I review recent progress in understanding and modeling galaxy clustering in cosmological simulations, with emphasis on models based on high-resolution dissipationless simulations. During the last decade, significant advances in our understanding of abundance and clustering of dark matter halos allowed construction of accurate, quantitative models of galaxy clustering both in linear and non-linear regimes. Results of several recent studies show that dissipationless simulations with a simple, non-parametric model for the relation between halo circular velocity and luminosity of the galaxy they host, $V_{\text{max}} - L$, predict the shape, amplitude, and luminosity dependence of the two-point correlation function in excellent agreement with the observed galaxy clustering in the SDSS data at $z \sim 0$ and in the DEEP2 samples at $z \sim 1$ over the entire probed range of projected separations. In particular, the small-scale upturn of the correlation function from the power-law form in the SDSS and DEEP2 luminosity-selected samples is reproduced very well. At $z \sim 3 - 5$, predictions also match the observed shape and amplitude of the angular two-point correlation function of Lyman-break galaxies (LBGs) on both large and small scales, including the theoretically predicted strong upturn at small scales. This suggests that, like galaxies in lower redshift samples, the LBGs are fair tracers of the overall halo population and that their luminosity is tightly correlated with the circular velocity (and hence mass) of their dark matter halos.

1 Introduction

During the last decade, large observational surveys of galaxies both at low and high redshifts have tremendously improved our knowledge of galaxy clustering, its evolution, and the relation between the galaxy and matter distributions. A coherent picture has emerged in which bright galaxies are strongly biased with respect to the matter distribution at high redshifts, and in which the bias decreases with time in such a way that the amplitude of galaxy clustering is only weakly evolving, as expected in hierarchical structure formation. The bias is also in general scale-, luminosity-, and color-dependent. Bright (red) galaxies are more strongly clustered than faint (blue) galaxies both in the local universe and in the distant past.

These trends are in general consistent with the picture in which galaxies reside in extended dark matter (DM) halos, forming via hierarchical collapse and merging of peaks in the initial density field. Thus, for example, the stronger clustering of brighter galaxies can be readily understood if they tend to populate more massive halos, which are expected to be more clustered. Like galaxies, the halos are strongly clustered at high redshifts and their clustering strength evolves only weakly with time.

Clustering of halos of a given mass, formed in the standard structure formation scenario from a gaussian initial density field, is simple at large, linear scales, where it can be described
by a single number — the linear bias. Recently, it has been shown that in addition to the mass dependence, the halo bias depends on other halo properties, such as its formation time and mass concentration. At small scales, the clustering of halos is more complicated and bias is scale-dependent, the behavior resulting from dynamical evolution of halos in high-density environments. The non-linear clustering of halos on small scales and the processes shaping it have been extensively investigated during the last decade using dissipationless simulations.

One of the most important theoretical advances of the last several years is development of the Halo Model (HM) framework, in which galaxy clustering on both linear and nonlinear scales is described quantitatively using spatial and mass distribution of DM halos calibrated against cosmological simulations and the Halo Occupation Distribution (HOD) — the probability distribution for a halo of mass $M$ to host $N$ galaxies with specified properties (e.g., luminosity, color, etc.). In its simplest form, the HOD is assumed to depend solely on the halo mass. This appears to be a fairly good approximation. However, in general the HOD can depend on other halo properties or large-scale halo environment.

This framework proved to be extremely useful both in theoretical forecasts and interpretation of observed clustering data. For example, in the halo model the two-point correlation function is a sum of two separate contributions: the one-halo term, which arises from pairs of galaxies within the same dark matter halo, and the two-halo term, which arises from pairs of galaxies from two different halos. The one-halo contribution dominates on small scales, while at scales larger than the size of the largest virialized regions clustering is due to the two-halo term. In general, the two terms are not expected to combine so as to give a perfect power-law correlation function. Departures from power-law are thus generically expected in this model. In addition, the model predicted that deviations of the correlation function from a power-law should be even stronger at higher redshifts. This is because at high redshifts the merger rate is higher and halos are more likely to have massive subhalos of comparable mass and luminosities. When the merger rate decreases, such massive companions disappear as they merge due to dynamical friction. These predictions have now been convincingly confirmed by observations both at $z = 0$ and higher redshifts.

