Measuring the total and baryonic mass profiles of the very massive CASSOWARY 31 strong lens. A fossil system at $z \approx 0.7$?

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ABSTRACT

We investigate the total and baryonic mass distributions in deflector number 31 of the Cambridge And Sloan Survey Of Wide ARcs in the sky (CASSOWARY). We confirm spectroscopically a four-image lensing system at redshift $1.4870$ with VLT/X-shooter observations. The lensed images are distributed around a bright early-type galaxy at redshift 0.683, surrounded by several smaller galaxies at similar photometric redshifts. We use available optical and X-ray data to constrain the deflector total, stellar, and hot gas mass through, respectively, strong lensing, stellar population analysis, and plasma modelling. We derive a total mass projected within the Einstein radius $R_{\text{E}} = 70$ kpc of $(40 \pm 1) \times 10^{12} M_{\odot}$, and a central logarithmic slope of $-1.7 \pm 0.2$ for the total mass density. Despite a very high stellar mass and velocity dispersion of the central galaxy of $(3 \pm 1) \times 10^{12} M_{\odot}$ and $(450 \pm 80)$ km s$^{-1}$, respectively, the cumulative stellar-to-total mass profile of the deflector implies a remarkably low stellar mass fraction of 20% (3%–6%) in projection within the central galaxy effective radius $R_e = 25$ kpc ($R = 100$ kpc). We also find that the CSWA 31 deflector has properties suggesting it to be among the most distant and massive fossil systems studied so far. The unusually strong central dark-matter dominance and the possible fossil nature of this system renders it an interesting target for detailed tests of cosmological models and structure formation scenarios.

Key words: gravitational lensing: strong – dark matter – galaxies: structure – galaxies: stellar content

1 INTRODUCTION

Strong gravitational lensing has become a powerful tool that can be used to address a number of problems in modern cosmology and galaxy evolution (e.g., Bartelmann 2010; Treu 2010). Given the fact that the gravitational deflection of light is determined only by the gravitational field through which light propagates, the gravitational lensing effect is independent of the nature of the matter and of its state. This implies that lensing is able to measure both dark and baryonic matter, in equilibrium or far out of it. From the image configuration of a lensing system the total mass of the lens, within a cylinder with a diameter of the average image separation and centred on the lens, can be estimated very accurately. Mass measurements with a precision of a few percent can be achieved by means of detailed lens models in multiple image systems (e.g., Grillo et al. 2010; Zitrin et al. 2012). These are by far the most precise mass determinations in extragalactic astronomy. Strong gravitational lensing has already yielded groundbreaking results detecting low-mass dark-matter sub-haloes without visible stars in a few lens galaxies (e.g., Vegetti et al. 2010, 2012). Thanks to the combination of strong gravitational lensing with stellar dynamics and/or population synthesis models (e.g., Grillo 2012; Newman et al. 2013; Barnabe et al. 2012; Sonnenfeld et al. 2012), the prospects for making a step forward in our understanding of the nature of dark matter are very promising. The combination of these different mass diagnostics has also proved to be extremely successful in the exploration of several other astrophysical and cosmological topics, such as the study of the inner projected dark over total mass fractions (e.g., Grillo et al. 2009; Auger et al. 2009; Eichner, Seitz & Bauer 2012), stellar initial mass function (e.g., Grillo et al. 2009; Treu et al. 2010, Spinello et al. 2011), and tilt of the Fundamental Plane (e.g., Grillo et al. 2009; Grillo & Gobat 2010) of massive early-type galaxies and the investigation of the values of the cosmological parameters (e.g., Grillo, Lombardi & Bertin 2008; Schwab, Bolton & Rappaport 2010; Suyu et al. 2010, 2013).

In this paper, we study the total and baryonic mass distributions of the deflector number 31 (CSWA 31) of the Cambridge And Sloan Survey Of Wide ARcs in the sky (CASSOWARY) survey (Belokurov et al. 2009). This complex strong lensing system
of the system is presented in Fig. 1. In this figure, we label the five innermost and most massive galaxies that we associate with the deflector (i.e., BG and G1-G4) and the lensed objects (i.e., i1-i4 and j1) that will be discussed in the following. The brightest galaxy (BG) coordinates from the Gemini data and spectrum from the SDSS are shown, respectively, in Table 1 and Fig. 2. In the same table, we also list the Gemini coordinates of the four galaxies (G1-G4), detected in the SDSS, with photometric redshift values $z_{ph}$ that are consistent, given the errors, with the spectroscopic redshift value $z_{ph} = 0.683$ of the BG, their projected distances $d$ from the luminosity centre of the BG and the values of their $i$-band effective angles $\theta_{e_i}$ estimated by fitting the SDSS luminosity profiles.

