RECONSTRUCTING THE TRIAXIALITY OF THE GALAXY CLUSTER A1689: SOLVING THE X-RAY AND STRONG LENSING MASS DISCREPANCY

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ABSTRACT

We present the first determination of the intrinsic triaxial shapes and three-dimensional physical parameters of both dark matter (DM) and the intracluster medium for the galaxy cluster A1689. We exploit the novel method we recently introduced in order to infer the three-dimensional physical properties in triaxial galaxy clusters by combining jointly X-ray and strong lensing data. We find that A1689 can be modeled as a triaxial galaxy cluster with DM halo axial ratios $1.24 \pm 0.13$ and $2.37 \pm 0.11$ on the plane of the sky and along the line of sight, respectively. We show that accounting for the three-dimensional geometry allows us to solve the discrepancy between the mass determined from X-ray and strong gravitational lensing observations. We also determined the inner slope of the DM density profile $n$; we measure $n = 0.90 \pm 0.05$ by explicitly accounting for the three-dimensional structure for this cluster, a value which is close to the cold dark matter (CDM) predictions, while the standard spherical modeling leads to the biased value $n = 1.16 \pm 0.04$. Our findings dispel the potential inconsistencies that arise in the literature between the predictions of the CDM scenario and the observations, providing further evidences that support the CDM scenario.

Key words: cosmology; observations -- galaxies: clusters: general -- galaxies: clusters: individual (A1689) -- gravitational lensing: strong -- gravitational lensing: weak -- X-rays: galaxies: clusters

1. INTRODUCTION

A1689 is a massive cluster with a redshift of $z = 0.183$ and with the largest Einstein radius, around 45 arcsec for $z_t = 1$, observed to date (Broadhurst et al. 2005; Limousin et al. 2007). It has been proposed as a standard example of a relaxed object in hydrostatic equilibrium (Xue & Wu 2002; Lemze et al. 2010), but the mass derived from the X-ray measurement is twice as small as that found from strong gravitational lensing at most observations (Broadhurst et al. 2005; Limousin et al. 2007).

For the SL analysis we refer to the findings of Limousin et al. (2007), who presented a reconstruction of the mass distribution of the galaxy cluster A1689 using detected SL imaged systems, and they inferred two large-scale dark matter (DM) clumps, one associated with the center of the cluster and the other with a northeastern substructure. We masked out the northeastern sector of both the two-dimensional projected mass map and the X-ray data in order to avoid the contribution from this secondary substructure. We also masked out the central 30 kpc, which is affected by the mass distribution of the cD galaxy. From the lensing analysis, the major clump of the cluster looks elongated with a minor--major axial ratio on the plane of the sky of $1.24 \pm 0.13$ and a position angle of $0.4 \pm 1.0$. The two-dimensional projected mass map has been rebinned into elliptical annuli, whose eccentricity, centroid, and position...
angle are the same as those inferred from Limousin et al. (2007). Then we calculated average values of the elliptical symmetric projected mass profile \( k(R) \), \( R \) being the minor radius of the twodimensional elliptical annuli, once we masked out the central 30 kpc, which is affected by the mass distribution of the cD galaxy. We also calculated the covariance matrix \( C \) among all the measurements of \( k(R) \).

### 2.2. X-ray Data Reduction

For the X-ray analysis, we take advantage of the two Chandra X-ray observations (observation IDs 6930 and 7289) from the NASA HEASARC archive with a total exposure time of approximately 150 ks. We summarize here the most relevant aspects of the X-ray data reduction procedure for A1689. The observations were carried out using the ACIS-I CCD imaging spectrometer. We reduced these observations using the CIAO software (version 4.1.2) distributed by the Chandra X-ray Observatory Center by considering the gain file provided within CALDB (version 4.1.3) for the data in VFAINT mode. Then, we filtered the data to include the standard event grades 0, 2, 3, 4, and 6 only, and therefore we filtered for the good time intervals supplied, which are contained in the \( \text{f}	ext{lt1}.\text{fits} \) file. We checked for unusual background rates through the \( \text{l}	ext{c}_{\text{sigma}}\text{clip} \), so we removed those points falling outside \( \pm 3\sigma \) from the mean value. Finally, we filtered ACIS event files on energy, selecting the range 300–9500 keV, and on CCDs, so as to obtain an event 2 file.

