Detection of galaxy assembly bias

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ABSTRACT

Assembly bias describes the finding that the clustering of dark matter haloes depends on halo formation time at fixed halo mass. In this paper, we analyse the influence of assembly bias on galaxy clustering using both semi-analytical models (SAMs) and observational data. At fixed stellar mass, SAMs predict that the clustering of central galaxies depends on the specific star formation rate (sSFR), with more passive galaxies having a higher clustering amplitude. We find similar trends using SDSS group catalogues, and verify that these are not affected by possible biases due to the group finding algorithm. Low mass central galaxies reside in narrow bins of halo mass, so the observed trends of higher clustering amplitude for galaxies with lower sSFR is not driven by variations of the parent halo mass. We argue that the clustering dependence on sSFR represent a direct detection of assembly bias. In addition, contrary to what expected based on clustering of dark matter haloes, we find that low-mass central galaxies in SAMs with larger host halo mass have a lower clustering amplitude than their counter-parts residing in lower mass haloes. This results from the fact that, at fixed stellar mass, assembly bias has a stronger influence on clustering than the dependence on the parent halo mass.

Key words: galaxies: formation – galaxies: haloes

1 INTRODUCTION

Empirical models that link galaxy properties statistically with their hosting dark matter (sub)halo masses include the Halo Occupation Distribution (HOD) method (Berlind & Weinberg 2002; Yang et al. 2003; Wang et al. 2004), and the abundance matching method (Vale & Ostriker 2006; Guo et al. 2010; Moster et al. 2010). The HOD method places galaxies into dark matter haloes by modeling the number and the spatial distribution of galaxies in haloes of given mass. The abundance matching method assumes a one-to-one correspondence between galaxies and subhaloes, with higher mass galaxies residing in subhaloes of higher mass at the time of accretion. Both methods assume that galaxy properties depend only on halo mass, and are independent of any other properties of the parent halo. This assumption, which also applies to the excursion set (Extended Press-Schechter) formalism (Bond et al. 1991), however, is challenged by the discovery of the assembly bias effect found by Gao et al. (2005) for haloes less massive than about $10^{13}h^{-1}M_\odot$. Assembly bias indicates the finding that at the same halo mass, earlier assembled haloes cluster more than the ones that assemble late. Evidence that galaxy properties might depend on other properties than halo mass has also been found in different galaxy formation models Zhu et al. (2006; Croton et al. 2007).

From an observational point of view, Yang et al. (2006) found that the clustering of galaxy groups of fixed halo masses depends on the star formation rate of the central galaxies which are located at the centres of dark matter haloes. This is probably the first claim of observational detection of halo assembly bias. Along this line, subsequent studies have also searched for a correlation between galaxy properties and halo properties at fixed halo mass. Wang et al. (2008; Tinker et al. 2011, 2012; Kauffmann et al. 2012) have found interesting evidence that central galaxy properties are correlated with the properties of their neighbours beyond the virial radius of their parent haloes (“galactic conformity” Weinmann et al. 2006). The existence of assembly bias in the real Universe is, however, still debated (also because of uncertainties in esti-
mates of halo masses), and it remains unclear if (and to what extent) assembly bias influences the observed properties of galaxies. In this paper, we analyse the dependence of galaxy clustering on different galaxy and halo properties in both semi-analytic galaxy formation models (SAMs) and in a group catalogue based on the SDSS DR7. Our main result is that central galaxies with lower specific star formation rate cluster more than the ones with more active star formation at fixed stellar mass, both in SAM and observations. As we argue below, this may provide evidence for assembly bias in the real Universe.

The outline of our paper is as follows. In Section 2, we show the dependence of galaxy clustering on halo mass, halo formation time, and specific star formation rate of galaxies for two SAMs. In Section 3, observational correlation functions for central galaxies split by specific star formation rate and halo mass are calculated using group catalogues, and are compared with the predictions from mock galaxy catalogues from the two SAMs we analysed. Conclusions and discussions are presented in Section 4. All model results shown below are based on dark matter halo trees from the Millennium Simulation (Springel et al. 2005). The resolution of the simulation gives a lower limit in the dark matter halo mass of around $6 \times 10^9 M_\odot$.

