Mass, shape and thermal properties of Abell 1689 using a multiwavelength X-ray, lensing and Sunyaev–Zel’dovich analysis

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Accepted 2012 October 10. Received 2012 October 9; in original form 2012 July 30

ABSTRACT

Knowledge of the mass and concentration of galaxy clusters is crucial for an understanding of their formation and evolution. Unbiased estimates require an understanding of the shape and orientation of the halo as well as its equilibrium status. We propose a novel method to determine the intrinsic properties of galaxy clusters from a multiwavelength data set, spanning from X-ray spectroscopic and photometric data to gravitational lensing to the Sunyaev–Zel’dovich effect. The method relies on two non-informative geometrical assumptions: the distributions of total matter or gas are approximately ellipsoidal and co-aligned; they have different, constant axial ratios but share the same degree of triaxiality. Weak and strong lensing probe the features of the total mass distribution in the plane of the sky. X-ray data measure the size and orientation of the gas in the plane of the sky. Comparison with the Sunyaev–Zel’dovich amplitude fixes the elongation of the gas along the line of sight. These constraints are deprojected as a result of Bayesian inference. The mass distribution is described as a Navarro–Frenk–White halo with arbitrary orientation, and the gas density and temperature are modelled with parametric profiles. We have applied the method to Abell 1689. Independently of the priors, the cluster is massive, $M_{200} = (1.3 \pm 0.2) \times 10^{15} M_{\odot}$, and overconcentrated, $c_{200} = 8 \pm 1$, but it is still consistent with theoretical predictions. The total matter is triaxial (minor to major axial ratio $\sim 0.5 \pm 0.1$, exploiting priors from $N$-body simulations) with the major axis nearly orientated along the line of sight. The gas is rounder (minor to major axial ratio $\sim 0.6 \pm 0.1$) and deviates from hydrostatic equilibrium. The contribution of non-thermal pressure is $\sim 20–50$ per cent in the inner regions, $\lesssim 300$ kpc, and $\sim 25 \pm 5$ per cent at $\sim 1.5$ Mpc. This picture of A1689 was obtained with a small number of assumptions and in a single framework, suitable for application to a large variety of clusters.

Key words: methods: statistical – galaxies: clusters: general – galaxies: clusters: individual: Abell 1689 – galaxies: clusters: intracluster medium.

1 INTRODUCTION

Clusters of galaxies, the most recent bound structures to form in the Universe, are excellent laboratories for precision astronomy (Voit 2005). Their use in cosmological tests relies on accurate measurements of their mass and concentration (Meneghetti et al. 2010; Rasia et al. 2012). Assessing the equilibrium status is also crucial in determining the evolution and mechanisms of interaction of baryons and dark matter (Lee & Suto 2003; Kazantzidis et al. 2004). An unbiased look at the cluster properties must also take into account their shape and orientation (Oguri et al. 2005). The intrinsic form shows how material aggregates from large-scale perturbations (West 1994; Jing & Suto 2002). However, estimations of mass, inner matter density slope and concentration might be biased if derived under the assumption of spherical symmetry (Gavazzi 2005; Meneghetti et al. 2010; Rasia et al. 2012).

When comparing observations with theoretical predictions, it is also critical to assess the intrinsic shape and orientation. The slope of the concentration–mass $c(M)$ relation of galaxy clusters is

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consistent with N-body simulations, although the normalization factor is higher (Comerford & Natarajan 2007; Ettori et al. 2010). Galaxy clusters that are selected according to their gravitational lensing (GL) strength or X-ray flux might form biased samples (Meneghetti et al. 2011). Triaxial haloes are more efficient lenses than their more spherical counterparts (Oguri & Blandford 2009) with the strongest lenses in the Universe expected to be a highly biased population, preferentially orientated along the line of sight. In fact, the problem of overconcentration is less prominent in analyses that account for triaxiality (Oguri et al. 2005; Sereno & Zitrin 2012).

We can test the intrinsic three-dimensional (3D) form of a population of astronomical objects with statistical approaches (Hubble 1926; Noordlinger 1979; Binggeli 1980; Binney & de Vaucouleurs 1981; Fasano & Vio 1991; de Theije, Katgert & van Kampen 1995; Mohr et al. 1995; Basilakos, Plionis & Maddox 2000; Cooray 2000; Thakur & Chakraborty 2001; Alam & Ryden 2002; Ryden 1996; Plionis, Basilakos & Tovmassian 2004; Paz et al. 2006; Kawahara 2010). Clusters of galaxies can be observed with very heterogeneous data sets at very different wavelengths from X-ray surface brightness and spectral observations of the intracluster medium (ICM), to GL observations of the total mass distribution to the Sunyaev–Zel’dovich effect (SZe) in the radio band. This enables us to tackle the structure of a cluster using a multiprobe approach (Zaroubi et al. 1998; Rebinsky 2000; Doré et al. 2001; Puchwein & Bartelmann 2006). Only a few authors have tried to infer the shape or orientation of single objects. A combined use of X-ray and SZe data enables us to constrain the shape of the ICM without any assumption regarding equilibrium. De Filippis et al. (2005) and Sereno et al. (2006) were the first to study a sample of 25 clusters, and they have found signs of a general triaxial morphology. Mahdavi & Chang (2011) constrained the minimum line-of-sight extent of the hot plasma of the Bullet cluster using a model-independent technique.

Lensing observations offer an alternative way to study triaxiality. Projected mass distributions from either weak lensing (WL) or strong lensing (SL) can be deprojected, exploiting some a priori assumptions on the intrinsic shapes (Oguri et al. 2005; Corless, King & Clowe 2009; Sereno, Jetzer & Lubini 2010a; Sereno, Lubini & Jetzer 2010b; Morandi et al. 2011; Sereno & Umetsu 2011).

Abell 1689 (A1689) is a very luminous cluster at redshift $z = 0.183$ (Broadhurst et al. 2005; Limousin et al. 2007). The mass distribution in the inner $\lesssim 300$ kpc regions of the cluster has been accurately determined by SL analyses that favour a concentrated mass distribution (Broadhurst et al. 2005; Halkola, Seitz & Pannella 2006; Limousin et al. 2007; Coe et al. 2010). On the larger virial scale, different WL analyses suggest somewhat different degrees of concentration (Limousin et al. 2007; Umetsu & Broadhurst 2008; Corless et al. 2009; Umetsu et al. 2009). A further puzzle is the conflict between X-ray and lensing analyses, with lensing masses exceeding estimates derived under the hypothesis of hydrostatic equilibrium by $30–40$ per cent in the inner regions (Peng et al. 2009).

A1689 has been the object of a number of triaxial analyses (Oguri et al. 2005; Corless et al. 2009). Sereno & Umetsu (2011) have analysed WL and SL data and found evidence for a mildly triaxial lens (minor to major axial ratio $\sim 0.5 \pm 0.2$) with the major axis nearly aligned with the line of sight. The halo was overconcentrated but still consistent with theoretical predictions. Peng et al. (2009) have recognized that a prolate configuration, aligned with the line of sight and with an axial ratio of $\sim 0.6$, could solve the central mass discrepancy between lensing and X-ray mass estimates. Morandi et al. (2011) have combined lensing and X-ray data, assuming the cluster to be aligned with the line of sight and fixing the relation between gas and matter shape. They have found an axial ratio for the matter distribution of $\sim 0.5$. Sereno, Ettori & Baldi (2012) have combined X-ray and SZe data to model the gas shape and orientation by using Bayesian inference. Their analysis favours a mildly triaxial gas distribution with a minor to major axial ratio of $0.70 \pm 0.15$, preferentially elongated along the line of sight, as expected for massive lensing clusters.

