How are Bright Galaxies Embedded within their Dark Matter Halos?

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Abstract

Recent studies suggest that the orientations of large, bright galaxies within their dark matter halos are related to the morphologies of the galaxies themselves. Elliptical galaxies tend to be oriented such that, in projection on the sky, the mass (i.e., the dark matter) is well-aligned with the luminous galaxy. On the other hand, disk galaxies tend to be oriented such that their angular momentum vectors are aligned with the angular momenta of their halos. This results in a misalignment of mass and light, and has important implications for future studies that seek to measure the shapes of the dark matter halos that surround disk galaxies.

1. Bright Galaxies and Dark Matter Halos

The idea that large, bright galaxies reside within massive, invisible halos of dark matter is well-accepted. In fact, if the currently-favored theory of structure formation, known as Cold Dark Matter (CDM), is correct, then the dark matter halos of galaxies like our own Milky Way are expected to completely dwarf the visible galaxies that reside within them. High-resolution computer simulations of CDM universes suggest that the dark matter halos of large, bright galaxies should extend to radii that are at least a factor of 10 larger than the radii of the visible galaxies (see, e.g., [1] and references therein). In addition, the simulations suggest that the dark matter halos should be 100 to 200 times more massive than the sum total of the visible material contained within the galaxies (i.e., the stars, the gas, and the dust). For all intents and purposes, then, the "mass" of a galaxy is the mass of its dark matter halo.

Although the existence of dark matter halos is well-accepted, relatively few direct constraints exist for the sizes and shapes of the halos that surround the galaxies we observe in our Universe. The reason for this is simple: at present we cannot directly detect the dark matter halos at any wavelength of light. (In the future, however, it may be possible to detect the gamma rays that are produced when CDM particles in the dark matter halos annihilate.) If we wish to place strong constraints on the nature of the dark matter halos, we need a way to "see" that which is invisible. In the past, a number of different techniques have been used to study the dark matter halos of galaxies, and in all cases the techniques use some type of luminous material as a "tracer" of the gravitational potentials of the halos. Here I will focus on recent work that has been carried out with two of these techniques: satellite galaxies that orbit large "primary" galaxies, and weak gravitational lensing.

Observationally, the most poorly constrained property of the dark matter halos is their overall shape distribution. CDM predicts that the halos are not spherical. Rather, they

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are mildly-triaxial (i.e., they are “flattened” compared to spherical halos), and the more massive is a halo, the “flatter” it is expected to be (see [2]). If we could measure the shape distribution of the dark matter halos that surround the galaxies in our Universe, this would constitute a strong test of the CDM model. This, however, is a much bigger challenge than measuring the mass distribution of the halos and, in practice, it may be impossible. Whether or not it should be possible to measure the shape distribution of the halos using current techniques depends upon one important detail: the way in which the large, bright galaxies are embedded within their halos.

To understand this, let us start by considering what the dark matter halo of a galaxy would look like if we could actually see its image on the sky. If the halo were spherically-symmetric, the image of the halo would always appear to be circular. If the halo were triaxial, its image would be elliptical, and the degree of ellipticity would depend upon the orientation of the halo relative to our line of sight. This is in exact analogy with the images of elliptical galaxies, except that instead of the image that results from the luminous stars within the galaxy, here we are concerned with the shape of the invisible halo, as projected on the sky.

If the dark matter halos of galaxies are non-spherical, this will result in certain anisotropies, associated with the fact that the gravitational potentials of the halos are flattened. In the case of small, faint satellite galaxies that orbit within the dark matter halos of large “primary” galaxies, we know from CDM simulations that the satellites are distributed anisotropically. As viewed in the plane of the sky, the locations of the satellite galaxies generally trace the shapes of the extensive dark matter halos in which they orbit (e.g., [3]). In other words, in the plane of the sky, the locations of the satellite galaxies fill an elliptical region that is nearly identical to the shape and orientation of the elliptical region corresponding to the dark matter halo. Relative to the major axis *of the dark matter*, then, the locations of the satellite galaxies are anisotropic: more satellites are found near the major axis of the dark matter halo than are found near the minor axis of the dark matter halo. In the case of weak gravitational lensing, the lensing signal (known as the “shear”) will be isotropic about the lens galaxy if the dark matter halo is spherical, and it will be anisotropic about the lens galaxy if the dark matter halo is flattened. Specifically, at fixed angular radius from the center of a flattened dark matter halo, distant galaxies that are observed to be closest to the major axis of the halo (as viewed in projection on the sky) will have their images distorted more than those that are observed to be closest to the minor axis of the halo (e.g., [4]).

