The Stellar Mass, Star Formation Rate and Dark Matter Halo Properties of LAEs at $z \sim 2$

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Received (2017 July 28); Accepted (2017 November 22)

Abstract

We present average stellar population properties and dark matter halo masses of $z \sim 2$ Ly$\alpha$ emitters (LAEs) from SED fitting and clustering analysis, respectively, using $\sim 1250$ objects ($NB387 \leq 25.5$) in four separate fields of $\sim 1$ deg$^2$ in total. With an average stellar mass of $10.2 \pm 1.8 \times 10^8$ M$_\odot$ and star formation rate of $3.4 \pm 0.4$ M$_\odot$ yr$^{-1}$, the LAEs lie on an extrapolation of the star-formation main sequence (MS) to low stellar mass. Their effective dark matter halo mass is estimated to be $4.0^{+5.1}_{-2.9} \times 10^{10}$ M$_\odot$ with an effective bias of $1.22^{+0.16}_{-0.18}$ which is lower than that of $z \sim 2$ LAEs ($1.8 \pm 0.3$), obtained by a previous study based on a three times smaller survey area, with a probability of 96%. However, the difference in the bias values can be explained if cosmic variance is taken into account. If such a low halo mass implies a low HI gas mass, this result appears to be consistent with the observations of a high Ly$\alpha$ escape fraction. With the low halo masses and ongoing star formation, our LAEs have a relatively high stellar-to-halo mass ratio (SHMR) and a high efficiency of converting baryons into stars. The extended Press-Schechter formalism predicts that at $z = 0$ our LAEs are typically embedded in halos with masses similar to that of the Large Magellanic Cloud (LMC); they will also have...
similar SHMRs to the LMC, if their SFRs are largely suppressed after $z \sim 2$ as some previous studies have reported for the LMC itself.

Key words: galaxies: evolution — galaxies: high-redshift — galaxies: star formation — galaxies: halos

1 Introduction

Galaxies assemble their stellar mass through star formation and galaxy merging under the gravitational influence of their host dark matter halos, which also grow through mass accretion and merging (e.g., Somerville & Davé 2015). Hence, observations of the intrinsic properties of galaxies and their dependence on halo mass in the past are key to tracing the history of the mass growth of galaxies and constraining the physical processes that control star formation (SF).

Low-mass galaxies at high redshift are “building blocks” of present-day galaxies over a wide mass range. Nebular emission lines are useful to detect faint (or low-mass) galaxies at high redshift ($z$), among which Lyα line has been used most commonly. Tens of thousands of Lyα emitters (LAEs) have been selected so far by narrowband (NB) imaging observations ($z \sim 2$–7: e.g., Malhotra & Rhoads 2002; Taniguchi et al. 2005; Shimasaku et al. 2006; Gronwall et al. 2007; Ota et al. 2008; Ouchi et al. 2009; Guaita et al. 2010; Hayes et al. 2010; Hu et al. 2010; Ouchi et al. 2010; Ciardullo et al. 2012; Nakajima et al. 2012; Yamada et al. 2012; Konno 2014; Sandberg et al. 2015; Ota et al. 2017; Shimakawa et al. 2017; Shibuya et al. 2017a) and/or spectroscopically identified ($z \sim 0$–7: e.g., Shapley et al. 2003; Kashikawa et al. 2006; Reddy et al. 2008; Cowie et al. 2010; Blanc et al. 2011; Dressler et al. 2011; Kashikawa et al. 2011; Curtis-Lake et al. 2012; Mallery et al. 2012; Nakajima et al. 2013; Erb et al. 2014; Hayes et al. 2014; Hashimoto et al. 2013; Hathi et al. 2016; Karman et al. 2017; Shibuya et al. 2017b) and they are one of the important populations of high-$z$ star forming galaxies.

Typical LAEs at high redshifts have low stellar masses ($M_* \lesssim 10^7 M_\odot$: Ota et al. 2010a; Guaita et al. 2011; Kusakabe et al. 2015; Hagen et al. 2016; Shimakawa et al. 2017). They are also dust poor (Lai et al. 2008; Blanc et al. 2011; Kusakabe et al. 2015) and metal poor (Nakajima et al. 2012, 2013; Nakajima & Ouchi 2014; Kojima et al. 2017), and have young stellar populations (Pirzkal et al. 2007; Gawiser et al. 2007; Hagen et al. 2014), although a small fraction of them are attributed to dusty galaxies with high stellar masses (Nilsson et al. 2009; Ono et al. 2010b; Pentericci et al. 2010; Oteo et al. 2012).

Since their dust emission is typically too faint to be detected by current infrared (IR) telescopes without gravitational lensing, estimates of their star formation rates (SFRs) vary greatly depending on the method of measurement, making it difficult to determine their mode of star formation (i.e., starburst or more typical of main-sequence (MS) galaxies) (Finkelstein et al. 2015; Hagen et al. 2016; Hashimoto et al. 2017; Shimakawa et al. 2017). Only at $z \sim 2$ has the average SFR of LAEs been estimated from ultraviolet (UV) and dust emission, by means of stacking, from which they are found to lie on the star formation main sequence (SFMS: e.g., Daddi et al. 2007), although the analysis is limited to only a single survey field (Kusakabe et al. 2015). Recent observations have revealed that the stellar properties of LAEs are similar to those of other emission line galaxies at $z \sim 2$ (Hagen et al. 2016). Shimakawa et al. (2017) have also found that LAEs at $M_* \lesssim 10^{10} M_\odot$ obey the same $M_* - \text{SFR}$ and $M_* - \text{size}$ relations as Hα emitters (HAEs) at $z = 2.5$. Thus, there is a possibility that LAEs are normal star-forming galaxies in the low stellar mass regime at high redshift.

With regard to their dark matter halos, LAEs have been found to reside in low-mass halos from clustering analysis ($M_h \sim 10^{10} - 10^{12} M_\odot$ over $z \sim 2$–7: e.g., Ouchi et al. 2005; Kovač et al. 2007; Gawiser et al. 2007; Shioya et al. 2009; Guaita et al. 2010; Ouchi et al. 2010; Bielby et al. 2016; Diemer et al. 2017; Ouchi et al. 2017). These results imply that LAEs at $z \sim 4$–7 and $z \sim 2$–3 evolve into massive elliptical galaxies and $L_*$ galaxies at $z = 0$, respectively. For both cases, high-$z$ LAEs are likely candidates of the “building blocks” of mature galaxies in the local Universe (see also Rauch et al. 2008; Dressler et al. 2011) because they are embedded in the lowest-mass halos among all the high-$z$ galaxy populations.

With stellar masses, SFRs, and halo masses in hand, one can obtain the stellar to halo mass ratios ($\equiv M_*/M_h$: SHMR) and baryon conversion efficiencies ($\equiv \text{SFR}/\text{baryon accretion rate}: \text{BCE}$) to quantify the star formation efficiency in dark matter halos. The SHMR measures the time-integrated (time-averaged) efficiency of star formation up to the observed epoch, while the BCE measures the efficiency at the observed epoch. Previous studies show tight relations of the SHMR and BCE of galaxies as a function of $M_h$ over a wide redshift range (e.g., Behroozi et al. 2013; Moster et al. 2013; Rodríguez-Puebla et al. 2017). These relations are usually given as the average relations in the literature thus presented here as such. The SF mode also tells us the nature of star formation in terms of stellar mass growth.

For LAEs, these parameters are most reliably measured at $z \sim 2$, because this redshift is high enough that the Lyα line is redshifted into the optical regime where a wide-field ground-based Lyα survey, critical for clustering analysis, is possible, and low enough that deep rest-frame near-infrared (NIR) photometry, critical for SED fitting of faint galaxies like LAEs, is
still possible with Spitzer/IRAC. This redshift is also scientifically interesting because star-formation activity in the universe is at a global maximum (Madau & Dickinson 2014).

To date, there is only one clustering study carried out at \( z \sim 2 \), by Guaita et al. (2010), for which they obtain a relatively high halo mass of \( \log_{10}(M_{\text{halo}}/M_{\odot}) \sim 11.5^{+0.4}_{-0.5} \), which implies an SHMR comparable to or lower than the average relations by Behroozi et al. (2013) and Moster et al. (2013) at the same dark halo mass. Their LAEs are estimated to have a comparable BCE with the average relation by Behroozi et al. (2013) but its uncertainty is as large as \( \sim 1 \) dex. However, this halo mass estimate may suffer from statistical uncertainties due to a small sample size (\( N \sim 250 \) objects) and systematic uncertainties from cosmic variance due to a small survey area (\( \sim 0.3 \text{deg}^2 \)). A larger number of sources from a larger survey area with deep multi-wavelength data is needed to obtain SHMRs and BCEs accurately and to overcome these uncertainties.

In this paper, we study star forming activity and its dependence on halo mass for \( z \sim 2 \) LAEs using \( \sim 1250 \) NB-selected LAEs from four deep survey fields with a total area of \( \sim 1 \text{deg}^2 \). Section 2 summarizes the data and sample used in this study. In section 3 we estimate halo masses from clustering analysis. In section 4 we perform SED fitting to stacked imaging data to measure stellar population parameters. The SHMR and BCE are calculated and compared with literature results in section 5. Section 6 is devoted to discuss the results obtained in the previous sections. Conclusions are given in Section 7.

Throughout this paper, we adopt a flat cosmological model with the matter density \( \Omega_m = 0.3 \), the cosmological constant \( \Omega_k = 0.7 \), the baryon density \( \Omega_b = 0.045 \), the Hubble constant \( H_0 = 70 \text{km s}^{-1}\text{Mpc}^{-1} \left( h_{100} = 0.7 \right) \), the power-law index of the primordial power spectrum \( n_s = 1 \), and the linear amplitude of mass fluctuations in the universe \( \sigma_8 = 0.8 \), which are consistent with the latest Planck results (Planck Collaboration 2016). We assume a Salpeter initial mass function (IMF: Salpeter 1955). Magnitudes are given in the AB system (Oke & Gunn 1983) and coordinates are given in J2000. Distances are expressed in comoving units. We use “log” to denote a logarithm with a base 10 (\( \log_{10} \)).

2 Data and Sample

2.1 Sample Selection

Our LAE samples are constructed in four deep survey fields, the Subaru/XMM-Newton Deep Survey (SXDS) field (Furusawa et al. 2008), the Cosmic Evolution Survey (COSMOS) field (Scoville et al. 2007), the Hubble Deep Field North (HDFN: Capak et al. 2004), and the Chandra Deep Field South (CDFS: Giacconi et al. 2001). We select LAEs at \( z = 2.14–2.22 \) using the narrow band \( NB387 \) (Nakajima et al. 2012) as described in selection papers (Nakajima et al. 2012, 2013; Kusakabe et al. 2015; Konno et al. 2016). The threshold of rest-frame equivalent width, \( EW_{\alpha} \), of Ly\( \alpha \) emission is \( EW_{\alpha}(\text{Ly}\alpha) \geq 20–30 \text{\AA} \) (Konno et al. 2016). While the SXDS field consists of five sub-fields, we use the three regions (SXDS-C, N and S) with deeper \( NB387 \) images. The 5\( \sigma \) depths in a 2" diameter aperture are \( \sim 25.7 \) (SXDS-C.N,S), 26.1 (COSMOS), 26.4 (HDFN), and 26.6 (CDFS). For accurate clustering analysis, we remove LAEs in regions with short net exposure times, resulting from the dither pattern. In the SXDS field (SXDS-C, N, and S), we use the overlapping regions to examine if there exists an offset in the \( NB387 \) zero point. A non-negligible offset of 0.06 mag is found in SXDS-N and appropriately corrected. In the other three fields, we examine the \( NB387 \) zero point using the colors of the Galactic stars from Gunn & Stryker (1983) and apply a 0.1 mag correction to LAEs in CDFS. Note that such a correction values change the Ly\( \alpha \) luminosities only slightly. Our entire sample consists of 2441 LAEs from \( \sim 1 \) square degree (each survey area size is shown in table 1). Of these, we use 1937 LAEs with \( NB387 \leq 26.3 \), where \( NB387 \) is the NB387 total magnitude, for the clustering analysis to examine the halo mass dependence on \( NB387 \) (see figure 1, table 2 and section 3.1). Note that 1248 LAEs with \( NB387 \leq 25.5 \) are used to calculate a four-field average effective bias (see section 3.3) and derive the SHMR and BCE of our LAEs.

2.2 Contamination Fraction

Possible interlopers in our LAE samples are categorized into (i) spurious sources without continuum, (ii) active galactic nuclei (AGNs), (iii) low-\( z \) line emitters whose line emission (not Ly\( \alpha \)) is strong enough to meet our color selection, (iv) low-\( z \) line emitters with weaker emission lines which happen to meet the color selection owing to photometric errors in the selection bands, (v) low-EW (\( \lesssim 20 - 30 \text{\AA} \)) LAEs at our target redshift selected owing to photometric errors in the selection bands, and (vi) continuum sources at any redshifts selected as LAEs owing to photometric errors in the selection bands. We describe each in further detail here.

(i) Spurious sources without continuum are possibly included in our LAE sample even after visual inspection was performed as described in the original papers based on selectivity. However, while the SXDS field consists of five sub-fields, we use the three regions (SXDS-C, N and S) with deeper NB387 images. The 5σ depths in a 2" diameter aperture are ∼ 25.7 (SXDS-C.N,S), 26.1 (COSMOS), 26.4 (HDFN), and 26.6 (CDFS). For accurate clustering analysis, we remove LAEs in regions with short net exposure times, resulting from the dither pattern. In the SXDS field (SXDS-C, N, and S), we use the overlapping regions to examine if there exists an offset in the NB387 zero point. A non-negligible offset of 0.06 mag is found in SXDS-N and appropriately corrected. In the other three fields, we examine the NB387 zero point using the colors of the Galactic stars from Gunn & Stryker (1983) and apply a 0.1 mag correction to LAEs in CDFS. Note that such a correction values change the Lyα luminosities only slightly. Our entire sample consists of 2441 LAEs from ∼ 1 square degree (each survey area size is shown in table 1). Of these, we use 1937 LAEs with NB387 ≤ 26.3, where NB387 is the NB387 total magnitude, for the clustering analysis to examine the halo mass dependence on NB387 (see figure 1, table 2 and section 3.1). Note that 1248 LAEs with NB387 ≤ 25.5 are used to calculate a four-field average effective bias (see section 3.3) and derive the SHMR and BCE of our LAEs.