Although the general idea of a galaxy-halo connection is definitely reasonable and is not disputed, the key question is how tight this connection is and whether properties of halos are tightly related to the properties of galaxies they host. Theoretical models of galaxy clustering, partially reviewed here, and their comparison to the wealth of current observational data start to shed light on these fundamental questions of galaxy formation theory.

## 2 Theoretical Models of Galaxy Clustering

Ultimately, one would like to simulate the distribution of galaxies in a large, representative volume of the Universe, while reliably and self-consistently modeling their internal properties at the same time. Given that this is not yet feasible with the current state of our understanding of galaxy formation and the capabilities of the most powerful supercomputers, some phenomenological modeling and assumptions have to be made. Historically, galaxy clustering in cosmological simulations has been modeled using a variety of approaches.

The most direct approach is to use cosmological simulations which include both dark matter and baryonic components, as well as galaxy formation processes of radiative dissipation and phenomenological recipes for star formation and stellar feedback. Although properties of galaxies are not yet modeled reliably in such simulations, they allow for unambiguous identification of galaxies as dense clumps of gas and stars, as well as measurement of basic galaxy properties such as stellar and baryonic mass, stellar ages, luminosities and colors. These observables, in turn, allow for extensive comparisons with observations. The main disadvantage is
Figure 1: Left: Dark matter distribution in a flat ΛCDM simulation of a $60h^{-1}$ Mpc volume. Particles are color-coded on a greyscale according to the logarithm of the local density. One can see a network of filaments interconnecting groups and clusters. The network is filled with small, dense dark matter halos. Right: distribution of dark matter within the virial radius of a cluster-sized halo. The virial radius of the cluster is shown by the large circle. The volume enclosed by the cluster virial radius is filled with smaller dense subhalos, which are bound to the cluster and orbit within its potential. The circles indicate the individual objects identified by an automated halo finder (see Kravtsov et al. 2004 for details); the radii of the circles are proportional to the subhalo maximum circular velocity ($r_h \propto V_{\text{max}} \propto M_h^{1/3}$).

that such simulations are generally computationally expensive, forcing one to sacrifice the size of the simulated volume or spatial resolution to make the simulations feasible.

The most popular approach to modeling galaxy clustering employs semi-analytic modeling, which uses phenomenological recipes for specifying when, where, and how galaxies form and evolve within dark matter halos, in conjunction with high-resolution dissipationless simulations modeling spatial distribution and merger histories of dark matter halos. Such hybrid models of increasing degree of sophistication have been used to model evolution of galaxy clustering, as well as trends with luminosity, color, and other galaxy properties. These methods provide flexibility to explore the dependence of predictions on particular assumptions about galaxy formation physics, albeit at the expense of a fairly large number of free parameters, assumptions, and (often uncertain) parameterizations of the complex physical processes.

The third, considerably simpler approach, is to use high-resolution dissipationless, DM-only simulations capable of following the evolution of both isolated, distinct halos and subhalos — the bound, self-gravitating dark matter clumps orbiting in the potential of their host halo. Subhalos are the descendants of halos accreted by a given system throughout its evolution, which retain their identity in the face of disruption processes such as tidal heating and dynamical friction (see Figure 1). In the context of galaxy formation, there is little conceptual difference between halos and subhalos, because the latter have also been genuine halos and sites of galaxy formation in the past, before their accretion onto a larger halo. We thus expect that each subhalo of sufficiently large mass should host a luminous galaxy and this is indeed supported by self-consistent cosmological simulations. The observational counterparts of subhalos are then galaxies in clusters and groups or the satellites around individual galaxies. In this sense, I will use the term halos to refer to both distinct halos (i.e., halos not located within the virial radius of a larger system) and subhalos.

