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# GALAXIES AND MASS: LENSING AND DYNAMICAL MEASUREMENTS FROM THE SDSS

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RESUMEN

El estudio de la relación entre galaxias y masa es uno de los principales objetivos del Sondeo Digital Sloan del Cielo (Sloan Digital Sky Survey). En este trabajo describimos mediciones de las correlaciones galaxia-masa utilizando tanto pruebas con lentes como dinámicas. Los observables que discutimos incluyen el contraste proyectado de densidad de materia medido en las imágenes del SDSS y los movimientos de partículas luminosas medidas como parte del sondeo de corrimientos al rojo del SDSS. Ambas pruebas de la masa son mediciones muy sensibles, que varían apreciablemente con la luminosidad galáctica, por ejemplo. La interpretación de los resultados es compleja. Como primer paso, obtenemos los parámetros del mejor ajuste para modelos muy simples. Este ejercicio revela la importancia de realizar la comparación entre teoría y observaciones a nivel observacional. Argumentamos que para la interpretación de las mediciones deben usarse simulaciones completas, que incluyan tanto estructura a gran escala como prescripciones para la formación de galaxias. Concluimos presentando un primer ejemplo de tal comparación.

ABSTRACT

Probing the relationship between galaxies and mass is a major goal of the Sloan Digital Sky Survey. In this contribution we describe measurements of galaxy-mass correlations using both lensing and dynamical probes. The observables we discuss include the projected mass density contrast measured in SDSS imaging data and luminous particle motions measured as part of the SDSS galaxy redshift survey. Both probes of mass are sensitive measures, varying significantly with galaxy luminosity for example. Interpreting these results is complex. As a first step, we obtain best fit model parameters for various toy models. This exercise reveals the importance of making the comparison between theory and observation at the observable level. We argue for the use of full simulations, including both large scale structure and galaxy formation prescriptions, in the interpretation of these measurements. We conclude with a first generation example of such a comparison.

*Key Words:* **DARK MATTER — GALAXIES: FUNDAMENTAL PARAMETERS — GALAXIES: HALOS — GRAVITATIONAL LENSING — LARGE-SCALE STRUCTURE OF THE UNIVERSE**

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## 1. PRELIMINARIES

Determinations of the mass distribution in the universe often rely on measurements of luminous galaxies. Relating the distribution of these galaxies to the mass field they occupy is essential to constraining models of structure formation. We review here some tools which are available for inferring mass on galaxy halo scales, including some cautionary comments. We then focus on SDSS lensing and dynamical measurements relating the luminous properties of galaxies to their dark matter environments. A key component in quantifying these relationships will be detailed comparison with simulations, and we conclude with an example of such an analysis.

## 2. PROBES OF MASS ON HALO SCALES (50-1000 KPC)

In dynamical measurements of mass, the observables are the positions and velocities for a set of luminous test particles. The test particles sample the velocity field around the objects of interest, and probe the dynamical effect of gravity on the test particles.

In lensing measurements of mass, the observable is a shear field and the geometry associated with it. Lensing probes the space-time curvature around the objects of interest. It provides a probe of the projected mass density contrast.

It is important to remember that neither measures directly the mass we want. Inferring masses from these observables requires careful consideration of a variety of effects. In both cases, measurements can be made with high signal-to-noise in modern data sets, including the SDSS data. Essentially all

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the work from now on involves accurately understanding how the observables relate to theoretically favored quantities like $M_{200}$.

## 3. COMPLICATIONS IN MASS DETERMINATION

Deriving masses from the available observables is complicated by many observational and theoretical factors. Dynamical methods require the presence of luminous tracers, limiting utility of the method in dark matter dominated regions. On halo scales the luminous tracers are often galaxies themselves, whose finite masses can complicate modelling. Projection effects will always be present, so any method will need to account carefully for interlopers. Given a clean set of observations the modeling is still complex. Dynamical times are much longer than observation times, leaving uncertainty about the dynamical state of the system. Often the dynamical times are longer than a Hubble time, invalidating simple equilibrium models. Mass modeling also requires assumptions about velocity bias and the orbital structure of our tracers; assumptions which are difficult to test from observations.

