Spectroscopic properties of luminous Lyman-α emitters at $z \approx 6 - 7$ and comparison to the Lyman-break population

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ABSTRACT
We present spectroscopic follow-up of candidate luminous Lyα emitters (LAEs) at $z = 5.7 - 6.6$ in the SA22 field with VLT/X-SHOOTER. We confirm two new luminous LAEs at $z = 5.676$ (SR6) and $z = 5.632$ (VR7), and also present $HST$ follow-up of both sources. These sources have luminosities $L_{\text{Ly} \alpha} \approx 3 \times 10^{41}$ erg s$^{-1}$, very high rest-frame equivalent widths of $\text{EW}_0 \gtrsim 200$ Å and narrow Lyα lines (200-340 km s$^{-1}$). VR7 is the most UV-luminous LAE at $z > 6.5$, with $M_{1500} = -22.5$, even brighter in the UV than CR7. Besides Lyα, we do not detect any other rest-frame UV lines in the spectra of SR6 and VR7, and argue that rest-frame UV lines are easier to observe in bright galaxies with low Lyα equivalent widths. We confirm that Lyα line-widths increase with Lyα luminosity at $z = 5.7$, while there are indications that Lyα lines of faint LAEs become broader at $z = 6.6$, potentially due to reionisation. We find a large spread of up to 3 dex in UV luminosity for $> L^*$ LAEs, but find that the Lyα luminosity of the brightest LAEs is strongly related to UV luminosity at $z = 6.6$. Under basic assumptions, we find that several LAEs at $z \approx 6 - 7$ have Lyα escape fractions $\gtrsim 100 \%$, indicating bursty star-formation histories, alternative Lyα production mechanisms, or dust attenuating Lyα emission differently than UV emission. Finally, we present a method to compute $\xi_{\text{ion}}$, the production efficiency of ionising photons, and find that LAEs at $z \approx 6 - 7$ have high values of $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \approx 25.51 \pm 0.09$ that may alleviate the need for high Lyman-Continuum escape fractions required for reionisation.

Key words: galaxies: high-redshift – cosmology: observations – galaxies: evolution – cosmology: dark ages, reionisation, first stars

1 INTRODUCTION
Observations of galaxies in the early Universe help to constrain the properties of the first stellar populations and black holes and to understand the reionisation process and sources responsible for that. However, because of their high redshift, these galaxies are very faint and their rest-frame spectral features (i.e. UV lines) shift to near-infrared wavelengths. This makes spectroscopic observations challenging and currently limited to the brightest sources. Therefore, it has only been possible to study a few galaxies in detail (e.g. Ouchi et al. 2013; Sobral et al. 2015; Stark et al. 2015a,b; Zabl et al. 2015). Most of these galaxies are strong Lyman-α (Lyα, $\lambda_{\text{vac}} = 1215.7$ Å) emitters (LAEs). This is partly by selection, as LAEs can easily be identified with wide-field narrow-band surveys (e.g. Konno et al. 2014; Matthee et al. 2015) and are easier to follow-up spectroscopically, but also because the fraction of UV-bright galaxies with strong Lyα emission increases with redshift (e.g. Curtis-Lake et al. 2012; Stark et al. 2017), such that a large fraction of Lyman-break galaxies at $z \approx 5 - 6$ (after reionisation) are typically also classed as LAEs (e.g. Pentericci et al. 2011; Stark et al. 2011; Cassata et al. 2015), see e.g. Dayal & Ferrara (2012) for a theoretical perspective.
Lyα photons undergo resonant scattering by neutral hydrogen resulting in significant uncertainties when using Lyα luminosities to study intrinsic properties of galaxies (e.g. Hayes 2015). The fraction of observed Lyα photons depends on the spatial distribution of neutral hydrogen and the characteristics of the emitter (e.g. Matthee et al. 2016; Sobral et al. 2017). Hence, high resolution measurements of the Lyα line-profile and measurements of the extent of Lyα can provide information on the properties of both the inter-stellar medium (ISM) and the circum-galactic medium (CGM) (e.g. Møller & Warren 1998; Steidel et al. 2011; Verhamme et al. 2015; Arrigoni Battaia et al. 2016; Gronke & Dijkstra 2016). Furthermore, the prevalence of Lyα emitters and the Lyα equivalent width (EW) distribution can be used to study the neutral fraction of the inter-galactic medium (IGM) in the epoch of reionisation (e.g. Dijkstra 2014; Hutter et al. 2016), the neutral fraction of the inter-galactic medium (IGM) in the epoch of reionisation (e.g. Dijkstra 2014; Hutter et al. 2016), the neutral fraction of the inter-galactic medium (IGM) in the epoch of reionisation (e.g. Dijkstra 2014; Hutter et al. 2016). Several observations of LAEs indicate an increasingly neutral fraction at $z > 6.5$: at fixed UV luminosity, the fraction of typical Lyman-break galaxies with strong Lyα emission (observed in a slit) is observed to decrease with redshift (e.g. Pentericci et al. 2014; Tili et al. 2014): the observed number density of LAEs decreases at $z > 6$ (e.g. Konno et al. 2014; Matthee et al. 2015; Zheng et al. 2017) and at fixed central Lyα luminosity, there is more extended Lyα emission around faint LAEs at $z = 6.0$ than at $z = 5.7$ (Momose et al. 2014; Santos et al. 2016). These observations all indicate that a relatively larger fraction of Lyα photons are scattered out of the line of sight at $z > 6.5$ than at $z < 6.5$. Hence, the galaxies that are still observed with high Lyα luminosities at $z > 7$ (e.g. Oesch et al. 2015; Zitrin et al. 2015; Schmidt et al. 2016) are likely the signposts of early ionised bubbles (e.g. Stark et al. 2017).

Matthee et al. (2015) performed a survey of LAEs at $z = 6.6$, increasing the available number of bright LAEs that allowed detailed study. Two LAEs in this sample (‘CR7’ and ‘MASOSA’) have been spectroscopically confirmed in Sobral et al. (2015). Several more recent wide-area surveys at $z = 6.6$ and $z = 6.9$ are now also identifying LAEs with similar luminosities (e.g. Hu et al. 2016; Shibuya et al. 2017; Zheng et al. 2017). CR7 and ‘Himiko’ (Ouchi et al. 2009) have been the subject of detailed spectroscopic studies (e.g. Ouchi et al. 2013; Sobral et al. 2015; Zabl et al. 2015; Bowler et al. 2017b), which indicate that their ISM is likely metal poor and in high ionisation state. Such ISM conditions are similar to those in LAEs at $z \sim 2 - 3$ (e.g. Song et al. 2014; Trainor et al. 2015; Hashimoto et al. 2017; Nakajima et al. 2016; Trainor et al. 2016), although we note that the Lyα luminosities of the latter samples are typically an order of magnitude fainter. In order to obtain a comparable sample to those at $z \sim 7$, Santos et al. (2016) undertook a comparable survey at $z = 5.7$, just after the end of reionisation. A major limitation is that the nature of the most luminous LAEs is currently unknown. Are they powered by active galactic nuclei (AGN) or star formation? What are their metallicities?

In this paper, we present follow-up observations of candidate luminous LAEs at $z = 5.7$ and $z = 6.6$ using VLT/X-SHOOTER, which is a high resolution spectrograph with a wavelength coverage of $\lambda = 0.3 - 2.5 \mu m$. We assess the interloper and success fractions and use these to update the number densities of the most luminous LAEs. We present the properties of the Lyα lines, UV continua of newly confirmed luminous LAEs, and constrain rest-frame UV nebular lines. Together with a compilation of spectroscopically confirmed LAEs and Lyman-break galaxies (LBGs) from the literature, we study the evolution of Lyα line-widths between $z = 5.7 - 6.6$ and the relation between Lyα luminosity and UV luminosity. Finally, we explore the ionising properties (such as the production efficiency of ionising photons) using an empirical relation to estimate the Lyα escape fraction (e.g. Sobral et al. 2017).

The initial sample of luminous LAEs at $z = 5.7$ and $z = 6.6$, the observations and data reduction are presented in §2. We present the results in §3, which include updated number densities. In §4 we present the properties of newly confirmed LAEs. The properties of the sources are discussed and compared to the more general galaxy population at $z \approx 6 - 7$ in §5. This section includes a comparison of their Lyα line-widths ($\S 5.1$), the UV line-ratios to Lyα ($\S 5.2$) and their UV luminosity ($\S 5.3$). We discuss their production efficiency of ionising photons in $\S 5.3.1$. Finally, we summarise our conclusions in §6. Throughout the paper we use a flat $\Lambda$CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 SAMPLE & OBSERVATIONS

2.1 Sample

The target sample includes candidate luminous LAEs selected through NB816 and NB921 narrow-band imaging with Subaru/Suprime-Cam in the SA22 field over co-moving volumes of $6.3 \times 10^6$ Mpc$^3$ and $4.3 \times 10^6$ Mpc$^3$ at $z = 5.7$ and $z = 6.6$ as described in Santos et al. (2016) and Matthee et al. (2015), respectively.$^1$ The data in the SA22 field is very wide-field, yet shallow and single-epoch, and is aimed at identifying the brightest LAEs. Even though the expected number of contaminants and transients is significant, these sources are bright enough to be confirmed (or refuted) in relatively small amounts of telescope time.

The initial potential target samples included 6 objects at $z = 5.7$ and 21 at $z = 6.6$. Before choosing the final targets to follow-up spectroscopically, we investigated the individual exposures, instead of only inspecting the final reduced NB image. Nine sources from the NB921 sample were moving solar-system objects whose position changed by $\sim 0.2 - 0.5''$ between individual exposures. The stacked image of these sources then resulted in a slightly extended object. Such extended objects in the NB image resemble confirmed LAEs at $z = 6.6$ (e.g. Himiko and CR7), leading to their misidentification as candidates. We note that point-like sources may however still be other types of transients/variables. Six other sources from the NB921 sample have been identified as a detector artefact in a single exposure, which coincides with positive noise peaks in the other exposure. Due to PSF-homogenisation these artefacts were

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$^1$ This sample already included the confirmed LAEs Himiko (Ouchi et al. 2013), MASOSA and CR7 (Sobral et al. 2015). It furthermore includes 14 other spectroscopically confirmed LAEs at $z = 6.6$ from Ouchi et al. (2010) and 46 spectroscopic confirmed LAEs at $z = 5.7$ from Ouchi et al. (2008), Hu et al. (2010) and Mallery et al. (2012).
then not identified in our visual inspections of the final stack. These checks were also performed for the NB816 candidates, and were excluded already before the final analysis of Santos et al. (2016). These issues do not influence the search for LAE candidates in the fields with deeper coverage (COSMOS and UDS), as those fields have been observed with many more individual exposures. The final selection results in a sample of 6 LAE candidates at $z = 5.7$ and 6 at $z = 6.6$, all in the SA22 field, see Table 1.