### 2.3. X-ray Spatial and Spectral Analysis

We outline the methodology of spatial and spectral analysis in triaxial galaxy clusters. The general idea is to measure the gas density profile in a non-parametric way from the surface brightness recovered by a spatial analysis and to infer the observed projected temperature profile by spectral analysis. The images have been extracted from the event 2 files in the energy range 0.5–5.0 keV, corrected by the exposure map to remove the vignetting effects, by masking out the point sources. We constructed a set of \( n \) (\( n = 57 \)) elliptical annuli of minor radius \( r_m \) around the centroid of the surface brightness with eccentricity \( e_p(r) \) fixed to that predicted from the eccentricity \( e_p(r) \) of the DM halo on the plane of the sky from SL data (see Section 2.4). The minor radius of each annulus has been selected out to a maximum distance \( R_{\text{pat}} = 1139 \text{kpc} \), selecting the minor radii according to the following criteria: the number of net counts of photons from the source in the 0.5–5.0 keV band is at least 200–1000 per annulus and the signal-to-noise ratio is always larger than 2. The background counts have been estimated from regions of the same exposure that are free from source emissions.

The spectral analysis has been performed by extracting the source spectra from \( n^* \) (\( n^* = 9 \)) elliptical annuli of minor radius \( r_m \) around the centroid of the surface brightness and with eccentricity equal to that predicted from the eccentricity \( e_p(r) \) of the DM halo from SL data (see above). We have selected the minor radius of each annulus out to a maximum distance \( R_{\text{spec}} = 1089 \text{kpc} \), according to the following criteria: the number of net counts of photons from the source in the band used for the spectral analysis is at least 2000 per annulus and corresponds to a fraction of the total counts always larger than 30%.

All the point sources have been masked out by both visual inspection and the tool \text{celldetect}, which provide candidate point sources. Then we calculated the redistribution matrix files (RMF) and the ancillary response files (ARF) for each annulus.

For each of the \( n^* \) annuli, the spectra have been analyzed by using the XSPEC (Arnaud 1996; version 11.3.2) package, by simultaneously fitting absorbed MEKAL models multiplied by a positive absorption edge as described in Vikhlinin et al. (2005) to the two observations. The fit is performed in the energy range 0.6–7 keV (0.9–7 keV for the outermost annulus only) by fixing the redshift at \( z = 0.183 \), and the photoelectric absorption at the galactic value. We consider three free parameters in the spectral analysis for the \( i \)th annulus: the normalization of the thermal spectrum \( k_i \), the emission-weighted temperature \( T_i \), and the metallicity \( Z_i \) retrieved by employing the solar abundance ratios from Grevesse & Sauval (1998). Background spectra have been extracted from regions of the same exposure that are free from source emissions.

At last we recover the electron density \( n_e = n_e(r; \epsilon_c) \) both by deprojecting the surface brightness profile and the spatially resolved spectral analysis obtaining a few tens (\( n = 57 \)) of radial measurements in ellipsoidal shells. Note the dependency of \( n_e(r; \epsilon_c) \) on the eccentricity \( \epsilon_c \) of the ICM along the line of sight to be determined (for further details, see Appendix A of Morandi et al. 2010).

The global (cooling-core corrected) temperature \( T_{\text{ew}} \) has been estimated to be \( T_{\text{ew}} = 8.64_{-0.12}^{+0.13} \text{keV} \), with an abundance of \( 0.41 \pm 0.03 \) solar value. We classify this cluster as an intermediate cooling core source (Morandi & Ettori 2007): we estimated \( t_{\text{cool}} \approx 3 \times 10^9 \text{yr} \). The temperature profile is very regular once we masked out the northeastern quadrant, suggesting a relaxed dynamical state (see the upper panel of Figure 1).
2.4. Joint X-ray+Lensing Analysis: Measuring the Triaxial Physical Properties of ICM and DM

Here we briefly summarize the major findings of Morandi et al. (2010) for the joint X-ray+lensing analysis in order to infer triaxial physical properties: for further details, we refer to Morandi et al. (2007, 2010).

