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# Separating Galaxies from the Cluster Dark Matter Halo in Abell 611

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## ABSTRACT

We investigate the mass content of galaxies in the core of the galaxy cluster Abell 611. We perform a strong lensing analysis of the cluster core and use velocity dispersion measurements for individual cluster members as additional constraints. Despite the small number of multiply-imaged systems and cluster members with central velocity dispersions available in the core of A611, the addition of velocity dispersion measurements leads to tighter constraints on the mass associated with the galaxy component, and as a result, on the mass associated with the dark matter halo. Without the spectroscopic velocity dispersions, we would overestimate the mass of the galaxy component by a factor of  $\sim 1.5$ , or, equivalently, we would underestimate the mass of the cluster dark halo by  $\sim 5\%$ . We perform an additional lensing analysis using surface brightness (SB) reconstruction of the tangential giant arc. This approach improves by up to a factor  $\sim 10$  the constraints on the mass parameters of the 5 galaxies close to the arc. The resulting parameters are in good agreement with the  $\sigma - r_{\text{tr}}$  scaling relation derived in the pointlike analysis. The galaxy velocity dispersions resulting from the SB analysis are consistent at the  $1\sigma$  confidence level with the spectroscopic measurements. In contrast the truncation radii for 2-3 galaxies depart significantly from the galaxy scaling relation and suggest differences in the stripping history from galaxy to galaxy.

**Key words:** dark matter, galaxy cluster, galaxy haloes, gravitational lensing.

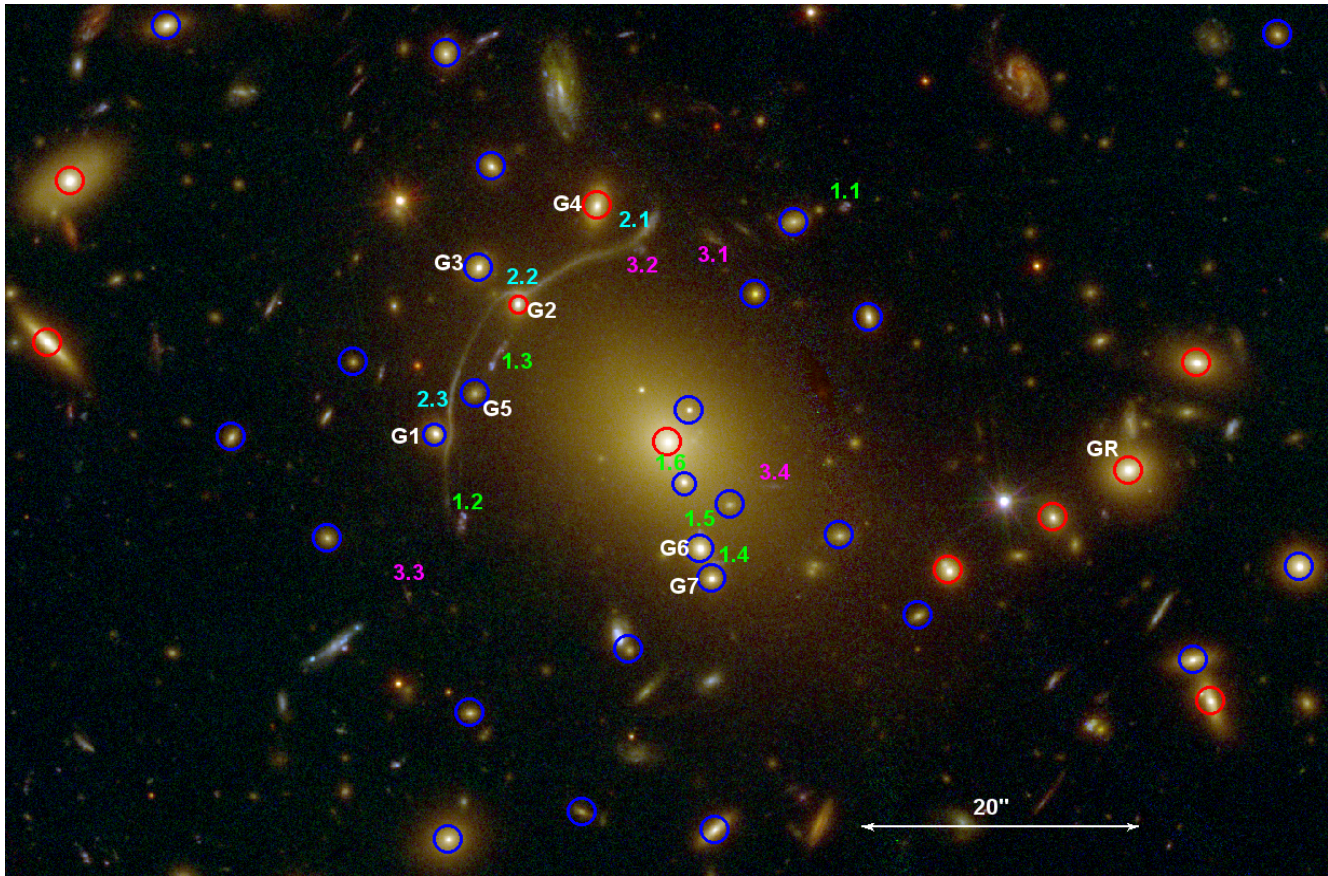
## 1 INTRODUCTION

Galaxies, and to a larger extent, clusters of galaxies, are dominated by *dark matter* (DM). Although DM cannot be observed directly, it can be detected through its gravitational effects. Thus gravitational lensing is a powerful tool for investigating the distribution of dark matter (e.g. see Schneider 2003; Bartelmann 2010; Kneib & Natarajan 2011). Lensing allows a direct probe of the total projected mass density of the lens. In the case of strong lensing (SL) by galaxy clusters, the location and redshift of sets of multi-

ple images enable mapping of the mass-density distribution. To disentangle the cluster-scale dark halo component from the galaxies' contribution, additional constraints sensitive to only one of the two components are necessary (Eichner et al. 2013; Monna et al. 2015).

A common assumption is that the DM content of galaxies scales in proportion to their light (e.g. see Koopmans et al. 2006). Luminosity scaling relations allow estimates of some properties of the galaxy dark halos including their mass or central velocity dispersion and their extent. Weak and strong lensing analyses reveal that the extent of a galaxy's DM halo also depends on its environment (e.g. see Narayan 1998; Geiger & Schneider 1999; Limousin et al. 2007; Halkola,

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**Figure 1.** Colour composite image of the core ( $\sim 1.5' \times 1.5'$ ) of A611 created using the CLASH HST dataset: Blue=F435W+F475W; Green=F606W+F775W+F814W+F850LP; Red=F105W+F110W+F140W+F160W. Blue circles mark the cluster members included in the SL analysis. Red circles mark the galaxies with a measured central velocity dispersions. “GR” indicates the galaxy used as reference for the luminosity scaling relation. “G1” to “G7” are the galaxies we model individually. The 3 multiply lensed systems used in the SL analysis are labelled in green (system 1), cyan (system 2) and magenta (system 3). North is up and East is left.

Seitz & Pannella 2007). Galaxy-galaxy lensing analyses show that typical radii of dark matter halos are of the order of hundreds of kpc (Brimioulle et al. 2013; Limousin et al. 2007). In denser environment, like galaxy clusters (Limousin et al. 2007, 2009), galaxies are stripped during interactions with each other and with the smooth extended cluster dark matter halo. Simulations predict that galaxies in the cluster core should be strongly truncated (Merritt 1983; Limousin et al. 2009) in agreement with lensing results. However uncertainties in the measurements of the truncation radii are large (Natarajan, Kneib & Smail 2002; Limousin et al. 2007; Halkola, Seitz & Pannella 2007; Donnarumma et al. 2011).

In parametric strong lensing analysis the mass of a galaxy is often represented by a velocity dispersion. For a singular isothermal sphere,  $M_{tot} \propto \sigma^2 r_{tr}$  (Elíasdóttir et al. 2007), where  $\sigma$  is the central velocity dispersion and  $r_{tr}$  is the halo truncation radius. Galaxy velocity dispersions are inferred directly from their luminosity through the Faber-Jackson relation ( $L_e \propto \sigma_0^4$ ) (Faber & Jackson 1976). The respective mass is then estimated through the luminosity – velocity dispersion – mass scaling relations. However, large scatter in the Faber-Jackson relation inherently introduces modelling biases in lensing analyses.

Direct measurement of the velocity dispersions of individual cluster members allows a more direct estimate of their

total mass, independent of the lensing signal. Spectroscopic velocity dispersion measurements are thus useful for separating the galaxy component from the global cluster DM halo. Monna et al. (2015) show that using velocity dispersion measurements in a SL analysis sets stronger constraints on the galaxy dark matter halos and breaks the internal degeneracy between their mass profile parameters. By using Hectospec (Fabricant et al. 2005, 2013) velocity dispersions for  $\sim 15$  cluster members in the core of the galaxy cluster Abell 383, Monna et al. (2015) improve constraints on the galaxy luminosity scaling relations by 50%. Furthermore, surface brightness reconstruction of the giant arc in Abell 383 measures the extent of the DM halos of some cluster members near the arc.

