The Lyα Luminosity Function and Cosmic Reionization at z ∼ 7.0: A Tale of Two LAGER Fields

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Received 2019 March 12; revised 2019 October 9; accepted 2019 October 9; published 2019 November 25

Abstract

We present the largest-ever sample of 79 Lyα emitters (LAEs) at z ∼ 7.0 selected in the COSMOS and CDFS fields of the LAGER project (the Lyman Alpha Galaxies in the Epoch of Reionization). Our newly amassed ultradeep narrowband exposure and deeper/wider broadband images have more than doubled the number of LAEs in COSMOS, and we have selected 30 LAEs in the second field CDFS. We detect two large-scale LAE-overdense regions in the COSMOS that are likely protoclusters at the highest redshift to date. We perform injection and recovery simulations to derive the sample incompleteness. We show that significant incompleteness comes from blending with foreground sources, which, however, has not been corrected in LAE luminosity functions (LFs) in the literature. The bright-end bump in the Lyα LF in COSMOS is confirmed with six (two newly selected) luminous LAEs ($L_{Ly\alpha} > 10^{43.3}$ erg s⁻¹). Interestingly, the bump is absent in CDFS, in which only one luminous LAE is detected. Meanwhile, the faint-end LFs from the two fields agree well with each other. The six luminous LAEs in COSMOS coincide with two LAE-overdense regions, while such regions are not seen in CDFS. The bright-end LF bump could be attributed to ionized bubbles in a patchy reionization. It appears associated with cosmic overdensities and thus supports an inside-out reionization topology at z ∼ 7.0, i.e., the high-density peaks were ionized earlier compared to the voids. An average neutral hydrogen fraction of $x_{HI} ∼ 0.2–0.4$ is derived at z ∼ 7.0 based on the cosmic evolution of the Lyα LF.

Key words: cosmology – observations – dark ages – first stars – galaxies: formation – galaxies: high-redshift – reionization

1. Introduction

Cosmic reionization is a critical epoch in the history of the universe, during which most of the neutral hydrogen is ionized by the hard UV photons arising from the star-forming galaxies and active galactic nuclei. Observations of the Gunn–Peterson troughs in the quasar spectra show that the epoch of reionization (EoR) ends at z ∼ 6 (Fan et al. 2006). Meanwhile, Planck Collaboration (2018) derived a midpoint reionization redshift $z ∼ 7.7 ± 0.7$ through measuring the Thompson scattering of cosmic microwave background (CMB) photons from free electrons. High-$z$ gamma-ray bursts, quasars, and galaxies are also probes to constrain the evolution of the neutral hydrogen fraction in the intergalactic medium (IGM; e.g., Greiner et al. 2009; Mortlock et al. 2011; Bouwens et al. 2015; Finkelstein et al. 2015; Bañados et al. 2018); however, the constraints are still poor, especially at $z ≥ 7$.

Lyα emitters (LAEs) are powerful probes to investigate cosmic reionization, as Lyα photons from galaxies in the early universe are resonantly scattered by the neutral hydrogen atoms in the intergalactic medium and thus are sensitive to the neutral hydrogen fraction $x_{HI}$ (for a review see Dijkstra 2014). High-redshift LAEs can be effectively selected with narrowband imaging surveys (e.g., Malhotra & Rhoads 2004; Hibon et al. 2010, 2011, 2012; Hu et al. 2010; Ouchi et al. 2010; Tilvi et al. 2010; Krug et al. 2012; Konno et al. 2014, 2018; Matthee et al. 2015; Santos et al. 2016). In the past two decades, more than 1000 LAE candidates have been selected at $z ∼ 5.7, 6.5,$ and $6.6$ (e.g., Jiang et al. 2017; Konno et al. 2018). However, a very small number of LAEs at $z ≥ 7$ have been selected. Prior to this study, the largest samples of LAEs at $z ≥ 7$ included three at $z ∼ 7.0$, i.e., the 23 candidates by Zheng et al. (2017), 20 candidates by Ota et al. (2017), and 34 candidates by Itoh et al. (2018).

Lyman Alpha Galaxies in the Epoch of Reionization (LAGER) is an ongoing large-area narrowband imaging survey for LAEs at $z ∼ 7.0$, using the Dark Energy Camera (DECam) installed on the Cerro Tololo Inter-American Observatory.
The sky OH emission lines are also plotted (COSMOS (14 Cerro Pachon sky emission lines smoothed with a Gaussian kernel of 4 Å)/ for illustration; see http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-background-spectra.

In this paper, we present new results of the Lyα luminosity function (LF) is revealed, suggesting the existence of ionized bubbles in a patchy reionization process. Six of the LAE candidates with 34 hr NB964 exposure is overplotted for direct comparison with NB964 on DECam. The sky OH emission lines are also plotted (green line).

In the first LAGER field COSMOS, we selected 23 $z \sim 7.0$ LAE candidates with 34 hr NB964 exposure (in the central 2 deg$^2$ region; Zheng et al. 2017). A bright-end bump in the Lyα luminosity function (LF) is revealed, suggesting the existence of ionized bubbles in a patchy reionization process. Six of the LAE candidates have been spectroscopically confirmed (Hu et al. 2017), including three luminous LAEs with Lyα luminosities of $\sim 10^{43}$ erg s$^{-1}$.

In this paper, we present new results of $z \sim 7.0$ LAEs selected in the deeper LAGER-COSMOS field and a second LAGER-CDFS field. In Section 2, we describe the observations and data reduction. We present the LAE selection in Section 3. The sample completeness and the derived Lyα LF are given in Section 4. In Section 5, we discuss the evolution of Lyα LF and the cosmic reionization at $z \sim 7.0$. Throughout this work, we adopt a flat $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Observations and Data Reduction

2.1. Observations

Our DECam NB964 exposures of two LAGER fields were obtained between 2015 December and 2017 December. The total exposure time is 47.25 hr in COSMOS and 32.9 hr in CDFS. The NB964 data were scientifically reduced and calibrated by the DECam Community Pipeline (Valdes et al. 2014), and the individual DECam frames were stacked with our customized pipeline (see Section 2.2).

In COSMOS, the recently released Hyper Suprime-Cam Subaru Strategic Program (HSC SSP) ultra-deep broadband images (grizY; Tanaka et al. 2017) are considerably deeper than the public DECam broadband images and the Subaru Suprime-Cam (SSC) images we used in Zheng et al. (2017). In this work we use the ultradepth HSC SSP broadband images for LAE selections, and the deep SSC-B band image is kept to extend the blue wavelength coverage down to 3500 Å. The merged HSC observations of COSMOS by the SSP team and the University of Hawaii (Tanaka et al. 2017; Aihara et al. 2018) were downloaded from HSC SSP archive. HSC-y band is selected as the underlying broad band (see Figure 1 for the total transmission curve$^{15}$) for comparison with the NB964 narrow band for emission-line selection.

In CDFS, ultra-deep DECam broadband exposures (grizY, together with much shallower u and Y exposures) are available and downloaded from the National Optical Astronomy Observatory (NOAO) Science Archive.$^{16}$ DECam-Y image is, however, too shallow. We opt to use DECam-z as the underlying broad band. Its bandpass, unlike that of HSC-z, does overlap with NB964 (see Figure 1 for the total transmission curve$^{17}$). The broadband DECam exposures were also stacked as described in Section 2.2. Note that the total transmission curves of DECam filters in Figure 1 are higher than those of HSC filters. This is mainly because the CCD detector of DECam (Diehl et al. 2008) has better quantum efficiency in the near-infrared than that of HSC.$^{18}$

All the broadband and narrowband images used in this paper, including the 5σ limiting magnitudes (for 2″ and 1.35 diameter aperture, respectively), are listed in Table 1.

2.2. Image Stacking

In this section, we describe our optimal weighted-stacking approach following Annis et al. (2014) and Jiang et al. (2014). Briefly, for each individual DECam frame, we obtain the point-spread function (PSF), atmospheric transmission, and exposure time to generate a weight mask using those parameters and the weight map provided by the DECam Community Pipeline. Below we provide details of the approach.