Here, we propose a method to infer the intrinsic shape and orientation of haloes based on WL and SL observations plus deep X-ray and SZe observations. Lensing gives a picture of the total projected mass distribution without any assumption on the equilibrium status of the cluster. X-ray plus SZe observations fix the size of the gas distribution along the line of sight and in the plane of the sky (Sereno 2007; Sereno et al. 2012). The method exploits Bayesian inference to study a number of variables larger than the number of observational constraints. This enables us to investigate both intrinsic shape and orientation. The version of the method detailed in this paper joins and integrates the lensing analysis in Sereno & Umetsu (2011) with the X-ray plus SZe investigation of Sereno et al. (2012).

The paper is organized as follows. In Section 2, we discuss how triaxial ellipsoids project, and we discuss the relation between total matter and gas distributions. In Section 3, we summarize the X-ray plus SZe analysis. Sections 4 and 5 are devoted to the WL and SL parts, respectively. In Section 6, we show how to combine the different data sets in order to infer the intrinsic properties. We discuss the results in Section 7, and the hydrodynamical status of the cluster in Section 8. We list comparisons with previous works in Section 9. We give our final considerations in Section 10.

Throughout the paper, we assume a flat cold dark matter (CDM) cosmology with density parameters $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and Hubble constant $H_0 = 100\ h\ km\ s^{-1}\ Mpc^{-1}$, $h = 0.7 \pm 0.014$ (Komatsu et al. 2011). At the A1689 distance, 1 arcsec corresponds to 2.15 kpc $h^{-1}$ ($\simeq 3.08$ kpc).

## 2 Triaxial Haloes

In this section, we describe how we model the total matter and the gas distribution and how we relate them.

### 2.1 Matter profile

The ellipsoidal Navarro–Frenk–White (NFW) density profile,

$$\rho_{\text{NFW}} = \frac{\rho_s}{(\xi/r_s)(1 + \xi/r_s)^2}, \quad (1)$$

provides a very good fit to the density distribution of dark matter haloes in high-resolution N-body simulations (Navarro, Frenk & White 1996, 1997; Jing & Suto 2002). In equation (1), $\xi$ is the ellipsoidal radius. The shape of the halo is determined by the axial ratios, which we denote as $q_1$ (minor to major axial ratio) and $q_2$ (intermediate to major axial ratio). The eccentricity is $e_1 = \sqrt{1 - q_1^2}$. The orientation of the halo is fixed by three Euler angles, $\theta$, $\varphi$ and $\psi$, with $\theta$ quantifying the inclination of the major axis with respect to the line of sight.

The NFW density profile can be described by two parameters: the concentration and the mass. By definition, $r_{200}$ is such that the mean density contained within an ellipsoid of semimajor axis $r_{200}$ is 200 times the critical density at the halo redshift, $\rho_{\text{cr}}$ (Corless et al. 2009; Sereno et al. 2010a; Sereno & Umetsu 2011). Then, the corresponding concentration is $c_{200} \equiv r_{200}/r_s$, and $M_{200}$ is the mass within the ellipsoid of semimajor axis $r_{200}$, $M_{200} = (800\pi/3)q_1 q_2 r_{200}^3 \rho_{\text{cr}}$. 
The projection into the sky of the ellipsoidal 3D NFW halo is an elliptical two-dimensional (2D) profile (Stark 1977; Sereno 2007; Sereno et al. 2010b). The convergence \( \kappa \) is the surface mass density in units of the critical density for lensing, \( \Sigma_{\text{cr}} = (c^2 D_s)/(4\pi G D_s D_{ls}) \), where \( D_s \), \( D_l \) and \( D_{ls} \) are the source, the lens and the lens–source angular diameter distances, respectively, and it can be written as
\[
\kappa_{\text{NFW}}(x) = \frac{2k}{1 - x^2} \left[ \frac{1}{\sqrt{1 - x^2}} \text{arccosh} \left( \frac{1}{x} \right) - 1 \right].
\] (2)

Here, \( x \) is the dimensionless elliptical radius,
\[ x \equiv \xi / r_{\text{lp}}, \]
\[ \xi = \left( x_1^2 + x_2^2 / (1 - \epsilon^2) \right)^{1/2}, \]
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 ellipse axes, respectively.

The strength \( \kappa_{\text{ic}} \) and the projected length-scale \( r_{\text{lp}} \) are related to mass and concentration, and also depend on the shape and orientation parameters. Explicit formulae can be found in Sereno et al. (2010a).

Because we can only observe projected maps, the problem of determining the 3D orientation and shape of haloes is intrinsically degenerate. Ellipsoids project into ellipses (Stark 1977). Even with an ideal multiprobe data set without noise, we can only measure three observable quantities that can help us to constrain the five unknown intrinsic properties (two axial ratios and three orientation angles) of the ellipsoidal halo (Sereno 2007). The three measurable quantities are the ellipticity \( \epsilon \), the orientation \( \theta_i \) and the elongation \( e_s \).

The parameters \( \epsilon \) and \( \theta_i \) characterize the projected ellipse in the plane of the sky. The ellipticity \( \epsilon \) gives a measurement of the width in the plane of the sky. It is defined as \( 1 - b_2/a_1 \), where \( b_2 \) and \( a_1 \) are the minor and major axes of the projected ellipse. The parameter \( \theta_i \) measures the orientation in the plane of the sky of this ellipse.

The parameter \( e_s \) quantifies the extent of the cluster along the line of sight. It is the ratio between \( a_1 \) and the size of the ellipse along the line of sight (Sereno et al. 2012, see their fig. 1). The smaller the value of \( e_s \), the larger the elongation along the line of sight. If \( e_s < 1 \), the cluster is more elongated along the line of sight than wide in the plane of the sky.

These three observable quantities depend on the intrinsic axial ratios and on the Euler angles (Binggeli 1980; Sereno 2007).

### 2.2 Intracell effect

Observations (Kawahara 2010) and theory (Buote & Humphrey 2012) also suggest that the density of the ICM is nearly constant for a family of similar, concentric, coaxial ellipsoids. Modelling both the gas and the matter distribution as ellipsoids with constant eccentricity is formally wrong in haloes in hydrostatic equilibrium. If the cluster of galaxies is in hydrostatic equilibrium, then the gas distribution traces the gravitational potential. Given an ellipsoidal gas density, the gravitational potential is also ellipsoidal and can turn unphysical for extreme axial ratios, with negative density regions or unlikely configurations. However, even in hydrostatic equilibrium, the ellipsoidal approximation for the gas is suitable in the inner regions or when small eccentricities are considered.

If the potential is ellipsoidal, the matter distribution that originates it cannot be ellipsoidal. However, dark matter haloes formed in cosmological simulations typically have radially varying shapes too (Kazantzidis et al. 2004), which might be compatible with an ellipsoidal potential.

If the matter halo isodensity surfaces are triaxial ellipsoids, the isodensity surfaces of the intracluster gas are well approximated as triaxial ellipsoids, with eccentricities slowly varying with the radius (Lee & Suto 2003, 2004). The ratio of eccentricities of gas \( (e_{\text{ICM}}) \) and matter \( (e_{\text{Mat}}) \) is nearly constant up to the length-scale, with \( e_{ICM}^2/e_{Mat}^2 \approx 0.7 \) for \( i = 1, 2 \). Furthermore, the variation in eccentricity is usually smaller than the observational error on the measured ellipticity of the X-ray surface brightness map.