Here we investigate a second cluster, Abell 611 (A611 hereafter) at  $z_{cl} \sim 0.288$ . Several previous SL analyses derive a mass distribution for A611 focusing on different aspects of mass modelling through strong lensing. For example, Richard et al. (2010) analyse 20 galaxy clusters from the LoCuSS survey, including A611, to constrain the total mass in cluster cores and to compare them with X-ray measurements. Donnarumma et al. (2011) combine SL and X-ray analyses of A611 and tested different approaches for modelling the mass associated with the cluster galaxy com-

**Table 2.** List of cluster members with measured velocity dispersion in the core of A611. Col.1 gives the ID, Col. 2 and 3 give the Ra and Dec in degrees, Col. 4 the spectroscopic redshift and Col. 5 the `auto_mag` extracted with SExtractor in the F814W filter. Col. 6 provides the effective radius measured with GALFIT in the HST/F814W band, and Col.7 lists the measured central velocity dispersion.

| ID  | RaJ2000   | DecJ2000 | $z_{sp}$ | mag <sub>F814W</sub> | $R_{\text{eff}}$ (kpc) | $\sigma_{sp}$ (km/s) |
|-----|-----------|----------|----------|----------------------|------------------------|----------------------|
| BCG | 120.23676 | 36.05657 | 0.287    | 16.6                 | 40.0                   | $330 \pm 19$         |
| GR  | 120.22530 | 36.05598 | 0.291    | 19.2                 | 5.4                    | $185 \pm 25$         |
| G2  | 120.24033 | 36.05950 | 0.283    | 20.0                 | 3.4                    | $124 \pm 45$         |
| G4  | 120.23850 | 36.06141 | 0.281    | 19.9                 | 1.9                    | $214 \pm 72$         |
| 243 | 120.22977 | 36.05394 | 0.287    | 19.9                 | 1.3                    | $251 \pm 37$         |
| 446 | 120.21320 | 36.06816 | 0.286    | 20.5                 | 2.3                    | $293 \pm 105$        |
| 123 | 120.25097 | 36.04291 | 0.283    | 19.0                 | 9.0                    | $251 \pm 24$         |
| 533 | 120.25350 | 36.07586 | 0.290    | 19.4                 | 3.5                    | $249 \pm 56$         |
| 489 | 120.25670 | 36.06833 | 0.284    | 19.4                 | 2.9                    | $235 \pm 42$         |
| 248 | 120.22717 | 36.05502 | 0.295    | 20.7                 | 1.3                    | $231 \pm 81$         |
| 159 | 120.25952 | 36.04721 | 0.283    | 19.4                 | 2.4                    | $228 \pm 41$         |
| 345 | 120.25213 | 36.05861 | 0.291    | 19.1                 | 4.1                    | $221 \pm 28$         |
| 316 | 120.22361 | 36.05819 | 0.297    | 19.6                 | 2.2                    | $217 \pm 43$         |
| 402 | 120.25158 | 36.06192 | 0.288    | 19.1                 | 4.2                    | $208 \pm 19$         |
| 380 | 120.21555 | 36.06329 | 0.287    | 20.3                 | 2.0                    | $178 \pm 44$         |
| 137 | 120.23792 | 36.04691 | 0.279    | 20.4                 | 1.3                    | $156 \pm 54$         |
| 512 | 120.21346 | 36.06996 | 0.278    | 20.3                 | 2.2                    | $139 \pm 54$         |

**Table 1.** CLASH Photometric Dataset: column (1) filters, column (2) HST instrument, column (3)  $5\sigma$  magnitude depth within  $0.6''$  aperture.

| Filter | Instrument | $5\sigma$ Depth |
|--------|------------|-----------------|
| f225w  | WFC3/UVIS  | 25.4            |
| f275w  | WFC3/UVIS  | 25.6            |
| f336w  | WFC3/UVIS  | 26.0            |
| f390w  | WFC3/UVIS  | 26.5            |
| f435w  | ACS/WFC    | 26.3            |
| f475w  | ACS/WFC    | 26.7            |
| f606w  | ACS/WFC    | 27.0            |
| f775w  | ACS/WFC    | 26.2            |
| f814w  | ACS/WFC    | 26.7            |
| f850lp | ACS/WFC    | 25.9            |
| f105w  | WFC3/IR    | 26.9            |
| f110w  | WFC3/IR    | 26.9            |
| f125w  | WFC3/IR    | 26.8            |
| f140w  | WFC3/IR    | 26.9            |
| f160w  | WFC3/IR    | 26.7            |

ponent. Within the cluster core ( $r < 100$  kpc), SL and X-ray mass measurements agree well, but in the outer region there are discrepancies. The disagreement at large radius suggests an incorrect estimate of the relative contributions of the baryonic and DM components to the cluster mass as a result of the degeneracy between the galaxy and the smooth large scale dark matter components. Newman et al. (2009, 2013a) combine kinematic data with strong and weak lensing to model the mass distribution of the cluster from the very central region out to well beyond the virial radius. They use measurement of the BCG velocity dispersion to constrain its stellar mass and thus to disentangle the baryonic and DM components in the very core. An NFW profile fails to describe the cluster DM alone; shallower profiles fit the data better. More recently, Zitrin et al. (2015) presented a statistical weak and strong lensing analysis of the complete CLASH cluster sample, including A611. They ex-

amine the effect of different mass parametrizations on the resulting mass model and show that systematic differences of 40% in the projected surface mass density can result from various lensing degeneracies.

We use a set of spectroscopic velocity dispersions measured with Hectospec (see Fabricant et al. 2005, 2013) mounted on the Multiple Mirror Telescope (MMT) to improve constraints on the mass distribution of A611 and its mass components. We carry out a SL analysis for A611, both with and without the velocity dispersion measurements and examine the impact of these measurements in constraining both the mass in galaxies and in the dark matter halo. We also use the surface brightness morphology of the giant arc to refine constraints on five cluster galaxies neighbouring the arc.

§2 describes the photometric and spectroscopic datasets. §3 describes the SL analysis, the mass components included in the mass model and the lensed systems used as constraints. The SL analysis results are in §4. We discuss the improvements resulting from the use of velocity dispersion measurements in the lensing analysis. §5 discusses the surface brightness reconstruction of the giant tangential arc. We conclude in §6. We assume a cosmological model with Hubble constant  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and density parameters  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ . Magnitudes are in the AB system.

## 2 PHOTOMETRIC AND SPECTROSCOPIC DATASET

A611 was observed in 2012 during the Hubble Space Telescope (HST) Cycle 19, as part of the CLASH survey. It was observed with the HST Advanced Camera for Surveys (HST/ACS) and the Wide Field Camera 3 (HST/WFC3) UVIS and IR cameras providing deep photometry in 15 different HST filters, to a depth of roughly  $\sim 27\text{AB}$

( $3\sigma$ ). The photometric dataset<sup>1</sup> was processed with the `Mosaicdrizzle` pipeline (see Koekemoer et al. 2011) to generate mosaic drizzled images with a common scale of 65mas/pixel, centred on the cluster. The field of view (FOV) is  $\sim 3.5' \times 3.5'$  in the ACS filters and  $\sim 2' \times 2'$  in the WFC3IR images. In Tab. 1 we list the filters of the photometric data with the respective  $5\sigma$  depths. We generate multi-band photometric catalogues of fluxes extracted within  $0.6''$  (9 pixels) diameter aperture using `SExtractor` 2.5.0 (Bertin & Arnouts 1996) in dual image mode. We use the weighted sum of all of the WFC3IR images as the detection image.

We measured redshifts and velocity dispersions with the Hectospec fiber spectrograph mounted on the MMT (Fabricant et al. 2005). Hectospec has 300 fibers deployable over a 1 degree field. The instrument has  $1.5''$  fibers and the spectra cover the wavelength range 3500 - 9150 Å. The resolution is of  $5.5 \text{ Å FWHM}$ , which corresponds to 105 km/s at 6000 Å. We acquired data under variable conditions with typical seeing of  $0.9''$  on February 9, April 5, and April 9-10, 2010, on November 22-23, 2011, and on October 8 and November 28, 2013 (Fabricant et al. 2013). The typical integration time was 1 hour. All redshifts are published in Lemze et al. (2013).

Within  $1.5'$  of the cluster centre, the Hectospec data provide redshifts for 27 cluster members and central velocity dispersions for seventeen of these members. We include a central velocity dispersion here only when its uncertainty is  $\lesssim 40\%$  of the dispersion.

We extract the velocity dispersions from the Hectospec spectra by applying the University of Lyon Spectroscopic analysis Software7 (UlySS; Koleva et al. 2009). Single age stellar population models calculated with the PEGASE-HR code (Le Borgne et al. 2004) and the MILES stellar library (Sánchez-Blázquez et al. 2006) provide the basis for fitting the observed spectrum. We limit the spectral fitting range to 4100 – 5500 Angstrom rest-frame wavelengths where we obtain the smallest velocity dispersion errors and the most stable velocity dispersions (Fabricant et al. 2013). Based on the measured line spread function, we convolve models to the wavelength dependent spectral resolution of the Hectospec data (Fabricant et al. 2013). We convolve models that are parametrized by age and metallicity with the line-of-sight velocity dispersion; we then use  $\chi^2$  minimization to determine the best-fit age, metallicity and velocity dispersion. Fabricant et al. (2013) discuss the details of these measurements. Zahid et al. (2015) carry out a further demonstration of the excellent agreement between these measurements and those derived for the same galaxies by the SDSS.

Following Jorgensen, Franx & Kjaergaard (1995), we correct the measured velocity dispersion  $\sigma_{obs}$  observed with the Hectospec  $1.5''$  aperture fibers, to estimate the galaxy central stellar velocity dispersion  $\sigma_{sp}$  within the effective radius of the galaxy,  $R_{eff}$ , according to

$$\sigma_{sp} = \sigma_{obs} \left( \frac{R_{eff}}{8 \times d/2} \right)^{-0.04}, \quad (1)$$

where  $d$  is the fiber aperture. We estimate the effective radii of cluster members with `GALFIT` (Peng et al. 2010) by fitting the surface brightness distribution of the galaxies in

the HST/F814W filter with de Vaucouleurs profiles. Table 2 lists all of the galaxies with measured velocity dispersions used in the lensing analysis.

### 3 STRONG LENSING MODELING

We model the mass distribution in the core of A611 using the software GLEE developed by A. Halkola and S. Suyu (Suyu & Halkola 2010; Suyu et al. 2012). We use the observed positions of the multiple images as constraints throughout the analyses; thus we refer to these models as *pointlike*. Spectroscopic redshifts of the lensed sources, if available, are additional constraints. The best fitting model is found through a simulated annealing minimization in the image plane. The most probable parameters and uncertainties for the cluster mass model are then obtained from Monte Carlo Markov Chain (MCMC) sampling.

#### 3.1 Multiple images

To reconstruct the mass distribution in the core of A611, we use three robust systems of multiple images as constraints (Fig. 1; see Newman et al. 2013a; Zitrin et al. 2015).

**System 1** is a quintuply lensed source spectroscopically confirmed at  $z_{sp} = 1.56$  (the redshift has been recently revised, see Newman et al. 2013a). A central image, embedded in the BCG light, is associated with this system and is included as a constraint, for a total of 6 multiple images.

**System 2** is a giant tangential arc at a distance of  $\sim 18''$  from the BCG, passing in between 5 bright galaxies (G1-G5). We use the positions of the three brightest knots of the arc as constraints in the analysis. This system has a spectroscopic redshift of  $z_{sp} = 0.9$ .

Finally **system 3** is a quadruply lensed source, for which no spectroscopic redshift is available. Thus its redshift is a free parameter and is optimized around the photometric redshift  $z_{phot} = 1.54$  of the brightest lensed image (3.1) using a flat prior in the range  $[0.5, 2.5]$ .

The position of all the multiple images are listed in Tab. 3 together with their respective redshifts.

We adopt errors of  $1''$  on the position of the observed multiple images to account for uncertainties due to density fluctuations along the line of sight (see Host 2012; D'Aloisio & Natarajan 2011).

