Triaxiality, principal axis orientation and non-thermal pressure in Abell 383

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\begin{abstract}
While clusters of galaxies are regarded as one of the most important cosmological probes, the conventional spherical modelling of the intracluster medium and the dark matter (DM), and the assumption of strict hydrostatic equilibrium (i.e. the equilibrium gas pressure is provided entirely by thermal pressure) are very approximate at best. Extending our previous works, we developed further a method to reconstruct for the first time the full 3D structure (triaxial shape and principal-axis orientation) of both DM and intracluster (IC) gas, and the level of non-thermal pressure of the IC gas. We outline an application of our method to the galaxy cluster Abell 383, taken as part of the Cluster Lensing and Supernova Survey with Hubble (CLASH) multicycle treasury programme, presenting results of a joint analysis of X-ray and strong lensing measurements. We find that the intermediate–major and minor–major axis ratios of the DM are $0.71 \pm 0.10$ and $0.55 \pm 0.06$, respectively, and the major axis of the DM halo is inclined with respect to the line of sight of $21.1 \pm 10.1$. The level of non-thermal pressure has been evaluated to be about 10 per cent of the total energy budget. We discuss the implications of our method for the viability of the cold dark matter (CDM) scenario, focusing on the concentration parameter $C$ and the inner slope of the DM, $\gamma$, since the cuspiness of DM density profiles in the central regions is one of the critical tests of the CDM paradigm for structure formation: we measure $\gamma = 1.02 \pm 0.06$ on scales down to 25 Kpc, and $C = 4.76 \pm 0.51$, values which are close to the predictions of the standard model, and providing further evidences that support the CDM scenario. Our method allows us to recover the 3D physical properties of clusters in a bias-free way, overcoming the limitations of the standard spherical modelling and enhancing the use of clusters as more precise cosmological probes.

\textbf{Key words:} gravitational lensing: strong – galaxies: clusters: general – galaxies: clusters: individual: Abell 383 – cosmology: observations – X-rays: galaxies: clusters.
\end{abstract}

1 INTRODUCTION

Clusters of galaxies represent the largest virialized structures in the present Universe, formed at relatively late times and arisen in the hierarchical structure formation of the Universe. As such, their mass function sensitively depends on the evolution of the large-scale structure and on the basic cosmological parameters, providing unique and independent tests of any viable cosmology and structure formation scenario.

Clusters are also an optimal place to test the predictions of cosmological simulations regarding the mass profile of dark haloes. A fundamental prediction of $N$-body simulations is that the logarithmic slope of the dark matter (DM) $\gamma$ asymptotes to a shallow power-law trend with $\gamma = 1$ (Navarro, Frenk & White 1996), steepening at increasing radii. Furthermore, the degree of mass concentration should decline with increasing cluster mass because clusters that are more massive collapse later, when the cosmological background density is lower (e.g. Bullock et al. 2001; Neto et al. 2007). Measurements of the concentration parameters and inner slope of the DM in clusters can cast light on the viability of the cold dark matter (CDM) scenario, focusing on the concentration parameter $C$ and the inner slope of the DM, $\gamma$, since the cuspiness of DM density profiles in the central regions is one of the critical tests of the CDM paradigm for structure formation: we measure $\gamma = 1.02 \pm 0.06$ on scales down to 25 Kpc, and $C = 4.76 \pm 0.51$, values which are close to the predictions of the standard model, and providing further evidences that support the CDM scenario. With this respect, recent works investigating mass distributions of individual galaxy clusters (e.g. Abell 1689) based on gravitational lensing analysis have shown potential inconsistencies between the predictions of the CDM scenario relating halo mass to concentration parameter, which seems to lie above the mass–concentration relation predicted by the standard $\Lambda$CDM model (Broadhurst et al. 2005; Limousin et al. 2007a; Oguri et al. 2009; Zitrin et al. 2011a,b).

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though other works (e.g. Okabe et al. 2010) found a distribution of the concentration parameter in agreement with the theoretical predictions. Lensing bias is an issue here for clusters which are primarily selected by their lensing properties, where the major axis of a cluster may be aligned preferentially close to the line of sight boosting the projected mass density observed under the assumption of standard spherical modelling (Gavazzi 2005; Oguri & Blandford 2009). For example, Meneghetti et al. (2010a) showed that, owing to the cluster triaxiality and to the orientation bias that affects the strong lensing (SL) cluster population, we should expect to measure substantially biased up concentration parameters with respect to the theoretical expectations. Indeed, departures from spherical geometry play an important role in the determination of the desired physical parameters (Morandi, Pedersen & Limousin 2010), and therefore to assess the viability of the standard cosmological framework.

In particular, the conventional spherical modelling of the intracluster medium (ICM) and the DM is very approximate at best. Numerical simulations predict that observed galaxy clusters are triaxial and not spherically symmetric (Shaw et al. 2006; Bett et al. 2007; Gottlöber & Yepes 2007; Wang & White 2009), as customarily assumed in mass determinations based on X-ray and lensing observations, while violations of the strict hydrostatic equilibrium (HE) for X-ray data [i.e. intracluster (IC) gas pressure is provided entirely by thermal motions] can systematically bias low the determination of cluster masses (Lau, Kravtsov & Nagai 2009; Meneghetti et al. 2010b; Richard et al. 2010; Zhang et al. 2010).

The structure of clusters is sensitive to the mass density in the Universe, so the knowledge of their intrinsic shape has fundamental implications in discriminating between different cosmological models and to constrain cosmic structure formation (Inagaki, Suginoohara & Suto 1995; Corless, King & Clowe 2009). Therefore, the use of clusters as a cosmological probe hinges on our ability to accurately determine both their masses and 3D structure.

By means of a joint X-ray and lensing analysis, Morandi, Ettori & Moscardini (2007), Morandi et al. (2010), Morandi, Pedersen & Limousin (2011a) and Morandi et al. (2011b) overcame the limitation of the standard spherical modelling and strict HE assumption, in order to infer the desired 3D shape and physical properties of galaxy clusters in a bias-free way.

In the present work, we outline an application of our updated method to the galaxy cluster Abell 383. This is a cool-core galaxy cluster at \( z = 0.189 \) which appears to be very relaxed. While in the previous works we assumed that the triaxial ellipsoid (oblative or prolate) is oriented along the line of sight, here we developed further our method by recovering the full triaxiality of both DM and ICM, i.e. ellipsoidal shape and principal axis orientation. We discuss the implications of our method for the viability of the CDM scenario, focusing on the concentration parameter and inner slope of the DM.