If we were able to actually see the symmetry axes of the dark matter halos, searching for an anisotropy in the locations of the satellite galaxies or in the weak lensing shear would be straightforward. The geometry of the anisotropies is determined by the geometry of the dark matter; i.e., the elliptical shape that results when the halo is viewed in projection on the sky. If we knew the exact orientations of the symmetry axes of the dark matter halos, we would simply measure the locations of the satellite galaxies or the weak lensing shear with respect to those symmetry axes. If the dark matter halos of the galaxies in our universe are made of CDM, we should then easily detect the predicted anisotropies using sufficiently large data sets.

The fundamental observational challenge, of course, is that we cannot see the symmetry axes of the dark matter halos that surround the luminous galaxies. Instead, the only symmetry axes that we can use to perform a search for the expected anisotropies are the symmetry axes of the luminous galaxies themselves. If the luminous material is aligned well with the dark matter, then using the symmetry axes of the visible galaxies to define the geometry is equivalent to using the symmetry axes of the halos. However, if the luminous material and the dark matter are substantially misaligned, this will lead to the symmetry axes of the visible galaxies being substantially offset from the symmetry axes of the dark matter halos. In this latter case, if anisotropies in the satellite locations and the weak lensing shear happen to exist, they are unlikely to be detected because the signals will be "washed out" due to the fact that, observationally, we must use the symmetry axes of the luminous galaxies (not those of their dark matter halos) to compute the signal.

The ability to obtain strong constraints on the shapes of the dark matter halos of galaxies with current techniques, therefore, hinges critically on the luminous material being aligned with the dark matter. In addition, the *interpretation* of observational searches for the above anisotropies depends critically upon whether or not the luminous and dark material are aligned. Suppose that for a given set of large, bright galaxies we find that the locations of the satellite galaxies and the weak lensing shear are *observed* to be isotropic. Is the observed isotropy caused by the fact that the dark matter halos of the galaxies are spherical (and are, therefore, intrinsically isotropic)? Or, is the observed isotropy caused by the fact that luminous and dark material are substantially misaligned in the galaxies and, therefore, intrinsically anisotropic signals have been washed out due to the fact that, out of necessity, we measured the signals with respect to the symmetry axes of the luminous galaxies, not their dark matter halos?

Here we will investigate the degree to which the locations of satellite galaxies and the weak lensing shear are observed to be anisotropic, and we will use the results to address the question of the way in which large, bright galaxies are embedded within their dark matter halos.

2. Anisotropic Locations of Satellite Galaxies

With the advent of extensive modern redshift surveys, it has become possible to gather statistically-significant samples of large primary galaxies and their satellites. Since distances to the galaxies are not generally known, the primary galaxies and their satellites are selected via proximity criteria in redshift space. Due to the fact that redshift surveys are magnitude-limited at relatively bright magnitudes, the samples of primary and satellite galaxies that are obtained from redshift surveys are restricted to only the very brightest satellites. In the case of the Sloan Digital Sky Survey (SDSS; [5], [6], [7], [8], [9]), the spectroscopic portion of the survey is complete to a Petrosian magnitude of $r' = 17.77$, while in the case of the Two Degree Field Galaxy Redshift Survey (2dFGRS; [10]) the galaxies were selected to have apparent magnitudes brighter than $b_J = 19.45$. In both surveys, the median redshift of the galaxies is $z \sim 0.1$. If the Local Group were viewed from a comparable redshift, and if similar magnitude limits were imposed, M33 would likely be the only satellite galaxy that was selected in the survey. Therefore, because of the bright limiting magnitudes, each primary galaxy typically has only one or two observed satellites. As a result, it is not possible to make definitive statements about the dark matter halo of any one individual primary galaxy since the statistics are too poor. However, by "stacking" many primary galaxies and their satellites together, it is possible to investigate the locations of the satellite galaxies using ensemble averages.

Since distances to the galaxies are generally not known, primary galaxies and their satellites are selected from large observational surveys using a set of proximity criteria that are implemented in redshift space. In other words, satellite galaxies are selected to be faint objects that are located "close to" bright objects, both in projected radial distance on the sky, R_p, and in relative line of sight velocity, $|dv|$. Typically, satellites have velocities $|dv| \leq 500$ km sec^{-1} relative to their primary galaxies and they are at least 6 times fainter than their primary galaxy. A maximum projected radial distance $R_{p,\mathrm{max}} = 500$ kpc is also typically imposed. Although the details of the selection criteria vary amongst the different published samples, the results for the observed locations of the satellite galaxies are essentially insensitive to the selection criteria (see, e.g., [11]). In addition, due to fiber collisions, the SDSS and 2dFGRS were unable to simultaneously obtain the spectra of pairs of galaxies that have small angular separations on the sky. As a result, very few satellites (less than a few percent of the sample) are found at projected distances $R_p \leq 50$ kpc from their primary galaxies. The nature of the selection criteria and the incompleteness of the redshift information for close pairs of galaxies ultimately affect the sample. Because the selection criteria do not make use of actual distances to the galaxies, some fraction of the objects that are selected as satellites are, in fact, not located physically nearby the primary galaxy. These objects are examples of interlopers (or "false" satellites), and their presence in the data can be a significant source of noise. Also, since the vast majority of satellites are located at large projected distances from their hosts, it is possible that many of these objects have only recently arrived within the dark matter halos of their primary galaxies and, hence, have not had sufficient time to reach dynamical equilibrium with their local gravitational environment. Despite these complications, however, it is possible to determine whether or not the observed locations of the satellite galaxies agree well with the theoretical predictions of CDM by comparing the locations of observed satellites to the locations of theoretical satellites that have been selected from high-resolution computer simulations using exactly the same criteria that were used to select the observational sample.

