Prepared for submission to JCAP

The Maximum Circular Velocity Dependence of Halo Clustering

Contents

1 Introduction

The halo model has been remarkably successful in describing observations of galaxy clustering at many scales and many redshifts (give some examples here). fundamental assumption clustering only depends on the halo mass; not true because of assembly bias on large scales but also ideas of eg. backsplashed halos. recent trend has been to populate galaxies according to their maximum circular velocity. Describe why this might be motivated — depends only on the central part of the potential, set early in the growth of the halo (point to Frank's recent paper here as an example). Also may be more robust to disruption in mergers.

goal here is to discuss the dependence of galaxy clustering on the central velocity dispersion both on small and large scales. We show that some of the features in a detailed halo model come from the effects of back-splash halos.

2 The Simulation

We use cosmological N-body simulations called the Bolshoi simulation and the MultiDark simulation, described in XXX and XXX respectively, to investigate the maximum circular velocity dependence of halo clustering. The Bolshoi simulation uses 2048^3 particles with a volume of $(250h^{-1}\mathrm{Mpc})^3$, while the MultiDark simulation uses the same number of particles as the Bolshoi simulation but with a volume of $(1h^{-1}\mathrm{Gpc})^3$. Both simulations assumes a flat ΛCDM model with density parameters $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_b = 0.0469$, and $\sigma_8 = 0.82$, $n = 0.95$, $h = 0.70$. (??Do I need to put a name for each constant?)The details of the simulations are described in XXX. For halo identification, we use the ROCKSTAR halo finder (XXX) where the halo masses and maximum circular velocities are computed from bound particles.

??Should I explain more about what bound particles mean (though my understanding is vague...) and am not so sure what other ways to define masses and circular velocity and also how the definitions can make things different...

??What other information do I need to put here?

3 The Maximum Circular Velocity Dependence of Halo Clustering

In this section, we investigate the maximum circular velocity dependence of halo clustering on both large and small scales. In order to do that, we compute correlation functions and measure halo biases for halo samples having different maximum circular velocities. We first describe how we select halos for each sample and then show how those samples have different clustering properties.

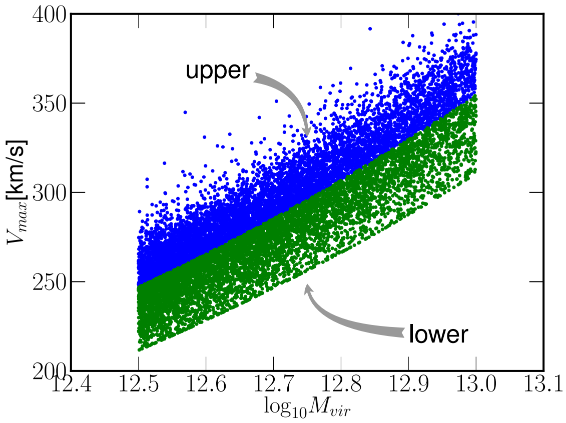

Figure 1. Distribution of halo mass and the maximum circular velocity at $z = 0.0$ for halos whose masses are between $10^{12.5}\mathrm{M}_\odot$ and $10^{13.0}\mathrm{M}_\odot$. The blue dots represent halos whose maximum circular velocity is greater than $\overline{V}_{mas}$, while the green dots are the ones with smaller $V_{max,obs}$ than $\overline{V}_{max}$. The boundary between blue and green dots corrspond to $\overline{V}_{max}$ computed from Eq. 3.1.

