SILVERRUSH. VIII. Spectroscopic Identifications of Early Large-scale Structures with Protoclusters over 200 Mpc at $z \sim 6–7$: Strong Associations of Dusty Star-forming Galaxies

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Abstract

We have obtained three-dimensional maps of the universe in ∼200 × 200 × 80 comoving Mpc3 (cMpc3) volumes each at $z = 5.7$ and 6.6 based on a spectroscopic sample of 179 galaxies that achieves $\gtrsim$90% completeness down to the Ly$\alpha$ luminosity of $log(L_{Ly\alpha}/[erg s^{-1}]) = 43.0$, based on our Keck and Gemini observations and the literature. The maps reveal filamentary large-scale structures and two remarkable overdensities made out of at least 55 and 12 galaxies at $z = 5.692$ (z57OD) and $z = 6.585$ (z66OD), respectively, making z66OD the most distant overdensity spectroscopically confirmed to date, with $\gtrsim$10 spectroscopically confirmed galaxies. We compare spatial distributions of submillimeter galaxies at $z \approx 4–6$ with our $z = 5.7$ galaxies forming the large-scale structures, and detect a 99.97% signal of cross-correlation, indicative of a clear coincidence of dusty star-forming galaxy and dust-unobscured galaxy formation at this early epoch. The galaxies in z57OD and z66OD are actively forming stars with star-formation rates (SFRs) $\gtrsim$5 times higher than the main sequence, and particularly the SFR density in z57OD is 10 times higher than the cosmic average at the redshift (a.k.a. the Madau-Lilly plot). Comparisons with numerical simulations suggest that z57OD and z66OD are protoclusters that are progenitors of the present-day clusters with halo masses of $\sim 10^{15} M_\odot$.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. Introduction

Galaxies are not uniformly distributed in the universe. Some of them reside in groups and clusters on scales of $\sim 1–3$ Mpc, while others lie in long filaments of galaxies extending over 10 Mpc, called large-scale structure (e.g., Gott et al. 2005). Investigating the large-scale structure is important for understanding galaxy formation, as there is observational evidence that galaxy properties depend on their environment. Indeed, at
low redshift, galaxies in clusters are mostly passive, early-type galaxies (e.g., Dressler 1980; Goto et al. 2003), and there is a clear trend that the star-formation activity of galaxies tends to be lower in high-density environment than low-density environment (Lewis et al. 2002; Tanaka et al. 2004), known as the morphology/star-formation-density relation. Because galaxies in dense environments appear to experience accelerated evolution, we need to go to higher redshifts to study the progenitors of low-redshift high-density environments.

Indeed, studies of the large-scale structure at high redshift have shown that galaxies in dense regions experience enhanced star formation (e.g., Kodama et al. 2001; Elbaz et al. 2007; Tran et al. 2010; Koyama et al. 2013), opposite to the relation at low redshift. In addition, recent cosmological simulations predict a significant increase of the contribution to the cosmic star-formation density from galaxy overdensities (Chiang et al. 2017). Thus, many galaxy overdensities have been identified and investigated at \( z > 1 \) to date, including protoclusters that grow to cluster-scale halos at the present day (e.g., Steidel et al. 1998, 2005; Shimasaka et al. 2003, 2004; Chiang et al. 2014, 2015; Dey et al. 2016, see Overzier 2016 for a review). At \( z > 3 \), as strong rest-frame optical emission lines are redshifted to mid-infrared, the Ly\( \alpha \) emission line is used as a spectroscopic probe for galaxies. Some of the high-redshift overdense regions are identified with UV continuum and/or Ly\( \alpha \) emission lines (e.g., Overzier et al. 2006; Utsumi et al. 2010; Toshikawa et al. 2016; Higuchi et al. 2018; Pavesi et al. 2018), and spectroscopically confirmed with Ly\( \alpha \) (e.g., Venemans et al. 2002; Ouchi et al. 2005; Dey et al. 2016; Jiang et al. 2018), including the galaxy overdensities at \( z = 6.01 \) (Toshikawa et al. 2012, 2014).

Because the Ly\( \alpha \) photons are easily absorbed by dust, it is important to investigate whether dust-obscured galaxies are also residing in high-redshift overdensities traced with the Ly\( \alpha \) emission. In addition, dusty star-forming galaxies, such as submillimeter galaxies (SMGs), are expected to trace the most massive dark-matter halos and overdensities at \( z > 2 \) (e.g., Casey 2016; Béthermin et al. 2017; Miller et al. 2018). Tamura et al. (2009) report 2.2\( \sigma \) large-scale correlation between SMGs and Ly\( \alpha \) emitters (LAEs) at \( z = 3.1 \) in the SSA22 protocluster. Umehata et al. (2014) improved the selection of SMGs using photometric redshifts, and detect stronger correlation between SMGs and LAEs in the SSA22 protocluster (see also Umehata et al. 2015, 2017, 2018). These results suggest that dust-obscured star-forming galaxies are also lying in the SSA22 protocluster traced by LAEs at \( z = 3.1 \). However, the association between SMGs and LAEs at higher redshift is not yet understood.

In this study, we investigate large-scale structures at \( z = 5.7 \) and 6.6 in the SXDS field using a large spectroscopic sample of 179 LAEs. Combined with our recent Keck/DEIMOS and Gemini/GMOS observations, we produce 3D maps of the universe traced with the LAEs in two \( \sim 200 \times 200 \times 80 \mathrm{cMpc}^3 \) volumes at \( z = 5.7 \) and 6.6. We investigate the correlation between the LAEs and dust-obscured high-redshift SMGs, and stellar populations to probe the environmental dependence of galaxy properties. We also compare our observational results with recent numerical simulations. One of the large-scale structures investigated in this study is a protocluster at \( z = 5.7 \) first reported in Ouchi et al. (2005). Ouchi et al. (2005) spectroscopically confirm 15 LAEs around this protocluster. Recently, Jiang et al. (2018) studied this protocluster with 46 spectroscopically confirmed LAEs in the SXDS field. In this study, we use 135 LAEs spectroscopically confirmed at \( z = 5.7 \), which allows us to obtain a more complete view of the 3D structure of this protocluster. In addition, we will investigate the correlation with high-redshift SMGs that are not investigated in these studies. This study is one in a series of papers from a program studying high-redshift galaxies, named Systematic Identification of LAEs for Visible Exploration and Reionization Research Using Subaru HSC (SILVERRUSH Ouchi et al. 2018). Early results are already reported in several papers (Harikane et al. 2018b; Higuchi et al. 2018; Inoue et al. 2018; Konno et al. 2018; Ouchi et al. 2018; Shibuya et al. 2018a, 2018b).