The lensing and the X-ray emission both depend on the properties of the DM gravitational potential well, the former being a direct probe of the two-dimensional mass profile and the latter an indirect proxy of the three-dimensional mass profile through the hydrostatic equilibrium equation applied to the gas temperature and density. In order to infer the model parameters of both the ICM and the underlying DM density profile, we perform a joint analysis of SL and X-ray data. We briefly outline the methodology used to infer physical properties in triaxial galaxy clusters: (1) we start with a generalized Navarro, Frenk, and White (gNFW) triaxial model of the DM as described in Jing & Suto (2002), which is representative of the total underlying mass distribution and depends on a few parameters to be determined, namely the concentration parameter c, the scale radius $r_s$, and the inner slope of the DM $\alpha$; (2) following Lee & Suto (2003, 2004), we recover the gravitational potential and surface mass profile $k$ of a dark halo with such triaxial density profile; (3) we solve the hydrostatic equilibrium equation for the density of the ICM sitting in the gravitational potential well previously calculated, in order to infer a theoretical three-dimensional temperature profile $T_{\text{gas}}$ in a non-parametric way; and (4) the joint comparison of $T_{\text{gas}}$ with the observed temperature and of $k$ with the observed surface mass gives us the parameters of the triaxial DM density model, and therefore all the desired physical properties of ICM and DM triaxial ellipsoids (see Figure 1).

The work of Lee & Suto (2003) showed that the ICM and DM halos are well approximated by a sequence of concentric triaxial distributions with different eccentricity ratio. We define $e_p$ ($e_p^*$) and $e_c$ ($e_c^*$) as the eccentricity of DM (ICM) on the plane of the sky and along the line of sight, respectively. The iso-potential surfaces of the triaxial dark halo also coincide with the iso-density (pressure, temperature) surfaces of the intracluster gas. Note that $e_p = e_p^*(e_p, u, \alpha)$ and $e_c = e_c^*(e_c, u, \alpha)$, with $u \equiv r/r_s$, unlike the constant $e_p, e_c$ for the adopted DM halo profile. In the entire range of $u$, $e_p/e_c$ is less than unity ($e_p/e_c \sim 0.7$ at the center), i.e., the intracluster gas is altogether more spherical than the underlying DM halo.

In order to infer the model parameters, we construct the likelihood, by performing a joint analysis for SL and X-ray data, to constrain the properties of the model parameters $q$ of both the ICM and the underlying gNFW triaxial model of the DM, with

$$q = (c, r_s, \alpha, e_c)$$

representing the concentration parameter, scale radius, inner slope of the DM, and eccentricity of the DM along the line of sight, respectively.

The method works by constructing a joint X-ray+lensing likelihood

$$\mathcal{L} = \mathcal{L}_x \cdot \mathcal{L}_{\text{lens}},$$

$\mathcal{L}_x$ and $\mathcal{L}_{\text{lens}}$ being the likelihoods coming from the X-ray and SL data, respectively.

For $\mathcal{L}_x$, $\chi^2$ is equal to

$$\chi^2_x = \sum_{i=1}^{n} \frac{(T_{\text{proj},i}(q) - T_{\text{proj},i}^{\ast})^2}{\sigma_{T_{\text{proj},i}}^2},$$

$T_{\text{proj},i}$ being the observed projected temperature profile in the $i$th ring and $T_{\text{proj},i}^{\ast}$ the convenient projection (following Mazzotta et al. 2004) of the theoretical three-dimensional temperature $T(q)$ recovered by solving the hydrostatic equilibrium equation, once we inferred the gas density $n_e(r; e_c)$ from the brightness and we assume a gNFW parameterization for the DM $\rho_{\text{DM}} = \rho_{\text{DM}}(r, q)$. $\mathcal{L}_{\text{lens}}$ reads

$$\mathcal{L}_{\text{lens}} = \exp\left[-\frac{1}{2}(k(q) - k^*)^2|C^{-1}[(k(q) - k^*)]|\right],$$

where $C$ is the covariance matrix referring to the projected mass profile from lensing data including systematic effects (see below), $|C|$ indicates the determinant of $C$, $k^* = (k_1^*, k_2^*, \ldots, k^*_m)$ are the observed measurements of the projected mass profile in the $m^*$ elliptical annuli, and $k(q)$ is the theoretical projected mass profile retrieved by our triaxial DM model.