### 2.2 Observations

We observed the candidate LAEs with the X-SHOOTER echelle spectrograph, mounted on UT2 of the VLT (Vernet et al. 2011). X-SHOOTER simultaneously takes a high resolution spectrum with a UVB, VIS and a NIR arm, providing a wavelength coverage from 300 nm to 2480 nm. Observations were done under clear skies with a seeing ranging from 0.7–0.9″, using 0.9″ slits in the NIR and VIS arm and a slow read-out speed without binning. This leads to a spectral resolution of 1.2 Å ($R \approx 7400$) and 3.6 Å ($R \approx 4000$) in the VIS and NIR arm, respectively. We first acquired a star (with $I$-band magnitudes 16-17 AB) and applied a blind offset to the target. In order to improve the NIR sky subtraction, we use the standard AutoNodOnSlit procedure, which nods between two positions A and B along the slit, offset by 3.5″. This is repeated two times in an ABBA pattern. At each position, we take a 730 s exposure in the VIS arm and four 195 s exposures in the NIR arm. This results in a total exposure time of 2.92 ks in VIS and 3.12 ks in NIR in a single observing block. Several sources have been observed in two or three observing blocks, doubling or tripling the total exposure time, see Table 1.

### 2.3 Data reduction

Data have been reduced with the recipes from the standard X-SHOOTER pipeline (Modigliani et al. 2010), which includes corrections for the bins from read-out noise (VIS arm) and dark current (NIR arm), sky subtraction and wavelength calibration. Since wavelength calibration is done in air, we convert the wavelengths to vacuum wavelengths following Morton (1991). The standard stars GD71, GD153, EG274 and Feige110 have been observed with a 5″ slit for flux calibration. We use the X-SHOOTER pipeline to combine the exposures from single observing blocks. In the case that a source has been observed with multiple observing blocks, we co-add the frames by weighting the sky background and by correcting for slight positional variations based on the position of the peak of observed Lyα lines.

### 2.4 Extraction

We extract 1D spectra in the VIS (NIR) arm by summing the counts in 10 (8) spatial pixels, corresponding to 1.6 (1.68)″, along the wavelength direction. These extraction boxes optimise the S/N in confirmed emission-line galaxies in our data-set. Slit losses are estimated by convolving the NB image to the PSF of spectroscopic observations and measuring the fraction of the flux that is retrieved within the slit compared to the flux measured with MAG-AUTO. Typical slit losses are $\approx 50–60 \%$. We measure the effective spectral resolution at $\sim 0.9 \mu m$ and $\sim 1.6 \mu m$ by measuring the FWHM of well separated, isolated skylines and find $R = 7500$ and $R = 4400$, respectively. We note that due to this high resolution, instrumental line-broadening of the emission-lines from the sources discussed in this paper are negligible.

The line-flux sensitivity is measured as a function of line-width as follows. First, we select the sub-range of wave-lengths in the collapsed 1D spectra that are within 30 nm from the targeted wavelength. Then, we measure the flux in 5000 randomly placed positions in this sub-range, with

| ID               | R.A. J2000 | Dec. J2000 | $L_{\text{Ly}\alpha, \text{NB}}$ $10^{43}$ erg s$^{-1}$ | Dates 2016 | $t_{\text{exp, VIS}}$ ks | $t_{\text{exp, NIR}}$ ks | Telluric Class | Class |
|------------------|------------|------------|-----------------------------------------------|-------------|---------------------|---------------------|----------------|-------|
| SA22-NB816-9442 | 22:18:00.68 | +01:04:30.53 | 8.4 5 Aug | 2.92 | 3.12 | GD153 | 2 |
| SA22-NB816-366911| 22:13:00.92 | +00:36:24.17 | 4.1 7 and 31 Aug | 5.84 | 6.24 | GD153, EG274 | 3 |
| SA22-NB816-360178| 22:12:54.85 | +00:32:54.76 | 3.8 3 Sep | 2.92 | 3.12 | GD71 | 4 |
| SA22-NB816-390412| 22:15:01.22 | +00:46:24.25 | 3.7 28 Aug | 5.84 | 6.24 | Feige110 | 3 |
| SR6              | 22:19:49.76 | +00:48:23.90 | 3.4 2 Sep | 5.84 | 6.24 | GD71 | 1 |
| VR7              | 22:21:09.92 | +00:47:19.52 | 3.3 3 Sep | 2.92 | 3.12 | GD71 | 3 |
| SA22-NB921-D10845| 22:18:54.82 | +00:06:24.26 | 1.2 14 Jul, 2, 3 Aug | 8.76 | 9.36 | GD153 | 3 |
| SA22-NB921-W210761| 22:14:38.63 | +00:56:02.98 | 4.1 2 Aug | 2.92 | 3.12 | EG274 | 3 |
| SA22-NB921-W219795| 22:15:29.18 | +00:29:17.90 | 3.8 3 Aug | 2.92 | 3.12 | EG274 | 3 |
| SA22-NB921-W6153 | 22:20:20.79 | +00:17:27.96 | 11.0 2 Aug | 2.92 | 3.12 | EG274 | 3 |
| SA22-NB921-W209855| 22:16:05.05 | +00:51:59.23 | 3.8 3 Aug | 2.92 | 3.12 | EG274 | 3 |
kernels corresponding to the targeted wavelength. We then calculate the noise as the r.m.s. of the 5000 measured fluxes. Note that, in the presence of skylines, this depth is a conservative estimate as it includes flux from skyline residuals, which could increase the noise by a factor $\approx 2.3$ depending on the specific wavelength.

3 RESULTS

3.1 NB816 targets - candidate LAEs at $z = 5.7$

Out of the six brightest candidate LAEs at $z = 5.7$ that we observed with X-SHOOTER, one is reliably confirmed as a Lyman-α emitter, one is identified as [OIII] interloper, one is identified as brown dwarf star interloper and three are not detected, indicating that their NB detection was likely due to a transient or variable source, see Table 1 for a summary.

SA22-NB816-9442 is identified as an [OIII] emitter at $z = 0.638$. The flux observed in NB816 can be attributed to both the 4959 and 5007 Å lines. We measure a combined line-flux of $0.8 \pm 0.1 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ and observed EW $> 393$ Å. We do not detect an emission-line or continuum in the expected wavelength range or anywhere else in the spectrum of SA22-NB816-360178 and SA22-NB816-390412. This may indicate that these sources are variable/transients, as they are also not detected in any of the broad-band images. Matthee et al. (2015) confirmed two of such transients in 0.9 deg$^2$ of similar NB data. Hence, it is not unlikely that our selection picked up three transients in the 3.6 deg$^2$ coverage (see also Hibon et al. 2010).

Although we do not detect a clear emission line in the NB816 wavelength coverage in SA22-NB816-508969 and SA22-NB816-360178, we detect a faint trace of continuum in the center of the slits. For SA22-NB816-508969 this continuum is detected at low significance, making it challenging to classify the object. The continuum features, such as the peak-wavelength, of SA22-NB816-360178 resemble those of a star with an effective temperature of $T \approx 3500 – 3700$ K, or a K or M-type star (Kurucz 1992). This interpretation is also strengthened by the point-like morphology in the available imaging.

The X-SHOOTER spectrum reliably confirms SR6$^2$ as a Lyman-α emitter at $z = 5.676 \pm 0.001$ (using the peak of Lyo), due to the asymmetric line-profile (see Fig. 1) and non-detection of flux blue-wards of the line. After correcting the VIS spectrum for slit losses of 56 % (estimated from NB imaging), we measure a line-flux of $7.6 \pm 0.4 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, consistent within the errors with the NB estimate of $9.2 \pm 1.2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$. We also identify faint [OII] emission from a foreground source at $z = 1.322$ offset by 2.4′′ in the slit. We discuss the detailed properties of SR6 in §4.1.

3.2 NB921 targets - candidate LAEs at $z = 6.6$

Out of the six luminous LAE candidates at $z = 6.6$ in the SA22 field, we confirm one as a LAE, while we firmly rule out the others at the expected line-fluxes from the NB921 imaging.

Based on its asymmetric line-profile, the source VR7$^3$ is confirmed reliably as a LAE at $z = 6.532 \pm 0.001$ (corresponding to the wavelength of peak Lyo emission, see Fig. 1). After correcting for an estimated 54 % of slit losses, we measure a line-flux of $4.9 \pm 0.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, which

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$^2$ SA22 Redshift 6, the brightest LAE at $z = 5.7$ in the SA22 field.
$^3$ Named after Vera Rubin, and chosen to resemble the name of LAE COSMOS Redshift 7 (CR7, Matthee et al. 2015), as it was the fifth (V) luminous LAE confirmed at $z \approx 6.6$ by the time of discovery.
3.3 Updated number densities of the most luminous LAEs at \(z \approx 6 - 7\)

Based on the spectroscopic follow-up, we provide a robust update on the number densities of luminous LAEs at \(z = 5.7 - 6.6\) and compare those with Santos et al. (2016). At \(z = 5.7\), the number density of LAEs with \(L_{\text{Ly}\alpha} = 10^{43.6 \pm 0.1}\) erg s\(^{-1}\) is \(10^{-5.26 \pm 0.17}\) Mpc\(^{-3}\), which is \(\approx 0.25\) dex lower than in Santos et al. (2016). At \(z = 6.6\), we find that the number density at \(L_{\text{Ly}\alpha} = 10^{43.4 \pm 0.1}\) erg s\(^{-1}\) is \(10^{-4.89 \pm 0.22}\) Mpc\(^{-3}\) and \(10^{-5.35 \pm 0.49}\) Mpc\(^{-3}\) at \(L_{\text{Ly}\alpha} = 10^{43.6 \pm 0.1}\) erg s\(^{-1}\). We note that all these number densities are consistent with the previous measurements within 1\(\sigma\) errors. The results here support little to no evolution in the bright-end of the Ly\(\alpha\) luminosity function between \(z = 5.7 - 6.6\), and even little to no evolution at \(L_{\text{Ly}\alpha} \approx 10^{43.6}\) erg s\(^{-1}\) up to \(z = 6.9\) (Zheng et al. 2017). After rejecting all candidate LAEs with a luminosity similar to CR7 (for which we measure a total luminosity of \(8.5 \times 10^{43}\) erg s\(^{-1}\) after correcting for the transmission curve of the NB921 filter), we constrain the number density of CR7-like sources to one per \(\geq 5 \times 10^6\) Mpc\(^3\). Catalogues of LAEs at \(z = 5.7\) and \(z = 6.6\) will be publicly available with the published version of this paper, see Appendix B.

