

Dark Matter Structures in the Universe:

Prospects for Optical Astronomy in the Next Decade

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The Cold Dark Matter theory of gravitationally-driven hierarchical structure formation has earned its status as a paradigm by explaining the distribution of matter over large spans of cosmic distance and time. However, its central tenet, that most of the matter in the universe is dark and exotic, is still unproven; the dark matter hypothesis is sufficiently audacious as to continue to warrant a diverse battery of tests. While local searches for dark matter particles or their annihilation signals could prove the existence of the substance itself, studies of cosmological dark matter in situ are vital to fully understand its role in structure formation and evolution. We argue that gravitational lensing provides the cleanest and farthest-reaching probe of dark matter in the universe, which can be combined with other observational techniques to answer the most challenging and exciting questions that will drive the subject in the next decade: What is the distribution of mass on sub-galactic scales? How do galaxy disks form and bulges grow in dark matter halos? How accurate are CDM predictions of halo structure? Can we distinguish between a need for a new substance (dark matter) and a need for new physics (departures from General Relativity)? What is the dark matter made of anyway? We propose that the central tool in this program should be a wide-field optical imaging survey, whose true value is realized with support in the form of high-resolution, cadenced optical/infra-red imaging, and massive-throughput optical spectroscopy.

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Figure 1: The color composite of the Bullet cluster 1E0657–56 (left) and MACS J0025.4–1222 (right). Overlaid in *blue* shade is the surface mass density map from the weak lensing mass reconstruction. The X-ray emitting plasma is shown in *red*. Both images subtend ~ 10 arcmin on the vertical axis. Credit (left): X-ray NASA/CXC/CfA Optical: NASA/STScI; Magellan/U.Arizona; Clowe et al. (2006); Bradač et al. (2006) (right) X-ray (NASA/CXC/Stanford/S.Allen); Optical/Lensing (NASA/STScI/UCSB/M.Bradač); Bradač et al. (2008b).

Introduction

It is remarkable that the conceptually-simplest numerical model of structure formation in the universe – an N-body simulation, where each particle interacts with others only via gravity – provides such a good match to the distributions of galaxies, groups and clusters we observe (e.g. Tegmark et al. 2004). The fact that the initial conditions for this Cold Dark Matter model can be set by a handful of parameters constrained self-consistently by multiple cosmological datasets (e.g. Reichardt et al. 2008; Komatsu et al. 2008) fully justifies its status as the “standard model” of cosmology.

The unsettling aspect of this standard model is that $\sim 80\%$ of the matter in it is of unknown form. This fact has led a number of researchers to look for alternative explanations for the phenomena attributed to dark matter: if we instead claim to understand the stress-energy tensor right-hand side of the Einstein equation of General Relativity, so the argument goes, then the left-hand side must be adjusted. However, such “modified gravity” theories that do not include dark matter have yet to be shown to be able to fit all the data. A striking example of this is provided by the “bullet” clusters studied by Clowe et al. (2006) and Bradač et al. (2006, 2008b). In these high-speed, plane-of-sky collisions, the positions of the gravitational potential wells – mapped using both the observed strong and weak gravitational lensing effects – and the dominant baryonic (stellar and hot gas) mass distributions, are well separated, leading us to infer the clear presence and domination of a dark matter component (see Figure 1). Note the key role played by gravitational lensing in this case study: it is the cleanest probe of mass distributions in the universe, allowing them to be mapped and modeled (albeit in projection) while avoiding the confusion introduced by tracers which may or may not be in equilibrium in their potential wells.

While it is hard to reconcile these lensing results with simply-modified gravity and no dark matter, this does not mean that GR holds in other regimes. Testing the laws of gravity on the largest scales, where the universal expansion appears to be accelerating, will be a major activity in the next decade, but many of these tests will rely on the CDM framework for understanding large scale structure. *It is not possible to fully test gravity theories, or probe dark energy, without understanding the behavior of dark matter.*

On the largest scales then, CDM has been initially successful. What are the outstanding problems that can be approached using astronomical observations? In this paper, we suggest the following four questions:

- What is the distribution of mass on sub-galactic scales?
- How do galaxy disks form and bulges grow in dark matter halos?
- How accurate are CDM predictions of halo structure?
- Can we distinguish between a need for a new substance (dark matter) and a need for new physics (departures from General Relativity)?