There is general agreement in the literature that, when averaged over all primary galaxies and all satellites, the satellites of relatively isolated primary galaxies are distributed anisotropically, with a preference for being found near the major axes of the primaries (e.g., [11], [12], [13]). Note that, although [14] originally claimed to detect the opposite effect, there was an error in their analysis and, when this was corrected, the results of their analysis showed an alignment of satellites with the major axes of the primaries (see [15], the erratum to [14]). When the locations of the satellite galaxies are computed as a function of various physical properties of the primary galaxies, clear trends are observed (see, e.g., [13], [16]). The locations of the satellites of the primary galaxies that have the reddest colors and the largest stellar masses are highly-anisotropic, and are found close the major axes of the primaries. However, the locations of the satellites of the primary galaxies that have the bluest colors and the lowest stellar masses show little to no anisotropy. The primary galaxies in this case are known to have stellar masses in the range $10^{10} M_{\mathrm{sun}}$ to $10^{12} M_{\mathrm{sun}}$ and, hence, their morphologies are likely to be "regular" (e.g., elliptical, spiral or lenticular). Therefore, the trend of observed satellite locations with the physical properties of the primaries is also a trend with the morphologies of the primaries since the reddest primaries are predominately elliptical while the bluest primaries are predominately spirals.

The question then arises as to what is the underlying cause of these trends. If the luminous primary galaxies are embedded within their dark matter halos such that the symmetry axes of the observed galaxies are aligned with the symmetry axes of their dark matter halos, one might simply conclude that the halos of spiral primary galaxies are substantially rounder than those of elliptical primary galaxies. However, over the mass range spanned by these particular primary galaxies, one would not expect the shapes of the halos to differ so drastically that in the one case a pronounced anisotropy in the locations of the satellite galaxies would be observed, while in the other case the locations of the satellites are essentially consistent with a random distribution. Instead, the key to understanding the observed trends of satellite locations with the physical properties of the primary galaxies may lie in the fact that elliptical and spiral galaxies are embedded within their halos in rather different ways.

To address this, [13] used a mock redshift survey of the ΛCDM Millennium Run Simulation (MRS; [1]) to select primary galaxies and their satellites using exactly the same selection criteria that they used to select primary galaxies and their satellites from the 7th data release of the Sloan Digital Sky Survey (SDSS; [17]). In the mock redshift survey, colors, stellar masses, star formation rates, and bulge-to-disk ratios are known for all of the simulated galaxies. However, there are no actual *images* of the luminous galaxies in the simulation or in the mock redshift survey. Instead, [13] used a number of different image assignment schemes to define the morphologies of the primary galaxies and to determine the orientations of the luminous galaxies with respect to their dark matter halos. The bulge-to-disk ratio was used to divide the primary galaxies into the broad categories of elliptical, lenticular, and spiral. To determine the orientations of the luminous primaries with respect to their dark matter halos, [13] adopted three different models: (i) the dark matter mass and the light from the primary galaxy were assumed to be perfectly aligned within all primaries, (ii) all primary galaxies were modeled as rotationally supported disks where the angular momentum vectors of the disks were aligned with the net angular momenta of their dark matter halos, (iii) the dark matter mass and the light were assumed to be perfectly aligned within the elliptical primaries, while the spiral and lenticular primaries were modeled as rotationally supported disks where the angular momentum vectors of the disks were aligned with the net angular momenta of their dark matter halos. That is, in (iii) the elliptical primaries and the disk primaries are embedded within their halos in different ways, while in (i) and (ii) all primaries are embedded within their halos using identical schemes, regardless of the actual morphology of the primary galaxy.