4 PROPERTIES OF NEWLY CONFIRMED LAES

4.1 SR6

SR6 is robustly confirmed to be a luminous Ly\(\alpha\) emitter at \(z = 5.676 \pm 0.001\) (Fig. 1). We measure a Ly\(\alpha\) line-width of \(\sigma_{\text{FWHM}} = 236 \pm 16\) km s\(^{-1}\) and Ly\(\alpha\) luminosity of \(2.7 \pm 0.2 \times 10^{43}\) erg s\(^{-1}\). We do not detect continuum in the X-SHOOTER spectrum (with a 1\(\sigma\) depth of \(3.0 \times 10^{-19}\) erg cm\(^{-2}\) A\(^{-1}\), smoothed per resolution element), such that we can only provide a lower limit on the EW, which is EW\(\alpha\) \(\geq 250\) A. Based on Kashikawa et al. (2006), we quantify the line-asymmetry with the S-statistic and weighted skewness agrees well with the NB estimate of \(4.8 \pm 1.2 \times 10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\). We present detailed properties of this source in §4.2.

We do not detect an emission-line or a continuum feature in the VIS spectra of SA22-NB921-D10845, SA22-NB921-W210761, SA22-NB921-W219795, SA22-NB921-W6153 or SA22-NB921-W209855, see Table 1 for a summary. We measure the sensitivity of the spectra as a function of redshift and velocity width of the line. For a line-width of 200 km s\(^{-1}\), the 1\(\sigma\) limiting flux for wavelengths within the NB921 filter is \(\approx 4.5(3.2) \times 10^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) for sources observed with 1 (2) observing blocks (see Table 1). The sensitivity decreases by a factor \(\approx 3\) for a line-width of 600 km s\(^{-1}\). However, even with such broad lines, the expected line-fluxes estimated from NB imaging would have been detected at the \(\geq 3\sigma\) level. This means that these sources are likely transients (note that Matthee et al. 2015 estimated that \(\sim 6\) transients were likely to be found within their sample), and that we can confidently rule out these six sources as Ly\(\alpha\) emitters at \(z = 6.6\). Therefore our results agree very well with the estimates from Matthee et al. (2015) on the fraction of transient interlopers.

Figure 2. Rest-frame UV image of SR6 from follow-up with HST (see §4.1.1). Green contours (at 3, 4 and 5\(\sigma\) level) highlight the spatial scales at which we detect Ly\(\alpha\) emission in the NB816 filter. The background image is the F140W image, which traces rest-frame wavelengths of \(\approx 2000\) Å. We note that the PSF of the NB816 imaging is significantly larger than the F098M imaging. SR6 is clearly detected in HST imaging, resulting in a (magnification corrected) UV luminosity of \(M_{1500} = \approx -21.1 \pm 0.1\) based on the F098M magnitude. HST imaging also reveals a foreground source at \(\approx 1\) that can be identified in the ground-based optical imaging, which could slightly contribute to the flux measured in NB816, explaining why the flux inferred from the NB is slightly higher than the flux inferred from spectroscopy. The foreground [O\(\text{II}\)] emitter identified in the slit at \(z = 1.322 \pm 0.001\), spatially offset by 2.4\(\prime\), is slightly magnifying SR6. We follow McLure et al. (2006) to compute the magnification from galaxy-galaxy lensing as follows:

\[
\mu = \frac{d_{\text{proj}}}{d_{\text{proj}} - \theta_E},
\]

where \(\mu\) is the magnification, \(d_{\text{proj}}\) is the projected separation in arcsec and \(\theta_E\) the Einstein radius in arcsec. Under the assumption of a Singular Isothermal Sphere, we compute \(\theta_E\) as follows (e.g. Furt & Mellier 1994):

\[
\theta_E = 30\arcsec(\frac{\sigma_{\text{1D}}}{1000\text{km}\text{s}^{-1}})^2 \frac{D_{ds}}{D_s},
\]

where \(\sigma_{\text{1D}}\) is the one-dimensional velocity dispersion of the foreground source, \(D_{ds}\) is the angular diameter distance from foreground source to the background source and \(D_s\) the angular diameter distance from observer to the background source. Using the measured \(\sigma_{\text{1D}} = 130 \pm 20\) km s\(^{-1}\), we estimate \(\theta_E = 0.24\arcsec\), resulting in a small magnification of \(\mu = 1.1\). We note that additional magnification by other foreground-sources is possible (for example by a faint source separated by \(\sim 1\)\(\arcsec\), see Fig. 2), although these sources are
likely lower mass due to their faintness, resulting in a further negligible magnification. This results in a magnification corrected Lyα luminosity of $2.5 \pm 0.3 \times 10^{43}$ erg s$^{-1}$.

After confirming Lyα, we investigate the optical and near-infrared spectra for the presence of other emission-lines in the rest-frame UV. In particular, we search for NV, CIV, HeII, OIII] and CII], and check for any other significantly detected potential line – but we do not detect any above $3\sigma$ significance. We measure limiting line-fluxes at the positions of the expected lines for a range of line-widths. For a line-width of $\sim 100 - 250$ km s$^{-1}$ and typical velocity offset with respect to Lyα of $\sim 200$ km s$^{-1}$, we find a $2\sigma$ limit of $2.0 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for NV after correcting for the same slit losses as Lyα (corresponding to EW$_0 < 48$ Å).

For the other lines (observed in the NIR slit), we estimate slit losses of 50%. This assumes that these lines are emitted over the same spatial scales as Lyα. Because sources are un-detected in the NIR continuum, we cannot estimate slit losses from the continuum emission itself. As Lyα is likely emitted over a larger spatial scale (e.g. Wisotzki et al. 2016), slit losses for the other rest-UV lines may be over-estimated (except potentially for CIV which is also a resonant line). Our upper limits are on the conservative side if this is indeed the case. For similar widths and offsets as NV, we measure $2\sigma$ limiting line-fluxes of $(7.3, 3.6, 3.5, 3.9) \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for (CIV, HeII, OIII], CII]), corresponding to EW$_0 < (174, 86, 84, 93)$ Å, respectively. These limits are not particularly strong because all lines are either observed around strong sky OH lines or at low atmospheric transmission, but also due to our modest exposure time and conservative way of measuring noise.

### 4.1.1 HST follow-up

We observed SR6 with our ongoing HST/WFC3 follow-up program (PI Sobral, program 14699), and is detected in the F098M and F140W filter, see e.g. Fig. 2, with a total integration time of 4076 s and 3176 s. The source is marginally resolved, consists of a single component that is separated by $\sim 0.2''$ from the peak Lyα flux. We measure magnitudes of F098M=$25.68 \pm 0.13$ and F140W=$25.60 \pm 0.10$ in a 0.4'' aperture. Correcting for magnification, this results in $M_{1500} = -21.1 \pm 0.1$, which corresponds to a dust-uncorrected SFR $\approx 10$ M$_\odot$ yr$^{-1}$ and is thus a $M_{UV}$ source at that redshift (Bouwens et al. 2015). Following the calibration from Schaerer et al. (2015), we estimate a stellar mass of $M_{star} \approx 4 \times 10^9$ M$_\odot$. The galaxy has a moderately blue UV slope, $\beta = -1.78 \pm 0.45$. In both HST filters, we measure a size of $r_{1/2} = 0.8 \pm 0.2$ kpc using SEXtractor (corrected for PSF broadening following e.g. Curtis-Lake et al. 2016; Ribeiro et al. 2016). We use the HST photometry to estimate the continuum around Lyα and measure $L_{Ly\alpha}$ EW$_0 = 802 \pm 155$ Å. While the SFR, size and UV slope are typical, and not very different from UV selected galaxies at $z \approx 6 - 7$ (e.g. Bowler et al. 2017a), the extremely high Lyα EW is challenging to explain with simple stellar populations (e.g. Charlot & Fall 1993), indicating an elevated production rate of ionising photons. Such high EWs are also found in numerous other Lyα surveys (e.g. Malhotra & Rhoads 2002; Hashimoto et al. 2017), although we note that those sources are typically of fainter luminosity. High EWs may be explained by extremely low metallicity stellar populations with young ages (e.g. Schaerer 2003). Other explanations include AGN activity and contributions from cooling radiation (Rosdahl & Blaizot 2012) and shocks (Taniguchi et al. 2015). However, these processes typically result in more extended Lyα emission, which is not observed with the current observational limits. Lyα EW may also be boosted in a clumpy ISM (e.g. Duval et al. 2014; Gronke & Dijkstra 2014), but we note that measurements of the UV slope indicate little dust.

#### 4.2 VR7

The source VR7 is a Lyα emitter at $z = 6.532 \pm 0.001$, see Fig. 1, with a Lyα luminosity of $2.4 \pm 0.2 \times 10^{43}$ erg s$^{-1}$. We do not detect continuum, allowing us to place a lower limit on the equivalent width of EW$_0 > 196$ Å. The Lyα line-width is $\nu_{FWHM} = 340 \pm 14$ km s$^{-1}$, the S-statistic is 0.33 ± 0.04, resulting in a Skewness of $6.9 \pm 0.8$ Å. This skewness is similar to those measured in fainter LAEs at $z = 6.5$ by Kashikawa et al. (2011).

