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Investigating the structure of cluster galaxies with combined strong lensing and stellar kinematics

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Summary. — Strong lensing (SL) is a powerful probe of the dark matter (DM) mass distribution in the cores of galaxy clusters, providing us with stringent tests of the cold DM (CDM) paradigm. SL models predict an excess of galaxy-galaxy SL events for observed galaxy clusters compared to simulated data based on cosmological simulations: this is reflected by a higher compactness for the observed cluster galaxies with respect to their simulated counterparts. We address this discrepancy by building improved SL models of cluster galaxies. We describe a SL model of the massive cluster Abell S1063, where the properties of the cluster galaxies are described more accurately than in previous studies using a parametrisation based on the Fundamental Plane relation, which we calibrated based on the observed kinematic properties of the members. We present new SL models for three galaxy lenses within the clusters MACS J0416.1−2403 and MACS J1206.2−0847; we have measured their truncation radius and their stellar-to-total mass fraction, extending current studies on lens galaxies to lower mass limits. We compare our results with a suite of cosmological hydrodynamical simulations, testing the effects of the resolution and of the feedback set-up, and confirming the lower compactness predicted for simulated cluster galaxies. This persistent mismatch could point towards new physics beyond CDM.

1. – Introduction: a discrepancy between the compactness of observed and simulated cluster galaxies

Galaxy clusters are a crucial bridge between Astrophysics and Cosmology: they are privileged tracers of the formation of massive structures by hierarchical mergers and of the evolution of galaxies in dense environments. During their formation, smaller haloes are subsequently accreted into larger ones, and they are subject to several physical processes:

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tidal stripping and heating can remove a significant fraction of their mass, and baryonic processes such as cooling or energy feedback can re-shape their internal structure and influence the star formation of the galaxy they host. As such, the DM mass distribution of galaxy clusters bears the traces of the processes that drive their formation and evolution, including, crucially, the micro-physics of DM and of its interplay with baryons. Λ CDM cosmological hydrodynamical simulations trace the history of clusters, allowing us to test our hypotheses on the processes that shape them. With the support of several dedicated photometric and spectroscopic surveys, SL has become an extremely accurate probe of the total mass distribution in the cores (out to a few hundreds of kiloparsecs from the centre) of massive galaxy clusters [1, 2]. When combined with baryonic mass probes, SL allows us to disentangle the mass distribution of cluster- and galaxy-scale DM haloes, which can be compared to the predictions of high-resolution cosmological simulations. Meneghetti *et al.* [3] compared the total mass distribution of a sample of observed galaxy clusters, as modelled by [4] using SL, with the predictions of the Dianoga cosmological hydrodynamical simulation suite [5, 6]. They reported a significant discrepancy between SL models and simulations in terms of the predicted number of galaxy-galaxy (GG) SL events within massive clusters, *i.e.*, the probability of observing SL events in which a cluster member galaxy acts as a primary lens (multiple images of the same source are observed close to it). This can be interpreted as a consequence of simulated cluster members being less compact than observed, as highlighted by a lower maximum circular velocity than their simulated counterparts with the same total mass. This discrepancy could shed light on galaxy formation and evolution in dense environments and point towards open issues with the Λ CDM paradigm.

Galaxy cluster members are typically introduced in SL models with a truncated isothermal total mass density profile [7]. Each of them is therefore described by two parameters: the central velocity dispersion, σ, and the truncation (or half-mass) radius, r_t. To reduce the number of free parameters, their values are obtained via power-law scaling relations with respect to the observed galaxy luminosity. Given the typical angular separation observed between multiple images strongly lensed by galaxy clusters, their positions mostly depend on the total mass of the cluster galaxies, but they are not very sensitive to the details of its galaxy-scale distribution. This leads to a degeneracy between the values of σ and r_t for the cluster members: the same total mass can be obtained with a higher (lower) value of the former and a lower (higher) of the latter, that is to say with a more (less) compact mass distribution. This degeneracy can only be broken with independent observational priors on the values of σ and r_t.

