

Mass, velocity anisotropy and pseudo phase space density profiles of Abell 2142

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ABSTRACT

Aims. We aim to compute the mass and velocity anisotropy profiles of Abell 2142 and, from there, the pseudo phase space density profile $Q(r)$ and the density slope - velocity anisotropy $\beta - \gamma$ relation, and compare them with theoretical expectations.

Methods. The mass profiles have been obtained by using three techniques based on member galaxy kinematics, namely the caustic method, the method of Dispersion - Kurtosis and MAMPOSSt. Through the inversion of the Jeans equation it has been possible to compute the velocity anisotropy profiles.

Results. The mass profiles, as well as the virial values of mass and radius, computed with the different techniques are in agreement with one another and with the estimates coming from X-ray and weak lensing studies. A concordance mass profile is obtained by averaging the lensing, X-ray and kinematics determinations. The cluster mass profile is well fit by an NFW profile with $c = 4.0 \pm 0.5$. The population of red and blue galaxies appear to have a different velocity anisotropy configuration, red galaxies being almost isotropic while blue galaxies are radially anisotropic, with a weak dependence on radius. The $Q(r)$ profile for the red galaxy population agrees with the theoretical results found in cosmological simulations. The $\beta - \gamma$ relation matches the theoretical relation only in the inner region when considering the red galaxies. The deviations might be due to the theoretical relations not taking into account the presence of baryons and using DM particles as tracers.

Key words.

1. Introduction

The measure of the mass of cosmological objects, such as clusters of galaxies, has proven to be an important tool for cosmological applications. The mass is not a direct observable, and many techniques have been developed to infer it by measuring observable quantities. Two methods that are widely used to infer the mass profile of galaxy clusters are the X-ray and the lensing techniques. The former makes use of the observations of the X-ray emission of the hot intracluster plasma (ICM hereafter). The lensing technique makes use of the relativistic effect of distortion of the trajectories of light emitted by distant background galaxies due to the mass of the observed cluster. These two methods have anyway some limitations. In the case of X-ray technique, the limitation comes from the usual assumption that the plasma of the cluster is in hydrostatic equilibrium, and the cluster approximately spherically symmetric (Ettori et al. 2002) with no important recent merger activity (Böhringer & Werner 2010). As for the lensing technique, its limitation is that it allows to compute the projected mass only, and this includes all the line-of-sight mass contributions. The complementarity of the different techniques is a great advantage to reliably constrain the mass of a cluster.

In this article, we use another kind of information, coming from the kinematics of the galaxies belonging to the observed cluster. In fact, the potential well of the cluster, due to the mass,

is the main driver of the orbital motion of the galaxies which, in the absence of mutual interactions, can be treated as test particles in the gravitational potential of the cluster. The kinematics of galaxies therefore carries the information about the mass content of the cluster. The motion takes place in a 6-dimensional phase space, but the observations are able to capture only 3 of these dimensions, namely 2 for the position and one for the line of sight (los, hereafter) velocity. This is one of the most important limitations of the mass estimate through the observation of the kinematics of galaxies. To overcome this issue, most methods assume spherical symmetry.

A spherically symmetric density profile following the universal relation provided by Navarro et al. (1996, 1997) (NFW hereafter) has often been adopted in these analyses. With the advent of simulations with higher and higher resolution, the universality of the NFW profile has been questioned (see e.g. Ludlow et al. 2013; Navarro et al. 2004; Vogelsberger et al. 2011). The self-similarity of the DM-only haloes seems to be broken, and substituted with the pseudo phase space density (PPSD hereafter) $Q(r) = \rho/\sigma^3$, where ρ is the total matter density profile and σ is the 3D velocity dispersion of the tracers of the gravitational potential (Ludlow et al. 2010; Taylor & Navarro 2001). The use of the radial velocity dispersion instead of the total one has proven to be a valid and robust alternative for the computation of the PPSD, in this case called $Q_r(r)$. The link between these two formulations of the PPSD is constrained by the velocity anisotropy

