Golden gravitational lensing systems from the Sloan Lens ACS Survey – II. SDSS J1430+4105: a precise inner total mass profile from lensing alone

Thomas Eichner,1,2⋆ Stella Seitz1,2 and Anne Bauer1,3

1Universit¨ats-Sternwarte M¨unchen, Scheinerstr. 1, 81679 Muenchen, Germany
2Max-Planck-Institut f¨ur extraterrestrische Physik, Giessenbachstraβe, 85748 Garching, Germany
3Institut de Ci`encies de l’Espai, CSIC/IEEC, F. de Ci`encies, Torre C5 par-2, Barcelona 08193, Spain

Accepted 2012 August 28. Received 2012 August 28; in original form 2012 June 28

ABSTRACT

We study the Sloan Lens ACS (SLACS) survey strong-lensing system SDSS J1430+4105 at zl = 0.285. The lensed source (zs = 0.575) of this system has a complex morphology with several subcomponents. Its subcomponents span a radial range from 4 to 10 kpc in the plane of the lens. Therefore, we can constrain the slope of the total projected mass profile around the Einstein radius from lensing alone. We measure a density profile that is slightly but not significantly shallower than isothermal at the Einstein radius. We decompose the mass of the lensing galaxy into a de Vaucouleurs component to trace the stars and an additional dark component. The spread of multiple-image components over a large radial range also allows us to determine the amplitude of the de Vaucouleurs and dark matter components separately. We get a mass-to-light ratio of Mde VLB ≈ (5.5±1.5) M⊙L⊙ and a dark matter fraction within the Einstein radius of ≈ 20 to 40 per cent. Modelling the star formation history assuming composite stellar populations at solar metallicity to the galaxy’s photometry yields a mass-to-light ratio of M⋆,salp ≈ 4.0±0.6 M⊙L⊙ and M⋆,chab ≈ 2.3±0.4 M⊙L⊙ for Salpeter and Chabrier initial mass functions, respectively. Hence, the mass-to-light ratio derived from lensing is more Salpeter like, in agreement with results for massive Coma galaxies and other nearby massive early-type galaxies. We examine the consequences of the galaxy group in which the lensing galaxy is embedded, showing that it has little influence on the mass-to-light ratio obtained for the de Vaucouleurs component of the lensing galaxy. Finally, we decompose the projected, azimuthally averaged 2D density distribution of the de Vaucouleurs and dark matter components of the lensing signal into spherically averaged 3D density profiles. We can show that the 3D dark and luminous matter density within the Einstein radius (REin ≈ 0.6 Reff) of this SLACS galaxy is similar to the values of Coma galaxies with the same velocity dispersions.

Key words: gravitational lensing: strong – galaxies: elliptical and lenticular, cD – galaxies: haloes – galaxies: individual: SDSS J1430+4105.

1 INTRODUCTION

Early-type galaxies contain a large fraction of the total stellar mass observed in the Universe (e.g. Fukugita, Hoogan & Peebles 1998; Bell et al. 2003). Studying the internal structure of early-type galaxies is crucial for understanding the baryonic physics that play a key role in the formation and evolution of these objects. Several studies have shown that the stars assembled in early-type galaxies are embedded in massive dark matter haloes (e.g. Gavazzi et al. 2008; Weijmans et al. 2008; Lagattuta et al. 2010), but the precise amount of dark matter contained in the galaxies’ inner regions is still under debate.

Dark matter only simulations have found indications of a universal density profile for dark matter haloes, present also in galaxies (the so-called NFW profile; Navarro, Frenk & White 1996). Nevertheless, more recent and realistic simulations that include also the physics of baryons (e.g. Blumenthal et al. 1986; El-Zant, Shlosman & Hoffman 2001; Jesseit, Naab & Burkert 2002; Bertin, Liseikina & Pegoraro 2003; Gnedin et al. 2004; Ma & Boylan-Kolchin 2004; Duffy et al. 2010), like radiative cooling and supernova and black hole feedback, have suggested that the inner profile of the dark matter component can be significantly affected by the interactions between baryonic and dark matter.

*E-mail: eichner@usm.lmu.de
The internal structure of nearby early-type galaxies has been for decades the object of intensive dynamical analyses (e.g. Saglia, Bertin & Stiavelli 1992; Gerhard et al. 2001; Thomas et al. 2007; Thomas et al. 2009; Pu et al. 2010; Thomas et al. 2011). One focus of these studies is to compare stellar with dynamical mass-to-light ratios. The dynamical studies, for example, Gerhard et al. (2001) and Thomas et al. (2011), find ratios for nearby elliptical galaxies of $M/L_\odot \approx 4$–10. Similar values are also found by Cappellari et al. (2006). Only in the last few years has gravitational lensing also contributed significantly to our understanding of the luminous and dark matter composition of early-type galaxies beyond the local Universe (Barnabè et al. 2009; Barnabè et al. 2010; Grillo et al. 2010). Strong gravitational lensing in early-type galaxies has also proved to be a powerful cosmological tool to probe the geometry of the universe independently of other diagnostics (e.g. Grillo, Lombardi & Bertin 2008a; Suyu et al. 2009, 2010).

By combining strong gravitational lensing and stellar dynamics in a sample of first 15, then 58 early-type galaxies, Koopmans et al. (2006) and Koopmans et al. (2009) have found that the average total (luminous and dark) mass density distribution within the effective radius – the radius of the isophote containing half of the total light of the galaxy – is well represented by an isothermal distribution ($\rho \propto r^{-2}$), although significant deviations from this result can be observed in individual galaxies. Only rare systems where an extended or several distinct sources are gravitationally lensed over an extended radial area on the lens plane can be used to determine the total mass density profile of the lens galaxy over a wide radial range through lensing only (e.g. Grillo et al. 2008b, 2010; Fadely et al. 2010). Moreover, combining lensing total mass measurements with photometric stellar mass estimates in these systems offers a unique way to disentangle their luminous and dark matter components.

In this paper, we study the gravitational lensing system SDSS J1430+4105 which is composed of a massive early-type galaxy acting as a lens for an irregular background source. This galaxy was part of the SLACS survey and has been studied as part of acting as a lens for an irregular background source. This galaxy $+\frac{\beta_{\text{eff}}}{\text{rest}} = 2.55$ arcsec-diameter fibre. At the bottom, the observed wavelength is stated, while at the top this is converted into the rest-frame wavelength of the lens ($\lambda = 0.285$). The dotted vertical lines give the SDSS emission-absorption-line sample at the redshift of the lens. The dashed vertical lines give some prominent emission lines at the redshift of the source. Over-plotted in the lower part of the figure is the flux uncertainty given again by the SDSS. The spectrum shows several absorption lines typical of an early-type galaxy at $z = 0.285$ and some additional emission lines at redshift $z = 0.575$ (e.g. the lines at 5872, 7661 and 7813 Å, which can be identified as the redshifted [OII] 3728, Hδ and [OIII] 4960 lines, respectively). Data taken from www.sdss.org (York et al. 2000).

2 OBSERVATIONS

The SLACS survey aimed at finding strong gravitational lenses among the galaxies observed in the Sloan Digital Sky Survey (SDSS). The lens detection strategy is presented in Bolton et al. (2004) and is based on the examination of the SDSS galaxy spectra, taken with a 3-arcsec-diameter fibre, to identify emission lines not associated with the primary target galaxy but with an additional source, aligned with the first galaxy and located at a higher redshift. The lens candidates are then ranked in terms of their probability of being lensing systems and are consequently observed with the Hubble Space Telescope (HST)/ACS and WFC2.

Up to now, 85 confirmed (grade A) lenses (Bolton et al. 2006, Auger et al. 2009) were discovered in this way, and SDSS J1430+4105 is one of these. In Fig. 1 we show the SDSS spectrum, from which lens and source redshifts of $z_l = 0.285$ and $z_s = 0.575$, respectively, are measured, together with the lens aperture velocity dispersion of $\sigma_{\text{SDSS}} = 322 \pm 32\, \text{km s}^{-1}$.

2.1 Galaxy light profile and lensing observables

The basic photometric and spectroscopic properties of SDSS J1430+4105, taken from Bolton et al. (2008a), are stated in Table 1. For these, Bolton et al. (2008a) fitted a de Vaucouleurs (de Vaucouleurs 1948) profile with elliptical isophotes to the galaxy’s surface brightness distribution. They obtained an effective radius of $R_{\text{eff}} = 2.55$ arcsec = 10.96 kpc, a minor-to-major-axis ratio of $q_e = 0.79$, and a major-axis angle of $\theta_{\text{phi}} = -12.8\, ^\circ$. The angles are transformed to the adopted local reference frame shown in Fig. 2, and measured counterclockwise with the y-axis equal to $0\, ^\circ$.

1 http://www.slacs.org

© 2012 The Authors, MNRAS 427, 1918–1939

Monthly Notices of the Royal Astronomical Society © 2012 RAS
The multiple-image systems that are identified after the lensing galaxy subtraction and used as input for the lensing analysis. The labels A1 to E2 mark the positions used for the strong-lensing analysis. The same letters correspond to images coming from the same source feature; the labelling is done according to Table 2. The cross marks the centre of the subtracted lens galaxy light distribution. Also indicated are the derived shear direction from Appendix B1 and the direction of galaxy I. For orientation, north is given as well. The angles are measured in the local coordinate system counterclockwise as (−x) over y if not stated otherwise. The image is rotated relative to the world coordinate system (WCS) J2000 by 47.21.

We retrieve the public HST images from the HST archive at ESO. Three filters were available for this system: HST/WFPC2 F606W with a total integration time of 4400 s, HST/WFPC2 F606W with a total integration time of 4400 s, HST/ACS F814W with a total integration time of 4400 s, and HST/ACS F814W with a total integration time of 2497 s. For the lensing analysis we use the ACS F814W filter observations, since the point spread function of the ACS camera is smaller than the one of the WFPC2 and WFC3. First, we subtract the lensing galaxy’s light contribution with GALFIT (Peng et al. 2002) by using a de Vaucouleurs profile, with the parameters of Table 1. Then, in order to refine the lens galaxy subtraction and especially remove the residuals still present in the central region, an additional Sérsic profile (Sérsic 1963) with index 1.2 is subsequently subtracted.

Fig. 2 shows the final galaxy subtracted image. The lensed source has a complex surface brightness distribution, with five surface brightness maxima which are imaged two times each. We mark and label the 5 × 2 multiple-image positions, identified as the brightest pixels, in Fig. 2. Their coordinates are reported in Table 2 together with approximate error estimates. We assume in the following that all subcomponents A–E are at the same redshift and not unlikely line-of-sight projections at different redshifts. The distances of the multiple images from the centre of the lens galaxy light distribution span a range from 0.93 to 2.32 arcsec. In the rest of this paper, if not otherwise stated, we adopt the coordinate system introduced in Fig. 2 which is rotated relative to the world coordinate system (WCS) J2000 by 47.21.

### 2.2 Observed environment

SDSS J1430+4105 is not an isolated galaxy. It coincides in redshift and location with a galaxy group at \( z = 0.287 \), listed in the maxBCG cluster catalogue (Koester et al. 2007). Therefore, we should consider the light deflection by the lens’ environment when we model this lens. We show the environment of SDSS J1430+4105 (labelled as A) in Fig. 3. The galaxy labelled as I was proposed to be the brightest cluster galaxy (BCG) of this group found in Koester et al. (2007). The photometric redshift of group GI is estimated to be \( z = 0.287 \) with a typical redshift error in the maxBCG catalogue of 0.01. Within this error the photometric redshift of the group is identical to the spectroscopic redshift (0.287) of the brightest cluster galaxy (BCG) of this group found in Koester et al. (2007). The photometric redshift of group GI is estimated to be \( z = 0.287 \) with a typical redshift error in the maxBCG catalogue of 0.01. Within this error the photometric redshift of the group is identical to the spectroscopic redshift (0.28496) of the lensing galaxy. The group consists of 12 members within 10 arcmin from the main lens of SDSS J1430+4105. We allow for galaxies that have at least one of the photometric redshift estimates [template based (Template-)] (Adelman-McCarthy et al. 2007) or neural network based (CC2-z and D1-z) (Oyaizu et al. 2007) consistent within 1 standard deviation with the spectroscopic redshift value of SDSS J1430+4105 and the photometric redshift of group GI.

