Statistical constraints on galaxy halo masses from weak lensing and satellite dynamics

Weak lensing: outside Einstein ring
Signal: weak distortion of images of background galaxy by foreground galaxy. Can't do for a single galaxy, need ensemble averages.

Q Why would imaging & redshift survey like the SDSS be good for this?

→ redshift of lensing foreground galaxy
→ images of lensed background galaxies

Q What factors might mess up this lensing measurement?

→ seeing
→ image distortions (coma, etc)
(expected signal is a systematic distortion of only ~1% in 69 image ellipticities)
FIGURE 2. a) Mean tangential shear computed about the lens centers in ~ 42 sq. deg. of the RCS [48]. Here foreground galaxies and background galaxies have been separated on the basis of apparent magnitude alone. Bright, lens galaxies have $19.5 < R_c < 21$ and faint, source galaxies have $21.5 < R_c < 24$. b) Same as in a) except that here each background galaxy image has been rotated by 45°. This is a control statistic and in the absence of systematic errors it should be consistent with zero on all scales. Figure kindly provided by Henk Hoekstra.

changed when Brainerd, Blandford & Smail [13] measured the orientations of 506 faint galaxies ($23 < r_f \leq 24$) with respect to the locations of 439 bright galaxies ($20 \leq r_b \leq 23$) and found that the orientation of the faint galaxies was inconsistent with a random distribution at the 99.9% confidence level. The faint galaxies showed a clear preference for tangential alignment with the direction vector on the sky that connected the centroids of the faint and bright galaxies, in agreement with the expectations of systematic weak lensing of the faint galaxies by the bright galaxies.

Almost immediately, a number of similar investigations followed in the wake of Brainerd, Blandford & Smail [13] ([49], [50], [51], [52], [53], [54], [55]). These studies made use of a wide variety of data and analysis techniques, and all were broadly consistent with one another and with the results of Brainerd, Blandford & Smail [13] (see, e.g., the review by Brainerd & Blandford [14]). The first truly undeniable detection of galaxy–galaxy lensing was obtained by Fischer et al. [53] with 225 sq. deg. of early commissioning data from the SDSS, and it was this result in particular that helped to make the study of galaxy–galaxy lensing into a respectable endeavor, whereas previously many had considered the whole field rather dodgy at best. Fisher et al. [53] demonstrated conclusively that even in the limit of somewhat poor imaging quality, including the presence of an anisotropic point spread function due to drift scanning, galaxy–galaxy lensing can be detected with very high significance in wide-field imaging surveys. In the last few years, detections of galaxy–galaxy lensing and the use of the signal to constrain the dark matter halos of field galaxies has improved dramatically ([24], [42], [48], [56], [57], [58], [59], [60], [61]) owing to a number of factors that include such things as very large survey areas, sophisticated methods for correcting image shapes due to anisotropic and spatially-varying point spread functions, and the use of distance information for large numbers foreground lens galaxies in the
Results from galaxy-galaxy weak lensing:

→ A typical $L^*$ galaxy has a mass of order $8 \times 10^9 M_\odot$, and a virial radius $\sim 250$ kpc.
  (consistent with MW, M31 results)

→ Masses of halos of $L^*$ ellipticals > masses of $L^*$ spirals by at least a factor of 2

Satellite galaxy dynamics

The large redshift surveys do not reach deep enough to study satellite dynamics as we did in Local Group (or low enough in surface brightness)

They typically detect $\sim 1$ satellite per galaxy
  (e.g. LMC)

Q: Let's do it statistically again. What are some possible problems now?
FIGURE 4. Points with error bars show the observed distribution of velocity differences, $N(|dv|)$, for a subset of host-satellite systems in the 2dFGRS for which the host morphologies have been visually classified. Solid lines show the best-fitting "Gaussian plus offset" function, from which the velocity dispersion of the satellites, $\sigma_v$, and the fraction of interlopers, $f_i$, is determined. Left panels: late-type hosts. Right panels: early-type hosts. Top panels: satellites located close to the host in projection on the sky. Bottom panels: satellites located far from the host in projection on the sky. A substantially larger value of $\sigma_v$ is obtained for the satellites of early-type hosts than for the satellites of late-type hosts. Note, too, that the fraction of interlopers increases significantly with the projected radius, $r_p$, of the satellites.

