A multiwavelength strong lensing analysis of baryons and dark matter in the dynamically active cluster AC 114

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Abstract: Context. Strong lensing studies can provide detailed mass maps of the inner regions even in dynamically active galaxy clusters. Aims. We illustrate the important role of a proper modelling of the intracluster medium, i.e., the main baryonic component. We demonstrate that the addition of a new contribution accounting for the gas can increase the statistical significance of the lensing model. Methods. We propose a parametric method for strong lensing analyses that exploits multiwavelength observations. The mass model accounts for cluster-sized dark matter halos, galaxies (whose stellar mass can be obtained from optical analyses), and the intracluster medium. The gas distribution is fitted to lensing data exploiting prior knowledge from X-ray observations. This gives an unbiased insight into each matter component and allows us to study the dynamical status of a cluster. The method was applied to AC 114, an irregular X-ray cluster. Results. We find positive evidence of dynamical activity, the dark matter distribution being shifted and rotated with respect to the gas. On the other hand, the dark matter follows the galaxy density in terms of both shape and orientation, illustrating the collisionless nature of dark matter. The inner region (250 kpc) is underluminous in optical bands, whereas the gas fraction (20 ± 5%) slightly exceeds typical values. Evidence of lensing and X-ray suggests that the cluster develops in the plane of the sky and is not affected by the lensing over-concentration bias. Despite the dynamical activity, the matter distribution seems to agree with predictions of N-body simulations. An universal cusped profile provides a good description of either the overall or the dark matter distribution, whereas theoretical scaling relations seem to be accurately fitted.

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A multi-wavelength strong lensing analysis of baryons and dark matter in the dynamically active cluster AC 114

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Strong lensing analyses can provide detailed mass maps of the inner regions even in dynamically active galaxy clusters. We propose a parametric method for strong lensing analyses which exploits multi-wavelength observations. The mass model accounts for cluster-sized dark matter halos, galaxies (whose stellar mass can be obtained from optical analyses) and the main baryonic component, the intracluster medium, modelled according to X-ray observations. This gives an unbiased look at each matter component and allows a study of the dynamical status of the cluster. The method has been applied to AC 114, an irregular X-ray cluster. We find positive evidence for dynamical activity, with the dark matter distribution shifted and rotated with respect to the gas. On the other hand, the dark matter follows the galaxy density both for shape and orientation, which probes its collisionless nature. The inner region ($\leq 250$ kpc) is under-luminous in optical bands whereas the gas fraction ($\sim 20 \pm 5\%$) slightly exceeds typical values. The dark matter distribution turns out to be in remarkable agreement with predictions from $N$-body simulations. An universal cusped profile is strongly favoured over an isothermal cored one; the inner slope of the density profile $\rho \sim r^{-\alpha}$ is slightly steeper ($\alpha \sim 1.3$) than the NFW prediction. The total matter distribution has concentration $c_{200} = 3.5 \pm 0.7$ and mass $M_{200} = (1.4 \pm 0.7) \times 10^{15} M_\odot$, which fit nicely theoretical scaling relations. Evidence from lensing and X-ray suggests that the cluster develops in the plane of the sky and is not affected by the lensing over concentration bias.

I. INTRODUCTION

Understanding the formation and evolution of galaxy clusters is an open problem in modern astronomy. On the theoretical side, $N$-body simulations are now able to make detailed statistical predictions on dark matter (DM) halo properties \cite{17, 30, 32, 61}. On the observational side, multi-wavelength observations from the radio to the optical bands to X-ray observations of galaxy clusters can provide a deep insight on real features \cite{19, 29, 41, 81}. Results are impressive on both sides, but further work is still required. Large numerical simulations can not still efficiently embody gas physics, whereas combining multi-wavelength data sets can be misleading if the employed hypotheses (hydrostatic and/or dynamical equilibrium, spherical symmetry, just to list a couple of very common ones) do not hold. So, areas of disagreement between predictions and measurements still persist.

Here, we want to consider a way to exploit multi-wavelength data sets in strong lensing data analyses. Strong lensing modelling can give detailed maps of the inner regions of galaxy clusters without relying on hypotheses on equilibrium and are negligibly affected by projection effects due to large-scale fields or aligned structures. However, massive lensing clusters build up a biased sample for statistical studies \cite{40, 62}. Multi-wavelength analyses of lensing galaxy clusters have been exploited following different approaches. Smith et al. \cite{81} compared X-ray and strong lensing maps of intermediate redshift clusters to infer equilibrium criteria. Detailed lensing features can reveal dynamical activity even in apparently relaxed clusters \cite{58}. Investigations of the bullet cluster clearly showed as dark matter follows the collisionless galaxies whereas the gas is stripped away in mergers \cite{19}. Comparison of snapshots of active clusters taken with weak lensing, X-ray surface brightness or galaxy luminosity revealed the relative displacement of the different components at different stages of merging \cite{64}.

The usual way to dissect dark matter from baryons in lensing analyses is first to obtain a map of the total matter distribution fitting the lensing features and then to subtract the gas contribution as inferred from X-ray observations \cite{13}. The total mass map can be obtained either with parametric models in which the contribution from cluster-sized DM halos can be considered together with the main galactic DM halos \cite{40, 59} or with non-parametric analyses, where dark matter meso-structures and galactic contributions are seen as deviation from smooth-averaged profiles \cite{73}. Mass in stars and stellar remnants is estimated converting galaxy luminosity to mass assuming suitable stellar mass to light ratios. Such approaches have obvious merits but also some unavoidable shortcomings.

Collisionless matter and gas are displaced in dynamical active clusters. Furthermore, in relaxed clusters, gas and dark matter profiles have usually different slopes. Since the gas follows the potential, its distribution is usually rounder than dark matter, so that even if the intracluster medium (ICM) and the dark matter are intrinsically aligned their projected masses cast on the sky with different orientation and ellipticity \cite{84}. Such features can be missed by usual approaches since the total matter profile may fall short in trying to account for the properties of each component. In fact, the parameters of the model can be not numerous enough to reproduce all the details whereas in non parametric approaches the fitting procedure

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must be weighted in order to prefer smooth distributions over clumpy ones, which may wash out small scale details such as gas and dark matter off-centred by few arcseconds.

We try to take a step further by exploiting a parametric model which has three kind of components: cluster-sized dark matter halos; galaxy-sized (dark plus stellar) matter halos; cluster-sized gas distribution. In our approach, the ICM distribution is embedded in the strong lensing modelling from the very beginning so avoiding unpleasant biases. In order to reduce the total number of parameters, the X-ray surface brightness data are fully exploited so that the gas contribution is fixed within the observational uncertainties. This allows to constrain the mass model using X-ray data without relying on the assumption of hydrostatic equilibrium. As far as the stellar component is concerned, we take the usual path: total galaxy masses (DM plus baryons) are derived through the lensing fitting procedure whereas the stellar contribution is inferred from optical galaxy luminosity. The main advantage we recognise in such an approach is that we are able to infer directly the dark matter mass. This is the component best (and under some points of view the only one) constrained in numerical simulations so that our novel approach eases the comparison which their theoretical predictions. Furthermore, we will be able to compare the gas distribution with the dark matter, which is an obvious improvement with respect to the usual way of comparing total projected mass distributions with surface brightness maps.

We apply our method to AC 114. There are two main reasons for this choice. First, the core region of AC 114 is rich in multiple images, allowing a very detailed analysis. Redshift contrast between multiple lensed sources can give a good measurement of the enclosed mass at two different radii, thus providing a good estimate of the mass profile in between [71]. The same kind of information can be obtained also combining strong and weak lensing data, but a multiple lensed sources allow us to consistently get the profile slope without mixing systematics from different methods. Furthermore, there are several images very near the cluster centre, which allows to accurately determine the radial slope of the matter distribution in the very inner regions. Despite the abundant data, AC 114 has been object of just a couple of lensing investigations. In the first one from Natarajan et al. [59], later on improved in Campusano et al. [18], weak lensing constraints were also used and the mass modelling, which was inspired by the optical galaxy distribution, considered a main clump and two additional cluster substructures. The second lensing analysis, inspired by the X-ray images, associated each of the two X-ray emitting regions to a dark matter clump in separate hydrostatic equilibrium [28]. Both approaches reproduced the image positions with an accuracy of $\gtrsim 1''$ but neither one used all of the image systems with confirmed spectroscopic redshifts. So, there is still room for substantial improvement.

