1. Introduction

Recently, there has been a great progress in observational studies of structures of the high-redshift Universe. Based on statistical analyses, strong clustering signals are detected in the angular correlation functions (ACFs) of Lyman break galaxies (LBGs; e.g. [1-3]) at $z = 3-5$ and Ly α emitters (LAEs; [4, 5]) at $z \approx 5$. These clustering results indicate that distribution of high-z galaxies is fairly inhomogeneous and highly biased against matter distribution predicted by the hierarchical model, i.e., the Cold Dark Matter (CDM) model (e.g. [6]). These biased distribution of high-z galaxies are well understood with the inhomogeneous distribution of dark halos and bias of galaxy formation (e.g. [7]). However, we have little knowledge about the relation between high-z galaxies and dark halos because of the small statistics.

On the other hand, various structures of high-z galaxies have been identified. A proto-cluster at $z = 3.1$ with a large population of LBGs was discovered by [8]. A significant excess of LAEs was found by [9] around a radio galaxy at $z = 4.1$, and a subsequent study concluded that this excess is indeed a proto-cluster with a size of $3-5$ Mpc [10]. More recently, clustering of 6 LAEs near a radio galaxy at $z \approx 5.2$ was reported [11]. For structures beyond cluster scales, wide-field narrow-band surveys revealed very inhomogeneous distribution of LAEs [4, 5, 12-14] at $z \approx 5-6$. [12] report an elongated overdense region of LAEs at $z = 4.86$ on the sky of 20 Mpc in width and 50 Mpc in length. However, on the same sky, there was no large-scale structure at $z = 4.79$ which is closer to us by 39 Mpc, indicating a large cosmic variance over their surveyed volumes [5]. Although a few segments of high-z structures have been found to date, the whole picture of high-z Universe is veiled. Moreover, we do not know when and how the structures of galaxies seen at present formed from the initial matter density fluctuations. We started a systematic survey to map the high-z Universe with LBGs and LAEs at $3 < z < 7$ in the 1 deg$^2$ sky of the Subaru/XMM-Newton Deep Field (SXDF; R.A.- $= 23^h44^m00^s$, decl. = $-5^\circ 00'00''$ [32000]; [15]). We obtain cosmic maps on scales of much larger than present-day LSSs to cover a network of LSSs at several redshifts between $z = 3$ and 7. In this contribution, we report the initial results of our survey about structures made of high-z galaxies at $z = 3-6$. Throughout this contribution, we present magnitudes in the AB system and adopt $H_0 = 70km s^{-1} Mpc^{-1}$ and $[\Omega_m, \Omega_{\Lambda}, n, \sigma_8] = [0.3, 0.7, 1.0, 0.9]$.

2. Data and Samples

We carried out deep optical broad-band and narrow-band imaging with Subaru/Suprime-Cam [16] in the 1 deg$^2$ sky of the SXDF. Our broad-band ($B$, $V$, $R$, $i'$, and $z'$) images reach $B \approx 28.3$, $V \approx 27.3$, $R \approx 27.6$, $i' \approx 27.5$, and $z' \approx 26.5$ with a 2$^\prime$-diameter circular aperture at the 3$\sigma$ level (Furusawa et al. in prep.; see [15]). We obtained narrow-band images with three bands, $NB503$ ($\lambda_c = 5030\AA$, $\Delta \lambda = 70\AA$), $NB570$ ($\lambda_c = 5700\AA$, $\Delta \lambda = 70\AA$), and $NB816$ ($\lambda_c = 8150\AA$, $\Delta \lambda = 120\AA$). The 5$\sigma$ sky noise of these narrow-band images are $NB503 \approx 25.2$, $NB570 \approx 25.0$, and $NB816 \approx 26.0$ in a 2$^\prime$-diameter circular aperture (see [17] for the $NB816$ data). These narrow-band filters enable us to identify LAEs, galaxies with a strong Ly$\alpha$ emission line, at $z \approx 3.1 \pm 0.03$, $3.7 \pm 0.03$, and $5.7 \pm 0.05$ with a small fraction of fore-
Table I High-z Galaxy Samples in the SXDF

