Interrelation of the Environment of Lyα Emitters and Massive Galaxies at $2 < z < 4.5$

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Abstract

We present a comparison of the spatial distributions of Lyα emitters (LAEs) and massive star-forming and quiescent galaxies (SFGs and QGs) at $2 < z < 4.5$. We use the photometric redshift catalog to select SFGs and QGs and an LAE catalog from intermediate/narrow bands obtained from the Subaru Telescope and Isaac Newton Telescope in the Cosmic Evolution Survey (COSMOS). We derive the auto-/cross-correlation signals of SFGs, QGs, and LAEs and the galaxy overdensity distributions at the position of them. Whereas the cross-correlation signals of SFGs and QGs are explained solely by their halo mass differences, those of SFGs and LAEs are significantly lower than those expected from their autocorrelation signals, suggesting that some additional physical processes are segregating these two populations. Such segregation of SFGs and LAEs becomes stronger for rest-frame ultraviolet faint LAEs ($M_{UV} > -20$). From the overdensity distributions, LAEs are located in less dense regions than SFGs and QGs, whereas SFGs and QGs tend to be in the same overdensity distributions. The different spatial distributions of LAEs compared to those of massive galaxies may be attributed to assembly bias or large amounts of neutral hydrogen gas associated with massive halos. These results reinforce the importance of exploring multiple galaxy populations in quantifying the intrinsic galaxy environment of the high-$z$ universe.

Unified Astronomy Thesaurus concepts: Galaxy environments (2029); High-redshift galaxies (734); Galaxy evolution (594)

1. Introduction

In the past few decades, galaxies at $z \geq 2$ have been energetically explored. To select high-redshift (high-$z$) galaxies, a large number of studies use continuum emission. The photometric redshift (photo-$z$) and the spectral energy distribution (SED) of multiple photometric data can classify star-forming galaxies (SFGs) and quiescent galaxies (QGs) (e.g., Ilbert et al. 2009; Mortlock et al. 2015; Laigle et al. 2016; Mawatari et al. 2020). In particular, QGs have been selected photometrically up to $z \sim 6$ (e.g., Ilbert et al. 2013; Davidzon et al. 2017; Merlin et al. 2019), and recent near-infrared (NIR) spectroscopy observations confirm their existence up to $z \sim 4$ (e.g., Glazebrook et al. 2017; Belli et al. 2019; Tanaka et al. 2019; Forrest et al. 2020; Valentino et al. 2020).

Another powerful tool to explore the high-$z$ universe is line-emitting galaxies. Lyα emitters (LAEs) are one of the most famous populations. LAEs are often selected through the excess in the narrow or intermediate band and are known to have lower stellar masses ($\log(M_*/M_\odot) \sim 9$; e.g., Santos et al. 2020), younger stellar populations (e.g., Gawiser et al. 2007; Hagen et al. 2014), and less dust obscuration (e.g., Gawiser et al. 2006; Kusakabe et al. 2015) than continuum-selected galaxies. In terms of their host dark matter halos, LAEs tend to reside in halos with lower mass than more massive galaxies (e.g., Kusakabe et al. 2018; Ouchi et al. 2018; Khostovan et al. 2019). Another important population of line-emitting galaxies are Hα emitters (HAEs; e.g., Geach et al. 2008; Kodama et al. 2013; Sobral et al. 2013). Unlike LAEs, they are known to be SFGs with similar properties to continuum-selected ones (e.g., Oteo et al. 2015).

One of the essential topics to be investigated in the high-$z$ universe are connections between galaxy properties and their surrounding environments, referred to as the “environmental effect.” At lower redshifts ($z < 1$), many studies report significant correlations (e.g., Dressler 1980; Peng et al. 2010). To understand its origin, exploration in the higher-$z$ universe is vital. Indeed, recent statistical studies have discussed the environmental effect at $z > 2$. In particular, the relation between the local density and the star formation rate (SFR; e.g., Chartab et al. 2020; Lemaux et al. 2020) and the environmental quenching (e.g., Lin et al. 2016) have been intensively investigated, though no consensus has been obtained. Lemaux et al. (2020) suggest a positive correlation between SFR and the overdensity, whereas Chartab et al. (2020) report a negative correlation. Also, Lin et al. (2016) do not find any strong dependence of the environment for the quiescent fraction at $z > 1.5$.

The characterization of the environment may depend on the population of tracer galaxies. The connection between galaxy properties and the large-scale environment at high $z$ has also been investigated by focusing on progenitors of galaxy clusters in the local universe, referred to as “protoclusters” (e.g., Hatch et al. 2011; Koyama et al. 2013; Cooke et al. 2014; Shimakawa et al. 2018; Tadaki et al. 2019; Ito et al. 2020). Protoclusters are often discovered through the projected number density of galaxies (e.g., Steidel et al. 1998; Hatch et al. 2011; Jiang et al. 2018; Toshikawa et al. 2018), but most protoclusters are selected using only SFGs. Whereas some studies report the
high number density of multiple galaxy populations in protoclusters (e.g., Kubo et al. 2013), some studies have reported that LAEs and massive SFGs trace different large-scale structures (e.g., Shimakawa et al. 2017; Shi et al. 2019, 2020). Such possible segregation of LAEs and massive galaxies can be related to the assembly time difference of host dark matter halo (e.g., Shi et al. 2019) or baryonic physics, such as the relation of surrounding H I gas and Lyα emission (e.g., Shimakawa et al. 2017). These observational results suggest the importance of comprehensively understanding the interrelationship of the distributions of multiple populations.

For quantifying the differences of the spatial distribution of multiple populations, the cross-correlation is an effective tool. It has been measured for different galaxy populations (e.g., Béthermin et al. 2014; Hatfield & Jarvis 2017) and used to determine the connections between galaxies and intergalactic media (IGM; e.g., Tejos et al. 2014; Momose et al. 2021; Liang et al. 2021). The overdensity, which is defined as the excess of the surface number density over the average value, is another tool for quantifying the environment. The overdensity is measured using a variety of methods. Some methods fix the scale in which the density is estimated, whereas others calculate the density based on the number of nearby galaxies. Recent studies have proposed a density measurement technique, called the Voronoi Monte Carlo Mapping, that does not assume any density scale (e.g., Tomczak et al. 2017; Lemaux et al. 2020). These methods are based on different assumptions, so it is essential to systematically apply a unified method to all populations to see the difference of their environments.

In this study, we examine the spatial distribution differences among multiple galaxy populations via analysis of their clustering and overdensity distributions to understand the general relationships among them in the large-scale structure. We focus on three populations: massive SFGs, massive QGs, and LAEs in the Cosmic Evolution Survey (COSMOS) field. SFGs and QGs are selected based on the multiphotometry catalog constructed in Laigle et al. (2016), whereas LAEs are taken from the extensive narrow- and medium-band-based survey in SC4K (Sobral et al. 2018). The large amounts of data in the COSMOS field enable us to investigate the differences in their distributions up to $z \sim 4.5$.

This paper consists of the following sections. In Section 2, we introduce our galaxy samples. In Section 3, we present our clustering analysis. In Section 4, we report a comparison of the overdensity distribution at the positions of sources in the different populations. In Section 5, we examine the result by using HAeCs at $z = 2.22$ and discuss the implications of our results to the environments of galaxies. Lastly, in Section 6, we summarize our paper.

In this study, we assume that the cosmological parameters are $H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} = 100 h \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$, and we use the AB magnitude system. We also use the annotations cMpc and pMpc to refer to comoving and physical scales, respectively.