Lensing methods, too, suffer from interpretive problems. First, the signals are very small. Systematic uncertainties in determining the signal need to be carefully considered. Second, lensing actually measures the total projected mass along a line of sight, filtered with an extremely broad lensing sensitivity curve. As a result, interpretation of lensing measurements requires careful separation of contributions from individual galaxies and from the clustering of galaxies.

Even on the theory side, there are major interpretive complications. In modern discussions of structure formation, we mostly consider dark matter halos. These halos are defined by various methods, and their masses are determined in various ways (White 2000). Dark matter halos are occupied by galaxies, but the details of this halo occupancy, especially in terms of the observed properties of galaxies, such as morphology and color, are not known from theory (Peacock and Smith 2000; Berlind and Weinberg 2002). There are important semantic issues. Do we assign all the mass we see to *some* galaxy, or does a fraction of the mass belong to the halo itself, independent of the galaxies? Structures in the universe do not have discrete boundaries. How do we we deconvolve the contributions of various halos?

## 4. SDSS LENSING AND DYNAMICAL PROBES OF HALO MASS

The data we use derive from the Sloan Digital Sky Survey (www.sdss.org). The SDSS is a large collaboration, involving perhaps 200 scientists at a number of institutions. It is designed to make comprehensive astronomical observations. Over the coming few years the SDSS will complete an imaging survey of $10^4$ square degrees of the sky, obtaining 5 color images for about $10^8$ galaxies. In addition to imaging, the SDSS will measure high quality spectra for about $10^6$ galaxies and $10^5$ quasars. This set of observations will support a very broad range of science goals, in much the same sense that gene sequencing data is useful for many purposes. For the analyses described here, both the imaging and spectroscopic data are important.

We begin with the lensing measurements; measuring the correlation between locations of foreground lens galaxies and distortions in the shapes of distant sources galaxies. We refer to this as the galaxy-mass correlation function (GMCF: Fischer et al. 2000).

The SDSS data used for this study are drawn from the commissioning period. From imaging and spectroscopic data we select a sample of 34,693 foreground 'lens' objects. Every one of these objects has a spectroscopic redshift and highly accurate 5-color photometry. We also select a fainter background sample of 3,615,718 'source' objects. While the foreground redshift distribution is accurately measured, the background source galaxy redshift distribution is estimated in a manner based on smaller redshift surveys which are complete to magnitudes fainter than the SDSS data. Details of these measurements are given in McKay et al. 2001 (M01).

The galaxy-mass correlation function is measured in each of the three most sensitive SDSS colors. While the three measurements are made independently, they measure the shapes of the same galaxies, so they are strongly correlated. The full correlation matrix is taken into account when the g', r', and i' data are combined. It is important to note that the signal we measure is extremely small. The peak distortion is only about 0.5%. Despite this tiny signal, the GMCF is detected at $S/N > 13$ in each color. A variety of stringent tests have been conducted to ensure that gravitational lensing is actually responsible for the observed signal.

How should we think about these measurements? The basic observable is the surface mass density contrast, what we call the projected mass correlation function. Given a sample of lens objects, this mea-

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surement is very clearly defined, and can in principle be easily compared to N-body simulations. There is one very difficult step in this comparison. All the measurements are strongly affected by the detailed selection of lens galaxies. Results described below demonstrate that the observed GMCF is strongly dependent on the luminous properties of the lens galaxies selected. To make accurate comparisons to simulations, we need to be able to select 'lenses' in the simulations in ways which are very similar to those used in the data. We will return to this issue later.

In the meantime, it is interesting to estimate the effect of the clustering of lenses. In doing this, there are important matters of sematics. First, each lens has neighbors which are both brighter and fainter than it. Which do we call galaxies? When do we decide that a small satellite is really part of the larger galaxies? Second, do we wish to assign all the matter in a region around a galaxy to the galaxy, or do we want to consider some of that mass as belonging to a group in which the galaxy sits? That is, does all mass get assigned to galaxies or not?