### Table 1. Photometric and spectroscopic quantities of the lens system. Given are the position of the galaxy (RA, Dec.), the redshifts of the galaxy and source (\( z_1, z_s \)), the axial ratio (\( q_L \)), the orientation (\( \Theta_{\alpha,L} \)), the effective radius (\( \theta_{\text{eff}} \)) of the lens’ light distribution and the velocity dispersion \( \sigma_{\text{SDSS}} \). Values are taken from Bolton et al. (2008a).

| ID  | RA (J2000) | Dec. (J2000) | \( z_1 \) | \( z_s \) | \( q_L \) | \( \Theta_{\alpha,L} \) | \( \theta_{\text{eff}} \) | \( \sigma_{\text{SDSS}} \) |
|-----|------------|-------------|---------|---------|--------|----------------|----------------|----------------|
|     | (s)        | (s)         |         |         | (arcsec) | (°)            | (arcsec)       | (km s\(^{-1}\)) |
| A1  | 14:30:04.10 | +41:05:57.1 | 0.285   | 0.575   | 0.79   | −12.8\(^a\)   | 2.55           | 322 ± 32       |

\(^a\)This angle is equivalent to −59:3 in the WCS coordinate system, defined as (−E) over N.

### Table 2. Observed positions of the multiple-image systems.

| ID  | \( \Theta_1 \)\(^a\) | \( \Theta_2 \)\(^a\) | \( z_s \) | \( \delta_{\phi} \) | \( d^a \) |
|-----|-----------------|-----------------|---------|---------------|-------|
|     | (arcsec)        | (arcsec)        |         | (arcsec)      | (arcsec) |
| A1  | −1.99           | −0.32           | 0.575   | 0.05          | 2.02  |
| A2  | 0.69            | 0.62            | 0.575   | 0.05          | 0.93  |
| B1  | −2.08           | 0.47            | 0.575   | 0.05          | 2.13  |
| B2  | 1.08            | 0.08            | 0.575   | 0.05          | 1.08  |
| C1  | −2.28           | 0.42            | 0.575   | 0.05          | 2.32  |
| C2  | 0.93            | 0.03            | 0.575   | 0.05          | 0.93  |
| D1  | −1.84           | 0.27            | 0.575   | 0.05          | 1.86  |
| D2  | 0.84            | 0.80            | 0.575   | 0.05          | 1.35  |
| E1  | 0.39            | −1.21           | 0.575   | 0.05          | 1.27  |
| E2  | −1.64           | 1.11            | 0.575   | 0.05          | 1.98  |

\(^a\)Relative to the centre of the galaxy light distribution.
3 STRONG GRAVITATIONAL LENSING

In this section, we model the lens mass distribution with the publicly available GRAVLENS (Keeton 2001) code (Section 3.1) assuming point sources and with the LENSVIEW (Wayth & Webster 2006) code (Section 3.3) using the 2D surface brightness distribution of the same system. Both approaches give consistent results. We give a description of the influence of the environment on the lens model of SDSS J1430+4105 in Section 3.2.

3.1 Parametric modelling using GRAVLENS

GRAVLENS is a publicly available code that uses parametric lens models to reconstruct the properties of an observed lensing system. The lens modelling we implement here is similar to the one of Grillo et al. (2010) where the reader can find more details. In this section, we use peaks in the surface brightness distribution of the lensed images as point-like position constraints for the lens model (see Table 2 and Fig. 2). Since the complex surface brightness distribution of the lensed galaxy makes it difficult to associate reliably a flux measurement to each multiple image, we neglect flux constraints. In GRAVLENS the convergence $\kappa$ for a (non-) singular isothermal ellipsoid [(N)SIE] or an ellipsoidal power law (PL) is parametrized as

$$\kappa(\theta_1, \theta_2) = \frac{b^{\beta-1}}{2(1-\epsilon)^{\frac{\beta+1}{2}}} \left(\frac{\theta^2_1}{1+\epsilon} + \theta^2_q + \frac{\theta^2_s}{\epsilon}\right)^{-\frac{1}{\beta}}$$

with

$$\epsilon = \frac{1 - q^2}{1 + q^2},$$

where $b$ is the lensing strength, $\beta$ denotes the steepness of the density profile ($\beta = 2$ in the case of an isothermal profile), $\theta_1$ and $\theta_2$ are the coordinates on the plane of the sky relative to the centre of mass of the lens, $\theta_q$ is the core radius and $q$ is the axial ratio of the isocurves of the convergence ($q = 1$ for a circular mass model). In the special case of a circular lens without core radius, $b$ equals the Einstein radius $\theta_{\text{Ein}}$ of the lens defined as $\kappa(\theta \leq \theta_{\text{Ein}}) = 1$.

Further we use a de Vaucouleurs Model (de Vaucouleurs 1948) parametrized as

$$I(r) = I_e^{-\frac{b}{b_{\text{Ein}}}} \left[\frac{b}{b_{\text{Ein}}}\right]^{1/4} \left[\frac{b}{b_{\text{Ein}}}\right]^{1/4},$$

with $r_{\text{eff}}$ being the effective radius (the radius which contains half the light) and $I_e$ the surface density at this radius. In GRAVLENS this is implemented as

$$\kappa = b_{\text{Ein}} \epsilon^{-\frac{3}{4}} \left[\frac{b}{b_{\text{Ein}}}\right]^{1/4}.$$

In this parametrization, $b_{\text{Ein}}$ is the value of the central convergence. The Einstein radius, however, depends also on $\theta_{\text{eff}}$ and $q$. Also a NFW profile (Navarro et al. 1996) is used, defined as

$$\rho(r) = \frac{\delta_c r_c}{r(1 + r/r_c)^2},$$

with $r_c$ denoting the critical density of the universe at the redshift of the lens, and $r_c$ and $\delta_c$ are characteristic properties of the individual halo. For an overview of its lensing properties, see Wright & Brainerd (2000).

The relation for the line-of-sight projected surface mass density $\Sigma$ of the lens and lensing convergence $\kappa$ is

$$\kappa = \frac{\Sigma}{\Sigma_{\text{crit}}} = \frac{4\pi G D_s D_{ls}}{c^2},$$

where $D_s$, $D_l$ and $D_{ls}$ are the angular diameter distances from the observer to the lens, from the observer to the source and from the observer to the lens.
Table 3. Observed environment of SDSS J1430+4105. Properties of the galaxies considered as part of the environment of SDSS J1430+4105. Given in the rows are the object name (Object), the position (RA, Dec.), its $i$-band magnitude $m_i$, and its error $\sigma_i$, and its various photometric redshift estimates together with their errors: first, the template method and its error, summarized in Adelman-McCarthy et al. (2007), followed by the neural network based method CC2 and its error and method D1 and its error (Oyaizu et al. 2007).

| Object | RA (J2000) | Dec. (J2000) | $m_i$ | $\sigma_i$ | Template-$\zeta$ Error | CC2-$\zeta$ Error | D1-$\zeta$ Error |
|--------|------------|-------------|------|-----------|------------------------|-------------------|-----------------|
| A      | 217.51704  | 41.0992     | 17.216 | 0.006 | 0.228 0.033 | 0.231 0.027 | 0.234 0.026 |
| B      | 217.44551  | 41.0456     | 18.729 | 0.018 | 0.202 0.015 | 0.216 0.073 | 0.260 0.067 |
| C      | 217.45406  | 41.0460     | 18.495 | 0.020 | 0.262 0.019 | 0.287 0.045 | 0.316 0.048 |
| D      | 217.45941  | 41.0625     | 18.657 | 0.019 | 0.179 0.032 | 0.312 0.055 | 0.309 0.064 |
| E      | 217.46171  | 41.1010     | 18.870 | 0.016 | 0.266 0.019 | 0.287 0.055 | 0.343 0.073 |
| F      | 217.46445  | 41.0738     | 19.134 | 0.020 | 0.286 0.082 | 0.309 0.096 | 0.344 0.073 |
| G      | 217.47010  | 41.1054     | 18.708 | 0.013 | 0.224 0.011 | 0.228 0.073 | 0.267 0.063 |
| H      | 217.49009  | 41.0825     | 19.356 | 0.024 | 0.200 0.024 | 0.259 0.070 | 0.339 0.060 |
| I      | 217.49493  | 41.1044     | 17.348 | 0.008 | 0.273 0.019 | 0.272 0.020 | 0.272 0.016 |
| J      | 217.50190  | 41.0995     | 17.987 | 0.018 | 0.251 0.021 | 0.293 0.062 | 0.326 0.063 |
| K      | 217.50544  | 41.0779     | 18.283 | 0.015 | 0.263 0.020 | 0.267 0.037 | 0.293 0.032 |
| L      | 217.51212  | 41.0655     | 18.008 | 0.010 | 0.268 0.015 | 0.273 0.022 | 0.279 0.023 |
| M      | 217.52402  | 41.1253     | 19.358 | 0.026 | 0.298 0.084 | 0.451 0.042 | 0.424 0.042 |
| N      | 217.54462  | 41.1407     | 18.947 | 0.026 | 0.275 0.063 | 0.284 0.057 | 0.296 0.048 |
| O      | 217.56441  | 41.0450     | 18.500 | 0.016 | 0.169 0.056 | 0.210 0.043 | 0.236 0.057 |
| P      | 217.58642  | 41.0746     | 19.373 | 0.027 | 0.371 0.088 | 0.401 0.059 | 0.403 0.064 |

where $p$ is the used parameter value, $p_{\text{prior}}$ its prior and $\sigma_{\text{prior}}$ its 1σ error. Results give best-fitting parameters and their 1σ errors. The likelihood of a parameter set is given by $L \propto e^{-\chi^2/2}$. In almost all cases, the best-fitting values are within the 68% error interval of the marginalized distributions.

The values of the parameters for the minimum-$\chi^2$ models are given in Tables 4 and 5. There we give the model number, type, the best-fitting parameters of the model together with the resultant $\chi^2$, the number of degrees of freedom (d.o.f) and the reduced $\chi^2_{\text{red}} = \chi^2 / \text{d.o.f}$ of each model. Also, the 1σ error intervals are given. These error estimates of the parameters are carried out using Markov chain Monte Carlo (MCMC) methods with several thousand steps each. For each model, 10 chains are calculated with different starting points. Convergence is reached by comparing the variance of the point distribution of each of these chains with their combined

Table 4. Minimum-$\chi^2$ values and parameter estimates derived with GRAVLENS for the isothermal and PL models.

| Model | $b$ (arcsec) | $q$ | $\Theta_g$ (°) | $\beta$ | $\chi^2$ | d.o.f | $\chi^2_{\text{red}}$ |
|-------|-------------|----|---------------|--------|---------|------|-----------------|
| Model I | SIE        | 1.49 | 0.71 | -21.6 | 2.00 | 11.5 | 7 1.6 |
|        |            | 1.47–1.51 | 0.69–0.73 | -24.1 to -19.3 |
| Model II | PL      | 2.76 | 0.86 | -21.9 | 1.59 | 10.1 | 6 1.7 |
|        |            | 1.60–2.72 | 0.74–0.85 | -24.7 to -20.1 |

*Fixed value.

