Resolving the problem of galaxy clustering on small scales: any new physics needed?

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ABSTRACT

Galaxy clustering sets strong constraints on the physics governing galaxy formation and evolution. However, most current models fail to reproduce the clustering of low-mass galaxies on small scales ($r < 1 \, \text{Mpc}/h$). In this paper we study the galaxy clusterings predicted from a few semi-analytical models. We firstly compare two Munich versions, Guo et al. (2011, Guo11) and De Lucia & Blazoi (2007, DLB07). The Guo11 model well reproduces the galaxy stellar mass function, but over-predicts the clustering of low-mass galaxies on small scales. The DLB07 model provides a better fit to the clustering on small scales, but over-predicts the stellar mass function. These seem to be puzzling. The clustering on small scales is dominated by galaxies in the same dark matter halo, and there is slightly more fraction of satellite galaxies residing in massive haloes in the Guo11 model, which is the dominant contribution to the clustering discrepancy between the two models. However, both models still over-predict the clustering at $0.1 \, \text{Mpc}/h < r < 10 \, \text{Mpc}/h$ for low mass galaxies. This is because both models over-predict the number of satellites by 30% in massive halos than the data. We show that the Guo11 model could be slightly modified to simultaneously fit the stellar mass function and clusterings, but that can not be easily achieved in the DLB07 model. The better agreement of DLB07 model with the data actually comes as a coincidence as it predicts too many low-mass central galaxies which are less clustered and thus bring down the total clustering. Finally, we show the predictions from the semi-analytical of Kang et al. (2012). We find that this model can simultaneously fit the stellar mass function and galaxy clustering if the supernova feedback in satellite galaxies is stronger. We conclude that semi-analytical models are now able to solve the small-scales clustering problem, without invoking of any other new physics or changing the dark matter properties, such as the recent favored warm dark matter.

Key words: methods: analytical – galaxies: mass function – galaxies: formation – cosmology: theory – dark matter – large-scales structure of Universe

1 INTRODUCTION

In the cold dark matter universe, structure formation is dominated by dark matter haloes, and their formation and distribution can be well studied using high-resolution N-body simulations (e.g., Navarro et al. 1997; Springel et al. 2005a; Li et al. 2012). However, the formation of galaxies involves baryonic process which are much more uncertain and complicated. To understand and constrain how galaxy population form and distribute in a statistical point of view, one often needs a few important observables: galaxy luminosity/stellar mass functions, clusterings, and color distributions. Luckily, local galaxy surveys, such as the Sloan Digital Sky Survey (SDSS, York et al. 2001), have accurately measured these observables in the last decade. They are now widely used as inputs to constrain the models for galaxy formation: such as the Halo occupation distribution (HOD, e.g., Peacock & Smith 2000; Seljak 2000; Ma & Fry 2000; Kang et al. 2002; Cooray 2002; Zheng et al. 2005), the conditional luminosity function (CLF, e.g., Yang et al. 2003; van den Bosch et al. 2007), and the abundance matching method (e.g., Vale & Ostriker 2004; Conroy & Wechsler 2009; Moster et al. 2010), and the semi-analytical models (SAMs, e.g., Kang et al. 2005; Croton et al. 2006; Bower et al. 2006; Somerville et al. 2008; Guo et al. 2011).

Among these models or techniques, SAMs are especially useful as they include baryonic physics regulating star formation process. Unlike the HOD models which often take both the stellar mass functions (hereafter SMFs) and galaxy clustering as inputs, the parameters of SAM are usually tuned to fit the local SMF or luminosity functions. Other observables, such as galaxy clustering and color distribution, are seen as model predictions. Recent years have witnessed great progress in achieving better agreement with the data from the SAMs. However, though they can now well re-
produce many observables separately, most of them are unable to reproduce the SMFs, galaxy clustering and color distribution simultaneously (however see recent progress made by Henriques et al. 2013). For example, the recent models (Bower et al. 2006; Guo et al. 2011, hereafter Guo11; Kang et al. 2012, hereafter K12) can well reproduce the measured local SMFs perfectly (Cole et al. 2001; Bell et al. 2003; Li & White 2008), but they over-predict the clustering on small scales. The model of De Lucia & Blaizot (2007, hereafter DLB07) over-predicts the local SMF, but is more successful in reproducing galaxy clustering (Wang et al. 2013). By introducing gradual strangulation of hot halo gas of satellite galaxy, SAMs (Kang & van den Bosch 2008; Font et al 2008) can also reproduce the observed color distribution of satellites from the SDSS (Weinmann et al. 2006; van den Bosch et al. 2008).

It seems to be quite puzzling and desperate that SAMs are unable to reproduce these important observables simultaneously. In particular, the failure to reproduce galaxy clustering on small scales (< 1 Mpc/h) has intrigued a few attempts to modify the cosmological parameters and dark matter properties. However, as found by a few recent works (K12; Guo et al. 2013), SAMs still over-produce galaxy clustering in a lower σ8 universe other than the WMAP1 one (Spergel et al. 2003). Kang et al. (2013) found that a warm dark matter cosmology, after tuning the model parameter to fit the local SMF, still over-predicts clusterings of low-mass galaxies on small scales.