Bergamini *et al.* [4] already took advantage of VLT/MUSE integral field spectroscopy to obtain a prior on the relation between the values of σ and of the total luminosity of the member galaxies. However, linking both the parameters describing the properties of the cluster members to their total luminosity with power-law scaling relations, without any scatter, remains a simplified approach. We take a further step forward by calibrating the Fundamental Plane ([8-10], FP) for the members of the massive galaxy cluster Abell S1063 (AS1063), at $z = 0.346$ [11], and use it to obtain a more complex description of the physical properties of the cluster galaxies in an improved SL model of AS1063. Our results are summarised in sect. **2** and detailed in [12]. On the other hand, the truncation radius can be measured with SL by analysing GGSL events, which provide us with detailed information on the mass distribution of the galaxy-scale lens. We build SL models for three lens galaxies within the clusters MACS J0416.1−2403 (MACS J0416), at $z = 0.397$ [13], and MACS J1206.2−0847 (MACS J1206), at $z = 0.439$ [14]. The results of this work are summarised in sect. **3** and presented in detail [15].

2. – An improved strong lensing model of Abell S1063 based on the fundamental plane

As a first step towards the calibration of the FP, we used *Hubble* Frontier Fields (HFF, [16]) photometry in the F814W band to measure the values of the structural parameters of all the cluster members of AS1063 that we wished to include in the model [17, 18], including theit effective radius (R_e) and the average surface brightness within R_e (SB_e). Then, VLT/MUSE integral field spectroscopy allowed us to determine the central (*i.e.*, measured within an aperture of $R_e/8$ from the galaxy centre) line-of-sight stellar velocity dispersion (σ_0) for a sizeable sub-set of 30 early-type members. We combined the photometric and spectroscopic information for these galaxies to calibrate the FP relation for the early-type cluster members

$$\log R_e = (0.99 \pm 0.17) \times \log \sigma_0 + (0.323 \pm 0.029) \times \mathrm{SB}_e + (-10.3 \pm 1.0), \tag{1}$$

where R_e is measured in kpc, and σ_0 in km s^{-1}, whereas SB_e is defined as $m\,[\mathrm{mag}] + 2.5 \times \log(2\pi(R_e\,[\mathrm{kpc}])^2)$, where m is the total magnitude of the member in the F814W band.

The FP presented in eq. (1) allowed us to measure the values of the velocity dispersion of all cluster members from their observed structural parameters, with a more realistic scaling relation compared to the power-law approach. Finally, we calibrated a proportionality relation between the truncation radius of the cluster galaxies and the observed value of R_e. We fixed the values of the velocity dispersion and the truncation radius, and thus of the total mass, of all the cluster members in a new and improved SL model. To understand the impact of adopting more accurate cluster member scaling laws on SL cluster modelling, we based our SL modelling on the work by [4]. In particular, we used their parametrisation for the diffuse DM and hot-gas mass distributions (the parameters of the intra-cluster medium (ICM) distribution are fixed from Chandra X-ray data [19]). The optimisation of the free parameters of the cluster-scale DM mass distribution was based on the same set of multiple images. The new procedure to determine the total mass of the cluster galaxies leads to a more accurate description of their properties. Their velocity dispersion is completely fixed from their observed structural parameters through the FP. This is a significant step forward in breaking the degeneracy between σ and r_t and obtaining meaningful information on the compactness of cluster galaxies. Combining the best-fit total mass distribution obtained from the lensing model with the ICM and stellar (see also [11]) mass distribution measurements derived from observations, we decomposed the mass profile of the cluster, mapping the DM component with unprecedented accuracy down to the scale of the single cluster galaxies (see fig. 9 in [12]).

