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Dark Matter in the Hubble Frontier Fields

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Abstract

We present results on the dark matter distribution of the Hubble Frontier Fields (HFF). The HFF represents the best collection of strong lensing data in merging clusters. We study the first two clusters from the HFF program using a free-form method that makes no assumptions about the mass distribution to reconstruct the dark matter that best fits the strong lensing data. Our reconstructed dark matter distributions exhibit some interesting features including very shallow profiles and possible offsets between the baryonic and dark matter distribution. For the first time, we find evidence that suggests that the strong lensing data seems to be sensitive to the mass of the X-ray plasma. Also, by analyzing the strong lensing in one individual galaxy we are able to constrain the shape of the dark matter halo around that galaxy. Our results support the standard models of dark matter and disfavours alternative models like MOND.

1 Introduction

The standard model of structure formation is built on the conclusion that about 85% of the mass in the universe is of an unknown form which only gravitates. The standard interpretation of this dark matter as massive fermionic particles has, so far, no experimental evidence from sensitive direct searches via nuclear recoil nor have such particles been generated at high energies with the LHC. Astronomically, the most extreme effects of dark matter can be found in massive galaxy clusters, where the general relativistic warping of space-time leads to extreme lensing distortions on a scale far in excess of that due to the observed stellar or gaseous cluster material. Gravitational lensing has become one of the most effective techniques to unveil the distribution of dark matter in galaxy clusters. Attempts to generalize lens modeling has been possible in terms of smooth grids or low order polynomials to permit some flexibility. A general free-form approach was developed by [1, 2], based on a pixelated grid representing the lens plane so that arbitrary mass distributions can be constructed up to the resolution of the grid scale which is effectively set by the surface density of strongly

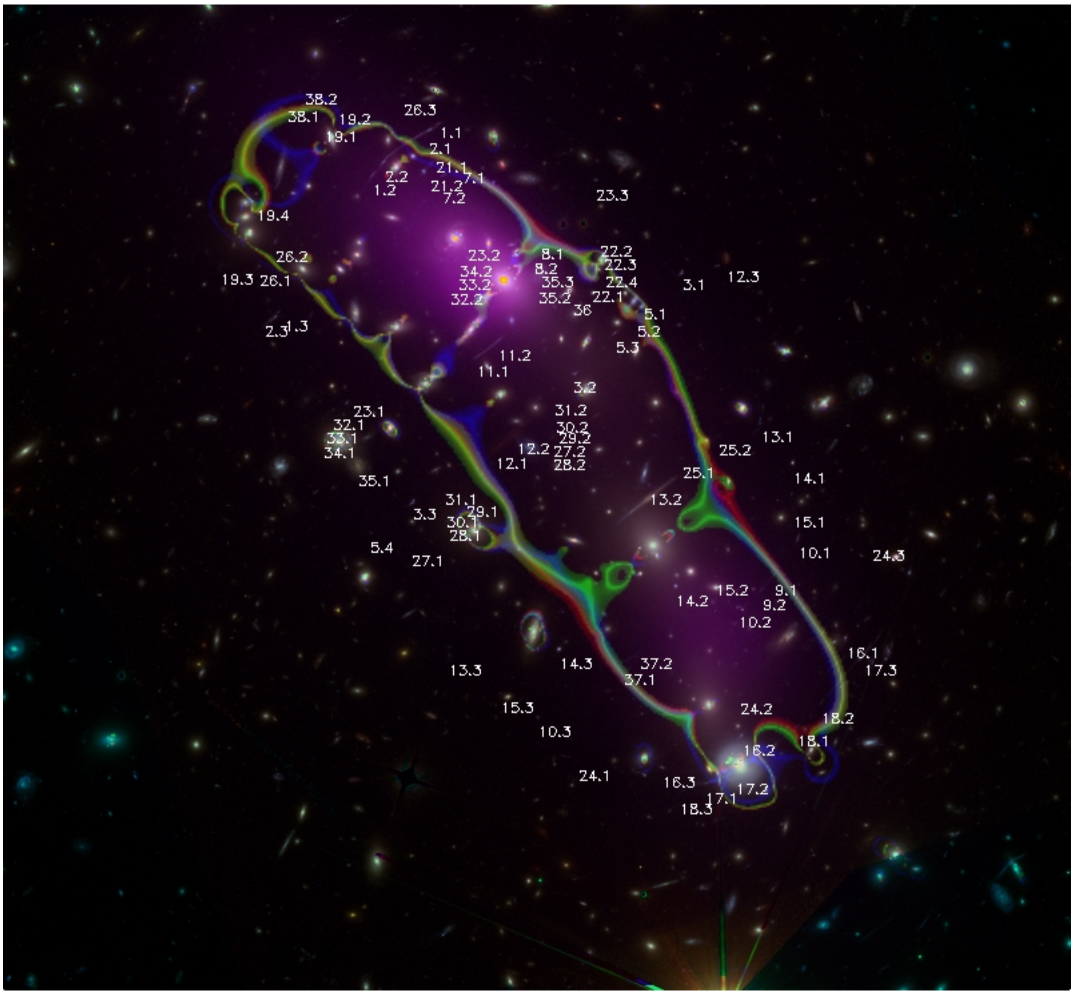

Figure 1: MACS0416 and strong lensing data set used in the reconstruction. The three color curves show the critical curves for three different solutions.

