The clustering of galaxies with pseudo bulge and classical bulge in the local Universe

Lan Wang\textsuperscript{1,2*}, Lixin Wang\textsuperscript{3†}, Cheng Li\textsuperscript{3}, Jian Hu\textsuperscript{2}, Houjun Mo\textsuperscript{3,4}, Huiyuan Wang\textsuperscript{5}

\textsuperscript{1}Key Laboratory for Computational Astrophysics, National Astronomical Observatory, Chinese Academy of Sciences, Datun Road 20A, Beijing 100101, China
\textsuperscript{2}National Astronomical Observatory, Chinese Academy of Sciences, Datun Road 20A, Beijing 100101, China
\textsuperscript{3}Tsinghua Center for Astrophysics and Physics Department, Tsinghua University, Beijing 100084, China
\textsuperscript{4}Department of Astronomy, University of Massachusetts Amherst, MA 01003, USA
\textsuperscript{5}Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, China

Accepted 2018 ???. Received 2018 ???.; in original form 2018 ???.

ABSTRACT
We investigate the clustering properties and close neighbour counts for galaxies with different types of bulges and stellar masses. We select samples of “classical” and “pseudo” bulges, as well as “bulge-less” disk galaxies, based on the bulge/disk decomposition catalog of SDSS galaxies provided by Simard et al. (2011). For a given galaxy sample we estimate: the projected two-point cross-correlation function with respect to a spectroscopic reference sample, \(w_p(r_p)\), and the average background-subtracted neighbour count within a projected separation using a photometric reference sample, \(N_{\text{neighbour}}(<r_p)\). We compare the results with the measurements of control samples matched in color, concentration and redshift. We find that, when limited to a certain stellar mass range and matched in color and concentration, all the samples present similar clustering amplitudes and neighbour counts on scales above \(\sim 0.1 h^{-1}\)Mpc. This indicates that neither the presence of a central bulge, nor the bulge type is related to intermediate-to-large scale environments. On smaller scales, in contrast, pseudo-bulge and pure-disk galaxies similarly show strong excess in close neighbour count when compared to control galaxies, at all masses probed. For classical bulges, small-scale excess is also observed but only for \(M_{\text{stars}} < 10^{10} M_\odot\); at higher masses, their neighbour counts are similar to that of control galaxies at all scales. These results imply strong connections between galactic bulges and galaxy-galaxy interactions in the local Universe, although it is unclear how they are physically linked in the current theory of galaxy formation.

Key words: galaxies: morphology – galaxies: clustering

1 INTRODUCTION

A bulge is a commonly existing central component of a spiral galaxy that has more concentrated light and stars compared to the more extended disk (Sandage 1961). In fact, a prominent bulge component is observed in at least half of the bright spiral galaxies with stellar mass greater than \(\sim 10^9 M_\odot\) (Fisher & Drory 2011). Bulges can be divided into two different subcategories: classical bulges which have similar properties as elliptical galaxies, and pseudo bulges which are more like spiral galaxies, being bluer, more disky, more rotation-dominated and more active in terms of star formation (Kormendy & Kennicutt 2004). In some studies, pseudo bulges have been further divided into flat “disky pseudobulges” and thick “boxy/peanut bulges”, depending on the structure of the central components (Athanassoula 2007). In many cases, different types of bulges have been found to coexist in the same galaxy. The fraction of composite bulges in barred galaxies can be as high as 70 percent (Méndez-Abreu et al. 2014).

Three physical processes have been proposed for the formation and growth of galactic bulges. The first process is galaxy merging, during which materials of two or more galaxies condense into the center of a galaxy (Aguerri et al. 2001; Hammer et al. 2003). Another process that could form bulge in a relative short timescale is the collapse and formation of bulges due to clumpy disc instability (Noguchi 1999; Elmegreen et al. 2008). The third one is secular evolution of
slow growth of bulges, due to bar-induced disk instability (Kormendy & Kennicutt 2004; Athanassoula 2003).

In general, the current theoretical picture is that classical bulges are produced during rapid processes like merger and clumpy disk instabilities which happen more often at high redshifts. On the other hand, secular evolution affects in a long term the appearance and growth of pseudo bulges, and is still shaping morphologies of galaxies at the present day (Obreja et al. 2013; Laurikainen et al. 2014). Detailed studies of the formation of bulges also indicate possibilities beyond this general picture. For example, mergers as well as external accretion of gas could also lead to the formation and growth of pseudo bulges (Eliche-Moral et al. 2013; Guedes et al. 2013; Querejeta et al. 2013; Sauvaget et al. 2018), while wet major mergers could produce a disk galaxy with both classical bulge and pseudo bulge (Athanassoula et al. 2016). On the other hand, secular evolution can build up some massive bulges in the early universe, without the help of major mergers (Gonzalez et al. 2008).

Nevertheless, the current picture can not fully explain the observational properties of bulges. In particular, many giant galaxies have been observed to have no sign of a classical bulge, a result that is inconsistent with the hierarchical clustering cosmology which predicts the opposite, indicating that bulge formation may be somehow suppressed in mergers (Laurikainen et al. 2010). This problem is a strong function of environment: while most of the giant galaxies in the Local Group are bulgeless or with pseudo bulges, galaxies in Virgo cluster are mostly ellipticals or with classical bulges. In order to loose the tension, minor mergers have been proposed, as an important channel particularly responsible for the formation of pseudo bulges (e.g. Eliche-Moral et al. 2013), without destroying the existing thin disk in galaxies (e.g. Moster et al. 2010). However, there has been little observational evidence in support of this picture. In fact, very few pseudo bulge galaxies show signs of tidal interactions of minor mergers (Kormendy & Kennicutt 2004).

