Photometric Objects Around Cosmic Webs (PAC) Delineated in a Spectroscopic Survey. II. Morphology, Color, and Size Dependences of the Stellar–Halo Mass Relation for Massive Galaxies

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Abstract
In this paper, we report a robust measurement of the morphology, color, and galaxy size dependences of the stellar–halo mass relation (SHMR) at the high-mass end \( (10^{11.5} M_\odot < M_\star < 10^{14} M_\odot) \) at redshift \( z_s \approx 0.6 \). Applying our method, Photometric objects Around Cosmic webs (PAC), developed in a previous work by Baryon Oscillation Spectroscopic Survey and Hyper Suprime-cam Subaru Strategic Program observations, we measure the excess surface density \( (\delta_2 w_p(r_p)) \) of satellites around massive central galaxies with different morphologies indicated by the Sérsic index \( n \). We find that more compact (larger \( n \)) central galaxies are surrounded by more satellites. With the abundance matching method, we estimate the halo mass for the central galaxies and find that it increases monotonically with \( n \), solid evidence for a morphology dependence of the SHMR. Specifically, our results show that most compact galaxies \( (n > 6) \) have a halo mass around 5.5 times larger than disk galaxies \( (n < 2) \). Similarly, using the effective radius \( R_e \) and the rest-frame \( u - r \) color, we find that red (large) galaxies reside in halos that are in average 2.6 (2.3) times more massive than those hosting blue (small) galaxies.

Unified Astronomy Thesaurus concepts: Galaxy formation (595); Galaxy dark matter halos (1880)

1. Introduction
The stellar–halo mass relation (SHMR) is one of the most fundamental relations in galaxy–halo connection (see Wechsler & Tinker 2018 for a review), in which larger dark matter halos host more massive galaxies with a relatively tight scatter. The SHMR has been measured with different data and methods in the past decade (Zheng et al. 2007; Guo et al. 2010; Wang & Jing 2010; Yang et al. 2012; Moster et al. 2013; Behroozi et al. 2019), and it reflects the sophisticated regulation of complex physical processes in galaxy formation, such as gas accretion and feedback processes at different mass scales.

The SHMR is a relation between the halo mass and galactic stellar mass, which was assumed to be independent of other properties of halos or galaxies in early studies. However, recent studies (e.g., Cooper et al. 2010; Zentner et al. 2014; Zu et al. 2021, 2022) have paid more attention on whether galaxies with different properties have different SHMRs, which is also related to the so-called galaxy assembly bias that causes the scatter in the SHMR. Until now, there is no consensus about the dependence on other galaxy properties. For example, some studies found that red central galaxies reside in more massive halos than blue ones (Cooper et al. 2010; Wang et al. 2013; Zentner et al. 2014; Hearin et al. 2015; Rodríguez-Puebla et al. 2015; Mandelbaum et al. 2016), while others found the opposite relation, that is, that blue galaxies have more massive host halos (Tinker et al. 2013; Moster et al. 2018; Guo et al. 2019). Using HI rotation curves, Posti et al. (2019) showed that local massive spiral galaxies are hosted by smaller dark matter halos, implying a morphology dependence of the SHMR. Moreover, this dependence does not show up in some of the current cosmological hydrodynamical simulations (Marasco et al. 2020), while it does exist in others (e.g., Cui et al. 2021).

The galaxy size dependence of the SHMR has also been investigated in some studies (Charlton et al. 2017; Desmond et al. 2017; Somerville et al. 2018), but a clear answer to this question does not exist yet. In summary, it is still under hot debate both in observations and in theories if there exist secondary parameters for the SHMR other than the stellar mass.

In this paper, using the method named Photometric objects Around Cosmic webs (PAC), which was developed in the first paper of this series (Xu et al. 2022), we measure the dependences of the SHMR on the morphology, galaxy size, and color for massive galaxies and report robust detections of both dependences, which show unambiguously that large, red or more compact galaxies are located in more massive halos.

We adopt a cosmology with \( \Omega_m = 0.268 \), \( \Omega_\Lambda = 0.732 \), and \( H_0 = 71 \text{ km s}^{-1} \text{Mpc}^{-1} \) throughout the paper.