Table 5. Minimum-$\chi^2$ values and parameter estimates derived with GRAVLENS for the two-component de Vaucouleurs plus dark matter models.

| Model | $M$ ($10^{11}$ $\text{M}_\odot$) | $q_d$ | $\Theta_{g_d}$ (°) | $c_d$ (arcsec) | $r_{200}$ | $b_{\text{group}}$ | $\chi^2$ | d.o.f | $\chi^2_{\text{red}}$ |
|-------|-----------------|------|-----------------|----------------|----------|----------------|--------|------|-----------------|
| Model III | de Vaucouleurs+NF | 7.4 | 0.79 | -26.1 | 1.7 | 514 | 7.9 | 5 1.6 |
|        | de Vaucouleurs+ GI | 6.9–10.1 | 0.62–0.82 | -28.3 to -23.3 | 1.4–2.8 | 277–534 | 8.0 | 18.9 | 8 2.4 |
| Model IV | de Vaucouleurs+NF+GI | 13.5 | 13.3–13.7 | 7.3–8.7 |
| Model V | de Vaucouleurs+GI | 9.5 | 0.79 | -24.6 | 2.2 | 280 | 3.7 | 7.8 | 4 2.0 |
|        | de Vaucouleurs+NF+GI | 8.7–11.8 | 0.68–0.90 | -27.1 to -12.8 | 1.0–2.6 | 168–463 | 3.2–6.5 |
distribution (see Fadely et al. 2010; Gelman et al. 1995). From the final chains, the second half of each chain is combined to the final MCMC point distribution. The acceptance rate typically lies between 0.25 and 0.3. We explore potential parameter correlations from these and derive 68 per cent confidence intervals on the parameters by exclusion of the lowest and highest 16 per cent of the MCMC points’ distribution; the central value is given by the median value of the MCMC points’ distribution, since there are only small deviations between the median and the average values of the 68 and 90 per cent error intervals.

We describe the most important different models without the lens environment in the following. To check for the basic properties of the system, we model the lens as a one-component SIE (Model I) and as a PL (Model II) model. To derive the de Vaucouleurs masses in this lens, we combine a de Vaucouleurs component with a dark matter halo model (Model III) and show that this result is not significantly affected by also taking the environment into account (Models IV and V).

Model I. The lens is modelled as a SIE (equation 1 with $\beta = 2$); the environment of the lens is ignored. The free parameters of this model are the lensing strength $b$, the axial ratio $q$, and its position angle $\Theta_\phi$. The best-fitting model is shown in Fig. 4. The results of the MCMC are shown in Fig. 5. The density contours describe the probability density for the parameter values, whereas the best-fitting model is marked with a cross. The reason for the apparent correlation between $q$ and $b$ in Fig. 5 lies in the definition of $\kappa$ in equation (1). The marginalized 68 per cent confidence errors are: $b = 1.49^{+0.02}_{-0.02}$ arcsec, $q = 0.71^{+0.02}_{-0.02}$ and $\Theta_\phi = -21.8^{+2.5}_{-2.3}$°. These values are in very good ($\approx 1\sigma$) agreement with the values derived by Bolton et al. (2008a) using a similar parametrization for the lens total mass distribution.

Model II. Model II follows a PL (equation 1 with arbitrary $\beta$ within the limits [1, 2.7]), and thus has one more free parameter relative to Model I. The values for the parameter distributions are shown in Fig. 6. The marginalized distributions change to $b = 2.12^{+0.02}_{-0.02}$ arcsec, $q = 0.81^{+0.04}_{-0.07}$, $\Theta_\phi = -22.2^{+2.3}_{-2.0}$°, and $\beta = 1.73^{+0.21}_{-0.13}$. We observe again (see Fig. 6) that the parameters $b$, $q$ and $\beta$ are correlated with each other. This is entailed by

---

4 All given errors in this section are the 68 per cent confidence values of the marginalized distributions, unless otherwise stated.

---
the definition of the convergence \( \kappa \) in equation (1). The steepness parameter \( \beta \) is constrained to a value shallower than isothermal on a 1.3σ level. The orientation \( \Theta \) stays at the same angle as in the SIE case, while its axial ratio moves towards rounder solutions, now being comparable to the axial ratio of the light distribution.

**Model III.** In the following, we split the mass distribution into different components. We use a de Vaucouleurs like component as traced by the stellar component and add dark matter with different profiles if needed. Since the de Vaucouleurs component for galaxy A alone does not provide a good model (see Appendix A), we add a dark matter component centred at galaxy A. We add an elliptical NFW-like component to the de Vaucouleurs profile. This composition resembles the common picture of galaxy mass distribution. For the dark matter halo, we impose a prior on the axial ratio based on the Bolton et al. (2008b) work of \( q_{\text{dark, prior}} = 0.79 \pm 0.12 \). Also we set the limit of the scale radius to values \(<500 \text{ arcsec}, \) approximately 10 times the value we find from Appendix B2 for the scale radius. The total mass of the de Vaucouleurs component is \( M_{\text{dV}} = (8.8^{+1.3}_{-1.1}) \times 10^{11} \, M_\odot \) while the parameters of the dark matter halo are (see Fig. 7): \( q_d = 0.72^{+0.1}_{-0.1} \), \( \Theta_d = -26.0^{+2.7}_{-2.3} \), \( c_d = 1.8^{+1.0}_{-0.5} \) and \( r_{200} = 406^{+128}_{-172} \) arcsec. We note that there is some degeneracy between the concentration \( c \) and \( r_{200} \). Further we have no constraints on \( r_{250} \) from the data, since we do not have observables outside 2.32 arcsec. Using a NSIE-like dark matter component yields similar results, as described in Appendix A, Model IIIb.

### 3.2 Lens modelling of the environment

As mentioned before, this galaxy is not an isolated field galaxy; hence, we investigate the possible impact on the derived lens parameters by taking the environment into account. In the following, we centre a smooth group contribution at galaxy I and calculate its convergence and shear at the position of SDSS J1430+4105. Further modelling of the group contribution by summing up the contributions of the individual members (‘clumpy group’) and by centring it at galaxy A itself is discussed in Appendix B.

#### 3.2.1 Smooth group mass distribution centred at galaxy I

According to Rozo et al. (2009), we can transform the group richness into a group mass of \( M_{500} = (0.72 \pm 0.29) \times 10^{14} \, M_\odot \) within 1σ. This mass can be converted into a velocity dispersion of \( \sigma_{\text{group}} = 519 \pm 107 \, \text{km s}^{-1} \), using the critical density of the universe

\[
500 \rho_c(z) = \frac{3M_{500}}{4\pi r_{500}^3}
\]

and the singular isothermal sphere (SIS) equation

\[
M_{500} = M(r_{500}) = \frac{2\sigma_{\text{group}}^2 r_{500}^3}{G}.
\]

In the first equation, \( \rho_c(z) \) denotes the critical density of the universe at redshift \( z \) and \( \sigma_{\text{group}} \) denotes the velocity dispersion of the group. Subsequently this gives an Einstein radius of \( \Theta_{\text{Ein}} = 3.6 \pm 1.5 \) arcsec, using again a SIS assumption (see Section 3.1 for details). This results in a convergence and shear of

\[
\begin{align*}
\kappa_{\text{SIS group}} &= 0.029, \\
\gamma_{\text{SIS group}} &= 0.029.
\end{align*}
\]

at galaxy A if galaxy I is assumed to be the group centre.

Alternatively, we model the smooth group as a ‘typical’ richness 12 galaxy group NFW (Navarro et al. 1996) halo with concentration

\[
c = 4.22 \quad \text{and} \quad r_{500} = 848 \, \text{kpc from} \text{Johnston} \text{et al. (2007). We obtain a convergence and shear of}
\]

\[
\begin{align*}
\kappa_{\text{NFW group}} &= 0.025, \\
\gamma_{\text{NFW group}} &= 0.026.
\end{align*}
\]

Further, we note that the angle of galaxy A towards galaxy I is \( -26^\circ \), therefore forming an angle of \( 16^\circ \) with the external shear value derived in Appendix B1. We examine the HST and SDSS frames which cover galaxy I and its vicinity for group-scale multiple images to further constrain the group mass distribution but do not find any sign for strong lensing.

**Model IV.** From Section 2.2 we expect that there is some environment dark matter present in this galaxy. We check whether using this group dark matter contribution with a de Vaucouleurs component for galaxy A is sufficient to explain the observations, even though modelling this system with a pure de Vaucouleurs component fails (see Appendix A). Therefore, in this model, we combine the de Vaucouleurs profile with a group halo centred at galaxy I. To account for the environment, we include the galaxy group explicitly as a SIS profile centred at galaxy I in Table 3. We use a prior on the group Einstein radius of \( b_{\text{group, prior}} = 3.6 \pm 1.5 \) arcsec. The de Vaucouleurs component has shape parameters as stated in Table 1. The group acts almost as a mass sheet. We get a \( \chi^2 = 18.9 \) for the best-fitting model. We get parameter estimates of \( M_{\text{dV}} = (13.5^{+5.7}_{-4.4}) \times 10^{11} \, M_\odot \) and \( b_{\text{group}} = 8.0^{+0.7}_{-0.8} \) arcsec as can be seen in Fig. 8. Besides being a worse fit than most of the other models, this model also needs a much more massive group present than what is like from the observations. Therefore, dark matter that is distributed almost uniformly within \( \Theta_{\text{Ein}} \) of the galaxy does not provide a good model for the system.

**Model V.** This model adds environmental effects to Model III. Therefore, we add group GI explicitly as above, yielding three components: group GI, the dark matter associated with the galaxy as an elliptical NFW profile and a stellar component modelled as a de Vaucouleurs profile. We use the same constraints as for Model III. We get the following parameters (see also Fig. 9):

\[
\begin{align*}
M_{\text{dV}} &= (10.4^{+1.4}_{-0.9}) \times 10^{11} \, M_\odot, \\
q_d &= 0.79^{+0.11}_{-0.11}, \quad \Theta_d = -21.6^{+8.8}_{-5.5} \text{ arcsec,} \\
c_d &= 1.4^{+1.2}_{-0.4} \quad \text{and} \quad r_{200} = 321^{+13}_{-14} \, \text{arcsec, and for the galaxy group} \\
b_{\text{group}} &= 4.9^{+1.9}_{-1.4} \text{ arcsec. We note that these parameter estimates do not significantly change compared to Model III; therefore, the inclusion of group GI has only a small influence on the estimated galaxy parameters; the } M_{\text{dV}} \text{ for the de Vaucouleurs component is slightly increased. Again, we are not able to constrain the concentration } c \text{ or } r_{200} \text{ of the dark matter halo. Models Va and Vb in Appendix A employ a NSIE-like galaxy dark matter halo (Model Va) and an external shear contribution instead of a explicit group contribution (Model Vb) and again give results very similar to Model V regarding the parameters for the lensing galaxy.}
\end{align*}
\]

### 3.3 Full surface brightness distribution using LENSVIEW

We also use LENSVIEW (Wayth & Webster (2006)) to derive models and mass estimates for SDSS J1430+4105 and to reproduce the full surface distribution of the lensed galaxy and its unlensed source. LENSVIEW is a publicly available program that fits parametric lens models to image data and uses the best-fitting lens model to reconstruct the source and image. The code uses the image data, a corresponding noise map, and an image mask to minimize \( \chi^2 = \lambda S \), where \( \chi^2 \) is the chi-square difference between the reconstructed
Figure 7. Error estimates of the MCMC for the NFW+de Vaucouleurs model (Model III); plotted are the 68 and 90 per cent confidence regions of the distribution. The crosses mark the minimum-$\chi^2$ value from Table 5. The bars on the axes mark the respective 68 per cent marginalized error intervals. The individual points of the MCMC are omitted for clarity.

Figure 8. Error estimates of the MCMC for the de Vaucouleurs+GI model (Model IV); plotted are the individual points of the MCMC together with the 68 and 90 per cent confidence regions of the distribution, indicated by the density contours. The crosses mark the minimum-$\chi^2$ value from Table 5. The bars on the axes mark the respective 68 per cent marginalized error intervals.

image and the data, $S$ is the entropy in the source, and $\lambda$ is internally adjusted such that $\chi^2$ approaches its target value. If the data are well fitted by the model, the entropy term serves to smooth the source. Because the flux of each unmasked data pixel is used in the fit, LENSVIEW is well suited to systems with extended flux like SDSS J1430+4105. The profile used here is defined, following Barkana (1998), as

$$\kappa(\Theta_1, \Theta_2) = \frac{b' \left( 3 - \beta \right)}{q} \left( \Theta_1^2 + \Theta_2^2 \right)^{-\frac{1}{2}},$$

where $b'$ gives the Einstein radius, $q$ the axial ratio and $\beta$ again the PL exponent of the profile. We note that the normalization of the profiles is different from equation (1), resulting in different values for the Einstein radius in both approaches.