We discuss briefly two approaches. And remember, they're mostly designed to probe the importance of neighbor or group mass contributions to the signal. In the first method, we measure W($\theta$) for the lenses, assume they all have the same truncated isothermal profile, and fit the observed GMCF to a convolution of the two. This is not enough to tease out some 'isolated galaxy', but it does give an idea of the contribution from neighbors.

Figure 1 shows the full GMCF for three samples, all lenses, lenses in dense regions, and lenses in underdense regions. In each case the derived 'deconvolved' galaxy profile is also shown. The contribution from these neighbors is about 10 at 250 kpc. Although this method is very simple, it does give consistent profiles when applied to galaxies in high and low density regions.

Jacek Guzik and Uros Seljak (2002) have recently taken a different approach to analyzing exactly the same data. In their paper they model the environments of galaxies in a halo occupancy distribution model. The observed GMCF is then thought of as arising from a galaxy contribution and a halo contribution. They make predictions for the expected profile from each, and fit the data to a combination of the two.

This method has the virtue of putting the decomposition into the language of a popular structure formation model. But in the end, it amounts to fitting the observations to two curves, and obtaining

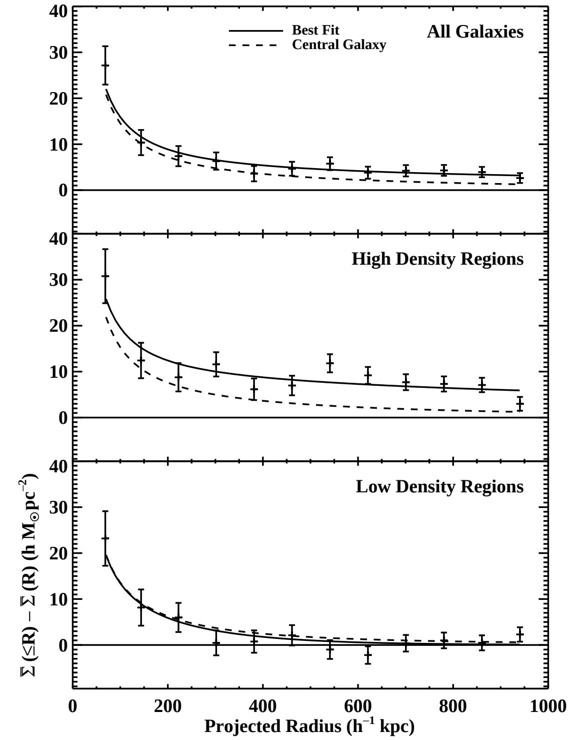


Fig. 1. This figure illustrates the results of the deconvolution method described in the text. The top panel shows the measured and deconvolved GMCF for all galaxies. The middle panel shows the same for galaxies in dense regions, and the bottom for galaxies in underdense regions. While the raw GMCF is very different in the dense and underdense samples, the derived deconvolved profiles are all consistent.

an amplitude for each. To determine these curves they have made a number of assumptions about the model which the data cannot test.

To a certain extent, both of these approaches oversell the information content of the data. Rather than fitting to models with ill-determined and perhaps unphysical parameters, it is preferable to work with simulations which model all the required physics.

We have described how we can use lensing to probe the mass around galaxies on halo scales. Now we discuss how we can do this dynamically.

What we need is a set of luminous test particles out in the halos of galaxies. In this initial study we prefer simple systems, so we look for a set of relatively isolated host galaxies surrounded by fainter, presumably less massive, satellites. When we use a 1.5 magnitude isolation criterion to select satellite galaxies, we find, unfortunately, that each host has only one or a few satellites. This would seem to pre-

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vent us from measuring masses.

But in fact its not a problem, at least if we are willing to make the same kind of correlation measurement we make for lensing. If we construct a velocity difference histogram for a class of galaxies, it represents their average dynamical effect in the same way that the GMCF represents their average projected surface mass density.