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Redshift</th>
<th>Number</th>
<th>Magnitude Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRi-LBG</td>
<td>4.0 ± 0.5</td>
<td>16,920</td>
<td>$i' &lt; 27.5$</td>
</tr>
<tr>
<td>Viz-LBG</td>
<td>4.7 ± 0.5</td>
<td>2,768</td>
<td>$z' &lt; 26.5$</td>
</tr>
<tr>
<td>Riz-LBG</td>
<td>4.9 ± 0.3</td>
<td>1,293</td>
<td>$z' &lt; 26.5$</td>
</tr>
<tr>
<td>i-dropout</td>
<td>5.9 ± 0.3</td>
<td>133</td>
<td>$z' &lt; 26.0$</td>
</tr>
<tr>
<td>NB503-LAE</td>
<td>3.1 ± 0.03</td>
<td>332</td>
<td>NB503 &lt; 25.2</td>
</tr>
<tr>
<td>NB570-LAE</td>
<td>3.7 ± 0.03</td>
<td>175</td>
<td>NB570 &lt; 25.0</td>
</tr>
<tr>
<td>NB816-LAE</td>
<td>5.7 ± 0.05</td>
<td>515</td>
<td>NB816 &lt; 26.0</td>
</tr>
</tbody>
</table>

ground contaminants (20-30%; [12, 14, 18]). Typical seeing sizes of these images are $\sim 0''.8$. The data were reduced with a software package SDFRED [19, 20].

We carry out object detection and photometry with SExtractor [21]. We detect 0.6 million objects with $i'' < 27.5$, and measure colors for these objects. We make 5 catalogs each of which is based on $i''$, $z''$, NB503, NB570, and NB816-band detection. We select LBGs based on the 3 sets of color-color diagram, $(B - R, R - i'')$, $(V - i'' , i'' - z'')$, and $(R - i'', i'' - z'')$. We refer LBGs selected with these color-color diagrams to $BRi$-LBGs, Viz-LBGs, and $Riz$-LBGs, respectively. Our i-dropouts are selected with a single color of $i'' - z''$ and constraints for the non-detection of blue continuum in $B$, $V$, and $R$ bands. We isolate LAEs with their narrow-band excess colors as well as with a continuum color if the broad-band photometry bluer than the narrow-band is available.

We define the color criteria for LBGs, i-dropouts, and LAEs as

\[
\begin{align*}
B - R > 1.2, & \quad R - i'' < 0.7, \quad B - R > 1.6(R - i'') + 1.9 \quad (BRi - LBGs), \\
V - i'' > 1.2, & \quad i'' - z'' < 0.7, \quad V - i'' > 1.8(i'' - z'') + 1.7, \quad B > 28.8 \quad (Viz - LBGs), \\
R - i'' > 1.2, & \quad i'' - z'' < 0.7, \quad R - i'' > 1.0(i'' - z'') + 1.0, \quad B > 28.8, \quad V > 27.8 \quad (Riz - LBGs), \\
i'' - z'' > 2.0, & \quad B > 28.8, \quad V > 27.8, \quad R > 28.1 \quad (i'' - dropouts), \\
(B + R)/2 - NB503 > 1.2 \quad (NB503 - LAEs), \\
(B + R)/2 - NB570 > 1.0, & \quad B - R > 0.5 \quad (NB570 - LAEs), \\
i'' - NB816 > 1.0, & \quad R - i'' > 0.7 \quad (NB816 - LAEs),
\end{align*}
\]

following [17, 20] and Ouchi et al. in prep. We identify about 20,000 LBGs and 1,000 LAEs from our data with these criteria. For each galaxy sample, the number of objects and the magnitude limits are summarized in Table I. $BRi$-LBGs, Viz-LBGs, and $Riz$-LBGs are located at $z = 4.0 \pm 0.5$, $z = 4.7 \pm 0.5$, and $z = 4.9 \pm 0.3$, respectively, as shown in [20], while i''-dropouts are at $z \approx 5.9 \pm 0.3$ [22]. The redshift-distribution of LAEs is determined with the central wavelengths and FWHMs of the narrow-band filters which pass a redshifted Ly$\alpha$ emission line.

