Are we witnessing the epoch of reionisation at \(z = 7.1\) from the spectrum of J1120+0641?

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ABSTRACT

We quantify the presence of Ly\(\alpha\) damping wing absorption from a partially-neutral intergalactic medium (IGM) in the spectrum of the \(z = 7.08\) QSO, ULASJ1120+0641. Using a Bayesian framework, we simultaneously account for uncertainties in: (i) the intrinsic QSO emission spectrum; and (ii) the distribution of cosmic H\(\upi\) patches during the epoch of reionisation (EoR). For (i) we use a new intrinsic Ly\(\alpha\) emission line reconstruction method (Greig et al.), sampling a covariance matrix of emission line properties built from a large database of moderate-\(z\) QSOs. For (ii), we use the Evolution of 21-cm Structure (EOS; Mesinger et al.) simulations, which span a range of physically-motivated EoR models. We find strong evidence for the presence of damping wing absorption redward of Ly\(\alpha\) (where there is no contamination from the Ly\(\alpha\) forest).

Our analysis implies that the EoR is not yet complete by \(z = 7.1\), with the volume-weighted IGM neutral fraction constrained to \(\bar{x}_{\text{H}\text{I}} = 0.40^{+0.21}_{-0.19}\) at \(1\sigma\) \((\bar{x}_{\text{H}\text{I}} = 0.40^{+0.41}_{-0.32}\) at \(2\sigma\)). This result is insensitive to the EoR morphology. Our detection of significant neutral H\(\upi\) in the IGM at \(z = 7.1\) is consistent with the latest Planck 2016 measurements of the CMB Thompson scattering optical depth (Planck Collaboration XLVII).

Key words: cosmology: observations -- cosmology: theory -- dark ages, reionization, first stars -- quasars: general -- quasars: emission lines

1 INTRODUCTION

The epoch of reionisation (EoR) signals the end of the cosmic dark ages, when ionising radiation from the first stars and galaxies spreads throughout the Universe, beginning the last major baryonic phase change. This EoR is rich in astrophysical information, providing insights into the formation, properties and evolution of the first cosmic structures in the Universe.

Several recent \(z \gtrsim 6\) observations have provided (controversial) information about the EoR (for a review, see eg., Mesinger 2016). These come either from integral constraints on H\(\upi\) provided by the Thomson scattering of CMB photons (e.g. Planck Collaboration XIII 2016) or Ly\(\alpha\) absorption by putative cosmic H\(\upi\) patches along the lines of sight towards \(z \gtrsim 6\) objects. Since the cross-section at the Ly\(\alpha\) line centre is large enough to saturate transmission even in the ionised intergalactic medium (IGM; requiring only trace values of neutral hydrogen: \(x_{\text{H}\text{I}} \gtrsim 10^{-4} - 10^{-5}\)), the latter constraints generally rely on the damping wing of the line. The relative flatness of the damping wing with frequency contributes a smooth absorption profile, which can result in optical depths of order a few during the EoR at frequencies around the redshifted Ly\(\alpha\) line.

For galaxies, constraining damping wing absorption must be done with large samples, using their redshift evolution and/or clustering properties (e.g. Haiman & Spaans 1999, Ouchi et al. 2010, Stark et al. 2010, Pentericci et al. 2011, Ono et al. 2012, Caruana et al. 2014, Schenker et al. 2014). QSOs however can be much brighter, allowing the detection of the EoR damping wing from a single spectrum. Most bright \(z \gtrsim 6\) QSOs have a large region of detectable flux blueward of the rest frame 1216 Å, where the flux from the QSO itself is thought to facilitate transmission even for photons redshifting into the Ly\(\alpha\) resonant core. If this so-called near zone is large, then the imprint of an EoR damping wing can be isolated as a smooth absorption component on top of the fluctuating resonant absorption (the Ly\(\alpha\) forest) inside the near zone (e.g. Mesinger et al. 2004, Bolton & Haehnelt...
The usefulness of a composite emission template. Thus, the file can vary significantly from object to object, complicating the analysis considerably. However, as it might contain a consistent with the subsample of objects with similar C IV high column density \((\log N_{\text{C IV}})\). If the IGM is indeed undergoing reionisation at \(z \approx 7.1\), cosmic H I patches along the line of sight might be close enough to the quasar to imprint a detectable damping wing signature away from the near zone edge, even redward of the Ly\(\alpha\) emission line centre. Redward of the Ly\(\alpha\) line centre (and redward of any redshifted cosmological infall; e.g. Barkana & Loeb 2001), there is no contribution from resonant absorption in the Ly\(\alpha\) forest (see Section 2.3). Not having to model the Ly\(\alpha\) forest simplifies the analysis considerably. However, as it might contain a damping wing imprint, the red side of the observed emission line can no longer be used to independently reconstruct the Ly\(\alpha\) line profile. Moreover, the intrinsic Ly\(\alpha\) emission profile can vary significantly from object to object, complicating the usefulness of a composite emission template. Thus, *any analysis of the IGM damping wing would need to fold-in the significant uncertainties in the shape and amplitude of the intrinsic Ly\(\alpha\) line profile.*

The difficulty in reconstructing the intrinsic emission of ULASJ1120 is further exacerbated by its peculiar emission line features. Mortlock et al. (2011) report an extremely large C IV blue-shift relative to its systemic redshift, which is larger than what has been observed in 99.9 per cent of all known QSOs. Bosman & Becker (2015) recently suggested that the observed Ly\(\alpha\) emission of ULASJ1120 might be consistent with the subsample of objects with similar C IV properties, potentially alleviating the need for additional damping wing absorption. Correctly accounting for correlations of line properties is therefore critical for any robust claims on reionisation from ULASJ1120.

