Triaxial strong-lensing analysis of the $z > 0.5$ MACS clusters: the mass–concentration relation

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ABSTRACT
The high concentrations derived for several strong-lensing clusters present a major inconsistency between theoretical $\Lambda$ cold dark matter ($\Lambda$CDM) expectations and measurements. Triaxiality and orientation biases might be at the origin of this disagreement, as clusters elongated along the line of sight would have a relatively higher projected mass density, boosting the resulting lensing properties. Analyses of statistical samples can probe further these effects and crucially reduce biases. In this work we perform a fully triaxial strong-lensing analysis of the 12 Massive Cluster Survey (MACS) clusters at $z > 0.5$, a complete X-ray-selected sample, and fully account for the impact of the intrinsic 3D shapes on their strong-lensing properties. We first construct strong-lensing mass models for each cluster based on multiple images, and fit projected ellipsoidal Navarro–Frenk–White haloes with arbitrary orientations to each mass distribution. We then invert the measured surface mass densities using Bayesian statistics. Although the Einstein radii of this sample are significantly larger than those predicted by $\Lambda$CDM, here we find that the mass–concentration relation is in full agreement with results from $N$-body simulations. The $z > 0.5$ MACS clusters suffer from a moderate form of the orientation bias as may be expected for X-ray-selected samples. Being mostly unrelaxed, at a relatively high redshift, with high X-ray luminosity and notable substructures, these clusters may lie outside the standard concentration–Einstein radius relation. Our results remark the importance of triaxiality and properly selected samples for understanding galaxy clusters properties and suggest that for higher-$z$, unrelaxed low-concentration clusters form a different class of prominent strong gravitational lenses. Arc redshift confirmation and weak-lensing data in the outer region are needed to further refine our analysis.

Key words: methods: statistical – galaxies: clusters: general – galaxies: clusters: individual: MACS $z > 0.5$ sample.

1 INTRODUCTION
The hierarchical cold dark matter (CDM) model with a cosmological constant [$\Lambda$ cold dark matter ($\Lambda$CDM)] is highly successful in explaining many features of galaxy clusters. The universal Navarro–Freank–White (NFW) density profile (Navarro, Frenk & White 1996, 1997) reproduces well their density profile over most radii, but the actual mass–concentration relation, $c(M)$, is still debated (Comerford & Natarajan 2007; Broadhurst et al. 2008).

The concentration measures the halo central density relative to outer parts and is known to correlate reversely with the virial mass and redshift, so that lower mass and lower redshift clusters would show higher concentrations (Bullock et al. 2001; Duffy et al. 2008). However, recent high-resolution simulations show different trends than have been expected before, with a turn around and decrease in concentrations towards very high virial mass clusters (Prada et al. 2011). The cluster baryonic content is also expected to play a fundamental role in shaping the cluster overall density profile, although the baryonic physics is yet to be fully accounted for in related simulations, so that the explicit effects of cooling, feedback and baryonic dark matter (DM) interplay on the mass profile and concentration are still ambiguous (e.g. Gnedin et al. 2004; Rozo et al. 2008; Duffy et al. 2010). Cluster observations have also yet to firmly assess the properties of the $c(M)$ relation due to the small numbers of clusters analysed to date. Extensive lensing analyses done in recent years (e.g. Oguri et al. 2009; Zitrin et al. 2009b, 2010; Okabe et al. 2010; Richard et al. 2010; Umetsu et al. 2011a) and ongoing cluster

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lensing surveys (e.g. CLASH, Postman et al. 2011) should help in characterizing further the observed relation.

Similar discrepancies in lensing clusters between the observed properties and those predicted by $\Lambda$CDM have been reported, such as the arc-abundance problem (Bartelmann et al. 1998) and the detection of several extremely large Einstein radii (Broadhurst & Barkana 2008; Oguri & Blandford 2009; Zitrin et al. 2011a,b). In fact, these discrepancies are highly related to the overconcentration problem, as there is a clear connection between the concentration and the Einstein radius (e.g. Sadeh & Rephaeli 2008) or the lensing cross-section and the efficiency for generating giant arcs (Hennawi et al. 2007). In addition, the existence of high-redshift massive clusters adds to this tension and may imply a non-Gaussian distribution of massive perturbations (Chongchitnan & Silk 2011; D’Aloisio & Natarajan 2011b) or an earlier growth of a structure than entailed by $\Lambda$CDM, so that clusters, sitting atop the hierarchical build-up, would have had more time to bind together and concentrate, increasing their inner mass and lensing properties.

The disagreement between theory and observation might be explained by some orientation and shape biases (Oguri et al. 2005; Sereno & Umetsu 2011). In clusters that are elongated along the line of sight the projected matter density is relatively higher, and the observed lensing properties are boosted (Hennawi et al. 2007). Correspondingly, neglecting halo triaxiality can lead to overestimate and underestimate of up to 50 per cent and a factor of 2 in halo mass and concentration, respectively (Corless, King & Clowe 2009). Assuming spherical symmetry also causes underestimate of statistical uncertainties (Corless et al. 2009; Sereno & Umetsu 2011). Sereno, Jetzer & Lubini (2010a) investigated a sample of 10 strong-lensing (SL) clusters considering which intrinsic shape and orientation the lensing haloes should have to account for both theoretical predictions and observations. They found that nearly one-half of the clusters seemed to be composed of outliers of the mass–concentration relation, whereas the second half supported expectations of $N$-body simulations which prefer mildly triaxial lensing clusters with a strong orientation bias. Recently, Sereno & Umetsu (2011) performed a full triaxial weak-lensing and SL analyses of A1689, a cluster usually seen as strongly overconcentrated. They found the halo to be slightly overconcentrated but still consistent with theoretical predictions. They also found some evidence for a mildly triaxial lens with the major axis orientated along the line of sight.

Here, we try to assess the impact of halo triaxiality and orientation on the mass–concentration relation of a properly defined statistical sample. Recently, Zitrin et al. (2011a) presented a detailed SL analysis of a complete sample of X-ray-selected clusters, the Massive Cluster Survey (MACS) high-redshift cluster sample (Ebeling et al. 2007). This sample comprises 12 very luminous X-ray galaxy clusters at $z > 0.5$. Zitrin et al. (2011a) reported a difference of $\sim$40 per cent between the observed and the theoretical distributions of Einstein radii in standard $\Lambda$CDM based on analytic models of galaxy clusters. Meneghetti et al. (2011) extracted clusters from the MareNostrum Universe to build up mock catalogues of clusters selected through their X-ray flux according to the criteria applied to the $z > 0.5$ MACS sample. Their simulated distribution of the Einstein ring sizes is also lower by $\sim$25 per cent than that found in observations. They also found that orientation biases together with triaxiality issues still affect the lenses with the largest cross-sections and that the concentrations of the individual MACS clusters inferred from the lensing analysis might be up to a factor of $\sim 2$ larger than expected. They suggested that for a significant fraction of $\sim 20$ per cent of the clusters in the MACS sample, the lensing-derived concentrations should be higher than expected by more than $\geq 40$ per cent.

