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Systematic or signal? How dark matter misalignments can bias strong lensing models of galaxy clusters

D. Harvey,¹★ J. P. Kneib^{1,2} and M. Jauzac^{3,4,5}

¹Laboratoire d'Astrophysique, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, CH-1290 Versoix, Switzerland

²Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille), UMR 7326, F-13388 Marseille, France

³Centre for Extragalactic Astronomy, Department of Physics, Durham University, Durham DH1 3LE, UK

⁴Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK

⁵Astrophysics and Cosmology Research Unit, School of Mathematical Sciences, University of KwaZulu-Natal, Durban 4041, South Africa

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ABSTRACT

We explore how assuming that mass traces light in strong gravitational lensing models can lead to systematic errors in the predicted position of multiple images. Using a model based on the galaxy cluster MACS J0416 ($z = 0.397$) from the Hubble Frontier Fields, we split each galactic halo into a baryonic and dark matter component. We then shift the dark matter halo such that it no longer aligns with the baryonic halo and investigate how this affects the resulting position of multiple images. We find for physically motivated misalignments in dark halo position, ellipticity, position angle and density profile that multiple images can move on average by more than 0.2 arcsec with individual images moving greater than 1 arcsec. We finally estimate the full error induced by assuming that light traces mass and find that this assumption leads to an expected rms error of 0.5 arcsec, almost the entire error budget observed in the Frontier Fields. Given the large potential contribution from the assumption that light traces mass to the error budget in mass reconstructions, we predict that it should be possible to make a first significant detection and characterization of dark halo misalignments in the Hubble Frontier Fields with strong lensing. Finally, we find that it may be possible to detect ~ 1 kpc offsets between dark matter and baryons, the smoking gun for self-interacting dark matter, should the correct alignment of multiple images be observed.

Key words: galaxies: clusters: general – dark matter.

1 INTRODUCTION

Mapping the distribution of total matter in galaxy clusters has become commonplace with the advent of high-resolution optical imaging from space (e.g. Merten et al. 2011; Jauzac et al. 2012, 2015). Deep images of galaxy clusters reveal the apparent distortion of distant background galaxies whose light has been split into many geodesics producing multiple images of the same galaxy. Strong gravitational lensing has become a vital tool in mapping out the distribution of matter in galaxy clusters as well as its behaviour during highly energetic collisions (e.g. Bradač et al. 2006; Merten et al. 2011). For a review see Bartelmann (2010).

Methods to reproduce the distribution of matter in galaxy clusters can be split into two categories: those that assume that light traces mass (e.g. Jullo et al. 2007; Zitrin et al. 2013) and those that do not (e.g. Bradač et al. 2005; Liesenborgs, De Rijcke & Dejonghe 2006; Merten et al. 2009). Under the light-traces-masses assumption, it

is assumed that wherever there is a galaxy there also exists a dark matter (DM) halo, the mass of which far out exceeds that of the baryonic component (e.g. Limousin et al. 2007). Specifically, the assumption is that the peak of the DM halo lies exactly coincident with the galaxy, with an equal ellipticity and equal position angle, the only difference in being the scale at which the light and dark haloes extend to. The main advantage of assuming that mass traces light is that by scaling the DM halo directly to the light distribution of the galaxy, it is possible to significantly reduce the number of free parameters in a strong lensing model of a galaxy cluster that may contain up to a few hundred individual galaxies. This reduces the computational time for a single reconstruction and increases the constraining power of the model by placing heavy priors on each galactic halo. However, conversely such an assumption may lead to inaccuracies, whereas free-form reconstructions that do not assume this may not impose a bias but will suffer in precision. It is in this paper that we explicitly examine these underlying assumptions. We ask whether these assumptions are suitable and in the event that they are not, how do they affect the small-scale properties of strong lensing models used. Similarly, we also determine whether

* E-mail: david.harvey@epfl.ch

the misalignment of DM could be detected for the first time with current data.