In this work, we re-analyse the spectrum of ULASJ1120, improving on prior work with a combination of the following:

- We use the recently developed intrinsic Ly\(\alpha\) emission line reconstruction method (Greig et al. 2016), which samples a covariance matrix of emission line properties from \(\sim 1500\) moderate-\(z\) unobscured QSOs.
- We use the latest, large-scale (1.6 Gpc on a side), physics-rich simulations of the EoR (Mesinger et al. 2016) to extract \(10^5\) sightlines of opacity from \(\sim 10^{-2} M_\odot\) halos (typical of bright QSOs; e.g. Fan et al. 2006) Mortlock et al. 2011.
- We fold all uncertainties into a Bayesian framework, recovering robust constraints on the IGM neutral fraction at \(z \approx 7.1\), which, for the first time, include rigorous statistical confidence intervals.

The remainder of this paper is organised as follows. In Section 2.1 we summarise the key components of the intrinsic Ly\(\alpha\) reconstruction method, the observed spectrum of ULASJ1120 to be used in this analysis and the recovery of the reconstructed Ly\(\alpha\) line profile. In Section 2.2 we discuss the semi-numerical reionisation simulations and the extraction of the synthetic damping wing profiles and in Section 2.3 we outline our combined analysis. In Section 3 we discuss the constraints on the IGM neutral fraction resulting from the imprint of the IGM damping wing, and in Section 4 we consider the possibility of a DLA contributing the damping wing imprint. Finally, in Section 5 we finish with our closing remarks. Throughout this work, we adopt the background cosmological parameters: \((\Omega_\Lambda, \Omega_M, \Omega_b, n, \sigma_8, H_0) = (0.69, 0.31, 0.048, 0.97, 0.81, 68 \text{ km s}^{-1} \text{ Mpc}^{-1})\), consistent with cosmic microwave background anisotropy measurements by the Planck satellite (Planck Collaboration XIII 2015) and unless otherwise stated, distances are quoted in comoving units.

## 2 METHOD

### 2.1 Reconstruction of the intrinsic Ly\(\alpha\) profile

The analysis of the IGM damping wing imprint within the spectrum of ULASJ1120 hinges on the recovery of the intrinsic Ly\(\alpha\) emission line profile. Already, in the previous section we have alluded to the difficulties in applying a QSO composite template to ULASJ1120. Within this work, we utilise the recently developed covariance matrix method of Greig et al. (2016) to obtain our reconstructed estimate of the intrinsic Ly\(\alpha\) emission line profile.

In this work, we make use of the Simcoe et al. (2012) from the different individual line profiles may lead to small biases in their determined velocity offsets.

A note that quantitative EoR constraints using just the apparent size of the near zone require assumptions about the QSO age, environment, and ionisation history (e.g. Mesinger et al. 2004 Maselli et al. 2007 Bolton et al. 2011). In principle, strong Ly\(\alpha\) attenuation could also be caused by a damped Ly\(\alpha\) absorber (DLA) intersected along the line of sight. However, such a system would have to have both an extremely large C IV blue-shift relative to its systemic redshift, which is larger than what has been observed in 99.9 per cent of all known QSOs. Bosman & Becker (2015) recently suggested that the observed Ly\(\alpha\) emission of ULASJ1120 might be consistent with the subsample of objects with similar C IV properties, potentially alleviating the need for additional damping wing absorption. Correctly accounting for correlations of line properties is therefore critical for any robust claims on reionisation from ULASJ1120.

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ULASJ1120 spectrum, obtained from the FIRE infrared spectrometer \cite{Simeco2008} on the Magellan/Baade telescope. This spectrum offers an order of magnitude improvement in spatial (frequency) resolution compared to the Mortlock et al. \cite{2011} discovery spectrum, with a similar signal to noise. Throughout this work, we report all results in the QSO rest-frame, with which we convert from the observed frame using the atomic [C \text{III}] transition. The resulting ULASJ1120 redshift is $z = 7.0842 \pm 0.0004$ \cite{Venemans2012}.

2.1.1 Reconstruction procedure

Within this section we briefly summarise the major steps of the intrinsic Lyα profile reconstruction method developed by \cite{Greig2016}, and refer the reader to that work for more in-depth discussions. Our approach is based on a covariance matrix characterising the emission line parameters. We first select a subsample of moderate-$z$ ($2.08 < z < 2.5$), high signal to noise ($S/N > 15$) QSOs from SDSS-III (BOSS) DR12 \cite{Dawson2013, Alam2015}. Each QSO in our final sample of 1673 (using the ‘Good’ sample, which provides tighter constraints on the reconstruction profile) is then fit with a single power-law continuum, and a set of Gaussian profiles to characterise the emission lines and any possible absorption features contaminating the observed QSO spectrum. Each Gaussian profile is described by three parameters: a line width, peak height and velocity offset from the systemic redshift. For Lyα and C\text{IV} we allow for both a broad and narrow component Gaussian to describe the line profile, and single components for all other high and low-ionisation lines. After fitting all QSOs, and performing a visual quality assessment to refine our QSO sample, we construct our covariance matrix from the four most prominent high-ionisation lines, Lyα, C\text{IV}, Si\text{IV} + O\text{IV}, and C\text{III}.