2 EFFECT OF ASSEMBLY BIAS IN SEMI-ANALYTIC MODELS

In our previous study (Wang et al. 2013), we have shown that the stellar masses of galaxies extracted from the semi-analytic models of De Lucia & Blaizot (2006), DLB07 and Guo et al. (2011, Guo11) depend not only on halo mass but also on halo formation time. In this section, we investigate further the correlation between galaxy properties and those of their parent haloes, with the aim of identifying likely indications of assembly bias. In the following, $M_{\text{infall}}$ is the mass of host halo when galaxy is/was last time a central object of its hosting FOF group. For centrals, $M_{\text{infall}} = M_{\text{halo}}$.

Fig. 1 shows the relation between the formation time of host haloes (defined as the redshift when half of $M_{\text{infall}}$ was first assembled into a single object) and $M_{\text{infall}}$ in two SAMs. For a satellite galaxy, we trace back its main progenitors to the time it formed its parent group. We also show in Fig. 1 the distribution of $M_{\text{infall}}$ for these galaxies. At low stellar masses, the distributions are quite narrow. We note that the bias varies very weakly as a function of halo mass for haloes with $M_{\text{halo}} \lesssim 10^{12.5} h^{-1} M_\odot$ (e.g. Sheth, Mo, & Tormen 2001): for the two lowest stellar mass bins considered, the maximum variation for the bias is at the level of 10–15%. Therefore, for low stellar masses, large variations in the clustering as a function of galaxy physical properties cannot be attributed to variations of halo masses. For massive galaxies, on the other hand, the distributions of halo masses are rather extended and for haloes more massive than $\sim 10^{12.5} h^{-1} M_\odot$ the bias increases rapidly as a function of halo mass. Therefore, for massive galaxies, one expects a stronger clustering variation due to a wider range of host halo masses.

In Fig. 2 we check the dependence of galaxy clustering on halo formation time, sSFR, and $M_{\text{infall}}$ at fixed stellar mass in the models of DLB07 and Guo11 in two stellar mass bins. For each stellar mass bin, galaxies are split into different sub-samples according to the median value of each physical parameter considered. We show results both for the full population of galaxies, and for centrals and satellites separately. The top two panels show that galaxies residing in earlier formed haloes cluster more strongly than their counterparts residing in haloes that formed later, which
reflects the halo assembly bias (Gao et al. 2003; Zhu et al. 2006; Croton et al. 2007).

When split by sSFR, we find that galaxies with lower sSFR cluster more. This is consistent with observations that old and red galaxies cluster more even at fixed stellar masses (Li et al. 2006; Bamford et al. 2009; Weinmann et al. 2011) and is mainly due to the higher clustering of satellites vs. centrals. However, we find that the result is still present when considering only central galaxies, or only satellite galaxies at scales smaller than 1\,h^{-1}\,Mpc in the Guo11 model. In both SAMs, for the small stellar mass bin considered, the clustering of central galaxies depends on their sSFR. We will show later that this trend is not driven by trends as a function of parent halo mass.

In Fig. 3 we show the relation between galaxy sSFR and galaxy assembly time, defined as the time when half of the galaxy stellar mass of the present day is assembled in a single progenitor of the galaxy. In general, for galaxies with stellar mass lower than 10^{10.77}M_\odot, galaxies with lower sSFR assemble earlier. Combining this result with the finding that low-mass central galaxies with lower sSFR cluster more, we find that the clustering of low-mass central galaxies in SAMs depends on the galaxy assembly time, i.e. there is an assembly bias.