Hereafter we assume the flat \( \Lambda \)CDM model, with matter density parameter \( \Omega_m = 0.3 \), cosmological constant density parameter \( \Omega_{\Lambda} = 0.7 \) and Hubble constant \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Unless otherwise stated, quoted errors are at the 68.3 per cent confidence level.

### 2 STRONG LENSING MODELLING

#### 2.1 Multiple images

Abell 383 has been previously studied using lensing techniques (Smith et al. 2001; Sand et al. 2008; Richard et al. 2010; Newman et al. 2011; Richard et al. 2011; Zitrin et al. 2011b). We benefit from these earlier works in order to propose multiply imaged system, in particular the most recent works based on the Cluster Lensing and Supernova Survey with Hubble (CLASH) Hubble Space Telescope data (Postman et al. 2011). We agree with the identifications proposed by Zitrin et al. (2011b) and we did not find any additional multiply imaged system, although we notice some blue features in the core of the cluster that may be multiply imaged. We use nine multiply imaged systems, five of them have a spectroscopic redshift measurement. For the remaining systems, the redshifts will be let free during the optimization. They are listed in Table 1 and shown in Fig. 1.

#### 2.2 Mass distribution

The model of the cluster mass distribution comprises three mass components described using a dual pseudo-isothermal elliptical mass distribution (dPIE; Limousin, Kneib & Natarajan 2005; Eliaśdöttrir et al. 2007), parametrized by a fiducial velocity dispersion \( \sigma \), a core radius \( r_{\text{core}} \) and a scale radius \( r_s \):\(^1\) (i) a cluster scale DM halo; (ii) the stellar mass in the brightest cluster galaxy (BCG) and (iii) the cluster galaxies representing local perturbation. As in earlier works (see e.g. Limousin et al. 2007a), empirical relations (without any scatter) are used to relate their dynamical dPIE parameters (central velocity dispersion and scale radius) to their luminosity (the core radius being set to a vanishing value, 0.05 kpc), whereas all geometrical parameters (centre, ellipticity and position angle) are set to the values measured from the light distribution.

\( ^1 \) Hereafter we use the notation \( r_s \) to indicate the scale radius in spherical symmetry, and \( R_t \) for the triaxial symmetry.

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**Table 1.** Multiply imaged systems considered in this work.

| ID   | RA     | Dec.    | \( z_{\text{spec}} \) | \( z_{\text{model}} \) |
|------|--------|---------|-----------------|------------------|
| 1.1  | 42.014543 | -3.528409 | 1.01             | -                |
| 1.2  | 42.014346 | -3.5287867 | -                | -                |
| 1.3  | 42.009577 | -3.5304728 | -                | -                |
| 2.1  | 42.012115 | -3.5330117 | 1.01             | -                |
| 2.2  | 42.011774 | -3.5327867 | -                | -                |
| 2.3  | 42.010140 | -3.5313950 | -                | -                |
| 3.1  | 42.009979 | -3.5331978 | 2.55             | -                |
| 3.2  | 42.009479 | -3.5331172 | -                | -                |
| 3.3  | 42.012463 | -3.5352256 | -                | -                |
| 4.1  | 42.011771 | -3.5352367 | 2.55             | -                |
| 4.2  | 42.009213 | -3.5339200 | -                | -                |
| 4.3  | 42.009082 | -3.5334061 | -                | -                |
| 5.1  | 42.013618 | -3.5263012 | 6.03             | -                |
| 5.2  | 42.019169 | -3.5328972 | -                | -                |
| 6.1  | 42.017633 | -3.5313868 | 1.93 ± 0.15     | -                |
| 6.2  | 42.013918 | -3.5331647 | -                | -                |
| 6.3  | 42.008825 | -3.5280806 | -                | -                |
| 6.4  | 42.015347 | -3.5266792 | -                | -                |
| 7.1  | 42.016975 | -3.5238458 | - >4.0          | -                |
| 7.2  | 42.014894 | -3.5231097 | -                | -                |
| 7.3  | 42.013315 | -3.5229153 | -                | -                |
| 8.1  | 42.015123 | -3.5234406 | 2.19 ± 0.29     | -                |
| 8.2  | 42.014163 | -3.5232253 | -                | -                |
| 9.1  | 42.016088 | -3.5336001 | - >4.0          | -                |
| 9.2  | 42.016702 | -3.5331010 | -                | -                |
| 9.3  | 42.016036 | -3.5264248 | -                | -                |
| 9.4  | 42.007825 | -3.5278831 | -                | -                |
2.3 Results

Results of the SL analysis are given in Table 2. The rms in the image plane is equal to 0.46 arcsec. In good agreement with previous works, we find that Abell 383 is well described by an unimodal mass distribution which presents a small eccentricity. This indicates a well-relaxed dynamical state. We note that the galaxy scale perturbers all present a scale radius which is smaller than the scale radius inferred for isolated field galaxies, in agreement with the tidal stripping scenario.

The LEnSTOOL software does explore the parameter space using a Monte Carlo Markov Chain (MCMC) sampler. At the end of the optimization, the tool has access to these MCMC realizations from which we can draw statistics and estimate error bars. For each realization, we build a 2D mass map. All these mass maps are then used to compute the mean mass map and the corresponding covariance. These information will then be used in the joint fit.

2.4 The case of system 6

Following Zitrin et al. (2011b), we have included the four images constituting system 6 in our analysis and our model reproduces it correctly. However, image 6.2 exhibits a serious problem of symmetry. This is the first time we observe such a problem in a SL configuration and we do not have any clear explanation for this. As can be seen on Fig. 2, images 6.1 and 6.3 are constituted by a bright spot linked to a faint tail. The symmetry between these images is correct. Image 6.2 does exhibit two tails. One may be tempted to naturally associate tail 1 with image 6.2. However, lensing symmetry requires the associated tail to point to the west. Tail 2 could be the associated feature, and an eventual perturber may bend this tail a bit north.

Another explanation could be that a undetected DM substructure does contract the expected tail into image 6.2.

3 X-RAY DATA SETS AND ANALYSIS

The cluster Abell 383 is a luminous cluster at redshift \( z = 0.189 \), which exhibits several indications of a well-relaxed dynamical state, for instance the absence of evident substructures and a central X-ray surface brightness peak, associated with a cool core. The global (cooling-core corrected) temperature \( T_{\text{ew}} \) has been estimated to be \( T_{\text{ew}} = 4.17 \pm 0.10 \text{ keV} \) and an abundance of \( 0.43 \pm 0.06 \) solar value (Section 3.1). We classify this cluster as a strong cooling core source (SCC; Morandi & Ettori 2007), i.e. the central cooling time \( t_{\text{cool}} \) is less than the age of the Universe \( t_{\text{age, z}} \) at the cluster redshift \( u_{\text{cool}}/u_{\text{age, z}} < 0.1 \): we estimated \( t_{\text{cool}} \simeq (5 \pm 3) \times 10^8 \text{ yr} \). As other SCC sources, Abell 383 shows a very low central temperature (\( \sim 2.7 \text{ keV} \)) and a strong spike of luminosity in the brightness profile. The temperature profile is very regular suggesting a relaxed dynamical state (see upper panel of Fig. 4).