It should also be noted that this high-$z$ MACS sample appears to consist of mostly unrelaxed clusters. The high X-ray luminosity, along with the relatively high redshift and recent Sunyaev–Zeldovich (SZ) effect images (private communication), is in support of this claim, in addition to notable substructure seen in the optical and the aforementioned lensing analysis (Zitrin et al. 2011a). The inner mass distribution of (most of) these clusters seems correspondingly rather widely distributed, which may account for their extensive lensing properties and large Einstein radii. In fact, it is known that for e.g. relaxed, lower-$z$ clusters, the Einstein radius correlates with the concentration (Sadeh & Rephaeli 2008). More concentrated clusters have more mass in the middle, thus boosting their Einstein radius. For higher-$z$, unrelaxed clusters, large Einstein radii may form due to a widely distributed inner mass distribution, so that the critical curves of the smaller substructures near the core, merge together to form a much larger Einstein radius curve (e.g. Torri et al. 2004; Fedeli et al. 2006; Zitrin et al. 2009a). If this is indeed the case, for such a sample, low concentrations and relatively shallow inner profiles should be expected (e.g. Neto et al. 2007), suggesting that unrelaxed (higher-$z$) clusters form a distinct class of impressive strong lenses.

In order to probe the 3D intrinsic shapes of the clusters, we apply here the 3D SL analysis method of Sereno & Umetsu (2011) apart from a main difference. In fitting the projected surface density, we adopt a non-parametric technique, as implemented in the PIXELENS software (Saha & Williams 2004), instead of a parametric modelling (though initially the multiple images were found using a parametric method, see below). As in Sereno & Umetsu (2011), we use Bayesian statistics to invert the measured projected surface mass densities. An additional important difference is that here we use only SL data, without implementing full range weak-lensing data, as no such analyses are currently available for this sample. In that context, upcoming weak-lensing analyses for these clusters (e.g. as part of the CLASH programme, Postman et al. 2011) will be important to further establish the results of our work.

Zitrin et al. (2011a), thanks to their minimalistic parametric approach to lensing and the low number of free parameters in their modelling, were able to find many multiple images across the $z > 0.5$ MACS cluster fields, which we use here as an input. It should be noted that although the mass distributions of these clusters (and resulting critical curves and Einstein radii) were credibly constrained therein, due to the lack of redshift information for most of the lensed features, only broad constraints were put on the (projected) mass profiles of the different clusters, following the models best reproducing the different multiple images (see Zitrin et al. 2011a). Here we use the Zitrin et al. (2011a) best-model-predicted redshifts for the different arcs in order to maintain consistency with their input mass distributions. These redshift estimates were found to be usually very accurate in following spectroscopic (e.g. Smith et al. 2009) and photometric (the CLASH programme, in preparation) measurements of some of these clusters.

Since our SL analysis with PIXELENS exploited the image positions and source redshifts inferred in Zitrin et al. (2011a), our modelling is not alternative. The main advantage of reanalysing the SL features with an independent non-parametric technique is that PIXELENS allows us to fully explore degeneracies in the projected mass density. We can then reproduce the best-fitting models of Zitrin et al. (2011a) and obtain a reliable estimate of the covariance matrices that could be then used for optimizing the deprojection procedure.
The paper is organized as follows: in Section 2 we detail the basics of a triaxial NFW description, whereas in Section 3 we discuss the theoretical predictions for the results. In Section 4 the high-z MACS sample is described, and in Section 5 the SL analysis procedure is laid out, followed by the deprojection procedure in Section 6. The results are detailed in Section 7. In Section 8 we review some systematics. Results are concluded in Section 9. Throughout the paper, we assume a flat ΛCDM cosmology with density parameters ΩM = 0.3, ΩΛ = 0.7 and Hubble constant H0 = 100 h km s⁻¹ Mpc⁻¹, h = 0.7 (Komatsu et al. 2011).

2 BASICS ON TRIAXIAL NFW HALOES

High-resolution N-body simulations have shown that the density distributions of DM haloes are successfully described as triaxial ellipsoidal NFW density profiles with aligned, concentric axes (Navarro et al. 1996, 1997; Jing & Suto 2002). The 3D distribution follows:

$$\rho_{\text{NFW}} = \frac{\rho_s}{(\zeta/r)(1 + \zeta/r)^2},$$

where \( \zeta \) is the ellipsoidal radius. The shape is determined by the axial ratios. The major (intermediate) to major axial ratio is denoted as \( q_1 (q_2) \) with \( 0 < q_1 \leq q_2 \leq 1 \); we also use the inverse ratios, \( 0 < e_1 = 1/q_1 \geq 1 \).

Three Euler’s angles, \( \theta, \varphi \) and \( \psi \) determine the orientation of the halo. \( \theta \) and \( \varphi \) fix the orientation of the line of sight in the intrinsic system. In particular, \( \theta \) quantifies the inclination of the major axis with respect to the line of sight. The third angle \( \psi \) determines the orientation of the cluster in the plane of the sky.

The radius \( \rho_{200} \) for an NFW spheroid can be defined such that the mean density contained within an ellipsoid of a semi-major axis \( \rho_{200} \) is \( \Delta = 200 \) times the critical density at the halo redshift, \( \rho_{c}\) (Corless et al. 2009; Sereno et al. 2010a; Sereno & Umetsu 2011); the corresponding concentration is \( c^{200} = \rho_{200}/\rho_c \). The mass within the ellipsoid of the semi-major axis \( \rho_{200} \), \( M_{200} = (800\pi/3)q_1 q_2^2 \rho_{c} \).