Recently, Wang et al. (2013, hereafter Wang13) carefully investigate the origin for the discrepancy between the two versions of the Munich models, namely the Guo11 and D LB07 ones. Both models adopted the same dark matter merger trees from the Millennium Simulation (Springel et al. 2005a). They also share very similar descriptions for the baryonic process of star formation. Slight differences are in the treatments of supernova feedback, gas cooling of satellites, satellite disruption, and etc. Wang13 found that the scatter around the stellar mass to halo mass relation can explain the discrepancy between the two models. They claimed that galaxies above the mean relation form earlier, and this effect is stronger in the Guo11 model. They thus concluded that this formation bias accounts for the clustering discrepancy between the two models.

The work of Wang13 provides an useful insight into the origin for the clustering discrepancy between the Guo11 and D LB07 models. Wang13 indicates that the halo formation bias (or assembly bias) is the reason for the difference of clustering on small scales. It was previously recognized that the halo assembly bias has an effect only on large scales (e.g., Gao et al. 2005; Wechsler et al. 2006; Jing et al. 2007). However, it is only recently found that the assembly bias also accounts for the mass distribution on small scales, such as halo concentration, subhalo fraction. (e.g., Gao et al. 2007). Thus in this paper we investigate this problem in more detail. For that purpose, we use the public available data from the German Astrophysical Virtual Observatory (Lemson & the Virgo Consortium 2006).

We compare the properties of galaxies from the Munich models, including their host halo mass distribution, galaxy density profile in the host halo, and the conditional stellar mass functions (CSMFs: stellar mass function in host haloes with given mass). We find that the main reason for the discrepancy of clustering between the Guo11 and D LB07 models is not from the halo assembly bias, but due to the fraction of satellite galaxies in massive haloes. Also both models over-predict the CSMFs in massive haloes by around 30% at \(M_* \sim 10^{10} M_\odot\). We discuss a few methods to rescale the models to best fit the global SMF and CSMFs, and show that after fixing the match to the SMFs, the galaxy clustering is also reproduced.

In addition to the investigation of the Munich models, we also study the predictions from the K12 model. This model also well reproduces the local SMF by introducing a lower gas cooling rate in low mass haloes compared to its previous version (Kang et al. 2005; Kang & van den Bosch 2008). However it also predicted higher clustering on small scales. We find that it is mainly due to the unreasonable description of supernova feedback in satellite galaxies. We slightly modify the efficiency of supernova feedback, and find that the new model can now well reproduce the global SMF and CSMFs. Also the galaxy clusterings are now well reproduced on all scales.

The paper is organized as follows. In Sec. 2, we briefly introduce the model implementation for the D LB07 and Guo11 models, and show their model predictions. In Sec. 3, we show the modification to the K12 model with compare the predictions to the data. We give our conclusion and simple discussions in Sec. 4.

2 MUNICH SEMI-ANALYTICAL MODELS

2.1 Description of the Model

The Munich model is mainly based on the papers by White & Rees (1978), White & Frenk (1991), and Kauffmann et al. (1999). It was improved with the inclusion of subhaloes by Springel et al. (2001), and a model for suppression of cooling flow by 'Radio AGN' in the model of Croton et al. (2006). The D LB07 model is very similar to that of Croton, with modifications to the stellar initial mass function and more realistic dust model, and use of slightly different merger trees. However, these previous models over-predict the SMF at \(z = 0\). Further improvement is implemented in the recent version of Guo11. In this new model, they include a more efficient supernova feedback and different treatments of satellite evolution, such as allowance of gas cooling in satellites, gradual stripping of hot halo gas and satellite disruption. The Guo11 model well reproduces the local stellar mass function from the SDSS data (Li & White 2008), but over-predicts the clustering on small scales (Wang13). In the following, we list the main physical implementations in the Guo11 model which are not included in the D LB07 model. For more details, we refer the readers to the papers of D LB07 and Guo11.

The Guo11 model introduces a few modifications and new physics prescriptions compared to the D LB07 model. The first is that Guo11 implemented a different description for gas reheat by supernova feedback, which is dependent on the gravitational potential and mainly affects the star formation efficiency in low mass haloes. The second is that satellite galaxies in Guo11 model could have more gas cooling as its host halo gas is now gradually stripped, unlike the instantaneous stripping adopted in the D LB07 model. Thirdly, satellite galaxy in the Guo11 model will be disrupted if the baryonic density of satellite is less than the dark matter density of the host halo at the pericenter. The tidal disruption is not included in the D LB07 model. Another modification in the Guo11 model is that the assignment of position for orphan galaxy (defined as that without associated subhalo, Gao et al. 2004) is different. In the D LB07 model, the position of an orphan galaxy is tagged by the nearest subhalo (defined as allowance of gas cooling in satellites, gradual stripping of hot halo gas and satellite disruption). The Guo11 model introduce a few modifications and new physics prescriptions compared to the D LB07 model. The first is that Guo11 implemented a different description for gas reheat by supernova feedback, which is dependent on the gravitational potential and mainly affects the star formation efficiency in low mass haloes. The second is that satellite galaxies in Guo11 model could have more gas cooling as its host halo gas is now gradually stripped, unlike the instantaneous stripping adopted in the D LB07 model. Thirdly, satellite galaxy in the Guo11 model will be disrupted if the baryonic density of satellite is less than the dark matter density of the host halo at the pericenter. The tidal disruption is not included in the D LB07 model. Another modification in the Guo11 model is that the assignment of position for orphan galaxy (defined as that without associated subhalo, Gao et al. 2004) is different. In the D LB07 model, the position of an orphan galaxy is tagged by the nearest subhalo (defined as...
the tracer particle as $R_{\text{tracer}}$, but scaled as