#### 3.2 Cluster mass component

##### Cluster smooth large scale halo

We describe the smooth dark halo (DH) mass component of the cluster with a Pseudo Isothermal Elliptical Mass Distribution (PIEMD) profile (Kassiola & Kovner 1993). Its projected surface density is

$$\Sigma(R) = \frac{\sigma^2}{2G} \left( \frac{1}{\sqrt{r_c^2 + R^2}} \right), \quad (2)$$

where  $\sigma$  and  $r_c$  are the halo velocity dispersion and core radius.  $R$  is the 2D radius, defined as  $R^2 = x^2/(1+e)^2 + y^2/(1-e)^2$  for a profile with ellipticity  $e = (1-b/a)/(1+b/a)$ , where  $b/a$  is the axis ratio. The asymptotic ( $b/a \rightarrow 1, r_c \rightarrow$

<sup>1</sup> available at <http://archive.stsci.edu/prepds/clash/>

**Table 3.** Multiply imaged systems used to constrain the SL model of A611. The columns are: Col.1 is the ID; Col.2-3 Ra and Dec; Col.4 is the source redshift  $z_s$  which is spectroscopic for System 1 and 2, and photometric for system 3 (Zitrin et al. 2015); Col. 5 is the final source redshift from the strong lensing model; col. 6 provide the difference between the observed and predicted position of each multiple image resulting from our final best cluster model (see Sec. 4).

| Id  | Ra         | Dec       | $z_s$ | $z_{sl}$        | $\delta\theta('')$ |
|-----|------------|-----------|-------|-----------------|--------------------|
| 1.1 | 120.232260 | 36.061430 | 1.56  | -               | 1.1                |
| 1.2 | 120.241820 | 36.055075 | 1.57  | -               | 0.6                |
| 1.3 | 120.241110 | 36.058144 | -     | -               | 0.4                |
| 1.4 | 120.235610 | 36.054100 | -     | -               | 0.1                |
| 1.5 | 120.235950 | 36.054732 | -     | -               | 0.2                |
| 1.6 | 120.236680 | 36.056140 | -     | -               | 0.8                |
| 2.1 | 120.237240 | 36.060997 | 0.91  | -               | 1.0                |
| 2.2 | 120.240480 | 36.059643 | -     | -               | 0.6                |
| 2.3 | 120.242150 | 36.057169 | 0.86  | -               | 0.6                |
| 3.1 | 120.235610 | 36.060708 | 1.54  | $1.68 \pm 0.20$ | 0.7                |
| 3.2 | 120.237380 | 36.060528 | 1.12  | "               | 0.3                |
| 3.3 | 120.243160 | 36.053450 | 1.52  | "               | 0.4                |
| 3.4 | 120.234070 | 36.055653 | -     | "               | 1.1                |

0) Einstein radius  $\theta_E$  for this profile is

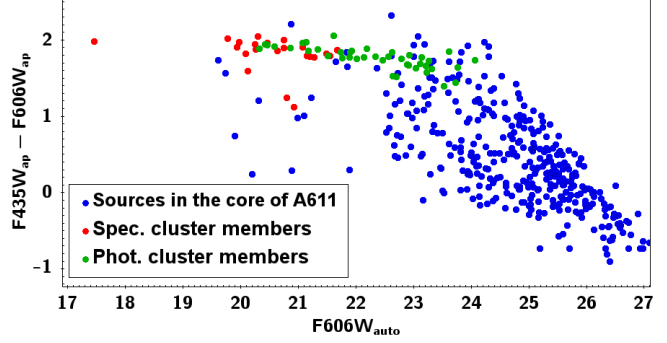
$$\theta_E = 4\pi \left( \frac{\sigma}{c} \right)^2 \frac{D_{ds}}{D_s} = \Theta_E \frac{D_{ds}}{D_s} \quad (3)$$

where  $\sigma$  is the halo velocity dispersion,  $c$  is the speed of light, and  $D_s$  and  $D_{ds}$  are the distances to the lensed source and between the lens and the source, respectively. The *Einstein parameter*  $\Theta_E$  is the Einstein radius for  $D_{ds}/D_s = 1$ . We use  $\Theta_E$  as a parameter to describe the mass amplitude of the lens halo. All the DH parameters are optimized using flat priors. The halo is initially centred on the BCG, and its position is optimized within 3 arcsec. The axis ratio and position angle (PA) vary within  $[0,1]$  and  $180^\circ$  respectively. The core radius varies within  $[0,60]$  kpc. The Einstein parameter  $\Theta_E$  is optimized in the range  $[4.5'', 65'']$  corresponding to a velocity dispersion of  $\sim [400, 1500]$  km/s.

### BCG

Newman et al. (2009, 2013a,b) perform a detailed analysis of the stellar mass profile of the BCG in A611 by combining SL and kinematic analyses. They model the BCG stellar mass profile using a dual pseudo elliptical isothermal profile (dPIE, see Elíasdóttir et al. 2007) to fit the surface brightness profile of the BCG. The effective radius of the BCG is consistent with the truncation radius of the dPIE profile ( $r_{tr,BCG} = 46.2 \pm 3.4$  kpc Newman et al. 2013a,b). By combining lensing and kinematic analysis they estimate the amplitude of the dPIE profile describing the BCG stellar mass. This amplitude is characterized by a central velocity dispersion  $\sigma_{0,BCG} = 164 \pm 33$  km/s.

In our lensing model, we also describe the BCG stellar mass component by using a dPIE profile. For this mass component we adopt the parameters estimated by Newman et al. (2013a,b) and we optimize them within their uncertainties using gaussian priors.



**Figure 2.** Colour-magnitude diagram for A611. We show all of the sources extracted in the core of A611 (blue), the cluster members with measured spectroscopic redshift (red), and the photometric candidate cluster members (green) included in the SL model.

### Cluster members

Our analysis includes cluster members within a FOV of  $\sim 1.5' \times 1.5'$  centred on the cluster core (RAJ2000=120.23676 and DECJ2000=36.05657). Within this FOV there are 27 spectroscopically confirmed cluster members from the Hectospec survey with  $|z_{sp} - z_{cl}| < 0.02$ . Further candidate cluster members are selected photometrically. We select bright galaxies ( $m_{auto,F606W} \leq 25$ ) on the cluster red sequence with  $1.3 \leq m_{F435W} - m_{F606W} \leq 2.3$  (Fig. 2). We also require that these galaxies have photometric redshift  $|z_{ph} - z_{cl}| \leq 0.03$ . Photometric redshifts are estimated using the CLASH dataset (see Tab. 1), based on the spectral energy distribution (SED) fitting code **LePhare**<sup>2</sup> (Arnouts et al. 1999; Ilbert et al. 2006), using the COSMOS galaxy spectra (Ilbert et al. 2009) as templates.

We select a total of 69 cluster members; 27 are spectroscopic members and 42 are photometric candidates. Galaxies are modelled with dPIE profiles (Elíasdóttir et al. 2007). This profile is characterized by a central velocity dispersion  $\sigma$ , a core radius  $r_c$  and a truncation radius  $r_{tr}$ , marking the region where the density slope changes from  $\rho \propto r^{-2}$  to  $\rho \propto r^{-4}$ .

The projected surface mass density is

$$\Sigma(R) = \frac{\sigma^2}{2GR} \frac{r_{tr}^2}{(r_{tr}^2 - r_c^2)} \left( \frac{1}{\sqrt{1 + \frac{r_{tr}^2}{R^2}}} - \frac{1}{\sqrt{1 + \frac{r_c^2}{R^2}}} \right) \quad (4)$$

where  $R^2 = x^2/(1+e)^2 + y^2/(1-e)^2$ , as for the PIEMD mass profile. The total mass is

$$M_{tot} = \frac{\pi \sigma^2}{G} \frac{r_{tr}^2}{r_{tr} + r_c}, \quad (5)$$

which, for  $r_c \rightarrow 0$ , reduces to

$$M_{tot} = \frac{\pi \sigma^2 r_{tr}}{G}. \quad (6)$$

For a vanishing core radius,  $r_{tr}$  corresponds to the radius containing half of the total mass of the galaxy (see Appendix A3 in Elíasdóttir et al. 2007). We adopt vanishing core radii for the cluster members, unless stated otherwise. Thus there are 2 free parameters associated with each galaxy,  $\sigma$  and  $r_{tr}$ .

<sup>2</sup> <http://www.cfht.hawaii.edu/~arnouts/lephare.html>

To reduce the total number of free parameters for the cluster members, we adopt luminosity scaling relations to derive the galaxy parameters  $\sigma$  and  $r_{\text{tr}}$  (e.g. see Jullo et al. 2007; Eichner et al. 2013). The Faber-Jackson relation (Faber & Jackson 1976) allows estimation of the central velocity dispersion of elliptical galaxies directly from the observed photometry:

$$\sigma_i = \sigma_{\text{GR}} \left( \frac{L_i}{L_{\text{GR}}} \right)^\delta, \quad (7)$$

where  $\sigma_{\text{GR}}$  and  $L_{\text{GR}}$  are the central velocity dispersion and luminosity of a fiducial reference galaxy.

The Fundamental Plane (e.g. see Dressler et al. 1987; Faber et al. 1987; Bender, Burstein & Faber 1992) also provides a luminosity scaling relation for the size of the halos. Following Hoekstra et al. (2003); Halkola, Seitz & Pannella (2007); Limousin et al. (2007) the truncation radii of galaxy halos scale with their luminosities according to

$$r_{\text{tr},i} = r_{\text{tr,GR}} \left( \frac{L_i}{L_{\text{GR}}} \right)^\alpha \propto r_{\text{tr,GR}} \left( \frac{\sigma_i}{\sigma_{\text{GR}}} \right)^{\frac{\alpha}{\delta}}, \quad (8)$$

where  $r_{\text{tr,GR}}$  and  $L_{\text{GR}}$  are the truncation radius and luminosity of the reference galaxy.