1.1 Does light trace mass?

In order to motivate the study of how assuming mass traces light affects strong lensing models, we must first question whether we would expect the profile of DM halo to mimic that of the baryonic component. In a Λ cold dark matter (Λ CDM) Universe, cosmological simulations predict that DM should lie coincident with the baryonic component, with no physical offset of $\delta r > 3$ kpc being observed (Schaller et al. 2015). However, extensions to the collisionless CDM model have been proposed that could lead to offsets between baryonic and dark component (Harvey et al. 2014; Kahlhoefer et al. 2014). For example, Williams & Saha (2011) and subsequently Massey et al. (2015) observed a 1.5 kpc offset between the two components in an elliptical galaxy in the cluster Abell 3827, at the 3σ level. This offset was attributed to potential DM self-interactions causing a lag on the DM halo. It is therefore possible that DM could indeed separate from its baryonic counterpart.

Aside from the peak position of the DM halo, it is not clear whether the DM halo should mimic the geometrical properties of the baryonic component. A recent study using the MassiveBlack II cosmological hydrodynamical simulations found that this was not true (Tenneti et al. 2015). They found that DM haloes tended to be rounder, by up to factors of 2, and that the major axes could become severely misaligned with offsets of $\theta = 90^\circ$ not uncommon. They found that the offsets were most common at galaxy-scale masses, with larger, cluster size haloes better aligned. These findings are consistent with others in the field (e.g. Bailin et al. 2005; Deason et al. 2011; Velliscig et al. 2015). Additionally, assuming that light traces mass often assumes an empirical relation between the size of the DM halo and the luminosity (e.g. Limousin et al. 2007). Although well constrained, these relations can exhibit a variance of up to 50 per cent (Wuyts et al. 2004; Fritz et al. 2005). Given that simulations predict that DM and baryonic haloes should not necessarily trace each other, we are motivated to test how this assumption can affect the strong lensing models.

Previous work studying the alignment of dark with light matter using strong lensing is limited. Minor & Kaplinghat (2008) first studied how multiple image separations can be altered by misalignments between the DM and galactic halo. They showed how the statistics of image separation can avoid the need to model each lens and hence can be useful for large-scale surveys. More recently, Bruderer et al. (2016) carried out a study of 11 lensing galaxies examining their alignment with their baryonic component. Similar to simulations they found that haloes are rounder than their galactic counterpart and those galaxies with large amounts of shear are highly misaligned. Although very interesting, this is limited to small number of galaxies in groups. In this work, we will look at carrying out a similar study except over large numbers of galaxies that reside within the high-density cluster environment.

2 METHOD

To study the effect that assuming light traces mass has, we use a model of a cluster based on real data that contains 174 small scale galaxy-scale haloes (spectroscopically identified by Grillo et al. 2015) embedded in two large, cluster-scale DM haloes (Jauzac et al. 2014; Grillo et al. 2015). In this study, we act only to study the effect of changes to the galaxy-scale haloes on the positions

of multiple images. We use the position of multiple images in the Hubble Frontier Field (HFF) galaxy cluster, MACS J0416 and the best-fitting cluster model that fits these multiple images as derived by the parametric strong lensing algorithm LENSPOOL (Jullo et al. 2007; Jauzac et al. 2014). This equates to 140 multiple images and 174 cluster members. Each potential was originally fitted with a pseudo-isothermal elliptical mass distribution (PIEMD; Kneib et al. 1996; Natarajan & Kneib 1997; Elíasdóttir et al. 2007; Jullo et al. 2007), which follows the analytical density profile,

$$\frac{\rho(r)}{\rho_0} = \frac{1}{\sqrt{r^2 + r_{\text{core}}^2}} - \frac{1}{\sqrt{r^2 + r_{\text{cut}}^2}}, \quad (1)$$