2. Data and Method
In Xu et al. (2022; hereafter Paper I), we developed a method for estimating the projected density distribution \( n_2 w_p(r_p) \) of photometric objects around spectroscopic objects in a spectroscopic survey, where \( n_2 \) is the mean number density of the photometric objects, and \( w_p \) is the projected cross-correlation function. This quantity describes the distribution of photometric sources with certain physical properties (e.g., luminosity, mass, color) that PAC traced in the spectroscopic objects. Since the halo mass is highly correlated with the satellite distribution (Wang et al. 2021), PAC is very powerful for studying the SHMR. For details on the method, we refer the readers to Paper I.
As in Paper I, we use the Hyper Suprime-cam (HSC) Subaru Strategic Program (SSP) public data release (PDR) 2 wide-field photometric catalog (Aihara et al. 2019) as the photometric sample. To obtain more accurate physical properties, we choose sources in the footprints observed with all five bands (grizy) to ensure that there are enough bands for the spectral energy distribution (SED). Sources around bright objects are masked using the {grizy, mask, pdr2, bright, object, center} flag provided by the HSC collaboration (Coupon et al. 2018). And we use the {grizy, extended, ness, value} flag to exclude stars in the sample. Finally, there are around 2 \( \times 10^5 \) galaxies in our photometric sample. We can also construct a random point catalog (100/\text{arcmin}^2) with the same selection criteria from the HSC database for PAC analysis. The effective area calculated from the random point number is 501 deg\(^2\).

We use the CMASS sample in the Baryon Oscillation Spectroscopic Survey (BOSS; Ahn et al. (2012); Bolton et al. (2012)) that consists of massive galaxies with \( i < 19.9 \) mag as the spectroscopic sample (population 1). We first select galaxies in the redshift range of 0.5 < \( z_s < 0.7 \) and then cross match it with the HSC photometric sample we constructed above and the Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Surveys DR9 catalog (Dey et al. 2019). After that, we get the magnitudes in seven bands grizyW1W2 for each CMASS galaxy in the footprint of HSC. Then we calculate the physical properties (e.g., stellar mass and rest-frame colors) for these galaxies using the SED fitting code CIGALE (Boquien et al. 2019). The details of the SEDs have been described in Paper I. As noticed by previous studies (Maraston et al. 2013; Leauthaud et al. 2016; Guo et al. 2018), the CMASS sample is complete in terms of the stellar mass \( M_\ast \approx 10^{11.5} M_\odot \). Therefore, we adopt a stellar mass cut at \( 10^{11.5} M_\odot \) in this study. Moreover, we only consider central galaxies in the spectroscopic sample, so we select galaxies that do not have more massive neighbors within the projected distance of 1 Mpc \( h^{-1} \). Finally, there are 8028 massive (>\( 10^{11.5} M_\odot \)) central galaxies left in the spectroscopic sample.

To study the morphology and size of galaxies, we fit the HSC \( z \)-band images with a Sérsic profile (Sérsic 1963) for all the galaxies in our spectroscopic sample. The radial luminosity distribution of a galaxy is described by the Sérsic form:

\[
I(R) = I_e \exp \left(-b_n \left( \frac{R}{R_e} \right)^{1/n} - 1 \right),
\]

where \( b_n \) satisfies:

\[
\gamma(2n; b_n) = \frac{1}{2} \Gamma(2n).
\]

\( I_e \) is the intensity at the half-light radius \( R_e \), and \( n \), called the Sérsic index, describes the compactness of a luminosity profile. \( \Gamma \) and \( \gamma \) are, respectively, the Gamma function and lower incomplete Gamma function. Generally speaking, disk galaxies have exponential profiles with \( n = 1 \), and ellipticals follow the de Vaucouleurs profiles with \( n = 4 \). The 2D image fitting is performed using GALFIT (Peng et al. 2002) with the pointspread function taken into account. Other sources falling in the fitting regions are detected and masked out using SExtractor (Bertin & Arnouts 1996). Since an ongoing merger with companions may lead to a meaningless fitting result with a low \( n \), we visually inspect the images of galaxies with \( n < 2 \) and abandon those with apparent major mergers.