This paper is organized as follows. In Section 2, we present our LAE sample. We describe our spectroscopic observations in Section 3. We present our results in Section 4, and in Section 5 we summarize our findings. Throughout this paper we use the recent Planck cosmological parameter sets constrained with the temperature power spectrum, temperature-polarization cross spectrum, polarization power spectrum, low-/polarization, CMB lensing, and external data (TT, TE, EE +lowP+lensing+ext result; Planck Collaboration et al. 2016): \( \Omega_m = 0.3089, \Omega_L = 0.6911, \Omega_b = 0.049, h = 0.6774, \) and \( s_9 = 0.8159 \). We assume a Chabrier (2003) initial mass function (IMF) with lower and upper mass cutoffs of 0.1\( M_\odot \) and 100\( M_\odot \), respectively. All magnitudes are in the AB system (Oke & Gunn 1983).

## 2. LAE Sample

We use LAE samples at \( z = 5.7 \) and 6.6 (Shibuya et al. 2018b) selected based on the Subaru/Hyper Suprime-Cam Subaru strategic program (HSC-SSP) survey data (Aihara et al. 2018a, 2018b), reduced with the HSC data processing pipeline (Bosch et al. 2017). The LAEs at \( z = 5.7 \) and 6.6 are selected with the narrowband filters NB816 and NB921, which have central wavelengths of 8170Å and 9210Å, and FWHMs of 131Å and 120Å to identify LAEs in the redshift range of \( z = 5.64-5.76 \) and \( z = 6.50-6.63 \), respectively. The HSC-SSP survey has three layers, UltraDeep (UD), Deep, and Wide, with different combinations of area and depth. In this study, we use LAE samples in the UD-SXDS field, where rich spectroscopic data are available (see Section 3). We select 224 and 58 LAEs at \( z = 5.7 \) and \( z = 6.6 \), respectively, in the UD-SXDS field with the following color criteria:

\[
\begin{align*}
\text{NB816} < \text{NB816}_{G5} \text{ and } \text{NB816} > 1.2 \text{ and } \\
g > g_{3\sigma} \text{ and } [(r < r_{5\sigma} \text{ and } r - i > 1.0) \text{ or } r > r_{3\sigma}].
\end{align*}
\]

\[
z = 5.7:
\]

\[
\begin{align*}
\text{NB816} < \text{NB816}_{G5} \text{ and } \text{NB816} > 1.2 \text{ and } \\
g > g_{3\sigma} \text{ and } [(r < r_{5\sigma} \text{ and } r - i > 1.0) \text{ or } r > r_{3\sigma}].
\end{align*}
\]

The subscripts “5\( \sigma \)” and “3\( \sigma \)” indicate the 5\( \sigma \) and 3\( \sigma \) magnitude limits for a given filter, respectively. Based on spectroscopic observations in Shibuya et al. (2018a), the contamination rate is 0%–30%. In addition, we use fainter LAE samples at \( z = 5.7 \) and 6.6 selected with Subaru/Suprime-Cam.
images in Ouchi et al. (2008, 2010). The total numbers of LAEs are 563 and 247 at \( z = 5.7 \) and 6.6, respectively.

To identify LAE overdensities, we calculate the galaxy overdensity, \( \delta \), that is defined as follows:

\[
\delta = \frac{n - \pi}{\pi}.
\]

where \( n \) is the number of LAEs in a cylinder and \( \pi \) is its average. To draw two-dimensional (2D) projected overdensity contours, we choose a cylinder whose height is \( \sim 40 \) cMpc corresponding to the redshift range of the narrowband-selected LAEs at each redshift. The radius of the cylinder is 0.07 deg, which corresponds to \( \sim 10 \) cMpc at \( z \approx 6 \), which is a typical size of the protoclusters growing to \( \sim 10^{15} M_\odot \) halo at \( z = 0 \) in simulations in Chiang et al. (2013). We use LAEs brighter than \( NB816 < 24.5 \) and \( NB921 < 25.0 \) at \( z = 5.7 \) and 6.6, respectively, to keep high detection completeness. The average numbers of LAEs in a cylinder are \( \pi = 0.48 \) and 0.26 at \( z = 5.7 \) and 6.6, respectively. The masked regions are excluded in the calculations. In Figure 1, we plot the calculated overdensities smoothed with a Gaussian kernel of \( \sigma = 0.07 \) deg. Here, we define overdensities as regions whose overdensity significances are higher than 4\( \sigma \) levels. We identify overdensities previously reported in Higuchi et al. (2018); \( z6PCC1 \), \( z6PCC3 \), and \( z6PCC4 \) at \( z = 5.7 \), and \( z7PCC24 \) and \( z7PCC26 \) (see also Chanchaiworawit et al. 2017, 2019) at \( z = 6.6 \).\(^{30}\) \( z6PCC1 \) is the same structure reported in Ouchi et al. (2005) and Jiang et al. (2018, see Section 4.1). Hereafter, we refer to \( z6PCC1 (n = 6, \delta = 11.5, 7.2\sigma) \) and \( z7PCC24 (n = 4, \delta = 14.3, 6.8\sigma) \), the most overdense regions at \( z = 5.7 \) and 6.6 in the UD-SXDS field, as \( z57OD \) and \( z66OD \), respectively.

\(^{30}\) We regard \( z7PCC26 \) as an overdensity following Higuchi et al. (2018).

3. Spectroscopic Data

Out of 563 and 247 LAEs at \( z = 5.7 \) and 6.6, 135 and 36 LAEs are spectroscopically confirmed, respectively, in previous studies (Ouchi et al. 2005, 2008, 2010; Harikane et al. 2018b; Higuchi et al. 2018; Jiang et al. 2018; Shibuya et al. 2018a). Four LAEs around \( z66OD \), \( z66LAE-1, -2, -3 \), and \( -4 \) are already spectroscopically confirmed. In addition, we conducted Gemini and Keck spectroscopy targeting LAEs of \( z66OD \).

We used Gemini Multi-Object Spectrographs (GMOS) on the 8 m Gemini North telescope in 2017 and 2018. We used a total of two GMOS masks with the OG515 filter and R831 grating, and the total exposure times were 5400 and 10,220 s. Our exposures were conducted with spectral dithering of 50 Å to fill CCD gaps. The spectroscopic coverage was between 7900 and 10000 Å. The spatial pixel scale was 0.0727 pixel^{-1}. The slit width was 0.75” and the spectral resolution was \( R \sim 3000 \). The seeing was around 0.9”. The reduction was performed using the Gemini IRAF packages.\(^{31}\) Wavelength calibration was achieved by fitting to the OH emission lines.

We also used DEep Imaging Multi-Object Spectrograph (DEIMOS) on the 10 m Keck II telescope in 2018. We used one DEIMOS mask with the OG550 filter and 830G grating, and the total exposure time was 4900 s. The spectroscopic coverage was between 6000 and 10000 Å. The spatial pixel scale was 0.1185 pixel^{-1}. The slit width was 0.8” and the spectral resolution was \( R \sim 3000 \). The seeing was around 0.8”. The reduction was performed using the spec2d IDL pipeline developed by the DEEP2 Redshift Survey Team (Davis et al. 2003). Wavelength calibration was achieved by fitting to the arc emission lines.