2. Data Set

2.1. Star-forming Galaxies and Quiescent Galaxies

2.1.1. Sample Construction

We use the COSMOS multiband catalog constructed in Laigle et al. (2016). This catalog consists of photometricities of $\sim 30$ bands, i.e., near-UV of GALEX (Zamojski et al. 2007), $u'$ band of the Canada–France–Hawaii Telescope, $BVri^{++}$ and several intermediate/narrow bands of Suprime-Cam (Taniguchi et al. 2007, 2015), $Y$ band of Hyper Suprime-Cam of the Subaru Telescope, $YJHK_s$ of VISTA InfraRed Camera (VIRCAM) of the VISTA telescope (McCracken et al. 2012), $HK_s$ of Wide-field InfraRed Camera (WIRCam) from the Canada–France–Hawaii Telescope (McCracken et al. 2010), and Channels 1, 2, 3, and 4 of the Infrared Array Camera (IRAC) of the Spitzer telescope from the SPLASH survey. This catalog is based on detection in the $\chi^2$ sum of the $YJHK_s$ and $z^{++}$ images. For more details, please refer to Laigle et al. (2016).

In this study, SFG and QG samples are constructed to be magnitude limited based on the $3\sigma$ limiting magnitude of $K_s$ band ($K_s < 24$), where $K_s$ is the $3\sigma$-aperture magnitude of $K_s$ band. Objects are further selected with flags ($\text{FLAG}_{\text{COSMOS}}$ and $\text{FLAG}_{\text{PETER}}$) to focus on objects with the clean photometry. We then estimate the photometric redshift using the MIZUKI code (Tanaka 2015). One advantage of this code is that we are able to simultaneously derive the photometric redshifts and physical properties (e.g., $M_*$, SFR, and dust extinction) with their Bayesian priors. This allows us to include the uncertainty of the photometric redshift in the estimate of the physical properties. It should be noted that the photo-$z$ between MIZUKI and Laigle et al. (2016) is consistent with each other with $\delta z/(1+z) = 0.003$, after excluding objects with the bad chi-squares ($\chi^2 > 4$) at $2 < z < 4.5$.

MIZUKI conducts the fitting based on spectral templates from Bruzual & Charlot (2003), Chabrier initial mass function (Chabrier 2003), and Calzetti dust attenuation curve (Calzetti et al. 2000). We use an exponentially declining SFR, i.e., $\text{SFR} \propto \exp(-t/\tau)$, where $t$ is time. The $\tau$ is assumed to be $0.1 \text{yr} < \tau < 11 \text{Gyr}$ in addition to $\tau = 0$, $\infty$, which is equivalent to the single stellar population model and the constant SFR model. The age is assumed to be between $0.05$ and $14 \text{Gyr}$. Also, the optical depth in the $V$ band ($\tau_V$) is between 0 and 2 with a step of 0.1, in addition to $\tau_V = 2.5$, 3, and 4. Because the templates mentioned above include only stellar emissions, the nebular emissions are included according to Inoue (2011). Similar to Kubo et al. (2018), which select QGs at $3.5 < z < 4.5$ in the ultradeep survey (UDS) region using the MIZUKI code, galaxies with bad chi-squares ($\chi^2 > 4$) in the SED fitting are excluded ($\sim 4\%$ of the total sample in the target redshift). Objects with large reduced chi-squares have generally poor photometry owing to the affection of nearby bright stars or blending. Also, apparent active galactic nuclei (AGNs) can be excluded from this criterion since any AGN template is not included in the fitting. The typical uncertainty of the estimated redshift, $M_*$, and SFR of objects at $2 < z < 4.5$ are $\delta z/(1+z) \sim 0.05$, $\delta M_*/M_* \sim 0.2$, and $\delta\text{SFR}/\text{SFR} \sim 0.4$, respectively.

SFGs and QGs are distinguished based on the specific star formation rate (sSFR) derived by the SED fitting, as in our other studies (Kubo et al. 2018; K. Ito et al. 2021, in preparation). We define galaxies with $\text{sSFR}_{1\sigma,\text{upper}} < 10^{-9.5} \text{yr}^{-1}$ as QGs and classify the others as SFGs. Here $\text{sSFR}_{1\sigma,\text{upper}}$ is the upper limit of sSFR, which is defined as the ratio of the 1$\sigma$ upper limit of SFR to the 1$\sigma$ lower limit of stellar mass, derived from the SED fitting. We note that our result does not change even if we modify this classification, for example, by considering the redshift evolution of the star formation main sequence (i.e., a stricter threshold for lower-$z$ objects) or by defining SFGs with
sSFR$_{\text{1r,lower}} > 10^{-9.5}$ yr$^{-1}$ to exclude overlapped regions with QGs.

We focus on sources at $2 < z < 4.5$, where the number of sources is sufficient to quantify the average spatial distributions. The relationship between the stellar mass and SFR of SFGs and QGs is shown in Figure 1. The threshold is located ~1 dex lower than the main sequence. Also, we see that QGs are mainly selected from the outer envelope of the main sequence of galaxies. It should be noted that this threshold selects not only passive galaxies, which are completely quenched, but post-starburst galaxies as well. The stellar mass of LAEs of SC4K used in this study is reported to have a median value of $\log(M_*/M_\odot) = 9.0 - 9.5$ (Santos et al. 2020), so our photo-$z$-selected galaxies tend to be much more massive than them.

In addition, powerful AGNs, which are detected in X-ray, are not included in this study because the SED fitting may incorrectly estimate their host galaxy properties. We use the X-ray image of the Chandra COSMOS Legacy Survey (Civano et al. 2016), which reaches $8.9 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ in the 0.5–10 keV band. We crossmatch with the multiphotometric catalog of this survey (Marchesi et al. 2016) by using coordinates from optical and NIR images and exclude objects with counterparts with a separation of $\leq 1''$. The fraction of excluded objects is 2%–7% and depends on the stellar mass and the redshift. Some AGNs that are not bright enough to be detected in this catalog may be included in our sample, but their emission is expected to hardly affect the outcome of the SED fitting.

### 2.1.2. Stellar Mass Completeness

We estimate the stellar mass completeness of our SFG and QG sample from the method employed in the previous studies (e.g., Pozzetti et al. 2010; Laigle et al. 2016; Davidzon et al. 2017). First, the rescaled stellar mass ($M_{\text{resc}}$) expected at the magnitude limit ($K_{\text{s,lim}}$) is estimated from the $M_*$ and $K_s$-band magnitude of galaxies. Here, we focus on objects brighter than the limiting magnitude. The $M_{\text{resc}}$ is derived as follows:

$$\log M_{\text{resc}} = \log M_* + 0.4(K_* - K_{\text{s,lim}}).$$

The stellar mass completeness limit is defined as the bottom 90th percentile of the $M_{\text{resc}}$ distribution in each redshift bin. We see the evolution of the stellar mass completeness limit of SFGs and QGs in Figure 2, which shows those in every $\varepsilon_z = 0.5$. The stellar mass limit is often fitted by the power-law function (e.g., Davidzon et al. 2017). The best fits are described as $M_* = 10^{8.18} \times (1 + z)^{4.11} M_\odot$ for SFGs and $M_* = 10^{8.30} \times (1 + z)^{3.30} M_\odot$ for QGs. The stellar mass completeness limit is generally higher for QGs than for SFGs because the mass-to-light ratios of QGs are higher than those of SFGs. In the following sections, we estimate the stellar mass completeness limit for each group by following this procedure and employing their value.

### 2.2. Lyα Emitters

We use the LAE catalog of Sobral et al. (2018), who construct a systematic LAE sample at $z \sim 2 – 6$, referred to as the SC4K sample. This catalog is based on the intermediate-band (IB) data of Suprime-Cam and narrowband (NB) data of the Wide Field Camera (WFC) of the Isaac Newton Telescope and Suprime-Cam. They select LAEs by using an observed equivalent width (EW) threshold and imposing the color selection and the nondetection of broadband blueward Lyα emissions at the target redshift. Spurious objects are excluded from the sample via visual inspection. Contaminants found by previous spectroscopic surveys are also excluded. They finally select 3908 sources as LAEs in 16 redshift slices.

