

<table>
<thead>
<tr>
<th>LBG’s Ly$\alpha$ redshift</th>
<th>$z = 6.177$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ly$\beta$ transmission spike</td>
<td>$z = 6.185$</td>
</tr>
<tr>
<td>Lower limit to the H I bubble size$^a$</td>
<td>&gt; 1.9 pMpc (9.4 $h^{-1}$ cMpc)</td>
</tr>
<tr>
<td>Photoionization rate of the LBG$^b$</td>
<td>$f_{H I}^{Ly\beta} = 2.1 \times 10^{-15}$ s$^{-1}$</td>
</tr>
<tr>
<td>Photoionization rate at the Ly$\beta$ spike$^c$</td>
<td>$f_{spike}^{Ly\beta} = 5.7 \times 10^{-13}$ s$^{-1}$</td>
</tr>
<tr>
<td>OI absorbers’ redshift</td>
<td>$z = 6.1293, 6.1968, 6.2555$</td>
</tr>
<tr>
<td>(distance to the Ly$\beta$ spike)</td>
<td>(3.2, 0.7, 4.0 pMpc)</td>
</tr>
</tbody>
</table>

$^a$From the distance between the LBG and Ly$\beta$ spike.

$^b$At the Ly$\beta$ spike (i.e. 1.9 pMpc distance from the LBG) and for SFR = 28 $M_{\odot}$ yr$^{-1}$, $f_{esc} = 0.1$, and $\xi_{ion} = 10^{25.2}$ erg$^{-1}$ Hz$^{-1}$.

$^c$The expected median value of the photoionization rate at the location of the Ly$\beta$ spike (see Fig. 12).

---

Figure 9. Constraints on the average LyC escape fraction ($f_{esc}$) and the minimum UV luminosity $M_{UV}^{min}$ with 68 per cent and 95 per cent confidence intervals for the fiducial galaxy–LyC cross-correlation analysis (red: $\times_{spike} = 6$ pMpc, $T = 10^{4}$ K) and with a lower value of mean free path (grey: $\times_{spike} = 4.8$ pMpc) and with a temperature–density relation (blue: $T_0 = 10^{4}$ K, $\gamma = 1.3$). The quoted constraint is from the fiducial analysis.

Figure 10. Redshift evolution of the population-averaged LyC escape fraction of galaxies. The $z \sim 6$ constraint from the galaxy–LyC forest cross-correlation in Q1148 field is indicated by the filled red circle. A compilation of previous $2 < z < 4$ constraints is indicated by open symbols. These include direct LyC imaging (Vanzella et al. 2010; Mostardi et al. 2013; Grazian et al. 2016; Matthee et al. 2019) and GRB N-stacking (Chen, Prochaska & Gnedin 2007; Fynbo et al. 2009), and ISM absorption line studies (Leethochawalit et al. 2016). The model mean LyC escape fractions adopted by Haardt & Madau (2012) (solid) and Puchwein et al. (2018) (dotted) are overlaid. The shaded region indicate ($f_{esc}$) > 10 per cent required for galaxies to drive reionization.
indeed indicates that the Lyα transmission spike is a fully neutral medium. The expected value of \( \tau_{\alpha} \times x_{HI} \) at the location of the Lyα transmission spike \( z = 6.185 \) (solid). For comparison, the dashed line shows a hypothetical case without a Lyα transmission spike (assuming the Lyα optical depth can reach the Gunn–Peterson optical depth of a fully neutral medium, \( \tau_{\alpha} = 1.8 \times 10^{-4} \)).

The IGM is highly ionized to \( x \lesssim 10^{-4} \). As discussed in Section 4.2, the association of individual galaxies and transmission spikes is probabilistic owing to the gas density fluctuations. Thus, we should assess the probability distribution of the neutral hydrogen fraction \( x \) at the location of the Lyβ transmission spike given an observed Lyα optical depth. Using the simulated probability distribution function of gas density fluctuations and \( \tau_{\alpha} = \tau_{G-P, H I} \Delta_{a} \) where \( \tau_{G-P} = 1.8 \times 10^{-3} \) is the Gunn–Peterson optical depth of a fully neutral medium at mean density, we find that

\[
P(x_{HI}|\tau_{\alpha}) = \int \delta_{D} \left( x_{HI} - \frac{\tau_{\alpha}}{\tau_{G-P}} \Delta_{a}^{-1} \right) P_{V}(\Delta_{a}) d\Delta_{a}.
\]

(26)

Fig. 12 (left) shows the resulting probability distribution of the neutral fraction \( x \) after marginalizing over the observed bound of the Lyα optical depth. The presence of a Lyβ transmission spike indeed indicates that the \( z = 6.185 \) IGM is highly ionized to the expected value of \( x \simeq 10^{-4} \). Note that this analysis does not assume the medium is photoionized a priori. Thus, a UV luminous galaxy at the reionization epoch (\( z > 6 \)) is clearly located in a highly ionized environment.

