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Detecting CDM substructure via gravitational millilensing (15'+5')

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While the cold dark matter (CDM) scenario has been very successful in explaining structure formation on large scales, its predictions on the scales of individual galaxies have yet to be confirmed. In particular, the number of galaxy substructures predicted by CDM simulations is orders of magnitudes higher than the number of satellite galaxies observed in the vicinity of the Milky Way. A possible way out of this dilemma could be that the majority of these subhalos so far have evaded detection. One promising possibility for detecting such dark substructures could be their gravitational lensing effects on background sources. It has been claimed that dark matter subhalos in the $10^6 - 10^{10}$ $M_\odot$ mass range should cause strong gravitational lensing on milliarcsecond scales. We study the feasibility of a strong-lensing detection of dark subhalos by deriving the image separations expected for density profiles favoured by current simulations and comparing it to the angular resolution of both existing and upcoming observational facilities. We find that although this search strategy is likely to be considerably more challenging than suggested in previous studies, there is a reasonable probability to observe subhalo lensing effects in high resolution observations at radio wavelengths.

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1. Introduction

Gravitational lensing may in principle offer a route to put the cold dark matter (CDM) subhalo predictions to the test. It has been suggested that one should target quasars which are already known to be gravitationally lensed on arcsecond scales, as one can then be sure that there is a massive halo well-aligned with the line of sight, which substantially increases the probability for subhalo millilensing [1]. Indeed, the magnification associated with millilensing has long been suspected to be the cause of the flux ratio anomalies seen in such systems [2, 3]. Subhalo millilensing has also been advocated as an explanation for strange bending angles of radio jets [4] and image positions which smooth halo models seem unable to account for [5].

Here, we take a critical look at the prospects for strong-lensing detections of dark subhalos in the dwarf-galaxy mass range. Throughout the paper, we assume a ΛCDM cosmology with Ω_Λ = 0.762, Ω_M = 0.238 and $h = 0.73$ (H_0 = 100 h km s^{-1} Mpc^{-1}) in concordance with the WMAP 3-year data release [6].

2. Image separations

To first order, the image separation produced through strong lensing by an extended object with a density that decreases as a function of distance from the centre is given by

$$\Delta\theta \approx 2R_\mathrm{E}/D_\mathrm{ol}, \tag{2.1}$$

where D_ol represents the angular-size distance between observer and lens, and R_E represents the linear Einstein radius. The latter is defined as the radius inside which the mean surface mass density $\bar{\Sigma}$ of the lens equals the critical surface mass density

$$\bar{\Sigma}(< R_\mathrm{E}) = \Sigma_\mathrm{c} = \frac{c^2 D_\mathrm{os}}{4\pi G D_\mathrm{ol} D_\mathrm{ls}}, \tag{2.2}$$

where D_os and D_ls are the angular-size distances between observer and source, and lens and source, respectively.

Thus, the resulting image separations will heavily depend on the subhalo surface mass density profiles $\Sigma(r)$. Previously proposed strategies to detect image splitting [1, 7] assume that the subhalo lenses possess singular isothermal sphere (SIS) density profiles. Unfortunately, this assumption is difficult to justify since theoretical arguments, simulations, and observations do not favour this form of density profile for dark matter halos in the relevant mass range. We have studied the feasibility of strong-lensing detection of dark subhalos by deriving the image separations expected for (more realistic) density profiles favoured by recent simulations. These are NFW [8], M99 [9], N04 [10], H03 [11] and K04 [12] where we also have taken the impact of stripping and truncation into account. Details on these density profiles and a comparison of the resulting mean surface mass density profiles $\bar{\Sigma}(< r)$, can be found in [13].

Fig. 1 shows the image separations predicted for 10^4–10^{11} $M_\odot$ subhalos at a redshift $z_\mathrm{l} = 0.5$ and a source at $z_\mathrm{s} = 2.0$. We compare these to the angular resolution of a number of planned or existing observational facilities, operating at a wide range of wavelengths (for more information, see [13]). Please note that here we consider only the best resolution limits attainable with these