In these observations, we identified emission lines in eight LAEs, \( z66LAE-5, -6, -7, -8, -9, -10, -11, \) and \( -12 \). We evaluate asymmetric profiles of these emission lines by calculating the weighted skewness, \( S_w \) (Kashikawa et al. 2006).

\(^{31}\) https://www.gemini.edu/sciops/data-and-results/processing-software
4. Results and Discussions

4.1. Large-scale Structure at $z = 5.7$ and $z = 6.6$ and Spectroscopic Confirmation of z66OD at $z = 6.585$

We obtain the three-dimensional (3D) map using the 179 spectroscopic confirmed LAEs. We calculate the 3D overdensity using the LAE sample with a sphere whose radius is 10 cMpc (15 cMpc) at $z = 5.7$ ($z = 6.6$). Note that velocity offsets of the Ly$\alpha$ emission lines to the systemic redshifts are typically $\sim 300$ km s$^{-1}$ or $\sim 2.5$ cMpc (e.g., Erb et al. 2014; Faisst et al. 2016; Hashimoto et al. 2018), smaller than the radius of the sphere. In Figure 3, we plot the locations of the LAEs and the 3D overdensity smoothed with a Gaussian kernel of $\sigma = 10$ cMpc (15 cMpc) at $z = 5.7$ ($z = 6.6$). Figure 4 shows the 2D maps with the redshift slices of $\Delta z \sim 0.02$. These maps reveal the filamentary 3D large-scale structures made by the LAEs at $z = 5.7$ and 6.6.

In the 3D maps, we identify z57OD ($z = 5.692$) and z66OD ($z = 6.585$) with 44 and 12 LAEs spectroscopically confirmed, respectively, which are located within $\sim 1\sigma$ contours in Figures 5 and 6. The $1\sigma$ contours are roughly corresponding to the 20 cMpc-radius aperture. According to theoretical studies in Chiang et al. (2017), the 20 cMpc-radius aperture at $z \sim 6$ includes $\geq 90\%$ members of clusters at $z = 0$. We include z66LAE-8 located just outside the $1\sigma$ contour, because it is within 20 cMpc from the center of z66OD. Figures 5 and 6 show the locations of LAEs, 2D projected contours, and spectra of the LAEs of z57OD and z66OD, respectively. Tables 1 and 2 summarize properties of LAEs of z57OD and z66OD, respectively. The average redshift of the LAEs of z66OD ($z = 6.585$) suggests that z66OD is the most distant overdensity with $>10$ galaxies spectroscopically confirmed to date (see, 3 galaxies at $z = 7.1$ in Castellano et al. 2018). Properties of overdensities in this work and in the literature are summarized in Table 3, which is based on objects listed in Table 5 in Chiang et al. (2013) and new objects discovered since.

Both z57OD and z66OD are located in the filamentary structures made by LAEs around these overdensities, extending over 40 cMpc. We evaluate the extension of these overdensities in the redshift direction by calculating velocity dispersions of LAEs. We select LAEs within 0.07 deg from the centers (defined as the highest density peaks) of z57OD and z66OD, and calculate the rms of their velocities as velocity dispersions. The calculated velocity dispersions are $1280 \pm 220$ km s$^{-1}$ and $670 \pm 200$ km s$^{-1}$, respectively, similar to the value of galaxies in overdensities found in Lemaux et al. (2018), 1038 $\pm$ 178 km s$^{-1}$ and Toshikawa et al. (2012, 647 $\pm$ 124 km s$^{-1}$), respectively. These velocity dispersions are compared with simulations in Section 4.2.

Jiang et al. (2018) identify SXDS_gPC in their spectroscopic survey. Since the coordinate and redshift of SXDS_gPC are the same as those of z57OD, we conclude that SXDS_gPC is the same structure as z57OD. Jiang et al. (2018) spectroscopically confirm 46 LAEs at $z = 5.7$ in the UD-SXDS field. 34 LAEs among the 46 LAEs overlap with our LAE catalog, and traces similar large-scale structures to the ones we identify. However, the overdensity value and its significance ($\delta = 5.6$, $\sim 5\sigma$) are different from our measurements ($\delta = 15.0$, 8.4$\sigma$). This is because the aperture size and magnitude limit of LAEs for the $\delta$ calculation are different between our measurements (10 cMpc-radius circular aperture and 24.5 mag) and Jiang et al. (35$^2$ cMpc$^2$ aperture and 25.5 mag). If we calculate by adopting...
the same aperture size and magnitude limit as Jiang et al. (2018) for spectroscopically confirmed LAEs, we obtain $\delta = 4.8 (4.1\sigma)$, comparable to the measurements of Jiang et al. (2018).

4.2. Comparison with Simulations

We compare our results with numerical simulations of Inoue et al. (2018) to estimate halo masses of z57OD and z66OD. Inoue et al. (2018) use N-body simulations with 4096$^3$ dark-matter particles in a comoving box of 162 Mpc. The particle mass is $2.46 \times 10^6 M_\odot$ and the minimum halo mass is $9.80 \times 10^7 M_\odot$. Halos' ionizing emissivity and IGM H I clumpiness are produced by an RHD simulation with a 20 comoving Mpc$^3$ box (K. Hasegawa et al. 2019, in preparation). LAEs have been modeled with physically motivated analytic recipes as a function of halo mass. LAEs are modeled based on the radiative transfer calculations by a radiative hydrodynamic simulation (K. Hasegawa et al. 2019, in preparation). In this work, we use the LAE model G with the late reionization history, which reproduces all observational results, namely the neutral hydrogen fraction measurements, Ly$\alpha$ luminosity functions, LAE angular correlation functions, and Ly$\alpha$ fractions in LBGs at $z \geq 6$. Thus, we expect that similar systems to z57OD and z66OD are found in the simulations.

We slice the 162$^3 \times 162$ cMpc$^3$ box into four slices of $162 \times 162 \times 40.5$ cMpc$^3$ whose depth ($\sim 40$ cMpc) is comparable to the redshift range of the narrowband-selected LAEs at $z = 5.7$ and 6.6. Magnitudes of the LAEs are calculated based on the transmission curves of the HSC filters. We select $z = 5.7$ and 6.6 mock LAEs with $-\alpha L_{10} > \text{NB}_{816} > 24.5$ mag and $\text{NB}_{921} > 25.0$ mag at $z = 5.7$ and 6.6, respectively, and calculate the galaxy overdensity in each slice with a cylinder whose depth and radius are 40 cMpc and 10 cMpc, respectively. The average number densities of LAEs in the cylinder are $n = 0.39$ and 0.32 at $z = 5.7$ and 6.6, respectively, which agree with observations within 1$\sigma$ fluctuations. We show the calculated overdensity in each slice in Figure 7. We define overdensities as regions whose overdensity significances are higher than 4$\sigma$. We calculate velocity dispersions of LAEs in

Figure 3. 3D overdensity maps of LAEs at $z = 5.7$ (left) and $z = 6.6$ (right). The black dots show the positions of the LAEs. The large dots are LAEs brighter than $L_{\text{Ly}\alpha} > 10^{43}$ erg s$^{-1}$. Higher-density regions are indicated by the bluer colors, smoothed with a Gaussian kernel of $\sigma = 10$ cMpc (15 cMpc) at $z = 5.7$ ($z = 6.6$).