Second, AC 114 has significant evidence of experiencing an ongoing merging. So, we will able to study the details of the dark matter distribution in a dynamical active cluster, constraining at the same time the properties of the dark matter and the evolution of this interesting cluster. The lensing analysis of the cluster will put us in position to compare estimates with theoretical predictions.

The paper is as follows. In Sec. II we discuss the galaxy distribution and portray the luminosity and the number density. Stellar mass inferred from the measured luminosity is considered as well. Section III is devoted to dynamics. We first obtain an updated estimate of the galaxy velocity dispersion $\sigma_{\text{los}}$ and then use $\sigma_{\text{los}}$ to get some estimates of the virial mass that will be compared to the lensing results later on. In Sec. IV we review literature results on the X-ray observations of the cluster and add some new considerations on its dynamical status. Section V and VI are devoted to the lensing analysis. In Sec. V we review the optical data and the parametric models employed; in Sec. VI we present our statistical investigation. Section VII lists the results obtained with our multi-wavelength approach whereas Sec. VIII is devoted to some final considerations. Throughout the paper, we assume a $\Lambda$CDM cosmology with density parameters $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and an Hubble constant $H_0 = 100h\,\text{km}\,\text{s}^{-1}\text{Mpc}^{-1}$, $h = 0.7$. This implies a linear scale of 3.22 kpc/$h$ per arcsec at the cluster redshift $z = 0.315$. We quote uncertainties at the 68.3% confidence level.

![FIG. 1: Grey-scale WFC@ACS image (F850 band) of the core of AC 114 from the HST archive. North is up and east is to the left. The field covers $3'\times3'$. Overlaid are the linearly spaced adaptively-smoothed Chandra surface brightness X-ray inner (black) contours and the inner $R_{702}$ light (white) contours. Light isophotes have been obtained smoothing the luminosity map with a Gaussian kernel with a dispersion of $30''$. NX and SX are the centroids of the main X-ray clump and the southern tail, respectively; NW and SE locate likely mass clumps.](image-url)
II. GALAXY DISTRIBUTION

The galaxy catalogue we work with is taken from Couch et al. [25], who morphologically classified galaxies recorded on images taken with WFPC2 at HST down to $R_{702} = 23.00$. AC 114 is a prototypical example of the Butcher-Oemler effect with a higher fraction of blue, late-type galaxies than in lower redshift clusters, rising to 60% outside of the core region [25]. The fraction of interacting galaxies ($\sim 12\%$) is also high [25]. AC 114 was classified as a Bautz-Morgan type II-III cluster [46], suggesting a young dynamical age. The cluster is significantly elongated in the southeast-northwest direction [24], see Fig. 1. Galaxy distribution in the inner regions is quite irregular. Two clumps of galaxies, the first one northwest (NW clump) and the second one southeast (SE clump) of the BCG were noted in Natarajan et al. [59]. According to a combined weak and strong lensing modelling [18], the NW clump at $\{\theta_1, \theta_2\} \sim \{80'', 30''\}$ and the SE clump at $\{-75'', -75''\}$ have a mass $\sim 20\%$ and $\sim 35\%$, respectively, of the mass of the main clump associated with the central cD galaxy. Actually, the main galaxy in the NW clump is as luminous as the central BCG galaxy [25, 83]. A clump of galaxies looking like a group with its own cD-like galaxy at $\sim 1.1 \text{ Mpc}/h$ northwest of the BCG was noted in [40], who also found evidence for associated intracluster light emission. The luminosity map reveals also other features, most notably a filament towards

FIG. 2: Surface matter density distribution in the core region of AC 114, in units of the projected critical density for a source redshift at $z_s = 3.347$, $\Sigma_c = 2154.2 M_\odot /\text{pc}^2$ ($h = 0.7$). Contours represent linearly spaced values of the convergence $\kappa$. NW and SE denote the positions of two matter clumps; NX and SX mark the location of the X-ray surface brightness peak for the main clump and the tail, respectively. The cold front CF and the shock front SF are plotted as dashed lines. Top-left: Contour plot of the total matter distribution density as inferred from lensing. $\kappa$-contours are plotted from 0.1 to 0.8 with a step $\Delta \kappa = 0.1$. Top-right: contours of the cluster-sized dark matter halo density as derived from the lensing analysis. $\kappa$-contour values go from 0.1 to 0.7 with a step $\Delta \kappa = 0.1$. Bottom-left: projected gas mass density as derived from X-ray observations. The convergence contours run from 0.07 to 0.12 with a step $\Delta \kappa = 0.01$. Bottom-right: density map of the projected mass density in stars as derived from galaxy luminosities. The thick (thin) contours have been obtained by smoothing the stellar mass density with a Gaussian kernel with dispersion of $10''$ ($30''$). $\kappa$-values run from $0.2 \times 10^{-3}$ to $0.12 \times 10^{-2}$ with a step of $0.2 \times 10^{-3}$ for the thick contours and from $0.2 \times 10^{-3}$ to $0.2 \times 10^{-2}$ with a step of $0.2 \times 10^{-3}$ for the thin contours.
northest in the very inner region, nearly perpendicular to the overall orientation. The coordinate system in the plane of the sky, \( \{ \theta_1, \theta_2 \} \), is centred on the BCG galaxy and aligned with the equatorial system with positive numbers being to the west and north of the central galaxy.

Here we want to perform some analysis on the galaxy density distribution. We consider either the luminosity or the number density. Our method is as follows. We first smooth the spiky density distribution convolving with a Gaussian kernel whose fixed width is based on the mean galaxy distance in the region of interest. The features of the surface distribution are then obtained by considering a sample of maps generated resampling data by the original distribution. This takes care of the finite size error. For each map, we perform a parametric fit with Poisson weights to an elliptical density distribution. Parameter central values and confidence intervals are finally obtained considering median and quantile ranges of the final population of the sets of best fit parameters. As surface density model, we consider a projected King-like \( \beta \) distribution,

\[
\Sigma = \Sigma_0 \left[ 1 + \left( \frac{\theta_{\text{c}}}{\theta_p} \right)^2 \right]^{(1-3\beta)/2} + \Sigma_B,
\]

where \( \theta_{\text{c}} \) is a projected elliptical radius, which measures the major axis length of concentric ellipses in the plane of the sky centred in \( \{ \theta_{1,0}, \theta_{2,0} \} \), with ellipticity \( \epsilon \) and orientation angle \( \theta_e \), \( \theta_p \) is the projected core radius, \( \beta \) parameterizes the slope and \( \Sigma_B \) is a constant background. We consider two circular regions in the sky with external radius \( \theta_{\text{max}} = 60'' \) and \( \theta_{\text{max}} = 120'' \), containing 104 and 329 galaxies, respectively. For the dispersion of the Gaussian kernel we used 10'' and 12'', respectively. Results are listed in Table I. The central BCG galaxy is slightly shifted from the luminosity centroid, located northwest, but the statistical significance of such a displacement is low. Most notably we retrieve a significant southeast-northwest elongation. Differences between the luminosity and number density maps are due to the abundance of late-type galaxies outside the core region. Ellipticity and orientation of the luminosity distribution within 2'' strictly follow the ellipticity parameters of the cD galaxy, which we estimated using the \texttt{ellipse} task in the IRAF package to be \( \{ \epsilon, \theta_e \} = \{0.42 \pm 0.05, (-32.8 \pm 0.5) \text{ deg} \} \).

### A. Stellar mass

Baryonic contribution in stars and stellar remnants can be estimated by converting galaxy luminosities in stellar masses. We convert \( R_{702} \) to infrared \( K \) luminosity, which is less sensitive to ongoing star formation and is a more reliable tracer of stellar mass distribution. As a first step, we corrected \( R_{702} \) photometry reported in the SExtractor catalogue of Couch et al.\textsuperscript{[25]} for background overestimate as discussed in Smith et al.\textsuperscript{[81]} and then we converted \( R_{702} \) photometry to Cousins \( R \), using suitable corrections per morphological type\textsuperscript{[82]}. Then we obtained \( K \) magnitudes subtracting the typical \( (R - K) \) colours corrected for reddening for cluster elliptical and spiral\textsuperscript{[83]}. Finally, we converted to rest-frame luminosities adopting \( M_{K,\odot} = 3.28 \)\textsuperscript{[7]} Galaxy extinction of \( A_K = 0.023 \)\textsuperscript{[25]} and using \( K \)-corrections from Mannucci et al.\textsuperscript{[54]}.