First, we use PSFEx (Bertin et al. 2011) to extract the PSF of each image and run SExtractor (Bertin & Arnouts 1996) to detect objects in the image. To perform relative photometric calibration, we take one photometric frame for each band with low PSF FWHM as a standard image and select a set of bright, unsaturated pointlike sources as standard stars. We obtain the zero-point of each frame relative to the standard image by cross-matching the standard stars in the images with a matching radius of 1″. We use these zero-point offsets to normalize the images to the same flux level.

We utilize a 4σ-clipping method to reject artifacts in each frame (i.e., satellite trails, meteors, etc.) that have not been masked out by the bad pixels masks provided by the DECam Community Pipeline. Since PSF varies in different images,

$^{13}$ Please find more information about the filter at http://www.ctio.noao.edu/noao/content/Properties-N964-filter.

$^{14}$ Cerro Pachon sky emission lines smoothed with a Gaussian kernel of 4 Å for illustration; see http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-background-spectra.

$^{15}$ https://hsc-release.mtk.nao.ac.jp/doc/index.php/survey/

$^{16}$ http://archive.noao.edu/

$^{17}$ http://www.ctio.noao.edu/noao/node/13140

$^{18}$ https://www.naoj.org/Observing/Instruments/HSC/sensitivity.html
which will affect the clipping, we allow a fraction of 30% flux variation per pixel during the clipping.

We assign each exposure a weight based on their exposure time \(t_e\), PSF FWHM, atmospheric transmission \(T_i\), and background variance \(\sigma_i^2\):

\[
    w_i = \frac{T_i^2 l_i^2}{\text{FWHM}_i^2 \sigma_i^2}.
\]

This is similar to inverse variance weighting to minimize the variance of the stacked image. Here, the background variance \(\sigma_i^2\) is given by the DECam Community Pipeline, named \textit{wtmap}, which is the inverse variance of the local background. The atmospheric transmission \(T_i\) is calculated with the relative zero-point of each individual frame aforementioned.

Finally, we use \textsc{SWarp} (Bertin et al. 2002) to resample and stack flux-normalized images with weight masks, and we obtain a stacked science image and a composite weight map.

### 2.3. Photometric Calibration

We use SExtractor dual-image mode to extract sources from the images and measure photometry. The magnitude zeropoints of broadband images in CDFS and COSMOS are calibrated using the DES DR1 catalog (Abbott et al. 2018) and the COSMOS/ULtraVISTA catalog (Muzzin et al. 2013), respectively. The NB964 images are photometrically calibrated with \(\sim 900\) A- and B-type stars in each field. More specifically, we use the Python package SED Fitter (Robitaille et al. 2007) to perform spectral energy distribution fitting to the broadband photometries of stars with Castelli & Kurucz (2004) models (Castelli & Kurucz 2004), and then we convolve the spectra with the NB964 transmission curve to calculate the magnitudes of these stars in the NB964 images.

### 3. LAE Candidates

#### 3.1. Selection Criteria

Our selection criteria of \(z \sim 7.0\) LAEs consist of three components: (1) significant detection in NB964 image, (2) color excess of NB964 relative to the underlying broadband, and (3) nondetection in the bluer broadband (veto band) to filter out foreground galaxies.

We require our LAE candidates to be detected in the NB964 image with signal-to-noise ratio (S/N) \(> 5\) in \(2''\) diameter aperture. In order to rule out “diffuse” artificial signals in the images, we find it is useful to further apply a cut of S/N \(> 5\) in a \(1''\)35 aperture. The completeness of such detection criteria is more complex than a single aperture photometry cut but can still be estimated with injection and recovery simulations (see Section 4.1).

NB964-selected LAEs at \(z \sim 7.0\) would exhibit flux excesses between the narrowband and the underlying broadband images (HSC-\(y\) for COSMOS, and DECam-\(z\) for CDFS). To estimate the color excess, we simulate the photometric properties of \(z \sim 7\) LAEs from the model spectrum following Itoh et al. (2018). We assume a \(\delta\)-function-like Ly\(\alpha\) line profile and power-law UV continuum \((f_{\lambda} \propto \lambda^3\) with \(\beta = -2\)). The UV spectra are attenuated by the neutral IGM with the model from Madau (1995). We convolve the model spectrum with filter transmission (convolved with instrument response and atmospheric transmission, hereafter the same) to calculate the expected color excess for \(z \sim 6.5\)–7.0 LAEs with various Ly\(\alpha\) line equivalent widths. As shown in Figure 2, we adopt color cuts of BB–NB \(> 1.9\) and 0.8 for DECam-\(z\) and HSC-\(y\), respectively.
respective, corresponding to rest-frame \( \text{EW}_0 \) of Ly\( \alpha \) line \( \geq 10 \, \text{Å} \). Following Ota et al. (2017), we also plot the expected colors of the M/L/T dwarfs using the spectra from the SpeX Prism Library\(^{19} \) to examine whether dwarfs could be selected with our color cuts. Clearly, none of these dwarfs satisfy our criteria.

For COSMOS, we select LAEs using NB964 and Subaru HSC-\( g, r, i, z, y \) Ultradeep plus SSC-\( B \) images with the following criteria:

\[
S/N_{2y}(\text{NB964}) > 5 \text{ and } S/N_{135}(\text{NB964}) > 5; \\
\text{and } [(y - \text{NB964} > 0.8 \text{ and } S/N_{135}(y) > 3) \text{ or } S/N_{135}(y) < 3].
\]

where we utilize SExtractor AUTO magnitudes (measured with the dual imaging model on narrow- and broadband images) to calculate the color excess, as it is known that the Ly\( \alpha \) emission in LAEs is more extended than the UV continuum (e.g., Momose et al. 2016; Leclercq et al. 2017; Yang et al. 2017). In such a case, the AUTO magnitudes, measured within regions defined by the narrowband image, could better recover the intrinsic color compared with the common approach using aperture magnitudes (PSF-matched) to measure the color (see Appendix A for detailed comparison).

We note that sources with \( S/N_{135}(y) < 3 \) automatically satisfy the color-excess criterion \( (y - \text{NB964} > 0.8) \), as the underlying broadband image is much deeper than the narrowband image (see also Figure 3).

After masking out regions with significant CCD artifacts and bright stellar halos, we select LAEs in the central region of the NB964 exposure for which the NB964 image is covered with the HSC-\( y \) ultradeep exposure (with a total effective sky area of 1.90 deg\(^2 \)). For a small region of 0.45 deg\(^2 \) with no coverage of HSC-\( r \) ultradeep exposure, we employ HSC-\( r \) deep data from Aihara et al. (2018). All HSC and SSC images are resampled to match the DECam pixel scale.

\(^{19} \)http://pono.ucsd.edu/~adam/browndwarfs/spexprism

Similarly, for CDFS, we select LAEs using NB964 and DECam-\( u, g, r, i, z \) band with the following selection criteria:

\[
S/N_{2y}(\text{NB964}) > 5 \text{ and } S/N_{135}(\text{NB964}) > 5; \\
\text{and } [(z - \text{NB964} > 1.9 \text{ and } S/N_{2y}(z) > 3) \text{ or } S/N_{2y}(z) < 3];
\]

again, sources with \( S/N_{2y}(y) < 3 \) automatically satisfy the color-excess criterion \( (y - \text{NB964} > 1.9) \); see also Figure 3. Since DECam broadband images were obtained without significant dithering, we lost a significant portion of sky coverage owing to CCD gaps. The final selection was performed in a total effective area of 2.14 deg\(^2 \) with both deep broad- and narrowband coverage.

Note that we adopt a 2″ aperture for veto band photometry in CDFS but a 1′35 aperture for COSMOS. This is because COSMOS broadband images generally have better seeing than those in CDFS. We find that the 2″ aperture veto band photometry of some good candidates would be contaminated by nearby foreground sources. Measuring photometry with the 1′35 aperture avoids the loss of such candidates. We note that blending with foreground galaxies in the veto bands can still yield significant incompleteness in the final selected LAE sample, which we calculate with injection and recovery simulations in Section 4.1 and correct in the calculation of our LF.