1 To rescale stellar masses in previous studies assuming a Chabrier or Kroupa IMF (Kroupa 2001; Chabrier & Chabrier 2003), we divide them by a constant factor of 0.81 or 0.66, respectively. Similarly, to convert SFRs in the literature with a Chabrier or Kroupa IMF, we divide them by a constant factor of 0.63 or 0.67, respectively.
All sources detected in either X-ray, UV, or radio are regarded as AGNs and have been removed as described in the selection papers. Their fraction of the entire sample is about 2%. Obscured faint AGNs at these wavelengths may contaminate our sample, although heavily obscured AGNs are unlikely to have emission lines strong enough to pass our color selection. Following (Guaita et al. 2010), we estimate the possible fraction of obscured AGNs in our LAE sample to be ~2%, i.e., similar to that of X-ray, UV, or radio detected AGNs (i.e., Xue et al. 2010; Stern et al. 2012; Heckman & Best 2014; Aird et al. 2017; Ricci et al. 2017).

Candidate emitters are [O II] λ3727 emitters at z ≃ 0.04, Mg II λ2798 emitters at z ≃ 0.4, and CIVλ1550 and CIII] λ1909 emitters at z ≃ 1.5. However, the survey volume of [O II] emitters at z ≃ 0.04 is three orders of magnitude smaller than that of LAEs at z = 2.2. Moreover, the EW$_{OII}$ of the vast majority of [O II] emitters is too small (∼8 Å) to meet our color selection of EW$_{OII}$ ≥ 70 Å (see Konno et al. 2016; Ciardullo et al. 2013). [O II] emitters with such a large EW$_{OII}$ should be AGNs. Mg II, CIV and CIII] emitters which satisfy our selection criteria are also likely to be AGNs. X-ray, UV, or radio detected AGNs have been removed. Therefore, the fraction of contaminants (iii) is expected to be negligibly small and is included in the possible fraction of obscured AGNs as described in category (ii).

We evaluate the contamination fraction contributed by (iv), (v) and (vi) sources that do not satisfy the selection criteria if they have no photometric error (hereafter, intrinsically unselected sources), using Monte Carlo simulations. We use bright sources with N$B_{387}$$\leq$24.0 mag where photometric errors are negligible in all three selection bands of $U$ (or $u^*$), B, and N$B_{387}$ in the four fields. Assuming that the relative distribution of N$B_{387}$-detected objects in the two-color selection plane, $U$ (or $u^*$) - N$B_{387}$ vs. B - N$B_{387}$, is unchanged with N$B_{387}$ magnitude intrinsically, we create a mock catalog by adding photometric errors to the three selection bands. Here, the distribution of NB387 magnitudes of simulated sources is set equal to that of real N$B_{387}$-detected objects down to the 5σ limiting magnitude of N$B_{387}$ in each of the four fields as described in section 2.1.

We then apply the same selection as for the real catalog to obtain the number of objects passing the selection. The contamination fraction is calculated by divid-
Table 1. Details of the data

| band | SXDS (∼1240 arcm²) | COSMOS (∼740 arcm²) | HDFN (∼780 arcm²) | CDFS (∼580 arcm²) |
|------|-------------------|-------------------|-------------------|-------------------|
|      | PSF aperture (")  | aperture (")      | PSF aperture (")  | PSF aperture (")  |
|      | diameter (")      | correction (mag)  | diameter (")      | correction (mag)  |
|      |                   |                   |                   |                   |
| NB387| 0.88 2.0 0.17     | 0.95 2.0 0.25     | 0.89 2.0 0.14     | 0.85 2.0 0.13     |
| B    | 0.84 2.0 0.17     | 0.95 2.0 0.12     | 0.77 2.0 0.15     | 1.0 2.0 0.20      |
| V    | 0.8 2.0 0.15      | 1.32 2.0 0.33     | 1.24 2.0 0.20     | 0.94 2.0 0.18     |
| R(r')| 0.82 2.0 0.16     | 1.04 2.0 0.19     | 1.18 2.0 0.22     | 0.83 2.0 0.16     |
| i'(I)| 0.8 2.0 0.16      | 0.95 2.0 0.12     | 0.80 2.0 0.13     | 0.95 2.0 0.22     |
| z'   | 0.81 2.0 0.16     | 1.14 2.0 0.25     | 0.81 2.0 0.15     | 1.1 2.0 0.24      |
| J    | 0.85 2.0 0.15     | 0.79 2.0 0.3      | 0.84 2.0 0.17     | 0.80 2.0 0.22     |
| H    | 0.85 2.0 0.15     | 0.76 2.0 0.2      | 0.84 2.0 0.17     | 1.5 2.0 0.55      |
| K(Ks)| 0.85 2.0 0.16     | 0.75 2.0 0.2      | 0.84 2.0 0.18     | 0.70 2.0 0.18     |
| IRAC ch1 | 1.7 3.0 0.52 | 1.7 3.0 0.52 | 1.7 3.0 0.52 | 1.7 3.0 0.52 |
| IRAC ch2 | 1.7 3.0 0.55 | 1.7 3.0 0.55 | 1.7 3.0 0.55 | 1.7 3.0 0.55 |

Note. The FWHM of PSF, aperture diameter, and aperture correction are shown. The value in parentheses shows the area used in clustering analysis.
SXDS fields The images used for SED fitting are as follows: \(B, V, R, i',\) and \(z'\) images with Subaru/Suprime-Cam from the Subaru/XMM-Newton Deep Survey project (Furusawa et al. 2008, SXDS); \(J, H,\) and \(K\) images from the data release 8 of the UKIRT/WFCAM UKIDSS/UDS project (Lawrence et al. 2007, Almaini et al. in prep.); Spitzer/IRAC 3.6 \(\mu m\) (ch1) and 4.5 \(\mu m\) (ch2) images from the Spitzer Large Area Survey with Hyper-Suprime-Cam (SPLASH) project (SPLASH: PI: P. Capak; Laigle et al. 2016). All images are publicly available except the SPLASH data. The aperture corrections for optical and NIR images are given in Nakajima et al. (2013). The catalog used to clean IRAC photometry is constructed from the \(K\)-band image of the UKIDSS/UDS data release 11 (Almaini et al. in prep).

COSMOS field We use the publicly available \(B, V, r', i',\) and \(z'\) images with Subaru/Suprime-Cam by the Cosmic Evolution Survey (COSMOS: Capak et al. 2007; Taniguchi et al. 2007) and \(J, H,\) and \(Ks\) images with the VISTA/VIRCAM from the first data release of the UltraVISTA survey (McCracken et al. 2012). We also use Spitzer/IRAC ch1 and ch2 images from the SPLASH project. The aperture corrections for the optical images are derived in Nakajima et al. (2013) and those for the NIR images follow McCracken et al. (2012). The catalog used to clean IRAC photometry is from Laigle et al. (2016), for which sources have been detected in the \(z'\)YJKHs images.

HDFN field The images used for SED fitting are: \(B, V, R, I,\) and \(z'\) images with Subaru/Suprime-Cam from the Hubble Deep Field North Survey (HDFN: Capak et al. 2004); \(J\) (Lin et al. 2012), \(H\) (Hsu et al. 2017 in prep.), and \(Ks\) (Wang et al. 2010) images with CFHT/WIRCam (PI of the \(J\) & \(H\) imaging observations: L. Lin); Spitzer/IRAC ch1 and ch2 images from the Spitzer Extended Deep Survey (SEDS: Ashby et al. 2013). We use reduced \(J\)-band and \(Ks\)-band images given in Lin et al. (2012). All images are publicly available. The aperture corrections for the optical images are given in Nakajima et al. (2013). Those of the NIR images with a 2\(''\) radius aperture are evaluated using bright and isolated point sources in each band. We measure fluxes for 20 bright point sources in a series of apertures from 2\(''\) with an interval of 0.7\(''1\) and find that the fluxes level off for > 7.8 apertures. We measure the difference in magnitude between the 2\(''\) and 7.8 apertures of 100 bright and isolated sources and perform Gaussian fitting to the histogram of differences. We adopt the best-fit mean as the aperture correction term. The catalog used to clean IRAC photometry is constructed from the \(K\)-band image (Wang et al. 2010).

CDFS fields We use the publicly available \(B, V, R,\) and \(I\) images with the MPG 2.2m telescope/WFI by the Garching-Bonn Deep Survey (GaBoDS: Hildebrandt et al. 2006; Cardamone et al. 2010), the \(z'\) image with the CTIO 4m Blanco telescope/Mosaic-II camera from the Multiwavelength Survey by Yale-Chile (MUSYC: Taylor et al. 2009; Cardamone et al. 2010), the \(H\) image with the ESO-NTT telescope/SOFI camera by the MUSYC (Moy et al. 2003; Cardamone et al. 2010), and the \(J\) and \(Ks\) images by the Taiwan ECDFS Near-Infrared Survey (TENIS: Hsieh et al. 2012). We also use the Spitzer/IRAC ch1 and ch2 images from the Spitzer IRAC/MUSYC Public Legacy Survey in the Extended CDF-South (SIMPLE: Damen et al. 2011). The aperture corrections for optical and NIR photometry are derived in a similar manner to those in HDFN. The catalog used to clean IRAC photometry is from Hsieh et al. (2012), for which sources have been detected in the \(J\) image.

The FWHM of the PSF, aperture diameters, and aperture corrections are summarized in table 1.

3 Clustering Analysis

3.1 Subsamples Divided by \(NB387\) Magnitude

![Fig. 1. \(B - NB387\) (\(NB387\) excess) plotted against \(NB387\) total magnitude. Orange, green, magenta, and blue points show LAEs in SXDS, COSMOS, HDFN, and CDFS, respectively. LAEs are divided into cumulative subsamples with different limiting magnitudes shown by gray solid lines: \(NB387_{tot} \leq 25.0\) mag, \(25.3\) mag, \(25.5\) mag, \(25.8\) mag, and \(26.3\) mag. (Color online)](image)

The distribution of \(B - NB387\) as a function of total \(NB387\) magnitude, \(NB387_{tot}\), is shown in figure 1. To examine the dependence of halo mass on the total \(NB387\) magnitude, we divide our LAE sample of each field in up to five cumulative subsamples with different limiting magnitudes, as shown in table 2 and figure 1. There are 1937 LAEs with \(NB387_{tot} \leq 26.3\) used in the clustering analysis.
### 3.2 Angular Correlation Function

Angular correlation functions of our LAEs are derived from clustering analysis. The sky distributions of the LAEs in the four fields are shown in figure 2. We measure the angular two-point correlation function (ACF), $\omega_{\text{obs}}(\theta)$, for a given (sub) sample using the calculator given in Landy & Szalay (1993):

$$\omega_{\text{obs}}(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)},$$

where $DD(\theta)$, $RR(\theta)$, and $DR(\theta)$ are the normalized numbers of galaxy-galaxy, galaxy-random, and random-random pairs, respectively:

$$DD(\theta) = \frac{DD_0(\theta) \times 2}{N_D(N_D - 1)},$$

$$RR(\theta) = \frac{RR_0(\theta) \times 2}{N_R(N_R - 1)},$$

$$DR(\theta) = \frac{DR_0(\theta)}{N_D \times N_R}.$$

Here, $N$ is the total number of pairs with subscripts “D” and “R” indicating galaxies and random points, respectively, and subscript “0” indicates the raw number of pairs. We use a random sample composed of 100,000 sources with the same geometrical constraints as the data sample (see figure 2). The 1 $\sigma$ uncertainties in ACF measurements are estimated as:

$$\Delta \omega_{\text{obs}}(\theta) = \frac{1 + \omega(\theta)}{\sqrt{DD_0(\theta)}}$$

following Guaita et al. (2010). While Norberg et al. (2009) find that Poisson errors underestimate the 1 $\sigma$ uncertainties in ACF measurements and that bootstrapping errors overestimate them 40% using a large number of sources ($\sim 10^5$ to $10^6$), Khostovan et al. (2017) show that Poisson errors and bootstrapping errors are comparable in the case of a small sample size using $\sim 200 H\beta + [O III]$ emitters at $z \sim 3.2$ (see also our footnote 5 and figure 5(b)).

We approximate the spatial correlation function of LAEs by a power law:

$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma},$$

where $r$, $r_0$, and $\gamma$ are the spatial separation between two objects in comoving scale, the correlation length, and the slope of the power law, respectively (Totsuji & Kihara 1969; Zehavi et al. 2004). We then convert $\xi(r)$ into the ACF, $\omega_{\text{model}}(\theta)$, following Simon (2007), and describe it as:

$$\omega_{\text{model}}(\theta) = C \omega_{\text{model}, 0}(\theta),$$

where $\omega_{\text{model}, 0}(\theta)$ is the ACF in the case of $r_0 = 1 h^{-1}_0 \text{Mpc}$ and $C$ is a normalization constant:

$$C = \left(\frac{r_0 h^{-1}_0 \text{Mpc}}{1 h^{-1}_0 \text{Mpc}}\right)^{\gamma}.$$  

The correlation amplitude of the ACF at $\theta = 1''$, $A_\omega$, is

$$A_\omega = C \omega_{\text{model}, 0}(\theta = 1'')$$

An observationally obtained ACF, $\omega_{\text{obs}}(\theta)$, includes an offset due to the fact that the measurements are made over a limited area. This offset is given by the integral constraint (IC),

$$\omega(\theta) = \omega_{\text{obs}}(\theta) + IC,$$

$$IC = \frac{\Sigma_d RR(\theta) C \omega_{\text{model}, 0}(\theta)}{\Sigma_d RR(\theta)},$$

where $\omega(\theta)$ is the true ACF. We fit the $\omega_{\text{model}}(\theta)$ to this $\omega(\theta)$ over $\sim 40'' - 1000''$ by minimizing $\chi^2$:

$$\chi^2 = \sum_\theta \frac{\left(\omega_{\text{obs}}(\theta) + IC - \omega_{\text{model}}(\theta)\right)^2}{\Delta \omega_{\text{obs}}(\theta)}$$

where $IC_0 = IC/C$. This $\theta$ range is determined conservatively avoiding the one-halo term at small scales and large sampling noise at large scales. We fix $\gamma$ to the fiducial value 1.8 following previous clustering analyses (e.g., Ouchi et al. 2003). The analytic solution of the best-fit correlation amplitude is

$$A_\omega = \frac{\sum_\theta \frac{\left(\omega_{\text{obs}}(\theta) - \omega_{\text{model}, 0}(\theta)\right)^2}{\Delta \omega_{\text{obs}}(\theta)^2}}{\sum_\theta \frac{IC_0 - \omega_{\text{model}, 0}(\theta)^2}{\Delta \omega_{\text{obs}}(\theta)^2}}\omega_{\text{model}, 0}(\theta = 1'').$$

#### Table 2. Number of objects in each subsample.

| Field  | $NB387_{\text{tot}}$ magnitude limit (mag) |
|--------|---------------------------------------------|
| SXDS   | 25.0 25.3 25.5 25.8 26.3                   |
| COSMOS | 119   205 297 (21) 526                    |
| HDFN   | 119   200 299 (56) 588                    |
| CDFS   | 27    41 51 (4) 92 222                    |

Note. The value in parentheses shows the number of objects used for SED fitting.