The target redshift range ($2 < z < 4.5$) corresponds to LAEs selected from NB392, IA427, IA464, IA484, IA505, IA527, IA574, and IA624 bands at $2.20 < z < 2.24$, $2.42 < z < 2.59$, $2.72 < z < 2.90$, $2.89 < z < 3.08$, $3.07 < z < 3.26$, $3.23 < z < 3.43$, $3.63 < z < 3.85$, and $4.00 < z < 4.25$, respectively. In this study, we construct an Lyα luminosity ($L_{\text{Lyα}}$) complete sample by imposing a $\sigma$ Lyα luminosity limit cut for each selection band. The $\sigma$ limiting luminosity of the sample is $L_{\text{Lyα}}(\text{erg s}^{-1}) = 42.3$–42.8, dependent on the selection filter (see Sobral et al. 2018, for details). We note that NB392 LAEs are selected with a loose threshold (EW $> 5 \times (1 + z)$ Å) compared to other IB LAEs (EW $> 50 \times (1 + z)$ Å).

The spatial coverage of the LAE survey is slightly different from the surveys from which SFGs and QGs are selected. Thus, this study focuses on the region where all of SFGs, QGs, and LAEs exist. We note that the survey fields for most of the selection filters are larger than the field of photo-$z$ galaxies, but that of NB392 is 22% smaller.

It is known that bright LAEs can be AGNs (e.g., Konno et al. 2016; Sobral et al. 2018). Such objects can have different properties from those of typical LAEs described in Section 1. Therefore, LAEs with high Lyα luminosity ($L_{\text{Lyα}}(\text{erg s}^{-1}) > 43.3$) are excluded from the sample. The fraction of these objects is quite small (~3% of the total), and if they are included, the following results do not change. We also exclude objects with counterparts in the Chandra COSMOS Legacy Survey catalog in the same manner as that for photo-$z$ galaxies.

### 3. Clustering Analysis

In this section, we estimate autocorrelation function (ACF) and cross-correlation function (CCF) signals among SFGs,
QGs, and LAEs and discuss the difference in spatial distributions of these galaxy populations.

3.1. Group Construction

LAEs are constructed in discrete redshifts, as summarized in Section 2.2. By comparison, the samples of SFGs and QGs have continuous redshift distributions. To increase the signal-to-noise ratio of CCFs, we construct four redshift groups at $z = 2.05, 2.39, 2.40, 2.85$, and $3.50$. These four redshift groups are $2.05 < z < 2.20$, $2.39 < z < 2.40$, $2.40 < z < 2.85$, $2.85 < z < 3.50$, and $3.50 < z < 4.50$. Hereafter, we refer to these groups as $-group1$, $-group2$, $-group3$, and $-group4$, respectively. The redshift range is determined to include possible photo-$z$ galaxies located in the same redshift of LAEs.

The redshift range of the lowest redshift bin is defined to match that of NB392 LAEs ($2.20 < z < 2.24$), including the photo-$z$ uncertainty $(\delta z/(1 + z) \sim 0.05)$, which leads to a narrower range than those of other bins. For the highest redshift group, we select objects within a broader redshift range $(\delta z = 1)$ to enhance the signal-to-noise ratio of cross-correlation. Noticeably, a slight duplication exists between the second and the third group, but this does not affect our overall result.

Also, we divide SFG and QG samples into four subgroups in terms of their stellar mass, which includes only objects whose stellar masses are $\log(M_*/M_\odot) \geq 10.4, 10.6, 10.8, \text{and } 11.0$, respectively. Hereafter, we refer to these groups as $M_*/-group1$, $M_*/-group2$, $M_*/-group3$, and $M_*/-group4$, respectively. From the method summarized in Section 2.1.2, the stellar mass completeness limit of $-group1$, $-group2$, $-group3$, and $-group4$, respectively. From the method summarized in Section 2.1.2, the stellar mass completeness limit of $-group1$, $-group2$, $-group3$, and $-group4$, respectively. From the method summarized in Section 2.1.2, the stellar mass completeness limit of $-group1$, $-group2$, $-group3$, and $-group4$, respectively.

The redshift distributions of each group of SFGs and QGs are estimated using the summation of the probability distribution function (pdf) of the photo-$z$ of galaxies in each group, similar to the method used in Coupon et al. (2012). The photo-$z$ pdf often has a complex shape, but for simplicity, we choose to represent each pdf with a normalized Gaussian centered at the median pdf and its 68% confidence interval as $\pm 1\sigma$. We sum up these Gaussian functions of all objects in a group and construct the average redshift distribution of a group. Meanwhile, the redshift distribution of LAEs is assumed to be a number-weighted sum of the Ly$\alpha$ detection rate predicted from each NB/IB transmission curve. The redshift distribution of each sample is summarized in Figure 3.

Figure 2. Stellar mass completeness evolution (orange circles) for SFGs (left) and QGs (right). The orange lines show the best power-law fits of observed value in every $\delta z = 0.5$. The background color map shows the distribution of observed galaxies with $K_s < 24$ mag.

3.2. Autocorrelation Function

We calculate the ACF using the method from Landy & Szalay (1993), who propose an estimator as follows:

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

where $DD$, $DR$, and $RR$ are the normalized numbers of galaxy–galaxy, galaxy–random, and random–random pairs, respectively.

The ACF is often expressed in the power-law form

$$\omega_{\text{ACF}} = A_\omega \theta^{1-\gamma}.$$

In this study, we fix $\gamma$ to a fiducial value ($\gamma = 1.8$), following previous studies of LAEs (e.g., Kusakabe et al. 2018; Ouchi et al. 2018) and photo-$z$ galaxies (e.g., Coupon et al. 2012).

Random objects are generated with a number density of $\sim 200 \text{ arcmin}^{-2}$, which is more than 200 times higher than those of photo-$z$ galaxies and LAEs. Random objects are distributed in the same region as that of galaxies, including flags.

It is known that the observed ACF based on Equation (2) is underestimated because of the finite observation field, referred to as “integral constraint.” To correct this bias, the integral
constraint C is derived using the following equation:

\[ C = \frac{\sum_i \theta_i^{1-\gamma} RR(\theta_i)}{\sum_i RR(\theta_i)}. \]  

(4)

In this study, the C is estimated to be \( C = 1.46 \) for \( z\)-group1 and \( C = 1.36 \) for the others. Because the survey field is smaller in NB392 (see Section 2.2), the C is higher in \( z\)-group1 than in other bins. The C provides a corrected ACF \( \omega_{\text{ACF}} \) according to the following equation:

\[ \omega_{\text{ACF}} = \omega_{\text{ACF,obs}} \theta^{1-\gamma} - C. \]  

(5)

The error of the ACFs is estimated based on the Jackknife resampling. We divide the observed field into \( 5 \times 5 \) regions, and removing one region at a time, we estimate \( \omega_{i,k} \) in the kth trial. This procedure repeats 25 times and we compute the variance of \( \omega_{\text{ACF}}(\theta) \) for each bin:

\[ \text{Var}_i = N \left( 1 - \frac{1}{N} \sum_{k=1}^N (\omega_{i,k} - \bar{\omega}_i)^2 \right), \]  

(6)

where \( N \) is the number of resampling trials and \( \bar{\omega}_i \) is the mean of \( \omega_{i,k} \). For calculating the variance, we do not consider the trial when the subtracted region is overlapped by over 50% mask region.