For the covariance matrix $C$, the following expression holds:

$$C = C' + \sigma_{\text{sys}}^2 I.$$

Here, $C'$ is the covariance matrix among the lensing measurements, $I$ is the identity matrix, and $\sigma_{\text{sys}}$ is a bias parameter estimator arising from measurements of systematics involved in the SL analysis. In order to calculate $\sigma_{\text{sys}}$, we assumed that systematic errors can be described as Gaussian errors via a diagonal matrix $\sigma_{\text{sys}}^2 I$ with the same value in each of the diagonal elements. We checked that this simplified assumption does not significantly affect the average value of the physical parameters, while it slightly increases (10%–20%) their errors.

We marginalized over $(q, \sigma_{\text{sys}})$ and therefore we have $\mathcal{L} = \mathcal{L}(q, \sigma_{\text{sys}})$. So, we can determine the physical parameter of the cluster, for example, the three-dimensional temperature $T_j = T_j(q)$ in the $j$th shell and the elongation $e_c(e_c)$ of the ICM(DM) along the line of sight, just by relying on the hydrostatic equilibrium equation and on robust results of the hydrodynamical simulations of the DM profiles. In Figure 1, we present an example of a joint analysis for A1689: note that in the joint analysis both X-ray and lensing data are very well fitted by our model, with a total $\chi^2_{\text{tot}} = \chi^2_x + \chi^2_{\text{lens}} = 7.4$ (11 degrees of freedom), $\chi^2_x = 5.5$ (five degrees of freedom), and $\chi^2_{\text{lens}} = 1.9$ (two degrees of freedom), with $\chi^2_{\text{lens}} \propto -2\log(\mathcal{L}_{\text{lens}})$.

3. RESULTS

In Table 1, we present the best-fit model parameters for our analysis of A1689. In Figure 2, we present an image of the core of A1689 from optical (Hubble Space Telescope) observations, with projected total mass contours computed from the gravitational lensing analysis (blue line) and from the X-ray surface brightness (green line) overplotted. Our findings outline a picture where A1689 is a triaxial galaxy cluster with DM halo axial ratios $\eta_{\text{DM},br} = 1.24 \pm 0.13$ and $\eta_{\text{DM},ec} = 2.37 \pm 0.11$, where $\eta_{\text{DM},br}$ is the axial ratio of the DM on the plane of the sky inferred from lensing measurements and $\eta_{\text{DM},ec}$ is the axial ratio of the DM along the line of sight inferred through our joint analysis (see Table 1). Note that these elongations are statistically significant, i.e., it is possible to disprove the spherical geometry assumption.

The axial ratio of the gas is $\eta_{\text{gas},br} \sim 1.1–1.06$ (on the plane of the sky) and $\eta_{\text{gas},ec} \sim 1.6–1.3$ (along the line of sight), moving from the center toward the X-ray boundary.
Here we focus on the implications of our method on the CDM scenario and on the discrepancy between X-ray and lensing masses on A1689, showing that this is dispelled if we explicitly account for a three-dimensional geometry.

### 3.1. Probing the CDM Scenario

Measuring the three-dimensional mass distribution on galaxy cluster scales is a crucial test of the CDM scenario for structure formation models, providing constraints on the nature of DM. Recent works investigating mass distributions of individual galaxy clusters (e.g., A1689) based on gravitational lensing analysis have shown potential inconsistencies between the predictions of the CDM scenario relating halo mass to concentration parameter, and the relationships as measured in massive clusters.

For example, Broadhurst & Barkana (2008) using the distribution of halo profiles from Neto et al. (2007) found that the predicted Einstein radii under the assumption of spherical geometry are a factor of two below the observed Einstein radii of four massive clusters with spectacular Einstein rings (among them A1689). Relatively high concentration parameters of ~8–14 are derived from lensing analysis of A1689 (Broadhurst et al. 2005; Limousin et al. 2007). These values are larger than the concentration parameter expected based on simulations of the standard CDM model (c ~ 4; Neto et al. 2007). Given that the predicted mass profile is too shallow compared with the observed ones, the question arises whether the projected critical surface density for lensing can be exceeded within a substantial radius for this model.