To determine spectroscopic redshifts of the multiplied images sources we obtained slit spectra with VLT/X-shooter (Vernet et al. 2011) on April 26, 2012 (programme ID 089.A-0222(A)) using several different pointings. Despite poor observing conditions with variable seeing, high wind and humidity, we were able to secure spectra of three of the lensed images (i1, i3, and j1). In a first observational configuration, we nodded between images i1 and j1 with exposures of 900 seconds on each position in an ABBA sequence. The objects were placed on the X-shooter 11′′-long slit in such a way that the alternate position could be used for the sky subtraction in the NIR, while in the UVB and VIS the background sky was measured in the same slit. The chosen slit widths were 1.0/0.9/0.9 arcsec in the UVB, VIS and NIR arms, respectively. In a second configuration, we obtained a single integration of 900 seconds on image i3 and a faint blue galaxy 16.5′′ away from the centre of the NIR. For the sky subtraction, we used a separate integration of 900 seconds of a nearby blank sky region. Due to a higher seeing the slit widths were increased to 1.3/1.2/1.2 arcsec in the three arms.

The data were reduced with the ESO pipeline version 1.3.7 (Modigliani et al. 2010). The entire wavelength range from 300 to 2500 nm was examined for the presence of emission lines to measure the redshift of the sources. Typically, the continuum emission was very faint and could only be recognised in binned versions of the 2D spectra (see Christensen et al. 2012). In the spectrum of images i1 and i3, we detect a single bright line in the NIR. This emission line is interpreted as H$_{\beta}$ at $\lambda = 1.4870 \pm 0.0003$. Weaker lines corresponding to [NII] $\lambda$6548,6586 can also be seen, as illustrated in Fig. 3 in the apposite wavelength range of the observed two-dimensional spectrum. H$_{\beta}$ and [OIII] are detected at the 5- and 4-sigma significance level in the extracted 1D spectra, respectively, at the wavelengths corresponding to the previously cited redshift. The 1D spectra of the two exposures of the different images shown in Fig. 5 prove that the two objects are lensed multiple images of the same background source. The spectrum of image j1 reveals a single, bright emission line at 18859.4 Å. No other emission lines

Table 1. The Gemini and SDSS data of the lens galaxies.

| Object | R.A. (J2000) | Dec. (J2000) | $z_{ph}$ | $d$ (″) | $\theta_{e_i}$ (″) |
|--------|--------------|--------------|----------|--------|-------------------|
| BG     | 09:21:25.74  | 18:10:17.3   | 0.64 ± 0.04$^b$ | 0.0 | 3.54 |
| G1     | 09:21:25.89  | 18:10:09.2   | 0.71 ± 0.09 | 8.2 | 0.29 |
| G2     | 09:21:25.37  | 18:10:30.5   | 0.78 ± 0.22 | 13.7 | 2.36 |
| G3     | 09:21:26.24  | 18:10:32.1   | 0.78 ± 0.05 | 16.3 | 1.13 |
| G4     | 09:21:24.82  | 18:10:28.9   | 0.73 ± 0.09 | 17.5 | 0.48 |

$^a$ Relative to the BG luminosity centre.
$^b$ Spectroscopic redshift $z_{ph} = 0.683$.

2 OBSERVATIONS

The CSWA 31 strong lensing system was observed with GMOS on Gemini South on February 21, 2009 (programme ID GS-2009A-Q-64; Brewer et al. 2011), and the data were retrieved through the Gemini science archive. The total integration times were 20 minutes per filter in the g, r and i-band split into 4, 4 and 8 exposures, respectively, with offsets between each exposure. The data were reduced and combined using standard methods, and a colour image...
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3 TOTAL MASS MEASUREMENTS THROUGH STRONG LENSING MODELLING

In this section we focus on the measurement of the projected total mass profile of the deflector by modelling the observed multiple images.