The minimum-$\chi^2$ results are stated in Table 6. The SIE best-fitting parameter values derived here agree with those found in
Section 3.1, when directly compared to Model I in Table 4. For the PL model, we see a consistency of the different models from GRAYLENS and LENSVIEW within the stated errors for $q$, $\Theta_q$, and $\beta$. Since, as mentioned before, the normalization of the convergence profiles is different, the $b\, b'$ values do not compare directly to each other. For the models including the environment, the direct comparison of the SIE+ES model with Model Ia shows again a consistency within the errors derived in Appendix A for the lens parameters. However, the external shear angle shows a discrepancy – the angle is offset relative to the expected value derived in Section 2.2. Since the external shear contributes no mass, this will not have a significant effect on the mass estimates in Section 4. The same is true for the PL+ES case – a comparison with Model IIa gives an agreement within the given errors in all parameters besides $\Theta_y$. The best-fitting SIE model, residual and source are shown in Fig. 10.

### 3.4 Tests on the strong-lensing assumptions

For all but the single, pure de Vaucouleurs model, the centre of the light and mass distribution does not necessarily have to coincide. To

---

**Table 6.** Minimum-$\chi^2$ values derived with LENSVIEW.  

| Model | $b$ (arcsec) | $q$ | $\Theta_q$ ($^\circ$) | $\gamma$ | $\Theta_y$ | $\beta$ | $\chi^2_{\text{red}}$ |
|-------|-------------|-----|-----------------|---------|-----------|-------|----------------|
| SIE   | 1.49        | 0.69| $-19.5$         | $0^\circ$| $0^\circ$ | 2.00  | 1.4           |
| SIE+ES| 1.45        | 0.80| $-23.0$         | 0.046   | $-105$    | 2.00  | 1.02          |
| PL    | 1.53        | 0.77| $-20.2$         | $0^\circ$| $0^\circ$ | 1.83  | 1.02          |
| PL+ES | 1.50        | 0.85| $-22$           | 0.047   | $-106$    | 1.89  | 0.99          |

*The external shear at the position of galaxy A.

*Fixed value.
the details of the group model representation do not change the results for the lensing galaxy significantly; therefore, including the most simple SIS model for group GI is sufficient.

4 RESULTS FOR THE GALAXY MASS PROFILE

The total masses $M(<R)$ within a cylinder of radius $R$ and their derivatives obtained from the lensing analysis for Models I–V are shown in Figs 12 and 13. We have calculated these values within several concentric apertures with radii ([0.46 0.92 1.26 1.59 1.95 2.32 2.78] arcsec), chosen to lie in the radial regions covered by the lensed images plus extrapolations towards smaller/larger radii. For Models I–V of Sections 3.1 and 3.2, the masses are estimated by randomly taking 1000 MCMC points and creating convergence maps for each one of these 1000 models. The 68 per cent (90 per cent) errors are estimated by taking the central 680 (900) models at each radius.

4.1 Mass profiles for the single-component isothermal and PL models

First, we focus on the masses derived for Models I and II in Table 4. The Einstein radii are defined as the radii within which the mean convergence equals 1. For this, we calculate the mean convergence around the Einstein radius in 0.03-arcsec-distance bins. The results of this calculation are stated in Table 7. Since all models agree on an Einstein radius of $\Theta_{\text{Ein}} = 1.51$ arcsec $\approx 6.48$ kpc $= R_{\text{Ein}}$, we adopt this value as ‘the’ Einstein radius of this lens with an uncertainty of 0.03 arcsec $\approx 0.13$ kpc. We get a mean Einstein mass of $(5.37 \pm 0.06) \times 10^{11} M_\odot$ for Models I and II with a fixed Einstein radius of $\Theta_{\text{Ein}} = 1.51$ arcsec. These values are in good agreement with the ones stated by Auger et al. (2009) for this system also based on strong lensing.

We also extrapolate the models to the effective radius $r_{\text{eff}} = 2.55$ arcsec $\approx 10.96$ kpc of the galaxy, and calculate the mass and its derivative. We find an enclosed mass between $M_{\text{tot,enc}} = 8.9 \times 10^{11} M_\odot$ and $M_{\text{tot,enc}} = 11.3 \times 10^{11} M_\odot$ on a $\sigma_1$ level, depending on the model used. The azimuthally averaged results of the included masses are plotted in Fig. 12. For an SIE model, the mass included within radius $r$ grows linearly with the radius, so the derivative of it is expected to be independent of the radius. This is the case for the singular isothermal model (Model I) in Table 4. If we allow the steepness to vary (Model II) the mass profile tends to be steeper at the Einstein and effective radii. For the radial mass derivative at the Einstein radius, we calculate values between $\frac{dM_{\text{tot,enc}}}{dr} = 0.8 \times 10^{11}$ and $1.2 \times 10^{11} M_\odot kpc^{-1}$. The extrapolation to the effective radius ranges from $\frac{dM_{\text{tot,enc}}}{dr} = 0.8 \times 10^{11} M_\odot kpc^{-1}$ for Model I to $\frac{dM_{\text{tot,enc}}}{dr} = 1.6 \times 10^{11} M_\odot kpc^{-1}$ for Model II. These values are plotted in Fig. 11. Here and in Table 4 we state the 68 per cent CL errors.

4.2 Mass profiles for the de Vaucouleurs plus dark matter halo models

From the single-component lens analyses in Section 4.1, we conclude that the total projected mass density profile is isothermal or slightly shallower than isothermal. The de Vaucouleurs mass density drops faster with radius than the isothermal profile. Therefore, we expect the pure de Vaucouleurs profile to be a poor description of this lens’ mass profile (as seen in Model IV in Section 3.2 and...
the matter profile, effectively yielding a single-component model. Because the light distribution is well fitted by a de Vaucouleurs profile, we require a non-zero de Vaucouleurs component for this two-component fit; hence, we do not consider Model IIIa in the following. The Models IIIb, Va and Vb in Appendix A give similar results to Models III and V in Section 3.1. Therefore, in the following, we mostly consider Models III and V, which model the lens using an NFW profile for the dark matter component.

Besides the stars and the dark matter, an elliptical galaxy or a galaxy group also contains some amount of gas. Since we do not model this component individually, this gas needs to be incorporated in either the dark matter or the de Vaucouleurs component, effectively limiting the accuracy of our mass estimates to the gas mass fraction in elliptical galaxies and groups of galaxies. Young et al. (2011) get typical molecular gas masses of early-type galaxies in the ATLAS3D project of $M_{H_2} \lesssim 10^8 M_\odot$, less than 1 per cent of the total galaxy masses derived here. The hot gas component in an elliptical galaxy or a group of galaxies can contribute up to 10 per cent of the total mass in the centre of the galaxy or group of galaxies (see e.g. Sanderson et al. 2003). Hence, the uncertainty of our mass estimates due to the neglected gas is $\approx 10$ per cent.

We again adopt $\Theta_{\text{Ein}} = 1.51$ arcsec for the Einstein radius. First, we focus on the masses within this radius (see Table 8). For the total masses within the Einstein radius of Models III and V, we measure $M_{\text{tot,Ein}} = (5.33 \pm 0.04) \times 10^{11} M_\odot$. The radial mass derivative is $\frac{dM_{\text{tot,Ein}}}{dR} = 0.86^{+0.09}_{-0.07} \times 10^{11} M_\odot$ kpc$^{-1}$. The extrapolations to the effective radius give $M_{\text{tot,eff}} = 9.5^{+0.6}_{-0.5} \times 10^{11} M_\odot$ for the mass and $\frac{dM_{\text{tot,eff}}}{dR} = 1.06^{+0.14}_{-0.11} \times 10^{11} M_\odot$ kpc$^{-1}$ for its derivative. These values are plotted in Fig. 11. As can be seen, the enclosed masses and their derivatives at the Einstein radius and the effective radius agree with each other throughout Models I, II, III and V. We state the de Vaucouleurs mass within the Einstein and effective radii of Model III as Component IIIA in Table 8. We get a mass of $M_{\text{deV,Ein}} = (3.2^{+0.5}_{-0.7}) \times 10^{11} M_\odot$, meaning that $\frac{M_{\text{deV,Ein}}}{M_{\text{Ein}}} \approx 35$ per cent of the total de Vaucouleurs mass is concentrated within the Einstein radius for this lens. For Model V, we get similar values for the de Vaucouleurs component (see Component VA in Table 8).

In Fig. 13 and Fig. A3 in Appendix A, the projected, enclosed lens masses and their derivatives are plotted versus radius for the Galaxy part only; the mass contribution of GI is ignored.

### Table 7. The masses and mass derivatives at the Einstein radius, the globally adopted Einstein radius and the effective radius for the different models. Given are the projected, enclosed masses and their derivatives.

| Model       | $\Theta_{\text{Ein}}$ (arcsec) | $M_{\text{Ein}}$ ($10^{11} M_\odot$) | $\frac{dM}{dR}(\Theta_{\text{Ein}})$ ($10^{11} M_\odot$ arcsec$^{-1}$) | $\kappa_{\text{Ein}}$ | $M(<1.51$ arcsec) ($10^{11} M_\odot$) | $\frac{dM}{dR}(\Theta = 1.51$ arcsec) ($10^{11} M_\odot$ arcsec$^{-1}$) | $M(<2.55$ arcsec) ($10^{11} M_\odot$) | $\frac{dM}{dR}(\Theta = 2.55$ arcsec) ($10^{11} M_\odot$ arcsec$^{-1}$) |
|-------------|-------------------------------|--------------------------------------|------------------------------------------------|----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Model I     | 1.51 $\pm$ 0.03               | 5.35 $^{+0.07}_{-0.06}$              | 3.55 $^{+0.04}_{-0.05}$                           | 0.497 $^{+0.006}_{-0.005}$  | 3.53 $^{+0.07}_{-0.06}$         | 3.55 $^{+0.04}_{-0.05}$         | 9.04 $^{+0.11}_{-0.10}$         | 3.55 $^{+0.04}_{-0.05}$         |
| Model II    | 1.54 $\pm$ 0.03               | 5.54 $^{+0.06}_{-0.05}$              | 4.5 $^{+0.6}_{-0.8}$                            | 0.68 $^{+0.08}_{-0.10}$   | 5.40 $^{+0.05}_{-0.05}$         | 4.5 $^{+0.6}_{-0.7}$            | 10.4 $^{+0.09}_{-1.1}$          | 5.1 $^{+0.11}_{-1.3}$           |

*Galaxy part only; the mass contribution of GI is ignored.