The distance to the Lyβ transmission spike from LBG J1148+5250 provides a lower limit to the size of the cosmological \( H I \) region,

\[
R_{HI} > d_{\text{spike}} = 1.9 \text{ pMpc} (9.4 \text{ h}^{-1} \text{cMpc}) \quad \text{at} \quad z = 6.18.
\]

(27)

Can this luminous galaxy alone produce such a large ionized bubble? The UV luminosity \( L_{UV} = 2.25 \times 10^{29} \text{ erg s}^{-1} \text{ Hz}^{-1} \) corresponds to a star formation rate \( \text{SFR} = 28.1 \text{ M}_{\odot} \text{ yr}^{-1} \) assuming a Salpeter IMF and solar metallicity (Madau, Pozzetti & Dickinson 1998) before any correction for dust extinction. We can estimate the size of the \( H I \) region

\[
R_{HI} = \left[ \frac{3}{4\pi} \frac{\bar{N}_{H I} \Delta_{a}^{1/3}}{\bar{T}_{H I}(z)} \right]^{1/3},
\]

\[
\approx 1.0 \left( \frac{f_{\text{esc}}}{0.1} \left( \frac{\xi_{\text{ion}}}{10^{25.2} \text{ erg}^{-1} \text{ Hz}^{-1}} \right) \left( \frac{\Delta_{a}}{300 \text{ Myr}} \right) \right)^{1/3} \text{ pMpc}
\]

(28)

assuming a constant star formation history over the median age of UV luminous galaxies \( (L > L^\ast) \) at \( z \simeq 6 \) of \( \simeq 200-300 \) Myr (Curtis-Lake et al. 2013). Even for a hard \( \log_{10}\xi_{\text{ion}} = 25.6 \), the radius becomes \( R_{HI} \approx 1.4 \) pMpc below the observed lower limit. It therefore seems necessary to invoke a contribution from fainter galaxies clustered around the luminous LBG.

The probability distribution of the photoionization rate inside the \( H I \) region can be estimated as in equation (26) by integrating the Dirac delta function at \( \Gamma_{HI} \propto \tau_{\alpha} \Delta_{a}^{-1} \) with \( P_{V}(\Delta_{a}) \). Fig. 12 shows that the expected photoionization rate at the Lyβ transmission spike may be as high as \( \Gamma_{HI} \simeq 10^{-12}-10^{-13} \text{ s}^{-1} \), close to the value indicated by the statistical analysis in Section 4.2. Such a high photoionization rate cannot be maintained by the luminous LBG alone, which contributes up to \( \Gamma_{HI}^{\text{LBG}}(r) \approx 7.6-19.0 \times 10^{-15} \text{ (r/1 pMpc)}^{-2} \text{ s}^{-1} \) for \( f_{\text{esc}} = 0.1 \) and \( \log_{10}\xi_{\text{ion}} = 25.2-25.6 \).

Becker et al. (2006) report the discovery of four \( O I \) absorbers at \( z = 6.0097, 6.1293, 6.1968, 6.2555 \), which indicates the location of low-luminosity galaxies (Finlator et al. 2013) below the LBT detection limit \( (M_{UV} \simeq -21) \). The closest \( z = 6.1968 \) \( O I \) absorber is separated by \( \simeq 0.7 \) pMpc from the Lyβ transmission spike. Such a surprising excess of \( O I \) absorbers near the \( z = 6.18 \) luminous LBG - Lyβ transmission spike association supports the presence of clustered faint galaxies around the LBG, and their collective ionizing contribution.

In summary, the discovery of a Lyβ transmission spike near the \( z \simeq 6.18 \) LBG further supports the conclusion of our statistical analysis. Accelerated reionization is likely driven by the collective ionizing contribution from fainter galaxies clustered around luminous LBGs, possibly enhanced with a harder ionizing spectrum.

Figure 11. A zoom-in of Fig.7 around the luminous LBG J1148+5250 at \( z_{\text{Ly}\alpha} = 6.177 \) adopting the same colour bar for the galaxy luminosity. Solid and dashed vertical lines indicate the location of wavelet-identified Lyα and Lyβ transmission spikes. The Lyβ forest region is offset by 0.1 in \( y \)-axis.

Figure 12. The probability distribution of (left-hand panel) the neutral hydrogen fraction and (right-hand panel) the \( H I \) photoionization rate at the location of the Lyβ transmission spike \( z = 6.185 \) (solid). For comparison, the dashed line shows a hypothetical case without a Lyβ transmission spike (assuming the Lyα optical depth can reach the Gunn–Peterson optical depth of a fully neutral medium, \( \tau_{\alpha} = 1.8 \times 10^{-3} \)). The UV luminosity of UV luminous galaxies \( (L > L^\ast) \) at \( z \simeq 6 \) is clearly located in a highly ionized environment.
The black hole (SMBH) mass is estimated to be $M_{\text{BH}} \approx 8.2 \times 10^{10} M_{\odot}$ at 2.02 pMpc and 3.07 pMpc away from the AGN, respectively.

Photoionization rate of the AGN $\alpha = 1.0, 2.2 \times 10^{-13} \text{s}^{-1}$.

Assuming a broken power-law spectrum $L_{\nu} \propto \nu^{\alpha}$, the AGN is somewhat larger than a luminous LBG, with $z = 5.701$ and $z = 5.657, 5.729$ located $3 \pm 1$ pMpc, the faint AGN alone gives an optical depth $\tau_{\alpha} \approx 6 \times 10^4 K$.

The size of the He III region so produced is $R_{\text{He III}} \approx 3.2 \times 10^4$ photons s$^{-1}$.