Figure 4. Two-dimensional map of LAEs at $z = 5.7$ (upper) and $z = 6.6$ (lower) with the redshift slices. The black dots show the positions of the LAEs in the $\Delta z \sim 0.02$ redshift depth. The large dots are LAEs brighter than $L_{\text{Ly}\alpha} > 10^{43}$ erg s$^{-1}$. Higher-density regions are indicated by the darker colors, smoothed with a Gaussian kernel of $\sigma = 10$ cMpc (15 cMpc) at $z = 5.7$ ($z = 6.6$).
the overdensities, using LAEs within 10 cMpc from the centers of the overdensities, a similar aperture size to the one used in the velocity dispersion calculations for z57OD and z66OD.

We compare the significances and velocity dispersions of the overdensities in the simulations with z57OD and z66OD in Figure 8. At $z = 5.7$, we find three overdensities, simOD1 ($\delta = 19.5$, 10.8$\sigma$, $\sigma_V = 1100$ km s$^{-1}$), simOD2 ($\delta = 11.8$, 6.6$\sigma$, $\sigma_V = 750$ km s$^{-1}$), and simOD3 ($\delta = 9.3$, 5.1$\sigma$, $\sigma_V = 1500$ km s$^{-1}$), whose significance and velocity dispersion are comparable with z57OD with $\lesssim 2\sigma$ uncertainties. The masses of the most massive halos in these three overdensities are $1.0 \times 10^{12} M_\odot$, $4.7 \times 10^{11} M_\odot$, and $7.7 \times 10^{11} M_\odot$, respectively, at $z = 5.7$. At $z = 6.6$, we identify one overdensity, simOD4 ($\delta = 13.7$, 7.3$\sigma$, $\sigma_V = 610$ km s$^{-1}$), whose significance and velocity dispersion are comparable with z66OD with $\lesssim 1\sigma$ uncertainties. The mass of the most massive halo in simOD4 is $3.9 \times 10^{11} M_\odot$ at $z = 6.6$. Because the simulations do not go to $z \sim 0$, we use the extended Press-Schechter model of Hamana et al. (2006) to estimate the present-day halo masses of the $z = 5.7$ and 6.6 halos. We find that these four overdensities in the simulations will grow to the cluster-scale halo ($M_h \sim 10^{14} M_\odot$) at $z \sim 0$ with scatters of $\sim 1$ dex in $M_h$, indicating that z57OD and z66OD are protoclusters. Note that Overzier et al. (2009) reached the same conclusion on the progenitor of z57OD.

We also estimate present-day halo masses of z57OD and z66OD using another method following previous studies (Steidel et al. 1998; Venemans et al. 2005; Toshikawa et al. 2012). The halo mass at $z = 0$ of a protocluster $M_h$ is given by

$$M = \bar{\rho}V(1 + \delta_m),$$

where $\bar{\rho} = 4.1 \times 10^{10} M_\odot$ Mpc$^{-3}$ is the mean matter density of the universe, $V$ is the comoving volume of the protocluster that collapses into the cluster at $z = 0$, and $\delta_m$ is the mass overdensity. The mass overdensity $\delta_m$ is related to the galaxy
overdensity $\delta$ with
\begin{equation}
1 + b\delta_i = C(1 + \delta),
\end{equation}
where $b$ is the bias factor of galaxies and $C$ is the correction factor for the redshift space distortion. We assume $C = 1$ because this value is close to 1 at high redshift (Lahav et al. 1991). The biases of LAEs at $z = 5.7$ and 6.6 are estimated to be $b = 4.1$ and $b = 4.5$ in Ouchi et al. (2018). Assuming $V = (4/3)\pi \times 10^3 \text{ Mpc}^3$ (typical size of a protocluster in Chiang et al. 2013), we estimate the present-day halo masses of $z57$OD and $z66$OD to be $4.8 \times 10^{14} M_\odot$ and $5.4 \times 10^{14} M_\odot$, which agree with those estimated with the simulations. These estimated present-day halo masses support that $z57$OD and $z66$OD are protoclusters.

As discussed in the previous paragraph, we identify similar overdensities to $z57$OD in the simulation. However, Jiang et al. (2018) report that they do not find overdensities similar to $z57$OD in their cosmological simulation that is an update of a previous work (Chiang et al. 2013). This difference may be due to the different sizes of apertures used to search overdensities. We use a 10 cMpc-radius circular aperture, while Jiang et al. (2018) use a larger, $35^2$ cMpc$^2$ aperture. Thus, the simulations could reproduce overdensities on a small scale, but not on a large scale.

4.3. Correlation with Red SMGs

In Section 4.1, we identify the large-scale structures made by LAEs, typically dust-poor star-forming galaxies. It is important to investigate whether dust-obscured star formation also traces the large-scale structures. We select high-redshift SMGs at $z \approx 4–6$ (hereafter red SMGs) from the JCMT/SCUBA-2 Cosmology Legacy Survey 850 \micron source catalog (Geach et al. 2017) using Herschel/SPIRE fluxes. It should be noted that $\sim 850$ \micron offers the negative K-correction to study SMGs with the same sensitivity at $z \sim 2–3$.

To estimate Herschel/SPIRE fluxes and partially overcome a confusion problem due to the large beam size, we apply a deblending approach using higher-resolution positional priors.
We adopt positions of SCUBA-2 sources detected with $>4\sigma$ total noise and then apply a simultaneous source-fitting routine available via SUSSEXtractor task in HIPE (Savage & Oliver 2007; Ott 2010). The PSF of the JCMT/SCUBA-2 image is $14''8$ (Geach et al. 2017). The PSFs of the Herschel/SPIRE images are assumed to be Gaussian, with FWHM being $17''6$, $25''1$ and $35''2$ at $250\,\mu m$, $350\,\mu m$, and $500\,\mu m$ respectively. Total flux uncertainties are estimated by quadratically adding the instrument and confusion noise. We further fully evaluate our selection via realistic end-to-end simulation based on the galaxy model of Béthermin et al. (2017), which includes physical clustering based on abundance matching and galaxy–galaxy lensing. Using this simulation, we simulate the exact criteria we applied on our real maps. The typical flux density error is $9\, mJy$ at $500\,\mu m$, which is in agreement with a value predicted by simulations.
To select red SMGs, we adopt the following criteria (Donevski et al. 2018):