A further complication is that microphysical processes, such as radiative cooling, turbulence or feedback mechanisms, strongly affect the shape of the baryonic component and make the ICM shape more triaxial, and with a distinctly oblate shape towards the central cluster regions compared to the underlying dark matter potential shape (Lau et al. 2011). The gas traces the underlying gravitational potential better outside the core, even if radiative processes can make the ICM shape rounder. These mechanisms can be effective, so that the assumption that the overall triaxiality of the gas is strictly because of the underlying shape of the dark matter potential can be misleading.

Finally, the density and shape of the gas distribution have a strong correlation, whereas the temperature is essentially uncorrelated (Samsing, Skielboe & Hansen 2012). Then, the proper modelling of a varying eccentricity would require an independent measurement of the density profile.

Under these circumstances, we can make two simplifying but non-informative working hypotheses to relate gas and total matter distributions. First, we conservatively model both the total matter density and the gas distribution as 

\[ q_0 = q_{\text{ICM}} + q_{\text{Mat}}. \]

Under these assumptions limit the number of free axial ratios to three: \( q_0/2 \). If the potential is ellipsoidal, then, the proper modelling of the gas distribution is that the overall triaxiality of the gas is strictly because of the underlying shape of the dark matter potential can be misleading.

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Under these circumstances, we can make two simplifying but non-informative working hypotheses to relate gas and total matter distributions. First, we conservatively model both the total matter density and the gas distribution as co-aligned ellipsoids with fixed, but different, axial ratios. Secondly, we set the two distributions to have the same triaxiality parameter \( T = \left( e_{1}^2 / e_{2}^2 \right) \). If two distributions have the same triaxialities, then the misalignment angle between the orientations in the plane of the sky is zero (Romanowsky & Kochanek 1998). This is in agreement with what has been observed in A1689, where the centroid and the orientation of the surface brightness map (Sereno et al. 2012) coincide with those of the projected mass distribution, as inferred from lensing (Sereno & Umetsu 2011).

The axial ratios of the gas distribution, \( q_{\text{ICM}} \), can be expressed in terms of the corresponding axial ratios of the matter distributions as
\[
q_{\text{ICM}} = \sqrt{1 - (e_{\text{ICM}}/e_{\text{Mat}})^2 (1 - q_{0}^2)}. \] (4)

If \( T_{\text{Mat}} = T_{\text{ICM}} \), then \( e_{\text{ICM}} / e_{\text{Mat}} = e_{\text{ICM}} / e_{\text{Mat}} = e_{\text{ICM}} / e_{\text{Mat}} \). The above assumptions limit the number of free axial ratios to three: \( q_1 \) and \( q_2 \) for the matter and \( q_{\text{ICM}} \) for the gas. Thus, \( q_{\text{ICM}}^2 \) is determined by \( T(q_1, q_2) \) and \( q_{\text{ICM}}^2 \):
\[
q_{\text{ICM}}^2 = \sqrt{1 - \left( q_{\text{ICM}}^2 \right)^2 / (T_{\text{Mat}}^2)}. \] (5)

In a triaxial analysis, the results strongly depend on the minor to major axial ratio, whereas the inference about the intermediate axis is more affected by priors. Then, using \( q_1 \) and \( q_2 \) and \( q_{\text{ICM}} \) as free parameters is not really a limitation with respect to considering all four axial ratios as free. Finally, as expected from both theory and observations, we require that the gas distribution is rounder than the matter distribution, \( q_{\text{ICM}}^2 \leq q_{\text{Mat}}^2 \).

Under these hypotheses, total matter and gas have different ellipsities and elongations but share the same orientation \( \theta_i \). Because we model the gas isodensities as ellipsoids, they project into ellipses in the plane of the sky. The same degeneracy that plagues the
inference of the shape and orientation of the matter distribution also affects the gas.

3 X-RAY AND SUNYAEV–ZEL’DOVICH EFFECT

The shape and orientation of the gas distribution can be inferred using a combined analysis of X-ray and SZ data (Sereno et al. 2012). The first set of constraints comes from the analysis of the projected maps. The ellipticity and the orientation of the isophotes, which can be measured with either X-ray or the SZ alone, are related to the size of the gas distribution in the plane of the sky. The inference of the elongation along the line of sight requires a combined analysis, which can be carried out because of the different dependences of X-ray and SZ observables on the gas density.

Sereno et al. (2012) have performed an analysis of the X-ray and SZ data of A1689. Here, we summarize the main results and what is needed in the present paper. We refer to Sereno et al. (2012) for details. Images in the 0.7–2 keV band taken by Chandra are well approximated by a series of concentric, co-aligned ellipses with $\epsilon = 0.15 \pm 0.03$ and orientation angle $\theta_X = 12 \pm 3$ deg (measured north over east). The 3D electronic density was modelled with the following parametric profiles (Vikhlinin et al. 2006; Ettori et al. 2009):

$$n_x = n_0 \left[ 1 + \left( \frac{\epsilon}{r_c} \right)^3 \right]^{-\beta/2} \left[ 1 + \left( \frac{\epsilon}{r_t} \right)^3 \right]^{-\gamma/3}. \quad (6)$$

Here, $n_0$ is the central electron density, $r_c$ is the core radius, $r_t (\geq r_c)$ is the tidal radius, $\beta$ is the slope in the intermediate regions and $\gamma$ is the outer slope. For the temperature profile, we have used

$$T = \frac{T_0}{\left[ 1 + (\xi/r_t)^3 \right]^0.5}, \quad (7)$$

where $T_0$ is the central temperature and the radius $r_t$ describes a decrement at large radii. The parametric forms in equations (6) and (7) were motivated by the absence of a cool core.

The profiles based on equations (6) and (7) were then compared to observations of X-ray surface brightness, spectroscopic temperature and SZ decrement. The surface brightness observed by Chandra was collected in 68 elliptical annuli up to $\xi \leq 1200$ kpc. The temperature profile from the XMM satellite was binned in five elliptical annuli up to $\xi \leq 900$ kpc. We have considered the integrated Compton parameters $Y$ within the circle of radius $r_{500}$ $\sim$ 600 kpc measured from seven observatories: the Berkeley–Illinois–Maryland Association (BIMA), Owens Valley Radio Observatory (OVRO), the Array for Microwave Background Anisotropy (AMIBA), the Sunyaev–Zel’dovich Infrared Experiment (SuzIE), the Wilkinson Microwave Anisotropy Probe (WMAP), the Sunyaev–Zel’dovich Array (SZA) and the Submillimetre Common-User Bolometer Array (SCUBA). We have repeated the analysis as in Sereno et al. (2012), but we have used an improved version of the code, with some better numerical algorithms for numerical integration.

To assess the realistic probability distributions for the parameters, we have performed a statistical Bayesian analysis. The Bayes theorem states that

$$p(P | d) \propto L(P | d) p(P), \quad (8)$$

where $p(P | d)$ 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.

Figure 1. Probability distribution of the elongation of the gas distribution as inferred from the X-ray plus SZ analysis.

The posterior probability distribution for the elongation of the gas $\epsilon_{\Delta}^{ICM}$ is plotted in Fig. 1. Together with the projected ellipticity and orientation, the elongation enables us to constrain the intrinsic shape of the gas.

4 WEAK LENSING

We have fitted the surface mass density of A1689 with a projected ellipsoidal NFW halo. The WL convergence map, described as ‘2D MEM’ by Umetsu & Broadhurst (2008), was obtained from Subaru data and covers a field of $\sim 30 \times 24$ arcmin$^2$ (21 x 17 grid pixels with pixel size of 1.4 arcmin; Umetsu & Broadhurst 2008; Umetsu et al. 2009). We have closely followed the method employed by Sereno & Umetsu (2011), which we refer to for more details. The likelihood can be written in terms of $\chi_{WL}^2$ (Oguri et al. 2005, 2010), with

$$\chi_{WL}^2 = \sum_{i,j} \frac{[\kappa_{obs}(r_i) - \kappa(r_i)] (V^{-1})_{i,j} [\kappa_{obs}(r_j) - \kappa(r_j)]}. \quad (9)$$

Here, $\kappa_{obs}$ is the measured convergence map and $V^{-1}$ is the inverse of the pixel–pixel covariance matrix.