Prada et al. [27] used numerical simulations to show that this is a sensible way in which to correct for the effects of interlopers. Moreover, both Brainerd & Specian [66] and Prada et al. [27] have pointed out that an accurate determination of the velocity dispersion profile, $\sigma_v(r_p)$, for satellite galaxies depends on a proper determination of the interloper fraction as an explicit function of the projected radius. That is, by purely geometrical effects, the interloper fraction is necessarily an increasing function of $r_p$. An example of fitting a “Gaussian plus offset” to the distribution of velocity differences for late-type galaxies and early-type galaxies in the 2dFGRS is shown in Figure 4. One can clearly see from this figure that the velocity dispersion of the satellites is a function of the morphology of the host galaxy (being larger for early-type hosts than late-type hosts), and that the interloper fraction increases with projected radius.

The above “Gaussian plus offset” fit to the distribution of host-satellite velocity differences accounts for the fact
background galaxies 'interlopers'

What does it mean that we have detections of mass as far as 700 kpc from these galaxies?

Summary

Statistical studies using weak lensing & satellite velocities agree.

Virial mass of 'average' L* galaxy = \(8-10 \times 10^9 h^{-1} M_\odot\)
SUMMARY

There has been a long period of time over which it has been perfectly acceptable to write papers on investigations into the nature of the dark matter halos of field galaxies that begin with a statement along the lines of “Although modern theories of galaxy formation posit that all large galaxies reside within massive halos of dark matter, the characteristic properties of those halos (e.g., mass, radial extent, and shape) are not well-constrained by the current observations”. That time is now coming to an end. The wealth of data that has been acquired in recent years is truly beginning to place strong, direct constraints on the dark matter halos of field galaxies.

Weak lensing and satellite dynamics have proven themselves to be excellent probes of the gravitational potentials of large, bright galaxies on physical scales \( r \geq 100 \, h^{-1} \text{ kpc} \). While one might be skeptical and discount the results that come from one technique or the other, the fact that both are yielding consistent constraints cannot be ignored. Both weak lensing and satellite dynamics lead to statistical constraints on the halo population as a whole, rather than constraints on any one particular galaxy halo, and it is especially the acquisition of extremely large data sets that has allowed these techniques to begin to fulfill their promise of mapping out the gravitational potentials associated with large, massive halos. Weak lensing and satellite dynamics have inherent advantages and disadvantages, but since their systematic errors and selection biases are completely uncorrelated, they are extremely complementary to each other. At least at the moment, when strong constraints are only just beginning to emerge from each technique, this complementarity is very reassuring.

Based upon my own critical, and hopefully unbiased, reading of the recent literature, I think it is fair to say that, both individually and in combination, weak lensing and satellite dynamics are pointing toward the following scenario for the nature of large, bright field galaxies and their halos:

- The dark matter halos are well-characterized by NFW-type objects in terms of their gravitational properties. The dynamics of satellite galaxies strongly prefer NFW halos to isothermal halos.

- The virial masses that are inferred for large field galaxies are in good agreement with the predictions for galaxy–mass halos in the context of cold dark matter. Specifically, the virial mass of the halo of an “average” \( L^* \) galaxy is in the range \((8 - 10) \times 10^{11} h^{-1} \text{ M}_{\odot}\) when NFW profiles are fit to the data.

- There are clear differences in the depths of the potential wells of the halos that surround galaxies of differing morphology and differing intrinsic luminosity. Specifically, the virial masses of the halos of \( L^* \) ellipticals exceed those of \( L^* \) spirals by a factor of at least 2. The actual value of the mass excess depends upon details of the data and its analysis. In addition, the virial masses of the halos of high luminosity galaxies exceed those of low luminosity galaxies. Again, however, the amount by which they differ depends upon details of the data and its analysis.

- Averaged over all galaxies with \( L \geq L^* \), the mass–to–light ratio computed on scales larger than the optical radii of the galaxies is, at most, weakly–dependent upon the luminosity of the galaxy. At the 2\( \sigma \) level, the mass–to–light ratio of the average galaxy with \( L \geq L^* \) is consistent with a constant value.

- The dark matter halos are flattened, rather than spherical, and the degree of flattening on large scales (~ 100 kpc to ~ 200 kpc) is consistent with the predictions of cold dark matter.

It is worth noting that the above list comes from quite a diverse set of data. In particular, the data are spread over a wide range in redshift. With the exception of preliminary data from DEEP2, the satellite dynamics studies have median redshifts of \( z_{\text{med}} \sim 0.07 \). The weak lenses in the SDSS data have a median redshift of \( z_{\text{med}} \sim 0.16 \) and the weak lenses in the RCS and COMBO–17 data have considerably higher redshifts, \( z_{\text{med}} \sim 0.4 \). Since it is clear that the field galaxy population has evolved since \( z \sim 0.5 \), it is not entirely fair to lump the results from all of these studies together, and I think the big challenge to the weak lensing community in particular will be to eventually place constraints on the evolution of field galaxies and their halos from, say, \( z \sim 1 \) to the present.