Figure 1 shows the geometry that is used to define the locations of the satellite galaxies. The angle ϕ is simply the angle between the major axis of the luminous primary galaxy and the direction vector on the sky that connects the centroid of the primary to the centroid of the satellite. Since we are only interested in whether the satellites have a preference for being located close to either the major axis or the minor axis of the primary, the angle ϕ is restricted to the range $0^\circ \le \phi \le 90^\circ$. Here $\phi = 0^\circ$ indicates a satellite location along the major axis of the primary and $\phi = 90^\circ$ indicates a satellite location along the minor axis of

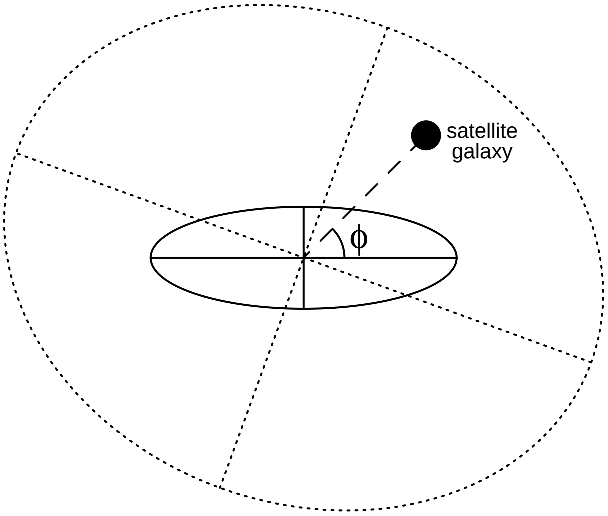

Figure 1: Schematic representation of a primary galaxy (solid lines), its satellite, and its dark matter halo (dotted lines). The location of the satellite, ϕ, is defined to be the angle between the observed major axis of the primary and the direction vector that connects the centroids of the primary and its satellite. Here mass and light are misaligned, so that in the plane of the sky the major axis of the luminous primary galaxy does not coincide with the major axis of its dark matter halo.

the primary.

Figure 2 shows the observed locations of satellite galaxies in the SDSS as a function of the color of the primary (left panel) and the stellar mass of the primary (right panel). From this, it is clear that the locations of the SDSS satellite galaxies depend upon both the color and the stellar mass of the primaries. Also shown in Figure 2 are the locations of the satellite galaxies from the MRS, computed under the assumption that the dark matter mass and the light are perfectly aligned. From this, it is clear that if mass and light are perfectly aligned in all primaries, the locations of the satellite galaxies in the CDM universe have essentially no dependence on either the color or the mass of the primary galaxies (in conflict with observation).

Figure 3 again shows the locations of satellite galaxies in the SDSS, along with the locations of the satellite galaxies from the MRS, computed under the assumption that all primary galaxies can be modeled as disks, and that the angular momentum vectors of the disks are aligned with the angular momentum of the surrounding dark matter halos. As in Figure 3, there is essentially no dependence of the locations of the satellite galaxies in the CDM universe on the physical properties of the host galaxies. However, it is also clear that this image assignment scheme results in a distribution of satellite locations that is *much less anisotropic* than it is for the case of mass and light being perfectly aligned. This is due to the fact that the angular momentum vectors of CDM halos are not aligned with any of the principal axes (e.g., [18]), resulting in a net misalignment of mass and light. In the case of the MRS galaxies, using the angular momentum image assignment scheme results in a median offset between the major axes of the dark matter halos and those of the luminous