One major difference from Sereno & Umetsu (2011) is in the priors used to determine the NFW projected parameters. Whereas Sereno & Umetsu (2011) used uniform priors, here we exploit constraints from the X-ray analysis on centroid position and ICM orientation. The position of the centroid of the X-ray surface brightness, $[\alpha, \delta] = (197.87274, -1.3400533)$ deg with an accuracy of $\sim 1.2$ arcsec, is consistent with the centre of the brightest cluster galaxy (BCG) and with the centroid of the total matter distribution, as estimated from lensing (Sereno & Umetsu 2011). The orientation of the X-ray map is also consistent with the orientation of the matter halo, as estimated from lensing. The posterior probability is then

$$p \propto \exp \left( -\chi_{WL}^2/2 \right) \times \mathcal{N}(\theta_1: \theta_L^X, \delta \theta_L^X) \times \mathcal{N}(\theta_2: \theta_L^X, \delta \theta_L^X). \quad (10)$$

Here, $\mathcal{N}(P; \mu, \sigma)$ denotes a normal distribution for the parameter $P$ centred in $\mu$ and with variance $\sigma$, $\theta_{1,0}$ and $\theta_{2,0}$ are the Cartesian coordinates of the projected centre of the matter distribution in a reference system centred in the BCG galaxy and $\theta_L^X$ and $\theta_L^X$ are the observed coordinates of the X-ray centroid.

The parameter space was explored using Markov chains. Chain convergence was checked by requiring that the standard var(chain mean)/mean(chain var) indicator was less than 1.2. The results are summarized in Table 1.
Analyses based on WL alone are not very effective in determining the projected ellipticity. The relative constraints on the intrinsic axial ratios are not sharp and are dominated by the a priori hypothesis employed. Here, because we have exploited the X-ray information on the halo orientation in the plane of the sky, the ellipticity is better constrained. With respect to the WL only analysis in Sereno & Umetsu (2011), the final distributions on the projected parameters are more peaked and with reduced tails. This is clearly seen in the probability function for $\epsilon$, which would be nearly flat without the X-ray priors.

### 5 STRONG LENSING

We have performed a SL analysis of the inner regions of A1689 and have obtained a pixellated map of the surface mass density, using the **PIXELENS** software (Saha & Williams 2004). We have considered multiple image systems with confirmed spectroscopic redshift, whose detailed description can be found in Limousin et al. (2007) and Coe et al. (2010). In a second step, we have fitted the map with a projected NFW profile. The method is described in detail by Sereno & Zitrin (2012).

**PIXELENS** cannot handle all the multiple image systems of A1689 at once. Thus, we have divided the SL systems in two groups and we have analysed each group separately. The first group includes the systems 1, 2, 7, 10, 11, 18, 22, 24 and 40, according to the notation in Limousin et al. (2007), for a total of 31 multiple images. The second group includes the systems 4, 5, 15, 17, 19, 29, 33 and 35 (28 multiple images). For each group, we have computed 500 convergence maps within a radius of 94 arcsec around the BCG on a grid of 861 pixels with a pixel size of 12.6 kpc $h^{-1}$.

As explained by Sereno & Zitrin (2012), we have excised a central region of 40 kpc $h^{-1}$ to minimize the effects of miscentring and baryonic physics (Umetsu et al. 2011). We have also excluded the outer pixels where the logarithmic density slope artificially takes values smaller than $-3$.

Then, we modelled the convergence with a projected NFW profile. For each convergence map, we looked for the minimum of

$$\chi^2 = \sum_i [\kappa_{\text{obs}}(r_i) - \kappa_{\text{NFW}}(r_i)]^2,$$

where the sum runs over the pixels. From the derived ensemble of maximum likelihood parameters, we obtained the posteriori distribution of projected NFW parameters. We repeated the procedure for the two groups of images, ending up with results statistically not distinguishable.

The results were consistent with previous SL analyses based on the same image systems (Limousin et al. 2007; Coe et al. 2010; Sereno & Umetsu 2011, and references therein). Mass density profiles obtained with **PIXELENS** are usually shallower than reconstructions based on parametric models (Grillo et al. 2010; Umetsu et al. 2012). In comparison with the mass profiles in Limousin et al. (2007), who used **LENSTOOL**, or Sereno & Umetsu (2011), who used **GRAVLENS**, **PIXELENS** retrieves a profile shallower in the inner $\lesssim 90$ kpc $h^{-1}$. However, the projected masses within the Einstein radius ($\lesssim 300$ kpc) are fully consistent. The excision of the inner 40 kpc $h^{-1}$ in our analysis makes the impact of the differences between different methods nearly negligible.

The results from SL are marginally consistent with the WL analysis (see Table 1). WL favours more concentrated profiles but the strong degeneracy between the lensing strength $\kappa_s$ and the projected length-scale $r_p$ makes the two analyses compatible.

The measurement of the orientation angle with the SL analysis of the core region is in very good agreement with the estimate from the X-ray analysis. This further supports the working hypothesis that the gas and the total matter distribution share the same triaxiality degree and are then co-aligned in projection.

### 6 DEPROJECTION

The results from either GL or X-ray plus SZe measurements can be combined to deproject the observations and to infer the 3D structure and orientation of the matter and gas distributions. The combined X-ray plus SZe analysis has enabled us to infer the width of the ICM in the plane of the sky (parametrized in terms of the ellipticity $\epsilon_{\text{ICM}}$) and its size along the line of sight (expressed as the elongation $\Delta_{\text{ICM}}$).

The lensing analysis describes how the total matter density projects in the plane of the sky. The orientation and the ellipticity of the projected surface density are related to the intrinsic shape and orientation of the total matter halo. The way in which the convergence varies with the radius (i.e. the information contained in the parameters $\kappa_s$ and $r_p$ of the NFW halo) constrains the functional form of the density (i.e. the mass and the concentration).

The orientation and the shape of the matter halo significantly affect lensing. The more the cluster is elongated along the line of sight, the more the apparent convergence is boosted and the smaller the projected length-scale in the plane of the sky.

Information from X-ray, SZe and lensing can be brought together. The likelihood function that combines the results from the previous sections can be written as

$$\mathcal{L} = \mathcal{L}_{\text{GL}} \times \mathcal{L}_{\text{ICM}},$$

where

| NFW         | $\kappa_s$ | $\theta_{1,0}$ (arcsec) | $\theta_{2,0}$ (arcsec) | $\epsilon$ | $\theta_s$ (deg) | $r_p$ (kpc) |
|-------------|------------|--------------------------|--------------------------|-------------|------------------|--------------|
| Weak lensing | 0.62 ± 0.18 | 0.20 ± 0.10             | 11.6 ± 2.9               | 220 ± 50    |                  |              |
| Strong lensing | 0.27 ± 0.02 | 0.16 ± 0.03             | 13.6 ± 5.6               | 910 ± 120   |                  |              |
| Weak plus strong lensing | 0.35 ± 0.01 | 0.11 ± 0.02             | 12.7 ± 2.4               | 410 ± 20    |                  |              |
where \( L_{\text{GL}} = L_{\text{WL}} \times L_{\text{SL}} \) and \( L_{\text{WL,SL}} = L(\kappa_0, r_{\text{d}}, \epsilon, \theta) \) (Sereno & Umetsu 2011). For the likelihood of the X-ray plus SZ part (Sereno et al. 2012),

