The Subaru HSC Galaxy Clustering with Photometric Redshift. I. Dark Halo Masses versus Baryonic Properties of Galaxies at $0.3 \leq z \leq 1.4$

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Abstract

We present the clustering properties of low-$z$ ($z \leq 1.4$) galaxies selected by the Hyper Suprime-Cam Subaru Strategic Program Wide layer over 145 deg$^2$. The wide-field and multiwavelength observation yields 5,064,770 galaxies at $0.3 \leq z \leq 1.4$ with photometric redshifts and physical properties. This enables the accurate measurement of angular correlation functions, and the subsequent halo occupation distribution (HOD) analysis allows us to identify the connection between baryonic and dark halo properties. The fraction of less-massive satellite galaxies at $z \leq 1$ is found to be almost constant at $\sim 20\%$, but it gradually decreases beyond $M_\star \sim 10^{10.4}h^{-2}M_\odot$. However, the abundance of satellite galaxies at $z > 1$ is quite small even for less-massive galaxies due to the rarity of massive centrals at high-$z$. This decreasing trend is connected to the small satellite fraction of Lyman break galaxies at $z > 3$. The stellar-to-halo mass ratios at $0.3 \leq z \leq 1.4$ are almost consistent with the predictions obtained using the latest empirical model; however, we identify small excesses from the theoretical model at the massive end. The pivot halo mass is found to be unchanged at $10^{12.0-12.2}h^{-1}M_\odot$ at $0.3 \leq z \leq 1.4$, and we systematically show that $10^{12}h^{-1}M_\odot$ is a universal pivot halo mass up to $z \sim 5$ that is derived using only the clustering/HOD analyses. Nevertheless, halo masses with peaked instantaneous baryon conversion efficiencies are much smaller than the pivot halo mass regardless of redshift, and the most efficient stellar-mass assembly is thought to be in progress in $10^{11.0-11.5}h^{-1}M_\odot$ dark halos.

Unified Astronomy Thesaurus concepts: Observational cosmology (1146); Large-scale structure of the universe (902); Dark matter (353); Galaxy dark matter halos (1880); Dark matter distribution (356); Galaxy formation (595); Galaxy evolution (594)

1. Introduction

The ΛCDM paradigm predicts that small density fluctuations in the early universe that are imprinted in the cosmic microwave background evolve into the large-scale structure of the universe (e.g., Davis et al. 1985; Jenkins et al. 1998; Springel et al. 2005). In the context of the ΛCDM cosmological model, dark matter forms self-bounding clumps, known as dark halos, and galaxies are born in the center of these halos by trapping baryonic matter using their gravitational potential (e.g., White & Rees 1978; Blumenthal et al. 1984; White & Frenk 1991; Cole et al. 1994; Mo & White 1996). Therefore, galaxies are biased tracers toward invisible underlying dark matter distribution. Many studies have attempted to elucidate the biased relationship between dark matter and baryons, based on the notable success in mapping the 3D distribution of galaxies using large extensive galaxy redshift surveys (e.g., de Lapparent et al. 1986; Peacock et al. 2001; Zehavi et al. 2005).

To achieve an in-depth understanding of the coevolution between visible baryonic matter and invisible dark matter, some observational methodologies for the measurement of dark halo mass, which is one of the fundamental parameters for galaxy formation efficiency, have been proposed and performed over several decades including X-ray observations (e.g., Evrard et al. 1996; Vikhlinin et al. 2006; Piffaretti & Valdarnini 2008; Kravtsov et al. 2018), measurements of a weak-lensing signal (e.g., Smith et al. 2001; Mandelbaum et al. 2006), and kinematics of satellite galaxies (e.g., More et al. 2011; Wojtak & Mamon 2013), and the use of two-point statistics of galaxy clustering (e.g., Peebles 1980; Zehavi et al. 2011). However, almost all observational approaches have their pros and cons. For example, X-ray observations provide information on the total gravitational masses of individual groups/clusters of galaxies by assuming the hydrostatic equilibrium state for their intracluster medium. However, this
method can only be applied to massive objects in the local universe ($M_\odot \gtrsim 10^{14} M_\odot$), halos at $z \lesssim 0.2$ in typical cases). Satellite kinematics can directly connect the baryonic properties of central galaxies to their host dark halo mass by measuring the velocity dispersion of orbiting satellite galaxies. Weak-lensing signals are indicative of foreground matter-density fluctuations based on observations of distorted shapes of background galaxies. However, these techniques can only be used for low-$z$ galaxies (only for $z < 1$ galaxies in typical cases) due to the faintness of key signals.

Compared to these observational approaches, the galaxy clustering signal provides averaged statistical information on galaxy distribution and underlying matter fluctuation of targeted galaxies. Quantitative estimates of clustering signals of galaxies can be achieved by the autocorrelation function (ACF), which indicates how strongly galaxies are bound to each other by their gravity. Moreover, constraining galaxy bias via galaxy clustering observations has been successful in extending the redshift range compared to other galaxy–halo connection techniques (Wechsler & Tinker 2018, for a review of the galaxy–halo connection), even at $z > 7$ (Barone-Nugent et al. 2014). In addition, halo-model approaches, such as the abundance-matching (AM) technique (e.g., Kravtsov & Klypin 1999; Vale & Ostriker 2004; Conroy et al. 2006) and the halo occupation distribution (HOD) model (e.g., Ma & Fry 2000; Seljak 2000; Berlind & Weinberg 2002; Berlind et al. 2003; van den Bosch et al. 2003), facilitate the derivation of the properties of dark halos by assuming that dark halos hosting galaxies are virialized, and characterizing the level of galaxy bias by defining the conditional probability as $P(N|\Delta M)$ (see Cooray & Sheth 2002 for a review of the halo-model approach). Furthermore, recent massively parallel large hydrodynamical simulations such as the Illustris/ IllustrisTNG simulations (Vogelsberger et al. 2014; Springel et al. 2018) and the EAGLE simulations (Crain et al. 2015; Schaye et al. 2015) have contributed to our understanding and interpretation of galaxy clustering by direct comparison between the simulated visible and invisible universe.

Toward constraining the biased relationship between dark matter and baryons, and elucidating the physical processes of galaxy formation and evolution, ACFs of various galaxy populations have been measured by utilizing the cutting-edge observational data of spectroscopic galaxy redshift surveys (e.g., SDSS, BOSS, VIPERS, and FastSound), as well as extensive multiwavelength photometric surveys (e.g., COSMOS, UltraVISTA, CFHTLS, and DES). Given that accurate positions on the three-dimensional coordinate are available, spectroscopic surveys have significant advantages in clustering studies; precise two-dimensional ACFs can be evaluated by projecting real-space correlation functions. This real-space correlation function contains cosmological information and can be used to test the general relativistic theory and constrain the cosmic growth rate by analyzing the redshift-space distortion effect (e.g., Racanelli et al. 2013; Alam et al. 2017).

However, clustering studies that use extensive photometric surveys have unique characteristics and advantages. First, photometric surveys can be used to select faint galaxies. Galaxy redshift surveys are confined to bright objects in order to detect apparent emission line(s), while photometric surveys can be used to select faint galaxies even if they only satisfy the detection limit of each image. Therefore, compared to spectroscopic surveys, galaxy clustering studies based on photometric surveys can address a variety of galaxy populations and baryonic characteristics. Moreover, the targeted redshift range is further broadened for studies based on photometric surveys; i.e., clustering-signal measurement using spectroscopic observations is up to $z \sim 3$ (Durkalec et al. 2015, 2018) and typically confined to $z < 1$ due to the strict flux threshold, whereas those based on photometric data exceed $z \sim 5$ with a high S/N ratio (e.g., Hildebrandt et al. 2009; Ishikawa et al. 2017; Harikane et al. 2018). Second, photometric observations are free from the fiber/slit-collision effect. In some fiber spectroscopic observations, it is necessary to allocate fibers on a fiber plug plate. Moreover, the minimum physical scale between galaxy pairs is limited by the finite physical size of fibers. Similar limitation for slit allocation is inevitable in slit spectroscopy. A minimum physical scale in photometric observations is determined by a seeing size and small-scale clustering, which is a key clustering signal to constrain the satellite galaxy formation, can be well measured.

In this paper, we aim to describe the relationship between galaxy clustering properties and the fundamental physical parameters of baryons; i.e., galaxy stellar mass and star formation rate (SFR), with high-precision statistics based on large galaxy samples obtained by the Hyper Suprime-Cam Subaru Strategic Program (HSC SSP; Aihara et al. 2018a) Wide layer S16A internal Data Release (Aihara et al. 2018b). The unique capability of the Subaru Hyper Suprime-Cam (HSC; Miyazaki et al. 2018) and the latest sophisticated SED-fitting technique (Tanaka 2015) facilitates the acquisition of $\sim 5,000,000$ photometric-redshift selected galaxies over $\sim 145$ deg$^2$ with deep limiting magnitude down to $i = 25.9$ compared to other wide-field surveys. These characteristics of the HSC SSP Wide layer allow the selection of a sufficiently large number of both less-massive galaxies ($M_* \sim 10^9 M_\odot$) and massive galaxies ($M_* \sim 10^{11} M_\odot$) over a wide redshift range ($0.3 \lesssim z \lesssim 1.4$) in order to precisely study the redshift evolution and physical parameter dependence of galaxy clustering.

This is the first paper in a series of clustering analyses using the photometric-redshift catalog of the HSC SSP. We will extend the targeted redshift range and stellar-mass limit using photometric catalogs in the Deep/ UltraDeep layers in addition to galaxy populations by dividing them into star-forming galaxies and passive galaxies, and investigate the evolutionary history of galaxies by connecting the results presented in this paper to future studies. The main goal of this series on photo-$z$ galaxy clustering is to understand and gain insights into the galaxy–dark halo coevolution history at $z \lesssim 3$ using common galaxy catalogs and the uniform analysis method.

This paper is organized into several sections. In Section 2, we describe the details of the photometric data and the sample selection method using the photometric-redshift catalog generated by the HSC SSP S16A data. In Section 3, we review the methodology of the clustering and HOD analysis, and the ACFs of our galaxy samples obtained via clustering analysis and the results of the HOD-model analysis are shown in Section 4. We discuss the relationship between galaxies and their host dark halos at $0.3 \leq z \leq 1.4$ and compare them with other observational studies as well as numerical simulations and theoretical models in Section 5. A summary of the major findings of the halo-model analysis are presented in Section 6.

All of the photometric magnitudes are quoted in the absolute bolometric (AB) magnitude system (Oke & Gunn 1983).
Throughout this paper, we employ the Planck 2015 cosmological parameters: the density parameters are $\Omega_m = 0.309$, $\Omega_{\Lambda} = 0.691$, and $\Omega_b = 0.049$, the Hubble parameter is assumed as $H_0 = 100h$ with the dimensionless Hubble parameter as $h = 0.677$, the normalization of the matter fluctuation power spectrum is $\sigma_8 = 0.816$, and the spectral index of the primordial power spectrum is $n_s = 0.967$, respectively (Planck Collaboration et al. 2016). Galaxy stellar mass and dark halo mass are represented as $M_*$ and $M_h$, respectively. All of the logarithms in this paper are common logarithms with base 10.

2. Data and Sample Selection

2.1. Photometric Data

We use the HSC SSP S16A internal data that were released in August 2016 and obtained between 2014 March and 2016 April (Aihara et al. 2018b). The HSC SSP data is composed of three layers: Wide, Deep, and UltraDeep (Aihara et al. 2018a). In this study, photometric data is obtained only in the Wide layer with the aim of achieving a high S/N ratio of clustering signals and imposing strong constraints on massive ends at $z \leq 1.4$. The data of the Deep and UltraDeep layers will be used in our future studies to connect faint, high-redshift galaxies to their host dark halos using clustering/HOD analyses.