(hereafter, anisotropy) of the system, which plays a non trivial role in shaping the structure of a system. The density profile and the anisotropy profile are in fact found to correlate. A best-fit relation is provided by Hansen & Moore (2006) and Ludlow et al. (2011), linking the logarithmic slope of the density profile $\gamma = d \ln \rho / d \ln r$ and the anisotropy $\beta(r) = 1 - (\sigma_t / \sigma_r)^2$, where σ_r and σ_t are, respectively, the velocity dispersions of the radial component and of one of the two tangential components. Hereafter we will refer to anisotropy as β or the equivalent $\sigma_r / \sigma_t = 1 / \sqrt{1 - \beta^2}$. We also denote the relation between anisotropy and logarithmic slope of the density profile as the β - γ relation.

In this article, we study Abell 2142 (A2142 hereafter), a rich galaxy cluster at $z \sim 0.09$. The great amount of galaxy members allows us to derive the total mass profile, testing different models, as well as performing dynamical analyses deriving the anisotropy of the orbits of galaxies, and computing the pseudo phase space density profile and the $\beta - \gamma$ relation. This cluster shows evidence of some recent mergers. In fact, the X-ray emission appears to have an elliptical morphology elongated in the Northwest-Southeast direction (Akamatsu et al. 2011; Markevitch et al. 2000). The merging scenario is supported also by the presence of substructures of galaxies lying along the direction of the cluster elongation, as found in the SZ maps by Umetsu et al. (2009), lensing analysis by Okabe & Umetsu (2008) and analysis of the distribution of los velocities of Owers et al. (2011). However, analysing *XMM-Newton* images to investigate the cold fronts of A2142, Rossetti et al. (2013) exclude the mergers to be major ones, but rather of an intermediate degree.

Throughout this paper, we adopt a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$. The virial quantities are computed at radius r_{200} .

2. The data

The photometric information has been obtained from the SDSS DR7 database¹, searching for the galaxies having $238^\circ 983 < \text{RA} < 240^\circ 183$, $26^\circ 633 < \text{DEC} < 27^\circ 834$ and $\text{petroMag}_r < 22$. The spectroscopic information has been provided by Owers et al. (2011). The full sample is composed of 1631 galaxies with both photometric and spectroscopic information. The cluster center is assumed to coincide with the X-ray center provided by De Grandi & Molendi (2002).

Two algorithms have been used to select cluster members, those of den Hartog & Katgert (1996) and Mamon et al. (2013), hereafter dHK and *clean*, respectively. Both identify cluster members on the basis of their location in projected phase-space²: R , v_{rest} , using the spectroscopic values for the velocities. We adopt the membership determination of dHK, resulting in 996 members. In fact, the *clean* algorithm removes one more galaxy but it is very close to the distribution of selected members and it seems unlikely to be an interloper. Anyway, this galaxy is at $\approx 3 \text{ Mpc}$ from the cluster center, which should make no difference in the analysis here. Fig. 1 shows the location of galaxies in the projected phase-space diagram and the members identification of the two methods.

¹ <http://cas.sdss.org/astro/en/tools/chart/chart.asp>

² R is the projected radial distance from the cluster center (we assume spherical symmetry in the dynamical analyses). The rest-frame velocity is defined as $v = c(z - \bar{z}) / (1 + \bar{z})$. The mean cluster redshift \bar{z} is re-defined at each new iteration of the membership selection, until convergence.