A fiducial AGN lifetime of order $10^8$ yr can be estimated from the time-scale required to grow the relevant SMBH. For Eddington-limit accretion, even a massive $100 M_{\odot}$ black hole seed requires $t = t_{\text{BH}} \ln(M_{\text{BH}}/M_{\text{seed}}) \approx 5 \times 10^8$ yr where $t_{\text{BH}} \approx 4.4 \times 10^7 (\epsilon_0/0.1)$ yr. Therefore, based on the BH growth time-scale and outflow time-scale arguments, during the plausible AGN lifetime, the two broad Lyα transmission spikes lie within the region of influence of the He III I-front of the AGN.

The upper age limit can be estimated from the non-detection of metal line absorbers at the redshift of RD J1148+5253 AGN. There is broad absorption blueward of $\lambda 1240$, indicating an outflow of $v_{\text{outflow}} \approx 1000$–10 000 km s$^{-1}$. This constrains the AGN lifetime to $t \lesssim 10^8$ yr where $d_{\text{gale}} \approx 3.1$ pMpc.

**Table 4.** Summary of the IGM environment of the $z = 5.701$ faint AGN.

<table>
<thead>
<tr>
<th>AGN's Lyα redshift</th>
<th>$z = 5.701$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad Lyα transmission spikes</td>
<td>$z = 5.657, 5.729$</td>
</tr>
<tr>
<td>(distance to the AGN)</td>
<td>(3.07, 2.02 pMpc)</td>
</tr>
</tbody>
</table>

The expected median value of the photoionization rate at the location of the broad Lyα spikes $\alpha_{\text{He II}} \approx 6.6 \times 10^4$ photons s$^{-1}$.

**Figure 13.** A zoom-in of Fig. 7 around the faint AGN RD J1148+5253 at $z_{\text{Lyα}} = 5.701$. Solid vertical lines indicate the wavelet-identified Lyα transmission spikes. The red lines mark the two broad Lyα transmission spikes.

**Figure 14.** Histogram of the widths of wavelet-identified Lyα transmission spikes in the redshift range of $5.5 < z < 5.9$. The two values with $\pm 220$ km s$^{-1}$ width are those indicated by the red lines in Fig. 13.
The He II photoheating across the He II I-front raises the temperature approximately by (e.g. Kakiichi et al. 2017)

$$\Delta T_{\text{He II}} = \frac{2G_{\text{He II}}/\Gamma_{\text{He II}}}{3k_B} = \frac{3}{2} \frac{2(2 + \alpha_{\text{eff}}^Q)}{2.5} \approx 6400 \left(\frac{2 + \alpha_{\text{eff}}^Q}{2.5}\right)^{-1},$$

where we adopt a EUV spectral index of $\alpha_{\text{eff}}^Q = 0.5$ to include the effect of spectral hardening $\alpha_{\text{eff}}^Q < \alpha_Q$, resulting in the IGM temperature of $\pm 16,000$ K immediately after the He II I-front (Meiksin, Titlley & Brown 2010; Bolton et al. 2012; Ciardi et al. 2012; Khrykin, Hennawi & McQuinn 2017). Such He II photoheating reduces the optical depth by a factor of $(1.6 \times 10^4 K/10^4 K)^{-0.72} = 0.71$. While a small decrease, now a slightly less underdense gas below $\Delta_z \gtrsim 0.30$ can give rise to a transmission spike. This He II heating by AGN doubles the occurrence probability of a transmission spike from $P(\Delta_{\text{He II}} = 0.25) = 5.6$ per cent at $T = 10^4$ K to $P(\Delta_{\text{He II}} = 0.30) = 8.0$ per cent at $T = 1.6 \times 10^4$ K. The AGN He II photoheating is also a convenient hypothesis as the spatially coherent increase in the Lyα transmission in the He II photoheated region could produce broader transmission spikes (e.g. $220$ km s$^{-1}$ corresponds to $\sim 330$ pkpc patch of the IGM) whereas the other spikes widths ($100$ km s$^{-1}$) are of order the Jeans length of the H I-photoionized IGM.

Hence, the association between the $z \approx 5.7$ AGN and the proximate broad Lyα transmission spikes suggests that while faint AGN are unlikely a main driver of H I reionization, the hard ionizing spectra of AGN may be important to drive the spatial fluctuations of the ionization and thermal state of the IGM, via possibly an early onset of He II reionization.

7 DISCUSSION AND SUMMARY

We have initiated a spectroscopic programme involving the 3D mapping of $5 < z < 7$ galaxies around the Lyα forest region illuminated by background QSOs which enables us to examine the ionizing capabilities of galaxies and AGN at high redshift. In this paper we describe a science verification of this method using DEIMOS spectroscopy of $5.3 < z < 6.4$ LBGs in the SDSS 11418+5251 field. Although our sample of confirmed sources is modest, cross-correlation of the spectroscopically confirmed LBGs with the Lyα forest reveals tentative, but promising, evidence for a ‘statistical H I proximity effect’ indicating that the Lyα transmission of the IGM is preferentially higher in the vicinity of the galaxies. We have interpreted this signal as evidence for an enhanced UV background around luminous LBGs caused by their ionizing radiation together with that arising from fainter undetected sources clustered around them. We demonstrate that the required ionizing radiation from the luminous LBGs alone is insufficient. This conclusion is supported by independence evidence from deeper imaging observations as well as the expectations of hierarchical clustering in ΛCDM cosmology. This explanation for the statistical H I proximity effect is preferred over alternative hypotheses based solely on gas density or thermal fluctuations of the IGM. Such explanations would produce an anticorrelation yielding an excess Lyα absorption around galaxies. Only UV background fluctuations driven by ionizing radiation from galaxies can predict the H I proximity effect. Balancing the UV background required by the statistical H I proximity effect with the abundance of spectroscopically confirmed LBGs and their fainter associates has enabled us to constrain the average escape fraction of LyC photons at $f_{\text{esc}} \approx 0.08^{+0.08}_{-0.02}$ with $M_{\text{UV}}^{\text{lim}} \approx -15 \pm 3$ at $z \approx 5.8$ using the CLF/HOD framework.