We fit a power-law function (Equation (3)) to ACFs via the Python module lmfit by the least-squares method. The distribution of satellite galaxies around the central galaxy is not within the scope of this study, and we are only interested in the larger scale outside of the single halo. Therefore, the angular scale corresponding to within a halo, referred to as the “one-halo term,” is excluded from the ACF fitting range. Specifically, we do not consider \( \theta < 40'' \) for photo-z galaxies and \( \theta < 10'' \) for LAEs, where the one-halo term dominates as implied by previous studies (e.g., Ishikawa et al. 2015; Ouchi et al. 2018).

We note that the amplitude can decrease owing to contaminants. Balmer breaks of low-z galaxies can be misclassified as Lyman breaks at the target redshifts in the case of photo-z galaxies. \([\text{O II}], \text{H}\beta, \text{and [O III]} \) emitters are contaminant candidates for LAEs (see Sobral et al. 2018, for more concrete discussion). Nonetheless, as will be discussed in Section 3.7, these contaminants do not affect our overall results related to the distribution difference. Therefore, we do not correct these contaminants for the value of the amplitude.

Figure 4 shows the estimated ACFs with the best-fit power-law functions. The observed ACFs are well described in the power-law form in the large scale. Focusing on smaller-scale correlation, QGs have a significant deviation from the power law, especially in \( z\)-group1 and 2. Such enhancement of the one-halo term for QGs is seen in other studies (e.g., Cowley et al. 2019) and can be related to the higher satellite fraction. The best-fit values of \( \omega_{\text{ACF}} \) are summarized in Table 2.

### 3.3. Cross-correlation Function

The CCF of samples 1 and 2 is estimated as follows:

\[ \omega_{\text{CCF,obs}}(\theta) = \frac{D_1D_2 (\theta) - D_1R(\theta) - D_2R(\theta) + RR(\theta)}{RR(\theta)}, \]  

(7)

where \( D_1, D_2, D_1R, \) and \( D_2R \) are the normalized numbers of pairs of samples 1 and 2, sample 1 and random, and sample 2 and random, respectively. The integral constraint correction and the error estimation are performed in the same manner as for the ACF.

In this study, we measure the difference in the clustering of each population with respect to SFGs. Therefore, we estimate CCFs between SFGs and LAEs and those between SFGs and QGs. The latter cases are determined for the same stellar mass thresholds for both populations. We do not discuss CCFs between QGs and LAEs because we do not obtain any meaningful constraints about the distribution differences owing to the poor statistics. The estimated CCFs are shown in Figure 5. As with ACFs, we fit using the power law with the fixed \( \gamma = 1.8 \). The CCFs of \( \theta > 40'' \) are used to avoid the one-halo term for photo-z galaxies. The results are summarized in Table 3. There is no clear stellar mass dependence of the amplitude of CCF of photo-z galaxies.

### 3.4. Correlation Length and Halo Mass

The ACFs and CCFs are evaluated based on projected separations on the sky. The spatial correlation function \( \xi(r) \) can be estimated from ACFs and CCFs. The galaxy spatial
correlation function is often approximated as follows:
\[
\xi(r) = \left( \frac{r}{r_0} \right)^\gamma,
\]
where \( r_0 \) is the correlation length. To derive the \( r_0 \) from ACFs, we employ the Limber equation (Peebles 1980; Efstathiou et al. 1991),
\[
A_w = C g_0^2 \int_0^\infty F(z)D_b(z)^{1-\gamma}N(z)^2g(z)dz \left[ \int_0^\infty N(z)dz \right]^2,
\]
\[
g(z) = \frac{H_0}{c}(1+z)^2 [1 + \Omega_m z + \Omega_\Lambda [(1 + z)^{-2} - 1]]^{1/2},
\]
\[
C = \frac{\sqrt{\pi} \Gamma[(\gamma - 1)/2]}{\Gamma(\gamma/2)},
\]
where \( D_b(z) \) is the angular diameter distance and \( N(z) \) is the redshift distribution of the sample. \( F(z) \) describes the redshift evolution of \( \xi(z) \), which is modeled as \( F(z) = [(1 + z)/(1 + \bar{z})]^{(3+\epsilon)} \) with \( \epsilon = -1.2 \) (Roche & Eales 1999). The \( \bar{z} \) is the average redshift of the sample; \( c \) and \( \Gamma \) are the light speed and the Gamma function, respectively. The derived correlation lengths are summarized in Table 2.

In Figure 6, the correlation lengths are compared with those in previous studies. We see that our correlation measurement is consistent with previous results within the uncertainty. The correlation length of SFGs at the lowest redshift bin is located in a similar range to that of HAEs with \( \log(M_*/M_\odot) > 10.1 \) reported in Cochrane et al. (2018). HAEs are typical star-forming galaxies and expected to have the same correlation length as our SFGs at fixed stellar mass. Those of LAEs at \( z > 2.4 \) are also consistent with those in Khostovan et al. (2019), which also use SC4K LAEs. Though LAEs of \( z \)-group I are higher than those at similar redshift in Kusakabe et al. (2018), their LAEs reach fainter luminosity than ours. Such a difference can cause the different value.

In addition, Figure 6 shows that more massive SFGs have slightly higher correlation lengths at fixed redshift, being also consistent with previous studies (e.g., McCracken et al. 2015).

For QGs, we do not see such a trend owing to a large uncertainty.

The correlation length of the spatial CCF are also derived from the amplitude of its CCFs via the following equation, which is a slightly modified version of Equation (9) (Croom & Shanks 1999):
\[
A_w = C g_0^2 \int_0^\infty F(z)D_b(z)^{1-\gamma}N_1(z)N_2(z)g(z)dz \frac{\int_0^\infty N_1(z)dz \int_0^\infty N_2(z)dz}{\int_0^\infty N(z)dz},
\]
where \( N_1(z) \) and \( N_2(z) \) are the redshift distribution functions of samples 1 and 2, respectively. The best-fit correlation lengths are summarized in Table 3.

From the derived correlation length of the spatial ACFs, we also calculate the mean dark matter halo mass. First, the galaxy matter bias \( b_g \) is estimated as follows:
\[
b_g(r) = \frac{\int \xi(8 \ h^{-1} \text{Mpc})}{\sqrt{\xi_{DM}(8 \ h^{-1} \text{Mpc}, z)}},
\]
where \( \xi_{DM}(8 \ h^{-1} \text{Mpc}, z) \) is the correlation function for the dark matter, estimated from the dark matter power spectrum computed using the transfer function approximation reported in Eisenstein & Hu (1998). Second, the mean dark matter halo mass \( \langle M_h \rangle \) is estimated based on an assumption that the mean dark matter halo mass has a galaxy bias equal to the measured value:
\[
b_g = b(\langle M_h \rangle).
\]
We discuss the difference of distributions of three galaxy populations by comparing spatial correlation functions estimated from ACFs and CCFs. As reported in Tejos et al. (2014), the following relation among spatial ACFs and CCFs exists according to the Cauchy–Schwarz inequality:

\[ \xi_{D1D2} \leq \xi_{D1D1} \xi_{D2D2}, \]

where \( \xi_{D1D2} \) is the spatial CCF between samples 1 and 2, and \( \xi_{D1D1} \) and \( \xi_{D2D2} \) are the spatial ACFs of samples 1 and 2, respectively. When the equality is valid, distributions of two populations are determined based only on their dark matter halo masses, whereas an inequality sign implies that the spatial CCF is not determined by halo mass alone and that some additional physics affects their distributions. Therefore, we derive the spatial correlation function ratio \( \xi_{D1D2}^2 / (\xi_{D1D1} \xi_{D2D2}) \) and examine whether or not their distribution is explained only by the dark matter halo mass. With the assumption of power-law forms of spatial ACFs and CCFs with the same \( \gamma \), the ratio is expressed by the correlation lengths:

\[ \frac{\xi_{D1D2}^2}{\xi_{D1D1} \xi_{D2D2}} = \left( \frac{r_{0D1D2}^2}{r_{0D1D1} r_{0D2D2}} \right) \gamma, \]

where \( r_{0D1D2}, r_{0D1D1}, \) and \( r_{0D2D2} \) are the correlation lengths of the spatial CCF between samples 1 and 2 and their spatial ACFs, respectively. We use the correlation lengths derived in Section 3.4.