While mergers happen more often in denser environment where galaxies have more companions, merger-induced bulges might cluster more strongly than bulges formed through internal processes. In this work, we use the SDSS decomposition catalogue provided by Simard et al. (2011) to select observed galaxies with different morphologies, and compare their clustering properties. We also obtain neighbour counts of these selected galaxy samples, to study their small scale environment. By examining these statistical properties, rather than looking into individual galaxy for possible merger indicators, we hope to understand further the role merger and environment play in the formation of different types of galactic bulges.

The paper is organized as follows. In section 2.1 we introduce briefly the Simiand et al. decomposition catalogue, and how we select galaxies of different morphologies from it. Methods of measuring galaxy correlation functions and close neighbour counts are described in Section 2.2. In section 3 we first show clustering results of different types of galaxies in four stellar mass bins, then both clustering and close neighbour count results of matched samples that have the same distributions in redshift, color and concentration. Conclusions and discussions are presented in section 4.

### 2 DATA AND METHODOLOGY

#### 2.1 SDSS galaxy samples

In this work, we make use of the SDSS galaxy catalogue of Simard et al. (2011) to select samples of classical and pseudo bulges. Simard et al. (2011) performed a two-dimensional photometric decomposition of bulge and disk components, with the point spread function being convolved, for over a million galaxies in the SDSS Data Release 7 (DR7; Abazajian et al. 2009). Three different fitting models were applied to each galaxy: a pure Sersic profile, a two-component model consisting of a Sersic profile for the bulge and an exponential profile for the disk, and the same two-component model except that the Sersic index $n_b$ is fixed to $n_b = 4$. To quantify the robustness of the model fitting, two F-test probabilities are provided: 1) $P_{bS}$: the probability that the two-component model with a free Sersic index $n_b$ is not required compared to a pure Sersic model, and 2) $P_{n4}$: the probability that the two-component model with a free $n_b$ is not required compared to the two-component model with a fixed index of $n_b = 4$. Simard et al. (2011) showed that, a system truly consisting of both bulge and disk components can be robustly identified by requiring $P_{bS} < 0.32$. In their catalog 26% galaxies meet this requirement. However, a Sersic index $n_b$ is robustly determined only for 9% of the bulge+disk systems, for which $P_{n4} < 0.32$ is required.

Nevertheless, given the large size of the parent catalog, we’re able to select samples of galaxies with well classified bulge types, which are substantially large for our purpose.

We start with all the galaxies in the Simard et al. (2011) catalog with spectroscopically measured redshifts available from SDSS/DR7. This forms our parent sample, consisting of 692292 galaxies, from which we construct a number of subsamples according to the presence of a bulge and/or the bulge type. First, we select two subsamples of galaxies, with either a “pseudo bulge” or a “classic bulge” in their center.

For this purpose, following Simard et al. (2011), we first select galaxies with $P_{bS} < 0.32$ and $P_{n4} \geq 0.32$, which are expected to be truly a two-component system consisting of an exponential disk plus a bulge with a free index parameter of $n_b$. We further divide these galaxies into two sub-categories, with a bulge type of “pseudo” or “classic”, according to the empirical divider of $n_b = 2$ (Kormendy & Kennicutt 2004). Pseudo bulges are selected to have $n_b < 2$, and classical bulges are the ones with $n_b \geq 3$. Galaxies with $n_b = [2, 3]$ are not considered in order to minimize uncertainty in the classification. In addition, we select the galaxies with $P_{n4} \geq 0.68$ as the third subsample. These galaxies also have two components, a disk plus a bulge, but the bulge component can be well fitted only if the Sersic index is fixed to $n_b = 4$. Therefore these galaxies are also in the class of classical bulge.

For comparison, we also select bulge-less pure disk galaxies and elliptical galaxies from the same parent catalog. Galaxies with $P_{bS} \geq 0.68$ are the ones better fitted by a pure Sersic model than a bulge + disk model, and are considered as either a pure disk galaxy or an elliptical galaxy. We then divide the two types according to best-fit Sersic index, requiring a pure disk to have $n_b < 2$ and an elliptical to have $n_b > 3$. Galaxies with an intermediate $n_b$ are not considered for the same reason as above.

In summary, we have selected five samples: three samples for galaxies with different types of bulges, one for pure-
Comparing pseudo bulge galaxies with classical bulge galaxies, we find the former to be generally less massive, less concentrated. As expected, pseudo bulge galaxies are similar to disk galaxies in distributions of stellar mass and color, while galaxies with classical bulges are more like ellipticals in these properties. The distributions of bulge galaxies in concentrations, however, are much wider than that of disk/elliptical galaxies, showing a relative flat trend in a large range of concentration.