The HSC SSP Wide layer is composed of six distinct patches: XMM-LSS, GAMA09H, GAMA15H, HectoMAP, VVDS, and WIDE12H. The objective of the Wide layer is to observe 1400 deg$^2$ in total by 916 pointings with 1.8 deg$^2$ fields of view of the HSC (Miyazaki et al. 2018) when the HSC SSP is completed. However, the data of the S16A is available over ~178 deg$^2$. Each patch of the Wide layer is observed using five optical wavelengths: g, r, i, z, and y-bands (Kawanomoto et al. 2018) that satisfy depths of $g < 26.5, r < 26.1, i < 25.9, z < 25.1$, and $y < 24.4$ (5σ limiting magnitudes with 2″ diameter apertures), respectively.

Data of the HSC SSP are reduced using the optical imaging data processing pipeline, hscpipe (Bosch et al. 2018). The hscpipe is developed based on the pipeline of the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2019; Axelrod et al. 2010; Jurić et al. 2017). Pixels around bright stars are masked according to the procedure of Coupon et al. (2018). We also exclude pixels at the edge of photometric images, on cosmic rays, saturated pixels, and pixels with flags of `flags_pixel_edge`, `flags_pixel_interpolated_center`, `flags_pixel_saturated_center`, `flags_pixel_cr_center`, and `flags_pixel_bad` (Aihara et al. 2018b). The total survey area of this paper is 144.68 deg$^2$ after masking.

2.2. Photometric-redshift Catalog

The HSC SSP provides multiple photometric-redshift catalogs (Tanaka et al. 2018). In this study, we use an HSC photometric-redshift catalog constructed by using an SED-fitting code with Bayesian physical priors, MIZUKI (Tanaka 2015). We briefly describe characteristics of the SED-fitting code below. See Tanaka (2015) for more details.

MIZUKI is a template-fitting code and galaxy SED templates are generated by GALAXEV, which is the spectral synthesis model developed by Bruzual & Charlot (2003). A star formation history of galaxy SED templates is assumed to be an exponential-time decay model with varying decay timescale, $\tau$. The solar metallicity abundance is only assumed for the SED templates; however, results of the SED fitting are not significantly changed when including the SED templates with subsolar metallicity abundance. The initial-mass function (IMF) is assumed to be a Chabrier IMF (Chabrier 2003) and the dust attenuation follows the Calzetti curve with varying optical depth, $\tau_V$ (Calzetti et al. 2000). Nebular emission lines are added to the galaxy SED templates generated by Bruzual & Charlot (2003), with the intensity ratios of Inoue (2011) and the differential dust-extinction law proposed by Calzetti (1997).

The best-fitting photometric redshifts are evaluated through the likelihood:

$$\mathcal{L} \propto \exp(-\chi^2_{\text{SEDfit}}/2),$$

where the $\chi^2_{\text{SEDfit}}$ is a value of the chi-square fitting of the SED-fitting procedure and can be computed as follows:

$$\chi^2_{\text{SEDfit}} = \sum_i \frac{(f_{i,\text{obs}} - \alpha f_{i,\text{model}})^2}{\sigma_{i,\text{obs}}^2}.$$ 

Here, $f_{i,\text{obs}}$ and $f_{i,\text{model}}$ are the observed and model SED fluxes of the $i$th filter, $\sigma_{i,\text{obs}}$ is the uncertainty of the $i$th observed flux, and $\alpha$ is a normalization parameter that controls the amplitude of the model SED. Physical priors (e.g., the redshift distribution, the main sequence of star-forming galaxies, the initial-mass function, the amount of attenuation ($\tau_V$) versus SFR relation, and the redshift versus SFR relation) are multiplied by the likelihood to obtain posteriors.

The HSC photometric-redshift catalog using MIZUKI is constructed by independently detecting sources from HSC science image frames of each optical band ($g, r, i, z$, and $y$-bands). The detection threshold is $5\sigma$, where $\sigma$ is a dispersion of the sky fluctuation, compared to RMSs by convolving the point-spread function. The fluxes of detected objects are measured without matching their shapes and centroids across optical bands to determine the reference band for each object, then the cModel flux of each object is measured with matching shapes and centroids to their values on reference images ($i$-band images for most cases).

The SED-fitting technique is applied to objects with clean cModel magnitudes of at least three bands. In the construction of galaxy samples for this study, we set the magnitude limits as $g \leq 26.0, r \leq 25.6, i \leq 25.4, z \leq 24.2$, and $y \leq 23.4$, and the brightest magnitude of each band is 18.0 for the selection of reliable galaxy samples. Refer to Aihara et al. (2018b), Tanaka et al. (2018), and Bosch et al. (2018) for more information.

2.3. Galaxy Sample Selection and Physical Properties

2.3.1. Photo-z Quality Cut

Galaxy samples are extracted from the HSC photometric-redshift catalog using MIZUKI. We use the “photo-z best ($z_p,best$)” parameter, which is evaluated to minimize a risk parameter in the SED fitting procedure, for characterizing the redshift of each object. To avoid selecting galaxies with a multiple-peak probability distribution function (PDF) or a catastrophic photo-z error, we set conditions of $\chi^2_{\text{SEDfit}}/\text{dof} \leq 3.0$ and risk $\leq 0.1$. Refer to Tanaka et al. (2018) for more details of photometric-redshift catalogs of the HSC SSP. Hereafter, we quote the photo-z best parameter as a photometric redshift of each galaxy.
Figure 1. Galaxy number counts of our catalog in g-, r-, and i-band magnitudes. We show our results from both the raw galaxy catalog without the photo-z quality cut (red open circles) and the galaxy catalog with the photo-z quality cut (red filled circles with error bars). It should be noted that almost all of the error bars of our number counts with the photo-z quality cut are hidden behind the filled red circle symbols. For comparison, we also plot the results obtained in the WHDF (purple crosses; Metcalfe et al. 2001), CDF-S (blue stars; Arnouts et al. 2001), SDSS (cyan squares; Yasuda et al. 2001), CADIS (green upward triangles; Huang et al. 2001), VVDS (yellow plus crosses; Mc Cracken et al. 2003), COSMOS (golden downward triangles; Capak et al. 2004), SDF (orange pentagons; Kashikawa et al. 2004), and the Lockman Hole (magenta half-filled circles; Rovilos et al. 2009), respectively.

We check the number count of galaxies measured by the g-, r-, and i-band magnitudes (Figure 1). In each band, our galaxy counts with the photo-z quality cut are in good agreement with other studies and those without the photo-z quality cut (especially for g- and r-bands) slightly exceed those from the literature, indicating that the photo-z quality cut provides a pure galaxy catalog. On the other hand, the faint ends of our number counts with the photo-z quality cut are suppressed compared to those from the literature. This incompleteness can be partially attributed to operations of the photo-z quality cut since faint galaxies tend to have relatively large uncertainties on their photo-z; however, the photo-z quality cut and magnitude limits ensure that our galaxy catalog is pure and reasonable.

2.3.2. Redshift Binning and Trimming

We divided our photo-z galaxy samples into four redshift bins: $0.30 \leq z_1 < 0.55$, $0.55 \leq z_2 < 0.80$, $0.80 \leq z_3 < 1.10$, and $1.10 \leq z_4 < 1.40$, to investigate the redshift evolution of the clustering properties. It is noted that our targeted redshift starts from $z = 0.30$ in order to capture the Balmer/4000 Å break using g- and r-band photometry. The total survey comoving volume of this study is $\sim 1.13$ Gpc$^3$ and the total number of galaxies that satisfy the aforementioned condition is $5,064,770$.

Galaxies with large photo-z uncertainties can contaminate other redshift bins (foreground/background galaxies account for $\sim 15\%$ (30\%) of the total galaxies at $0.4 < z < 0.6$ ($1.2 < z < 1.4$) for this photometric-redshift galaxy catalog). To construct a pure redshift-binned galaxy catalog avoiding redshift bin-to-bin contaminations, we select galaxies by trimming the edges of each redshift bin by the following condition:

$$\left( z_{\text{min}} \leq z_{p,\text{best}} - dz_{-1\sigma} \right) \cap \left( z_{p,\text{best}} + dz_{+1\sigma} \leq z_{\text{max}} \right),$$

where $dz_{+1\sigma}$ ($dz_{-1\sigma}$) represents the upper (lower) bound of the $1\sigma$ confidence interval and $z_{\text{max}}$ ($z_{\text{min}}$) is the upper (lower) bound of $i$th redshift bin. The redshift distribution of our selected galaxies is shown in Figure 2. The number of galaxies in the final catalog of this study is $4,531,285$.

In Figure 2, it is observed that the $z_1$ bin has two peaks in the redshift distribution. This may be due to the fact that the Balmer/4000 Å break, which is a key spectral feature to determine photometric redshift, falls into the gap between g- and r-band transmission wavelength and the weak constraint on $z_p \lesssim 0.5$ caused by the lack of NUV photometry. However, we use the redshift distributions that account for the PDFs of each galaxy in the HOD-model fitting. The double-peak feature of the redshift distribution with PDFs at $z_1$ will be diluted compared to the distribution of $z_{p,\text{best}}$ and it is expected that the effect of the double-peak distribution is negligible on the results of the HOD-fitting analysis (see Section 3.2).

Reduced galaxies by the redshift trimming at $z_1$ and $z_2$ bins are shown in Figure 3. On average, about 20\% (30\%) of galaxies at the $z_1$ ($z_2$) bin are reduced by the redshift trimming. The difference of the fraction of trimmed galaxies can be due to the relatively large uncertainties of photometric redshift at high-z. Although the redshift trimming introduces about
20%–30% incompleteness into our galaxy catalog, removing galaxies by random selection does not have a large impact on galaxy clustering signals (e.g., Meneux et al. 2008). Therefore, we adopt the galaxy catalog that implemented the redshift trimming as well as the aforementioned photo-z quality cut to guarantee the original clustering signals at each redshift bin by excluding the suspicious objects.

2.3.3. Star–Galaxy Separation

Galaxy samples of our catalog are separated from stars using the classification_extendedness parameter as well as the above photo-z quality cut. Objects are classified according to their extendedness, which is inferred by the hscPipe (Bosch et al. 2018) using the classification_extendedness parameter; i.e., compact, point-like sources are assumed to be AGNs or stars and excluded from our galaxy catalog. Huang et al. (2018) found that the hscPipe can properly classify most of the faint galaxies satisfying $i > 24.0$.

In addition to the above classification based on the extendedness of objects, we only select objects that are successfully fitted by galaxy templates with high accuracy by imposing the aforementioned photo-z quality cut. To check the accuracy of the classification of the bright objects, we calculate the fraction of stars that are misclassified as galaxies using the objects that have already been spectroscopically observed by other surveys. By imposing the same selection conditions as in our galaxy catalog, the largest stellar contamination (the number of misclassified stars over all spectroscopically confirmed objects) is found to be <6.5% at a $1.10 < z < 1.40$ ($z_4$) redshift bin and the stellar contamination in the total galaxy sample is much smaller than this value since most of the faint objects are galaxies. Therefore, we conclude that our galaxy catalog is conservative and less contaminated by stars and the clustering analyses and the results in this study are hardly affected by stellar contaminations even at the highest-z bin.

2.3.4. Baryonic Properties of Galaxies

Apart from the photometric redshifts, we also use galaxy stellar masses and SFRs calculated via SED fitting to characterize the baryonic properties of galaxies. Stellar masses and SFRs are median values, $M_{*\text{med}}$ and $\text{SFR}_{\text{med}}$, that are evaluated by integrating the PDFs of each parameter:

$$\int_{M_{*,\text{min}}}^{M_{*,\text{med}}} P(M_*)dM_* = 0.5,$$

and

$$\int_{\text{SFR}_{\text{min}}}^{\text{SFR}_{\text{med}}} P(\text{SFR})d\text{SFR} = 0.5,$$

where $M_{*,\text{min}}$ and $\text{SFR}_{\text{min}}$ are the minimum values of the stellar mass and the SFR in the SED-fitting procedure, and $P(M_*)$ and $P(\text{SFR})$ are the PDFs of each parameter derived by marginalizing over all the other fitting parameters, respectively. It is noted that these physical parameters are also computed for 1σ confidence intervals. Hereafter, we use $z_{p,\text{best}}$ and median values of $M_*$ and SFR for the physical quantities of each galaxy and just quote $z$, $M_*$, and SFR to represent them. Our galaxy samples are resampled according to their stellar mass and SFR, and details of each redshift bin are summarized in Table 1 for stellar-mass limited subsamples and Table 2 for SFR-limited subsamples.