3.1 The Maximum Circular Velocity

As shown in Fig. 1, the maximum circular velocity and halo mass has tight correlation, and yet the scatter between the maximum circular velocity and halo mass becomes larger with decreasing halo masses. In fact, we can compute an expected maximum circular velocity from halo mass

$$\overline{V}_{\mathrm{max}} = 0.465 M_{\mathrm{vir}}^{1/3} \sqrt{G(\frac{4}{3}\pi\Delta_{\mathrm{h}}\rho_{\mathrm{crit}}\Omega_m)^{1/3}\frac{c}{\ln(1+\mathrm{c}) - \mathrm{c}/(1+\mathrm{c})}}, \tag{3.1}$$

where V_{max} is the maximum circular velocity and M_{vir} is the halo mass, Δ_{h} is the overdensity limit which defines the virial radius, and c is the concentration parameter. Eq. 3.1 comes from an NFW profile (citation). To obtain Eq. 3.1, we use the concentration of

$$\log_{10}c = -0.097\log_{10}\mathrm{M}_{\mathrm{vir}} + 2.148. \tag{3.2}$$

(??Ask Frank how he obtain this concentration value and why this is a reasonable value) In Fig. 1, this $V_{\mathrm{max}} - M_{\mathrm{vir}}$ relation with the above concentration (shown as a red solid line) intersects the peak of the distribution, which means that many of the halos follow this relation.

3.2 Samples

The above equation is a one to one mapping between the virial mass of the halo and its maximum circular velocity. Given this mapping, we can translate clustering measurements as a function of halo mass into predicted clustering measurements as a function of maximum circular velocity. Our goal below is to determine whether this conversion describes the measured clustering or if there is a residual dependence on the maximum circular velocity. In order to explore this, we first split the sample into a sequence of virial mass bins, chosen such that there are the same numbers of halos in each bin. This process is reminiscent of an abundance-matching procedure (cite XXX). We then further split each bin into two subsamples with their observed $V_{\mathrm{max,obs}}$ greater than (denoted by "upper") or less than (denoted as "lower") $V_{\mathrm{max}}(M_{\mathrm{vir}})$. This selection ensures that both the upper and lower subsamples have the same mean halo mass. Therefore, in the absence of an additional M_{vir} dependence (??isn't this M_{vir} dependence?) on clustering, these samples should have the same clustering properties. Note that this would not be true if we had simply split the sample along V_{max}, since the two resulting subsamples would have different mean halo masses.