$$\Delta R_{\text{new}} = \left(1 - \Delta t/t_{\text{friction}}\right)^{0.5} \Delta R_{\text{tracer}}$$

where $\Delta t$ is the time since the merger clock of satellite is reset when its associated subhalo is not resolved any more, and $t_{\text{friction}}$ is the dynamical friction time which indicates how long it will take for the satellite to merger with its central galaxy.

As shown by Wang13, the effect of the first modification in the Guo11 model is that the star formation in low-mass halo is suppressed, leading to fewer low-mass galaxies, thus fitting better with the global SMF. The introduction of satellite disruption also decreases the number of satellites, and it agrees better with the CSMFs (we show these in Fig. 4). The new assignment of satellites’ positions leads to a slightly steeper density profile of galaxies (we will show its effect in Fig. 2).

The Munich galaxy catalogue is now publicly available\(^1\). For each galaxy, one can obtain its stellar mass, multi-wavelength magnitudes, position and velocity. The database also includes the information of the host halo for each galaxy, including halo mass and formation history. In this paper, we use the galaxy catalogues of DLB07 and Guo11 models based on the Millennium Simulation (Springel et al. 2005a). This simulation uses the first-year WMAP cosmology with $\Omega_m = 0.25$, $\Omega_{\Lambda} = 0.75$, $\sigma_8 = 0.9$ (Spergel et al. 2003). It includes $2160^3$ particles in a cub box with each side of 500 Mpc/h. Each particle has mass of $1.18 \times 10^9 M_\odot$, and Guo11 have shown that galaxies with stellar mass above $M_\ast = 10^{9.9} M_\odot$ are well resolved in this simulation.

\(^1\) There was a typo in the original formula of Guo11 (private communication).

\(^2\) http://gavo.mpa-garching.mpg.de/MyMillennium

2.2 Results of the Munich model

Wang13 have compared the predicted galaxy clusterings from the DLB07 and Guo11 models. They found that for massive galaxies, both models predictions agree with the data. For low-mass galaxies ($M_\ast < 10^{10.2} M_\odot$), the predicted clusterings from the DLB07 model agree better with the data on small scales, and the Guo11 model is higher than the data by a factor of 2 at $r < 0.1\text{Mpc}/h$. In this section, we explore the origin of the discrepancy between their predicted clusterings on small scales. As galaxy clustering is mass dependent, we therefore select galaxies within a narrow mass range ($10^{9.75} M_\odot < M_\ast < 10^{10.25}$). In the next section we will focus on the model discrepancy with the real data.

To begin with our analysis, we show in fig. 1 the projected two-point correlation functions (2PCFs) from the DLB07 and Guo11 models for galaxies with our selected mass. The data points are from Li et al. (2006) measured from the SDSS, and the solid lines are the model predictions. It is found that on large scales (at $r > 1\text{Mpc}/h$) both models agree with each other. On small scales, the DLB07 model fits better to the data, and the Guo11 model is higher by a factor of 2 at $r < 0.1\text{Mpc}/h$. We note that even for the DLB07 model, the clustering is still higher than the data by around 20% (also see fig.20 in Guo11). We will later investigate their discrepancy with observation in Section 2.3.

Fig. 1 further shows the clusterings of different galaxy samples. In the left panel we plot the auto-correlation functions of central and satellite galaxies. It shows that the 2PCFs of central galaxies in both models have similar amplitude. Satellite galaxies have stronger clusterings and they dominate the total 2PCFs. The right panel shows the contributions from galaxies in the same halo (one-halo term) and in different haloes (two-halo term). It is found that the total clustering on small scales is dominated by the one-

![Figure 1](http://gavo.mpa-garching.mpg.de/MyMillennium)
do not support the argument of Wang13, as the position of orphan galaxy in Guo11 model is not given.

Their conclusions seem to indicate that the clustering difference in the DLB07 and Guo11 is from their predictions on the one-halo terms. Wang13 have also investigated the origin for the discrepancy between the DLB07 and Guo11 models. They found that the clustering difference arises from the scatter of the halo mass- stellar mass relation. Galaxies above the median stellar mass-halo mass relation reside in haloes that form earlier, while galaxies that lie below the median relation reside in haloes formed later. Such an effect is stronger in the Guo11 model. However, it is not apparent how this effect leads to the clustering difference at given stellar mass. Their conclusions seem to indicate that the clustering difference in the two models is ascribed to the formation bias of haloes that early formed haloes are strongly clustered (e.g., Gao et al. 2005; Jing et al. 2007)

Our results in fig. 1 do not support the argument of Wang13, as the halo bias should affect clustering more strongly on large scales (or two-halo terms). Our results agree with the prediction from the HOD models that clustering on small scales is dominated by the one-halo term (e.g., Kang et al. 2002). The one-halo term is then determined by the galaxy density profile in the host dark matter haloes and the mass function of host haloes (see Equation.6 in Kang et al. 2002). In the following we compare the predictions on the two ingredients from the DLB07 and Guo11 models to check which is the dominant contribution to their clustering discrepancy.