Figure 8 is the main result of this study. The top panel shows the spatial correlation function ratio for SFGs and LAEs. We find that the ratios are below unity for most of the bins, implying that the spatial CCFs between SFGs and LAEs are not determined by the halo mass alone, and that some additional physics segregate the spatial distributions of SFGs and LAEs. This trend is independent of the stellar mass threshold of SFGs.

In the second-lowest redshift (\( z \sim 2.7 \)) bin, the correlation function ratio for SFGs and LAEs in \( M_* \)-group 2 and 3 is consistent with unity if we consider the uncertainty. We do not know the exact origin of the peculiar behavior in this redshift.
bin, but we show several possibilities. In this redshift bin, LAEs are selected mainly from IA427, leading to a focus on smaller volumes in terms of line of sight compared to those of other bins in higher redshifts. This may induce to trace a peculiar structure by chance. Also, Cucciati et al. (2016) report a “proto-supercluster” at \( z = 2.45 \) in the COSMOS field, within the scope of this bin. This may cause different behavior in that bin.

The limiting magnitude for LAEs is different depending on the selection filter, as mentioned in Section 2.2. In particular, the limiting magnitude of higher-redshift LAEs is shallower. This may cause a bias in the value of each bin. To check this possible bias, we derive the spatial correlation function ratios between SFGs and LAEs brighter than \( \log(L_{\lambda_{Ly}\alpha})/\text{erg s}^{-1} > 42.8 \) in \( z \)-group1. This threshold corresponds to the maximum 3\( \sigma \) limiting luminosity of our LAE sample. The ratios are 0.21 \pm 0.38, 0.12 \pm 0.18, 0.43 \pm 0.76, and 1.54 \pm 2.56 for SFGs of \( M_g \)-group1, 2, 3, and 4, respectively. Though the last two cases have too large uncertainty to state any trend, possibly due to the small sample number of LAEs, these values imply that the limiting \( \lambda_{Ly\alpha} \) luminosity difference does not impact our results.

The bottom panel of Figure 8 shows the spatial correlation function ratios for SFGs and QGs. Unlike the spatial correlation function ratios for SFGs and LAEs, those for SFGs and QGs maintain unity, suggesting that only their dark matter halo masses can account for the distributions for SFGs and QGs. If we derive the CCFs of SFGs and QGs adopting the different stellar mass threshold to each population and estimate the ratio, we find that the result generally does not change.

### 3.6. The Dependence of the Correlation Function Ratio on the Rest-UV Magnitude of LAEs

To investigate the effect of the stellar mass of LAEs on the results, we divide LAEs in terms of their rest-UV absolute magnitude. The absolute magnitude of SC4K LAEs is calculated based on \( i^\text{+} \)-band photometry summarized in Laigle et al. (2016), under the assumption of a flat continuum. With the assumption of LAEs located in the main sequence and with small dust attenuation, the rest-UV luminosity is proportional to SFR and thus to stellar mass. The LAE sample is divided into two subsamples; one with \( M_{i^\text{+}} \) greater than \( -20 \), i.e., “UV-faint LAEs,” and the other with \( M_{i^\text{+}} \) less than \( -20 \), i.e., “UV-bright LAEs.” LAEs undetected in the \( i^\text{+} \) band are classified under the former subsample. The 3\( \sigma \) limiting magnitude of this \( i^\text{+} \)-band photometry is 26.2 mag in 3\( \text{\textdegree} \) aperture (Laigle et al. 2016), which corresponds to...
$M_{UV} \sim -20.0$ mag at $z = 4.5$. This ensures that we completely select UV-bright LAEs at all redshift bins. Moreover, this threshold corresponds to $\log(M_{\ast}/M_\odot) \sim 9.5 - 10$ according to the star formation main sequence and UV magnitude–UV slope relation of SC4K LAEs (Santos et al. 2020). Therefore, in terms of the stellar mass, the UV-bright LAE sample is more similar to QGs and SFGs than the total LAE sample.

We derive ACFs and CCFs for these subsamples and estimate the spatial correlation function ratios from the correlation lengths in the same manner as in Section 3.5. Figure 9 shows the ratio $\xi_{SFG-LAE}^2/\xi_{SFG-LAE}^2$ as a function of the redshift for the cases of UV-bright LAEs and UV-faint LAEs. Interestingly, the ratios for UV-bright LAEs tend to be higher than those for UV-faint LAEs or have at least the same values for some bins within the uncertainty. Moreover, some bins for UV-bright LAEs have ratios equal to unity, suggesting that a distribution difference does not exist, whereas those bins for UV-faint LAEs exhibit ratios less than 1. For $z$-group2 cases, this trend may be related to the unity value of the correlation function ratio between the total LAEs and SFGs, but this overall trend implies that the distribution difference between SFGs and LAEs depends on the UV magnitude of LAEs.

3.7. Impact of the Catastrophic photo-$z$ Error

Here, we evaluate the impact of the catastrophic error of photo-$z$ on the results. The correlation for $M_{\ast}$-group3 SFGs and LAEs in the $z$-group3 bin is used as an example because these
have the largest numbers of LAEs, and their Poisson errors do not govern the uncertainty. Galaxies at 0.2 < z < 0.4, whose Balmer breaks can be misclassified as Lyman breaks at z ∼ 3, are possible interlopers to our SFG sample at that redshift.

We randomly select galaxies in our sample and replace them with randomly selected galaxies at 0.2 < z < 0.4 from our photo-z catalog. The fraction of the replaced sample corresponds to the contamination fraction of the sample. Although its precise value is not certainly determined, we tentatively assume 10% of our sample. This is of the same order as the fraction of the catastrophic errors of photo-z summarized in Laigle et al. (2016). We derive ACFs and a CCF between the SFGs and LAEs and a spatial correlation function ratio. We
conduct this procedure 50 times in the same manner as in Section 3. Figure 10 shows the results in terms of the spatial correlation function ratios. The average of the 50 procedures is consistent with the original value, and the value of individual trials is always below unity. This trend implies that the catastrophic error of photo-$z$ does not change the spatial correlation function ratio.

This trend can be explained by the dependence of the contamination fraction $f$ on the correlation length inferred from the Limber equation (Equations (9) and (12)). The correlation lengths of spatial ACFs decrease by a factor of $(1-f)^{2/5}$, whereas those of spatial CCFs decrease by a factor of $(1-f)^{1/5}$. These factors are compensated in the ratio $\xi_{\text{SFG-LAE}}^2/(\xi_{\text{SFG-LAE}}^2)$, and the ratio equals the original value. The same can be applied to the low-$z$ contaminants of LAEs. By matching the spectroscopic redshift in the literature, Sobral et al. (2018) estimate the contamination fraction of SC4K LAEs to be 10%–20%, which is similar to the assumption in the above test. We admit that this is derived from a limited sample; nonetheless, this information supports its insignificant impact on our result.

4. Overdensity Distribution Comparison

Galaxy overdensity is another often-used quantity for characterizing the galaxy environment (e.g., Peng et al. 2010; Kawinwanichakij et al. 2017). We estimate the overdensity at the positions of SFGs, QGs, and LAEs to examine whether the spatial distribution difference suggested from the clustering analysis can be seen. Because we discuss the spatial distribution difference with reference to SFGs in the clustering analysis, the surface number density of SFGs is used as an index of overdensity.

