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Investigating the discrepancy in sub-halo compactness between observed and simulated galaxy clusters with improved strong lensing modelling

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Abstract. A discrepancy between the observed number of galaxy-galaxy strong lensing events in massive galaxy clusters and the predictions of high-resolution cosmological hydrodynamical simulations has recently emerged. Observed cluster members are, on average, more compact than their simulated counterparts, as indicated by their higher values of the maximum circular velocity at fixed total mass. The introduction of kinematic priors on the velocity dispersion of cluster galaxies significantly reduces the degeneracy between the parameters that describe their compactness in strong lensing (SL) models. We take advantage of measured kinematics and structural parameters of the cluster galaxies to calibrate the Fundamental Plane (FP) for the members of the massive cluster Abell S1063. We use the FP to build an improved SL model of the cluster, based on a more accurate description of the cluster galaxies and more reliable scaling laws between their physical properties. The comparison is also repeated with new implementations of the cosmological simulations, considering different resolutions and feedback schemes. However, the discrepancy with simulations is not completely reconciled, pointing towards a new challenge for the Λ CDM paradigm.

Key words. gravitational lensing: strong – galaxies: clusters: general – galaxies: clusters: individual (Abell S1063) – galaxies: kinematics and dynamics – dark matter – cosmology: observations

1. Introduction

With the support of several dedicated photometric and spectroscopic surveys, strong gravitational lensing (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 (Caminha et al. 2016; Limousin et al. 2016; Bergamini et al. 2022). 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. This makes galaxy clusters excellent astrophysical laboratories to test the Λ cold dark matter (CDM) paradigm and our hypotheses on the nature of DM (Grillo et al. 2015; Natarajan et al. 2017).

Meneghetti et al. (2020) reported a significant discrepancy between the probability of observing galaxy-galaxy (GG) SL events in massive galaxy clusters, as predicted by a sample of state-of-the-art SL models of observed clusters, and by galaxy clusters of similar mass extracted from the Dianoga cosmological hydrodynamical simulation suite (Planelles et al. 2014; Rasia et al. 2015). The lower GGSL cross-section predicted by simulations can be interpreted as a consequence of simulated cluster members being less compact than observed. This is highlighted by the fact that at a fixed total sub-halo mass, observed cluster galaxies have, on average, a higher maximum circular velocity than their simulated counterparts.

Galaxy cluster members are typically described in SL models with a truncated isothermal mass density profile. 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 calibrated power-law scaling relations with respect to the observed galaxy luminosity. This leads to a significant degeneracy between the two parameters, which needs to be broken in order to obtain meaningful information on the compactness of the cluster galaxies. Bergamini et al. (2019) showed that the degeneracy can be significantly reduced by obtaining an observational prior on the values of σ. This has been made possible by VLT/MUSE integral field spectroscopy. 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 calibrate the Fundamental Plane (FP) for the members of the massive galaxy cluster Abell S1063 (AS1063, see Sartoris et al. 2020; Mercurio et al. 2021) 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 detailed in Granata et al. (2022).

2. An improved strong lensing model of Abell S1063

To understand the impact of adopting more accurate cluster member scaling laws on SL cluster modelling, we follow the model by Bergamini et al. (2019). In particular, we use their parametrisation for the diffuse DM and hot-gas mass distributions. The parameters of the intra-cluster medium (ICM) distribution are determined from Chandra X-ray data (Bonamigo et al. 2018), and considered fixed. The optimisation of the free parameters of the cluster-scale DM mass distribution is based on the same set of multiple images.

We use Hubble Frontier Fields photometry (HFF, Lotz et al. 2017) in the F814W band to measure the values of the structural parameters of all cluster members included in the model (Tortorelli et al. 2018, 2023). MUSE-VLT integral field spectroscopy allows us to determine the central line-of-sight central velocity dispersion for a sizeable sub-set of the early-type members. We therefore combine the photometric and spectroscopic information for these galaxies to calibrate the FP relation. The FP allows us to obtain the values of the velocity dispersion of all cluster members from their measured structural parameters, with a more realistic scaling relation compared to the power-law approach. Finally, we calibrate a proportionality relation between the truncation radius of the cluster galaxies and their observed half-light radius. We fix the values of the velocity

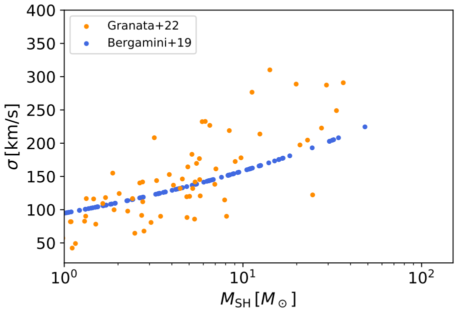

Fig. 1. Compactness of the sub-haloes: velocity dispersion of the cluster galaxies as a function of their total mass in the SL models of AS1063 by Granata et al. (2022) and Bergamini et al. (2019).

dispersion and the truncation radius, and thus of the total mass, of all the cluster members in a new and improved SL model.

3. Compactness of the cluster galaxies

The new procedure to determine the total mass of the cluster galaxies leads to a more accurate description of their properties. Their velocity dispersion values are 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. As shown in Fig. 1, our new technique allows us to find a more realistic relation between σ (which is proportional to the maximum circular velocity) and the total mass of the cluster members, with a significant scatter. However, the two relations are consistent and agree in the mass range considered, indicating that the average predicted compactness of the sub-haloes does not significantly change.

To quantify the impact on the discrepancy of the numerical resolution and of the baryonic feedback scheme of hydrodynamical simulations, Meneghetti et al. (2022) and Ragagnin et al. (2022) have repeated the same comparison performed by Meneghetti et al. (2020) with a set of re-simulations of the Dianoga suite. These have different mass and force resolutions, softening lengths and/or implementations of the active galactic nuclei feedback. However, none of the simulations manages to match the observed compactness. If a less efficient feedback scheme is chosen, the discrepancy is reduced but overly massive galaxies, not found in observations, are predicted. This is illustrated in the top and bottom panels of Fig. 8 of Ragagnin et al. (2022), where the compactness and stellar-to-total mass ratio of cluster galaxies in every Dianoga re-simulation are compared with observations.

Neither a more complex parametrisation of the total mass profile of the cluster galaxies in SL models, nor a different implementation of cosmological simulations significantly reduces the reported discrepancy in the sub-halo compactness. Several questions are thus still open and will surely benefit from further analyses. For instance, Granata et al. (in prep.) will analyse separately some GGSL systems in massive clusters, to directly constrain the compactness of the lens galaxies.

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