We carried out spectroscopic follow-up observations for these galaxies with Subaru/FOCAS [23] and VLT/VIMOS. Although it is quite difficult to obtain spectra for all the galaxies, we took spectra for part of galaxies selected from each sample. So far, we have identified about 20 LBGs and 26 LAEs, respectively. Our spectroscopic results will be summarized in Akiyama et al. in prep. The contamination rates of these galaxy samples are estimated to be 10 – 30%. Most of contaminants are foreground galaxies at $z \approx 1$. We show spectra of securely identified eight $NB816$-LAEs in Figure 1, together with those of foreground contaminants [17].

We show the sky distribution of $BRi$-LBGs at $z = 4.0 \pm 0.5$ and $NB816$-LAEs at $z = 5.7 \pm 0.05$ in Figures 2 and 3 for examples of our LBG and LAE samples.

3. Results and Discussion

3.1. Angular Correlation Functions of Lyman Break Galaxies

3.1.1. Definitive Detection of Excess of Small-Scale Clustering for $BRi$-LBGs

We investigate $BRi$-LBGs detected in our data with a visual inspection, and find that a number of LBGs have close-companion LBGs. We have found 1385 pairs of $BRi$-LBGs with the angular distance of $2'' - 5''$, corresponding to 14-35 kpc in physical units at $z = 4$, which is beyond scales of internal structures of galaxies (\lesssim 10 kpc). In order to quantitatively measure the small-scale as well as large-scale clustering of LBGs, we derive the ACF $\omega(\theta)$. According to [24], the ACF is calculated by:

\[
\omega(\theta) = [DD(\theta) - 2DR(\theta) + RR(\theta)]/RR(\theta),
\]
where \(DD(\theta)\), \(DR(\theta)\), and \(RR(\theta)\) are numbers of galaxy-galaxy, galaxy-random, and random-random pairs normalized by the total number of pairs in each of the three samples. We create the random sample composed of 100,000 sources with the same geometrical constraints as of the data sample. We estimate bootstrap errors for \(\omega(\theta)\) [25]. The top panel of Figure 4 shows the ACF of \(BRI\)-LBGs at \(z = 4.0 \pm 0.5\), together with that of dark-matter, \(\omega_{\text{dm}}(\theta)\) predicted by the non-linear model of [26] (see [27] for more de-
Figure 3: The distribution of $z = 5.7 \pm 0.05$ NRB816-LAEs in the SXDF. The positions of LAEs are shown with yellow dots. The red lines correspond to contours of galaxy overdensity from $\delta_{12} = -0.25$ to 3.25 with a step of $\Delta = 0.50$. The characters, A and B, denote the positions of the two dense regions. The scale on the map is marked in both degrees and (comoving) megaparsecs. The large and small squares in the bottom left corner show the sizes of the surveyed areas in the previous proto-cluster searches by [9] and [10], respectively.

Figure 4: Top: The ACF, $\omega(\theta)$, of $BRi$-LBGs at $z = 4$. The squares and error bars indicate the ACF and bootstrap $2\sigma$ errors of $BRi$-LBGs. The solid curve is the ACF of dark matter predicted by the non-linear model of [26]. The scale on the top axis denotes the projected distance in comoving megaparsecs at $z = 4.0$. The ticks with R(1E10), R(1E11), R(1E12), and (1E13) correspond to the predicted virial radii of dark halos with a mass of $1 \times 10^{10} h^{-1}_{70} M_\odot$, $1 \times 10^{11} h^{-1}_{70} M_\odot$, $1 \times 10^{12} h^{-1}_{70} M_\odot$, and $1 \times 10^{13} h^{-1}_{70} M_\odot$, respectively, within which the mean enclosed density is 200 times the mean cosmic value (see [7]). Bottom: The galaxy-dark matter bias, $b$, of $BRi$-LBGs as a function of angular distance. The squares and error bars indicate biases and $2\sigma$ errors. The ticks with $b(1E11)$, $b(1E12)$, and $b(1E13)$ show biases of dark halos with a mass of $1 \times 10^{11} h^{-1}_{70} M_\odot$, $1 \times 10^{12} h^{-1}_{70} M_\odot$, and $1 \times 10^{13} h^{-1}_{70} M_\odot$, respectively, predicted by the analytic CDM model of [6].