3. – Insights into the mass structure of cluster galaxies with galaxy-scale strong lensing

As a following step in the study of the compactness of cluster galaxies, we aimed at a direct measurement of the truncation radius of a few selected galaxy-scale lenses in massive clusters, testing the accuracy of the scaling laws adopted to describe the members in SL models of galaxy clusters. We selected the multiply imaged sources ID14 ($z = 3.221$) and ID16 ($z = 2.095$), both lensed by the cluster MACS J0416, and ID14 ($z = 3.753$), in the lensed field behind the cluster MACS J1206. Eight multiple images were observed for the first SL system, and six for the latter two. We focussed on the main deflector of each galaxy-scale SL system (members 8971 and 8785 of MACS J0416, and member 3910 of MACS J1206, respectively), and modelled its total mass distribution with a truncated isothermal sphere. To account for the lensing effects of the remaining components of the cluster, we took the most accurate SL model of its mass distribution available ([2,4]). We explored the posterior probability distribution of the parameters of the cluster-scale mass models and extracted 100 realisations of the mass distribution of the cluster. For each of them, we optimised the mass parameters of the galaxy-scale lens: the bootstrapping procedure allowed us to obtain a realistic estimate of the uncertainty on their values. We measured a truncation radius value of $6.1^{+2.3}_{-1.1}$ kpc, $4.0^{+0.6}_{-0.4}$ kpc, and $5.2^{+1.3}_{-1.1}$ kpc for members 8971, 8785, and 3910, corresponding to total mass values of $M = 1.2^{+0.3}_{-0.1}\times10^{11}\,M_{\odot}$, $M = 1.0^{+0.2}_{-0.1}\times10^{10}\,M_{\odot}$, and $M = 6.3^{+1.0}_{-1.1}\times10^{10}\,M_{\odot}$, respectively. Alternative non-truncated models with a higher number of free parameters do not lead to an improved description of the SL system and show some parametric degeneracies. We measured the stellar-to-total mass fraction within the effective radius for the three cluster members, finding 0.51 ± 0.21, 1.0 ± 0.4, and 0.39 ± 0.16, respectively.

We find that a parameterisation of the physical properties of cluster galaxies in SL models based on power-law scaling relations with respect to the observed total luminosity cannot accurately describe the compactness of the members over their full total mass range. Our results, instead, agree with the modelling of the cluster members based on the Fundamental Plane relation presented in sect. **2**. Finally, we report good agreement between our predicted values of the stellar-to-total mass fraction within the effective radius and those of early-type galaxies from the Sloan Lens ACS Survey, as clear from fig. 1. Our work significantly extends the regimes of the current samples of lens galaxies, towards the mass range that will be probed by the *Euclid*, *Rubin*, and *James Webb* Telescopes.

4. – Compactness of the cluster sub-haloes and conclusions

The two studies we have presented in the previous sections provide us with the chance to perform a more meaningful comparison between the properties of observed and simu-

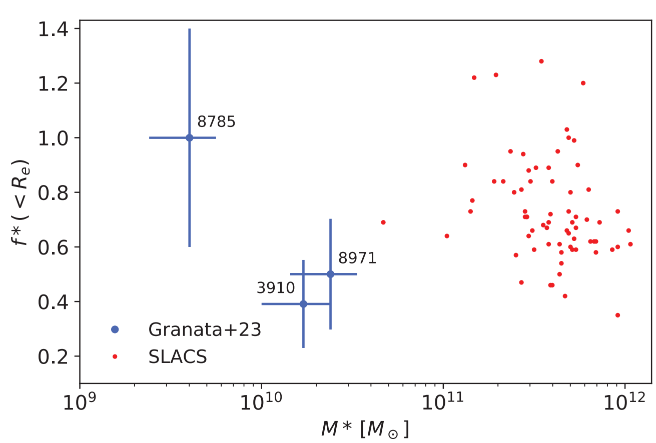

Fig. 1. – Stellar-to-total mass fraction of lens galaxies measured within the effective radius: comparison between [15] and the 85 SLACS lens galaxies presented in [20].