Fig. 1 displays the distributions of redshift, stellar mass, g-r color and the concentration parameter for our samples. Stellar masses are taken from the MPA-JHU SDSS catalogue, publicly available at http://www.sdss.org/dr12/spectro/galaxy/mpajhu/. The concentration parameter is defined as the ratio of two radii, enclosing 90 and 50 percent of the galaxy light in the r band (see Stoughton et al. 2002). Compared with the whole sample without selection of galaxy morphologies as shown in black dotted lines, the galaxies selected in our samples have in general lower redshifts, which can be understood from the fact that closer galaxies are better determined in morphology type. Disk galaxies peak at low stellar mass, blue color and low concentration, while ellipticals peak on the opposite ends. As expected, pseudo bulge galaxies are similar to disk galaxies in distributions of stellar mass and color, while galaxies with classical bulges are more like ellipticals in these properties. The distributions of bulge galaxies in concentration, however, are much wider than that of disk/elliptical galaxies, showing a relative flat trend in a large range of concentration.

Table 1. Samples of galaxies with different morphologies and bulge types selected from the Simard et al. (2011) catalogue.

| Sample               | Selection Criteria | Size   |
|----------------------|--------------------|--------|
| Pseudo bulge A       | $P_{ps} < 0.32, P_{p4} < 0.32, n_b < 2$ | 19,813 |
| Classical bulge A    | $P_{ps} < 0.32, P_{p4} < 0.32, n_b > 3$ | 18,214 |
| Classical bulge B    | $P_{ps} < 0.32, P_{p4} > 0.68, n_b > 4$ | 7,219  |
| Pure disk            | $P_{ps} < 0.68, n_g < 2$ | 11,102 |
| Elliptical           | $P_{ps} > 0.68, n_g > 3$ | 1,065  |

indicating that these properties can not be simply used as criteria to distinguish classical bulges from pseudo bulges.

2.2 Methodology

2.2.1 Two-point cross-correlation functions

In this work we use two-point cross-correlation function (2PCCF) to quantify the clustering of our galaxies. Below we describe briefly the methodology of measuring the 2PCCF. Detailed description can be found in Li et al. (2006b, 2012).

For a given galaxy sample $Q$, the 2PCCF is measured with respect to a reference galaxy sample $G$, which is a magnitude-limited galaxy catalog selected from the SDSS/DR7-based NYU-VAGC catalog dr72, consisting of about half a million galaxies with r-band Petrosian apparent magnitude limited to $r < 17.6$. r-band absolute magnitude in the range of $-24 < M_r^0 < -16$, and spectrophotically-measured redshift in the range of $0.01 < z < 0.5$. Both $r$ and $M_r^0$ are corrected for Galactic extinction, and $M_r^0$ is also corrected for evolution and K-corrected to its value at $z = 0$. The NYU-VAGC catalog is publicly available at http://sdss.physics.nyu.edu/vagc/, and described in detail in Blanton & Roweis (2007). We have constructed a random sample $R$, which has the same selection effects as, but 10 times larger than the reference sample, following the method described in Li et al. (2006a).

A redshift-space 2PCCF, $\xi(s)(r_p, \pi)$, between Samples $Q$ and $G$, is first estimated by:

$$\xi(s)(r_p, \pi) = \frac{N_{QG}}{N_Q N_G} \frac{QG(r_p, \pi)}{QR(r_p, \pi)} - 1,$$

where $r_p$ and $\pi$ are the pair separations perpendicular and parallel to the line of sight; $N_Q$ and $N_G$ are the number of galaxies in the random sample ($R$) and in the reference sample $G$; $QG(r_p, \pi)$ and $QR(r_p, \pi)$ are the counts of cross pairs between samples $Q$ and $G$, and between samples $Q$ and $R$. The projected 2PCCF, $w_p(r_p)$, is then obtained by integrating $\xi(s)(r_p, \pi)$ over $\pi$:

$$w_p(r_p) = \int_{-\infty}^{+\infty} \xi(r_p, \pi) d\pi = \sum \xi(r_p, \pi_i) \Delta \pi_i.$$
Figure 2. Upper panels: clustering of galaxies in different stellar mass bins, indicated in range of $\log(M_{\text{stars}}/M_\odot)$ in black. Blue, red, green, cyan and gold lines are results of pseudo, classical A, classical A+B, disk and elliptical samples. Black dots are results of the whole Simard et al. sample, matched with the same stellar mass criterion. Bottom panels: for given stellar mass bin, the ratio between 2PCCF of galaxies in selected morphology samples and that of galaxies in the whole sample.

Figure 3. For four stellar mass bins as indicated in range of $\log(M_{\text{stars}}/M_\odot)$ in black, panels in each row show at the given stellar mass bin, the distributions of redshift, color and concentration of galaxies in matched samples. Black dashed lines are distributions of the corresponding control samples.

2.2.2 Close neighbour counts

In addition to 2PCCFs, we count the number of companion galaxies in the vicinity of the galaxies in our samples, using a photometric reference sample which is also constructed from the NYU-VAGC version dr72 by selecting galaxies with $r$-band apparent magnitude down to $r < 21$. The photometric reference sample includes about 2.5 million galaxies over the same sky area of the galaxy samples being studied. We make a statistical correction for the effect of chance projections on the neighbour counts, by subtracting the average count at the same scale around a large number of randomly placed galaxies. When compared to 2PCCFs, close neighbour counts are not affected by fiber collisions on small scales, and can include much fainter companion galaxies thanks to the photometric sample which is much deeper than the spectroscopic sample, thus probing the effect of close companions over a broader range of mass ratios. Detailed description of the method of estimating close neighbour counts, as well as tests and example applications can be found in Li et al. (2008a,b).