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1 In the COSMOS field, Matthee et al. (2016, hereafter M16) find an overdense region in their HAE sample at $z = 2.211 \pm 0.016$ (see their figure 2) and a part of their survey region overlaps with that of our LAEs at $z = 2.14 - 2.22$. In their overdense region, two X-ray sources at $z = 2.219$ and $z = 2.232$ have bright $L_{\text{X, 0.5-2 keV}}$ emission. The first one is roughly at the center of the overdense region but just outside of our $NB387$ image coverage (ID:1199: see figure 2 and table 2 in M16). The second one is included in our coverage but not selected by our color-color criteria probably because its redshift is too large (ID:1037). Indeed, we do not find, by eye inspection, any overdense region in figure 2(d) as significant as the one discovered by M16.
Fig. 2. Sky distribution of LAEs in SXDS (panel [a]), COSMOS ([b]), HDFN ([c]), and CDFS ([d]). Filled and open black circles represent objects with $NB_{387} \leq 25.5$ mag and $NB_{387} > 25.5$ mag, respectively. Gray points indicate 100,000 random sources used in the clustering analysis. Masked regions are shown in white.
Fig. 3. ACF measurements for LAEs with $NB387_{\text{tot}} \leq 25.0$ mag (panel [a]), $NB387_{\text{tot}} \leq 25.3$ mag (panel [b]), $NB387_{\text{tot}} \leq 25.5$ mag (panel [c]), $NB387_{\text{tot}} \leq 25.8$ mag (panel [d]), and $NB387_{\text{tot}} \leq 26.3$ mag (panel [e]). For each panel, colored symbols (orange squares, green circles, magenta inverted triangles, and blue triangles) represent measurements in SXDS, COSMOS, HDFN, and CDFS, respectively. Colored lines, as labeled in the lower right panel, indicate the best-fit ACFs with fixed $\beta = 0.8$ in SXDS, COSMOS, HDFN, and CDFS, respectively. A dotted black line shows the average of the best-fit ACFs over the four fields. In panels (a)-(d), we slightly shift all data points along the abscissa by a value depending on the field for presentation purposes. (Color online)
The $1\sigma$ fitting error in $A_\omega$, $\Delta A_\omega$, is estimated from $\chi^2_{\text{min}} + 1$, where $\chi^2_{\text{min}}$ is the minimum $\chi^2$ value. We also derive, for each limiting magnitude, the field-average correlation amplitude over the four survey fields by minimizing the summation of $\chi^2$ over the four fields:

$$A_{\omega,\text{ave}} = \frac{\sum_{\theta,i,f} \left( \frac{\omega_{\text{corr},\theta,i}(\theta) - \omega_{\text{obs},\theta,i}(\theta) - IC_{0,i}}{\omega_{\text{corr},\theta,i}(\theta)} \right)^2 \omega_{\text{model},\theta,i}(\theta) \theta = \theta_{\text{min}}}{\sum_{\theta,i,f} \left( \frac{\omega_{\text{corr},\theta,i}(\theta)}{\omega_{\text{corr},\theta,i}(\theta)} \right)^2 \omega_{\text{model},\theta,i}(\theta)}.$$

The best-fit ACFs are shown in figure 3.

Contaminations by randomly-distributed foreground and background interlopers dilute the apparent clustering amplitude. The correlation amplitude corrected for randomly distributed interlopers, $A_{\omega,\text{corr}}$, is given by

$$A_{\omega,\text{corr}} = \frac{A_{\omega}}{(1 - f_c)^2},$$

where $f_c$ is the contamination fraction. The contamination fraction of our LAEs is estimated to be $10 \pm 10\%$ (0–20%) conservatively from the Monte Carlo simulations and spectroscopic follow-up observations (see section 2.2). This $A_{\omega,\text{corr}}$ is the maximum permitted value because interlopers themselves are also clustered in reality. Indeed, some previous clustering studies (e.g., Khostovan et al. 2017) have not applied any contamination correction. In this study, we apply this equation assuming $f_c = 10 \pm 10\%$ so that the error range in $A_{\omega,\text{corr}}$ include both the no correction case and the maximum correction case. The $1\sigma$ error in the contamination-corrected correlation amplitude, $\Delta A_{\omega,\text{corr}}$, is derived by summing the $1\sigma$ error in the ACF fitting, $\Delta A_\omega$, and the uncertainty in the contamination estimate, $\Delta f_c = 0.1$, in quadrature (error propagation):

$$\frac{\Delta A_{\omega,\text{corr}}}{A_{\omega,\text{corr}}} \approx \sqrt{\left( \frac{\Delta A_\omega}{A_\omega} \right)^2 + \left( 2 \Delta f_c / f_c \right)^2}.$$  

The value of the contamination-corrected correlation length, $r_{6,\text{corr}}$, and its $1\sigma$ error are calculated from $A_{\omega,\text{corr}}$ and $\Delta A_{\omega,\text{corr}}$. Table 3 summarizes the results of the clustering analysis.

### 3.3 Bias Factor

The galaxy-matter bias, $b_g$, is defined as

$$b_g(r) = \frac{\xi(r)}{\xi_{\text{DM}}(r,z)},$$

where $\xi_{\text{DM}}(r,z)$ is the spatial correlation function of underlying dark matter,

$$\xi_{\text{DM}}(r,z) = \int \frac{k^2 dk \sin(kr)}{2\pi^2 k^2} P_m(k,z),$$

where $P_m(k,z)$ is the linear dark matter power spectrum as a function of wave number, $k$, at redshift $z$ (Eisenstein & Hu 1999) with the Eisenstein & Hu (1998) transfer function. We estimate the effective galaxy-matter bias, $b_{g,\text{eff}}$, at $r = 8 h^{-1}_{100} \text{Mpc}$ following previous clustering analyses (e.g., Ouchi et al. 2003) using a suite of cosmological codes called Colossus (Diemer & Kravtsov 2015).

Figure 4(a) shows $b_{g,\text{eff}}$ for the cumulative subsamples in the four fields, where $L_{\text{Ly}\alpha}$ luminosity limits are calculated from the limiting $NB387$ magnitudes of the subsamples. We find that the average bias value of our LAEs (represented by black stars in panel (a) and also by red stars in panel (b)) does not significantly change with the $L_{\text{Ly}\alpha}$ luminosity limit. A possible change in $b_{g,\text{eff}}$ over $L_{\text{Ly}\alpha,\text{corr}} \approx 3\times10^{41}\text{erg s}^{-1}$ is less than 20% since the uncertainties in the average biases are $\sim 20$–20%.

This weak dependence may be partly due to radiative transfer effects on $L_{\text{Ly}\alpha}$ photons. Star forming galaxies in more massive (i.e., larger bias) halos are thought to have higher $SFR$s and thus brighter nebular emission lines. Indeed, Cochrane et al. (2017) have found a significant positive correlation between $H_\alpha$ luminosity and bias for bright $z = 2.23$ HAEs, indicating a similarly strong correlation between intrinsic $L_{\text{Ly}\alpha}$ luminosity and bias for bright galaxies. However, such a strong correlation, if any, weakens when observed $L_{\text{Ly}\alpha}$ luminosity is used in place, because brighter (i.e., more massive) galaxies have lower $L_{\text{Ly}\alpha}$ escape fractions, $f_{\text{esc}}$, (e.g., Vanzella et al. 2009; Matthee et al. 2016). Indeed, our cumulative subsamples do not show a significant correlation between the observed $L_{\text{Ly}\alpha}$ luminosity and the total $SFR$ (derived from SED fitting in the same manner as described in section 4) but rather show a positive correlation between the observed $L_{\text{Ly}\alpha}$ luminosity and the $L_{\text{Ly}\alpha}$ escape fraction, where the intrinsic $L_{\text{Ly}\alpha}$ luminosity is calculated from the total $SFR$ (Brocklehurst 1971; Kennicutt 1998).

Moreover, some previous studies have found that high-redshift UV-selected galaxies with comparably faint UV luminosities ($L_{\text{UV}}$) to our LAEs (the average absolute magnitude of our LAEs is $M_{\text{UV}} \sim -19$ mag) have weak dependence of $b_g$ on UV luminosity ($z \sim 3$–4 Lyman break galaxies (LBGs): Ouchi et al. 2004, 2005; Harikane et al. 2016; Bielby et al. 2016, see however, Lee et al. (2006) who find significant dependence for $z \sim 4$–5 LBGs), suggesting that the correlation between intrinsic $L_{\text{Ly}\alpha}$ luminosity and bias is not so strong for typical LAEs with modest $L_{\text{Ly}\alpha}$ luminosities.

The faintest limiting $L_{\text{Ly}\alpha}$ luminosity at which $b_{g,\text{eff}}$ measurements are available for all four fields is $L_{\text{Ly}\alpha} = 6.2 \times 10^{41}\text{erg s}^{-1}$ (corresponding to 25.5 mag in $NB387$). In order to reduce the uncertainty due to cosmic variance as much as possible, we adopt the average $b_{g,\text{eff}}$ at this limiting luminosity, $b_{g,\text{eff}}^{\text{ave}} = 1.22^{+0.16}_{-0.18}$, as the average $b_{g,\text{eff}}$ of our entire sample.

This average bias is lower than that of the previous work on narrow-band-selected LAEs at $z \sim 2.1$, $b_{g,\text{eff}} = 1.8 \pm 0.3$ (Guaita et al. 2010, see the blue point in panel (b) of figure 4), with a probability of 96%. The median $L_{\text{Ly}\alpha}$ luminosity of their sample is $L_{\text{Ly}\alpha} = 1.3 \times 10^{42}\text{erg s}^{-1}$ and their 5σ detection limit in $L_{\text{Ly}\alpha}$ luminosity is $L_{\text{Ly}\alpha} = 6.3 \times 10^{41}\text{erg s}^{-1}$, which
is similar to the luminosity limit of our $NB387 \leq 25.5$ samples. Our clustering method is essentially the same as of Guaita et al. (2010) and in both studies the bias value is calculated at $r = 8h^{-1}_{100}\text{Mpc}$. Although we use a slightly different cosmological parameter set, $(\Omega_m, \Omega_{\Lambda}, h, \sigma_8) = (0.3, 0.7, 0.7, 0.8)$, from theirs, $(\Omega_m, \Omega_{\Lambda}, h, \sigma_8) = (0.26, 0.74, 0.7, 0.8)$, using Guaita et al. (2010)’s set changes $b_{g, \text{eff}}$ only negligibly. Our contamination fraction, $f_c = 10 \pm 10\%$, is comparable to or slightly conservative than theirs, $f_c = 7 \pm 7\%$. The error in Guaita et al. (2010)’s $b_{g, \text{eff}}$ is a quadrature sum of the uncertainty in $f_c$ and the fitting error (statistical error), with the latter dominating because of the small sample size (250 objects). As discussed in section 3.4, their high $b_{g, \text{eff}}$ value is attributable to cosmic variance since their survey area is approximately one third of ours (see figure 5(b)). Indeed, the sky distribution of their LAEs has a large scale excess at the north-west part and the ACF measurements seem to deviate to higher values from the best-fit power law at large scales because of it.$^4$

$^4$ We do not include the result of Guaita et al. (2010) when calculating the average bias.

3.4 Cosmic Variance on Bias Factor

Our average effective bias value and that of Guaita et al. (2010) are not consistent within the 1σ uncertainties in spite of similar limiting Lyα luminosities. Biases derived from limited survey areas possibly suffer from cosmic variance due to spatial variations in the ACF of dark matter. We analytically estimate cosmic variance in the bias value derived from clustering analysis for the first time. With the ACF the galaxy-matter bias can be expressed as $b(\theta) = \sqrt{\omega_{\text{gal}}(\theta)/\omega_{\text{DM}}(\theta)}$. Assuming that the cosmic variance in $b$ originates solely from the spatial variation of the dark matter ACF, we can express the $b$ of a given galaxy sample in a given survey field as:

$$b(\text{field}) = \sqrt{\omega_{\text{DM}}(\text{field})/\omega_{\text{gal}}(\text{field})} = \sqrt{\omega_{\text{DM}}(\text{field})/\omega_{\text{DM}}}b_{\text{int}}$$

where $\omega_{\text{DM}}$ is the cosmic variance of the dark matter ACF, $\omega_{\text{DM}}(\text{field})$ is the dark matter ACF in the field, $\omega_{\text{gal}}(\text{field})$ is the observed galaxy ACF in the field, and

$$b_{\text{int}} \equiv \sqrt{\omega_{\text{gal}}(\text{field})/\omega_{\text{DM}}}$$

### Table 3. Clustering Measurements of our LAEs.

| Field   | $A_{\omega}$ | $A_{\omega, \text{corr}}$ | $r_{\text{corr}}$ | $b_{g, \text{eff}}$ | $M_1$ | reduced $\chi^2_7$ | $IC$ |
|---------|--------------|--------------------------|-------------------|--------------------|-------|-------------------|------|
| $NB387_{\text{tot}}$ (mag) | | | | | | | |
| SXDS   | 4.70 ± 2.86  | 5.80 ± 3.75  | 2.79 ± 0.80       | 1.40 ± 0.40        | 10.1 ± 28.8 | 1.74  | 0.0137 |
| COSMOS | 3.88 ± 3.03  | 4.79 ± 3.88  | 2.50 ± 0.98       | 1.27 ± 0.44        | 5.5 ± 25.3 | 0.89  | 0.0176 |
| HDFN   | 6.89 ± 3.77  | 8.51 ± 5.03  | 3.44 ± 1.01       | 1.70 ± 0.44        | 29.3 ± 55.5 | 0.81  | 0.0319 |
| CDFS   | 3.78 ± 11.89 | 4.67 ± 14.72 | 2.47 ± 2.97       | 1.26 ± 1.30        | 5.0 ± 170.0 | 0.71  | 0.0215 |
| Field average (number of fields) | | | | | | | |
| $\leq 25.0$ | 4.69 ± 1.70 | 5.80 ± 2.46 | 2.76 ± 0.60       | 1.40 ± 0.27        | 10.1 ± 17.0 | 0.75  | 0.0137 |
| $\leq 25.3$ | 4.04 ± 0.90 | 4.99 ± 1.57 | 2.54 ± 0.49       | 1.30 ± 0.19        | 6.3 ± 8.5  | 2.04  | 0.0290 |
| $\leq 25.5$ | 3.55 ± 0.88 | 4.39 ± 1.21 | 2.30 ± 0.36       | 1.22 ± 0.18        | 4.0 ± 3.9  | 1.01  | 0.0311 |
| $\leq 25.8$ | 2.75 ± 0.45 | 3.40 ± 0.94 | 2.07 ± 0.30       | 1.07 ± 0.10        | 1.5 ± 1.2  | 1.08  | 0.0348 |
| $\leq 26.3$ (1) | 8.62 ± 1.49 | 10.64 ± 2.99 | 3.90 ± 0.65       | 1.90 ± 0.25        | 50.2 ± 32.9 | 1.66  | 0.0490 |

Note. (1) The best fit correlation amplitude without $f_c$ correction; (2) the best fit correlation amplitude with $f_c$ correction used to derive (3)–(5); (3) the best fit (contamination-corrected) correlation length; (4) the best fit effective bias factor (contamination-corrected); (5) the best fit effective dark matter halo mass (contamination-corrected); (6) reduced chi-squared value; (7) the best fit integral constant; The value in parentheses shows the number of fields used to calculate the field-average correlation amplitude using equation 15.
is the intrinsic bias of this galaxy population which we assume to be unchanged from field to field (parameter \( \theta \) is omitted for clarity). This assumption is the same as the one assumed to predict cosmic variance in number density (e.g., Moster et al. 2011), as explained below. Field to field fluctuations of number density, \( \sigma_{ND, g'} \), are assumed to come from field to field fluctuations of dark matter distribution (i.e., cosmic variance in the density of dark matter), \( \sigma_{ND, DM} \), as

\[
\sigma_{ND, g'} = b_{g'} \sigma_{ND, DM}, \tag{22}
\]

where the intrinsic galaxy bias, \( b_{g'} \), is uniform and independent of fields by definition. We also assume that \( \omega_{DM}^2 \text{(field)} \) is proportional to \( \omega_{DM}^2 \text{(tot)} \) by a factor of \( b_{\text{tot}} \).