The left panel of fig. 2 compares the normalized galaxy density profiles from the DLB07 and Guo11 models. The density profile is normalized by the total number of galaxies inside the virial radius of the dark matter haloes. The long dash lines indicate the slopes in the inner and outer region of an NFW profile (Navarro et al. 1997), which are -1 and -3 respectively. We find that the profile in the DLB07 model (blue dotted line) is more like an NFW profile, and the Guo11 model predicts a steeper slope in the inner halo (red solid). Observations (e.g., Lin et al. 2004; Budzynski et al. 2012;) have found that galaxy density profile in cluster is well described by an NFW profile or a slightly shallower one (e.g., Adami et al. 1998; Sales & Lambas 2005). Weinmann et al. (2011) also compared the dwarf galaxy profile in clusters to the data, they claimed that the model of Guo11 agree better with the data, but they also noted that the model prediction is still slightly higher at halo center. The same conclusion is also obtained by Guo11 themselves by comparing galaxy profiles to the SDSS data.

Now we check whether the steeper profile in the Guo11 model is from their assignment on satellite positions. As we stated in section 2 the position of orphan galaxy in Guo11 model is not given by the tracer particle, but shifted by a factor. Now we shift the positions in Guo11 catalogue back to those tracer particles. The green dashed lines in fig. 2 show the effects of shifting the positions of galaxies. The left panel shows that after shifting the positions of orphan galaxies back to those tracer particles, as used in DLB07, the density profile now agrees with the DLB07 one perfectly. This clearly demonstrates that the steeper profile in the Guo11 model is purely due to their rescale of galaxy positions. The green dashed line in the right panel shows the predicted 2PCF. However, it is found that the clustering is suppressed only on very small scales ($r < 0.1 Mpc/h$). At scales $r > 0.1 Mpc/h$, the clustering from the Guo11 model is still higher than the DLB07 one.

Fig. 2 indicates that the difference in the clusterings predicted by the two models is not from the spatial distribution of galaxies within the dark matter haloes. Therefore the only possible contribution is from the mass function of the host halo in the models. For each galaxy with mass in our selected range ($lg M_\star = [9.77, 10.27]$), we can obtain the virial mass of its host halo from the public catalogue. In the left panel of fig. 3 we show the distributions for the host halo mass from the two models (DLB07: blue dotted, Guo11: red solid lines). At first glance it is found that the distributions from the two models are very similar, and there is a sharp peak at $M_{\text{vir}} = 10^{11.25}M_\odot$, and a broad distribution in massive haloes ($M_{\text{vir}} > 10^{12}M_\odot$). It is easy to understand that this distribution is from the large (wide) range of the host halo mass for central (satellite) galaxies, respectively.

Actually fig. 3 shows that there is slight difference for the distributions of host haloes in the two models, that Guo11 model...
has a slightly larger fraction of satellite galaxies residing in massive haloes. For example, we found that the fraction of galaxies in haloes with \( M_{\text{vir}} > 5 \times 10^{12} M_\odot \) is 33.7% in the Guo11 model, but it is 30.3% in the DLB07 model. Although the difference is small, its effect on the clustering is non-negligible. To see its effect, we make a simple test that we randomly remove some fraction of galaxies with \( M_{\text{vir}} > 5 \times 10^{12} M_\odot \) in the Guo11 model so as to produce the same fraction of galaxies as that in the DLB07 model. To achieve that, we have to remove the fraction of galaxies with \( M_{\text{vir}} > 5 \times 10^{12} M_\odot \) by 15% in the Guo11 model. The green dashed line in the left panel show the distribution after this removal. It is found that now the fraction of galaxies in massive haloes matches better that in the DLB07 model.

The green dashed line in the right panel of fig. 3 shows the predicted clustering in the Guo11 model with this removal of satellites. Remarkably, it is found that now the predicted clustering in the Guo11 model is very similar to the DLB07 model. We note that the removed galaxies is only 5% of the total selected galaxy (\( lgM_* = [9.77, 10.27] M_\odot \)). This plot shows that satellite galaxies in massive haloes contribute most to the clustering on small scales, and a small fraction of satellites will produce non-negligible effect. This is because the clustering from the one-halo term is proportional to \( \rho(r)^2 \), seen from the equation 6 in Kang et al. (2002).

Our results above have clearly shown that galaxy clustering on small scales is dominated by galaxies residing in the same dark matter halo. It is found that the steeper density profile of galaxies in the Guo11 model contributes to its higher clustering only on very small scales, and the dominant contribution to the discrepancy between the models is from the fraction of satellite galaxies in massive haloes. There are slightly more fraction of satellites residing in massive haloes in the Guo11 model, leading to a higher clustering on small scales. It is not clear why there are more satellites in massive haloes in the Guo11 model. One possible reason is that the infall halo mass of satellites is slightly larger than that from the DLB07 model (see Wang13), and on average only massive haloes have accreted subhaloes with higher infall mass. Another possibility is that Guo11 have introduced tidal disruption for satellites, and the disruption efficiency may be higher in lower-mass host haloes as they formed at early times and satellites are more likely to be disrupted as they have orbited in the host halo (especially in inner region) for longer time. Unfortunately, due to the hardness to extract halo formation information from the Munich catalogue, we are unable to determine which leads to the higher fraction of satellites in massive haloes in the Guo11 model.