lated galaxy-scale lenses in massive clusters. As in [3], we adopt the maximum circular velocity of the cluster members as a proxy for their compactness (see [3,21-23]). In fig. 2, we compare the $v_{\rm max}$-to-M relations for our SL models presented in sects. **2** and **3**, and in [12, 15], with those found in [22] for a set of zoom-in re-simulations of the Dianoga suite of simulated galaxy clusters. These setups differ from one another in terms of their softening lengths and feedback schemes. As in [22], we refer to the three models considered as R15 (presented in [6]), RF18 (presented in [24]), and B20 (presented in [25]). The setups are also referred to as 1× or 10× if they have the same mass resolution as the Dianoga suite, or a ten times lower particle mass, respectively. We limit our comparison to the total sub-halo mass range ($M > 10^{10}\,M_\odot$), to guarantee that all the cosmological simulations considered have a sufficient mass resolution to describe the structure of sub-haloes. As such, in this analysis we have not included member 8785 of MACS J0416, whose total mass is smaller than $10^{10}\,M_\odot$.

Figure 2 shows that the cluster-scale SL model of AS1063 based on the FP and the galaxy-scale SL models of members 8971 of MACS J0416 and 3910 of MACS J1206 predict higher values of the maximum circular velocity at a fixed total sub-halo mass compared to those found for simulated sub-haloes. This is true irrespective of the feedback scheme or the resolution considered in [22]. On one hand, this suggests that the discrepancy between the properties of observed and simulated cluster galaxies cannot be entirely ascribed to systematics emerging from the scaling relations adopted to describe them in SL models: the FP relations allows for a more realistic description of the sub-halo compactness, and confirms the previously reported offset with simulations. On the other hand, changing the mass resolution, softening length, and feedback scheme of cosmological hydrodynamical simulations does not significantly impact on the $v_{\rm max}$-M relation either, and all the simulations considered in [22] are unable to reproduce the observed sub-halo compactness. In conclusion, the question of whether the discrepancy between observations and simulations descends from issues within our galaxy formation models or within the CDM paradigm remains open, and addressing it could provide us

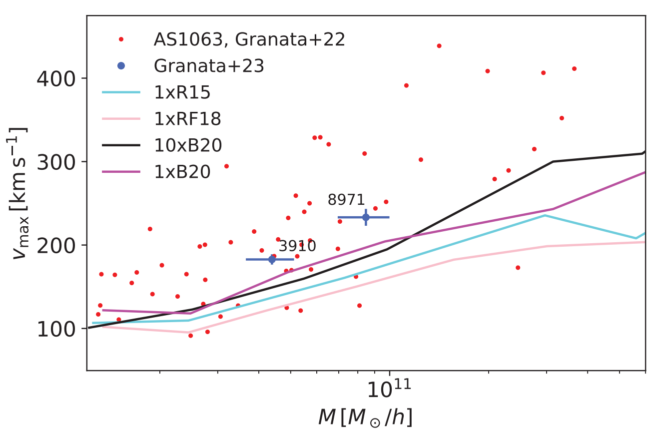

Fig. 2. – Comparison between the $v_{\rm max}$-to-M relation obtained from our studies and those predicted by the cosmological hydrodynamical simulations described in [22]. We indicate the cluster members of AS1063 as described in [12] with red points and the galaxy-scale lenses modelled in [15] with blue points, identified as members 8971 and 3910 as in sect. **3**. For the different simulation suites, we adopt the naming convention presented in sect. **3**.

with crucial insights on the evolution of cluster galaxies and on the micro-physics of DM. Several observations at the *Hubble*, *James Webb*, and *Euclid* Space Telescopes will focus on a much larger sample of SL clusters than currently available, prompting spectroscopic follow-up, and the development of improved SL models, which will allow comparison with the next generation of cosmological hydrodynamical simulations.

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