Strong Gravitational Lensing in the Era of Big Data
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Extended surface brightness modeling of three sources strongly lensed by an ultra-massive elliptical galaxy

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Abstract. Rare systems with multiple sources strongly lensed by a single galaxy provide the most robust way to explore the geometry of the Universe and to study the inner mass structure of lens galaxies. We present here a study of the SDSS J0100+1818 deflector, analyzing its total and baryonic mass distributions. The system comprises an ultra-massive early-type galaxy, surrounded by ten multiple images of three background sources. Exploiting high-resolution HST photometry and VLT/X-shooter spectroscopy we conduct a strong lensing analysis with the software `GLEE` to reconstruct the complex surface brightness distributions of the background sources over approximately 7200 HST pixels. These results are presented in our recent paper, Bolamperti et al. (2023). Finally, we present some preliminary results from new VLT/MUSE observations, that will allow us to build a new strong lensing+dynamics joint model and measure the values of the total matter density and of the cosmological constant parameters, Ω_m and Ω_Λ.

Keywords. gravitational lensing: strong - galaxies: evolution - dark matter - cosmology

1. Multiple sources strongly lensed by the same galaxy-scale deflector

Strong gravitational lensing is a valuable tool for delving into galaxy evolution and exploring the properties of the Universe (e.g., Bartelmann 2010; Treu 2010). It offers precise measurements of total mass, including both luminous and dark matter components, with relative errors typically at the few percent level (e.g., Grillo 2010; Zitrin et al. 2012). Additionally, strong lensing facilitates the study of lensed background sources thanks to the magnification effect. By reconstructing their surface brightness distribution during the modeling process (e.g., Rizzo et al. 2021; Wang et al. 2022), or utilizing high magnification factors to investigate faint and small high-z galaxies, we gain valuable insights into the local feedback mechanisms driving the galaxy evolution (e.g., Förster Schreiber et al. 2009; Cañameras et al. 2017a; Cava et al. 2018).

The most massive gravitational lenses, like galaxy clusters, can generate dozens of multiple images from sources in a large redshift range, and have provided in the last decades crucial insights into the mass density slope of dark matter halos in their inner regions (Sand et al. 2004; Grillo et al. 2015; Bergamini et al. 2019), the measurement of the cosmological density parameter values (Jullo et al. 2010; Caminha et al. 2016; Grillo et al. 2020), and of the Hubble constant H_0 (Grillo et al. 2018). On the other hand, they have a complex total mass distribution which includes several mass components, that might introduce degeneracies between the model parameters. The study of galaxy-scale strong lenses allows for the reconstruction of the total and dark matter mass distributions, the determination of dark matter over total mass fraction (Gavazzi et al. 2007; Grillo et al. 2009; Suyu and Halkola 2010; Sonnenfeld et al. 2015; Schuldt et al. 2019), the inference of the stellar initial mass function (IMF) of the lens (e.g., Cañameras et al. 2017b; Barnabè et al. 2013; Sonnenfeld et al. 2019), and the detection of dark matter substructures (e.g., Vegetti et al. 2012; Hezaveh et al. 2016; Ritondale et al. 2019). Unfortunately, they do not usually present the features needed to pursue cosmological studies. In fact, it is only possible when kinematic data of the lenses are available (e.g., Grillo et al. 2008; Cao et al. 2012), when a variable source is lensed (e.g., a quasar, Suyu et al. 2013, 2017) and when several background sources are multiply imaged by the same lens galaxy, and the mass sheet degeneracy can be broken (Schneider 2014).

In this scenario, the discovery of ultra massive galaxies that act as lenses for two or more background sources plays a key role in measuring the values of cosmological parameters through strong lensing modeling. In fact, by considering the ratio of the two Einstein radii observable in a double-source system, one can constrain the value of Ω_m independently of that of H_0 (Collett et al. 2012). The presence of more than two multiply-imaged sources can further reduce the uncertainties on the total mass profile of the lens and on the cosmological parameters, but is extremely rare, with only a few known cases to date (Collett and Smith 2020; Tu et al. 2009; Tanaka et al. 2016; Schuldt et al. 2019; Wang et al. 2022).