Nevertheless, I think we have reached a particularly gratifying time in which we are really being able to measure some of the fundamental properties of dark matter halos on physical scales that extend well beyond the visible images of the galaxies at their centers. A remarkably consistent picture of the large–scale gravitational properties of the halos is emerging from the observations and, at least for now, that picture seems entirely in accord with a cold dark matter universe.
DIFFUSE UNIVERSE

(ism/igm/cgm)

Basic difference from terrestrial atmosphere or stellar interior: density

Atmosphere of Earth $2 \times 10^8 \text{ /cm}^3$

Inside molecular cloud $10^6 \text{ /cm}^3$

Milky way disk at solar radius $0.3 \text{ /cm}^3$

Q In our atmosphere, atoms collide every few nanoseconds. In a molecular cloud, every few days. How might this change the physics?

→ more time to lose energy by radiation & return to ground state in molecular cloud
Atoms in diffuse astrophysical plasmas are usually in ground state

\[ \text{cf} \]

Local Thermodynamic Equilibrium (LTE) in Earth's atmosphere

Dynamical balance with collisions

\[ \text{cf Every possible atomic state fed by collisions & depleted by collisions} \]

At temperature \( T \) in LTE number density in excited state \( j \) \((N_j)\) of # in ground state \((N_i)\):

\[
\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-\left(\frac{\Delta E_m}{kT}\right)}
\]

\( \Delta E_m \) energy difference between \( i \) & \( j \)

\( g_i \) statistical weight of state \( j \)

(no of quantum states of that energy)
In LTE, energy distribution given by Maxwell-Boltzmann dist

\[ n(E) = \frac{2N}{\pi^{1/2} (kT)^{3/2}} E^{1/2} e^{-E/kT} dE \]

In astrophysical densities, radiative decay is important in determining populations of excited states.

For example, [OIII]5007 is one of the brightest lines emitted by a planetary nebula. At higher densities the atom will collisionally de-excite before radiatively decaying to this level. It is called a 'forbidden line' for this reason.
1. What Is the Diffuse Universe?

Fig. 1.2. Densities and characteristic sizes of diffuse astrophysical plasmas in the universe. For each class of objects, the characteristic size in log(cm) is given. The approximate boundary between plasmas in LTE and non-LTE plasmas is marked as a dash-dot line. The diffuse universe lies approximately below the horizontal line marked with arrows. The thin solid curve connects the dominant phases of galactic and intergalactic diffuse media.

spectrum generated in the shell provides insight into particle acceleration mechanisms and the origin of cosmic-rays.

With each generation of stars, some of the ISM is lost forever in the dying embers of stars – in the white dwarfs, in neutron stars formed during supernova explosions, or in black holes formed in the collapse of the cores of massive stars. In addition, some matter is effectively lost in low-mass stars which frugally burn their nuclear fuel over timescales much longer than the
Phases in the ISM

Stable balance of heating & cooling at a given pressure can often be achieved at >1 temperature.

leads to multiphase medium in ISM:

- molecular gas
- cold neutral gas
- warm neutral gas
- warm ionized gas
- hot ionized gas

Matter constantly in flux between different phases
What are examples of a given set of atoms moving between phases?

eg how does molecular gas get transformed to atomic gas?
- to hot ionized gas?

etc

Note: This may be yet more complicated because there are variations in pressure across the ISM too.
"Sticky stuff": gas and stars behave very differently.

Q: Can you think of any examples of stars losing kinetic energy?
   
   e.g. once thick disk stars are heated into a thick disk, do the stars keep the extra orbital k.e.?

→ Stars don't lose orbital k.e. easily

→ Gas is very different
   
   * When gas clouds collide, their k.e. is turned into heat via shocks, then radiated away
   
   Such collisions are almost completely inelastic: energy not conserved
• Shocks can be highly compressive
  - help cold, dense gas form
  - this aids star formation
    etc

life time in hot phase:

Q What will determine how long
the gas stays in the hot phase?

- heat content
- how fast it can radiate it away

eg. before universe formed metals, cooling was harder \( \rightarrow \) favored massive
star formation
(i) dust can be detected by the difference it causes between temp of star from color & temp of star from spectral type.

eg spectral type A, color not blue but red ⇒ significant dust along line of sight.