The ellipsoidal 3D NFW halo projects on an elliptical 2D profile. The projected surface density profile has the same functional form of a spherically symmetric profile (Stark 1977; Sereno 2007; Sereno, Lubini & Jetzer 2010b). The convergence \( k_s \), i.e. the surface mass density in units of the critical surface mass density for lensing, \( \Sigma_{c}\) = \( (c^2 D_s)/(4\pi G D_s D_s) \), where \( D_s, D_s 1\) and \( D_s 2\) are the source, the lens and the lens–source angular diameter distances, respectively, for an ellipsoidal NFW halo is

$$k_{\text{NFW}}(x) = 2 \kappa_s \frac{1}{1 - x^2} \left[ \frac{1}{\sqrt{1 - x^2}} \text{arc\cosh} \left( \frac{1}{x} - 1 \right) \right],$$

where \( x \) is the dimensionless elliptical radius,

$$x \equiv \xi/r_{2\text{D}}, \quad \xi = [x_1^2 + x_2^2/(1 - \epsilon^2)]^{1/2},$$

where \( \epsilon \) is the ellipticity and \( x_1 \) and \( x_2 \) are the abscissa and the ordinate in the plane of the sky oriented along the the ellipse axes, respectively.

The ellipticity and the orientation of the projected ellipses depend only on the intrinsic geometry and orientation of the system. The axial ratio of the major to the minor axis of the observed projected isophotes, \( e_\rho = (1 - \epsilon)^{-1} \), can be written as (Binggeli 1980)

$$e_\rho = \sqrt{\frac{j + 1}{j - 1}} \left( \frac{j - 1}{j + 1} \right)^{1/2} + \frac{4k^2}{4k^2},$$

where \( j, k \) and \( l \) are defined as

$$j = e_1^2 e_2^2 \sin^2 \theta + e_2^2 \cos^2 \theta \cos^2 \varphi + e_2^2 \cos^2 \varphi \sin^2 \varphi,$$

$$k = (e_1^2 - e_2^2) \sin \varphi \cos \varphi \cos \theta,$$

$$l = e_1^2 \sin^2 \varphi + e_2^2 \cos^2 \varphi.$$
As reference, we follow Duffy et al. (2008), who used the cosmological parameters from Wilkinson Microwave Anisotropy Probe (WMAP5) and found \( \{A, B, C\} = \{5.71 \pm 0.12, -0.084 \pm 0.006, -0.47 \pm 0.04\} \) for a pivot mass \( M_{\text{pivot}} = 2 \times 10^{12} M_\odot h^{-1} \) in the redshift range 0–2 for their full sample of clusters. The scatter in the concentration about the median \( c(M) \) relation is lognormal:

\[
p(\ln c|M) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\ln c - \ln c(M)}{\sigma} \right)^2 \right].
\]

with a dispersion \( \sigma(\ln c_{200}) = 0.15 \) for a full sample of clusters (Duffy et al. 2008). Recently, Prada et al. (2011) claimed that the dependence of concentration on halo mass and its evolution can be obtained from the root-mean-square fluctuation amplitude of the linear density field. They noted a flattening and upturn of the relation with increasing mass and estimated concentrations for galaxy clusters substantially larger than the results reported in equation (15).

The distribution of minor to major axial ratios can be approximated as (Jing & Suto 2002)

\[
p(q_1) \propto \exp \left[ -\frac{(q_1 - q_0/r_0)}{2\sigma_z^2} \right],
\]

where \( q_0 = 0.54, \sigma_z = 0.113 \) and

\[
r_q = (M_{\text{vir}}/M_\odot)^{-0.25(1+z)^{0.3}},
\]

with \( M_\odot \) being the characteristic non-linear mass at redshift \( z \) and \( M_{\text{vir}} \) the virial mass. The conditional probability for \( q_2 \) goes as

\[
p(q_1/q_2) = \frac{3}{2(1 - r_{\text{min}})} \left[ 1 - \frac{2q_1/q_2 - 1 - r_{\text{min}}}{1 - r_{\text{min}}} \right]
\]

for \( q_1/q_2 \geq r_{\text{min}} = \max[q_1, 0.5] \), whereas is null otherwise. The axial ratios’ distribution of the lensing population mimics that of the total cluster population (Hennawi et al. 2007).

For the orientation, we considered a population of randomly oriented clusters with

\[
p(\cos \theta) = 1,
\]

for \( 0 \leq \cos \theta \leq 1 \) and

\[
p(\psi) = \frac{1}{\pi}
\]

for \( -\pi/2 \leq \psi \leq \pi/2 \). The distribution for \( \psi \) is the same as that for \( \varphi \). For comparison, we also considered a biased population. Semi-analytical (Oguri & Blandford 2009) and numerical (Hennawi et al. 2007) investigations showed a large tendency for lensing clusters to be aligned with the line of sight. This condition can be expressed as (Corless et al. 2009)

\[
p(\cos \theta) \propto \exp \left[ -\frac{(\cos \theta - 1)^2}{2\sigma_\theta^2} \right].
\]

A value of \( \sigma_\theta = 0.115 \) can be representative of the orientation bias for massive SL clusters.

### 4 THE MACS HIGH-REDSHIFT CLUSTER SAMPLE

The MACS supplies a complete sample of the very X-ray luminous clusters in the Universe (Ebeling, Edge & Henry 2001; Ebeling et al. 2010). From this catalogue, a complete sample of 12 high-z MACS clusters (\( z > 0.5 \), see Table 1) was defined by Ebeling et al. (2007), which have proved very interesting in several follow-up studies including deep X-ray, SZ and Hubble Space Telescope imaging (see Zitrin et al. 2011a, and references therein). In particular, here we use the multiple images identified in Zitrin et al. (2011a) as an input for our non-parametric mass reconstruction.