### 3.2. Selected Candidates

A sample of 75 and 50 likely candidates were selected in COSMOS and CDFS, respectively, after excluding tens that were identified as obviously artificial owing to CCD artifacts, stellar halos, bleeding trails, and significant veto band signals in quick visual examinations. Three transients were further excluded in COSMOS using NB964 exposures obtained at different epochs. We then perform a careful visual inspection of the candidates. Although we adopt 3σ rejection in veto bands, 11 and 12 candidates in COSMOS and CDFS show weak counterparts in at least one of the veto broad bands and are excluded. These sources are more likely foreground transients or extreme emission-line galaxies (see also Section 3.3).
also remove 10 and 8 candidates in COSMOS and CDFS, respectively, whose NB964 signals appear more like weak CCD artifacts or noise spikes or are too close to adjacent bright objects. Though such steps are somewhat subjective, inspections from various team members often yield consistent classifications, and slight inconsistencies from various inspectors do not significantly alter the scientific results presented in this work. As foreground emission-line galaxies (ELGs) may trace the overdense regions (e.g., Hayashi et al. 2018), we further reject two candidates in the COSMOS field that are adjacent to foreground ELGs (those NB964 excess sources with veto band detections) within 3″.

We then examine the stacked veto band images (which is deeper than a single veto band) of the remaining candidates, and none of them show $S/N > 2$ in the stacked veto band. Finally, we obtain a clean sample of 49 and 30 LAE candidates in the COSMOS and CDFS fields, respectively, the thumbnail images of which are presented in Appendix B; the catalog will be released in a future work, together with candidates to be selected in upcoming new LAGER fields. In Figure 3 we plot the color–magnitude diagrams and the spatial distribution of our selected LAEs in COSMOS and CDFS, in which two possible elongated overdense regions are seen in COSMOS. Each has a two-dimensional scale of $\sim 75 \times 40$ cMpc$^2$ and contains $\sim 12$ LAEs, including 3 of which are luminous with $L_{\text{Ly} \alpha} > 10^{43.3}$ erg s$^{-1}$. Such large-scale structures of high-redshift LAEs probe the protoclusters in the early universe and have been reported at redshifts of 5.7 and 6.6 (Ouchi et al. 2005; Wang et al. 2005; Jiang et al. 2018; Harikane et al. 2019) and smaller (Shimasaku et al. 2003; Zheng et al. 2016). We note that five members of the large-scale structures...
have been spectroscopically confirmed using Magellan/IMACS (Hu et al. 2017), with a remarkably high success rate of 2/3. This indicates that these two structures are physically real. Spectroscopic follow-up of the remaining members is ongoing to further secure their identifications and will be presented in future work.

Using a 34 hr NB964 exposure, an overlapping UltraVISTA Y-band image, and deep Subaru SSC broadband images in the central 2 deg² region, Zheng et al. (2017) selected 23 LAEs at \( z \approx 7.0 \) with \( EW \geq 10 \) Å. Among them, 21 were recovered in this work using a 47.25 hr NB964 exposure and considerably deeper broadband images. One of the other two was detected in the 47.25 hr NB964 image with \( S/N < 5.0 \). It is a transient source, as the NB964 signal disappears in the latest 13.25 hr exposure. The final one passed the selection criteria but was also rejected as a variable source with new NB964 data.

The total number of LAEs selected in COSMOS in this work is 49, more than doubling the number of Zheng et al. (2017). Among the 28 new LAE candidates selected in this work but not in Zheng et al. (2017), 10 had NB964 \( S/N < 5 \) in the 34 hr exposure image, 7 had no SSC broadband coverage, 6 had too shallow or noisy broadband coverage, 1 was contaminated by a nearby source in veto band in 2" aperture, 2 were identified as possible noise spikes by visual examination of the faint narrowband signal (but reclassified as good candidates in this work with deeper NB964 exposure), and 2 were rejected owing to a visually identified marginal signal in one of the Subaru SSC veto bands. These two were reclassified as good candidates in this work using new and deeper HSC veto band images. The marginal veto bands signals previously seen for those two sources were due to a data processing flaw and disappear in reprocessed images.

The Ly\( \alpha \) line fluxes are calculated using the narrowband and the underlying broadband photometry by solving the following equation (Jiang et al., in preparation):

\[
\tilde{f}_{\nu,\text{NB}/\text{BB}} = \frac{\int (\tilde{f}_{\lambda,\text{line}} + \tilde{f}_{\lambda,\text{cont}}) T_{\lambda,\text{NB}/\text{BB}} d\lambda}{\int T_{\lambda,\text{NB}/\text{BB}} d\lambda} \times \frac{\tilde{\lambda}_{\text{NB}/\text{BB}}^2}{c},
\]

where \( \tilde{f}_{\nu,\text{NB}}, \tilde{f}_{\nu,\text{BB}} \) are the detected flux densities in the NB964 and the underlying broadband; \( T_{\lambda,\text{NB}}, T_{\lambda,\text{BB}} \) the corresponding filter transmission; \( \tilde{f}_{\lambda,\text{line}}, \tilde{f}_{\lambda,\text{cont}} \) the Ly\( \alpha \) line and UV continuum flux at wavelength \( \lambda \); and \( \tilde{\lambda}_{\text{NB}}, \tilde{\lambda}_{\text{BB}} \) the central wavelengths of the NB964 and broadband filter, respectively. During the calculation, we assume an Ly\( \alpha \) profile resembling a \( \delta \)-function at the center of the NB964 filter and a power-law UV continuum with slope of \( -2 \) that suffered neutral IGM attenuation with the model from Madau (1995).

For nondetections in the underlying broadband, we choose to calculate their broadband flux densities using 2\( \sigma \) limiting magnitudes. Note that while this approach provides a conservative estimation of Ly\( \alpha \) flux, it would systematically underestimate the line flux if the underlying broadband were not sufficiently deep (see Section 4.3 for further discussion). If the output continuum flux from the equation is 0 or negative, we fix the continuum flux to 0, which means that the NB964 flux is completely contributed by the Ly\( \alpha \) line. Although several LAEs have been spectroscopically confirmed, we still use photometric fluxes to obtain their Ly\( \alpha \) fluxes owing to the considerably large uncertainties in spectroscopic flux calibration.

### 3.3. Foreground Contaminant Emission-line Galaxies

The Ly\( \alpha \) emission line is often the only detectable feature of high-\( z \) LAEs with optical/IR spectroscopic follow-up observations (e.g., Wang et al. 2009). Particularly, in many cases the spectral quality is limited, and the line profile is unresolvable. Can we safely identify such single line detections as high-\( z \) LAEs? Foreground ELGs are potential contaminants in such cases, especially the extreme emission-line galaxies (EELGs), which have relative faint continua (e.g., Huang et al. 2015). Below we estimate the number of expected contaminant foreground ELGs in our sample.

Possible contaminant lines are \([\text{O} \text{ II}], [\text{O} \text{ III}], \) and \( H\alpha \) emission lines at \( z \approx 1.59, 0.93, \) and 0.47, respectively. With Hubble Space Telescope (HST) slitless grism spectroscopic data, Pirzkal et al. (2013) obtained the LFs and rest-frame EW\( \alpha \) distributions of \([\text{O} \text{ II}] \) line emitters at \( z \approx 0.5–1.6, [\text{O} \text{ III}] \) emitters at \( z \approx 0.1–0.9, \) and \( H\alpha \) emitters at \( z \approx 0–0.5. \) Assuming no strong evolution in these redshift bins and luminosity-independent EW distributions, we build artificial samples of \([\text{O} \text{ II}], [\text{O} \text{ III}], \) and \( H\alpha \) emitters at \( z \approx 1.59, 0.93, \) and 0.47, respectively, utilizing the LFs and EW distributions of Pirzkal et al. (2013). For each artificial ELG with assigned line luminosity and EW, we generate its mock spectrum by shifting the composite ELG spectrum from Zhu et al. (2015) to place the correspondent line at the central wavelength of NB964, adjust the strength of the line relative to continuum to match the assigned line EW, and further normalize the spectrum to match the assigned line luminosity. Conservatively, the EWs of other lines are fixed to values in the composite spectrum. Note that the \([\text{O} \text{ III}] \) doublet was unresolved by Pirzkal et al. (2013), but only one of the lines is covered by our narrowband image. We adopt a line ratio of \( [\text{O} \text{ III}] \lambda 4959/[\text{O} \text{ III}] \lambda 5007 = 0.40 \) based on the ELG composite spectrum.