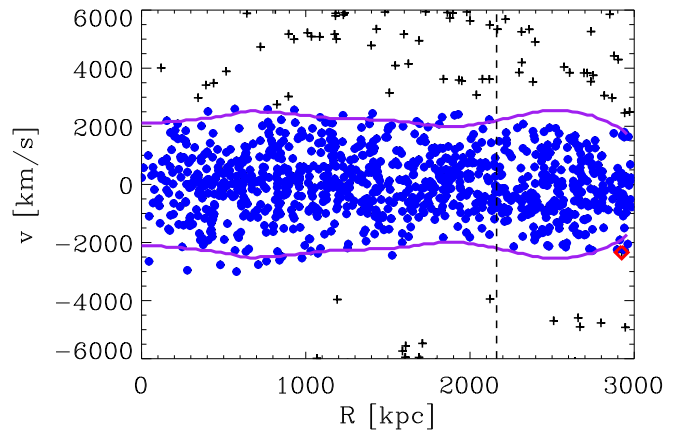


Fig. 1. Distribution of the galaxies of Abell 2142 in the projected phase-space of projected radii and line-of-sight rest-frame velocities. Cluster members, as identified by both dHK and *clean* algorithms, are denoted by blue filled dots. The red diamond is the galaxy identified as member by dHK but not by the *clean* algorithm. The purple solid lines are the caustic, described in Sect. 3. The vertical dashed line locates the virial radius of the concordance model (see Sect. 4).

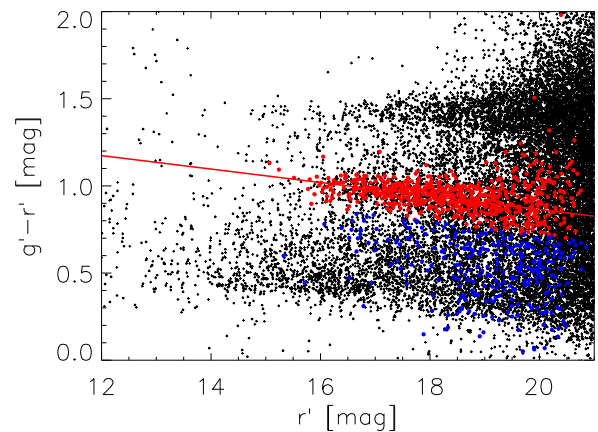


Fig. 2. Color magnitude diagram $g' - r'$ vs. r' . Red (blue) points are relative to red (blue) member galaxies. Black points are galaxies, for which we have photometric information, that are not identified as members. The red solid line locates the Red Sequence.

The cluster mean redshift and line-of-sight velocity dispersion, as well as their uncertainties, have been computed using the biweight estimator (Beers et al. 1990) on the redshifts and rest frame velocities of the members: $\langle z \rangle = 0.08999 \pm 0.00013$, $\sigma_{\text{los}} = 1193^{+58}_{-61} \text{ km/s}$.

2.1. The color identification

We identify the Red Sequence iteratively by fitting the $g' - r'$ vs. r' color-magnitude relation of galaxies with $r' < 19.5$ and $g' - r' > 0.7$, then selecting galaxies within $\pm 2\sigma$ of the found sequence (where σ is the dispersion around the best fit relation). We refer to the cluster members within $\pm 2\sigma$ of the Red Sequence, and those above this range, as Red Sequence galaxies, and to the cluster members more than 2σ below the Red Sequence as blue galaxies, as shown in Fig. 2.

Table 1. Coordinates, with respect to the cluster center, and radii of the areas of the three main substructures, as found by Owers et al. (2011)

	x_c [Mpc]	y_c [Mpc]	r [Mpc]
S2	0.600	0.763	0.467
S3	2.007	1.567	0.700
S6	2.327	-0.180	0.812

Table 2. Number of galaxies in the three samples.

Sample	n_{tot}	n_{200}
ALL	996	706
RED	564	447
BLUE	278	162

Notes. For each sample, the total number of member galaxies and the number of member galaxies within r_{200} , the latter being the value of the concordance model (see Sect. 4), are shown.

2.2. Removal of substructures

Owers et al. (2011) found some substructures in A2142, probably groups that have been recently accreted by the cluster. These substructures can alter the kinematics of the system since they still retain memory of the infall kinematics. For this reason, we compute the mass profile of the system excluding the galaxies belonging to these substructures. In particular we consider the largest substructures in this cluster, namely S2, S3 and S6, following the nomenclature of Owers et al. (2011). Therefore, we remove galaxies inside circles, the centers and radii of which are reported in Table 1.

2.3. The samples

Some of the techniques (described in Sect. 3) that we use to compute the mass profile of the cluster rely upon the assumption of equilibrium of the galaxy population. Red galaxies are likely an older cluster population than blue galaxies, probably closer to dynamical equilibrium (e.g. Moss & Dickens 1977; van der Marel et al. 2000). For this reason, red galaxies constitute a better sample for the application of such techniques. Among red galaxies, those outside substructures (see Sect. 2.2) are the most likely to be in dynamical equilibrium. We therefore use these galaxies for the determination of the mass profile.