| MACS       | \( \alpha \) (J2000.0) | \( \delta \) (J2000.0) | \( z \) | \( \sigma \) (\( \text{km s}^{-1} \)) | \( L_{X,\text{Chandra}} \) (10\(^{45}\)\( \text{erg s}^{-1} \)) | \( K_T \) (keV) | M.C.E. | \( \theta_{\text{UL}} \) (arcsec) |
|-----------|----------------------|----------------------|------|----------------|-----------------|------------|--------|----------------------|
| J0018.5+1626 | 00 18 33.835 | +16 26 16.64 | 0.545 | 1420\(^{140}\)\(^{-150}\) | 19.6 \pm 0.3 | 9.4 \pm 1.3 | 3 | 24 \pm 2 |
| J0025.4+1222 | 00 25 29.381 | –12 22 37.06 | 0.584 | 740\(^{+90}\)\(^{-100}\) | 8.8 \pm 0.2 | 7.1 \pm 0.7 | 3 | 30 \pm 2 |
| J0257.1+2325 | 02 57 09.151 | –23 26 05.83 | 0.505 | 970\(^{+200}\)\(^{-250}\) | 13.7 \pm 0.3 | 10.5 \pm 1.0 | 2 | 39 \pm 2 |
| J0454.1+0300 | 04 54 11.125 | –03 00 53.77 | 0.538 | 1250\(^{+130}\)\(^{-140}\) | 16.8 \pm 0.6 | 7.5 \pm 1.0 | 2 | 13\(^{+3}\)\(^{-2}\) |
| J0647.7+7015 | 06 47 50.469 | +70 14 54.95 | 0.591 | 900\(^{+120}\)\(^{-180}\) | 15.9 \pm 0.4 | 11.5 \pm 1.0 | 2 | 28 \pm 2 |
| J0717.5+3745 | 07 17 30.927 | +37 45 29.74 | 0.546 | 1660\(^{+120}\)\(^{-140}\) | 24.6 \pm 0.3 | 11.6 \pm 0.5 | 4 | 55 \pm 3 |
| J0744.8+3927 | 07 44 52.470 | +39 27 27.34 | 0.698 | 1110\(^{+130}\)\(^{-150}\) | 22.9 \pm 0.6 | 8.1 \pm 0.6 | 2 | 31 \pm 2 |
| J0911.2+1746 | 09 11 11.277 | +17 46 31.94 | 0.505 | 1150\(^{+200}\)\(^{-250}\) | 7.8 \pm 0.3 | 8.8 \pm 0.7 | 4 | 11\(^{+3}\)\(^{-2}\) |
| J1149.5+2223 | 11 49 35.093 | +22 24 10.94 | 0.544 | 1840\(^{+120}\)\(^{-140}\) | 17.6 \pm 0.4 | 9.1 \pm 0.7 | 4 | 27 \pm 3 |
| J1423.8+2840 | 14 23 47.663 | +28 04 40.14 | 0.543 | 1300\(^{+120}\)\(^{-170}\) | 16.5 \pm 0.7 | 7.0 \pm 0.8 | 1 | 20 \pm 2 |
| J2129.4–0741 | 21 29 26.214 | –07 41 26.22 | 0.589 | 1400\(^{+120}\)\(^{-200}\) | 15.7 \pm 0.4 | 8.1 \pm 0.7 | 3 | 37 \pm 2 |
| J2214.9–1359 | 22 14 57.415 | –14 00 10.78 | 0.503 | 1300\(^{+90}\)\(^{-110}\) | 14.1 \pm 0.3 | 8.8 \pm 0.7 | 2 | 23 \pm 2 |

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Although the MACS clusters are not selected by their lensing features and therefore are not biased in that sense, they are expected to comprise some of the most massive clusters in the Universe and thus can be expected to produce impressive lenses. As also discussed above in Section 1, by the SL analysis, Zitrin et al. (2011a) deduced the distribution of Einstein radii for this sample, which are found to be notably larger than expected by ΛCDM (see also Meneghetti et al. 2011), even after taking the lensing bias into account.

Here, we deduce the triaxial 3D mass distribution of these clusters in order to examine whether the c(M) relation of this sample suffers the same discrepancy as found for the Einstein radii. In this context, this high-z MACS sample is of unique interest. Being at a relatively high redshift, and mostly consisting of unrelaxed clusters (see also Table 1), this sample cannot be expected to follow the usual Einstein radius–concentration relation (e.g. Sadeh & Refaeli 2008). Instead, it can shed more light on the relaxation epoch of massive clusters and show that if concentrations are low, unrelaxed (and mostly higher-z) clusters indeed form a different class of prominent gravitational lenses (than well-relaxed and concentrated lower-z clusters), as previously implied (Torri et al. 2004; Fedeli et al. 2006; Neto et al. 2007; Zitrin et al. 2011b).

5 STRONG-LENSING ANALYSIS

We performed SL analyses of the inner regions of the high-redshift MACS sample. A detailed description of the SL features of the sample can be found in Zitrin et al. (2011a). We adopted a two-step procedure. First, we obtained the surface mass density for each cluster. Secondly, we modelled the map with a projected NFW profile.

We obtained a pixelated map of the surface mass density of each cluster by use of the PIXELENS software (Saha & Williams, 2004). PIXELENS generates a statistical ensemble of models which can exactly reproduce the positions and parities of all multiple image. The ensemble automatically explores degeneracies in convergence and provides uncertainties. For each cluster, we computed 200 convergence maps. Parameters set to run the code are listed in Table 2. For each lens, we analysed a circular area centred on the brightest cluster galaxy (BCG). The external radii are listed in Table 2; they extend just beyond the outermost image. These criteria select a region larger than that enclosed by the Einstein radius, see Tables 1 and 2. The effectiveness of PIXELENS is consequently poorer in the outer pixels. We then excised these pixels as explained in the following. In determining the optimal pixel resolution we had to counterbalance two competing effects. On one side, a more refined grid of pixels allows for a better constraining of small scale structures. On the other side, a too large number of pixels slow the code to a not sustainable extent. It can also induce oversampling effects. From the analysis of lensing in simulated systems, we found that a radius of ~14–15 pixels gives the best compromise. The explicit resolutions are listed in Table 2.

PIXELENS may offer a poor description of the mass profile in the very outer pixels, with an unphysical sharp drop in density just outside the Einstein radius. We preliminarily computed the slope profile of the surface density in spherical annuli centred at the denser pixel and checked for logarithmic density slope values smaller than −2, the minimum allowed slope for a projected NFW profile. We required at least two consecutive annuli with a slope lower than the threshold. We fixed the minimum convergence at the averaged convergence of the first spherical region with an unphysical slope and excluded from the analysis pixels with convergence lower than the minimum. With the aid of simulated images, we checked that the fitting procedure fares very well. In the radial span of just a couple of pixels near the Einstein radius, the logarithmic slope suddenly falls from $\gtrsim -1$ in the internal region (where $\xi \ll r_p$) to values $< -3$ or even steeper. We retrieved this feature, which is the artefact of PIXELENS, in both simulated or observed clusters. We checked that the value of the minimum allowed convergence was negligibly affected by the use of different cutting criteria, such as either a different minimum value for the slope ($\gtrsim -1.5$) or by requiring that the allowed slope variation between adjacent annuli was smaller than a maximum difference.

We also excluded the central pixels. Umetsu et al. (2011a, 2011b) found a small offset of typically $\lesssim d_{\text{off}} = 20 \text{kpc} h^{-1}$ between the BCG and the DM centre of mass recovered from strong lens modelling. Even if in PIXELENS the centre position is left free and only a preliminary geometrical centre (usually coinciding with the position of the BCG) is used, we conservatively limited our analysis to radii greater than $2 d_{\text{off}}$ from the pixel with the maximum convergence, beyond which the cluster miscentering effects are negligible. For $z > 0.5$, this criterion usually cuts only the very central dense pixel. The exclusion of the central pixels is also conservative with regard to the effects of baryons on the total matter profile. In fact, in the investigated range the total distribution is dominated by DM, whose behaviour is very well modelled in numerical simulations. An example of pixels which passed the cuts is plotted in Fig. 1.