where r is the radial distance from the centre of the halo, and the profile is parametrized by the core radius, r_{core} , and the cut radius, r_{cut} . The cluster itself has a measured mass within a 200 kpc aperture of $(1.6 \pm 0.01) \times 10^{14} M_\odot$ (Jauzac et al. 2014), and the mass of each galaxy has a lognormal distribution centred around $\log(M/M_\odot) = 10.1 \pm 0.6$. The distribution of ellipticities peaks at 0.1 and decreases towards larger ellipticities. The galaxies span the entire range between 0 and 0.9. We split each galaxy halo potential into two components: a baryonic core and a DM halo. We separate the halo into two PIEMDs with the baryonic $r_{\text{core}}^{\text{B}} = r_{\text{core}}$. For the baryonic cut radius, we conservatively cut it to a quarter of the original cut radius $r_{\text{cut}}^{\text{B}} = \frac{r_{\text{cut}}}{4}$ (Velander et al. 2014), although this could be smaller. We also force the dark matter core radius to the baryonic cut radius, $r_{\text{core}}^{\text{DM}} = r_{\text{cut}}^{\text{B}}$ and the dark matter cut radius as the original cut radius $r_{\text{cut}}^{\text{DM}} = r_{\text{cut}}$. Separating the halo like this means that the mass of each halo is conserved with respect to the pre-split halo. Given this two-component galaxy model, we project the images back to the source plane to create a list of background sources for the cluster. To do this, we use the same redshift information for the sources as that in Jauzac et al. (2014).

Fig. 1 shows the makeup of the model. The top panel shows the cluster model with the position of the multiple images as white stars, log of the normalized projected surface density (convergence) map in grey-scale and the critical lines in the white solid line. The bottom panel of Fig. 1 gives the two PIEMD component model of the galaxy. The solid black line is a galaxy with $r_{\text{core}} = 5$ kpc and $r_{\text{cut}} = 100$ kpc, and the resulting baryonic (dotted) and DM (dot-dashed) components when the galaxy is split into two. The dotted, dot-dashed and solid vertical lines give the scales of the baryonic core radius, the DM core and baryonic cut radius and finally the DM cut radius, respectively.

To test the validity of assuming that light traces mass, we shift the DM component of the lensing model however keeping the baryonic component constant. We project the sources back through to the image plane with the new DM model and calculate the shift in position of each multiple image. We test four shifts in the DM component:

- (i) position: offsetting the peak position of the DM halo from the baryonic;
- (ii) ellipticity: stretching or squashing the DM halo with respect to the baryonic component;
- (iii) position angle: rotating the halo such that the DM and baryonic component are misaligned;
- (iv) cut radius: we vary the cut radius and velocity dispersion of the DM halo to change the profile of the galaxy however conserving the total mass of the DM halo.

Additionally, for each case, we will either shift the halo systematically in the same direction or randomly with a mean of zero and a standard deviation of the given value.