With the assumptions that 1) there is one-to-one correspondence between halos in dissipationless simulations and luminous galaxies and 2) there is a tight relation between halo properties...
and properties of the galaxy they host, one can use halo distribution self-consistently modeled in such simulations to make detailed predictions for galaxy clustering. Confronting these predictions with observations can test the validity of the assumptions above and constrain the relations between galaxies and their halos. In the remainder of this contribution, I will describe such studies in more detail. Their results show that this simple approach is remarkably accurate in describing the luminosity-dependence and evolution of galaxy clustering.

3 Modeling galaxy clustering in dissipationless simulations

3.1 Relating galaxies and halos

Assuming that all luminous galaxies live in the dark matter halos identified in high-resolution dissipationless simulations, the key question is how we relate a galaxy of a given luminosity to a specific halo. In what follows, I will consider only luminosity among the possible properties of galaxies. Although it may be possible to relate other properties, such as color, to halo properties, these relations are considerably more uncertain and are likely to exhibit large scatter. Luminosities (especially in the red and infrared bands), on the other hand, are related to the total stellar mass of the galaxies. The stellar masses, in turn, can be expected to be related to the depth of the potential well of the halo and hence to its maximum circular velocity \( V_{\text{max}} \) (note that potential energy of a halo scales as \( W \propto V_{\text{max}}^2 \)). This relation is thought to be the basis of the observed Tully-Fisher relation. Indeed, tight relations between halo circular velocity and stellar mass of the galaxies they host are expected in all models of galaxy formation.

The use of \( V_{\text{max}} \) as a halo property in simulations is attractive because it is unambiguous both for distinct halos and subhalos, which is not the case for the total mass. It should be noted that \( V_{\text{max}} \) measured in dissipationless simulations will not correspond directly to observed
rotation velocity of galaxies because dissipationless simulations do not take into account the effect of baryon condensation on circular velocity. For our purposes, however, it is sufficient that a monotonic correlation between luminosity and halo $V_{\text{max}}$ is expected.

The existence of such a monotonic relation allows for a simple, non-parametric model relating halo $V_{\text{max}}$ and galaxy luminosity. Specifically, the $V_{\text{max}}-L$ relation is derived from the measured abundance of halos as a function of their circular velocity and the requirement that the relation matches the observed luminosity function of galaxies. In the simplest version of the model, no scatter is assumed and the $V_{\text{max}}-L$ relation is derived by matching the circular velocity and luminosity functions: $n(> V_{\text{max}}) = n(> L)$.

Such a simple model is bound to be too simplistic. First, there is certainly scatter between observed galaxy luminosity and their halo circular velocities. Such scatter can be added into the model at the expense of introducing a free parameter. It is interesting that the amount of scatter between luminosity and $V_{\text{max}}$ may be constrained by joint comparisons of the model predictions for galaxy-galaxy and galaxy-mass correlations because the two statistics have different sensitivity to scatter and this sensitivity depends on luminosity.

Second, circular velocity of halos measured at the epoch of observations is not expected to be the optimal choice for subhalos. For distinct isolated halos, the current circular velocity is
a measure of their potential well assembled during evolution, and can therefore be expected to be tightly correlated with the stellar mass (or more generally the baryonic mass) of the galaxy the halo hosts. The circular velocity of subhalos in dissipationless simulations, on the other hand, is a product of both mass buildup during the period when the halo evolved in isolation and tidal mass loss, with an associated decrease of $V_{\text{max}}$, after the halo starts to orbit within the virialized region of a larger object and experience strong tidal forces. The stellar component of galaxies in centers of halos, which should be more tightly bound than halo dark matter, should be less affected by tidal forces and can stabilize the mass distribution (and hence $V_{\text{max}}$) in the inner regions. We can therefore expect that luminosity and stellar mass of galaxies hosted by halos in dissipationless simulations should be correlated with the subhalo mass or circular velocity, $V_{\text{acc}}$, at the epoch of accretion, rather than with its current value.