### 2.3 Rescaled SAMs

In the above section, we have explored the origin for the discrepancy between the predicted galaxy clustering from the DLB07 and Guo11 models. However, we find that even after eliminating their model discrepancy, both models still predict higher clustering than the data at large scales at \( r > 1 \text{Mpc}/h \). In this section, we focus on the comparison between the model and the data, and in particular, we investigate if we can achieve better agreements with the clustering data by rescaling their models.

Guo11 have made great progress to achieve better results on the galaxy stellar mass functions compared to the DLB07 one. However, the agreement with the data is still not perfect. The fig.1 of Wang13 have shown that the global SMF is over-predicted by about 10% and 60% at \( M_* = 10^{10} M_\odot \) by the Guo11 and DLB07 models, respectively. We need to check where these over-predicted galaxies come from. In fig. 4 we show the conditional stellar mass functions (CSMFs) in host haloes with different mass bins. The solid and dotted lines are for the Guo11 and DLB07 models, and the red (blue) lines for satellites (centrals). The data points are from the group catalogues constructed by Yang et al. (2009) from the SDSS DR4.

Overall, there are marginal agreement between the model and the data. Better agreement is seen for central galaxies on average. However, the mass of central galaxies in massive haloes is over-estimated (upper left panel), but under-estimated in low mass haloes, especially for the Guo11 model (lower right panel). The
same effect is also seen from the K12 model (fig. 7). However, as shown by Wang13, the predicted stellar mass to halo mass relation of central galaxy from the Munich model agrees with the data from weak lensing and satellite kinematics (e.g., Mandelbaum et al. 2007; More et al. 2009) for both high and low-mass galaxies. This is puzzling and we do not know what causes this discrepancy between the data of Yang et al and the models. One possibility is that the estimation of halo mass in the data is different from that in the simulations. This is beyond the limits of our work, and we do not go into the details.

Fig. 4 shows that both models over-predict the number of low-mass satellites, and worse agreement for the DLB07 model. At our selected galaxy mass, $M_* \sim 10^{10} M_\odot$, both models predict almost equal number of satellites which are about 30% higher than the data in haloes with mass larger than $10^{12.3} M_\odot$. It is hard to constrain the CSMFs in lower mass haloes ($M_{\text{vir}} < 10^{12} M_\odot$) as the group catalogue in Yang et al is incomplete below this mass. So for a conservative estimate, we assume that satellites with mass around $10^{10} M_\odot$ are over-predicted by 30% only in haloes with mass larger than $10^{12.3} M_\odot$. We use this as a constraint in the following analysis. Note that the higher CSMFs of low-mass satellites do not conflict with the claim that Guo11 model fits the local SMF. Wang13 have shown that the predicted global SMF at $M_* = 10^{10} M_\odot$ from the Guo11 model does not match perfectly.

Figure 4. Conditional stellar mass functions (CSMFs) in different halo mass bins. The data points are from the group catalogue of Yang et al. (2009), and red (blue) lines are for satellites (central) galaxies. Here comparisons are only shown for haloes with mass larger than $M_{\text{vir}} > 2 \times 10^{12} M_\odot$, below which the group catalogue is incomplete.
Figure 5. Projected 2PCFs of all galaxies in the rescaled DLB07 and Guo11 models. Left panel is for the Guo11 model and right panel for the DLB07 model. The solid lines are results from their original models. The dotted and dashed lines show the predictions from the rescaled models, see the text for details.

with the data, but is about 10% higher. The over-predicted number of satellites at $M_\star = 10^{10} M_\odot$ in halo with virial mass larger than $10^{12.3} M_\odot$ is about 9% of all galaxies with the same stellar mass. Thus it could be these over-predicted satellites contributing to the over-prediction of global SMF.

Now we investigate whether better agreement can be achieved if we rescale both models to match the global SMF and the CSMFs. Wang13 have tested two simple models to resale the DLB07 model to fit the global SMF. In the first case, they randomly removed a faction of galaxies to reproduce the SMF, regardless of centrals or satellites. They found that random removal of galaxies does not change the original DLB07 results. This is easy to understand because simply decreasing the density itself does not change the clustering. In their second model, they removed only satellite galaxies and found that the small-scale clustering is largely suppressed to lower than the data in the DLB07 model.