The overdensity at the position of the $i$th galaxy is defined as follows (Chartab et al. 2020):

$$\delta(X_i) = \sum_j \omega_j \left( \frac{\sigma_j(X_i)}{\bar{\sigma}_j} - 1 \right),$$  \hspace{1cm} (17)

where $X_i$ is the position of the $i$th galaxy and $\omega_j$ is its probability of residing in the $j$th redshift slice. $\sigma_j(X_i)$ is the surface number density of galaxies at that position, and $\sigma_j$ is the average surface number density in the entire field in the $j$th redshift slice. The redshift slice is generated with an interval of $\Delta z/(1+z) = 0.01$, which is of the same order as the typical photo-$z$ uncertainty of photo-$z$ galaxies. The $\omega_j$ is determined via integration of the pdf distribution of the redshift for the range of each redshift slice. The pdf of photo-$z$ galaxies is assumed to be Gaussian centered at the median pdf and its 68% confidence interval as $\pm \sigma$. For LAEs, we derive their pdf from the expected Ly$\alpha$ detection rate based on the IB transmission curve.

The surface number density map at each redshift slice is estimated using the weighted Gaussian kernel density method. The surface number density at the position of $X_i$ is derived as

$$\sigma_{j,\text{obs}}(X_i) = \frac{\sum_k \omega_j^k K(X_i, X_k)}{\sum_k \omega_j^k}.$$  \hspace{1cm} (18)

This method sums the contributions of all galaxies with the weight $\omega_j^k$ of the probability of the $k$th galaxy being located at the $j$th redshift slice. We consider the 2D Gaussian kernel $K(X_i, X_k)$,
\( K(X_k, X_i) = \frac{1}{2\pi a^2} \exp \left[ -\frac{r(X_k, X_i)^2}{2a^2} \right] \), \hspace{1cm} (19)

where \( r(X_k, X_i) \) is the projected distance between two positions and \( a \) is the bandwidth parameter. It is important to carefully select the bandwidth for estimating the adequate scale of the density. Several previous studies determine the bandwidth to minimize the variance of the density map (e.g., Chartab et al. 2020; Bădescu et al. 2017), but this leads to bandwidth sizes that differ with redshift. Therefore, we apply a constant bandwidth of 5 cMpc, which is the typical correlation length of SFGs. It is noted that the surface number density at an SFG is systematically higher than the density elsewhere because there is always one galaxy, making it impractical to compare the number density distributions for several populations. Therefore, the contribution from itself is subtracted from \( \sigma_{j,\text{obs}}(X_i) \) when the surface number density at an SFG is calculated.

Given the finite observed field, it is essential to correct the boundary effect and the masked region. The intrinsic surface number density can be expressed as follows (Jones 1993):

\[ \sigma_f(X_i) = \frac{\sigma_{j,\text{obs}}(X_i)}{\int_S K(X_i, X) dS} \], \hspace{1cm} (20)

where \( S \) is the area of the observed field with the masking. The denominator in Equation (20) is equal to unity if the position \( X_i \) is near the center of the observed field and free from the masked region, whereas it becomes smaller if the position \( X_i \) is at the edge of the field or covered by the mask. We apply the correction for each galaxy.

We compare the overdensity distributions of galaxies in \( z \)-group 2 and 3. We focus on this redshift range because it has enough sample numbers for all galaxy populations. We do not consider \( z \)-group 1, because LAEs exist only in a smaller survey field than other samples (see Section 2.2), which will make it difficult to calculate the density continuously at all redshift ranges. Furthermore, we assign the same stellar mass threshold to SFGs and QGs, which means that photo-\( z \)-galaxies with \( \log(M_*/M_\odot) > 10.8 \) in \( z \)-group 2 and those with \( \log(M_*/M_\odot) > 11.0 \) in \( z \)-group 3 are discussed. There is an overlap between the redshift range of these groups, and we conservatively impose the latter threshold for galaxies in that overlapped range.

The overdensity distributions at the position of three galaxy populations are shown in Figure 11. The overdensity at LAEs tends to be lower than those at SFGs and QGs. We test whether the distribution difference between LAEs and SFGs is significant using two statistical tests, the Anderson–Darling (AD) test and the Kolmogorov–Smirnov (K-S) test. The AD test is sensitive to the difference at the edge of the distribution, whereas the K-S test is sensitive to the difference at the center. The \( P \)-value from both the AD test and the K-S test is less than 0.01, so we reject the null hypothesis that the overdensity distributions of LAEs and SFGs are the same, suggesting that this distribution difference is significant. On the other hand, the overdensity distributions of SFGs and QGs appear to be consistent, suggesting that the QGs are located in a similar environment to SFGs. The statistical tests do not suggest a significant difference between these two overdensity distributions, according to \( P = 0.10 \) from the AD test and \( P = 0.23 \) from the K-S test. The median values of the overdensity also support these trends. These suggest that we see the distribution difference between SFGs and LAEs not only from the clustering but also from the overdensity distribution, whereas we do not see it between SFGs and QGs.

5. Discussion

5.1. Test of Clustering among HAEs, LAEs, and SFGs at \( z = 2.22 \)

Thus far, we report that massive SFGs and LAEs are distributed differently beyond the difference of their halo masses. We confirm that the correlation function ratio \( \xi_{\text{SFG-LEAE}}/\xi_{\text{SFG-LAE}} \) is less than unity, and this is not affected by the catastrophic failure of the photo-\( z \) estimation of some objects. Here, we conduct the same clustering analysis for HAEs instead of photo-\( z \)-selected SFGs. HAEs are typical star-forming galaxies more massive than LAEs and have smaller redshift uncertainty than photo-\( z \)-selected galaxies. Therefore, this test can be used to examine whether or not the trend in Section 3 is caused by the large redshift uncertainty of photo-\( z \)-selected SFGs. An HAE sample at \( z = 2.22 \) constructed as a part of the HiZELs survey (Sobral et al. 2013) is used. This sample was constructed based on the flux excess of NB\(_K\) at 2.121 \( \mu \)m compared to the \( K \) band and the color selection on the \( BK \) diagram. Their redshift uncertainty is as small as that of LAEs, and the survey covers 2.34 deg\(^2\) in the COSMOS field. Objects with higher fluxes than the average limiting flux \( \log(F_{\text{lim}}/\text{erg s}^{-1} \text{cm}^{-2}) \sim -16.5 \) (Figure 7 in Sobral et al. 2013), at which the completeness of the sample is \( \sim 50\% \), are used in the study. We use LAEs selected from NB392 from SC4K, which are identical to the sample used in Section 3, because the selection redshift range is almost the same (Figure 1 in Sobral et al. 2017).

The survey area of LAEs is slightly different from that of HAEs. We focus only on regions where LAEs and HAEs coexist and are not affected by any masks of Laigle et al. (2016). There are three duplications between LAEs and HAEs. For the same reason mentioned in Section 3.1, we exclude two duplications from the HAE sample. The total numbers of HAEs and LAEs are 406 and 87, respectively.

The ACFs and the CCF are estimated in the same manner as in Section 3. We fit the power law at \( \theta > 10'' \) for the ACF of the
LAEs and $\theta > 40''$ for the ACF of the HAEs and the CCF. The measured correlation function is shown in Figure 12. The amplitude of CCF is lower than those of ACFs of HAEs and LAEs. The correlation lengths of the ACFs and the CCF are estimated in the same manner as in Section 3, and the spatial correlation function ratio $\xi_{\text{HAE-LAE}}/\langle \xi_{\text{HAE-LAE}} \rangle$ is estimated to be $0.27 \pm 0.12$, which is less than unity. This value suggests that the spatial CCF signal cannot be explained by only their halo mass difference, which is the same as in photo-$z$ SFGs.

