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. We use both simulations to get large dynamic mass range. The effective mass ranges is $M_{\mathrm{vir}} > XXX$ for the MultiDark simulation and $M_{\mathrm{vir}} > XXX$ for the Bolshoi simuation.

Q: What is the lower limit of mass for each simulation and how do we justfy those numbers?

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. We first start with an analytic expression of the maximum circular velocity computed from the halo mass and its concentration. Then, we explain how we select halos to remove the halo mass dependence from the samples using the analytic expression of the maximum circular velocity.

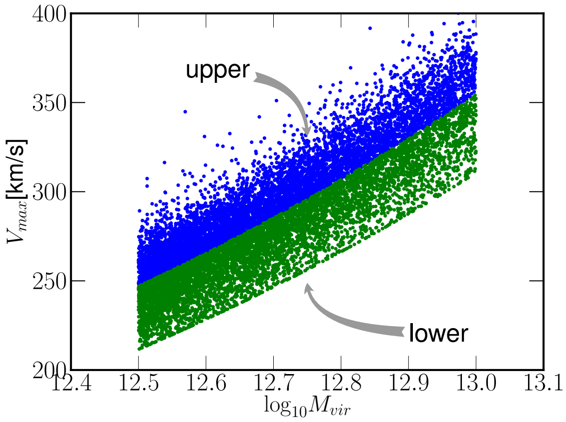

Figure 1. Distribution of halo mass and maximum circular velocity at $z = 0.0$ for halos whose masses are between $10^{12.5}\mathrm{M}_\odot$ and $10^{13.0}\mathrm{M}_\odot$. The blue dots represent halos whose maximum circular velocity is greater than $\overline{V}_{mas}$, while the green dots are the 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

Here, we assume that dark matter halos are defined as a spherical halo with a virial radius. Those halos have average density equal to $\Delta_{\rm h}\rho_{\rm crit}$ where $\Delta_{\rm h} = 360$ for the MultiDark and Bolshoi simulations. We also assume that those spherica halos have an NFW density profile (XXX). Then, the maximum circular velocity $\overline{V}_{\rm max}$ as a function of the halo mass $M_{\rm vir}$ and its concentration c is given by:

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

The median concentration-mass relation at $z = 0$ obtained from the Bolshoi simulation in Ref. XXX(Klypin et al. 2011) is:

$$\log_{10} c = -0.097 \log_{10} {\rm M_{vir}} + 2.148. \tag{3.2}$$

By using the above median concentration to Eq. 3.1, we obtain a one to one mapping between the virial halo mass and its maximum circular velocity, denoted as $\overline{V}_{\rm max}$ hereafter. 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.

3.2 Samples

In order to explore a dependence on the maximum circular velocity, 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 $V_{\rm max,obs}$ greater than (denoted by "upper") or less than (denoted as "lower") $\overline{V}_{\rm max}$. Fig. 1 shows the distribution of halo mass and maximum circular velocity classified into "upper" (blue dots) and "lower" (green dots) samples as an example. As you can see, the number of halos in each sample is almost half for any halo mass bins. 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 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 $V_{\rm max}$, since the two resulting subsamples would have different mean halo masses.

3.3 Halo Bias

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. 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" (i.e., $V_{\max} > \overline{V}_{\max}$) and "lower" (i.e., $V_{\max} < \overline{V}_{\max}$) maximum circular velocity halos. The halos which have different maximum circular velocity have different linear bias values. On large mass end, halos with $V_{\max} < \overline{V}_{\max}$ have a larger linear bias, which is consitent to the result discussed in Ref. XXX(Dalal et al. 2008). On the other hand, as halo masses decrease, halos with $V_{\max} > \overline{V}_{\max}$ start having larger linear biases than those with $V_{\max} < \overline{V}_{\max}$, and the difference between those two samples increases up to 40%. We think that the drop of the ratio on the low mass end is due to mass resolution of the simulation not resolving all the halos for the low mass.

things that I want to write (possibly with the histogram): Halos which have larger maximum circular velocity than the one predicted from its halo mass have high concentration. Those halos which have high concentration are the halos which should have grown to larger halo mass but somehow the mass growth was suppressed or its mass was stripped from other larger halos...want to explain things more clearly...any good papers which explain about this physical picture?

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, shown in Fig. 3. By normalizing by their linear biases, the ratios go to one on large scales. Fig. 3 clearly shows different scale-dependence between "upper" and "lower" subsamples, and the difference becomes larger as halo masses decrease. We particlularly see that there is a characteristic bump around 1 to 2 h^{-1}Mpc. This implies that many halos in the "upper" samples, expecially low mass halos, cluster very closely to each other.