In each of these areas we can look for clues relating to the single most important question about dark matter: *what is it?* Direct searches for dark matter are underway: some use solid state devices deep underground to detect the dark matter wind resulting from our motion through our own galaxy's halo. Others involve looking for DM particle annihilation signals, coming from nearby galaxy cores predicted to host the required densities, in the gamma-ray part of the EM spectrum. However, there is a need to extrapolate the results of these experiments to the universe outside the local group: we seek a complete understanding of dark matter, connecting the largest scales to the smallest, over the whole span of cosmic time. Distinguishing between different proposed types of dark matter (self-interacting, decaying, etc. etc.) will take experiments on many different length and mass scales, and so requires the study of more halos than just the one that we live in. We recommend here a program of gravitational investigations into structures at cosmological distance as a necessary complement to the local studies.

This paper is structured as follows. We focus on three approximate length scales, and explore in more detail a battery of dark matter experiments we would like to carry out at each one, based on the questions listed above. We sketch out the facilities required to carry out each experiment, and finally summarize our findings.

Clusters and groups of galaxies

On cluster scales, the key questions are: How accurate are CDM predictions of halo structure? and Can we distinguish between dark matter and departures from General Relativity? One of the most accessible predictions of CDM N-body simulations has been, and will continue to be as simulations improve, that of a universal density profile of the collapsed halos (e.g. Navarro et al. 1997), and how its parameters change with mass scale and time (e.g. Bullock et al. 2001). Clusters of galaxies are good places to try and measure this, since they are dark matter-dominated systems whose size and mass lead to relatively easily measured gravitational lensing effects. However, to date only a few dozen clusters have been measured in detail (see e.g. Comerford & Natarajan 2007, for an example compilation). Initial results are intriguing, with massive clusters seeming to be more concentrated (e.g. Umetsu et al. 2005), or to have shallower inner slopes (Sand et al. 2008, Figure 2), than predicted. This test of CDM is still in its infancy, and more work (both observational and theoretical) is needed to disentangle the effects of baryons on the dark matter profiles. Large numbers of well-measured clusters are needed: not only to ensure a fair selection (the easiest clusters to measure may not be representative of the population), but also to accurately probe the *distribution* of density profiles, and to allow us to compare their *evolution* to that predicted by the simulations.