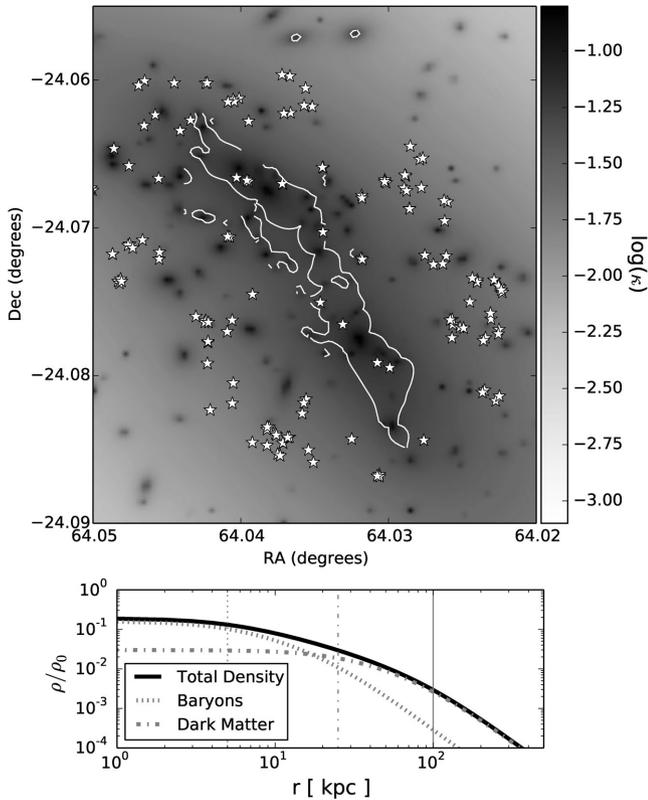


Figure 1. The cluster model we used. The top panel shows the galaxy cluster with the convergence map in grey-scale and the resulting critical lines in white. The white stars represent the true position of multiple images. The bottom panel shows an example of how we split a galaxy with a total PIEMD profile of $r_{\text{core}} = 5$ kpc and $r_{\text{cut}} = 100$ kpc, into two PIEMDs of $r_{\text{core}}^{\text{B}} = 5$ kpc (vertical dotted line), $r_{\text{cut}}^{\text{B}} = 25$ kpc and $r_{\text{core}}^{\text{DM}} = 25$ kpc (vertical dot-dashed line), $r_{\text{cut}}^{\text{DM}} = 100$ kpc (vertical solid line).

3 RESULTS

We first test each assumption individually, beginning with peak position offset. We start by systematically shifting the DM haloes position away from the peak of the light distribution. We shift the halo in a direction anti-parallel to the centre of mass of cluster, to imitate a shift in the DM halo due to self-interactions (see Kahlhoefer et al. 2014). The first panel on the top row of Fig. 2 shows the mean multiple image offset as a function of DM halo offset. In each case, the solid black line gives the root mean square (rms) of all the multiple images for a given offset, and the fainter coloured lines the offset of each individual image. We find that for a given offset δp , the mean multiple image offset $\delta r_{\text{im}} \approx 0.2\delta p$.

Following this, we then shift the position of the DM halo by a random amount, sampled from a normal distribution with a mean of zero and an increasing standard deviation. The first panel of the bottom row of Fig. 2 gives the multiple image offset as a function of the input standard deviation. We find that for random offsets with a standard deviation of δp , the mean multiple image offset is slightly less sensitive at $\delta r_{\text{im}} \approx 0.1\delta p$.

The following three tests study the sensitivity of multiple image position to a scalar quantity, and therefore, unlike the position, do not require a reference point in which to be systematically offset. We therefore show in the top row of Fig. 2 how a common offset in ellipticity, position angle and mass can alter the position of multiple images (second, third and fourth columns, respectively) and the bottom row how a random offset, selected from a normal distribution

with a mean of zero and an incrementally larger standard deviation, can alter the mean position of multiple images.

Our tests reveal that highly elliptical DM haloes result in very large shifts in the position of multiple images, with shifts of > 1 arcsec not uncommon. More circular haloes also gave an offset, except less significant. We also find that the changing position angle of the DM halo has sinusoidal relation, with some multiple images experiencing highly sensitive angles. Finally, varying the cut radius but conserving mass has a symmetric effect, whether we decrease the cut radius and increase the velocity dispersion or vice versa. We find that a shift in the position angle or cut radius results in similar magnitude offsets, both in systematically and randomly, with mean offsets of roughly ~ 0.2 arcsec.

3.1 Sensitivity of the model rms to individual images

The bottom row in Fig. 2 shows that in all four tests carried out we find that the position of individual images can be very sensitive to misalignment of DM and baryons. This can be important since in a strong lensing reconstruction individual images can significantly bias the rms value of predicted image position to actual image position. Not only this, but it may bias the rest of the reconstruction and any derived deflection maps. We illustrate this point further by binning the shift in multiple image position into a histogram and overlaying the rms. Fig. 3 shows the result for each test in the systematic offset mode (same as the top row of Fig. 2). We see that in all cases except ellipticity, the thick solid line which represents the rms is significantly above the majority of the actual image offsets. Particularly, the offset due to position angle, whereby the majority are < 0.1 arcsec however some images at 0.8 arcsec can bias the rms very high. However, interestingly, the rms statistic well represents the error imposed by an ellipticity offset.

