Dark matter millilensing and VSOP-2

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Abstract.   According to the cold dark matter scenario, a large number of dark subhalos should be located within the halo of each Milky-way sized galaxy. One promising possibility for detecting such subhalos is to try to observe their gravitational lensing effects on background sources. Dark matter subhalos in the 10^6 – 10^{10} $M_\odot$ mass range should cause strong gravitational lensing on the (sub)milliarcsecond scales, which can be observed only using space VLBI. 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 show that the detection of subhalos is likely much more difficult than suggested in previous studies, due to the smaller image separations predicted for subhalo density profiles more realistic than the singular isothermal sphere models often adopted.

1. Introduction

The quest to unravel the nature of the dark matter, estimated to contribute around 23% to the energy density of the Universe (e.g. Spergel et al. 2006), remains one of the most important tasks of modern cosmology. While the cold dark matter (CDM) scenario – in which the dark matter particles are assumed to be non-relativistic at the epoch of decoupling and to interact predominantly through gravity – has been very successful in explaining the formation of large-scale structures in the Universe (see e.g. Primack 2003 for a review), its predictions on scales of individual galaxies have not yet been confirmed in any convincing way.

In particular, CDM predicts a large number of subhalos, typically accounting for $\simeq$ 5-10% of the total mass of a galaxy-sized CDM halo. However, these subhalos do not appear to correspond to luminous structures, as the Milky Way would then be surrounded by a factor of 10–100 more satellite galaxies than observed, provided that each subhalo hosts a luminous dwarf galaxy (Moore et al. 1999). One way out of this dilemma is to assume that most of these subhalos correspond to so-called dark galaxies (Verde, Oh, & Jimenez 2002), i.e. objects which either do not contain baryons or in which the baryons formed very few stars. While a number of very faint missing-satellite candidates have recently been detected (Simon et al. 2006; Zucker et al. 2006), it is still far from clear

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that these exist in sufficient numbers to account for the subhalos predicted by CDM (e.g. Simon & Geha 2007).

Since several other CDM predictions of dark halo properties have recently been called into question (see e.g. Zackrisson et al. 2006 and references therein), it is of paramount importance to investigate whether these CDM subhalo predictions really hold true.

While dark matter cannot be seen directly in current telescopes, its presence can be inferred from the gravitational lensing effects that spatially clustered dark matter will have on background light sources. If a sufficiently dense and massive dark object happens to be located along the line of sight to some distant astronomical object – in most cases a quasar – the light may reach the observer along several different paths, thereby producing multiple images in the sky of a single light source. One tell-tale signature of dark matter subhalos in the 10^6–10^{10} $M_\odot$ mass range could be gravitational millilensing (sometimes also referred to as mesolensing), i.e. image splitting at a characteristic separation of milliarcseconds (e.g. Yonehara, Umemura, & Susa 2003).

Based on a null detection of millilensing in a sample of 300 quasars observed with the VLBI, Wilkinson et al. (2001) demonstrated that the vast majority of quasars do *not* show any signs of millilensing in the angular range $1.5 - 50$ milliarcseconds, and were able to impose upper limits of $\Omega < 0.01$ on the cosmological density of dark point-mass objects in the 10^6–10^8 $M_\odot$ mass range. Unfortunately, this constraint is still insufficient to rule out the subhalos predicted by CDM, since their lensing optical depth is expected to be at least one order of magnitude lower.

2. Subhalo millilensing

To put the CDM subhalo predictions to the test, Yonehara et al. (2003) suggested that one should target quasars which are already known to be gravitationally lensed by galaxies on arcsecond scales, as one can then be sure that there is a massive halo well-aligned with the line of sight. In this case there should be a significant probability (optical depth $\tau \simeq 0.01 - 0.1$) of detecting image splitting by subhalos at scales of milliarcseconds (millilensing). Indeed, millilensing has long been suspected to be the cause of the flux ratio anomalies seen in such systems (e.g. Mao & Schneider 1998; Kochanek & Dalal 2004). Subhalo millilensing has also been advocated as an explanation for strange bending angles of radio jets in these multiply-imaged quasars (Metcalf 2002) and for image positions which smooth halo models seem unable to account for (Biggs et al. 2004). In cases where the quasar images are sufficiently resolved, the technique proposed by Yonehara et al. would not only allow the *detection* of subhalos, but will also impose interesting constraints on their internal density profiles (Inoue & Chiba 2005).