As a second step, we modelled the pixelated maps with a projected NFW profile. We looked for the minimum of

$$\chi^2 = \sum_i \left[ k_i - \kappa_{\text{NFW}}(r_{i1}; \theta_{0,1}, \theta_{0,2}, \kappa_s, r_p, \epsilon, \theta_0) \right]^2,$$

where the sum runs over the pixels and $k_i$ is the measured convergence of the $i$th pixel of coordinates $x_{i1}$, $x_{i2}$, $\kappa_{\text{NFW}}$ is the theoretical prediction. Each pixel was given the same weight. We fitted six free parameters: the halo centre coordinates, $\theta_{0,1}$ and $\theta_{0,2}$; the strength $\kappa_s (>0)$ and the projected radius $r_p (>0)$; the ellipticity $0 < \epsilon (\leq 1)$ and the orientation angle $\theta_0$. In Fig. 1 we plot the result of such fitting procedure for a mean convergence map.

We carried out the fitting procedure for each map. From the derived ensemble of maximum likelihood parameters, we obtained the posteriori distribution of projected NFW parameters. For each map, we considered only the best-fitting parameters. Since we fitted each map separately, correlation effects and convergence stability for each pixel were not considered at the level of equation (23).
errors reflect the inability of the fitting procedure to effectively constrain the scalelength. Strong lensing focuses on the very inner regions, whereas a precise determination of $r_p$ would require a coverage up to larger radii, as in weak-lensing analyses. Degeneracy effects make even very large values of $r_p$ compatible with multiple-image positions. As a consequence, the central momentum of the distribution is pushed to large values too. This can be seen in the marginalized PDF distribution for $\kappa_s$ and $r_p$, see Fig. 2. Most likely values for $r_p$ are at small values, but the tail at large values is really extended. The large uncertainty on $r_p$ will carry over into a large uncertainty on halo mass and concentration.

### 6 DEPROJECTION

Deprojecting a surface density map to infer the intrinsic 3D shape is an underconstrained astronomical problem. Apart from three coordinates fixing the halo centre, the 3D NFW halo features seven parameters: the density profile is described by two parameters ($M_{200}$ and $c_{200}$), the shape by two axial ratios ($q_1$ and $q_2$), the orientation by three angles, $\theta$ and $\varphi$ and $\psi$. On the other hand, since lensing is dependent on the projected mass density, from lensing observations we only get four constraints relating the intrinsic parameters: the lensing strength $\kappa_s$, the projected radius $r_p$, the ellipticity $\epsilon$ and the orientation $\theta_s$. Even combining multi-wavelength observations, from X-ray through the optical and to radio bands, one can only constrain the elongation of the cluster along the line of sight (Sereno 2007).

To assess realistic probability distributions for the intrinsic parameters we performed a statistical Bayesian analysis. The use of some a priori hypotheses on the cluster shape can help to disentangle degeneracies. We applied some methods already employed in gravitational lensing analyses (Oguri et al. 2005; Corless et al. 2009; Sereno et al. 2010a). In particular, we followed Sereno & Umetsu (2011), where further details on the method can be found.

The Bayes theorem states that

$$p(P|d) \propto \mathcal{L}(P|d)p(P)$$

\hspace{1cm} (24)

### Table 3. Observed projected NFW parameters of the $z > 0.5$ MACS sample

| MACS   | $\kappa_s$     | $r_p$ (kpc) | $\epsilon$ | $\theta_s$ (deg) |
|-------|----------------|-------------|-------------|------------------|
| J0018 | 0.29 ± 0.06    | 2200 ± 1300 | 0.32 ± 0.12 | −50 ± 17        |
| J0025 | 0.26 ± 0.04    | 8100 ± 4500 | 0.21 ± 0.09 | −25 ± 24        |
| J0257 | 0.37 ± 0.06    | 1200 ± 500  | 0.12 ± 0.08 | 2 ± 45          |
| J0451 | 0.28 ± 0.05    | 2700 ± 1500 | 0.20 ± 0.10 | 6 ± 64          |
| J0647 | 0.28 ± 0.01    | 3500 ± 400  | 0.07 ± 0.02 | 11 ± 36         |
| J0717 | 0.26 ± 0.07    | 5700 ± 4000 | 0.07 ± 0.04 | −58 ± 29        |
| J0744 | 0.74 ± 0.03    | 2000 ± 300  | 0.59 ± 0.02 | −0.6 ± 1        |
| J0911 | 0.39 ± 0.19    | 850 ± 780   | 0.29 ± 0.10 | −17 ± 34        |
| J1149 | 0.23 ± 0.02    | 3900 ± 1100 | 0.10 ± 0.03 | −65 ± 17        |
| J1423 | 0.29 ± 0.07    | 1700 ± 1000 | 0.34 ± 0.09 | −25 ± 8         |
| J2129 | 0.31 ± 0.06    | 3700 ± 2600 | 0.07 ± 0.04 | −2 ± 40         |
| J2214 | 0.29 ± 0.07    | 2000 ± 1200 | 0.32 ± 0.10 | 54 ± 20         |

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where \( p(d|P) \) is the posterior probability of the parameters \( P \) given the data \( d \), \( L(P|d) \) is the likelihood of the data given the model parameters, and \( p(P) \) is the prior probability distribution for the model parameters.

Using the functional dependence of the projected parameters on the intrinsic ones, the likelihood for the intrinsic parameters is the likelihood \( L(\kappa, \psi, \epsilon, \theta) \) derived in Section 5. This distribution was smoothed using a Gaussian kernel estimator (Vio et al. 1994; Ryden 1996).

As prior for the axial ratios \( q_1 \) and \( q_2 \), we considered the N-body predictions in equations (17)–(19). We always put a lower bound \( q_1 \geq 0.1 \). For the alignment angle \( \theta \) and the azimuth angle \( \psi \), we considered a random distribution. For the mass, we always used a flat prior \( p(M_{200}) = \text{const.} \) in the range \( 10^{15} \leq M_{200}/(M_\odot h^{-1}) \leq 10^{16} \), whereas the prior for the concentration was flat in the range \( 0 < c_{200} \leq 30 \) and null otherwise. Posterior PDFs were computed by running four Markov chains. We checked for chain convergence by verifying that the standard var(chain mean)/mean(chain var) indicator was less than 1.1. We computed at least 10 000 samples per chain and eventually added 10 000 more until the convergence criterion was satisfied.