3.2 Sensitivity of image position to individual cluster members

In order to better understand the origin of the rms for each offset, we take a multiple image that is particularly sensitive to a shift and we study its environment and how it changes with respect to the change in its DM halo. The top panel of Fig. 4 (20 arcsec \times 20 arcsec) shows how the position of one multiple image is sensitive to the position angle of nearby galaxies. We carry out a study whereby we rotate the nearby DM haloes by incremental amounts, as represented by each coloured ellipse. For each incremental rotation, we calculate the resulting position of the image, which we represent as a star whose colour matches that of the DM position angle that caused it. In the bottom panel, the stars correspond to the stars of the same colour in the top panel except shown as a magnitude offset from the original position. The coloured diamonds show the offset when *just the closest lens* is altered (as shown by the lens with the arrow). It can be seen that when the major axis of the rotated DM halo aligns radially (points towards) with the image, the resulting error in the image is largest; however, when the galaxy lies tangentially, then the error is very small. This also explains the smooth sinusoidal function observed in Fig. 2. Furthermore, we find when we alter just a single galaxy (diamonds), this can contribute the majority of the error in the position of a multiple image, showing that this perturbative effect is a local one concerning only very near massive haloes. We confirm this by testing the correlation between the observed offset of an image and distance to the closest lens weighted by its mass. We find a positive correlation for all offsets except the cut radius, for which we find no such dependence.

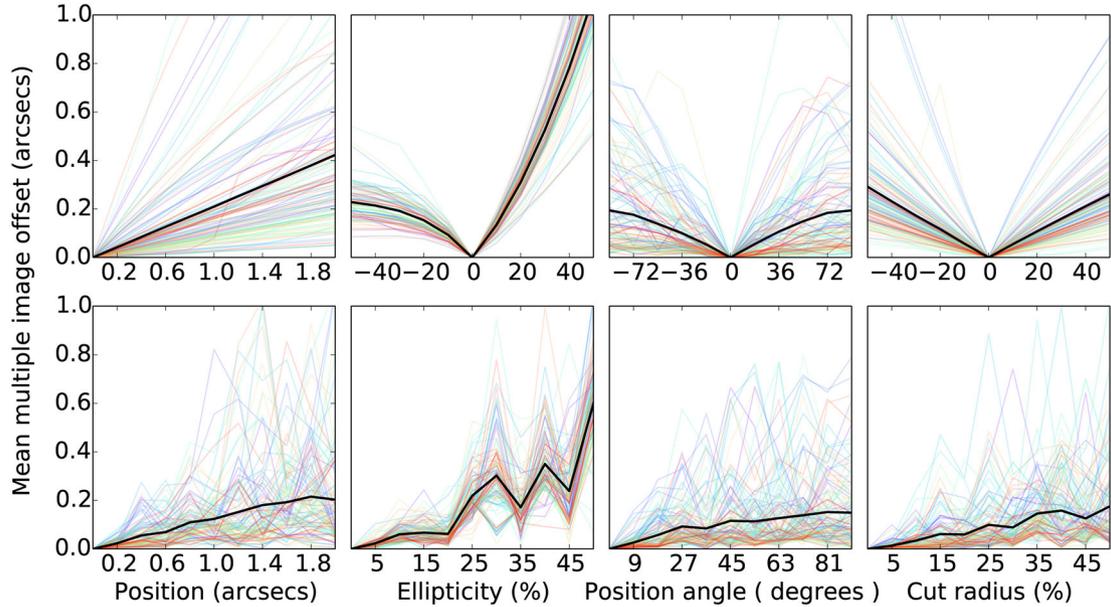


Figure 2. Results from MACS J0416 simulation. In each case, the faint lines show the track of individual images, and the black line represents the rms of all of the images with respect to the original catalogue. In each case in the top row the DM components in all the galaxies have been systematically changed (such that all galaxies have the same offset), and the bottom row gives the standard deviation of the normal distribution from which the offset has been randomly selected (such that each galaxy in the model has a different offset). In the case of the position offset (first column and top row), each galaxy has had their DM halo pushed away from the centre of mass of the cluster.