Here we use a similar method as Wang13 to rescale the Guo11 and DLB07 models. However, we do not randomly remove galaxies, but use the CSMFs as an additional constraint. Now for the DLB07 model, we consider two cases. In the first case we randomly remove 30% of satellites with $M_\star = 10^{10} M_\odot$ in haloes with $M_{\text{vir}} > 2 \times 10^{12} M_\odot$ (seen from fig.4). Note that the global SMF is still higher than the data in this case. In the second case we remove satellites as in the first case, and also remove about 58% of central galaxies so as to fit the local SMF. The predicted galaxy clusterings are plotted in Fig. 5. The left panel shows the results of Guo11 model and the right one for the DLB07 model. It is found from the left panel that the scaled Guo11 model now matches the data quite well on scales $r_p > 1 Mpc/h$, but the small scale clustering is slightly above the data. However, we find that if we use the shifted positions of satellites (dotted line), the clustering is now perfectly reproduced on very small scales. The right panel shows that if only 30% of satellites is removed in the DLB07 model (dashed line), the agreement with the data is also quite good except at very small scales. We note that this conclusion is not in conflict with the result of Wang13 as they remove many more satellites to fit the global SMF, thus the clustering is suppressed too much.

The dotted line in the right panel of Fig. 5 shows the second case of rescaling the DLB07 model in which we remove 30% of satellites in massive haloes and 58% of all centrals so as to fit the local SMF. It is seen that compared to other cases, partial removal of central galaxies does not reduce the clustering, but increases it instead. This result seems to be surprising. From Fig. 1 we know that the clustering of centrals is much lower than the satellites. This is because for given stellar mass, central galaxies often live in haloes with mass lower than the host of the satellites. As the halo bias is strongly dependent on its mass, the effect of central galaxies is to suppress the global clustering of all galaxies.

The results in fig. 5 show that if we have correctly rescaled the DLB07 model to fit the global SMF, the predicted galaxy clustering is higher than the data. However, the scaled Guo11 model agrees quite well with the data. It indicates that the better agreement with data from DLB07 model comes as a coincidence. It is closer to the data than the Guo11 one because it wrongly predicts too many centrals.

Our test indicates that the Guo11 model can be further improved by simply introducing a slightly stronger effect of satellite disruption in massive haloes. However, such an improvement may not work for the DLB07 model. For the DLB07 model, the star formation efficiency in low-mass haloes should be suppressed, otherwise the number of centrals is too high. In that sense, the Guo11 model is an improved version of the DLB07 model as it already introduces stronger feedback to suppress star formation in low-mass haloes.
we show the mean mass growth rate of satellites after infall in the K12 model, and the new prediction is close to the data, and it is seen that the quenching of star formation in massive, high-velocity galaxies is much higher than the previous assumption as the virial velocity of its host halo when the satellite was lastly a central galaxy. We keep the efficiency is higher than the previous assumption as the virial velocity of satellite galaxy is usually lower than its host halo. We keep the efficiency is higher than the previous assumption as the virial velocity of satellite galaxy is usually lower than its host halo. We keep the efficiency is higher than the previous assumption as the virial velocity of satellite galaxy is usually lower than its host halo. We keep the efficiency is higher than the previous assumption as the virial velocity of satellite galaxy is usually lower than its host halo. We keep the efficiency is higher than the previous assumption as the virial velocity of satellite galaxy is usually lower than its host halo.

Figure 6. Predicted mass growth rate of satellites after infall in the K12 model. The dashed line shows the result with stronger supernova feedback. Data points are from the constraints by Wetzel et al. (2013) from the SDSS DR7 and N-body simulations.

3 SEMI-ANALYTICAL MODEL OF K12

In this section, we study galaxy clustering and CSMFs using the slightly modified SAM of K12. The K12 model is based on Kang et al. (2005; 2006; 2010) and Kang & van den Bosch (2008). This SAM self-consistently models the physical processes governing stellar mass evolution, such as gas cooling, star formation, supernova and active galactic nucleus feedback. For model details we refer the reader to the paper of Kang et al. (2005). Compared to its previous versions, K12 introduces a cooling factor $f_c$. For low-mass haloes, the cooling rate is then described as $M_{\text{cool}} = f_c m_{\text{hot}} / t_{\text{dyn}}$, where $t_{\text{dyn}}$ is the halo dynamical time. As described in K12, this cooling factor takes into account the gas outflow due to reheating by supernova feedback, and it was shown to produce better match to the local SMF at the low-mass end.

The N-body simulation used here is the one presented in K12 which adopted the cosmological parameters from the WMAP7 data release (Komatsu et al. 2011), namely: $\Omega_L = 0.73, \Omega_m = 0.27, \Omega_b = 0.044$ and $\sigma_8 = 0.81$ and $h = 0.7$. This simulation was run using the GADGET-2 code (Springel 2005b) in a box of L=200 Mpc/h using 1024$^3$ particles.

The K12 model the same problem as other model that the clustering of low-mass galaxies on small scales is over-predicted. K12 have shown that adopting a low-$\sigma_8$ cosmology can not solve this problem. They suggested that this over-clustering is due to the over-prediction of low-mass satellite galaxies in massive haloes (or Equally the masses of satellites are too large). The mass of satellites are too large either because they were too large at accretion when they were lastly as central galaxies, or the mass growth after accretion are over estimated. The mass of central galaxies can be constrained by the data at $z = 0$. K12 have shown that the stellar mass - halo mass relation of central galaxies at $z = 0$ is well constrained by the data from weak lensing. However, such a direct constraint is not available at high redshift (but see Leauthaud et al. 2012; Skibba et al. in preparation). Also the stellar mass function at $z > 0$ is also poor constrained at low-mass end. Thus here we do not consider the first possibility that the mass of satellite galaxies are too large at the time of accretion.