3 RESULTS

3.1 Joint dependence of clustering on galaxy mass and morphology

Galaxy clustering depends on stellar mass, with more massive galaxies being clustered more strongly (Li et al. 2006a). Therefore, we first divide galaxies in each of our samples into four intervals of stellar mass, and estimate the 2PCCF $w_p(r_p)$ for each of them. For each of the stellar mass interval, Fig. 2 compares the $w_p(r_p)$ measurements for galaxies of different morphological types. The bottom panels in the same figure display the ratios of the $w_p(r_p)$ measured from our samples relative to the $w_p(r_p)$ measured for all the galaxies.
in the same stellar mass range as selected from the whole sample of Simard et al. (2011).

Overall, the figure shows that all the samples appear to cluster similarly at both smallest scales \( r_p \lesssim 0.1h^{-1}\text{Mpc} \) and scales larger than a few Mpc. At intermediate scales, different samples show different clustering behaviors. First, galaxies with classical bulges present stronger clustering than those with pseudo bulges, with larger differences at lower masses, and the difference becomes indistinguishable when stellar mass exceeds \( 10^{11} M_\odot \). Second, although the error bars are large for the disk and elliptical galaxies due to small sample sizes, there is still an obvious trend that disk galaxies show weakest clustering and ellipticals appear to cluster most strongly, in a given stellar mass range. It is interesting that galaxies with pseudo bulges seem to show very similar clustering behaviors to the disk galaxies of similar mass, while galaxies with classical bulges are more like ellipticals in terms of mass dependence of clustering. Finally, when compared to the whole sample, the pseudo bulges are clustered more weakly at all masses except the highest mass bin, while the clustering amplitude of classical bulges is comparable to that of the whole sample at all masses except the lowest masses at which the classical bulges are more strongly clustered.

Previous studies have well established that, at given stellar mass, galaxy clustering depends also on other properties, such as color and structural parameters, with stronger clustering for galaxies with redder colors and more centrally concentrated light distributions (e.g. Li et al. 2006a). In order to exclude the effect of such residual dependence, for a certain stellar mass bin, we have trimmed the galaxy samples in such a way that they have the same distributions in \( q - r \) color, concentration parameter and redshift. From what follows we will not consider the elliptical galaxy sample which is too small after trimmed to allow any meaningful statistics. As mentioned above, we will combine the two bulge samples “classical A” and “classical B” into a single sample in order for better statistics. We note that we have repeated all the following analyses using the sample of “classical bulge A” alone, finding pretty much the same results as what we find from the merged sample. Fig. 4 shows the distributions of redshift, \( q - r \) and concentration for the three samples: “pseudo bulge”, “classical bulge” and “disk”, after they are trimmed. At given stellar mass, the three samples are matched very well in all these parameters.

For each given stellar mass bin, we have constructed a set of 20 control samples to be compared with the three matched samples. The control samples are randomly selected from the reference sample G as mentioned in sec. 2.2.3, each required to have the same distributions in redshift, color and concentration as the galaxy samples. The number of galaxies included in each control sample is the same as the largest of the matched samples in the stellar mass bin considered. The distributions of redshift, color and concentration for the control samples are plotted as black dashed lines in Fig. 3

The clustering results of the matched galaxy samples and control samples in different stellar mass bins are shown in Fig. 4. For control samples, the median of the 20 control samples is shown as black circles. Ratios of the 2PCCF of the three matched samples relative to the corresponding control samples (black circles) are presented in the lower panels. In general, the differences between different morphology samples and control samples are small, mostly within error bars, except for the most massive bin. Therefore, the significant differences between classical bulge galaxies and pseudo bulge/disk galaxies as seen in Fig. 2 should be largely attributed to their different distributions of redshift, color and concentration. For the most massive bin, there seems to have a trend that both disk galaxies and pseudo bulge galaxies cluster less strongly than classical bulge galaxies and the control samples. We would not overemphasize this trend, however, given the large errors in the mass bin.

We note that, at smallest scales with \( r_p \lesssim 0.1h^{-1}\text{Mpc} \) and in some stellar mass bins, both the disk galaxies and the pseudo bulge galaxies tend to present a sharply increasing \( w_p(r_p) \) when compared to the control samples. However, considering both the small number of pair counts at these small scales and the possible residual effect of SDSS fiber collisions, we are unable to make any firm conclusions based on the \( w_p(r_p) \) measurements at these scales. In the next subsection, we will focus on these small scales by estimating close neighbour counts. To summarize the analyses presented in this subsection, we have found no significant differences in clustering at scales above \( 0.1h^{-1}\text{Mpc} \) for all the samples considered in our study.

### 3.2 Probing the small-scale environment by counting close neighbours

We have estimated the background-subtracted close neighbour count as a function of projected radius, \( N_{\text{neighbour}}(< r_p) \), in the vicinity of both the samples of different morphology types and the corresponding control samples, using the photometric reference sample down to a given limiting magnitude of \( r_{\text{lim}} \), as described in § 2.2.2. Fig. 5 displays the results obtained with \( r_{\text{lim}} = 20 \), separately for the different stellar mass bins. In a given stellar mass bin, all the samples including the samples of pseudo bulge, classical bulge and pure disk galaxies, as well as the control samples, are closely matched in \( q - r \) color, concentration and redshift as in the previous subsection. First of all, we see that the neighbour counts at scales larger than \( \sim 0.1h^{-1}\text{Mpc} \) are quite similar for all the samples when the stellar mass is limited to a certain range. This is well consistent with the 2PCCF comparison results as presented above.