We convolve the mock spectra with the transmission curves of the narrow- and broadband filters to calculate the expected magnitudes. We then apply our LAE selection criteria to the artificial ELG samples. The selection incompleteness described in Section 4.1 is also considered in the calculation. The estimated numbers of \([\text{O} \text{ II}], [\text{O} \text{ III}], \) and \( H\alpha \) emitters in our LAE samples are 0.14, 0.52, and 0.06 in COSMOS and 0.24, 0.83, and 0.35 in CDFS, respectively. In total, we predict the number of contaminant ELGs to be 0.72 in COSMOS and 1.42 in CDFS. The expected contamination in CDFS is higher, mainly because in this field the broadband images are slightly shallower (see Table 1) compared with COSMOS.

We note that only extreme ELGs can possibly contaminate our LAE sample. Such EELGs have continua steeper than the ELG composite spectrum, and the rest emission lines are also stronger than those in the ELG composite spectrum (Forrest et al. 2017). These factors would elevate the veto broadband flux densities we estimated above. Therefore, the number of contaminant foreground ELGs in the LAE sample we presented above has been conservatively overestimated. On the other hand, if the LF of ELGs strongly evolves with redshift (e.g., the density of \([\text{O} \text{ II}] \) emitters at \( z \approx 1.59 \)) is higher than the average value at \( z \approx 0.5–1.6 \), we would expect slightly more contaminants than expected above. We finally note that some of such contaminants may have been excluded with our visual examination (Section 3.2). Overall, we expect negligible foreground emission-line contaminants in our LAE sample, thanks to the ultradepth veto band images available.
4. Lyman α Luminosity Function

4.1. Sample Incompleteness

It is essential to correct the sample incompleteness for the calculation of the LF. Such incompleteness can be estimated through injection and recovery simulations, as described below.

We first run the Python package Balrog (Suchyta et al. 2016), which utilizes GALSIM (Rowe et al. 2015), to simulate pseudo-LAEs, apply PSF convolution, and randomly insert the galaxies into the NB964 images. The pseudo-galaxies have a Sérsic profile with a Sérsic index $n$ of 1.5 and half-light radius of 0.9 kpc, corresponding to 0.7 at $z \sim 7$. The adopted Sérsic index and half-light radius are similar to the recent UV continuum profile measurements of high-redshift LAEs and Lyman break galaxies (LBGs) in the EoR (e.g., 0.5–0.7 kpc for narrowband-selected LAEs and 0.9–1.0 kpc for broadband-selected LBGs; Jiang et al. 2013; Allen et al. 2017; Shibuya et al. 2019). The magnitudes of pseudo-galaxies in the narrow band are randomly given in the range of 21–26. We then run SExtractor on the NB964 images after injections, with the identical configuration we used for detecting true LAEs.

Note that the Lyman α emission in LAEs could be more extended than the UV continuum (e.g., Finkelstein et al. 2011; Momose et al. 2016; Leclercq et al. 2017; Yang et al. 2017). For instance, with HST narrowband imaging data, Finkelstein et al. (2011) reported that three $z \sim 4.4$ LAEs have an averaged Lyman α emission half-light radius of 1.1 kpc, larger than that of the UV continuum (0.7 kpc). Leclercq et al. (2017) reported the detection of extended Lyman α halos around $z \sim 3–6$ LAEs, observed with the Multi-Unit Spectroscopic Explorer at ESO-VLT. Through two-component (continuum-like and halo) decomposition, they reported an exponential scale length of $3.8 \pm 1.3$ kpc for the halo and $0.3 \pm 0.1$ kpc for the core in their highest-redshift bin ($z \sim 5–6$). Directly taking their measured Lyman α profiles, we calculate the effective half-light radius of the total Lyman α emission (core plus halo) for each LAE and find a medium value of 1.5 kpc at $z \sim 5–6$. To address such an effect, we also simulate pseudo-LAEs with larger half-light radius of 1.2 and 1.5 kpc and find negligible difference in the incompleteness measurements. Thus, in this work we adopt a half-light radius of 0.9 kpc to be consistent with previous works (e.g., Zheng et al. 2017; Konno et al. 2018).

We plot the fraction of the pseudo-galaxies that are detected (with S/N > 5 in both 2″ and 1″35 apertures) as a function of magnitude in Figure 4 (detection completeness hereafter). Though masking out the regions around the bright stellar halos and CCD artifacts is a common approach for LAE selection (e.g., Ota et al. 2017; Itoh et al. 2018), the detection completeness is still slightly less than unity even for the bright pseudo-galaxies. This is because they might still blend with bright foreground sources, making them undetectable by SExtractor in NB964 images. The detection completeness gradually drops with decreasing pseudo-galaxy brightness before reaching the limiting magnitudes, as blending with foreground galaxies could hinder their detections.

However, not all the NB964-detected pseudo-LAEs passed our LAE selection criteria, since many of them were blended with foreground sources that were not bright enough to block them from NB964 detections but sufficiently bright to make them fail the requirement of veto band nondetection and/or color excess. We apply our LAE selection criteria on the NB964-detected pseudo-galaxies and plot the recovery fraction (relative to the number of NB964-detected pseudo-objects, hereafter “selection completeness”) in Figure 4. Note that we insert the pseudo-galaxies only into the NB964 image and assume their underlying broadband fluxes to be zero. The effects if we insert also pseudo-underlying broadband fluxes based on Lyman α line EW are rather complicated (see Zheng et al. 2014). Basically, while high-EW pseudo-LAEs can be easily recovered by the selection procedure, some low-EW sources could be missed by our selection owing to photometric fluctuations. However, a contrary effect is that some pseudo-LAEs with intrinsic line EWs below our EW limit could also have their line EWs boosted by photometric fluctuations and thus be picked up. The net effect is an Eddington type bias, which can be quantitatively estimated with an accurate EW distribution, which is yet unavailable at $z \sim 7$. Nevertheless, 20 A further note is that the effect of the extended halo relies on both its size and relative brightness, which are yet unknown for $z \sim 7$ LAEs. Our simulations could be insufficient for large Lyman α blobs or LAEs with strong and extended halos.
as shown by Zheng et al. (2014), such bias is rather weak, as long as the underlying broadband image is >0.5–1.0 mag deeper than the NB image, a condition that is well satisfied by our data sets. Thus, in this work we do not consider broadband fluxes of pseudo-galaxies in the simulations.

Clearly, the effect of “selection incompleteness” is remarkable and shall not be neglected. Such incompleteness is mainly due to foreground contamination in the veto broadband photometry. The effect of blending with foreground sources in the veto band can also be roughly estimated with random aperture photometry. For example, only 74.9% of the 1°35 randomly placed apertures in the COSMOS HSC-g band image yield S/N < 3σ. The fraction further decreases to 68.3% and 59.6% if the aperture diameter increases to 2′′ and 3′′, respectively. Therefore, deriving veto band photometry using a larger aperture would yield stronger sample incompleteness due to foreground contaminations. The incompleteness is also sensitive to the depth and PSF of the veto broadband images, i.e., the foreground contamination to the veto broadband would be more severe for deeper images, or those with poorer PSF.