\[ S_{250\,\mu m} < S_{350\,\mu m} < S_{500\,\mu m}, \]  

where \( S_{250\,\mu m} \), \( S_{350\,\mu m} \), and \( S_{500\,\mu m} \) are the Herschel 250 \( \mu m \), 350 \( \mu m \), and 500 \( \mu m \) fluxes, respectively. Equation (6) allows us to select \( z \gtrsim 4 \) SMGs whose modified blackbody emission peaks at \( >500 \mu m \) (see Figure 6 in Donevski et al. 2018).\(^{32}\) When using Equation (6), we adopt the following three criteria to measure the Herschel colors correctly. First, we use only sources whose 500 \( \mu m \) fluxes are measured at \( >2\sigma \) levels. Second, if the sources are not detected in the 250 \( \mu m \) and/or 350 \( \mu m \) bands at the 2\( \sigma \) levels, we replace fluxes with \( 2\sigma \) flux limits. Third, we remove sources that are detected in 250 \( \mu m \) but not in 350 \( \mu m \). After adopting these criteria and Equation (6), we reduce low-redshift interlopers using ALMA and Subaru/HSC data. We cross-match the SCUBA-2 sources with ALMA sources in archival data (see also Stach et al. 2018) within 10\( '' \), and identify ALMA counterparts of the SCUBA-2 sources if present. The ALMA data we use are taken in band 7, with typical 1\( \sigma \) noise levels and angular resolutions of 0.2 milliarcsecond and 0\( ''/2 \), respectively. We identify the ALMA counterparts of more than 70\% of the SCUBA-2 sources, and most of the rest are not observed with ALMA. We then measure fluxes at the positions of the ALMA counterparts in the HSC \( g \) and \( r \) images, and exclude SCUBA-2 sources with detection at \( >3\sigma \) levels in the HSC \( g \)- or \( r \)-band images (bluer than the Lyman break at \( z \approx 4-6 \)). Finally, we apply masks of diffraction spikes and halos from bright objects in the same fashion as for our LAEs, and obtain the red SMG sample.

We also define SMGs not selected with the above criteria as blue SMGs, which will be used for a null test. In addition, we select LAEs at \( z = 5.7 \) located in the sky coverage of the SCUBA-2 observation. Finally, we obtain 44 red SMGs, 673 blue SMGs, and 227 LAEs (77 spectroscopically confirmed). Note that there is no overlap between the LAEs and the ALMA sources within 2\''.

Because LAEs are typically dust-poor weak 850 \( \mu m \) and [C\( II \)]158 \( \mu m \) emitters (Harikane et al. 2018b), finding no overlap is reasonable. According to Geach et al. (2017), the false detection rate is \(<6\% \) at the \( >4\sigma \) detection. We will test whether the red SMGs are at \( z = 5.7 \) or not by the cross-correlation analysis later, so we do not take this false detection rate into account here.

The left panel in Figure 9 shows the locations of the red SMGs and \( z = 5.7 \) LAEs. We find that some of the red SMGs are clustering around z57OD (R.A. = 34.26, decl. = −5.54). We calculate the cross-correlation function (CCF) of the 227 LAEs at \( z = 5.7 \) and the 44 red SMGs using the estimator in Landy & Szalay (1993):

\[ \omega(\theta) = \frac{DD_{\theta}DR_{\theta} - DR_{\theta}RD_{\theta} + RD_{\theta}DR_{\theta}}{RR_{\theta}}, \]  

where \( DD, DR, RD, \) and \( RR \) are the numbers of galaxy–galaxy, galaxy–random, random–galaxy, and random–random pairs for groups 1 and 2. We also calculate the CCF between the 77 spectroscopically confirmed LAEs and red SMGs, the CCF between the 227 LAEs and 775 blue SMGs, and angular autocorrelation functions (ACFs) of the 227 LAEs for reference. Using SCUBA-2 SMGs may have the blending bias effect on the correlation function measurements, due to confusion introduced by the coarse angular resolution (Karim et al. 2013; Stach et al. 2018). However, the effect is expected to be small, a factor of \( \sim 1.2-1.3 \) (Cowley et al. 2017). We estimate statistical errors of the CCFs and ACF using the Jackknife estimator. We divide the samples into 47 Jackknife subsamples of about 500\(^2 \) arcsec\(^2 \), comparable to the maximum angular size of the correlation function measurements. Removing one Jackknife subsample at a time for each realization, we compute the covariance matrix as

\[ C_{ij} = \frac{N - 1}{N} \sum_{l=1}^{N} (\omega(\theta_l) - \bar{\omega})[\omega(\theta_i) - \bar{\omega}][\omega(\theta_j) - \bar{\omega}], \]  

\(^{32}\) Although Donevski et al. (2018) showed that most of the galaxies lie at \( z < 5 \), this is because the number density of \( z > 5 \) SMG is low (e.g., Ivison et al. 2016).
### Table 3
An Overview of High-redshift Protoclusters