In the left panel of Figure 1, we show the rest-frame \( u - r \) color versus morphology diagram of the CMASS sample. The color of the galaxies is distributed bimodally and weakly correlated with \( n \). We adopt \( u - r = 2.25 \) as the color cut for blue and red galaxies with average Sérsic indexes of 3.06 and 4.86, respectively. The right panel of Figure 1 shows the galaxy size \( R_e \) versus morphology diagram, in which the galaxy size slightly increases with increasing \( n \). We use the median galaxy size \( R_e = 9.7 \) kpc as the dividing line for large- and small-size galaxies.

In Figure 2, we show the stellar mass distributions for galaxies with different morphologies (left), colors, and sizes.
The completeness of the photometric resampling by further dividing each spectroscopic subsample is robust within 0.1 Mpc.

To better illustrate the results, we only show the results for the same mass bin but with different morphologies, while the conclusion remains the same for three morphology bins, as we will show in the next section, is independent of the stellar mass. However, large and/or red galaxies tend to be more massive than small and/or blue ones. To eliminate the stellar mass dependence, we control a sampled sample of large and red galaxies that has the same stellar mass distribution as the small and blue one (dashed lines) and will use it in the following analysis.

3. Results

Following Paper I, we calculate $r_2w_p(r_p)$ between the photometric sample in two mass bins $[10^{9.5}, 10^{10.0}, 10^{11.0} M_\odot]$ and the spectroscopic sample within the stellar mass range $10^{11.3} M_\odot < M_\ast < 10^{11.7} M_\odot$ that contains most of the CMASS galaxies. In addition, to study the morphology, color, and size dependences, we divide the spectroscopic sample into six subsamples according to $n$, two subsamples according to $u-r$ color or $R_e$. Errors are estimated using jackknife resampling by further dividing each spectroscopic subsample into 50 subsamples. The completeness of the photometric sample is considered using the z-band completeness limit $C_{35}(M_\ast)$ defined in Paper I (see their Figure 1).

The measurements are shown in Figure 3. Each panel shows the results for the same mass bin but with different morphologies, colors, or sizes. To better illustrate the results, we only show the measurements for three morphology bins, while the conclusion holds for all six morphology bins. The measurements are overall robust within 0.1 Mpc $h^{-1} < r_p < 10$ Mpc $h^{-1}$. For galaxies with different morphologies, $r_2w_p(r_p)$ increases with $n$, indicating that galaxies with more compact structure have more satellites. Since the halo mass of central galaxies is highly correlated with their satellite distribution, it implies that compact galaxies reside in more massive dark matter halos. Similarly, red (large) galaxies have higher $r_2w_p(r_p)$ than their blue (small) counterparts and are expected to have larger host halos.

To quantify the halo mass difference between galaxies with different morphologies, colors, and sizes, we use abundance matching (AM; Wang & Jing 2010; Moster et al. 2013; Behroozi et al. 2019) to estimate the halo mass of galaxies. As in Paper I, we use the ΛCDM Cosmic Growth Simulation (Jing & Suto 2002; Jing 2019) with cosmological parameters $\Omega_m = 0.268$, $\Omega_\Lambda = 0.732$, and $\sigma_8 = 0.831$. The box size is 600 Mpc $h^{-1}$ with 3072$^3$ dark matter particles and softening length $\eta = 0.01$ Mpc $h^{-1}$. The SHMR can be described by a formula of double power-law form:

$$M_s = \left[\frac{M_{\rm acc}}{M_\odot}\right]^{-\alpha} + \left[\frac{M_{\rm acc}}{M_\odot}\right]^{-\beta} k,$$

where $M_{\rm acc}$ is defined as the virial mass $M_{\rm vir}$ of the halo at the time when the galaxy was last the central dominant object. We use the fitting formula in Bryan & Norman (1998) to find $M_{\rm vir}$. The scatter in $\log(M_\ast)$ at a given $M_{\rm acc}$ is described with a Gaussian function of the width $\sigma$. We populate galaxies to halos using results from Paper I with $M_0 = 10^{11.65} M_\odot h^{-1}$, $\alpha = 0.33$, $\beta = 2.39$, $k = 10^{10.50} M_\odot$, and $\sigma = 0.22$.