Q: How can I describe this characteristic bump aroun 1Mpc/h?

Q: Do I need to describe what's going on physically? Are there any good reference for that?

Q: Also, how can I connect from this plot to the plot without ejected halos?

Using the merger trees, there are three types of halos: host halos, subhalos, and ejected halos. Thier definitions are found in Ref. XXX(Frank's paper). Up to now, we use both host halos and ejected halos to compute halo biases. Ejected halos are sometimes called "backsplash" halos, which passed through the virial region of other halos before $z = 0$. Those ejected halos tend to exist around a more massive halos (any reference?), and some of them may be gravitationally bound to the massive halos. To test this, we compute halo-matter cross correlation functions without the ejected halos. Fig. 4 shows the same figures as Fig. 2 and Fig. 3 without ejected halos from the Bolshoi simulation. Due to mass resolution, we could not find many ejected halos in the MultiDark simulation. The ratios of linear biases between "upper" and "lower" samples are somewhat suppressed, but still there are more than 20% deviations. On the ther hand, the different scale dependence of halo bias appeared on small scales significantly goes down to to less than 10%, which implies that difference in small scale halo biases are mostly due to the ejected halos.

We conclude that halos which have different $V_{\max}$ cluster differently even when those halos have the same virial mass. Halos which have high $V_{\max}$ are the ones which could have grown to a larger halo mass, but did not due to suppression of mass growth caused by tidal fields in high density regions (any references for this picture, and also how can I phrase this better?), and therefore they have larger halo biases than the ones which low $V_{\max}$.

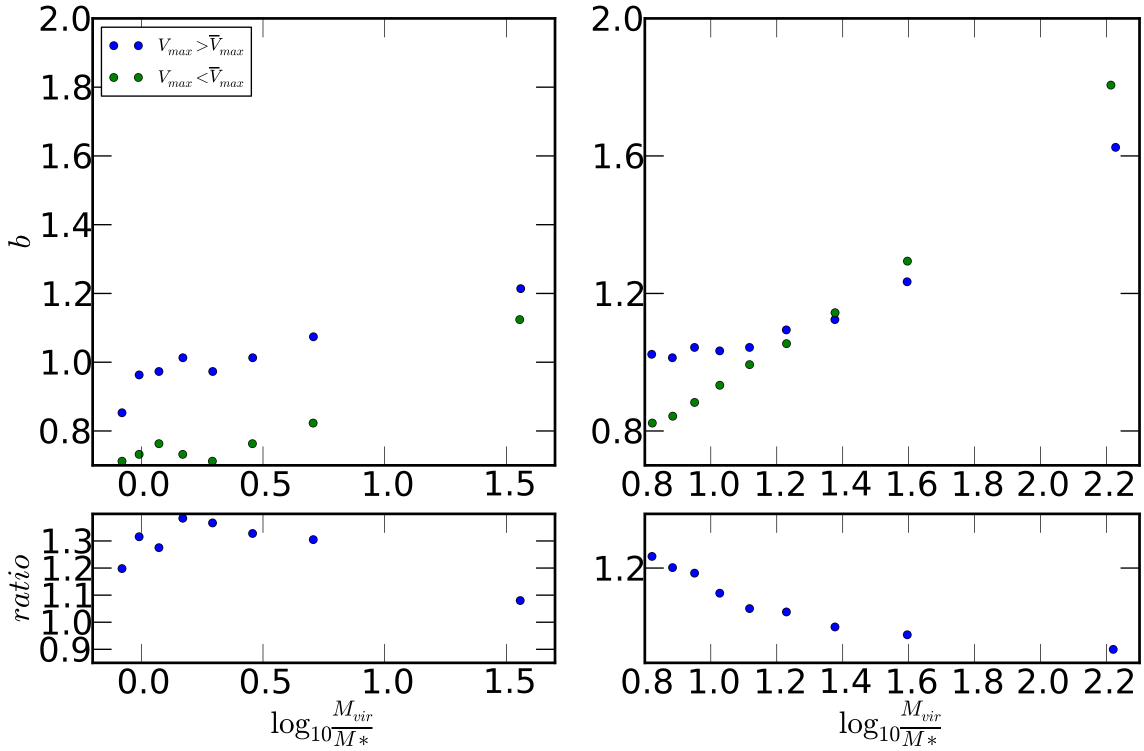

Figure 2. Upper panel: Linear bias at $z = 0.0$ as a function of halo mass from the Bolshoi simulation (left) and the MultiDark simulation (right). The blue circles represents a linear bias for halos whose maximum circular velocities are greater than $\overline{V}_{\rm max}$, while the green circles correspond to halos whose maximum circular velocities are smaller than $\overline{V}_{\rm max}$. Lower panel: Ratio of linear biases between "upper" (i.e., $V_{\rm max} > \overline{V}_{\rm max}$) and "lower" (i.e., $V_{\rm max} < \overline{V}_{\rm max}$) 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, $M* = 10^{12.4}{\rm M}_\odot$ (Is the unit M_{\odot} or with h?).

