Strong Gravitational Lensing in the Era of Big Data
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Lensed radio arcs at milli-arcsecond resolution: Methods, science results, and current status

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Abstract. Strong gravitational lensing by galaxies provides us with a powerful laboratory for testing dark matter models. Various particle models for dark matter give rise to different small-scale distributions of mass in the lens galaxy, which can be differentiated with sensitive observations. Th. The sensitivity of a gravitational lens observation to the presence (or absence) of low-mass dark structures in the lens galaxy is determined mainly by the angular resolution of the instrument and the spatial structure of the source. Here, I discuss results from the analysis of a global VLBI observation of a gravitationally lensed radio jet. With an angular resolution better than 5 milli-arcseconds and a highly extended, spatially resolved source, we are able to place competitive constraints on the particle mass in fuzzy dark matter models using this single observation. I also discuss preliminary results from our analysis of warm dark matter models using this lens system.

Keywords. gravitational lensing – dark matter – data analysis – radio continuum – quasars – galaxies

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1. Introduction

Strong gravitational lensing by galaxies is a powerful observational tool for constraining the particle nature of dark matter. By modeling the distribution of mass inside a lens galaxy (or a sample of lens galaxies) given the observed lensed images, it is possible to rule out dark matter models based on their expected astrophysical phenomenology. For instance, the fiducial cold dark matter (CDM) paradigm predicts that galaxies will contain large populations of gravitationally-bound subhaloes even down to Earth-mass scales (Angulo et al. 2017). By contrast, warm dark matter (WDM) models predict a cutoff in the halo mass function, strongly suppressing the halo population below a certain mass, depending on the mass of the dark matter particle, m_χ (Benson et al. 2013, e.g.). A more exotic model of interest is fuzzy dark matter (FDM), consisting of an ultra-light particle $\mathcal{O}(10^{-21}$ eV), that produces kiloparsec-scale wave-interference structures in the lens galaxy (Schive et al. 2014). Each of these models (we discuss CDM, WDM, FDM here, though there are several other candidates) predicts different small-scale distributions of dark matter in a lens galaxy.

Gravitational lens observations used to test dark matter models fall broadly into two categories. The first are the unresolved lensed quasars, which are lens systems containing quadruply-imaged point sources. The relative positions and fluxes of the images reveal information about the underlying gravitational landscape. Dark matter inferences using lensed quasars require samples of many lenses in order to increase their statistical power (Gilman et al. 2017, 2020; Laroche et al. 2022, e.g.). The second are lens observations containing resolved images and arcs. Such systems contain more information in principle,

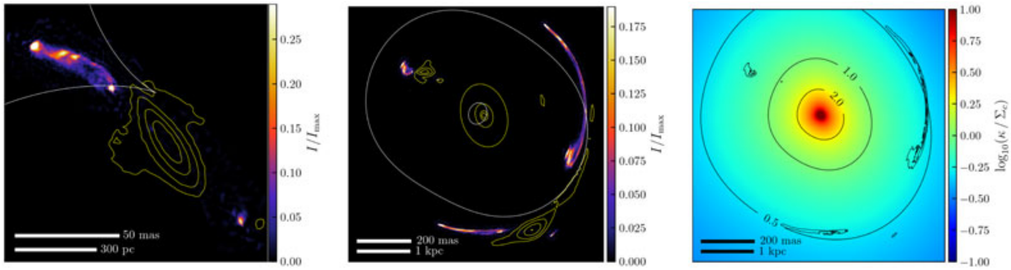

Figure 1. The best composite (baryons plus dark matter) model for MG J0751+2716 from Powell et al. (2022). The continuum radio emission appears in the violet color map, while yellow contours show the infrared emission observed with Keck AO. Critical curves and caustics are shown in white.

but the analysis is more complicated. Individual detections of low-mass dark structures have so far been made in several resolved observations of lens systems observed at angular resolutions $\gtrsim 30$ mas (Vegetti et al. 2010, 2012; Hezaveh et al. 2016b).

In this proceeding, I focus on the case of galaxy-scale lenses containing *resolved* images, specifically those observed at ~ 5 milli-arcsecond resolution using very long baseline interferometry (VLBI). Resolving long, thin arcs at such high resultion can probe mass scales down to $\sim 10^6$ $M_\odot$. In previous work, I presented a computational method for forward-modeling VLBI lens observations directly in the visibility plane (Powell et al. 2021). The 1.6 GHz VLBI data were observed by John McKean and reduced by Spingola et al. (2018). In the rest of this paper, I discuss scientific results to date obtained using these observations and methods.

2. Gravitational lenses are more complex than elliptical power-laws

The first step in modeling a gravitational lens system is to fit a "macro-model", a large-scale parametric mass profile. In past work where lens systems have been observed at relatively low angular resolution ($\gtrsim 70$ mas), macro-models consisting of simple elliptical power-law profiles have been employed successfully.

