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MASS & LIGHT IN GALAXY CLUSTERS: PARAMETRIC STRONG-LENSING APPROACH

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Abstract. In the cold dark matter paradigm, the association between the hypothetic dark matter and its stellar counterpart is expected. However, parametric strong lensing studies of galaxy clusters often display "misleading features": group/cluster scale dark matter components without any stellar counterpart, offsets between both components larger than what might be allowed by neither Cold Dark Matter nor self interacting Dark Matter models, or significant unexplained external shear components. I am revisiting mass models where such "misleading" (and interesting) features have been reported, adopting the following working hypothesis: any group or cluster scale dark matter clump introduced in the modelling should be associated with a luminous counterpart, and any well motivated and reliable prior should be considered, even when this degrades the fit. The goal is to derive a physically motivated description of the dark matter component which might be compared to theoretical expectations. I succeed doing so in galaxy clusters AS 1063, MACS J0416 and MACS J1206, finding that the shape of the inner dark matter component has a flat density profile. These findings may be useful for the interpretation within dark matter scenario, such as self-interacting dark matter. I fail in Abell 370: a three dark matter clumps mass model (each clump being associated with its stellar counterpart) is unable to reproduce the observational constraints with a precision smaller than 2.3". In order to provide a sub-arcsec precision, I need to describe the dark matter distribution using a four dark matter clumps model, one having no stellar counterpart, and another one presenting a significant offset with its associated stellar counterpart, as found in earlier works. Investigating this solution, I present a class of such models which can accurately reproduce the multiple images, but whose parameters for the dark matter component are poorly constrained, limiting any insights on its properties. Examining the *total* projected mass maps, I however find a good agreement between the total mass and the stellar distribution in Abell 370, both being, to first order, bimodal. I interpret the "misleading features" of the four dark matter clumps mass model and the failure of the three dark matter clumps mass model as being symptomatic of the lack of realism of a parametric description of the dark matter distribution in such a complex merging cluster. I encourage caution and criticism on the outputs of parametric strong lensing modelling.

Keywords: Strong Gravitational Lensing, Galaxy Clusters

1 Introduction

Dark matter (DM) is an elusive component that is thought to largely dominate the mass budget in astrophysical objects over a wide range of scales, in particular in galaxy clusters. However, more than 80 years after the first indirect evidence for DM in galaxy clusters (Zwicky 1937), we have no definitive clues about its existence, even though it is sometimes taken for granted. Evidence for DM is indirect only, and no well-understood and characterised particle detector has detected it so far, despite intense effort of the community. As long as no such direct detection is reliably achieved, DM remains, from my point of view, a hypothesis.

Both observations and numerical simulations do support the association between DM and light (the associated stellar component, in most cases in the form of the brightest cluster galaxy (BCG) at the galaxy cluster scale). Observationally, no cluster scale DM clump without any associated light concentration has been reliably detected so far. Besides, in hydrodynamical simulations, stars do form in the potentiel well of DM halos. This results into the hierarchical formation of a bright galaxy found at the centre of the underlying DM halo.

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If DM is collisionless as proposed in the Cold Dark Matter (CDM) scenario, the association between mass and light should be perfect, *i.e.* the offset between the peaks of each component should be equal to 0 (Roche et al. 2024). If DM is self interacting (SIDM), such an offset is possible and should be at most of the order of a few dozen of kpc, according to simulations (*e.g.* Kim et al. 2017; Tulin & Yu 2018; Adhikari et al. 2022).

Strong lensing (SL) is an essential probe of the DM distribution in the centre of galaxy clusters, where the mass density is so high that space time is locally deformed such that multiple images of background sources can form. This provides valuable constraints on the *projected* mass distribution.

Parametric SL mass modelling relies on the following working hypothesis, supported by N-body simulations: A galaxy cluster is an object composed of different mass clumps. Each component is associated with a luminous counterpart and can (to some extent) be described parametrically. One advantage of parametric SL modelling is that the description of these mass clumps can be directly compared with theoretical expectations. However, a parametric description is sometimes not accurate nor adapted, emphasising the limit of parametric mass modelling and the need for more flexible approaches. We usually consider two types of mass clumps in parametric SL modelling: cluster-scale DM clumps (whose typical projected mass within a 50" aperture is about $10^{14}\mathrm{M_O}$ at $z \sim 0.2$) and galaxy-scale DM clumps associated with individual galaxies. Added to this description of the dominant DM component, the mass component associated with the X-ray gas can also be considered (Bonamigo et al. 2018; Beauchesne et al. 2024).