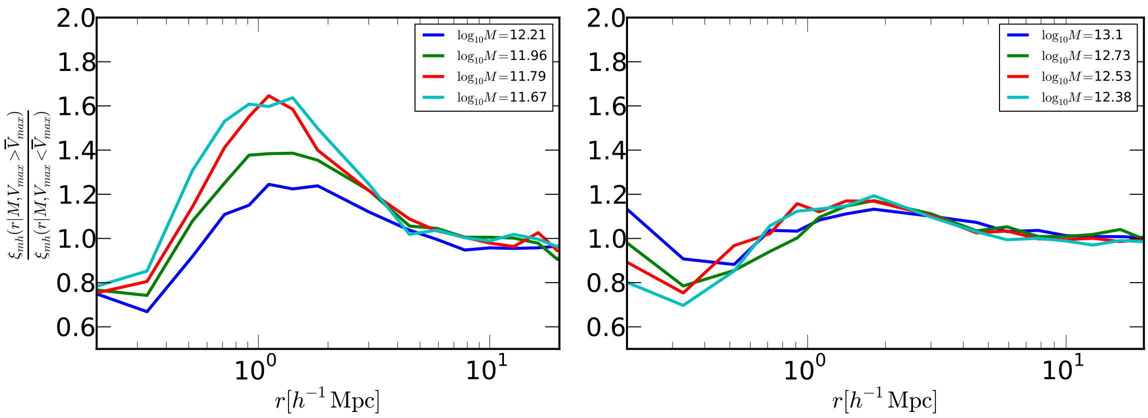

Figure 3. Ratio of halo-matter cross correlation functions between "upper" and "lower" subsamples normalized by their linear biases. The plots are from the Bolshoi simulation (left) and the MultiDark simulation (right) at z = 0.0. Each line corresponds to different halo mass bins labeled in the plots. 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.

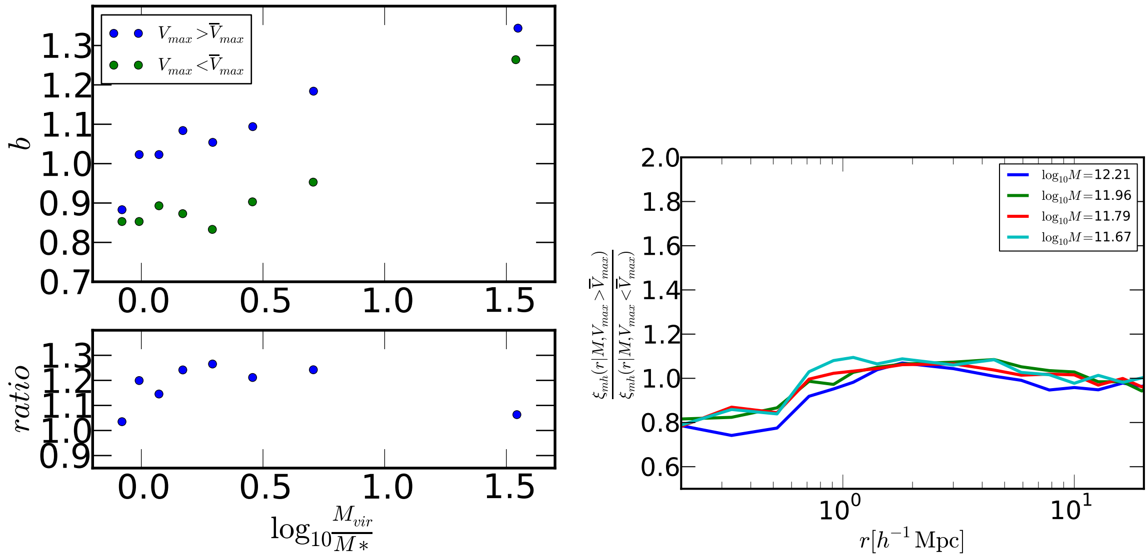

Figure 4. The same figures as Fig. 2 (left) and Fig. 3 (right) without ejected halos from the Bolshoi simulation. As can be seen by comparing these results to those in Fig. 2 & 3, the Vmax-dependence of halo bias on small scales is dramatically reduced by excluding ejected subhalos, while the Vmax-dependence of linear bias is suppressed but not completely removed. This implies an intimate connection between assembly bias and subhalo back-splashing.