With the covariance matrix in hand, we can reconstruct the intrinsic Lyα line profile of ULASJ1120 as follows:

- Using the fitting procedure described above, we fit the spectrum of ULASJ1120 far redward of the extent of the Lyα line profile. We chose $\lambda > 1275\AA$ as the blue edge for the fit somewhat arbitrarily, but verify that this choice does not have an impact on the results.
- From this fit (shown in Figure 1), we obtain estimates of ULASJ1120’s continuum and of its Si\text{IV} + O\text{IV}, C\text{IV} and C\text{III} line profiles.
- Using these estimates, we collapse the 18-dimensional (Gaussian distributed) covariance matrix into a six-dimensional estimate of the intrinsic Lyα emission line profile (two component Gaussian each with an amplitude, width and velocity offset).
- We apply a prior within the range $1230 < \lambda < 1275\AA$. This is performed by simultaneously fitting the Lyα + N\text{v} (1240.81\AA) and Si\text{II} (1262.90\AA) lines (where we sample the Lyα profile from the six dimensional distribution), using the observed noise from the FIRE spectrum to obtain a $\chi^2$ likelihood for the reconstructed profile. In other words, we require our profiles to fit the observed spectrum over the range $1230 < \lambda < 1275\AA$. This final step notably reduces the errors on the reconstructed Lyα profile (shown in Figure 2), ruling out extreme profiles which are inconsistent with the actual observed spectrum. We note that the wavelength range by construction has to be redward of any significant damping wing absorption.

It is important to note that the actual range of the prior is not important for the reconstruction of the Lyα line profile \cite{Greig2016}. However, since we fit the IGM damping wings far redward of the line center, out to 1230\AA it is critical that this prior range includes sufficient information to allow for the fitting of the nearby N\text{v} line. While near the Lyα line centre, the total QSO flux is expected to be solely dominated by the Lyα line, further redward of the line centre one can expect an increasing contribution from the N\text{v} line as its line centre is approached. Unfortunately, simultaneously reconstructing the Lyα and N\text{v} emission lines would yield uncertainties which are too large. Thus we impose a prior just blueward of the N\text{v} line. As this lower limit is increased from our adopted 1230\AA moving into the line, the spread in the allowed QSO flux will increase, broadening the recovered constraints on the IGM neutral fraction.

2.1.2 Reconstruction of ULASJ1120+0641

In Figure 1 we present the MCMC template fitting of ULASJ1120 at $\lambda > 1275\AA$. In the top panel, the red-dashed curve corresponds to the best-fit QSO continuum, whereas in the remaining zoomed-in panels we present the best-fits to the various emission line profiles, using either a single or double component Gaussian as described above. Compared to the QSO spectra used in the construction of the covariance matrix in \cite{Greig2016}, the FIRE spectrum is considerably noisier.

Immediately obvious from Figure 1 is the significant blueshift observed amongst all the high-ionisation lines. In addition to the already reported strong blueshift of C\text{IV} \cite{Mortlock2011}, we note that the N\text{v} (not fit), Si\text{IV} + O\text{IV} and C\text{III} lines appear to be equally strongly blue shifted. At the same time, the low ionisation lines, O\text{i} and C\text{II} do not appear to be blue shifted at all. Furthermore, while not shown in Figure 1 or observed in the Simeco et al. \cite{2012} FIRE spectrum, the Mg\text{II} line also does not have a significant blue shift \cite{Mortlock2011}. This behaviour is well known, which highlights that the physics governing the low and high ionisation lines stem from different processes or physical regions. We stress that this strong observed blueshift in all high-ionisation lines is automatically accounted for by the covariance matrix reconstruction pipeline.

Note that, in the FIRE spectrum, the Si\text{IV} + O\text{IV} line is strongly affected by both night sky OH lines and telluric absorption bands. While attempts were made to correct this
in the spectrum, they will still leave an imprint in the form of lower signal to noise and larger residuals. Within this work we attempt to mask out the worst of these lines, however we caution that the Si IV + O IV line may still be contaminated. However, we note that the Si IV + O IV emission line is the least important of the three high-ionisation lines used to reconstruct the intrinsic Lyα line profile. Therefore, while the characterisation of the Si IV + O IV line profile is likely to be contaminated, the uncertainties arising from this will not greatly impact our reconstructed Lyα line profile.

In Figure 2 we show the reconstructed intrinsic Lyα emission line profile. The red curve is the best-fit reconstructed profile (shown for visualisation purposes only) obtained by jointly sampling the Lyα line profile and the wavelength range 1230 < λ < 1275Å, while the black curve is the observed spectrum sampled in 0.1Å bins. Given that our reconstruction procedure returns a six-dimensional likelihood function, in order to characterise the scale of the 68 per cent uncertainties on the reconstructed Lyα profile we randomly sample this likelihood function to extract representative profiles. In Figure 2 we present a subsample of 300 reconstructed Lyα line profiles denoted by the thin grey lines which are within the 68 per cent uncertainties. These profiles highlight the relative scale of the variations in the total Lyα line profile peak height, width and location. Note, our analysis pipeline operates directly on a large number of these sampled profiles (drawn from the full distribution),