(ii) dust can also be detected via blackbody emission (at far IR wavelengths since it is found in cooler regions)

If there is dust (ie grains) there is also gas, although dust-to-gas ratio may not be constant.

Ca²⁺, Na → narrow absorption lines & allows study of velocity structure of ISM too.
8.1 Detection of interstellar matter

Figure 8.14 The reddening \( E(B-V) \) down various lines of sight is approximately proportional to the column density of hydrogen, \( N(H_{\text{tot}}) \), along that line of sight. The straight line is given by equation (8.49). [From data published in Bohlin et al. (1978)]

\[
N(H_{\text{tot}}) = 5.8 \times 10^{25} E(B-V) \text{ m}^{-2} \text{mag}^{-1}, \tag{8.49}
\]

Figure 8.14 plots for various lines of sight the reddening \( E(B-V) \) (see §3.7.1) against \( N(H_{\text{tot}}) \), the column density of hydrogen in all its forms. Although there is appreciable scatter of the points, the linear relationship

\[
N(H_{\text{tot}}) = 1.9 \times 10^{25} A_V \text{ m}^{-2} \text{mag}^{-1}. \tag{8.50}
\]

Thus, since we have shown that \( A_V \) is proportional to the column density of dust, to a first approximation, a given mass of gas contains a characteristic mass of dust, independent of whether the gas is in molecular or atomic form. Closer examination of data for individual interstellar clouds shows that fast-moving clouds tend to contain less dust than clouds that move more slowly relative to the surrounding material (Spitzer 1982). This difference is thought to arise because fast-moving clouds have been recently shocked, and dust grains tend to fall to pieces in the hot gas downstream from a shock wave.

Equations (8.46) and (8.48) establish an intimate connection between emission by dust and extinction. In fact, measurements of \( A_v \), the albedo \( \gamma_v \), and the emissivity enable one to predict the temperature of the emitting dust.

Several lines of argument indicate that there are significant numbers of grains comparable in size to the wavelength of blue light. For example, in §3.7.1 we mentioned that in the \( B \) band the albedo is high \( \sim 0.6 \) and that there is evidence for forward rather than isotropic scattering. Grains much smaller than 500 nm would scatter little light, and do so isotropically.

Grains that are a fraction of a micron in size radiate fairly efficiently at temperatures much in excess of tens of Kelvin, with the result that they...
→ depletion of elements onto dust grains might can be a problem

- What would be good & bad choices for the ‘searchlights’ that we use to look for interstellar absorption lines?

Curve of growth relates strength of absorption features to number density of absorbing atoms along line of sight
Chapter 8: The Interstellar Media of Galaxies

Figure 8.2 A curve of growth. The point W shows the location of a weak line on the linear portion of the curve of growth, while the point S shows the location of a saturated line on the flat part of the curve of growth. The lower and upper dashed lines have slopes of unity and a half, respectively.

Figure 8.3 The depletion factor (abundance relative to solar) of various elements along the line of sight to the star ζ Ophiuchi plotted against an estimate of the Temperature at which each element would condense onto dust grains. [After Morton (1974)]

the number of atoms available to absorb them. At higher column densities, atoms begin to ‘shadow’ one another. Thus once most photons of the right energy have been absorbed, adding further atoms to the column does not appreciably increase the number of photons absorbed because atoms which are added near the observer are hardly exposed to absorbable photons, while atoms added near the source star cast the rest of the column into the shade.

When most absorbable photons are absorbed, one says that the line is saturated. In a well-resolved spectrum, a saturated line reaches almost to zero intensity, while in the \((\log(N), \log(W))\) plane it lies on the almost horizontal or ‘flat’ portion of the curve of growth, as shown in Figure 8.2. Since the measured quantity \(W\) is very insensitive to \(N\) on the flat part of the curve of growth, column densities cannot normally be reliably estimated from saturated absorption lines. Fortunately, a given species is usually capable of absorbing photons at a series of different energies, and the cross-section for absorption generally decrease strongly with increasing energy. Hence if one spectral line is saturated, another at shorter wavelength will not be. In this way the abundances of many elements have been determined along the lines of sight to several bright stars.

Figure 8.3 displays the results for one particular star as a plot of the ratio of the abundance of an element to the temperature at which it condenses onto grains. Nearly all elements other than those from the solar system; one says that these elements are primordial.