In each redshift bin, stellar-mass limits are determined as the 70% stellar-mass completeness compared to the stellar-mass functions in the COSMOS field, which are calculated using a publicly available COSMOS/UltraVISTA $K_s$-selected photometric-redshift catalog (Muzzin et al. 2013a). It should be noted that the SFR-resampled bins also satisfy the stellar-mass limit of each redshift bin. The stellar mass and the SFR distributions of each redshift bin are presented in Figures 4 and 5.
Table 1
Details of Cumulative Stellar-mass Limited Subsamples

| Stellar-mass Limit | $z_1$ (0.30 ≤ $z$ < 0.55) | $z_2$ (0.55 ≤ $z$ < 0.80) | $z_3$ (0.80 ≤ $z$ < 1.10) | $z_4$ (1.10 ≤ $z$ ≤ 1.40) |
|--------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 8.60               | N | $M_{\text{med}}$ | N | $M_{\text{med}}$ | N | $M_{\text{med}}$ | N | $M_{\text{med}}$ |
| 8.80               | 727,385 | 9.45 | ... | ... | ... | ... | ... | ... |
| 9.00               | 592,648 | 9.62 | 1,038,903 | 9.72 | ... | ... | ... | ... |
| 9.20               | 479,783 | 9.79 | 876,600 | 9.86 | ... | ... | ... | ... |
| 9.40               | 384,732 | 9.94 | 723,725 | 10.00 | 818,934 | 9.85 | ... | ... |
| 9.60               | 305,332 | 10.08 | 590,583 | 10.12 | 625,246 | 10.00 | ... | ... |
| 9.80               | 235,427 | 10.21 | 470,783 | 10.24 | 447,467 | 10.18 | 461,539 | 10.11 |
| 10.00              | 173,907 | 10.35 | 361,233 | 10.37 | 314,364 | 10.36 | 306,547 | 10.26 |
| 10.20              | 121,214 | 10.48 | 257,323 | 10.50 | 216,952 | 10.53 | 181,690 | 10.43 |
| 10.40              | 76,394 | 10.62 | 166,123 | 10.64 | 145,143 | 10.67 | 101,175 | 10.61 |
| 10.60              | 41,422 | 10.77 | 93,603 | 10.78 | 88,953 | 10.81 | 52,664 | 10.80 |
| 10.80              | 17,827 | 10.92 | 43,658 | 10.94 | 46,228 | 10.96 | 26,123 | 10.98 |
| 11.00              | 4,967 | 11.08 | 15,944 | 11.11 | 18,878 | 11.12 | 12,222 | 11.16 |
| 11.20              | ... | ... | 4,356 | 11.30 | 5,662 | 11.29 | 4,960 | 11.31 |

Notes.

- Threshold stellar mass of each subsample in units of $h^{-2}M_\odot$ in a logarithmic scale.
- The number of galaxies of each subsample.
- Median stellar mass of each subsample in units of $h^{-2}M_\odot$ in a logarithmic scale.

Table 2
Details of Cumulative SFR-limited Subsamples

| SFR Limit | $z_1$ (0.30 ≤ $z$ < 0.55) | $z_2$ (0.55 ≤ $z$ < 0.80) | $z_3$ (0.80 ≤ $z$ < 1.10) | $z_4$ (1.10 ≤ $z$ ≤ 1.40) |
|-----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| $\leq$1.50 | N | SFR$_{\text{med}}$ | N | SFR$_{\text{med}}$ | N | SFR$_{\text{med}}$ | N | SFR$_{\text{med}}$ |
| −1.50     | 728,514 | −0.40 | 879,443 | −0.14 | ... | ... | ... | ... |
| −1.00     | 687,106 | −0.37 | 824,188 | −0.11 | 777,669 | 0.12 | ... | ... |
| −0.50     | 432,225 | −0.15 | 685,552 | −0.01 | 671,234 | 0.19 | 419,436 | 0.67 |
| 0.00      | 150,447 | 0.23 | 333,221 | 0.28 | 479,151 | 0.33 | 370,153 | 0.72 |
| 0.50      | 25,761 | 0.65 | 79,414 | 0.67 | 141,518 | 0.69 | 280,701 | 0.83 |
| 1.00      | ... | ... | ... | ... | 15,806 | 1.12 | 83,908 | 1.18 |

Notes. All galaxies of the SFR sample satisfy the stellar-mass limit of each redshift bin.

- Threshold SFR of each subsample in units of $h^{-2}M_\odot$ yr$^{-1}$ in a logarithmic scale.
- The number of galaxies of each subsample.
- Median SFR of each subsample in units of $h^{-2}M_\odot$ yr$^{-1}$ in a logarithmic scale.

3. Methodologies: Clustering and HOD Analysis

3.1. Angular Correlation Function

We measure angular two-point ACFs to quantitatively estimate the strength of galaxy clustering (Totsuji & Kihara 1969; Peebles 1980). The ACFs, $\omega(\theta)$, are calculated using an estimator proposed by Landy & Szalay (1993):

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

where DD, DR, and RR are the number of normalized pairs of galaxy–galaxy, galaxy–random, and random–random with a separation angle of $\theta \pm b\theta$, respectively. In this study, the angular scale is in units of degree and the angular range is $-3.4 \leq \log_{10}(\theta/\text{degree}) \leq 0.2$ with 0.2 dex separations. Random samples are generated over the same region of the galaxy samples. To minimize the Poisson noise, we generate at least 100 times more homogeneous random samples compared to galaxy samples over real galaxy distributions on each patch.

The ACFs can be approximated by a power-law form as:

$$\omega(\theta) = A_w \theta^{1-\gamma},$$

where $A_w$ and $\gamma$ are the amplitude of the ACF and the power-law slope, respectively. It is known that the ACFs of Landy & Szalay are underestimated due to the limitation of the survey field, especially for large-angular scales, called the “integral constraint (IC).” The integral constraint, which corresponds to the underestimation of observed ACFs from the approximated power law at large-angular scales, can be calculated as:

$$\text{IC} = \sum \frac{\theta_i^{1-\gamma} \text{RR}(\theta_i)}{\sum \text{RR}(\theta_i)}.$$

where $\theta_i$ is the $i$th angular scale, and $\text{RR}(\theta_i)$ is the number of random–random pairs of the $\theta_i$ bin (Roche et al. 1999). We first derive the power-law slope of each ACF by fitting the power law (Equation (7)) for varying $A_w$ and $\gamma$, and then evaluate the integral constraints. However, the survey area of the HSC SSP
is sufficiently wide to accurately compute ACFs even at large-angular scales ($\theta \sim 1^\circ$), so that the values of the integral constraints are quite small ($\text{IC} \sim 0.5$). The IC corrected ACFs, $\omega_{\text{cor}}(\theta)$, can be evaluated as follows:

$$\omega_{\text{cor}}(\theta) = \omega_{\text{meas}}(\theta) \times \frac{\theta^{1-\gamma}}{\theta^{1-\gamma} - \text{IC}},$$

where $\omega_{\text{meas}}$ is a measured ACF.

The errors of the ACF are estimated by computing the covariance matrix (Norberg et al. 2009), which is calculated using a “delete-one” jackknife method (Shao & Wu 1989). We divide our survey field into 157 subfields and evaluate the ACF by excluding one subfield. This procedure is repeated 157 times by changing the excluded subfield. The covariance matrix is calculated as follows:

$$C_{ij} = \frac{N - 1}{N} \sum_{k=1}^{N} (\omega_k(\theta_i) - \bar{\omega}(\theta_i)) \times (\omega_k(\theta_j) - \bar{\omega}(\theta_j)),$$

where $C_{ij}$ is an ($i, j$) element of the covariance matrix, $\omega_k(\theta_i)$ is the ACF of the $i$th angular bin of the $k$th jackknife resampling, and $\bar{\omega}(\theta_i)$ is the averaged ACF of the $i$th angular bin, respectively.

3.2. HOD Model

We adopt an HOD formalism to interpret the observed galaxy clustering. In the standard HOD model, physical characteristics, including the galaxy occupation, depend only on the dark halo mass; however, recent studies have reported that the clustering strengths of dark halos also depend on their age, concentration, and spin (e.g., Gao et al. 2005; Dalal et al. 2008; Lacerna & Padilla 2011), and the large-scale environment and the formation time of host dark halos affect the characteristics of galaxies (e.g., Artale et al. 2018; Zehavi et al. 2018), known as a halo assembly bias. Some advanced HOD models have been proposed to consider the effect of the halo assembly bias effect (e.g., Hearin et al. 2016). However, we employ the standard HOD model, which does not consider the halo bias parameters to achieve a fair comparison of our results with previous clustering studies.

The HOD model assumes that the number of galaxies within dark halos is a function of the dark halo mass. The expected
The total number of galaxies within dark halos with masses of $M_h$, $N(M_h)$, can be written as,

$$N(M_h) = N_c(M_h) \times [1 + N_s(M_h)],$$

(11)

where $N_c(M_h)$ and $N_s(M_h)$ represent the expectation number of central and satellite galaxies within dark halos with mass of $M_h$, respectively. We adopt a standard halo occupation model proposed by Zheng et al. (2005):

$$N_c(M_h) = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log_{10} M_h - \log_{10} M_{\text{min}}}{\sigma_{\log M}} \right) \right].$$

(12)

and

$$N_s(M_h) = \left( \frac{M_h - M_0}{M_1} \right)^0 \text{ (for } M_h > M_0).$$

(13)

In this parameterization of galaxy occupation, there are five free HOD parameters: $M_{\text{min}}$, $M_1$, $M_0$, $\sigma_{\log M}$, and $\alpha$, and a physical interpretation can be performed for each parameter. The central galaxy occupation is controlled by two parameters: $M_{\text{min}}$ is the dark halo mass at which half of the dark halos possess a central galaxy, and $\sigma_{\log M}$ is the deviation from the step-function-like occupation of central galaxies. Three other parameters control the occupation of satellite galaxies: $M_1$ is a typical dark halo mass that consists of one satellite galaxy, $M_0$ is the threshold dark halo mass for the formation of satellite galaxies, and $\alpha$ is the formation efficiency of satellite galaxies, respectively.

For the physical characteristics of dark halos, we employ the following analytical formulae: the halo density profile is assumed to be an NFW profile (Navarro et al. 1997), the halo mass function is a Sheth & Tormen mass function (Sheth & Tormen 1999; Sheth et al. 2001), the large-scale halo bias is a model constructed by Tinker et al. (2010) with a scale-dependent halo bias relation of Tinker et al. (2005), and the halo mass–concentration relation is assumed in the model proposed by Takada & Jain (2002, 2003). The nonlinear matter power spectrum is computed by the prescription presented by Smith et al. (2003) with the transfer function proposed by Eisenstein & Hu (1998). We adopt a “photo-z mc,” which is randomly drawn from the photo-z PDF of each galaxy, to calculate redshift distributions of each redshift bin. The redshift distributions of total galaxy samples are presented in Figure 6.

**Figure 5.** Star formation rate (SFR) distributions of each redshift bin. SFRs are expressed in units of $h^{-2} M_\odot$ yr$^{-1}$ in a logarithmic scale. All the galaxies satisfy the stellar-mass limit of their redshift bins.
where $\xi_{gg}$ and $\xi_{DM}$ are spatial ACFs of galaxies and dark matter, respectively. Zehavi et al. (2011) reported that the large-scale galaxy biases calculated using both methods are almost comparable, and we employ the large-scale galaxy bias based on the HOD modeling (Equation (16)) in the following analyses.

4. Results: Clustering and HOD-model Analysis

4.1. Measurement of Angular ACFs

We measure the ACFs of both stellar-mass limited samples (hereafter, SM samples) and SFR-limited samples (hereafter, SFR samples) and they are shown in Figures 7 and 8, respectively. The observed ACFs are well approximated by a power law at a large-angular scale, since the HSC SSP survey covers a sufficiently wide area to precisely calculate degree-scale clustering. At a small-angular scale, the apparent excesses from the power law known as a one-halo term is evident. The one-halo term is prominent for massive stellar-mass bins regardless of its redshift.