The covariance in \( \omega_{DM}^2 \) between two angular separations for area \( \Omega_a \) is given by the first term of equation 19 of Cohn (2006)\(^5\):

\[
\omega_{DM}^2(\Delta \mu, \Delta \Omega) = \omega_{DM}^2 \text{(tot)} \left( 1 + \frac{\Delta \omega_{DM}^2}{\omega_{DM}^2} \right). \tag{19}
\]

\( \Delta \omega_{DM}^2 \) is given by the first term of equation 19 of Cohn (2006)\(^5\):

\[
\Delta \omega_{DM}^2(\Delta \mu, \Delta \Omega) = \frac{\Delta \mu^2}{\Omega a} \omega_{DM}^2(\Delta \Omega). \tag{20}
\]

\( \Delta \mu \) is the angular separation between the fields (\( \mu = \text{arcsec}^{-1} \)), \( \Omega a \) is the area of the survey (\( \text{deg}^2 \)), and \( \omega_{DM}^2(\Delta \Omega) \) is the covariance in \( \omega_{DM}^2 \) over an angular separation \( \Delta \Omega \).

\( \omega_{DM}^2 \text{(tot)} \) is the full covariance including all objects, and the subsequent terms correspond to the uncertainty shown in

\[\text{COHEN (2006) } \text{equation (19) corresponds to the full covariance including those due to a discrete sampling with a finite number of objects; the second term is proportional to } P_2(K)/N\Omega_b, \text{ where } N \text{ is the number density of objects, and the subsequent terms correspond to the uncertainty shown in}\]
\[ \text{Cov}(\omega_{DM}(\theta), \omega_{DM}(\theta')) = \frac{1}{\pi \Omega_s} \int K \, dK \, J_0(K\theta) \, P_2(K) \, \Omega_s^2, \]  
(23)

where \( K, P_2(K) \) and \( J_0(K\theta) \) are the Fourier transform of \( \theta \), the projected power spectrum calculated using the redshift distribution defined by the filter, and the zeroth-order Bessel function of the first kind, respectively. With this equation we calculate \( \omega_{DM} \) and its standard deviation, \( \sigma_{DM} \), for the three angular bins used to determine the \( A_c \) of our LAEs. We then fit a power-law correlation function to those values in the same manner as for observed data but also considering the intrinsic covariance given in equation (23), and obtain the relative uncertainty in \( A_c \) due to the variation in \( \omega_{DM} \). According to equation (23), the relative uncertainty in \( A_c \) depends on \( \Omega_s \) as:

\[ \frac{\Delta \omega_{DM}}{\omega_{DM}} \propto \Omega_s^{-0.5}, \]  
(24)

as shown by a light gray solid line in figure 5(a).

We find \( \Delta \omega_{DM} / \omega_{DM} \approx 53\% \) for \( \Omega_s = 0.25 \text{ deg}^2 \), a typical area of the four survey fields, and \( \approx 26\% \) for the entire survey area (\( \approx 1 \text{ deg}^2 \)).

Sobral et al. (2010) have empirically estimated relative uncertainties in ACF measurements for NB-selected \( z = 0.85 \) HAEs as a function of area by dividing their survey regions, \( \approx 1.3 \text{ deg}^2 \) in total, into sub regions with different sizes (green squares in figure 5(a)). This empirical relation has been used to estimate cosmic variance in ACF measurements in a \( \approx 2 \text{ deg}^2 \) survey area of emission line galaxies at \( z \approx 0.8-4.7 \) in Khostovan et al. (2017). Our analytic method applied to the Sobral et al. (2010) survey with their own NB filter (over the same fitting range of \( \theta \) as that for our LAEs for simplicity), however, gives larger uncertainties as shown by a green solid line in figure 5(a). This may be partly because the area of Sobral et al. (2010)’s survey is not large enough to catch the total variance. Our analytic estimation seems to be more conservative than theirs.

We expect that Guaita et al. (2010)’s \( b_{g, \text{eff}} \) obtained from \( \approx 0.28 \text{ deg}^2 \) area has also a \( \approx 51\% \) uncertainty using their \( NB3727 \) filter (solid blue line in figure 5(a)). The 1σ uncertainty in an observed bias including cosmic variance, \( \Delta b_{g, \text{eff}, CV} \), is given by:

\[ \frac{\Delta b_{g, \text{eff}, CV}}{b_{g, \text{eff}} \approx \frac{1}{2} \sqrt{\left( \frac{\Delta A_c}{A_c} \right)^2 + \left( \frac{2 \Delta f_c}{f_c} \right)^2 + \left( \frac{\Delta \omega_{DM}}{\omega_{DM}} \right)^2}, \]  
(25)

where \( \Delta b_{g, \text{eff}} \) is the 1σ error in \( b_{g, \text{eff}} \).

By updating the errors using this equation (where for our \( b_{g, \text{eff}} \) the plus and minus errors are treated separately), our average effective bias and that of Guaita et al. (2010) are written

our equation 5. Inclusion of the second term in our equation 23 increases \( \Delta \omega_{DM} \) by \( \approx 30\% \) for our LAE survey, although in this study we neglect this term and only consider cosmic variance not dependent on \( N \).

3.5 Dark Matter Halo Mass

We estimate the effective dark matter halo masses from \( b_{g, \text{eff}} \) directly assuming that each halo hosts only one galaxy and that our sample has a narrow range of dark matter halo mass. We use the formula of bias and peak height in the linear density field, \( \nu_c \), given in Tinker et al. (2010), which is based on a large set of collisionless cosmological simulations in flat \( \Lambda \)CDM cosmology.

The obtained \( \nu_c \) is converted to the effective dark matter halo mass with the top-hat window function and the linear dark matter power spectrum (Eisenstein & Hu 1998, 1999) using a cosmological package for Python called Cosmolopy\(^6\).

The effective halo mass of each sub-sample is listed in table 3. The field average of effective halo masses corresponding to the field average of effective biases of our LAEs with \( NB387_{\text{tot}} \leq 25.5 \text{ mag} \), \( b_{g, \text{eff}}^{\text{ave}} = 1.22^{+0.23}_{-0.26} \) and \( b_{g, \text{eff}} = 1.8 \pm 0.55 \), respectively, thus becoming consistent with each other within the errors (see figure 5(b)). We also note that the relatively large scatter of \( b_{g, \text{eff}} \) among the four fields at each limiting Lyα luminosity seen in figure 4(a) may be partly due to cosmic variance although the observational errors are too large to confirm it (see figure 5(b)). All the best-fit \( b_{g, \text{eff}} \) values for the four fields fall within the \( 1\sigma \) uncertainty range from cosmic variance shown by a shaded light gray region in figure 5(b).

\(^6\) http://roban.github.com/Cosmolopy/
(2017) assume a constant dust attenuation against Hα luminosity, $A_{H\alpha} = 1.0$ mag, for all HAEs, which is larger than that of our LAEs, $A_{H\alpha} \sim 0.13 \pm 0.04$ mag, derived from the average $E(B-V)$ in section 4. If the extrapolated relation overestimates $L_{H\alpha,\text{corr}}$ at low halo masses owing to overestimation of $A_{H\alpha}$, then the true log-log slope of $L_{H\alpha,\text{corr}}$ as a function of $M_\bullet$ would be steeper, implying that our LAEs would lie above the relation (see also section 5.2 and figure 10).

4 SED fitting

We derive parameters that characterize the stellar populations of LAEs with $NB tot \leq 25.5$ mag in each of the four fields by fitting SEDs based on stacked multiband images. This threshold magnitude is the same as that adopted in the clustering analysis to determine the average halo masses. We only use 170 objects ($\sim 14\%$ of the entire sample, 1248) that have data in ten broadband filters ($B, V, R, i, z, J, H, K$, ch1, and ch2) and are not contaminated by other objects in the IRAC images (sec. 2.1 and table 2). The procedure to select ‘IRAC-clean’ objects is described in the next subsection.

4.1 Selection of IRAC-clean Objects

The IRAC images have lower spatial resolution (i.e., larger FWHMs of the PSF) compared with images in other bands. Moreover, they have large-scale residual backgrounds (contaminated sky regions) around bright objects and in crowded regions due to the extended profile of the IRAC PSF. Contamination by nearby objects and large-scale sky residuals can give significant systematic errors in the photometry of stacked images because our LAEs are expected to have very low stellar masses, or very faint IRAC magnitudes. To minimize such contamination, we select clean LAEs through a two-step process.

First, we exclude all LAEs which have one or more neighbors. Assuming that objects bright in IRAC are similarly bright in the $K$ band, we exclude all LAEs which have one or more $K$-detected objects with a separation between 0.$\arcsec$85 and 4.$\arcsec$5; an object within 0.$\arcsec$85 separation is considered to be the counterpart to the LAE conservatively (the typical separation is $\sim 0.8\arcsec$; see section 2.3 for the $K$-detected catalogs$^7$. 4.$\arcsec$.5 is 2.5 times larger than the PSF size of IRAC ch1.

Second, we exclude all LAEs with a high sky background as determined in the following manner. For each field, we randomly select 5,000 positions with no $K$-band objects within 4.$\arcsec$.5 (i.e., passing the first step) and measure the sky background in an annular region of 3.$\arcsec$.5 radius centered at these positions. We then make a histogram of the sky background values, which is skewed toward higher values because of contamination by bright or crowded objects outside of the 4.$\arcsec$.5 radius. We fit a Gaussian to the low-flux side (including the peak) of the histogram and obtain its average, $\mu_{\text{rand}}$, which we consider to be the true sky background. If cutout images at all the random positions are median-stacked, its annular-region sky background will be brighter than $\mu_{\text{rand}}$. A similar systematic sky-background difference will also be seen when all LAEs are stacked, possibly introducing some systematic errors in photometry. The sky background of the median-stacked random image becomes equal to $\mu_{\text{rand}}$ if positions whose sky background is higher than a certain threshold, $\text{sky}_{\text{thres}}$, are removed, where $\text{sky}_{\text{thres}}$ can be determined so that the total number of the remaining positions (i.e., positions with faint sky background below $\text{sky}_{\text{thres}}$) is twice as large as the number of positions below $\mu_{\text{rand}}$. Thus, we conservatively remove LAEs with a higher annular-region sky background than $\text{sky}_{\text{thres}}$ and are left with 93, 21, 56, and 4 IRAC-clean LAEs in SXDS, COSMOS, HSFN, and CDFS, respectively. The stacked flux densities of the IRAC-clean LAEs in the $B$ to $K$ bands are mostly consistent with those of the all LAEs before cleaning.

4.2 Stacking Analysis and Photometry

We perform a stacking analysis for each subsample in almost the same manner as Nakajima et al. (2012) and Kusakabe et al. (2015). Images of size 50$''$ × 50$''$ are cut out at the position of LAEs in the $NB387$ image with IRAF/imcopy task. For each of the $B$ to $K$ bands of the SXDS field, PSFs are matched to the largest among the SXDS-Center, North, and South subfields using IRAF/imcombine task (see table 1). We use the task IRAF/imcombine to create a $NB387$-centered median image. While a stacked SED is not necessarily a good representation of individual objects (Vargas et al. 2014), stacking is still useful for our faint objects to obtain a SED covering rest-frame $\sim 1000$–10000 Å.

An aperture flux is measured for each stacked image using the task PyRAF/phot. Following Ono et al. (2010a), we use an aperture diameter of 2$''$ for the $NB387$, optical, and NIR band images and 3$''$ for the MIR (IRAC) images. For the $NB387$ to $K$-band images, the inner radius of the annulus to measure the sky flux is set to twice the FWHM of the largest PSF among these images$^8$, and the area of the annulus is set to five times larger than that of the aperture. For each of the ch1 and ch2 images, we obtain the net 3$''$-aperture flux density of LAEs by subtracting the offset, between the annular-region and the 3$''$-aperture flux densities of the stacked image of IRAC-clean random positions generated in the previous subsection, from the 3$''$-aperture flux density of the LAE image (output of the

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$^7$ 0.$\arcsec$85 is the largest PSF FWHM among the $K$ (or $K_s$) bands shown in table 1.