The total mass-to-light ratio for the cluster members is

$$\frac{M_{\text{tot}}}{L} \propto L^\epsilon, \quad (9)$$

which, given Eq. 8, implies

$$M_{\text{tot}} \propto \sigma^{\frac{1}{\delta}(\epsilon+1)}. \quad (10)$$

Combining Eq. 6, 8 and 10 we derive a relation among the exponents of the luminosity scaling relations

$$2\delta + \alpha - \epsilon = 1. \quad (11)$$

Measurements of the exponent  $\delta$  from photometric analysis give value between 0.25 and 0.3 (see e.g., Kormendy & Bender 2013; Focardi & Malavasi 2012): measurements through strong and weak lensing analysis provide a value of  $\delta = 0.3$  (see Rusin et al. 2003; Brimiouille et al. 2013). From our sample of galaxies with measured velocity dispersion in A611,  $\delta = 0.3$  in the F814W band. Thus we adopt this value. Following our previous analysis, we assume a constant mass-to-light ratio ( $\epsilon = 0$ ) (see Eichner et al. 2013; Monna et al. 2015), which then implies  $\alpha = 0.4$  from Eq. 11. The exponents of the scaling relations are fixed to these values throughout our analysis. The constraints available in the field of the cluster are insufficient for further investigation of the choice of values of the exponents. Throughout our analysis we do investigate the amplitude of the luminosity scaling relation by tuning the parameters  $\sigma_{\text{GR}}$  and  $r_{\text{tr,GR}}$  of the reference galaxy. Thus the velocity dispersion  $\sigma_i$  and truncation radius  $r_{i,\text{tr}}$  of the  $i$ -th cluster member follow the scaling relation

$$\sigma_i = \sigma_{\text{GR}} \left( \frac{L_i}{L_{\text{GR}}} \right)^{0.3} \quad r_{\text{tr},i} = r_{\text{tr,GR}} \left( \frac{L_i}{L_{\text{GR}}} \right)^{0.4} \quad (12)$$

where  $\sigma_{\text{GR}}$  and  $r_{\text{GR,tr}}$  are the values for the reference galaxy GR.

As fiducial galaxy GR we adopt a bright elliptical ( $b/a \sim 0.9$ ,  $f814w_{\text{best}} = 19.2$ )  $\sim 30''$  west of the BCG, slightly outside the critical lines for a source at redshift

$z_s = 2$ . This galaxy has a measured velocity dispersion  $\sigma_{\text{sp,GR}} = 185 \pm 25$  km/s (Table 2). We optimize the velocity dispersion through the lensing analysis with a gaussian prior consistent with the measurement uncertainties. The GR truncation radius is a free parameter optimized with a flat prior in the range  $[0.3'', 20'']$ .

The cluster members with measured  $\sigma_{\text{sp}}$  are assigned their central velocity dispersions fixed to the spectroscopic measurement throughout the modelling. Thus we assume that the measured central stellar velocity dispersion  $\sigma_{\text{sp}}$  is a robust estimate of the central velocity dispersion of the galaxy halo.

In addition seven galaxies located very close to the tangential arc and to the central multiple images of system 1 (G1 to G7, see Fig. 1), are individually optimized. Two of these galaxies, G2 and G4, have measured  $\sigma_{\text{sp}}$  that are optimized with a gaussian prior within the measurement errors. The central velocity dispersions for the other galaxies (G1, G3, G5, G6 and G7) are optimized with a flat prior in the range  $[10, 400]$  km/s. For these 5 cluster members, the truncation radii are free parameters optimized within  $[0.3'', 20'']$ .

The position, axis ratio  $b/a$ , and PA of all the galaxies are fixed to the values extracted from the photometry in the F814W filter. Only for the galaxies G1 to G5, the axis ratio and PA are optimized with a gaussian prior.

Finally, we also allow for an external shear component to account for the large scale environmental contribution to the lensing potential.

## 4 POINTLIKE MODEL

Given the model in Section 3, we perform a  $\chi^2$  minimization analysis on the position of the observed multiple images. Then we run MCMC chains to obtain the final best model and the relative uncertainties. The final best model has  $\chi^2 = 0.7$  and reproduces the multiple images with a mean accuracy of  $0.7''$ . Fig. 3 shows the distance  $\delta\theta$  between the predicted and the observed positions of the multiple images as a function of the projected distance of the lensed image from the BCG. These  $\delta\theta$  are in Tab. 3, together with the model prediction of the source redshift for system 3. System 3 has a mean rms of  $0.6''$  for the multiple image reproduction and a redshift  $z_{\text{sl}} = 1.7 \pm 0.2$ , consistent with the photometric redshift.

The model yields a cluster dark halo centred at  $x = -0.5 \pm 0.6$  arcsec,  $y = 1.0 \pm 0.6$  arcsec with respect to the BCG, its axis ratio is  $b/a = 0.8 \pm 0.1$  with P.A. =  $126^\circ \pm 6^\circ$ . The core radius is  $25 \pm 8$  kpc and the Einstein parameter  $\Theta_E = 20.2 \pm 1.4$  arcsec corresponding to  $\sigma = 837 \pm 29$  km/s. For a source at  $z_s = 2$ , the halo has a fiducial Einstein radius  $\theta_E = 15.7 \pm 1.1$  arcsec. The total mass of the cluster within the Einstein radius  $\theta_E$  is  $M_{\text{tot}} = 3.8 \pm 0.1 \times 10^{13} M_\odot$ . The external shear component has magnitude of  $\gamma = 0.5 \pm 0.3 \times 10^{-2}$ .

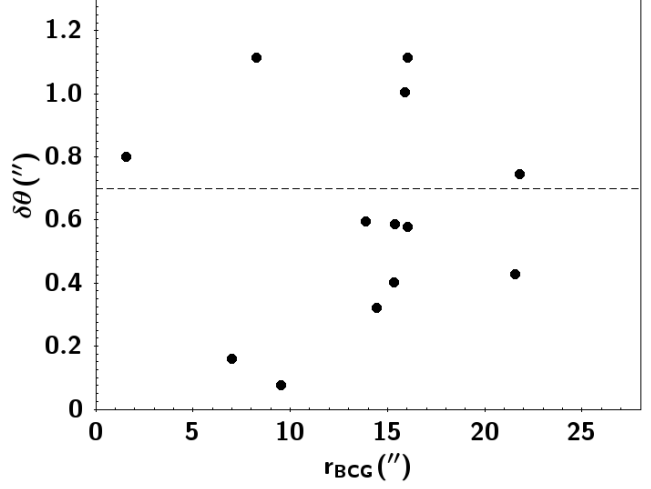
The final velocity dispersion for the reference galaxy is  $\sigma_{\text{GR}} = 186 \pm 28$  km/s and its truncation radius is  $r_{\text{tr,GR}} = 42 \pm 26$  kpc. The galaxy scaling relation is then

$$\sigma = 186 \pm 28 \text{ km/s} \left( \frac{r_{\text{tr}}}{42 \pm 26 \text{ kpc}} \right)^{3/4}. \quad (13)$$

Although the error in  $r_{\text{tr}}$  is large, the relation implies that

**Table 4.** Final parameters of the mass components of A611 resulting from modelling the mass distribution with (“w/ $\sigma$ ”) or without (“wo/ $\sigma$ ”) the measured velocity dispersions. The uncertainties are 68% confidence limits from the MCMC sampling. x and y position are given in kpc with respect to the BCG. Core and truncation radii are given in kpc, velocity dispersions are in km/s and Einstein radii parameters are in arcseconds. PA are in radians measured counter-clockwise from the west direction.

|                   | wo/ $\sigma$           | w/ $\sigma$       |
|-------------------|------------------------|-------------------|
| DH                |                        |                   |
| x                 | $0.0 \pm 3.5$          | $-2.2 \pm 2.6$    |
| y                 | $5.6 \pm 3.5$          | $4.3 \pm 2.6$     |
| b/a               | $0.8 \pm 0.1$          | $0.8 \pm 0.1$     |
| PA                | $2.1 \pm 0.2$          | $2.2 \pm 0.1$     |
| $\theta_e$        | $18 \pm 2$             | $20 \pm 1$        |
| $r_{\text{core}}$ | $20^{+13}_{-9}$        | $25^{+9}_{-7}$    |
| BCG               |                        |                   |
| $\sigma$          | $167 \pm 31$           | $167 \pm 31$      |
| $r_{\text{core}}$ | 1.3                    | 1.3               |
| $r_{\text{tr}}$   | $44 \pm 8$             | $43 \pm 9$        |
| GR                |                        |                   |
| $\sigma$          | $250 \pm 63$           | $186 \pm 27$      |
| $r_{\text{tr}}$   | $55^{+22}_{-29}$       | $42^{+28}_{-26}$  |
| G1                |                        |                   |
| b/a               | $0.8 \pm 0.2$          | $0.8 \pm 0.2$     |
| PA                | $1.3 \pm 0.2$          | $1.3 \pm 0.2$     |
| $\sigma$          | $270 \pm 71$           | $212 \pm 49$      |
| $r_{\text{tr}}$   | $25^{+38}_{-19}$       | $42^{+32}_{-27}$  |
| G2                |                        |                   |
| b/a               | $0.7 \pm 0.2$          | $0.7 \pm 0.2$     |
| $\sigma$          | $234 \pm 59$           | $132 \pm 40$      |
| $r_{\text{tr}}$   | $33^{+34}_{-24}$       | $41^{+30}_{-28}$  |
| G3                |                        |                   |
| b/a               | $0.8 \pm 0.2$          | $0.8 \pm 0.2$     |
| $\sigma$          | $257 \pm 81$           | $264 \pm 53$      |
| $r_{\text{tr}}$   | $37^{+34}_{-26}$       | $39^{+32}_{-28}$  |
| G4                |                        |                   |
| b/a               | $0.5 \pm 0.2$          | $0.5 \pm 0.2$     |
| $\sigma$          | $212 \pm 74$           | $195 \pm 36$      |
| $r_{\text{tr}}$   | $41^{+31}_{-29}$       | $34^{+35}_{-25}$  |
| G5                |                        |                   |
| $\sigma$          | $186 \pm 65$           | $83 \pm 21$       |
| $r_{\text{tr}}$   | $35^{+35}_{-26}$       | $40^{+31}_{-27}$  |
| G6                |                        |                   |
| b/a               | $0.8 \pm 0.2$          | $0.8 \pm 0.2$     |
| $\sigma$          | $186 \pm 47$           | $186 \pm 28$      |
| $r_{\text{tr}}$   | $41 \pm 31$            | $40^{+32}_{-30}$  |
| G7                |                        |                   |
| b/a               | $0.9 \pm 0.1$          | $0.9 \pm 0.1$     |
| PA                | $0.8 \pm 0.2$          | $0.8 \pm 0.2$     |
| $\sigma$          | $195 \pm 62$           | $156 \pm 33$      |
| $r_{\text{tr}}$   | $37^{+33}_{-27}$       | $42 \pm 30$       |
| $\gamma$          | $0.01^{+0.02}_{-0.01}$ | $0.005 \pm 0.003$ |



**Figure 3.** Distance  $\delta\theta$  between the predicted and observed multiple images as a function of the distance of the respective multiple images from the BCG. The multiple images are reproduced with mean accuracy of  $0.7''$ .

galaxies are tidally truncated in the cluster core consistent with previous analyses (e.g. Natarajan, Kneib & Smail 2002; Limousin et al. 2007; Donnarumma et al. 2011; Monna et al. 2015). These results are in excellent agreement with Donnarumma et al. (2011), who perform a detailed strong lensing and X-ray analysis of A611. They test different approaches to modelling the mass associated with the cluster galaxy component. They individually optimize the mass parameters of galaxies which have strong impact on the observed lensing features just as we do in our analysis. In case 6 of their analysis, the velocity dispersion and truncation radius of six galaxies close to the lensed systems are individually optimized in the ranges [90, 190] km/s and [2, 35] kpc, respectively for  $\sigma$  and  $r_{\text{tr}}$ . In contrast with our approach, their scaling relation reference galaxy GR has a fixed truncation radius of 43 kpc (in agreement with results from galaxy-galaxy lensing presented in Natarajan et al. (2009)) and has  $\sigma_{\text{tr,GR}}$  optimized in the range [120, 200] km/s. They perform the lensing analysis in the source plane and obtain a total reduced  $\chi^2_{\text{src}} = 0.7$ . The final velocity dispersion for their reference galaxy GR is  $\sigma_{\text{GR}} = 150 \pm 18$  km/s, consistent at the  $1\sigma$  level with our results. We also find overall agreement for the galaxies that we individually optimized. However, in both analyses the mass parameters have large uncertainties (see Fig. 6 in the next section).