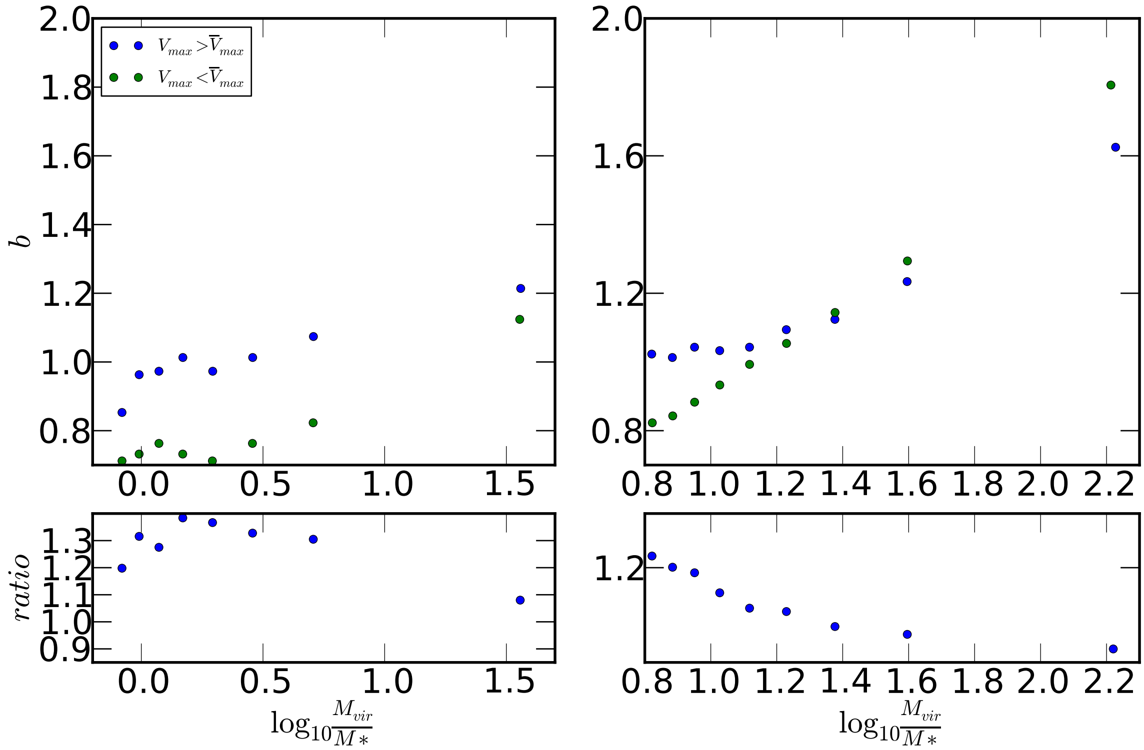

Figure 2. Upper panel: Linear bias at $z = 0.0$ as a function of halo mass from the Bolshoi simulation (left) and the MultiDark simulation (right). The blue circles represents a linear bias for halos whose maximum circular velocities are greater than $\overline{V}_{max}$, while the green circles correspond to halos whose maximum circular velocities are smaller than $\overline{V}_{max}$. Lower panel: Ratio of linear biases between "upper" (i.e., $V_{max,obs} > \overline{V}_{max}$) and "lower" (i.e., $V_{max,obs} < \overline{V}_{max}$) samples from the Bolshoi simulation (left) and the MultiDark simulation (right). As halo masses decrease, the difference on linear bias between "upper" and "lower" subsamples becomes larger up to 40%. Here, $M* = 10^{11.5}M_{\odot}$.

3.3 Mvir-based samples

In order to measure halo biases, we compute halo-matter cross correlation functions for each subsample and measure a linear bias

$$b_{lin} =< \xi_{hm}(r)/\xi_{mm}(r) >, \tag{3.3}$$

where ξ_{hm} and ξ_{mm} are halo-matter and matter-matter correlation functions and we take the average of the ratio on r from $10h^{-1}$Mpc to $20h^{-1}$Mpc (??may change to jackknife samplings). Here, instead of using full DM particles, we subsample 1000000 particles to compute matter auto correlation functions. The reason we use cross correlation functions is to reduce the shot noise effect on the error.

In Fig. 2, we show how linear biases depend on the maximum circular velocity as a function of halo mass. We compute linear biases for each mass bin classifying into "upper" and "lower" maximum circular velocity halos. The halos which have different maximum circular velocity clearly cluster differently. Furthermore, the relative bias of "upper" versus "lower" subsamples increases with decreasing halo mass to almost 40% on low mass end.

In Fig. 3, we investigate the maximum circular velocity dependence of halo bias on small scales. On small scales, a halo bias is scale-dependent. The question here is whether halos with different maximum circular velocity have different scale-dependence on their biases. In order to find that, we take the ratio of halo-matter cross correlation functions between "upper" and "lower" subsamples and normalize it by their linear biases. Fig. 3 clearly shows that the scale-dependence depends on the maximum circular velocity and its Vmax-dependence is mass-dependent. As halo mass decreases, the relative scale-dependence between "upper" and "lower" subsamples increases, especially halos with large maximum circular velocities heavily clustered around $1h^{-1}$Mpc.