The present method for constraining $f_{\text{esc}}$ has some advantages over previous approaches. It examines the direct influence of galaxies on the IGM as well as the bias of ionizing sources estimated from the galaxy-Lyα cross-correlation; this allows us to deduce the relative contributions of luminous and feeble sources as well as that of AGN. The largest uncertainty at present arises from application to a single QSO sightline and small number statistics. Fortunately, this is easy to remedy with further observations. While a number of assumptions have been made in deriving this value of $f_{\text{esc}}$, we have argued that the uncertainties affecting assumed values for the mean free path and thermal fluctuations in the IGM are likely to increase the derived fraction, strengthening the conclusion that the galaxy population is capable of driving cosmic reionization. Fundamental to our method however, is the assumption that our spectroscopically confirmed sample is unbiased and independent of the surrounding gaseous environment. Since the bulk of our redshifts are based on detecting Lyα emission, if such photons are attenuated by nearby gas this may lower the spectroscopic success rate and may bias the cross-correlation. Such a problem may however be mitigated by examining Lyα haloes as the postulated reduced visibility of Lyα line from galaxies would still produce a bright halo detectable with integral field spectroscopy (Kakiichi & Dijkstra 2017).

As discussed above, the widely held view that the abundant population of intrinsically faint galaxies drives cosmic reionization is supported by this work. This is also consistent with the belief that the typical escape fraction rises at higher redshift as younger, lower mass, galaxies are more susceptible to feedback from intense star-forming activity creating a porous interstellar medium (e.g. Kimm & Cen 2014; Wise et al. 2014). Although there is evidence that reionization may be accelerated around luminous star-forming galaxies (Stark et al. 2017), the statistical H I proximity effect can only be understood if there are intrinsically fainter galaxies clustered around the luminous systems. We note this need not conflict with suggestions that the some of the most luminous systems have harder ionizing radiation (Laporte et al. 2017).

Finally, we explored the specific role of one luminous LBG and a faint AGN where proximate transmission spikes can be directly (as opposed to statistically) associated. A discovery of individual transverse proximity effect via a Lyβ transmission spike in the vicinity of a luminous LBG at $z = 6.177$ suggests that luminous star-forming systems preferentially reside in highly ionized environments. This supports a deduction from the high fraction of Lyα emission in luminous LBGs at $z > 6$ (Curtis-Lake et al. 2012; Stark et al. 2017), for which the visibility of Lyα is boosted by large ionized bubbles (e.g. Dijkstra 2016, for a review). Accelerated reionization around the luminous system likely requires clustered fainter galaxies, whose presence may be indicated by excess O I absorbers (Becker et al. 2006). This scenario may gain further support from an observed galaxy overdensity around a pair of bright Lyα emitting galaxies at $z \sim 7$ (Vanzella et al. 2011; Castellano et al. 2016). The broad Lyα transmission spikes in the vicinity of $z = 5.701$ faint AGN suggests that the hard ionizing spectra may have an important contribution to the large-scale spatial fluctuations of the UV background and thermal state of the IGM. An interesting possibility is that a patchy early ($z > 5.7$) onset of He II reionization by AGN (Bolton et al. 2012) heats the IGM through He II photoionization heating. This late-time He II heating induces thermal fluctuations so that the intergalactic Lyα opacity is preferentially reduced around luminous systems, without conflicting with the observed statistical H I proximity effect. This may explain the large scatter of intergalactic Lyα opacity at the tail end of reionization (Becker et al. 2015b) without need for a large ($\geq 50$ per cent) contribution of AGN to the UV
background (Chardin et al. 2015, 2017, 2018; D’Aloisio et al. 2017, see also Finlator et al. 2016) or extreme thermal injection via H I photoheating at the early time of H I reionization (D’Aloisio et al. 2015).

Putting all together, a hypothesis emerging from the initial DEIMOS spectroscopy in the QSO field J1148+5251 is that while the faint galaxies with high escape fraction primarily drive reionization, luminous galaxies and AGN may play an increasingly important role towards the end of the reionization process by sourcing the large-scale spatial fluctuations of the UV background and thermal state of the IGM. This demonstrates the potential of spectroscopic survey of 5 < z < 7 galaxies towards QSO fields for making a progress with existing facilities before the JWST and Extremely Large Telescopes, allowing us to tackle the most challenging aspect of cosmic reionization: ‘What reionized the Universe?’.