Figure 1. A zoom-in highlighting the MCMC QSO fitting procedure of Greig et al. (2016) applied to the rest-frame FIRE spectrum (Simcoe et al. 2012). This method includes the identification of ‘absorption’ features (e.g. the bottom left and bottom right panels), which improves our ability to recover the emission line profiles. The flux is normalized to unity at 1450Å rest-frame (1 A. U. = 10^{-17} erg cm^{-2} s^{-1} Å^{-1}). Arrows denote the systemic redshift of each line, obtained from the recovered atomic [C II] redshift (Venemans et al. 2012). Top: A single power-law continuum component fit to the QSO spectrum (red dashed curve). Middle left: The obscured Lyα peak profile (not-fit). Middle centre: Two low-ionisation lines, O I/Si II (cyan) and C II (magenta). Middle right: Single component Gaussian fit to the Si IV + O IV blended line complex. Bottom left: Two-component fit to C IV. Bottom centre: Low ionisation lines, He II (cyan; no prevalent emission, therefore the line profile is unconstrained) and O III (within the excised region, therefore not fit). Bottom right: Single component fit to C III] (magenta) and single Gaussian Al III component (cyan).
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Figure 2. The reconstructed maximum likelihood Lyα emission line profile (red curve; shown for visualisation purposes only) recovered from our covariance matrix method including an additional prior on the flux amplitude within the wavelength range 1230 < λ < 1275 Å. The thin grey curves denote a subsample of 300 Lyα line profiles extracted from the reconstructed six-dimensional Lyα likelihood function (note, we sample 10^5 profiles in our full analysis). These curves are selected to be within 68 per cent of the maximum likelihood profile, and highlight the relative scale of the errors on the reconstructed Lyα line profile and fully encapsulate the intrinsic object-to-object variation of the QSO sample. The black curve denotes the observed spectrum of ULASJ1120, which has been resampled onto 0.1 Å bins purely for the purposes of this figure (the full analysis pipeline uses the unaltered spectrum as shown in Figure 1). Lower panel: The corresponding unaltered error spectrum of ULASJ1120 averaged onto 0.1 Å bins. Inset: A zoom-in around Lyα highlighting the recovered imprint of the IGM damping wing profile (Section 2.3). The yellow (blue) shaded region denotes the 1σ (2σ) span of total (intrinsic + damping wing absorption) flux over the fitted region. For reference, the red curve is the maximum likelihood intrinsic profile (same as main figure). The stretch between 1222 – 1227 Å is especially difficult to match without the aid of the IGM damping wing from an incomplete reionisation.

Qualitatively, the reconstructed Lyα line profile is similar to the composite QSO spectrum presented in Mortlock et al. (2011) and in Simcoe et al. (2012), albeit with a slightly higher amplitude at the Lyα line centre. A notable advantage of our approach is the statistical characterisation of the Lyα line offset, using the covariance matrix. As shown in Bosman & Becker (2013), the location of the Lyα line centre of the reconstructed profile is crucial for the analysis of the IGM damping wing. Unfortunately, the blue shifts observed in ULASJ1120 exceed those found in all of the 1673 QSOs from which we construct the covariance matrix. The mean blue shift of the C iv ionisation line profile of ULASJ1120 (obtained from combining the narrow and broad components), Δv ∼ 2500 km/s, is a ∼ 4σ outlier from our QSO sample. Thus in the reconstruction procedure for ULASJ1120, we have to extrapolate the Gaussian covariances.

We can test this extrapolation in two ways: (i) by testing our reconstruction approach against the most heavily blue shifted QSOs within the sample used to construct the
covariance matrix and (ii) by artificially removing the strong observed blue-shift. In Appendix A we explore the former, finding little evidence for a reduction in the quality of reconstituted Lyα profiles for the 50 most extreme objects in our sample. For the latter, we take the systemic redshift to be that from the C II line (instead of our fiducial atomic [C II]). As noted in Section 2.1.2, the C II emission line appears equally strongly blue shifted as C IV and the other high ionisation lines; therefore, by using the C II redshift we can artificially remove the strong C IV velocity offset. After performing the Lyα reconstruction pipeline on this artificially corrected spectrum, we recover a quantitatively similar Lyα line profile shape, well within our 1-σ uncertainties. Therefore, following these two tests, we can be relatively confident in the extrapolation of these Gaussian covariances to the values found in ULASJ1120.

2.2 The IGM damping wing during the EoR

As stated above, the observed spectrum redward of the Lyα line centre depends on the intrinsic emission (discussed in the previous section), and the damping wing absorption from (putative) cosmic H I patches along the line of sight (LoS). To statistically characterise the latter, we make use of the publicly-available Evolution of 21-cm Structure (EOS; Mesinger et al. 2016) 2016 data release. These semi-numerical reionisation simulations are 1.6 Gpc on a side with a 1024^3 grid, and include state-of-the-art sub-grid prescriptions for inhomogeneous recombinations and photo-heating suppression of star-formation. The 2016 EOS data release corresponds to two simulation runs, with the efficiency of supernovae feedback adjusted to approximately bracket the expected EoR contribution from faint galaxies. The two runs are:

- **Faint galaxies** – the EoR is driven by galaxies residing in haloes with masses of \(10^8 < M_h / M_\odot < 10^9\), and is characterised by numerous small cosmic H II regions. Hereafter we will refer to the EoR morphologies resulting from this simulation as **Small H II**.

- **Bright galaxies** – the EoR is instead driven by galaxies residing in haloes with masses of \(M_h \sim 10^{10} M_\odot\), and is characterised by spatially more extended H II structures. We refer to these simulated EoR morphologies as **Large H II**.

We note that the large H II ionisation fields have a factor of \(\sim\)few–10 times more power on large scales during the EoR, compared to the Small H II ionisation fields. Although these are two opposite extremes in terms of H II region sizes, the Small H II EoR morphology is likely more realistic (see the discussion in Mesinger et al. 2016), and so we use this simulation as our fiducial model. Nevertheless, we include both extremes to explore the dependence of our results on EoR morphology.