The three samples that will be used hereafter are as follows. We will refer to the sample made of all the member galaxies to as the ALL sample. BLUE will be the sample made of blue galaxies. RED will be the sample made of red galaxies not belonging to the substructures described in Sect. 2.2. See Table 2 for a summary of the number of galaxies belonging to each sample.

3. The techniques

The methods we use, described hereafter, all assume spherical symmetry.

3.1. Methods

DK: The dispersion kurtosis technique, hereafter shortened to DK, first introduced by Łokas (2002), relies upon the joint fit of the los velocity dispersion and kurtosis profiles of the cluster galaxies. In fact, fitting only the los velocity dispersion profile to the theoretical relation coming from the projection (see Mamon & Łokas 2005b for single integral formulae for the case of simple anisotropy profiles) of the Jeans equation (Binney & Tremaine 1987) does not lift the intrinsic degeneracy between mass profile and anisotropy profile determinations (as Łokas & Mamon 2003 showed for the Coma cluster). This technique assumes spherical symmetry and dynamical equilibrium of the system, and it allows to estimate the virial mass, the scale radius and the value of the cluster velocity anisotropy, considered as a constant with radius.

MAMPOSSt: The MAMPOSSt technique, recently developed by Mamon et al. (2013), performs a maximum likelihood fit of the distribution of galaxies in projected phase space, assuming models for the mass profile, the anisotropy profile, the projected number density profile and the 3D velocity distribution. In particular, for our analysis we have used an NFW model for the mass and the projected number density profiles, either a simplified Tired (Tired et al. 2007) profile or a constant value for the anisotropy profile and a Gaussian profile for the 3D velocity distribution. As in the DK method, to apply MAMPOSSt we must assume spherical symmetry and dynamical equilibrium of the system. By this method we estimate the virial mass, the scale radius of the mass density profile and the value of anisotropy of the tracers.

Caustic: The caustic technique, introduced by Diaferio & Geller (1997), is different from the other two methods, as it does not require dynamical equilibrium, but only spherical symmetry. Hence, this technique also provides the mass distribution beyond the virial radius. In projected phase space, member galaxies tend to gather together. Measuring the velocity amplitude \mathcal{A} of the galaxy distribution gives information about the escape velocity of the system. In turn, the escape velocity is related to the potential, hence the mass profile: $M(r) = M(r_0) + (1/G) \int_{r_0}^r \mathcal{A}^2(s) \mathcal{F}_\beta(s) ds$, where $\mathcal{F}_\beta(r) = -2\pi G (3 - \beta)/(2 - \beta) r^2 \rho(r)/\Phi(r)$ (Diaferio 1999).

Since the DK and MAMPOSSt techniques make use of the assumption of dynamical equilibrium of the system, the use of the RED sample allows a more correct application of those techniques, since this sample is likely to be the most relaxed sample. On the other hand, we use the ALL sample for the caustic technique.

3.2. Practical implementation

To compute the parameter values with the MAMPOSSt technique, we performed a Markov Chain Monte Carlo (MCMC) procedure (see, e.g., Lewis & Bridle 2002), using the public CosmoMC code of A. Lewis.³ In MCMC, the parameter space is sampled following a procedure that compares the posterior (likelihood times prior) of a point in this space with that of the previous point, and decides or not to accept the new point following a criterion that depends on the two posteriors (we use the Metropolis-Hastings algorithm). The next point is chosen at random from a hyperellipsoidal gaussian distribution centered

³ <http://cosmologist.info/cosmomc>

on the current point. This procedure ensures that the final density of points in the parameter space is proportional to the posterior probability. MCMC then returns probability distributions as a function of a single parameter, or for several parameters together. Here, the errors on a single parameter are computed by marginalising the posterior probabilities over the other two free parameters.