To convert stellar luminosity in stellar mass we followed Lin et al.\textsuperscript{[50]}. For ellipticals, we took the estimates for the central mass-to-light ratio as a function of galaxy luminosity from Gerhard et al.\textsuperscript{[36]}; for spiral galaxies, we used the values in Bell & de Jong\textsuperscript{[6]}. Estimating the mass-to-light ratios is the major source of uncertainty. Different modellings of stellar populations predict stellar mass-to-light ratios as different as 0.7 \( M_\odot/L_\odot \) and 1.3 \( M_\odot/L_\odot \)\textsuperscript{[20]}. Additional errors are due to either interlopers included in the catalogue or missed member galaxies. Furthermore, we did not consider stars contributing to the intracluster light, whose total fraction in AC 114 is \((11 \pm 2)\% \) in \( r \) and \((14 \pm 3)\% \) in \( B \)\textsuperscript{[46]}. It is then safe to consider an overall uncertainty \( \geq 40\% \). The projected mass density in stars is plotted in Fig. 2. Alike to the light density, the distribution of the mass in stars is elongated from northwest to southeast. The resulting integrated mass profile in the inner core is plotted in Fig. 5. The parameters of the distribution modelled as a King profile are reported in Table II.

### III. DYNAMICS

Cluster galaxy velocity dispersion is a crucial source of information. We collected positions and redshifts of galax-

<table>
<thead>
<tr>
<th>Density</th>
<th>( \theta_{\text{max}} )</th>
<th>( \beta )</th>
<th>( \theta_e )</th>
<th>( \theta_{1,0} )</th>
<th>( \theta_{2,0} )</th>
<th>( \epsilon )</th>
<th>( \theta_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>60 ( 1.2^{+0.7}_{-0.4} )</td>
<td>50 ( ^{+30}_{-30} )</td>
<td>10 ( ^{+4}_{-4} )</td>
<td>( 6^{+4}_{-4} )</td>
<td>( 0.25^{+0.12}_{-0.11} )</td>
<td>( -40^{+20}_{-20} )</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>120 ( 1.07^{+0.30}_{-0.15} )</td>
<td>( 140^{+20}_{-30} )</td>
<td>( 10^{+4}_{-4} )</td>
<td>( 4^{+4}_{-4} )</td>
<td>( 0.53^{+0.03}_{-0.04} )</td>
<td>( -41^{+3}_{-3} )</td>
<td></td>
</tr>
<tr>
<td>Stellar mass</td>
<td>60 ( 1.6^{+2.3}_{-0.5} )</td>
<td>( 36^{+50}_{-13} )</td>
<td>( 7^{+3}_{-3} )</td>
<td>( 7^{+3}_{-5} )</td>
<td>( 0.22^{+0.10}_{-0.15} )</td>
<td>( -30^{+30}_{-30} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120 ( 0.8^{+0.60}_{-0.10} )</td>
<td>( 42^{+70}_{-20} )</td>
<td>( 13^{+5}_{-5} )</td>
<td>( 11^{+6}_{-6} )</td>
<td>( 0.42^{+0.06}_{-0.08} )</td>
<td>( -26^{+9}_{-10} )</td>
<td></td>
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</table>

TABLE I: Properties of the galaxy distributions, modelled as \( \beta \) profiles, within circular regions of outer radius \( \theta_{\text{max}} \). Angles are measured North over East.
ies in the vicinity of AC 114 from the NASA/IPAC Extragalactic Database (NED). We retrieved 248 galaxies within \( \lesssim 1.5 \text{ Mpc}/h \) in the redshift range \( 0.1 \leq z \leq 0.5 \). A careful treatment of interlopers is required in dynamical modelling. Many approaches have been proposed and their efficiency has been tested using numerical simulations \[11, 88\]. Here, we propose a method of interloper removal which combines several of them.

In order to select member galaxies, we first exploit velocity information using an adaptive kernel technique \[67, 68\]. Such a nonparametric method evaluates the underlying density probability function from the observed discrete data-set. We identify the main peak in the distribution and reject galaxies not belonging to this peak. This cut has been successfully employed a number of times \[33, 37\]. To evaluate the optimal smoothing parameter, we minimise the integrated square error \[67\] fixing the initial value to the estimate proposed by Vio et al. \[87\]. As a second step, we take into account both the position and the velocity information by using the procedure of the shifting gapper \[33, 37\]. Such a method combine velocity information with the clustercentric radial distance. In each bin, shifting along the radial distance form the centre, a galaxy is removed if separated from the main local body by more than a fixed gap in velocity. We use a gap of \( \geq 1000 \text{ km s}^{-1} \) in the cluster rest frame and a bin of \( 0.3 \text{ km s}^{-1} \) Mpc.

As a third and final step, we employ a Bayesian technique \[3\]. The effect of a contaminating population can be inferred by considering that data \( v_i \) come from a Gaussian-distributed intensity super-imposed on an homogeneous random process \[3, 52, 66\].

\[
p(v_i; f_{cl}, v_{cl}, \sigma_{\text{los}}, \Delta v) = f_{cl} \mathcal{N}(v_{cl}, \sigma_{\text{los}}) + (1 - f_{cl})/\Delta v, \tag{2}
\]

where \( f_{cl} \) is the fraction of member galaxies, \( \mathcal{N} \) is a normal distribution centered on \( v_{cl} \) and with dispersion \( \sigma_{\text{los}} \) and \( \Delta v \) is the velocity range spanned by data. The likelihood is then

\[
\mathcal{L} \propto \prod_i p(v_i; ...) \tag{3}.
\]

After considering a sharp prior on \( \Delta v = \max\{v_i\} - \min\{v_i\} \) and homogeneous priors on the other parameters, we get the final probability. Such a powerful statistical method, which guesses the total fraction of interlopers without actually picking them out, has been employed to constrain the phase-space probability function \[52, 66\], but is rarely used to constrain the velocity dispersion \[3\]. After marginalization, we obtain estimates of \( v_{cl} = 3.1528 \pm 0.0007 \) for the cluster mean redshift and \( \sigma_{\text{los}} = 1900 \pm 100 \text{ km s}^{-1} \) for the velocity dispersion, the estimated fraction of interlopers being \( (11 \pm 6)\% \), in good agreement with the estimates from numerical simulations that showed that using non-Bayesian methods \( \sim 18\% \) of selected members are unrecognized interlopers \[11\]. Standard corrections for cosmological effects and velocity errors \( (\Delta v \sim 150 \text{ km s}^{-1}) \) have been applied \[27\]. Our final estimates of \( z \) and \( \sigma_{\text{los}} \) are remarkably stable for different thresholds and gaps in the first steps of our selection procedure. Only the estimated fraction of non members is sensitive to the details of the previous cuts. The results of the Bayesian technique just employed are also stable in the case of an intrinsically skewed velocity distribution \[3\].

Our expected value for \( \sigma_{\text{los}} \) is lower, but compatible within errors, than the recent estimate from Martini et al. \[56\], but higher, despite still marginally compatible, with early estimates from Couch & Sharples \[29\] and Mahdavi & Geller \[38\]. On the other hand, the estimate from Girardi & Mezzetti \[38\], who considered only a sample of non active galaxies, is quite lower.

### A. Viral mass

The total mass can now be derived using the virial theorem. Assuming the cluster to be approximately spherical, non rotating and in equilibrium, the viral mass can be expressed as

\[
M_V = \frac{3\pi}{2} \frac{\sigma_i^2 R_{\text{PV}}}{G} - C_{\text{PV}}, \tag{4}
\]

where \( R_{\text{PV}} \) is the projected virial radius of the observed sample of \( N \) galaxies,

\[
R_{\text{PV}} = \frac{N(N-1)}{\sum_{i<j} R_{ij}^{-1}}, \tag{5}
\]

with \( R_{ij} \) being the projected distance between galaxies \( i \) and \( j \). The surface term \( C_{\text{PV}} \), accounts for the fact that the system is not entirely enclosed in the observational sample. On average, for clusters observed out to an aperture radius of \( 1.5 \text{ Mpc}/h \), the correction due to \( C_{\text{PV}} \) is \( \sim 16\% \) \[11\].