### Table 8. Same as Table 7 for the two-component models.

| Model       | $\Theta_{\text{Ein}}$ (arcsec) | $M_{\text{Ein}}$ ($10^{11} M_\odot$) | $\frac{dM}{dR}(\Theta_{\text{Ein}})$ ($10^{11} M_\odot$ arcsec$^{-1}$) | $\kappa_{\text{Ein}}$ | $M(<1.51$ arcsec) ($10^{11} M_\odot$) | $\frac{dM}{dR}(\Theta = 1.51$ arcsec) ($10^{11} M_\odot$ arcsec$^{-1}$) | $M(<2.55$ arcsec) ($10^{11} M_\odot$) | $\frac{dM}{dR}(\Theta = 2.55$ arcsec) ($10^{11} M_\odot$ arcsec$^{-1}$) |
|-------------|-------------------------------|--------------------------------------|------------------------------------------------|----------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Model III   | 1.51 $\pm$ 0.03               | 5.34 $^{+0.06}_{-0.04}$              | 3.54 $^{+0.08}_{-0.06}$                           | 0.55 $^{+0.08}_{-0.06}$  | 5.34 $^{+0.05}_{-0.05}$         | 3.54 $^{+0.05}_{-0.05}$         | 9.8 $^{+0.9}_{-0.7}$            | 4.6 $^{+1.1}_{-0.8}$            |
| Component IIIA* |                     | 3.2 $^{+0.5}_{-0.7}$               | 1.4 $^{+0.2}_{-0.3}$                              | 4.4 $^{+0.5}_{-0.4}$   | 5.2 $^{+0.7}_{-0.6}$            | 4.4 $^{+0.7}_{-0.6}$            | 9.0 $^{+1.1}_{-0.9}$            | 3.9 $^{+0.8}_{-0.9}$            |
| Model V     | 1.48 $\pm$ 0.03               | 5.21 $^{+0.06}_{-0.05}$              | 3.5 $^{+0.4}_{-0.3}$                             | 0.50 $^{+0.06}_{-0.05}$  | 5.32 $^{+0.06}_{-0.05}$         | 3.5 $^{+0.4}_{-0.3}$            | 9.1 $^{+0.6}_{-0.5}$            | 3.9 $^{+0.8}_{-0.9}$            |
| Component VA* |                    | 3.8 $^{+0.5}_{-0.6}$               | 1.6 $^{+0.2}_{-0.3}$                              | 5.2 $^{+0.7}_{-0.6}$   | 5.2 $^{+0.7}_{-0.6}$            | 5.2 $^{+0.7}_{-0.6}$            | 1.0 $^{+0.15}_{-0.17}$          | 3.3 $^{+1.1}_{-0.8}$            |
| Component VB* |                    | 4.91 $^{+0.09}_{-0.08}$             | 3.2 $^{+0.5}_{-0.4}$                             | 0.47 $^{+0.07}_{-0.06}$  | 5.11 $^{+0.10}_{-0.09}$         | 3.2 $^{+0.5}_{-0.4}$            | 8.5 $^{+0.8}_{-0.7}$            | 3.3 $^{+1.1}_{-0.8}$            |

*de Vaucouleurs like part only; the dark matter contribution is ignored.

*Galaxy part only; the mass contribution of GI is ignored.
different two-component strong-lensing models. The measurements are done using circular apertures, so all of these values are azimuthally averaged. As one can see, including an explicit group halo GI (Model V) has only a minor influence on the mass estimates and their derivatives. The total masses agree very well with the one-component estimates in Fig. 12. Also, all models agree very well on the total masses and their radial derivatives, tending to give a shallower than isothermal mass profile in the centre. For Models III and V in Fig. 13, the dark matter haloes modelled as NFW haloes agree very well with each other, meaning that the environment has only minor influence on the mass estimates. This is also true for the de Vaucouleurs component. We note that the uncertainties on the individual components are larger than the uncertainties on the total masses and derivatives, giving a well-constrained total mass.

4.3 3D spherical reconstruction

Further, we also reconstruct the 3D matter densities from the 2D data for Model III. For this, we employ the inverse Abel transform:

\[
\rho(r) = -\frac{1}{\pi} \int_0^\infty \frac{d\Sigma}{dR} \frac{dR}{\sqrt{R^2 - r^2}},
\]

transforming a 2D circular density function \(\Sigma\) into a 3D spherical density function \(\rho\). Since this only transforms circular to spherical profiles and vice versa, we start from the mass measurements within a cylinder in Fig. 13(a) for the azimuthally averaged profile. In equation (9) the integration extends to infinity, which is not possible due to our limited range of reliable data. To estimate the radial range at which we can use equation (9) only integrating up to our last data bin, we test it on a SIS toy model. For a SIS toy model, we know both the spherical and the projected circular density. We then consider this radial range reliable where the deviation of the reconstructed 3D density from the analytical SIS density does not exceed \(2 \times 10^7 M_\odot \) kpc\(^{-3}\). From this comparison, we conclude that this inverse Abel transformation is only reliable up to \(7\) kpc with a systematic error smaller than 30 per cent, given our limited radial range of data. The reconstructed 3D profile is shown in Fig. 14. The errors plotted are only statistical, not taking any systematic effects into account. The dark matter accounts for only a minor fraction of the total mass in the 3D centre of the galaxy. We now turn to fig. 7 in Thomas et al. (2011). In the lower part of fig. 7, they have displayed the ratios of the mean dark matter density to mean total density within the Einstein radius of Coma galaxies as a function of their velocity dispersion. (For the definition of the synthetic Einstein radius for Coma galaxies, see Thomas et al. 2011). To see whether there are structural differences for the Coma and the higher redshift SLACS sample, one would like to enter the corresponding deprojected values for SLACS galaxies in these figures as well. These were not available until now because the dark-to-total matter ratios were only calculated for the line-of-sight projected densities within the Einstein radii (i.e. cylindrical averages) by gravitational lensing. The corresponding projected values are shown for SLACS (and Coma) galaxies in the upper part of fig. 7 of Thomas et al. (2011). The projected and deprojected values differ, since the projection along the line of sight mixes scales: parts of the matter that have a large physical distance from the centre of the galaxy but lie on the line of sight are taken into account when calculating the projected dark matter fractions. Due to the monotonic increase of the dark-to-total matter density ratios as a function of radius, the projected ratios displayed in the upper part of fig. 7 of Thomas et al. (2011) are upper limits to the central, 3D density ratios at the Einstein radius. With the analysis described in this work we are able to measure the 3D densities of the (spherically averaged) dark matter and de Vaucouleurs components of the lensing galaxy separately from gravitational lensing alone due to the large radial coverage of multiple images in the image plane by one source. Since the source

---

Figure 12. The mass within radius \( R, M(< R) \), from Models I and II, analysed in Section 3 is plotted in panel (a). For each model, 1000 random entries from the MCMC are used to calculate the errors. Each time, the means and 90 per cent errors are shown, with the respective means in the bold lines. The bars at the bottom mark the radii of the apertures used to calculate the enclosed projected masses. The masses are in units of \( 10^{11} M_\odot \) and the radii are stated in kpc in the lens plane. The mass estimates for Models I and II are shown as the solid and dashed lines, respectively. The vertical lines indicate the Einstein and effective radii in both plots. Panel (b) is the same as panel (a) but for the LENSVIEW derived masses. The errors are estimated by an increase of the reduced \( \chi^2 \) of the extended model by 1. As can be seen, the masses agree with each other in terms of derived masses within the errors.
Figure 13. The mass within radius $R$, $M(<R)$, from Models III and V analysed in Section 3. For each model, 1000 random entries from the MCMC are used to calculate the errors. All errors plotted are the 90 per cent error intervals with the respective means in bold symbols. The bars at the bottom mark the radii of the apertures used to calculate the enclosed projected masses or its derivatives. The masses are in units of $10^{11} M_\odot$ and the radii are stated in kpc in the lens plane. In panel (a), the mass estimates of Model III for the de Vaucouleurs (dashed line), NFW (dot–dashed line) parts and their sum (solid line) are plotted. While the sum of these two is fairly well constrained, the errors on the individual parts are bigger. In panel (b), the same mass estimates are plotted for Model V, together with its 90 per cent error intervals, split into de Vaucouleurs (dashed line), NFW (dot–dashed line) and GI (dotted line) parts and their sum (solid line). The radial mass derivatives are plotted in panel (c) for Model III and panel (d) for Model V, keeping the line coding. Plotted is the change in enclosed mass with radius. This can also be interpreted as the mass in a thin ring with width $dR$ at radius $R$, $M(R)$. Again, the vertical lines indicate the Einstein and effective radii in both plots.

is only one background object, we do not need to take the systematic uncertainties into account that arise in systems with multiple-image systems from sources at different redshifts (see e.g. Gavazzi et al. 2008). At the Einstein radius we obtain [using Fig. 14, displaying Model III (de Vaucouleurs+NFW)] a dark-to-total density ratio of 22 per cent. Doing the same for Model V where SDSS J1430+4105 (consisting of a de Vaucouleurs and a dark matter component) is embedded in a dark matter halo centred on galaxy I, we find that the ratio of dark to total matter density at the Einstein radius is about 14 per cent. Since the dark matter fraction increases towards the outskirts, these ratios of densities at the Einstein radius are upper limits for the mean dark matter-to-total matter density ratios of SDSS J1430+4105 within the same Einstein radius. On a 90 per cent CL basis, the dark-to-total matter density ratios at the Einstein radius are larger than 15 per cent (Model III) and 5 per cent (Model V).
5 MASS-TO-LIGHT RATIOS FOR THE DE VAUCOULEURS COMPONENT AND DARK-TO-TOTAL MASS RATIO

Since we calculated the de Vaucouleurs masses for this galaxy, we now want to estimate the rest-frame mass-to-light ratios of this galaxy. Further, we evolve these mass-to-light ratios to present-day values in order to compare it with those of Coma galaxies. First, we calculate the dark matter fractions within the Einstein radius. In Fig. 15, we plot the dark over total enclosed mass fraction within the Einstein radius. The error bars are estimated as before from the central 68 and 90 per cent entries of the random sample drawn from the MCMC for Models III and V, respectively. The fractions for Models III and V are: \( \frac{M_{\text{dm}}}{M_{\text{tot}}} = 0.40_{-0.09}^{+0.13} \) and \( \frac{M_{\text{dm}}}{M_{\text{tot}}} = 0.27_{-0.11}^{+0.12} \). These fractions indicate a substantial amount of dark matter within the Einstein radius of this lens. As can be seen, this picture is not significantly altered by locating the group at I in Model V. Although the actual numbers change, we still need dark matter associated with the lens in the centre of the galaxy. Since we ignore the dark matter contribution associated with group GI in Model V for the total mass, we get a lower dark matter fraction for Model V compared to Model III.

For Models III and V, we calculate the mass-to-light ratios for the de Vaucouleurs component at the redshift of the lens. We use the masses from lensing and the light (in the rest-frame \( B \) and \( R \)) as obtained from photometric data. To compare the mass-to-light ratios with present-day galaxies, we also need the luminosity evolution to redshift zero in these bands. We take the observed griz SDSS photometry for this system which covers the rest frame \( B \) and \( R \) filters to calculate the \( B - R \) rest-frame colour. We calculate a colour of \( B - R = 0.80 \pm 0.03 \) and luminosities of \( L_{B,rf} = (1.66 \pm 0.03) \times 10^{11} L_{\odot,B} \) and \( L_{R,rf} = (1.92 \pm 0.02) \times 10^{11} L_{\odot,B} \) from the absolute rest-frame magnitudes. To estimate the luminosity evolution until today, we fit three extinction-free Bruzual & Charlot (2003, hereafter BC) composite stellar population (CSP) models to the observed griz SDSS photometry: a Salpeter initial mass function (IMF) (Salpeter 1955) with solar metallicity (Model A) and two models with a Chabrier IMF (Chabrier 2003) and solar/super-solar metallicity (Models B and C) (see Drory et al. 2001, 2004). The best-fitting results are stated in Table 9 together with the luminosity evolutions in the \( B \) and \( R \) bands and the best-fitting stellar masses, which agree with Grillo et al. (2009). From the best-fitting star formation histories (SFHs) to the spectral energy distribution, we obtain a stellar age of typically 8 Gyr and a \( B - R \) colour of 0.8. Therefore, this galaxy has a formation redshift of approximately 2–3 which is a typical value for elliptical galaxies. If we divide the de Vaucouleurs masses derived by lensing in Section 3 by the luminosities derived from the SDSS photometry, we obtain the mass-to-light ratios for the de Vaucouleurs component of this galaxy. For Models III and V, we find a mass-to-light ratio of \( \frac{M_{\text{dm}}}{M_{\text{tot}}}(5.3_{-1.1}^{+1.3}) \times 10^{11} M_{\odot} \) and \( \frac{M_{\text{dm}}}{M_{\text{tot}}}(6.2_{-0.5}^{+0.3}) \times 10^{11} M_{\odot} \) in the \( B \)-band rest frame at the redshift of the lens. These two models give the same mass-to-light ratio within the errors, although including group GI explicitly increases the most likely mass-to-light ratio. We compare this with the total light of

![Figure 14](https://academic.oup.com/mnras/article-abstract/427/3/1918/1095096)

![Figure 15](https://academic.oup.com/mnras/article-abstract/427/3/1918/1095096)
Figure 16. Cumulative probability distribution functions of the mass-to-light ratios for the de Vaucouleurs components of Models III and V. Models III, IIIb, V and Va are marked by red, blue, turquoise and green, respectively. The vertical lines mark the derived stellar mass-to-light ratios with their 1σ errors from Grillo et al. (2009) for this system fitting SFH to broad-band SDSS photometry using a Salpeter IMF (solid line) and a Chabrier IMF (dashed line). The mass-to-light ratios are as observed at z = 0.285 and not corrected for luminosity evolution to redshift zero.

the galaxy and the stellar mass derived in Grillo et al. (2009), who use CSP models with a Salpeter or Chabrier IMF, a delayed exponential SFH, and solar metallicity to model the SDSS multiband photometry. First, we compare in the rest-frame B band. In Fig. 16 we plot the cumulative distribution function for the stellar mass-to-light ratios derived from the respective de Vaucouleurs parts of Models III and V and Models IIIb and Va from Appendix A. We overplot the stellar mass-to-light ratios derived in Grillo et al. (2009) for this system and get the best agreement for a NFW like halo and a Salpeter IMF.