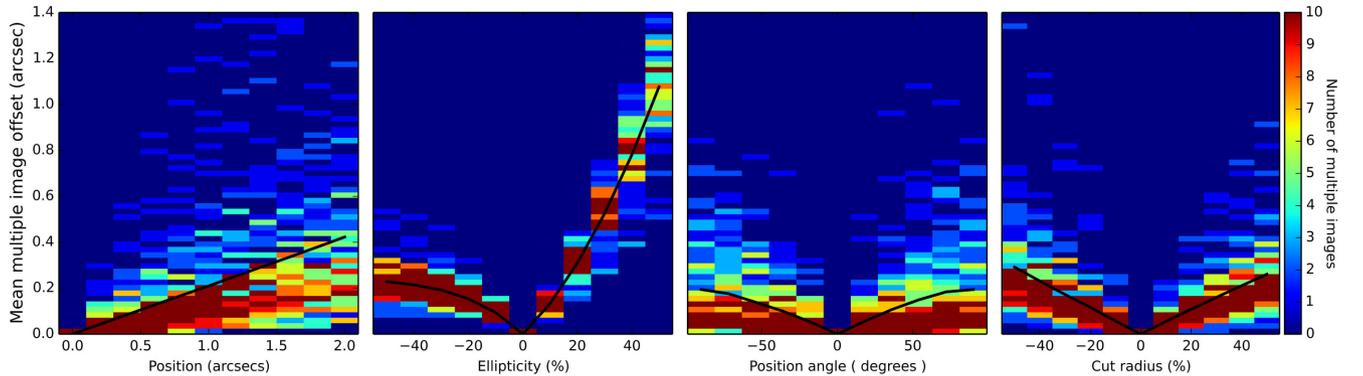


Figure 3. Histograms of the distribution of multiple images w.r.t. the rms of all the images. In each case, the systematic offset (top row of Fig. 2) is shown with the distribution of multiple image offset with the solid line showing the rms of the multiple images. It can be clearly seen that the rms is biased high by one or two individual spuriously offset haloes.

We finally test the three remaining shifts (ellipticity, position angle and cut radius) and how perturbing the closest lens affects the position of the image. The inset in Fig. 4 ($2 \text{ arcsec} \times 2 \text{ arcsec}$) shows the results from these tests, with the arrow indicating the direction in which we shift the DM peak position. We find that when the ellipticity, position angle and DM peak position of the nearest lens are altered, the effect is a tangential movement on the image and completely degenerate. However, when we change the cut radius of the galaxy, this results in a radial movement of the multiple image. This orthogonal movement will allow future models to constrain which effect is causing the rms offset.

Given that the positional test is only for a shift in one direction, we test all other possible directions. Fig. 5 (same dimensions as Fig. 4) shows the behaviour of the multiple image when shifting the lens in every possible way. The coloured arrows define the offset direction of the potential, and the corresponding coloured lines in the inset show the movement of the multiple image from the original

position given by the star. We find that the movement of the image is always tangential with some small range of angle. We confirm this by studying other cluster members and find the same effect.

3.3 Combined all the offsets: testing the assumption

In practice, all four assumptions will affect the predictability of a strong lensing model. Here we estimate how these offsets combine and what the expected rms would be. To do this, we produce many realizations of the same cluster using fixed offset parameters for the galaxy-scale haloes and continuing to keep the large-scale cluster halo fixed. We select at random offsets in position, ellipticity, position angle and cut radius for each galaxy within the cluster with standard deviations of $\sigma_p = 0.1 \text{ arcsec}$, $\sigma_e = 20 \text{ per cent}$, $\sigma_a = 20^\circ$ and $\sigma_{\text{cut}} = 10 \text{ per cent}$. These values are physically motivated and based on the results of Tenneti et al. (2015) and the offset observed in A3827 (Massey et al. 2015). We simulate the positions of the