This is borne out by cosmological simulations that include gas dynamics, cooling, and star formation. Such simulations show that selection using $V_{\text{acc}}$ results in subhalo distribution similar to the selection based on stellar mass of galaxies hosted by subhalos (see Figure 2). One can therefore argue that a reasonable approach is to relate galaxy luminosity to the current halo circular velocity for distinct halos and to the circular velocity at accretion for subhalos. The models based on the halo properties at accretion were recently used in several studies. The results discussed below show that such simple luminosity assignment model reproduces the luminosity-dependence of galaxy clustering at different epochs with remarkable, and perhaps surprising, accuracy.

3.2 (Sub)Halo Occupation Distribution

As I noted in §1, the halo occupation distribution plays a central role in the modeling of galaxy clustering in the framework of the halo model. Given the assumption that every galaxy corresponds to a DM halo in high-resolution simulation, it is interesting to ask what form of the HOD the simulations predict. Analysis shows that for samples of halos with circular velocities larger than a certain threshold, the HOD is quite simple and can be parameterized with only a few parameters. Specifically, the HOD can be understood as a combination of the probability for a halo of mass $M$ to host a central galaxy, associated with the halo itself and the probability to host a given number $N_s$ of satellite galaxies, associated with the subhalos (Figure 3). Such logical division makes physical sense, because central galaxies occupy a special location in the halo near the minimum of the potential well. Observational analogs of the central galaxies are, for example, the Milky Way with its system of satellites or a cD galaxy in a galaxy cluster. The HOD of the central galaxies can be approximated by a step-like function, while the satellite HOD can be well approximated by a Poisson distribution, fully specified by its first moment. The first moment of the satellite HOD can be well described by a simple power-law $\langle N_s \rangle \propto M^\beta$ with $\beta \approx 1$ for a wide range of number densities, redshifts, and different power spectrum normalizations.

An important feature of the HOD shown in Figure 4 is the “shoulder” near the minimum mass of the sample. The total HOD in the region of the shoulder is narrower than the Poisson distribution — the fact that produces a nearly power-law correlation function of galaxies at lower redshifts. At higher redshifts, the shortening and steepening of the shoulder due to the younger age of host halos and more frequent presence of massive subhalos results in strong departures from power-law correlation function at small scales (see §3.4 and Figure 5).

Remarkably, the form of the HOD derived for subhalos in dissipationless simulations is very

\footnote{The distinction between circular velocity at accretion and current epoch has little effect at $z \gtrsim 1$. This is because both the accretion and disruption rates are high at high redshifts. The accreted halos do not survive for a prolonged period of time, so that at each high-$z$ epoch most of identified subhalos are recently accreted objects, which are yet to experience significant tidal mass loss.}
similar to galaxy HOD measured in N-body+gasdynamics SPH simulations and models employing semi-analytic models with dissipationless simulations. This supports the general framework of a close galaxy-halo connection. An additional important implication is that the physics shaping the HOD is relatively simple and is not sensitive to the details and specific assumptions of galaxy formation model.

If halo circular velocity correlates with the luminosity of galaxies they harbor, we can expect that galaxy occupation distribution should have a similar form. Indeed, halo model fits to the galaxy clustering measurements in the SDSS survey using the HOD form described above provide an excellent description of the data. Moreover, the HOD parameters derived from the data fits are in general agreement with the values expected from simulations.

3.3 Modeling luminosity-dependent clustering in the SDSS survey

Galaxy clustering as a function of luminosity at $z = 0$ predicted using halo catalogs from dissipationless simulations and a simple, non-parametric model relating galaxy luminosity to halo $V_{\text{max}}$, described in §3.1 is shown in the right panels of Figure 4. The figure shows remarkably good agreement between predictions and clustering of the SDSS galaxies at all luminosities. Note that both the normalization and shape of the correlation function are reproduced. It is critical to realize that the agreement on scales $r_p \lesssim 1h^{-1}$ Mpc is due to the luminosity assignment scheme using $V_{\text{max}}^{\text{acc}}$. The luminosity assigned using present $V_{\text{max}}$ for subhalos would result in a significant under-prediction of amplitude of $\omega_p$ at small scales, especially for fainter samples.