Non-members can strongly affect the mass estimate. Inclusion of interlopers that are currently infalling toward the cluster along a filament causes the underestimate of the harmonic mean radius, and, at the same time, the underestimate of the velocity dispersion. Using early-type galaxies as tracers might substantially reduces the interloper contamination in the virial mass estimate \[11, 38\]. In our approach, we accounted for this issue by estimating the interloper fraction statistically. The error on \( R_{\text{PV}} \) was estimated applying a statistical jackknife to the galaxy sample that passed the shifting gapper cut. The estimate of the virial mass is then

\[
M_{200} = (3.4 \pm 0.8) \times 10^{15} M_\odot/h. \tag{6}
\]

An alternative mass estimator can be based entirely on the line-of-sight velocity dispersion. As inferred from fitting to simulated clusters, the \( M_{200} - \sigma \) scaling relation is remarkably independent of cosmology. Using a cubic relation, Biviano et al. \[11\] obtained

\[
M_{200} = (1.50 \pm 0.02) \left( \frac{\sqrt{3} \sigma_{\text{los}}}{10^3 \text{ km s}^{-1}} \right)^3 \times 10^{14} h^{-1} M_\odot \tag{6}
\]

The intrinsic velocity distribution of early-type may be slightly biased relative to that of the dark matter particles \[11\], so that when using Eq. \[6\] it is safer to not distinguish among morphological types. To properly apply the \( M_{200} - \sigma \) in Eq. \[5\], we correct our estimate of the intrinsic velocity dispersion, which was obtained within a given observational
aperture, according to the prescription in Biviano et al. \[11\]. Eventually, we get $M_{200} = (4.8 \pm 0.8 \pm 0.06) \times 10^{15} M_{\odot}/h$, where the second error is due to the theoretical uncertainty in the relation. We will follow this convention throughout the paper. We can see how the two mass estimates of $M_{200}$ are in agreement within the errors.

The concentration parameter can be estimated using scaling relations fitted to numerical simulations as well. According to agreement within the errors.

The parameter $\delta_{DS}$ test \[31\] looks for significant deviations in local groups that either have an average velocity $v_{\text{loc}}$ that differs from the cluster mean, $\bar{v}_{\text{glo}}$, or have a velocity dispersion, $\sigma_{\text{loc}}$, that differs from the global one, $\sigma_{\text{glo}}$. For our analysis, we considered the classic version of the test, which considers all possible subgroups of ten neighbors around each cluster galaxy \[31\], with the only slight difference that for calculating location and scale we consider the bitwise estimators instead of mean and standard deviation \[5\]. Then, the deviation for each galaxy can be expressed as \[31\]

$$\delta_{DS}^2 = \frac{11}{\sigma_{\text{glo}}} \left[ (\bar{v}_{\text{loc}} - \bar{v}_{\text{glo}})^2 + (\sigma_{\text{loc}} - \sigma_{\text{glo}})^2 \right]. \tag{7}$$

The parameter $\Delta_{DS} = \sum \delta_{DS}$ quantifies the overall presence of substructures. The $\Delta_{DS}$ statistic is then obtained by comparing the measured value with those obtained from simulated samples generated randomly shuffling velocities. The probability $P_{\Delta_{DS}}$ that the observed value is due to noise is then given by the fraction of samples with a value of $\Delta_{DS}$ larger than the observed one. We get $P_{\Delta_{DS}} \lesssim 0.1$. We also considered modified versions of the test \[10\]. Results are not affected.

The scope of the method can also be adapted to find which galaxies have the highest likelihood of residing in subclusters. This can be done considering the $\delta_{DS}$-statistic in a similar way to what just done for $\Delta_{DS}$. The $\delta_{DS}$-analysis picks out a potential substructure $320'' \sim 1.0 \text{ Mpc}/h$ northeast of the BCG. In fact, four galaxies located at $\{\theta_1, \theta_2\} \sim \{-200'', 250''\}$ ($\sim \{0.64, 0.80\} \text{ Mpc}/h$) have a chance in excess of $99.8\%$ to belong to a substructure. In conclusion, the $\Delta_{DS}$ and the $\delta_{DS}$-test bring further evidence for a dynamical activity.

IV. X-RAY OBSERVATIONS

AC 114 has a strongly irregular X-ray morphology \[28\], see Fig.\[1\]. The cluster does not show a single X-ray peak. Noticeable emission is associated with the cluster cD galaxy but the centroid of the overall X-ray emission is located about $10''$ northwest from the cD galaxy. Emission is dominated by two main components: the cluster, roughly centered on the optical position, and a diffuse filament which originates close to the core and curves to the south-east for approximately $1.5'$ ($\sim 0.3 \text{ Mpc}/h$), connecting the cluster core with the location of the SE clump. Such a tail shows a significant excess of soft emission.

The northern part of the cluster reveals further signs of dynamical activity. Two discontinuities both in surface brightness and temperature are observed north-east close to the cluster centre: a cold front at $20''$ ($\sim 70 \text{ kpc}/h$) from the core center and a likely shock front at $90''$ ($\sim 0.3 \text{ Mpc}/h$). A second hard region is observed on the western side of the cluster core opposite to the shock front, but drastic jumps in the surface brightness and temperature are not observed there. The location of the cold front might be compatible with a sloshing core \[53\], \[85\], but the single front, the hard ratio regions and the filament are more consistent with an ongoing major merger.

The tail and the fronts might be independent phenomena. Diffuse X-ray emission is detected near the SE clump, whereas no X-ray emission is associated to the NW clump located at opposite end of the filament. The NE substructure detected with the $\delta_{DS}$-test, see Sec.\[11\], \[10\] was not targeted by X-ray observations. One possible scenario is that the south-east clump, in its motion from the northwest through the cluster, has been ram-pressure stripped of most of its intra-group gas, now still visible as the soft southern tail. The interaction with the cluster might have also distorted the intra-cluster gas, causing the asymmetrical stretch of the cluster emission detected toward south-east. The NW clump might have been stripped as well.

The fronts suggest the motion of a sub-structure toward north-east which compresses and heats intra-cluster gas ahead of its path. Shock fronts associated with moving substructures are short-living phenomena, and are therefore signs of recent merging processes. From the Mach number \[= 1.3 \pm 0.1\] and the post-shock gas temperature \[T = 7.0^{+1.5}_{-1.1} \text{ keV}\] measured in De Filippis et al. \[28\], we derive a shock velocity of \[\sim 1800 \text{ km s}^{-1}\]. Assuming that the bullet subcluster velocity is close to the shock velocity and that the distance between the centres of the merging sub-clusters is of the order of the shock clustercentric distance, the two subclusters would have passed through each other just $0.15 \text{ Gyr}$ ago.

The cluster bolometric luminosity is $L_X = (6.7^{+0.4}_{-0.2}) \times 10^{44} \text{ erg s}^{-1}/h^2$ \[28\]. Based on scaling relations between luminosity and velocity dispersion \[70\], we would expect $L_X = (5 \pm 1 \pm 1) \times 10^{45} \text{ erg s}^{-1}/h^2$, significantly larger than the observed value. This might suggest that on one hand the gas has still to settle down in the cluster potential well and on the other hand, the clumpy structure of AC 114 might bring about an overestimate of the velocity dispersion.

The gas mass can be estimated from the X-ray emission. The surface brightness was modelled in De Filippis et al. \[28\] as a sum of two elliptical components, a main core plus an extended south-east tail. In order to infer the projected mass associated to each component, we have to project the corresponding 3D ellipsoid, modelled in De Filippis et al. \[28\].
as isothermal $\beta$-profiles, on turn obtained de-projecting the observed intensity map. Then, the projected mass is known modulus a correction geometrical factor which depends on the unknown intrinsic axial ratios and the orientation angles, see App. A. The projected mass map, whose parameters are listed in Table II is plotted in Fig. 2. The integrated ICM mass is plotted in Fig. 5. The main sources of errors for the gas mass are the projection effects and the assumption of isothermal emission. In the inner core, the contribution of the tail is sub-dominant. Note that the central convergence for the ICM is $\kappa_0 \lesssim 0.13$, so that, as expected, the gas mass is subcritical for lensing.

\section{Strong lensing analysis}

\subsection{Optical data}

Many multiple image systems have been detected in the core of AC 114, see Fig. 3. The first ones were discovered in a survey for bright gravitational lensing arcs by Smail et al. \[80\]. Two images of the prominent three-image system S were first identified by Smail et al. \[79\], whereas the third image S3 and the systems A, B, C and D, were discovered by Natarajan et al. \[59\]. The last image system E has been located by Camposano et al. \[18\], who also measured source redshifts through spectroscopic observations.