We do not detect any emission-line besides Lyα in the optical or near-infrared spectrum, and place the following $2\sigma$ limits (assuming line-widths of $\sim 200$ km s$^{-1}$, narrower than Lyα, but similar to other studies): (1.0, 2.3, 2.3, 2.2,
Luminous LAEs at $z \approx 6 - 7$

In order to investigate the nature of luminous LAEs at $z = 5.7 - 6.6$ using their Lyα line-profile, we compare the measurements with a reference sample of luminous LAEs at $z \approx 2 - 3$ (Sobral et al. in prep). These comparison sources have been selected with wide-area narrow-band surveys (e.g. Sobral et al. 2017; Matthee et al. 2017a), and we match the minimum EW criterion to $>20$ Å. Even when we exclude broad-line AGN from the $z \approx 2 - 3$ sample, we find that luminous LAEs at $z = 5.7 - 6.6$ have Lyα line-widths (typically $290 \pm 20$ km s$^{-1}$) that are a factor 2-3 narrower than those at $z \approx 2 - 3$. These sources at lower redshift are a mix of narrow-line AGN and star-forming galaxies. This indicates that, besides non-detections of AGN associated lines as $\text{Civ}$ or $\text{Mgii}$, the Lyα lines do not clearly indicate AGN activity in luminous LAEs at $z = 5.7 - 6.6$.

Due to resonant scattering, the presence of neutral hydrogen broadens Lyα emission lines (e.g. Kashikawa et al. 2006; Dijkstra et al. 2014). Theoretically, Haiman & Cen (2005) show that the observed Lyα line FWHM increase mostly at faint luminosities, $L_{\text{Ly}\alpha} \approx 10^{42}$ erg s$^{-1}$, with a more prominent evolution with higher neutral fraction and narrower intrinsic line-width. Therefore, evolution in the observed Lyα profiles at $z \geq 6$ may provide hints on how reionisation happened. We investigate whether we find evidence for increasingly broad Lyα profiles as a function of redshift, by controlling for differences in Lyα luminosities.

In Fig. 4 we show the dependence of Lyα line-width on Lyα luminosity for samples at $z = 5.7$ and $z = 6.6$. We include samples from Hu et al. (2010), Ouchi et al. (2010), Kashikawa et al. (2011) and Shibuya et al. (2017) and the compilation of Lyα selected sources from Table 3, which includes the two sources confirmed in this paper. This compilation also includes the luminous LAEs at $z = 5.7$ discovered by Westra et al. (2006), studied in detail in Lidman et al.

### Table 2

| Measurement                  | SR6       | VR7       |
|------------------------------|-----------|-----------|
| $\lambda_{\text{spec.Ly}\alpha}$ | 5.676 ± 0.001 | 6.532 ± 0.001 |
| $f_{\text{Ly}\alpha}/10^{43}$ erg s$^{-1}$ | 2.5 ± 0.3  | 2.4 ± 0.2  |
| EW$_{\text{Ly}\alpha}$/Å | > 250 Å  | > 196 Å   |
| EW$_{\lambda=1215}$/Å | 802 ± 155 Å | 207 ± 10 Å |
| $\text{vFWHM}_{\text{Ly}\alpha}$/km s$^{-1}$ | 236 ± 16  | 340 ± 14   |
| Skewness/Å | 9.7 ± 0.8  | 6.9 ± 0.8  |
| M$_{1500}$/M$_\odot$ | -21.1 ± 0.1 | -22.5 ± 0.1 |
| SFR$_{UV}$/M$_\odot$ yr$^{-1}$ | 10         | 38         |
| $\text{M}_{\text{star}}$/M$_\odot$ | $4 \times 10^{9}$ | $1.7 \times 10^{10}$ |
| $\text{log}$(f$_{\text{Ly}\alpha}$/Hz erg$^{-1}$) | ≥ 25.25 ± 0.23 | ≥ 24.66 ± 0.17 |
| $\beta$ | -1.78 ± 0.45 | -1.97 ± 0.31 |
| $r_{1/2}$/kpc | 0.9 ± 0.1  | 1.7 ± 0.1  |
| $f_{\text{NV}}$ (EW$_{\lambda=1215}$) | < 2.0 (< 48) | < 1.0 (< 9) |
| $f_{\text{CIV}}$ (EW$_{\lambda=1548}$) | < 7.3 (< 174)  | < 2.3 (< 21) |
| $f_{\text{HeII}}$ (EW$_{\lambda=1640}$) | < 3.6 (< 86) | < 2.3 (< 21) |
| $f_{\text{OIII]}$ (EW$_{\lambda=1667}$) | < 3.5 (< 84) | < 2.2 (< 20) |
| $f_{\text{CII]}$ (EW$_{\lambda=1334}$) | < 3.9 (< 93) | < 2.1 (< 19) |

2.1) $\times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for (NV, CIV, Heii, OIII][, CIII][), see Table 2. These error estimates are also measured including sky OH lines, and even though the lines themselves may avoid skylines, and are thus conservative. Assuming a continuum level of 1.3 $\times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, these flux limits translate into EW$_{0}$ limits of $< (9, 21, 21, 20, 19, 19, 19)$ Å, respectively.

#### 4.2.1 HST follow-up

VR7 is detected at $3\sigma$ significance in the UKIDSS DXS J band imaging ($J = 24.2$), resulting in an absolute UV magnitude of M$_{1500} = -22.5 \pm 0.2$. This luminosity places the source in the transition region between luminous galaxies and faint AGN (e.g. Willott et al. 2009; Matsunaka et al. 2016) and is $\approx 0.3$ dex brighter than CR7 (e.g. Sobral et al. 2015). We also obtained HST/WFC3 imaging in the F110W and F160W filters (PI Sobral, program 14690), with integration times of 2612 s and 5223 s. These observations reveal a relatively large elongated galaxy ($r_{1/2} = 1.7 \pm 0.1$ kpc, elongation of 1.4), with F110W=24.33 ± 0.09 and F160W=24.32 ± 0.10 in a 0.6′ aperture, see Fig. 3. We constrain the UV slope to $\beta = -1.97 \pm 0.31$. The UV luminosity corresponds to a SFR of 38 M$_\odot$ yr$^{-1}$, under the assumptions that the UV luminosity originates from star-formation (as noted above, we do not detect any signs of AGN activity such as CIV or Mgii emission at the current detection limits), a Chabrier IMF and that dust attenuation is negligible. Based on the calibration from Schaerer et al. (2015), the stellar mass is $M_{\text{star}} \approx 1.7 \times 10^{10}$ M$_\odot$. Similar to SR6, we constrain the Lyα EW using HST photometry, and find EW$_{0} = 207 \pm 10$ Å, which is higher than the typically assumed maximum EW possible due to star-formation (e.g. Charlot & Fall 1993), and indicates strongly ionising properties. Because of these properties, VR7 is an ideal target for further detailed follow-up observations.

### Table 3

| ID     | Redshift | vFWHM$_{\text{Ly}\alpha}$/km s$^{-1}$ | Luminous LAEs at $z \approx 6 - 7$ |
|--------|----------|-------------------------------------|----------------------------------|
| SGP 8884 | 5.65     | 250 ± 30                            |                                  |
| SR6    | 5.67     | 236 ± 16                            |                                  |
| Ding-1 | 5.70     | 340 ± 100                           |                                  |
| S11 5236 | 5.72     | 300 ± 30                            |                                  |
| VR7    | 6.53     | 340 ± 14                            |                                  |
| MASOSA | 6.54     | 386 ± 30                            |                                  |
| Himiko | 6.59     | 251 ± 21                            |                                  |
| COLA1  | 6.59     | 194 ± 42                            |                                  |
| CR7    | 6.60     | 266 ± 15                            |                                  |
results indicate that line-widths at $z = 5.7$ increase slightly with increasing Ly$\alpha$ luminosity (at $\approx 3\sigma$ significance, see also Hu et al. 2010), while this is not necessarily the case at $z = 6.6$. In order to estimate the error on the bins as conservatively as possible, we combine the formal error ($\sigma/\sqrt{N}$, where $\sigma$ is the observed standard deviation and $N$ the number of sources in each bin) and the $1\sigma$ uncertainty on the mean estimated through bootstrap resampling the sample in the bins 1000 times in quadrature. By fitting a linear relation through the binned points at $z = 5.7$, we find that line-width increases with luminosity as:

$$v_{\text{FWHM}} = 35^{+16}_{-13}\log_{10}\left(\frac{L_{\text{Ly}\alpha}}{10^{43}\text{erg s}^{-1}}\right) + 267^{+11}_{-11}\text{km s}^{-1}. \quad (3)$$

Secondly, the average values in bins of Ly$\alpha$ luminosity indicate that LAEs with luminosities $L_{\text{Ly}\alpha} = 10^{42.4-42.8}$ erg s$^{-1}$ have broader line-widths at $z = 6.6$ ($v_{\text{FWHM}} \approx 330$ km s$^{-1}$) than at $z = 5.7$ ($v_{\text{FWHM}} \approx 250$ km s$^{-1}$). We test the significance of these results by taking the uncertainties due to the limited sample size into account as follows. We bootstrap the sample in the low luminosity bins at both $z = 5.7$ and $z = 6.6$ 1000 times and we compute the mean $v_{\text{FWHM}}$ in each realisation. The $1\sigma$ error on the mean is then the standard deviation of these 1000 measurements. At $z = 5.7$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.pdf}
\caption{Ly$\alpha$ line-widths as a function of Ly$\alpha$ luminosity. Blue points show LAEs at $z = 5.7$, while red points show LAEs at $z = 6.6$. The red and blue horizontal bands indicate the mean line-widths and its error, while stars show the mean in bins of Ly$\alpha$ luminosity. At $z = 5.7$ Ly$\alpha$ line-widths increase slightly with increasing luminosity. While the average over the full sample indicates no significant evolution in line-widths from $z = 5.7 - 6.6$, the binned-averages indicate that line-widths of faint LAEs at $z = 6.6$ are a factor $\sim 1.2$ higher than at $z = 5.7$.}
\end{figure}