Table 4 summarizes the parameters for all of the cluster mass components, including the individually optimized galaxies, G1 to G7.

To examine the impact of incorporating the measured velocity dispersions of the 17 cluster members in the lensing analysis, we model the cluster core without using the  $\sigma_{\text{sp}}$  (“wo/ $\sigma$ ”). The best model wo/ $\sigma$  predicts the multiple images positions with a mean accuracy of  $0.8''$ ; with the measured velocity dispersions we obtain  $\text{rms}_{\text{img}} = 0.7''$ . Constraints on the parameters of the mass components are similar in both models (Tab. 4). However the velocity dispersions  $\sigma_{\text{sl}}$  predicted by lensing show some deviations from the available spectroscopic measurements  $\sigma_{\text{sp}}$ . Fig. 4 shows

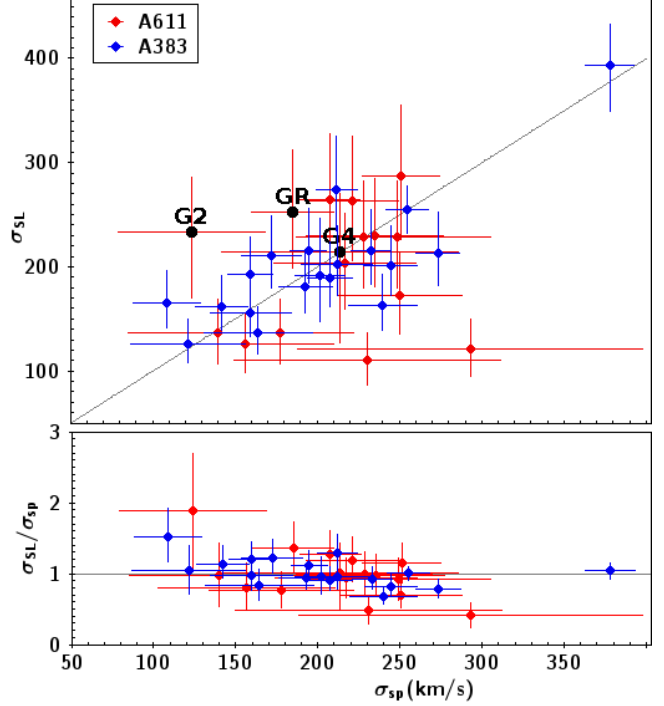
**Table 5.** 2D projected mass for the DH and galaxy mass components of A611. We extract the mass enclosed within the Einstein parameter ( $\Theta_E \sim 20''$ ) and within a larger radius of  $50''$ , covering the cluster core. Masses are in  $10^{13}M_\odot$ .

|                          | $w_0/\sigma$  | $w/\sigma$    |
|--------------------------|---------------|---------------|
| DH                       |               |               |
| $M_{\text{DH}}(< 20'')$  | $2.7 \pm 0.1$ | $2.9 \pm 0.1$ |
| $M_{\text{DH}}(< 50'')$  | $6.6 \pm 0.7$ | $7.0 \pm 0.6$ |
| Galaxies                 |               |               |
| $M_{\text{gal}}(< 20'')$ | $0.5 \pm 0.2$ | $0.3 \pm 0.1$ |
| $M_{\text{gal}}(< 50'')$ | $1.8 \pm 0.4$ | $1.2 \pm 0.5$ |

the measured  $\sigma_{\text{sp}}$  versus the value predicted from lensing ( $\sigma_{\text{sl}}$ ) for the model  $w_0/\sigma$ . For comparison we also plot the results for A383 in Monna et al. 2015. In A383 the spectroscopically measured  $\sigma_{\text{sp}}$  and the lensing prediction agree well. The difference between A611 and A383 probably depends on the sample of cluster members for which we have  $\sigma_{\text{sp}}$ . In the case of Abell 383 (Monna et al. 2015), there are 8 cluster members with  $\sigma_{\text{sp}}$  inside the cluster critical lines, and another 5 slightly outside. Thus in A383 we constrain the galaxy truncation radii with an error of  $\sim 50\%$ . In A611 we derive much weaker constraints on the truncation radii because the sample of cluster members with measured  $\sigma_{\text{sp}}$  includes fewer galaxies (only 5 inside the critical lines) which have a strong impact on the lensing potential. Furthermore A611 has the fewer robust SL features identified in the core of the cluster than A383 does. Fig. 5 shows the two clusters to highlight the difference between them. The figure marks the galaxies with measured  $\sigma_{\text{sp}}$  over a field of  $50'' \times 50''$  centred on the BCG along with the multiple images and the critical curves.

The use of velocity dispersion measurements of cluster members properly weights the galaxy contribution to the total mass of the cluster. The lensing analysis  $w_0/\sigma$  predicts  $r_{\text{tr}} = 55^{+29}_{-22}$  kpc and  $\sigma_{\text{GR}, w_0/\sigma} = 250 \pm 63$  km/s for GR. This velocity dispersion is overestimated by a factor of 1.4 with respect to the spectroscopic measurement  $\sigma_{\text{sp}, \text{GR}} = 185 \pm 25$  km/s. The total mass associated with GR is  $M_{\text{tot}, \text{GR}}^{w_0/\sigma} = 2.5 \times 10^{12} M_\odot$  compared with  $M_{\text{tot}, \text{GR}}^{w/\sigma} = 1.1 \times 10^{12} M_\odot$  estimated using the measured  $\sigma_{\text{sp}}$  values in the analysis.

Overestimation of the mass of GR translates into a global overestimate of the total galaxy mass component in the cluster. Table 5 lists the projected mass for the cluster galaxy contribution and for the large scale dark halo. The mass associated with the cluster members is over-estimated by a factor of  $\sim 1.5$  without use of the velocity dispersions in the analysis. Consequently the mass associated with the large scale dark halo is underestimated by  $\sim 5\%$  in the model “ $w_0/\sigma$ ”. In spite of the small sample of cluster members with measured velocity dispersions in A611, these spectroscopic measurements allow proper weighting of the mass associated with the galaxies relative to the large scale dark matter halo.

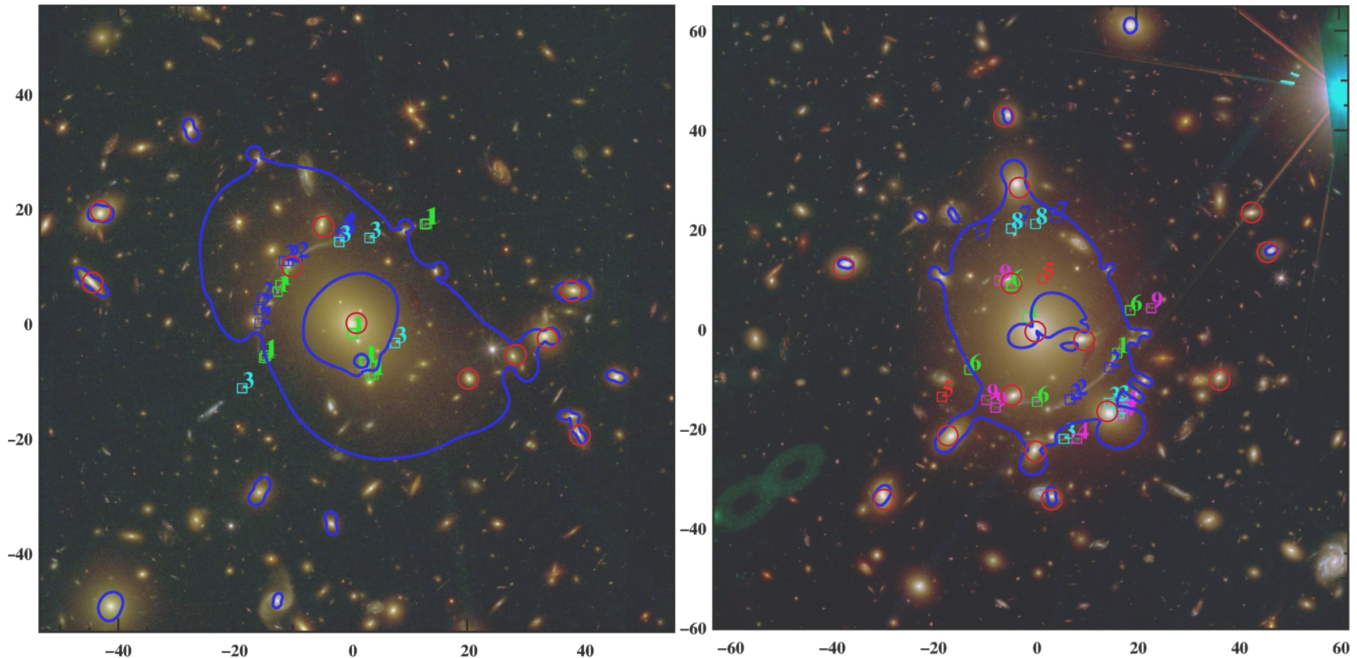


**Figure 4.** Spectroscopic velocity dispersions ( $\sigma_{\text{sp}}$ ) versus the prediction from lensing. We show the relation for A611 (red) along with the individually optimized objects (black). For comparison we also show the results for A383 (in blue) from Monna et al. (2015). Note the tighter relation for A383.

## 5 SURFACE BRIGHTNESS RECONSTRUCTION OF THE GIANT ARC

In the pointlike analysis, we individually optimized some of the cluster members which reside very close to multiple images and thus probably contribute significantly to the local lensing distortion. However, the mass profiles for these galaxies are actually poorly constrained by the pointlike modelling.