For our strong lensing model, we exploited only the image systems with confirmed spectroscopic redshift, i.e. A, E and S. The other systems have not been considered, as they are strongly perturbed by some cluster galaxies or lack precise redshift measurements. The image system S is composed of three hook-shaped images, see Fig. 4 whose source redshift is $z_s = 1.867$. In order to take into account the parity and the orientation of the images and to exploit the information carried by the shape, each S-image was sampled by two points. We considered an uncertainty of 0.4", which will be the default error for each positional data. The image system E is composed of five nearly point-like images at redshift $z_e = 3.347$, see Fig. 4. The multiple image system A is composed of five images of a single source at redshift $z_a = 1.691$. The images A1, A2 and A3 are only weakly stretched by the lens and it can be seen morphologically that they are images of the same source, see Fig. 4. We distinguished two conjugate knots in each image. On the other hand, A4 and A5 are strongly stretched because they are merging into a single arc across the radial critical curve near the BCG. As the knots in these two central images can not be distinguished, they have been furnished with a larger uncertainty (1.6").

The adopted positional uncertainties are larger than the HST astrometric resolution. Clusters are complex systems and simple models can not account for all the mass complexities. A coarser positional error allows to perform the lensing analysis without adding too much parameters and, at the same time, avoiding that the region in parameter space explored is overly confined \[74\]. This approach can be effective when dealing with galaxy clumps as those revealed by the AC 114 luminosity map, see Sec. II which are usually associated with meso-structures \[73\].

\subsection{Mass components}

We performed a strong lensing analysis in the core of the galaxy cluster AC 114 which exploits optical observations, see Sec. II, as well as measurements in the X-ray band, see Sec. IV. This multi-wavelength approach allowed us to model the cluster-sized ICM and dark matter halo and the observed galaxies, each one modelled with a separate parametric mass component. The projected surface mass density $\Sigma$ of these density profiles is expressed in terms of the convergence $\kappa$, i.e. in units of the critical surface mass density for lensing, $\Sigma_{cr} = (c^2 D_s)/(4\pi G D_l D_{ds})$, where $D_s$, $D_l$ and $D_{ds}$ are the source, the lens and the lens-source angular diameter distances, respectively. We consider mass distributions with elliptical symmetry, so that the convergence can be written in terms of the elliptical radius $\theta_{el}$.

To model the cluster-sized dark-matter component, we considered parametric mass models with either isothermal or Navarro-Frenk-White (NFW) density profiles. DM halos are successfully described as NFW profiles \[60, 61\], whose 3D distribution follows

\begin{equation}
\rho_{\text{NFW}} = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2},
\end{equation}

where $\rho_0$ is the characteristic density and $r_s$ is the characteristic length scale. The convergence for this mass profile is obtained by replacing the polar radius with the elliptical coordinate in the resulting projected surface mass density. The strength of the lens is given in terms of a parameter $\kappa_{\text{NFW}}$, see Eq. (A7).

An alternative description for DM components is in terms of isothermal mass density. The non-singular isothermal profiles are parametrized by a softened power-law ellipsoid (NIE), and represent a special case of $\beta$-models with $\beta = 2/3$, see Eq. (1). The mass scale parameter is usually written as $b = 2\kappa_0 r_{e,P}$ \[45\], where $\kappa_0$ is the central convergence and $r_{e,P}$ is the projected core radius, see App. A.

The two gas components, i.e. the main X-ray clump and the soft tail, can be modelled as $\beta$-profiles, see Eq. (1). Unlike the DM component, which was modelled as isothermal, the slope for each gas component is fixed from the X-ray observations, see Table II. We note that the mass distribution of the main X-ray emitting clump is quite flat.

For an accurate lens modeling, the mass distribution of the galaxies has to be considered too. Galaxies are small compared to the whole cluster, but they have high local mass densities and can strongly perturb the cluster potential in their neighborhood. Therefore, galaxies which affect the considered image systems are taken into account. The selection has been limited to the region of the cluster where the multiple image systems are located. We selected the eight brightest galaxies and other six bright galaxies close to the lensed images in the inner $\sim 80'' \times 80''$.

Galaxy-sized halos can be modeled by pseudo-Jaffe mass models, which are obtained subtracting a NIE with core radius
FIG. 3: HST/WFPC-2 image of AC 114 with the observed multiple image systems. The coordinates $\theta_1$ and $\theta_2$, both measured in arcseconds are in direction west and north, respectively. The critical lines are represented by the black lines and are referred to the image system E ($z_s = 3.347$). Circles surround multiple images (A, B, C, D, E and S systems), while the filled squares, small circles and triangles mark the predicted image positions for the system A (green in the electronic version of the paper), E (red) and S (blue), respectively.

FIG. 4: A mosaic of the zoomed-in regions ($\sim 8'' \times 8''$) surroundings the images A3 (left panel), E2 (middle panel) and S1(right panel). A3 has an elongated shape wherein distinct points can be recognized. For E2, the intrinsic morphology of the source can not be recognised, whereas the hook-shaped source of the image system S is shown by S1. The white crosses are the coordinates of the sampled points used into the strong lensing analysis.

In order to accomplish the strong lensing analysis, we performed a $\chi^2$ analysis by fitting the image positions. We made use of the gravlens software \cite{44, 45}. The total number of constraints ($= 42$) is given by the coordinates of the observed image positions. The number of free parameters allowed to vary, i.e. the free parameters in the mass models plus radius $r_t$. To minimize the number of parameters, a set of scaling laws has been adopted \cite{14}: $\sigma_{\text{DM}} = \sigma_{\text{DM}}^* (L/L^*)^{1/4}$ and $r_t = r_t^* (L/L^*)^{1/2}$. The core radius $r_c$ is scaled in the same way as $r_t$. We let $\sigma_{\text{DM}}^*$ vary as a free parameter, whereas $r_c^*$ and $r_t^*$ were fixed to 0.15 kpc and 25 kpc, respectively \cite{18}. The dispersion $\sigma_{\text{DM}}$ is related to the total mass through $M = (9/2G)\sigma_{\text{DM}}^2 r_t$ \cite{59}. The typical luminosity $L^*$ for the galaxy catalogue used in our analysis, see Sec. II, was approximately given by the median of the morphologically selected early-type galaxies \cite{59}.
TABLE II: Best fit parameters inferred from the lensing analysis for each matter component, i.e. total mass, DM, gas (from the X-ray analysis) and galaxies. The DM was modelled as a NFW distribution. The orientation angle $\theta_0$ is measured north over east. $r_{sP}$ ($r_{cP}$) is the projected length scale (core radius) for the NFW ($\beta$) profile.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass scale</th>
<th>$\theta_{1,0}$</th>
<th>$\theta_{2,0}$</th>
<th>$\epsilon$</th>
<th>$\theta_0$</th>
<th>length scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>$k_{NFW}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$r_{sP}$</td>
</tr>
<tr>
<td>NFW</td>
<td>0.216 $\pm$ 0.012</td>
<td>1.7 $\pm$ 0.2</td>
<td>$-0.41 \pm 0.19$</td>
<td>0.502 $\pm$ 0.018</td>
<td>$-38.6 \pm 0.3$</td>
<td>210 $\pm$ 20</td>
</tr>
<tr>
<td>Dark Matter</td>
<td>$k_{NFW}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$r_{sP}$</td>
</tr>
<tr>
<td>NFW</td>
<td>0.187 $\pm$ 0.008</td>
<td>1.4 $\pm$ 0.2</td>
<td>$-0.1 \pm 0.2$</td>
<td>0.549 $\pm$ 0.017</td>
<td>$-39.9 \pm 0.4$</td>
<td>199 $\pm$ 14</td>
</tr>
<tr>
<td>ICM</td>
<td>$\kappa_0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$r_{cP}$ $\beta$</td>
</tr>
<tr>
<td>Main Clump</td>
<td>0.100 $\pm$ 0.008</td>
<td>3.7 $\pm$ 1.0</td>
<td>8.7 $\pm$ 1.0</td>
<td>0.39 $\pm$ 0.05</td>
<td>$-13 \pm 4$</td>
<td>13.6 $\pm$ 1.0</td>
</tr>
<tr>
<td>Southern Tail</td>
<td>0.033 $\pm$ 0.006</td>
<td>$-23.4 \pm 1.0$</td>
<td>$-37.6 \pm 1.0$</td>
<td>0.50 $\pm$ 0.02</td>
<td>$-37 \pm 2$</td>
<td>170 $\pm$ 40</td>
</tr>
<tr>
<td>Galaxy Halos $\sigma_{DM}$ (km s$^{-1}$)</td>
<td>$r_{cP}$ (kpc)</td>
<td>$r_{cP}$ (kpc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L$^*$ Galaxy</td>
<td>62 $\pm$ 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.15</td>
</tr>
</tbody>
</table>