Description of the X-ray analysis methodology can be found in Morandi et al. (2007, 2010). Here we briefly summarize the most relevant aspects of our data reduction and analysis of Abell 383.

3.1 X-ray data reduction

We performed our X-ray analysis on three data sets retrieved from the NASA High Energy Astrophysics Science Archive Research Center (HEASARC) archive (observation ID 2320, 2321 and 524) with a total exposure time of approximately 50 ks. We summarize here the most relevant aspects of the X-ray data reduction procedure for Abell 383. Two observations have been carried out using Chandra Advanced CCD Imaging Spectrometer (ACIS-I) CCD imaging spectrometer (ID 2320 and 524), one (ID 2321) using ACIS-S CCD imaging spectrometer. We reduced these observations using the CIAO software (version 4.3) distributed by the Chandra X-ray Observatory Center, by considering the gain file provided within CALDB (version 4.4.3) for both the observations telemetered in very faint mode (ID 2320 and 524) and faint mode (ID 2321).

We reprocessed the level-1 event files to include the appropriate gain maps and calibration products. We used the ACIS_process_events tool to check for the presence of cosmic ray background events, correct for spatial gain variations due to charge transfer inefficiency and recompute the event grades. Then we have filtered the data to include the standard events grades 0, 2, 3, 4 and 6 only, and therefore we have filtered for the good time intervals supplied, which are contained in the filt1.fit file. We then used the tool dmextract to create the light curve of the background. In order to clean the data sets of periods of anomalous background rates, we used the declare script, so as to filter out...
the times where the background count rate exceeds ±3σ about the mean value. Finally, we filtered ACIS event files on energy selecting the range 0.3–12 keV and on CCDs, so as to obtain an level-2 event file.

3.2 X-ray spatial and spectral analysis

We measure the gas density profile from the surface brightness recovered by a spatial analysis, and we infer the projected temperature profile by analysing the spectral data.

The X-ray images were extracted from the level-2 event files in the energy range (0.5–5.0 keV), corrected by the exposure map to remove the vignetting effects, masking out point sources and by rebinning them of a factor of 4 (1 pixel = 1.968 arcsec).

We determined the centroid (x, y) of the surface brightness by locating the position where the X and Y derivatives go to zero, which is usually a more robust determination than a centre of mass or fitting a 2D Gaussian if the wings in one direction are affected by the presence of neighbouring substructures. We checked that the centroid of the surface brightness is consistent with the centre of the BCG, the shift between them being evaluated to be ≤1.5 arcsec; note that the uncertainty on the X-ray centroid estimate is comparable to the applied rebinning scale on the X-ray images.

The three X-ray images were analysed individually, in order to calculate the surface brightness for each data set.

The spectral analysis was performed by extracting the source spectra in circular annuli of radius r_{proj} around the BCG. We have selected n^* = 7 annuli out to a maximum distance R_{proj} = 1056 kpc in order to have a number of net counts of photons of at least 2000 per annulus. All the point sources have been masked out by both visual inspection and the tool celldetect, which provide candidate point sources. Then we have calculated the redistribution matrix files (RMF) and the ancillary response files (ARF) for each annulus; in particular we used the CIAO specextract tool both to extract the source and background spectra and to construct the ARF and RMF of the annuli.

For each of the n^* annuli, the spectra have been analysed by using the XSPEC (Arnaud 1996) package, by simultaneously fitting an absorbed MEKAL model (Kaastra 1992; Liedahl, Osterheld & Goldstein 1995) to the three observations. The fit is performed in the energy range 0.6–7 keV by fixing the redshift at z = 0.189, and the photoelectric absorption at the galactic value. We grouped the photons of the spectra into bins of 20 counts per energy channel and then we applied the χ²-statistics. Thus, for each of the annuli, the free parameters in the spectral analysis were the normalization of the thermal spectrum K_e ∝ \int n_e^2 dV, the emission-weighted temperature T_{proj} and the metallicity Z_e.

The three observations were at first analysed individually, to assess the consistency of the data sets and to exclude any systematic effects that could influence the combined analysis. We then proceeded with the joint spectral analysis of the three data sets.

The background spectra have been extracted from regions of the same exposure for the ACIS–I observations, for which we always have some areas free from source emission. We also checked for systematic errors due to possible source contamination of the background regions. Conversely, for the ACIS–S observation we have considered the ACIS-S3 chip only and we used the ACIS ‘blank-sky’ background files. We have extracted the blank-sky spectra from the blank-field background data sets provided by the ACIS calibration team in the same chip regions as the observed cluster spectra. The blank-sky observations underwent a reduction procedure comparable to the one applied to the cluster data, after being reprojected.
on to the sky according to the observation aspect information by using the reproject_events tool. We then scaled the blank-sky spectrum level to the corresponding observational spectrum in the 9–12 keV interval, where very little cluster emission is expected. We also verified that on the ACIS-I observations the two methods of background subtraction provide very similar results on the fitting parameters (e.g. the temperature).

4 3D STRUCTURE OF GALAXY CLUSTERS

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 2D mass map via the lensing equation and the latter an indirect proxy of the 3D mass profile through the HE equation applied to the gas temperature and density. In order to infer the model parameters of both the IC gas and of the underlying DM density profile, we perform a joint analysis of SL and X-ray data. We briefly outline the methodology in order 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, the inner slope of the DM γ, the two axis ratios (η_{DM,a} and η_{DM,b}) and the Euler angles ψ, θ and φ; (2) following Lee & Suto (2003, 2004), we recover the gravitational potential (equation 8) and 2D surface mass Σ (equation 14) of a dark halo with such triaxial density profile; (3) we solve the generalized HE equation, i.e. including the non-thermal pressure P_{th} (equation 10), for the density of the IC gas sitting in the gravitational potential well previously calculated, in order to infer the theoretical 3D temperature profile T_{gas} in a non-parametric way; (4) we calculate the surface brightness map S_{X} related to the triaxial ICM halo (equation 13); and (5) the joint comparison of T_{gas} with the observed temperature, of S_{X} with observed brightness image and of Σ with the observed 2D mass map gives us the parameters of the triaxial ICM and DM density model.

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, as well as the improvements added in the current analysis; additional details can be found in Morandi et al. (2007, 2010, 2011a,b).