Moreover, the degree of depletion varies strongly from element to element. Although the curve of growth is strongly saturated for some elements, it is not necessarily so for others. In effect, the wings are all that is proportional to the number of atoms available to absorb them.

Clearly, to exploit the depletion factor one must first identify how the depletion factor varies with temperature. This can be done by measuring the depletion factor for a given element as a function of temperature for a given element in a laboratory, and then applying the result to the star. The depletion factor is given by

\[
\frac{Z_i}{Z_{\odot}} = \frac{N_i}{N_{\odot}}
\]

where \(N_i\) and \(N_{\odot}\) are the number densities of the element \(i\) in the gas and in the solar system, respectively. The depletion factor is defined as

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Unfortunately, one cannot measure the unknown temperature of the clouds that lie along the line of sight to the star. The second factor that extends, is the line’s ‘natural width’. The natural width of a line is the width at which the line is no longer a stationary state of the gas and therefore will interact with the ambient gas and dust.

The cosmic abundance of a given element is determined by the rate at which it is produced in nucleosynthesis and the rate at which it is destroyed by radioactive decay.

\[\phi_D = \frac{\lambda}{\Delta v} \approx \frac{1}{c} \left( \frac{v}{c} \right)^2\]

Throughout this chapter we use the approximation that the velocity of the gas is much less than the speed of light, i.e.

\[\Delta v \approx (v/c) \lambda \approx 0.05\]

The velocity of the gas is a Gaussian function of velocity, and the wings of the line are proportional to the velocity dispersion of the gas.

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The velocity of the gas is a Gaussian function of velocity, and the wings of the line are proportional to the velocity dispersion of the gas.
Detecting the stuff

Q Think of all the possible phases of the ISM. How could we detect each one?

Absorption of starlight

Dust produces reddening & absorption but these effects occur over a large wavelength range.

Q Why might it be very useful to find narrow spectral features associated with dust in some way?
Dust & gas are always found together, or ions absorption by interstellar atoms such as Ca\(^+\) and Na in the optical can be very useful:

- gives fine tracer of velocity structure
  (\(\rightarrow\) distance in disk)

- allows some estimate of metal content of gas

UV spectra important for, say, ratio of Ca to Ca\(^+\)
Absorption by molecules

Molecules like $\text{H}_2$ rarely have absorption features in the optical.

Why?

Molecules store energy via:

- promoting electrons to excited states
- vibration (distance between nuclei oscillates)
- rotation (as if molecule was a rigid rotating body)

Consider most common molecule in the universe, $\text{H}_2$. It has absorption features in the UV. Which of the above processes might be involved?
4 Rotation transitions can be made radiatively only if the molecule has a non-zero electric dipole moment. A homonuclear molecule such as H$_2$ has a non-zero electric dipole moment only in excited electronic states.

5 The energies and wavelengths of photons are related by $E/\text{eV} = 1240 \text{ nm}/\lambda$. 

Figure 8.4 Absorption by H$_2$ molecules on the line of sight to ζ Ophiuchi. [After Spitzer & Jenkins (1975)]
Absorption of UV photon:

- 11.2 eV moves e⁻ from ground to first excited state.

- Can have states reached by adding small amount of energy to ground state: e.g., spin of molecule.

  Spin quantum no. \( J = 0, 1, \ldots \)

  e.g., vibration of molecules.

  Vibrational quantum no. \( \nu = 0, 1, 2, \ldots \)

This all boils down to photons with energy \( \approx 11.5 \text{ eV} \) since spin & rotational transitions are of energies of \( \frac{1}{100} \) or even smaller.

\( \rightarrow \) Wavelength \( \approx 1000 \ \text{Å} \)

\( \rightarrow \) vacuum UV.
Small differences in energy between rotational or vibrational energy levels lead to clusters or bands of lines near 1000 Å. (spacing ~ 13 Å or 1 Å)

We talk in general about molecular bands e.g. G-band, TiO, MgH in stellar spectra: they are collections of many fine lines due to rotational or vibrational energy levels.

Problem: In reality, since these transition probabilities are very low, we only detect H₂ features in spectra of very nearby stars.
$^2$H molecule in ground state is symmetric.

So it can't radiate in normal, dipole emission; radiates only thru quadrupole emission, which is orders of magnitude weaker.

As telescopes & instruments become more sensitive, we are beginning to detect these very weak lines.

eg 180 satellite for IR spectra

Forbidden lines round 2:

Allowed transitions radiate as dipole emission

Forbidden transitions can't (due to same symmetry) & so only radiate via weaker quadrupole or magnetic dipole emission.