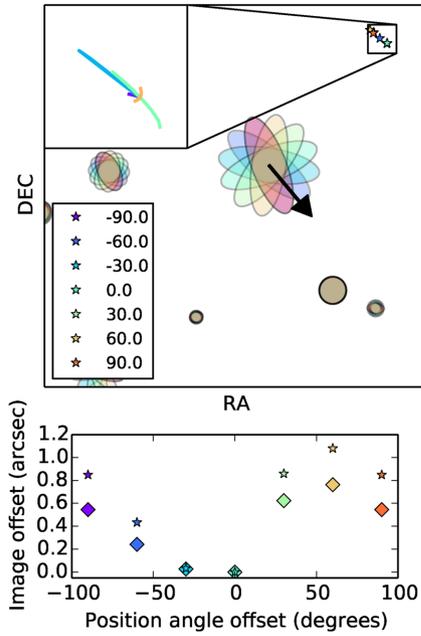


Figure 4. Top: dependence of a given multiple image on the position angle of cluster member position angles. The main image ($20 \text{ arcsec} \times 20 \text{ arcsec}$) gives the position of one multiple image as a function of cluster member position angle. The colours relate the position angle of the DM to the position of a multiple image, and how this corresponds to a radial offset from the original position in the bottom panel. The stars in this panel correspond to the star positions in the top; the diamonds give the image offset in the event that only the lens near the image is rotated. Top panel (inset) ($2 \text{ arcsec} \times 2 \text{ arcsec}$) shows how the same multiple image moves w.r.t. different changes in the DM halo of only the lens nearest image. Orange track shows the effect of changing the cut radius, green shows the movement due to changing the ellipticity, blue the position angle and purple the peak position of the DM halo.

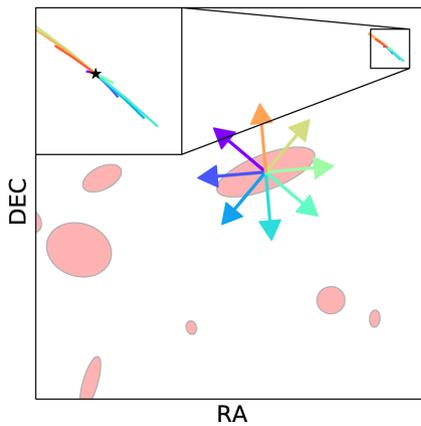


Figure 5. The same as Fig. 4 (with the same dimensions) except this shows how shifting the DM halo peak position in any direction results only in a tangential movement of the multiple image.

multiple images 20 times and find the mean positional offset of each image and the expected rms given the assumption that light traces mass. We also test the hypothesis that the images that are apparently closer to lenses on the sky will be the most sensitive to a misaligned DM halo. Fig. 6 gives the mean and 1σ standard error in the position offset for each multiple image as a function of the distance the image is from the closest lens. The solid black line shows the mean rms over all realizations. The bars in each

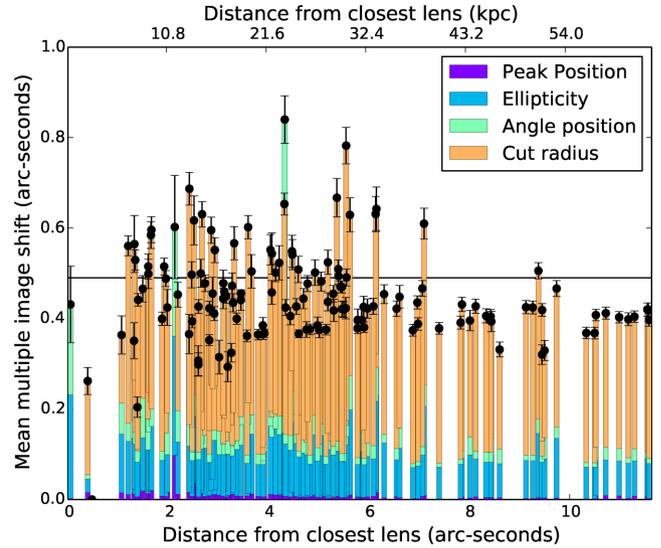


Figure 6. We include variations in all parameters associated with assuming that mass traces light and randomly offset the DM haloes in four ways in order to measure the expected rms in the multiple image position. Using $\sigma_p = 0.1 \text{ arcsec}$, $\sigma_e = 20 \text{ per cent}$, $\sigma_a = 20^\circ$ and $\sigma_{\text{cut}} = 10 \text{ per cent}$ all with means of zero, and iterated over 20 realizations. We measure the mean and variance in the position of each multiple image and the *expected rms* as a function of distance from the closest lens in angular and proper distances. We show the mean rms over all the images with the solid black line. We also determine the approximate contribution for each parameter to the mean image shift.