We start by describing in Section 4.1 the adopted geometry, the triaxial DM density and gravitational potential model, focusing on the relation between elongation of ICM and DM ellipsoids. We describe the relevant X-ray and lensing equations in Section 4.2; then we discuss how to jointly combine X-ray and lensing data in Section 4.3.

4.1 ICM and DM triaxial haloes

Extending our previous works, in the present study we allow the DM and ICM ellipsoids to be oriented in an arbitrary direction on the sky. We introduce two Cartesian coordinate systems, x = (x, y, z) and x’ = (x’, y’, z’), which represent respectively the principal coordinate system of the triaxial dark halo and the observer’s coordinate system, with the origins set at the centre of the halo. We assume that the z’-axis lies along the line-of-sight direction of the observer and that the y’-x’ axes identify the direction of west and north, respectively, on the plane of the sky. We also assumed that the x-, y- and z-axes lie along the minor, intermediate and major axis, respectively, of the DM halo. We define ψ, θ and φ as the rotation angles about the x-, y- and z-axes, respectively (see Fig. 3). Then the relation between the two coordinate systems can be expressed in terms of the rotation matrix M as

$$x’ = M x,$$

where M represents the orthogonal matrix corresponding to counterclockwise/right-handed rotations M_{x}(ψ), M_{y}(θ), M_{z}(φ) with Euler angles ψ, θ, φ, and it is given by

$$M = M_{x}(ψ)M_{y}(θ)M_{z}(φ),$$

where

$$M_{x}(ψ) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos ψ - \sin ψ & 0 \\ 0 & \sin ψ & \cos ψ \end{bmatrix};$$

$$M_{y}(θ) = \begin{bmatrix} \cos θ & 0 & \sin θ \\ 0 & 1 & 0 \\ - \sin θ & 0 & \cos θ \end{bmatrix};$$

$$M_{z}(φ) = \begin{bmatrix} \cos φ & - \sin φ & 0 \\ \sin φ & \cos φ & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

The lensing and X-ray intensity maps are then reprojected to a 2D plane according to the aspect information by using the reproject_events tool. We then scaled the blank-sky spectrum level to the corresponding observational spectrum in the 9–12 keV interval, where very little cluster emission is expected. We also verified that on the ACIS-I observations the two methods of background subtraction provide very similar results on the fitting parameters (e.g. the temperature).

**Figure 3.** The orientations of the coordinate systems. The Cartesian axes (x, y, z) represent the DM and ICM halo principal coordinate system while the axes (x’, y’, z’) represent the observer’s coordinate system with z’-axis aligned with the line of sight (l.o.s.) direction. We define ψ, θ and φ as the rotation angles about the x-, y- and z-axes, respectively. The labels N and W indicate the position of the north and west, respectively, on the plane of the sky.

The lensing and X-ray intensity maps are then reprojected to a 2D plane according to the aspect information by using the reproject_events tool. We then scaled the blank-sky spectrum level to the corresponding observational spectrum in the 9–12 keV interval, where very little cluster emission is expected. We also verified that on the ACIS-I observations the two methods of background subtraction provide very similar results on the fitting parameters (e.g. the temperature).
the Universe at redshift $z$, $H_i = E$, $H_0, E_i = \left[\Omega_M (1 + z)^3 + \Omega_A\right]^{1/2}$, and
\begin{equation}
\delta_c = \frac{200}{3} \frac{C^3}{F(C, \gamma)},
\end{equation}
where $C \equiv R_{200}/R_\epsilon$ is the concentration parameter. $F(C, \gamma)$ is defined as (Wyithe, Turner & Spergel 2001)
\begin{equation}
F(C, \gamma) \equiv \int_0^C s^{2-\gamma} (1 + s)^{\gamma-3} ds.
\end{equation}

The radius $R$ can be regarded as the major axis length of the isodensity surfaces:
\begin{equation}
R^2 = c^2 \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right)^{2/3},
\end{equation}
(a ≤ b ≤ c).
We also define $\eta_{DM,a} = a/c$ and $\eta_{DM,b} = b/c$ as the minor–major and intermediate–major axis ratios of the DM halo, respectively.

The gravitational potential of a dark halo with the triaxial density profile (equation 4) can be written as a complex implicit integrals (Binney & Tremaine 1987). While numerical integration is required in general to obtain the triaxial gravitational potential, Lee & Suto (2003) retrieved the following approximation for the gravitational potential $\Phi$ under the assumption of triaxial gNFW model for the DM (equation 4):
\begin{equation}
\Phi(u) \simeq C_0 F_1(u) + C_0 \frac{e_1^2 + e_2^2}{2} F_2(u) + C_0 \frac{e_2 \sin^2 \theta \sin ^2 \varphi + e_1 \cos^2 \theta}{2} F_3(u),
\end{equation}
with $u = r/R_\epsilon$, $C_0 = 4\pi G \rho_{c,\text{ICM}} R_\epsilon^2$, and the three functions $F_1(u)$, $F_2(u)$ and $F_3(u)$ have been defined in Morandi et al. (2010), $e_1 (e_2)$ and $e_2 (e_1)$ are the eccentricity of DM (IC gas) with respect to the major axis (e.g. $e_2 = \sqrt{T_{\text{ICM}}}/c^2$).

The work of Lee & Suto (2003) showed that the isopotential surfaces of the triaxial dark halo are well approximated by a sequence of concentric triaxial distributions of radius $R_{\text{ICM}}$ with different eccentricity ratio. For $R_{\text{ICM}}$ it holds a similar definition as $R$ (equation 7), but with eccentricities $e_\phi$ and $e_\theta$. Note that $e_\phi = \sqrt{1 - (b/c)^2} - (b/c)^2$.

The isopotential surfaces of the triaxial dark halo coincide also with the isodensity (pressure, temperature) surfaces of the IC gas. This is simply a direct consequence of the X-ray shape theorem (Buote & Canizares 1994); the HE equation (10) yields
\begin{equation}
\nabla P \times \nabla \Phi = \nabla P_{\text{gas}} \times \nabla \Phi = 0.
\end{equation}

4.2 X-ray and lensing equations

For the X-ray analysis we rely on a generalization of the HE equation (Morandi et al. 2011b), which accounts for the non-thermal pressure $P_{\text{nt}}$ and reads
\begin{equation}
\nabla P_{\text{tot}} = -\rho_{\text{gas}} \nabla \Phi,
\end{equation}
where $\rho_{\text{gas}}$ is the gas mass density, $\Phi$ is the gravitational potential, $P_{\text{tot}} = P_{\text{th}} + P_{\text{nt}}$, and with the non-thermal pressure of the gas $P_{\text{nt}}$ assumed to be constant fraction $\xi$ of the total pressure $P_{\text{tot}}$, i.e.
\begin{equation}
P_{\text{nt}} = \xi P_{\text{tot}}.
\end{equation}

Note that X-ray data probe only the thermal component of the gas $P_{\text{th}} = n_e k T_{\text{gas}}$, $k$ being the Boltzmann constant. From equations (10) and (11), we point out that neglecting $P_{\text{nt}}$ (i.e. $P_{\text{tot}} = P_{\text{th}}$) systematically biases low the determination of cluster mass profiles roughly of a factor $\xi$.