At the same time, the figure shows that galaxies of different luminosity exhibit different amplitude and scale dependence of their bias with respect to the overall matter correlation function in simulation. Although the bias appears to be complicated and scale- and luminosity-dependent, it is faithfully reproduced by halos.

The right panel of Figure 4 shows the first moment of the HOD (the mean number of galaxies in halos of mass $M$) for the luminosity samples shown in the left panels. The HOD shows explicitly that galaxies of higher luminosity reside in more massive halos. The overall shape of the HOD, however, is similar for all luminosities.
3.4 Modeling galaxy clustering through cosmic time

Figure 5 shows similar comparisons with galaxy clustering as a function of luminosity at $z \sim 1$ in the DEEP2 survey and clustering of Lyman Break Galaxies (LBGs) in the Subaru survey at $z \sim 4$. At both redshifts, the overall agreement is again excellent on all scales. Small discrepancies at $r_p \lesssim 0.5h^{-1}\text{Mpc}$ for the $M_B - 5\log h < -20.5$ DEEP2 sample may be attributed to cosmic variance and poisson noise.

It is worth stressing again that this remarkable agreement between observed and model clustering is achieved using the halo distribution in dissipationless simulations with a simple, non-parametric relation between galaxy luminosity and halo circular velocity. The luminosity-dependent bias at all redshifts hence seems to be driven entirely by the fact that brighter galaxies reside in more massive halos, with the correspondence between halo and luminosity determined by matching the observed luminosity function to the dark matter halo circular velocity function. This may appear as a reasonable and not unexpected result for lower redshift galaxies where luminosity may be expected to be a good tracer of stellar mass. The agreement for the LBG galaxies is more surprising and suggests that, like galaxies in lower redshift samples, the LBGs are fair tracers of the overall halo population and that their restframe UV luminosity is tightly correlated with the circular velocity (and hence mass) of their dark matter halos.

Note that at $z \sim 4$ the correlation function of the LBG galaxies exhibits strong departures from the power law at small scales, the behavior that was expected based on the halo model arguments and simulations. Similar behavior was also recently observed in clustering of LBG galaxies in the GOODS survey at $z = 4$ and $z = 5$. The analysis of the HOD of the $z = 4$ halos in the simulation supports the model in which most LBGs are the central galaxies in their host halos with luminosity tightly related to the halo circular velocity and mass. Most LBGs have no neighbors within the same halo. However, a fraction of them do and it is this fraction that is responsible for the strong upturn in the correlation function at small scales. The reason that small-scale upturn in the correlation func-
Figure 6: Comparison of the projected two-point correlation function for SDSS galaxies with luminosities $M_r < -20$ and predictions from dissipationless simulations with different assumptions about fraction of orphan satellite galaxies (galaxies with subhalos disrupted by tides, See §3.5). The solid line black line consistent with the data is the prediction without orphans (i.e., using only subhalos in the simulation; this is the same line as in Figure4). Other lines correspond to orphan fraction increase by 10% (the lines thus show effect of orphan fractions between 10% and 50%). Orphan fractions of $\gtrsim 10\%$ modify the amplitude and shape of $\omega_p$ sufficiently to break the agreement with the data. Figure courtesy of S.C. Conroy.

Figure 6: Comparison of the projected two-point correlation function for SDSS galaxies with luminosities $M_r < -20$ and predictions from dissipationless simulations with different assumptions about fraction of orphan satellite galaxies (galaxies with subhalos disrupted by tides, See §3.5). The solid line black line consistent with the data is the prediction without orphans (i.e., using only subhalos in the simulation; this is the same line as in Figure4). Other lines correspond to orphan fraction increase by 10% (the lines thus show effect of orphan fractions between 10% and 50%). Orphan fractions of $\gtrsim 10\%$ modify the amplitude and shape of $\omega_p$ sufficiently to break the agreement with the data. Figure courtesy of S.C. Conroy.