However, we emphasize that the previous analyses employ standard spherical modeling of the DM halo, while numerical simulations predict that DM halos show axis ratios typically of the order of ~0.7 (Shaw et al. 2006), disproving the spherical geometry assumption. Morandi et al. (2010) demonstrated that the halo triaxiality can cause a significant bias in estimating the desired physical parameters—i.e., concentration parameter c, inner slope of the DM α, and total mass—if a spherical halo model is a priori assumed for the model fitting. As a consequence, the projected mass distributions of the clusters have a larger concentration parameter and inner slope of the DM compared with typical clusters with similar redshifts and masses.

In light of the previous considerations, we evaluated the Einstein radius for A1689 via our triaxial joint X-ray+SL analysis. The Einstein radius θ_E occurs at a projected radius where the mean enclosed convergence is equal to 1. Our triaxial joint X-ray+SL analysis predicts θ_E = 42.7 ± 3.1 arcsec for z_c = 1, which is in agreement with the observed value of 45 arcsec (Broadhurst et al. 2005; Limousin et al. 2007; Richard et al. 2010). We conclude that the large Einstein radius observed in A1689 is not in conflict with CDM predictions, as long as the triaxiality of the DM halos is taken into account. With this perspective, we also find that the minor–major principal axis ratio η_{DM,c} = 2.37 ± 0.11 is consistent with the results from numerical simulations within ~2.5 σ (Shaw et al. 2006).

Then, we focus on the determination of the other parameters of the DM halos, namely the concentration parameter and the inner slope of the DM. With this perspective, one of the main results of the presented work is the measurement of a central slope of the DM α = 0.90 ± 0.05 by explicitly accounting for the three-dimensional structure for A1689. This value is close to the CDM predictions of Navarro et al. (1997; i.e., α = 1), but it is in even better agreement with the more recent numerical simulations of Merritt et al. (2006), which predict a slightly shallower inner slope. The value of the concentration parameter is 4.58 ± 0.34, in agreement with the theoretical expectation from hydrodynamical simulations of Neto et al. (2007), where c ~ 4 for a cluster with the virial mass and at the redshift of A1689, and with an intrinsic scatter of ~20%. This lends support to our insights about the role of the effects of geometry on the physical properties and allows to solve the arisen potential inconsistencies between the predictions of the CDM scenario and the measurements in massive clusters.

If we carry out a standard spherical modeling, we obtain the biased value α = 1.16 ± 0.04 for an X-ray-only analysis, which is larger than that in Table 1. The different values of α in the triaxial and spherical case shows that the systematics involved in neglecting elongation/flattening of the sources along the line of sight are relevant: this likely explains the large scatter of α found in the literature (Ettori et al. 2002; Gavazzi 2005; Sand et al. 2008; Bradač et al. 2008; Limousin et al. 2008; Biviano & Salucci 2006).

### Table 1

| c    | r_e | α   | η_{DM,c} | σ_{sys} | M_{200} | R_{200} | θ_E(c_s = 1) |
|------|-----|-----|----------|---------|---------|---------|--------------|
| 4.58 ± 0.34 | 445 ± 35 | 0.90 ± 0.05 | 2.37 ± 0.11 | 0.004 ± 0.002 | 8.58 ± 0.23 | 556 ± 12 | 42.7 ± 3.1 |

**Notes.** Columns 1–5 refer to the best-fit parameters c, r_e, α, η_{DM,c}, and σ_{sys}, while the last three columns refer to the mass and radius at Δ = 2500, respectively, and to the Einstein radius.

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**Figure 2.** Optical image of the core of A1689 from the NASA/ESA Hubble Space Telescope, with the overplotted projected total mass contours computed from the gravitational lensing analysis (blue line) and from the X-ray surface brightness (green line). The northeastern sector has been masked out in our joint SL+X-ray analysis.
3.2. Resolving the Discrepancy between X-ray and Strong Lensing Masses

Here we briefly summarize the major findings in the literature for A1689 in order to study the discrepancy between the mass determined from X-ray and gravitational lensing observations.