The result that galaxies with low sSFR cluster more than their counter-parts with higher sSFR could be due to a dependence of galaxy clustering on halo mass: the clustering amplitude increases with increasing halo mass, so if galaxies with lower sSFR are sitting in more massive haloes, this would explain the trends found. However, this is not the case for low mass galaxies. In the bottom two rows of Fig. 2, we show the galaxy correlation functions (CFs) split by \( M_{\text{infall}} \). For low mass galaxies, those with smaller \( M_{\text{infall}} \) actually cluster more strongly in both SAMs, for both centrals and satellites. This can be understood as follows: as shown in Fig. 4 at fixed stellar mass, less massive haloes form earlier. And earlier formed haloes cluster more due to halo assembly bias. In addition, the bias of the host haloes of
low mass galaxies varies little as mentioned before, which results into little variations of galaxy clustering amplitude due to varying host halo mass. Therefore, for the lower stellar mass bin considered, the dependence of clustering on halo formation time has a larger influence than the dependence of clustering on halo mass. For the higher stellar mass bin, the dependencies on halo mass and halo formation time compensate, and CFs of galaxies with different \( M_{\text{total}} \) are quite similar, with only slight differences for satellites on small scales.

3 ASSEMBLY BIAS IN OBSERVATION

Can we find assembly bias as seen in the SAMs also in reality? While it is impossible to measure the halo formation time for observational results, we can check galaxy clustering as a function of halo mass and sSFR, which could be affected by assembly bias, as shown in Section 2.

For satellite galaxies, besides the possible effect of assembly bias on their clustering property, there are other complications due to the fact that they can be accreted over a range of cosmic epochs. Therefore, in the following, we focus only on central galaxies.

3.1 SDSS results

We make use of the galaxy (Blanton et al. 2005) and group (Yang et al. 2007) catalogues extracted from the SDSS DR7 data, and use these catalogues to distinguish between central and satellite galaxies. For central galaxies within different stellar mass bins, we split galaxies into two subsamples with equal numbers of galaxies, according to the median value of sSFR and \( M_{\text{halo}} \) respectively in this mass bin, and calculate the projected CFs for each subsample. The details of how to get the projected 2PCFs of SDSS DR7 galaxies can be found in Appendix A of Yang et al. (2012).

In Fig. 3, CFs of subsamples in observation are shown for four different stellar mass bins. At low stellar masses, central galaxies with lower sSFR cluster more than those with higher sSFR, which is consistent with the trends found in the SAM. As argued in Section 2, this trend possibly indicates a signature of galaxy assembly bias in the data. Fig. 4 also shows that there is no significant difference between the clustering properties of sub-samples split by \( M_{\text{halo}} \) in the group catalogues. Note, however, that in the SDSS observations (as well as in the mock catalogues that we will use in the next subsection), halo masses are estimated from a simple ranking of the group stellar masses. In this way, splitting the sample as a function of halo mass just reflects trends as a function of stellar mass. Any possible formation time information associated with the mass of haloes in the real Universe will be erased due to the halo mass measurement adopted in the data.

3.2 Comparison between SDSS and SAM mock catalogue

To ensure a fair comparison with SAMs, we build mock catalogues for both DLB07 and Guo11 models, to mimic volumes and apparent magnitude limits of the observational data and to take into account the observational selection effects. The mock redshift catalogues are constructed in a way similar to that described in Yang et al. (2004), where the detailed sky coverage of the SDSS DR7 including the angular variations in the magnitude limits and completeness of the data is taken into account (see e.g. Li et al. 2007). Then, we adopt the same method used for the SDSS galaxies to define central and satellite galaxies, and to compute their CFs. The results from these models are also shown in Fig. 4. Similar to what shown in Fig. 2 for SAMs, central galaxies with lower sSFR cluster more than the ones with higher sSFR. The trend is consistent with SDSS measurements. Note that for central galaxies, the ratios between subsamples split in sSFR in the Guo11 model are closer to the observational data, with respect to predictions from the DLB07 model. When satellite galaxies are also taken into account, however, the CFs in the Guo11 model over-predicts the observational measurements for low-mass galaxies (Guo et al. 2011, Wang et al. 2013).

