Lens Galaxies vs. CDM

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Abstract. By directly probing mass distributions, gravitational lensing offers several new tests of the CDM paradigm. Lens statistics place upper limits on the dark matter content of elliptical galaxies. Galaxies built from CDM mass distributions are too concentrated to satisfy these limits, so lensing extends the “concentration problem” in CDM to elliptical galaxies. The central densities of the model galaxies are too low on \( \sim 10 \) pc scales to agree with the lack of central images in observed lenses. The flux ratios of four-image lenses imply a substantial population of dark matter clumps with a typical mass \( \sim 10^6 \) \( M_{\odot} \). Thus, lensing implies the need for a mechanism that reduces dark matter densities on kiloparsec scales without erasing structure on smaller scales.

1 Introduction

The popular Cold Dark Matter (CDM) paradigm is facing several challenges on small scales (e.g., \cite{26}). The dynamics of spiral galaxies, especially rotation curves and fast-rotating bars, suggest that in observed galaxies dark matter halos are much less concentrated than predicted by CDM (e.g., \cite{11}, \cite{13}), although this conclusion is still controversial (e.g., \cite{32}). The number of satellite dwarf galaxies in the Local Group is much smaller than the number of subhalos in CDM simulations \cite{20}, \cite{25}, although the discrepancy may be explained by the astrophysics of star formation rather than by the physics of the dark matter particle \cite{6}. These tests of CDM are limited, however, by uncertainties in interpreting luminous tracers of the potential. Gravitational lensing offers a different test that probes mass distributions directly. Strong lensing by galaxies robustly determines the total mass in the inner 5–10 kpc of lens galaxies, which are predominantly elliptical galaxies. It also offers the possibility to detect small-scale mass concentrations in galaxy halos \cite{8}, \cite{10}, \cite{19}, \cite{22}, \cite{24}. Lensing thus offers new tests of CDM that avoid dynamical uncertainties and extend the tests from spiral galaxies to ellipticals.

2 Star+Halo Models

I construct new models for lens statistics that include both stellar and dark matter components (see \cite{18} for details). In principle, I take a CDM dark matter halo, add baryons, let the baryons condense into a galaxy, and use the adiabatic
contraction formalism to compute how the dark matter distribution is modified by the baryons. In practice, I fix the stellar galaxies and use the models to place dark matter halos around them. The stellar components are treated as Hernquist models for elliptical galaxies, normalized by observed galaxy luminosity functions, Fundamental Plane relations, and Bruzual & Charlot model mass-to-light ratios (which are reliable for the old stellar components of elliptical galaxies).

Two free parameters apply to the dark matter halos. First, halos with the Navarro, Frenk & White dark matter profile are described by a concentration parameter. A halo’s concentration is determined by its mass and redshift, but with a scatter of 0.18 dex. I include the scatter and take the median concentration to be a free parameter. Second, to relate the total, virial mass of the dark matter halo \( M_d \) to the mass of the stellar component \( M_s \), I define the “cooled mass fraction” \( f_{\text{cool}} = M_s / (M_d + M_s) \). I take the cooled mass fraction to be the second free parameter in the models, assuming only that it is smaller than the global baryon fraction, \( f_{\text{cool}} \leq \Omega_b / \Omega_M \).

3 Lens Statistics and Galaxy Masses

Lens statistics can be used to test the CDM models, because changes to galaxy dark matter halos affect the number of lenses and the distribution of lens image separations. Figure 1a demonstrates the test by comparing the model predictions with the data from the Cosmic Lens All-Sky Survey (CLASS; e.g., [16]), which is the largest homogeneous survey for lenses. Increasing the concentration of dark matter halos raises the amount of dark matter in the inner parts of galaxies, leading the models to predict more and larger lenses. Because the stellar components of the galaxies are fixed, decreasing the cooled mass fraction increases the amount of dark matter, again leading to more and larger lenses.

Using statistical tests to compare the models to the data leads to confidence intervals in the \((C, f_{\text{cool}})\) plane, as shown in Fig. 1b. Lensing requires the models to have low concentrations or high cooled mass fractions. Adding the constraint on \( f_{\text{cool}} \) from the baryon content of the universe leaves only a small region of parameter space where the models are acceptable. Fiducial CDM models predict a median concentration \( C \simeq 7.7 \) for galaxies (indicated in Fig. 1b). This value is allowed by lens statistics only if galaxies are nearly 100% efficient at cooling their baryons \( f_{\text{cool}} \simeq \Omega_b / \Omega_M \), which is implausible (e.g., [2]). The constraints in Fig. 1b are conservative, because most of the systematic effects in the lensing analysis strengthen the lensing constraints (see [13]). Changing the cosmology (increasing \( \Omega_M \)) has little effect on the lensing analysis but reduces the upper limit \( f_{\text{cool}} \leq \Omega_b / \Omega_M \).