We use the public code Gravlens ([Keeton 2001a]) to perform our analysis. We describe the total mass distribution of the deflector in terms of a one-component model, chosen to be either a singular isothermal ellipsoid (SIE) or an elliptical power-law (EPL) profile (for further details on these mass profiles, see Keeton [2001b]). We fix the total mass centre of the deflector to the luminosity centre of the BG. Since images i1, i2, i3, and i4 have very similar colours (see Fig. [I]), we assume that i2 and i4 are additional multiple images of the source at redshift 1.4870 (see Sect. 2) that is lensed into i1 and i3. We approximate the four multiple images i1-i4 to point-like objects and conduct a standard strong lensing chi-square optimisation on the model parameters (e.g., Grillo et al. 2008, 2010; Grillo & Christensen [2011]) with three and two degrees of freedom for the SIE and EPL models, respectively. We adopt a positional uncertainty of 0.3" (corresponding to two image pixels) on all image positions and repeat the strong lensing analysis starting from the measurements of the luminosity peaks of the multiple images in each of the three (g, r, and i) available Gemini images. We obtain best-fitting (minimum) $\chi^2$ values of 10.8 and 9.0, respectively, for the SIE and EPL models. This translates into average differences between observed and model-predicted positions of approximately three pixels per image. Given the approximation to point-like objects centred on their luminosity peaks for the extended images and the assumption of a single total mass component fixed on the deflector luminosity centre, we conclude that our simplified modelling choices can reproduce well the observations and do not need to be further refined, having as main goal here the measurement of the projected total mass profile of the deflector. In particular, we decide to avoid introducing an unnecessary, at this stage, external shear term for the following reasons: first, as discussed, the strong lensing configuration can be reconstructed in a satisfactory way by a single total mass component; second, the limited number of degrees of freedom available from the use of only four multiple images would not allow to disentangle the contribution of a possible external shear term from that of the main deflector mass ellipticity; third, an external shear term would not affect the projected total mass estimates, that are the most important quantities for the deflector mass decomposition presented in Sect. 5.1.

To estimate the statistical errors on the projected total mass profile, we rerun the chi-square optimisation on 3000 resampled positions of the multiple images. For these last quantities, we assume normal distributions with mean and standard deviation values equal to the observed positions and adopted positional uncertainties, respectively. We calculate the median values and the 68% (95%) confidence level (CL) intervals of the lens parameters by removing from the 3000 optimised values the 480 (75) lower and higher values and show the results in Table 2. We remark that the values of the total mass minor-to-major axis ratio, $q$, and of the position angle of the major axis, $\theta_p$, are in line with those derived from a fit to the extended light distribution in the i-band of the BG ($\theta_{\text{BG}} = 0.47 \pm 0.01$ and $\theta_{\text{BG},\text{i}} = -41 \pm 1$). We notice that the reconstructed total mass distribution does not show an unusually large elongation, further supporting the adequacy of a one-component model (without external shear) to represent the deflector mass profile.

Table 2. The median values and 68% CL intervals (relative errors are shown in square brackets) of the lens parameters from bootstrapping analyses on 3000 resampled positions of the multiple images.

| Model | $b^a$ (") | $q$ | $\theta_p$ (deg) | $\gamma_T$ |
|-------|-----------|-----|------------------|------------|
| SIE   | 9.0$^{+0.2}_{-0.1}$ [2%] | 0.53$^{+0.05}_{-0.03}$ [9%] | $-46^{+1}_{-1}$ [2%] | $-0.1^{+0.1}_{-0.1}$ [12%] |
| EPL   | 14$^{+3}_{-3}$ [21%] | 0.73$^{+0.06}_{-0.10}$ [11%] | $-45^{+1}_{-1}$ [2%] | $-1.7^{+0.2}_{-0.2}$ [12%] |

$^a$ Note that Gravlens provides the value of the lens strength $b$ multiplied by a function $f(c)$ of the minor-to-major axis ratio, $q$, and of the exponent of the three-dimensional density distribution, $\gamma_T$ (see Keeton [2001a,b]).