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APPENDIX A: THEORETICAL FRAMEWORK

A1 Cosmological radiative transfer

Here, we present a more complete treatment of cosmological radiative transfer of ionizing photons. The equation of cosmological radiative transfer follows (e.g. Gnedin & Ostriker 1997; Meiksin 2009)

\[ \frac{1}{c} \frac{\partial I_r}{\partial t} + n \cdot \nabla I_r - \frac{H}{c} \left( \frac{\partial I_r}{\partial \nu} - 3H I_r \right) = -\alpha_r I_r + \epsilon_r, \quad (A1) \]

where \( \alpha_r \) is the absorption coefficient and \( \epsilon_r \) is the emissivity. The direct solution to this clearly requires expensive numerical radiative transfer simulations. Instead, we seek an approximate statistical solution following the approach of Zuo (1992a,b), Meiksin & White (2003), Kakiichi, Meiksin & Tittley (2012). First, consider a small patch of the universe at position \( r \) with volume \( \nu \) so that the cosmological redshifting can be ignored, which should have a minor impact at \( z > 5 \) (Becker & Bolton 2013). The number of galaxies above a luminosity \( L_{\text{min}} \) in the patch follows the Poisson distribution

\[ P(N) = \frac{\bar{N}^N}{N!} e^{-\bar{N}} \]

where \( \bar{N} \) is the mean density of galaxies in the patch, which is quantified by the HI column density

\[ N_{\text{HI}}(\nu, z) \]

and \( \beta_N = 1.33 \pm 0.05 \) (Becker & Bolton 2013), it may be written as \( \lambda_{\text{LAMP}} = 1.33 \pm 0.05 \). This produces a systematic error, underestimating the mean photoionization rate by a small factor of \( 3 + \alpha_g - 3(\beta_N - 1)/(3 + \alpha_g) \approx 0.84 \) when \( \alpha_g = 3 \) and \( \beta_N = 1.33 \) because ignoring the effect that higher frequency photons can reach longer distance before being attenuated. Although adopting a constant spatially uniform mean free path is clearly an oversimplification, it gives a first-order approximation to the mean free path.

To derive the statistically averaged specific intensity around galaxies, we take the ensemble-averaging over many realizations of patches with various numbers of galaxies. Using the statistical method of characteristic functions (Meiksin & White 2003; Kakiichi et al. 2012) or otherwise (Zuo 1992a,b), this gives the average specific intensity

\[ \langle I_r(r) \rangle = \langle J_0(r) \rangle + \sum_{N=0}^{\infty} P(N) \int J_r(r) P[J_r(r)|N] dJ_r(r), \quad (A4) \]

where \( P[J_r(r)|N] \) is the probability distribution function of specific intensity in a patch with \( N \) galaxies. When the positions and luminosities of surrounding galaxies are statistically independent to each other (but can be correlated with the LBG) (e.g. van Kampen 2007), we may express \( P[J_r(r)|N] \) as a product of the probabilities of finding each galaxy at a position \( r_k \) with a luminosity \( L_k \),

\[ P[J_r(r)|N] dJ_r(r) = \prod_{k=1}^{N} \Phi(L_k) \int L_k dL_k \left[ 1 + \xi_k(r_k, L_k) \right] d^3r_k \]

where \( \xi_k(r_k, L_k) = \int L_k \Phi(L) dL \) and \( \xi_k(r, L) \) is the correlation function of LBGs with galaxies of luminosity \( L \). Therefore, by substituting equations (A3) and (A5) into (A4) we obtain after some algebra,

\[ \langle I_r(r) \rangle = \langle J_0(r) \rangle + \frac{\bar{\lambda}_{\text{LAMP}}}{4\pi} \int_0^{\infty} k^2 dk \int J_k(r) \sin kr \frac{R(k\lambda_{\text{LAMP}})}{kr} \]
where $R(x) = \arctan(x)/x$ comes from the Fourier transform of the radiative transfer kernel and the luminosity-dependent galaxy power spectrum is

$$\langle P_g(k) \rangle_L = \int_0^\infty \langle \xi_g(r) \rangle_1 4\pi r^2 \frac{\sin kr}{kr} dr.$$  \hfill (A11)

The expression reduces to the local approximation of the Poisson-distributed sources ($\langle J(x) \rangle = \xi_x \lambda_{\text{gal}}/(4\pi)$) when there is no galaxy clustering around LBGs, $\langle P_g(k) \rangle_L = 0$.

Finally, we suppose that all galaxies have the same spectral energy distribution with the EUV ($>13.6$ eV) slope $\alpha_s$ to evaluate a typical photoionization rate at a distance $r$ from a LBG, in which the EUV emissivity from star-forming galaxies is

$$\bar{\varepsilon}_e = h\alpha \left( \frac{v}{1012} \right)^{-\alpha_s} n_{\text{ion}}(>L_{\text{min}}).$$  \hfill (A12)

Hence, using the approximate statistical solution (A10) of the radiation field, we obtain the typical photoionization rate at a distance $r$ from a LBG:

$$\langle \Gamma_{\text{H}_1}(r) \rangle = \int_{\Gamma_{\text{H}_1}} \sigma_{\text{H}_1}(4\pi L_{\text{H}_1}(r))/L \, dv,$$

$$= \langle \Gamma_{\text{LBG}}(r) \rangle + \bar{\Gamma}_{\text{H}_1} \left[ 1 + \int_0^\infty \frac{k^2 dk}{2\pi^2} R(k\lambda_{\text{gal}})(P_g(k))_L \frac{\sin kr}{kr} \right].$$  \hfill (A13)

where the first term $\langle \Gamma_{\text{LBG}}(r) \rangle = \bar{\alpha}_{\text{LBG}} a_{\text{LBG}} e^{-\gamma_{\text{LBG}}/\gamma}$ is the local contribution from the central LBGs and the second term is the clustering contribution from the surrounding galaxies. We use equation (A13) throughout the analysis presented in this paper.