We further note that the “selection completeness” is not constant but magnitude dependent (Figure 4). The “selection completeness” gradually increases with increasing magnitude. This is because a fainter pseudo-LAE, if blended with foreground source(s), would more likely be treated as part of the adjacent object(s) and simply not detected in the narrowband image by SExtractor. Such an effect, which is more important toward fainter magnitudes, would suppress the detection completeness. Consequently, those non-detected pseudo-LAEs would be pre-excluded from the calculation of “selection completeness,” which in turn gets boosted (as seen in Figure 4). Near the detection limit where the detection completeness sharply drops, the effect is so strong that most of the detected pseudo-LAEs are located in sparse regions, i.e., free from contaminations, and the selection completeness even exhibits a significant peak. Meanwhile, the “selection completeness” significantly drops at faintest magnitudes, as most of the faintest pseudo-LAEs could be detected solely because they were injected by coincidence on top of foreground sources.

The total sample completeness (the product of detection completeness and selection completeness, i.e., the fraction of injections that can be recovered as LAEs) is plotted in Figure 4. We note that the “detection incompleteness” in the narrowband images has usually been corrected for the Lyα LF reported in the literature. Unfortunately, the “selection incompleteness,” which is indeed more prominent as we demonstrated above, has not been considered in previous studies.

4.2. Lyα Luminosity Function at z ~ 7

Following Zheng et al. (2017), we calculate the z ~ 7 LAE LF using the formula

$$\Phi(L) dL = \frac{1}{V_{\text{eff}} f_{\text{comp}}(NB)} \sum_{L_c \leq L_c - \Delta L/2} dL,$$

(5)

where $V_{\text{eff}}$ is the effective volume of the survey, which is calculated from sky coverage and redshift coverage, and $f_{\text{comp}}$ is the completeness described in Section 4.1 for each LAE with NB964 magnitude $N_B$. The effective volume is 1.29 × 10⁶ cMpc³ and 1.14 × 10⁶ cMpc³ for the CDFS and COSMOS fields, respectively, with bad regions, such as CCD artifacts and bright stellar halos, removed. We do not take the contamination into account, since we expect that only a few foreground ELGs can be included in our LAE sample (see Section 3.3).

The resulting LFs are plotted in Figure 5. The bright-end luminosity bump in COSMOS, first reported by Zheng et al. (2017), is confirmed with a doubly large sample size. A detailed comparison with the LF in Zheng et al. (2017) is presented in Section 4.3. We interpret the bump in COSMOS as evidence of ionized bubbles at z ~ 7 (see Section 5.1). Remarkably, while the faint-end LFs from two fields agree with each other, the bright-end bump is not seen in CDFS.

We fit a Schechter function to the LFs as

$$\Phi(L) dL = \Phi^* \left( \frac{L}{L^*} \right)^{\alpha} \exp \left( - \frac{L}{L^*} \right) d\left( \frac{L}{L^*} \right).$$

(6)

where $L^*$ and $\Phi^*$ are the characteristic luminosity and number density, respectively. We fix the faint-end LF slope $\alpha$ of the Schechter function to −2.5, consistent with those observed at z ~ 5.7 and 6.6 (e.g., Matthee et al. 2015; Santos et al. 2016; Konno et al. 2018). The three LAEs in the lowest-luminosity bin in COSMOS have selection completeness $f_{\text{comp}} < 0.1$ (see Equation (5)). This indicates that this luminosity bin suffers from incompleteness too strong to be accurately estimated and
corrected, and thus we exclude it from further analyses. In Figure 5 we fit the LFs from both fields in the luminosity range of $10^{42.65-43.4} \text{ erg s}^{-1}$, i.e., excluding the two brightest luminosity bins for COSMOS, as there are no LAEs in CDFS in these two bins. We use the Cash statistics (a maximum-likelihood-based statistics for Poisson data, i.e., low number of counts; Cash 1979) to estimate the best-fit value and error of $L^*$ and $\Phi^*$. The best-fit curves are plotted in Figure 5, and the best-fit Schechter parameters are listed in Table 2. To better illustrate the bright-end bump in COSMOS, we plot the Schechter function elevated and truncated at the bright end to match the two brightest bins.

We also present the LF averaged over two fields in the middle panel of Figure 5, together with the best-fit Schechter function (over the full luminosity range of $10^{42.64-43.6} \text{ erg s}^{-1}$). For comparison, we overplot the “selection incompleteness” uncorrected LF, e.g., with only “detection incompleteness” corrected. Leaving the “selection incompleteness” uncorrected clearly yields underestimated LF. The $z \sim 7.0$ LFs from Itoh et al. (2018) and Ota et al. (2017) are also overplotted, in both of which the “selection incompleteness” correction was unavailable and thus not applied.

4.3. The Effect of the Underlying Broadband Depth

In Figure 6 we compare the Ly$\alpha$ LF in COSMOS obtained in this work with that reported in Zheng et al. (2017). To enable a direct comparison, the selection incompleteness described in Section 4.1 is ignored in this plot, as it was uncorrected in Zheng et al. (2017). While at the highest luminosity bins both LFs appear consistent, the new LF obtained in this work is considerably higher at fainter luminosity bins. However, this is only partly due to the fact that we select more candidates in this work.

Another and dominant reason is the depth of the underlying broadband image. As described in Section 3.1, for an LAE candidate that is not detected in the underlying broadband, a widely used approach is to place a 2($\sigma$) upper limit to its broadband flux density and use such an upper limit and narrowband flux density to estimate the Ly$\alpha$ flux. As we demonstrate below, this step would yield significantly underestimated Ly$\alpha$ flux and bias the LF if the underlying broadband were not sufficiently deep.

![Figure 6](image-url)
Zheng et al. (2017) adopted NB964 and the UltraVISTA Y-band image to calculate the Ly$\alpha$ fluxes. For most of the faint candidates, UltraVISTA Y-band detections are not available and 2$\sigma$ upper limits were given to their broadband photometry. In this work, the underlying broadband in COSMOS is HSC-γ, which is considerably deeper than UltraVISTA Y (by ~1.1–2.5 mag, as the depth of UltraVISTA Y is not uniform). To simply illustrate such an effect, we recalculate the Ly$\alpha$ line luminosity and the LF of 23 LAE candidates selected by Zheng et al. (2017) with old NB964 photometry but new HSC-γ photometry. For sources that are not detected in HSC-γ, we adopt the 2$\sigma$ limiting magnitude of HSC-γ. The comparison of the resulted Ly$\alpha$ luminosities is given in the top panel of Figure 6, where we see that for a significant fraction of faint LAEs the Ly$\alpha$ luminosities had been underestimated with shallower underlying broadband photometry. As shown in Figure 6, the deeper underlying broadband could significantly elevate the faint-end LF to a level more consistent with this work. The bright-end LF does not change much because most of the luminous LAEs were already detected in UltraVISTA Y.

With simulations, Zheng et al. (2014) showed that the depth of the underlying broadband could significantly affect the LAE selection, and a broadband image ∼0.5–1.0 mag deeper than the narrowband is most efficient in selecting emission-line sources. In this work, we show an additional effect of the underlying broadband depth, which would affect the calculation of line flux and thus LF. This effect could be particularly significant for faint LAEs with large line equivalent width, for which we expect very weak underlying broadband signal, and whose line flux measurements would be obviously biased by an upper limit from the broadband image if it were not sufficiently deep. To estimate the required broadband depth that would eliminate this bias, we assume an extreme case with Ly$\alpha$ line only. The line signal is detected in the narrow band with S/N > 5, and we expect to detect it in the underlying broad band with S/N > 20. The underlying broad band is thus required to be 2.5 log(W$_{NB}$/W$_{SB}$) − 2.5 log(5/2) deeper than the inside narrow band, where W$_{NB}$ and W$_{BB}$ are the width of the narrow- and broadband filters. Practically, LAEs have finite line EW; thus, we expect continuum signal in both narrow band and the underlying broad band, and broad band ∼1.0–1.5 mag deeper than the narrow band would be sufficient, depending on the bandpass of the filters. The underlying broad bands adopted in this work are indeed sufficiently deep, and the LFs we obtained are free from significant bias.