On small scales with \( r_p \) less than a few \( \times100h^{-1}\text{kpc} \), the neighbour counts reveal a number of interesting results, which could not be seen above from the 2PCCFs. First, galaxies with classical bulges have similar numbers of neighbours to the control samples, and this is true for all the scales probed and at stellar masses above \( 10^{10} M_\odot \). In the lowest mass bin, the classic bulges have significantly higher counts at \( r_p < 0.1h^{-1}\text{Mpc} \) than all the other samples, about a factor of 5 higher than the control sample at the smallest scales. Second, in contrast to classic bulges, pseudo bulges in the highest mass bin show almost no enhancement in the small-scale neighbour count compared to control samples, but the ratio of the neighbour counts increases to \( \sim 2 - 3 \) for all the other mass bins. Finally, for disk galaxies, a positive correlation with stellar mass is clearly seen, in the sense that the neighbour count ratio is flat at unity at the lowest masses but increases with increasing mass, reaching a factor of \( \sim 5 \) at the smallest scales in the highest mass bin.
Figure 4. Clustering of galaxies in four stellar mass bins, for galaxy samples matched with the same distributions of redshift, color and concentration in given stellar mass bin. The stellar mass intervals are indicated in range of \( \log(M_{\text{stars}}/M_\odot) \) in black. For each stellar mass interval, the upper panels give 2PCCF clustering results of pseudo bulge galaxies (blue line), classical A+B bulge galaxies (red lines), and disk galaxies (cyan lines). Black circles are the median result of the 20 control samples constructed. Error bars on matched galaxy samples are bootstrap errors. The corresponding lower panel shows the ratios between 2PCCF of selected galaxy samples and that of the control sample. Black error bars indicate the 68 percentile distributions of the 20 control samples constructed.

Figure 5. Neighbour counts of galaxies in four stellar mass bins indicated in range of \( \log(M_{\text{stars}}/M_\odot) \) in black, for galaxy samples matched with the same distributions of redshift, color and concentration in each panel. Upper panels are the average counts of galaxies in the photometric sample to an r-band limiting magnitude of \( r_{\text{lim}} = 20 \) within a given projected radius \( r_p \) from the selected galaxies. Blue/red solid line gives result of pseudo/classical A+B bulge samples, and cyan solid line is for disk samples, with bootstrap errors shown. Black circles give the median results of the 20 control samples in each stellar mass bin. Lower panels are the ratios between the neighbour counts of the morphology selected samples to the median results of the control samples, with black error bars indicating the 68 percentile distributions of the 20 control samples.

In the stellar mass range of \( 10^{10-11}M_\odot \), pseudo bulge and disk galaxies show similar excess of neighbour counts with respect to the control samples. At lowest and highest mass bins, the error bars become relatively large, due to the small sizes of the matched galaxy samples when all the samples of pseudo bulge, classical bulge and disk in a given stellar mass bin are required to be closely matched in various properties. In order to see the difference between pseudo bulge and disk galaxy samples with better statistics, we have repeated the analysis in Fig. 5 but matching only pseudo bulge and disk samples to have similar color, concentration and redshift. The results in the stellar mass range of \( 10^{9-11}M_\odot \) are shown in Fig. 6. The errors of the neighbour counts and their ratios to the control samples are reduced.
Clustering of pseudo bulge and classical bulge galaxies

Figure 6. Similar as Fig. 5, but for pseudo bulge and disk galaxies matched with the same distributions of redshift, color and concentration, while control samples are also constructed to have the same distributions. Stellar mass bins are in the range of $10^9 - 10^{11} \, M_\odot$.

Figure 7. The ratio between neighbour counts of the matched pseudo bulge (left panel) and disk (right panel) galaxy samples and that of the corresponding control sample, for four stellar mass bins indicated by different color. Error bars show bootstrap errors of the matched galaxy samples.

as expected, particularly for disk galaxy samples, and qualitatively the results remain the same as what we see from Fig. 5 — the neighbour count amplitudes at scales smaller than $\sim 0.1 \, h^{-1}\text{Mpc}$ are significantly enhanced when compared to control galaxies of similar mass, for both pseudo bulges and disk galaxies and at all stellar masses.

Fig. 6 shows that, quantitatively, the $N_{\text{neighbour}}$ ratio of the pseudo bulges presents a clear anti-correlation with stellar mass, with the small-scale $N_{\text{neighbour}}$ ratio decreasing from $\sim 3$ at the lowest masses to $\sim 2$ at the highest masses. For disk galaxies, the $N_{\text{neighbour}}$ ratio at the small scales depends on stellar mass in a non-monotonic manner — the small-scale enhancement in the neighbour count is lowest at $M_{\text{stars}} = 10^{9.5} - 10^{10} \, M_\odot$, and increases at both higher and lower masses.