Here we use the surface brightness (SB) reconstruction of the giant arc to improve the constraints on the mass parameters of the galaxies, G1 to G5, that are close to the arc by using the entire pixel to pixel lensing information encoded in the arc. The analysis is performed in the HST/ACS/F775W image. We subtract the neighbouring cluster members from the image of the arc using GALFIT (Peng et al. 2010) thus removing light that would otherwise contaminate the arc SB reconstruction. We start the SB modelling from the final best model obtained in the pointlike analysis. The SB reconstruction of giant arcs is a powerful tool for placing strong constraints on the mass distribution of the lens, but it is only effective in the local neighbourhood of the reconstructed arc. The pixel to pixel constraints associated with the giant arc are of the order of  $10^3$  higher than the pointlike constraints associated with the other multiple image systems used in the analysis. Thus the minimization and the MCMC analyses are dominated by the constraints from the arc. Throughout the SB analysis we must fix the parameters of the mass components which do not play a major role in the local distortion of the giant



**Figure 5.** HST colour composite images of A611 ( $z=0.288$ ; left) and A383 ( $z=0.189$ ; right). We show the multiple image (numbered), the cluster members with measured  $\sigma_{sp}$  (red circles), and the critical lines for a source at redshift  $z_s = 2$  (blue). Axis labels are in arcseconds with respect to the BCG.

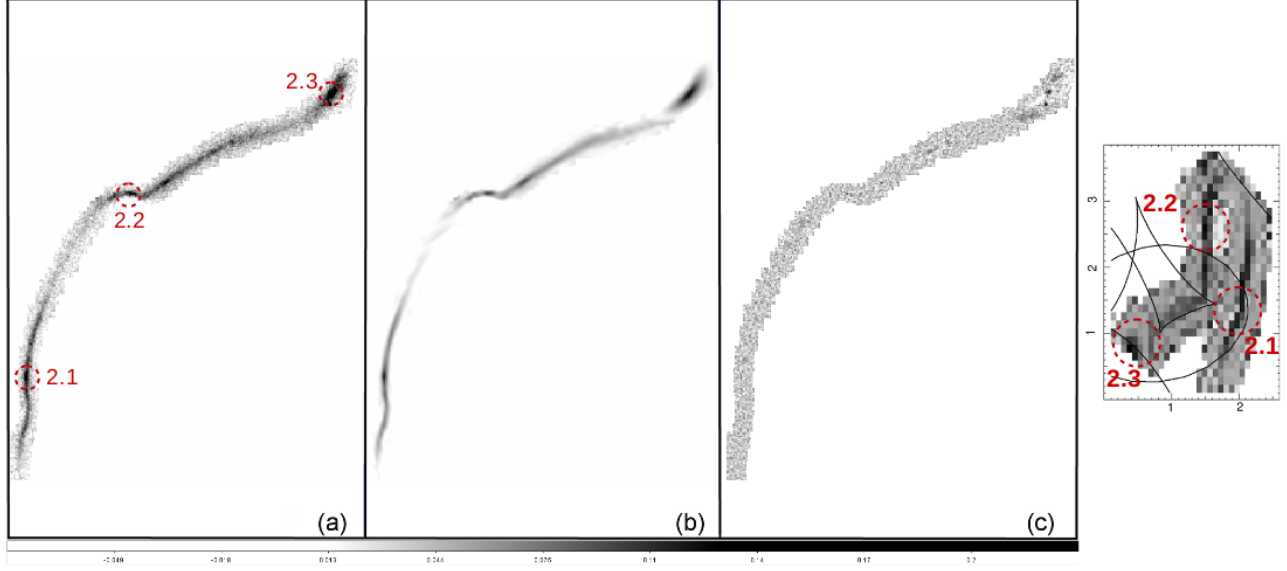
arc. In Appendix A we show the MCMC resulting from the pointlike analysis. The parameters describing the mass component of galaxies G1-G5 have no degeneracies with the parameters of the large scale dark halo, the BCG and the reference galaxy GR. Thus through the SB reconstruction of the giant arc, the parameters describing the DH, BCG and GR are fixed to the values of the final best model of the pointlike analysis. Only the five galaxies G1-G5 close to the giant arc (see Fig. 1), are individually optimized in the SB reconstruction. Their ellipticity, position angle, velocity dispersions and truncation radii are free parameters. Given the larger number of constraints provided by the SB analysis, we also release the core radii for these galaxies to infer a more detailed profile of the local mass distribution. Two of these galaxies, G2 and G4, have measured velocity dispersions (see Tab. 2) optimized within the spectroscopic error with a gaussian prior. We perform the SB reconstruction through a linear inversion method (Warren & Dye 2003) which reconstructs the pixellated brightness distribution of the source, with regularization of its intensity, through a Bayesian analysis (Suyu et al. 2006). The first model resulting from the SB reconstruction has a large reduced  $\chi^2_{SB} = 1.6$ . For consistency with the pointlike analysis, where we adopt larger uncertainties in the multiple images position of  $1''$ , at this stage of the SB analysis we increase the pixel noise associated with the HST/ACS/F775W image by a factor of  $\sqrt{1.6}$ .

Fig. 6 shows the results of the surface brightness reconstruction of the arc in the F775W filter as well as the reconstructed source. The giant arc is reconstructed well (panel b in Fig. 6) with  $\chi^2_{SB} = 0.8$  on the pixel intensities and with residuals lower than  $10^{-3}$  (panel c in Fig. 6). Large residuals remain close to the upper multiple image 2.3, where a bright compact object is clearly identified. Our

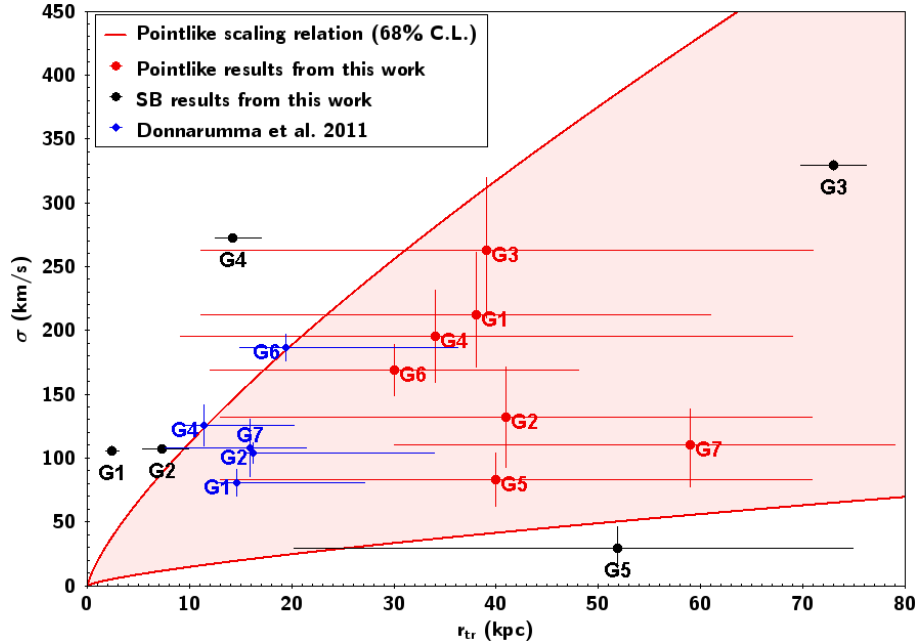
reconstruction does not reproduce this object as part of the lensed system. This compact object is unlikely to be part of the lensed source. Otherwise it would be possible to identify such a substructure close to the other multiply lensed structures of the arc as well (i.e. close to image 2.1 and 2.2). On the right side of Fig. 6 we show the source reconstruction of the lensed system. We obtain a good SB reconstruction of the giant arc in the image plane. In the source plane, however, the substructures of the arc have an offset of  $\sim 1.5 - 2.5$  arcseconds, which corresponds to  $\sim 10$  kpc at the redshift of the source.

Tab. 6 summarizes the resulting mass parameters for galaxies G1-G5 optimized through this analysis with their respective  $1\sigma$  uncertainties. The halo axis ratio  $b/a$  and position angles are consistent with the results from the pointlike analysis, as well as with the values measured from the photometry. Only G4 obtains a considerably larger axis ratio  $b/a=1$  with respect to the  $b/a=0.5$  measured from the photometry and resulting from the pointlike model. The velocity dispersions for G2 and G4 are both consistent with the spectroscopic measurements (see Tab. 2), although G4 has a higher value compared with the estimates from the pointlike analysis. The other galaxies obtain velocity dispersions which depart significantly from the previous pointlike results.

Overall the SB modelling yields improved constraints on the galaxy truncation radii and masses. The truncation radii for G3, G4 and G5 agree at the  $1\sigma$  level with the pointlike estimate. For G1 and G2 we obtain quite small radii ( $< 15$  kpc) indicating that the dark matter halos of these objects are highly truncated. The total mass associated with each galaxy is consistent within the  $1\sigma$  uncertainties with the mass estimated through the pointlike analysis,



**Figure 6.** Surface brightness reconstruction of the giant arc in the core of A611. Panel (a) is a cutout ( $\sim 16'' \times 20''$ ) of the arc in the HST/ACS/F775W filter; Panel (b) is the arc reconstruction resulting from the SB lensing modelling; Panel (c) shows their residuals. On the right side we show the reconstruction of the source, which is at  $z_{sp} = 0.91$ . The source cut out has size of  $\sim 4'' \times 2.5''$ , the scale shown is in arcseconds. The black lines are the caustic for the source redshift. The red dotted circles mark substructures identified in the arc (Panel (a)) and their respective position in the source plane. See text for more details.