Translating the constraints into enclosed mass leads to the conclusion that dark matter can account for no more than 33% of the mass within 1 \( R_e \) and 40%
Fig. 1. (a, left) Image separation histograms for the CLASS data (solid lines) and for sample models (dotted lines). The model concentration $C$ and cooled mass fraction $f_{\text{cool}}$ are indicated in each panel. (b, right) Confidence intervals in the $(C, f_{\text{cool}})$ plane. The hatched region is excluded at 95% confidence by the distribution of lens image separations, and the cross-hatched region is further excluded by the number of lenses. The shaded region at the top is excluded at 95% confidence by measurements of $\Omega_b$ (e.g., [12], [31]). All results are shown for a cosmology with $\Omega_M = 0.2$ and $\Omega_\Lambda = 0.8$.

of the mass within $2R_e$ (95% confidence limits on average mass fractions). Note that these limits are for the mass in spheres, whereas lensing limits on the mass in cylinders indicate that dark matter halos are still important in ellipticals. The lensing limits are consistent with the mass estimates from dynamical analyses of nearby elliptical galaxies [14]. By contrast, the CDM models predict dark matter mass fractions of $\sim 28\%$ inside $1R_e$ if baryon cooling is 100% efficient, and even higher fractions for more reasonable cooling efficiencies.

4 Odd Images and Galaxy Centers

Nearly all observed lenses have an even number of images (usually two or four). Lens theory, by contrast, predicts that each lens should have an additional “odd” image located near the center of the lens galaxy, although it is demagnified by high central density of the lens galaxy. At optical wavelengths an odd image would be swamped by light from the lens galaxy, but in a radio lens an odd image should be detectable. The lack of odd images in radio lenses thus places strong lower limits on the central densities of lens galaxies [28].

The CDM model galaxies predict that $> 30\%$ of (radio) lenses should have detectable odd images, implying that the model densities are much too low on $\sim 10$ pc scales (see [13] for details). Steep central cusps ($\rho \propto r^{-\alpha}$ with $\alpha \simeq 2$) and/or central black holes can help suppress odd images, but for realistic parameter ranges neither offers an attractive solution. The lack of odd images
in observed lenses thus remains a puzzle whose resolution will reveal interesting new constraints on the very inner parts of distant galaxies.

5 Lensing and CDM Substructure

One claimed problem with CDM is that the number of subhalos in CDM model galaxies is much larger than the number of satellite dwarf galaxies in the Local Group, which suggests that CDM overpredicts the amount of substructure in galaxy-mass halos \(^{20},^{25}\). Two solutions have been proposed. On the one hand, changing the nature of the dark matter could reduce the power on small scales and eliminate the substructure \(^{4},^{9}\). On the other hand, astrophysical processes such as photoionization could inhibit star formation in low mass systems, meaning that the CDM subhalos exist but are dark \(^{6}\). Dwarf galaxy surveys cannot distinguish between these scenarios. Tidal streams offer an alternate test, because they can be disrupted by encounters with subhalos \(^{17},^{23}\), but the observational evidence is not yet available.

Lensing offers a better test by being directly sensitive to mass in subhalos. Mass clumps in the lens galaxy introduce small-scale variations in the lensing potential that alter the flux ratios of the lensed images \(^{8},^{22},^{24}\). Dalal & Kochanek \(^{10}\) show that the incidence of “anomalous” flux ratios in 4-image lenses requires that \(\sim 2\%\) of the mass be in small clumps on the scale \(\sim 10^4–10^8 M_\odot\), which is in good agreement with the amount of substructure predicted by CDM. In other words, lensing strongly supports the scenario in which many subhalos exist but lack stars, and opposes changes to the nature of the dark matter that eliminates substructure.

To complement statistical analyses like \(^{10}\), I have studied a single 4-image lens in detail using data at a variety of wavelengths to obtain constraints on individual mass clumps \(^{19}\). In B1422+231, the optical A/C flux ratio is largely consistent with smooth lens models while the radio A/C flux ratio is not (Fig. 2). Simultaneously explaining the optical and radio flux ratios and the shape of the radio image requires a mass clump in front of image A. A highly concentrated, point mass clump must have a mass \(\sim 10^4–10^5 M_\odot\), while a more extended isothermal sphere must have a mass \(\sim 10^6–10^7 M_\odot\). This is the first measurement of a particular clump lying in a distant galaxy (\(z_l = 0.34\)) and detected by its mass. Interestingly, there also appears to be a clump passing in front of image B, but this clump is probably just a star in the lens galaxy. In the future, detailed analyses of individual clumps as in B1422+231 will be combined with statistical analyses like \(^{10}\) to constrain not only the substructure mass fraction but also the masses, densities, and sizes of dark subhalos, and the substructure mass function.

\(^3\) Flux ratios that cannot be explained by smooth lens models.
6 Conclusions

Lens statistics imply that the dark matter densities in the inner parts of elliptical galaxies are lower than predicted by CDM, in agreement with the conclusion from dynamical analyses of spiral galaxies. The CDM paradigm must therefore be modified to reduce dark matter densities on kiloparsec scales. Various mechanisms have been proposed ranging from astrophysics (disk bars that erase dark matter cusps [33]) to cosmology (a tilted power spectrum [1]) to particle physics (dark matter that is not collisionless and cold [4], [9], [30]).

Lensing also implies that lens galaxies have high densities on small scales (≤ 10 pc). The central densities of galaxies must be much higher than predicted in CDM model galaxies to explain the absence of central or “odd” images in observed lenses. The flux ratios in four-images lenses imply that a substantial fraction of the dark matter (∼ 2%) lies in small-scale clumps rather than a smooth halo component [10], and B1422+231 suggests that a typical clump mass is ∼ 10^6 M☉ [19]. Thus, while lensing supports other evidence that a mechanism is needed to reduce dark matter densities on kiloparsec scales, it also suggests that the mechanism must not remove structure on small scales — which argues against changing the nature of the dark matter particle.

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