1 http://redfive.rutgers.edu/~keeton/gravlens/
total mass. We also find that the total mass has a slightly less elliptical distribution than the light (of the BG), as already observed in several previous strong lensing studies (e.g., [Barnabé et al. 2011; Sonnenfeld et al. 2012]). For the more general EPL model, we estimate a total mass value $M_T$ of $(4.0\pm0.1)\times10^{13}$ M$_\odot$, projected within a cylinder of radius of 70 kpc, which is the approximate value of the Einstein radius $R_\text{Ein}$ of this strong lensing system. We plot in the top panel of Fig. 4 the median, 68% and 95% CL values of the cumulative total projected mass of the deflector (we have checked that the differences between the reconstructed SIE and EPL total mass profiles do not have a significant impact on our overall conclusions). From the results of the same resampling analysis, we also estimate a median value of $-1.7$ and a 68% CL uncertainty of 0.2 for the three-dimensional, radially averaged, logarithmic slope of the total density profile $\gamma_T = d \log [\rho_T (r)] / d \log (r)$ of the deflector (see Table 2), without assuming any prior on this parameter. The inspection of the $\chi^2$ distribution as a function of the parameter $\gamma_T$ analogously reveals a rather sharply peaked global minimum at approximately $-1.7$. Furthermore, we will show in Sect. 5.1 that this measurement is consistent, given the errors, with the outcome of an initial lensing+dynamics study.

We have explicitly tested through simulations that our resampling technique with point-like images allows to recover for the deflector not only the total projected mass within the Einstein radius, but also the slope of the total mass density profile with sufficient accuracy (i.e., the true and reconstructed values agree well within the uncertainties). This is possible because the four multiple images observed in CSWA 31 are not all located at the same projected distance from the deflector centre (see Fig. 1). The position of image $i_4$, significantly closer than the other images to the adopted mass centre of the deflector (see also Fig. 4), is particularly useful to estimate the slope of the deflector total mass density. In detail, we have simulated three strong lensing configurations very similar to that of the quad in the CSWA 31 system and measured the values of the deflector total density slopes with the same method used above. We have chosen three different values, i.e. $-1.7, -2.0$, and $-2.3$, of the density slope $\gamma_T$ of the elliptical power-law profile adopted to describe the total mass distribution of the deflector and left all the other parameters of the deflector unchanged. The source has been fixed approximately at the reconstructed position of the source for the quad of the CSWA 31 system. The redshifts of deflector and source have been chosen equal to those of the CSWA 31 system. For each of the three models we have used the ray-tracing equation to obtain the positions of the corresponding four multiple images and estimated the approximate Einstein radii of the systems as the mean distances of the images from the deflector centre. Then, for each model, we have resampled 1000 times the positions of the four images assuming normal distributions with mean and standard deviation values equal to the positions previously derived and 0.3″ and minimised the chi-square varying the deflector parameters and starting from the approximate Einstein radius values and an initial value of $\gamma_T$ of $-2$. We have used the optimised deflector parameters to calculate the median values and the 68% CL intervals of $\gamma_T$. We can always find the true values of $\gamma_T$ within our measured 68% CL intervals and the median values of the estimated $\gamma_T$ are relatively close to the corresponding true values, despite some modest systematic bias towards larger values. The origin of this small overestimation of the median values might be associated to the particular geometrical configuration of the multiple images chosen in our simulations to mimic the CSWA 31 system or to the slightly asymmetric shape of the $\chi^2$ distribution as a function of $\gamma_T$ (less steep on the side of larger values of $\gamma_T$). Considering that we never use in our analysis a single value of $\gamma_T$, but always the 68% and 95% CL intervals for this parameter, we are confident that the measurements presented in this work for $\gamma_T$ in CSWA 31 are robust and not significantly biased. As already mentioned, the remarkably good consistency of the lensing-only and lensing+dynamics (see Sect. 5.1) results for the value of $\gamma_T$ in CSWA 31 reinforces this last point.

We notice that $j_1$ seems to have colours similar to those of the radially extended image located close in projection to the BG, between $i_1$ and $i_4$. If $j_1$ and this object were multiple images of the same source at $z = 1.8737$ (see Sect. 2), according to our lensing models we would expect to observe two additional images, like in the $i_1$-$i_4$ system. If instead a counter image of $j_1$ were the tangentially elongated object angularly adjacent to G2 (as assumed by [Brewer et al. 2011]), we would also predict the presence of other multiple images near $i_2$. We do not detect any clear four-image system for $j_1$ in the actual data. Because of the not obvious geometrical configuration of the lensing system to which $j_1$ belongs, we decide not to include this last system in our models until new photometric and/or spectroscopic data become available.

## 4 BARYONIC MASS MEASUREMENTS

In this section we concentrate on the estimate of the baryonic (stellar and hot gas) matter component associated with the deflector.