So we begin by picking a sample of host and satellite galaxies. For each host and satellite pair we calculate a velocity difference. Then we group the galaxies by luminosity and construct a velocity difference histogram for hosts of each luminosity. The basic observable is a set of positions and velocities for galaxy satellites. The presence of massive hosts is revealed by the dispersion in the velocities of the satellites.

Given these two probes of halo mass, lensing and satellite dynamics, we can now examine the scaling of halo mass with host light.

## 5. SIMPLE MASS-TO-LIGHT SCALINGS

To derive a simple mass estimate from the lensing signal we fit the galaxy mass correlation function in the central 260 kpc to a simple SIS model. This amounts to simply extracting the overall amplitude of the GMCF. We then compare this 'SIS mass' to luminosity in each of the 5 SDSS colors. In each case we fit the relationship between mass and luminosity to a power law of the form $M_{260} = \Upsilon(L/10^(10)L_{\odot})^{\beta}$. Figure 2 shows for each color the actual mass-to-light scaling, and then $\chi^2$ contours for the best fit normalization and power law index in each color.

For this sample of galaxies, there is little relationship between mass and light in u'. But the relationship between mass and light in the other bands is strong, and in every case consistent with linear. Since the relationship is linear, it makes sense to speak of a mass- to-light ratio in the redder bands. Caution is called for in interpreting this. It is really only correct to treat this as what it is, the normalization of a power law fit to the relationship between this particular mass estimator $M_{260}$and the luminosity of the central galaxy. We can relate this to theoretically favored quantities like $M_{200}$only if we understand in detail the relationship between the observable $M_{260}$and $M_{200}$.

We stress that the same statement is true for every mass-to-light estimate yet obtained. Since mass is not an observable, we're really talking about scalings between model fit parameters and light.

What happens if we do a similarly straightforward modeling of the dynamical measurements? We

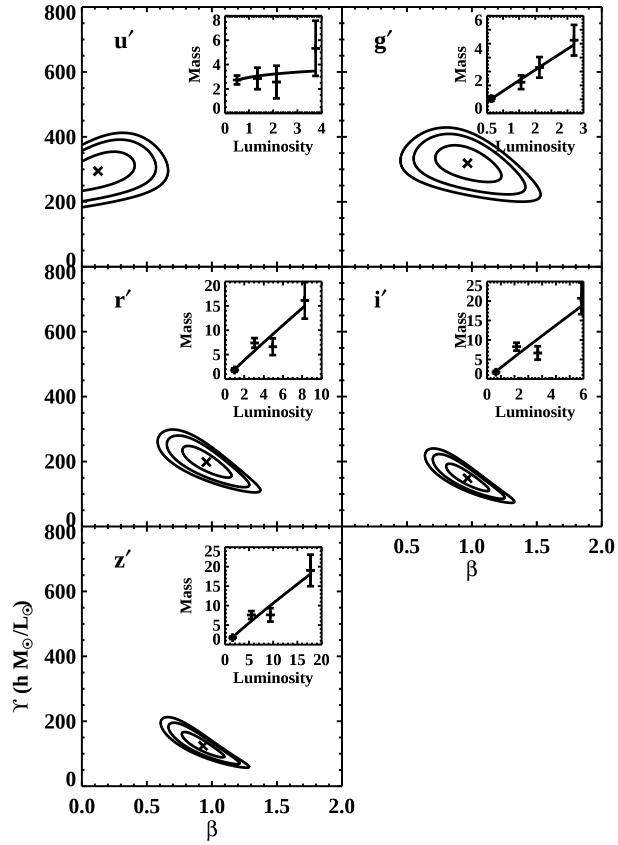


Fig. 2. The five panels in this figure summarize the relation between $M_{260}$ and luminosity in each of the five SDSS bands. For each band the small inset figure shows this directly. Points in these inset figures are the measured $M_{260}$ and mean luminosity of galaxies in four luminosity bins. The line in these inset figures shows the best fit to a power law relation between $M_{260}$ and luminosity of the form: $M_{260} = \Upsilon \times \left(L_{central}/10^{10}L_{\odot}\right)^{\beta}$. The larger figure shows 68%, 95%, and 99% confidence contours for the fit parameters $\Upsilon$ and $\beta$.