**Figure 7.** Velocity dispersions and truncation radii for galaxies G1 to G5 resulting from the SB (black) and the pointlike (red) modelling. The red shaded region shows the cluster galaxy scaling relation derived from the pointlike analysis. In blue we plot results for the same galaxies from the pointlike SL analysis performed by Donnarumma et al. (2011). The galaxies G2, G3 and G5 are consistent at the  $1\sigma$  confidence level: galaxies G1 and G4 deviate by  $2\sigma$  or more.

but now the masses are better constrained by a mean factor of 70%. Fig. 7 compares  $\sigma$  and  $r_{tr}$  derived through the surface brightness reconstruction with the pointlike results. At the  $1\sigma$  confidence level, the galaxies are consistent with the scaling relation derived in the pointlike analysis, except for G1 and G2 which deviate substantially from the relation. Fig. 7 also shows results from Donnarumma et al. (2011) for com-

parison. The Donnarumma et al. (2011) results for galaxies G1-G5 are generally consistent with our scaling relation and with the results from the pointlike analysis. However, they predict smaller  $\sigma$  and  $r_{tr}$  for these galaxies as a result of the smaller range adopted for the parameter optimization ( $[120, 200]$  km/s for velocity dispersions and  $[2, 35]$  kpc for truncation radii). Nevertheless overall both approaches

**Table 6.** Final parameters of the mass components describing galaxies G1-G5 for the pointlike model and the SB model. The uncertainties are the 68% confidence levels from the MCMC sampling. The radii are in kpc, the velocity dispersions are in km/s, the PA are in degrees measured counter-clockwise from the west direction. The masses are in  $10^{12}M_{\odot}$ .

|           | Pointlike model     | SB model            |
|-----------|---------------------|---------------------|
| <b>G1</b> |                     |                     |
| b/a       | $0.8 \pm 0.2$       | $0.8 \pm 0.1$       |
| PA        | $75 \pm 11$         | $71 \pm 4$          |
| $\sigma$  | $212^{+49}_{-41}$   | $105 \pm 3$         |
| $r_{tr}$  | $38^{+32}_{-27}$    | $2 \pm 1$           |
| $r_c$     | —                   | $0.1 \pm 0.1$       |
| $M_{tot}$ | $1.2^{+1.6}_{-1.2}$ | $0.20 \pm 0.05$     |
| <b>G2</b> |                     |                     |
| b/a       | $0.7 \pm 0.2$       | $0.8 \pm 0.1$       |
| PA        | [86]                | $93 \pm 6$          |
| $\sigma$  | $132 \pm 39$        | $107 \pm 2$         |
| $r_{tr}$  | $41^{+30}_{-28}$    | $7 \pm 3$           |
| $r_c$     | —                   | $0.7 \pm 0.2$       |
| $M_{tot}$ | $0.5^{+0.7}_{-0.5}$ | $0.6 \pm 0.2$       |
| <b>G3</b> |                     |                     |
| b/a       | $0.8 \pm 0.2$       | $0.6 \pm 0.1$       |
| PA        | [45]                | $41 \pm 1$          |
| $\sigma$  | $263^{+57}_{-53}$   | $329 \pm 4$         |
| $r_{tr}$  | $39^{+32}_{-28}$    | $73 \pm 3$          |
| $r_c$     | —                   | $0.1 \pm 0.1$       |
| $M_{tot}$ | $2.0^{+2.4}_{-2.0}$ | $5.8 \pm 0.3$       |
| <b>G4</b> |                     |                     |
| b/a       | $0.5 \pm 0.2$       | $1^{+0.0}_{-0.01}$  |
| PA        | [82]                | $83 \pm 3$          |
| $\sigma$  | $195 \pm 36$        | $279 \pm 1$         |
| $r_{tr}$  | $34^{+35}_{-25}$    | $14 \pm 3$          |
| $r_c$     | —                   | $4 \pm 1$           |
| $M_{tot}$ | $1.0^{+1.3}_{-1.1}$ | $0.8 \pm 0.1$       |
| <b>G5</b> |                     |                     |
| $\sigma$  | $83 \pm 21$         | $30 \pm 15$         |
| $r_{tr}$  | $40^{+31}_{-27}$    | $59^{+20}_{-30}$    |
| $M_{tot}$ | $0.2 \pm 0.2$       | $0.5^{+0.3}_{-0.4}$ |

predict that these galaxies are highly truncated. According to the SB reconstruction, G1 has  $r_{tr,G1} = 2 \pm 1$  kpc, only twice its effective radius ( $R_{eff,G1} = 1$  kpc) as measured in the HST/F814W image. This galaxy has a total mass  $M_{tot,G1} = 2.0 \pm 0.5 \times 10^{11} M_{\odot}$ . Comparing its total mass with a prediction for field galaxies (e.g. Brimiouille et al. 2013), G1 has probably been stripped of 99% of its original dark matter halo. G2 and G4 have also apparently lost most of their dark halos through stripping processes (98% and 97% respectively); G3 and G5 have lost 85% and 90%, respectively. Variations in the stripped mass may be explained by differences in the stripping processes resulting from different orbits through the cluster (Warnick, Knebe & Power 2008).

## 6 CONCLUSION

We use central velocity dispersion measurements for 17 members of the galaxy cluster A611 as constraints to refine a SL model for the cluster. The inclusion of velocity dispersion measurements improves determination of the mass associated with galaxies in the cluster relative to the mass contained in the extended dark matter halo. Without the spectroscopically determined  $\sigma_{sp}$ , the mass associated with the galaxies is overestimated by a factor  $\sim 1.5$ , and consequently the mass of the large scale dark matter is underestimated by  $\sim 5\%$ .

In contrast with the cluster A383 (Monna et al. 2015) where the use of central velocity dispersions substantially improves constraints on the truncation radii of cluster galaxies, there is little change in these constraints in the case of A611. Errors in the truncation radii for galaxies in A611 are  $\sim 75\%$  comparable with the errors from the SL modelling without using  $\sigma_{sp}$ . This result for A611 relative to A383 is due to both the size of the samples of cluster members with measured velocity and the number of lensed features. In A383 (Monna et al. 2015) there are  $\sim 10$  galaxies with measured  $\sigma_{sp}$  inside the critical lines and the constraints on the truncation radii improve by  $\sim 50\%$ . In A611, there are only 5 galaxies inside the region probed robustly by SL. Furthermore, A611 has only 3 systems of multiple images in the cluster core whereas A383 has 10.

SB reconstruction of the tangential giant arc associated with A611 does provide additional constraints on 5 cluster members projected near the arc. The galaxies G2 and G4 get velocity dispersions from the SB analysis which are consistent at the  $1\sigma$  confidence level with the respective spectroscopic measurements. Overall the parameters of the galaxies are in agreement with the scaling relation derived in the pointlike analysis. In contrast two of these galaxies depart substantially from the galaxy scaling relation. Their small truncation radii may reflect differing stripping history among individual cluster members (Warnick, Knebe & Power 2008).

More extensive samples of spectroscopically measured velocity dispersions for members of a set of clusters will eventually provide a platform for refining the relative contribution of the cluster members and the dark matter halo to the overall cluster mass distribution as a function of total cluster mass and as a function of the evolutionary state of the cluster. Combined with large redshift surveys of the central cluster region they promise insight into the stripping processes that govern the evolution of galaxies in dense cluster environments.

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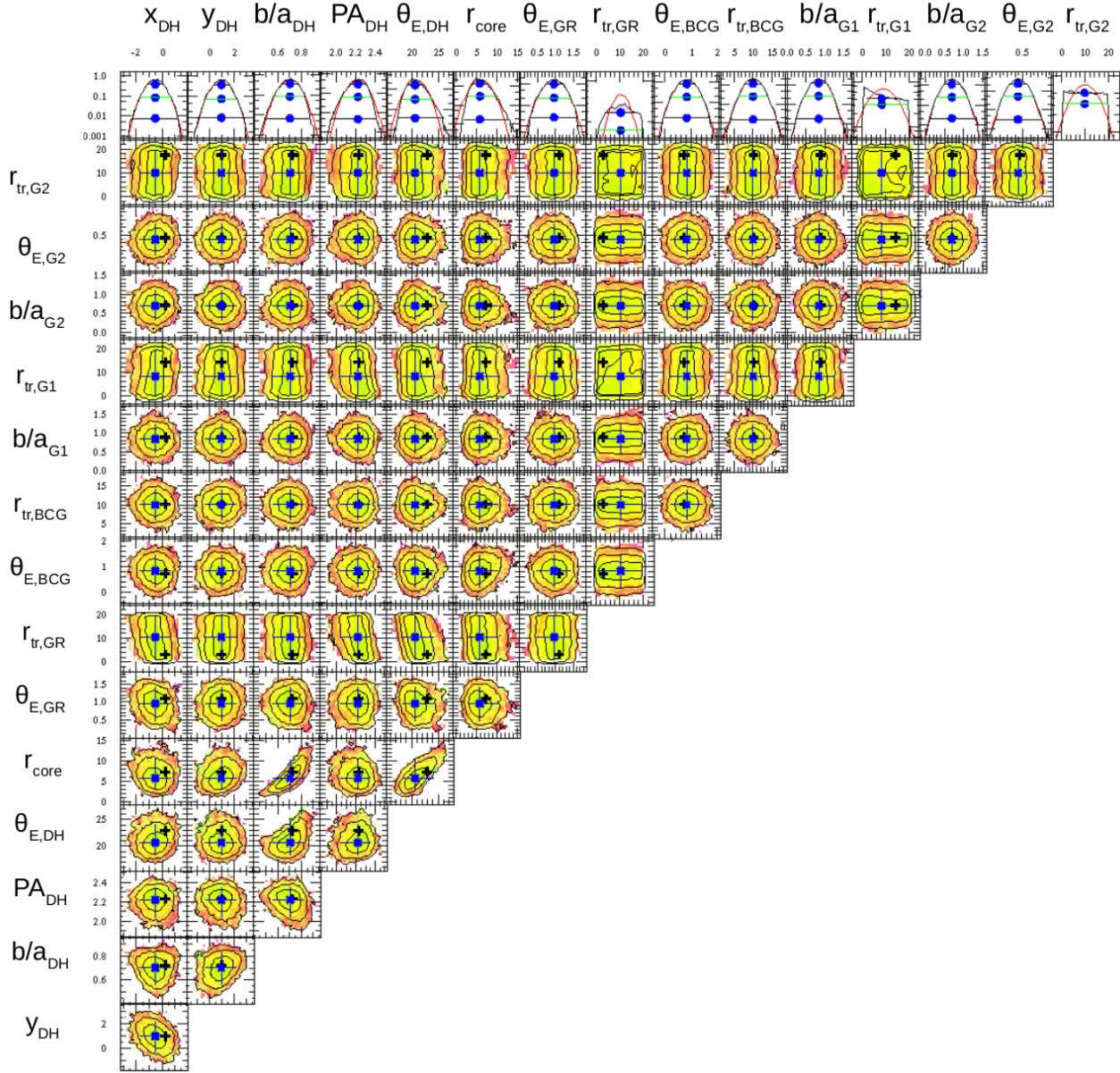
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## REFERENCES