case give the approximate contribution from each effect to the total offset. We find that assuming that light traces mass results in an estimated $\sim 0.5 \text{ arcsec}$ rms error in the position of multiple images. The majority of the offset is contributed by a shift in the cut radius and angle position; however, these appear not to depend on distance from the nearest lens. We do find though that the position and ellipticity have a slight tendency to have a larger effect as the lens is closer to the image. Given the accuracy of current HFF, the 0.5 arcsec here accounts for the majority of this error, and any future survey attempting to go below this limit will not be able to assume that mass traces light.

3.4 Prospects of detecting misaligned haloes in the HFF

Models in the HFF currently report an rms error of 0.6 arcsec for a single cluster (Jauzac et al. 2014), of which most could be accounted for by assuming that light traces mass. The separation observed in A3827 was of the order of $\sim 2 \text{ kpc}$, which is $\approx 0.4 \text{ arcsec}$ at a redshift of $z \sim 0.397$. We found that should all galaxies have their DM component coherently offset by this amount, we would observe a mean shift of $\sim 0.05\text{--}0.1 \text{ arcsec}$, which is currently beyond the accuracy of strong lensing models. However, given that this is based on one cluster and individual images very close to a lens can be shifted significantly, it is highly likely that future Frontier Fields should observe a configuration of multiple images that are sensitive to the offset between DM and baryons in particular lenses. Apart from this, cosmological simulations predict that the position angle of haloes can be misaligned by large amounts and DM haloes can be rounder than their baryonic counterparts by factors of 2. The predicted shift in multiple images for these two properties means that it is possible to make a first detection of misalignment in the Frontier Fields. Having said this, the movement of multiple images

with respect to each offset is highly degenerate, and hence in order to characterize the statistical properties of the misalignments, it will require a high density of multiple images around the lenses. Such a discovery would have far-reaching implications for galaxy formation models and also intrinsic alignments that have become a vital systematic in the measurement of cosmological gravitational lensing (see Joachimi et al. 2015 for review).

4 CONCLUSION

The assumption that light traces mass is often used when modelling the distribution of mass in galaxy clusters. Strong gravitational lensing models, which assume this, report rms errors between the predicted position of multiple images and actual positions of ~ 0.6 arcsec. In this study, we test the validity of this assumption by altering the DM halo of galaxies in a model based on the HFF cluster MACS J0416 whilst keeping the large-scale cluster component and stellar component fixed. Assuming that light traces mass often requires the peak DM halo and baryonic halo to be exactly coincident, the ellipticity and the position angle of the halo to be aligned and the cut radius to have some kind of relation with the luminosity. In this study, we test all four assumptions individually. We find whether we commonly shift DM haloes or individually randomly offset them, each individual case produces a mean offset of ~ 0.2 arcsec in the position of multiple images. We find that although the mean offset for each image is of the order of ~ 0.2 arcsec, some images can be very sensitive to perturbations in the galactic DM halo with some misalignments resulting in a multiple image shift of ~ 1 arcsec.

Following this, we study how individual massive lenses in close proximity to images can significantly perturb the image position finding that some individual galaxy misalignments can induce image shifts of > 1 arcsec. Additionally, we also find that the peak position, position angle and ellipticity offset result in a tangential movement of images, whereas a change in the cut radius results in a radial movement, meaning that future studies should be able to discern between misalignments in the halo and departures from mass–luminosity relations.

We finally combine all four effects and find that the mass-to-light assumption can result in ~ 0.5 arcsec rms error in the position of multiple images, almost the entire error budget of the Frontier Field lensing models.

Given that misalignments are of physical interest to galaxy formation models and as a systematic error for measurements of cosmic shear, we find that given the current sensitivity and depth of the HFF, it should be possible to detect and characterize misalignments between DM and baryonic haloes in the HFF galaxy clusters. We also find that given an expected offset of ~ 2 kpc between DM and baryons, the smoking gun for self-interacting DM, it maybe possible to detect some offset in the HFF, given the correct multiple image configuration.

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