| Name                | $z$  | $N_{\text{spec}}$ | $\delta$ | Sample Type | Window Size | $d_z$  | $\sigma_v$ | $M_h$  | Reference     |
|---------------------|------|-------------------|----------|-------------|-------------|--------|------------|--------|---------------|
|                     | (1)  | (2)               | (3)      | (4)         | (5)         | (6)    | (7)        | (8)    | (9)           | (10)         |
| z66OD               | 6.59 | 12                 | 14.3     | LAE         | $\pi \times 4.2^2$ | 0.1    | 670 $\pm$ 200 | 5.4 $\times 10^{14}$ | This work    |               |
| HSC-z7PCC26         | 6.54 | 14                 | 6.8      | LAE         | $\pi \times 4.2^2$ | 0.1    | 572 $\pm$ 3      | 8.4 $\times 10^{14}$ | C17,19,Hi18  |               |
| SDF                 | 6.01 | 10                 | 16.7     | LBG         | $\pi \times 4.2^2$ | $\sim$0.5 | 647 $\pm$ 124  | (2$-$4) $\times 10^{14}$ | To12,14      |               |
| z57OD               | 5.69 | 44                 | 11.5     | LAE         | $\pi \times 4.2^2$ | 0.1    | 1280 $\pm$ 220 | 4.8 $\times 10^{14}$ | O05,18This work |               |
| SPT2349-56          | 4.31 | 14                 | $\sim$1000 | SMG  | $\pi \times 0.16^2$ | 0.1    | 408$^{+40}_{-36}$ | 1.16 $\times 10^{13}$ | M18           |               |
| TNJ1338-1942        | 4.11 | 37                 | 3.7      | LBG/LBG     | $\pi \times 7(\times 2)$ | 0.049  | 265 $\pm$ 65   | (6$-$9) $\times 10^{14}$ | V02,05,07,M04, | Z05,06,08     |
| DRC-protocluster    | 4.00 | 10                 | 5.5      | SMG         | $\pi \times 0.730$ | ...    | 794 $\pm$ (3.2$-$4.4) $\times 10^{13}$ | O18           |               |
| PC1721-96+23.2      | 3.79 | 65                 | 14       | LAE         | $\pi \times 1.2^2$ | 0.035  | 350 $\pm$ 40   | (0.6$-$1.3) $\times 10^{15}$ | Lee14,D16,S19 |               |
| D4GD01              | 3.67 | 11                 | ...      | LBG         | $\pi \times 1.8^2$ | ...    | 352 $\pm$ 140 | ...   | To16          |               |
| CJ0227-0421         | 3.29 | 19                 | 10.5     | Spec        | $\pi \times 6.2^2$ | 0.09   | 995 $\pm$ 343 | (1.9$-$3.3) $\times 10^{14}$ | Lem14         |               |
| TNJ2009-3040        | 3.16 | $\sim$11           | 0.7      | LAE         | $\pi \times 7$ | 0.049  | 515 $\pm$ 90   | ...   | V07           |               |
| MRC0316-257         | 3.13 | 31                 | 2.3      | LBG         | $\pi \times 7$ | 0.049  | 640 $\pm$ 195 | (3$-$5) $\times 10^{14}$ | V05,07        |               |
| SSA22FLD            | 3.09 | $\sim$15           | 3.6      | LBG/        | $\pi \times 11.5$ | 0.034  | ...         | (1$-$10) $\times 10^{15}$ | S98,00,M05,Y12,U17,18 |
| MRC0943-242         | 2.92 | 28                 | 2.2      | LAE         | $\pi \times 0.2^2$, | 0.056  | 715 $\pm$ 105 | 4.5 $\times 10^{14}$ | V07           |               |
| PK012                | 2.90 | 12                 | 12       | Spec        | $\pi \times 7$ | 0.016  | 270 $\pm$ 80   | 8.1 $\times 10^{14}$ | C14           |               |
| MRC0052-241         | 2.86 | 37                 | 2.0      | LBG         | $\pi \times 7$ | 0.054  | 980 $\pm$ 120 | (3$-$4) $\times 10^{14}$ | V07           |               |
| HS1549              | 2.85 | 26                 | 5.0      | SMG/LBG     | ...         | 0.060  | ...         | ...     | M13,Lac18      |               |
| PCL100              | 2.45 | 11                 | 10       | Spec/       | $\pi \times 2.8^2$ | 0.016  | 426 $\pm$ 10^{-15} | 10^{4}$\pm$10^{-15} | D15,Ch15,CA15 |               |
| HS1700FLD           | 2.30 | 19                 | 6.9      | SMG         | $\pi \times 8$ | 0.030  | ...         | 1.4 $\times 10^{15}$ | S05,Lac18      |               |
| PKS1138-262         | 2.16 | 15                 | 3        | SMG         | $\pi \times 7$ | 0.053  | 900 $\pm$ 240 | (3$-$4) $\times 10^{14}$ | K00,04a,04b,P00,02, | V07,K13,Z18   |

**Note:** (1) Object name. (2) Redshift. (3) Number of spectroscopically confirmed galaxies. (4) Galaxy overdensity. (5) Method of sample selection: (LAE) narrowband LAE, (HAE) narrowband H alpha emitter, (LGB) Lyman break galaxy, (BX) “BX” galaxy of Adelberger et al. (2005), (SMG) submillimeter galaxy, (Spec) spectroscopic survey. (6) Approximate field size or the size of the structure used to calculate overdensity in units of arcmin$^2$. (7) Full width redshift uncertainty associated with the $\delta$ quoted. (8) Velocity dispersion (where available) in units of km s$^{-1}$. (9) Inferred total halo mass of the overdensity or expected halo mass at $z = 0$ in units of $M_h$. (10) Reference (B17: Bädesch et al. 2017, C11: Capak et al. 2011, C14: Cucciati et al. 2014, C15: Casey et al. 2015, C18: Castellano et al. 2018, C17:19: Chancharwawit et al. 2017, 2019, D15: Dieri et al. 2015, D16: Dey et al. 2016, H11: Hatch et al. 2011, H12: Hayashi et al. 2012, H18: Higuchi et al. 2018, H16: Ishigaki et al. 2016, J18: Jiang et al. 2018, K00,04a,04b: Kurk et al. 2000, 2004a, 2004b, K11: Kneib et al. 2011, K13: Koyama et al. 2013, Lee14: Lee et al. 2014, L14, Lemaux et al. 2014, L17: Laporte et al. 2017Lac18: Lacaille et al. 2018, L18: Lemaux et al. 2018 M04: Milei et al. 2004, M05: Matsuda et al. 2005, M13: Mostardi et al. 2013, M18: Miller et al. 2018, O05, Ouchi et al. 2005, O06,08: Overzier et al. 2006, 2008, O18: Oteo et al. 2018, P00,02: Pentericci et al. 2000, 2002, P04: Palunas et al. 2004, P08: Prescott et al. 2008, P18: Pavesi et al. 2018, S98,00,05: Steidel et al. 1998, 2000, 2005, S03: Shimakawa et al. 2003, S19: Shi et al. 2019, T11: Tanaka et al. 2011, T12,14,16: Toshikawa et al. 2012, 2014, 2016, H12: Trenti et al. 2012 U10: Utsumi et al. 2010, U17,18: Umehata et al. 2017, 2018, V02,04,05,07: Venemans et al. 2002, 2004, 2005, 2007, Y12: Yamada et al. 2012, Z05: Zirm et al. 2005, Z18: Zeballos et al. 2018).
where \( N \) is the total number of the Jackknife samples, and \( \omega^l \) is the estimated CCFs or ACF from the \( l \)th realization. \( \bar{w} \) denotes the mean CCFs and ACF. We apply a correction factor (typically \( \sim 1.1 \)) given by Hartlap et al. (2007) to an inverse covariance matrix in order to compensate for the bias introduced by the statistical noise.

The calculated CCFs and ACF are presented in the right panel of Figure 9. We detect the signal of the cross-correlation between the LAEs at \( z = 5.7 \) and red SMGs. We evaluate the significance of the correlation by calculating the \( \chi^2 \) value,

\[
\chi^2 = \sum_{ij} [\omega(\theta_j) - \omega_{\text{model}}(\theta_j)] C^{-1}_{ij} [\omega(\theta_i) - \omega_{\text{model}}(\theta_i)],
\]

where \( \omega_{\text{model}} = 0 \) for the non-detection case. We obtain \( \chi^2 = 13.0 \), indicating the 99.97% significance correlation. If we use the spectroscopically confirmed LAEs, the significance level of the cross-correlation is still 96%. We do not detect the \( >2\sigma \) correlation signal between the LAEs and blue SMGs, nor the LAEs and all SMGs. These significant correlations between the LAEs and red SMGs indicate that the red SMGs also trace the large-scale structure with \( z_{57\text{OD}} \) made by the LAEs, similar to the SSA-22 protocluster at \( z = 3.1 \) (Tamura et al. 2009; Umehata et al. 2014). We also calculate cross-correlation functions between the LAEs at \( z = 6.6 \) and red SMGs, but do not detect a significant correlation signal beyond \( 2\sigma \).