In the R band, we get a mass-to-light ratio for Models III and V of \( \frac{M_{\text{de}V}}{L_R} = (4.5^{+0.6}_{-0.8}) \) and \( (5.4^{+0.7}_{-0.8}) \), respectively. To compare the lensing galaxy SDSS J1430+4105 with present-day Coma galaxies (Thomas et al. 2011), we have to account for the luminosity evolution between redshift 0.285 and now. We use the average evolution factor from the SFH models stated in Table 9, derived from the extrapolations of the fitted SFH models to redshift 0, which increases the mass-to-light ratio in the R band by a factor of 1.48 for \( z = 0 \), giving \( \frac{M_{\text{de}V}}{L_R} = (6.8^{+1.2}_{-1.6}) \) and \( (9.0^{+1.3}_{-1.5}) \) for Models III and V, respectively. In Fig. 17, we plot this R-band de Vaucouleurs mass-to-light ratio at redshift zero against the present-day R-band mass-to-light ratio for a Kroupa IMF (Kroupa 2001), obtained again from the SFH fit of Grillo et al. (2009), translated to the R band and evolved to redshift zero. We added the results from a dynamical study of Coma galaxies by Thomas et al. (2011). This allows us to conclude that SDSS J1430+4105 evolves into a galaxy with mass-to-light ratio similar to the Coma galaxies, and shows the same conflict with respect to a Kroupa IMF as they do. This conflict to a Kroupa IMF would be resolved if, for example, the de Vaucouleurs component is not made of stars only but contains dark matter as well.

6 DISCUSSION AND CONCLUSIONS

In this paper, we studied the lensing properties of SDSS J1430+4105. From the complex source, we identified five double-image systems, spanning a radial range from below 0.9 arcsec to almost 2.1 arcsec. The source is spectroscopically confirmed at a redshift of 0.575. Parametric models can match the observed image positions well with an average scatter in the position comparable to the pixel size of the ACS camera input image, which is 0.05 arcsec. Our results are as follows:

(i) The best-fitting reconstruction of the profile favours a profile slope shallower than isothermal for the best-fitting model. However, profiles with free slope for the density steepness are consistent with an isothermal profile at 90 per cent CL. This is also true
when combining an explicit model for the de Vaucouleurs like light distribution with a NFW-like dark matter component. Auger et al. (2010) found a steepness for the 3D density profile for this system of \( \rho \sim r^{-2.06 \pm 0.18} \) by using the location of the Einstein radius only and combining this with stellar dynamics, in agreement with our results for the one-component PL total mass distribution of \( \rho \sim r^{-(1.73^{+0.22}_{-0.15})} \) within the errors.

(ii) The galaxy is part of a group of galaxies listed in the \text{maxBCG} cluster catalogue. Using a lens mass component following the stellar light, we cannot model the strong-lensing signal for this galaxy if we use this component alone or combine it with a dark matter halo not centred on SDSS J1430+4105, called galaxy A. Therefore, this leads to two possibilities: either galaxy A is indeed the centre of the galaxy group or galaxy A is a satellite of this group, residing in its own dark matter halo. Since we cannot distinguish between these two cases, neither from the lensing signal nor from external data, we model both scenarios and show that these lead to similar results regarding the mass distribution of the galaxy. We show that the dark matter halo of galaxy A must not be singular and isothermal at the same time, since this would suppress the de Vaucouleurs component. Both a non-singular, isothermal halo and a NFW-like halo for the dark matter halo of galaxy A fit the data well. We find agreeing dark matter fractions and distributions for both cases. From the lensing data, we cannot distinguish whether the dark matter halo follows a NFW or a NSIE profile in the centre, since we cannot constrain the concentration \( c \) and \( r_{200} \) or \( \Theta_* \) for a NSIE dark matter halo – of the dark matter component well. From the models, taking explicitly the environment into account, we conclude that the dark matter and the light of the galaxy have the same axial ratio and are likely coaligned.

(iii) We estimate the rest-frame B-band mass-to-light ratios for the lensing galaxy from the de Vaucouleurs lensing component. For the case of a de Vaucouleurs+NFW mass model, we obtain a total mass of \( M_{\text{tot}} = (8.8^{+1.3}_{-1.2}) \times 10^{11} M_\odot \) for the de Vaucouleurs component. Grillo et al. (2009) have obtained stellar mass estimates for the luminous component using the \text{ugriz} broad-band SDSS photometry and SFH fits. They assumed solar metallicity CSPs with a delayed exponential SFH, and examined the Salpeter IMF [with BC and Maraston (2005, hereafter MAR) single stellar populations (SSPs)], and the Chabrier and Kroupa IMFs (based on BC SSPs). They obtained stellar masses of \( M_* = (5.6\pm1.8) \times 10^{11}, (3.9\pm1.3) \times 10^{11}, (3.2\pm1.2) \times 10^{11} \) and \( (2.9^{+0.6}_{-0.5}) \times 10^{11} M_\odot \) for these four cases. The stellar mass agrees best with the mass of the de Vaucouleurs component obtained from lensing if we assume a Salpeter IMF. In the mass-to-light ratios also depend on the age of the galaxy and its metallicity. According to De Lucia et al. (2006), solar metallicity and a formation redshift of 3–5 as used in Grillo et al. (2009) are good assumptions for a galaxy of the measured stellar mass. Thus, the IMF must not be Chabrier or Kroupa-like unless a fraction of the de Vaucouleurs component is not of stellar origin, that is, part of the dark matter follows the light distribution. We measure a mass-to-light ratio for the stellar component of \( M_{\Delta V}/M_{\Delta L} = (5.3^{+0.5}_{-0.4}) \times \mu_{\Delta V}/\mu_{\Delta L} \) using gravitational lensing and assuming a NFW-like dark matter halo. If we allow for a group halo at galaxy I, we obtain \( \mu_{\Delta V}/\mu_{\Delta L} = (6.2^{+0.6}_{-0.5}) \times \mu_{\Delta V}/\mu_{\Delta L} \). These results again favour a Salpeter IMF, and are in agreement with the Fundamental Plane results for this galaxy from Grillo et al. (2009). These results hold as long as the metallicity is approximately solar. We compare the mass-to-light ratio, passively evolved to \( z = 0 \), to those of Coma galaxies analysed in Thomas et al. (2011). We confirm their trend towards a Salpeter IMF, again disfavouring a Kroupa IMF. This trend is also seen in Cappellari et al. (2012) for the most massive galaxies. Their data indicate a more Salpeter-like IMF for high velocity dispersion galaxies. The dark-to-total mass ratio of SDSS J1430+4105 rises from the centre outwards, giving a value of \( M_{\text{dark}}/M_{\text{tot}} = 0.4^{+0.14}_{-0.10} \) at the Einstein radius. In this galaxy, we need a significant amount of dark matter in its projected centre to explain the observations.

(iv) We compare the 3D densities of total, dark and luminous dark matter to those of Coma galaxies analysed by Thomas et al. (2007), based on dynamical modelling, especially their fig. 5. Our galaxy has an effective radius of 10.96 kpc and a velocity dispersion of \( 322 \pm 32 \) km s\(^{-1}\). Concerning the effective radius, it is most similar to the Coma galaxies GMP 0144, GMP 4928 and GMP 2921, a cD galaxy, which have effective radii of 8.94, 14.31 and 16.43 kpc (Thomas et al. 2007) and effective velocity dispersions of 211.8 ± 0.4 and 314.8 ± 2.9 and \( 400 \) km s\(^{-1}\), respectively (Thomas et al. 2007; Corsini et al. 2008). Since our 3D matter densities are reliably known only between 3 and about 6.5 kpc, we decide to compare the matter densities at 3 kpc. At this radius the matter density values of Thomas et al. (2007) are reliable as well. At the same time this radius is within the core radius (\( r_c \) in table 2 of Thomas et al. 2007) for all three GMP galaxies and thus the densities at this radius define the central dark matter densities in these galaxies. We read off the dark matter and total densities of \( 6 \times 10^{-2} \) and \( 3 \times 10^{-1} M_\odot \) pc\(^{-3}\) for GMP 0144, \( 1.5 \times 10^{-2} \) and \( 2 \times 10^{-1} M_\odot \) pc\(^{-3}\) for GMP 4928 and \( 1 \times 10^{-1} \) and \( 3 \times 10^{-1} M_\odot \) pc\(^{-3}\) for GMP 2921. For SDSS J1430+4105 these numbers are \( 4 \times 10^{-2} \) and \( 3.5 \times 10^{-1} M_\odot \) pc\(^{-3}\) for the dark matter and the total density, respectively, at 3 kpc with fractional errors of about 25 per cent. This means that the dark matter and total densities at 3 kpc for our galaxy and the three Coma galaxies are comparable, and that the ratio of dark to total matter density of about 1:10 is consistent within the error with the ratios of 1:5 and 1:13 for the non-central Coma galaxies.

ACKNOWLEDGMENTS

We acknowledge the support of the European DUEL Research Training Network, Transregional Collaborative Research Centre TRR 33, and Cluster of Excellence for Fundamental Physics, and further the use of data from the SDSS and the HST. Further we are grateful to the SLACS collaboration for the discovery and follow-up observations of the galaxy-scale lens sample SDSS J1430+4105 is part of. Based on observations made with the NASA/ESA HST, obtained from the data archive at the Space Telescope Science Institute (STScI). The STScI is operated by the Association of Universities for Research in Astronomy, Inc., under the NASA contract NAS 5-26555. We thank Natascha Greisel for making SFH fits for us and Niv Drory for providing us with his SFH-fitting code SEDFIT. We thank Claudio Grillo for many discussions and comments on this topic. We thank Jens Thomas for discussions about dynamical constraints on Coma galaxies. We thank Ralf Bender for discussions. We want to thank the anonymous referee for the numerous and elaborate comments which helped us to improve the manuscript and make it more concise and understandable.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/.
The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, the Max-Planck-Institute for Plasma Physics, Princeton University, the United States Naval Observatory, the Max-Planck-Institute for Remote Sensing, the Max-Planck-Institute for Solar System Research, the Max-Planck-Institute for Nuclear Physics, the Netherlands Institute for Space Research, the Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory and the University of Washington.