The non-monotonic mass dependence of disk galaxies can be seen more clearly in Fig. 6 (see the right panel), where we show the disk galaxy-to-control ratio as a function of $r_p$ for all the stellar mass bins in a single panel. The $N_{\text{neighbour}}$ ratios are consistent at unity on scales larger than $\sim 0.1 \, h^{-1}\text{Mpc}$, and increases significantly at smaller scales, reaching a value of 5 or 6 at the smallest scales in both the lowest mass bin ($10^9 < M_{\text{stars}} < 10^{9.5} \, M_\odot$) and the highest mass bin ($10^{10.5} < M_{\text{stars}} < 10^{11} \, M_\odot$). At the intermediate masses, the ratio is at levels of 2-3. In the left-hand panel of the same figure, the results are plotted in the same way for the samples of pseudo-bulge galaxies. The $N_{\text{neighbour}}$ ratios also go beyond unity at small scales with $r_p < 0.1 \, h^{-1}\text{Mpc}$, but they are highest at the lowest masses and decreases with increasing mass monotonically at fixed scale.

© 2018 RAS, MNRAS 000.
It is striking to see the highly enhanced neighbour counts with respect to the control samples, which are observed at \( r_p < 0.1 h^{-1}\text{Mpc} \) for all the samples of both pseudo-bulge galaxies and disk galaxies, although the \( N_{\text{neighbour}} \) ratio ranges from \( \sim 2 \) to \( \sim 6 \) depending on mass. At \( r_p = 0.1 h^{-1}\text{Mpc} \), the average count of neighbours around both types of galaxies is around 0.4 for stellar mass in the range \( 10^{9.5-11} M_\odot \), and can be well exceeds 0.5 for \( 10^{9.5-11} M_\odot \), which means, more than 50\% of the galaxies in these samples have a companion within 100 \( h^{-1}\)kpc. This fraction is unexpectedly high, which is comparable to or even higher than the neighbour counts found (\( \sim 0.4 \)) for the most strongly star-forming galaxies in the SDSS, as measured by Li et al. (2008a) using the same photometric reference sample and the same methodology (see their Fig. 11).

Since both pseudo bulge galaxies and disk galaxies may have strong star formation, their large neighbour counts at small scales as seen in Fig. 5 and Fig. 6 may be partly (if not entirely) a result of their high star formation rates. This is not the case, however, as can be seen from Fig. 5 which compares the distribution of our samples in the plane of specific SFR (sSFR=\( \text{SFR}/M_{\text{stars}} \)) versus stellar mass. The pseudo-bulge galaxies and disk galaxies in our sample present very similar distributions, which are also similar to the distribution of the galaxies with classical bulges, as well as the distribution of control galaxies. Therefore, the connection between \( N_{\text{neighbour}} \) and sSFR as found in Li et al. (2008a) is unlikely the reason for the strong \( N_{\text{neighbour}} \) enhancements found for the pseudo bulges and disk galaxies. For this figure we have taken the SFR measurements from the MPA-JHU SDSS catalogue (see § 2).

We have further examined the possible contribution of the \( N_{\text{neighbour}} \)-sSFR connection to our results by additionally matching the pseudo-bulge samples with the control samples in sSFR. The neighbour counts and the ratio to the control sample are shown in Fig. 9. Although the overall amplitudes of the \( N_{\text{neighbour}} \) ratio become lower and more noisy, the general trends and our conclusions remain unchanged. Apparently the small-scale enhancement in the neighbour counts as found in our samples and the similar enhancement as previously found by Li et al. (2008a) in strongly star-forming galaxies are not the same effect.

The neighbour counts we have obtained so far are based on the photometric sample down to a \( r \)-band limiting magnitude of \( r_{\text{lim}} = 20 \). In Fig. 10 we examine the dependence of neighbour counts on \( r_{\text{lim}} \), showing the \( N_{\text{neighbour}} \) ratios between the matched galaxy samples and the control samples for three different magnitude limits: \( r_{\text{lim}} = 20 \), 19, and 18. Each panel compares the results of the three limiting magnitudes but for a given stellar mass bin, and results for the pseudo-bulge samples and those for the disk galaxy samples are shown in upper and lower panels, respectively. In general, for a given stellar mass bin, the \( N_{\text{neighbour}} \) ratio depends very weakly on \( r_{\text{lim}} \). This indicates that the excess of the neighbour counts on small scales is dominated by relatively bright companions with \( r < 18 \), while fainter neighbours contribute little.

![Figure 8](image-url)

**Figure 8.** sSFR of the matched bulge galaxy samples and disk samples (solid lines are median value, and error bars give 68 per cent distribution) as a function of galaxy stellar mass. Blue, red and cyan lines are for pseudo bulge, classical bulge and disk samples respectively. Results of the corresponding control samples are shown by black dashed lines.