In our analysis of COLA1, we find that it is detected at $> 5\sigma$ in the public HST F814W imaging (Koekemoer et al. 2007), with a magnitude of 26.2 $\pm$ 0.2. Even though the F814W filter has significant transmission above 920 nm, this magnitude indicates that a fraction of the flux density measured in F814W originates from $\lambda_0 < 1216$ Å. The F814W imaging also shows a Neighboring source within the PSF-FWHM of the NB921 imaging band Suprime-Cam images. These detections are unexpected for a source at $z = 6.6$ (because they trace below the Lyman break), and could indicate that the emission-line is the $[\text{OII}]_{3727,3729}$ doublet at $z = 1.477$ (similar to the photometric redshift of the source in the Laigle et al. 2016 catalogue). On the other hand, while the double-peak separation in the spectrum presented in Hu et al. (2016) may be explained with the $[\text{OII}]$ doublet, the asymmetric red wing challenges this explanation. Thus, currently none of the scenarios is completely satisfactory. Follow-up observations in the NIR are required to fully distinguish between these scenarios.
we find $v_{\text{FWHM}} = 252 \pm 17$ (error on mean) $\pm 112$ (dispersion) km s$^{-1}$, while at $z = 6.6$ we find $v_{\text{FWHM}} = 323 \pm 36$ (error on mean) $\pm 192$ (dispersion) km s$^{-1}$. This means that the offset is only marginally significant. We also perform a Kolmogorov-Smirnov test on 1000 realisations of the sample where we have perturbed each measured $v_{\text{FWHM}}$ with its uncertainty assuming that the uncertainty is gaussian. We find a mean P-value of $0.12 \pm 0.05$ and a KS-statistic of 0.27 $\pm 0.02$. This means that the two distributions are not drawn from the same parent distribution at $\approx 85 \%$ confidence level. This difference in the line-widths between the samples at $z = 5.7$ and $z = 6.6$ resembles the prediction from Haiman & Cen (2005) and may be used to constrain the neutral fraction of the IGM. As the dispersion is relatively large and the difference is significant at only $\approx 85 \%$ confidence level, larger samples are required to better constrain this evolution.

The trends that Ly$\alpha$ line-width increases slightly with luminosity at $z = 5.7$ and that the faintest LAEs may have broader Ly$\alpha$ lines at higher redshift, may explain why neither Hu et al. (2010), Ouchi et al. (2010) or Kashikawa et al. (2011) report increasing Ly$\alpha$ line-widths between $z = 5.7 - 6.6$. This is because they only studied the average over all luminosities (which does not change significantly), or probed a different Ly$\alpha$ luminosity regime. Interestingly, the luminosity at which line-widths may increase might correspond to the luminosity where the number density (at fixed Ly$\alpha$ spatial scale) drops most strongly between $z = 5.7 - 6.6$ (Matthee et al. 2015), and where there is relatively more extended Ly$\alpha$ emission at $z = 6.6$ than at $z = 5.7$ (Santos et al. 2016). This strengthens the idea that we are witnessing the effect of patchy reionisation affecting the number densities, line-widths and spatial extents of faint Ly$\alpha$ emitters at $z = 6.6$.

### 5.2 UV (metal) line-ratios to Ly$\alpha$

As described in §4, no rest-UV metal-lines are detected in SR6 or VR7. Such lines have also not been detected in Himiko (Zabl et al. 2015) or CR7 (Sobral et al. 2015). In this section we explore whether this is due to the limited depth of the observations or may be attributed to any peculiar physical condition (for example due to a low metallicity). As a comparison sample, we made a compilation of UV and Ly$\alpha$ selected galaxies at $z \gtrsim 6$ for which limits on other UV emission-lines besides Ly$\alpha$ are published, see Table 4. These sources have all been spectroscopically confirmed through their Ly$\alpha$ emission. All upper limits are converted to 2$\sigma$ and we compute Ly$\alpha$ luminosities and absolute UV magnitudes based on the published observed magnitudes and fluxes in the case luminosities and absolute magnitudes have not been provided. We show limits on the strength of NV, CIV, HeII, OIII[σ] and CIII] compared to Ly$\alpha$. A more detailed description on the compiled sample is provided in Appendix A. In addition, we also compare our sources with a sample of luminous LAEs at $z \approx 2 - 3$ (Sobral et al. in prep).

Based on Table 4, it is already clear that the limits on CIII] and CIV with respect to Ly$\alpha$ for SR6 and VR7 are higher than, or at most similar to, known detections at $z \approx 6 - 7$, indicating that our observations are not deep enough. As we illustrate in Fig. 5, we find that the current detections and upper limits at $z \approx 6 - 7$ indicate that CIV/Ly$\alpha$ increases towards faint UV luminosities, while it decreases or stays constant at $z \approx 2 - 3$. Contrarily, relatively high CIII]/Ly$\alpha$ ratios are detected among UV bright galaxies at $z \approx 6 - 7$, similarly to $z \approx 2 - 3$. In Fig. 6, we compare the ratios of CIII] and CIV to Ly$\alpha$ as a function of the Ly$\alpha$ EW$_f$.

The physics driving the Ly$\alpha$ escape fraction are complex (e.g. Hayes et al. 2015; Henry et al. 2015), with dust, H I column density, outflows and (especially at $z > 6$) the neutral fraction of the IGM all playing an important role. However, a rough estimate of the Ly$\alpha$ escape fraction may be obtained from the Ly$\alpha$ EW$_f$, as for example shown at $z = 2.2$ in Sobral et al. (2017), see also e.g. Yang et al. (2017) at $z \sim 0$. Therefore, we use the EW$_f$ to provide a rough estimate of the Ly$\alpha$ escape fraction, and thus the intrinsic Ly$\alpha$ emission (that is, strongly related to the ionising emissivity). An important caveat here is that the IGM transmission decreases between $z = 2.2 - 6.6$ at wavelengths around Ly$\alpha$ (even into the red wing, Laursen et al. 2011), such that the ‘effective’ Ly$\alpha$ escape fraction (including the effect from the IGM) may be underestimated. On the other hand, this decreasing transmission may be mitigated in the presence of galactic outflows (e.g. Dijkstra et al. 2011). We fit the following relation to the data-points from Fig. 11 (right panel) in Sobral et al. (2017) to estimate the escape fraction:

$$f_{\text{esc},\text{Ly} \alpha} = 0.006 \text{EW}_{\text{Ly} \alpha,0} - 0.05 \quad [5 < \text{EW}_{\text{Ly} \alpha,0} < 175],$$

where $f_{\text{esc},\text{Ly} \alpha}$ is the Ly$\alpha$ escape fraction. Then, we use this relation to estimate observed line-ratios from their theoretically predicted values:

$$f_{\text{CIII]} / \text{Ly} \alpha} = \frac{\alpha}{f_{\text{esc},\text{Ly} \alpha}}; \quad f_{\text{CIV} / \text{Ly} \alpha} = \frac{\alpha}{f_{\text{esc},\text{Ly} \alpha}},$$

where $\alpha$ is the estimated intrinsic line-ratio with respect to Ly$\alpha$. We use the results from Cloudy (Ferland et al. 2013) modelling (to be presented in Alegre et al. in prep) to model the intrinsic line-ratios. The ionisation sources in these models are either a range of blackbodies (with temperatures ranging from 20 kK to 150 kK, approximating stellar populations and including populations with extreme temperature $> 70$kK) and a range of power-laws (with spectral slopes of typical AGN), and the metallicities range from 0.001 $Z_{\odot}$ to solar, see also Sobral et al. in prep. For CIV, we use models with values of $\alpha$ between 0.015 (for a blackbody with effective temperature $\approx 70$kK and a metallicity of 0.01 $Z_{\odot}$) and $\alpha = 0.11$ (for a typical AGN power-law slope and a metallicity 0.1 $Z_{\odot}$). $\alpha$ decreases rapidly in the case of a lower metallicity or lower effective temperatures. For CIII], we use values from $\alpha = 0.005$ ($T_{\text{eff}} \approx 70$kK, $Z = 0.01$ $Z_{\odot}$) to $\alpha = 0.022$ for the same AGN model as described above. The results of this modelling is shown in dashed lines in Fig. 6.

We find that current CIV detections at $z \approx 6 - 7$ lie

\[ \text{MNRA} 2000, 1-16 (2017) \]
Table 4. Compilation of Lyα luminosities, EWs, absolute UV magnitudes and line-ratios between Lyα and rest-frame UV lines. Galaxies are either categorised as Lyα (narrow-band) selected, or UV (Lyman-break) selected, and are ordered by increasing redshift (see Table A1). For the doublets CIV CIII] and OIII], we use the combined flux. Upper limits are at the 2σ level.