To model the density profile in the triaxial ICM halo, we use the following fitting function:
\begin{equation}
n_p(R_{\text{ICM}}) = n_0 \left( R_{\text{ICM}}/r_e \right)^{-3} \left( 1 + R_{\text{ICM}}/r_e \right)^{-3/2 + \delta/2}
\end{equation}
with parameters ($n_0$, $r_e$, $\delta$, $\delta$). We computed the theoretical 3D temperature $T_{\text{gas}}$ by numerically integrating the equation of the HE (equation 10), assuming triaxial geometry and a functional form of the gas density given by equation (12).

The observed X-ray surface brightness $S_X$ is given by
\begin{equation}
S_X = \frac{1}{4\pi(1+z)^2} \Lambda(T_{\text{proj}}, Z) \int n_p n_0 d'z',
\end{equation}
where $\Lambda(T_{\text{proj}}, Z)$ is the cooling function. Since the projection on the sky of the plasma emissivity gives the X-ray surface brightness, the latter can be geometrically fitted with the model $n_p(R_{\text{ICM}})$ of the assumed distribution of the gas density (equation 12) by applying equation (13). This has been accomplished via fake Chandra spectra, where the current model is folded through response curves (ARF and RMF) and then added to a background file, and with absorption, temperature and metallicity measured in the neighbouring ring in the spectral analysis (Section 3.2). In order to calculate $\Lambda(T_{\text{proj}}, Z)$, we adopted a MEKAL model (Kaastra 1992; Liedahl et al. 1995) for the emissivity.

For the lensing analysis, the 2D surface mass density $\Sigma$ can be expressed as
\begin{equation}
\Sigma = \int_{-\infty}^{\infty} \rho(R) dz'.
\end{equation}
We also calculated the covariance matrix $\mathbf{C}$ among all the pixels of the observed surface mass (see Morandi et al. 2011b, for further details).

4.3 Joint X-ray+lensing analysis

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 projected mass profile and the latter an indirect proxy of the mass profile through the HE equation applied on the gas temperature and density. In this sense, in order to infer the model parameters, we construct the likelihood performing a joint analysis for SL and X-ray data, to constrain the properties of the model parameters of both the ICM and of the underlying DM density profile.

The system of equations we simultaneously rely on in our joint X-ray+lensing analysis is
\begin{equation}
T_{\text{gas}} = T_{\text{gas}}(C, R, \gamma, \eta_{DM,a}, \eta_{DM,b}, \psi, \theta, \phi, n_0, r_e, \epsilon, \delta, \xi),
\end{equation}
\begin{equation}
S_X = S_X(C, R, \gamma, \eta_{DM,a}, \eta_{DM,b}, \psi, \theta, \phi, n_0, r_e, \epsilon, \delta),
\end{equation}
\begin{equation}
\Sigma = \Sigma(C, R, \gamma, \eta_{DM,a}, \eta_{DM,b}, \psi, \theta, \phi),
\end{equation}
where the 3D model temperature $T_{\text{gas}}$ is recovered by solving equation (10) and constrained by the observed temperature profile, the surface brightness is recovered via projection of the gas density model (equation 13) and constrained by the observed brightness, and the model 2D mass $\Sigma$ is recovered via equation (14) and constrained by the observed surface mass.

The method works by constructing a joint X-ray+lensing likelihood $L \propto \exp(-x^2/2)$:
\begin{equation}
x^2 = x^2_{\text{SL}} + x^2_{\text{X}},
\end{equation}
where $x^2_{\text{SL}}$ and $x^2_{\text{X}}$ are the SL and X-ray likelihoods, respectively.
with $\chi^2_{\nu}$, $\chi^2_{\Sigma}$ and $\chi^2_{\text{gas}}$ being the $\chi^2$ coming from the X-ray temperature, X-ray brightness and lensing data, respectively.

For the spectral analysis, $\chi^2_{\nu}$ is equal to

$$\chi^2_{\nu,T} = \sum_{i=1}^{n^*} \left( \frac{T_{\text{proj},i} - T_{\text{proj},i}^*}{\sigma^2_{\text{proj},i}} \right)^2,$$

(17)

$T_{\text{proj},i}$ being the observed projected temperature profile in the $i$th circular ring and $T_{\text{proj},i}^*$ the azimuthally averaged projection (following Mazzotta et al. 2004) of the theoretical 3D temperature $T_{\text{gas}}$; the latter is the result of solving the HE equation, with the gas density $n_c(R_{\text{cm}})$.

For the X-ray brightness, $\chi^2_{\nu,S}$ reads

$$\chi^2_{\nu,S} = \sum_j \sum_{i=1}^{n_j} \left( \frac{S_{X,i} - S_{X,i}^*}{\sigma_{S,i}^2} \right)^2,$$

(18)

with $S_{X,i}$ and $S_{X,i}^*$ theoretical and observed counts in the $i$th pixel of the $j$th image. Given that the number of counts in each bin might be small ($<5$), then we cannot assume that the Poisson distribution from which the counts are sampled has a nearly Gaussian shape. The standard deviation (i.e. the square root of the variance) for this low-count case has been derived by Gehrels (1986):

$$\sigma_{S,i} = 1 + \sqrt{S_{X,i} + 0.75},$$

(19)

which has been proved to be accurate to approximately 1 per cent. Note that we added background to $S_{X,i}$ as measured locally in the brightness images, and that the vignetting has been removed in the observed brightness images.

For the lensing constraints, the lensing contribution is

$$\chi^2_{\text{lens}} = \left[ \Sigma - \Sigma^* \right] \mathbf{M}^{-1} \left[ \Sigma - \Sigma^* \right]^t,$$

(20)

where $\mathbf{C}$ is the covariance matrix of the 2D projected mass profile from SL data, $\Sigma^* = (\Sigma_1, \Sigma_2, ..., \Sigma_n)$ are the observed measurements of the projected mass map in the $i$th pixel, and $\Sigma$ is the theoretical 2D projected mass within our triaxial DM model. Note that we removed the central 25 kpc of the 2D projected mass in the joint analysis, to avoid the contamination from the cD galaxy mass.