For the caustic technique, we use the ALL sample, since the equilibrium of the sample is not required, also considering the galaxies beyond the virial radius. To apply the caustic technique, the \mathcal{F}_β parameter (Diaferio 1999) must be chosen. The choice of the parameter is quite arbitrary, hence we have tested 3 different choices: the constant value 0.5, as first suggested in Diaferio (1999), the constant value 0.7 as suggested in Serra et al. (2011), and the profile described in Biviano & Girardi (2003). When using the value 0.7 and the profile of Biviano & Girardi (2003), the estimated virial masses are much greater than those obtained with the other techniques relying on the dynamics of galaxies as well as the results coming from the X-ray and the weak lensing analysis (see below). Therefore we decided to consider only the caustic technique with $\mathcal{F}_\beta = 0.5$ (the same value has been recently adopted by Geller et al. 2013). We adopt $r_0 = 0$, which relieves us from the choice of a mass at some finite radius r_0 . Once we have computed the mass profile, we fit it with a NFW profile to obtain the estimate of the scale radius.

3.3. The scale radius of galaxy distribution

The NFW scale radius of the galaxy distribution is used as input for the DK and MAMPOSSt analyses, therefore it has been computed for the RED sample. The number density profile of the spectroscopic sample is affected by the incompleteness issue. We have corrected it using the completeness profile provided by Owers et al. (2011).

We have divided the cluster in radial bins and counted the galaxies inside each bin. In the bins where galaxies belonging to substructures have been removed and where the presence of a bright star in the cluster field caused a lack of detection, the number density of galaxies is artificially reduced. In order to take this into account, we have assumed the galaxy density in the affected regions to be equal to the mean density in the rest of the bin.

The RED galaxy number density profile is well fit by a projected NFW profile (Łokas & Mamon 2001) with scale radius equal to 0.95 ± 0.14 Mpc. The fit is an MLE fit performed on all RED members with $\chi^2_{\text{reduced}} = 0.83$. The ALL and BLUE samples are less concentrated, the values of the scale radius being 1.84 ± 0.25 Mpc for the ALL sample with $\chi^2_{\text{reduced}} = 2.08$ and 16 ± 11 Mpc for the BLUE sample with $\chi^2_{\text{reduced}} = 0.88$. In Fig. 3 the surface number density profiles for the different samples are shown. The scale radius for the BLUE sample is very high and is due to a very flat distribution of these galaxies.

4. Mass profiles

4.1. Mass profiles obtained from the different methods

We have used the velocities of the galaxies within r_{200}^4 to compute the mass profile of A2142. In Fig. 4, the velocity dispersion profiles are shown, along with the best-fit profiles coming from the DK and MAMPOSSt analyses.

⁴ r_Δ is the radius within which the mean density is Δ times the critical density of the Universe.

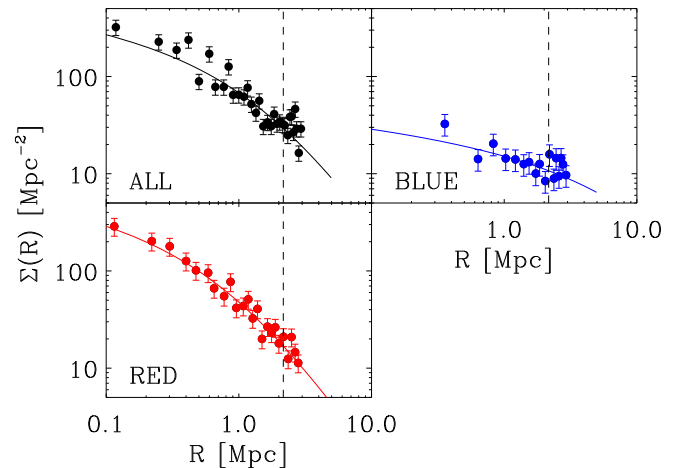


Fig. 3. Surface number density profiles for the ALL, RED and BLUE samples, along with their best-fit projected NFW profiles. The dashed vertical line locates the virial radius of the concordance model (see Sect. 4).