Results are summarized in Table 4. Central location and dispersion for each parameter are computed as bi-weight estimators of the corresponding marginalized posterior PDF (Beers et al. 1990). Interesting results can be obtained on the mass, concentration and elongation of the clusters. Since we exploited only SL data in the inner regions, we cannot determine the virial halo mass accurately. Our typical error on \( M_{200} \) is then \( \geq 60 \) per cent. This reflects the large uncertainty in the projected scale radius, discussed in Section 5. A better determination would require either weak-lensing data at larger radii or a much larger number of multiple image systems. The statistical uncertainty in the concentration measurement is large too (\( \leq 50 \) per cent), but better than the mass accuracy.

Dealing with a triaxial analysis, we have five more parameters (three orientation angles and two axial ratios) with respect to a spherical analysis. The errors on \( M_{200} \) and \( c_{200} \) are consequently larger than when assuming spherical symmetry (Sereno & Umetsu 2011). Elongation can be somewhat constrained since it is directly connected to the lensing strength. On the other hand, the PDFs of the intrinsic axial ratio \( q_1 \) and \( q_2 \) and of the angle \( \psi \) are dominated by the a priori assumptions. Our SL data are not constraining in this regard and we do not discuss them. The posterior distribution of \( \psi \) just reflects the likelihood on \( \theta \), and is not significant in this context.

The final balance is that, with respect to a standard spherical analysis, we can constrain a third parameter, i.e. the elongation, at the expense of a poorer accuracy on halo mass and concentration. Our Bayesian analysis also cuts unphysical models, such as those corresponding to extremely large values of \( r_{sp} \) which are still represented by the likelihood.

7 RESULTS

7.1 Mass and concentration

The estimated mass–concentration relation for the high-redshift MACS sample is plotted in Fig. 3. Our SL analysis could naturally not determine the total cluster masses very accurately, whereas the constraints on the concentrations were slightly tighter. However, the overconcentration problem can be addressed even if uncertainties are large. We found that the \( z > 0.5 \) MACS clusters are very massive as expected \( (M_{200} \gtrsim 10^{15} M_\odot h^{-1}) \), with quite low concentrations \( c_{200} \lesssim 3 \). Usually, SL-selected clusters with the mass of this order were found to be overconcentrated to the extent of \( c_{200} \sim 10 \). Even with a quite large error of \( \delta c_{200} \lesssim 1.2 \) we can distinguish clusters in agreement with the theoretical \( c(M) \) relation from outliers. Furthermore, most of the theoretical studies on the \( c(M) \) relation predict a quite shallow dependence of the concentration on the mass (Neto et al. 2007; Duffy et al. 2008; Gao et al. 2008; Macciò et al. 2008), so that the comparison with our results can be meaningful even with large uncertainties \( \delta M_{200} \). However, large errors prevent us from determining the slope in the observed \( c(M) \) relation.

We find a noteworthy agreement between observations and predictions for the MACS sample. All of the measured concentrations are compatible within 1\( \sigma \) with the predicted values. A small decrement of concentrations with increasing masses seems to be in order, but large errors asks for caution.

| MACS      | \( M_{200} \) \( (10^{15} M_\odot h^{-1}) \) | \( c_{200} \) | \( \cos \theta \) |
|-----------|--------------------------------|----------------|----------------|
| J0018     | 4.1 \( \pm \) 2.7              | 1.9 \( \pm \) 0.9 | 0.59 \( \pm \) 0.29 |
| J0025     | 4.3 \( \pm \) 3.2              | 1.6 \( \pm \) 1.1 | 0.73 \( \pm \) 0.27 |
| J0257     | 2.7 \( \pm \) 1.7              | 2.7 \( \pm \) 1.1 | 0.76 \( \pm \) 0.26 |
| J0451     | 4.8 \( \pm \) 2.5              | 1.6 \( \pm \) 0.7 | 0.74 \( \pm \) 0.25 |
| J0647     | 6.8 \( \pm \) 1.4              | 1.0 \( \pm \) 0.2 | 0.81 \( \pm \) 0.12 |
| J0717     | 4.5 \( \pm \) 3.0              | 1.5 \( \pm \) 1.2 | 0.57 \( \pm \) 0.20 |
| J0744     | 8.0 \( \pm \) 1.3              | 3.1 \( \pm \) 0.5 | 0.38 \( \pm \) 0.23 |
| J0911     | 1.8 \( \pm \) 1.7              | 3.6 \( \pm \) 2.2 | 0.57 \( \pm \) 0.30 |
| J1149     | 5.1 \( \pm \) 1.9              | 0.9 \( \pm \) 0.3 | 0.85 \( \pm \) 0.11 |
| J1423     | 2.9 \( \pm \) 2.2              | 2.0 \( \pm \) 0.9 | 0.59 \( \pm \) 0.29 |
| J2129     | 3.5 \( \pm \) 3.1              | 1.7 \( \pm \) 1.1 | 0.80 \( \pm \) 0.12 |
| J2214     | 3.2 \( \pm \) 2.8              | 2.3 \( \pm \) 1.2 | 0.61 \( \pm \) 0.29 |
7.2 Orientation

Very low values of the orientation angles $\theta$ for the MACS sample would suggest an orientation bias. Measured values are listed in Table 4. Predicted versus observed values are plotted in Fig. 5. To account for the observational uncertainty, theoretical predictions were convolved with a Gaussian function with dispersion equal to the average uncertainty on $\cos \theta$ ($\sim 0.23$). With respect to a randomly oriented sample, there is an excess at low orientation angles, $\cos \theta \gtrsim 0.5$. The more inclined clusters ($\cos \theta \gtrsim 0.8$) are those which appear nearly circular in the plane of the sky ($\epsilon \lesssim 0.1$).

The Kolmogorov–Smirnov (KS) test can provide further insight. Neither of the two extreme cases considered (SL orientation bias with $\sigma_{\cos \phi} = 0.115$ or random orientations) provides a very good description of the data, but the strongly biased case is slightly preferred. The KS significance level is of 0.9 per cent for the biased case or 0.4 per cent for the random case. To assess the size of any orientation bias, we run the KS test for different values of $\sigma_{\cos \phi}$, see Fig. 6. The significance level is maximum for $\sigma_{\cos \phi} = 0.4$, suggesting that a mild form of the orientation bias affects the X-ray-selected MACS sample.

Figure 4. Effective $Einstein$ radii versus concentrations for the $z > 0.5$ MACS clusters. The full line is the theoretical prediction for unrelaxed clusters at $z \approx 0.56$. Concentrations for relaxed clusters are expected to be significantly higher.