However, it is becoming increasingly apparent that lens models should include azimuthal degrees of freedom as well. Overly simplistic models can bias inferences on dark matter subhalo populations, as disks and other baryonic structures can be mistaken for dark matter if not properly accounted for (Gilman et al. 2017; Hsueh et al. 2018; He et al. 2022). Contraints on H_0 using time delays between lensed images can also suffer from biases if angular structure is not taken into account (Kochanek 2021; Cao et al. 2022; Van de Vyvere et al. 2022).

In Powell et al. (2022), we found that the VLBI observation of MG J0751+2716 could not be fit by a simple power-law alone, but required a macro-model with angular structure in the form of multipoles (see Figure 1). This result showcased the power of VLBI strong lens observations in probing higher-order complexity in the lens galaxy. This smooth composite model of MG J0751+2716 from Powell et al. (2022) fits the data remarkably well on its own (Figure 1); we use it as the fiducial model for dark matter inferences. However, as I will discuss in following sections, there still exists ambiguity between multipole structure in the lens and the effect of the subhalo population around the lens galaxy.

3. Detecting low-mass dark structures in lens observations

The first application of the MG J0751+2716 VLBI observation and computational method of Powell et al. (2021) to constraining dark matter models was for the case of

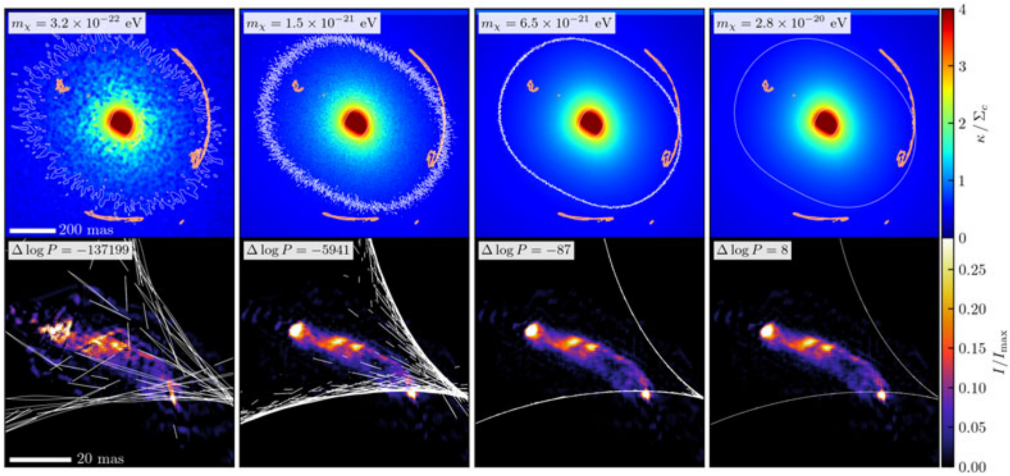

Figure 2. Surface mass density maps with the model lensed images in orange contours (top row) and the corresponding reconstructed source surface brightness maps (bottom row) a sample of random realizations of MG J0751+2716 in an FDM cosmology. Critical curves and caustics are plotted in white. The lensing effect of the FDM granules is apparent: the morphology of the inferred source is disrupted as the model attempts to fit the observation to an incorrect lens model.

fuzzy dark matter (FDM), published in Powell et al. (2023). The main phenomenological feature of galaxy-scale FDM haloes is the presence of wave-interference structures known as "granules" (Schive et al. 2014). The size and density contrast of these granules is determined by the particle mass m_χ.

In Powell et al. (2023), we generated thousands of sample lens realizations in an FDM cosmology and quantified their compatibility with the observed data using their relative log-likelihoods (Figure 2). Extremely light particles produce a very lumpy mass distribution in the lens, and the reconstructed source image is severely disrupted in an attempt to fit the observed data. This is strongly penalized in the log-likelihood. Quantitatively, we ruled out $m_\chi \leq 4.4 \times 10^{-21}$ eV with a 20:1 posterior odds ratio (POR) relative to the fiducial smooth model.

Inferring constraints on the FDM particle is more straightforward than for WDM/CDM for several reasons. First, it is a one-parameter model (m_χ) with relatively simple physics (a classical wave in a potential well). Second, the granule perturbations are non-local and must necessarily appear all along the gravitationally lensed arcs. Third, in the mass range of $m_\chi \sim \times 10^{-21}$ eV, the subhalo population is virtually non-existent. These factors drastically simplify the sampling procedure relative to what is needed to make robust inferences for WDM/CDM halo populations.

In the WDM/CDM case, we are interested in measuring properties of the low-mass halo population, rather than looking for wave-interference granules. WDM haloes have a much more complex formation history (Benson et al. 2013; Ludlow et al. 2016, e.g.), and their gravitational effects are much more localized than FDM granules. There are two main consequences of this localized gravitational effect. The first is that, due to more concentrated objects having a higher lensing efficiency, the detection of individual low-mass haloes with a high concentration is more likely and may bias inferences on population characteristics. The second is that in order for an individual detection to occur, the halo must lie directly on top of a lensed image.