We present here the results of the next unique case, SDSS J010049.18+181827.7 (hereafter, SDSS J0100+1818), presented in a recent paper by Bolamperti et al. (2023). This system is part of the Cambridge And Sloan Survey Of Wide ARcs in the skY (CASSOWARY) survey (Belokurov et al. 2009; Stark et al. 2013). The exceptionally large Einstein radius of ≈ 42 kpc, together with the results from our follow-up observations with the Nordic Optical Telescope (NOT), the Very Large Telescope (VLT) and the Hubble Space Telescope (HST) suggest that the SDSS J0100+1818 deflector is an uncommon strong lens and a candidate fossil system at intermediate redshift. Initially, only the background sources A and B, at the same redshift, were identified (see Figure 1), but now we recognize a total of six background sources. Finally, we report some preliminary results from new VLT/MUSE observations, that will allow us to build a new lensing+dynamics joint model and measure the values of the cosmological parameters Ω_m and Ω_Λ.

2. SDSS J010049.18+181827.7

Given its peculiar features, SDSS J0100+1818 benefits from a large collection of photometric and spectroscopic data from the most advanced facilities. It was firstly observed with the 2.5 m Nordic Optical Telescope (NOT; program 56-032, PI: R. Cañameras), to obtain color information for galaxies in the lens environment and to characterize their spectral energy distributions (SEDs). Later, it was observed with the HST Wide Field Camera 3 (WFC3) (program GO-15253; PI: R. Cañameras), in the F438W and F160W filters. HST observations reduced the PSF full width at half maximum (FWHM) by a factor ~ 10, allowing us to resolve AB into two different sources at the same redshift (see Figure 1). In order to measure the lens and source spectroscopic redshifts, and the lens stellar velocity dispersion, SDSS J0100+1818 was observed with VLT/X-shooter (program 091.A-0852, PI: L. Christensen) targeting the lens and the multiple images AB 1-3-4.

We measure the lens redshift $z = 0.581$, and a joint redshift of $z = 1.880$ for the two source components forming the image families A and B. We measure a stellar velocity dispersion value of the deflector of (451 ± 37) km s^{-1}, confirming the ultra massive nature of SDSS J0100+1818, that is among the rarest, most massive elliptical galaxies known at its redshift (Loeb and Peebles 2003). We also fit its surface brightness distribution

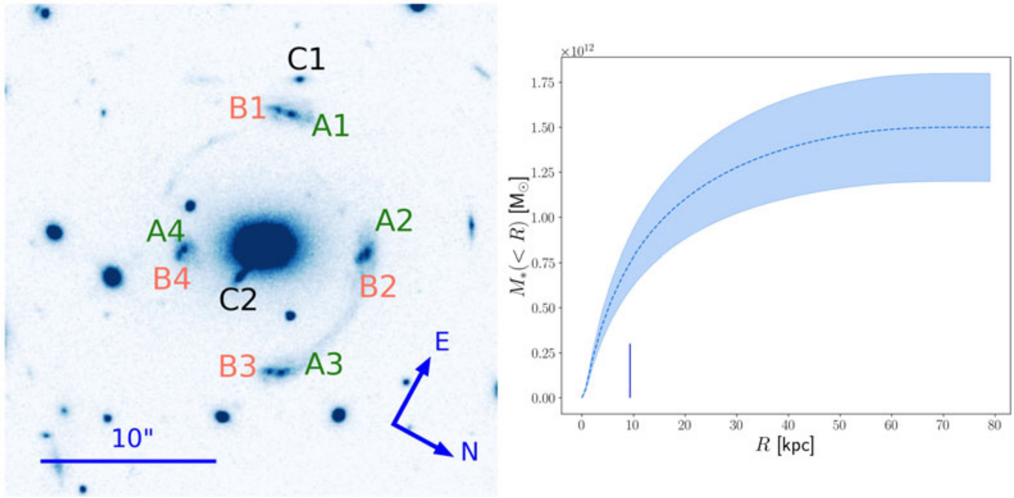

Figure 1. Left: scheme of the multiple images of SDSS J0100+1818, superimposed on the HST observations in the F160W filter. Multiple images of the same background source are labeled with the same letter. In Bolamperti et al. (2023), sources A and B are spectroscopically confirmed and included in the modeling, while C is included with its redshift as a free parameter. Right: cumulative stellar mass (M_*) profile and $\pm 1\sigma$ uncertainties of the main lens. It is measured from the total stellar mass measured through the SED fitting and assuming a constant stellar mass-to-light ratio. The blue vertical line shows the half-light radius of the lens galaxy.

and, by assuming a constant mass-to-light ratio, we estimate a total stellar mass value of $(1.5 \pm 0.3) \times 10^{12}$ M$_\odot$. Through a combination of photometric observations in the two available HST filters and preliminary strong lensing models of the system, we identify an additional candidate background source. In Figure 1, we label its two multiple images as C1 and C2. Although spectroscopic confirmation was unavailable, we incorporate source C into our strong lensing models, considering its redshift as a free parameter. This decision stems from the compelling evidence of two images having similar colors and being confidently predicted at the same positions by the strong lensing models. Given that C1 and C2 are, respectively, the furthest and closest images from the deflector, they play a key role in constraining the total mass distribution of the lens.