We construct samples of sightlines through our simulations which are terminated on one end at a halo, and then extended in a random direction through the simulation volume for a distance of 200 comoving Mpc. Along each sightline, we sum the contributions from all encountered H I patches to construct a composite optical depth for the damping wing (e.g. Miralda-Escudé 1998). We purposefully exclude the H I contribution from pixels \(\lesssim 16\) comoving Mpc (2 physical Mpc) from the QSO host halo. This corresponds to the minimum possible radius of the H II region around ULASJ1120 inferred from measurements of its near zone (Mortlock et al. 2011). We do not explicitly include the flux from the QSO in our reionisation maps. Doing so would require assumptions about the QSO lifetime and ionising luminosity. Neglecting the QSO ionising contribution implies that the surrounding H II region could be larger than predicted by our EoR models. For a given \(x_{\text{HI}}\) a larger surrounding H II region implies a smaller integrated damping wing optical depth. Thus if the QSO contributes in growing the surrounding H II region, our modelled optical depths should be associated with even higher values of \(x_{\text{HI}}\), shifting the PDFs we present below towards larger \(x_{\text{HI}}\).

At \(z = 7.1\), we select \(10^4\) identified haloes in the mass range \(6 \times 10^{11} < M_h / M_\odot < 3 \times 10^{12}\), consistent with the inferred dynamical mass of the host halo of ULASJ1120 (Venemans et al. 2012). Importantly, these higher host halo masses, made possible by the large-scale EOS simulations, are a notable improvement over previous studies (e.g. Bolton et al. 2011) as they better capture the bias and scatter of the QSOs locations inside reionisation fields. Though the lines of sight begin 16 Mpc from the host haloes, this bias and scatter may still be important (see e.g. fig. 2 of Mesinger & Furlanetto 2008 and fig. 3 of Mesinger 2010). We use 10 LoSs per host halo, resulting in a total sample of \(10^5\) synthetic IGM damping wing profiles for each sampled \(x_{\text{HI}}\) and EoR morphology (Small H II and Large H II). Since we wish to leave the IGM neutral fraction at \(z = 7.1\) as a free parameter, we follow the common practice of sampling ionisation fields at various redshifts corresponding to a given \(x_{\text{HI}}\). That is, we use the same halo list obtained from the \(z = 7.1\) snapshot to define the locations for our synthetic damping wing profiles, but vary the mean IGM neutral fraction by sampling the corresponding ionisation fields obtained from different redshift outputs. Such an approach is justified as the ionisation fields are largely redshift independent, when compared at a fixed \(x_{\text{HI}}\) (e.g. McQuinn et al. 2007a,b; Sobacchi & Mesinger 2015).

2.3 Joint fitting of the intrinsic emission and IGM damping wing

Having outlined the reconstruction of the intrinsic Lyα line profile of ULASJ1120 in Section 2.1 and the IGM damping wing profiles in Section 2.2 we now combine them to simultaneously fit the observed spectrum. Our fitting procedure consists of the following steps:

(i) The intrinsic Lyα line profile recovered in Section 2.1 is fully described by a six dimensional likelihood function (three parameters for each of the two Gaussian components), characterising the uncertainties and correlations amongst the Lyα line profile parameters, constrained by the spectrum at \(\lambda > 1230\AA\). We draw \(\sim 10^5\) Lyα line profiles directly from this six dimensional likelihood.

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8 Note that the C IV blueshifts for this sample of 50 QSOs were between 1,300 - 2,000 km/s, smaller than the recovered 2,500 km/s of ULASJ1120 (see Figure A1).

9 http://homepage.sns.it/mesinger/EOS.html
Figure 3. 1D PDFs of the IGM neutral fraction drawn from a subsample of 1000 lines of sight for each of the two EoR simulations used in our analysis (Mesinger et al. 2016). Colour bars denote the amplitude of the PDFs, $P(\bar{x}_{\text{HI}})$. Note that the peaks of the PDFs of each sightline are normalised to unity purely to aid the visualisation. The shifting locations of the peaks per sightline are indicative of the sightline-to-sightline variation. In the left panel, the individual sightline PDFs correspond to the Small H II EoR simulations (reionisation driven by faint galaxies producing small cosmic H II regions) whereas the right panel corresponds to the Large H II EoR simulations (reionisation driven by bright galaxies producing large cosmic H II regions). Averaging over the full sample of $10^5$ sightlines (i.e. collapsing along the vertical direction) results in the 1D PDFs of $\bar{x}_{\text{HI}}$ shown in the following figure.

(ii) Each line profile is then multiplied by each of the $10^5$ EoR damping wing absorption profiles, resulting in a total sample of $\sim 10^5 \times 10^5$ mock spectra for each value of $\bar{x}_{\text{HI}}$.

(iii) Each mock spectrum is then compared with the observed spectrum of ULASJ1120 in the wavelength range $1218\,\text{Å} < \lambda < 1230\,\text{Å}$ The quality of the fit is characterized by ensuring that we are sufficiently far from the influence of any infalling or local gas (e.g. Barkana & Loeb 2004), which is not

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\footnote{The choice of $1230\,\text{Å}$ is motivated by the blue edge of the prior discussed in Section 2.1.2 while the choice of $1218\,\text{Å}$ is motivated by ensuring that we are sufficiently far from the influence of any infalling or local gas (e.g. Barkana & Loeb 2004), which is not...}
by a (χ² based) likelihood, using the observational errors of the spectrum.

(iv) The resulting likelihood, averaged over all ∼ 10⁵ mock spectra, is then assigned to that particular \( \bar{x}_{\text{HI}} \).