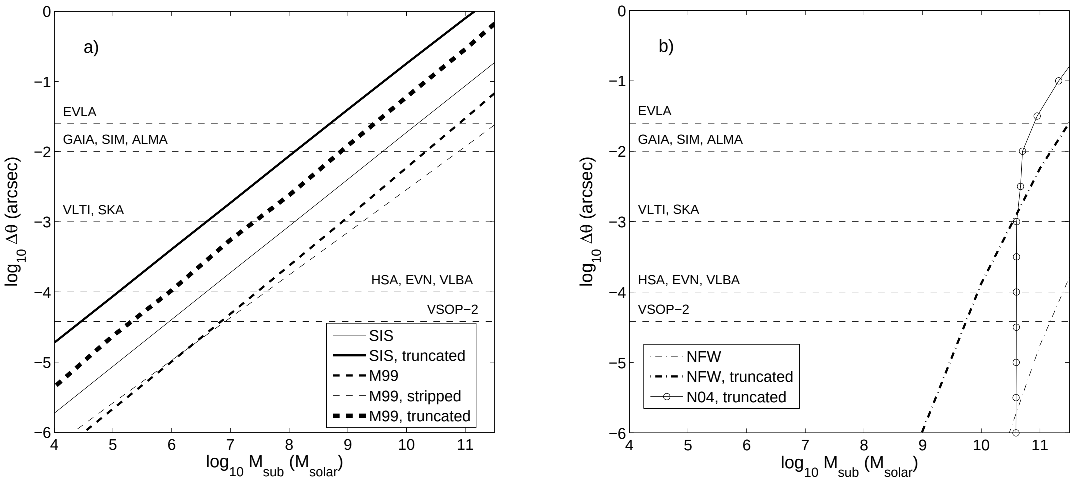

Figure 1: Subhalo mass versus image separation $\Delta\theta$ for those density profiles that give rise to image separations on scales larger than microarcseconds. The angular resolution of a number of existing and planned observational facilities have been indicated by horizontal dashed lines, marked with labels (see main text for details). a) The different diagonal lines represent SIS (thin solid), truncated SIS (thick solid), M99 (medium dashed), stripped M99 (thin dashed) and truncated M99 (thick dashed) subhalo models. b) The different diagonal lines represent NFW (thin dash-dotted), truncated NFW (thick dash-dotted) and truncated N04 (solid with circles) subhalo models.

telescopes, whereas the resolution at the wavelengths that maximise the number of observable high-redshift sources may be considerably worse.

As becomes obvious from Fig. 1, there are large differences between the image separation predicted by the various halo models. As the discrepancy between the number densities of luminous galaxies and dark matter halos does not start to become severe until the halo mass drops below $10^{10}\ M_\odot$, substructures at masses below this limit need to produce measurable image separations ($\theta \gtrsim 4\times10^{-5}$ arcsec for VSOP-2, which has the best theoretical resolution among the telescopes included in Fig. 1) in order for dark galaxies to be detectable through image-splitting effects. Out of the halo models tested, only two actually meet this criterion without adhering to sharp truncations: the SIS and the M99 halos. The H03 and K04 profiles both give image separations smaller than 10^{-6} arcsec for all the halo masses considered and are therefore completely outside the plotted region. Even in the optimistic case of an M99 halo, the image separations are a factor of $\approx$ 3–7 smaller than those predicted for a SIS (and $\approx$ 30–60 times smaller than those of a truncated SIS), rendering only the few most massive subhalos ($\sim 10^{10}\ M_\odot$ or slightly higher) detectable at ~ 0.01 arcsec resolution (*GAIA*, *SIM*, and ALMA). At milliarcsecond resolution (VLTI and SKA), dark galaxies with masses $\gtrsim 10^9\ M_\odot$ may become detectable. To probe further down the subhalo mass function, submilliarcsecond-resolution facilities (HSA, EVN, VLBA or VSOP-2) will be required. These estimates are based on the assumption that the subhalos can be treated as isolated objects. Taking the effects of external convergence κ and shear γ into account can in rare cases give a high boost to the image separations produced. However, this effect is not sufficient to change our conclusions considerably (see [13] for details).