Parametric SL modelling displays interesting and puzzling features that can be "misleading". These are the following:

- First, it sometimes requires DM clumps whose position does not coincide with that of any luminous counterpart. This is the case in complicated merging clusters, like Abell 370, but also in apparently unimodal clusters as MACS J1206. These dark clumps are usually added in order to improve the fit significantly, but the physical interpretation of these clumps is not straightforward. Moreover, when they are taken for granted, their inclusion in the mass budget might be misleading. We might wonder whether we are really witnessing a dark clump.
- Second, offsets between DM clumps and the associated light peak are reported, larger than what might be allowed by SIDM scenarios.
- Third, some mass models require a non-negligible external shear component ($\gamma_{\rm ext}$) in order to significantly improve the goodness of the reconstruction, but the physical origin of this external shear is not always clear.
- Finally, large core radii (sometimes larger than 100 kpc) are sometimes reported in parametric SL studies (e.g. Newman et al. 2013; Lagattuta et al. 2019; Richard et al. 2021). A thorough SIDM investigation of the size of the core radii in the galaxy cluster mass regime is still lacking, but we have some indications about its order of magnitude, which should be smaller than ∼50 kpc (Rocha et al. 2013; Robertson et al. 2017; Fischer et al. 2021).

From these considerations, I have been revisiting some mass models where former studies reported "misleading features", within the following working assumption: any group or cluster scale DM clump introduced in the modelling should be associated with a luminous counterpart (within the SIDM allowance), and any well motivated and reliable, observationnaly motivated prior should be considered, even when this degrades the fit, quantified by the root mean square between the observed and model-generated images. The goal is to see if I can get rid of these features, present a physically motivated model and probe DM physics, in particular its inner slope. For each cluster I have studied, I list the misleading features present in former works and I summarize the main results, which can be found in the following papers: Limousin et al. (2022) and Limousin et al. (2024). A former paper (Limousin et al. 2016) might be of interest when it comes to degeneracies in parametric SL modelling.

2 AS 1063

AS 1063 is the only Hubble Frontier Fields (HFF, Lotz et al. 2017) cluster that appears to be unimodal and dominated by a BCG, with which a DM halo is associated. However, a galaxy group generating additional SL features is located in the north-east. Former study by Bergamini et al. (2019, B19 hereafter) associate a mass clump with this group, but its location does not coincide at all with it (separation of 40"). I did revisit the

B19 mass model, forcing the position of this second mass clump to coincide with the light distribution of the most luminous galaxy of this group. I obtained an RMS of 0.67" (versus 0.55" reported by B19). The main DM component has a core radius equal to 89±5 kpc. I then forced the core radius to be smaller than 10 kpc and redid the modelling, in order to see if a non cored mass model can reproduce the SL constraints. The RMS goes up to 3.83". This suggests that a cored DM profile is favoured in AS 1063.

3 MACS J0416

The HFF cluster MACS J0416 is multimodal, with three well defined light peaks. The last study by Bergamini et al. (2021) reproduced 182 multiple images using a 4 DM mass clumps, reaching an RMS of 0.40". Two of these DM mass clumps are associated with a light peak, and two are located in the south-west of the cluster core, none of which being clearly associated with the brightest galaxy located in this area. Considering a three DM mass clumps model, each being associated with a light peak, I reached an RMS of 0.63". The core radii of each clump are larger than 50 kpc. If I impose them to be smaller than 10 kpc, the RMS goes to 2.07". Therefore, a cored mass model is preferred.

4 MACS J1206

MACS J1206 is a unimodal cD dominated galaxy cluster. Former works (*e.g.* B19) reproduced 82 multiple images using a mass distribution composed of three DM haloes and a strong external shear ($\gamma_{\rm ext}$=0.12), reporting an RMS equal to 0.46". If one of these mass clumps is coincident with the cD galaxy, the others are not associated with any luminous counterpart, and are claimed to be necessary to reproduce the apparently elongated asymmetry of the cluster. Using a single DM clump associated with the cD galaxy does not allow to reach a decent fit (RMS=2.24"), suggesting that MACS J1206 cannot be reliably described by a pure parametric model in which each mass component would be associated with a luminous counterpart.