The probability distribution function of model parameters has been evaluated via MCMC algorithm. Errors on the individual parameters have been evaluated by considering average value and standard deviation on the marginal probability distributions of the same parameters.

So we can determine the physical parameters of the cluster, for example the 3D temperature $T_{\text{gas}} = T_{\text{gas}}(C, R_s, \gamma, \eta_{\text{DM},a}, \eta_{\text{DM},b}, \Psi, \theta, \phi, r_c, \varepsilon, \delta, \xi)$, the shape of DM and ICM, just by relying on the HE equation and on the robust results of the hydrodynamical simulations of the DM profiles. In Fig. 4 we present an example of a joint analysis for $T_{\text{gas}}, S_X$ and $\Sigma$: for $S_X$ and $\Sigma$ the 1D profile has been presented only for visualization purpose, the fit being applied on the 2D X-ray brightness/surface mass data. Note that in the joint analysis both X-ray and lensing data are well fitted by our model, with a $\chi^2_{\text{red}} = 1.23$ (65 837 degrees of freedom).

5 RESULTS AND DISCUSSION

In the previous section we showed how we can determine the physical parameters of the cluster by fitting the available data based on the HE equation and on a DM model that is based on robust results of hydrodynamical cluster simulations. In this section we present our results and discuss their main implications. We particularly focus on the implications of our analysis for the determination of the full triaxiality, viability of the CDM scenario, the discrepancy between X-ray and lensing masses in Abell 383 and the presence of non-thermal pressure.

5.1 Best-fitting parameters

In Table 3 we present the best-fitting model parameters for our analysis of Abell 383. Our work shows that Abell 383 is a triaxial

| Table 3. Best-fitting model parameters of Abell 383. |
|-----------------------------------------------|
| $C$ | $4.76 \pm 0.51$ |
| $R_s$ (kpc) | $511.2 \pm 73.6$ |
| $\gamma$ | $1.02 \pm 0.06$ |
| $\eta_{\text{DM},a}$ | $0.55 \pm 0.06$ |
| $\eta_{\text{DM},b}$ | $0.71 \pm 0.10$ |
| $\Psi$ (°) | $-13.6 \pm 5.5$ |
| $\theta$ (°) | $21.1 \pm 10.1$ |
| $\phi$ (°) | $-16.9 \pm 15.9$ |
| $r_c$ (kpc) | $26.4 \pm 1.7$ |
| $\varepsilon$ | $0.55 \pm 0.01$ |
| $\delta$ | $0.02 \pm 0.01$ |
| $\xi$ | $0.11 \pm 0.05$ |
galaxy cluster with DM halo axial ratios $\eta_{DM,a} = 0.55 \pm 0.06$ and $\eta_{DM,b} = 0.71 \pm 0.10$, and with the major axis inclined with respect to the line of sight of $\theta = 21^\circ \pm 10^\circ$. Note that these elongations are statistically significant, i.e. it is possible to disprove the spherical geometry assumption. We also calculated the value of $M_{200}$:

$$M_{200} = \frac{800\pi}{3} \eta_{DM,a} \eta_{DM,b} R_{200}^3 \rho_c \cdot$$

(21)

We have $M_{200} = 7.3 \pm 0.5 \times 10^{14} M_\odot$ and $R_{200} = 2401.1 \pm 166.8$ kpc.

The axial ratio of the gas is $\eta_{gas,a} \sim 0.70-0.82$ and $\eta_{gas,b} \sim 0.80-0.88$, moving from the centre towards the X-ray boundary.

Another important result of our work is the need for non-thermal pressure support, at a level of $\sim 10$ per cent.

We also observe that the small value of the inclination of the major axis with respect to the line of sight is in agreement with the predictions of Oguri & Blandford (2009), who showed that SL clusters with the largest Einstein radii constitute a highly biased population with major axes preferentially aligned with the line of sight, thus increasing the magnitude of lensing.

In Fig. 5 we present the joint probability distribution among different parameters in our triaxial model. For example, we observe that there is a positive (negative) linear correlation between $\gamma$ and $\theta(C)$. This proves that the inclination with respect to the line of sight, and more in general the geometry, is important in order to characterize the inner slope of the DM (and the concentration parameter), and therefore to assess the viability of the standard cosmological framework.

We also compared the azimuthal angle $\phi = 103:8 \pm 9.0$ and the eccentricity on the plane of the sky ($e = 0.08 \pm 0.03$), with the values on the total 2D mass from the analysis from LENSSTool ($\phi = 111^\circ \pm 2^\circ$ and $e = 0.05 \pm 0.01$); note the good agreement. For the method to recover $e$ and $\phi$ we remand to Morandi et al. (2010).

5.2 Probing the inner DM slope and implications for the viability of the CDM scenario

A central prediction arising from CDM simulations is that the density profile of DM haloes is universal across a wide range of mass scales from dwarf galaxies to clusters of galaxies (Navarro, Frenk & White 1997); within a scale radius, $r_s$, the DM density asymptotes to a shallow power-law trend, $\rho_{DM}(r) \propto r^{-\gamma}$, with $\gamma = 1$, while external to $r_s$, $\rho_{DM}(r) \propto r^{-3}$. Nevertheless, the value of the logarithmic inner slope $\gamma$ is still a matter of debate. Several studies suggested steeper central cusp (Moore et al. 1998, 1999); with one recent suite of high-resolution simulations, Diemand, Moore & Stadel (2004) argued for $\gamma = 1.16 \pm 0.14$. Taylor & Navarro (2001) and Dehnen & McLaughlin (2005) developed a general framework where there is the possibility that $\gamma$ might be shallower than 1 at small radii, while other studies suggested the lack of cusp in the innermost regions (Navarro et al. 2004).

Conventional CDM simulations only include collisionless DM particles, neglecting the interplay with baryons. It is not clear how the inclusion of baryonic matter would affect the DM distribution; although their impact is thought to be smaller in galaxy clusters than in galaxies, baryons may be crucially important on scales comparable to the extent of typical BCGs and may thus alter the DM distribution, particularly the inner slope (Sand et al. 2008; Sommer-Larsen & Limousin 2010). With this respect, the cooling of the gas is expected to steepen the DM distribution via adiabatic compression (Gnedin et al. 2004). Dynamical friction between infalling baryons and the host halo may counter and surpass the effects of adiabatic contraction in galaxy clusters, by driving energy and angular momentum out of the cluster core, thus softening an originally cuspy profile (El-Zant, Kim & Kamlionkowski 2004). Mead et al. (2010) shows that active galactic nucleus (AGN) feedback suppresses the build-up of stars and gas in the central regions of clusters, ensuring that the inner density slope is shallower and the concentration parameter smaller than in cooling-star formation haloes, where $C$ and $\gamma$ are similar to the DM-only case.