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.

–possibly, I want to show the distrbution of halo mass and Vmax for ejected halos and check how many of them are actually gravitationally bound to more massive halos.

–use jackknife sampling to put error bars

4 Applications

In this section, we demonstrate possible observational relevances of the results in the previous section to complement the halo theory results. We start with the abundance matching (citation?) technique based on halo mass and the maximum circular velocity, and then compute $\Delta\Sigma(\mathrm{R})$ using those two difference abundance matching.

4.1 Mvir-based v.s. Vmax-based

In abundance matching, we assume that a big galaxy lives in a big halo in a herachical manner to link galaxies to halos. The question is what "big" halos really mean. To rank order halos, we want to identify what the thing to characterize "size" of halos is. We compare clustering of samples selected by using the abundance matching based on M_{vir} and V_{max} (When can I use those short notations?).

First, we check the correspondence between $\overline{n}(M_{\mathrm{vir}})$ and $\overline{n}(V_{\mathrm{max}})$ as shown in Fig. 5. The red line represents the boundary where $\overline{n}(M_{\mathrm{vir}} <) = \overline{n}(V_{\mathrm{max}} <)$ (how can I phrase this differently?). This boundary overlaps with $\overline{V}_{\mathrm{max}}$ from Eq. 3.1, which implies that XXX.

Similar to the previous section, we compute halo-matter correlation functions for the abundance matched samples by splitting halos into a sequence of halo mass bins or the maximum circular velocity bins chosen such that each bin has the same number of halos. Fig. 6 and 7 are the same as Figure 2 and 3 with the ejected halos (left panel) and without the ejected halos (right panel).

–$b_{\mathrm{lin}}(V_{\mathrm{max}})$ is larger than $b_{\mathrm{lin}}(M_{\mathrm{vir}})$ about 5% on low mass

–By excluding the ejected halos, the difference in linear biases is suppressed to 2 to 3%. -¿check the actual numbers

–how to describe the result for small scale biases?
–interpretation/implication
–what's the possible problem if any
–what's interesting
–check the number of ejected halos in Vmax and Mvir

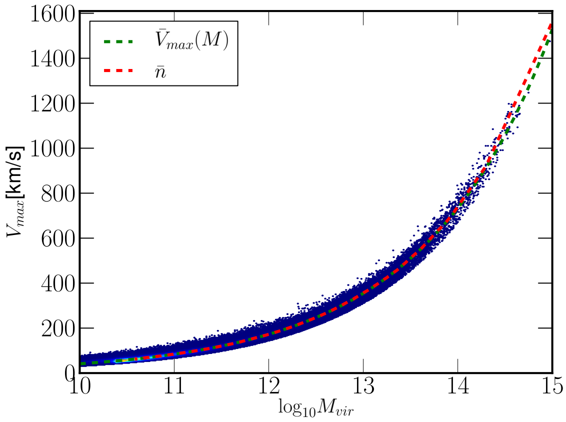

Figure 5. Distribution of halo mass and the maximum circular velocity as a countour plot, overplotted $\overline{V}_{max}$ (as a green dashed line) and the correspondence between M_{vir} and V_{max} in abundance matching (as a red dashed line labeled as $\overline{n}$). The plot shows that $\overline{V}_{max}$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