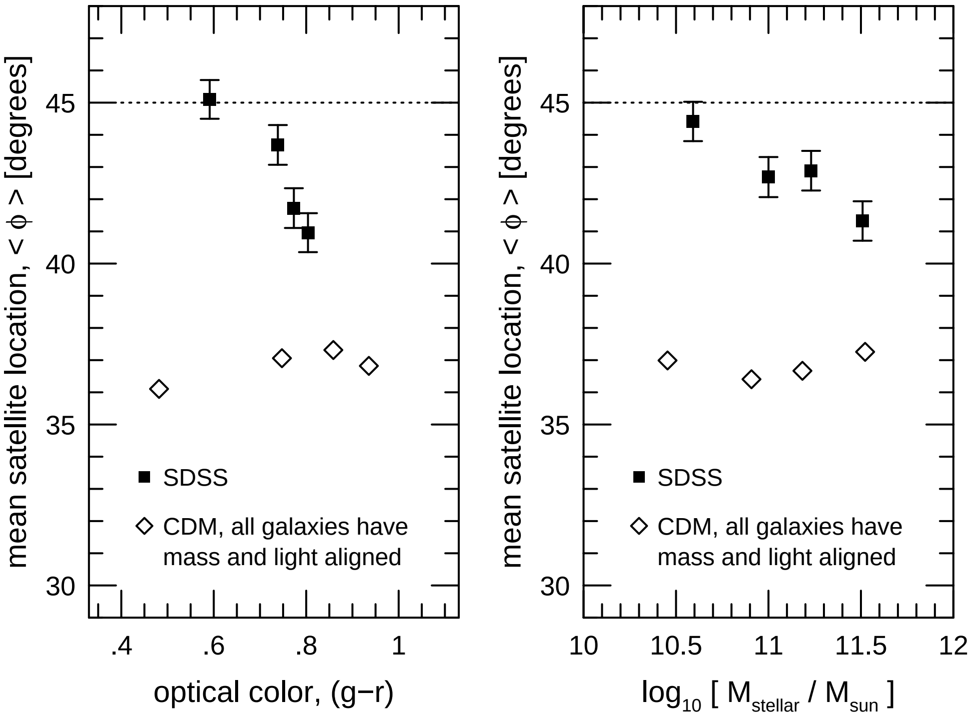

Figure 2: Mean location of satellite galaxies in the SDSS (solid squares with error bars) and in a CDM universe (open diamonds). Here it is assumed that mass and light are aligned in all of the simulated galaxies. *Left:* Satellite locations as a function of the optical colors of the primaries. *Right:* Satellite locations as a function of the stellar masses of the primaries.

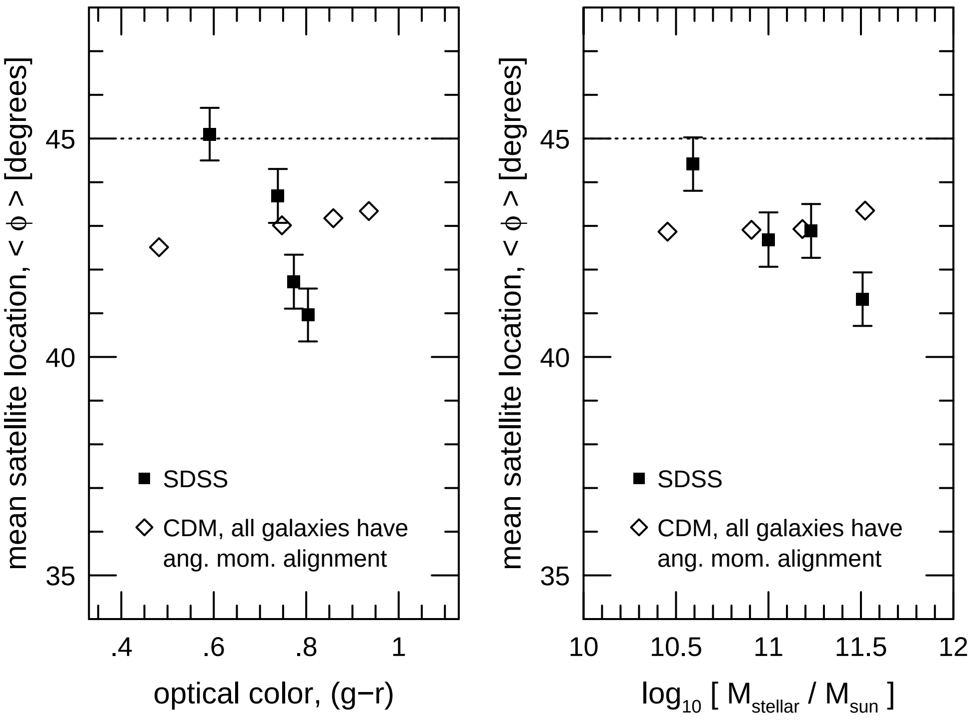

Figure 3: Same as Figure 2, except here it is assumed that all of the simulated primary galaxies are circular disks, oriented such that their angular momentum vectors align with the net angular momentum of their halos.

disk galaxies of ~ 30° in projection on the sky.

Figure 4 shows the result when two distinct image assignment schemes are used for the MRS galaxies: mass and light are aligned in ellipticals, while in the case of disk galaxies, mass and light are misaligned due to the fact that the orientations of the luminous galaxies are determined from their angular momentum vectors. In this case, the trends that are observed for the satellites of SDSS primary galaxies are reproduced well by CDM: the satellites of the reddest, most massive primaries are distributed much more anisotropically than are the satellites of the bluest, least massive primaries. In all cases, the anisotropy is greater in the simulation than it is in the observed Universe, and this is likely due to a combination of two things. First, the orientations of the SDSS primaries are not known to infinite accuracy (i.e., there are measurement errors in the position angles of observed primary galaxies), and this has not been accounted for. Second, the image assignment schemes used in the simulation are "idealized" because they assume truly perfect alignment in all cases (mass or angular momentum), and such truly perfect alignment is unlikely to be the case.