$^8$ The PSF size of the CDFS $H$-band image is exceptionally large and we determine the radius of the annulus for this image independently.
Table 4. Results of SED fitting.

| field | $M_\star$ $(10^9 M_\odot)$ | $E(B - V)_\star$ [A1600] (mag) | Age ($10^8$ yr) | SFR ($M_\odot$ yr$^{-1}$) | $\chi^2$ |
|-------|-----------------|----------------------|------------|-----------------|--------|
| SXDS  | $9.7^{+6.6}_{-1.7}$ | $0.05^{+0.01}_{-0.02}$ [0.6$^{+0.1}_{-0.2}$] | $3.6^{+2.8}_{-1.1}$ | $3.3^{+0.5}_{-0.7}$ | 0.604 |
| COSMOS| $14.6^{+3.4}_{-3.6}$ | $0.07^{+0.02}_{-0.02}$ [0.8$^{+0.2}_{-0.2}$] | $4.1^{+2.4}_{-1.8}$ | $4.2^{+1.2}_{-0.8}$ | 0.473 |
| HDFN  | $7.6^{+4.0}_{-1.9}$ | $0.06^{+0.02}_{-0.03}$ [0.7$^{+0.2}_{-0.4}$] | $3.2^{+4.0}_{-1.4}$ | $2.9^{+0.8}_{-0.8}$ | 1.298 |
| CDFS  | $10.3^{+7.7}_{-2.0}$ | $0.02^{+0.07}_{-0.01}$ [0.2$^{+0.8}_{-0.1}$] | $5.7^{+5.7}_{-6.6}$ | $2.2^{+0.4}_{-0.4}$ | 1.020 |

Average $10.2 \pm 1.8$ $0.06 \pm 0.01$ [0.6$ \pm 0.1$] $3.8 \pm 0.3$ $3.4 \pm 0.4$

Note. (1) The best fit stellar mass; (2) the best-fit color excess [UV attenuation]; (3) the best fit age; (4) the best fit SFR; (5) reduced chi-squared value. The UV attenuation is derived from a SMC-like attenuation curve. Metallicities, redshifts, and $f_{esc}^{tot}$ are fixed to 0.2$Z_\odot$, 2.18, and 0.2, respectively.

PyRAF/phot task$^9$.

$^9$ The sky background value on a 3.′′5-radius annulus placed at the image center is consistent between the stacked LAE images and the stacked images of IRAC-clean random positions. For stacked images of random positions, annular-region sky flux densities are brighter than aperture-region sky flux densities with differences corresponding to $\sim$ 7–28% of the aperture fluxes of median-stacked LAEs.

We use the original zero-point magnitudes (ZP) from references given in Section 2.3, although some previous work argues that some ZPs need to be corrected (e.g., Yagi et al. 2013; Skelton et al. 2014), especially since the direction of the correction fluxes of median-stacked LAEs.

Fig. 6. Results of SED fitting to stacked LAEs with $N_{3938,rest} \geq 25.5$ mag in the SXDS, COSMOS, HDFN, and CDFS fields from panels (a) to (d). For each panel, a gray solid line and a light gray dotted line show the best-fit model spectrum and its stellar continuum component, respectively. The difference of these two lines shows a contribution of its nebular continuum component. Red filled circles and black filled triangles represent the observed flux densities and the flux densities calculated from the best-fit spectrum, respectively. (Color online)
tion given by Yagi et al. (2013) is opposite to that by Skelton et al. (2014) for optical bands of the SXDS field. All aperture magnitudes are corrected for Galactic extinction, $\text{E}(B-V)_b$, of $0.020, 0.018, 0.012,$ and $0.008$ for the SXDS, COSMOS, HDFN, and CDFS fields, respectively (Schlegel et al. 1998).

The aperture magnitudes are then converted into total magnitudes using the aperture correction values summarized in table 1 (see also section 2.3). The stacked SEDs thus obtained for individual subsamples are shown in figure 6. The errors include photometric errors and errors in aperture correction and the ZP. For the ch1 and ch2 data, errors in sky subtraction, $\sim 0.02$–0.17 mag, are also included. The photometric errors are determined following the procedure of Kusakabe et al. (2015). The aperture correction errors in the $\text{NB}387$, optical, and NIR bands are estimated to be less than 0.03 mag, and those in the ch1 and ch2 bands are set to 0.05 mag. We adopt 0.1 mag as the ZP error for all bands, which is the typical value of the offsets of the images used in this paper (e.g., Yagi et al. 2013; Skelton et al. 2014) and is twice as large as those adopted in previous studies (e.g., Nakajima et al. 2012).

4.3 SED Models

We perform SED fitting on the stacked SEDs to derive stellar population parameters in a similar manner to Kusakabe et al. (2015). Nebular emission (lines and continuum) is added to the stellar population synthesis model of GALAXEV with constant star formation history and 0.2Z⊙ stellar metallicity, following previous SED studies of LAEs (Bruzual & Charlot 2003; Ono et al. 2010a; Vargas et al. 2014). We assume a SMC-like dust extinction model for the attenuation curve (hereafter a SMC-like attenuation curve; Gordon et al. 2003), which is suggested to be more appropriate for LAEs at $z \sim 2$ than the Calzetti curve (Calzetti et al. 2000) used by Kusakabe et al. (2015) and at $z \geq 2$ by Reddy et al. (2017) for star forming galaxies. We also examine the case of the Calzetti attenuation curve for comparison (see appendix 1.1). We also assume $\text{E}(B-V)_{\text{gas}} = \text{E}(B-V)_{\star}$, (Erb et al. 2006). The Lyman continuum escape fraction, $f_{\text{ion}}^{\text{esc}}$, is fixed to 0.2 considering recent observations of $f_{\text{ion}}^{\text{esc}} \sim 0.1$–0.3 for $z \sim 3$ LAEs by Nestor et al. (2013). This means that 80% of ionizing photons produced are converted into nebular emission (see Ono et al. 2010a).

For each field’s stacked SED we search for the best-fitting model SED that minimizes $\chi^2$ and derive the following stellar parameters: stellar mass ($M_\star$), color excess ($\text{E}(B-V)_{\star}$), or UV attenuation of $A_{V\mu m}$, age, and $SFR$. Stellar masses are calculated by solving $\frac{\partial \chi^2}{\partial M_\star} = 0$ since it is the amplitude of the model SED. $SFR$ is not a free parameter in the fit but determined from $M_\star$ and age and thus the degree of freedom is 7. The 1σ confidence interval in these stellar parameters is estimated from $\chi^2_{\text{min}} + 1$, where $\chi^2_{\text{min}}$ is the minimum $\chi^2$ value.

4.4 Results of SED Fitting

Table 4 summarizes the best-fit parameters and figure 6 compares the best-fit SEDs with the observed SEDs. The mean value for each parameter over the four fields is: $M_\star = 10.2 \pm 1.8 \times 10^{8} M_\odot$, $A_{1600} = 0.6 \pm 0.1$ mag, age = $3.8 \pm 0.3 \times 10^8$ yr, and $SFR = 3.4 \pm 0.4 M_\odot$ yr$^{-1}$. We discuss the infrared excess and the star formation mode in the following subsections using the results with a SMC-like curve.

While the SMC-like and Calzetti attenuation curves fit the data equally well, the resulting parameter values are different (see Appendix 1.1 and figure 13). The Calzetti curve tends to give a smaller stellar mass, a higher attenuation, a younger age, and a higher SFR as the best fit value compared with a SMC-like curve. The difference in the average stellar mass is a factor of $\sim 3$ but that in the average SFR reaches a factor of $\sim 4$.  

4.4.1 $M_\star$–$IRX$ relation

As shown in figure 7, galaxies with higher stellar masses tend to have higher infrared excesses, $IRX \equiv L_{IR}/L_{UV}$, where $L_{IR}$ is the IR luminosity (see also footnote 13), which is an indicator of dustiness (the consensus relation: Reddy et al. 2010; Whitaker et al. 2014; Bouwens et al. 2016). The dust emission of typical LAEs with $M_\star \sim 10^{8} M_\odot$ is too faint to be detected, although a few LAEs at $z \sim 2$–3 are detected by Herschel/PACS and Spitzer/MIPS (e.g., Pentericci et al. 2010; Oteo et al. 2012). In order to compare $IRX$ and stellar masses of LAEs with the consensus relation, we convert the $A_{1600}$ of our LAEs obtained above to $IRX$s using equation (1) in Overzier et al. (2011). We find that our LAEs are located near an extrapolation of the consensus relation (see filled color symbols in figure 7). Their $IRX$ values are also consistent with that $(\lesssim 2.0$ (3σ)) of typical LAEs obtained by Kusakabe et al. (2015) who constrain the upper limit of the IR luminosity from stacked Spitzer/MIPS 24 µm images. While unlikely, for our LAEs to require a Calzetti attenuation curve, they would be dusty galaxies whose values of $IRX$ are more than 10 times higher than expected from the

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10While Hagen et al. (2017) have found that the SMC indeed has a flatter extinction curve in average than the classical (Pei 1992; Gordon et al. 2003), we adopt the classical curve which is consistent with recent observations of high-$z$ galaxies including LAEs. Reddy et al. (2017) find that galaxies at $z = 1.5$–2.5 prefer a SMC-like attenuation curve combined with sub-solar metallicity stellar population models.

11We also perform SED fitting with models without nebular emission, $f_{\text{ion}}^{\text{esc}} = 1$, to examine to what extent $SFR$s and $M_\star$ change in appendix 1.2.

12The uncertainties in the best fit parameters in the CDFS are large since the number of LAEs used in stacking analysis is smaller than those in the other fields as shown in table 2. Moreover, the $i$, $z$, and $H$ band images in this field are $\sim 0.5$–2 mag shallower than those in the other fields.

13We shift the derived $IRX$s downward by 10% because the $L_{IR}$ of the consensus relation is defined as $L_{IR} \equiv L_{1800} - 1000\mu m$ instead of $L_{IR} \equiv L_{1000\mu m}$.

14This $IRX$ has also been 10% corrected from the original value in Kusakabe et al. (2015, see our footnote 13).
Fig. 7. $IRX$ vs $M_\star$. Dim gray squares, dim gray circles, a black square, and a light gray solid band represent, respectively, 3D-HST galaxies at $z \sim 2$ in Whitaker et al. (2014), UV selected galaxies at $z \sim 2$ in Reddy et al. (2010), LBGs at $z \sim 2 \sim 3$ in Bouwens et al. (2016), and the consensus relation of them determined by Bouwens et al. (2016), with its extrapolation indicated by a gray striped band (see also footnote 1). A filled (open) orange square, green circle, magenta inverted triangle, and blue triangle indicate the SXDS, COSMOS, HDFN, and CDFS fields, respectively, on the assumption of a SMC-like attenuation curve (the Calzetti curve). An open blue square represents the $3\sigma$ upper limit of stacked LAEs at $z \sim 2$ with IR observations in Kusakabe et al. (2015, hereafter HK15). All data are rescaled to a Salpeter IMF according to footnote 1. (Color online)

extrapolated consensus relation (see open colored symbols in figure 7) and comparable to those of 10 times more massive average galaxies.
Fig. 8. SFR plotted against $M_\star$. Panel (a). An orange square, green circle, magenta inverted triangle, and blue triangle represent stacked LAEs with $NB387_{\text{tot}} \leq 25.5$ mag in the SXDS, COSMOS, HDFN, and CDFS fields, respectively, and a red star shows the average over the four fields. The orange square and the red star overlap with each other. A blue open rectangle denotes the permitted range for stacked LAEs from $L_{\text{UV}}$ and $L_{\text{IR}}$ in Kusakabe et al. (2015). Light gray dots, dim gray squares, and dim gray circles indicate BzKs from Rodighiero et al. (2011), BzKs from Lin et al. (2012), and 3D-HST galaxies from Whitaker et al. (2014), respectively. Black thin middle-width, and thick solid lines represent the star formation main sequence at $z \sim 2$ in Tomczak et al. (2016, hereafter T16), Shivaei et al. (2017, hereafter S17), and Daddi et al. (2007), respectively (determined well using $L_{\text{UV}}$ and $L_{\text{IR}}$), with extrapolated parts shown by dashed lines. (b) Same as panel (a) but LAEs taken from the literature are also plotted. Cyan squares and light green pentagons show individual LAEs at $z \sim 2$ in Hagen et al. (2016) and Shimakawa et al. (2017), respectively. A blue circle indicates stacked LAEs at $z \sim 2$ in Guaita et al. (2011). SFRs in Hagen et al. (2016) and Shimakawa et al. (2017) are derived from the $I RX - \beta$ relation with the Calzetti curve (Meurer et al. 1999) and SFRs in Guaita et al. (2011) are derived from SED fitting with the Calzetti curve, while SFRs in this work are derived from SED fitting with a SMC-like curve. We also show our results with the $I RX - \beta$ and SED fitting with the Calzetti curve in figure 15. All data are rescaled to a Salpeter IMF according to footnote 1. (Color online)
4.4.2 $M_* - SFR$ Relation

The mode of star formation in star-forming galaxies can be divided into two categories: the main-sequence (MS) mode where galaxies form stars at moderate rates, making a well-defined sequence in the $SFR - M_*$ plane (SFMS; e.g., Elbaz et al. 2007; Speagle et al. 2014), and the burst mode where galaxies have much higher specific star formation rates, $sSFRs = SFR / M_*$, than MS galaxies with similar masses (e.g., Rodighiero et al. 2011). While it is well established that LAEs are mostly low-mass galaxies, which mode they typically have is still under some debate because of differences in $SFR$ estimates.

The SFMS itself at $z \approx 2$ has been determined well using rest UV to far-infrared (FIR) data at $M_* \gtrsim 10^{10} \, M_\odot$ (e.g., Whitaker et al. 2014; Tomczak et al. 2016). Below this stellar mass, the SFMS is suggested to continue at least down to $M_* \sim 10^9 - 10^8 \, M_\odot$ keeping its power-law slope unchanged (e.g., by Santini et al. 2017, using gravitationally-lensed galaxies in the HST Frontier Fields), although SFRs have large uncertainties since without FIR data. In this paper, we simply extrapolate the SFMS, given in the literatures (Daddi et al. 2010; Vargaz et al. 2014) with a counterpart in the 3D-HST catalogue (Skelton et al. 2014). They also derive $SF$s from the $IRX - \beta$ with the Calzetti curve, while stellar masses are derived from SED fitting without IRAC photometry. Since their LAEs have blue $\beta$ ($\sim -1.9$ in average), their $SFR$s and stellar masses do not change so much if a SMC-like curve is used instead. Hashimoto et al. (2017) have also examined six LAEs with $EW_{0}(L_{\alpha}) \simeq 200 - 400 \, \AA$ selected from the same sample as ours and found that they are star-burst galaxies with $M_* \sim 10^7 - 10^8 \, M_\odot$. However, as suggested in Hashimoto et al. (2017), their high $sSFR$s are probably a consequence of high $EW_{0}(L\alpha)$s (because younger galaxies have a larger $EW_{0}(L\alpha)$) and the stellar population properties of these six LAEs do not represent those of our LAE sample.

We infer that our sample better represents the majority of $z \sim 2$ LAEs because of a wide luminosity coverage ($\sim 0.1 - 2 \times L_{\alpha}$: see Konno et al. 2016) and a simple selection based only on $EW_{0}(L\alpha) \geq 20 - 30 \, \AA$, being less biased toward against other quantities such as UV luminosity. The majority of $z \sim 2$ LAEs are probably normal star-forming galaxies with low stellar masses in terms of star formation mode.

5 Stellar and Halo Properties

In this section, we combine the stellar masses, $SFR$s, and halo masses derived in the previous sections (summarized in tables 3 and 4) to evaluate the star formation efficiency in dark matter halos.