- Arnouts S., Cristiani S., Moscardini L., Matarrese S., Lucchin F., Fontana A., Giallongo E., 1999, *Mon. Not. Roy. Astron. Soc.*, 310, 540
- Bartelmann M., 2010, *Classical and Quantum Gravity*, 27, 233001
- Bender R., Burstein D., Faber S. M., 1992, *ApJ*, 399, 462
- Bertin E., Arnouts S., 1996, *A&AS*, 117, 393
- Brimouille F., Seitz S., Lerchster M., Bender R., Snigula J., 2013, *Mon. Not. Roy. Astron. Soc.*, 432, 1046
- D’Aloisio A., Natarajan P., 2011, *Mon. Not. Roy. Astron. Soc.*, 411, 1628
- Donnarumma A. et al., 2011, *A&A*, 528, A73
- Dressler A., Lynden-Bell D., Burstein D., Davies R. L., Faber S. M., Terlevich R., Wegner G., 1987, *ApJ*, 313, 42
- Eichner T. et al., 2013, *ApJ*, 774, 124
- Elíasdóttir Á. et al., 2007, *ArXiv e-prints*
- Faber S. M., Dressler A., Davies R. L., Burstein D., Lynden-Bell D., 1987, in *Nearly Normal Galaxies. From the Planck Time to the Present*, Faber S. M., ed., pp. 175–183
- Faber S. M., Jackson R. E., 1976, *ApJ*, 204, 668
- Fabricant D., Chilingarian I., Hwang H. S., Kurtz M. J., Geller M. J., Del’Antonio I. P., Rines K. J., 2013, *PASP*, 125, 1362
- Fabricant D. et al., 2005, *PASP*, 117, 1411
- Focardi P., Malavasi N., 2012, *ApJ*, 756, 117
- Geiger B., Schneider P., 1999, *Mon. Not. Roy. Astron. Soc.*, 302, 118
- Halkola A., Seitz S., Pannella M., 2007, *ApJ*, 656, 739
- Hoekstra H., Franx M., Kuijken K., Carlberg R. G., Yee H. K. C., 2003, *Mon. Not. Roy. Astron. Soc.*, 340, 609
- Host O., 2012, *Mon. Not. Roy. Astron. Soc.*, 420, L18
- Ilbert O. et al., 2006, *A&A*, 457, 841
- Ilbert O. et al., 2009, *ApJ*, 690, 1236
- Jorgensen I., Franx M., Kjaergaard P., 1995, *Mon. Not. Roy. Astron. Soc.*, 276, 1341
- Jullo E., Kneib J.-P., Limousin M., Elíasdóttir Á., Marshall P. J., Verdugo T., 2007, *New Journal of Physics*, 9, 447
- Kassiola A., Kovner I., 1993, in *Liege International Astrophysical Colloquia*, Vol. 31, *Liege International Astrophysical Colloquia*, Surdej J., Fraipont-Caro D., Gosset E., Refsdal S., Remy M., eds., p. 571
- Kneib J.-P., Natarajan P., 2011, *A&ARv*, 19, 47
- Koekemoer A. M. et al., 2011, *ApJS*, 197, 36
- Koleva M., Prugniel P., Bouchard A., Wu Y., 2009, *A&A*, 501, 1269
- Koopmans L. V. E., Treu T., Bolton A. S., Burles S., Moustakas L. A., 2006, *ApJ*, 649, 599
- Kormendy J., Bender R., 2013, *ApJ*, 769, L5
- Le Borgne D., Rocca-Volmerange B., Prugniel P., Lançon A., Fioc M., Soubiran C., 2004, *A&A*, 425, 881
- Lemze D. et al., 2013, *ApJ*, 776, 91
- Limousin M., Kneib J. P., Bardeau S., Natarajan P., Czoske O., Smail I., Ebeling H., Smith G. P., 2007, *A&A*, 461, 881
- Limousin M., Sommer-Larsen J., Natarajan P., Milvang-Jensen B., 2009, *ApJ*, 696, 1771
- Merritt D., 1983, *ApJ*, 264, 24
- Monna A. et al., 2015, *Mon. Not. Roy. Astron. Soc.*, 447, 1224
- Narayan R., 1998, *New Astronomy Reviews*, 42, 73
- Natarajan P., Kneib J.-P., Smail I., 2002, *ApJ*, 580, L11
- Natarajan P., Kneib J.-P., Smail I., Treu T., Ellis R., Moran S., Limousin M., Czoske O., 2009, *ApJ*, 693, 970
- Newman A. B., Treu T., Ellis R. S., Sand D. J., 2013a, *ApJ*, 765, 25
- Newman A. B., Treu T., Ellis R. S., Sand D. J., Nipoti C., Richard J., Jullo E., 2013b, *ApJ*, 765, 24
- Newman A. B., Treu T., Ellis R. S., Sand D. J., Richard J., Marshall P. J., Capak P., Miyazaki S., 2009, *ApJ*, 706, 1078
- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, *AJ*, 139, 2097
- Richard J., Kneib J.-P., Limousin M., Edge A., Jullo E., 2010, *Mon. Not. Roy. Astron. Soc.*, 402, L44
- Rusin D. et al., 2003, *ApJ*, 587, 143
- Sánchez-Blázquez P. et al., 2006, *Mon. Not. Roy. Astron. Soc.*, 371, 703
- Schneider P., 2003, *ArXiv Astrophysics e-prints*
- Suyu S. H., Halkola A., 2010, *A&A*, 524, A94
- Suyu S. H. et al., 2012, *ApJ*, 750, 10
- Suyu S. H., Marshall P. J., Hobson M. P., Blandford R. D., 2006, *Mon. Not. Roy. Astron. Soc.*, 371, 983
- Warnick K., Kneib A., Power C., 2008, *Mon. Not. Roy. Astron. Soc.*, 385, 1859
- Warren S. J., Dye S., 2003, *ApJ*, 590, 673
- Zahid H. J., Damjanov I., Geller M. J., Hwang H. S., Fabricant D. G., 2015, *ArXiv e-prints*
- Zitrin A. et al., 2015, *ApJ*, 801, 44

## APPENDIX A: MCMC SAMPLING OF THE POINTLIKE MODELS

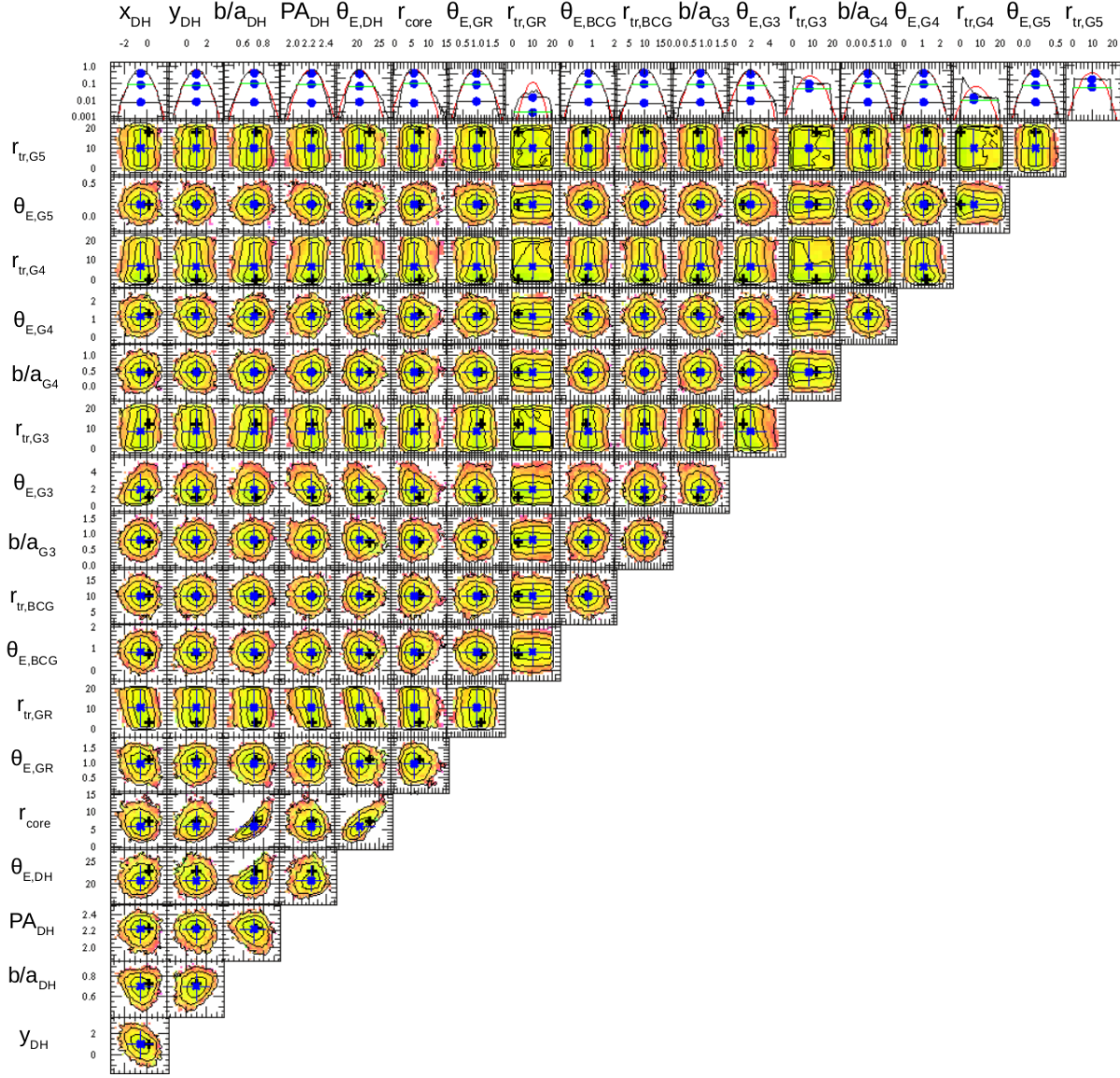
In this section we present the Monte Carlo Markov Chain sampling of the parameters describing the mass components of A611 resulting from the pointlike analysis, presented in Sec. 4. The color scale correspond to 68.3% (green), 95.5% (yellow) and 99.7% (orange). The blue dot indicate the median of the distribution, the black cross is the best value. Fig. A1 shows the MCMC sampling for the parameters of the smooth dark halo, the BCG, the reference galaxy GR and the galaxies G1 and G2. Fig. A2 shows the sampling of the mass parameters for DH, BCG, GR together with the galaxies G3, G4 and G5. In both plots there is no degeneracy between the parameters of the galaxies in the neighborhood



**Figure A1.** MCMC sampling of the parameters for the DH, BCG, GR and the galaxies G1 and G2 close to the giant arc. The coordinates  $x_{\text{DH}}$  and  $y_{\text{DH}}$  are in arcseconds with respect to the BCG position. Position angles are in radians. The radii  $r_{\text{core}}$  and  $r_{\text{tr}}$  are in arcseconds. The Einstein radii ( $\theta_E$ ) are also in arcseconds for  $D_{ds}/D_d = 1$ .

of the giant arc (G1-G5) and the mass components of the large scale halo, the BCG and the reference galaxy.

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**Figure A2.** Results of the MCMC analysis for the parameters of the DH, GR and BCG mass components of A611, together with the mass parameters for the galaxies G3, G4 and G5. The units are as in the previous figure.