An observational verification of the CDM predictions, via a convincing measurement of $\gamma$ over various mass scales, has proved controversial despite the motivation that it offers a powerful test of the CDM paradigm. Observationally, efforts have been put on probing the central slope $\gamma$ of the underlying DM distribution, through X-ray (Arabadjis, Bautz & Garmire 2002; Ettori et al. 2002; Lewis, Buote & Stocke 2003; Zappacosta et al. 2006), lensing (Tyson, Kochanski & dell’Antonio 1998; Smith et al. 2001; Sand, Treu & Ellis 2002; Dahle, Hannestad & Sommer-Larsen 2003; Gavazzi et al. 2003; Sand et al. 2004, 2008; Gavazzi 2005; Bradač et al. 2008; Limousin et al. 2008) or dynamics (Kelson et al. 2002; Biviano & Salucci 2006). However, analyses of the various data sets have given conflicting values of $\gamma$, with large scatter from one cluster to another, and many of the assumptions used have been questioned. Indeed these determinations rely e.g. on the standard spherical modelling of galaxy clusters: possible elongation/flattening of the clusters along the line of sight has been proved to affect the estimated values of $\gamma$ (Morandi et al. 2010, 2011a). Another major observational hurdle is the importance of separating the baryonic and non-baryonic components (Sand et al. 2008).

With this perspective, one of the main results of the presented work is to measure a central slope of the DM $1.02 \pm 0.06$ by accounting explicitly for the 3D structure for Abell 383; this value is in agreement with the CDM predictions from Navarro et al. (1997) (i.e. $\gamma = 1$). Yet, a comparison with such simulations, which do not account for the baryonic component, merits some caution. Note that in this analysis we did not subtract the mass contribution from the X-ray gas to the total mass. Nevertheless, the contribution of the gas to the total matter is small; the measured gas fraction is 0.03–0.05 in the spatial range 25–400 kpc, and we checked that the slope of the density profile is very similar to that of the DM beyond a characteristic scale $r_c \sim 20–30$ kpc, a self-similar property of the gas common to all the SCC sources (Morandi & Ettori 2007). This suggests that our assumption to model the total mass as a gNFW is reliable, and therefore a comparison with DM-only studies is tenable. Similar conclusions have been reached by Bradač et al. (2008) and Sommer-Larsen & Limousin (2010).

It is also possible that the DM particle is self-interacting; this would lead to shallower DM density profiles with respect to the standard CDM scenario (Spergel & Steinhardt 2000). Nevertheless, the lack of a flat core allows us to put a conservative upper limit on the DM particle scattering cross-section; indeed e.g. Yoshida et al. (2000) simulated cluster-sized haloes and found that relatively small DM cross-sections ($\sigma_{dm} = 0.1 \text{ cm}^2 \text{ g}^{-1}$) are ruled out, producing a relatively large ($40 h^{-1} \text{kpc}$) cluster core, which is not observed in our case study.

Morandi et al. (2010, 2011a) analysed the galaxy clusters Abell 1689 and MACS J1423.8+2404 in our triaxial framework; we found that $\gamma$ is close to the CDM predictions ($\gamma = 1$) for these clusters, in agreement with the results in the present paper.

Recently, Newman et al. (2011) combined strong and weak lensing constraints on the total mass distribution with the radial (circularized) profile of the stellar velocity dispersion of the cD galaxy. They adopted a triaxial DM distribution and axisymmetric...
Figure 5. Marginal probability distribution among different parameters in our triaxial model. The solid(dashed) line represents the $1\sigma$($2\sigma$) error region, while the big point represents the expectation value.
5.3 Implications on X-ray/lensing mass discrepancy

Here we outline our findings in probing the 3D shape of ICM and DM, and the systematics involved in using a standard spherical modelling of galaxy clusters. In particular, we will focus on the long-standing discrepancy between X-ray and lensing masses on clusters, showing that this is dispelled if we account explicitly for a triaxial geometry.

There are discrepancies between cluster masses determined based on gravitational lensing and X-ray observations, the former being significantly higher than the latter in clusters with prominent lensing features. 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, thus increasing the magnitude of lensing. Given that lensing depends on the integrated mass 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 bias up the 3D with mass respect to the X-ray masses (Gavazzi 2005); on the other hand, X-ray-only masses hinges on the goodness of the strict HE assumption: the presence of bulk motions in the gas can bias low the 3D mass profile between 5 and 20 per cent (Meneghetti et al. 2010b).

In Fig. 6 we compare the 3D mass enclosed within a spherical apertures of radius $R$ for lensing, X-ray-only data and from a joint X-ray-lensing analysis taking into account the 3D geometry, which can be regarded as the true mass profile. Note that 3D mass profile for lensing has been recovered via Abel inversion (assuming spherical symmetry) of the 1D projected mass profile, while for X-ray-only data by assuming a spherical NFW. With respect to a joint analysis based on our triaxial modelling, a lensing-only analysis based on the standard spherical modelling predicts systematically higher masses by a factor 1.3–1.1 in the radial range out to 400 kpc, moving from the centre towards the SL boundary.

An X-ray-only analysis based on the standard spherical modelling and strict HE predicts systematically lower masses by a factor of 1.5–1.2 in the radial range out to 1050 kpc compared to the true mass profile, moving from the centre towards the X-ray boundary. Note that correcting the X-ray-only mass by $\xi$, e.g. by assuming a typical value from hydrodynamical numerical simulations, would lower this discrepancy by a factor $\sim \xi$. This confirms our insights about the role of the effects of geometry and non-thermal pressure
on the physical properties. We also point out that the 3D mass discrepancy tends to get smaller with increasing radii, as already pointed out by Gavazzi (2005). This trend of the X-ray versus true mass discrepancy is a consequence of the fact that the IC gas is more spherical in the outer volumes than in the centre, besides being altogether more spherical than the underlying DM halo; this is intuitively understood because the potential represents the overall average of the local density profile, and also because the gas pressure is isotropic unlike the possible anisotropic velocity ellipsoids for collisionless DM.

We also point out that in Gavazzi (2005) both the SL and X-ray 3D masses are systematically larger than the true 3D mass distribution for clusters with prominent SL features, unlike in Fig. 6. Indeed, he considered a toy model where the ICM and DM ellipsoids are azimuthally symmetric with the major axis oriented along the line of sight, the gas is wholly thermalized and it can be described as an isothermal $\beta$-model, and all the physical parameters but the elongation along the line of sight are kept frozen. On the contrary, in the present analysis, owing to the full triaxiality, i.e. the two axis ratios and the three Euler angles, to non-thermal pressure support and to a physically accurate description of the IC gas, we fitted this triaxial model to the data, allowing all the physical parameters to simultaneously change in the joint fit.