5.1 Relation between $M_*$ and $M_h$

The stellar to halo mass ratio ($= M_*/M_h$: $SHMR$) indicates the efficiency of star formation in dark matter halos integrated over time from the onset of star formation to the observed epoch, which we refer to as the integrated SF efficiency. The $SHMR$ as a function of halo mass is known to have a peak and the halo mass at the peak (pivot mass) is $\sim 2 - 3 \times 10^{12} \, M_\odot$ at $z \sim 2$ (e.g., Behroozi et al. 2013; Moster et al. 2013). The shape of the average relation show almost no evolution at $z \sim 0 - 5$, although the behavior of the $z \sim 2$ $SHMR$ below $M_h \sim 10^{11} \, M_\odot$ has not been constrained well. We plot the $SHMR$s of LAEs at $z \sim 2$ comparing them with the average relations for the first time and discuss the typical $SHMR$ of our LAEs with largest survey area so far.

$^3$Hagen et al. (2016) suggest either that their LAEs are undergoing starbursts, that the SFMS becomes shallower at low stellar masses and their LAEs are distributed around it, or that their LAEs are biased towards high $L\alpha$ luminosities, not representing typical LAEs.
Figure 9(a) shows $M_\star$ and $M_h$ of our LAEs in each of the four fields (pink symbols) and those values averaged over the four fields: $M_\star = 10.2 \pm 1.8 \times 10^8 \, M_\odot$ and $M_h = 4.0^{+5.1}_{-2.4} \times 10^{10} \, M_\odot$ (a red star). Those of LAEs at $z = 2.1$ (Guaita et al. 2010)$^{16}$, star forming galaxies based on clustering analysis (Lin et al. 2012; Ishikawa et al. 2016; Ishikawa 2017)$^{17}$, and the average relation based on abundance matching (Behroozi et al. 2013; Moster et al. 2013)$^{18}$ at $z \sim 2$ are shown in figure 9 (a) and (b) for comparison. In contrast to Guaita et al.’s result (a blue circle), our LAEs averaged over the four fields (a red star) lie above a simple lower-mass extrapolation (without changing the slope in the log-log space) of the $M_\star$-$M_h$ relation of star forming galaxies and the average relation. Due to the high stellar mass and low halo mass, our LAEs have a SHMR of $0.02^{+0.07}_{-0.01}$ as high as galaxies at the pivot mass, $M_h \approx 2 - 3 \times 10^{12} \, M_\odot$. Here, the errors in this SHMR value indicate the $\pm 1 \sigma$ (68%) range. The inset of figure 9(b) shows the two-dimensional probability distribution of our four-field average $M_h$ and SHMR values calculated from a Monte Carlo simulation with 500,000 trials. A magenta contour presents the 68% confidence interval, while brown dots indicate randomly selected 150,000 trials. Although the contour touches the $+1 \sigma$ limit of the average relation, only $\sim 2.5\%$ of the entire trials reach the $+1 \sigma$ limit (an orange dashed line).

We discuss whether there are any systematic differences in $M_\star$ and/or $M_h$ between our LAEs and the average relation, which result in the departure of our results from the relations. The average relation by Moster et al. (2013) expresses the mean stellar mass of the central galaxy as a function of halo mass and has a double power-law form, while that by Behroozi et al. (2013) uses the median stellar mass and has five fitting parameters, whose functional form at low halo masses is approximated by a power law$^{19}$. Although the definitions of stellar masses of the two relations are different, the relations are similar to one another. Our average stellar mass is a field-average median stellar mass since stellar masses are derived from SED fitting for median-stacked SEDs, which are commonly used to prevent contamination (see section 4). The field-average median stellar mass of our sample is possibly higher than the field-average median. In fact, the mean value of $K$-band flux densities, which is an approximation of stellar mass, is approximately twice as high as the median one in the SXDS field, the field with the deepest $K$ data. We derive effective halo masses of our LAEs from effective biases directly (see section 3.5) assuming a one-to-one correspondence between galaxies and dark matter halos with a narrow range of halo mass. Our field-average effective halo mass probably corresponds to the true mean and/or median within the large uncertainty whose $1 \sigma$ permitted range is $\sim 1$ dex. Even though the uncertainty by cosmic variance discussed in section 3.4 is added to the total uncertainty in the field-average halo mass, by which the halo mass and SHMR are written as $M_h, cv = 4.0^{+8.4}_{-3.5} \times 10^{10} \, M_\odot$ and $SHMR = 0.02^{+0.18}_{-0.01}$, respectively, our result is not consistent with the extrapolated average relations within $1 \sigma$. Therefore, the departure of our field-average LAEs (a red star) from the average relation are not caused by neither a systematic difference of the definition of $M_\star$ nor $1 \sigma$ cosmic variance on $M_h$.

On the other hand, if LAEs represent average galaxies, the average $M_h$–SHMR relation must have an upturn at $M_h \lesssim 10^{11} \, M_\odot$. This, however, appears to be unphysical because no such upturn is seen at $z \sim 0$, the only epoch at which the average relation below $M_h \sim 10^{11} \, M_\odot$ has been constrained well (Behroozi et al. 2013), unless the low-mass slope of the average relation evolves drastically from $z \sim 2$ to $\sim 0$. Another possibility is that the scatter of the average relation become significantly larger at lower halo masses and the SHMR of our LAEs is within the scatter.

Note that the SHMRs in the HDFN and CDFS are consistent with the average relations although with large uncertainties. We obtain consistent stellar masses between the four fields and it is just the halo masses that are different. The difference in $M_h$, and hence in $b_{g, eff}$, among the four fields seen in figure 4 (see also sections 3.3 and 3.5) is not due to a difference in the limiting magnitude because all four fields have the same limit, $NB387_{tot} = 25.5$. As shown in figure 9, fitting errors and contamination fraction errors possibly drive the offsets of $M_h$ in the two fields to the average values. The difference is also explained by cosmic variance as shown in figure 5(b) (see also section 3.4) and averaging over the four fields reduces the effect of cosmic variance.

$^{16}$The SFR and stellar mass in Guaita et al. (2010, 2011) are derived from SED fitting to a median-stacked SED and their halo mass is a median halo mass. We plot them without any correction (see also section 3.3).

$^{17}$We recalculate halo masses in Lin et al. (2012) from the effective biases given in their table using the same method as ours.

$^{18}$The values of cosmological parameters adopted in Behroozi et al. (2013) and Moster et al. (2013) are slightly different from ours, but we have not corrected for those differences in this study. The $M_h$ value in Behroozi et al. (2013) becomes $\sim 0.15$ dex higher at $M_h \leq 10^{12} \, M_\odot$ when our values are used (P. Behroozi 2017, private communication).

$^{19}$The Behroozi et al. (2013) relations including extrapolated parts in figures 9–11 are taken from the website of P. Behroozi: http://www.peterbehroozi.com/data.html. see also footnote 18.
Fig. 9. (a) $M_\star$ vs $M_h$ and (b) SHMR vs $M_h$. For each panel, a filled pink square, circle, inverted triangle, and triangle represent average (stacked) LAEs with $NB_{387}^{\text{tot}} \leq 25.5$ mag in the SXDS, COSMOS, HDFN, and CDFS fields, respectively, and a large red star shows the average over the four fields. A blue circle indicates median (stacked) LAEs at $z \sim 2$ in Guaita et al. (2011). Black thick and thin solid lines represent the average relation of galaxies at $z \sim 2$ in Behroozi et al. (2013) and Moster et al. (2013), respectively; their extrapolations are shown by dotted black lines. A gray shaded region indicates the $1\sigma$ uncertainty in $M_\star$ in the relation in Behroozi et al. (2013). Gray circles and gray triangles denote BzK galaxies in Lin et al. (2012) and gzK galaxies in Ishikawa et al. (2016) and Ishikawa (2017), respectively. For each data point, the horizontal error bars indicate the $\pm 1\sigma$ ($68\%$) range of the $M_h$ measurement, and the vertical error bars the $\pm 1\sigma$ ($68\%$) range of the $M_\star$ (panel [a]) and SHMR (panel [b]) measurement. The inset of the panel (b) shows the two-dimensional probability distribution of our four-field average $M_h$ and SHMR values calculated from a Monte Carlo simulation with 500,000 trials. A magenta contour presents the $68\%$ confidence interval while brown dots indicate randomly selected 150,000 trials for the presentation purpose. An orange dashed line indicates the $+1\sigma$ limit of the average relation. All data are rescaled to a Salpeter IMF according to footnote 1. See also footnotes 16–19. (Color online)
5.2 Baryon Conversion Efficiency

The baryon conversion efficiency (BCE), defined as:

\[ BCE = \frac{\dot{M}_b}{\dot{M}_h} \]  

(27)

measures the efficiency of star formation in dark matter halos at the observed time, where \( \dot{M}_h \) is the baryon accretion rate (BAR). Here we assume that most of the accreting baryons are in a (cold) gas phase (i.e., the BAR is equal to the inflow rate of cold gas). The average BAR at a fixed halo mass is proportional to the halo mass accretion rate, \( \dot{M}_h(z, M_h) \), which is estimated as a function of redshift and halo mass from cosmological simulations (Dekel et al. 2009):

\[ \text{BAR} = f_b \times \dot{M}_h(z, M_h) \sim 6 \times \left( \frac{M_h}{10^{12} M_\odot} \right)^{1.15} \times (1 + z)^{2.25} M_\odot \text{ yr}^{-1}, \]  

(28)

where \( f_b \equiv \Omega_b/\Omega_m = 0.15 \).

Figure 10 shows the BCE against halo mass. Our LAEs have \( BCE = 1.6^{+0.0}_{-0.0} \) and, as shown by a red star, lie above an extrapolation (keeping the slope unchanged) of the average relation by Behroozi et al. (2013) and most of the BzK galaxies in Lin et al. (2012). Here, the errors in our BCE value indicate the \( \pm 1 \sigma \) (68%) range. The inset of figure 10 shows the two-dimensional probability distribution of our four-field average \( \dot{M}_h \) and BCE values calculated from a Monte Carlo simulation with 500,000 trials. A magenta contour presents the 68% confidence interval, while brown dots indicate the 500,000 trials. Only \( \sim 0.3\% \) of the entire trials reach the \( +1 \sigma \) limit of the average relation (an orange dashed line). On the other hand, Guaita et al. (2010, 2011)’s LAEs at \( z \sim 2 \) have a moderate BCE, although with large uncertainties, which is consistent with the average relation as shown by a blue circle. The average SFRs of both samples are nearly equivalent and it is the clustering measurements that differ and drive our BCE up. So the difference in the clustering affects the discrepancy in both axes in figure 10 making the offset worse.

We discuss whether there are any systematic differences in SFR and/or \( \dot{M}_h \) between our LAEs and the average relation, which result in the departure of our results from the relations. The average relation by Behroozi et al. (2013) expresses the mean SFR as a function of halo mass. Our field-average SFR is derived from SED fitting for median-stacked SEDs and probably does not overestimate the true average SFR, since the median of B-band flux densities, which trace rest-frame UV, is similar to the average B-band flux density. Even when we neglect dust attenuation at UV, \( A_{1600} = 0.6 \pm 0.1 \) mag, the field-average SFR (\( \sim 3.4 \pm 0.4 M_\odot \text{ yr}^{-1} \)) decreases only a factor of \( \sim 2 \). Moreover, even when the uncertainty by cosmic variance discussed in section 3.4 is added to the measured value, \( BCE = 1.6^{+0.0}_{-0.0} \), the \( 1 \sigma \) lower limit of the field-average BCE is still larger than 0.4. Thus, it seems difficult for our LAEs to fall on the average relation shown in figure 10.

As described in section 5.1, logically we cannot rule out the possibilities that our LAEs lie indeed on or near the average relation which changes the slope and/or scatter below \( \dot{M}_h \sim 1 \times 10^{11} M_\odot \) for some reason.

6 Discussion

In this section, we interpret our results on LAEs in terms of the general evolution of galaxies and discuss the physical origin of their high SHMR and BCE, as well as predicting their present-day descendants. We assume that the three average relations shown in figures 8, 9, and 10 do not change either the slope (in log-log plane) or the scatter at low masses. We also assume that our LAEs are central galaxies. If they are satellite galaxies, their dark matter halo (sub halo) masses will be overestimated and their true SHMR and BCE would be higher than reported in this study.

6.1 Duty Cycle

The duty cycle of LAEs, \( f_{\text{duty}}^{\text{LAEs}} \), is defined as the fraction of dark matter halos hosting LAEs. Previous studies find \( f_{\text{duty}}^{\text{LAEs}} \) at \( z \sim 3 \) is a few tenths to a few percent (Ouchi et al. 2010; Chiang et al. 2015). We estimate the duty cycle of our LAEs to be:

\[ f_{\text{duty}}^{\text{LAEs}} = \frac{N_{D_{\text{LAE}}}}{N_{D_{\text{DMH}}}} \sim 2\%, \]  

(30)

where \( N_{D_{\text{LAE}}} \) and \( N_{D_{\text{DMH}}} \) are the number density of LAEs with \( N_{B_{\text{tot}}} \leq 25.5 \) mag and that of dark matter halos estimated from the halo mass function at \( z \sim 2 \) using the calculator provided by Murray et al. (2013), respectively. For this calculation, we assume that dark matter halos hosting our LAEs have a one dex range of mass, \( 10^{10} - 10^{11} M_\odot \), since the K-band magnitudes, an approximation of stellar mass, of our LAEs are distributed with FWHM of \( \sim 3.2 \) mag, or \( \sim 1.3 \) dex. Our result is comparable with those of previous studies.