We consider the second possibility that the mass of satellites grow too much after accretion. In the K12 model the physics governing satellite evolution is gas cooling from satellites' hot halo and star formation. In their model, they considered the impact of supernova feedback using energy conservation such that the amount of cold gas reheated by the energy from supernova is modeled as,

$$\Delta m_{\text{reheated}} = \frac{4}{3} \frac{\eta_{\text{SN}} E_{\text{SN}}}{V_{\text{vir}}^2} \Delta m_*,$$

where $\epsilon$ describes the feedback efficiency, $\eta_{\text{SN}} E_{\text{SN}}$ is the energy release by supernova associated with massive stars for a unit of solar mass of newly formed stars, and $V_{\text{vir}}$ is the virial velocity of the host halo. This equation is under assumption that the cold gas is reheated to the virial temperature of the host halo. For satellite galaxies, Kang et al. (2005) assumed that the cold gas is also reheated to the virial temperature of the host halo. However, this assumption is not reasonable as supernova feedback should be a local effect, and apparently the satellite galaxy knows nothing about its host potential. So here we assume that cold gas is reheated to the virial temperature of the subhalo it resides in, and we use the virial velocity of its host halo when the satellite was lastly a central galaxy before its accretion. We note that such a description of supernova feedback is also implemented in the Munich models.

Under the above prescription, the supernova feedback efficiency is higher than the previous assumption as the virial velocity of satellite galaxy is usually lower than its host halo. We keep all the model parameters fixed as that of K12. As we found, the total SMF is almost identical to the K12 one as the low-mass end of SMF is dominated by central galaxies, and our modification to the satellite supernova feedback has little effect on the evolution of central galaxies.

In Fig. 6 we show the mean mass growth rate of satellite galaxies after accretion. The solid line is the prediction from the K12 model, and the dashed line shows the new prediction. It is found that in the K12 model satellites can grow their mass by large amount, especially for low-mass satellites. The mass growth in the new model is largely suppressed. Observationally, there are few direct constraints on the mass growth of satellites. The points are data constraints from Wetzel et al. (2013) using the SDSS DR7 group catalogue and N-body simulations. It shows that stellar mass growth of satellite are typically less than a factor of 2. Similar results on mass evolution of satellites are also recently obtained by Watson & Conroy (2013). Our model result is still slightly above the data, and it is seen that the quenching of star formation in massive satellites is still not efficient.

Fig. 7 plots the CSMFs from the K12 model and our new one using the solid and dashed lines. It is seen that in the K12 model there are more low-mass satellites in all halo mass bins. The revised model agrees much better with the data for satellites. For central galaxies, the two model have similar results and better agreement with the data is found in high-mass haloes. In low-mass haloes ($M_{\text{vir}} < 10^{13.2} M_\odot$) the stellar mass of central galaxies is lower by a factor of 2 than the data. Our results for the CSMFs of central galaxies are very similar to the Guo11 results shown in Fig. 4. As we stated before, we are not clear what contributes to the over-prediction of central galaxy mass in high-mass haloes and the under-prediction in low-mass haloes. We leave this for future work.
Now we show the predicted galaxy clusterings in Fig. 8 for low and high-mass galaxies. The solid and dashed lines are the results of K12 model and the new one. As it was previously shown the K12 model can correctly predict the clustering of massive galaxies (right panel), but it over-predicts the clustering of low-mass galaxies on small scales (left panels). The new model predictions are in good agreement with the data on all scales.

The clustering of galaxies on small scales has attracted great interest recently. K12 have shown that adopting a low-$\sigma_8$ could not solve this problem, and this conclusion is recently also obtained by Guo et al. (2013). This is because although the number of low-mass haloes is decreased in the low-$\sigma_8$ model, the stellar formation efficiency in low-mass haloes has to be increased so as to fit the local stellar mass function. It compensates the decrease of subhalo in massive haloes, and still over-predicts the clustering. Besides a higher $\Omega_m$ adopted in a low-$\sigma_8$ universe will also compensate the decrease in $\sigma_8$.

Our results from the new model indicate that the physics, governing the evolution of satellites, such as supernova feedback or disruption, is crucial to solve the over-clustering on small scales. For the current Guo11 model, it can be slightly modified by introducing a stronger satellite disruption rate by about 30% in massive haloes. As this percent of satellites is only about 10% of the total galaxy population, it will not violate the agreement on the stellar mass function. For the DLB07 model, reduction of satellites alone will not do the job as there are too many centrals in low-mass...
haloes. In this model galaxies should form in slightly bigger haloes, so the number density of both central and satellites will decrease. In that sense, the DLB07 model will converge with the Guo11 model.

4 CONCLUSIONS AND DISCUSSIONS

In this paper, we study the problem of galaxy clustering on small scales, which has become more puzzling recently. For this purpose, we utilize the public data from the Munich model with its two recent versions, namely Guo11 and DLB07. These two models are very similar in spirit: the same merger tree from the Millennium Simulation, similar descriptions of gas cooling, star formation and feedback from supernova and AGNs. However, the Guo11 model has slightly modified supernova feedback, which is more efficient in low-mass haloes, and they also introduce satellite disruption and use a new algorithm to assign the positions of orphan galaxies. Our results for the Munich models are as followings,

• Although the Guo11 model fits better the local stellar mass function, it over-predicts the clustering of low-mass galaxies on small scales. The DLB07 model over-predicts the number of low-mass galaxies, but it gives a reasonable fit to the clustering on small scales. On larger scales (10 > r > 1 Mpc/h), the predicted clustering in both models is still not perfect, but higher than the data by around 30%.