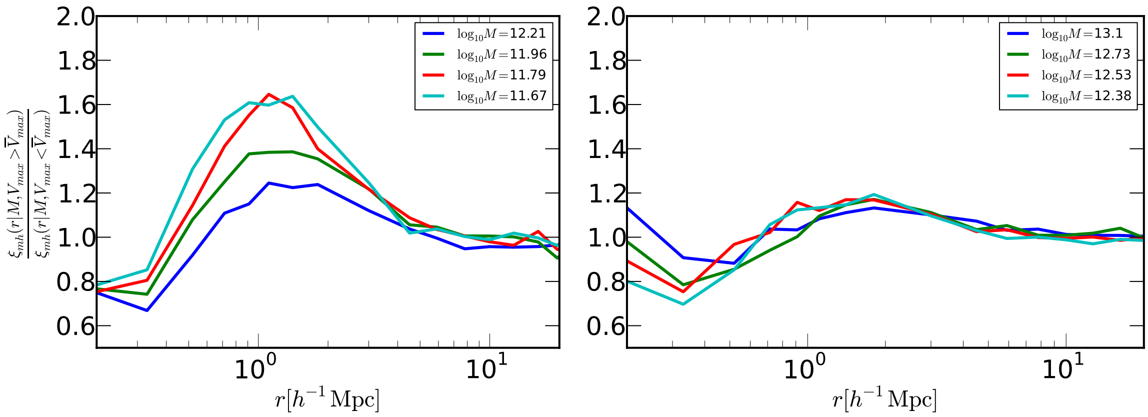

Figure 3. Ratio of halo-matter cross correlation functions between "upper" and "lower" subsamples normalized by their linear biases. The plots are from the Bolshoi simulation (left) and the MultiDark simulation (right) at z = 0.0. Each line corresponds to different halo mass bins labeled in the plots. Those plots show that "upper" and "lower" subsamples have different scale-dependence on small scales and the relative scale-dependence between those subsamples increases smoothly with decreasing halo mass.

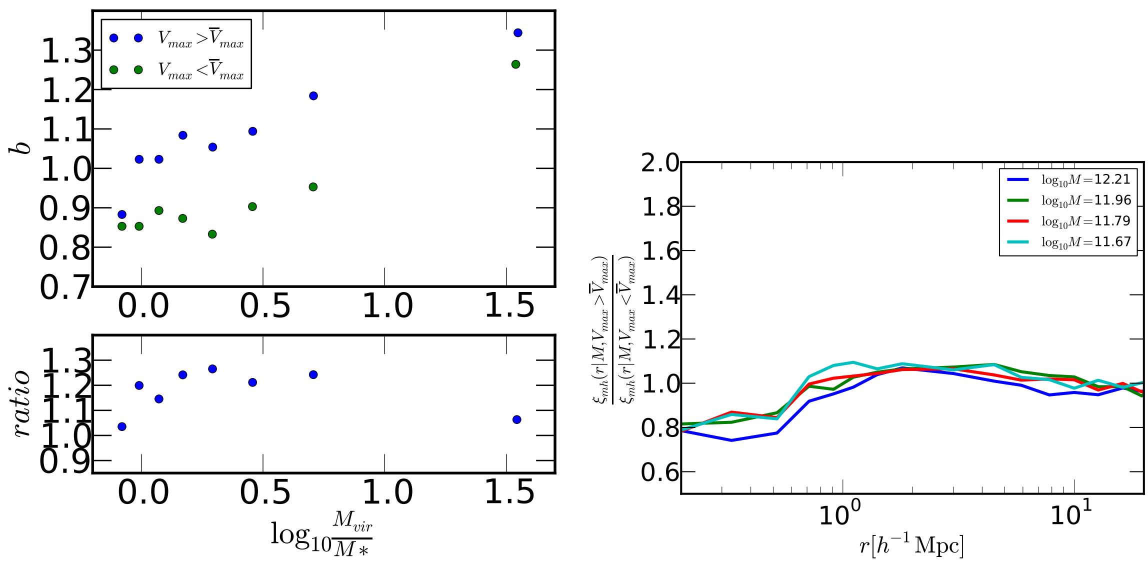

Figure 4. The same figures as Fig. 2 (left) and Fig. 3 (right) without ejected halos. We use halos from the Bolshoi simulation at $z = 0.0$, because we could not find many ejected halos in the MultiDark simulation due to its mass resolution. The left panel shows the linear bias as a function of halo mass for the halos whose V_{max} greater/less than $\bar{V}_{max}$ and their ratio between those subsamples. The difference in linear biases without ejected halos is suppressed on small halos close to M^*, while there is little difference between the ratio with and without ejected halos on large mass end. The right panel shows the ratio of halo-matter cross correlation functions between "upper" and "lower" subsamples normallized by their linear biases. It is obvious that the scale-dependent clustering difference is now mostly removed by excluding ejected halos from samples.