### A2 Galaxy abundance from HOD framework

We use the HOD framework to estimate the number of fainter, undetected, galaxies clustered around LBGs. We use the conditional luminosity function (CLF) approach (e.g. Yang et al. 2003) to the halo occupation distribution (HOD) framework. The CLF, $\Phi(L|M_h)$, specifies the average number of galaxies with luminosities in the range of $L \pm dL/2$ that reside in a halo of mass $M_h$. Thus, by combining the best-fitting CLF with the theoretical estimate of the clustering of dark matter haloes around the LBG-host haloes from N-body simulations (e.g. Tinker et al. 2008, 2010), we can infer the number of (undetected) galaxies around the detected (observed) LBGs.

To this end, we constrain the CLF model by simultaneously fitting to the observed UV luminosity function (Bouwens et al. 2015) and angular correlation function of $z \sim 6$ LBGs (Harikane et al. 2016). We follow the CLF model of van den Bosch et al. (2013), which is summarized below. We drop the subscript $UV$ of $L_{\text{UV}}$ for notational clarity.

We split the CLF from the contribution from central galaxies, $\Phi_{\text{cen}}(L|M_h)$, and satellite galaxies, $\Phi_{\text{sat}}(L|M_h)$:

$$\Phi(L|M_h) = \Phi_{\text{cen}}(L|M_h) + \Phi_{\text{sat}}(L|M_h).$$  \hfill (A14)

We model the CLF of central galaxies model as a log-normal distribution,

$$\Phi_{\text{cen}}(L|M_h) dL = \frac{\log_{10} e}{\sqrt{2\pi}\sigma_c} \exp \left[ -\frac{(\log_{10} L - \log_{10} L_c)^2}{2\sigma_c^2} \right] dL,$$  \hfill (A15)

where $\sigma_c$ quantifies the scatter in UV luminosity of central galaxies and halo mass and we adopt a following parametrization for the central UV luminosity–halo mass relation,

$$L_c(M_h) = L_0 \frac{(M_h/M_{*})^{\gamma_1}}{[1 + (M_h/M_{*})^{\gamma_2}]^{\gamma_2}}.$$  \hfill (A16)

where $L_0$ is the normalization, $M_{*}$ is a characteristic halo mass, $\gamma_1$ and $\gamma_2$ are the power-law slope at low-mass ($M_h \ll M_{*}$) and high-mass ($M_h \gg M_{*}$) ends, respectively. The CLF for satellite galaxies is modelled as a modified Schechter function,

$$\Phi_{\text{sat}}(L|M_h) dL = \phi_0 \left( \frac{L}{L_{\text{sat}}} \right)^{\alpha_s+1} \exp \left[ -\left( \frac{L}{L_{\text{sat}}} \right) \right] \frac{dL}{L}.$$  \hfill (A17)

where $L_{\text{sat}}(M_h)$ is $0.562L_c(M_h)$ (Yang, Mo & van den Bosch 2008) and

$$\phi_{*}(M_h) = \phi_0 \left( \frac{M_h}{10^{12.3}\text{h}^{-1}\text{M}_\odot} \right)^{\beta_s}.$$  \hfill (A18)

Therefore, the CLF model contains eight free parameters, $\theta_{\text{CLF}} = (\log L_0, \log M_{*}, \gamma_1, \gamma_2, \alpha_s, \log \phi_0, \alpha_s, \beta_s)$ (strictly speaking, we express $\log L_0$ in terms of the corresponding UV magnitude $M_{\text{UV}}$).

Once the CLF is specified, we can compute the luminosity function and the correlation function (power spectrum) of galaxies. The luminosity function is given by

$$\Phi(L) = \int \Phi(L|M_h) \frac{dn}{dM_h} dM_h,$$  \hfill (A19)

where $dn/dM_h$ is the halo mass function for which we use Tinker et al. (2008) halo mass function.

The galaxy power spectrum is computed using the standard HOD framework. Using the CLF, the halo occupation number of central galaxies above a limiting luminosity threshold of sample $L_{\text{th}}$ is given by,

$$\langle N_{\text{cen}}(M_h) \rangle = \int_{L_{\text{th}}}^{\infty} \Phi_{\text{cen}}(L|M_h) dL,$$  \hfill (A20)

and for satellite galaxies, $\langle N_{\text{sat}}(M_h) \rangle = \int_{L_{\text{th}}}^{\infty} \Phi_{\text{sat}}(L|M_h) dL$. The number density of galaxies is $\bar{n}_h(>L_{\text{th}}) = \langle N(M_h) \rangle / \pi_2 M_h dM_h$ where $\langle N(M_h) \rangle = \langle N_{\text{cen}}(M_h) \rangle + \langle N_{\text{sat}}(M_h) \rangle$ is the total halo occupation number of galaxies. In the halo model (e.g. Cooray 2006), the power spectrum of galaxies is expressed in terms of one-halo and two-halo terms containing all possible combinations of central and satellites,

$$P_g(k) = 2P_{cs}^{1h}(k) + P_{ss}^{1h}(k)$$

$$+ P_{cs}^{2h}(k) + 2P_{ss}^{2h}(k) + P_{ss}^{2h}(k).$$  \hfill (A21)