We also estimate the fraction of galaxies in a given stellar mass range classified as LAEs (LAE fraction), \( f_{\text{gals}}^{\text{LAEs}} \). Assuming that our LAEs have a one dex range of stellar mass, \( 10^{9.5} - 10^{9.5} M_\odot \), we obtain:

\[ f_{\text{gals}}^{\text{LAEs}} = \frac{N_{D_{\text{LAE}}}}{N_{D_{\text{gals}}}} \sim 10\%, \]  

(31)

where \( N_{D_{\text{gals}}} \) is the number density of galaxies estimated by extrapolating Tomczak et al. (2013)’s stellar mass function at \( z \sim 2-2.5 \) below \( 10^9 M_\odot \). This result is comparable with those of previous spectroscopic observations of star forming galaxies at \( z \sim 2-2.5 \) (\( \sim 10\% \), Hathi et al. 2016) and BX galaxies at \( z \sim 1.9-2.7 \) (\( \sim 12\% \) with \( EW_{\text{Ly} \alpha} \geq 20 \) Å; Reddy et al. 2008). Note that typical galaxies embedded in dark matter halos with \( \dot{M}_h = 10^{10} - 10^{11} M_\odot \) have lower stellar masses than...
Fig. 10. Baryon conversion efficiency (BCE) as a function of \( M_h \). A filled pink square, circle, inverted triangle, and triangle represent average (stacked) LAEs with \( NB_{387\nu} \leq 25.5 \) mag in the SXDS, COSMOS, HDFN, and CDFS fields, respectively, and a red star shows the average over the four fields. A blue circle indicates median (stacked) LAEs at \( z \sim 2 \) in Guaita et al. (2011). A black thick solid and gray circles show the average relation of galaxies at \( z \sim 2 \) in Behroozi et al. (2013) and measurements for BzK galaxies in Lin et al. (2012), respectively. For each data point, the horizontal (vertical) error bars indicate the \( \pm 1\sigma \) range of the \( M_h \) (BCE) measurement. Extrapolations and 1\( \sigma \) scatter of BCE at fixed \( M_h \) are shown by a dotted black line and vertical gray bands, respectively. The scatter of BCE is estimated from the scatter of SFRs at \( M_h = 1 \times 10^{11}, 1 \times 10^{12}, \) and \( 1 \times 10^{13} \). The inset shows the two-dimensional probability distribution of our four-field average \( M_h \) and BCE values calculated from a Monte Carlo simulation with 500,000 trials. A magenta contour presents the 68\% confidence interval while brown dots indicate the entire trials. An orange dashed line indicates the +1\( \sigma \) limit of the average relation. All data are rescaled to a Salpeter IMF according to footnote 1. See also footnotes 16–19 (Color online)

\[ M_\star = 10^{8.5} - 10^{9.5} \ M_\odot \] because of the high \( SHMR \) of our LAEs. The low fractions obtained above imply that only a few percent of galaxies within these mass ranges studied here can evolve into LAEs and/or that galaxies within these mass ranges can experience the LAE phase only for a very short time.

6.2 Physical Origin of \( Ly\alpha \) Emission

The result that our LAEs have a higher \( SHMR \) than average galaxies with the same stellar mass may explain why they have strong \( Ly\alpha \) emission. A higher \( SHMR \) at a fixed \( M_\star \) means a lower \( M_h \) and hence a lower gas mass \( (M_{gas}) \), since the \( M_{gas} \) of a galaxy is written as \( M_{gas} \simeq f_b M_h - M_\star \). Galaxies with a low \( M_{gas} \) likely have a low HI column density, thus making it easier for \( Ly\alpha \) photons to escape because of a reduced number of resonant scatterings. Indeed, Pardy et al. (2014) have found a tentative anticorrelation of HI gas mass with the \( Ly\alpha \) escape fraction and the \( Ly\alpha \) equivalent width using 14 local galaxies (\( Ly\alpha \) Reference Sample; Hayes et al. 2013; Östlin et al. 2014).

Furthermore, our LAEs may have high outflow velocities because a high BCE means a high SFR at a fixed \( M_h \) (recall \( BAR \propto M_h^{1.15} \)) and hence a high kinetic energy from star formation at a fixed gravitational binding energy of dark mater halos. In high-velocity outflowing HI gas, the probability of the resonant scattering of \( Ly\alpha \) photons is reduced because of reduced cross sections of HI atoms due to large relative velocities (e.g., Kunth et al. 1998; Verhamme et al. 2006; Hashimoto et al. 2015). Note also that our LAEs have absolutely low dust attenuation due probably to a low stellar mass as shown in figure 7, which also helps \( Ly\alpha \) photons survive in galaxies. To summarize, the high \( SHMR \), high \( BCE \), and moderate \( SFR \) obtained for our LAEs are in concord with the strong \( Ly\alpha \) emission observed.

6.3 Physical Origin of Moderate Star Formation Mode, High SHMR, and High BCE

Our LAEs have a higher \( SHMR \) and a higher \( BCE \) than average galaxies but have a moderate \( SFR \), being located on the (extrapolated) SFMS defined by average galaxies. Indeed, it is
not trivial for galaxy formation models to reproduce these three properties simultaneously.

Dutton et al. (2010) have used a semi-analytic model to study the evolution of the SFMS and its dependence on several key parameters in the model. As shown in their figure 12 and our figure 11, model galaxies (at $z \sim 2$) at a fixed halo mass move along the SFMS upward when the supernova (SN) feedback is weakened or the halo’s spin parameter is reduced, thus having a higher $SHMR$ and a higher $BCE$ on the SFMS. With a lower feedback efficiency, a larger amount of cold gas can be stored, thus resulting in a higher $SFR$ and a higher stellar mass. A lower spin causes the gas density to be higher, thereby the $SFR$ per unit gas mass is elevated. Although these results may not necessarily be applicable to our LAEs whose halo mass is ten times lower, it is interesting to note that there is a relatively simple way to explain MS galaxies with an elevated SHMR and BCE.

It is beyond our scope to identify the mechanism(s) by which our LAEs acquire a high $SHMR$ and a high $BCE$. If, however, the high $SHMR$ and $BCE$ of our LAEs are due to some systematic differences in one or more parameters controlling the star formation and/or internal structure of halos similar to Dutton et al. (2010)’s study, then it implies that not all but only a certain fraction of (low-mass) halos at $z \sim 2$ experience the LAE phase.

6.4 Present-day Descendants of Our LAEs

LAEs are found to reside in low-mass halos with $M_h \sim 10^{10} - 10^{12} M_\odot$ over the wide redshift range $z \sim 2$–7 as found in section 3.5 (e.g., Ouchi et al. 2005, 2010; Kovač et al. 2007; Gawiser et al. 2007; Shioya et al. 2009; Guaita et al. 2010; Bielby et al. 2016; Diener et al. 2017; Ouchi et al. 2017). In other words, the bias value of LAEs tends to decrease with decreasing redshift more rapidly than that of dark matter halos (see figure 7 in Ouchi et al. 2017). Although this trend may be biased because faint LAEs in lower-mass halos are missed at high redshifts, it implies that at lower redshifts, only galaxies with relatively lower masses in the halo mass function can be LAEs, which is analogous to and/or maybe related to downsizing (Cowie et al. 1996).
A roughly constant halo mass with redshift also implies that local descendants of LAEs vary depending on their redshift. The growth of dark matter halos is statistically predicted by the extended Press-Schechter (EPS: Press & Schechter 1974; Bond et al. 1991; Bower 1991) model. An application of the EPS model to distant galaxies can be found in, e.g., Hamana et al. (2006). Previous studies suggest that LAEs at $z \sim 4$–7 evolve into massive elliptical galaxies at $z = 0$ (Ouchi et al. 2005; Kováč et al. 2007; Ouchi et al. 2010), while LAEs at $z \sim 3$ are expected to be progenitors of present-day $L_*$ galaxies (Gawiser et al. 2007; Ouchi et al. 2010). Gualia et al. (2010) show that LAEs at $z \sim 2$ could be progenitors of present-day $L_*$ galaxies like the Milky Way (MW) and that they could also be descendants of $z \sim 3$ LAEs, depending on star formation and dust formation histories (see also Aquaviva et al. 2012).

With the EPS model\(^2\), we find that at $z = 0$ our LAEs are embedded in dark matter halos with a median mass similar to the mass of the Large Magellanic Cloud (LMC: $M_{\text{h}} \sim 0.2$–$3 \times 10^{11} \, M_\odot$; van der Marel & Kallivayalil 2014; Peñarrubia et al. 2016, and references therein), not in MW-like halos ($M_{\text{h}} \sim 8 \times 10^{11}$–$2 \times 10^{12} \, M_\odot$; e.g., Wilkinson & Evans 1999; Kafle et al. 2014; Eadie et al. 2015, summarized in figure 1 in Wang et al. 2015), as shown in figure 12. This is consistent with the prediction by Aquaviva et al. (2012) from SED fitting that LAEs at $z \sim 3$, which are progenitors of present-day $L_*$ galaxies, do not evolve into LAEs at $z \sim 2$. Combined with the previous studies, our result imply that the mass of present-day descendants of halos hosting LAEs depends on the redshift at which they are observed, with higher-z LAEs evolving into more massive halos.

Since the stellar mass of our LAEs, $10.2 \pm 1.8 \times 10^8 \, M_\odot$, is comparable to that of the LMC within only a factor of $\sim 3$ ($M_* \sim 2.9 \times 10^9 \, M_\odot$; van der Marel et al. 2002), their star-formation has to be largely suppressed over most of the cosmic time until $z = 0$, or even be quenched, if they really become LMC-like galaxies. The star formation history of the LMC has been inferred to have multiple components, i.e., an initial burst and subsequent periods with moderate or quiescent star formation (e.g., Harris & Zaritsky 2009). For example, Rezaei Kh. et al. (2014) argue that it consists of two components: an initial burst of $\sim 10$ Gyr ago, or at $z \sim 2$, with a $SFR \sim 2.4 \, M_\odot \text{yr}^{-1}$ assembling $\sim 90\%$ of the total mass, and a much milder star formation with $SFR \sim 0.3 \, M_\odot \text{yr}^{-1}$ after that as shown in their figure 4 (see however Weisz et al. 2013, who obtained a much lower $SFR$). If our LAEs follow such a history with suppressed star formation over $\sim 5$–$10 \times 10^9$ Gyr, they will grow to be LMC-like galaxies at $z = 0$. In this case, if at $z \sim 2$ they lie above the average $M_{\text{h}}$–SHMR relation, they will evolve into galaxies with an SHMR consistent with the average relation at $z \sim 0$ (Behroozi et al. 2013; Moster et al. 2013).

6.5 Future Survey

In the near future, we will extend this work using new $NB387$ data from $\sim 25$ deg$^2$ taken with Hyper Supreme-Cam as part of a large imaging survey program (Aihara et al. 2017). This program uses five broadband and four NB filters, among which the new $NB387$ is included. We call the LAE surveys with the four NB filters SILVERRUSH (Ouchi et al. 2017; Shibuya et al. 2017a). The survey volume for $NB387$ ($z \sim 2$) LAEs is $6 \times 10^8 \, (h^{-1}_5 \text{Mpc})^3$ with an expected number of $\sim 9000$ objects. As shown in figures 5(a) and 5(b), the uncertainty from cosmic variance is expected to be negligibly small, $\sim 3\%$, compared with other uncertainties. With the HSC data, we will be able to determine the SHMR and BCE of $z \sim 2$ LAEs without suffering from cosmic variance.

7 Conclusions

We have investigated stellar populations and halo masses of LAEs at $z \sim 2$, low-mass galaxies at cosmic noon, using $\sim 1250$ $NB387$-selected LAEs from four separate fields with $\sim 1$ deg$^2$ in total. In particular, we have derived the average SF mode, SHMR, and BCE of objects with $NB387 \leq 25.5$ for which measurements for all four fields are available, and discussed star formation activity and its dependence on halo mass. Our main results are as follows.

1. The bias parameter of $NB387 \leq 25.5$ objects averaged over the four fields is $b_{g,\text{eff}} = 1.22^{+0.16}_{-0.18}$, which is lower than that in Gualia et al. (2010) from 0.3 deg$^2$ with a probability of 96\%. We estimate an external error from cosmic variance which inversely scales with the square root of the survey area. The high bias value obtained by Gualia et al. (2010) becomes consistent with our value if the uncertainties from cosmic variance, $\pm 26\%$ and $\pm 51\%$ for this work and Gualia et al. (2010), are considered. We have also found that $b_{g,\text{eff}}$ does not significantly change with limiting NB387 magnitude, or limiting Ly$\alpha$ luminosity, which may be partly due to two trends canceling out with each other: galaxies in more massive halos have brighter intrinsic Ly$\alpha$ luminosities but lower Ly$\alpha$ escape fractions.

2. The halo mass corresponding to the above $b_{g,\text{eff}}$ value is $4.0^{+2.9}_{-2.9} \times 10^{10} \, M_\odot$. This value is roughly comparable to previous measurements for $z \sim 3$–7 LAEs with similar Ly$\alpha$ luminosities, $M_h \sim 10^{10}$–$10^{12} \, M_\odot$ (e.g., Ouchi et al. 2010), suggesting that the mass of dark halos which can host typical LAEs is roughly unchanged with time.

3. The mean of each stellar parameter over the four fields is: $M_* = 10.2 \pm 1.8 \times 10^8 \, M_\odot$, $A_{1600} = 0.6 \pm 0.1$ mag, Age$= 3.8 \pm 0.3 \times 10^8$ yr, and $SFR = 3.4 \pm 0.4 \, M_\odot \text{yr}^{-1}$. Our

\(^2\)We use a publicly released code by T. Hamana: http://th.nao.ac.jp/MEMBER/hamanat/OPENPRO/index.html.
LAEs are thus located near an extrapolation of the consensus relation of \( IRX \) against stellar mass with an assumption of a SMC-like attenuation curve (see figure 7). We have also found that our LAEs are on average placed near a lower-mass extrapolation of the SFMS, confirming the results obtained by Kusakabe et al. (2015) with a ~6 times larger survey area (shown in figure 8).

4. With \( SHMR = 0.02^{+0.07}_{-0.01} \), our LAEs lie above a simple lower-mass extrapolation of the average \( M_M - M_b \) relation (figure 9). The higher \( SHMR \) than average galaxies with the same \( M_M \) may make it easy for \( Ly\alpha \) photons to escape since they are expected to have lower gas masses (baryon mass) and thus lower HI column densities. Our LAEs also have a high \( BCE = 1.6^{+0.0}_{-0.0} \), lying above the average \( BCE-M_b \) relation (figure 10). Thus, our LAEs have been converting baryons into stars more efficiently than average galaxies with similar \( M_b \) both in the past and at the observed epoch but with a moderate SF similar to average galaxies. Galaxies with weak SN feedback and small halo’s spin parameters possibly have such properties according to the semi-analytic model by Dutton et al. (2010).

5. The duty cycle of LAEs (fraction of \( M_M \sim 3 \times 10^{10} M_\odot \) halos hosting LAEs) is estimated to be \( \sim 2\% \), and the LAE fraction (fraction of \( M_M \sim 1 \times 10^9 M_\odot \) galaxies classified as LAEs) is found to be \( \sim 10\% \). These low fractions imply either that only a small fraction of all galaxies can evolve into LAEs and/or that even low-mass galaxies can emit \( Ly\alpha \) only for a very short time.

6. We have calculated the halo mass evolution of our LAEs with the EPS model, to find that at \( z = 0 \) our LAEs are embedded in dark matter halos with a median halo mass similar to the mass of the Large Magellanic Cloud (LMC). If their star-formation is largely suppressed after the observed time until \( z = 0 \) similar to the star-formation history of the LMC, they would have a similar \( SHMR \) to the present-day LMC. This result, combined with the previous studies, implies that the mass of present-day descendant halos of LAEs depends on the redshift at which the LAEs are observed, with higher-\( z \) LAEs evolving into more massive halos.