The situation becomes more pronounced at higher redshifts is that a larger fraction of the high-$z$ halos has a satellite of comparable mass relative to the lower-$z$ objects. In terms of the HOD, these differences manifest in a shorter and less flat “shoulder” of $\langle N(M) \rangle$ near the minimum mass of the sample at higher redshifts.

By accurately reproducing both the small-scale upturn in $\omega(\theta)$ and the large-scale clustering, our model accurately predicts not only the correct distinct halos to associate with LBGs (the ‘2 halo term’ in halo model jargon) but also the number of LBGs within a distinct halo (the corresponding ‘1 halo term’).

### 3.5 Are we missing galaxies in dissipationless simulations?

In dissipationless simulations, subhalos experience tidal heating and mass loss by the tidal field of the host halo. Such tidal mass loss and disruption are not numerical artefacts but are real physical processes affecting evolution of subhalos. However, one can argue that baryonic dissipation effects may greatly enhance resistance of galaxies and their halos to tidal disruption. A decision thus has to be made as to subsequent evolution of galaxy when its subhalo is disrupted by host halo tides. One extreme is to assume that stellar components of galaxies are always resistant to tidal disruption and are thus never disrupted. Such an assumption leads to up to

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*Operationally, disruption should be understood as a significant tidal mass loss which brings the total mass of a halo below a threshold of a halo sample or resolution of the simulation.*
\( \approx 30 - 40\% \) of satellite galaxies without subhalos in dissipationless simulations. Another extreme is to assume that stellar systems get tidally disrupted at the same time or shortly after the host halo is disrupted (as is assumed in the model used for comparisons with data above).

In order to assess the quantitative impact of such possible “orphan” galaxies on clustering statistics, the following simple test can be performed. The fraction of subhalos in a simulation is increased in such a way that the subhalo occupation function, \( \langle N(M) \rangle_{\text{sat}} \), increases in amplitude while maintaining the same shape. In order to match the observed galaxy luminosity function, the overall \( V_{\text{max}} \) threshold for a given sample is simultaneously increased, such that the number density does not change. Figure 6 shows the predicted projected 2-point correlation function of galaxies with \( M_r < -20 \) (results are similar for other luminosities) with different assumed fractions of orphan satellite galaxies. Even a small, \( \gtrsim 10\% \), contribution of orphan galaxies breaks the excellent agreement of the model with the data. Note that the amplitude of the correlation function is more sensitive to the presence of orphan galaxies at small scales (\( r_p \ll 1h^{-1}\text{Mpc} \)). Thus, addition of a significant fraction of the orphans changes not only the amplitude, but also the shape of the correlation function.

The existence of a significant (\( \sim 30 - 40\% \)) fraction of orphan galaxies in the real universe would imply that the excellent agreement with the observed amplitude and shape of the correlation function at different luminosities and at different redshifts is fortuitous. The disruption of stellar systems by tides is therefore an important problem which should be tackled with high-resolution numerical simulations that include stellar component.

3.6 Future prospects

The presented results indicate that the clustering can be modeled quite successfully with dissipationless simulations. As the amount and quality of data on galaxy clustering continues to improve, we can expect more stringent model tests. It would not be surprising if data soon reveals limitations of such a simple model. As I noted above, an interesting avenue is to perform joint comparison of the model to the galaxy-mass and galaxy-galaxy correlations. Such comparison can potentially constrain the level of scatter in the \( L - V_{\text{max}} \) relation.

On the theoretical side, comparisons with data can be done with simulations of larger volumes to reduce statistical and cosmic variance errorbars. Smaller error bars should allow us to see subtle deviations from the data. At the same time, the \( L - V_{\text{max}} \) model used in dissipationless simulations can be directly and thoroughly tested with \( N \)-body+hydro simulations with cooling and star formation. One important question that can be addressed in simulations is tidal disruption of galaxies and their DM halos and existence of “orphan” galaxies. This work is currently underway.

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