In a second step, I added a (mild) perturbation to the parametric modelling to see whether this might help to provide a decent fit. This perturbation consists of a surface of 2D B-spline functions that are added to the lensing potential (Beauchesne et al. 2021). First, I verified that this perturbation is mild enough to avoid modifying the parameters of the associated parametric mass model significantly, which would make us lose the advantages of the parametric mass modelling. I tested the inclusion of these perturbations on AS 1063, which is already well described by a parametric mass model, looking at the response of the reference mass model to this perturbation. The RMS is improved, and the parameters of the reference model do agree within the 3σ error bars with the parameters obtained with the perturbation.

Encouraged by this test, I reconsidered the mass model of MACS J1206 using a single DM mass clump and the perturbation, reaching an RMS of 0.53". Moreover, no external shear is required. The core radius of this DM mass clump equals to 57 kpc. If I impose it to be smaller than 10 kpc, the resulting RMS is 7", which definitely favors a cored mass model.

5 Abell 370

Abell 370 is a multimodal merging HFF cluster. The light distribution is dominated by the light associated with two dominant bright galaxies (BCG-N and BCG-S). We also observe a light concentration in the east/north-east.

Former SL studies described Abell 370 parametrically by a four dark matter clumps model, as well as a significant external shear component, which physical origin remained a challenge. The dark matter distribution features a mass clump with no stellar counterpart located between BCG-N and BCG-S, and a significant offset (larger than what is allowed by SIDM) between the northern dark matter clump and its associated stellar counterpart. I began by revisiting this mass model. Sampling this complex parameter space with MCMC techniques, I found a four dark matter clumps solution which does not require any external shear and provides a slightly better RMS compared to previous models (0.7" compared to 0.9"). Investigating further this new solution, in particular playing with the parameters leading the MCMC sampler, I presented a class of models which can accurately reproduce the strong lensing data, but whose parameters for the dark matter component are poorly constrained, limiting any insights on its properties, in particular its inner shape.

I then investigated a model where each large scale dark matter clump is associated with a stellar counterpart. This three dark matter clumps model is unable to reproduce the observational constraints with an RMS smaller than 2.3”, and the parameters describing this dark matter component are also poorly constrained. The addition of a B-spline perturbation did not help.

Still, the total projected mass is well-constrained and is linked to the stellar component, the two main *total mass peaks* being coincident with the two BCGs. I therefore concluded that the *total mass is traced by light in Abell 370.* Having said that, it is relevant to discuss what is learned about the underlying DM distribution, which, taken as such, might be misleading. What is the interpretation of this ”dark clump”: are we detecting a ”dark clump”? What is the interpretation of the offset between the Northern DM clump and BCG-N, which is larger than what might be allowed by SIDM? These interesting features are clearly required by the data in order to reproduce the observed positions of the multiple images with a sub-arcsecond precision. I do interpret these as not being ”real” but rather being necessary to compensate for the lack of reality of the parametric description of DM clumps during a cluster merging process. Indeed, the DM component is described using idealised parametric mass profiles (e.g. dPIE or NFW). This description, though simple, can be reliable, which is remarkable. This is the case in AS 1063, MACS J1206 and MACS J0416. In Abell 370, such a simple description of the different DM components involved in the merging process might not fully capture the complex underlying physics, hence, some features, as the ones reported here, are needed to account for the deviations from our idealised parametric descriptions.

6 Conclusions

Overall, this analysis suggests evidence for cored cluster-scale dark matter haloes in the three clusters for which I have been able to propose a model where each DM clump is associated with a luminous counterpart. These findings may be useful for the interpretation within alternative dark matter scenario, such as self-interacting dark matter.

Even in the JWST era, where hundreds of multiple images are observed, SL mass reconstructions still suffer from degeneracies, in particular in merging clusters, and caution and criticism should be taken when reading and interpreting the results of any SL model. Furthermore, authors could discuss more the limitations of their models, and help the reader understand and interpret their results. We therefore encourage caution and criticism on the outputs of parametric SL modelling.

These results also have some implications for high redshift studies using clusters as natural telescopes.

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