3. Anisotropic Weak Gravitational Lensing

To first order, weak gravitational lensing alters the intrinsic shape of a galaxy via a

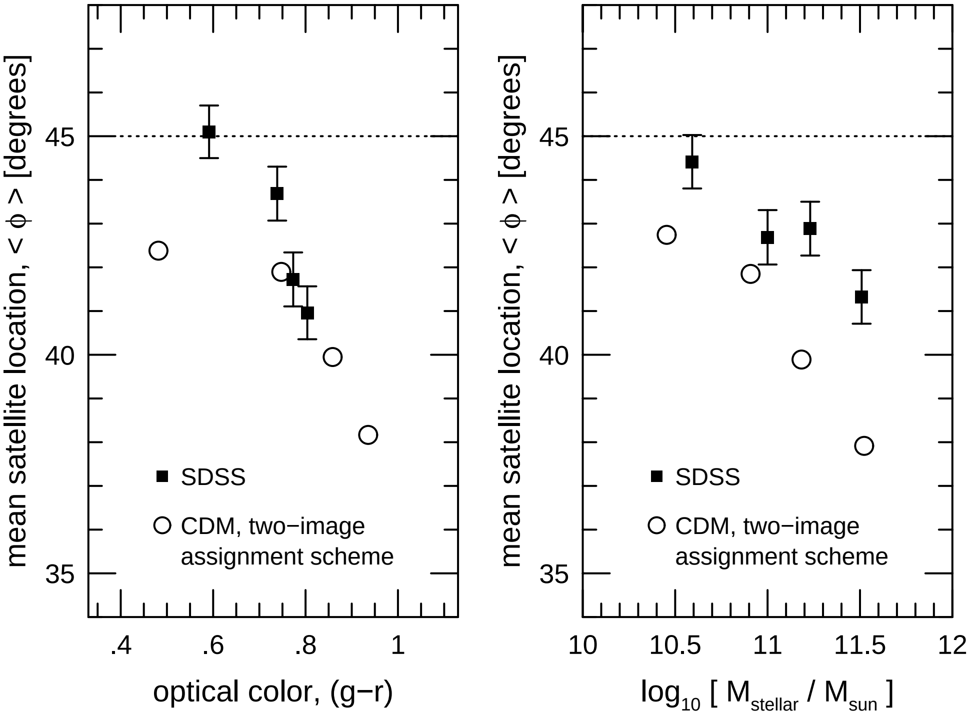

Figure 4: Same as Figure 2, except here two distinct schemes are used to assign images to the simulated primaries. Mass and light are assumed to be aligned in the elliptical primaries, while disk primaries are modeled as circular disks, oriented such that their angular momentum vectors align with the net angular momentum of their halos. It is only when the two distinct image assignment schemes are adopted that the general trends of satellite locations with the properties of the primary galaxies can be reproduced by the simulation.

combination of two effects: a stretch in the direction that is tangential to the location of the lens on the sky and a compression along the direction towards the lens on the sky. If a distant galaxy has an intrinsically circular image, weak lensing will transform the circular image into an ellipse that is oriented tangentially with respect to the direction vector on the sky that connects its centroid to that of the lens galaxy. When galaxies act as weak lenses, the image distortions that they induce are typically $< 1\%$. This distortion is so small that it could never be detected for any one, single lensed galaxy (known as a "source"). However, like the satellite locations above, weak lensing can be detected with high statistical significance by computing ensemble averages using large numbers of source galaxies. In this sense, satellite locations and weak lensing by galaxies are complimentary methods.

Weak lensing by galaxies is generally known as "galaxy-galaxy" lensing, and it has become a standard tool for constraining the masses of the dark matter halos of galaxies (see [4] and references therein). A number of recent studies have attempted to use galaxy-galaxy lensing to measure the shapes of the dark matter halos of galaxies by searching for an anisotropy in the distortion pattern caused by lensing. That is, if the dark matter halos of galaxies are elliptical in projection on the sky (as would be expected for CDM halos) and, crucially, if the dark matter mass is well-aligned with the luminous galaxies, then weak lensing should result in a distinctly anisotropic pattern over a particular range of lens-source separations on the sky. The shear due to weak lensing (which is responsible for altering the shape and orientation of a galaxy image) is usually denoted by γ, and is a strong function of the angular separation between the lens and the source. The smaller is the angular separation, the greater is the distortion.

Figure 5 illustrates the geometry of lensing by an elliptical lens (i.e., a triaxial halo, seen in projection on the sky). Source galaxies that are closest to the major axis will experience a shear denoted as γ^+, while source galaxies that are closest to the minor axis will experience a shear denoted as γ^-. Over angular scales, θ, that are sufficiently small for the gravitational potential of the lens to be markedly non-spherical, an anisotropy in the shear will result: $\gamma^+(\theta)/\gamma^-(\theta) > 1$. Since the dark matter halos of galaxies have finite sizes, the gravitational potential will become indistinguishable from a spherically-symmetric potential for sufficiently large angular separations (i.e., the lens will begin to act like a point mass), in which case the anisotropy will cease to exist and $\gamma^+(\theta)/\gamma^-(\theta) = 1$.