A recent joint Chandra, HST/ACS, and Subaru/Suprime-Cam analysis by Lemze et al. (2008) suggested that the temperature of A1689 could be as high as $T = 18$ keV at 100 $h^{-1}$ kpc, almost twice as large as the observed value at that radius. The derived three-dimensional temperature profile was based on the X-ray surface brightness, the lensing shear, and the assumption of hydrostatic equilibrium. From the disagreement between the observed X-ray temperature and the deduced one, they concluded that denser, colder, and more luminous small-scale structures could bias the X-ray temperature. Nevertheless, Peng et al. (2009) proved that if the temperature profile of the ambient cluster gas is in fact that of Lemze et al. (2008), the cool clumps would have to occupy 70%-90% of the space within a 250 kpc radius, assuming that the two temperature phases are in pressure equilibrium. They conclude that the scenario proposed by Lemze et al. (2008) is unlikely.

Since lensing is sensitive to the integrated mass contrast along the line of sight, either fortuitous alignments with mass concentrations that are not physically related to the galaxy cluster or departures of the DM halo from spherical symmetry can justify the discrepancy in the literature between cluster masses determined from X-ray and strong gravitational lensing observations, the latter being significantly higher than the former (Gavazzi 2005).

Lokas et al. (2006) pointed out that A1689 has a complex structure in velocity space, suggesting the presence of dynamically independent structures along the line of sight, which would affect lensing mass estimates, but Lemze et al. (2009) disagree with this projection view and argued that there is no evidence for such substructure in their velocity data. They conclude that there is only one identifiable substructure at +3000 km s$^{-1}$, 1.50 arcmin to the NE, which is seen in the SL mass analysis but is determined not to be massive (less than 10% of the total mass in the SL region). Nonetheless, the higher than usual velocity dispersion in the cluster center, $\sim$2100 km s$^{-1}$, indicates that the central part is quite complex (Czoske 2004). This may also imply that the halo is elongated in the line-of-sight direction, as galaxies move faster along the major axis.

When it comes to a “superlens” clusters as A1689, halo sphericity is never a justified assumption. Indeed, Oguri & Blandford (2009) showed that SL clusters with the largest Einstein radii constitute a highly biased population with major axes preferentially aligned with the line of sight increasing the dispersion in the cluster center, $\sim$2100 km s$^{-1}$, indicates that the central part is quite complex (Czoske 2004). This may also imply that the halo is elongated in the line-of-sight direction, as galaxies move faster along the major axis.

In this paper, we have employed a triaxial halo model for the galaxy cluster A1689 to extract more reliable information on the three-dimensional shape and physical parameters, by combining X-ray and SL measurements.

We demonstrated that the halo triaxiality can cause a significant bias in estimating the desired physical parameters, i.e., concentration parameter $c$, inner slope of the DM $\alpha$, and total mass, if a spherical halo model is a priori assumed for the model fitting.

We focused on the implications of our method on the CDM scenario, proving that the values of $c$ and $\alpha$ are in agreement with the CDM predictions, once we properly accounted for the three-dimensional shape of the cluster. Departures of $c$ and $\alpha$ from the theoretical expectation of the CDM scenario found in the literature can be explained by a halos having the major axis preferentially oriented toward the line of sight. In particular, accounting for the three-dimensional geometry allows us to resolve the long-standing discrepancy between X-ray and SL mass of A1689 in the literature and predicts an Einstein radius in agreement with the observations.

4. SUMMARY AND CONCLUSIONS

In this paper, we have employed a triaxial halo model for the galaxy cluster A1689 to extract more reliable information on the three-dimensional shape and physical parameters, by combining X-ray and SL measurements.

We demonstrated that the halo triaxiality can cause a significant bias in estimating the desired physical parameters, i.e., concentration parameter $c$, inner slope of the DM $\alpha$, and total mass, if a spherical halo model is a priori assumed for the model fitting.

We focused on the implications of our method on the CDM scenario, proving that the values of $c$ and $\alpha$ are in agreement with the CDM predictions, once we properly accounted for the three-dimensional shape of the cluster. Departures of $c$ and $\alpha$ from the theoretical expectation of the CDM scenario found in the literature can be explained by a halos having the major axis preferentially oriented toward the line of sight. In particular, accounting for the three-dimensional geometry allows us to resolve the long-standing discrepancy between X-ray and SL mass of A1689 in the literature and predicts an Einstein radius in agreement with the observations.

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