(v) Steps (ii)–(iv) are repeated for each trial value of \( \bar{x}_{\text{HI}} \). We sample the range \( 0.01 \leq \bar{x}_{\text{HI}} \leq 0.95 \), with 40 (28) individual snapshots for the \text{Small H II} (\text{Large H II}) simulations (note that the EoR proceeds more rapidly in the \text{Large H II} model, resulting in a coarser \( \bar{x}_{\text{HI}} \) sampling for outputs at fixed redshift intervals).

(vi) We normalise the resulting relative likelihoods, ending with a final 1D probability distribution function (PDF) of \( \bar{x}_{\text{HI}} \) for each of the EoR morphologies.

The above steps effectively result in the construction a 3D likelihood which is a function of: (i) \( \bar{x}_{\text{HI}} \); (ii) the EoR damping wing sightline; and (iii) the intrinsic emission profile. Our final constraints on \( \bar{x}_{\text{HI}} \) are obtained by marginalising over (ii) and (iii).

### 3 RESULTS

In the inset of Figure 2, we present the confidence intervals on the product of the reconstructed Lyα line profile and the synthetic IGM damping wing profiles within the fitting interval 1218Å < \( \lambda \) < 1230Å. For reference, the red curve is the intrinsic Lyα emission line profile with the maximum likelihood from our reconstruction procedure. The impact of the damping wing contribution is highlighted by the offset of the shaded regions and the red curve. In the main panel of Figure 2, we present a small subset (300) of recovered Lyα line profiles to convey the relative uncertainties in the reconstruction pipeline. Note that the wavelength stretch between 1222 – 1227 Å is especially difficult to fit purely with the intrinsic profiles alone (in. As we shall see below, we require a non-zero IGM damping wing contribution to fit the observed spectrum of ULASJ1120.

Before presenting our final constraints on \( \bar{x}_{\text{HI}} \), we showcase the EoR sightline-to-sightline scatter in Figure 3. For each of a randomly selected subsample of 1000 sightlines shown in the figure, we average over the full distribution of the reconstructed Lyα intrinsic profiles, in order to generate a \( \bar{x}_{\text{HI}} \) PDF for that sightline. Collapsing (marginalising) over the vertical direction (sightline number) for the entire sample of 10⁹ LoSs recovers the full 1D marginalised PDF (step (vi) of Section 2.3; see Figure 4). Sightlines extracted from the \text{Small H II} and \text{Large H II} simulations appear on the left and right, respectively.

On average, we recover a similar range for the preferred IGM neutral fraction for both EoR morphologies. However, there is significant sightline-to-sightline variation, shifting the peaks of the \( \bar{x}_{\text{HI}} \) distributions by tens of per cent. This highlights the importance of sampling a large number of IGM damping wing profiles. Our full sample consists of 10⁵ sightlines through inhomogeneous reionisation, compared with 100 sightlines through homogeneous reionisation in the preliminary studies of [Bolton et al. (2011)] and [Keating et al. (2015)].

Finally, in Figure 4, we present the main result of this work: 1D PDFs of \( \bar{x}_{\text{HI}} \). These are obtained by marginalising over all combinations of reconstructed intrinsic Lyα line profiles and synthetic IGM damping wing sightlines for a given \( \bar{x}_{\text{HI}} \). The blue curve corresponds to the \text{Small H II} EoR morphology, while the red curve corresponds to the \text{Large H II} EoR morphology. Dotted (dashed) curves correspond to the 1 (2σ) constraints on \( \bar{x}_{\text{HI}} \) for the respective morphologies:

- **Small H II**: \( \bar{x}_{\text{HI}} = 0.40^{+0.21}_{-0.19} \) (1σ) and \( 0.40^{+0.41}_{-0.32} \) (2σ)
- **Large H II**: \( \bar{x}_{\text{HI}} = 0.46^{+0.21}_{-0.21} \) (1σ) and \( 0.46^{+0.39}_{-0.37} \) (2σ).

As mentioned earlier (and discussed in [Mesinger et al. (2016)]), the \text{Small H II} model is likely more accurate and we adopt it as our fiducial constraint. We note that the constraints on \( \bar{x}_{\text{HI}} \) are very similar for both \text{Small H II} and \text{Large H II}. This indicates that the damping wing imprint is not very sensitive to how the cosmic neutral patches are distributed at a fixed value of \( \bar{x}_{\text{HI}} \).

In Appendix B, we explore the impact of potential errors in the flux calibration of ULASJ1120, and how this could impact the overall constraints on the IGM neutral fraction. By including a conservative 10 per cent error on the QSO continuum we find, for the \text{Small H II} model, constraints consistent with the main results of this paper.
A damping wing coming from the red side of the Lyα line of ULASJ1120, and quantifying the corresponding constraints on the IGM neutral fraction. We find that the IGM neutral fraction at a fixed global neutral fraction (see Figure 4).

For (i), we use a covariance matrix of emission line properties (Greig et al. 2016) to reconstruct the intrinsic Lyα line profile. For (ii), we use the latest, large-scale simulations of patchy reionisation (Mesinger et al. 2016). After marginalising over (i) and (ii), we obtain robust constraints on the IGM neutral fraction. For our fiducial reionisation model, these are: $\Delta x_{\text{HI}} = 0.40^{+0.21}_{-0.19}$ (1σ) and $0.40^{+0.42}_{-0.32}$ (2σ). We note that the constraints are very insensitive to the EoR model, at a fixed global neutral fraction (see Figure 3).

Our results correspond to the first measurement of the ionisation state of the IGM at $z \sim 7$, with a well-defined confidence range (as opposed to upper/lower limits). They are consistent with the latest Planck measurements of the Thompson scattering optical depth, which independently appeared as this work was nearing completion (Planck Collaboration XVII 2016).