We evaluate the fraction of red SMGs located at \( z = 5.7 \). If all of the SMGs and LAEs are at \( z = 5.7 \), the large-scale amplitude of the CCF between the LAEs and red SMGs is expressed as \( b_{\text{LAE}} b_{\text{SMG}} \xi_{\text{DM}} \), where \( b_{\text{LAE}} \), \( b_{\text{SMG}} \), and \( \xi_{\text{DM}} \) are the large-scale bias of the LAE, the large-scale bias of the SMG, and the dark-matter correlation function. If some of the red SMGs are not at \( z = 5.7 \), the CCF amplitude will decrease by a factor of \( 1 - f_c \), where \( f_c \) is a fraction of the red SMGs that are not at \( z = 5.7 \). The large-scale amplitude of the ACF of LAEs is \( b_{\text{LAE}}^2 \). Because the observed amplitudes of the CCF between the LAEs and red SMGs are comparable to that of the ACF of LAEs, we get

\[
b_{\text{LAE}} b_{\text{SMG}} \xi_{\text{DM}} (1 - f_c) = b_{\text{LAE}}^2 \xi_{\text{DM}},
\]

and

\[
(1 - f_c) = \frac{b_{\text{LAE}}}{b_{\text{SMG}}^2}.
\]

The large-scale bias of LAEs at \( z = 5.7 \) is typically \( b_{\text{LAE}} \simeq 4 \) (Ouchi et al. 2018). The bias of SMGs is expected to be larger than that of LAEs (\( b_{\text{SMG}} > b_{\text{LAE}} \)), because SMGs are thought to be more massive than LAEs. For example, the large-scale bias of SMGs is typically \( \sim 3 \) times larger than that of LAEs.
at \( z \approx 2\)–3 (e.g., Webb et al. 2003; Gawiser et al. 2007; Weiß et al. 2009; Ouchi et al. 2010). On the other hand, the effective volume of our narrowband data is \( \sim 200 \times 200 \times 80 \) cMpc\(^3\). Only one halo as massive as \( M_h \approx 10^{13} M_\odot \) is expected to exist in this volume, on average (Tinker et al. 2008). Thus, we get the upper limit of the bias of the SMGs as \( b_{\text{SMG}} < b(M_h = 10^{13} M_\odot) \approx 14 \). From the lower and upper limits obtained, \( 4 < b_{\text{SMG}} < 14 \), we expect that the fractions of red SMGs at \( z = 5.7 \) are \( \sim 30\%–100\% \), suggesting that \( \sim 10–40 \) red SMGs are at \( z = 5.7 \). This is higher than the expectation from the redshift distribution in Donevski et al. (2018, their Figure 7), hinting that large numbers of red SMGs are clustering at \( z = 5.7 \). ALMA follow-up observations for these red SMGs are now being prepared. It is interesting that the CCF shows a strong correlation between the LAEs and the red SMGs even at the \(<20''\) scale, while the ACF does not. It indicates that LAE-red SMG pairs can be more easily found in the \(<20''\) scale than LAE-LAE pairs.

4.4. Star Formation Activity in \( z57OD \) and \( z66OD \)

To understand star-formation activities in \( z57OD \) and \( z66OD \), we investigate spectral energy distributions (SEDs) of the LAEs of \( z57OD \) and \( z66OD \). We use the images of Subaru/HSC grizyNB stacked images, UKIRT/WFCAM JHK in the UKIDSS/UDS project (Lawrence et al. 2007), and Spitzer/IRAC [3.6] and [4.5] bands in the SPLASH project (P. Capak 2019, in preparation). Some LAEs are detected in the NIR images, and we can constrain SEDs of them. Regarding LAEs not detected in the NIR images, we stack images of these LAEs, and make subsamples (“non detection stack” subsamples) in \( z57OD \) and \( z66OD \). We also stack images of all LAEs in \( z57OD \) and \( z66OD \) (“all stack” subsamples) to investigate averaged properties.

First, we run T-PHOT (Merlin et al. 2016) and generate residual IRAC images where only the LAEs under analysis are left. As high-resolution prior images in the T-PHOT run, we use HSC grizyNB stacked images whose PSFs are \( \sim 0''7\). Then, we visually inspect all of our LAEs and exclude sources due to the presence of bad residual features close to the targets that can possibly affect the photometry. We cut out \( 12'' \times 12'' \) images of the LAEs in each band, and generate median-stacked images of the subsamples in each bands with IRAF task imcombine. We show the SEDs of the “all stack” subsamples at \( z = 5.7 \) and 6.6 in the left and center panels in Figure 10, respectively.

We generate the model SEDs at \( z = 5.7 \) and 6.6 using BEAGLE (Chevallard & Charlot 2016). In BEAGLE, we use the combined stellar population and photoionization models presented in Gutkin et al. (2016). Stellar emission is based on an updated version of the population synthesis code of Bruzual & Charlot (2003), while gas emission is computed with the standard photoionization code CLOUDY (Ferland et al. 2013) following the prescription of Charlot & Longhetti (2001). The IGM absorption is considered following a model of Inoue et al. (2014). In BEAGLE we vary the total mass of stars formed, ISM metallicity (\( Z_{\text{neb}} \)), ionization parameter (\( U_{\text{ion}} \)), star-formation history, stellar age, and V-band attenuation optical depth (\( \tau_V \)), while we fix the dust-to-metal ratio (\( \xi_d \)) to 0.3 (e.g., De Vis et al. 2017), and adopt the Calzetti et al. (2000) dust extinction curve. We choose the constant star-formation history because it reproduces SEDs of high-redshift LAEs (Ono et al. 2010; Harikane et al. 2018b). The choice of the extinction law does not affect our conclusions, because our SED fittings infer dust-poor populations such as \( \tau_V = 0.0–0.1 \). We vary the four adjustable parameters of the model in vast ranges, \( -2.0 < \log(Z_{\text{neb}}/Z_\odot) < 0.2 \) (with a step of 0.1 dex), \( -3.0 < \log(U_{\text{ion}}) < -1.0 \) (with a step of 0.1 dex), \( 6.0 < \log(Age/yr) < 9.0 \) (with a step of 0.1 dex), and \( \tau_V = [0, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 2] \). We assume that the stellar metallicity...
is the same as the ISM metallicity, with interpolation of original templates. We fit our observed SEDs with these model SEDs, and derive stellar masses and SFRs for the subsamples and individuals. In the “all stack” subsample at $z = 5.7$, we can constrain the stellar mass, SFR, and metallicity. In the other subsamples, we fix the metallicity to log($Z/Z_\odot$) = −0.6 that is the best-fit value of the “all stack” subsample at $z = 5.7$, because we cannot constrain the metallicity due to the poor signal-to-noise ratio.