### 4.1 Composite stellar population modelling

Optical colors are known to correlate well with the galactic effective mass-to-light ratio (e.g., [Bell & de Jong 2001; Zibetti, Charlot & Rix 2009]. In order to derive constraints on the stellar mass content of the deflector we interpret the SDSS optical photometry of the five members listed in Table 1 by means of a Monte Carlo library of star formation histories (SFH) and dust attenuation adopting a Bayesian approach, as in [Gallazzi et al. 2005]. The SFHs are modelled with exponentially declining laws on top of which random burst$^2$ can occur with a probability such that 50% of the models in the library experience a burst in the last 2 Gyr (see also [Salim et al. 2005]). Attenuation by dust follows the [Charlot & Fall 2000] model and is parametrized by the total effective optical depth $\tau_v$ experienced by young stars in their birth clouds (which can vary between 0 and 6) and the fraction $\mu$ contributed by the interstellar medium (which can vary between 0.1 and 1). Our library of models is constructed adopting a [Chabrier 2003] IMF, however for the following analysis we decide to rescale the derived stellar masses to a [Salpeter 1955] IMF, assuming a conversion factor of 1.8.

This is motivated by the results of several recent analyses (e.g., [Grillo et al. 2009; van Dokkum & Conroy 2010; Grillo & Gobat 2010; Treu et al. 2010; Conroy & van Dokkum 2012], according to which massive early-type galaxies (as those studied here) are better represented by a bottom-heavy stellar IMF.

Because of the low and very uncertain flux level in the $u$ and $g$ bands, resulting in colours inconsistent with the other colours at

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$^2$ The formation time is required to be younger than the age of the Universe at the redshift of the BG, $z = 0.683$. The star formation timescale can vary between 0 and 1 Gyr$^{-1}$. The fraction of stellar mass produced in a burst is logarithmically distributed between 0.03 and 4, and the duration of the burst can vary between $3 \times 10^7$ and $3 \times 10^8$ yr. The models span a range of metallicities from 0.1 to 2 times solar.
redder wavelengths predicted by the models, we decide to discard the observed magnitudes in these two bands and use only the observed r, i, z SDSS model magnitudes, corrected for foreground galactic reddening (see also Grillo et al. 2009, Grillo & Christensen 2011). These are compared with those computed on all the model spectra in the library. The stellar mass of each model is obtained by multiplying the mass currently present in stars (i.e. not including the fraction returned to the ISM by evolved stars) with the scaling factor to the observed fluxes. We then construct the probability density function of stellar mass, the median of which is our fiducial $M_*$, estimate while the 16th and 84th percentiles define the 1-$\sigma$ confidence interval. The results are summarized in Table 3.

We find a very high stellar mass of approximately $3 \times 10^{12} M_\odot$ for the BG with a formal uncertainty of approximately 40%, and stellar masses around or above $10^{11} M_\odot$ for other three members of the system, albeit with very large uncertainties. We explored the systematic effects on the derived stellar masses due to our assumptions for the model library. In particular we repeated the fit 1) using only metallicities around solar, 2) excluding bursty SFHs or 3) assuming very low levels of dust attenuation. In Table 3 we provide the difference between our default fit and the modified one as an estimate of the possible systematic uncertainty. We find that the assumption on metallicity does not affect the results, as the red colors of the galaxies require a high metallicity. Removing the younger component introduced by the bursts typically provides higher stellar masses by up to 0.1 dex. Assuming negligible dust attenuation results in lower stellar masses by 0.1 dex for the BG and more than 0.2 dex for the other members. We note however that models without dust hardly reach the red $r-i$, $i-z$ observed colours providing thus a worse fit to the data.

Finally, we mention that according to the recent study by Cappellari et al. (2012a), the most massive ellipticals might have a maximal IMF, resulting in stellar mass-to-light ratios approximately 1.5 times higher than those obtained from a Salpeter IMF. In our system, this difference would apply at most to the BG galaxy. The other, smaller, galaxies should have a lighter IMF, thus bringing their estimated mass to lower values than for a Salpeter IMF. The final effect on the stellar mass profile shown in Fig. 4 would be a small shift of 0.17 dex higher than what we find now (the contribution of the other galaxies would be even smaller). We notice that this possible shift can be accommodated by our present 95% CL interval plotted in Fig. 4. Therefore, this would not change significantly our final results.