With the assumption that the halo mass is completely determined by the satellite distribution (Han et al. 2016; Wang et al. 2021) and with the mock galaxy catalog constructed above, the mean halo mass of central galaxies with specific properties can be estimated through matching the observed excess surface density $\bar{n}_2 w_p(R_e)$ to halos with certain halo mass in simulations. To compare observation with simulation, we define:

$$\chi^2 = \frac{1}{N_p} \sum_{i=1}^{N_p} \left( \frac{\log(n_2w_p(r_p))_{\rm obs} - \log(n_2w_p(r_p))_{\rm sim}}{\sigma(\log(n_2w_p(r_p))_{\rm obs})} \right)^2,$$

where $N_p$ is the total number of points over which $\bar{n}_2 w_p(r_p)$ is compared. We use the Markov chain Monte Carlo sampler emcee (Foreman-Mackey et al. 2013) to perform a maximum likelihood analysis.
The halo mass estimated from AM for the spectroscopic sample for different morphologies and colors is shown in Figure 4. With respect to the morphology (green dots) dependence, halo mass increases monotonically with the Sérsic index \( n \), and the most compact galaxies \( (n > 6) \) have a halo mass around 5.5 times larger than that of disk galaxies \( (n < 2) \). With respect to the color (squares), red galaxies reside in halos 2.6 times more massive than those hosting blue galaxies. With respect to the galaxy size, large galaxies reside in halos 2.3 times more massive than those hosting small galaxies.

**4. Conclusion and Discussion**

In this paper, we report the morphology, color, and size dependences of the SHMR for massive \( (10^{11.3} M_\odot < M_* < 10^{11.7} M_\odot) \) central galaxies. Using CMASS and HSC-SSP samples and with PAC developed in Paper I, we calculate the excess surface density \( \bar{n}_2 w_2(r_p) \) of satellites and neighbors for the massive central galaxies with different morphologies \( (n) \), colors \( (u - r) \), and sizes \( (R_e) \). We find that, at the same stellar mass, galaxies with more compact morphology, red color and/or large size are surrounded by more satellites. Using AM, we estimate the halo mass for central galaxies with different morphologies, colors, and sizes. The results show that more compact, red and/or large central galaxies reside in more massive halos. Specifically, the most compact galaxies \( (n > 6) \) have a halo mass 5.5 times larger than that of the disk ones \( (n < 2) \), red galaxies reside in halos 2.6 times more massive than the blue counterparts, and galaxies with large size have a halo mass 2.3 times larger than that in galaxies with small size.

The physical origin of the morphology or color dependence of the SHMR is still not well understood. One possible picture is that, for the same halo mass, compact galaxies assemble and transform their morphology earlier and then their star formation is quenched by mechanisms, such as active galactic nucleus feedback. After the quenching, their halos still keep growing under the hierarchical formation framework. For more disky galaxies, the star formation is quenched later or even continues, resulting in a larger stellar mass at a fixed halo mass. Our results also show that the morphology and color dependences are in some way degenerate, and it seems that the morphology dependence is more fundamental at least for massive galaxies.
The size dependence of the SHMR may be explained by the minor merger scenario (Naab et al. 2009; Hopkins et al. 2010), where the rate of minor mergers is higher in more massive halos, and minor mergers result in size increase. If minor mergers are more frequent in more massive halos, this may introduce a halo mass–size correlation at fixed stellar mass.

In the future, with larger photometric and spectroscopic samples, we plan to check whether the morphology, color and, size dependences of the SHMR hold for lower mass central galaxies. We also plan to verify the estimated halo mass from AM using weak lensing measurements.

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**References**

Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2012, *ApJS*, 203, 21

Aihara, H., AlSayyad, Y., Ando, M., et al. 2019, *PASJ*, 71, 114

Behroozi, P., Wechsler, R. H., Hearin, A. P., & Conroy, C. 2019, *MNRAS*, 488, 3143

Bertin, E., & Arnouts, S. 1996, *A&AS*, 117, 393

Bolton, A. S., Schlegel, D. J., Aubourg, É., et al. 2012, *AJ*, 144, 144

Boquien, M., Burgarella, D., Roelilly, Y., et al. 2019, *A&A*, 622, A103

Bryan, G. L., & Norman, M. L. 1998, *ApJ*, 495, 80

Charlton, P. J. L., Hudson, M. J., Balogh, M. L., & Khati, S. 2017, *MNRAS*, 472, 2367

