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1. Dark Matter

Dark matter comprises 27% of the universe – ordinary, atomic matter takes up only 5%, and the remaining 68% consists of dark energy (Planck Collaboration 2013). A wealth of evidence, including baryon-to-matter ratio estimates from big bang nucleosynthesis, cosmic microwave background (CMB) anisotropies, and observations of baryonic matter in the universe, all indicate that some type of non-baryonic matter must make up the majority of matter in the universe (Dodelson 2003). A number of dark matter particle theories exist; we will concentrate on three – cold dark matter (CDM), warm dark matter (WDM), and self-interacting dark matter (SIDM). The leading theory, CDM, says that dark matter particles were nonrelativistic during structure formation (Porter et al. 2011). Weakly interacting massive particles (WIMPs) and axions are the two most popular incarnations of CDM. WDM refers to a dark matter model in which the particles are moderately relativistic. As such, they have energies higher than the escape velocity, which wipes out low mass substructure. SIDM is a model of cold dark matter that is self-interacting (Spergel and Steinhardt 2000).

Where is all the dark matter? Cold Dark Matter (CDM) simulations predict that a galaxy with a halo the size of the Milky Way should have many times more dark matter satellites of mass $\gtrsim 10^8 M_\odot$ than observed (Moore et al. 1999; Klypin et al. 1999; Boylan-Kolchin et al. 2012). We call this the "Missing Satellites Problem". There are two possibilities: (i) the satellites are out there, and we simply cannot see them, or (ii) the simulations overestimate the number of satellites. In the first scenario, dark matter satellites may not be visible because they they do not contain sufficient baryons, or star formation has been suppressed (Kravtsov 2010). There are a number of reasons why simulations may overestimate the number of satellites, in the second case. For instance, these simulations only modeled dark matter, not baryons. Adding baryons to the dark matter distributions will increase tidal stripping, and can destroy satellites which would otherwise remain in DM-only simulations (A. Brooks, 2013, HST theory proposal, submitted).

Alternate models of dark matter may provide an escape from the missing satellites problem. N-body simulations of WDM show fewer satellites (Lovell et al. 2012; Macciò and Fontanot 2010). WDM solves some other problems with CDM, as well. It is a better fit to the satellite luminosity functions (Nierenberg et al. 2013), the field galaxy velocity function (Papastergis et al. 2011), and the densities of the bright Milky Way (MW) satellites (Boylan-Kolchin et al. 2011, 2012; Lovell et al. 2012). SIDM simulations also show fewer satellites than CDM models (Rocha et al. 2013).

Our goal is to use gravitational millilensing to discover dark matter satellites and derive a substructure mass fraction. We further seek to constrain the dark matter models by pushing down the mass function.

2. Substructure Lensing

Dark matter satellites can be detected with gravitational millilensing. Subhalos perturb the lensing potential, so they can be detected by comparing flux ratios, relative positions, and time delays of multiply-imaged systems. Each of these three strong lensing probes uncovers information about dark matter substructure that differs from and complements information gleaned through the other efforts, so using all three methods in conjunction can teach us more about dark matter than any method alone (Keeton and Moustakas 2009; Keeton 2009). Table 1 summarizes various sensitivities pertaining to the three strong lensing probes of dark matter substructure.

Strong lensing dark matter substructure probe	Dark matter mass function moment dependence	Dark matter substructure mass range sensitivity	Sensitivity to area around each lensed image	Sensitivity to the internal structure of substructure	Main observational challenges
Time delays	$\left(\langle m^2\rangle/\langle m\rangle\right)^2$	High mass ($<10^9$ M_{sun})	Long-range	Little	High time domain precision
Relative positions	$\left(\langle m^2\rangle/\langle m\rangle\right)^{3/2}$	Intermediate to high mass	Intermediate	Modest	High astrometric precision; lens modeling
Relative fluxes	$\left(\langle m^2\rangle/\langle m\rangle\right)$	Full mass range	Quasi-local	Sensitive	Microlensing; lens modeling

Table 1: Table from Moustakas et al. (2009).

Flux ratios are sensitive to nearby subhalos. When a source lies near a cusp, the signed magnifications of all three images should add up to near zero (Keeton et al. 2003). The same applies to a pair of images in a fold configuration (Keeton et al. 2005). When they do not, we have a flux ratio anomaly, which indicates substructure (Keeton et al. 2003). For additional background information on flux ratios, we refer the reader to Mao and Schneider (1998); Metcalf and Madau (2001); Chiba (2002); Dalal and Kochanek (2002). Position perturbations are partly degenerate with a smooth model (Chen et al. 2007). These astrometric perturbations are most likely to be due to substructure when the clumps are near the Einstein radius of the lens. Time delay millilensing in gravitational lens systems with multiple images can detect dark matter substructure (Keeton and Moustakas 2009). Subhalos perturb the time delay ratios between images, and can even reverse the arrival-time order of the images located at the local minima of the time delay surface in a cusp image configuration. The subhalo mass function, abundance of substructure, and internal structure of subhalos all affect the strength of the perturbations. Unlike flux ratio anomalies, time delay millilensing is unaffected by dust extinction or microlensing by low-mass objects such as stars. This means we can study dark matter substructure using optical and X-ray observations, in addition to the radio data already being used in astrometric millilensing and flux ratio comparisons.

The flux ratios and positions in the lens HE 0435-1223 can be modeled as either a single clump near image A, or as a population of clumps throughout the lens Fadely and Keeton (2012). Since our goal in the use of gravitational millilensing here is to discover dark matter satellites and derive a substructure mass fraction, we should be concerned that we cannot distinguish between a single subhalo and an entire population. Since time delays are sensitive to subhalos located in a long-range distance from the lensed images (Keeton and Moustakas 2009; Moustakas et al. 2009), they would be able to differentiate between the two scenarios.

