Modeling the galaxy/light-mass connection with cosmological simulations

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I review some results on the galaxy/light-mass connection obtained by dissipationless simulations in combination with a simple, non-parametric model to connect halo circular velocity to the luminosity of the galaxy they would host. I focus on the galaxy-mass correlation and mass-to-light ratios obtained from galaxy up to cluster scales. The predictions of this simple scheme are shown to be in very good agreement with SDSS observations.

Keywords: galaxy-mass correlation; mass-to-light ratio; cosmological simulations

1. Introduction

During the last decade, large observational galaxy surveys have greatly improved the information we have about the relation of galaxies and/or light with the underlying mass distribution. However, our understanding of these relations is at best incomplete, largely because they are shaped by processes of galaxy formation that are too numerous and complicated to be included in cosmological simulations. As a result, often other either semi-analytic or empirical ways are adopted to investigate these connections.

In this paper I summarize some results on the galaxy/light-dark matter relation predicted by a simple scheme used to assign luminosities to dark matter halos formed in cosmological simulations. In this scheme, simulated dark matter halos of a certain number density are assigned the luminosity of observed galaxies with the same number density. When calculating these number densities, we rank galaxies with respect to their SDSS r-band luminosity — i.e., we use the observed SDSS r-band luminosity function — while we rank the simulated dark matter halos using as tag the maximum of their rotation velocity, $V_{\text{max}}$. Thus, the assumption we make is that
there is a one-to-one relation between the luminosity of a galaxy and the gravitational potential of the halo within which the galaxy is formed, with the latter being described by \( V_{\text{max}} \). This is a reasonable assumption since we expect the ability of a halo to make baryons cool and form a galaxy to increase with the halo gravitational potential depth. Furthermore, \( V_{\text{max}} \) is particularly good as a potential depth indicator in the case of subhalos. Assuming that the initial — prior to accretion potential — is the one relevant for galaxy formation in subhalos, \( V_{\text{max}} \), being a property of the inner parts of halos is not affected as much by tidal processes as other halo properties (e.g., the mass). Thus, it is a fair indicator of the initial potential within which the galaxy formed. In addition, we assign magnitudes in the remaining four SDSS bands \((u, g, i, \text{and} \ z)\) using the observed relation between local galaxy density and color. More specifically, we use as a measure of density the distance to the 10th nearest neighbor above a certain luminosity. We measure this quantity for both our mock galaxies and actual observed SDSS galaxies. For each mock galaxy, we then choose a real SDSS galaxy which has a similar \( r \)-band luminosity and nearest neighbor distance, and assign the colors of this galaxy to the mock galaxy.

In what follows I present results obtained after assigning luminosities in halos simulated in collisionless simulations using the above scheme. More details and references can be found in Refs. 1–4.

2. Galaxy-mass clustering

The most recent observational study of galaxy-galaxy lensing by the SDSS collaboration\(^5\) (hereafter S04), has significantly improved the accuracy of galaxy correlation measurements. The observable is \( \Delta \Sigma \) defined as \( \Delta \Sigma = \bar{\Sigma}(\leq R) - \Sigma(R) \), where \( \bar{\Sigma}(\leq R) \) is the mean surface density within the projected radius \( R \), \( \Sigma(R) \) is the azimuthally averaged surface density at \( R \), and \( \Sigma_{\text{crit}} \) is the critical density for lensing which depends on the angular diameter distances of the lens and the source. S04 also deprojected their \( \Delta \Sigma \) to obtain the actual 3D galaxy–mass correlation function, \( \xi_{gm} \).

We calculate \( \Delta \Sigma \) and \( \xi_{gm} \) in simulations by selecting and weighting objects in accordance with S04. A comparison between our results and the S04 results is shown in Fig. 1. Our faintest bin is not exactly the same as that of S04, but the faintest galaxies that are missing from our sample have only a small contribution to the total signal. Given these small differences and the simplicity of our luminosity assignment scheme the agreement between simulations and observations is quite good. From the left panel we see that, in agreement with S04, the amplitude of the correlation function increases
Fig. 1. Left panel: $\Delta \Sigma$ as a function of projected separation $R$ as measured by SDSS\(^5\) (points) and as calculated from the simulations (lines). Results are shown for two $r$-band luminosity bins: $-22.2 \leq M_r \leq -21.7$ (triangles/dashed line) and $-21.7 \leq M_r \leq -17.0$ (squares and solid line, respectively). The effect of $\sigma_8$ can be seen for the fainter sample for which we plot the results for the $\sigma_8 = 0.75$ (dotted line) and $\sigma_8 = 0.9$ (solid line) runs. Right panel: Comparison of the simulation galaxy–mass correlation function (lines) with the SDSS observations (points) in the $u$, $g$, $i$, and $z$ SDSS bands for the fainter sample. The numbers in parentheses denote the actual faint magnitude limit of the sample of Ref. 5. Reproduced from Ref. 1.