\[
L_{\text{ICM}} = \frac{1}{(2\pi)^{3/2}} \sigma_p \exp \left[ \frac{-\left( q_1 - \frac{q_{\text{sys}}}{r_{\text{d}}} \right)^2}{2\sigma_p^2} \right] \times P(\epsilon_{\text{sys}}^\text{ICM}) \times \frac{1}{(2\pi)^{1/2}} \delta_{\epsilon_{\text{sys}}}^\text{ICM} \exp \left[ -\frac{1}{2} \left( \frac{\delta_{\epsilon_{\text{sys}}}^\text{ICM}}{\sigma_{\epsilon_{\text{sys}}}^\text{ICM}} \right)^2 \right],
\]

where \( P(\epsilon_{\text{sys}}^\text{ICM}) \) is the marginalized posterior probability distribution for the elongation parameter of the gas obtained in Section 3. The parameter \( \Delta \epsilon_{\text{sys}}^\text{ICM} \) quantifies the additional unknown statistical and systematic uncertainty on the elongation. We allow it to follow a normal distribution (D’Agostini 2003), centred on 0 and with dispersion \( \delta_{\epsilon_{\text{sys}}}^\text{ICM} \approx 0.13 \) (Sereno et al. 2012).

The overall ellipsoidal model describing both ICM and dark matter has nine free parameters. For the total matter, there are two parameters determining the profile (i.e. the mass \( M_{\text{vir}} \) and the concentration \( c_{\text{vir}} \)), and the ellipticity \( \epsilon \) of the ICM, and one parameter, \( \Delta \epsilon_{\text{sys}}^\text{ICM} \), quantifying the systematic uncertainty on the elongation of the gas distribution. Mass and gas share the same orientation angles, whereas the second axial ratio of the ICM is fixed by the remaining parameters because of the priors.

The distributions of matter and gas project into ellipses into the plane of the sky. Lensing constraints reduce to four parameters. The analysis of the ICM adds two more measured quantities. Then, the intrinsic parameters have to be determined from a smaller number of observational constraints. The problem is underconstrained (Sereno 2007).

From the lensing analysis, we can measure the four projected parameters of the NFW halo: the lensing normalization \( \kappa_0 \), the projected length-scale \( r_{\text{d}} \), the ellipticity \( \epsilon \) and the orientation \( \theta_\epsilon \). From the analysis of the ICM, we can estimate the size of the gas in the plane of the sky (\( \epsilon_{\text{sys}}^\text{ICM} \)) and along the line of sight (\( \epsilon_{\text{sys}}^\text{ICM} \)). The information on the orientation of the X-ray isophotes in the plane of the sky, \( \epsilon_{\text{sys}}^\text{ICM} \), was exploited as a prior in the WL analysis to better constrain \( \theta_\epsilon \). The estimate for the systematic error \( \delta_{\epsilon_{\text{sys}}}^\text{ICM} \) provides another constraint.

Let us summarize the dependences of each observed quantity. The ellipticity \( \epsilon_{\text{sys}}^\text{ICM} \) and the elongation \( \epsilon_{\text{sys}}^\text{ICM} \) of the gas distributions are functions of \( q_1 \) and \( q_2 \), and of the orientation angles \( \theta_\epsilon \) and \( \varphi \). Because of the imposed equality of triaxiality between the mass and gas distributions, we can express \( q_2 \) in terms of \( q_1 \) and \( q_2 \). The systematic shift \( \Delta \epsilon_{\text{sys}}^\text{ICM} \) is an additional parameter, which will be marginalized over.

The ellipticity \( \epsilon \) of the total matter distribution is a function of \( q_1 \) and \( q_2 \), and of the orientation angles \( \theta_\epsilon \) and \( \varphi \). The orientation angle \( \theta_\epsilon \) also depends on the third Euler angle, \( \psi \). The mass \( M_{\text{vir}} \) and the concentration \( c_{\text{vir}} \) of the total matter halo determine the lensing strength \( \kappa_0 \) and the projected length-scale \( r_{\text{d}} \). Also, \( \kappa_0 \) and \( r_{\text{d}} \) depend on the elongation and, in turn, on \( q_1 \), \( q_2 \), \( \theta_\epsilon \) and \( \varphi \).

Some a priori hypotheses on the cluster shape are needed to disentangle the intrinsic degeneracies. We have applied some Bayesian methods already employed in either GL investigations (Oguri et al. 2005; Corless et al. 2009; Sereno et al. 2010a; Sereno & Umetsu 2011) or X-ray plus SZ analyses (Sereno et al. 2012) and we have extended them for our GL plus X-ray plus SZ analysis.

We have considered two kind of priors for the axial ratio of the matter distributions. The distribution of \( q_1 \) obtained in high-resolution N-body simulations can be approximated as (Jing & Suto 2002)

\[
p(q_1) \propto \exp \left[ -\frac{(q_1 - q_\text{sys}^\text{ICM})^2}{2\sigma_q^2} \right].
\]

Here, \( q_\text{sys} \approx 0.54, \sigma_q = 0.113 \) and

\[
r_{\text{sys}} = \frac{M_{\text{vir}}}{M_{\text{vir}}} \times 0.0152 \omega_{\text{vir}}^{0.3} \rho_{\text{vir}}^{-0.7},
\]

where \( M_{\text{vir}} \) is the characteristic non-linear mass at redshift \( z \) and \( M_{\text{vir}} \) is the virial mass. The conditional probability for \( q_1 \) is

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

for \( q_1-q_2 \geq r_{\text{min}} \equiv \max[q_1, 0.5] \), whereas it is null otherwise.

We have also considered a uniform distribution for the axial ratios in the range \( q_{\text{min}} < q_1 \leq 1 \) and \( q_1 \leq q_2 \leq 1 \). Probabilities are defined such that the marginalized probability \( P(q_1) \) and the conditional probability \( P(q_2 | q_1) \) are constant. The probabilities can then be expressed as

\[
p(q_1) = 1/(1 - q_{\text{min}})
\]

for the full range \( q_{\text{min}} < q_1 \leq 1 \),

\[
p(q_2 | q_1) = (1 - q_1)^{-1}
\]

for \( q_2 \geq q_1 \), and zero otherwise. A flat distribution is also compatible with very triaxial clusters (\( q_1 \approx q_2 \ll 1 \)), which are preferentially excluded by N-body simulations. We have fixed \( q_{\text{min}} = 0.1 \).

For the axial ratio of the gas, we have considered a uniform distribution in the interval \( q_1 \leq q_{\text{sys}}^\text{ICM} \leq 1 \). The prior on \( q_1 \) is then similar to that of \( q_2 \) in the case of the uniform distribution for the matter axial ratios.

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

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

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

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

for \( -\pi/2 \leq \varphi \leq \pi/2 \).

For the remaining parameters, we have employed uniform distributions.

7 RESULTS

The trends and correlations retrieved in a triaxial analysis are predictable based on simple considerations. The efficiency of a halo as a lens is larger, when either the mass or the concentration are larger, all the rest being equal. The strength of a lens also increases with triaxiality and elongation along the line of sight, which boost convergence and cross-section for lensing. A spherical analysis cannot account for orientation and shape effects, so the mass and concentration estimates are systematically biased higher if the halo is oriented along the line of sight. However, a full triaxial analysis is not affected by such bias, and the search for the best values of mass and concentration is not artificially constrained in a biased niche of the parameter space.