The measured ACFs are fitted using a power law (Equation (7)) after IC correction. The high S/N ACFs based on a wide survey field of the HSC SSP allow the amplitude of ACFs and the power-law slope to be simultaneously constrained. We present the fitting results for the amplitudes of ACFs at $1^\circ$ and the power-law slopes of ACFs at a large-angular scale for each subsample in Tables 3 and 4. The amplitudes of galaxy clustering increase monotonically with the stellar-mass limit. However, the power-law slope of ACFs, $\gamma$, is almost constant as $\gamma \sim 1.7$–1.8, although less-massive subsamples tend to have shallower power-law slopes compared to massive subsamples. We investigate and discuss the dependence of clustering strengths on galaxy stellar masses and SFRs by measuring correlation lengths in Section 4.4.

4.2. HOD-model Fitting

We implement the HOD-model fitting to interpret the observed HSC galaxy clustering. In the standard HOD model presented in Section 3.2, there are five free HOD parameters. By comparing the observed ACFs with those predicted by the HOD model, we investigate the best-fitting HOD parameters to represent the observed galaxy clustering signals that originate from the environmental and physical properties of the residing dark halos.

4.2.1. The HOD Fitting on Stellar-mass Samples

According to the stellar mass–halo mass relation (Leauthaud et al. 2012; Matthee et al. 2017), massive dark halos tend to possess massive central galaxies. Therefore, in the cumulative SM samples, less-massive dark halos can stochastically possess less-massive central galaxies, whereas massive dark halos should have one massive central galaxy and several satellite galaxies. This situation can be treated by the halo occupation function of the HOD formalism.
The best-fitting parameters are evaluated through the least $\chi^2$ fitting procedure as follows:

$$
\chi^2 = \sum_{i,j} \left[ \omega_{\text{obs}}(\theta_j) - \omega_{\text{HOD}}(\theta_j) \right] (C_{ij}^{-1}) \left[ \omega_{\text{obs}}(\theta_i) - \omega_{\text{HOD}}(\theta_i) \right] + \frac{(n_{g,\text{obs}} - n_{g,\text{HOD}})^2}{\sigma_{n_g}^2}.
$$

(18)

where $\omega_{\text{obs}}(\theta_j)$ and $\omega_{\text{HOD}}(\theta_j)$ are the ACFs of $i$th angular bin calculated by observation and the HOD model, $C_{ij}^{-1}$ is an $(i,j)$ element of an inverse covariance matrix (Equation (10)), $n_{g,\text{obs}}$ and $n_{g,\text{HOD}}$ are the number density of galaxies computed by observation and the HOD model (Equation (14)), and $\sigma_{n_g}$ is an uncertainty of the observed number density of galaxies, respectively. The correlation factor presented by Hartlap et al. (2007) is introduced to obtain an unbiased inverse covariance matrix. We consider the uncertainty of the number of galaxy samples due to errors associated with photometric redshifts as well as the selection incompleteness. The selection incompleteness at each stellar-mass bin is evaluated by comparing with the stellar-mass functions measured in the UltraVISTA field (Muzzin et al. 2013b). The lower stellar-mass bins suffer from relatively large selection incompleteness; therefore, the HOD parameters of less-massive subsamples cannot be strongly constrained due to the large uncertainties of the galaxy abundance.

The best-fitting HOD parameters on the SM samples are presented in Table 5 and part of the results of the HOD parameter fitting are shown in Figure 7. One can find that the HOD model obviously succeeds in reconstructing the observed galaxy clustering for all stellar-mass ranges and wide dynamical scales at $0.3 \leq z \leq 1.4$.

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Figure 7. The observed ACFs of the SM samples (circles) and their best-fitting ACFs derived using the HOD model (solid lines) at $0.3 \leq z < 0.55$ (top left panel), $0.55 \leq z < 0.80$ (top right panel), $0.80 \leq z < 1.10$ (bottom left panel), and $1.10 \leq z \leq 1.40$ (bottom right panel) redshift bins, respectively. In the HOD-model fitting procedure, the correlations between the angular bins are considered using the covariance matrices based on the jackknife resampling method. For clarity, amplitudes of ACFs are normalized arbitrarily.
4.2.2. The HOD Fitting on SFR Samples

In addition to the SM samples, we also implement the HOD-model analysis on the SFR samples. However, the occupational relation of galaxies selected according to their SFR has not been established, and the halo occupation function of Equation (11) is not ensured for the galaxy occupation of the SFR samples. To verify the halo occupation pattern of the SFR samples, we examined the expected number of galaxies per halo as a function of the dark halo mass using the publicly available data of the EAGLE simulations (Schaye et al. 2015; McAlpine et al. 2016) and part of the results are shown in Figure 9. We determined that the cumulative SFR samples including low-SFR galaxies can be approximated as the same occupation function of the SM samples, although the occupation of central galaxies confined to high-SFR samples has an offset compared to the error function. To avoid the discrepancy between the high-SFR galaxy occupation and the standard halo occupation function, we performed the HOD-model fitting only on galaxies with moderate SFR limits, assuming the halo occupation function of Equation (11).

In the HOD analysis of the SFR samples, one should also consider the possibility of a lack of passive centrals. When some passive galaxies are excluded by applying a threshold to the SFR, a portion of the dark halos do not possess their central galaxy and the expected number of galaxies within the dark halos will never reach one. As discussed in Béthermin et al. (2014), stochastic occupation of the central galaxy does not have an impact on the shape of the ACFs predicted by the HOD model. However, the calculation of the number density of galaxies using the HOD model is associated with a certain problem, given that the halo occupation function plays a role in controlling the weight of the number of galaxies per halo mass. To deal with the stochastic occupation of SFR samples, we exclude the constraint on the galaxy abundance in the $\chi^2$ fitting procedure, in a similar manner to Béthermin et al. (2014).

We show the results of the HOD-model fitting on the SFR samples in Figure 8 and the best-fitting HOD parameters are given in Table 6. As in the case with the SM samples, the HOD model can well represent observed galaxy clustering with a wide dynamical range, SFR thresholds, and redshift. Due to the lack of constraint on the galaxy number density, the best-fitting
HOD parameters are less constrained compared to the results of SM samples. To precisely investigate the relationship between dark halo properties and the SFR, it is necessary to develop the halo occupation function for SFR samples and/or a sophisticated halo-model analysis method.

### 4.3. Effect of Scatter and Systematic Bias

Clustering signals can be affected by the scatter and the systematic bias in the physical properties that could possibly be caused in the SED-fitting procedure. Before discussing the results of the HOD-model analysis, we check the effect of those uncertainties on the results.

According to Tanaka et al. (2018), physical quantities of our photo-z catalog contain \( \pm 0.25 \) dex level scatter compared with results of other photo-z studies. Therefore, we introduce \( \pm 0.25 \) dex scatter into stellar masses and SFRs using the Monte Carlo method for galaxy samples at each redshift bin and implement the clustering/HOD analyses.

We find that the \( M_{\text{min}} \) parameter, which is a fundamental parameter to evaluate properties of central galaxies, is unchanged within \( 1\sigma \) errors for both stellar-mass and SFR samples at all redshift bins. On the other hand, the \( M_1 \) parameter at the lowest-z bin exceeds the \( \sim 2\sigma \) level by introducing the scatter; however, the difference of \( M_1 \) at the lowest-z bin does not change all of the results and discussion. Hence, scatters on the stellar mass and the SFR do not have significant impacts on the final results throughout this study.

In addition to the scatter, this study also tests the effects of the systematic bias on parameter values. Stellar masses and SFRs in our galaxy catalog could be overestimated by 0.2 and 0.1 dex (Tanaka et al. 2018), respectively. Considering the redshift dependence of the systematic bias, we correct stellar masses as follows:

\[
M_{\text{cor}} = \frac{M_*}{1 + z},
\]

where \( M_* \) and \( M_{\text{cor}} \) represent an original and corrected stellar mass, and \( z \) is a photometric redshift of each galaxy. It should be noted that the above stellar-mass correction is roughly estimated by comparing the stellar masses derived by MIZUKI with those from the NEWFIRM Medium-band Survey (NMBS; Whitaker et al. 2011). See the appendix of Tanaka et al. (2018) for more details.
Table 4
Clustering Properties of Cumulative Star Formation Rate Limited Subsamples

| SFR Limit\(^a\) | \(A_s(\times 10^{-3})\) | \(\gamma\) | \(r_0\) | \(A_s(\times 10^{-3})\) | \(\gamma\) | \(r_0\) |
|-----------------|----------------|-----|-----|----------------|-----|-----|
| \(-1.50\)       | 6.44 ± 1.36  | 1.73 ± 0.08 | 3.36 ± 0.15 | 7.11 ± 1.31  | 1.73 ± 0.07 | 3.75 ± 0.26 |
| \(-1.00\)       | 6.44 ± 1.32  | 1.72 ± 0.08 | 3.62 ± 0.14 | 6.72 ± 1.28  | 1.73 ± 0.07 | 3.71 ± 0.15 |
| \(-0.50\)       | 6.80 ± 1.52  | 1.72 ± 0.08 | 3.70 ± 0.17 | 6.12 ± 1.26  | 1.74 ± 0.08 | 3.73 ± 0.21 |
| 0.00            | 8.28 ± 2.57  | 1.74 ± 0.09 | 3.84 ± 0.21 | 5.22 ± 1.30  | 1.78 ± 0.09 | 3.78 ± 0.36 |
| 0.50            | 19.61 ± 11.29| 1.77 ± 0.10 | 5.32 ± 0.44 | 5.77 ± 2.54  | 1.77 ± 0.10 | 4.96 ± 0.38 |
| \(0.80 \leq z < 1.10\) | \(A_s(\times 10^{-3})\) | \(\gamma\) | \(r_0\) | \(A_s(\times 10^{-3})\) | \(\gamma\) | \(r_0\) |
| \(-1.00\)       | 4.77 ± 1.01  | 1.83 ± 0.09 | 3.92 ± 0.16 | 6.60 ± 1.35  | 1.73 ± 0.08 | 3.91 ± 0.12 |
| \(-0.50\)       | 4.49 ± 0.97  | 1.83 ± 0.09 | 3.87 ± 0.13 | 6.11 ± 1.44  | 1.75 ± 0.09 | 4.32 ± 0.16 |
| 0.00            | 4.43 ± 1.00  | 1.81 ± 0.10 | 3.91 ± 0.40 | 5.83 ± 1.41  | 1.76 ± 0.09 | 4.56 ± 0.55 |
| 0.50            | 4.68 ± 1.88  | 1.79 ± 0.10 | 4.84 ± 0.70 | 7.26 ± 3.28  | 1.77 ± 0.10 | 5.64 ± 0.74 |
| 1.00            | 15.28 ± 10.79| 1.78 ± 0.11 | 7.42 ± 0.83 | 7.26 ± 3.28  | 1.77 ± 0.10 | 5.64 ± 0.74 |

Notes.
\(^a\) Threshold SFR of each subsample in units of \(h^{-3}M_\odot\ yr^{-1}\) in a logarithmic scale.
\(^b\) Amplitude of the ACF at \(1^\circ\).
\(^c\) Power-law slope of the ACF at a large-angular scale.
\(^d\) Correlation length in units of \(h^{-1}\)Mpc.

We resample our catalog according to the corrected stellar masses and carry out clustering/HOD analyses using the total samples at each redshift bin. As is the case with the test of the scatter, all of the \(M_{\text{bin}}\) (and almost all of the \(M_1\)) parameters of stellar-mass bins are not changed within 1\(\sigma\) confidence levels. Besides the above result, systematic biases in the photo-z studies are inevitable since it is difficult to determine the normalization of physical quantities. The SFR also has its systematic bias but it can be negligible since the amplitude of the SFR systematic bias is smaller than that of the stellar mass. Therefore, it is determined that the results and discussions of this study are not affected by introducing the systematic bias.

In summary, we conclude that the scatter as well as the systematic bias on stellar masses and SFRs do not have significant impacts on the final results and conclusion of this study.