Acknowledgments

We thank the anonymous referee for his/her helpful comments and suggestions. We are grateful to Lihwai Lin and Li-Ting Hsu for kindly providing us with \( J, H \) and \( K_s \) images of the HDFN field and data in Lin et al. (2012) plotted in figures 8, 9 and 10. We are also grateful to Yoshiaki Ono for giving insightful comments and suggestions on SED fitting. We would like to show our appreciation to Takashi Hamana for helpful comments on cosmic variance and computer programs of the covariance of dark matter angular correlation function and the EPS model.

We would like to express our gratitude to David Sobral, Naveen A. Reddy, Giulia Rodighiero, and Shogo Ishikawa for kindly providing their data plotted in figures 5(a), 7, 8, and 9, respectively. We would like to thank Alex Hagen, James E. Rhoads, Jorryt Matthee, and Peter S. Behroozi for useful comments on their results. We also would like to thank Akio K. Inoue, Cai-Na Hao, Hidenobu Yajima, Ikko Shimizu, Ken Mawatari, Kotaro Kohno, Kyoungho Soo Lee, Tsutomu T. Takeuchi, Mana Niida and Yuki Yoshiura for insightful discussion. We acknowledge Ryota Kawamata, Taku Okamura, and Kazushi Irikura for constructive discussions at weekly meetings. This work is based on observations taken by the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. Based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under ESO programme ID 179.A-2005 and on data products produced by TERAPIX and the Cambridge Astronomy Survey Unit on behalf of the UltraVISTA consortium. This research made use of IRAF, which is distributed by NOAO, which is operated by AURA under a cooperative agreement with the National Science Foundation and of Python packages for Astronomy: Astropy(The Astropy Collaboration et al. 2013), Colossus, CosmoPy and PyRAF, which is produced by the Space Telescope Science Institute, which is operated by AURA for NASA. H.K acknowledges support from the JSPS through the JSPS Research Fellowship for Young Scientists. This work is supported in part by KAKENHI (16K05286) Grant-in-Aid for Scientific Research (C) through the JSPS.

Appendix 1 Result of SED fitting with different assumptions

We show the SED fitting results with the Calzetti curve and without nebular emission below.

A.1.1 The Calzetti Curve

We also examine the cases of the Calzetti curve for comparison. The best-fit parameters with a SMC-like curve and the Calzetti curve are listed in table 5. Figures 6 and 13 show the best-fit SEDs with the observed ones in the case with a SMC-like curve and the Calzetti curve, respectively. We compare the best-fit parameters in subsection 4.4.
A.1.2 Without nebular emission

It is well known that considering nebular emission generally leads to a lower stellar mass (e.g., de Barros et al. 2014). To obtain upper limits of stellar mass and determine the star formation mode of our LAEs, we also examine the case without nebular emission, $f_{\text{ion}}^{\text{esc}} = 1$. The best-fit parameters with a SMC-like curve and the Calzetti curve are listed in table 6. Figure 14 shows the best-fit SEDs with the observed ones in the case with a SMC-like curve and the Calzetti curve.

When we assume a SMC-like curve, the average stellar mass and SFR without nebular emission, $M_\star = 11.2 \pm 1.2 \times 10^8 \, M_\odot$ and $SFR = 3.2 \pm 0.6 \, M_\odot \, \text{yr}^{-1}$, are consistent with those with nebular emission, $M_\star = 10.2 \pm 1.8 \times 10^8 \, M_\odot$ and $SFR = 3.4 \pm 0.4 \, M_\odot \, \text{yr}^{-1}$. This means that the average stellar mass and star formation mode of our LAEs are insensitive to $f_{\text{ion}}^{\text{esc}}$ when a SMC-like curve is used. On the other hand, if we assume the Calzetti curve, the average SFR without nebular emission, $SFR = 51.8 \pm 4.5 \, M_\odot \, \text{yr}^{-1}$, is about four times higher than that with nebular emission, $SFR = 12.7 \pm 1.0 \, M_\odot \, \text{yr}^{-1}$. Their average stellar mass without nebular emission, $M_\star = 4.7 \pm 0.7 \times 10^8 \, M_\odot$ is slightly higher than that with nebular emission, $M_\star = 3.4 \pm 0.8 \times 10^8 \, M_\odot$. With this high SFR, our LAEs lie above the SFMS at $z \sim 2$. However, this case seems unrealistic because our LAEs have Ly$\alpha$ emission, one of nebular emission lines. Indeed, the reduced $\chi$ square values in the case without nebular emission are larger than those with nebular emission in all the fields except SXDS. In addition, results with $f_{\text{ion}}^{\text{esc}} = 1$ give a high UV attenuation of $A_{1600} = 2.9 \pm 0.2 \, \text{mag}$ and hence a high $IRX = 22^{+5}_{-4}$, which is significantly higher than predicted by the consensus relation (see figure 7).

Appendix 2 SFMS based on the IRX-/$\beta$ relation with the Calzetti curve

In the discussion of the star formation mode of LAEs at $z \sim 2$ in section 4.4.2, we derive the average SFR of our LAEs using SED fitting with a SMC-like curve, while Hagen et al. (2016) and Shimakawa et al. (2017) derive SFRs using the $IRX - \beta$
Table 5. Results of SED fitting with a SMC-like curve and the Calzetti curve ($f_{ion} = 0.2$).

|           | $M_*$ (10$^8$M$_\odot$) | $E(B-V)_* [A1600]$ | Age (10$^8$ yr) | $SFR$ (M$_\odot$yr$^{-1}$) | $\chi^2_r$ |
|-----------|-------------------------|---------------------|----------------|-----------------------------|------------|
| SXDS      |                         |                     |                |                             |            |
| SMC       | 9.7$^{+3.6}_{-1.7}$    | 0.05$^{+0.01}_{-0.02}$ | 0.6$^{+0.1}_{-0.2}$ | 3.6$^{+2.8}_{-1.1}$ | 3.3$^{+8.5}_{-0.7}$ | 0.604 |
| Calzetti  | 7.8$^{+3.4}_{-1.9}$    | 0.11$^{+0.02}_{-0.03}$ | 1.1$^{+0.2}_{-0.3}$ | 1.6$^{+2.4}_{-0.7}$ | 5.7$^{+8.2}_{-2.3}$ | 0.665 |
| COSMOS    |                         |                     |                |                             |            |
| SMC       | 14.0$^{+3.4}_{-3.6}$   | 0.07$^{+0.02}_{-0.03}$ | 0.8$^{+0.2}_{-0.4}$ | 4.1$^{+2.4}_{-1.8}$ | 4.2$^{+8.2}_{-0.8}$ | 0.473 |
| Calzetti  | 7.9$^{+5.1}_{-2.5}$    | 0.18$^{+0.03}_{-0.05}$ | 1.8$^{+0.3}_{-0.5}$ | 0.7$^{+1.6}_{-0.4}$ | 12.3$^{+6.4}_{-5.5}$ | 0.648 |
| HDFN      |                         |                     |                |                             |            |
| SMC       | 7.6$^{+4.0}_{-1.9}$    | 0.06$^{+0.02}_{-0.03}$ | 0.7$^{+0.2}_{-0.4}$ | 3.2$^{+4.0}_{-1.4}$ | 2.9$^{+8.8}_{-0.8}$ | 1.298 |
| Calzetti  | 3.2$^{+5.6}_{-0.8}$    | 0.20$^{+0.02}_{-0.03}$ | 2.0$^{+0.3}_{-0.4}$ | 0.3$^{+0.2}_{-0.1}$ | 13.3$^{+5.1}_{-3.9}$ | 0.866 |
| Average   |                         |                     |                |                             |            |
| SMC       | 10.2$^{+1.8}_{-0.6}$   | 0.06$^{+0.02}_{-0.03}$ | 0.6$^{+0.1}_{-0.2}$ | 3.8$^{+2.0}_{-1.3}$ | 3.4$^{+8.0}_{-1.2}$ | 0.473 |
| Calzetti  | 3.4$^{+0.4}_{-0.1}$    | 0.19$^{+0.02}_{-0.03}$ | 0.9$^{+0.1}_{-0.2}$ | 0.3$^{+0.2}_{-0.1}$ | 12.7$^{+5.1}_{-2.6}$ | 0.665 |

Note. (1) The best fit stellar mass; (2) the best-fit color excess [UV attenuation]; (3) the best fit age; (4) the best fit SFR; (5) reduced chi-squared value. The UV attenuation is derived from the attenuation curve listed in the first column. Metallicity, redshift, and $f_{ion}$ are fixed to 0.2Z$_\odot$, 2.18, and 0.2, respectively.

Table 6. Results of SED fitting without nebular emission, $f_{ion} = 1$.

|           | $M_*$ (10$^8$M$_\odot$) | $E(B-V)_* [A1600]$ | Age (10$^8$ yr) | $SFR$ (M$_\odot$yr$^{-1}$) | $\chi^2_r$ |
|-----------|-------------------------|---------------------|----------------|-----------------------------|------------|
| SXDS      |                         |                     |                |                             |            |
| SMC       | 11.4$^{+2.7}_{-1.3}$   | 0.06$^{+0.02}_{-0.02}$ | 0.7$^{+0.2}_{-0.2}$ | 3.6$^{+2.8}_{-1.1}$ | 3.9$^{+8.8}_{-0.8}$ | 0.350 |
| Calzetti  | 5.1$^{+7.1}_{-0.4}$    | 0.27$^{+0.03}_{-0.04}$ | 2.7$^{+0.2}_{-0.2}$ | 0.3$^{+0.2}_{-0.1}$ | 45.3$^{+12.0}_{-10.9}$ | 0.586 |
| COSMOS    |                         |                     |                |                             |            |
| SMC       | 14.6$^{+2.1}_{-2.7}$   | 0.08$^{+0.02}_{-0.02}$ | 1.0$^{+0.2}_{-0.2}$ | 3.6$^{+2.8}_{-1.3}$ | 4.9$^{+8.4}_{-1.2}$ | 0.611 |
| Calzetti  | 6.6$^{+1.5}_{-0.7}$    | 0.29$^{+0.01}_{-0.01}$ | 2.9$^{+0.1}_{-0.2}$ | 0.3$^{+0.2}_{-0.1}$ | 56.2$^{+12.8}_{-26.4}$ | 0.821 |
| HDFN      |                         |                     |                |                             |            |
| SMC       | 9.8$^{+2.4}_{-1.0}$    | 0.05$^{+0.04}_{-0.04}$ | 0.6$^{+0.4}_{-0.4}$ | 4.5$^{+2.7}_{-2.0}$ | 2.1$^{+1.0}_{-0.5}$ | 1.865 |
| Calzetti  | 4.4$^{+0.8}_{-0.5}$    | 0.30$^{+0.02}_{-0.04}$ | 3.0$^{+0.3}_{-0.3}$ | 0.8$^{+0.3}_{-0.3}$ | 51.8$^{+15.9}_{-18.9}$ | 1.653 |
| HDFN      |                         |                     |                |                             |            |
| SMC       | 13.1$^{+10.9}_{-8.9}$  | 0.02$^{+0.01}_{-0.01}$ | 0.2$^{+0.1}_{-0.1}$ | 7.1$^{+8.9}_{-6.2}$ | 2.3$^{+8.0}_{-0.8}$ | 0.148 |
| Calzetti  | 12.1$^{+12.7}_{-10.0}$ | 0.05$^{+0.04}_{-0.04}$ | 0.5$^{+0.4}_{-0.4}$ | 5.1$^{+11.9}_{-5.1}$ | 2.9$^{+35.8}_{-1.0}$ | 0.157 |
| Average   |                         |                     |                |                             |            |
| SMC       | 11.2$^{+1.2}_{-0.6}$   | 0.06$^{+0.01}_{-0.01}$ | 0.6$^{+0.1}_{-0.1}$ | 4.1$^{+0.5}_{-0.5}$ | 3.2$^{+0.6}_{-0.6}$ |            |
| Calzetti  | 4.7$^{+0.4}_{-0.2}$    | 0.29$^{+0.02}_{-0.02}$ | 2.9$^{+0.2}_{-0.2}$ | 0.9$^{+0.1}_{-0.1}$ | 51.8$^{+4.5}_{-4.5}$ |            |

Note. (1) The best fit stellar mass; (2) the best-fit color excess [UV attenuation]; (3) the best fit age; (4) the best fit SFR; (5) reduced chi-squared value. The UV attenuation is derived from the attenuation curve listed in the first column. Metallicity, redshift, and $f_{ion}$ are fixed to 0.2Z$_\odot$, 2.18, and 1, respectively.

The relation with the Calzetti curve. For a fair comparison, figure 15(c) shows our results with the IRX – β relation with the Calzetti curve (Meurer et al. 1999). We find our LAEs to have higher SFRs similar to LAEs in Hagen et al. (2016). Note that the selections of these three samples are different as described in section 4.4.2. We also compare our results by the three different methods discussed in appendix 1.1 and in this section (see figures 15(a) and (b)).
Fig. 14. Same as figure 6 but without nebular emission, $f_{\text{ion}}^{\text{esc}} = 1$. Panels (a) to (d) show results with a SMC-like curve for SXDS, COSMOS, HDFN, and CDFS, respectively. Panels (e) to (h) show results with the Calzetti curve for SXDS, COSMOS, HDFN, and CDFS, respectively. (Color online)
Fig. 15. SFR plotted against $M_*$. Panels (a) and (b) compare different SFR calculation methods for our LAEs; in panel (a) SFRs calculated from SED fitting with two different attenuation curves are compared; in panel (b) SFRs from SED fitting are compared with those from the $IRX-\beta$ relation, where the Calzetti curve is used in both calculations. Panel (c) uses the $IRX-\beta$ relation with the Calzetti curve and compares our LAEs with Hagen et al. (2016)’s and Shimakawa et al. (2017)’s. In panel (a), orange squares, green circles, magenta inverted triangles, and blue triangles represent stacked LAEs with $NB_{387_{tot}} \leq 25.5$ mag in the SXDS, COSMOS, HDFN, and CDFS fields, respectively; filled and open symbols are for a SMC-like curve and the Calzetti curve, respectively. In panel (b), encircled symbols indicate that SFRs are derived from the $IRX-\beta$ relation with the Calzetti curve (Meurer et al. 1999). In panel (c), cyan squares and light green pentagons show individual LAEs at $z \sim 2$ in Hagen et al. (2016) and Shimakawa et al. (2017), respectively; in both studies, SFRs are derived from the $IRX-\beta$ relation with the Calzetti curve (Meurer et al. 1999). Our results based on the $IRX-\beta$ relation with the Calzetti curve are also plotted (encircled symbols). In all panels, several SFMS measurements in previous studies are shown by black lines in the same manner as figure 8. All data are rescaled to a Salpeter IMF according to footnote 1. (Color online)
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