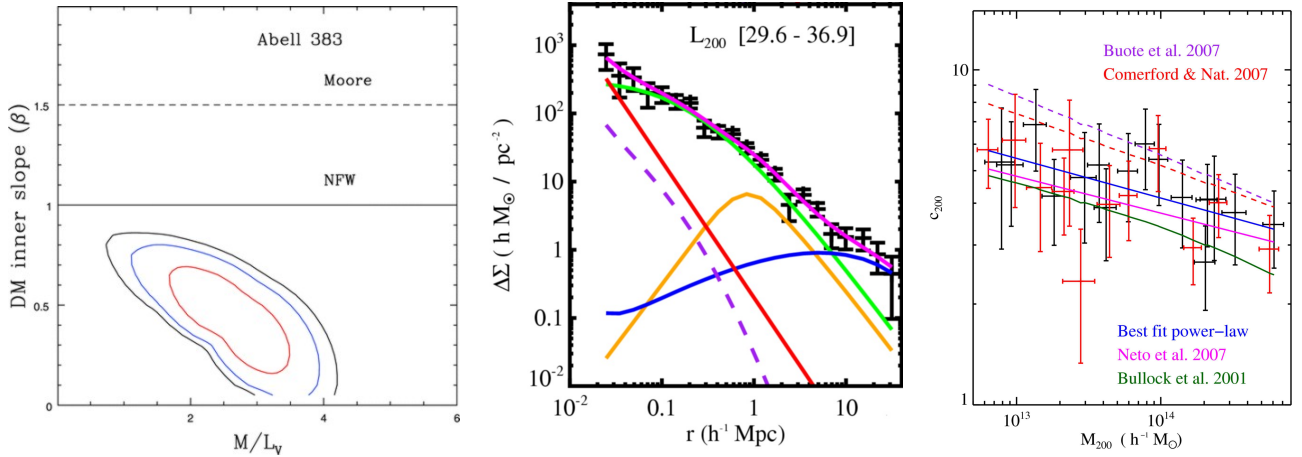


Figure 2: Recent results on cluster structure. Left: measuring the inner density profile slope in a detailed analysis of a strong lensing cluster, including the stellar kinematics in the BCG (Sand et al. 2008). Center: stacking optically-selected cluster shear signals measured in the SDSS imaging (Johnston et al. 2007) allows the concentration-mass relation to be probed (right).

A complementary route towards understanding CDM halo profiles is to stack the weak lensing signals of large numbers of clusters, a technique shown to be very powerful even using the low-resolution SDSS imaging (in, e.g. the MaxBCG project, Johnston et al. 2007). Smaller mass scales are accessible with this approach, which also allows the mean density profile at very large radii to be measured and compared against CDM predictions of $\rho \sim r^{-3}$ outside the virial radius. Moreover, a comparison of the stacked weak lensing signal to the stacked velocity dispersion profile in the same cluster sample will also test gravity on cluster scales. Dynamics (velocities) are sensitive to one metric potential Ψ , while lensing measures the sum of the metric potentials $\Psi + \Phi$. In General Relativity, $\Phi = \Psi$, but this is not the case for many modified gravity theories. Bolton et al. (2006) performed an analogous test of gravity on kpc scales using a handful of strong lens galaxies; a much larger cluster sample would extend the bounds up to Mpc scales and beyond. A key requirement for this will be an intensive spectroscopic follow-up program to measure the velocities of cluster members.

Plane-of-sky merging clusters (Figure 1) can be used to help answer the question of what the dark matter is, placing constraints on the self-interaction cross-section of the putative dark matter particle itself: currently $\sigma/m \lesssim 0.7 \text{cm}^2 \text{g}^{-1}$ (Randall et al. 2008). The most stringent constraints come from comparing the relative positions of the centers of total mass (from gravitational lensing) and stellar mass (from optical imaging), indicating that we can consider expanding this study to use many more clusters as dark matter laboratories in this way. Only a fraction of clusters will be suitable: large samples of objects are needed to find the most powerful examples. Systematic errors dominate: in this, and the profile measurement test, closer comparisons with more physically-realistic simulations will be needed.

A $\sim 10^4$ square degree optical imaging survey, such as that envisioned with JDEM or LSST, will naturally contain a sample of clusters large enough to carry out the tests described here with close-to-ultimate precision, provided it is deep enough (and red enough) to allow accurate measurement of the weak lensing signal behind clusters at $z \simeq 1$ (a challenge for the photometric redshift calibration). It is the strong and weak lensing combination that is key in constraining the cluster density profile (e.g. Bradač et al. 2008a); strong lensing demands high ($\sim 0.1''$) resolution multi-filter imaging, needed to identify candidate multiple-image systems (HST really enabled the beginning of this work in the last decade). The next generation AO facilities will provide a viable alternative to HST and

JWST in providing the high resolution images needed. Measuring redshifts for the multiple-image systems is also vital in pinning down the density profiles in the core – as is accounting for the stellar mass in the BCG via its stellar kinematics. With most source emission lines and cluster galaxy absorption lines falling in the optical, high-throughput multi-object spectroscopy with 8-10m class telescopes will continue to be important in building significant samples of density-profile clusters.

Galaxies

Galaxy-scale dark matter studies are complicated by the greater role played by baryonic matter – stars and gas – in the structure and evolution of their halos. This is an opportunity though – we would very much like to understand how galaxies form and develop! CDM provides a robust framework for understanding galaxies: improved observations are driving an iterative cycle of ever-improving hydrodynamical simulations and semi-analytic modeling, enabling us to learn more about the astrophysical processes going on. However, as with clusters, gravitational lensing studies of galaxies can provide important insights into the dark matter properties of galaxies, providing accurate measurements of total projected mass, independent of their luminous properties or dynamical state. The key questions are: How accurate are CDM predictions of galaxy halo structure? and How do galaxy disks form and bulges grow in dark matter halos?