4.4. Correlation Length

We measure the correlation lengths of each ACF to quantify the dependence of clustering strength on their baryonic properties. Correlation length is a three-dimensional clustering strength that can be evaluated by a spatial correlation function. The spatial two-point correlation function, \(\xi(r)\), can be described in a power-law form as:

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

where the normalization factor \(r_0\) is the correlation length and \(\gamma\) is the gradient of power-law approximation of the spatial correlation function.

Provided that the redshift distribution of galaxies is known, one can transform the amplitude of ACF into the correlation length using “Limber’s approximation” (Limber 1953, 1954). The correlation length can be evaluated by determining the amplitude of ACFs (Peebles 1980; Efstathiou et al. 1991) and many clustering studies adopt this approximation formula (e.g., Hildebrandt et al. 2009; McCracken et al. 2010; Ishikawa et al. 2015). However, the accuracy of the correlation length becomes worse with the increase of the redshift range of the galaxy sample. This is because the Limber’s approximation converts the projected clustering amplitude into the real-space clustering strength.

To avoid the uncertainties that originate from Limber’s approximation, we evaluate the correlation lengths by definition; i.e., the correlation length is a scale in which the real-space two-point correlation function becomes unity. Using the halo-model approach (e.g., Ma & Fry 2000; Seljak 2000), a galaxy power spectrum, \(P_g\), can be computed using the halo occupation function (Equation (11)). To calculate the galaxy power spectrum, we use the best-fitting HOD parameters of each stellar-mass/SFR bin estimated in Section 4.2. The real-space two-point correlation function from the halo model can be obtained by performing a Fourier transformation of the galaxy power spectrum as follows:

\[
\xi_{\text{HOD}}(r) = \frac{1}{2\pi^2} \int dk k^2 \sin kr P_g(k).
\]

The correlation length is a scale that satisfies \(\xi_{\text{HOD}}(r_0) = 1\) and the error of the correlation length is evaluated by the standard deviation of the process that calculates the correlation length repeatedly by varying the best-fitting HOD parameters within 1\(\sigma\) errors.

4.4.1. \(M_\odot\) versus \(r_0\) Relation

The stellar-mass dependence of the correlation length is shown in Figure 10 and the details are presented in Table 3. Regardless of the redshift bins, the correlation lengths monotonically increase with the threshold stellar mass, which is also seen in other observational studies as well as the hydrodynamical simulations, and this trend is also observed up to \(z \sim 2\) (e.g., Bielby et al. 2014; Ishikawa et al. 2015). This
implied that massive galaxies occupy more massive dark halos compared to less-massive galaxies. The correlation lengths gradually increase with the stellar-mass threshold, whereas the amplitude of the correlation lengths increase significantly when galaxy samples are confined to massive ones. The knee stellar-mass threshold is log_{10}(M_{lim}/h^{-2}M_{\odot})~10.4 irrespective of its redshift, indicating that galaxies with larger masses than this threshold are highly biased objects. The steep increase of the correlation length at the massive end has already been reported in previous studies (e.g., Wake et al. 2011; Hatfield et al. 2016).

However, we determined that it continues up to the most massive galaxies by observation. The redshift evolution of the correlation length is almost consistent with the results of previous studies as shown in Figure 10. By fixing the stellar-mass threshold, our results indicate a small redshift evolution over 0.3 ≤ z ≤ 1.4, which is also seen in the results of McCraken et al. (2015) and Springel et al. (2018). These studies measured correlation lengths without assuming the Limber’s approximation. Springel et al. (2018) determined that by fixing the stellar-mass threshold, the
correlation lengths are stronger for less-massive low-$z$ galaxies and this trend is reversed for massive galaxies. Our results support the trend of redshift evolution and show good consistency with the results obtained from the numerical hydrodynamical simulations. The discrepancy in the massive end between our highest-$z$ result (red circles) and the result of Springel et al. (2018) at $z = 1.5$ (red line) is caused by the difference in the effective redshift. The effective redshift of our result is $z = 1.23$, whereas Springel et al. (2018) calculated the exact result at $z = 1.5$ using a snapshot at that epoch. McCracken et al. (2015) also measured a small redshift evolution of the correlation length. However, their results clearly show a weaker clustering strength compared to other studies (1–1.5σ lower than our results). The origin of this discrepancy is still unclear. The possible reason is that the COSMOS field is a relatively small survey field and it is difficult to measure the angular correlation function with sufficient dynamical range and the S/N ratio to compute an

Figure 9. The expected number of galaxies per dark halo calculated using the data from the EAGLE simulation. Left (right) panel shows the result for the galaxies at $0.30 \leq z < 0.55$ ($1.10 \leq z \leq 1.40$) and the dashed (solid) lines represent the expected number of central (total) galaxies. All the galaxies satisfy the magnitude and stellar-mass limits that are imposed on the HSC galaxy samples. The errors of total galaxy number are evaluated using the Poisson error.

Table 6

Best-fitting HOD Parameters of Cumulative Star Formation Rate Limited Samples

| Redshift      | SFR Limit | $\log_{10}M_{\text{min}}$ | $\log_{10}M_1$ | $\log_{10}M_2$ | $\sigma_{\log M}$ | $\alpha$ | $\chi^2$/dof |
|---------------|-----------|---------------------------|----------------|----------------|-----------------|----------|-------------|
| $0.30 \leq z < 0.55$ | –1.50    | 10.746 ±0.213             | 12.937 ±0.234  | 9.598 ±0.210  | 3.749            | 0.378 ±0.312 | 0.900 ±0.195 | 0.455 |
|               | –1.00    | 10.815 ±0.356             | 12.848 ±0.269  | 10.996 ±0.219 | 2.431            | 0.670 ±0.312 | 1.04 ±0.209  | 0.277 |
|               | –0.50    | 11.231 ±0.086             | 12.926 ±0.185  | 9.789 ±0.385  | 2.406            | 0.537 ±0.210 | 0.977 ±0.181 | 0.419 |
|               | 0.00     | 11.656 ±0.045             | 13.441 ±0.191  | 8.259 ±2.221  | 2.227            | 0.493 ±0.246 | 0.738 ±0.224 | 0.545 |
|               | 0.50     | 12.451 ±0.107             | 14.274 ±0.142  | 8.980 ±2.742  | 2.799            | 0.520 ±0.230 | 1.160 ±0.213 | 0.269 |
| $0.55 \leq z < 0.80$ | –1.50    | 10.736 ±0.227             | 12.028 ±1.326  | 11.851 ±0.340 | 1.147            | 0.494 ±0.244 | 0.747 ±0.266 | 0.272 |
|               | –1.00    | 11.009 ±0.147             | 12.596 ±0.306  | 10.363 ±2.217 | 2.154            | 0.574 ±0.218 | 1.013 ±0.202 | 0.332 |
|               | –0.50    | 11.159 ±0.132             | 12.675 ±0.366  | 8.576 ±2.988  | 2.496            | 0.536 ±0.240 | 1.004 ±0.273 | 0.459 |
|               | 0.00     | 11.535 ±0.067             | 13.043 ±0.218  | 9.694 ±1.895  | 1.943            | 0.480 ±0.260 | 0.841 ±0.178 | 0.447 |
|               | 0.50     | 12.265 ±0.064             | 14.210 ±0.432  | 8.863 ±2.949  | 2.831            | 0.485 ±0.255 | 0.960 ±0.314 | 0.161 |
| $0.80 \leq z < 1.10$ | –1.00    | 11.297 ±0.147             | 12.621 ±0.356  | 8.414 ±2.358  | 2.338            | 0.082 ±0.299 | 1.100 ±0.218 | 0.241 |
|               | –0.50    | 11.376 ±0.116             | 12.675 ±0.909  | 7.527 ±1.724  | 1.764            | 0.633 ±0.353 | 1.049 ±0.257 | 0.254 |
|               | 0.00     | 11.495 ±0.069             | 12.852 ±0.309  | 8.545 ±2.499  | 2.462            | 0.520 ±0.234 | 1.054 ±0.256 | 0.148 |
|               | 0.50     | 12.118 ±0.033             | 13.420 ±0.614  | 8.557 ±2.391  | 2.341            | 0.519 ±0.224 | 1.050 ±0.224 | 0.150 |
|               | 1.00     | 12.884 ±0.055             | 14.323 ±0.199  | 9.106 ±2.796  | 2.796            | 0.525 ±0.202 | 1.270 ±0.146 | 0.099 |
| $1.10 \leq z \leq 1.40$ | –0.50    | 11.406 ±0.060             | 12.649 ±0.087  | 8.064 ±2.108  | 2.148            | 0.697 ±0.337 | 1.134 ±0.074 | 0.630 |
|               | 0.00     | 11.681 ±0.044             | 13.064 ±0.086  | 8.388 ±2.286  | 2.286            | 0.256 ±0.150 | 1.234 ±0.071 | 0.220 |
|               | 0.50     | 12.027 ±0.071             | 13.354 ±0.147  | 9.484 ±2.277  | 3.467            | 0.682 ±0.206 | 1.105 ±0.216 | 0.414 |
|               | 1.00     | 12.451 ±0.065             | 13.409 ±0.594  | 10.406 ±3.917 | 3.917            | 0.573 ±0.475 | 1.040 ±0.337 | 0.358 |

Note. The SFR limit is in units of $h^{-2}M_\odot$ yr$^{-1}$ on a logarithmic scale, whereas all halo mass parameters are in units of $h^{-1}M_\odot$. 
Figure 10. The stellar-mass dependence and redshift evolution of the correlation length. Our results are shown by the blue $(0.30 \leq z < 0.55)$, green $(0.55 \leq z < 0.80)$, orange $(0.80 \leq z < 1.10)$, and red $(1.10 \leq z < 1.40)$ circles, respectively. For comparison, we plot previous observational results reported by Wake et al. (2011; upward triangles) at $0.9 < z < 1.3$, Hatfield et al. (2016; downward triangles) at $0.50 < z < 0.75$ (green), $0.75 < z < 1.00$ (orange), $1.00 < z < 1.25$ (pink), and $1.25 < z < 1.70$ (red), McCracken et al. (2015; squares) at $0.5 < z < 0.8$ (green), $0.8 < z < 1.1$ (orange), $1.1 < z < 1.5$ (red), and Marulli et al. (2013; crosses) at $0.5 < z < 0.7$ (green), $0.7 < z < 1.1$ (orange), respectively. In addition to the above observational studies, results obtained using the hydrodynamical simulations (IllustrisTNG; Springel et al. 2018, solid lines) at $z = 0.5$ (blue), $z = 0.8$ (green), $z = 1.0$ (orange), and $z = 1.5$ (red) are also shown.

Figure 11. The SFR dependence of the correlation lengths. We show our results at $0.30 \leq z < 0.55$ (blue), $0.55 \leq z < 0.80$ (green), $0.80 \leq z < 1.10$ (orange), and $1.10 \leq z < 1.40$ (red) as a function of the SFR limit. We also plot correlation lengths of red galaxies at $0.74 < z < 1.05$ (magenta squares) and blue galaxies at $0.74 < z < 1.40$ (cyan triangles) reported by Mostek et al. (2013). For clarity, our results are slightly shifted along the horizontal axis.

Bielby et al. (2014) and the correlation lengths of our low-SFR samples could be diluted by the mixture of strong clustering of red galaxies and weak clustering of small blue galaxies. The discrepancy between our study and the red galaxies of Mostek et al. (2013) can be explained based on the same reason.

As previously indicated, the SFR is not an adequate indicator of halo masses due to the lack of an established halo occupation model and the absence of a constraint on the galaxy abundance. Therefore, we use only SM samples for the following discussions.

4.4.2. SFR versus $r_0$ Relation

We also measure the correlation lengths of SFR samples as shown in Figure 11. The correlation lengths of red and blue galaxies presented by Mostek et al. (2013) that are separated on the $(U - B)$ color versus $B$-band magnitude diagram are plotted for the comparison, and our correlation lengths are consistent with the results of the blue galaxies. Increasing the correlation length with the SFR is reasonable since galaxies with high SFR tend to be massive according to the main sequence of star-forming galaxies (e.g., Brinchmann et al. 2004; Daddi et al. 2007). Galaxies with the highest SFR at $z > 0.8$ exhibit significantly strong galaxy clustering. The results of observational studies have shown that galaxies with high SFR reside in the high-density environment at $z \sim 1$ (e.g., Cooper et al. 2008; Tran et al. 2010). In addition, the strong clustering signals support the idea that a high SFR at $z \sim 1$ is mainly induced by galaxy mergers/interactions (e.g., Bekki 2001) in highly dense regions, where galaxies are strongly clustered with each other.