REFERENCES

Abazajian K. et al., 2009, ApJS, 182, 543
Adelman-McCarthy J. K. et al., 2007, ApJS, 172, 634
Auger M. W., Treu T., Bolton A. S., Gavazzi R., Koopmans L. V. E., Marshall P. J., Bundy K., Moustakas L. A., 2009, ApJ, 705, 1099
Auger M. W., Treu T., Bolton A. S., Gavazzi R., Koopmans L. V. E., Marshall P. J., Moustakas L. A., Burles S., 2010, ApJ, 724, 511
Barkana R., 1998, ApJ, 502, 531
Barnabé M., Czoske O., Koopmans L. V. E., Treu T., Bolton A. S., Gavazzi R., 2009, MNRAS, 399, 21
Barnabé M., Auger M. W., Treu T., Koopmans L. V. E., Bolton A. S., Czoske O., Gavazzi R., 2010, MNRAS, 406, 2339
Bell E. F., McIntosh D. H., Katz N., Weinberg M. D., 2003, ApJ, 585, 117
Bertin G., Lisieksina T., Pogoraro F., 2003, A&A, 405, 73
Blumenthal G. R., Faber S. M., Flores R., Primack J. R., 1986, ApJ, 301, 27
Bolton A. S., Burles S., Schlegel D. J., Eisenstein D. J., Brinkmann J., 2004, ApJ, 127, 1860
Bolton A. S., Burles S., Koopmans L. V. E., Treu T., Moustakas L. A., 2006, ApJ, 638, 703
Bolton A. S., Burles S., Koopmans L. V. E., Treu T., Gavazzi R., Moustakas L. A., Wayth R., Schlegel D. J., 2008a, ApJ, 682, 964
Bolton A. S., Treu T., Koopmans L. V. E., Gavazzi R., Moustakas L. A., Burles S., Schlegel D. J., Wayth R., 2008b, ApJ, 684, 248
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000 (BC)
Cappellari M. et al., 2012, Nat, 484, 485
Cappellari M. et al., 2006, MNRAS, 366, 1126
Chabrier G., 2003, PASP, 115, 809
Cohn J. D., Kochanek C. D., McLeod B. A., Keeton C. R., 2001, ApJ, 554, 1216
Corsini E. M., Wegner G., Saglia R. P., Thomas J., Bender R., Thomas D., 2008, ApJS, 175, 462
De Lucia G., Springel V., White S. D. M., Croton D., Kauffmann G., 2006, ApJ, 667, 1046
Gelman A., Carlin J. B., Stern H. S., Rubin D. B., 1995, Bayesian Data Analysis. Chapman & Hall/CRC, New York
Gerhard O., Kronawitter A., Saglia R. P., Bender R., 2001, AJ, 121, 1936
Gnedin O. Y., Kravtsov A. V., Klypin A. A., Nagai D., 2004, ApJ, 616, 16
Grillo C., Lombardi M., Bertin G., 2008a, A&A, 477, 397
Grillo C. et al., 2008b, A&A, 486, 45
Grillo C., Gobat R., Lombardi M., Rosati P., 2009, A&A, 501, 461
Grillo C., Eicher T., Seitz S., Bender R., Lombardi M., Gobat R., Bauer A., 2010, ApJ, 710, 372
Jesseit R., Naab T., Burkert A., 2002, ApJ, 571, 89
Johnston D. E. et al., 2007, preprint (arXiv:0709.1159)
Keeton C. R., 2001, ApJ, 561, 46
Koester B. P. et al., 2007, ApJ, 660, 239
Koopmans L. V. E., Treu T., Bolton A. S., Burles S., Moustakas L. A., 2006, ApJ, 649, 599
Koopmans L. V. E. et al., 2009, ApJ, 703, L51
Kroupa P., 2001, MNRAS, 322, 231
Kovac J., 2007, MNRAS, 377, 1216
Kroupa P., 2001, MNRAS, 322, 231
Kroupa P., 2001, MNRAS, 322, 231
Lagattuta D. J. et al., 2010, ApJ, 716, 1579
Ma C.-P., Boylan-Kolchin M., 2004, Phys. Rev. Lett., 93, 1301
Maraston C., 2005, MNRAS, 362, 799 (MAR)
Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563
Ogawa H., Lim, M., Cunha C. E., Lin H., Frieman J., Sheldon E. S., 2008, ApJ, 674, 768
Peng C. Y., Ho L. C., Impey C. D., Rix H. W., 2002, AJ, 124, 266
Pu S. B., Saglia R. P., Fabricius M. H., Thomas J., Han Z., 2010, A&A, 516, A4
Rozo E. et al., 2009, ApJ, 699, 768
Saglia R. P., Bertin G., Fasano C., 1992, ApJ, 384, 433
Salpeter E. E., 1955, ApJ, 121, 161
Sanderson A. J. R., Pommern T. J., Finoguenov A., Lloyd-Davis E. J., Markevitch M., 2003, MNRAS, 340, 989
Sérisic J. L., 1963, Bol. Sociedad Astron. de Argentina., 6, 41
Song I., Mohr J. J., Barkhouse W. A., Warren M. S., Rude C., 2011, ApJ, 747, 58
Suyu S. H., Marshall P. J., Blandford R. D., Fassnacht C. D., Koopmans L. V. E., McKeen P. J., Treu T., 2009, ApJ, 691, 277
Suyu S. H., Marshall P. J., Auger M. W., Hilbert S., Blandford R. D., Koopmans L. V. E., Fassnacht C. D., Treu T., 2010, ApJ, 711, 201
Thomas J., Saglia R. P., Bender R., Thomas D., Gebhardt K., Magorrian J., Corsini E. M., Wegner G., 2007, MNRAS, 382, 657
Thomas J., Saglia R. P., Bender R., Thomas D., Gebhardt K., Magorrian J., Corsini E. M., Wegner G., 2009, ApJ, 691, 770
Thomas J. et al., 2011, MNRAS, 415, 1, 545
Wayth R. B., Webster R. L., 2006, MNRAS, 372, 3, 1187
Weijmans A.-M., Krajnovic, van de Ven G., Oosterloo T. A., Morganti R., de Zeeuw P. T., 2008, MNRAS, 383, 1343
Wright C. O., Brainerd T. G., 2000, ApJ, 534, 34
Xanthopoulos E. et al., 1998, MNRAS, 300, 649
York D. G. et al., 2000, AJ, 120, 1579
Young L. M. et al., 2011, MNRAS, 414, 940

APPENDIX A: ADDITIONAL STRONG-LENSING MODELS

To check for the robustness of the previously derived lensing results, we also examine some strong-lensing models different from the ones presented in Sections 3.1 and 3.2. These models confirm the previous results without adding new implications for the results; therefore, we add these models in this appendix. The minimum $\chi^2$ values and parameter estimates of the models are shown in Tables A1 and A2.

(i) Model Ia. To account for the environment, we include the galaxy group explicitly as a SIS profile centred at galaxy I in Table 3. We use a prior on the group Einstein radius of $b_{\text{group, prior}} = 3.6 \pm 1.5$ arcsec, as derived in Section 3.2. The results and 68 per cent

© 2012 The Authors, MNRAS 427, 1918–1939
Monthly Notices of the Royal Astronomical Society © 2012 RAS

Downloaded from https://academic.oup.com/mnras/article-abstract/427/3/1918/1095096 by guest on 29 July 2018
Golden gravitational lensing systems – II

Table A1. Minimum-χ² values and parameter estimates, derived with GRAYLENS for the one-component isothermal and PL models.

| Model   | SIE+GI | b (arcsec) | q | Θ₉ (°) | β | Θ₀ (arcsec) | b_group (arcsec) | χ² | d.o.f. | x²/ν d.o.f. |
|---------|--------|------------|---|--------|---|-------------|------------------|----|--------|-------------|
| Model Ia | SIE+GI | 1.45 | 0.80 | -17.6 | 2.00 | 4.4 | 8.7 | 6 | 1.5 |
|         |        | 1.43–1.47 | 0.77–0.85 | -21.4 to -13.5 | 3.2–6.2 |
| Model Ib | SIE+es | 1.50 | 0.82 | -7.2 | 2.00 | 4.6 | 9.1 | 5 | 1.8 |
|         |        | 1.48–1.52 | 0.74–0.89 | -22.1 to -0.9 |
| Model Ia | PL+GI | 2.53 | 0.93 | -13.0 | 1.60 | 4.3 | 7.6 | 5 | 1.5 |
|         |        | 1.40–2.9 | 0.80–0.96 | -20.9 to -5.1 |
| Model Ib | NSIE | 1.49 | 0.71 | -21.6 | 2.00 | 3.8 × 10⁻⁵ | 11.5 | 6 | 1.9 |
|         |        | 1.53–1.80 | 0.72–0.78 | -23.8 to -19.5 | 0.035–0.24 |

*Fixed value.

Table A2. Minimum-χ² values and parameter estimates, derived with GRAYLENS for the two-component de Vaucouleurs plus dark matter models.

| Model | de Vaucouleurs | M (10¹¹ M☉) | qa | Θ₀q (°) | bₐ (arcsec) | Θ₀ (arcsec) | b_group (arcsec) | χ² | d.o.f. | x²/ν d.o.f. |
|-------|----------------|-------------|----|---------|-------------|-------------|------------------|----|--------|-------------|
| Model IVa | de Vaucouleurs | 15.0 | 0.0004 | 0.72 | -21.5 | 1.50 | 118 | 9 | 13.1 |
|         |                | 14.8–15.2 |     |        |             |             |                  |    |        |             |
| Model IIIa | de Vaucouleurs+SIE | 0.2–1.3 | 0.69–0.73 | -24.5 to -19.8 | 1.38–1.48 | 7.6–11.8 | 4 | 1.5 |
| Model IIIb | de Vaucouleurs+NSIE | 8.2 | 0.79 | -26.9 | 4.3 | 9.1 | 11.8–40.2 |
| Model Va | de Vaucouleurs+NSIE+GI | 7.8–9.6 | 0.70–0.83 | -28.4 to -23.4 | 9.1–32.2 | 7.6–11.8 |
|         |                | 10.0 | 0.79 | -25.5 | 2.1 | 3.6 | 7.6 | 4 | 1.9 |
|         |                | 10.0–12.2 | 0.64–0.86 | -27.1 to -15.1 | 2.5–9.6 | 7.3–28.5 | 3.5–6.4 |

The CL marginalized errors of this SIE+GI (Model Ia) case are: b = 1.45 ± 0.03 (arcsec), q = (0.81 ± 0.04), Θ₀q = -1.74 ± 0.5 ° and b_group = 4.6 ± 1.4 (arcsec) (see Fig. A1 for the derived parameter errors). This plot shows an anticorrelation between b and b_group. This is expected since the total convergence needed at the position of the main lens can be provided either by the main lens or by the mass associated with GI. We also include the environment as external shear, as calculated in Appendix B1 (see Model Ib in Appendix A). This has only small effects on the derived parameter values.

(ii) Model Ib. Model Ib is for a SIE with external shear γ; hence, it has one more free parameter relative to Model Ia. The external shear priors are based on the environment models described in Section 2.2 and Appendix B: we use γprior = 0.012 ± 0.031 and Θ₀q= -10° ± 25°. The marginalized errors are b = 1.50 ± 0.02 (arcsec), q = 0.81 ± 0.08, Θ₀q = -1.5 ± 0.2 °, β = 0.050 ± 0.025 °, and Θ₀q = -29.6 ± 7.9 °. There is a correlation present between the axial ratio q and the external shear γ, reflecting the fact that the shear and the ellipticity can compensate each other in its effects on the deflection angle, since both are pointing in the same direction within ±16°.

(iii) Model IIa. If we add group GI, we obtain a marginalized steepness value of β = 1.71 ± 0.13 (arcsec) together with b = 2.09 ± 0.80 (arcsec), q = 0.91 ± 0.05, Θ₀q = -15.3 ± 10.2 ° and b_group = 4.5 ± 1.3 (arcsec). Since there is no correlation between β and b_group, the details of the environment implementation have no systematic influence on the derived steepness of the lens mass profile. The shear and convergence provided by the group are γGI = κGI = 0.037 in agreement with our expectations.