In the right panel in Figure 10, we plot the measured stellar masses and SFRs for the LAEs of z57OD and z66OD. We compare them with the star-formation main sequence that is determined with field LBGs. All the subsamples including “all stack,” “non detection stack,” and individual galaxies show SFRs more than $\sim 5$ times higher than the main-sequence galaxies in the same stellar masses, indicating that the LAEs in z57OD and z66OD are actively forming stars.

We then calculate the SFR densities of z57OD and z66OD, and compare them with the cosmic average (a.k.a the Madau-Lilly plot). We measure the SFR densities using observed galaxies located within 1 physical Mpc (pMpc) from the centers of the overdensities, following previous studies (e.g., Clements et al. 2014; Kato et al. 2016). We find that 16 LAEs and 3 red SMGs (5 LAEs and 1 red SMG) are within the 1 pMpc-radius aperture around z57OD (z66OD). For z57OD, we measure the total SFR density of the observed LAEs and red SMGs, because the cross-correlation signal suggests that 30%–100% of the red SMGs trace the LAE large-scale structures. We assume that the average SFR of one LAE is $\sim 10 M_\odot$ yr$^{-1}$ based on the SED-fitting results. We calculate SFRs of the red SMGs from the 850 µm fluxes assuming the redshift of $z = 5.7$, the dust temperature of $T_{\text{dust}} = 40$ K (Remy-Ruyer et al. 2013; Faisst et al. 2017), and the emissivity index of $\beta = 1.5$ (Chapman et al. 2005). The effect of these assumptions is not significant for our conclusions. For example, the $\Delta T_{\text{dust}} = 10$ K or $\Delta \beta = 1.5$ difference changes the SFR density only by a factor of $< 2$. With this assumed temperature, the CMB effect is negligible ($< 5$%; da Cunha et al. 2013). The uncertainty of the SFR density corresponds to the uncertainty of the fraction of the red SMGs residing at $z = 5.7$ (30%–100%). The orange lower limit only takes into account the observed LAEs. Note that we do not include contributions from faint galaxies not detected in our data. The black curve is the cosmic average of the SFR density (Madau & Dickinson 2014). The SFR density of z57OD is more than $\sim 10$ times higher than the cosmic average.
These results indicate that star formation is enhanced at least in z57OD. This active star formation in the overdense region may be explained by high inflow rates in the overdense region. Recent observational studies reveal that there are tight correlations between the gas inflow rate and star-formation rate (Behroozi et al. 2018; Harikane et al. 2018a; Tacchella et al. 2018). Enhanced star formation of LAEs in the overdense region may be due to high inflow rates in overdensities whose halo is massive. Indeed, the halo masses of z57OD and z66OD are expected to be $4-10 \times 10^{11} M_\odot$ (see Section 4.2), larger than those of LAEs in normal fields, $1 \times 10^{11} M_\odot$ (Ouchi et al. 2018).

5. Summary

We have obtained 3D maps of the universe in the $200 \times 200 \times 80$ cMpc$^3$ volumes each at $z = 5.7$ and $6.6$ based on the spectroscopic sample of 179 LAEs that accomplishes the $\geq$80% completeness down to $\log(L_{Ly\alpha}/[\text{erg s}^{-1}]) = 43.0$, based on our Keck and Gemini observations and the literature. We compare spatial distributions of our LAEs with SMGs, investigate the stellar populations, and compare our LAEs with the numerical simulations. Our major findings are summarized below.

1. The 3D maps reveal filamentary large-scale structures extending over 40 cMpc and two remarkable overdensities made of at least 44 and 12 LAEs at $z = 5.692$ (z57OD) and $z = 6.585$ (z66OD), respectively. z66OD is the most distant overdensity spectroscopically confirmed to date, with $>10$ spectroscopically confirmed galaxies.

2. We have identified similar overdensities to z57OD and z66OD in the simulations regarding the overdensity significance and the velocity dispersion of LAEs. The halo masses of the overdensities in simulations are $(4-10) \times 10^{11} M_\odot$, which will grow to cluster-scale halos ($M_h \sim 10^{14} M_\odot$) at the present day, suggesting that z57OD and z66OD are protoclusters.

3. We have selected 44 red 850 $\mu$m selected SMGs that are SMGs expected to reside at $z \approx 4-6$ based on their red Herschel color, and calculated the cross-correlation functions between the LAEs and the red SMGs. We have detected 99.97% cross-correlation signal between $z = 5.7$ LAEs and the red SMGs. This significant correlation suggests that the dust-obscured SMGs are also tracing the same large-scale structures as the LAEs, which are typically dust-poor star-forming galaxies.

4. Stellar population analyses suggest that LAEs in z57OD and z66OD are actively forming stars with SFRs ~5 times higher than the main sequence at a fixed stellar mass. Given the significant correlation between the LAEs and the red SMGs at $z = 5.7$, the SFR density in z57OD is 10 times higher than the cosmic average (a.k.a. the Madau-Lilly plot).

We thank the anonymous referee for a careful reading and valuable comments that improved the clarity of the paper. We are grateful to Renyue Cen, Yi-Kuan Chiang, Tadayuki Kodama, and Ken Mawatari for their useful comments and discussions.

The Hyper Suprime-Cam (HSC) collaboration includes the astronomical communities of Japan and Taiwan, and Princeton University. The HSC instrumentation and software were developed by the National Astronomical Observatory of Japan (NAOJ), the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo, the High Energy Accelerator Research Organization (KEK), the Academia Sinica Institute for Astronomy and Astrophysics in Taiwan (ASIAA), and Princeton University. Funding was contributed by the FIRST program from Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University.

This paper makes use of software developed for the Large Synoptic Survey Telescope. We thank the LSST Project for making their code available as free software at http://dm.lsst.org.

This work is based on observations obtained at the Gemini Observatory processed using the Gemini IRAF package, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina), and Ministerio da Ciência, Tecnologia e Inovação (Brazil).

This work is supported by the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan, and a KAKENHI (15H02064, 17H01110, and 17H01114) Grant-in-Aid for Scientific Research (A) through the Japan Society for the Promotion of Science (JSPS). Y.H. acknowledges support from the Advanced Leading Graduate Course for Photon Science (ALPS) grant and the JSPS Research Fellowship for Young Scientists. N.K. acknowledges support from the JSPS grant 15H03645. I.R.S. acknowledges supports from STFC / ST/P00541/1 and the ERC Advanced Grant DUSTYGAL (321334). M.I. acknowledges the support from National Research Foundation of Korea (NRF) grant No. 2017R1A3A3001362.

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