The framework we developed can easily be applied to future QSO observations. Moreover, the analysis can be extended to incorporate the transmission statistics in the QSO near zone (blueward of Lyα). This would introduce additional uncertainties, but would allow the analysis to be extended to other bright $z \sim 6$–7 QSOs which have a much larger near zone, and thus a correspondingly weaker damping wing imprint on the red side of the line (Schroeder et al. 2013). We defer this to future work.

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From the recovered PDF of the IGM neutral fraction we can strongly infer the presence of a damping wing signature, with no IGM damping wing contribution being inconsistent at $> 2\sigma$. This is despite the fact that at first glance in Figure 2, the reconstructed Lyα profiles (without damping wing absorption) appear to be consistent with the observed spectrum of ULASJ1120 in the lower end of the $1218$–$1221$ Å wavelength range used in our analysis. In Appendix C, we quantify this in detail by performing our full analysis pipeline on smaller, equally spaced 3 Å sub-regions. The recovered constraints from the sub regions are consistent with each other at $1\sigma$, with the strongest evidence for a damping wing coming from the $1222$–$1227$ Å region of the observed spectrum.

How do these constraints tie into the existing picture of reionisation? The best available, model independent constraints on the end stages of reionisation are obtained from the dark fraction of pixels in QSO spectra (McGreer et al. 2015), which imply the IGM neutral fraction to be $x_{\text{HI}} \lesssim 0.11$ (1σ). Therefore the $\Delta x_{\text{HI}} = 0.40^{+0.19}_{-0.19}$ constraints obtained here, imply an evolution of $\Delta x_{\text{HI}} \sim 0.1$–$0.5$ over the redshift interval $z \sim 7$–$6$. This is consistent with the currently available EoR constraints (see Greig & Mesinger 2016 and references therein).

4 COULD THE DAMPING WING COME FROM A DAMPED LYMAN ALPHA SYSTEM?

In this work we found evidence of a damping wing imprint on the red side of the Lyα line of ULASJ1120, and quantifying the corresponding constraints on the IGM neutral fraction. However, a damping wing could instead be produced by an intervening damped Lyα system, at least in principle. Indeed most high-$z$ gamma-ray bursts (GRBs) show evidence of a DLA in their spectra (e.g. Chornock et al. 2013, 2014; Totani et al. 2014). However, the GRB DLAs are associated with the GRB host galaxy, while a DLA in the spectra of ULASJ1120 would have to be at least 16 Mpc away from the QSO host galaxy. As has been pointed out previously, finding such an object in a random skewer —, 2007a, MNRAS, 374, 493 —, 2007b, MNRAS, 374, 493
APPENDIX A: EXTRAPOLATING OUR MODEL TO ULASJ1120

In this section, we explore the validity of extrapolating the Gaussian covariances between various line profile parameters recovered from [Greig et al. (2016)] in order to perform the Lyα profile reconstruction of ULASJ1120. The necessity of performing this extrapolation arises due to ULASJ1120’s extremely large C iv blueshift, which is larger than any of the 1673 ‘good’ QSOs originally considered for the construction of the covariance matrix in [Greig et al. (2016)]. Owing to the rarity of these extremely blue-shifted sources, rather than searching for a sufficient statistical sample of similar sources in the BOSS database, instead we investigate a subsample of the 50 most blueshifted QSOs within our existing QSO sample.

In Figure A1 we present the recovered C iv velocity offset of the narrow line component (double Gaussian line profile) against the ratio of the reconstructed QSO flux compared to the original QSO flux at 1220 Å. In [Greig et al. (2016)] we use this ratio as a metric to define how well the reconstruction pipeline performs. In this work, we distinguished a good characterisation of the reconstructed Lyα profile being when this ratio was within 15 per cent of the original fit to the QSO flux. As such, the horizontal red dashed line in Figure A1 denotes this 15 per cent limit. The vertical red dashed line corresponds to the smallest C iv velocity offset of the 50 most blueshifted QSOs. The solid red box encompasses the QSOs which match both these criteria.

For the total sample of 1673 QSOs, at 1220 Å, [Greig et al. (2016)] found that the QSO flux could be recovered within 15 per cent for 90 per cent of all QSOs. Applying this same criteria to the 50 most blue shifted QSOs, we recover the QSO flux to within 15 per cent for 88 per cent of this sample. By recovering similar fractions for the 50 most blueshifted QSOs compared to the full sample (88 compared with 90 per cent), it is clear that there is no obvious decrease

12 This choice of 15 per cent was an arbitrary definition.
in performance of the reconstruction procedure with increasingly larger CIV blueshifts. Furthermore, Figure A1 shows no correlation between the quality of reconstruction and the CIV velocity offset. Finally, four of the five most extremely blueshifted QSOs in our sample are recovered to less than 10 per cent error in the reconstructed QSO flux compared to the original QSO flux. Therefore, given that this reconstruction procedure performs equally well irrespective of the CIV blueshift, we find that it is reasonable to extrapolate the covariance matrix to the extreme CIV blueshift of ULASJ1120.

APPENDIX B: IMPACT OF CONTINUUM ERRORS OWING TO INCORRECT FLUX CALIBRATION

In this work, our observed spectrum of ULASJ1120 was obtained from the FIRE infrared spectrometer on the Magellan/Baade telescope. This data was measured using a narrow slit echelle spectrum, which are difficult to accurately flux calibrate. In this section, we explore what impact any potential flux calibration errors may have had on our inferred constraints on the IGM neutral fraction.