5. Discussion

5.1. The Bright-end Bump in the Ly$\alpha$ Luminosity Function at z ∼ 7.0

Zheng et al. (2017) first detected a bright-end bump in the LF of z ∼ 7.0 LAEs in the COSMOS field with four luminous LAEs (L$_{Ly\alpha}$ > 10$^{43.3}$ erg s$^{-1}$). This suggests the existence of ionized bubbles at z ∼ 7 that reduce the opacity of neutral IGM around the luminous LAEs (see Section 4.3 in Zheng et al. 2017). Such a bright-end LF bump is confirmed in this work, with six luminous LAEs (L$_{Ly\alpha}$ > 10$^{43.5}$ erg s$^{-1}$) selected in the COSMOS field. One of the newly selected luminous LAEs did not pass the selection in Zheng et al. (2017) because it is close to a nearby bright source and its 2″ aperture veto band photometry is significantly contaminated. It is selected in this work, as we adopt a 1″ aperture in our veto band photometry. Another newly selected luminous LAE was classified as a possible foreground source in Zheng et al. (2017) owing to visually identified marginal signal in one of the previously adopted veto bands. With the deeper HSC ultradeep images used in this work (also with better seeing), we did not reveal any signal in any of the new veto bands. The marginal signal in the old veto band is indeed due to a data processing flaw and was confirmed to be artificial with improved reprocessing of the old veto band images.

Strikingly, while the faint-end LF from a second LAGER field CDFS is quite consistent with that from COSMOS, the bright-end LF bump is not seen in CDFS, in which only one luminous LAE is selected. Such field-to-field variation in the bright-end LF is also visible when comparing with other z ∼ 7.0 LAE samples in the literature. Ota et al. (2017) identified 20 z ∼ 7.0 LAE candidates using SSC and the NB973SSC filter. The sample was selected in a smaller volume (0.61 × 10$^{6}$ Mpc$^3$) with no LAEs with L$_{Ly\alpha}$ > 10$^{43.3}$ erg s$^{-1}$. Itoh et al. (2018) identified 34 z ∼ 7.0 LAE candidates using Subaru HSC and the NB973HSC filter in two fields (COSMOS: 1.15 × 10$^{6}$ Mpc$^3$, SXDS: 1.04 × 10$^{6}$ Mpc$^3$). While Itoh et al. (2018) claimed no evidence of bright-end LF bump, they did identify four luminous LAEs in COSMOS, but zero in SXDS. Such field-to-field variation is similar to what we see in the two LAGER fields. Additional reasons that Itoh et al. (2018) did not detect the bright-end LF bump include that (1) Itoh et al. (2018) adopted larger luminosity bins in their LFs (0.2 dex compared with 0.125 dex adopted in this work and Zheng et al. 2017), and (2) the NB973HSC filter that Itoh et al. (2018) used has a Gaussian-like transmission curve with clear wings (Itoh et al. 2018), while the transmission curve of our NB964 filter is more boxcar shaped (see Zheng et al. 2019 and Figure 1). A Gaussian-like transmission curve would yield large uncertainties in the Ly$\alpha$ luminosity derived from narrowband photometry and would significantly underestimate the luminosity and number of LAEs whose Ly$\alpha$ lines fall on the wings of the bandpass. Such large uncertainties could likely smear out the bump feature in the LF.

As the bandpasses of NB973HSC and our NB964 overlap (Zheng et al. 2019), we compare our LAEs with that of Itoh et al. (2018) in COSMOS and find seven common LAEs selected by both programs. Particularly three out of the four luminous LAEs selected by Itoh et al. (2018) are included in our sample. Two of them (HSC-z7LAE3 and HSC-z7LAE25) were classified as luminous LAEs by Itoh et al. (2018), but only after they recalibrated their Ly$\alpha$ luminosities using our spectroscopic redshifts (Hu et al. 2017), i.e., they fall on the NB973HSC transmission curve wing. We select another (HSC-z7LAE2) that coincides with the core of one LAE-overdense region in Figure 3, but its NB964-based Ly$\alpha$ luminosity (10$^{42.7}$ erg s$^{-1}$) is considerably lower than 10$^{43.4}$ from Itoh et al. (2018). The last luminous LAE (HSC-z7LAE1) selected by Itoh et al. (2018) is also significantly detected in our NB964 image. This source, however, did not pass our selection owing to foreground contamination in the veto bands. After excluding the

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21 Whether the bandpasses of the broad and narrow bands overlap also matters. For instance, the bandpass of UltraVISTA Y in fact does not overlap with that of NB964; thus, in UltraVISTA Y we only expect UV continuum signal but not the Ly$\alpha$ line. In this sense, an overlapping broad band (like HSC-γ) is preferred.

22 We examine the effect of the luminosity bin using our own data set and confirm that adopting the 0.2 dex luminosity bin could weaken the bright-end LF bump we see with the 0.125 dex bin in COSMOS.

23 Furthermore, we also detected HSC-z7LAE7 of Itoh et al. (2018) in our NB964 image, but it did not pass our selection owing to contamination by adjacent sources. Its NB964-derived Ly$\alpha$ luminosity is 10$^{43.16}$ erg s$^{-1}$, similar to 10$^{43.18}$ from Itoh et al. (2018).
corresponding best-fit Schechter function. The \( z \sim 7 \) LFs from Itoh et al. (2018) and Ota et al. (2017) are plotted with red crosses and diamonds, respectively, which agrees well with ours. The blue squares and circles are the \( z \sim 5.7 \) LFs at \( z \sim 5.7 \) from Ouchi et al. (2008) and Konno et al. (2018), respectively. The green open squares and circles are the Ly\( \alpha \) LFs at \( z \sim 6.6 \) from Ouchi et al. (2010) and Konno et al. (2018), respectively. The purple open triangles are the Ly\( \alpha \) LFs at \( z \sim 7.3 \) from Konno et al. (2014). The blue, green, and purple solid lines are the corresponding best-fit Schechter function from \( z \sim 5.7, 6.6, \) and 7.3 LFs.

Contamination, the NB964-derived Ly\( \alpha \) luminosity of HSC-z7LAE1 is \( 10^{43.5} \) erg s\(^{-1}\), also considerably lower than \( 10^{43.5} \) from Itoh et al. (2018). Both HSC-z7LAE1 and HSC-z7LAE2 might fall on the transmission curve wing of our NB964 filter, i.e., have underestimated NB964-based Ly\( \alpha \) luminosity.

If HSC-z7LAE1 and HSC-z7LAE2 are included as luminous LAEs in our sample, the number of luminous LAEs selected in LAGER-COSMOS rises to eight, further strengthening the robustness of the bright-end LF bump and the field-to-field variation. We also stress that the three luminous LAEs in the COSMOS field and the single luminous LAE in CDFS have been spectroscopically confirmed (Hu et al. 2017; Yang et al. 2019). Meanwhile, as shown in Figure 7, our new Ly\( \alpha \) LF at \( z \sim 7.0 \), averaged over two LAGER fields, is well consistent with those from Ota et al. (2017) and Itoh et al. (2018).

All six luminous LAEs are located within the two large-scale structures (Figure 3). This indicates that large ionized bubbles at \( z \sim 7.0 \) are closely associated with cosmic overdensities. Note that two \( z \sim 7 \) LAEs with projected distance of \( \sim 90 \) pkpc are confirmed by Castellano et al. (2018), which are also selected in an overdense region identified with several LBG candidates (Castellano et al. 2016). These provide direct observational supports to the inside-out reionization topology (e.g., Iliev et al. 2006; Choudhury et al. 2009; Friedrich et al. 2011). Further clustering analysis and follow-up observations of the overdense regions in COSMOS are essential to study the patchy reionization. The clear field-to-field variation of the bright-end LF manifests the need of LAE searches in even more fields to probe the reionization and large-scale structures in the early universe.