Figure 5. Theoretical PDFs for the orientation ($\cos \theta$) of randomly oriented (full line) or biased ($\sigma_{\cos \phi} = 0.115$, dashed line) $N$-body-like clusters versus measured values for the $z > 0.5$ MACS sample (normalized histogram). The predicted distributions were convolved with a Gaussian distribution with dispersion of $\sim 0.23$.

7.3 Elongation and ellipticity

A combined analysis of elongations and ellipticities can provide further information on the orientation bias. Estimated elongations are listed in Table 5. The observed versus the predicted values of the elongations are plotted in Fig. 7. The cumulative distributions are plotted in Fig. 8. As theoretical distributions we considered a population of clusters with $N$-body-like axial ratios. The masses and the redshifts of the theoretical distribution are fixed to the average values of the $z > 0.5$ MACS sample. As before, we considered two cases for the orientation: either randomly oriented lenses or clusters strongly inclined towards the line of sight ($\sigma_{\cos \phi} = 0.115$). Theoretical distributions were smoothed to account for observational uncertainties by convolving with a Gaussian function with dispersion equal to the average observational error on the measured elongations, i.e. $\sim 0.5$. The biased population makes a better job in reproducing observed measured elongations, with a KS significance level of 0.3 per cent compared to 0.1 per cent for the randomly oriented clusters.

Menegotti et al. (2011) found that three clusters in the sample, namely MACS J0717, MACS J0025, and MACS J1219, have extremely large lensing cross-sections. Triaxiality might help to

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Table 5. Inferred elongations $e_\Delta$ of the $z > 0.5$ MACS sample. The lower the $e_\Delta$, the more prominent the elongation along the line of sight. Central values and dispersions are computed as bi-weight estimators of the marginalized PDFs.

| MACS    | $e_\Delta$ |
|---------|------------|
| J0018   | 1.6 ± 0.6  |
| J0025   | 1.3 ± 0.6  |
| J0257   | 1.2 ± 0.5  |
| J0451   | 1.3 ± 0.5  |
| J0647   | 1.0 ± 0.3  |
| J0717   | 0.9 ± 0.4  |
| J0744   | 2.1 ± 0.6  |
| J0911   | 1.5 ± 0.5  |
| J1149   | 0.9 ± 0.4  |
| J1423   | 1.6 ± 0.6  |
| J2129   | 0.9 ± 0.4  |
| J2214   | 1.5 ± 0.6  |

Figure 7. Theoretical PDFs for the elongations of either randomly oriented (full line) or biased ($\sigma_{\cos \theta} = 0.115$, dashed line) $N$-body-like clusters versus measured values for the $z > 0.5$ MACS sample (normalized histogram).

understand these outliers. In fact, two out the the three clusters, i.e. MACS J0717 and MACS J2129, have two of the smaller $e_\Delta$ values ($\sim 0.9$) in the sample. Convergence is proportional to $1/e_\Delta$, and elongation can enhance the cross-section. MACS J0717 is known to sit at the tip of a prominent filament, which further supports the view of an elongated structure.

The same analysis can be applied to the measured ellipticities, see Table 3. Note that $\epsilon$ is directly inferred from the SL analysis, whereas $e_\Delta$ was estimated through the deprojection method. The observed versus the predicted values of the ellipticities are plotted in Fig. 9. The cumulative distributions are plotted in Fig. 10. We considered the same theoretical distributions as for the elongations. This time, the convolving normal function accounting for observational uncertainties had a dispersion of $\sim 0.07$. You can see by eye that the biased population can reproduce the observed values much better than the random one; in particular, it predicts the observed excess at small values. In more quantitative terms, the KS significance level for the biased population is a robust 10 per cent, whereas for the random sample we got a negligible $2 \times 10^{-4}$ per cent.

Figure 8. Predicted cumulative distribution functions for elongation versus measurements of the $z > 0.5$ MACS sample. The step line is for the observed sample. The smooth full and dashed lines are the predicted distributions for $N$-body-like clusters with either random or biased ($\sigma_{\cos \theta} = 0.115$) orientations, respectively.

Figure 9. The same as Fig. 7 for the projected ellipticity.

Figure 10. The same as Fig. 8 for the projected ellipticity.

A further element in favour of an orientation bias is given by the analysis of the 2D distributions, see Fig. 11. Randomly oriented or biased populations in our analysis share the same axial ratio distribution. On the other hand, the orientation bias is compatible with a significant number of inclined clusters which are at the same time nearly circular when projected in the plane of the sky (small values of $\epsilon$) and quite elongated along the line of sight (small values
of $\epsilon_\Delta$). This feature is seen in the distribution of observed values. All pairs of measured $\epsilon$ and $\epsilon_\Delta$ are compatible within the 2σ confidence level with the biased population.

8 SYSTEMATICS

Let us discuss some systematic uncertainties that might affect our analysis. The well-established modelling method used in Zitrin et al. (2011a) to identify many sets of multiply lensed images has been very successful in determining source redshifts. Furthermore, within the PIXELENS approach, statistical uncertainties in the modelling due to unknown source redshifts (as far as the error on $z_s$ is $\lesssim 0.5$) are lower than degeneracies in the parameter space due to variations in the mass density (Saha & Williams 2004). Effects of redshift uncertainties are then expected to be negligible. First, over-(under) estimating the source redshift would decrease the lensing strength of the lens, and in turn the estimations of mass and concentration. This trend would not solve any overconcentration problem in ΛCDM, which would be artificially solved only for mass and concentration systematically changed in opposite directions. Secondly, the main effect of redshift uncertainties would be on the determination of the profile slope. Here, we were interested in comparison with numerical simulations which assumed an NFW profile for the matter halo. Then, we could keep the profile slope fixed, and we did not determine it from the data. Thirdly, any variation of $\delta_{z_s} \sim 0.5$ for a typical lensed source at $z_s \sim 2$ would change the image position by 6–10 per cent. At a typical Einstein radius of 30 arcsec, this would translate into an astrometric error of $\lesssim 2$–3 arcsec. Since we used a pixelated map to reproduce the mass density, the effect on parameter degeneracy is then negligible. In fact, our typical pixel resolution for the $z > 0.5$ MACS clusters is of $\sim 2$–3 arcsec, see Table 2, which is worse than the redshift uncertainty.