3. Subhalo density profiles and image separation

The proposed observations to detect image splitting (e.g. Yonehara, Umemura, & Susa 2003) assume that the image separations of subhalo lenses are similar to those produced by a singular isothermal sphere (SIS). Unfortunately this
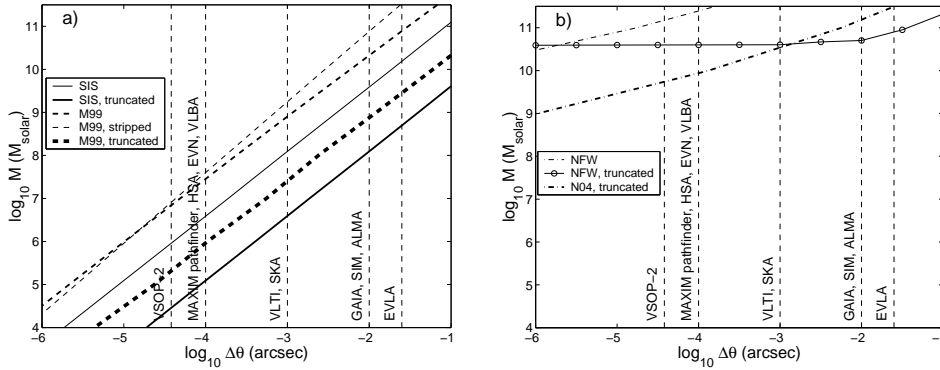
Figure 1. Image separation $\Delta\theta$ versus subhalo mass for those density profiles that give rise to image separations on scales larger than microarcseconds. SIS (thin solid), truncated SIS (thick solid), NFW (thin dash-dotted), truncated NFW (solid with circles), truncated N04 (thick dash-dotted), M99 (medium dashed), stripped M99 (thin dashed) and truncated M99 (thick dashed). The angular resolution of a number of existing and planned observational facilities has been indicated by vertical dashed lines.

assumption is difficult to justify because 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 current simulations (Zackrisson et al. 2008).

In Fig. 1 we have plotted the calculated image separation for four density profiles that exceeded one microarcsecond. These are SIS, NFW (Navarro et al. 1996), M99 (Moore et al. 1999), and N04 (Navarro et al. 2004). These profiles are all based on simulations for relatively isolated halos. When such objects are accreted by more massive halos and become subhalos, substantial mass loss occurs, preferentially from the outer regions of the satellites. To account for this, the models are truncated or gradually stripped. For details, see Zackrisson et al. (2008).

4. Discussion

It is clear from Fig. 1 that detection of subhalos is likely considerably more difficult than suggested by previous studies. We stress however that these simulations do not necessarily represent the final word on this issue. If the subhalos have central density slopes steeper than $\rho \propto r^{-1}$ (e.g. of M99 type; with $\rho \propto r^{-1.5}$) , these would give rise to image separations that could be resolved even with current telescopes.

Inoue & Chiba (2005) proposed to search already known multiply-imaged quasars (macrolensed objects) for substructures. If the true density profile of subhalos is shallow and leads to small image separations, and hence small optical depths, perhaps the number of the known suitable lensed AGN is insufficient even for a single detection. We are going to investigate if the detection probability would increase by targeting AGN with larger impact parameters, by trying

to estimate the average detectable area of AGN jets using data from the published surveys and compare that with the predicted optical depth of the subhalo objects. At lower frequencies the sources are larger in area but the resolution is worse. Another goal is to find the optimum frequency for millilensing search with the VSOP-2.

To increase the detection probability, *all images* that are produced by VSOP-2 should be looked at with this effect in mind. This could be done either after the data has become public or in a core science project that would produce 'quick look' images using a pipeline immediately after the data has been correlated.

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