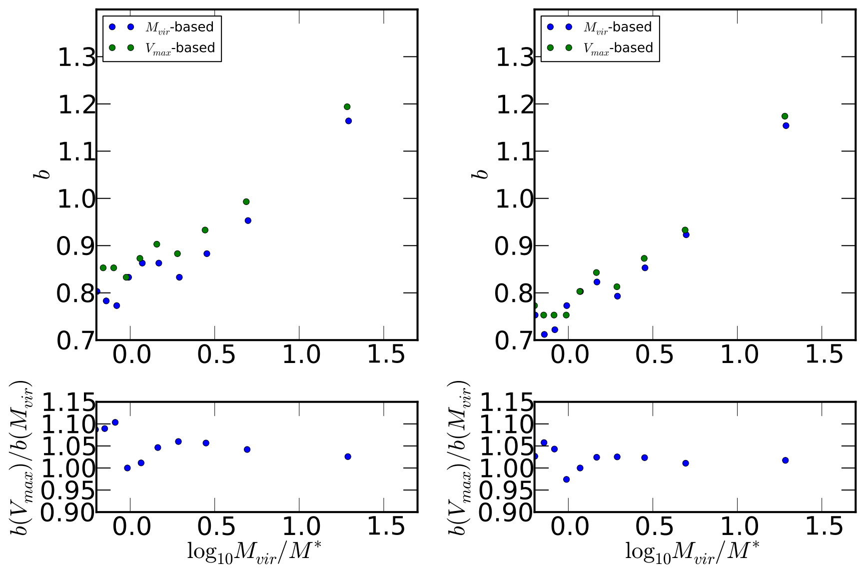

Figure 6. Upper panel: We compare linear biases for halos selected by abundance matching for halo mass (blue dots) and the maximum circular velocity (green dots) as a function of halo mass where $M^* = 10^{11.5}\mathrm{M}_\odot$. As shown in Fig. 5, we can find a corresponding V_{max} for those samples 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.

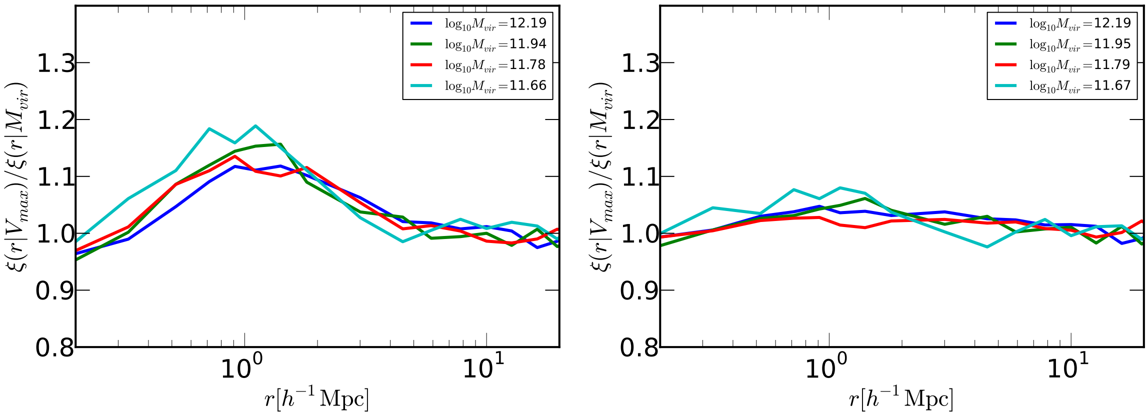

Figure 7. Ratio of halo-matter cross correlation functions between M_{vir}-based and V_{max}-based abundance matching samples with ejected halos (left) and without ejected halos (right). The ratios are normalized by their linear biases. Each line corresponds to different halo mass bins labeled in the 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 $\Delta\Sigma(r)$

(Both are from Andrew's comments)

–Select a bin of Milky Way mass host halos, and select their number-density-matched Vmax-selected equivalent. Use Peter Behroozi's stellar-to-halo mass relation to estimate the stellar mass of the central galaxy that would be found in these halos, then plot the halo-matter cross-correlation as a function of scale, over-plotting the two results.

–want to show: We show that the galaxy-galaxy lensing signal of low-mass centrals is impacted at the xxx-yyy% level, in a highly scale-dependent fashion, by the theoretical choice to empirically connect stellar mass to either host halo Vmax or Mvir.

4.3 HOD(?)

5 Discussion

(Option)

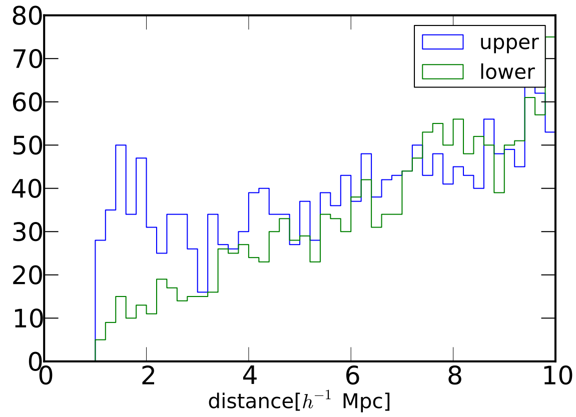

Figure 8. Histogram of distances to the nearest Clusters (defined as $M_{vir} > 10^{14}\mathrm{M}_{\odot}$) for non-ejected halos and ejected halos: Right now, I only have the one for all the halos...may change to the plot of fractions: Is it reasonable to play with the cluster masses? Also, make the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