TABLE III: Best fit parameters inferred from the lensing analysis for the DM cluster-sized halo (modelled as a NIE) and the galaxy-sized halos. The remaining component, i.e. the gas, was modelled as in Table II.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass scale</th>
<th>$\theta_{1,0}$</th>
<th>$\theta_{2,0}$</th>
<th>$\epsilon$</th>
<th>$\theta_0$</th>
<th>$r_{sP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dark Matter</strong></td>
<td>$b$ (&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIE</td>
<td>41.1 $\pm$ 1.4</td>
<td>2.0 $\pm$ 0.2</td>
<td>0.0 $\pm$ 0.3</td>
<td>0.531 $\pm$ 0.014</td>
<td>$-40.1 \pm 0.6$</td>
<td>17.2 $\pm$ 0.9</td>
</tr>
<tr>
<td>Galaxy Halos $\sigma_{DM}$ (km s$^{-1}$)</td>
<td>$r_{cP}$ (kpc)</td>
<td>$r_{cP}$ (kpc)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L$^*$ Galaxy</td>
<td>82 $\pm$ 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.15</td>
</tr>
</tbody>
</table>

Performing the fitting to just a single image system leads to almost the same $\chi^2$-value for all the considered models independently of the system (A, E or S), since constraints associated to a single image are not enough to reliably determine the parameters. Only computing the $\chi^2$ for all the image systems simultaneously, leads to clear statements on the mass models. The uncertainty of the parameters have been obtained in a Bayesian way, i.e. by marginalising the likelihood function. We assumed homogeneous priors for the parameters. We took care of performing the $\chi^2$ analysis in the image plane, which improves the statistical accuracy of the results.

A. NFW profile

We first considered a NFW model for the dark matter mass component. As a first step, we considered a single NFW density profile, representing the total matter distribution (DM+ICM+galaxies). The parameters of this mass component are listed in Table II. The scale radius $r_s$ affects the mass profile only through higher order effects for $r \ll r_s$. Only through the combined fit, i.e. using all the three image systems simultaneously, we were able to determine $r_s$ and its uncertainty. This is crucial in the estimate of the concentration, see Sec. [VII]. With this simple mass model we were able to reproduce the observed images much better than assuming an isothermal profile, see Sec. [VII]. All the images of the image systems were reproduced with a mean distance of $\chi^2 \approx 39$.

The subsequent addition of ICM and galaxy-sized halos slightly improved the fit ($\chi^2 \approx 0.54''$, $\chi^2 \approx 31$), but above all helped to achieve a physically more consistent model, which better describes the features of the cluster. Note that the inclusion of both galaxies and ICM is needed to improve the fit, whereas accounting only for the gas is not helpful. The parameters of each component for the best fit model are given in Table III. The addition of the ICM, which is quite flattened,
caused a slight decrease of the projected scale length, $r_{sP}$, for the DM component, whose orientation experienced a clockwise rotation of $\sim 2^{\prime}$ deg. These changes are slight, as the ICM has a relative low mass compared to the dark matter, but nevertheless interesting. The decrease of $r_{sP}$ shows that the dark matter component is more compact than the ICM. The total projected mass for this combined DM+ICM+galaxies model within 75 kpc (150 kpc) is $(3.8 \pm 0.3) \times 10^{13} M_{\odot}$ $(11.3 \pm 1.0) \times 10^{13} M_{\odot}$, in good agreement with previous estimates [28, 59]. Note that in order to limit the total number of free parameters, we scaled the BCG as the other galaxies so that in our modelling the NFW cluster-sized profile makes up for most of the DM associated with the BCG halo.

Ellipticity and orientation of the dark matter component are almost the same as the ones of the southern component of the ICM, whereas the northern component, which is the main baryonic component in the cluster core, compared to the dark matter, is less elliptical and rotated counter-clockwise of $\sim 27^{\prime}$ deg. Its centroid is displaced of $\sim 40$ kpc form the center of the dark matter distribution. This evident spatial offset between the dark matter and the main baryonic component in the cluster core brings evidence that the cluster is not in equilibrium. The fact that between the center of the dark matter component and the position of the BCG there is no significant offset portends that the dark matter behaves like collisionless particles during the merging process.

In order to investigate the inner slope, we considered a total matter distribution modelled as a singular softened power law ($r_c = 0$), which represents a power law mass profile, i.e. $\rho \propto r^{-\alpha}$. This mass profile is able to reproduce all the images of the observed systems, and for the slope we obtained a best fit value of $\alpha = 1.38 \pm 0.01$.

### B. Isothermal profile

Alternatively to the NFW model, we considered an isothermal profile for the main mass component. As a first step, we modelled the total mass component. We considered a single NIE centred in the neighbourhood of the BCG galaxy, representing all the matter present in the galaxy cluster. This model turned out to be inadequate, since it was only able to produce three images for the image system A. The mean distance between the predicted and the observed images for the other system was $\sim 2.4^{\prime}$ deg. The reason is that the central density of this model is too low and therefore the central caustic too narrow, which in turn implies the vanishing of the merging images A4 and A5.

To solve this issue we added the mass distribution from galaxy-sized halos. Accounting for the BCG made possible to fit also A4 and A5, and the mean distance between observed and predicted images was $\leq 1^{\prime}$.

We finally considered at the same time the ICM, the galaxy sized halos and the dark matter component modelled as a NIE profile, see Table [III]. For the gas mass, we assumed the parameters from the X-ray analysis, see Table [III]. The addition of the ICM mass components was not able to significantly improve the fit, since its mass distribution is widely distributed, with a subcritical surface density which is unable to produce any strong lensing. Only its total mass has an influence on the lensing properties of the cluster. The value of $\sigma_{DM}$ for the $L^*$ galaxy have to be much higher assuming an isothermal profile for the DM than for a NFW distribution. In fact, the cored NIE is quite inadequate as a model for the DM so that galaxies, and in particular the BCG, have to supply additional convergence to broaden the central caustic. The average distance between observed and best fit image positions is $\sim 0.84^{\prime}$ ($\chi^2 \approx 85$), while the total mass for this model within circles with radii 75 kpc (150 kpc) is $(4.0 \pm 0.3) \times 10^{13} M_{\odot}$ $(11.2 \pm 0.9) \times 10^{13} M_{\odot}$, in agreement with the estimate based on the assumption of DM distributed as a NFW model. The fit obtained with an isothermal profile is significantly worse than assuming a NFW. This difference is due to the consideration of images near the central radial caustic, which are very sensible to the inner slope.

### VII. RESULTS

#### A. Dynamical status

The strong lensing analysis of the inner regions of AC 114 brings new evidence about its dynamical status. The multi-wavelength approach we took, in which the baryonic components were fixed using observations either in the X-ray or optical band, allowed us to infer directly the dark matter distribution. The gas is displaced from the dark matter. The main X-ray clump and the cluster sized dark DM halo are off-centered by $\sim 9^{\prime}$, an offset much larger than the Chandra accuracy of $\sim 1^{\prime}$ which determines the accuracy in the X-ray peak position. The relative orientation differs by $(27 \pm 4)^{\prime}$ deg. On the other hand, the DM clump is nearly aligned with the X-ray tail. This provides further evidence that the X-ray surface brightness in the core is strongly perturbed by the dynamical activity. The likely motion of a sub-structure toward northeast, as suggested by the fronts, might have distorted the local emission causing a rotation of the overall surface brightness of the central X-ray clump towards east and the relative misalignment of gas and dark matter.