| ID         | Lyα selected | SGP 8884 | 3.4 × 10^{43} | 166 | <0.01 | <0.09 | <0.13 |
|------------|--------------|----------|---------------|-----|-------|-------|-------|
|            | SR6          | 2.5 × 10^{43} | >250 | -21.1 | <0.26 | <0.96 | <0.47 |
|            | Ding-3       | 0.7 × 10^{43} | 62 | -20.9 | - | - | - |
|            | Ding-4       | 0.2 × 10^{43} | 106 | -20.5 | - | - | - |
|            | Ding-5       | 2 × 10^{43} | 79 | -20.5 | - | - | - |
|            | Ding-2       | 0.2 × 10^{43} | - | -22.2 | - | - | - |
|            | Ding-1       | 1 × 10^{43} | 21 | -22.2 | - | - | - |
|            | J2334108     | 4.8 × 10^{43} | >260 | >-20.8 | <0.05 | 0.08 | <0.01 |
|            | S11 5236     | 2.5 × 10^{43} | 160 | <0.03 | <0.13 | 0.21 | <0.18 |
|            | J2334154     | 4.9 × 10^{43} | 217 | -21.0 | <0.05 | <0.01 | <0.01 |
|            | J021835      | 4.6 × 10^{43} | 107 | -21.7 | <0.07 | <0.02 | <0.03 |
|            | WISP302      | 4.7 × 10^{43} | 798 | -19.6 | - | 0.41 | <0.29 |
|            | VR7          | 2.4 × 10^{43} | >196 | >-22.5 | <0.16 | <0.36 | <0.35 |
|            | LAE SDF-LEW-1| 1 × 10^{43} | 872 | >-32 | - | <0.01 | <0.02 |
|            | J162126      | 7.8 × 10^{43} | 99 | -20.5 | <0.05 | <0.01 | <0.02 |
|            | J160940      | 1.9 × 10^{43} | >31 | >-22.1 | <0.14 | <0.19 | <0.30 |
|            | J100550      | 3.9 × 10^{43} | >107 | >-21.5 | <0.08 | <0.01 | <0.01 |
|            | J160234      | 3.3 × 10^{43} | 81 | -21.9 | <0.11 | <0.12 | <0.23 |
|            | Himiko       | 4.3 × 10^{43} | 65 | -22.1 | <0.03 | <0.10 | <0.05 |
|            | CRT (recalibrated) | 8.5 × 10^{43} | 211 | -22.2 | <0.03 | <0.12 | 0.14 ± 0.06 |

| ID         | UV selected | A383-5.2 | 0.7 × 10^{43} | 138 | -19.3 | - | 0.05 ± 0.01 |
|------------|-------------|----------|---------------|-----|-------|---|-------|
|            | RXCJ2248.7-4431-ID3 | 0.3 × 10^{43} | 40 | -20.1 | <0.05 | 0.42 ± 0.12 | <0.05 |
|            | RXCJ2248.7-4431 | 0.8 × 10^{43} | 68 | -20.2 | <0.48 | 0.45 ± 0.12 | <0.28 |
|            | SDF-46975 | 1.5 × 10^{43} | 43 | -21.5 | <0.13 | - | - |
|            | IOK-1       | 1.1 × 10^{43} | 42 | -21.3 | <0.17 | - | <0.12 |
|            | BDF-521     | 1.0 × 10^{43} | 64 | -20.6 | <0.26 | - | <0.16 |
|            | A1703_2d46  | 0.3 × 10^{43} | 65 | -19.3 | - | 0.28 ± 0.03 | <0.07 |
|            | BDF-3299    | 0.7 × 10^{43} | 50 | -20.6 | <0.26 | - | <0.06 |
|            | GLASS-stack | 1 × 10^{43} | 210 | -19.7 | <0.4 | <0.3 | <0.2 |
|            | EGS-eas2-8 | 0.5 × 10^{43} | 9 | -21.9 | - | - | <0.41 |
|            | FIGS_GN1_1292 | 0.7 × 10^{43} | 49 | -21.2 | 0.85 ± 0.25 | - | - |
|            | GN-108036   | 1.5 × 10^{43} | 33 | -21.8 | <0.33 | - | 0.09 ± 0.05 |
|            | EGS-eas-81 | 1.2 × 10^{43} | 21 | -22.1 | - | - | 0.46 ± 0.10 |

closer to expected line-ratios from AGN than those from star-forming galaxies (c.f. Mainali et al. 2017). However, we note that assuming a higher effective temperature of a stellar population would result in a higher CIV/Lyα ratio (compare for example the 60 kK, 0.1 Z⊙ line with the 70 kK, 0.1 Z⊙ line). Another issue is that Lyα luminosities from these sources are estimated from slits, such that a significant fraction may be missed due to (slightly) more extended emission. On the one hand, the detected CIII]/Lyα ratios are already close to those modelled with star-formation as powering source. The CIV limits observed in Himiko prefer a star-forming ionising source, or an AGN with a very low metallicity (∼0.01 Z⊙). With the current limits for SR6, CRT and VR7 this analysis is not very meaningful, and we estimate that we would have to go a factor 5 – 10 deeper to detect CIV or CIII. |

5.3 UV luminosities and SFRs of luminous LAEs

In order to investigate how Lyα luminosity is related to the UV luminosity, which traces SFR of timescales of ∼ 100 Myr, we use near-infrared data to measure rest-frame UV luminosities (M_{1500}) for LAEs at z = 5.7 – 6.6. In addition to the new sources presented in this paper, we also add remaining candidate LAEs at z = 5.7 – 6.6 from Matthee et al. (2015) and Santos et al. (2016) and several sources from the literature as described below.

Rest-frame absolute UV magnitudes of LAEs are estimated from ground-base Y and J band photometry, converted to rest-frame M_{1500} at z = 5.7 and z = 6.6 respectively. Y band imaging is available in the UltraVISTA (DR2) coverage of the COSMOS field (McCracken et al. 2012). J band imaging is available in the UDS field through UKIDSS UDS (we use DR8; Lawrence et al. 2007), in the COSMOS field through UltraVISTA and in the SA22 field through the UKIDSS DXS. Photometry is measured in 2″ apertures with SEXTRACTOR (Bertin & Arnouts 1996) in dual-image mode with the narrow-band image as detection image (i.e. the
apertures are centred at the peak \( \lambda \) emission). Because the survey depth may vary from source to source (in particular in the COSMOS field due to the UltraVISTA survey design), we measure the depth locally. 2\( \sigma \) limits are assigned to sources that are undetected in the NIR imaging. We do not make any corrections for the fact that the effective wavelengths of the filters are not exactly at 1500 \( \AA \). However, for a typical UV slope of \( \beta \approx -2.3 \) (e.g. Ono et al. 2010; Jiang et al. 2013a), such a correction would only be on the order of \( \Delta \text{M}_{1500} \approx 0.004 \) (0.03) for LAEs at \( z \approx 5.7 \) (6.6). For a more extreme blue or relative red UV slope of \( \beta = -3.0 \) or \( \beta = -1.0 \), the correction would be up to 0.1 magnitude.

We also add the information from LAEs in the Subaru Deep Field (Kashikawa et al. 2011) that have been observed with HST NIR imaging by Jiang et al. (2013a), LAEs observed by Ding et al. (2016), recently spectroscopically confirmed LAEs at \( z = 5.7 – 6.6 \) by Shibuya et al. (2017) and our compilation of UV selected galaxies between \( z = 6.2 – 7.2 \) with \( \text{Ly}_\alpha \text{EW}_0 > 20 \) \( \AA \) (see Table 4; green symbols in the right panel of Fig. 7). In addition to the sources from this compilation, we also added two sources from Huang et al. (2016), see Table A1.

Fig. 7 clearly shows that at fixed \( \text{Ly}_\alpha \) luminosity, there is a large spread in UV luminosities, and vice versa (at
both $z = 5.7$ and $z = 6.6$). Spectroscopically confirmed UV
selected galaxies have similar $L_{Ly\alpha}$ luminosities as LAEs.
Around $L^*$ ($L_{Ly\alpha} \approx 10^{43}$ erg s$^{-1}$), absolute UV magnitudes
can range from up to $3 \times 10^{40}$ (M$_{1500} \approx -21.0$), down to
$\approx 0.3 \times M_{1500}$, with a 1σ spread of 0.9 dex. This means that
relatively shallow, wide area Ly$\alpha$ surveys can be an efficient
tool to select relatively UV-faint galaxies up to $z \approx 7$,
thought to be signification contributors to the reionisation
process (e.g. Robertson et al. 2013; Faisst 2016). It also means that it is challenging to predict Ly$\alpha$ luminosities of UV-continuum selected galaxies, even outside the reionisation
epoch.

Fig. 7 also shows that there is little evidence for a rela-
tion between the Ly$\alpha$ luminosity and M$_{1500}$ for Ly$\alpha$
selected sources at $z = 5.7$ in our UV and Ly$\alpha$ luminosity
range. As both M$_{1500}$ and L$_{Ly\alpha}$ are, to first order, related
to the SFR, we would have expected a correlation. To illus-
trate this, we show lines at constant Ly$\alpha$ escape fractions
(based on the assumption that SFR$_{UV}$=SFR$_{Bol}$, case B re-
combination with $T = 10000$K and $n_e = 100$ cm$^{-3}$ and
no attenuation due to dust). This result resembles the well
known Ando et al. (2006) diagram, which reveals a de-
ciency of luminous LAEs with bright UV magnitudes be-
tween $z \approx 5 - 6$. More recently, other surveys also revealed
that the fraction high EW Ly$\alpha$ emitters increases towards fainter UV magnitudes (e.g. Schaerer et al. 2011; Stark et al.
2011; Cassata et al. 2015). The lack of a strong correlation
between M$_{1500}$ and L$_{Ly\alpha}$ might indicate that the SFRs are
bursty (because emission-line luminosities trace SFR over a
shorter time-scale than UV luminosity), or that the Ly$\alpha$
escape fraction is anti-correlated with M$_{1500}$ (such that Ly$\alpha$
photons can more easily escape from galaxies that are fainter
in the UV). A possible explanation for the latter scenario is
that slightly more evolved galaxies (which are brighter in the
UV) have a slightly higher dust content (e.g. Bouwens et al.
2012), affecting their Ly$\alpha$ luminosity more than the
UV luminosity. It is interesting to note that several galaxies lie
above the 100 % Ly$\alpha$ escape fraction line. This implies bursty or stochastic star-formation (which is more likely in lower mass galaxies with faint UV luminosities, e.g. Mas-
Rihas et al. 2016), alternative Ly$\alpha$ production mecha-
nisms to star-formation (such as cooling), a higher ionising pro-
duction efficiency (for example due to a top-heavy IMF or
binary stars, e.g. Gotberg et al. 2017), or dust attenuating
Ly$\alpha$ in a different way than the UV continuum (e.g. Neufeld
1991; Finkelstein et al. 2008; Gronke et al. 2016).