The lensing analysis provides a reliable estimate of the projected total mass. The projected ellipticity can be estimated either for the total mass from lensing or the ICM from X-ray maps. Methods
Figure 2. Contour plots of the bi-dimensional marginalized PDFs derived under the prior assumptions of uniform $q$-distribution and random orientation angles. Contours are plotted at fraction values $\exp(-2.3/2)$, $\exp(-6.17/2)$ and $\exp(-11.8/2)$ of the maximum, which denote confidence limit regions of $1\sigma$, $2\sigma$ and $3\sigma$ in a maximum likelihood investigation, respectively. In the $M_{200} - c_{200}$ plane (top-left panel), the thin and thick solid lines are the predictions from Duffy et al. (2008) and Prada et al. (2012), respectively. The dashed and long-dashed lines enclose the $1\sigma$ and $3\sigma$ regions for the predicted conditional probability $c(M)$ relation of Duffy et al. (2008), respectively. In the $q_1 - q_2$ plane, the thick solid, long-dashed and dashed lines limit the $1\sigma$, $2\sigma$ and $3\sigma$ confidence regions for the N-body-like expected distributions.

Mass, concentration and shape and orientation parameters then have to be chosen such that they reproduce the total lensing efficiency measured by GL within the geometrical limits. These limits come from the knowledge of the size of the ICM along the line of sight and in the plane of the sky, as well as from knowledge of the size of the total matter in the plane of the sky.

The resulting counterbalancing effects can be seen in Figs 2 and 3. Lesser values of mass and concentration are compatible with haloes elongated along the line of sight ($\cos \theta \lesssim 1$); that is, elongation supplies the lensing strength lost because of the decline in mass or concentration. Because the size in the plane of the sky is fixed by observations, such an elongation has to be fuelled by a larger degree of triaxiality (lower values of $q_1$). To account for the X-ray plus SZe constraints, the gas also has to be more triaxial (larger values of $e_{\text{ICM}}/e_{\text{Mat}}$).

A full triaxial analysis is required to quantify these trends and correlations. The results of our analysis are summarized in Table 2. They agree with our previous lensing (Sereno & Umetsu 2011) or X-ray plus SZe analysis (Sereno et al. 2012). This is expected because we have used the same data sets and a similar methodology. There are two main improvements: (i) intrinsic halo parameters are derived with a better accuracy; (ii) we rely on a considerably smaller number of hypotheses. In particular, the X-ray plus SZe data give
Figure 3. Contour plots of the bi-dimensional marginalized PDFs derived under the prior assumptions of $N$-body-like axial ratios and random orientation angles. Contours and lines are as in Fig. 2.

Table 2. Intrinsic parameters of the matter distribution inferred assuming different priors on the axial ratios. The reported values are the mean and the variance of the posterior PDF.

| Priors     | $M_{200}$ ($10^{15} M_\odot$) | $c_{200}$ | $q_1$   | $q_2$   | $\cos \vartheta$ |
|------------|-------------------------------|-----------|---------|---------|-----------------|
| Flat       | 1.33 $\pm$ 0.17               | 7.8 $\pm$ 0.7 | 0.72 $\pm$ 0.11 | 0.86 $\pm$ 0.11 | 0.57 $\pm$ 0.29 |
| $N$-body   | 1.34 $\pm$ 0.18               | 7.6 $\pm$ 1.0 | 0.51 $\pm$ 0.07 | 0.69 $\pm$ 0.12 | 0.76 $\pm$ 0.21 |

The results that assume either a flat distribution of axial ratios or inputs from $N$-body simulations are in very good agreement. Because of the information from X-ray plus SZe, which positively constrains the orientation, the alignment of the cluster is clearly seen, whatever the priors.

The posterior distributions were investigated by running four Markov chains and checking for convergence. The marginalized 1D posterior probabilities are plotted in Fig. 4, whereas the bi-dimensional probabilities are represented in Figs 2 and 3. The results for mass and concentration are sensitive to the assumed priors to a very small extent. The multiprobe approach is dominated by the data, and in turn by the likelihood, whereas the priors play a negligible role.
As already mentioned in Section 5, our SL and WL constraints on the projected NFW parameters are marginally consistent, and it makes sense to combine them. We have used the lensing data sets already exploited in previous works (Limousin et al. 2007; Umetsu & Broadhurst 2008; Coe et al. 2010; Umetsu et al. 2011) and we have found consistent results. In particular, we refer to Sereno & Umetsu (2011) for a detailed discussion of the compatibility of WL and SL results for A1689 in a triaxial context. For completeness, here we quote the results for our multiprobe approach that exploits just one lensing data set. Exploiting only the WL, we found $M_{200} = (1.39 \pm 0.32) \times 10^{15} M_\odot$ and $c_{200} = 13.7 \pm 3.9$. SL alone favours less concentrated haloes, $c_{200} = 4.8 \pm 0.8$, whereas the mass is poorly constrained.

7.1 Mass and concentration

The final results on mass and concentration are independent of the assumed priors. A1689 is a very massive cluster with a high concentration. Comparisons with theoretical predictions point to an overconcentrated cluster (see Figs 2, 3 and 4). We have considered the $c(M)$ relation from the analysis of a full sample of clusters performed by Duffy et al. (2008). The estimated concentration is in agreement with the tail at large values of the population of clusters of that given mass. Recently, Prada et al. (2012) have claimed that the $c(M)$ relation features a flattening and upturn with increasing mass with substantially larger estimated concentrations for galaxy clusters. In that case, the agreement with theoretical predictions further improves.

The distribution of the ellipsoidal radius $r_{200}$ can also be derived. We have found $r_{200} = 5060 \pm 290$ kpc $= (2530 \pm 280)$ kpc for a priori $N$-body (uniform) axial ratios. The spherical $r_{200}^{ sph}$, which comprises the same overdensity and mass of the ellipsoidal $r_{200}$, and which can be more useful for comparison with works based on spherical analyses, is $2135 \pm 90$ kpc in both cases.

Concentration and orientation are strongly correlated (see Figs 2 and 3). For $N$-body axial ratios, the concentration corresponding to orientation angles $40 \, \text{deg} \lesssim \theta \lesssim 45 \, \text{deg}$ is $c_{200} = 8.2 \pm 0.4$. For $0 \, \text{deg} \lesssim \theta \lesssim 5 \, \text{deg}$, $c_{200} = 6.2 \pm 0.3$. Even if the a posteriori probability distribution in the full parameter space peaks at lower concentrations and more pronounced alignments with the line of sight, the tail corresponding to larger values of the orientation angle shifts the peak of the marginalized distribution towards larger concentration values.

7.2 Shape and orientation of the matter distribution

We have found evidence for a triaxial matter distribution. This claim comes mainly from the observed ellipticity of the total projected matter. The measured value of $\epsilon$ deviates from the spherical case, $\epsilon = 0$, by $2\sigma$ and $5\sigma$ in the WL or SL analyses, respectively (see Table 1). The case of a prolate/oblate ellipsoid with the symmetry axis along the line of sight is ruled out at the same confidence level.

When assuming an a priori flat distribution, the posterior probability of $q_1$ peaks at $\sim 0.8$ with a tail in correspondence with more triaxial shapes, which brings the mean value at $q_1 \sim 0.7$. The large tail at small values makes the results fully consistent with theoretical predictions. When assuming the prior from $N$-body simulations, the posterior probability of $q_1$ follows the prior, but with a marginal shift towards rounder values and a smaller dispersion.

The intermediate to major axial ratio is less constrained. The prior plays a heavier role for the final distribution of $q_2$, even if values of $q_2 \sim 0.7$–0.9 perform well under different assumptions. Prolate configurations ($q_1 = q_2$) are slightly preferred over oblate configurations ($q_2 = 1$), but triaxial shapes give much better fits than axially symmetric haloes.