4 SUMMARY AND DISCUSSION

In this work we have investigated the clustering and close neighbour counts for galaxies with different types of galactic bulges and stellar masses. For this purpose, we have selected samples of galaxies with “classic” or “pseudo” bulges, as well as samples of “bulge-less” disk galaxies, using the photometric catalog of Simard et al. (2011) who performed a careful bulge-disk decomposition on the optical image of a large sample of galaxies in the SDSS. For a given galaxy sample, we have estimated the projected two-point cross-correlation function \( w_p(r_p) \) with respect to a reference sample consisting of about half a million spectroscopically observed galaxies, and the average background-subtracted neighbour count within a projected separation \( N_{\text{neighbour}}(< r_p) \) using a photometric reference sample down to \( r \)-band limiting magnitude of \( r_{\text{lim}} = 20 \). In order to isolate out the known correlations between the local environment and galaxy properties such as stellar mass, color and structural parameters, we have divided the galaxies into narrow ranges of stellar mass and closely matched the samples in a given mass range, so that the samples of different morphologies and bulge types have similar distributions in redshift, \( g-r \) and concentration parameter \( R_{\text{e0}}/R_{\text{e}} \).

Our main conclusions can be summarized as follows:

- When limited to a certain stellar mass range and closely matched in redshift, color and concentration, all the samples are found to present similar clustering amplitudes and average neighbour counts on scales larger than \( \sim 0.1 h^{-1}\text{Mpc} \). This indicates that neither the presence of a galactic bulge nor the type of the bulge is linked to intermediate-to-large scale environments.
- On scales less than \( \sim 0.1 h^{-1}\text{Mpc} \), the galaxies with a classic bulge present similar clustering properties and neighbour counts to control galaxies of similar mass, color and
Clustering of pseudo bulge and classical bulge galaxies

Figure 9. Similar as Fig. 5, but for control samples matched to have the same distributions of redshift, color, concentration and sSFR, with the pseudo bulge samples as shown in Fig. 5.

Figure 10. The ratio between neighbour count of matched pseudo bulge (upper panels) and disk (bottom panels) galaxy samples and that of the corresponding control sample, for four stellar mass bins. Solid, dotted and dashed lines corresponds to the results of r-band limiting magnitude of $r_{lim} = 20$, 19, and 18 respectively. Error bars on the dotted lines show bootstrap errors for results of $r_{lim} = 19$.

concentration, and this is true for all the scales probed and at all the masses except the lowest mass bin of $10^{9.5} < M_{stars} < 10^{10}M_\odot$. In the lowest mass bin, galaxies of classic bulges appear to have more neighbours than the control galaxies, indicating that the presence of a classic bulge in low-mass galaxies is linked to galaxy-galaxy interactions or mergers.

- Galaxies with a pseudo bulge have more close neighbours within $\sim 0.1h^{-1}\text{Mpc}$ when compared to control galaxies of similar mass, color and concentration, with the average neighbour count being enhanced by a factor of 2-3 at the smallest scales. The enhancement is weakly anti-correlated with stellar mass, with the sample-to-control $N_{neighbour}$ ratio slightly decreasing with increasing mass.

- Disk galaxies with no bulges also show enhanced close neighbour counts within $\sim 0.1h^{-1}\text{Mpc}$ compared to the control galaxies, but the enhancement depends on stellar mass in a non-monotonic way, with the highest sample-to-control $N_{neighbour}$ ratio occurring at both high and low masses. As a consequence, galaxies at intermediate masses ($M_{stars} \sim 10^{9.5-10}M_\odot$) present the weakest signal. The $N_{neighbour}$ ratio increases to the levels of 5-6 at $M_{stars} > 10^{10.5}M_\odot$ and $M_{stars} < 10^{9.5}M_\odot$, an effect which is similar or even stronger than the previous measurement of the same quantity for the most strongly star-forming galaxies in the SDSS.

On scales larger than a few $\times100h^{-1}\text{kpc}$ we see no difference in both the two-point cross-correlations and the neighbour counts for all of our samples, when they are matched to have similar mass, color and concentration parameter. This implies that the presence of a central bulge and the bulge type in a galaxy are not affected by environmental effects occurring at intermediate-to-large scales.
Figure 11. Fraction of galaxies in different large scale structures (left panel: sheet; middle panel: filament; right panel: halo) as a function of galaxy stellar mass, for galaxy samples and control samples matched with the same distributions of redshift, color and concentration in each panel. The error bars of the bulge samples are Poisson errors, where for the control samples, dashed lines with error bars give the median value and the variation range of the 20 control samples constructed for given stellar mass bin.

This result is well consistent with previous studies of galaxy clustering and environment. For instance, Li et al. (2006a) estimated the two-point auto-correlation function of SDSS galaxies as a function of their stellar mass, optical color and galaxy structure for spatial scales above $0.1 h^{-1}$Mpc, and found the clustering amplitude at given scale shows obvious dependence on color but no dependence on concentration and surface mass density when stellar mass is limited to a narrow range. Studies of the local environment of SDSS galaxies have led to the same conclusion: the environment of a galaxy does not relate to its overall structure once the stellar population age and stellar mass are fixed (see a review by Blanton & Moustakas 2004 and reference therein).

For pure-disk galaxies without an obvious bulge component, some of the recent studies have suggested that this class of galaxies are preferentially found in low-density regions (e.g. Kantsch et al. 2009), and that a subset of them with a very thin disk tend to avoid filamentary structure on large scales (Bizyaev et al. 2017). We have examined the latter effect using our galaxy samples and the large-scale structure type provided by Wang et al. (2016). These authors obtained the initial density field for the local Universe based on the distribution of galaxy groups in the SDSS volume, and reconstructed the three-dimensional density field of the local Universe, as well as its formation history, by running a high-resolution $N$-body constrained simulation. The density field reconstruction provides not only the local density averaged over 1-3 Mpc scale for each real galaxy in the SDSS volume, but also the type of the large-scale structure (LSS) in which the galaxy resides. The large-scale structures in the density field are classified into four different types: void, sheet, filament, and halo, determined from the density field in a dynamical way following Hahn et al. (2007). The density field is limited to local galaxies with redshifts less than $z \sim 0.12$, and includes more than 70% of our galaxies.