At $z = 6.6$, however, current detections indicate a rela-
tion between M$_{1500}$ and L$_{Ly\alpha}$, albeit with significant scatter
(Fig. 7). In order to be unbiased due to the depth of J band
imaging, we fit a linear relation between log$_{10}(L_{Ly\alpha})$
and M$_{1500}$ for LAEs with M$_{1500} < -21.2$ using a least squares
algorithm, resulting in:

$$\log_{10}(L_{Ly\alpha}/\text{erg s}^{-1}) = 20.8^{+4.2}_{-4.2} - 1.0^{+0.2}_{-0.2} M_{1500}$$ (6)

This fit indicates that for LAEs at $z \approx 6.5 - 7$, M$_{1500}$ and
L$_{Ly\alpha}$, are related at 5σ significance in the current data (see
also Jiang et al. 2013a). We measure a (large) 1σ scatter of
0.26 dex around this relation. We note that excluding UV
selected galaxies results in a lower significance ($\approx 3.5\sigma$), but
does not significantly change the fit parameters. The fitted
slope between M$_{1500}$ and L$_{Ly\alpha}$ is steeper than the slope that
is expected at fixed L$_{bol,Ly\alpha}$, which could indicate that the
Ly$\alpha$ escape fraction (or its production rate) increases to-
wards brighter magnitudes (for Ly$\alpha$ selected sources). At
fainter UV luminosities, we find that the slope is consistent
with being flat (within the error-bars) and many of these
sources only have upper limits on their UV magnitude. We
also note that for a cut at high Ly$\alpha$ luminosity, no clear
relation is seen between Ly$\alpha$ and UV luminosity. The pres-
ence of very luminous LAEs with luminous UV luminosities
at $z = 6.6$ is at odds with the Ando et al. (2006) result,
indicating additional physical processes playing a role.
We note that the most UV luminous sources at $z = 6.6$ have multiple UV-components (CR7, Himiko and VR7), which could help facilitating the escape of $\text{Ly}\alpha$ photons. For example, outflows caused by earlier star formation episodes could boost the escape of $\text{Ly}\alpha$ photons through the ISM, while the same previous star formation episodes could have ionised a large enough fraction of the IGM around the galaxy such that $\text{Ly}\alpha$ can escape. This could be particularly important in the reionisation era at $z \gtrsim 6.5$. Similarly, Jiang et al. (2013b) found that their most UV-luminous LAE at $z = 5.7$ and 4 out of the 6 LAEs with $M_{1500} < -20.5$ at $z = 6.6$ are interacting/merging. Moreover, the galaxy IOK-1, a confirmed LAE at $z = 6.96$ (Iye et al. 2006) also consists of two UV-bright components. We note that the spectroscopic follow-up presented in Furusawa et al. (2016) included two luminous UV selected galaxies ($M_{1500} = -22.4, -22.7$) at $z \sim 7$ from Bowler et al. (2014), that have multiple components in the HST imaging (Bowler et al. 2017a). These sources are not detected with strong $\text{Ly}\alpha$ emission (with a limiting $L_{\text{Ly} \alpha} \lesssim 3 \times 10^{42} \text{erg s}^{-1}$), indicating that while multiple components could boost $\text{Ly}\alpha$ observability, they do not imply observable $\text{Ly}\alpha$ emission at $z \sim 7$.

5.3.1 The production efficiency of ionising photons

We combine the $\text{Ly}\alpha$ and UV measurements to estimate $\xi_{\text{ion}}$, the ionising photon production efficiency, which is an important parameter in assessing the ionising budget from star-forming galaxies, particularly in the reionisation era (e.g. Robertson et al. 2013; Bouwens et al. 2016; Matthee et al. 2017b). Under the assumption that the escape fraction of ionising photons is close to zero, $\xi_{\text{ion}}$ is defined as the number of produced ionising photons per second, per unit UV magnitude:

$$\xi_{\text{ion}} = \frac{Q_{\text{ion}}}{L_{\text{UV}}},$$

(7)

where $Q_{\text{ion}}$ is the number of emitted ionising photons per second, and $L_{\text{UV}}$ the UV luminosity at $\lambda_0 \approx 1500 \text{ A}$. Ideally, $Q_{\text{ion}}$ is estimated from Ha measurements, as $L_{\text{H}\alpha} = 1.36 \times 10^{-12} Q_{\text{ion}}$ under the assumption that $f_{\text{esc,Ly}\alpha} = 0$ % (e.g. Kennicutt 1998). Unfortunately, Ha measurements can only be performed at $z > 2.5$ after the launch of the James Webb Space Telescope (JWST). Therefore, we use the calibration of the $\text{Ly}\alpha$ escape fraction with EW6 (see Eq. 4), which relates the $\text{Ly}\alpha$ luminosity to Ha luminosity under the assumption of case B recombination. Rewriting the equations results in:

$$\xi_{\text{ion}} = \frac{L_{\text{Ly}\alpha}}{8.7 \times 1.36 \times 10^{-12} \times f_{\text{esc,Ly}\alpha} \times L_{\text{UV}}}.$$  

(8)

Here, the factor 8.7 is the case B recombination ratio between $\text{Ly}\alpha$ and Ha under typical ISM conditions of $T_e = 10,000 \text{ K}$ and $n_e = 350 \text{ cm}^{-3}$ (e.g. Henry et al. 2015). $f_{\text{esc,Ly}\alpha}$ is obtained through Eq. 4, with a maximum of 1.0 (for EW6 $> 175$ A). $L_{\text{UV}}$ is computed using the measured $M_{1500}$, assuming negligible dust attenuation (see Bouwens et al. 2016 for a discussion on how dust attenuation affects $\xi_{\text{ion}}$). This empirically motivated method to estimate $\xi_{\text{ion}}$ can easily be tested with follow-up observations with JWST.

Using this prescription, we calculate values of $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \gtrsim 25.25 \pm 0.23$ and $\gtrsim 24.66 \pm 0.17$ for SR6 and VR7, respectively. We write these as upper limits because the $\text{Ly}\alpha$ EWs of SR6 and VR7 indicate $f_{\text{esc,Ly} \alpha} = 100$ %, which may be an over-estimate (in the case of 50 % $\text{Ly}\alpha$ escape, $\xi_{\text{ion}}$ would increase by 0.3 dex). For CR7 and Himiko we measure $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \gtrsim 25.33 \pm 0.06$ and $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.55 \pm 0.07$, respectively. Except for VR7, these values are similar to the measurements of faint LAEs at $z \approx 3$ (Nakajima et al. 2016) and $z \approx 4 - 5$ Lyman-break galaxies (Bouwens et al. 2016). The median value of $\xi_{\text{ion}}$ for our compilation in Table 4 is $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.51 \pm 0.09$ (Fig. 8), which is similar to the mean value of the reference sample of luminous LAEs at $z \approx 2 - 3$, for which we measure a mean $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.45 \pm 0.05$ using the same method, and slightly lower than those measured by Schaerer et al. (2016) in a sample of low redshift Lyman-Continuum leakers.

We also compare our method to the values of $\xi_{\text{ion}}$ obtained independently by Stark et al. (2015b, 2017) using photo-ionisation modelling of UV metal lines. While we measure a higher value of $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 26.63 \pm 0.36$ for EGS-zs8-2, our results for A1703 (see Table 4) and COS zs7-1 are $\log_{10}(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.52 \pm 0.18, 25.64 \pm 0.12$ and $25.63 \pm 0.15$, encouragingly consistent with the estimates from Stark et al. Under the model-assumptions, these results indicate that luminous $\text{Ly}\alpha$ emitters produce ionising photons a factor two more efficiently than typically assumed (e.g. Robertson et al. 2013), and similar to the estimated $\xi_{\text{ion}}$ based on the evolution of the $\text{Ha}$ EW / specific SFR (Matthee et al. 2017b), see Fig. 8.
implies that a significant amount of photons that reionised the Universe may have been produced in LAEs, in particular if the ISM conditions in these galaxies are also facilitating LyC photons to escape (e.g. Dijkstra et al. 2016), which can be constrained with future observations with JWST (e.g. Zackrisson et al. 2017).

6 CONCLUSIONS

We have presented the results of X-SHOOTER follow-up observations of a sample of luminous LAE candidates at $z = 5.7 - 6.6$ in the SA22 field. We present the properties of newly confirmed LAEs (summarised in Table 2) and compare them with other LAEs and LBGs at similar redshifts. The main results are:

(i) We spectroscopically confirm SR6, the most luminous LAE at $z = 5.676$ in the SA22 field. While SR6 has a high Lyα luminosity and extreme EW ($L_{\text{Ly}\alpha} = 2.5 \pm 0.3 \times 10^{43}$ erg s$^{-1}$, $EW_\alpha > 250$ Å), it has a typical UV continuum luminosity ($L_{\text{UV}} = -21.1 \pm 0.1$) and a narrow Lyα line ($236 \pm 16$ km s$^{-1}$).

(ii) We confirm VR7, the most luminous LAE at $z = 6.532$, in the SA22 field ($L_{\text{Ly}\alpha} = 2.4 \pm 0.2 \times 10^{43}$ erg s$^{-1}$, $EW_\alpha > 196$ Å and $EW_{\text{FWHM}} = 340 \pm 14$ km s$^{-1}$, see §4.2). Among the luminous LAEs known at $z \sim 6.5$, VR7 is also the most luminous in the UV found so far ($L_{\text{UV}} = -22.5 \pm 0.2$). Despite this luminosity, we do not detect any signs of AGN activity (such as CIV or MgII emission) in the spectrum at the current depths ($f \lesssim 2 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$, $EW_\alpha \lesssim 20$ Å). In contrast, essentially all LAEs at $z \approx 2 - 3$ with similar Lyα and UV luminosities are AGN.

(iii) Lyα line-widths increase slowly with Lyα luminosity at $z = 5.7$, while such a trend is not seen at $z = 6.6$. We find indications that the line-widths of LAEs with $L_{\text{Ly}\alpha} \approx 10^{42.5}$ erg s$^{-1}$ increase between $z = 5.7 - 6.6$ (§3.1), although at relatively low statistical significance due to small sample sizes. This evolution occurs at the same luminosity where the number densities decrease, and Lyα spatial scales increase (Santos et al. 2016), all indicating patchy reionisation.

(iv) In §5.2, we argue empirically that rest-UV lines besides Lyα are most easily observed in galaxies with relatively low Lyα EWs. This explains why carbon lines have been detected in luminous UV-continuum selected sources, while they have not been easily detected in Lyα selected sources.

(v) Combining our sources with a compilation of LAEs and LBGs at $z \approx 6 - 7$, we do not detect a clear relation between the Lyα luminosity and absolute UV magnitude at $z = 5.7$ indicating a lower Lyα escape fraction at brighter UV luminosities, for example due to dust ($\xi_\alpha$). There is a large dispersion in absolute UV magnitudes of $L^\star$ LAEs of $\sigma = 0.9$ dex.