The DK technique assumes a constant value for the anisotropy, while we have chosen 2 profiles for the anisotropy model in MAMPOSSt, a constant value and a Tired profile $\beta(r) = \beta_0 + (\beta_\infty - \beta_0) r / (r + r_{\text{anis}})$. Here, we set $\beta_0 = 0$ (inner isotropy) and set r_{anis} to the scale radius of the galaxy number density profile. In Sect. 5, we compute the anisotropy profile for the RED sample and find that it is not compatible with a Tired profile, therefore we made the *a posteriori* decision not to consider the result of MAMPOSSt with a Tired profile.

We have also tried to assume different mass profiles and velocity anisotropy models in MAMPOSSt, namely a Burkert (Burkert 1995), a Hernquist (Hernquist 1990) and a Softened Isothermal Sphere profile (Geller et al. 1999), all with both constant and Tired profile for the anisotropy. The resulting estimates of virial mass and mass profile concentration are very similar to the case of NFW mass profile with constant anisotropy, with differences of the order of very few percent. We therefore only considered the NFW model for the mass profile.

The results are summarised in Tab. 3. Fig. 5 shows the detailed results of our MAMPOSSt MCMC analysis.

In Fig. 6, we show the mass profiles obtained from the different methods, along with the virial values of mass and radius. The results coming from the X-ray (Akamatsu et al. 2011) and weak lensing (Umetsu et al. 2009, WL hereafter) analysis are also shown.

4.2. Concordance mass profile

We now combine the constraints from the different mass modelling methods to build a *concordance* mass profile. We attempt to give the same weight to kinematics, X-ray and WL in the final estimate of the parameters, so we now compute a single value coming from kinematical techniques for the scale radius, and one for the virial radius. For this we take the mean of the values r_s and r_{200} of the different methods, inversely weighting by the symmetrized errors. Since the measures of these two quantities by the various methods are not independent (as they are based on essentially the same data-sets) we multiply the error on the average by $\sqrt{3}$, 3 being the number of values used to compute