### Table 3. Stellar mass estimates from r, i, z SDSS model magnitudes for the BG and the other four galaxies G1-G4, assuming a Salpeter IMF. The last three columns give an estimate of the possible systematic uncertainties associated with different assumptions on metallicity, burstiness of the SFHs and dust attenuation, respectively.

| Object | log($M_*/M_\odot$) | $\Delta Z_{z=0}$ | $\Delta_{\text{busts}}$ | $\Delta_{\text{dust}}$ |
|--------|------------------|-----------------|-----------------|-----------------|
| BG     | 12.48$^{+0.16}_{-0.14}$ | -0.02 | -0.09 | +0.10 |
| G1     | 10.84$^{+0.14}_{-0.13}$ | -0.02 | +0.10 | +0.20 |
| G2     | 11.27$^{+0.13}_{-0.13}$ | 0.00 | +0.04 | +0.24 |
| G3     | 11.89$^{+0.15}_{-0.08}$ | 0.00 | -0.10 | +0.27 |
| G4     | 11.34$^{+0.14}_{-0.08}$ | +0.01 | -0.06 | +0.24 |

### 4.2 X-ray emission modelling

To estimate the mass of any hot intracluster medium (ICM) within the central regions, we searched for known X-ray sources close to the BG. X-ray data for this field are limited to those of the ROSAT All-Sky Survey (RASS), in which the nearest detected source lies (26 $\pm$ 13)$''$ away from the BG position. With only 7 net counts, the source is listed as point-like but with a poorly constrained spatial extent. The X-ray error circle includes none of the CSWA 31 candidate members but does overlap with an SDSS galaxy at unknown redshift. If representing extended cluster emission with a spectrum described by a thermal plasma (APEC) model, the quoted RASS hardness ratios of the source would imply a gas temperature.
$T > 2\, \text{keV}$ for any subsolar metallicity. However, the hardness ratios can be equally well reproduced by a (potentially intrinsically obscured) power-law spectrum with photon index $\Gamma < 2$, characteristic of AGN. Furthermore, the spatial offset from the BG/deflector centre of $(26 \pm 13)^\prime$ would correspond to a projected distance of $(184 \pm 92)\, \text{kpc}$ at $z = 0.683$, implying an offset between the dark matter and X-ray peaks comparable to that of the famous Bullet cluster (Clowe et al. 2006). This large offset, combined with the presence of a galaxy within the X-ray error circle, the fact that a power-law nature of the X-ray spectrum cannot be excluded, and that the emission appears point-like (albeit with low robustness), lead us to conclude that this source is unlikely to represent ICM emission from CSWA 31.

The region covered by Fig. 4 would appear point-like in RASS, so any ICM signal within this aperture must have a count rate below that of the nearby source discussed above. This constraint can be translated into a limit on the corresponding gas mass for a given ICM temperature. To this end, we first assume that the emission appears point-like (albeit with low robustness), the power-law nature of the X-ray spectrum cannot be excluded, and that the emission appears point-like (albeit with low robustness), lead us to conclude that this source is unlikely to represent ICM emission from CSWA 31.

The results of our strong lensing plus stellar population analysis (assuming a Salpeter IMF) can equivalently be interpreted as a very high projected dark over total mass fraction of about 80% within a cylinder of radius given by the effective radius of the BG galaxy. Taken at face value, this dark matter fraction appears exceptional when compared to central dark matter fractions estimated for low- and intermediate-redshift massive galaxies, either from strong lensing analysis or dynamical modelling. In particular, Grillo et al. (2009) (see also Auger et al. 2010) from a combined strong lensing and stellar population analysis of 57 early-type galaxies from the SLACS survey, and assuming a Chabrier IMF, derive dark over total mass fractions, projected within approximately half the values of the galaxy effective radii, that vary between 0.4 and 0.7 over a stellar mass range of $10^{10.5}-10^{12}\, M_\odot$. Similar central dark matter fractions are found in five higher-redshift lenses with an analogous analysis performed by More et al. (2011). Stellar population analyses combined with dynamical mass estimates of SDSS early-type galaxies also provide central projected dark over total mass fractions between 0.2 and 0.7, over a similar mass range and assuming a Chabrier IMF (Gallazzi et al. 2006; Grilli 2010). These values are consistent with the typical central three-dimensional dark-matter fractions estimated by dynamical modelling by Tortora et al. (2012), but higher than those obtained by Cappellari et al. (2012b) with 3D JAM dynamical modelling of 260 early-type galaxies in the ATLAS3D survey and without any assumption on the universality of the IMF. Thus, also considering the different IMF assumptions, the central dark over total mass fraction of CSWA 31 is at the highest end (or larger) than those typically measured in early-type galaxies of similar mass.