We also derive the CCFs between HAEs and SFGs. We use SFGs that are in the lowest redshift bin constructed in Section 3 and located in the same survey region as HAEs. In the same way as in Section 3, four stellar mass thresholds are employed, and ACFs and CCFs are estimated for each. Because both HAEs and SFGs are thought to be similar galaxy populations, many of them are duplicated. Here, we do not exclude these duplications, to make the HAE sample analysis consistent with that performed for the LAEs. The values for the ratio $\xi_{\text{HAE-SFG}}^2/\langle \xi_{\text{HAE-SFG}} \rangle^2$ are calculated to be $0.70 \pm 0.34$, $0.68 \pm 0.42$, $0.37 \pm 0.33$, and $1.35 \pm 0.84$ for SFGs’ stellar mass thresholds of $M_*/M_*> 10.4$, $10.6$, $10.8$, and $11.0$, respectively. These values are higher than the case of HAEs and LAEs, and most of the bins equal unity. This implies that, unlike the clustering between HAEs and SFGs, the clustering between HAEs and SFGs is explainable only by their halo mass.

These tests support the trends shown in Section 3. Thanks to the smaller redshift uncertainty of HAEs, the spatial correlation function ratio between HAEs and LAEs implies that uncertainties in the photo-$z$ estimates do not cause the trend. The fact that the spatial correlation function ratios for HAEs and SFGs are equal to unity also supports the hypothesis that these differences in distribution do not occur for all line emitters, but only for LAEs. Moreover, these results imply that trends are seen even for less massive SFGs. The H$\alpha$ flux limit corresponds to SFR of $\sim 24 M_\odot$ yr$^{-1}$, based on an assumption of 1 mag dust extinction and the standard calibration method by Kennicutt (1998). Such an SFR corresponds to a stellar mass of $\log(M_*/M_*) > 9.8$, according to the relation between SFR and $M_*$ of HAEs reported in Oteo et al. (2015), which is $\sim 0.6$ dex smaller than the minimum stellar mass threshold of photo-$z$-selected SFGs.

It should be noted that the depth of H$\alpha$ flux of this HAE sample has a variation from field to field (Sobral et al. 2013; Cochrane et al. 2017). In order to reduce the effect from the depth variance, we verify whether the result with brighter HAEs ($\log(F_{H\alpha}/\text{erg s}^{-1} \text{ cm}^{-2}) > -16.0$) is consistent with the original result. The value of the spatial correlation function ratio is consistent within the $1 \sigma$ uncertainty both for the correlation function of HAE-LAE and those of HAE-SFG. This suggests that the field variance does not significantly affect our result.

5.2. Why Are LAEs Located in a Different Environment?

We have investigated the spatial distribution difference among SFGs with $\log(M_*/M_*) > 10.4$, QGs with $\log(M_*/M_*) > 10.6$, and LAEs by two methods, i.e., the clustering analysis and the overdensity analysis. The small signal of CCFs between SFGs and LAEs requires some additional physics to account for it, whereas CCFs between SFGs and QGs can be perfectly explained by their halo mass differences. The CCFs among HAEs, SFGs, and LAEs support the existence of that distribution difference in the case of the stellar mass of SFGs down to $\log(M_*/M_*) > 9.8$ and suggest that the trend is unlikely to be due to the photo-$z$ uncertainty.

The overdensity distribution also reveals that LAEs are statistically located in regions that are underdense of SFGs on the scale of $\sim 5$ cMpc, whereas SFGs and QGs are located in the same density field. These trends suggest that LAEs are somehow distributed differently compared to SFGs and QGs.

Several previous studies report hints of this distribution difference, indirectly or in peculiar environments. For example, Momose et al. (2021) measure CCFs between HI IGM tomography data and several galaxy populations and find that the CCF of LAEs is flat up to $r \sim 3$ h$^{-1}$ cMpc, which is different from the behavior of other SFGs. This trend indirectly suggests a potential distribution difference between LAEs and SFGs. In addition, the segregation of LAEs and SFGs is found in protoclusters. Shi et al. (2019) measure the LAE distribution in a known Lyman break galaxy (LGB) protocluster at $z = 3.13$ (Toshikawa et al. 2016) and find that LAEs are segregated from the overdensity of LBGs on scales of a few tens of cMpc. Shimakawa et al. (2017) also report the segregation of LAEs and HAEs in a protocluster core region at $z = 2.5$ (please refer to Hough et al. 2020 for perspectives from semianalytic simulations). This study directly suggests that such distribution segregation between SFGs and LAEs is ubiquitously seen at $z \sim 2 - 4.5$.

On the other hand, Bielby et al. (2016) calculated the CCFs between LAEs and spectroscopically confirmed LBGs at $z = 3.1$ and demonstrated the ratio $\xi_{\text{LBG-LAE}}^2/\langle \xi_{\text{LBG-LAE}} \rangle^2 = 1.28 \pm 0.46$, which is consistent with unity. The result seems to be inconsistent with ours. However, their spectroscopic confirmation of LBGs is mainly based on Ly$\alpha$ emission or absorption, and the dominant fraction of LBGs seems to have Ly$\alpha$ emission, as seen from their stacked spectra (see Figure 15 in Bielby et al. 2013). This may have led to tracing similar populations from both samples, which may have caused a higher amplitude in the CCF.

The distribution difference between LAEs and SFGs can be explained by the assembly bias (e.g., Gao & White 2007), which is similar to a scenario suggested in Shi et al. (2019). LAEs are typically younger in terms of the luminosity-weighted age (e.g., approximately 10 Myr in Nakajima et al. 2012; Hagen et al. 2014) than massive galaxies, such as the
SFGs (e.g., approximately 100 Myr in Hathi et al. 2013) or QGs (e.g., approximately 1 Gyr in Gobat et al. 2012; Belli et al. 2019). Such differences in age can be related to the different formation time of galaxies and eventually that of their host halos. The different formation epoch of halos is known to cause an impact on the signal of the correlation function. Zehavi et al. (2018) suggest that, even at similar halo mass, the clustering signal can change depending on their formation epoch. The assembly bias tends to increase the clustering signal. If this trend exists in our case, the CCFs between later-formed halos and earlier-formed halos (i.e., LAEs and SFGs) are expected to be weaker than that expected from each ACF. We find that UV-brighter LAEs tend to have a higher ratio $c^2_{SFG\rightarrow LAE}/(c^2_{SFG\rightarrow SFG})$ than UV-fainter LAEs. The UV-brighter LAEs are expected to reside in more evolved halos, or in other words, in earlier-forming halos, thus reducing such an effect.

The large amount of H I gas in their circumgalactic media or surrounding IGM associated with massive halos is another possible explanation. This gas absorbs the Lyα photons and prevents us from detecting the Lyα emission of galaxies, which means that galaxies around or in massive halos are preferentially observed as non-LAEs. This makes the distribution of LAEs different from others. Other studies indirectly argue a similar hypothesis. Toshikawa et al. (2021) demonstrate a smaller Lyα equivalent width in an LBG-selected protocluster at $z = 3.67$ than in field galaxies. Shimakawa et al. (2017) infer that the accretion of cold streams, which provide pristine H I gas to the protocluster core, could prevent Lyα photons from escaping from the dense regions. Meanwhile, Momose et al. (2021) have shown that LAEs tend to avoid H I overdensity peaks, whereas Liang et al. (2021) present a similar trend from the correlation of the optical depth of the sight lines of quasi-stellar objects (QSOs) and the spatial distribution of LAEs. We note that these results are on different scales. Shimakawa et al. (2017) show the distribution segregation on a scale of a few hundred pkpc, whereas other studies have focused on a few pMpc. Regardless, the typical scale of this effect and the amount of H I gas around massive galaxies remain unclear. It is possible that both effects contribute to the distribution difference.