Comparing SAM mock catalogues and the results as presented in Fig. 2 we find some discrepancies. At small scales, the clustering in mock catalogues is somewhat enhanced which might due to a small fraction of mis-classified centrals. Nevertheless, for the low-mass bin, at intermediate scales of \( r_p=0.5-20 \) kpc, results are quite consistent between the mock group catalogue and the original SAM catalogues, and the dependence of clustering on sSFR is not affected by the algorithm used to detect groups and identify central and satellite galaxies. Thus, we conclude that the finding that low sSFR centrals in the SDSS cluster more than their more active counterparts of the same stellar mass is real, and not due to spurious effects introduced by the group finding algorithm.

When splitting galaxies by host halo masses, results from the SDSS and those from mock catalogues based on the SAMs used in our studies are consistent for galaxies less massive than \( 10^{10.77} M_\odot \). However, the assembly bias trends associated with \( M_{\text{total}} \) shown in the lower-left panels of Fig. 2 do not show up in the mock catalogues. The reason is already mentioned in previous subsection that in assigning halo masses to groups, no additional information like formation time is kept.

4 CONCLUSION AND DISCUSSIONS

In this paper, we find indications that the strong assembly bias of low-mass galaxies in the semi-analytic galaxy formation models of De Lucia & Blaizot (2007) and Guo et al. (2011) leaves a signature on galaxy clustering as a function of halo mass and sSFR. In particular, we find that central galaxies with low sSFR galaxies cluster more than their counterparts with the same stellar mass but higher sSFR.

A similar trend is found in group catalogues based on the SDSS DR7. For low mass galaxies, this is likely a signature of assembly bias in the real Universe. Alternative explanations are possible: for example, the central galaxies with lower sSFR could be associated with a ‘back-splash’ population of galaxies that have been satellites in the past. These galaxies are found to form earlier than central galaxies that did not experience such an event (Wang et al. 2007, Li et al., in preparation), which may contribute to assembly bias. However, the fraction of central backsplash galaxies is
Figure 3. The sSFR – galaxy assembly time relation in different stellar mass bins in the two SAMs, for central (blue lines) and satellite (red lines) galaxies. Error bars indicate 68 percentile distribution.

Figure 4. CFs of central galaxies split by sSFR (upper two rows) and \( M_{\text{halo}} \) (lower two rows) in the mock group catalogues of DLB07 and Guo11 (solid/dashed lines), compared with the results of SDSS group catalogue (filled/open circles), in four different stellar mass bins. The ratios of CFs of subsamples with lower and higher sSFR (second row) and the ratios of CFs of subsamples with higher and lower \( M_{\text{halo}} \) (fourth row) are also presented, where error bars are the relative errors of the CFs for subsamples with higher sSFR and lower \( M_{\text{halo}} \), respectively.

lower than 10 per cent, and therefore does not dominate the assembly bias effect, as shown by Wang et al. (2009).

In SAMs, low mass central galaxies show a halo mass dependence that seems to contradict the halo model predictions: here, low mass haloes cluster stronger than high mass haloes. The reason is that, for these low mass central galaxies, there is a strong correlation between host halo mass and halo formation time, with less massive haloes forming earlier. Haloes that form early cluster more than haloes of similar mass that form later (assembly bias). In addition, the clustering amplitude of the parent haloes of low-mass central galaxies varies very little. Therefore, the dependence of the clustering amplitude on halo formation time has a larger impact than the dependence due to variations of parent halo mass.

More generally, we have found evidence that the clus-
tering of central galaxies does not only depend on host halo mass, but additionally on secondary parameters like the specific star formation rate. While the physical reason for these trends remains unclear – it may be solely assembly bias or a combination of different effects – our results show that the simple picture that galaxy properties depend only on halo mass is incomplete. This has to be taken into account in empirical models like HOD and abundance matching that are based on this assumption, and for precision measurements of cosmological parameters using clustering studies.

ACKNOWLEDGMENTS

LW acknowledges support from the National basic research program of China (973 program under grant No. 2009CB24901), the NSFC grants program (No. 11103033, No. 11133003), and the Partner Group program of the Max Planck Society. SMW acknowledges funding from ERC grant HIGHZ no. 227749. GDL acknowledges financial support from the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n. 202781.