We also compare the results in our triaxial framework with those of Newman et al. (2011), who adopted a triaxial DM distribution on the total mass distribution from lensing (assuming major axis of the DM halo along the line of sight) and with the radial profile of the stellar velocity dispersion of the cD galaxy. They also accounted for hydrostatic mass estimates from X-ray data under the assumption of spherical geometry from Allen et al. (2008), who used older Chandra calibrations with respect to those adopted in the present work, which lead to a higher spectral temperature (and therefore mass) profile by $\sim10$ per cent. They corrected the X-ray masses for violation of strict HE assumption by assuming a typical value of $\xi \sim 10$ per cent from hydrodynamical numerical simulations. They assumed that the X-ray-only masses are recovering the true spherically averaged masses, regardless of the halo shape. While the results from hydrodynamical numerical simulations (Lau et al. 2009) indicate that the bias involved in this assumption is just a few per cent, this is strictly speaking correct for an average cluster, so this assumption likely merits some caution when we consider highly elliptical clusters like Abell 383; as previously discussed, we found that the X-ray versus true 3D mass discrepancy is appreciable (see Fig. 6).

Indeed, they found physical parameters dissimilar from ours: $1/R_{\text{DM,a}} = 1.97^{+0.28}_{-0.10}$, $\gamma = 0.59^{+0.30}_{-0.35}$ and $R_c = 112^{+16}_{-30}$ kpc. Note that we used a different definition of $R_c$, which refers to the major axis of the triaxial DM halo, so to make a comparison with Newman et al. (2011) we should multiply their $R_c$ by $\sim 1/R_{\text{DM,a}}$; still their $R_c$ would be smaller than ours.

The disagreement between the two works about physical parameters, in particular with respect to the inner slope of the DM, suggests the following considerations: (i) there is the possibility that the fit of Newman et al. (2011) is dominated by the high-quality data for the circularized stellar velocity dispersion, therefore they might probe only the very central slope, whereas in the current paper we do probe the mass profile from 25 kpc out to $\sim 1000$ kpc; (ii) for this cluster the gNFW may not be the correct density profile, which could have a slope that varies with radius (Navarro et al. 2004), though further data (e.g. stellar velocity dispersion) in a triaxial framework are needed to prove this: with this respect, both works might simply measure different part of the density profile; (iii) the bias in the stellar velocity dispersion resulting from projection effects (Dubinski 1998) might affect mass estimates of Newman et al. (2011).

A more thorough comparison between the two works is beyond the purpose of this paper, and it would involve a complex understanding of how their simplified assumptions e.g. on the X-ray data constraints would affect the parameter estimates.

6 SUMMARY AND CONCLUSIONS

In this paper we employed a physical cluster model for Abell 383 with a triaxial mass distribution including support from non-thermal pressure, proving that it is consistent with all the X-ray and SL observations and the predictions of CDM models.

We managed to measure for the first time the full triaxiality of a galaxy cluster, i.e. the two axis ratios and the principal axis orientation, for both DM and ICM. We demonstrated that accounting for the 3D geometry and the non-thermal component of the gas allows us to measure a central slope of the DM and concentration parameter in agreement with the theoretical expectation of the CDM scenario, dispelling the potential inconsistencies arisen in the literature between the predictions of the CDM scenario and the observations, providing further evidences that support the CDM paradigm.

We also measured the amount of the non-thermal component of the gas ($\sim 10$ per cent of the total energy budget of the IC gas); this has important consequences for estimating the amount of energy injected into clusters from mergers, accretion of material or feedback from AGN.

The increasing precision of observations allows testing the assumptions of spherical symmetry and HE. Since a relevant number of cosmological tests are today based on the knowledge of the mass and shape of galaxy clusters, it is important to better characterize their physical properties with realistic triaxial symmetries and accounting for non-thermal pressure support. Galaxy clusters play an important role in the determination of cosmological parameters such as the matter density (Allen et al. 2008), the amplitude and slope of the density fluctuations’ power spectrum (Voevodkin & Vikhlinin 2004) and the Hubble constant (Inagaki et al. 1995), to probe the nature of the dark energy (Albrecht & Bernstein 2007) and discriminate between different cosmological scenarios of structure formation (Gastaldello et al. 2007). It is therefore extremely important to provide a more general modelling in order to properly determine the 3D cluster shape and mass, in order to pin down DM properties and to exploit clusters as probes of the cosmological parameters with a precision comparable to other methods [e.g. cosmic microwave background (CMB), supernovae (SNe)].

The application of our method to a larger sample of clusters will allow us to infer the desired physical parameters of galaxy clusters in a bias-free way, with important implications on the use of galaxy clusters as precise cosmological tools.

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REFERENCES

Albrecht A., Bernstein G., 2007, Phys. Rev. D, 75, 103003
Allen S. W., Rapetti D. A., Schmidt R. W., Ebeling H., Morris R. G., Fabian A. C., 2008, MNRAS, 383, 879
Arabadjis J. S., Bautz M. W., Garmire G. P., 2002, ApJ, 572, 66
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
Barkana R., Loeb A., 2010, MNRAS, 405, 1969
Bett P., Eke V., Frenk C. S., Jenkins A., Helly J., Navarro J., 2007, MNRAS, 376, 215
Binney J., Tremaine S., 1987, Galactic Dynamics. Princeton Univ. Press, Princeton, NJ
Biviano A., Salucci P., 2006, A&A, 452, 75
Bradač M. et al., 2008, ApJ, 681, 187
Broadhurst T. et al., 2005, ApJ, 621, 53
Bullock J. S., Kolatt T. S., Sigad Y., Somerville R. S., Kravtsov A. V., Klypin A. A., Primack J. R., Dekel A., 2001, MNRAS, 321, 559
Buote D. A., Canizares C. R., 1994, ApJ, 427, 66
Corless V. L., King L. J., Clowe D., 2009, MNRAS, 393, 1235
Dahle H., Hannestad S., Sommer-Larsen J., 2003, ApJ, 588, L73
Dehnen W., McLaughlin D. E., 2005, MNRAS, 363, 1057
Diemand J., Moore B., Stadel J., 2004, MNRAS, 353, 624
Dahle H., Hannestad S., Sommer-Larsen J., 2003, ApJ, 588, L73
El-Badry K., McLaughlin D. E., 2010, ApJ, 717, 531
Ettori S., Fabian A. C., Allen S. W., Rapetti D. A., Schmidt R. W., Ebeling H., Morris R. G., Fabian A. C., 2008, MNRAS, 383, 879

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