We should however keep in mind on the one hand the very high stellar mass of the BG analysed here and on the other the high-density environment in which it resides. Both these points could make an important difference in the expected amount of dark matter. The amount of dark matter that we measure in CSWA 31 is likely the sum of the halo of the BG and of a more extended halo of the group, which would clearly provide more dark matter than that estimated for early-type galaxies in lower density environments (although we note that no significant environmental dependence is detected by Tortora et al. 2012). Gastaldello et al. (2007) modelled the mass profiles of 16 galaxy groups with X-ray data and they found that a non-negligible stellar mass component is required in only half of their sample. For these systems the central dark over total mass fractions are on average approximately 60% (from their figures 3, 4, 5, 6 and the effective radii in their table 2). Our system, with a BG about an order of magnitude more massive than those in Gastaldello et al. (2007), has a dark matter fraction higher than their average (interestingly, in Gastaldello et al. 2007).
the central dark matter fraction reaches 90% only in the system with the least massive BG). A central dark matter fraction similar to what we derive in CSWA 31 is instead found in the fossil group RXC2315.7–0222 (Démoclès et al. 2010), where we infer a value of 86% according to their NFW profile.

Next, we use the SDSS spectrum shown in Fig. 2 to estimate the stellar velocity dispersion $\sigma_*$ of the BG. The signal-to-noise ratio per pixel of the spectrum is relatively low and varies approximately from 3 at 6500 Å to 5 at 8000 Å. We use the pixel-fitting method of Cappellari & Fasano (2004) by first shifting the spectrum to the rest-frame from the measured redshift $z = 0.683$ and compare the rest-frame spectrum at wavelengths 3820–5290 Å with template stellar spectra from the MILES library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011).

The resulting stellar velocity dispersion value is remarkably large ($450 \pm 80$ km s$^{-1}$) with a best-fit that gives a value of reduced $\chi^2$ equal to 1.03. We caution that this last result might change if a higher signal-to-noise spectrum were available, but, we also notice that such a high stellar velocity dispersion is consistent with an extrapolation of the $\sigma_*, M_*$ relation observed in massive early-type lens galaxies (e.g., Auger et al. 2010). We remark that according to the estimated values of $M_*$ and $\sigma_*$, the BG might be among the most massive central galaxies identified so far and offer an interesting case for testing galaxy formation physics at the extreme end of the galaxy mass function (e.g., Maraston et al. 2012; Thomas et al. 2013). Moreover, following the prescriptions detailed in Agnello, Auger & Evans (2013), i.e., assuming a power-law, spherical, total density profile for the deflector and using the virial theorem and the ray-tracing equation, we find that the combination of the dynamics and lensing observables provides an estimate of $\gamma_1$ of $\sim 1.65 \pm 0.05$, almost completely insensitive to any orbital anisotropy assumption and projection effect. This result is consistent with the values presented in Sect. 3 and obtained from strong lensing only. An unambiguous confirmation of the existence at intermediate redshifts of objects with values of $\sigma_*$ of approximately 500 km s$^{-1}$ would open some interesting cosmological questions about the star formation history of massive early-type galaxies and the value of the inner slope of their dark matter haloes (e.g., Loeb & Peebles 2003).

5.2 CSWA 31 as a possible fossil system

The stellar component of the CSWA 31 core is heavily dominated by that of the BG, with a magnitude difference with respect to the second brightest galaxy, G3, of $\Delta m_{12} = 2.1 \pm 0.2$ and $1.9 \pm 0.1$ mag in the observer-frame $r$- and $i$-band, respectively. As such, CSWA 31 is optically reminiscent of “fossil” groups/clusters, defined as systems with $\Delta m_{12} \geq 2.0$ in rest-frame $R$ within a projected radius of $0.5 R_{200}$, and with a $X$-ray luminosity from intergalactic gas of $L_X > 10^{43}$ erg s$^{-1}$ (Jones et al. 2003).