The halo turns out to be elongated along the line of sight. Biased orientations are favoured even if, a priori, the orientations were random. The a priori probability of a randomly oriented cluster to have $\theta \lesssim 45$ deg is $\sim 29$ per cent. A posteriori, such a probability is $\sim 75$ (42) per cent assuming $N$-body-like (flat) axial ratios. This result can be obtained only combining the lensing analysis with the information from X-ray and SZ. For their pure lensing analysis, Sereno & Umetsu (2011) had to assume, a priori, a biased orientation to obtain similar results on mass and concentration. Orientations in the plane of the sky or intermediate inclinations are compatible with
This analysis differs from that of Sereno et al. (2012) in the priors used. Sereno et al. (2012) used a flat prior on $q_1^\text{ICM}$, whereas here $q_1^\text{ICM} \geq q_1$, so that a prior $p(q_1^\text{ICM})$ is not flat but peaks at $q_1^\text{ICM} = 1$. Because the analysis is dominated by the likelihood, this brings about only a small difference in the final results.

### 7.3 Shape of the gas distribution

The X-ray plus SZe part of the inversion method directly constrains the size of the gas distribution along the line of sight and in the plane of the sky. The axial ratios for the ICM, $q_1^\text{ICM}$ and $q_2^\text{ICM}$, are determined with a better accuracy than their counterparts for the matter distribution, $q_1$ and $q_2$. The results are summarized in Table 3. Posterior density functions (PDFs) are plotted in Fig. 5. Final results are nearly independent of the priors. The estimate of the elongation $e_\text{ICM}$ for the gas and the exquisite accuracy in the measured ellipticity of the X-ray surface, $e_\text{X}$, drive the final results on orientation. Even if there is some interplay with GL, the ICM shape and cluster orientation are mainly determined by the X-ray plus SZe likelihood. Thus, the results are very similar to those of Sereno et al. (2012). The gas is mildly triaxial, $q_1^\text{ICM} \sim 0.6$–0.8. A tail of the distribution extends to very low values, $q_1^\text{ICM} \lesssim 0.4$, which are associated with very well aligned configurations ($\cos \vartheta \lesssim 1$).

Some trends between gas shape and matter halo parameters can be seen in Fig. 6. For $e_\text{ICM}/e_\text{Mat} \lesssim 1$, the total matter would be forced to follow the gas shape and orientations, which are well determined by the X-ray plus SZe part of the analysis. The matter would then be slightly rounder and very well elongated along the line of sight. As a consequence, concentration and mass would be lower.

We have made the theoretical assumption that the gas is rounder than the matter distribution and data further support this view. The ellipticity of the ICM, $e_\text{ICM} \sim 0.15$, is lower than that of the projected total mass (see Table 1), although not by a large margin. From the 3D analysis, we have found $e_\text{ICM}/e_\text{Mat} \sim 0.95$ (see Table 3). Very low values of $e_\text{ICM}/e_\text{Mat}$ correspond to a nearly spherical gas distribution, which is excluded. However, very high values of $e_\text{ICM}/e_\text{Mat}$ would mean that the gas follows the matter distribution rather than the gravitational potential, and these values are not excluded by the data.

We have found $q_1^\text{ICM} - q_1 = 0.05 \pm 0.04 (= 0.04 \pm 0.04)$, for an $N$-body-like (flat) prior. The probability that the difference $q_1^\text{ICM} - q_1$ is larger than 0.1 is $\sim 15$ (6) per cent for an $N$-body-like (flat) prior.

### 7.4 Comparison with the spherical approach

The deprojection method that we have employed was based on a minimum set of hypotheses. Because we did not assume hydrostatic equilibrium, the analyses of the ICM, based on X-ray and SZe observations, and that of the total mass, relying on lensing, are mostly independent. Their only tie is of a geometrical nature, because we required the ICM to share the same orientation of the total mass, both in the space and in the plane of the sky. This can be seen in equation (12), where the mass and concentration enter the likelihood only through the lensing part, whereas the X-ray and SZe contribution is only related to the ICM shape and, as a consequence, to the orientation of the matter halo. Because the total lensing strength depends on the shape and orientation, the X-ray and SZe can then play a role in the overall properties of the halo.

By assuming a spherical geometry, the ellipticity and elongation of the total and gas mass distribution are fixed ($\epsilon = 0$, $e_A = 1$). Therefore, the likelihood in equation (13) is reduced just to the lensing part, with the ICM that can affect the mass reconstruction from lensing only through the constraints of the halo centroid, because the orientation is no longer a parameter. Under these assumptions, $M_{200} = (1.26 \pm 0.12) \times 10^{15} M_\odot$ and $c_{200} = 7.8 \pm 0.2$. As expected, the central values are compatible with the full triaxial analysis but have associated a statistical error that is small, because it does not include the systematic part resulting from the relaxation of the assumption on the geometrical shape.

The values of $c_{200} \sim 6$, which are fully compatible with the triaxial analysis in the likely case of nearly alignment with the line of sight, are excluded when assuming a spherical shape. As discussed in Section 7, the SL and WL analyses are marginally consistent when assuming a triaxial form. The conflict between the results in the two lensing regimes is further aggravated in the spherical hypothesis.

### 8 HYDROSTATIC EQUILIBRIUM

A significant part of the X-ray analysis relies on the assumption of hydrostatic equilibrium,

$$\nabla P_{\text{tot}} = -\rho_\text{ICM} \nabla \phi_\text{ICM},$$

where $P_{\text{tot}} = P_{\text{th}} + P_{\text{nh}}$ is the total pressure, $\rho_\text{ICM}$ is the gas density and $\phi_\text{ICM}$ is the gravitational potential. When hydrostatic equilibrium holds, the pressure is only thermal, $P_{\text{th}} = k_B T_{\text{ICM}}$ for an ideal gas, where $k_B$ is the Boltzmann constant. If we neglect a non-thermal contribution $P_{\text{nh}}$, such as bulk and/or turbulent motions, this systematically gives a low bias to the X-ray mass determination of the cluster (Meneghetti et al. 2010; Rasia et al. 2012).

The assessment of the level of hydrostatic equilibrium in a cluster can be problematic, and it usually relies on either multiple data sets (Morandi et al. 2012) or numerical simulations (Molnar et al. 2010). Because we have determined the mass and shape of A1689 without relying on any assumption on the status of the cluster, we can check if and how A1689 departs from hydrostatic equilibrium.

First, we know that gas in equilibrium follows the gravitational potential of the halo. In that case, gas and matter eccentricities are related and $e_\text{ICM}/e_\text{Mat} \sim 0.7$ (Lee & Suto 2003). This prediction can be compared with our results (see Fig. 5 and Table 3). We have found that the gas distribution is more triaxial than the shapes expected under the assumption of complete hydrostatic equilibrium.

The distribution of $e_\text{ICM}/e_\text{Mat}$ peaks at $\lesssim 1$, and significance at 0.7 is very low. The chance of having $e_\text{ICM}/e_\text{Mat} \lesssim 0.8$ is of the order of $\lesssim 1$ per cent. We can conclude from this first test that the shapes of gas and matter are only marginally compatible with the hypothesis.
of hydrostatic equilibrium, the gas being decisively more triaxial than expected. Radiative processes can make the gas more triaxial in the central regions (Lau et al. 2011), which would explain the high degree of gas triaxiality found in A1689.