Following the notation of van den Bosch et al. (2013), we have defined the necessary one-halo $P_{xy}^{1h}(k)$ and two-halo terms $P_{xy}^{2h}(k)$ as

$$P_{xy}^{1h}(k) = \int dM_h \mathcal{H}_x(k, M_h) \mathcal{H}_y(k, M_h) \frac{dn}{dM_h},$$  \hfill (A22)

and

$$P_{xy}^{2h}(k) = P_m(k) \int dM_h \mathcal{H}_x(k, M_h) b_h(M_h) \frac{dn}{dM_h}$$

$$\times \int dM_h \mathcal{H}_y(k, M_h) b_h(M_h) \frac{dn}{dM_h}.$$  \hfill (A23)

where ‘x’ and ‘y’ are either ‘c’ (for central) or ‘s’ (for satellite), and

$$\mathcal{H}_x(k, M_h) = \frac{\langle N_{\text{cen}}(M_h) \rangle}{\bar{n}_h(>L_{\text{th}})}, \quad \mathcal{H}_c(k, M_h) = \frac{\langle N_{\text{sat}}(M_h) \rangle}{\bar{n}_h(>L_{\text{th}})}.$$

\hfill (A24)
For the dark matter power spectrum $P_m(k)$, we use the non-linear fitting formula of Peacock & Dodds (1996). The result is marginally affected even if we use the linear matter power spectrum. For the halo bias factor $b_h(M_h)$, we adopt the fitting function of Tinker et al. (2010). Here, $\bar{u}(k|M_h)$ is the Fourier transform of the NFW halo profile and for the halo concentration parameter we use Duffy et al. (2008) fitting function.

Finally, we compute the angular correlation function of galaxies from the galaxy power spectrum. Using the Limber approximation, the angular correlation function at a perpendicular separation $r_\perp$ is given by

$$\omega_\perp(r_\perp) = \frac{d \mathcal{N}^2(z)}{dz} \left[ \frac{d \nu}{dz} \right]^{-1} \int_{k_{\min}}^{k_{\max}} dk |P_j(k)| J_0(k r_\perp),$$

(A25)

where $\mathcal{N}(z)$ is the normalized redshift distribution of galaxies, $|d \nu/dz| = c H(z)$, and $J_0(k r_\perp)$ is the zeroth-order Bessel function of the first kind. We use $\mathcal{N}(z)$ from the Monte Carlo simulation of i-dropouts by Bouwens et al. (2015).

To specify the CLF parameters, we simultaneously fit the model with the $z \sim 6$ UV luminosity function of Bouwens et al. (2015) and the angular correlation function of LBGs of Harikane et al. (2016), using the MCMC method using emcee package (Foreman-Mackey et al. 2013). We assume a Gaussian likelihood and only use the diagonal element of the error covariance matrix. We assume flat priors for all CLF parameters. The best-fitting parameters are computed as the 50 percentiles of the posterior distributions. We use the best-fitting CLF parameters in the analysis throughout this paper. The result of joint fitting procedure is shown in Fig. A1 and the best-fitting parameters are tabulated in Table A1. With a larger data set we can readily improve our analysis by simultaneously fitting the CLF parameters, $\langle f_{esc} \rangle$, and $M_{UV}^{\text{best}}$ in a full MCMC framework.

### Table A1. The best-fitting CLF parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best-fitting value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{UV,0}$</td>
<td>$-21.43^{+0.36}_{-0.35}$</td>
</tr>
<tr>
<td>$\log M^*_h$</td>
<td>$11.56^{+0.28}_{-0.31}$</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>$2.10^{+0.04}_{-0.05}$</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>$0.25^{+0.06}_{-0.04}$</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>$0.2$ (fixed)</td>
</tr>
<tr>
<td>$\log \phi_0$</td>
<td>$-0.94^{+0.04}_{-0.05}$</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>$-1.15^{+0.03}_{-0.07}$</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>$1.11^{+0.05}_{-0.03}$</td>
</tr>
</tbody>
</table>

For the purpose of the paper, we keep the CLF parameters to be fixed at the best-fitting values for simplicity.

For the application to cosmological radiative transfer, we need to specify the luminosity-dependent cross-power spectrum between our LBG samples ($M_{UV} < -21$) and galaxies with luminosity $L$. In halo model, this is given by

$$P_s(k, L) = P_{cs}^{1h}(k, L) + P_{cs}^{1h}(k, L) + P_{cs}^{1h}(k, L)$$

$$+ P_{cs}^{2h}(k, L) + P_{cs}^{2h}(k, L) + P_{cs}^{2h}(k, L) + P_{cs}^{2h}(k, L).$$

(A26)

where

$$P_{xy}^{1h}(k, L) = \int dM_h \mathcal{H}_{xy}(k, M_h) C_s(k, L, M_h) \frac{dn}{dM_h},$$

(A27)

$$P_{xy}^{2h}(k, L) = P_{xy}^{1h}(k, L) \int dM_h \mathcal{H}_{xy}(k, M_h) b_w(M_h) \frac{dn}{dM_h}$$

$$\times \int dM_h' C_s(k, L, M_h') \frac{dn}{dM_h'}.$$ (A28)

and $\mathcal{H}_{xy}(k, M_h)$ is defined in the same way as equation (A24) but using a luminosity threshold $L_{th}$ corresponding to our LBG samples, and

$$C_s(k, L, M_h) = \frac{\Phi_{esc}(L|M_h)}{\Phi(L)} C_s(k, M, M_h) = \frac{\Phi_{esc}(L|M_h)}{\Phi(L)} \bar{u}(k|M_h).$$

(A29)

Finally, using the best-fitting CLF parameters we evaluate and substitute equation (A26) into the luminosity-weighted galaxy power spectrum, equation (14), to model the enhanced photoionization rate around LBGs throughout this paper.