Considering the substantial angular separation between the multiple images, we explore the possibility of the main lens galaxy residing within a rich and overdense environment, as observed in other high-mass lens early-type galaxies at intermediate redshift (e.g., Newman et al. 2015; Johnson et al. 2018; Wang et al. 2022). We estimate the photometric redshifts of galaxies in a 2.5'×2.5' field of view, and our measurements broadly support the presence of an overdensity surrounding the main deflector. However, given the wide distribution of candidate members throughout the field, we opt to model its effect on the light deflection with an external shear component.

3. Strong lensing modeling

We employ the Gravitational Lens Efficient Explorer (`GLEE`; Suyu and Halkola 2010; Suyu et al. 2012) software to develop several strong lensing models of the deflector, combining different mass density profiles such as (cored or singular) pseudo-isothermal total mass distribution (PIEMD+rc, cored; Kneib et al. 1996) and singular power law elliptical mass distribution (SPEMD; Barkana 1998), with or without an external shear component. Initially, we treat the sources as point-like objects, exploiting the observed

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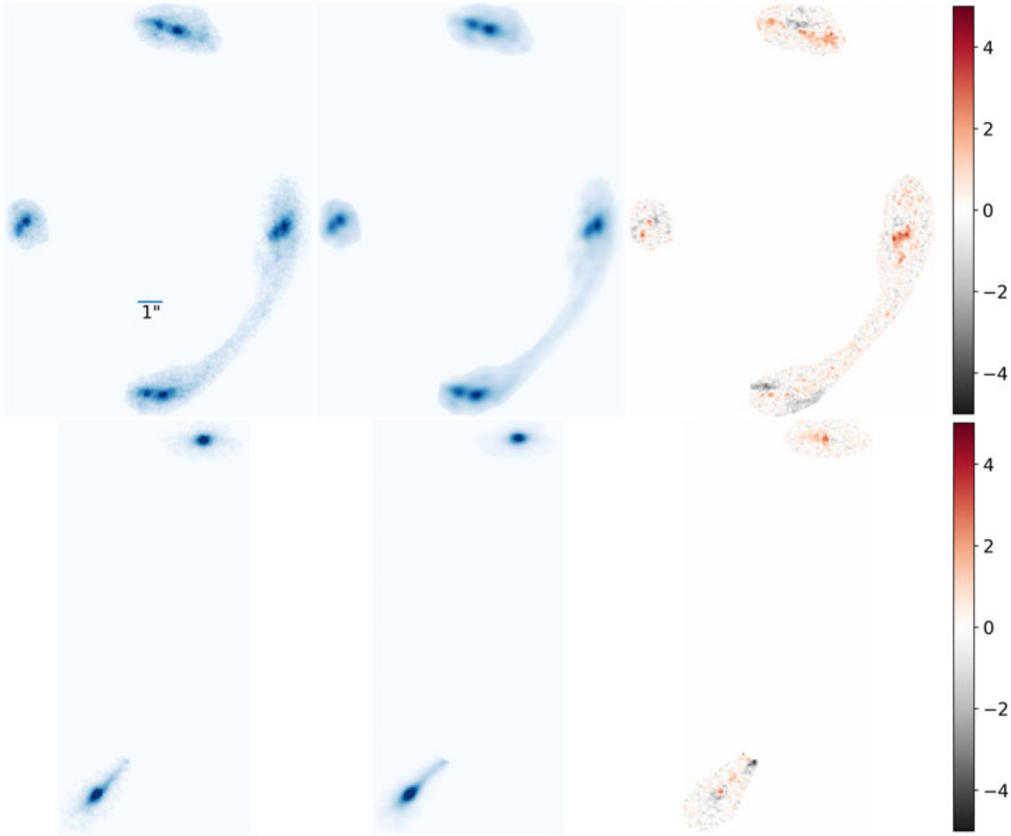

Figure 2. From the left to the right: observed SB in the F160W band of the multiple images considered in the extended strong lensing modeling; best-fit model-predicted SB, obtained by assuming a SPEMD model; normalized residuals in the range from -5σ to $+5\sigma$. The top row shows the sources A and B, while the bottom row shows the source C.

positions of the multiple images of source AB (four multiple images for each of the two components) and the two observed positions of the multiple images of source C.