In contrast to high-SFR galaxies, the low-SFR end is almost constant and this trend could be caused by the mixture of galaxy populations in our samples. Red, passive galaxies are measured with strong clustering compared to blue, star-forming galaxies (e.g., McCracken et al. 2010; Zehavi et al. 2011; 2013). The observed results show that both $M_{\text{min}}$ and $M_1$ of our HSC galaxies as a function of the stellar-mass limit in Figure 12. The results of previous HOD studies that adopt the same halo occupation function (Equation (11)) and SM samples are also shown.

The observed results show that both $M_{\text{min}}$ and $M_1$ monotonically increase with the stellar-mass limit, albeit with a small fluctuation in $M_1$. For $M_{\text{min}}$, this increasing trend indicates that the less-massive dark halos can only possess less-massive centrals and vice versa. This is consistent with the trend of the stellar mass–halo mass relation of central galaxies that was derived using the AM technique (Behroozi et al. 2010, 2013a; Moster et al. 2010, 2013) as well as observational studies (Leauthaud et al. 2012; Coupon et al. 2015). The increasing trend of $M_1$ indicates that massive satellite galaxies form only in the massive dark halos. This implies that a large fraction of satellite galaxies originally comprised massive central galaxies that became satellite galaxies through halo mergers.

Considering the other observational results, $M_{\text{min}}$ shows little redshift evolution from $z = 1.5$ to 0.3, indicating that central galaxies form a similar condition in the underlying dark matter.
fluctuation at least at $z = 0.3$–1.5. This result is consistent with the trend of the small evolution of the stellar mass–halo mass relation of central galaxies from $z = 1.5$ to $z = 0.5$ with dark halo mass of $M_h = 10^{11–13} M_\odot$ presented by Moster et al. (2013).

$M_1$ shows an increasing trend with redshift, although there is large fluctuation compared to $M_{\text{min}}$. It can be determined that $M_1$ at $1.1 \lesssim z \lesssim 1.4$ (especially for massive galaxies) clearly shows the excess compared to galaxies at $z < 1.1$, implying that satellite galaxies rarely form at $z \gtrsim 1$. The discussion of the satellite fraction (Section 4.6) considers the case of a small number of satellite galaxies at $z \gtrsim 1$.

4.6. Satellite Fraction

We calculate the satellite fraction of HSC galaxy samples following Equation (15) as a function of stellar-mass limit using the best-fitting HOD parameters. The results are shown in Figure 13 compared with results at similar redshift ranges from the literature. Overall, our results are in good agreement with the trends outline in previous studies; i.e., satellite fractions of less-massive galaxies at $z \lesssim 1$ are almost constant. A rapid decrease of the satellite fraction can be found at the massive end and the decreasing trend is predominant for $z > 1$ galaxies. In addition, satellite fraction decreases with redshift by fixing the stellar-mass threshold.

The satellite fraction at $z \lesssim 1$ remains almost constant up to $\log_{10} (M_{\text{stellar}}/h^{-2} M_\odot) \sim 10.4$, whereas it decreases drastically at the massive end. The steep decrease at the massive end can be caused by the efficient merging of massive infalling galaxies due to the short dynamical friction timescale (e.g., Colpi et al. 1999; Gan et al. 2010; Lotz et al. 2010), and less-massive infalling galaxies can survive longer as satellite galaxies by orbiting their central galaxy.

The reason for the steep decrease of the satellite fraction at the massive ends is also attributed to the small frequency of major mergers. Lotz et al. (2011) calculated the merger fraction of galaxies as a function of the baryonic mass ratio using the semi-analytical galaxy formation models and showed that the fraction of the major mergers with the baryonic mass ratio of 1:1 is less than 10% compared to that of the minor mergers with a 5:1 mass ratio. Satellite fractions of massive galaxies do not increase unless major mergers among massive galaxies frequently happen in the universe; therefore, the satellite fractions of our massive ends are much smaller due to the low major merger fraction. For these reasons, the low satellite fraction of our massive galaxies can be explained by the low major merger rate as well as the short dynamical friction timescale for massive galaxy pairs.

The satellite fraction of our highest-$z$ bin ($1.10 \leq z \leq 1.40$) shows a significant drop compared to those at $z < 1$ even for less-massive galaxies, which is also seen in the $z > 3$ results using LBG samples (Ishikawa et al. 2017; Harikane et al. 2018). This may be due to the rarity of massive galaxies in high-$z$; less-massive galaxies live as central galaxies rather than satellite galaxies in the vicinity of massive galaxies, which are quite rare objects compared to the low-$z$ universe. In addition to the small abundance of massive galaxies, efficient tidal disruption and high merger rate in high-$z$ can also be attributed to the small satellite fraction. Wetzel (2011) found that the high-$z$ subhalos show more radial orbits and sink deeper into the host halos. It indicates that high-$z$ subhalos can merge to
the number of satellites in the HSC galaxy sample (Hatfield et al. 2015) and the number of satellites in the COSMOS field (0.201 deg$^2$; Scoville et al. 2007) and the AEGIS field (0.189 deg$^2$; Davis et al. 2007). Several studies have reported that the clustering strength in the COSMOS field at $z \sim 1$ differs from that of other fields due to the cosmic variance (McCracken et al. 2008; Meneux et al. 2009; Clowes et al. 2013). The ACF in the COSMOS field of Wake et al. (2011) at $0.9 < z < 1.3$ shows stronger clustering at large scales compared to that of the AEGIS field. In addition, averaged ACFs were obtained by combining the ACFs observed in both fields. Therefore, it is possible that the strong correlation in the large scales originated from the COSMOS-field-enhanced large-scale galaxy biases. It is noted that our galaxy biases only increased by a maximum of 10% by using the same condition as Wake et al. (2011), i.e., fixing the two HOD free parameters ($\theta_{\log M} = 0.15$ and $\alpha = 1.0$) and adopting the cosmological parameters of the 7 year WMAP results (Komatsu et al. 2011).

The difference between our results and those of Hatfield et al. (2016) at $z > 0.5$ can be attributed to the difference in the definition of the galaxy bias, although galaxy biases are comparable for different definitions in the local universe (Zehavi et al. 2011). In the studies highlighted in Figure 14, except for Hatfield et al. (2016), the averaged large-scale galaxy biases were calculated using Equation (16), whereas Hatfield et al. (2016) derived the galaxy bias based on its definition using Equation (17). It is reasonable for the consistency of $M_{\text{min}}$ among different studies that the difference of $b_g$ is due to its definition.

5. Discussion

5.1. Stellar-to-halo Mass Ratio

Our stellar-to-halo mass ratios (SHMRs) based on the HSC SSP galaxy samples are presented in Figure 15. In the $M_*$ versus $M_\text{eff}$ diagram, the stellar-mass limit, and the $M_{\text{min}}$ obtained using the HOD-model fitting analysis are used as the stellar mass and the dark halo mass of each stellar-mass bin, respectively. We also plot the theoretical predictions as well as the observational results: the latest results of the empirical models (Moster et al. 2018; Behroozi et al. 2019), the results from the EAGLE simulations (Crain et al. 2015; Schaye et al. 2015) and the IllustrisTNG simulations (Springel et al. 2018), and the results from the deep- (McCracken et al. 2015) and wide-field (Coupon et al. 2015) extensively multicolor photometric surveys. The SHMRs of the EAGLE simulations are calculated using central galaxies that satisfy the stellar-mass limits and the magnitude thresholds of this study. It should be noted that the definition of our SHMR (i.e., SHMR$(M_*, z) = M_{*, \text{lim}} / M_{\text{min}}$) is the same as those of Coupon et al. (2015) and
Behroozi et al. (2019), and the SHMRs of McCracken et al. (2015) and the EAGLE simulations are calculated by matching our definition.

Most strikingly, we succeeded in calculating the SHMRs that cover a wide halo mass range ($M_h \sim 10^{11-14} h^{-1} M_\odot$). The wide and relatively deep photometric data of the HSC Wide layer enable the capture of halo masses with peaked SHMR (pivot halo mass, $M_h^{\text{pivot}}$) and both massive/less-massive slopes at $0.3 \leq z \leq 1.4$. Our SHMRs are generally consistent with referenced studies; the SHMRs have a peak at $M_h^{\text{pivot}} \sim 10^{12} M_\odot$, the peak values of SHMRs are $\sim 0.01-0.02$ regardless of its redshift, and the SHMRs gradually decrease toward the high- and low-mass ends from its peak. However, our results differ slightly from Behroozi et al. (2019) in the slope of the massive end; i.e., our SHMRs show 1.5–2σ level excess compared to Behroozi et al. (2019) for $z \leq 1$ results. In this study, SHMRs are calculated using the massive galaxies selected by the HSC SSP Wide-layer over ~145 deg$^2$, in which the number of massive galaxies is large enough to apply HOD-model analysis and derive the halo mass precisely, and the accuracy of the SED fitting is thought to be reliable for massive, bright galaxies. The empirical model of Behroozi et al. (2019) used the stellar-mass function for the observational constraint and they adopted the stellar-mass function of Moustakas et al. (2013), which is derived based on the observation over 5.5 deg$^2$ in total. Therefore, the abundance of massive galaxies ($M_\ast \gtrsim 10^9 M_\odot$) could be underestimated in their study.

In contrast to the massive end, our SHMRs at smaller masses than $M_h^{\text{pivot}}$ halos are consistent with previous studies, but show systematically smaller values compared to the model predictions, as well as other observational studies, albeit within the 1σ confidence intervals of Behroozi et al. (2019). This difference can be caused by differences due to the stellar-mass estimation method. The method of stellar-mass estimation is different among the studies, i.e., this study, McCracken et al. (2015), and Coupon et al. (2015) use the SED-fitting technique and Behroozi et al. (2019) and Moster et al. (2018) are constrained by observational results, such as the stellar-mass function. Even among the studies using the SED-fitting technique, stellar-mass estimation can be affected by difference in the physical assumptions such as the main sequence of star-
Figure 16. Redshift evolution of observed SHMRs. Our observational results are plotted as blue (0.30 ≤ z < 0.55), green (0.55 ≤ z < 0.80), orange (0.80 ≤ z < 1.10), and red (1.10 ≤ z < 1.40) circles, respectively. The solid lines are the best-fitting SHMRs of each redshift bin fitted using the parameterized relation presented by Behroozi et al. (2013a) and the arrows above our SHMRs represent the $M_{h}^{\text{pivot}}$ of the fitted SHMRs. The dashed arrows on top of the panel also show the $M_{h}^{\text{pivot}}$ of z ~ 3 (blue), z ~ 4 (green), and z ~ 5 (red) dropout galaxies calculated by Ishikawa et al. (2017). The gray shaded region indicates the model prediction of SHMR at z = 0 with 1σ confidence level by Behroozi et al. (2019). To connect the SHMRs of the HSC SSP to higher-z, we also show the SHMRs using star-forming galaxies at 1.40 < z < 2.50 (magenta circles; Ishikawa et al. 2016), the photometric-redshift selected galaxies at 1.5 < z < 2.0 (blue triangles) and 2.0 < z < 3.0 (green triangles) by Cowley et al. (2018), and dropout galaxies at z ~ 4 (red downward triangles) by Harikane et al. (2018).

Table 7. To connect our results to those beyond z = 1.4, we also plot the observed SHMRs at z ~ 2 (szgK galaxies; Ishikawa et al. 2016), z = 1.5–2.0 and z = 2.0–3.0 (Cowley et al. 2018), and z ~ 4 (Harikane et al. 2018). It should be noted that these high-z galaxy populations are not necessarily the same population as we observed at z < 1.4.