Weak gravitational lensing provides information on the average halo density profile at large galacto-centric radii (e.g. Hoekstra et al. 2005; Mandelbaum et al. 2006b; Heymans et al. 2006). Strong lensing, which probes smaller radii, provides an excellent complement to weak lensing investigations of galaxy mass distributions (e.g. Gavazzi et al. 2007). Further mass measurements, such as those available from stellar dynamics (e.g. Treu & Koopmans 2004), lens image time delays (in lens systems where the source is time-variable), and microlensing densitometry (if the strongly-lensed source is a quasar, e.g. Pooley et al. 2008; Morgan et al. 2008), can provide valuable additional constraints. Even stronger constraints can come from compound lens systems in which two (or more) background objects are strongly lensed by the same foreground galaxy (e.g., SDSSJ0946+1006 Gavazzi et al. 2008) – the multiple source planes provide two high-precision mass estimates at different radii: one out of every 40-80 elliptical lenses will have multiple sources detectable in deep, high resolution imaging.

The above approaches have already produced important results. For example, massive elliptical galaxies have been found to be a remarkably structurally homogeneous population, with isothermal ($\rho(r) \propto r^{-2}$) total density profiles over a range of luminosities and scales (e.g. Bolton et al. 2008, and references therein). Understanding how the stellar and dark matter “conspire” to produce this end result is a challenge for galaxy formation models. In the next decade we should be looking to extend this study to higher redshifts and lower masses, to go with advances in the simulations of bulge formation.

With improved weak shear data, it will be possible to gain insights into misalignments between galaxy halos, and their disks and bulges: this is a key measurement that tells us about how galaxies are affected by the larger-scale environment as they form and evolve. This measurement is difficult with current data (Mandelbaum et al. 2006a): having a larger statistical sample will reduce shape noise, while surveys designed for weak lensing measurements will allow for better control of the systematics. Strong lensing observables can also provide insights on misalignments between halos and galaxy stellar components on smaller scales. This information may be particularly interesting in the case of disk lenses, where the orientation of the stellar component can be unambiguously

determined. Although the vast majority of known strong lenses are massive ellipticals, several lower-mass disk lenses are known and many more will be found (e.g. York et al. 2005; Bolton et al. 2008, Marshall et al. in prep).

What is needed for these galaxy structure measurements? Current ground-based weak lensing studies have been limited to massive galaxies at relatively low redshift. Deeper or space-based surveys (e.g. GEMS, AEGIS) provide higher background densities but have had limited precision due to the small survey areas covered. What is needed is a wide-field imaging survey that is deep enough to extend significant weak lensing measurements of halo structure to both lower-mass (and more varied type) galaxies and to higher redshifts; accurate photometric redshifts will be especially important to cleanly separate the sources and identify the lenses.

The main obstacle to using strong lenses to probe galaxy-scale dark matter halos is that these systems are rare: currently there are only ~ 200 known galaxy-scale strong lenses. It would be possible to detect 10^{4-5} galaxy-scale lenses with a $\sim 10^4$ square degree optical imaging survey of the kind needed for the high fidelity weak lensing measurements. The number of lenses detected is quite a strong function of angular resolution: with space-based instrumentation (0.1 arcsec PSF FWHM) we expect some 10 lenses per square degree (Marshall et al. 2005; Faure et al. 2008), while from the ground we expect to do perhaps an order of magnitude worse (Cabanac et al. 2007, Gavazzi et al. in prep). A 10^4 square degree JDEM survey in the optical (where the source galaxies are bright) to a depth of 27th magnitude would therefore discover 10^5 galaxy-scale lenses; LSST would likely see 5 times fewer than this in a 20000 square degrees to comparable depth, but would provide valuable time delays and microlensing signals for all of several thousand lensed quasars and supernovae. The powerful synergy afforded by the Square Kilometre Array in the radio is discussed in the white paper by L. Koopmans.