tails). The bottom panel of Figure 4 displays galaxy-dark matter bias as a function of angular distance in arcsecond. The bias, $b(\theta)$, is defined as

$$b(\theta) \equiv \sqrt{\omega(\theta)/\omega_{\text{dm}}(\theta)}.$$ (9)

Since our ACF is calculated from 16,920 $BRi$-LBGs whose number is one-order of magnitude larger than that of the previous LBG sample (c.f. [2]), measurements in Figure 4 have unprecedentedly high signal-to-noise ratios. In Figure 4 the ACF of $BRi$-LBGs shows a significant excess of small scale clustering, and indicates that a single power-law function, such
as $A_w \theta^{-\beta}$ with two free parameters of $A_w$ and $\beta$, does not represent the shape of the ACF in the range of $1'' - 1000''$. Comparing this ACF with the one of dark matter, we find that the small-scale excess extends up to $5'' - 8''$, i.e. 0.2 - 0.3 comoving Mpc, which is comparable to the virial radii of dark halos with a mass of $10^{11} - 10^{12} M_\odot$. Interestingly, the large-scale average bias at $2 - 20 h_{70}^{-1}$ Mpc ($60'' \lesssim \theta \lesssim 600''$) is estimated to be $\approx 3.0 \pm 0.05$ which is also comparable to the biases of dark halos ($b = 2.2 - 3.5$) with a mass of $10^{11} - 10^{12} M_\odot$ predicted with the analytic model of the CDM [6]. This coincidence of the dark-halo mass strongly supports that $z = 4$ LBGs reside in dark halos with a mass of $10^{11} - 10^{12} M_\odot$. Moreover, these pieces of information suggest the hypothesis that multiple LBGs occupy a single dark halo (e.g. [27, 28]). The bias in small-scale at $\theta < 2''$ is $b \gtrsim 10$ which is more than three times higher than the large-scale bias. This high small-scale bias of LBGs may imply that galaxy formation is very efficient in dark halos at high redshifts.

3.1.2. Magnitude Dependence of Angular Correlation Functions for BRL-LBGs

We made six subsamples of BRL-LBGs with the limiting magnitudes of $i' < 24.5, 25.0, 25.5, 26.0, 26.5,$ and 27.0. The ACFs and biases for these subsamples are derived, and presented in Figure 5, together with the ACF for all BRL-LBGs (with $i' < 27.5$). Figure 5 displays that the ACF depends on magnitude, and that a bright subsample shows a stronger ACF and a higher bias than faint subsamples. Both the small- ($\lesssim 5''$) and large- ($60'' \lesssim \theta \lesssim 600''$) scale biases monotonically decrease from $i' < 24.5$ to $i' < 27.5$. Especially, the small-scale bias shows stronger dependence on magnitude ($b \approx 10 - 20$) than the large-scale bias ($b \approx 3 - 4$). Comparing the bright samples of $i' < 24.5, 25.0,$ and 25.5 (the top to the third-top left panels in Figure 5) with the faint sample of $i' < 27.5$, we find that the small-scale bias of bright samples is about twice higher at $\theta \sim 2'' - 3''$ than that of the faint sample, and that the outskirts of small-scale excess extend to $\theta \sim 10''$. Moreover, the large-scale