The SHMRs at z < 0.8 rarely evolve from the model prediction at z = 0; both $M_{h}^{\text{pivot}}$ and peak amplitude exhibit little change. In comparison, the SHMRs at z > 1 show an apparent evolution from z = 0; $M_{h}^{\text{pivot}}$ clearly shifts toward a higher halo mass and the peak amplitude decreases with the redshift, which is consistent with a model prediction presented by Rodríguez-Puebla et al. (2017). The difference in evolutionary trend given that z ~ 1 can be interpreted to be attributed to the evolution of the stellar-mass function. Observational studies have revealed that the evolution of the stellar-mass function is quite small over 0.2 < z < 1.0 and the amplitude of the Schechter function decreases with redshift at z > 1 (e.g., Muzzin et al. 2013b; Tomczak et al. 2014). The decrease of the peak value of SHMR at z > 1 can be a result of the decrease of the total amount of stellar components in the high-z universe. An increase in $M_{h}^{\text{pivot}}$ with redshift, especially at z > 1, indicates that the supernova feedback mechanism for the suppression of the stellar-mass assembly in low-mass dark halos is more efficient than z ~ 0. The quenched fraction of central galaxies with stellar mass $M_{*} \sim 10^{10}h^{-1}M_{\odot}$, which is typically hosted by dark halos with $M_{h}^{\text{pivot}}$, evolves from ~0.4 at z ~ 0 into ~0.1 at z ~ 1; therefore, most of the galaxies at z > 1 are star-forming galaxies, even in the mass range in which quiescent galaxies are dominated in the local universe (e.g., Drory et al. 2009; Tinker et al. 2013). Active star-forming galaxies occupy relatively massive halos at z > 1 and $M_{h}^{\text{pivot}}$ gradually shifts to lower-mass halos by increasing the fraction of quiescent galaxies in $M_{h}^{\text{pivot}}$ halos toward z ~ 0.

Qualitatively, the peak amplitudes of SHMRs in z > 2 are smaller than the results for z < 2, suggesting that star formation is still in progress at high-z. The low-mass slopes of Cowley et al. (2018) that are derived using photo-z samples similar to this study exhibit a shallower gradient, implying that star formation activity in high-z galaxies hosted by $M_{h} \lesssim M_{h}^{\text{pivot}}$ halos are highly suppressed by the supernova feedback effect. The SHMR of Harikane et al. (2018) also distinctly shows the same trend; however, it should be noted that their galaxy sample consists only of star-forming galaxies.

5.3. Evolution of Pivot Halo Mass

The redshift evolution of our $M_{h}^{\text{pivot}}$ is presented in Figure 17. For comparison, we also plot other observational results for various redshifts as well as theoretical predictions using the AM technique. The observed results are obtained using the HOD-model analyses based on the luminosity-limited samples (Zehavi et al. 2011; Coupon et al. 2012; Martinez-Manso et al. 2015) and the SM samples (Leauthaud et al. 2012; McCracken et al. 2015; Ishikawa et al. 2016, 2017; Cowley et al. 2018), respectively. In addition to the aforementioned clustering studies, the results obtained via the empirical model (Behroozi et al. 2013a, 2019) and the subhalo AM technique (SHAM; Legrand et al. 2019) are also shown.

The $M_{h}^{\text{pivot}}$ in the HSC SSP are consistent with previous studies based on the SM samples. The most efficient star formation activity is in progress within dark halos with masses of $M_{h} \sim 10^{12}h^{-1}M_{\odot}$ up to z ~ 1, and $M_{h}^{\text{pivot}}$ gradually increases

forming galaxies, dust-extinction law, star formation histories, and metallicity. The pivot halo masses and gradients of massive-less/massive end slopes of our results are almost comparable to McCracken et al. (2015); thus, the gap of the SHMR amplitude between these studies may be caused by differences in the physical assumptions.

5.2. Connection to High-z SHMRs

We connect our SHMRs observed in 0.3 ≤ z ≤ 1.4 to higher-z results to trace the redshift evolution of the stellar-mass assembly of galaxies. To clearly show the characteristics of SHMRs, in this study, we use the formulated SHMR model. We employ the parameterized relation of the SHMR presented by Behroozi et al. (2013a). The best-fitting models for our observed SHMRs of each redshift bin are presented in Figure 16, and the pivot halo masses and values of peak SHMR in the best-fitting models are shown in
with the redshift. Although there is little evolution ($\sim \pm 0.2$ dex) in the pivot halo mass, we systematically show that the pivot halo mass is almost constant ($M_{\text{h, pivot}} \sim 10^{12}M_\odot$) up to $z \sim 5$, using only clustering and HOD-model analyses. The result suggests that most of the star formation occurs in a narrow range of halo masses, which is consistent with the theoretical predictions for galaxy formation models (e.g., Rees & Ostriker 1977; Wang et al. 2013; Dekel et al. 2019).

By tracing the redshift evolution, it is shown that $M_{\text{h, pivot}}$ monotonically increases with redshift, at least up to $z \sim 2$. Beyond $z \sim 2$, there are two scenarios for $M_{\text{h, pivot}}$ evolution: $M_{\text{h, pivot}}$ increases monotonically (Cowley et al. 2018; Legrand et al. 2019), otherwise it decreases with redshift (Behroozi et al. 2013a; Ishikawa et al. 2017). The latest result of the model prediction by Behroozi et al. (2019) is in the middle of these scenarios; $M_{\text{h, pivot}}$ increases monotonically up to $z \sim 3$ and then gradually decreases with redshift. However, the theoretical approach contains relatively large uncertainties in high-$z$. Observational studies suggest photo-$z$ selected galaxies show increasing evolution (Cowley et al. 2018; Legrand et al. 2019), whereas $M_{\text{h, pivot}}$ of star-forming dropout galaxies decrease with redshift (Ishikawa et al. 2017). To understand the star formation in high-redshift dark halos, it is necessary to measure $M_{\text{h, pivot}}$ in $z \gtrsim 2$ with higher statistical precision and various galaxy populations.

5.4. Baryon Conversion Efficiency (BCE)

We calculate the BCE of our galaxy samples. The BCE, $\epsilon (M_{\text{h}}, z)$, is defined as the mass ratio between accreted baryons and formed stellar components as,

$$\epsilon (M_{\text{h}}, z) = \frac{dM_\star}{dt} / \frac{dM_{\text{h}}}{dt},$$

where $dM_\star/dt$ and $dM_{\text{h}}/dt$ represent the SFR and a baryon accretion rate (BAR), respectively. The BAR can be calculated as follows:

$$\text{BAR} = f_b \times \frac{dM_{\text{h}}}{dt},$$

where $f_b$ and $dM_{\text{h}}/dt$ are the baryon fraction and the mass-growth rate of dark halos, respectively. In our cosmological parameters, the baryon fraction is $f_b = \Omega_b/\Omega_m \sim 0.159$. We employ the dark halo mass-growth rate as a function of the redshift and dark halo mass presented by Fakhouri et al. (2010), which is based on the results of the $N$-body simulations.

The BCEs of the SM samples are presented in Figure 18. Our BCEs are calculated using the BARs derived from $M_{\text{min}}$ and the averaged SFRs of each stellar-mass bin. In Figure 18, we also show BCEs calculated using the empirical models of Behroozi et al. (2013a) and Moster et al. (2018), as well as the observational result in $z > 4$ (Harikane et al. 2018). Our results are qualitatively consistent with the empirical models; the BCEs decrease with halo mass and the power-law slopes in massive ends are almost consistent with the models. For $0.30 < z < 0.55$, the BCE of our lowest stellar-mass bin shows the highest value, whereas the BCEs of both empirical models begin to decrease at the corresponding halo mass.

It is notable that the halo masses with the highest BCE are much smaller than the $M_{\text{h, pivot}}$ of the SHMRs for each redshift, although the peak halo masses are slightly different among the studies. This mass gap between the peak halo masses of the BCE and the SHMR (i.e., $M_{\text{h, pivot}}$) has already been shown using the empirical model at $z = 0$ (Behroozi et al. 2013b), but we show that the mass gap can be seen at least up to $z = 1.4$ by observation. Although accurate peak halo masses cannot be captured due to the lack of galaxies at the less-massive ends, the halo mass with the peak BCE are $\sim 10^{11.0-11.5}h^{-1}M_\odot$, and $M_{\text{h, pivot}}$ in the SHMR diagram is $\sim 10^{12}h^{-1}M_\odot$, regardless of its redshift. Therefore, this implies that the most efficient star-forming activity is in progress in less-massive galaxies hosted by $10^{11.0-11.5}h^{-1}M_\odot$ dark halos. It should be noted, however, that $10^{11.0-11.5}h^{-1}M_\odot$ are the upper limits of peak halo masses of BCFs since our observation does not capture the exact peak halo masses. Considering the amplitude of the SHMR, galaxies hosted in $10^{11.0-11.5}h^{-1}M_\odot$ dark halos rapidly assemble stellar components much faster than the growth of dark halo mass. Moreover, they evolve toward galaxies hosted by $M_{\text{h, pivot}}$ dark halos in which the mass ratio of total stellar masses to dark halos reaches its peak. Hence, $M_{\text{h, pivot}}$ is the halo mass where galaxies have sufficiently evolved their stellar components compared to the growth of dark halos, rather than the halo mass where galaxies can form stars most efficiently at that epoch.

Figure 19 shows the redshift evolution of our BCEs. It is determined that the BCEs are almost constant up to $z \sim 1$, whereas they show an apparent excess only at $z > 1$. Dark
N-body simulations have shown that the BAR is much higher at high-z (e.g., Fakhouri et al. 2010; Faucher-Giguère et al. 2011); therefore, the absence of evolution of BCEs at $z < 1$ suggests that, by fixing the halo mass, the SFR of galaxies at $z < 1$ decreases as fast as the decreasing rate of accreting baryonic matters. In contrast, $z \sim 1.4$ is near the era in which the cosmic SFR density is at a peak (e.g., Hopkins et al. 2000; Madau & Dickinson 2014) and star formation in the dark halo is thought to still be efficient. This causes the excess of BCEs in $1.1 < z < 1.4$. However, we should confirm whether the excess of BCEs occur only for $z > 1$ by further observations.

5.5. Relationship between Galaxies and Dark Halos at $0.3 \leq z \leq 1.4$

In the previous sections, we investigated the dark halo properties in the framework of the halo model. We will discuss several implications from this study, focusing on the galaxy evolution and its relation to their host dark halos at $0.3 \leq z \leq 1.4$ along with other studies.
5.5.1. Effect of Merging, In Situ/Ex Situ Star Formation, and AGN Feedback on Central and Satellite Galaxy Evolution

In our HOD analysis, the power-law slope in the $M_{\text{\tiny limit}}$ versus $M_{\text{\tiny min}}$ relation changes at $M_{\text{\tiny limit}} \sim 10^{10.5} h^{-2} M_\odot$ (Figure 12). Fitted to our results, dark halo masses of central galaxies evolve according to $M_{\text{\tiny min}} \propto M_{\text{\tiny limit}}^{1.7}$ for $M_{\text{\tiny limit}} < 10^{10.5} h^{-2} M_\odot$ galaxies and $M_{\text{\tiny min}} \propto M_{\text{\tiny limit}}^{0.5}$ for $>10^{10.5} h^{-2} M_\odot$ galaxies, respectively. This two-phase evolutionary trend can be understood as different growth modes of stellar mass: star formation activity within galaxies (in situ) and galaxy mergers (ex situ). According to the results of numerical simulations, Lackner et al. (2012) reported that only approximately 15% of the final stellar mass of galaxies with stellar masses of $M_* \sim 10^{10} M_\odot$ at $z \sim 0$ was acquired via galaxy merging (i.e., ex situ evolution), and Rodriguez-Gomez et al. (2016) showed that the ex situ stellar-mass fraction rapidly increase for $M_* > 10^{11} M_\odot$ galaxies and more than 90% of stellar masses of $M_* < 10^{11} M_\odot$ are in situ stars, at least up to $z \sim 2$. Therefore, the mass-growth rate between dark halos and baryons ($M_{\text{\tiny min}} / M_{\text{\tiny limit}}$) substantially increase by changing the origin of dominated stellar masses whose formation sites are internal/external environments, which can be seen in the power-law slope of our observed $M_{\text{\tiny min}}$ versus the $M_{\text{\tiny limit}}$ diagram (Figure 12).