lensed images. This method does not provide sufficient accuracy to find new systems so that it must rely on lensed systems secured by other models. More recently we have found it very advantageous to incorporate the known position of member galaxies in the grid solution, to account for the local deflections and additional multiple images typically produced by member galaxies, so that meaningful solutions can be found. Here we employ this method to model the complex merging cluster A2744 and MACSJ0416.1-2403 (or MACSJ0416 hereafter), relying on previously known and our own multiply lensed image identifications. Details of these works can be found in [5, 3]. In addition, we apply a parametric method to reconstruct the halo around an individual galaxy in the cluster MACS0416. This galaxy acts as a secondary lens over a background galaxy allowing a direct constrain on the mass and orientation of the DM halo. Details of this work can be found in [3, 4].

2 Reconstruction method

We use the improved method, WSLAP+, to perform the mass reconstruction. The method solves for the following system of linear equations

$$\Theta = \Gamma X, \tag{1}$$

where the measured strong lensing observables are contained in the array Θ of dimension $N_\Theta = 2N_{SL}$, the unknown surface mass density and source positions are in the array X of dimension $N_X = N_\mathrm{c} + N_\mathrm{g} + 2N_\mathrm{s}$ and the matrix Γ is known (for a given grid configuration and fiducial galaxy deflection field) and has dimension $N_\Theta \times N_\mathrm{X}$. N_SL is the number of strong lensing observables (each one contributing with two constraints, x, and y), N_c is the number of grid points (or cells) that we use to divide the field of view. In this paper we consider a regular grid of $N_\mathrm{c} = 32 \times 32 = 1024$ cells covering the field of view shown in Fig. 1 (2.4 arcmin). Each grid point contains a Gaussian function. The width of the Gaussians are chosen in such a way that two neighbouring grid points with the same amplitude produce a horizontal plateau in between the two overlapping Gaussians. N_g is the number of deflection fields (from cluster members) that we consider. N_s is the number of background sources (each contributes with two unknowns, β_x, and β_y). The solution is found after minimising a quadratic function that estimates the solution of the system of equations 1. For this minimisation we use a quadratic algorithm which is optimised for solutions with the constraint that the solution, X, must be positive.

3 Results on galaxy clusters

We apply our lensing reconstruction technique to the two clusters, A2744 and MACS0416. A2744 shows an elongated morphology with the dark matter following the distribution of galaxies in the cluster. We notice an enhancement in the projected mass at the position of a gas clump visible in X-rays. If confirmed, this would be the first time where plasma gas can be weighted through strong lensing data. A similar correlation between the reconstructed mass and the X-ray plasma is also found in our second cluster, MACS0416. In both clusters, we find positional offsets between the DM and plasma. In particular, in the case of MACS0416 the offset is more significant for the SW component, which we have shown is plausibly generated by displacement of the gas during the encounter. We also notice that for this cluster the two main dark matter components have very shallow profiles surrounding each of the two main cD galaxies. Our dynamical simulation shows that tidal stretching of the DM is expected to be observed at the post encounter stage of the collision indicated by our model and hence qualitatively may help to understand, the cores we find. These tidal effects highlight the importance of free form modeling over the parametric approach, for which idealised forms can only hope to approximate such interesting complexities. The bi-modal redshift distribution of the cluster members, together with results from hydrodynamical simulations, suggest that MACS0416 is colliding in a plane that is close to the line of sight. The two density profiles around the BCG galaxies of MACS0416 are almost identical suggesting a ratio close to 1:1 for this merging cluster. The profiles also exhibit a plateau at around 40–100 kpc which