![Figure 5: Magnitude dependence of the ACFs of BRL-LBGs at $z = 4.0$. In the top to third-top panels, the filled symbols are the ACFs of BRL-LBGs with the limiting magnitude indicated in the panels. Each of these panels shows the ACF of $i' < 27.5$ BRL-LBGs with the open squares. In the bottom panels, biases of LBGs for the each magnitude limit are presented with the filled symbols which correspond to those marks found in the top to third-top panels. The open squares are biases of the BRL-LBGs with $i' < 27.5$. The error bars indicate 1σ bootstrap errors in all the panels.](image-url)
bias of the bright samples \((b \sim 4)\) is also higher than that of the faint sample \((b \sim 3)\), which is consistent with the previous reports in [20] (see [1] for \(z = 3\) LBGs). These three features of bright LBGs suggest that bright LBGs reside in more massive dark halos than faint LBGs, since massive dark halos have a high large-scale bias as well as a more occupation number and a larger halo size than less-massive dark halos, which produces the high small-scale bias with the extended outskirts of bias.

### 3.1.3. Angular Correlation Functions of \(Viz\)-LBGs and \(Riz\)-LBGs at \(z \approx 5\) and \(i\)-dropouts at \(z \approx 6\)

Figure 6 presents the ACFs of \(Viz\)-LBGs at \(z = 4.7 \pm 0.5\), \(Riz\)-LBGs at \(z = 4.9 \pm 0.3\), and \(i\)-dropouts at \(z = 5.9 \pm 0.3\). There is a tendency that the bias becomes stronger at higher redshifts. This tendency is found, even if we compare biases of \(BRi\)-LBGs \((z = 4)\) with the other LBGs and \(i\)-dropouts \((z = 5 - 6)\) for the same absolute magnitude. (Note that the absolute magnitudes become brighter for \(z = 5 - 6\) samples than \(z = 4\) sample with the same observed magnitude, and that the difference in the absolute magnitudes are \(\Delta m = 0.27, 0.34,\) and \(0.64\) for \(Viz\)-LBGs, \(Riz\)-LBGs, and \(i\)-dropouts, respectively.) The strong biases of these high-\(z\) samples is especially found at small-scales, which reach about \(b = 20 - 30\) at \(1'' \lesssim \theta \lesssim 5''\). This tendency implies that higher-\(z\) dark halos produce galaxies more efficiently.

### 3.2. Primeval Large-Scale Structures at \(z = 5.7\)

Since LAEs are identified by their redshifted Ly\(\alpha\) emission line passing a narrow-band filter whose FWHM is only \(\sim 100\)\(\AA\)(section 2), the redshift range

<table>
<thead>
<tr>
<th>(\theta) (arcsec)</th>
<th>(b(\theta))</th>
<th>(Mpc)</th>
<th>(h^{-1}_{70})</th>
<th>(Mpc)</th>
<th>(h^{-1}_{70})</th>
</tr>
</thead>
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<td>0.1</td>
<td>10</td>
<td>0.1</td>
<td>10</td>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
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<td>1</td>
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</tr>
<tr>
<td>10</td>
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<td>0.1</td>
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<td>0.1</td>
</tr>
</tbody>
</table>
of identified LAEs is significantly narrower than that of LBGs. Thus the sky distribution of LAEs presents the cosmic map of high-z galaxies, which shows detailed structures with scales of a few tens of Mpc. Figure 3 is the cosmic map showing the distribution of 315 $NB816$-LAEs at $z = 5.7 \pm 0.05$ in the SXDF. The surveyed volume has a transverse dimension of 180 Mpc $\times$ 180 Mpc and a depth of $\sim 40$ Mpc in comoving units at $z = 5.7$. This is the first cosmic map, ever obtained, covering a $> 100$ Mpc square area of the Universe at any high redshifts ($z > 2$). In Figure 3, the $NB816$-LAEs have a very clumpy distribution, forming concentrations with a typical size of a few Mpc, comparable in size to the proto-cluster found by [9, 10] around a radio galaxy at $z = 4.1$. These concentrations are not isolated, but connected with one another by filamentary overdense regions. The elongated overdense region of LAEs found by [12] at $z = 4.86$ may be a segment of a descendant of such a filamentary structure. There are also found several voids of ellipsoidal shapes with sizes of 10-40 Mpc in which almost no galaxy exists. The characteristic sizes of filaments and voids seen in our map are comparable to those of the present-day Universe. Thus, this map marks the discovery of primeval LSSs at $z = 5.7$.