(vi) At $z = 6.6$, we find that, at $M_{\text{Ly}\alpha} < -21$, the Lyα and UV luminosity are strongly correlated, while there is no evidence for a relation at fainter UV luminosities. This means that the Lyα escape fraction and/or its production rate increases strongly among luminous LAEs between $z = 5.7 - 6.6$. Most luminous LAEs show multiple components in the rest-UV. This could indicate that such merging systems could boost effective Lyα transmission through the IGM at $z > 6.5$, increasing the effective Lyα escape fraction.

(vii) Under basic assumptions, we find that several LAEs at $z \approx 6 - 7$ would have Lyα escape fractions $\gtrsim 100\%$, which could indicate bursty star-formation histories, alternative Lyα production mechanisms, a higher ionising production efficiency, or dust attenuating Lyα in a different way than the UV continuum.

(viii) Using an empirical relation to estimate the Lyα escape fraction, we present a method to compute $\xi_\text{esc}$, the production efficiency of ionising photons, based on Lyα and UV continuum measurements (§5.3.1). Our results indicate that luminous LAEs at $z \approx 6 - 7$ produce ionising photons efficiently, with a median $\log_{10}(\xi_\text{esc}/\text{Hz erg}^{-1}) = 25.51 \pm 0.09$, similar to other recent measurements of LAEs and LBGs at $z \approx 2 - 5$. These measurements will easily be testable with JWST.

In the future, significant improvements can be made by observing a statistical sample of homogeneously selected Lyα emitters at $z = 5.7 - 6.6$ with IFU spectroscopy with JWST, which can measure Hα up to $z = 6.6$. Such measurements can constrain any evolution in the effective Lyα escape fraction directly (due to an increasingly neutral IGM), by controlling for the apertures/spatial scales and positions of the emission (hence the IFU), and allow us to test the empirical models to estimate Lyα escape fractions and $\xi_\text{esc}$. The bright, spectroscopically confirmed LAEs are the ideal targets to pioneer such studies as they already show extended/multiple component morphologies.

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APPENDIX A: GALAXY COMPILATION

Here we describe shortly the details of the sample of sources listed in Table A1. Part of this sample is narrow-band selected LAEs, where the Lyα flux is measured with a NB (except for WISP302, which is measured with the HST/WFC3 grism, Bagley et al. 2017). The other part of the sample are UV selected Lyman-break galaxies for which the Lyα flux and EW have been measured from slit spectroscopy, except for the grism measurements of RXCJ2248.7-4431 (Schmidt et al. 2017), the GLASS-stack (Schmidt et al. 2016) and FIGS_GN1_1292 (Tilvi et al. 2016). We note that due to extended Lyα emission and slit losses their Lyα luminosities may be under-estimated, in particular when Lyα is offset from the UV emission (e.g. Vanzella et al. 2017). For CR7, we use updated constraints on metal-lines from the recalibrated spectrum that will be presented in Sobral et al. in prep.

In the case Lyα luminosities are not published, we have computed them from the published line-flux and luminosity distance corresponding to the source redshift. For sources from Ding et al. (2016), we have used luminosities from their discovery-papers (Ouchi et al. 2005 and Shimasaku et al. 2006). If not published, $M_{1500}$ is computed based on the observed magnitude in the band closest to a rest-frame $\lambda = 1500$ Å, corrected for the distance modulus and bandwidth spreading and for possible lensing magnification. In the case of emission-line doublets (such as CIII[1907,1909]), we use the sum of both lines, except in the case of the OIII doublet of A1703, where only one component is measured due to adjacent skylines. Most measurements of/limits on rest-UV lines besides Lyα and NV have been performed with slit spectroscopy from the ground and are thus significantly hampered by the sky OH emission lines in the near-infrared.

APPENDIX B: CATALOGUES OF CANDIDATE LAES AT $Z = 5.7 - 6.6$

We publish catalogues of all candidate LAEs at $z = 5.7$ from Santos et al. (2016) and at $z = 6.6$ from Matthee et al. (2015) with the paper. The first five entries of these catalogues are shown in Table B1 and $z = 6.6$ Table B2.

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Table A1. Galaxies included in compilations of line-widths and rest-UV line-ratios.

| ID              | Redshift | Reference                                      |
|-----------------|----------|------------------------------------------------|
| **Lyα selected**|          |                                                |
| SGP 8884        | 5.65     | Westra et al. (2006); Lidman et al. (2012)     |
| SR6             | 5.676    | **This paper**                                 |
| Ding-3          | 5.69     | Ouchi et al. (2005); Ding et al. (2016)         |
| Ding-4          | 5.69     | Ouchi et al. (2005); Ding et al. (2016)         |
| Ding-5          | 5.69     | Ouchi et al. (2005); Ding et al. (2016)         |
| Ding-2          | 5.692    | Ouchi et al. (2005); Ding et al. (2016)         |
| Ding-1          | 5.70     | Shimazaki et al. (2006); Ding et al. (2016)     |
| J233408         | 5.707    | Shibuya et al. (2017)                          |
| S11 5236        | 5.72     | Westra et al. (2006); Lidman et al. (2012)     |
| J233454         | 5.732    | Shibuya et al. (2017)                          |
| J021835         | 5.757    | Shibuya et al. (2017)                          |
| WISP302         | 6.44     | Bagley et al. (2017)                           |
| VR7             | 6.532    | **This paper**                                 |
| LAE SDF-LEW-1   | 6.538    | Kashikawa et al. (2012)                        |
| J162126         | 6.545    | Shibuya et al. (2017)                          |
| J160940         | 6.564    | Shibuya et al. (2017)                          |
| J100550         | 6.573    | Shibuya et al. (2017)                          |
| J160234         | 6.576    | Shibuya et al. (2017)                          |
| Himiko          | 6.59     | Ouchi et al. (2009); Zabl et al. (2015)        |
| COLA1           | 6.593    | Hu et al. (2016)                               |
| CR7             | 6.604    | Sobral et al. (2015)                           |
| **UV selected** |          |                                                |
| WMH S           | 5.618    | Wilott et al. (2013)                           |
| WMH 13          | 5.983    | Wilott et al. (2013)                           |
| A383-5.2        | 6.0294   | Richard et al. (2011); Stark et al. (2015a)    |
| WMH 5           | 6.068    | Wilott et al. (2013)                           |
| RXCJ2248.7-4431-ID3 | 6.11  | Mainali et al. (2017)                          |
| RXCJ2248.7-4431 | 6.11    | Schmidt et al. (2017)                          |
| CLM 1           | 6.17     | Cuby et al. (2003)                             |
| MACS0454-1251   | 6.32     | Huang et al. (2016)                            |
| RXJ1347-1216    | 6.76     | Huang et al. (2016)                            |
| SDF-46975       | 6.844    | Ono et al. (2012)                              |
| IOK-1           | 6.96     | Iye et al. (2006); Cai et al. (2011); Ono et al. (2012) |
| BDF-521         | 7.01     | Vanzella et al. (2011); Cai et al. (2015)      |
| A1703_zd6       | 7.045    | Stark et al. (2015b)                           |
| BDF-3299        | 7.109    | Vanzella et al. (2011)                         |
| GLASS-stack     | < 7.2 >  | Schmidt et al. (2016)                          |
| GN-108036       | 7.213    | Ono et al. (2012); Stark et al. (2015a)        |
| EGS-zs8-2       | 7.477    | Stark et al. (2017)                            |
| FIGS_GN1_1292   | 7.51     | Finkelstein et al. (2013); Tilvi et al. (2016)  |
| EGS-zs8-1       | 7.73     | Oesch et al. (2015); Stark et al. (2017)       |
**Table B1.** First five entries of our candidate LAEs at $z = 5.7$ from Santos et al. (2016). Full electronic table is available online. Line-flux ($f_{NB816}$), Ly$\alpha$ luminosity (assuming a luminosity distance corresponding to $z = 5.7$) and EW$_0$ are measured in 2$''$ apertures. For sources with spectroscopically confirmed redshift, we corrected the luminosity for the narrow-band filter transmission at the wavelength where the line is observed.

| ID             | R.A. J2000 | Dec. J2000 | $f_{NB816}$ | $L_{Ly\alpha}$ | EW$_0$ |
|----------------|------------|------------|-------------|----------------|--------|
| SA22-NB816-480736 | 22:17:28.81 | +00:53:02.29 | 6.6 | 24.6 | 178 |
| SA22-NB816-444574 | 22:17:29.41 | +00:34:13.07 | 2.3 | 8.5 | 27 |
| SA22-NB816-429880 | 22:17:33.65 | +00:26:47.99 | 1.4 | 5.1 | 25 |
| SA22-NB816-429969 | 22:17:36.16 | +00:26:49.65 | 3.7 | 13.6 | 380 |
| SA22-NB816-438282 | 22:17:37.24 | +00:30:57.20 | 3.9 | 14.3 | 43 |

**Table B2.** First five entries of our candidate LAEs at $z = 6.6$ from Matthee et al. (2015). Full electronic table is available online. Line-flux ($f_{NB921}$), Ly$\alpha$ luminosity (assuming a luminosity distance corresponding to $z = 6.55$) and EW$_0$ are measured in 2$''$ apertures. For sources with spectroscopically confirmed redshift, we corrected the luminosity for the narrow-band filter transmission at the wavelength where the line is observed.

| ID             | R.A. J2000 | Dec. J2000 | $f_{NB921}$ | $L_{Ly\alpha}$ | EW$_0$ |
|----------------|------------|------------|-------------|----------------|--------|
| VR7            | 22:18:56.36 | +00:08:07.32 | 4.8 | 23.4 | 203 |
| COSMOS-NB921-20802 | 10:02:07.83 | +02:32:17.25 | 1.4 | 7.0 | 56 |
| COSMOS-NB921-5032 | 10:02:04.33 | +02:20:29.12 | 2.4 | 11.7 | 125 |
| COSMOS-NB921-100684 | 10:01:27.54 | +02:06:46.47 | 3.5 | 17.0 | 116 |
| COSMOS-NB921-107681 | 10:01:54.68 | +02:10:18.59 | 2.1 | 10.3 | 100 |