This is problematic for VLBI lenses, as the arcs are typically only a few mas wide, so the sensitive area is very low. In Figure 4, we show a test on a mock observation

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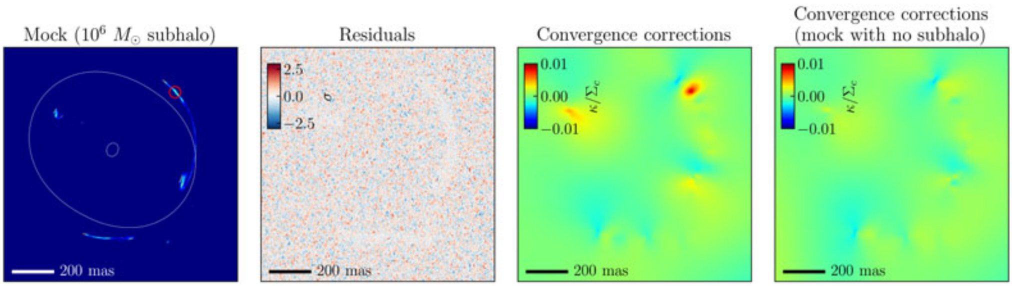

Figure 3. A simulated observation of MG J0751+2716 with a 10^6 $M_\odot$ subhalo on the arc (red circle in the leftmost panel). The subhalo is easily detected via gravitational imaging (second panel from right). While isolated low-mass subhaloes lying on a lensed arc can be individually detected with VLBI observations of this quality, robustly inferring properties of the population way from the lensed arcs remains challenging.

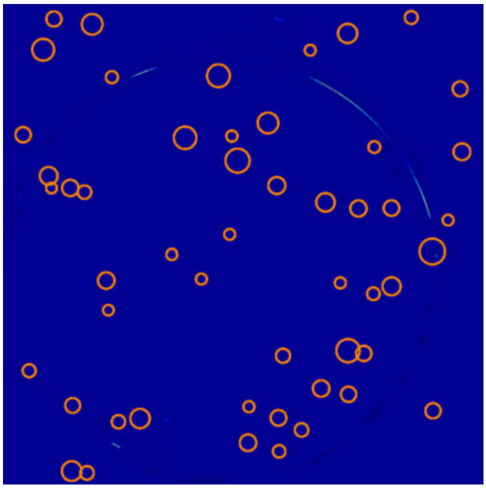

Figure 4. A simulated VLBI observation of the gravitational lens system B1938+666, with a population of dark matter subhaloes in the lens plane (orange circles; the size of each circle corresponds to the mass of the subhalo). The lensed arcs remain smooth in the presence of a collective gravitational perturbation by the subhalo population. (Credit: Simona Vegetti)

of MG J0751+2716 in which a 10^6 $M_\odot$ lies on top of the arc. Using the gravitational imaging (Vegetti and Koopmans 2009), we easily detect its presence. The picture changes, however, when there are no haloes directly on top of the arcs. Figure 3 shows a simulated VLBI observation of another lens system, B1938+666, which also displays long, thin arcs. In this realization, no single subhalo sits directly on an arc. The arcs remain smooth and unperturbed, and the overall effect of the subhalo population is absorbed into the macro-model.

Information on the population of subhaloes and line-of-sight haloes in a VLBI lens observation is contained in some combination of individual detections along the arc, non-detections along the arc (whose statistical significance is tricky to quantify, see e.g. O'Riordan et al. 2023), and smooth perturbations to the arcs caused by the collective off-arc population. While statistical approaches for inferring subhalo population characteristics exist (Vegetti et al. 2014; Hezaveh et al. 2016a), they are more suited to optical/IR observations where the lensed images are spatially extended in two dimensions.

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4. Conclusions and future prospects

Resolved VLBI observations of galaxy-scale strong lenses are extremely useful for probing the detailed mass structure of lens galaxies. We have already shown that the lens system MG J0751+2716 unambiguously contains angular structure beyond perfect ellipticity (Powell et al. 2022). The same observation was used to place strong constraints on the particle mass in an FDM cosmology (Powell et al. 2023).

Future work on these lens observations will focus on characterizing the halo mass function in WDM/CDM models, which is a more difficult task than the FDM case. There are two main challenges. First, while long, thin arcs are sensitive to very low-mass dark haloes, their sensitive area is small, so making robust inferences via individual detections or non-detections is difficult. Second, an off-arc population of low-mass haloes has a subtle perturbative effect, shifting the arcs around slightly but leaving them quite smooth. It is thus unclear how well the effects of a sub/LOS-halo population can be distinguished from instrinsic non-ellipticity in the smooth component of the lens galaxy.

We expect sensitivity to low-mass dark structures to scale with angular resolution, so pushing observations to higher frequency (10-100 GHz) will be an important step. The Square Kilometre Array (SKA) will also discover thousands of new radio-bright lenses with extended arcs like this one (McKean et al. 2015). We will continue to develop better modeling approaches to robustly extract as much information as possible from the data. High-resolution VLBI observations are still a relatively new tool in the effort to constrain the particle nature of dark matter with strong lensing. While there is still considerable work to be done on this effort, the future is bright for VLBI and strong lensing.

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