3. Mass-light relation

Our luminosity assignment scheme does not distinguish between isolated halos and subhalos, i.e. halos within larger (host) halos. Furthermore, there is scatter between mass and $V_{\text{max}}$. Thus, it is not obvious that our scheme can give the observed mass-light relation. In Fig. 2 we present a comparison of the mass-to-light ratios as a function of virial mass obtained for several of our simulations with results obtained by a more recent version of the M/L analysis of Ref. 6. These authors constrained the parameters of the...
Halo Occupation Distribution (HOD) by fitting the space density and the projected SDSS galaxy-galaxy correlation function. With this HOD they then calculated the mass-to-light ratios. The agreement between our results and those from the HOD analysis is astonishing. Furthermore, the mass-to-light ratio varies as expected, namely it has a minimum at some mass scale, and increases towards larger and smaller masses. It increases more rapidly towards smaller masses, and this increase is expected since below a certain mass one expects that galaxies cannot form given that halos are not massive enough to be able to cool the baryons. The increase towards high masses is not as steep and is expected on the basis that galaxy formation efficiency goes down with mass at large masses possibly because of feedback effects, e.g. from AGNs. Moreover, there seems to be a flattening of the mass-to-light ratio above a mass of $\sim 10^{14} h^{-1} M_\odot$. 

Fig. 2. Mass-to-light ratio against virial mass. For the top two panels the total luminosity of an object is calculated by summing up the luminosities of all galaxies with SDSS $r$-band magnitude $M_r < -19$. For the bottom panel this magnitude threshold is equal to $-20.5$. Simulations $L80_a$, $L120$ and $L250$ are for $\Omega_m = 0.3, \Omega_\Lambda = 0.3, \sigma_8 = 0.9$ and $h = 0.7$. Simulation $L80$, was run using the 3 year WMAP best fit parameters. The squares show the corresponding HOD predictions of a more recent version of the analysis of Ref. 6. In this analysis the authors fixed the power of the power law giving the mean number of satellite galaxies as a function of host mass, $\langle N_{sat}\rangle \propto M^\alpha$, to unity ($\alpha = 1$). Reproduced from Ref. 4.
4. Going a step further...

Since our simple scheme seems to be reproducing very well different kinds of observations (also see, e.g., Ref. 7 for comparisons with the galaxy autocorrelation function), we can use it to gain some insight, e.g., into interpreting/analyzing the observations. For example, the left panel of Fig. 3

addresses the question of how well weak lensing observations will be able to infer the typical mass of halos in a luminosity bin. Clearly, for finite luminosity bins as used in observations one has a distribution of halo masses. This may bias the estimated ‘mean mass’, especially if the distribution is asymmetric. As shown in the figure and for our assumed mass distribution, we find that the mass inferred via weak lensing \( M_{\Delta \Sigma} \) lies somewhere between the median and the mean of the mass distribution. Thus, the mass derived cannot be interpreted in a straightforward way as the mass for galaxies of
a given luminosity, unless one knows the mass distribution. Therefore, the mass–luminosity relations should be quoted and interpreted with caution. More discussion on the information we will be able to extract from weak lensing observations using the halo model formalism can be found in Ref. 2.

In addition, we can gain insight for quantities not directly observable. The right panel of Fig. 3 shows the correlation coefficient $r$ and bias $b$ for two volume-limited simulation samples of different luminosity. The top panel also shows comparisons of the cross-bias, $b_x^{-1}$, for the volume-limited sample of S04. If $\xi_{mm}$, $\xi_{gg}$ and $\xi_{gm}$ are the mass–mass, galaxy–galaxy and galaxy–mass correlation functions, respectively, then the above quantities are defined as: $b^2 = \xi_{gg}/\xi_{mm}$, $r = \xi_{gm}/(\xi_{mm}\xi_{gg})^{1/2}$ and $b_x = \xi_{gg}/\xi_{gm} = b/r$. The simulation results agree with observations within the error bars. A small offset of the simulation results toward smaller values of $b_x$ may be due to objects with $-23.0 < M_r < -22.5$, which are not present in our simulations due to the small box size and which could enhance the clustering signal somewhat. The correlation coefficient is approximately unity on scales $\geq 1 h^{-1} \text{Mpc}$ in our simulations. This means that on these scales the cross bias $b_x$ which is observable is a fair measure of the standard bias $b$ which is not directly observable.

Acknowledgments
I want to thank A.V. Kravtsov, R.H. Wechsler and J.R. Primack for allowing me to present here some of the results of our work. Also, I want to especially thank J. Tinker for making available the predictions of his HOD formalism for comparison with the simulation results.

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