5.2. Evolution of Ly\( \alpha \) Luminosity Function and Constraint to Neutral Hydrogen Fraction

In Figure 7, we plot our Ly\( \alpha \) LF (averaged over two LAGER fields) at \( z \sim 7.0 \) together with those at \( z \sim 5.7–7.3 \) (Ouchi et al. 2008, 2010; Konno et al. 2014, 2018). We stress that the “selection incompleteness” described in Section 4.1 was not corrected in this plot, as such incompleteness was not available for LFs given in literature. We assume that those LAE samples at redshift \( 5.7–7.3 \) suffer from similar “selection incompleteness” when we compare the uncorrected LFs to demonstrate cosmic evolution in the LF. A gradual evolution between redshifts of \( 5.7 \) and \( 7.3 \) is clearly seen in Figure 7. Note that the LF at \( z \sim 7.3 \) is based on a rather small photometric sample (seven LAEs; Konno et al. 2014); thus, the error bars are considerably larger. To further quantify the evolution of LFs from \( z \sim 5.7 \) to \( 7.3 \), we plot the contours of best-fit Schechter function parameters \( L^* \) and \( \phi^* \) for LFs at \( z \sim 5.7, 6.6, 7.0 \), and \( 7.3 \) in Figure 8. In this plot, for our LF at \( z \sim 7.0 \), we plot both “selection incompleteness” corrected (dashed red) and uncorrected (solid red) results to illustrate the effect of such incompleteness correction.

The luminosity density of Ly\( \alpha \) photons is derived by integrating our Ly\( \alpha \) LF in the luminosity range of \( \log L_{\text{Ly}\alpha} \) [erg s\(^{-1}\)] = 42.4–44. The evolution of Ly\( \alpha \) luminosity density from \( z \sim 5.7 \) to \( 7.3 \) is plotted in Figure 9. We also plot the UV luminosity density from Finkelstein et al. (2015), based on the galaxy LFs from \( z \sim 4 \) to 8 using galaxies selected by photometric redshift with Hubble Space Telescope (HST) imaging data. Below we estimate the effective IGM transmission factor \( T_{\text{IGM}} \) and neutral hydrogen fraction \( \chi_{\text{HI}} \) following Ouchi et al. (2010). The observed Ly\( \alpha \) luminosity density can be simply converted from UV luminosity density:

\[
\rho L_{\text{Ly}\alpha} = \kappa T_{\text{IGM}} f_{\text{esc}} \rho_{\text{UV}},
\]  

where \( \kappa \) is the conversion factor from UV photons to Ly\( \alpha \) photons, \( f_{\text{esc}} \) the Ly\( \alpha \) escape fraction through the ISM (Dijkstra et al. 2007a, 2010; Cai et al. 2014; Dayal et al. 2018) and \( T_{\text{IGM}} \) the transmission of the IGM. Assuming that the properties of ISM and stellar population are the same at \( z = 5.7 \) and 7.0, the
Figure 9. Evolution of Lyα luminosity density (dashed line, uncorrected for sample selection incompleteness) from z ∼ 5.7 to 7.3. The Lyα luminosity densities at z ∼ 5.7 and 6.6 are from Konno et al. (2018), and the Lyα luminosity densities at z ∼ 7.3 are from Konno et al. (2014). We also plot the evolution of UV luminosity density (inverse triangles) derived by Finkelstein et al. (2015). The large symbols and the solid line for Lyα luminosity density are corrected for LAE sample “selection incompleteness,” assuming a common correction factor of 0.3 dex as we derived for our z ∼ 7.0 LAE sample.

IGM transmission at z ∼ 7.0 can be calculated:

\[
\frac{T_{\text{IGM}}}{T_{5.7}} = \frac{\rho_{\text{Ly} \alpha}}{\rho_{5.7}} = \frac{\rho_{\text{Ly} \alpha}}{\rho_{5.7}}.
\]

We linearly interpolate the UV luminosity density in Figure 9 (Finkelstein et al. 2015) and estimate \(\rho_{5.7}/\rho_{5.7} = 0.63 \pm 0.09\). We then obtain \(T_{7.0} / T_{5.7} = 0.63 \pm 0.12\) with Equation (8), which indicates statistically significant evolution in the IGM suppression to the Lyα line.

It is model dependent to estimate the neutral hydrogen fraction \(\chi_{\text{HI}}\) based on the evolution of \(T_{\text{IGM}}\). Below we present \(\chi_{\text{HI}}\) inferred with several theoretical models. With an analytical approach, Santos (2004) calculated the Lyα emission transmission through IGM as a function of neutral hydrogen fraction \(\chi_{\text{HI}}\) in the early universe, considering the effects of IGM dynamics and galactic winds. Though the Lyα transmission through the IGM is highly sensitive to the Lyα line velocity offset, we can estimate the IGM neutral hydrogen fraction by comparing the observed \(T_{7.0} / T_{5.7}\) with Figure 25 of Santos (2004) while assuming no evolution in the Lyα line velocity offset between redshift 5.7 and 7.0. By doing so, we estimate a neutral hydrogen fraction of 0.25–0.50 for a galactic wind model with Lyα velocity offset of 360 km s\(^{-1}\) and 0.30–0.50 for the case of no Lyα velocity shift.

Second, the observed evolution of Lyα LFs can also be compared with radiative transfer simulations to constrain the reionization. McQuinn et al. (2007) calculated the effect of reionization on Lyα LFs at \(z = 6.6\) with 200 Mpc radiative transfer simulations. The expected suppression to Lyα-emitting galaxies and probe the cosmic reionization. We deploy a large-area survey for \(z \sim 7.0\) LAEs (LAGER) with a custom-made narrowband filter installed on DECam on board the CTIO 4 m Blanco telescope. In this paper, we present LAEs selected in the ultradeep LAGER-COSMOS field and a second deep field LAGER-CDFS. We present the Lyα LF at \(z \sim 7.0\) and new knowledge inferred about cosmic reionization. Our major results are listed below:

1. We accumulate a 47.25 hr DECam NB964 exposure in COSMOS and a 32.9 hr exposure in CDFS field. We select 49 \(z \sim 7.0\) LAEs in COSMOS and 30 in CDFS, building a largest-ever LAE sample at \(z \sim 7.0\).
2. We find obvious LAE sample incompleteness due to foreground contamination in bluer veto broadband photometry. Such selection incompleteness (30%–40% in this work), depending on the confusion level of the broadband images (seeing and depth), could cause underestimation of the LF of high-redshift galaxies and thus should be carefully corrected.
3. We show that while calculating the Lyα luminosity based on narrow- and underlying broadband photometry, placing an upper limit to the broadband flux for nondetection might significantly bias the calculation of Lyα flux and LF, if the broadband image is not sufficiently deep. We recommend that the underlying broad band be \(\sim 1.0–1.5\) mag deeper than the narrow band to avoid such bias.
4. Six luminous LAEs with \(L_{\text{Ly} \alpha} > 10^{43.3}\) erg s\(^{-1}\) constitute a bright-end bump in the LF in COSMOS, supporting the patch reionization scenario. The bump is, however, not seen in CDFS, in which only one luminous LAE is selected. Except for the bright-end bump, the LFs from two fields agree with each other and with those at \(z \sim 7.0\) in literature.
5. Two clear LAE-overdense regions are detected in COSMOS, making them the highest-redshift protoclusters observed to date. All six luminous LAEs in COSMOS fall in the overdense regions, further supporting the inside-out reionization topology.
6. We compare the LAGER LAE LF at \(z \sim 7.0\) with those at \(z \sim 5.7, 6.6,\) and 7.3 reported in the literature, assuming that they suffer similar “selection incompleteness.” We infer an average neutral hydrogen fraction of \(\chi_{\text{HI}} = 0.2 – 0.4\) at \(z \sim 7.0\).