#### B. Collisionless dark matter

Whereas the ICM is clearly displaced, the dark matter distribution strictly follows the galaxy density. The quite large errors in the parameters describing either the number, the luminosity or the stellar mass density distributions, see Table [IV] makes it difficult to distinguish if a certain galaxy density traces the dark matter distribution better than other ones. However, the good agreement between each other allows us to draw some conclusions. The galaxy and dark matter distribution share comparable centroid position, orientation and ellipticity. Since dark matter was modelled with a cusped profile whereas the galaxy density were fitted to a cored distribution, the comparison can not be extended to the remaining parameters. The agreement probes again the results from the
Figure 5: Mass, in units of $M_\odot$, enclosed within a given projected radius for each component. Total mass, DM halo, ICM mass and the stellar contribution from galaxies are plotted from the top to the bottom. DM halo refers to the cluster-sized dark matter component found in the multi-wavelength lensing analysis. To compare different mass components we fixed $h = 0.7$.

bullet cluster on the collisionless nature of dark matter [19]. This time, we could probe that the agreement between galaxies and dark matter concerns not only the location but also the shape of the distribution.

When comparing dark matter with the galaxy distributions the agreement becomes striking when we consider the number density distribution. As written before, errors are quite large and definite statements can not be drawn but the similarities between the expected values are nevertheless noteworthy. It is already well known that galaxy abundance is a very reliable proxy for the cluster mass [41]. Our result might provide further indication that galaxy number density is a dependable tracer also for DM shape and orientation.

C. Baryons and dark matter

Our multi-wavelength approach allows us to determine the mass profile of each component in the very inner regions. Figures 5 and 6 show the enclosed projected masses for cluster-centric distances less than 1$'$ ($R \lesssim 280$ kpc). We consider the two main baryonic components (stars in galaxies and hot ICM), the cluster-sized dark matter halo and the total projected mass (as modelled with a single NFW profile, see Sec. [VLA]). The mass values with the smaller errors are those from the lensing analysis. The estimates of the different mass components scale differently with the Hubble constant, so that for comparison we fixed $h = 0.7$. Note that we consider projected mass distributions for each component, which avoids biases due to comparing projected with intrinsic quantities.

Typical trends are retrieved [12]. The dark matter halo is the dominant component ($\sim 80\pm9\%$ at $R \sim 280$ kpc). In the very center ($\theta \lesssim 5''$) the baryonic budget is dominated by the stellar mass in the BCG, whereas the ICM contribution takes over at larger radii. The gas distribution is shallower than the dark matter profile, so that the ICM fraction increases from $\sim 10\pm3\%$ at $R \sim 50$ kpc to $\sim 20\pm5\%$ at $R \sim 280$ kpc. These values are larger but still compatible with typical values inferred with X-ray analyses of luminous clusters [1]. On the other hand, the stellar fraction seems to be less than usual [12].

The luminosity function of AC 114 has been extensively studied [1]. Adopting a total luminosity of $(1.5\pm0.2)\times10^{12}L_\odot$ in $r$ and $(1.9\pm1.2)\times10^{11}L_\odot$ in $B$ within 0.6 Mpc/$h$ [46], we get mass-to-light ratios of $M/L_r = (500\pm100)M_\odot/L_\odot$ and $M/L_B = (5000\pm3000)M_\odot/L_\odot$, which point to a underluminous cluster core. However, due to the large errors, especially in the $B$-band, the mass-to-light ratios are still slightly compatible with estimates from other clusters [5, 69].

D. Universal vs isothermal profiles

A main prediction of $N$-body simulations is that dark matter halos have a universal profile. NFW profiles are strongly favoured over isothermal models. On the scale of galaxy clusters, lensing observations are confirming such a view. Stacking weak lensing clusters, Okabe et al. [65] found that the isothermal profile is highly disfavoured with respect to the NFW model and that the measured profile at small radii is consistent with the inner NFW slope. An additional hint in this direction is also given by studies of arc magnification [78].

Both parametric and non parametric studies of other strong lensing clusters, which alike to AC 114 presents sets of multiple lensed sources at different redshifts, also support a universal profile ($\alpha \sim 1$) in the inner regions [49, 71, 72]. In fact, multiple lensed sources at different redshifts enables to break the degeneracy between the scale radius and the inner slope that can otherwise plague strong lensing analyses [74].
Even when the preferred value for $r_s$ is found larger than the clustercentric distance of images, lensed sources at different redshifts are actually sensitive to the scale radius \cite{49}. Our analysis of AC 114 is another probe that on cluster-scales an isothermal profile cannot provide an adequate description of the mass distribution.

E. Inner slope

Values of inner and outer slopes of density profiles coming out from $N$-body simulations are still debated with different parameterizations competing \cite{57, 71}. Baryons play a role too, since their infalling would steepen the dark matter profile. However, in large clusters this effect is expected to be small exterior to $\sim 20$ kpc \cite{39}. The general consensus is that in the inner regions of clusters the dark matter profile should go as $\rho \sim r^{-\alpha}$, with $\alpha$ between 1 and 1.4 \cite{30}.

We found $\alpha \simeq 1.38$ with a formal error of 0.01. The simple power-law used in our analysis make very prompt the comparison with previous analyses which employed the same parameterization, showing good agreement \cite{22}. On the other hand, the very small uncertainty on $\alpha$ is more due to not enough accurate modelling than to very precise statistical accuracy. Different modelling of the cD galaxies can bring about an uncertainty of $\sim 0.05$ on the inner slope \cite{49}. The main source of error ($\sim 0.1$) is due to the absence of a length scale in the simple power-law profile we used. Limousin et al. \cite{49} showed how fixing $r_s$ to a value smaller that the best fit estimate causes an underestimate of the slope. We can quantify the uncertainty according to the following simple reasoning. The slope of a NFW profile changes from $\alpha = 1$ in the very inner regions to $\alpha \simeq 1.18$ at $r \simeq 10^{-1}r_s$, with a mean value of $(\alpha) \simeq 1.12$. Then, for sets of multiple images covering nearly one tenth of the length scale, modelling the profile with a power-law causes an over-estimate of the inner slope $\alpha$ of $\sim 0.1$. Finally, as for the impact of the gas, we have showed that as far as the ICM mass distribution is modelled with a cored profile, the estimate of $\alpha$ does not depend on its inclusion in the fit procedure. Even after accounting for such systematics, we see that the estimated value of the inner slope of AC 114 is still steeper than a simple NFW profile and falls just in the middle of the range compatible with theoretical predictions \cite{30}.

F. Concentration

The concentration parameter reflects the central density of the halo, so bringing imprints of the halo assembly history and thereby of its time of formation. Dealing with ellipsoidal halos, we need generalized definitions for NFW parameters. We follow Corless & King \cite{22}, who defined a triaxial virial radius $r_{200}$ such that the mean density contained within an ellipsoid of semi-major axis $r_{200}$ is 200 times the critical density at the halo redshift; the corresponding concentration is $c_{200} \equiv r_{200}/r_s$. Then, the characteristic overdensity in terms of $c_{200}$ is the same as for a spherical profile. The virial mass, $M_{200}$, is the mass within the ellipsoid of semi-major axis $r_{200}$.

Such defined $c_{200}$ and $M_{200}$ have small deviations with respect to the parameters computed fitting spherically averaged density profiles, as done in $N$-body simulations. The only caveat is that the spherical mass obtained in simulations is significantly less than the ellipsoidal $M_{200}$ for extreme axial ratios \cite{22}.

If a cluster is elongated along the line of sight, the concentration parameter and the virial mass estimated from lensing are overestimated \cite{35, 64}. On the other hand, there are more inefficient lensing orientations for a triaxial halo than there are efficient ones \cite{23}. Investigations in the weak lensing regime demonstrated that neglecting halo triaxiality can lead to over- and under-estimates of up to 50% and a factor of 2 in halo mass and concentration, respectively \cite{22}. Even assuming statistical priors on the intrinsic shape, uncertainties are still large \cite{23}. A simple way to account for projection effects is detailed in App. A. The expected values of the geometrical correction factors can be estimated assuming random orientations and intrinsic axial ratios with probability density following results from $N$-body simulations \cite{42}. We obtain $c_{200} = 3.5 \pm 0.7$, in good agreement with the estimate derived in Sec. IIIA and $M_{200} = (1.4 \pm 0.7) \times 10^{15} M_\odot/h$, slightly lower than estimates based on the velocity dispersion, see Sec. IIIA. We get nearly the same value for $c_{200} (= 3.4 \pm 0.7)$ if we consider the cluster-sized dark-matter halo instead of the total mass distribution.

The halo concentration parameter is expected to be related to its virial mass, with the concentration decreasing gradually with mass \cite{17}. According to recent numerical simulations \cite{32}, the concentration of a cluster with the same mass just derived for AC 114 at its redshift should be $c_{200} = 2.90 \pm 0.13 \pm 0.13$. The agreement with our result is striking, something very unusual when comparing concentrations derived from lensing analyses to predicted values.