A conclusive origin for the distribution difference between SFGs and LAEs remains under debate, our result reinforces the importance of investigating multiple galaxy populations to reveal their environment.

5.3. Quenching and Environment

Our sample is large enough to investigate a possible correlation between SFR and the overdensity for different galaxy populations. From the overdensity values for the SFGs and QGs estimated in Section 4, we check the existence of that correlation at $2.4 < z < 3.5$. The top panel of Figure 13 shows the relationship between SFR and overdensity. SFGs and QGs are distinguished with their medians and their uncertainties estimated based on the normalized medians of the absolute deviations. The median values may seem to slightly increase toward higher overdensities for SFGs and QGs, especially at $\log(1 + \delta) > 0$, but the Spearman’s rank correlation test does not indicate any significant correlations (the correlation coefficient $\rho \sim 0.03$ with $P = 0.3$ for both populations). Therefore, we conclude that a significant correlation between the number density and SFR is not seen in our sample. Clear trends are also not identified for sSFR, as shown in the bottom panel of Figure 13.

This result is in contrast to what we observe in the local universe, where there is a clear anticorrelation between SFR and the number density (e.g., Lewis et al. 2002). Furthermore, at $z > 1$, the reversal of the relation has been reported (e.g., Elbaz et al. 2007; Lemaux et al. 2020). In particular, Lemaux et al. (2020) argue for the existence of a weak but significant positive correlation between the SFR and the overdensity of star-forming galaxies at $2 < z < 5$, based on density measurement via Voronoi Monte Carlo mapping. The difference in trends between our results and those of Lemaux et al. (2020), as shown in Figure 13, may be due to the different density estimation methods and/or sample difference. Their targets have a lower stellar mass completeness limit (80% complete to $\log(M_*/M_\odot) \sim 9.2 - 9.5$) than that in our study ($\log(M_*/M_\odot) > 10.8$). Moreover, they use a spectroscopically confirmed sample, with more accurate redshifts. This can lead to a clearer contrast for the density map and a larger dynamic range for the overdensity.

We also check the trend at lower redshift in the same manner and examine the existence of redshift evolution. We use SFGs and QGs in $M_\text{zgroup}2$ of $z$-group1 (2.05 < $z < 2.39$) in Section 3. Figure 14 shows their SFR–$\delta$ relation. Even a weak increasing trend in median values is not found. The correlation coefficient from Spearman’s rank correlation test also does not indicate a significant correlation. The disappearance of the apparently increasing median value trend could be due to the redshift evolution of the relation, which has been reported by Lemaux et al. (2020) at a similar redshift.

Figure 13. Top panel: relation of SFR and overdensity for SFGs (blue) and QGs (orange) at $2.4 < z < 3.5$. Their median values of bins that contain more than 10 objects are shown with blue triangles and orange circles. The median trend at $2 < z < 5$ reported in Lemaux et al. (2020) is shown with white circles for reference. Their median amplitude of SFR is different from ours because of slight differences in their redshift and stellar mass range. Bottom panel: relation of sSFR and the overdensity. Colors and markers are identical to those of the top panel.

Based on the previously presented results, including those from the clustering analysis and the overdensity distribution, our results possibly imply that the environment is not likely to significantly impact the star formation quenching of such massive galaxies at $z \geq 2$. Several studies support our trends. Hatfield & Jarvis (2017) estimate the CCF signal of SFGs and QGs and argue that the environment does not play a significant role in quenching at $z \sim 2$, based on their model for the
environmental quenching within the halo occupation distribution scheme. Lin et al. (2016) also report only little dependency on the local density for the quiescent fraction at $1.5 < z < 2.5$. Also, Kawinwanichakij et al. (2017) argue that mass and environmental quenching are comparable for massive galaxies at $0.5 < z < 2.0$ with stellar masses similar to those of photo-$z$ galaxies in this study. Their target redshift is lower than ours, so our results may suggest that environmental quenching at $z > 2$ is not significant compared to at lower redshift. On the other hand, Chartab et al. (2020) argue that the average SFR of galaxies with stellar masses similar to ours decreases if they are located in more overdense regions, even at $2.2 < z < 3.5$, suggesting that the galaxy environment does affect quenching at $z > 2$. This result may contrast with ours, but this can be related to the different number of the sample or the quality of the SED modeling.

Moreover, it should be emphasized that the methods used to measure the environments in previous studies and in this study have large variations in terms of techniques and target scales. For example, Kawinwanichakij et al. (2017) quantify environments based on the third-nearest neighbor, which tends to represent a much smaller scale environment than what we explore. Chartab et al. (2020) estimate the number density distribution based on a bandwidth of less than 1 $h^{-1}$ cMpc. Such scale differences may make it difficult to compare the results among different studies.

6. Summary

In this study, we have investigated the spatial distribution differences among massive ($\log(M_*/M_\odot) > 10.4$) SFGs and QGs selected by photometric redshift and LAEs selected by narrow/intermediate bands in the COSMOS field. Through the use of deep and multiband photometry, a systematic study has been performed for $2 < z < 4.5$.

We first derive the ACFs and CCFs of three populations. The spatial correlation function ratio $\xi_{\text{SFG}}(r)/\xi_{\text{QG}}(r)$ of SFGs and QGs is equal to unity, suggesting that their distribution can be explained only by their host halo mass. On the other hand, the ratios of SFGs and LAEs are significantly below the unity, implying that some additional physical processes spatially segregate these two populations. This segregation is also implied from the cross-correlation of HAEs and LAEs at $z = 2.22$.

We also investigate the overdensity at the position of three populations with the use of the surface number density of SFGs. LAEs are found to be located in less dense regions than SFGs and QGs at $2.4 < z < 3.5$. On the other hand, QGs are confirmed to be located in the same environments as SFGs.

With the use of overdensity distribution, we explore the relation between SFR and the overdensity. Neither SFGs nor QGs exhibit significant correlations between SFR and the overdensity. This trend and the results mentioned above suggest that the environment does not significantly impact the star formation quenching in our dynamic range of the overdensity and the scale of the environment.

There are several possible origins of LAEs exhibiting different spatial distributions to other galaxy populations. One is assembly bias, which is supported by the higher spatial correlation function ratios of UV-brighter LAEs and SFGs than those of UV-fainter LAEs. The other is a large amount of H I gas associated with massive halos in their circumgalactic media or surrounding IGM. Our results highlight the importance of exploring the galaxy environment through multiple populations.

Future instruments are expected to help understand better the results presented in this paper. First, an extensive NIR survey reaching galaxies with less massive stellar masses ($\log(M_*/M_\odot) \sim 9$) is essential to reveal the origins of the distribution difference between massive galaxies and LAEs. These breakthroughs should be achievable with future telescopes or instruments such as the Nancy Grace Roman Space Telescope or ULTIMATE on the Subaru Telescope. Also, large numbers of spectroscopic samples from the Prime Focus Spectrograph on the Subaru Telescope or the Multi-Object Optical and Near-infrared Spectrograph on the Very Large Telescope will provide us with catalogs of galaxies spanning a wide range of overdensities, leading to a clearer view of the relation between SFR and overdensity and revealing the impact of the assembly bias based on the stellar age derived from their spectrum.

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References

Bâdescu, T., Yang, Y., Bertoldi, F., et al. 2017, ApJ, 845, 172
Belli, S., Newman, A. B., & Ellis, R. S. 2019, ApJ, 874, 17
Béthermin, M., Kilbinger, M., Daddi, E., et al. 2014, A&A, 567, A103