We quantify the large-scale clumpiness of the galaxy distribution by estimating $\sigma_{20}$, the rms fluctuation of galaxy overdensity within a sphere of 20 Mpc (comoving) radius. Considering that the radial depth of the surveyed volume is about 40 Mpc, we estimate the fluctuation by $\sigma_{20} \approx \sigma_{220} = \left[ \left( \Sigma_{220} - \Sigma_{20} \right)^2 / \Sigma_{20}^2 \right]^{1/2}$, where $\Sigma_{220}$ is the rms surface overdensity within circles of 20 Mpc radius, and $\Sigma_{20}$ and $\Sigma_{220}$ are the observed number and the mean number of LAEs in a circle [29]. We obtain $\sigma_{20} = 0.4 \pm 0.2$. This $\sigma_{20}$ is comparable to or at least half the value for the present-day LSSs, i.e. $\sigma_{20}(z = 0) = 0.5-0.6$, obtained from galaxies with $b_j \leq 17.5$ [30]. The characteristic shapes and the rms fluctuations indicate that these primeval LSSs at $z \sim 6$ are similar to the present-day LSSs. We will present results of more detailed analyses for these primeval LSSs, such as counts-in-cell, in our forthcoming paper.

### 3.3. Two Clumps Identified by Spectroscopy: Forming Clusters?

We find that among the dense concentrations seen in Figure 3, the one at $2^h17^m47.2^s, -5^\circ28'40''$[J2000] has the highest density contrast, $\delta_c = 3.3$, with the 4.8$\sigma$ significance level, where $\delta_c$ is the surface overdensity for a circle of 8 Mpc radius. We refer to this concentration as Region A, Region B, a neighboring concentration at $2^h18^m19.6^s, -5^\circ32'52''$[J2000], also has a high density contrast of $\delta_c = 1.5 \ (2.2\sigma)$. In order to obtain three-dimensional distributions of $NB816$-LAEs in Regions A and B, we carried out spectroscopy for $NB816$-LAEs and obtained 19 LAEs with spectroscopic redshifts which includes LAEs out of Regions A and B (see [17]).

We plot in Figure 7 the three-dimensional distribution of $NB816$-LAEs for Regions A and B. The histogram of Figure 7 shows that these regions have two clumps made of 10 LAEs with a significant excess. Each of the clumps has a diameter of about 1 Mpc in physical units (7 Mpc in comoving units). For these clumps, the 1-dimensional velocity dispersion of galaxies is fairly small, $\sim 180 \text{ km s}^{-1}$ (Clump A) and $\sim 150 \text{ km s}^{-1}$ (B). Although these clumps may not be collapsed, the formal virial masses can be calculated from velocity dispersion, $\sigma_{1d}$, and radius, $r$, with $3\sigma_{1d}^2 r / G$, where $G$ is the gravitational constant. We obtain $\sim 1 \times 10^{13} M_\odot$ (Clump A) and $\sim 8 \times 10^{12} M_\odot$ (B). The three-dimensional density contrast of $NB816$-LAEs, $\delta_n = \delta n / n$, for the average of these clumps is $\sim 80$, which is comparable to those of present-day clusters, 100–200. These clumps have the highest density in our surveyed volume of $9 \times 10^3$ Mpc$^3$ in comoving units. In the present-day Universe, this volume typically contains two massive clusters with mass of $1 - 3 \times 10^{14} M_\odot$ [31]. Thus, the discovered clumps are likely proto-clusters which are ancestors of today’s such clusters.