Cooper, M. C., Gallazzi, A., Newman, J. A., & Yan, R. 2010, *MNRAS*, 402, 1942

Coupon, J., Czakon, N., Bosch, J., et al. 2018, *PASJ*, 70, S7

Cui, W., Davé, R., Peacock, J. A., Anglés-Alcázar, D., & Yang, X. 2021, *NatAs*, 5, 1069

Desmond, H., Mao, Y.-Y., Wechsler, R. H., Crain, R. A., & Schaye, J. 2017, *MNRAS*, 471, L11

Dey, A., Schlegel, D. J., Lang, D., et al. 2019, *AJ*, 157, 168

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, *PASP*, 125, 306

Guo, H., Yang, X., & Lu, Y. 2018, *ApJ*, 858, 30

Guo, H., Yang, X., Raichoor, A., et al. 2019, *ApJ*, 871, 147

Guo, Q., White, S., Li, C., & Boylan-Kolchin, M. 2010, *MNRAS*, 404, 1111

Han, J., Cole, S., Frenk, C. S., & Jing, Y. 2010, *MNRAS*, 407, 1208

Hearin, A. P., Watson, D. F., & van den Bosch, F. C. 2015, *MNRAS*, 452, 1958

Hopkins, P. F., Bundy, K., Hernquist, L., Wuys, S., & Cox, T. J. 2010, *MNRAS*, 401, 1099

Jing, Y. 2019, *SCPMA*, 62, 19511

Jing, Y. P., & Suto, Y. 2002, *ApJ*, 574, 538

Leauthaud, A., Bundy, K., Saito, S., et al. 2016, *MNRAS*, 457, 4021

Mandelbaum, R., Wang, W., Zu, Y., et al. 2016, *MNRAS*, 457, 3200

Marasco, A., Posti, L., Oman, K., et al. 2020, *A&A*, 640, A70

Maraston, C., Pforr, J., Henriques, B. M., et al. 2013, *MNRAS*, 435, 2764

Moster, B. P., Naab, T., & White, S. D. M. 2013, *MNRAS*, 428, 3121

Moster, B. P., Naab, T., & White, S. D. M. 2018, *MNRAS*, 477, 1822

Naab, T., Johansson, P. H., & Ostriker, J. P. 2009, *ApJL*, 699, L178

Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, *AJ*, 124, 266

Posti, L., Fraternali, F., & Marasco, A. 2019, *A&A*, 626, A56

Rodríguez-Puebla, A., Avila-Reese, V., Yang, X., et al. 2015, *ApJ*, 799, 130

Sérsic, J. L. 1963, *BAAA*, 6, 41

Somerville, R. S., Behroozi, P., Pandya, V., et al. 2018, *MNRAS*, 473, 2714

Tinker, J. L., Leauthaud, A., Bundy, K., et al. 2013, *ApJ*, 778, 93

Wang, L., & Jing, Y. P. 2010, *MNRAS*, 402, 1796

Wang, L., Weinmann, S. M., De Lucia, G., & Yang, X. 2013, *MNRAS*, 433, 515

Wang, W., Li, X., Shi, J., et al. 2021, *ApJ*, 919, 25

Wechsler, R. H., & Tinker, J. L. 2018, *ARA&A*, 56, 435

Xu, K., Zheng, Y., & Jing, Y. 2022, *ApJ*, 925, 31

Yang, X., Mo, H. J., van den Bosch, F. C., Zhang, Y., & Han, J. 2012, *ApJ*, 752, 41

Zentner, A. R., Hearin, A. P., & van den Bosch, F. C. 2014, *MNRAS*, 443, 3044

Zheng, Z., Coil, A. L., & Zehavi, I. 2007, *ApJ*, 667, 760

Zu, Y., Shan, H., Zhang, J., et al. 2021, *MNRAS*, 505, 5117

Zu, Y., Song, Y., Shao, Z., et al. 2022, *MNRAS*, in press

![Figure 4. Average halo mass estimated from AM for central galaxies with different morphologies, colors, and sizes. Green dots show the halo mass for different morphologies, blue and red squares show the halo mass and average n for blue and red galaxies, and blue and red triangles show the halo mass and average n for galaxies with small and large sizes.](image-url)