Additional work has been done with distorted Einstein rings; see Vegetti and Koopmans (2009); Vegetti et al. (2010, 2012).

3. Realistic Models

The next step in studying dark matter substructure is to employ realistic models of mass distribution in galaxies. Realistic models from Rachel Sommerville and Alyson Brooks (A. Brooks, 2013, HST theory proposal, submitted) will provide us with important adjustments to the simplified models used previously. Including baryons in galaxy formation simulations will decrease both the number and mass of dark matter subhalos (A. Brooks, 2013, HST theory proposal, submitted). They will also address several concerns voiced in Keeton and Moustakas (2009), namely modeling tidal truncation with realistic subhalo masses, and accretion of new subhalos with disruption of old subhalos. Furthermore, we will extend this analysis to semi-analytic models (SAMs) of WDM and SIDM cosmologies, and attempt to constrain dark matter properties.

The analysis in section 2 is limited to dark matter clumps with masses between $10^7 M_\odot$ and $10^9 M_\odot$ (Keeton and Moustakas 2009). This coincides with the minimum range predicted for WDM and SIDM subhalo mass – however, CDM models indicate the existence of substructure with even lower mass. By extending this work to simulate dark matter clumps of $< 10^7 M_\odot$, we look at lower constraints on substructure mass. If simulations show that these low mass subhalos perturb substructure lensing observables (time delays, positions, and/or flux ratios) in an identifiable manner, the presence or absence of these signatures in observations will constrain the dark matter mass function directly. Detection of low mass subhalos would rule out the WDM and SIDM models, while the lack of low mass substructure would cut off the subhalo mass function and challenge the possibility of CDM.

4. Multipole Expansion Approximation Tool

Detailed N-body simulations are difficult to work with, given that their level of detail makes them computationally prohibitive. SAMs make computations more feasible. To even begin to attack Sommerville's and Brooks' SAMs, we must start with this multipole expansion tool that will allow us to approximate the contribution of distant dark matter substructure to the lensing potential.

For a population of N dark matter clumps, the exact solution for the lens potential at some point $\vec{x}$ is

$$\phi\left(\vec{x}\right) = \sum_{i=1}^{N} \frac{\hat{M}_i}{\pi} \ln\left|\vec{x} - \vec{x}_i\right| \tag{1}$$

where $\hat{M}_i = \frac{M_i}{\Sigma_{\rm crit}}$ is a scaled clump mass. The exact solution is very computationally expensive — the CDM mass function is very steep, so lower mass limits mean many more subhalos, and many more terms in the summation — so it is not feasible for larger, more realistic dark mass clump populations. We can convert the potential into a multipole expansion, which remains exact providing we include an infinite number of terms. If we constrain the expression to a finite number of terms, however, the multipole expression serves as an approximation of the lens potential, and becomes computationally viable. Thus we must determine the minimum number of terms necessary for the approximation error of the multipole expansion to fall within a reasonable threshold.

We must also choose the region in which to use the multipole expansion. Distant dark matter clumps have a smaller effect on the observables we wish to quantify (Keeton and Moustakas 2009), so we will use the exact solution for any clumps interior to the radius at which we measure the potential, as well as those exterior to that radius, up until some threshold radius R_0. For any "distant" clumps beyond R_0 we will use the multipole expansion. Therefore the other parameter we must determine is the lowest radius R_0 at which the approximation remains sufficiently accurate. Furthermore, if the distant dark matter clumps are spherical, we can approximate them by point masses, which simplifies the expressions for the multipole moments. The multipole expansion of the lens potential ϕ resulting from dark matter clumps at radii $r_i \geq R_0$ is

$$\phi_{\rm ME}\left(r, \theta\right) = 2J_0^c - 2\sum_{m=1}^{m_{\rm max}} \frac{r^m}{m}\left[J_m^c \cos m\theta + J_m^s \sin m\theta\right] \tag{2}$$

where the multipole moments are

$$J_0^c = \frac{1}{2\pi}\sum_{i=1}^{N}\hat{M}_i \tag{3}$$

$$J_m^c = \frac{1}{2\pi}\sum_{i=1}^{N}\hat{M}_i r_i^{-m}\cos m\theta_i \tag{4}$$

$$J_m^s = \frac{1}{2\pi}\sum_{i=1}^{N}\hat{M}_i r_i^{-m}\sin m\theta_i \tag{5}$$

and $m_{\max}$ is the number of terms we deem necessary for sufficient accuracy.

To select a threshold radius for distant substructure and a number of multipole terms, we will generate random populations of dark matter clumps in two radial distributions, uniform and isothermal ($1/r$). For each clump realization, both the exact and multipole solutions will be calculated for some R_0 and a range of $m_{\max}$. To be precise, the solutions we refer to are the lens potential and its first and second derivatives with respect to x and y, on which the observables depend. By comparing the errors between exact and multipole solutions over a large sample of realizations for a range of R_0 and $m_{\max}$, we can select a combination of these two variables which optimizes accuracy while remaining computationally efficient.

5. Conclusion

CDM, WDM, and SIDM offer different predictions about the amount of low mass substructure. To hone in on which dark matter paradigm best describes the data, we seek to constrain the dark matter mass function. We can do this by examining realistic models of galaxy mass distribution, which necessitates the inclusion of more clumps. The multipole expansion approximation tool allows us to conduct this analysis in a computationally affordable way.

With LSST expected to find over 8000 lensed quasars over the next ten years (Oguri and Marshall 2010), and a combination of HST, all-sky ground-based surveys in optical or radio, and a galaxy redshift survey projected to discover around 10,000 gravitational lenses (Treu 2010), this analysis will be essential to reap the benefits of the expected harvest in the coming years.

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