There is also the prospect of detecting an entire dark galaxy in such a survey. These are not predicted to occur by the current simulations, at least not at typical halo masses and luminosities. Finding one – by focusing on detecting arc-like features unassociated with foreground light (e.g. Seidel & Bartelmann 2007) – would provide a significant challenge to the world model.

High accuracy strong lensing studies not only need large samples to map out the scatter and probe evolution, but also some intensive follow-up effort. High spatial resolution IFU spectroscopy will be particularly valuable, allowing the kinematic structure of the lenses to be mapped out and used as complementary mass constraints (Barnabè & Koopmans 2007; Czoske et al. 2008). Separating the stellar mass components of the galaxy needs high resolution infra-red imaging. We can imagine making all these observations routinely either with next-generation adaptive optics on 8-10m class telescopes from the ground, or with JWST from space.

Satellites of galaxies

It is on sub-galactic scales that CDM has been tested least rigorously: there remains the key question of the distribution of mass on sub-galactic scales. Recently there have been claims of the so-called substructure crisis being resolved, as the SDSS survey has turned up more and more Milky Way satellite galaxies: the remaining shortfall in nearby low-mass companion sub-halos is attributed to star formation inefficiency (see e.g. Simon & Geha 2007; Busha et al. 2009). This is perhaps a good example of how accepted CDM has become: the problem is assumed to be in the star formation physics, not the underlying dark matter model that still predicts 4 times as many dwarf satellites as have been detected! (Figure 3.) Modifications to CDM have been suggested that predict fewer

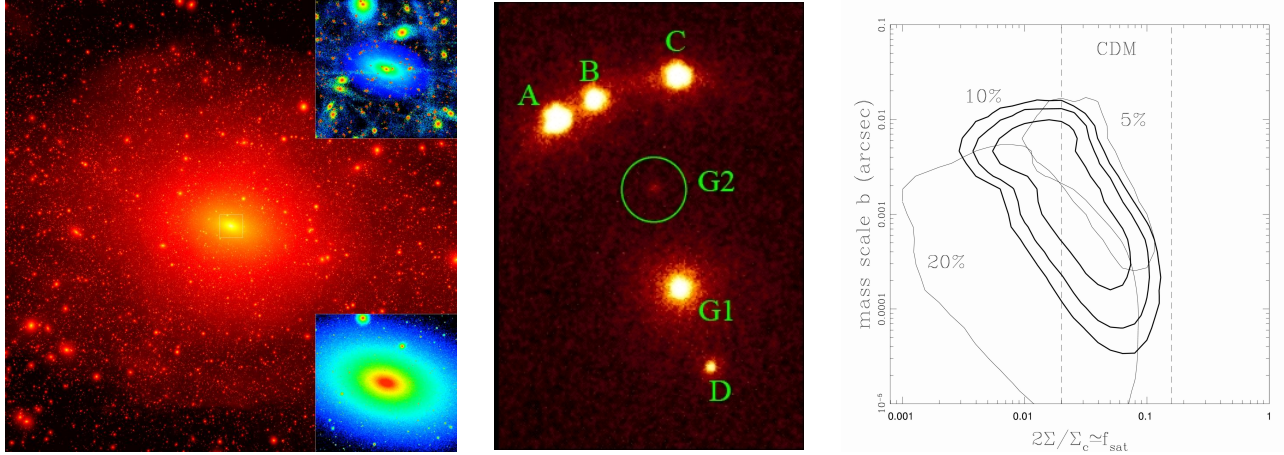


Figure 3: Left: high resolution numerical simulation of a galaxy-scale dark matter halo, showing the abundance of small-scale mass structure (Diemand et al. 2008). Center: Keck adaptive optics image of B2045+265 showing the lensing galaxy (G1) and four lensed images of the background AGN (A–D). This is one of the most extreme anomalous flux ratio systems known: image B should be the brightest of the three close lensed images, but instead it is the faintest, suggesting the presence of a small-scale perturbing mass. The adaptive optics imaging reveals the presence of a small satellite galaxy (G2) that may be responsible for causing the anomaly. Image from McKean et al. (2007). Right: inferred constraints on the fraction of galaxy mass in substructure, and the characteristic sub-halo mass, from an ensemble of 7 lenses showing anomalous flux ratios Dalal & Kochanek (2002).

satellites, either due to a lower mass for the DM particle (WDM) or an altered interaction cross-section (SIDM). Measuring the mass function of galaxy sub-halos is a way of probing the fundamental properties of dark matter; future optical imaging surveys more sensitive than SDSS and covering greater sky area will allow the direct detection of more faint MW satellites, and to probe their stellar kinematics.