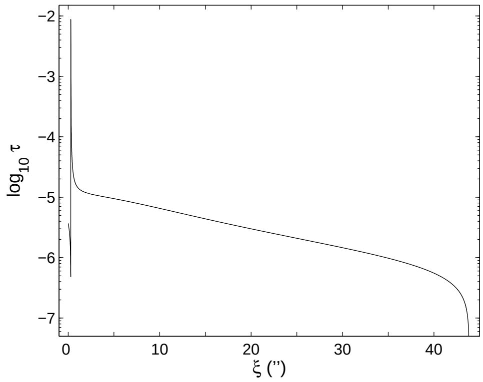

Figure 2: Optical depth for a point source at $z_s = 2$ as a function of projected radius. Here we assume a host halo at $z_l = 0.5$ of mass $M_{\rm host} = 1.8 \times 10^{12}\ M_\odot$ and subhalos in the mass range $4 \times 10^6 - 10^{10}\ M_\odot$. The peak has been cut with respect to a maximum magnification factor of 50 at the Einstein radius of the host halo.

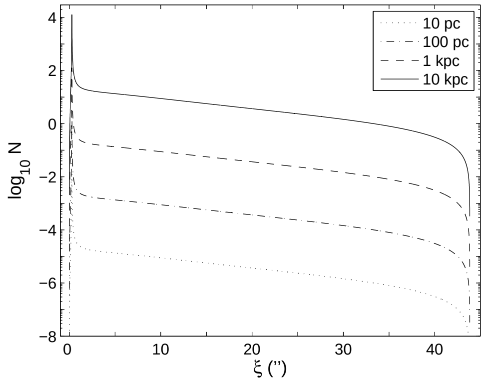

Figure 3: Number of substructures projected on an extended source at $z_s = 2$ as a function of projected radius and halo parameters as in fig. 2. Results are plotted for a source with radius r_s = 10 pc (dotted), 100 pc (dash-dotted), 1 kpc (dashed) and 10 kpc (solid), respectively. The peak magnification factor at the Einstein radius of the host has been cut to 30.

3. Lensing probabilities

We assume a subhalo population following the models proposed in [14] and [15] in order to estimate the subhalo lensing probability for a galaxy closely aligned to the line of sight to a background source (see [16] for details).

3.1 Point sources

Under the assumption that the lenses do not overlap along the line of sight, the optical depth τ represents the fraction of a given patch of the sky that is covered by regions in which a point source will be lensed. In the limit of small τ, the optical depth can directly be used as an estimate of the lensing probability. As can be seen in Fig. 2, the optical depth for a typical scenario does not exceed a value of 0.01 at any radius.

3.2 Extended sources

In Fig. 3, the expected number of subhalos covering an extended source at $z_s = 2$ as a function of projected radius from the host halo lens center is shown for several source radii r_s, ranging from 10 pc to 10 kpc. This can be compared to the virial radius $R_{200} \approx 260$ kpc for the host galaxy at $z_l = 0.5$. It becomes clear that for a sufficiently large source ($\gtrsim 1$ kpc) there is a good probability for the source image to be affected by subhalo lensing, not only close to the Einstein radius of the host halo but even at a rather large projected distance from the host halo lens center. For a source with r_s = 1 kpc, one would expect at least one intervening subhalo per 10 observed systems with a maximum projected distance of 10 arcseconds between the foreground galaxy and the source. For r_s = 10 kpc, this number increases to approximately 10 subhalos projected on the source out to a distance of 10 arcseconds from the host galaxy.

4. Conclusions

Our results indicate that the detection of dark matter substructures through gravitational image-splitting is likely to be considerably more challenging than suggested in previous studies, due to the smaller image separations predicted for subhalo density profiles more realistic than the SIS models often adopted. In fact, no currently planned telescope will be able to resolve the image separations produced by subhalos with density profiles of the type suggested by the most realistic simulations available (H03 & K04). Despite the somewhat bleak detection prospects presented here, there are at least two effects that can potentially improve the detectability of image splitting by subhalos: baryon cooling and the presence of intermediate mass black holes.

We have shown that the optical depth τ for subhalo lensing of point sources is lower than previously predicted [1]. We conclude that it is currently not feasible to use this technique to search for strong lensing signatures in point sources as e.g. quasars in the optical.

If one instead targets extended sources, such as quasars in the radio wavelength regime, there is a high probability for subhalo lensing of sources of sufficient size ($r_\mathrm{s} \gtrsim 1$ kpc) even at rather large projected distance of the source to the host halo center. This allows for a different search strategy than those previously proposed. Instead of only targeting multiply-imaged quasar systems, even quasar-galaxy pairs with a separation of several tens of arcseconds should show effects of strong lensing by substructures in the lens galaxy halo.

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