*need some explanations for the decrease of the relative bias on the lowest mass end? is it real or artificial?

*use jackknife sampling to put error bars

4 Applications

4.1 Mvir-based v.s. Vmax-based

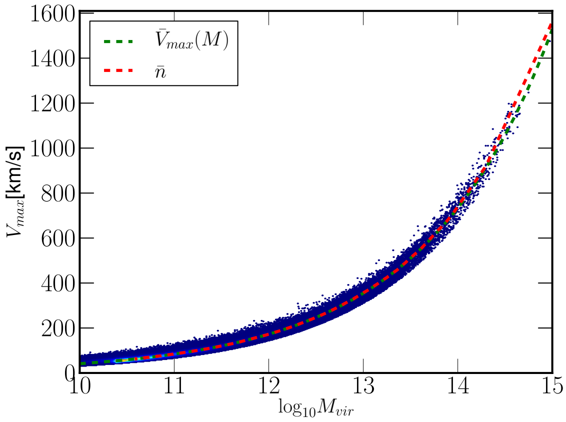

Figure 5. Distribution of halo mass and the maximum circular velocity as a countour plot, overplotted $\overline{V}_{max}$ (as a green dashed line) and the correspondence between M_{vir} and V_{max} in abundance matching (as a red dashed line labeled as $\overline{n}$). The plot shows that $\overline{V}_{max}$ and the correspondence in abundance matching overlaps on most of halo mass scales.

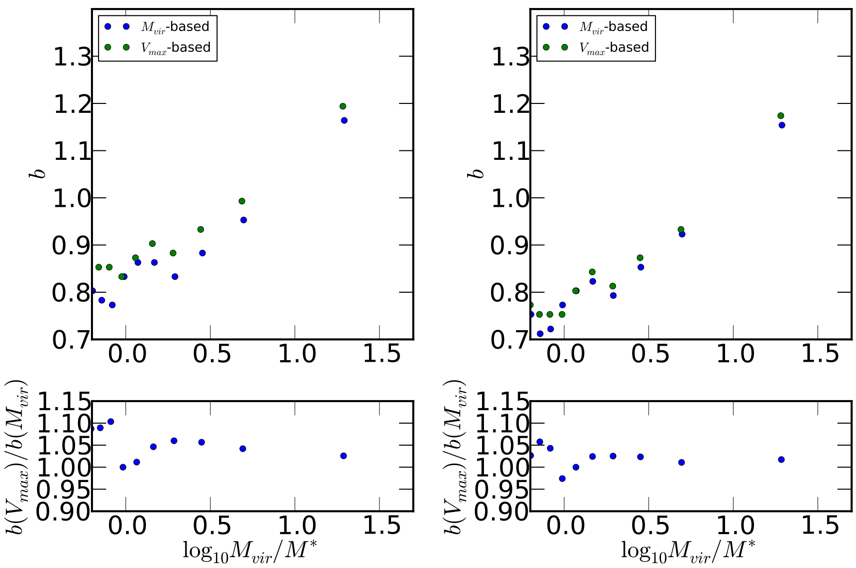

Figure 6. Upper panel: We compare linear biases for halos selected by abundance matching for halo mass (blue dots) and the maximum circular velocity (green dots) as a function of halo mass where $M^* = 10^{11.5}\mathrm{M}_\odot$. As shown in Fig. 5, we can find a corresponding V_{max} for those samples through Eq. 3.1. The left panel is the result including ejected halos, while the right panel is the one without ejected halos. The linear biases overall decrease by excluding ejected halos for both M_{vir}-based and V_{max}-based abundance matching samples. Lower panel: Ratio of linear biases between M_{vir}-based and V_{max}-based abundance matching samples with ejected halos (left) and without ejected halos (right). The difference between those samples become smaller by at most factor of 2.