As a second test, we have checked whether the hydrostatic equilibrium condition expressed in equation (21) is fulfilled. To this aim, we have recomputed the posteriori probabilities for the cluster parameters under the sharp prior of $e^{ICM}/e^{Mat} = 0.7$. We have exploited N-body-like priors for the axial ratios. The gravitational potential of the ellipsoidal NFW halo was computed using the approximated formulae of Lee & Suto (2003). The final result is summarized in Fig. 7, which was obtained by assuming that the gas follows the potential. Thermal pressure is systematically lower than necessary. Hydrostatic equilibrium is compatible with our results at the 3σ confidence level. The non-thermal contribution to the total pressure required for equilibrium (i.e. the value of $P_{Tot}$ solving equation 21) is of the order of 20–30 per cent in the outer regions at $\zeta \simeq 1.4$ Mpc, and even higher towards the centre ($\sim 20$–50 per cent).

High-resolution cosmological simulations have shown that there is a significant contribution from non-thermal pressure in the core region of relaxed clusters (Lau, Kravtsov & Nagai 2009; Molnar et al. 2010). From 10 simulated massive relaxed clusters, Molnar et al. (2010) have found that non-thermal pressure support from subsonic random gas motions can contribute up to 40 per cent in the inner regions and up to 20 per cent within one-tenth of the virial radius. They have also found that the non-thermal contribution increases with radius in the very outer regions. Lau et al. (2009) have found a similar level of non-thermal pressure of the order of 5–15 per cent at about one-tenth of the virial radius, also increasing with radius in the outer regions. These trends are retrieved in Fig. 7, although we should caution that the XMM spectroscopic data cover...
the cluster up to $\lesssim 900 \text{kpc}$ so that the decrement at large radii is an extrapolation of fitted profiles.

9 COMPARISON WITH PREVIOUS ANALYSES

Our multiprobe analysis of A1689, combining a data set spanning from X-ray to lensing to SZe data, can be compared to some recent works. Ettori et al. (2010) have performed an X-ray analysis and have recovered the profiles of gas and dark mass in A1689 under the assumption that hydrostatic equilibrium holds between the ICM and the gravitational potential. Although Ettori et al. (2010) have used different techniques from ours, they have still assumed a NFW functional form for the dark matter distribution and they have based their analysis on XMM data. So, their results are comparable to ours, and any discrepancy should be interpreted in terms of either triaxiality and orientation issues reducing the X-ray mass to be, as a result of the level of non-thermal pressure.

The multiprobe approach to galaxy clusters can efficiently tackle one of the classical problems in astronomy, the determination of mass. An unbiased estimate requires, at the same time, knowledge of the shape and the orientation of the halo, of the concentration and of the equilibrium status of the gas. This complete picture can be achieved with an analysis exploiting GL, which describes the total pressure required to balance the gravity predicted by GL under the hypothesis of spherical symmetry.

Our derived ratio of thermal to total pressure as a function of radius agrees with Molnar et al. (2010), who assumed spherical symmetry and used Chandra data for the temperature profile. The Chandra data are larger by 10–20 per cent than the XMM measurements considered here and, consequently, might overestimate the thermal contribution. Molnar et al. (2010) found $P_{\text{th}}/P_{\text{Tot}} \simeq 0.6$ within the core region.

10 CONCLUSIONS

The multiprobe approach to galaxy clusters can efficiently tackle one of the classical problems in astronomy, the determination of mass. An unbiased estimate requires, at the same time, knowledge of the shape and the orientation of the halo, of the concentration and of the equilibrium status of the gas. This complete picture can be achieved with an analysis exploiting GL, which describes the total mass, and X-ray and SZe observations, which directly constrain the gas.

We have proposed a novel method based on minimal geometrical principles. We have only assumed that the gas and the total matter distributions are approximately ellipsoidal and co-aligned. The matter and the ICM were separately modelled with parametric profiles, suitable for comparison with numerical simulations and theoretical predictions. We did not assume any hypothesis on the equilibrium status of the gas or the profile of non-thermal pressure.

In this regard, our method is different from other recently proposed multiprobe approaches (Morandi et al. 2011, 2012).
We have obtained pixellated maps of the projected mass density covering a large radial range by combining SL in the inner core and WL in the outer regions. The maps were then fitted with a NFW profile. Photometric and spectroscopic X-ray data, as well as the SZ temperature decrement, were described with a single parametrization for the gas density and temperature profile. The combined X-ray plus SZ analysis enabled us to determine the elongation of the gas along the line of sight, which is the only geometrical quantity not defined in the plane of the sky that can be directly derived from the combined analysis of projected maps (Sereno 2007) and which is crucial information to constrain gas shape and orientation. All pieces of information were finally combined in a single Bayesian statistical analysis to infer the intrinsic parameters of the halo.

The method was applied to A1689. We have proposed the first multiprobe analysis of A1689, combining a data set spanning from X-ray to lensing to SZe data. We can obtain an unbiased picture of the cluster. A1689 is massive, $M_{200} = (0.9 \pm 0.1) \times 10^{15} M_{\odot} h^{-1}$, and slightly overconcentrated, $c_{200} \approx 8 \pm 1$. The halo is triaxial $(q_t \approx 0.5 \pm 0.1)$ and aligned with the line of sight. The high degree of triaxiality $(q_t^{\text{ICM}} \sim 0.6-0.8)$ of the gas distribution shows a deviation from hydrostatic equilibrium, which would prefer rounder gas shapes. A significant contribution of non-thermal pressure is required for equilibrium, $\sim 20-50\text{ per cent in the centre and } \sim 20-30\text{ per cent in the outer regions}$. This level of non-thermal pressure support is consistent with that found by Molnar et al. (2010) using a sample of massive relaxed clusters drawn from high-resolution cosmological simulations. It is also consistent with recent findings in MS2137.3–2353 by Chiu & Molnar (2012), who found a 40–50 per cent contribution in the core when assuming a spherical model.

The measurement of non-thermal pressure requires an unbiased knowledge of the cluster shape. Chiu & Molnar (2012) have found that the effect of the alignment of the major axis with the line of sight is to decrease the non-thermal pressure support required for equilibrium at all radii, without changing the distribution qualitatively. Different counterbalancing factors can play a role in the determination of the cluster mass with X-ray methods, $M_{\text{X}}$. Under the hypothesis of hydrostatic equilibrium, neglecting non-thermal processes, $M_{\text{X}}$ is usually biased low by $\sim 20-30\text{ per cent}$ (Rasia et al. 2012). Non-thermal pressure would then make the lensing signal greater than expected, given the X-ray derived mass.

However, if a cluster aligned with the line of sight is considered to be spherical, $M_{\text{X}}$ is biased high by $\lesssim 5-10\text{ per cent}$ (Gavazzi 2005). The effect of the elongation on lensing is even more influential, because the central projected mass density of the lens is directly proportional to the extension of the halo along the line of sight.

In this regard, our method seems to be particularly promising. Shape and inclination are measured and the orientation bias is over-come. The condition for hydrostatic equilibrium is not used to derive the mass and it can be employed to determine the non-thermal contribution to the pressure. Degeneracies are broken because of the joint multiwavelength data sets that give a reliable picture of the cluster status and properties.

The assessment of the overconcentration depends on the real presence of an upturn in the mass–concentration relation for high-mass and redshift clusters (Prada et al. 2012). Massive systems are likely to be identified when they are substantially out of equilibrium and in a transient stage of high concentration (Ludlow et al. 2012). The upturn should disappear when only dynamically relaxed systems are considered. Our results seem to support this picture. A1689 is massive and still not settled in hydrostatic equilibrium, which propounds a high value of concentration, as observed.

ACKNOWLEDGMENTS
The authors thank M. Limousin for providing some results of the SL analysis in Limousin et al. (2007).

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