(iv) Model IIb. A mass density profile which is flatter than isothermal at the Einstein radius can also be achieved by an isothermal mass distribution with a finite core radius. Therefore, Model IIb is for an isothermal ellipsoid with a core radius (NSIE) with β = 2 and an arbitrary value for the core radius Θ₀. For such a model one expects to also find a demagnified third image, which is not observed. We assume that the demagnified third image in the centre produced by a non-singular mass profile could be detected if its flux exceeds 3σ of the sky-object noise in the image for the brightest source pixel. We exclude a region of 0.2 arcsec in the centre due to residuals of the galaxy subtraction, where we have no limits on the image fluxes at all. We then get the following marginalized errors: β = 1.63 ± 0.010 (arcsec), Θ₀q = 0.75 ± 0.03, Θ₀q = -21.5 ± 7.0 ° and a core radius of Θ₀q = 0.11 ± 0.073 (arcsec). However, the best-fitting model is identical to Model I, that is, purely isothermal. There is a linear dependency between b and Θ₀q due to the definition of the non-singular profile: a larger core radius needs to be compensated by a larger lensing strength b to get the same enclosed mass within the Einstein radius.

(v) Model IIIa. In Model IIIa we allow for a dark matter component that is centred on the lensing galaxy. Here we test if we can improve the modelling by combining the de Vaucouleurs profile with a SIE halo. For the dark matter SIE halo, we impose a prior on the axial ratio based on the Bolton et al. (2008b) work of qdark prior = (0.79 ± 0.12). For the errors, we get b = 1.43 ± 0.05 (arcsec), q = 0.71 ± 0.02, Θ₀q = -21.9 ± 1.1 ° and Mdark SIE = (6.9 ± 0.7) × 10¹¹ M☉. Since the best-fitting model has a χ² = 11.8 and almost zero de Vaucouleurs mass, this implies that a de Vaucouleurs like mass model for the light plus a purely isothermal density profile for the dark matter are not compatible with the data. The Einstein radius of the SIE component and the de Vaucouleurs mass are anticorrelated, forcing the total projected mass within the Einstein radius to be constant.

(vi) Model IIIb. Instead of the NFW component, we can also model the dark matter component with a NSIE. We limit the core radius of this component to be between 0 and 50 arcsec, and use the same prior on the axial ratio as before. For the mass of the de Vaucouleurs component, we get: Mdark SIE = (8.5 ± 1.1) × 10¹¹ M☉.
For the other parameters, we get (see Fig. A2): \( q_a = 0.78^{+0.05}_{-0.08} \), \( \Theta_q = -26.0^{+2.0}_{-2.6} \), \( b_d = 19.2^{+13.0}_{-10.1} \) arcsec and \( \Theta_c = 24.7^{+15.5}_{-12.5} \) arcsec. Again, we note that there is a degeneracy between \( b_d \) and \( \Theta_c \), emerging from the profile definition. Since there are no observed images for radii larger than 2.32 arcsec, this leaves the upper limit of the core radius \( \Theta_c \) totally unconstrained. Large \( \Theta_c \) make this dark matter distribution flat at the Einstein radius, with \( b_d \) giving its density value. The radial mass estimates and their derivatives are plotted in Fig. A3.

(vii) Model IVa. We model the mass distribution by a de Vaucouleurs model with the shape parameters following the light profile as stated in Table 1. Therefore, the mass of the de Vaucouleurs component is the only free parameter in this model. The best-fitting light model (Model IVa) in Table A2 has \( \chi^2 = 118 \), meaning that a pure de Vaucouleurs profile is a bad fit to the observations. The de Vaucouleurs mass in this case is \( M_{\text{deV}} = (15.0^{+0.2}_{-0.2}) \times 10^{11} \) M⊙. This badness of the fit implies that there must be a (dark) mass component not following a de Vaucouleurs profile.

(viii) Model Va. Here we do the same as in Model V before: we combine the two-component model (Model IIIb) with an explicit description for the galaxy group GI. For the de Vaucouleurs component, we get: \( M_{\text{deV}} = (11.5^{+1.2}_{-1.3}) \times 10^{11} \) M⊙. For the other parameters, we get \( q_a = 0.74^{+0.10}_{-0.10} \), \( \Theta_q = -21.8^{+6.7}_{-5.3} \), \( b_d = 5.5^{+4.1}_{-3.0} \) arcsec, \( \Theta_c = 16.4^{+12.1}_{-9.1} \) arcsec, and for group GI \( b_{\text{group}} = 5.1^{+1.3}_{-1.6} \) arcsec. As one can see, again there is no significant difference between this model’s parameters and the one of Model IIIb. As for the NFW-like dark matter halo, the \( M_{\text{NFW}} \) is increased relative to Model IIIb by introducing the group halo GI. Again, the radial mass estimates and their derivatives are plotted in Fig. A3.

(ix) Model Vb. Model Vb is motivated by the fact that for the preceding models (Models III and V), the axis of the dark matter halo is always offset from that of the light by about \(-10^\circ\), which is statistically significant on a more than 3\( \sigma \) level for Models III and IIIb (see Figs 7 and A2). At the same time, the axial ratio of the dark matter haloes is consistent with the axial ratio of the stellar component (see Table 1). This could be mimicked by a non-announced external shear which is present if galaxy A is not the centre of the group. From the results for Models Ia, IIa, V and Va, we conclude that if we include the group explicitly as centred on galaxy I the matter gets more aligned with the light. Looking at Model Ib we see that using an external shear instead of GI changes the best-fitting orientation of the total mass distribution more towards the observed light’s angle. So, in this model, we combine Model IIIb with the external shear of Model Ib. In numbers, we get here: \( M_{\text{deV}} = (9.9^{+5.2}_{-5.8}) \times 10^{11} \) M⊙, \( q_a = 0.77^{+0.10}_{-0.05} \), \( \Theta_q = -14.2^{+11.5}_{-10.5} \), \( c_d = 4.1^{+4.1}_{-1.7} \), \( r_{200} = 166^{+69}_{-55} \) arcsec, and for the external shear \( \gamma = 0.038^{+0.023}_{-0.021} \) and \( \Theta_{\gamma} = -35.5^{+5.6}_{-4.5} \). We also note that with this improvement, the dark matter profile becomes more concentrated, at a level expected for galaxies.

APPENDIX B: ALTERNATIVE DESCRIPTIONS
FOR THE LENS ENVIRONMENT

In this appendix, we discuss two alternative scenarios for the environment, first a scenario in which the group is only consisting of its members (‘clumpy group’) without a reference to a group halo, and, secondly, a scenario where the group is a typical group with 12 members, but centred on galaxy A instead of galaxy I.

B1 Clumpy group

A clumpy group model is obtained if all group mass is considered to be associated with the group galaxies. We describe the galaxies as SISs without truncation of their mass profiles and obtain at the position of the lens

\[
\kappa_{\text{group}} = \sum_n \kappa_{\text{SIS},n},
\]

\[
\gamma_{\text{group}} = \sum_n \gamma_{\text{SIS},n}.
\]

In this model, the shear and surface density at the location of the lens depends on the 2D galaxy distribution and not at all on the centre of mass of the group. The galaxies themselves are parametrized only by their positions and velocity dispersions \( \sigma_i \). The value of the velocity dispersion \( \sigma_i \) for SDSS J1430+4105 is taken from the central velocity dispersion measured by the SDSS. The estimates \( \sigma_i \) for the neighbouring galaxies are obtained from the Faber–Jackson relation (Faber & Jackson 1976)

\[
\sigma_i = \sigma_A \left( \frac{i_i}{i_A} \right)^{0.25},
\]

where \( i_i \) is the SDSS i-band flux of the neighbours and \( i_A \) is the flux of the lens galaxy A. The shear \( \gamma_{\text{SIS}, i} \) and convergence \( \kappa_{\text{SIS}, i} \) for a SIS at a projected angular distance \( d_{ni} \) from its centre are

\[
\kappa_{\text{SIS}, i}(d_{ni}) = \frac{2\pi\sigma_i^2}{c^2d_{ni}} \left( D_n / D_i \right),
\]

© 2012 The Authors, MNRAS 427, 1918–1939
Monthly Notices of the Royal Astronomical Society © 2012 RAS
with \( c \) denoting the speed of light and \( D_{\text{ls}} \) and \( D_s \) mark the angular diameter distances from the lens to the source and from the observer to the source, respectively. The proper (vector) addition of these convergence and shear values yields a prediction of

\[
\gamma_{\text{clumpy group}} = 0.012, \\
\kappa_{\text{clumpy group}} = 0.023. 
\]

The angle of the shear is \(-10^\circ\) in the local coordinate system. The fact that we model the galaxies as SISs, ignoring the finite halo sizes which would keep the mass associated with galaxies limited, is not relevant, since finite halo sizes can only lead to lower estimates for the convergence and shear at the position of galaxy A. Therefore, we get an upper limit of the clumpy group estimates using this assumption. As we see in Section 3.2, the parameters of the lensing galaxy only mildly depend on the assumptions about the group as long as it is centred on galaxy I. To calculate the mass of this clumpy group, we first need \( r_{200} \). We adopt the definition of Koester et al. (2007) of \( r_{200} \) as a function of the number of group members. We sum up all mass contributions of member galaxies in Table 3 within \( r_{200} = 3.8 \) arcmin centred on galaxy A or galaxy I and calculate the total projected mass of the group within its \( r_{200} \): \( M_{200} = 5.5 \times 10^{14} \, M_\odot \). This value gives an upper limit of the mass associated with the group, since SIS profiles for its members overestimate the densities of each member at large radii.
In principle, the assumption of the group being located at galaxy A could already be in conflict with the lensing observables. The most secure strong lensing estimate is the observed critical mass $\pi R_{\text{Ein}}^2 \Sigma_{\text{crit}} = 5.43^{+0.15}_{-0.16} \times 10^{11} M_\odot$ within the Einstein radius, obtained from all models in Section 4 consistently. We now can model the group—located at galaxy A as an NFW or SIS (see Section 3.1 for details) profile and estimate its projected mass within the observed Einstein radius. If this halo mass estimate exceeds the observed critical mass, the assumption of this group being a typical group with 12 members and with galaxy A as its centre is already in conflict with the lensing observables.

In Fig. B1 we show the $c$–$r_{200}$ diagram for a NFW profile. The levels of grey indicate the virial $M_{200}$ mass of a group with parameter values $c$ and $r_{200}$. The thick solid line marks the transition where the NFW group halo mass within the observed Einstein radius alone (without baryons and dark matter of the galaxy A) exceeds the critical mass, predicting a bigger than the observed Einstein radius. Therefore, all groups that lie above this line would—from its group halo mass alone—overpredict the observed total projected mass within the Einstein radius and cannot be centred at galaxy A.

In reality, some of the observed mass within the Einstein radius has to be contributed by the stars, giving an even smaller upper limit for the dark matter mass within the Einstein radius. Hence, we plot the analogous curves for the case where the dark matter makes up only a fraction of the total critical mass within the Einstein radius. The dark-to-total matter ratios shown also in Fig. B1 as the dot–dashed lines are $f_{\text{dark}} = 0.55, 0.62, 0.74$. To obtain these numbers,
Figure B1. This figure shows the concentration $c$--$r_{200}$ properties for a NFW halo profile. The levels of grey show the virial masses of the dark matter haloes. Overplotted are several different lines: the dashed lines are the Bullock et al. (2001) $c$--$r_{200}$ relation with its $1\sigma$ error. This marks the area typically populated by galaxy groups. Further we overplot the $c$--$r_{200}$ values for a typical richness $N = 12$ group halo as found by Johnston et al. (2007) with its error bars. This shows where we expect the group halo to lie approximately in this plane. The dot–dashed lines mark the transition above which more than 55, 62 and 74 per cent of the observed critical mass within the observed Einstein radius would be made up by the dark matter halo of the group. All group haloes above this dot–dashed line in this $c$--$r_{200}$ plane overpredict the observed total mass within the Einstein radius; therefore, these lines mark regions with excluded group haloes. Since the typical Johnston et al. (2007) group halo lies below these lines, the observed critical mass within the Einstein radius does not exclude galaxy A as the group centre. The thick solid 1.00 line marks the transition where the dark matter group halo alone would provide the observed critical mass within the Einstein radius. Hence, along this line no baryons (or dark matter) in the lensing galaxy A would be required at all.

This paper has been typeset from a TeX/LATEX file prepared by the author.