model the mass of this averaged system using a spherical Jeans model. We measure the galaxy density profile and the variation of satellite RMS velocity with radius, and assume (for the moment) that the velocity anisotropy $\beta = 0$. All this leads to a the simple dynamical mass estimator shown here. We evaluate this at 260 $h^{-1}$ kpc, just as with the lensing measurements, and examine how the inferred masses ($M_{260}^{dyn}$) scale with host galaxy luminosity. The result is a variation of mass with luminosity quite consistent with that deduced from lensing. The basic result is shown in Figure 3.

Now, to derive masses from both the lensing and dynamical observables we have used relatively simple models, models which cannot be precisely appropriate. Nevertheless, we find it very reassuring that

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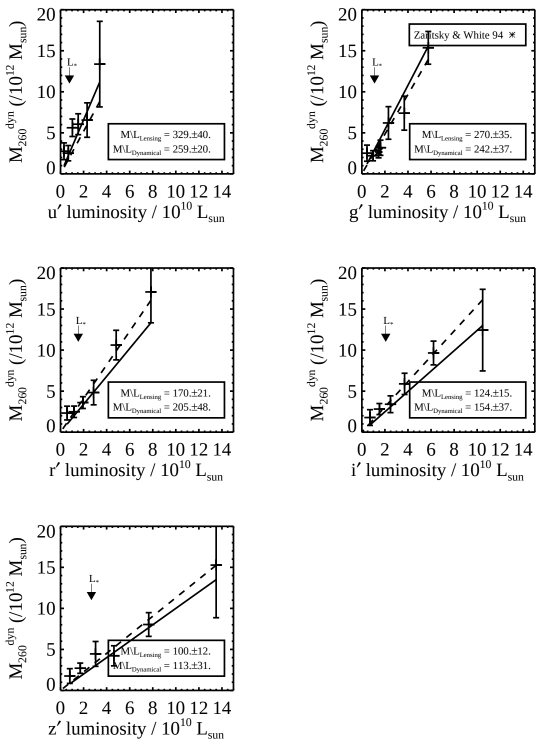


Fig. 3. This figure shows the relationship between $M_{260}^{dyn}$ and luminosity in each of the five SDSS bands. In each plot the data points are the $M_{260}^{dyn}$estimates for each luminosity bin. The vertical arrow in each plot marks the luminosity of an $L_*$ galaxy in each band. The solid line in each plot represents the best fit lensing $M/L$ for from M01. The dashed lines represent the best fit constant $M/L$ model from these dynamical measurements. Note that all five figures are on the same scale. Most of the variation of mass with luminosity is seen for $L > L_*$ galaxies.

these two completely different and independent ways of probing mass reveal comparable relationships between mass and light. Remember, they are subject to totally different systematic errors, and to totally different problems in interpretation. So while this is preliminary, it shows that these combined methods hold great promise for quantifying the relationship between galaxies and their dark matter environments. The signals are there. To measure these relationships precisely, we have only to reduce our systematic uncertainty in the modeling which relates the observables to mass.

Both lensing and dynamical measures show a strong variation of mass on halo scales with luminosity. Unfortunately, neither provides a particularly direct approach to theoretically favored quantities like $M_{200}$.

When we first obtained these results, we were surprised by the fact that the relationship between mass and light we observed did not agree with a naive expectation from the Tully-Fisher relation. We now suspect this is telling us something about the structure of galaxy halos. Tully-Fisher measurements relate a characteristic velocity at the optical radius to the luminosity. We are measuring instead a characteristic velocity at roughly the virial radius. The ratio of these two velocities is not constant, but varies with galaxy luminosity in a way which exaggerates the dependence of luminosity on the velocity at the optical radius. If this holds up, it is an important result, as it implies that the velocity at the optical radius does not relate simply to the halo mass.