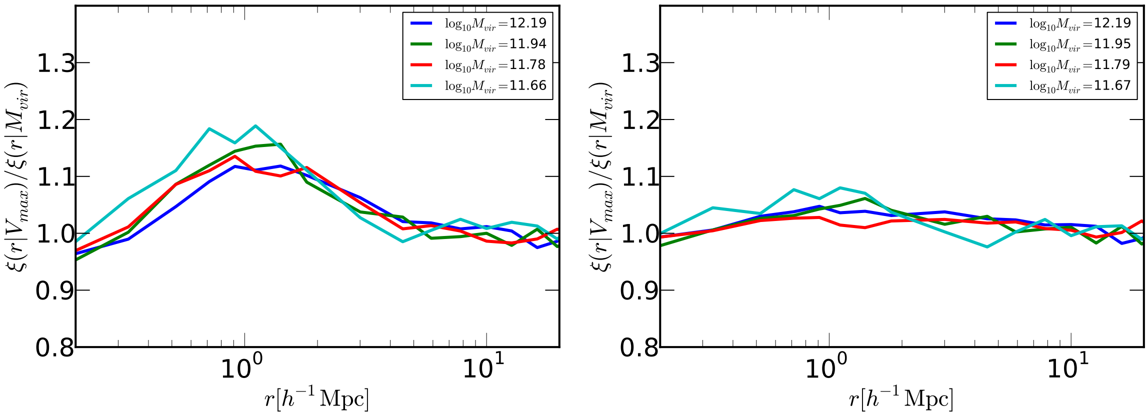

Figure 7. Ratio of halo-matter cross correlation functions between M_{vir}-based and V_{max}-based abundance matching samples with ejected halos (left) and without ejected halos (right). The ratios are normalized by their linear biases. Each line corresponds to different halo mass bins labeled in the plots (which can be translated into corresponding $\overline{V}_{max}$ through Eq. 3.1). When samples contain ejected halos, there is a strong scale-dependent difference between those two different abundance matching samples around $1h^{-1}$Mpc. By excluding ejected halos, the difference is more or less removed.

4.2 $\Delta\Sigma(r)$

4.3 MergerTree's Vmax v.s. Vmax,obs

5 Discussion

(Option)

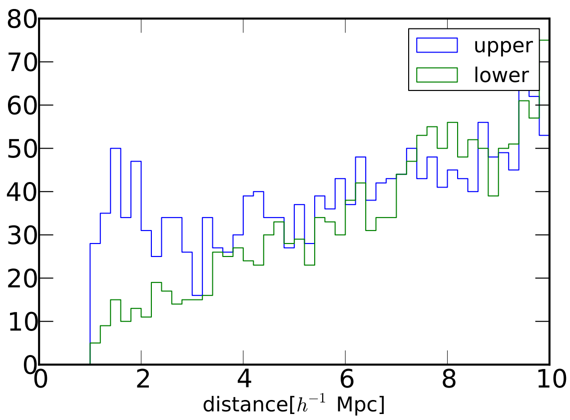

Figure 8. Histogram of distances to the nearest Clusters (defined as $M_{vir} > 10^{14}\mathrm{M}_\odot$) for non-ejected halos and ejected halos: Right now, I only have the one for all the halos...may change to the plot of fractions: Is it reasonable to play with the cluster masses? Also, make the similar plots for nearest massive halos by separating ejected and non-ejected halos (upper/lower)...