The simulation used in this paper was carried out as part of the programme of the Virgo Consortium on the Regatta supercomputer of the Computing Centre of the MaxPlanckSociety in Garching. The halo data, together with the galaxy data from two semi-analytic galaxy formation models, are publicly available at http://www.mpa-garching.mpg.de/millennium/.

REFERENCES

Bamford S. P., Nichol R. C., Baldry I. K., Land K., Lintott C. J., Schawinski K., Slosar A., Szalay A. S., Thomas D., Torki M., Andreescu D., Edmondson E. M., Miller C. J., Murray P., Raddick M. J., Vandenberg J., 2009, MNRAS, 393, 1324
Berlind A. A., Weinberg D. H., 2002, ApJ, 575, 587
Blanton M. R., et al., 2005, AJ, 129, 2562
Bond J. R., Cole S., Efstathiou G., Kaiser N., 1991, ApJ, 379, 440
Croton D. J., Gao L., White S. D. M., 2007, MNRAS, 374, 1303
De Lucia G., Blaizot J., 2007, MNRAS, 375, 2
Gao L., Springel V., White S. D. M., 2005, MNRAS, 363, L66
Guo Q., White S., Boylan-Kolchin M., De Lucia G., Kauffmann G., Lemson G., Li C., Springel V., Weinmann S., 2011, MNRAS, 413, 101
Guo Q., White S., Li C., Boylan-Kolchin M., 2010, MNRAS, 404, 1111
Kauffmann G., Li C., Zhang W., Weinmann S., 2012, ArXiv e-prints
Li C., Jing Y. P., Kauffmann G., Börner G., Kang X., Wang L., 2007, MNRAS, 376, 984
Li C., Kauffmann G., Jing Y. P., White S. D. M., Börner G., Cheng F. Z., 2006, MNRAS, 368, 21
Moster B. P., Somerville R. S., Maugebutsch C., van den Bosch F. C., Macciò A. V., Naab T., Oser L., 2010, ApJ, 710, 903
Sheth R. K., Mo H. J., Tormen G., 2001, MNRAS, 323, 1
Springel V., White S. D. M., Jenkins A., Frenk C. S., Yoshida N., Gao L., Navarro J., Thacker R., et al., 2005, Nature, 435, 629
Tinker J., Wetzel A., Conroy C., 2011, ArXiv e-prints
Tinker J. L., George M. R., Leauthaud A., Bundy K., Finoguenov A., Massey R., Rhodes J., Wechsler R. H., 2012, ApJ, 755, L5
Vale A., Ostriker J. P., 2006, MNRAS, 371, 1173
Wang H., Mo H. J., Jing Y. P., 2009, MNRAS, 396, 2249
Wang L., De Lucia G., Weinmann S. M., 2013, MNRAS, 431, 600
Wang L., Li C., Kauffmann G., De Lucia G., 2006, MNRAS, 371, 537
Wang Y., Yang X., Mo H. J., van den Bosch F. C., Weinmann S. M., Chu Y., 2008, ApJ, 687, 919
Weinmann S. M., van den Bosch F. C., Pasquali A., 2011, The Dependence of Low Redshift Galaxy Properties on Environment. p. 29
Weinmann S. M., van den Bosch F. C., Yang X., Mo H. J., 2006, MNRAS, 366, 2
Yang X., Mo H. J., Jing Y. P., van den Bosch F. C., Chu Y., 2004, MNRAS, 350, 1153
Yang X., Mo H. J., van den Bosch F. C., 2003, MNRAS, 339, 1057
Yang X., Mo H. J., van den Bosch F. C., 2006, ApJ, 638, L55
Yang X., Mo H. J., van den Bosch F. C., Pasquali A., Li C., Barden M., 2007, ApJ, 671, 153
Yang X., Mo H. J., van den Bosch F. C., Zhang Y., Han J., 2012, ApJ, 752, 41
Zhu G., Zheng Z., Lin W. P., Jing Y. P., Kang X., Gao L., 2006, ApJ, 639, L5

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