VIII. DISCUSSION

Exploiting in a combined way lensing observations with multi-wavelength data sets is a very powerful tool for constraining properties of galaxy clusters \cite{19, 34, 47, 76, 81}. Here, we have performed a lensing analysis in which the gas mass distribution, previously inferred from X-ray observations, has been embedded from the very beginning in the modelling. Gas is the main baryonic component and typically contributes for $\gtrsim 10\%$ of the total mass in galaxy clusters \cite{1}. Considering the ICM in the parameterization can be seen as an improvement with respect to the usual way of modelling only cluster-sized dark matter and galaxy-sized halos.

Comparison of the dark matter map directly obtained from lensing modelling with either the gas or the stellar mass distribution can give a deep insight on the properties of the cluster. Our analysis confirmed that the ICM is displaced from the dark matter in dynamically active clusters, whereas the collisionless nature of dark matter is probed by the good matching with the galaxy distribution.

The results for AC 114 are in remarkable agreement with predictions from $N$-body simulations. We found that: i) a
The cusped NFW mass model is highly preferred over an isothermal profile; ii) the inner slope is slightly steeper than a simple NFW; iii) the concentration parameter is in line with predictions from mass-concentration scaling relations.

Our estimated inner slope is in perfect agreement with estimates from numerical simulations. A value of $\alpha \gtrsim 1$ might be indication of steepening due to adiabatic contraction, but the very young dynamical age of AC 114 and its intense ongoing merging activity weaken such an interpretation. It is noteworthy that the recent modelling of the seemingly relaxed cluster A 1703 prefers an inner slope larger than one ($\alpha \sim 1.1$) too [49].

The observed concentration-mass relation for galaxy clusters has a slope consistent with what found in simulations, though the normalization factor is higher [21]. Lensing concentrations appear to be systematically larger than X-ray concentrations [21]. A similar, though less pronounced, effect is also found in simulations [40], which show how massive lensing clusters are usually elongated along the line of sight. Oguri & Blandford [62] showed how the larger the Einstein radius, the larger the over-concentration problem, with clusters looking more massive and concentrated due to the orientation bias.

However, the observational picture from lensing analyses is still not clear. Broadhurst et al. [15] derived lens distortion and magnification of four nearly relaxed high-mass clusters, inferring significantly high concentrations. Oguri et al. [63] found that the data from a sample of ten clusters with strong and weak lensing features were highly inconsistent with the predicted concentration parameters, even including a 50% enhancement to account for the lensing bias [62]. On the other hand, out of 30 X-ray clusters with significant weak lensing signal, using a spherical modelling Okabe et al. [65] found that the 19 clusters that were well fitted by a NFW profile showed a correlation in the $M - c$ relation which is marginally compatible with predictions for both slope and normalization. Following a different approach, triaxiality issues were addressed by Corless et al. [23], who put weak lensing constraints on three strong lensing clusters without assuming a spherical halo model. They found that that large errors that accompany triaxial parameter estimates can make observations compatible, even if marginally, with theoretical predictions. Furthermore, weak lensing analyses of stacked clusters of lesser mass does not exhibit the high concentration problem [43, 53], in agreement with the findings of Oguri & Blandford [62].

Several effects can play a role. Strong lensing clusters tend to preferentially sample the high-mass end of the cluster mass function [21]. While extreme cases of triaxiality are rare, such halos can be much more efficient lenses than their more spherical counterparts [62] with the strongest lenses in the universe expected to be a highly biased population preferentially oriented along the line of sight and with high levels of triaxiality. Lensing concentrations can be also inflated due to substructures close to the line of sight. Furthermore, contamination of weak lensing catalogues can lead to underestimate the concentration [48].

The analysis we performed provides some new elements. First, some peculiarities might make our results less affected from biases. We derived the concentration parameter using only strong lensing data and we did not use the spherical approximation for the halo profile. In fact, different definitions of parameters for spherically averaged profiles can play a role when comparing observations to predictions [16]. Second, AC 114 has some peculiar features that might make the high concentration problem much less pronounced. In particular, the very long tail in the X-ray morphology and the detection of a shock front suggest that the cluster develops in the plane of sky. The elongation of the cluster could be probed observationally combining lensing and X-ray data with measurements of the Sunyaev-Zeldovich effect [29, 34, 76, 77]. Unfortunately, detection for AC 114 is still marginal [2] and deeper radio observations are needed.

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APPENDIX A: PROJECTION EFFECTS

The projected map $F_{2D}$ of a volume density $F_{3D}$ which is constant on surfaces of constant ellipsoidal radius $\xi$ is elliptical on the plane of the sky [76, 84].

$$F_{2D}(\xi; l_p, p_i) = \frac{2}{\sqrt{3}} \int_0^\infty F_{3D}(\xi; l_s, p_i) \left( \frac{\xi}{\sqrt{\xi^2 - \xi^2_i}} \right) d\xi,$$

where $\xi$ is the elliptical radius in the plane of the sky, $l_s$ is the typical length scale of the 3D density, $l_p$ is its projection on the plane of the sky and $p_i$ are the other parameters describing the intrinsic density profile (slope, ...); the subscript P denotes measurable projected quantities. The parameter $f$ depends on the intrinsic shape and orientation of the 3D distribution,

$$f = c_1^2 \sin^2 \theta_{E1} \sin^2 \varphi_{E1} + c_2^2 \sin^2 \theta_{E2} \cos^2 \varphi_{E2} + \cos^2 \theta_{E2},$$

where $\varphi_{E1}, \theta_{E2}$ are the two Euler’s angles of the principal cluster axes with respect to the observer which fix the orientation of the line of sight and $c_i(\geq 1), i = \{1, 2\}$ are the two axial ratios [76]. The integral in Eq. (A1) must be proportional to $l_s$. The relation between a length measured along the major axis and its projection in the sky is

$$\frac{l_s}{\sqrt{3}} = \frac{l_p}{e_\Delta},$$

where the parameter $e_\Delta$ quantifies the elongation along the line of sight of the triaxial ellipsoid [76],

$$e_\Delta = \left( \frac{e_{P1}}{e_{P2}} \right)^{1/2} f^{3/4},$$
where $c_2P(\geq 1)$ is the projected axial ratio. Finally, the surface density can be expressed as

$$F_{2D} = \frac{f_{2D}}{f_\Delta} f_{2D}(\xi; \eta, p_i, ...),$$  \hspace{1cm} (A5)$$

where $f_{2D}$ has the same functional form as for a spherically symmetric halo. Then, when we deproject a surface density, the normalization of the volume density can be known only apart from a geometrical factor

$$f_{geo} = \frac{(\epsilon_1 \epsilon_2)^{1/2}}{f_3^{1/2}} = \frac{\epsilon_1^{1/2}}{\epsilon_\Delta}. \hspace{1cm} (A6)$$

When we estimate the gas mass from measurements of the surface brightness $S_X$, which is proportional to the squared density $n_X^2$, we first have to deproject $S_X$, so that, after inversion, the central squared density is known apart from a factor $f_{geo}^{1/2}$. Then we project along the line of sight the density $n_e$, which brings about an additional factor $f_{geo}$. The resulting central projected mass density is $\Sigma_0 \propto f_{geo}^{1/2}$. This geometrical factor is independent of the specific density profile of the ICM distribution.

When inferring the concentration parameter, we face a slightly different case. We have just a single projection, so that the central convergence of a NFW profile estimated from lensing can be written in terms of $c_{200}$ and the projected length scale modulus a factor $f_{geo}$.

$$\kappa_{NFW} = \frac{f_{geo}}{\sqrt{e_P}} \rho_{cr} r_s p^\eta. \hspace{1cm} (A7)$$

The estimate of the mass $M_{200}$ depends also on the scale-length $r_s$ which is known modulus a factor $\sqrt{f}/e_\Delta$. see Eq. (A3). Then

$$M_{200} = \frac{4\pi}{3} \times 200 \rho_{cr} \times (c_{200} r_s)^3 f_{geo} / e_P. \hspace{1cm} (A8)$$

The geometrical correction factors can be estimated under some working hypotheses. Assuming that the cluster is drawn from a population with random orientations and intrinsic axial ratios with probability density following results from $N$-body simulations [42], we can estimate for $f_{geo} (f_{geo}^{1/2})$ an expected value of 0.93 (0.95) with a dispersion of 0.37 (0.18).