A number of groups have searched for such "anisotropic" galaxy-galaxy lensing, and the results have been less conclusive than might have been expected based upon the size and quality of the data, as well as the care with which the analyzes were performed (see [4]). Two studies ([19], [20]) concluded that any deviation of the dark matter halos from spherical symmetry is more pronounced for the halos of red galaxies than it is for the halos of blue galaxies, but the statistical significance in both cases is somewhat low. It turns out that *interpreting* the anisotropic galaxy-galaxy lensing signal that one measures in an observational data set is rather tricky. In practice, the interpretation cannot be done in the absence of detailed Monte Carlo simulations that account for the fact that, in most galaxy-galaxy lensing data sets, the objects that one typically identifies as "lens" galaxies have, themselves, been lensed (see [4]). This lensing of the lens galaxies introduces a number of systematic effects that conspire to alter the signature of anisotropic galaxy-galaxy lensing from the expected result that $\gamma^+(\theta)/\gamma^-(\theta) > 1$ on small scales. In their simulations [4]

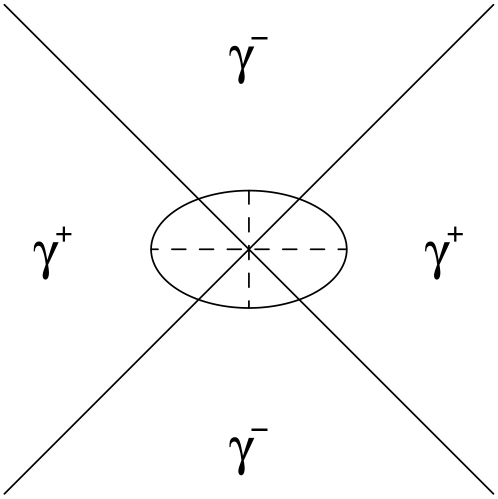

Figure 5: Schematic representation of the notation used for weak lensing by a flattened halo. Source galaxies that are located closest to the major axis of the lens will experience a weak lensing shear given by γ^+. Source galaxies that are located closest to the minor axis of the lens will experience a weak lensing shear given by γ^-.

showed that, depending upon how massive the dark matter halos of the galaxies were, it was possible to *observe* $\gamma^+(\theta)/\gamma^-(\theta) = 1$ on small scales, even though the dark matter halos were significantly flattened. In addition, [4] showed that it was possible to *observe* $\gamma^+/\gamma^-(\theta) < 1$ on small scales (i.e., the *opposite* of the expected signal), even though the (flattened) dark matter mass and the luminous lens galaxy were intrinsically aligned in the plane of the sky. However, all of the complications found by [4] in the analysis of observations of anisotropic galaxy-galaxy lensing can be avoided if the sample is simply restricted to isolated lens galaxies that have not, themselves, been lensed. This necessarily reduces the size of the sample, but will result in the "cleanest" detection of the signal, together with the most straightforward interpretation of the observed signal.

Figure 6 shows the result of a search for anisotropic galaxy-galaxy lensing using isolated lens galaxies in the SDSS ([21]). All of the isolated lens galaxies are known to be unlensed by virtue of the fact that there are no other galaxies with lower redshifts, within a projected distance of 500 kpc. The left panel of Figure 6 shows the result when the anisotropic shear is computed using all of the SDSS lenses. The right panel of Figure 6 shows the result when the lenses are split into a "red" sample, $(g' - r') \geq 0.7$, and a "blue" sample, $(g' - r') < 0.7$. From the left panel of Figure 6, we can see that the signal is consistent with what we would expect from galaxy-galaxy lensing by flattened dark matter halos: $\gamma^+(\theta) > \gamma^-(\theta)$, and the ratio approaches unity at large angular separations. From the right panel of Figure 6, the signal on small angular scales is much more anisotropic for the red lenses than it is for the blue lenses (which show little to no anisotropy in the signal). However, as with the locations of satellite galaxies, we have to ask where the difference in the anisotropic lensing signal around the red and blue lens galaxies originates. Is it due to the fact that the dark matter halos of the blue lens galaxies are much closer to being spherical than are the dark matter halos of the red lens galaxies? Or, is it due to the fact that the dark matter mass and the