Going beyond the point-like modeling, we consider the lensed sources as extended objects, enabling the reconstruction of their surface brightness (SB) distributions. This improvement allows us to leverage the detailed image structure and the extended arcs in which the sources were distorted, covering approximately 7200 HST pixels. The results are shown in Figure 2.

For each model, we estimate the total mass (M_T) distribution of the deflector. In the point-like source modeling, we obtain a projected total mass value within the Einstein radius (of approximately 42 kpc) of $(9.1 \pm 0.1) \times 10^{12}$ $M_{\odot}$, which remains consistent for both the PIEMD+rc and SPEMD models. The best-fit redshift estimate for source C is found to be $z_C = 1.72$ (1.98) for the PIEMD+rc (SPEMD) model. These measurements are consistent with the extended modeling. Considering the extended structure of the sources and their multiple images, the number of observables increases significantly to approximately 7200 (compared to the 20 observables in the point-like source modeling). As a result, the statistical uncertainties on the parameter values and derived quantities are drastically reduced (see Figure 3). This improvement in the modeling accuracy allows for a more precise characterization of the properties of the system and lensing effects on the background sources.

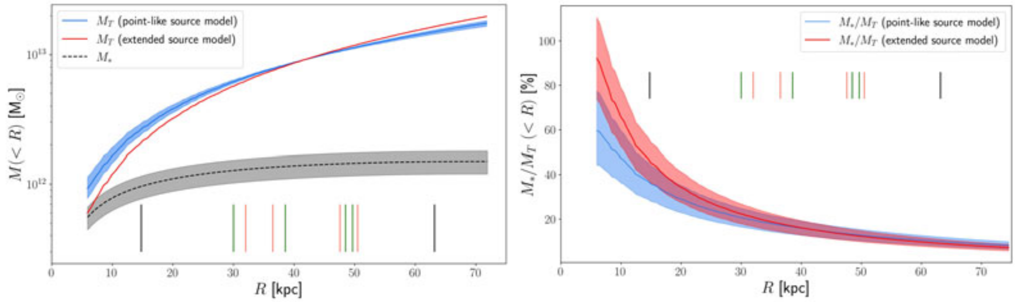

Figure 3. Left: cumulative projected total mass profiles for the SPEMD model, obtained from both point-like (blue) and extended source (red) modeling. The shaded areas represent the $\pm 1\sigma$ uncertainties, which are significantly reduced (smaller than the linewidth) for the extended source modeling. The vertical lines indicate the distances from the lens galaxy center of the various multiple images, color-coded as shown in Figure 1. Right: analogously to the left panel, but here we show the cumulative projected stellar-over-total mass fraction profiles.

4. VLT/MUSE observations

SDSS J0100+1818 has been targeted with VLT/MUSE (program 0110.A-0248, PI: A. Bolamperti) to obtain integral field spectroscopy of the system to identify other galaxies on the lens plane, spectroscopically confirm the redshift of system C, enhance our study on the total and dark-matter mass profiles, and measure the stellar velocity dispersion profile of the main deflector. In the 1'×1' MUSE field of view we find at least other 11 galaxies at $z \approx 0.58$, confirming that SDSS J0100+1818 is not an isolated galaxy, but it is more likely the brightest galaxy of a group residing in a dark matter halo. Furthermore, we confirm the stellar velocity dispersion measured with X-shooter, but we are now able to derive its radial profile. Most importantly, we spectroscopically confirm that C1 and C2 are two multiple images of the same background source and we identify, through their Lyman-α emission, two additional sources at higher redshift, each with four multiple images.

5. Discussion and conclusions

We have found SDSS J0100+1818 to be one of the few known galaxy-scale systems with several lensed sources at different redshifts (see e.g., Collett and Smith 2020). Such advancements hold great potential for refining our understanding of this complex gravitational lensing system. Our understanding of SDSS J0100+1818 will significantly benefit from additional integral field spectroscopy, offering several avenues for improvement:

(1) The presence of several background sources spanning a wide redshift range, and the simple mass distribution of the deflector, make SDSS J0100+1818 a unique system to probe the value of the cosmological parameters Ω_m and Ω_Λ.
(2) The inclusion of the redshift value of source C will help in breaking the degeneracy between the values of the Einstein radius and of the slope of the mass profile. Moreover, the redshift of C would enable a multi-plane lensing analysis, considering the mutual deflection of light between the different background sources.
(3) We can now include companions galaxies at the same redshift in the strong lensing model rather than treating them merely as an external shear component.
(4) By measuring the velocity dispersion profile of the main lens galaxy and combining the kinematic data with the strong lensing information, we could gain deeper insights into the dynamics of the system and its mass distribution.

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