For this, we consider a constant 10 per cent error on the fitted QSO continuum power-law from ULASJ1120 (obtained from our $>1275\,\text{Å}$ fit) over the full $1218–1230\,\text{Å}$ damping wing fitting region. Note that in our reconstruction procedure it is non trivial to include a direct uncertainty on the total flux amplitude. However, within this fitting region, the amplitude of the continuum constitutes $\sim 50$ per cent of the total flux, therefore a 10 per cent error on the continuum roughly equates to a error on the total flux amplitude of $\sim 5$ per cent. We then repeat our full analysis pipeline outlined in Section 3 fitting for the IGM damping wing imprint, adding in this 10 per cent error in quadrature. In Figure B1 we present the 1D PDFs of the IGM neutral fraction of the Small HII synthetic damping wing profiles. The blue curve corresponds to our fiducial constraints on the IGM neutral fraction (Figure 4) whereas the red curve highlights the impact of the 10 per cent error on the QSO continuum, mimicking a flux calibration error.

From Figure B1 it is evident that the inclusion of this additional source of error on the QSO continuum has very minimal impact on our constraints on the IGM neutral fraction. By including this error, we recover an IGM neutral fraction of $\bar{x}_{\text{HI}} = 0.38^{+0.22}_{-0.19} (1\sigma)$. This is essentially equivalent to our fiducial constraints of $\bar{x}_{\text{HI}} = 0.40^{+0.21}_{-0.19} (1\sigma)$, highlighting that our results are much more sensitive to the Lyo line recovery and the associated uncertainties, than the continuum.

This marginal reduction in the IGM neutral fraction arises from effectively broadening the distribution of reconstructed Lyo profiles which are capable of matching the observed spectrum (i.e. lowering the QSO continuum level of the reconstructed profiles, requiring smaller IGM neutral fractions to match ULASJ1120). This effect is most evident by the rising amplitude in the tail of the PDF near $\bar{x}_{\text{HI}} = 0$. Furthermore, as one would anticipate, by broadening the total errors applied to the recovery of the damping wing profile, the PDF of the IGM neutral fraction including this 10 per cent error, is marginally broader than the fiducial neutral fraction distribution. Importantly, given the very minor differences, we can confidently conclude that our IGM neutral fraction constraints are not strongly impacted by any
potential errors arising from problems in the flux calibration of FIRE spectrum of ULASJ1120.

APPENDIX C: EXPLORING VARIOUS FITTING RANGES

In Section 3 we presented our constraints on the IGM neutral fraction by fitting for a damping wing signature between 1218–1230 Å in the observed spectrum of ULASJ1120. In this section, we quantify how the different sub-regions within this wavelength range impact the final result. To test this, we break our fiducial fitting range into four, 3 Å chunks and recover the inferred IGM neutral fraction for each 3 Å region independently.

In Figure C1, we present the 1D PDFs of the IGM neutral fraction at \( z = 7.1 \) recovered from the \( \text{Small H} \ II \) simulation, for the various 3 Å intervals. The black curves correspond to our fiducial 1218–1230 Å fitting interval, whereas the red solid, dashed, dotted and dot-dashed curves correspond to the 1218–1221, 1221–1224, 1224–1227 and 1227–1230 Å sub-ranges, respectively. In Table C1, we summarise the recovered IGM neutral fractions and associated 1 and 2σ errors for each of the fitting intervals considered.

Importantly, in each 3 Å interval there is always a clear preference for a damping wing imprint, implying we have not artificially biased our results by selecting a specific wavelength range to a priori require a damping wing signature. Even in the 1218–1221 Å region, where from Figure 3 one might anticipate we would not require a strong damping wing signature (reconstructed Lyα profiles appear to pass through the observed spectrum), the highest likelihood is from an IGM neutral fraction of \( \bar{x}_{\text{HI}} \sim 0.17 \), although a fully ionized universe is consistent at 1σ. This interval, however, returns the largest uncertainties on the IGM neutral fraction. This is purely driven by the breadth in allowed QSO fluxes from the reconstructed Lyα profiles, due to the fact that this region is furthest from the edge of the applied prior in the reconstruction process (1230 Å).

In contrast, the 1222–1227 Å region of ULASJ1120 is particularly difficult to fit without requiring higher IGM neutral fractions. This behaviour is quantified by the two adjacent 3 Å intervals, 1221–1224 Å and 1224–1227 Å. Here, larger IGM neutral fractions of \( \bar{x}_{\text{HI}} = 0.44 \) and 0.47 are preferred.

Finally, we note that all of the sub-regions are consistent with one another at 1σ. Thus there is no obviously spurious spectral feature biasing our fiducial results in one direction or another.

**Table C1.** Tabulated values of the recovered IGM neutral fraction at \( z = 7.1 \) for the \( \text{Small H} \ II \) simulations when considering four smaller, equally spaced 3 Å regions within our fiducial fitting range of 1218–1230 Å.

| Fitting region (Small H \( II \)) | \( \bar{x}_{\text{HI}}(1\sigma) \) | \( \bar{x}_{\text{HI}}(2\sigma) \) |
|----------------------------------|---------------------------------|---------------------------------|
| 1218–1230 Å (fiducial)          | 0.40±0.23                      | 0.40±0.41                      |
| 1218–1221 Å                     | 0.17 (≤ 0.44)                  | 0.17 (≤ 0.82)                  |
| 1221–1224 Å                     | 0.44±0.27                      | 0.44±0.50                      |
| 1224–1227 Å                     | 0.47±0.23                      | 0.47±0.42                      |
| 1227–1230 Å                     | 0.28±0.19                      | 0.28 (≤ 0.70)                  |

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