• We find that the clustering on small scales is dominated by satellite galaxies in the same dark matter halo (so called one-halo term). The one-halo term is determined by the density profile of galaxies in the host halo and the mass function of host haloes. We find that the Guo11 model predicts a steeper density profile of galaxies. After using the same method to assign galaxy positions as that in the DLB07 model, the Guo11 model produces similar profiles as the DLB07 model, and the clustering on very small scales is suppressed. However, the discrepancy between the Guo11 and DLB07 models still exists at r > 0.1 Mpc/h.

• We compare the distribution of the host halo mass in the two models, and find that there are slightly more satellites residing in massive haloes in the Guo11 model. This over-prediction of satellites in massive haloes is the dominant contribution to the discrepancy on galaxy clustering between the two models. Our results do not support the argument that the stronger clustering in the Guo11 model is from the formation bias of the host haloes (Wang13).

• We compare the predictions on the stellar mass functions in given halo mass from the DLB07 and Guo11 models, and find that both models over-predict the number of satellites by the same amount at $M_* = 10^{10} M_\odot$ in massive haloes ($M_{vir} > 2 \times 10^{12} M_\odot$). The DLB07 model produces more low-mass satellites than the Guo11 model. By simply removing of 30% of satellites in the two models, they can both well fit the clustering data. Removal this percent of satellites also brings the Guo11 model into good agreement with the global SMF. However, for the DLB07 model we have to further remove about 60% of central galaxies so as to fit the global SMF. By doing so, we find that the total galaxy clustering is not suppressed on small scales, it is boosted instead.

We thus conclude that the 'correct' prediction of galaxy clusterings from the DLB07 model is just a coincidence. This is because it predicts too many central galaxies in low-mass haloes, which have lower clustering. The over-abundance of centrals suppress the global clustering of all galaxies. However, we note that our simple way of rescaling the central galaxies in the DLB07 model may not be very reasonable. This is because we can not simply throw away central galaxy arbitrarily, unlike for the satellites as we can argue that current consideration of satellite disruption is not included or inefficient. The right way of rescaling the DLB07 model is to move the centrals into host haloes with higher mass, but lower density. For example for central galaxies with $M_* = 10^{10} M_\odot$ we should use the positions of central galaxies with higher halo mass, but with number density about 60% of the current hosts. However, By doing so we have to also change the host of satellites for given stellar mass, this is not possible as we do not know how the stellar mass of satellites evolve after their accretion in the DLB07 model.

Regarding the Guo11 model, its main problem is that the fraction of satellite galaxies is higher than the data in massive haloes. This indicated that the tidal disruption effect in this model is less efficient. The Guo11 model can thus be improved by introducing a slightly stronger tidal disruption effect. By doing so it could simultaneously fit the global stellar mass function, conditional stellar mass function in different host haloes, and the galaxy clustering on small scales.
We also show in this paper the semi-analytical model of K12 with a slight modification to the supernova feedback in satellite galaxies. In its previous version, K12 assume that the cold gas reheated by supernova in satellite galaxy is reheated to the temperature of its host halo, not the host subhalo. Here we assume that the cold gas is reheated to the virial temperature of its host subhalo. Usually the virial temperature of subhalo is lower than that of the massive host halo, so the amount of heated cold gas is increased in the new description. We have found from the new model that,

- The mass growth for satellite galaxies is usually around a factor of 2, much less than that in the old model, but still slightly higher than the data. We find that the CSMFs of satellites now agree much better with the SDSS data. We note that the improvement in the K12 model is purely due to the mass growth of satellites, not to the effect of satellite disruption. In most cases decreasing the mass of satellites has the same effect of satellite disruption. The reason is simple as there is good correlation between stellar mass and (sub) halo accretion mass, and the subhalo mass function is a power law with negative index, thus decreasing the mass has the same effect of decreasing the number density.

- The clustering of galaxies is now well reproduced in the new model, as there are fewer low-mass satellites in the new model.

Galaxy clustering on small scales is a hot topic recently, being seen as a common problem of most semi-analytical models (e.g., Kim et al. 2008; Guo11; K12). Many attempts have been made to solve this problem, including adopting a low $\sigma_8$ cosmology or introducing the warm dark matter model (Kang et al. 2013). However, it is found that $\sigma_8$ has little effect on the predicted clustering (K12; Guo et al. 2013). This is because the decrease in dark matter clustering is almost entirely compensated by an increase in halo bias (Wang et al. 2008; Guo et al. 2013).

We have clearly shown in this paper that, for any kind of model, if one can simultaneously fit the global SMF and the CSMFs, combined with a distribution of galaxy density profile like the NFW one, we could succeed in producing the clustering on all scales. Thus for semi-analytical models, it can be achieved by constraining the physics governing satellite evolution, such as mass stripping and disruption.

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