To test whether CSWA 31 can in fact be classified as a fossil, we first note that our inferred upper limit on $L_X$ within $R = 150$ kpc is two orders of magnitude above the value of the Jones et al. (2003) criterion. In the absence of deeper $X$-ray data, we hence cannot exclude that the system is consistent with this fossil criterion. Moreover, the $L_X$ criterion was originally imposed in order to ensure the presence of a group-scale dark matter halo, but this is clearly already established from our lensing analysis. The second requirement, $\Delta m_{12} \geq 2.0$ within $0.5 R_{200}$, can be tested with the aid of our extrapolation of the total mass profile from Section 4.2. This suggests a value of $0.5 R_{200} = 0.7$–1.5 Mpc for a plausible range in NFW concentration parameters of $c_{200} = 3$–10 (with lower $c$ corresponding to higher $R_{200}$). We therefore searched for potential group members within $R \leq 1.5$ Mpc from the BG in projection, requiring them to be brighter than G3 and having a photometric redshift consistent with the spectroscopic value of the BG. A search within SDSS $i$-band data (which most closely match rest-frame $R$ at these redshifts) returned two such objects, at $z_{\text{phot}} = 0.63 \pm 0.08$ and $0.73 \pm 0.11$, with projected radii $R = 760$–1040 kpc and for which $\Delta m_{12} = 1.6$–1.8 mag. Under the assumption of an NFW mass profile, these galaxies would reside within $0.5 R_{200}$ for $c < 10$ and $< 5$, respectively, and so would violate the fossil criterion if belonging to CSWA 31. However, given the large uncertainties associated with extrapolating the mass profile out to such large radii from the BG centre, it is entirely possible that these two galaxies are located well beyond the true value of $0.5 R_{200}$. Verification of the fossil status of CSWA 31 would thus require a more reliable assessment of the value of $R_{200}$ from, e.g., weak lensing or $X$-ray data, along with spectroscopic redshift estimates of these two galaxies to assess their possible group/cluster membership.

With the available data, we can only identify CSWA 31 as a candidate fossil system. If confirmed, it would be among the most distant and massive fossils explored in detail so far (Ulmer et al. 2005; Khosroshahi et al. 2006), and represent only the second such system studied with lensing methods (Schirmer et al. 2010). Deep $X$-ray data would be required to test whether CSWA 31 meets the fossil $X$-ray criterion and is indeed a dynamically evolved system with an undisturbed hot gas morphology, as generally anticipated for fossils. It is also relevant to note that the large values of $\Delta m_{12}$ in these systems are commonly explained in terms of dynamical friction having caused all central intermediate-mass galaxies to be cannibalized by the BG. However, for galaxies on circular orbits, the timescale for this to occur in CSWA 31 would almost certainly exceed the age of the universe at $z \approx 0.7$ (D’Onghia et al. 2005). Confirmation of the presence of such a massive fossil already at these redshifts would therefore impose valuable constraints on the galaxy infall geometry and general formation history of fossils.

6 CONCLUSIONS

We have studied the gravitational lensing system CSWA 31 in which a bright early-type galaxy at redshift 0.683 (with several nearby, smaller companions) acts as primary lens on a background source. The observed four lensed images of this source provide a large Einstein radius of approximately 70 kpc. We have modelled available photometric and spectroscopic data, in the optical and $X$-ray wavelength ranges, to explore the deflector total and baryonic mass components, through a joint strong gravitational lensing, composite stellar population and $X$-ray emission analysis. The main results of this work can be summarized as follows:

- From the detected emission lines in our new VLT/X-shooter data, we derive a source redshift of 1.4870.
- For the deflector, we measure a total mass value projected within the Einstein radius of $(40 \pm 1) \times 10^{12}$ $M_\odot$ and an inner three-dimensional logarithmic slope of the total mass density of $\sim 1.7 \pm 0.2$.
- For the brightest galaxy, we obtain very high values of stellar mass and velocity dispersion of, respectively, $(3 \pm 1) \times 10^{12}$ $M_\odot$ (assuming a Salpeter stellar IMF) and $(450 \pm 80)$ km s$^{-1}$ (inside the SDSS 3rd-diameter fibre).
- We find an upper limit of approximately $3 \times 10^{12}$ $M_\odot$ within $R = 150$ kpc for the hot gas mass component of the deflector.

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• We measure low projected stellar-to-total mass fractions of 20% and 3–6% within apertures equal to, respectively, 25 kpc (i.e., the effective radius of the brightest galaxy) and 100 kpc.

We remark that atypical strong lensing systems as CSWA 31 are particularly useful to test our understanding of the baryonic and dark-matter mass assembly history of cosmological structures, as imprinted in the mass profile, in the currently accepted ΛCDM scenario. The high stellar mass value of the brightest galaxy and the large magnitude gap between this and the other lens galaxies might be precisely the inner steepness and mass of the dark matter halo associated with the deflector. These results would offer invaluable information to be compared against cosmological simulations.

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