Substructure and line-of-sight haloes might also play a role (D’Aloisio & Natarajan 2011a). A group-sized halo residing slightly behind the lens typically brings about an astrometric shift of $\sim 0.25$ arcsec, with largest deviations of $\sim 1$ arcsec. If the masses of the two line-of-sight structures are roughly equivalent, the deviations increase to $\sim 0.9$ arcsec on average and can be as high as a few arcseconds. The effect is more dramatic for uncorrelated line-of-sight structures which should perturb the image locations by $\lesssim 1$ arcsec for a lens at $z_s \sim 0.5$. These effects turn then out to be negligible when compared with our typical pixel resolution.

A different source of error might come from the use of priors in the Bayesian analysis. If the likelihood is not peaked, the final result might reflect the employed a priori hypotheses. Whenever the parameter values are limited from above and below, as it is conceivably for the mass of MACS clusters, which are known to be very massive, and the concentration, which by definition is positive and very hardly exceeds very large values, flat priors in the allowed range, as the ones we used in Section 6, are the best choice. However, an alternative might be to use priors uniform in logarithmically spaced decades, as usually done for parameters with only lower bounds. We then rerun the analysis with these alternative priors for mass and concentration. Results are summarized in Fig. 12. The agreement with the results obtained in Section 6 shows that our results were determined by the data and that the role of priors was secondary. The only effect of logarithmically spaced uniform priors was to favour slightly smaller masses. The shift was however much smaller than the estimated uncertainty, so that the determined trend for the $c(M)$ relation is unaffected.

9 CONCLUSIONS

The full understanding of the interplay between mass and concentration in galaxy clusters is an open problem. The rich SL features of the $z > 0.5$ MACS clusters offer the opportunity to study the $c(M)$ relation in a well-defined statistical sample. We exploited a full triaxial lensing analysis, where the matter haloes were modelled as triaxial NFW ellipsoids with arbitrary orientations. The method is not affected by systematics related to shape, so that the resulting estimated concentrations should not suffer from any orientation bias.

Our results are apt to comparison with Ν-body simulations. We find that the $c(M)$ relation of the $z > 0.5$ MACS sample is in

![Figure 11](https://example.com/figure11.png)  Ellipticities and elongations of the MACS sample (crosses) versus the theoretical predictions. Contours are plotted at fraction values $\text{exp}(-2.3/2)$, $\text{exp}(-6.17/2)$ and $\text{exp}(-11.8/2)$ of the maximum, which denote the confidence limit regions of 1, 2 and 3σ in a maximum likelihood framework, respectively. The shadowed regions are for a population of N-body-like haloes with a biased orientation ($\sigma_{\cos \theta} = 0.115$); the thick contours are for randomly oriented clusters.

![Figure 12](https://example.com/figure12.png) Estimated mass and concentration of the $z > 0.5$ MACS clusters versus theoretical predictions assuming priors for mass and concentration flat in logarithmic bins. Symbols and styles are the same of Fig. 3.
remarkable agreement with theoretical predictions. There is no hint to an overconcentration problem. The clusters turn out to be preferentially elongated along the line of sight, although this orientation bias is much smaller than for SL-selected clusters.

The obtained masses and concentrations are also in line with some general expectations based on the properties of the sample. The MACS clusters are X-ray selected. Gas distribution is usually rounder than the matter density, so triaxiality plays a smaller role in cluster selections (Gavazzi 2005). The orientation bias as well as the overconcentration problem should be then sensibly reduced with respect to SL-selected samples. On the other hand, the $z > 0.5$ MACS clusters are representative of the very high mass tail of the full cluster distribution, so that the role of a smaller bias might be amplified. We indeed retrieve such expected trends.

With more and more reliable observational estimates of the $c(M)$ relation, the onion seems now to be on the predictive theoretics from $N$-body analyses. Dark matter $N$-body simulations usually samples very few massive clusters and their predictions at the high redshift and massive end are mainly based on extrapolations of results of low $z$ haloes. Results from independent analyses are still in disagreement and estimated concentrations for massive clusters can differ by $\lesssim 50$ per cent (Prada et al. 2011). Baryonic physics can play an important role too, especially in the very inner regions probed by SL. The baryonic contribution to the assembling of haloes in large simulation volumes has yet to be fully understood. The explicit effects of cooling, feeding and baryonic-DM interplay on the mass profile and concentration are also still ambiguous (e.g. Gnedin et al. 2004; Rozo et al. 2008; Duffy et al. 2010). Continuous advancements in computational power may soon enable sufficiently high-resolution description to enlighten the true (theoretical) $c(M)$ relation for the most massive haloes.

Although we have found no discrepancy between theory and observations in the $c(M)$ relation of the high-$z$ MACS sample, we note that this sample appears to consist of mostly unrelaxed clusters. The high X-ray luminosity, along with the relatively high-redshift and recent SZ effect images (via private communication), is in support of this claim, in addition to notable substructure seen in optical and lensing analyses (Zitrin et al. 2011a). The inner mass distribution of (most of) these clusters seem corresponding rather widely distributed (see also Table 1), which may account for their extensive lensing properties and large Einstein radii. In this regard, the combined analysis of lensing data together with X-ray measurements and observations of the SZ effect seem to be a very promising approach to constrain the intrinsic structure of the mass and gas distributions even in unrelaxed clusters (De Filippis et al. 2005; Sereno et al. 2006; Morandi et al. 2011; Sereno, Ettori & Baldi 2011).

Unlike relaxed and highly concentrated clusters which correspondingly have more mass in the middle boosting their critical area and Einstein radius, in higher-$z$, unrelaxed clusters, large Einstein radii may however form due to a widely distributed inner mass distribution, so that the critical curves of the smaller substructures near the core merge together to form a much larger Einstein radius curve (Torr et al. 2004; Fedeli et al. 2006; Zitrin et al. 2009a). If this is indeed the case, low concentrations and relatively shallow inner profiles should be expected for clusters as those in the $z > 0.5$ MACS sample (Neto et al. 2007). Although the results of our analysis may not be projected on relaxed lower-$z$ samples or unambiguously resolve the claimed discrepancy in the $c(M)$ relation for relaxed haloes, they are of an additional high importance, since such information can help constrain and shed new light on the relaxation era of (massive) clusters and more generally on the evolution of the large-scale structure. Our finding of low concentrations suggests, as previously implied (e.g. Neto et al. 2007; Zitrin et al. 2011b), that high-$z$ unrelaxed clusters therefore form a different class of prominent and impressive gravitational lenses.

Our analysis would benefit from either arc redshift confirmation or data for different scales, as those provided by weak-lensing observations. Upcoming observations planned in the CLASH programme (Postman et al. 2011) are going to supply this information and will further establish the results of our work. However, combined strong plus weak-lensing analyses may be dominated by the SL part due to the lower systematics. Therefore, considering as a first step only SL can be reasonable.

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