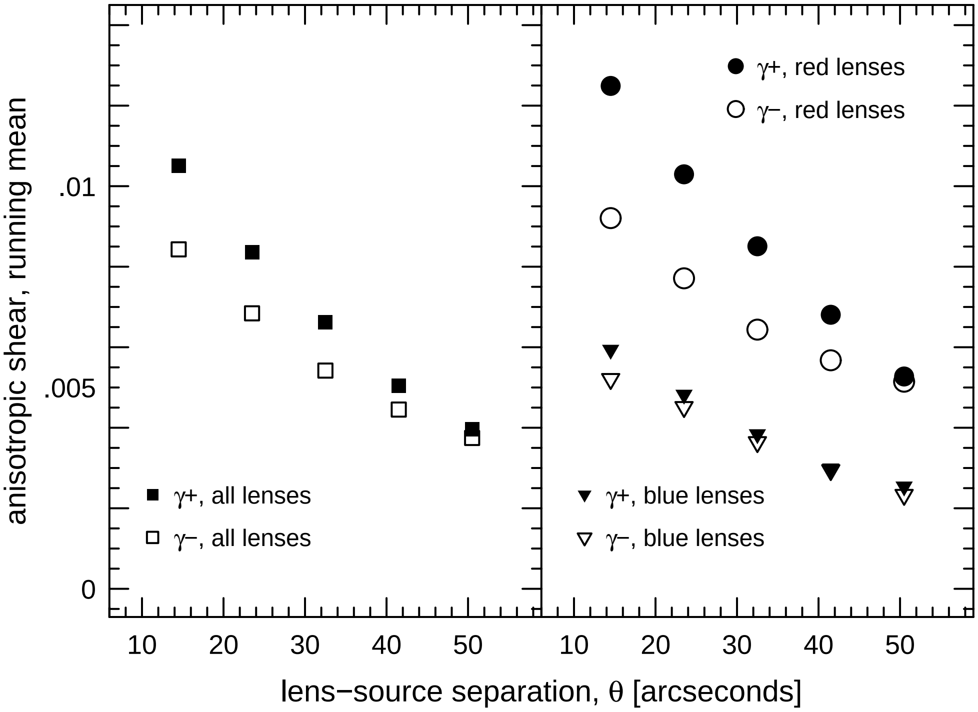

Figure 6: "Anisotropic" weak lensing shear due to isolated galaxy lenses in the SDSS. *Left:* Shear computed using all lenses. *Right:* Shear computed using red lenses (circles) and blue lenses (triangles). Averaged over scales $10'' \leq \theta \leq 60''$ the red lenses have a distinguishable anisotropy: $\langle\gamma^+\rangle = (1.4 \pm 0.2) \times 10^{-2}$, $\langle\gamma^-\rangle = (9.6 \pm 2.3) \times 10^{-3}$. The blue lenses do not have a distinguishable anisotropy: $\langle\gamma^+\rangle = (6.1 \pm 2.5) \times 10^{-3}$, $\langle\gamma^-\rangle = (7.0 \pm 2.6) \times 10^{-3}$. This is consistent with what we expect based on the results of [13], where mass and light where found to be well-aligned in red galaxies, but not well-aligned in blue galaxies.

luminous galaxies are much more closely aligned for the red lenses than they are for the blue lenses?

As with the primary galaxies in the previous section, here the differences in mass between the red lens galaxies and the blue lens galaxies are not sufficient for us to expect a measurable difference in the degree of halo flattening. Therefore, it is more likely that the differences in the weak lensing signals are caused by differences in the degree to which mass and light are aligned in the SDSS lens galaxies. Although morphologies are not known for all of the SDSS lens galaxies, we do know that the majority of the red lenses will be ellipticals and the majority of the blue lenses will be spirals. Calling on the results from the previous section, then, we would naturally expect to see little to no anisotropy in the galaxy-galaxy lensing signal around the blue lenses since mass and light are expected to be badly misaligned in these galaxies. However, we would expect to see a significant anisotropy in the galaxy-galaxy lensing signal around the red lenses since mass and light are expected to be well-aligned in these galaxies.

Conclusions

Based upon the results above, it would seem that elliptical galaxies are embedded within their dark matter halos in a manner that is different from that of disk galaxies. Like their dark matter halos, ellipticals are largely pressure-supported systems (i.e., their flattened shapes are primarily the result of an anisotropic velocity dispersion tensor, not net rotation). On the other hand, disk galaxies are rotationally-supported systems with large net angular momentum. It is reasonable, therefore, to suppose that the luminous galaxies would be embedded within their dark matter halos in a manner that reflects the underlying kinematics. The locations of satellite galaxies and the weak lensing shear both support the idea that the dark matter mass and the light are well-aligned for elliptical galaxies, while they are substantially misaligned for disk galaxies.

A key test of CDM, the shape distribution of the dark matter halos of galaxies, may be stymied by this result. A direct measurement of the shapes of the halos relies critically on the dark matter mass and the luminous central galaxy being well-aligned in the plane of the sky. Given the results shown here, it should be possible to use the locations of satellite galaxies and weak gravitational lensing to measure the shapes of the halos that surround elliptical galaxies. However, in the case of disk galaxies, the expected anisotropies in the satellite locations and the weak lensing shear are washed out because mass and light are so poorly aligned in disk galaxies. Therefore, it is unlikely that the shapes of the dark matter halos that surround disk galaxies will ever be measured directly using either of these techniques.

Acknowledgements

I am grateful to two of my students, Ingólfur Ágústsson and Paul Howell, for insights that have guided this work, and for numerous enlightening conversations. Support under NSF contract AST-0708468 is also gratefully acknowledged.

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