It is worth noting that the redshift and stellar-mass dependence of the merger rate can quantitatively be constrained if the power-law slope at the massive end can be accurately measured in future observations. The power-law slope increases as the major merger rate increases because the dark halo mass effectively increases through major merger events, and the massive end of the $M_{\text{\tiny min}}$ versus $M_{\text{\tiny limit}}$ relation exceeds the $M_{\text{\tiny min}} \propto M_{\text{\tiny limit}}^{0.7}$ power-law relation if massive galaxies frequently experience major mergers compared to less-massive galaxies. In this study, we find that the $M_{\text{\tiny min}} \propto M_{\text{\tiny limit}}^{1.7}$ relation is almost unchanged up to $z = 1.4$, indicating that the major merger rate does not largely depend on the stellar mass.

In contrast to the case of central galaxies, the evolution of $M_1$ and the resultant satellite fraction is complicated (Figures 12 and 13). Why is the abundance of satellite galaxies at $z > 1$ extremely small? As discussed in Section 4.6, the possible reasons for the deficit high-z satellite galaxies based on HOD analysis may be the lack of the galaxy pairs with comparable stellar masses. For instance, Márquez-Queralto et al. (2012) found that nearly 30% of massive galaxies at $z \sim 2$ form galaxy pairs with a $1:100$ stellar-mass ratio. Therefore, the large number of satellite galaxies at $z > 1$ cannot be attributed to satellite fraction for our stellar-mass range ($9.8 \lesssim \log_{10}(M_*/h^{-2} M_\odot) \lesssim 11.2$ for $z > 1$). The HOD analysis with a much wider stellar-mass range at $z > 1$ may resolve the discrepancy of satellite fraction at $z \sim 1$.

The small stellar masses of $z > 1$ satellites could be attributed to the AGN feedback in addition to the efficient disruption due to the tidal stripping as discussed in Section 4.6. Dushyan et al. (2019) investigated the effect of the feedback by the central AGNs on star formation of satellite galaxies based on cosmological zoom-in simulations and found that the AGN feedback significantly suppresses the star-forming activities of satellite galaxies at $z \sim 2$ at the earliest. Observational studies have shown that the AGN activity has a peak at $z \sim 2$ during the cosmic time, and the number density of the brightest AGNs steeply decreases after that epoch (e.g., Fan et al. 2001; Croom et al. 2009). Suppression of satellite galaxy formation will be reduced with the extinguishing of the AGNs, especially for luminous AGNs that have a large impact on the AGN feedback effect, and relatively massive satellites can start to evolve at $z < 1$. Therefore, when studying satellite galaxy formation, it is important to have a quantitative understanding of the AGN feedback effect, taking into consideration both mass and environment.

5.5.2. Downsizing of Star Formation at $0.3 < z < 1.4$

The small increase of $M_{\text{\tiny pivot}}$ over $0.3 \lesssim z \lesssim 1.4$ (Figure 17) is largely related to the redshift evolution of the BCEs (Figure 19) in the framework of the galaxy downsizing (e.g., Cowie et al. 1996; Fontanot et al. 2009). For a fixed dark halo mass, our observed BCEs at $z > 1$ are much higher than those at $z < 1$. This is indicative of the anti-hierarchical formation and evolution scenario of galaxies, wherein massive galaxies have almost completed their stellar-mass assembly at $z > 1$ (e.g., Bower et al. 2006; Collins et al. 2009). Here we discuss the downsizing of star formation with respect to the redshift evolution of the halo mass of the peak BCE and $M_{\text{\tiny pivot}}$.

There is a gap between peaks of the BCE and $M_{\text{\tiny pivot}}$ but it gradually decreases with redshift (Figure 18). The redshift evolution of this gap can be explained by the redshift evolution of the cosmic star formation. Juneau et al. (2005) investigated the star formation history over $0.8 < z < 2.0$ and found that the massive galaxies ($M_* > 10^{10.8} M_\odot$) have almost completed their star formation by $z \sim 1.5-2.0$, while the intermediate-mass galaxies ($M_* = 10^{10.2-10.8} M_\odot$) have a starburst phase at $z \sim 1$ and then they are in the quiescent evolution mode. Therefore, the slight difference of the peak halo mass between the BCE and the SHMR in our highest-z bin is indicative of the difference of this star formation history between the most massive and the intermediate-mass galaxies.

On the other hand, peaks of the BCE decrease significantly with cosmic time, whereas those of the $M_{\text{\tiny pivot}}$ show a small decrease. At $z < 1$, the intermediate-mass galaxies are in the passive evolution (Juneau et al. 2005), although less-massive galaxies continue to form stars (e.g., Ilbert et al. 2010), indicating that the cosmic star formation shifts toward less-massive galaxies after $z \sim 1$. According to studies of the star formation history of dwarf galaxies, massive dwarf galaxies with $M_* \sim 10^{8-9} M_\odot$, whose host halos correspond to masses with the peak BCE, have rapidly assembled their stellar components at $0 < z < 0.5$ (Garrison-Kimmel et al. 2019), which is consistent with the BCE peak in our study at $0.30 < z < 0.55$. Consequently, the peak of the BCE reflects the dark halo mass with the instantaneously high star-forming activities at each epoch and the evident decrease of the peak BCE supports the downsizing of star formation. However, the SHMR represents the integrated star formation within dark halos. The $M_{\text{\tiny pivot}}$ may be roughly determined by the high star-forming activities of massive galaxies at $z \gtrsim 2$ and the active star formation of less-massive galaxies at $z < 1$ cannot largely shift $M_{\text{\tiny pivot}}$ since the cosmic SFR density is small (e.g., Madonna & Dickinson 2014).

6. Summary

In this paper, we present the relationship between the baryonic properties of galaxies and their host dark halos via the precision clustering and HOD analyses using a large amount of galaxy samples selected via the HSC SSP S16A data. Using the galaxy samples observed in the HSC SSP Wide layer, we obtain
∼5,000,000 galaxies over the ∼145 deg² survey field down to i = 25.9, which is a sufficient amount of data to investigate the evolutionary history of galaxies at 0.30 ≤ z ≤ 1.40 and the stellar-mass range (8.6 ≤ log₁₀(M* / h⁻²M☉) ≤ 11.2) compared to other observational studies. The SED-fitting technique evaluates fundamental physical parameters of baryons, i.e., galaxy stellar mass, SFR, and photometric redshift of each galaxy at 0.3 ≤ z ≤ 1.4. We divide our galaxy sample into four distinct redshift bins, 0.30 ≤ z < 0.55, 0.55 ≤ z < 0.80, 0.80 ≤ z < 1.10, and 1.10 ≤ z ≤ 1.40, according to their photometric redshifts. Furthermore, galaxy samples of each redshift bin are also divided into subsamples according to their stellar mass and SFR to reveal the redshift evolution and baryonic characteristic dependence of the galaxy–dark halo coevolution.

We measure the angular two-point autocorrelation functions (ACFs) of our galaxy samples. Due to the large number of galaxy samples and the wide survey field of the HSC SSP Wide layer, the ACFs can be computed with a high S/N ratio even for a large-angular scale (∼1°). Moreover, ACFs of rare objects such as massive galaxies (log₁₀(M* / h⁻²M☉) ≥ 11.2) and highly star-forming galaxies (log₁₀(SFR / h⁻²M☉ yr⁻¹) ≥ 1.0) can also be determined well. The HOD-model analysis is applied to our ACFs and the HOD framework obviously evaluates fundamental physical parameters of baryons, i.e., galaxy stellar mass, SFR, and photometric redshift of each galaxy at 0.3 ≤ z ≤ 1.4.

Our major findings based on the halo-model analysis in this study can be summarized as follows:

1. For SM samples, the correlation lengths show a monotonic increase with the stellar-mass limit, irrespective of its redshift, and a steep increase at log₁₀(M* / h⁻²M☉) ≥ 10.4 for each redshift bin. This suggests that massive galaxies are hosted by more massive dark halos for each redshift. However, for SFR samples, correlation lengths are almost constant up to log₁₀(SFR / h⁻²M☉ yr⁻¹) ~ 0 and then increase steeply with the SFR limit. On the low-SFR end, the galaxy clustering signal is thought to be diluted by the mixture of the strong correlation of red, passive galaxies and the weak correlation of low-SFR blue galaxies. In contrast, galaxies with high SFRs show a strong correlation regardless of their redshift. We can interpret such strong clustering signals as being due to the fact that high SFR galaxies tend to reside in overdensity regions, where galaxies strongly cluster with each other if high SFRs are mainly induced by galaxy interactions and/or mergers.

2. Satellite fractions of HSC galaxies are mostly consistent with those of previous observational studies. The satellite fractions of less-massive galaxies at z ≤ 1 are almost constant at ∼20%, and they gradually decrease toward the high-mass end beyond log₁₀(M* / h⁻²M☉) ~ 10.4. The decreasing evolution of satellite fractions at the massive end can be understood as a result of the short dynamical friction timescale of galaxies within massive dark halos. The satellite fraction at z > 1 is significantly reduced from z ~ 1 even for less-massive galaxies, which is also seen in z > 3 results using LBG samples. This may be due to the rarity of massive galaxies in the high-z; i.e., less-massive galaxies live as central galaxies rather than satellite galaxies in the vicinity of massive galaxies, which are quite rare objects compared to the low-z universe. Moreover, the stellar-mass loss and/or dimming of high-z satellite galaxies due to the efficient tidal stripping/shocking, and the high merger rate can also be attributed to the small satellite fraction at z > 1.

3. The large-scale galaxy biases monotonically increase with the stellar-mass limit and redshift. The galaxy biases of the less-massive galaxies at 0.30 ≤ z < 0.55 show almost unity, indicating that low-mass galaxies in the low-z universe trace the underlying invisible dark matter distribution well.

4. The SHMR at z ≤ 1 shows good agreement with the prediction of the empirical model by Behroozi et al. (2019), although the results show a slight excess with 1.5–2σ levels at the massive ends. The discrepancy may be caused by an underestimate of the massive galaxy abundance in previous studies. SHMRs at a lower mass than the pivot halo mass show relatively smaller values compared to the theoretical predictions, although all of our results are within the 1σ confidence intervals of Behroozi et al. (2019).

5. Tracing the redshift evolution of the SHMRs reveals that the overall shape of the SHMR exhibits little evolution at 0 ≤ z ≤ 1. However, we can clearly identify two characteristics beyond z = 0.8: the peak SHMR decreases and the pivot halo mass shifts toward a higher halo mass with redshift. The redshift evolution of the SHMR can be explained by the redshift evolution of the stellar-mass function and the supernova feedback effect. By connecting our SHMRs to higher-z results, we systematically show that the pivot halo mass is almost constant (Mḥ pivot ~ 10¹²M☉) up to z ~ 5, using only the clustering and HOD-model analyses. This result is consistent with the theoretical predictions for galaxy formation models (e.g., Rees & Ostriker 1977; Wang et al. 2013; Dekel et al. 2019).

6. The BCES of our SM samples are almost consistent with the predictions of empirical models. The halo mass with the peak BCE is 10¹¹.⁰⁻¹¹.⁵ h⁻¹M☉, which is ∼0.5–1.0 dex smaller than the Mḥ pivot of the SHMR. This indicates that the most efficient star formation activity is thought to proceed in galaxies hosted by 10¹¹.⁰⁻¹¹.⁵ h⁻¹M☉ dark halos, rather than galaxies that reside in Mḥ pivot dark halos.

Subsequent to this study, we will extend our research to less-massive galaxies in the same redshift range as well as higher-z galaxies at 1.4 < z < 3.0 using the data set of the HSC SSP Deep/UltraDeep layers by combining with NIR data obtained by other extensive surveys (e.g., UKIDSS, VIKING) and u-band data obtained in the CLAUDS program (Sawicki et al. 2019). Moreover, we plan to investigate the relationship between dark halos and galaxies more precisely by separating galaxy populations into star-forming galaxies and passive galaxies, using more sophisticated halo-model analysis methods (e.g., Tinker et al. 2013; Cowley et al. 2019). By connecting the results in this study to future studies, we will be able to reveal the galaxy–dark halo coevolution history across a wide mass range and cosmic time.

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