We thank the anonymous referee for the valuable comments and Zhen-Yi Cai and Edmund Christian Herenz for the informative discussions. This work is supported by the National Science Foundation of China (grant Nos. 11421303 and 11890693) and the CAS Frontier Science Key Research Program (QYZDJ-SSW-SLH006). Z.-Y.Z. is sponsored by the...
effect is stronger for AUTO-color. In the middle panel of narrowband photometry. As our AUTO magnitudes are generally the broadband photometry is relatively more prominent than to the foreground sources show no color excess, the contamination to photometry in the narrow and broad bands, i.e., as most contamination from foreground sources to the pseudo-LAE faint end, behaves slightly better.

Figure 10, we exclude pseudo-LAEs with S<sub>N</sub> < 2 in veto bands (S/N < 2 in veto bands). In the top and middle panels, the injected sources have identical Sérsic profiles (with half-light radius of 0.9 kpc) in both the NB964 image and HSC-y image. Bottom panel: similar to the middle panel, but the injected sources have slightly larger size in the narrow band (with half-light radius of 1.2 kpc in NB964 and 0.9 kpc in HSC-y). The gray dashed lines indicate the input color.

Appendix A
On the Color Measurement

We examine the reliability of using SExtractor AUTO magnitudes to measure the narrowband to broadband color of LAEs, utilizing the injection and recovery simulations we introduced in Section 4.1. We use the COSMOS field to present our analyses and results.

Following Section 4.1, we insert pseudo-LAEs into the narrow band using a profile with Sérsic index of 1.5 and half-light radius of 0.9 kpc. We also insert corresponding signals into the underlying broadband HSC-y (assuming an intrinsic color excess of 1 mag) using an identical source profile. In the top panel of Figure 10, we plot the peak value and 1σ scatter (measured through fitting the distribution with a Gaussian) of the output colors, as a function of the detected narrowband magnitude. We find that while the AUTO-color could precisely recover the input value at the bright end, it slightly underestimates the color at the faint end. Meanwhile, the commonly used aperture color (using magnitudes measured on PSF-matched images within a fixed 2′ aperture; e.g., Ouchi et al. 2010; Ota et al. 2017), although it also underestimates the color at the faint end, behaves slightly better.

The color underestimation at the faint end is mainly due to contamination from foreground sources to the pseudo-LAE photometry in the narrow and broad bands, i.e., as most foreground sources show no color excess, the contamination to the broadband photometry is relatively more prominent than to the narrowband photometry. As our AUTO magnitudes are generally measured in regions larger than a 2′ aperture, the contamination effect is stronger for AUTO-color. In the middle panel of Figure 10, we exclude pseudo-LAEs with S/N > 2 in any veto band to minimize the effect of contamination. We then see negligible difference between two approaches, and both could reliably measure the input color at all magnitudes (though the AUTO-color shows slightly larger scatter). Since we need to exclude sources with foreground contaminations anyway, both approaches are similarly reliable from this respect.

However, it is known that the Lyα emission in LAEs at lower redshifts is more extended than the UV continuum (e.g., Momose et al. 2016; Leclercq et al. 2017; Yang et al. 2017). In this case the aperture color would underestimate the intrinsic value of LAEs. To depict such an effect, we perform injections adopting slightly larger Lyα emission size (1.2 kpc half-light radius in the narrow band, and 0.9 kpc in the broad band). The recovered color is presented in the bottom panel of Figure 10, in which we see that, in the case of more extended Lyα emission, the AUTO-color behaves better than aperture color, especially at the bright end. Note that the sizes and the Sérsic profiles here are adopted for illustration only. For instance, the half-light radius of 1.2 kpc we adopted is smaller than the typical size of the Lyα profile measured by Leclercq et al. (2017) at lower redshifts (see also Section 4.1), that is, if the Lyα spatial profile of z ~ 7.0 LAEs is similar to that seen at lower redshifts, the effect will be even more significant than the modest case we illustrate above.

Appendix B
Thumbnail Images of Our LAE Candidates

We show the thumbnail images of our LAE candidates in the COSMOS and CDFS fields in Figure 11. We plot the veto broadband images, stacked veto broadband images (hereafter BB in the Figure 11), NB964 images, and underlying broadband images for each LAE candidate.
Figure 11. Veto broadband images, stacked veto broadband images (namely, BB), NB964 images, and the underlying broadband images for LAE candidates in the COSMOS and CDFS fields. The size of each image is $\sim5''4 \times 5''4$. The images are sorted by NB964 AUTO magnitude. Note that the broadband images from HSC plotted here were before resampling (for illustration only).
Figure 11. (Continued.)

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**References**

Abbott, T. M. C., Abdalla, F. B., Allam, S., et al. 2018, *ApJS*, 239, 18
Aihara, H., Armstrong, R., Bickerton, S., et al. 2018, *PASJ*, 70, S8
Allen, R. J., Kacprzak, G. G., Glazebrook, K., et al. 2017, *ApJL*, 834, L11
Annis, J., Soares-Santos, M., Strauss, M. A., et al. 2014, *ApJ*, 794, 120
Baugh, E., Venmans, B. P., Muzzucelli, C., et al. 2018, *Natur*, 553, 473
Bertin, E. 2011, in ASP Conf. Ser. 442, Astronomical Data Analysis Software and Systems XX, ed. I. N. Evans et al. (San Francisco, CA: ASP), 435
Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393
Bertin, E., Mellier, Y., Radovich, M., et al. 2002, in ASP Conf. Ser. 281, Astronomical Data Analysis Software and Systems XI, ed. D. A. Bohlender, D. Durand, & T. H. Handley (San Francisco, CA: ASP), 228
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, *ApJ*, 803, 34
Cai, Z.-Y., Lapi, A., Bressan, A., et al. 2014, *ApJ*, 785, 65
Cash, W. 1979, *ApJ*, 228, 939
Castellano, M., Dayal, P., Pentericci, L., et al. 2016, *ApJL*, 818, L3
Castellano, M., Pentericci, L., Vanzella, E., et al. 2018, *ApJL*, 863, L3
Castelli, F., & Kurucz, R. L. 2004, *arXiv:astro-ph/0405087*
Choudhury, T. R., Hachnelt, M. G., & Regan, J. 2009, *MNRAS*, 394, 960
Dayal, P., & Ferrara, A. 2018, *PhR*, 780, 1
Diehl, H. T., Angstadt, R., Campa, J., et al. 2008, *Proc. SPIE*, 7021, 702107
Dijkstra, M. 2014, *PASA*, 31, e040
Dijkstra, M., Lidz, A., Wyithe, J., & Stuart, B. 2007a, *MNRAS*, 377, 1175
Dijkstra, M., Wyithe, J. S. B., & Haman, Z. 2007b, *MNRAS*, 379, 253
Dijkstra, M., Wyithe, J., & Stuart, B. 2010, *MNRAS*, 408, 352
Fan, X., Strauss, M. A., Becker, R. H., et al. 2006, *AJ*, 132, 117
Finkelstein, S. L., Cohen, S. H., Windhorst, R. A., et al. 2011, *ApJ*, 735, 5
Finkelstein, S. L., Ryan, R. E., Jr., Papovich, C., et al. 2015, *ApJ*, 810, 71
Forrest, B., Tran, K.-V. H., Brousard, A., et al. 2017, *ApJL*, 838, L12
Friedrich, M. M., Meli, G., Alvarez, M. A., Shapiro, P. R., & Iliev, I. T. 2011, *MNRAS*, 413, 1353
Furlanetto, S. R., Zaldarriaga, M., & Hernquist, L. 2006, *MNRAS*, 365, 1012
Greiner, J., Krühler, T., Fynbo, J. P. U., et al. 2009, *ApJ*, 693, 1610
Harikane, Y., Ouchi, M., Ono, Y., et al. 2019, *ApJ*, 883, 142
Hayashi, M., Tanaka, M., Shimakawa, R., et al. 2018, *PASJ*, 70, S17
Hibon, P., Cuby, J.-G., Willis, J., et al. 2010, *A&A*, 515, A97
Hibon, P., Kashikawa, N., Willott, C., Iye, M., & Shibuya, T. 2012, *ApJ*, 744, 89

**Figure 11.** (Continued.)