Different from what we’ve seen on large scales, on scales less than $\sim 0.1 h^{-1}$Mpc we have observed significant excess in the close neighbour counts around our galaxies when compared to control galaxies of similar mass, color and concentration. The strength of the excess depends on both morphology/bulge type and stellar mass. For classical bulges, the small-scale excess is seen only at low mass ($M_{stars} = 10^{9.5-10} M_{\odot}$), where the ratio between the classical bulge sample and the control sample reaches $\sim 5$ at the smallest scales ($r_p \sim 10h^{-1}$kpc, see Fig 4). If we believed...
that classical bulges form by major mergers as mentioned in (1) our result may be suggesting that classical bulges in massive galaxies with $M_{\text{stars}} > 10^{10} M_{\odot}$ are post-merger remnants, thus showing no excess in close neighbour count compared to control galaxies, and that less massive galaxies with $M_{\text{stars}} < 10^{10} M_{\odot}$ might still be forming bulges. However, we note that our sample of classical bulges in the lowest mass bin is quite small, resulting in large errors in the neighbour counting as can be seen form Fig. 3. The highly excess of close neighbour counts around classical bulges in low-mass galaxies as reported here need to be double checked in next works with larger samples. If it is proved by future larger samples, our result means that low mass classical bulges, unlike the more massive ones, prefer to live in relative denser local regions and may form from a different mechanism, such as interaction-induced clumpy disk instability that happens more often and form classical bulges at high redshifts.

The most striking result of our work is that both pseudo-bulge galaxies and pure-disk galaxies show significant enhancement in close neighbour counts when compared to control galaxies of similar mass, color and concentration. The result holds even when the distribution of specific star formation rate is additionally matched when constructing the control sample. In some cases, the close neighbour count enhancement is even stronger than the enhancement in the same quantity previously measured for the most-strongly star-forming galaxies in SDSS (Li et al. 2008). Furthermore, we found that the neighbour count enhancement doesn’t change much when we include fainter and fainter neighbour galaxies in the counting, which is done by increasing the limiting magnitude of the photometric reference sample. This indicates that the neighbour count enhancement is dominantly contributed by relatively bright neighbours. Our result implies strong connections between pseudo bulges, pure-disk galaxies and galaxy-galaxy interactions, although it is not quite clear how they are physically linked with each other.

Recent studies of bulge formation/growth have been mostly focusing on high-z galaxies, where galaxy-galaxy interactions appear to play less important roles than previously expected. For instance, Tadaki et al. (2017) found a large fraction of the extended rotating disks at $z \sim 2$ to be associated with extremely compact center, dusty and strongly star-forming, which can rapidly build up a central bulge in a few $\times 10^{8}$yr. Therefore, the authors suggested that bulges are commonly formed in high-z disks by internal processes, not requiring major mergers. However, the situation is quite different when one goes to lower redshifts. In another recent study, Sachdeva et al. (2017) studied bulges in bright disk galaxies at $z \lesssim 1$ using data from both the GOODS-South ($0.4 < z < 1$) and SDSS ($0.02 < z < 0.05$) samples, concluding that clump migration and secular processes alone cannot account for the bulge growth since $z \sim 1$, and that accretion and minor mergers would be required to explain their data. Our result is apparently along the same line with their work.

Note that in this work, we select only a very small fraction of galaxies with robust bulge type determinations based on the SDSS dr7 catalogue. Due to the limited numbers of galaxies selected, our matched samples are dominated by blue and low concentration galaxies (Fig.3). With future high spatial resolution observational data, and more accurate bulge-to-disk decomposition measurement that takes into account the components of nuclear and inner lenses/rings (Gao & Ho 2017), the clustering properties and other statistics of galactic bulges could be better derived, to set more constraints on the formation of galactic bulges. In addition, theoretical studies are also needed in order to have a full understanding of the formation process of bulges of both classical and pseudo types, as well as the physical relationship with pure-disk bulgeless galaxies. According to our study, these theoretical models must involve galaxy-galaxy interactions and other environment effects over a large range of spatial scales, as well as secular processes internal to galaxies.

ACKNOWLEDGEMENTS

We thank Cheng Du, Shude Mao, Liang Gao and colleagues of the YIPA galaxy discussion group at NAOC for helpful discussions. LW acknowledges support from the NSFC grants program (No. 11573031), and the National Key Program for Science and Technology Research and Development (2017YFB0203300). CL is supported by National Key Basic Research Program of China (No. 2015CB857004) and NSFC (grant No. 11173045, 11233005, 11325314, 11320101002). CL, HJM and HYW are also supported by the National Key Basic Research and Development Program of China (No. 2015YFA0404502, No. 2018YFA0404503).

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

This paper has been typeset from a TpX/ LpX file prepared by the author.

REFERENCES

Abazajian K. N., Adelman-McCarthy J. K., Agüeros M. A., Allam S. S., Allende Prieto C., An D., Anderson K. S. J.,