### APPENDIX B: LINEAR THEORY

Here, we quantify the effect of galaxy-gas density correlation on the mean Lyα transmitted flux around LBGs. While in the main analysis we use a fully non-linear galaxy–galaxy correlation function in the UV background around LBGs ($\Gamma_{HI}(r)$) (Appendix A), to examine the relative contribution of galaxy-galaxy and galaxy-gas density correlations, we use the linear theory so that a fair comparison of the two competing effects can be made at the same linear order. Taylor expanding our model of the mean Lyα transmitted flux around LBGs (equation 7) in terms of the photoionization rate, we
What reionized the Universe?

Figure B1. Effect of the galaxy–gas density correlation on the mean Lyα transmitted flux around LBGs in the linear regime. The BOSS-based estimate of Lyα forest bias \( b_\alpha \approx -1 \) at \( z = 5.8 \) (orange) shows only a modest effect of matter correlation on the galaxy–Lyα forest cross-correlation on the large-scale (\( \gtrsim 1 \) pMpc) presented in the paper. The galaxy–gas density correlation only case is also shown (black). All models assume \( \langle f_{\text{esc}} \rangle = 0.1, M_{\text{UV}} = -15, \lambda_{\text{mfp}} = 6 \) pMpc, \( T = 10^4 \) K, and the best-fitting CLF parameters.

\[
\langle \exp(-\tau_\alpha(r)) \rangle \approx F_\alpha [1 + b_\gamma \langle \delta(r) \rangle].
\]  

(B1)

where \( F_\alpha = \int \frac{d\Delta_b \, P_V(\Delta_b) e^{-\tau_\alpha(\Gamma_{\text{HI}}, T)} \Delta_b^2}{\bar{F}_{\text{HI}} - 1} \) is the mean Lyα transmitted flux of the IGM. The UV background fluctuation \( \langle \delta(r) \rangle = (\Gamma_{\text{HI}}(r))/\bar{\Gamma}_{\text{HI}} - 1 \) reduces to

\[
\langle \delta(r) \rangle \approx b_{\text{BG}} \langle \delta \rangle_L \int \frac{k^2 dk}{2\pi^2} R(k\lambda_{\text{mfp}}) P_{\text{lin}}^m(k) \frac{\sin kr}{kr}.
\]  

(B2)

in the linear regime, and the bias factor is the response of the Lyα transmitted flux to a small perturbation of UV background,

\[
b_\gamma = \frac{1}{\bar{F}_\alpha} \left. \frac{d\langle F_\alpha \rangle}{d\langle \delta \rangle} \right|_{\langle \delta \rangle = 0},
\]  

(B3)

This shows that our non-linear model is equivalent to the well-known linear theory (Font-Ribera et al. 2013; du Mas des Bourboux et al. 2017) at the correct limit.

Thus, following the linear theory model, the contribution of galaxy-gas density correlation can be included as (Font-Ribera et al. 2013; du Mas des Bourboux et al. 2017)

\[
\langle \exp(-\tau_\alpha(r)) \rangle \approx F_\alpha [1 + b_\gamma \langle \delta(r) \rangle + b_{\text{BG}} b_\alpha \xi_{\text{lin}}(r)],
\]  

(B4)

where \( b_\alpha \) is the Lyα forest bias factor and \( \xi_{\text{lin}}(r) \) is the linear matter correlation function. We estimate the Lyα forest bias using the BOSS Lyα forest result \( b_\alpha(z) \approx -0.134(1 + z)/(1 + 2.4)^{2.9} \) (Slosar et al. 2011; du Mas des Bourboux et al. 2017), leading \( b_\alpha \approx -1 \) at \( z = 5.8 \). To complement this large extrapolation, we also examine the cases with \( b_\alpha \approx -2 \) and \( -3 \).

In Fig. B1 we show the effect of the galaxy-gas density correlation on the mean Lyα transmitted flux around LBGs. The increasing mean gas overdensity around LBGs reduces the Lyα transmission at smaller radii as argued in the main text. The effect would become prominent only at smaller scale (\( \lesssim 1 \) pMpc), which is below the scale presented in the paper. The relative contribution is below 10 per cent for the BOSS-based estimate \( b_\alpha \approx -1 \) at the innermost bin (1.5 pMpc), and only modestly increases with Lyα forest bias at the scale of interest. The effect of galaxy-gas density correlation should thus be small. Note that, regardless of the precise value of the effect, the contribution of galaxy-gas density correlation requires more ionizing photons to match the observed Lyα transmitted flux in order to compensate the mean gas overdensity, leading to an even higher value of escape fraction. Our main result will therefore remain unchanged.