However, Milky Way studies will very soon become cosmic variance-limited. There is a clear need for a complementary approach, both to detect dark matter substructures independently of their luminous component, and also to extend the study to galaxies beyond our own. Strong lenses satisfy both these criteria. Galaxy-scale strong lenses showing almost complete Einstein rings can be used to search for dwarf satellites via the small perturbations these structures have on the ring morphology: subhalos with as little mass as $10^7 M_\odot$ are expected to be directly detectable in this way with high signal-to-noise, high resolution imaging data (Vegetti & Koopmans 2009). The normalization of the mass function can be constrained by statistical analysis of the residual images for large numbers of lenses. High resolution imaging with the next generation of AO instrumentation with 8-10m class telescopes would be the tool of choice, exploiting their improved astrometric accuracy over HST and JWST, and observing in the infra-red to maximize sensitivity to the old stellar populations of any luminous satellites. As lens samples grow, 30-m class telescopes would enable the follow-up to better keep pace with the surveys.

Lensed quasars (Figure 3) offer a similar but perhaps less expensive route to the subhalo mass function, along with the density profile and spatial distribution of subhalos. Indeed, this one approach is expanded upon in more detail in the white paper by L. Moustakas. There are three observables in a lensed quasar that are affected by “milli-lensing” by satellite galaxies: the fluxes, positions, and time delays of the images. Flux ratio perturbations are the easiest to measure (provided that microlensing can be modeled out over many years of cadenced surveying campaign). They primarily constrain the fraction of the galaxy mass contained in substructure, and to some extent the density profile of the subhalos themselves (Dalal & Kochanek 2002; Shin & Evans 2008). Astrometric perturbations are smaller, $\simeq 10$ mas (Chen et al. 2007), but measurable with AO imaging on 30-m class telescopes and

with VLBI in the radio. They are useful in combination with flux ratio perturbations because they measure a different moment of the subhalo mass function. Substructure perturbations to time delays are at the level of hours to days (Keeton & Moustakas 2008), and may require a dedicated high-precision photometric lens monitoring mission. They provide yet a third moment of the subhalo mass function, and more sensitivity to the spatial distribution of subhalos around the lens galaxy. The joint analysis of flux ratios with image positions and perhaps time delays would test not only predictions about the subhalo mass function, but also predictions that subhalos should follow (almost) the same universal density profile and concentration-mass relation as larger galaxy and cluster halos (Springel et al. 2008), and that subhalos may be (anti)biased with respect to the smooth dark matter halo.

Quasar lenses, although rarer than galaxy-galaxy strong lenses by a factor of 10 or more, can be efficiently detected optical imaging surveys by using the variability of the lensed objects (e.g. Kochanek et al. 2006), allowing ground-based surveys to recover more small-separation lenses than they would have otherwise resolved. This places a constraint on any survey we might be considering: that it be built up from multiple exposures taken over several years (to give the sources the chance to vary).

Conclusions

We expect that studies of dark matter structures outside the local group will remain one of the major lines of inquiry into this mysterious component of the universe, complementing direct searches and other astroparticle physics observations. For measuring the mass distributions of clusters and galaxies, and their respective subhalo populations, gravitational lensing is the tool of choice, particularly as we push out to higher redshifts to probe the evolution of these structures. A wide-field, multi-filter, preferably multi-epoch optical imaging survey, such as that proposed with LSST or a suitably-designed JDEM observatory, would enable a wide range of dark matter science, based on the (stackable) weak lensing signals from all halos, and the strong lensing effects due to some. To fully exploit these surveys, considerable numbers of supporting observations will be required, primarily including high resolution imaging and high throughput multi-object spectroscopy. The next generation of ground-based adaptive optics instrumentation should be capable of providing this support.

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