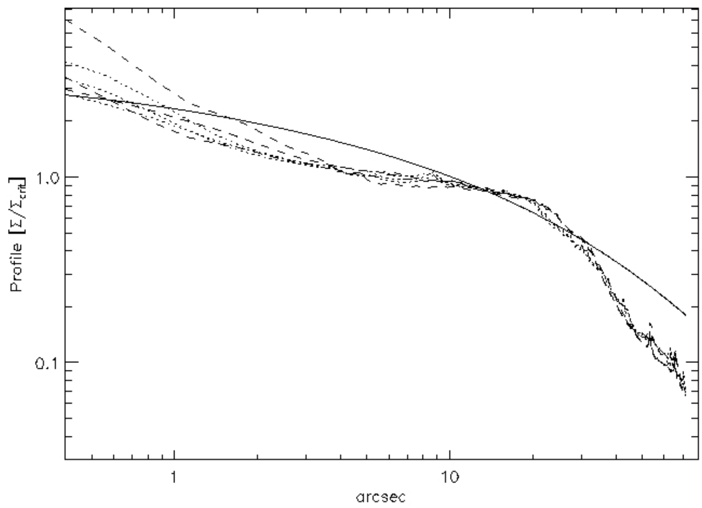

Figure 2: Profiles of the two cluster haloes in MACS0416 for the three different cases. The profiles are centred in the two main cD galaxies. The NE halo corresponds to the dotted lines and the SW halo corresponds to the dashed lines. In the computation of the profiles, we have masked the other half of the cluster. The solid line corresponds to a projected NFW model with a truncation radius of $R_{200} = 2.5\,\mathrm{Mpc}\,h^{-1}$ and $C = 10$.

could be interpreted as the result of dynamical distortions of the sub-cluster cluster profiles, or projection effects but also as possible evidence of self interacting DM with an increased probability of interaction during the collision. Detailed lensing observations of merging galaxy clusters, like those from the HFF, together with more detailed simulations of merging clusters may help clarify this situation.

4 EOSL

In the outskirts of the HFF field of view of MACS0416, we find an edge-on galaxy acting as a secondary lens (EOSL) EOSL galaxies offer a unique opportunity to study the DM distribution around galaxies. When an EOSL is embeded in a massive galaxy cluster, the monopole lensing component from the cluster helps in magnifying the background galaxy, effectively stretching the background source behind the secondary lens galaxy. The stretch provided by the galaxy cluster helps constraining the dark matter by reducing some of the degeneracies inherent to lensing reconstruction but also by producing a straight magnified background source that can be used to sample the lensing potential of the secondary lens to larger distances. We take advantage of our previous work where the galaxy cluster lens model is determined with accuracy to constrain the properties of the arc that is being lensed by the EOSL. We explore the space of solutions with a model containing 6 parameters (and an additional halo for the nearby spiral galaxy). After marginalizing over the space parameter we are able to constrain the total mass of the galaxy although some degeneracies still persist

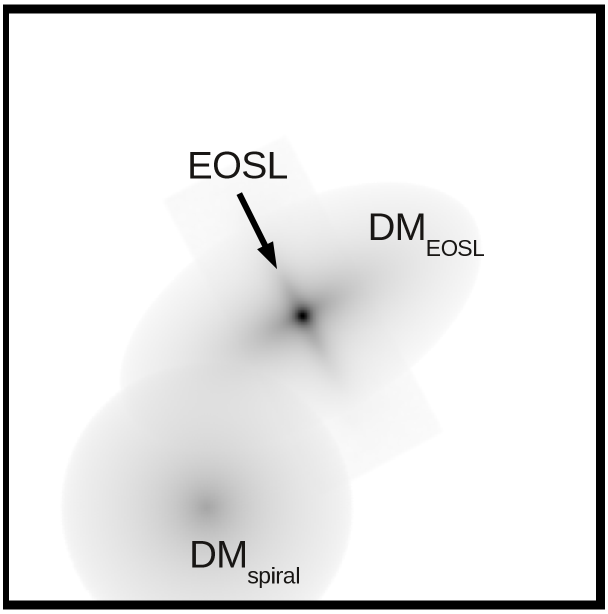

Figure 3: Geometry of the lens plane. The three elements of the lens plane are marked. The EOSL DM corresponds to the best model with ellipticity, $e = 0.15$, and orientation, $\alpha = 0°$.

between the baryonic and DM masses. However, regarding the spatial distribution of the DM, the marginalized probability shows a strong preference for prolate (or oblate) models that contain the bulk of the mass in a DM halo that aligns perpendicularly with the plane of the visible galaxy (see Fig. 3). This scenario, although consistent with some simulations, would contradict also other simulations, that predict that most of the times the inner part of the DM halo aligns in a direction that is in line with the visible galaxy. On the other hand, our conclusions are in agreement with some of the interpretations given to polar ring galaxies or the co-orbiting planes of sub-halos around M31 and our own Galaxy. The existence and geometry of the elongated DM halo, perpendicular to the galaxy, goes against the hypothesis of modified gravity theories. In these models, haloes aligned with the visible galaxy would be favoured if the baryonic component is responsible for the gravitational potential. Meanwhile, our results show the opposite. A simple change in the Newtonian potential may not be sufficient to eliminate the need for a dark component and would result only in different mass estimates but still with a preference for a dark component that aligns perpendicularly with the emitting light. A proper analysis that explicitly considers alternative theories of gravity could settle this situation.

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