A particularly interesting feature is that these clumps are very high concentrations of star-forming galaxies with a star-formation rate of $1 - 20 M_\odot \text{ yr}^{-1}$. The star-formation rate density (SFRD) in these clumps inferred from Ly$\alpha$ fluxes is about 130 times higher than in the mean of the whole 1 deg$^2$ field, mainly due to a large overdensity, $\delta_n \sim 80$, of $NB816$-LAEs. This very high SFRD implies that these clumps would be just producing a number of galaxies in a short period by a burst of galaxy formation. In contrast, present-day massive clusters are dominated by old early-type galaxies, and show a deficit of young star-forming galaxies [32, 33]. Since the formation epochs of early-type galaxies are estimated to be $z = 2 - 5$ or earlier (e.g. [34]), galaxies residing in these clumps are likely progenitors of the old early types seen in the core of present-day clusters. Therefore, we are probably witnessing forming clusters where a number of present-day early-type galaxies are just emerging as star-forming galaxies by a burst of galaxy formation.

### 3.4. Implications for Galaxy Formation

The Cold Dark Matter (CDM) model, the standard hierarchical scenario, predicts that very small initial fluctuations of mass density grow up gradually with time to evolve into galaxies and LSSs. However, the observed distribution of $NB816$-LAEs appears much more inhomogeneous than the dark-matter distribution, since the amplitude of the matter fluctuations
at \( z = 5.7 \) is predicted to be only 1/3 of the current value. If one wants to accept the CDM model, a solution to this discrepancy is to assume that LAEs are biased tracers of mass in a way to enhance the mass fluctuations. Previous observational studies of high-\( z \) galaxies discuss the clustering bias [1–3, 5, 35]. Theoretically, such biasing can be produced, if galaxies are formed at rare, highest peaks of yet small fluctuations of matter density (e.g. [7]). From \( \sigma_{20} \), we estimate that the bias parameter, \( b \), the ratio of galaxy overdensity to matter overdensity, is \( b = 3.4 \pm 1.8 \) on scales of LSSs (20 Mpc), which is comparable to the prediction at \( z \sim 5 \) from simulations of galaxy formation based on the CDM model [36, 37]. Thus, the CDM model may be consistent with the early formation of LSSs that we discovered, though the model needs to reproduce the characteristic shapes of observed LSSs, long filaments and large voids. On the other hand, we estimate the \( b \) value, in the CDM, which reproduces the observed number of forming clusters (two in \( 9 \times 10^9 \) Mpc\(^3 \)) with the size and the overdensity, \( \delta_n \sim 80 \), following the prescription of [12, 38]. Although this estimation of \( b \) is based on small statistics and might include a large error due to cosmic variance, we obtain \( b \sim 30 \) for the two forming clusters, which is about ten times higher than the value for LSS scales. This variety of \( b \) could be due to the dependence of \( b \) on the clustering scale or galaxy density [39]. In fact, section 3.1.3 shows that small-scale biases of \( z \sim 5 \) LBGs reach \( b = 20 - 30 \) at \( 1'' \lesssim \theta \lesssim 5'' \).

We note that the angular scale of such a large bias is very small (\( \lesssim 0.2 \) comoving Mpc in projection). How-

Figure 7: Three dimensional distribution of Regions A and B. The upper left panel shows the distribution of \( NB816 \)-LAEs in transverse (East to the West) vs. radial (redshift) directions, while the bottom panel represents the distribution of \( NB816 \)-LAEs projected on the sky. The red and blue circles correspond to the LAEs associated with the forming clusters (Clumps A and B), respectively, while the orange and cyan circles denote other LAEs in these regions. The white open circles plotted on the bottom panel denote the positions of LAEs without spectroscopic redshift. The vertical and horizontal bars indicate the length of 1 Mpc in physical units. The upper right panel shows the redshift distribution of LAEs with spectroscopic redshifts. The red and blue histograms correspond to LAEs in Regions A and B, respectively. The dotted line indicates the mean-expected number of LAEs for each region.
ever, it would be possible that these forming clusters are made of a massive dark halo with a larger outskirt of an actively galaxy-forming region than those of field LBGs. These very high bias may be also explained by a burst of galaxy formation that very efficient galaxy formation takes place in a dark halo at these high redshifts.

Acknowledgments

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