We have emphasized the importance of understanding the relationship between the observables and mass. The remainder of this proceeding describes a particular approach to this problem, by reference to numerical simulations which include, as accurately as possible, all the physics influencing the observables.

## 6. A WAY FORWARD: OBSERVATIONS OF SIMULATED UNIVERSES

Relating our observables to mass using simple analytic methods is a good start, but it can never allow us to determine masses with the precision our ultimate statistical uncertainties will allow. The assumptions we make to derive the analytic forms are just wrong.

Imagine that we have a simulation of the universe made with rich enough physics input to accurately represent the observable data. That is, imagine a simulated universe which contains not only dark matter, but luminous galaxies in something like their full variety. Given such simulations, we can repeat the same observations done in the real universe in an environment which contains all the physics we believe is relevant. We can then compare various predictions to reality at the level of the observables, rather than interposing models which involve untested assumptions.

As a preliminary example consider the GIF simulations of Kauffmann et al. 1999. These simulations are built on top of the VIRGO consortium N-body simulations. They add to the N-body outputs by identifying galaxies with the most massive subhalos. Semianalytic prescriptions are used to provide luminosities, colors, and stellar masses for all of these galaxies.

Most important for this study, each of these galaxies has velocity information derived from the

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full N-body simulation. This allows us to conduct the same dynamical analysis in the simulated data used in the real data. We can compare 'predictions' from the simulations to observations at the observable level (variation of velocity dispersion with luminosity) rather than at the level of model fits. Furthermore, we can then use the simulations to tell us how the observables relate to the theoretically favored masses of the systems. Details of this comparison are available in McKay et al. 2002.

Repeating the dynamical study of galaxy satellites in the GIF simulations, and applying the same selection criteria, yields a relation between the observables ($\sigma_v$ and luminosity) very much the same in the simulations as we saw in the real data. The most important thing about doing this in simulations is that we can directly probe the way in which an observable (like this $M_{260}^{dyn}$) relates to a theoretically interesting quantity, like $M_{200}$, the mass measured out to the point where the overdensity is 200 times the mean density. This first look suggests that these satellite dynamics are indeed probing masses on halo scales, at least up to a scale factor. In the simulations $M_{260}^{dyn} \approx 0.7\times\ M_{200}$.

## 7. SOME CONCLUSIONS

Where do we go from here? First, we have substantially more SDSS data in hand now. Right now we're preparing to do these analyses on roughly 2000 square degrees, an increase of about a factor of 5 in statistics. In addition, the data we have available is both better and richer than what we have used so far. We will use them to make a variety of new measurements.

We are comparing the galaxy-mass and galaxy-luminosity correlation functions. Doing this probes the large scale relationship between mass and light more directly, and will give estimates of bias and the total mass density.

Guinevere Kauffman and colleagues at MPE have recently begun fitting the SDSS spectra to extract stellar masses for all SDSS galaxies. It will be an interesting exercise to compare these stellar masses, instead of luminosities, to halo mass probes.

Extracting best fit parameters for galaxy halo models from lensing data can be done in various maximum-likelihood fits. It is unclear whether this will give very fundamental information about galaxies, but it will help us to understand the comparison between data and various popular models.

It is possible to use these methods to probe halo shape, as well as mass, at least to the extent that galaxy light is aligned with halo ellipticity. It is also possible to compare halo concentrations, by comparing stellar velocity measures at the optical radius to large scale halo mass measurements. Recent work by Uros Seljak (2002) suggests that differences in the effective circular velocity between the optical radius and the virial radius play an important role in the Tully-Fisher and Fundamental Plane relations. We can probe this directly. Most important, we need to work hard to extend these measurements to galaxies of lower luminosity.

Another major extension, well under way, is to the study of more massive objects than galaxies. Eventually we will stitch this all together into a coherent picture focusing on halos of all sizes, rather than maintaining artificial galaxy/group/cluster boundaries.

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