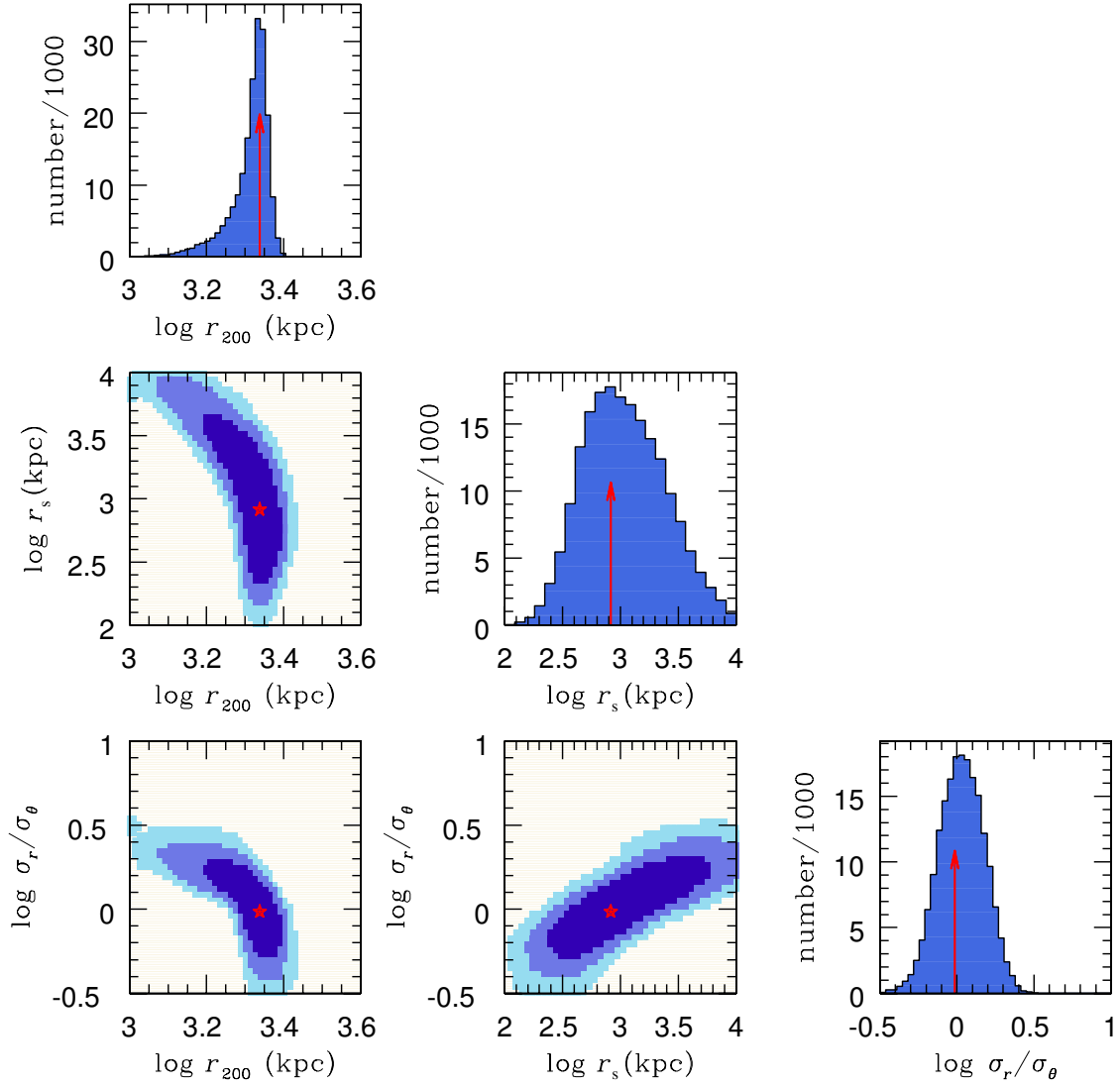


Fig. 5. Parameter space and probability distribution functions for the virial radius, mass profile scale radius and velocity anisotropy, as found by MAMPOSSt. The coloured regions are the 1,2,3 σ confidence regions, while the red stars and the red arrows locate the best-fit values. These are based upon an MCMC analysis with 6 chains of 40 000 elements each, with the first 5000 elements of each chain removed (this is the *burn-in* phase that is sensitive to the starting point of the chain). The priors were flat within the range of each panel, and zero elsewhere.

Table 3. Virial quantities of Abell 2142 obtained from different techniques

Method	sample	M_{200} [$10^{15}M_{\odot}$]	r_{200} [Mpc]	r_s [Mpc]	c	σ_r/σ_t
caustic ($\mathcal{F}_{\beta} = 0.5$)	ALL	$1.26^{+0.54}_{-0.42}$	$2.17^{+0.27}_{-0.28}$	$0.58^{+0.12}_{-0.10}$	3.7 ± 0.9	
DK	RED	$1.32^{+0.11}_{-0.21}$	$2.20^{+0.06}_{-0.12}$	$0.93^{+0.39}_{-0.10}$	2.4 ± 0.6	$1.0^{+0.20}_{-0.04}$
MAMPOSSt	RED	$1.28^{+0.14}_{-0.49}$	$2.18^{+0.08}_{-0.32}$	$0.83^{+1.73}_{-0.35}$	$2.6^{+2.0}_{-1.9}$	$1.0^{+0.50}_{-0.20}$
Kinematics		$1.31^{+0.26}_{-0.23}$	2.19 ± 0.14	0.64 ± 0.17	3.4 ± 0.9	
X-ray		$1.11^{+0.55}_{-0.31}$	$2.08^{+0.30}_{-0.22}$	0.74 ± 0.31	2.8 ± 1.1	
WL		$1.24^{+0.18}_{-0.16}$	2.16 ± 0.10	0.51 ± 0.08	4.3 ± 0.7	
Concordance model		1.25 ± 0.13	2.16 ± 0.08	0.54 ± 0.07	4.0 ± 0.5	

Notes. Values of virial mass, virial radius, scale radius and concentration for different techniques, the average value of the kinematical techniques after symmetrizing the errors, and the value of the concordance model, obtained as the result of the average of all the values coming from the different techniques (see Sect. 5 for the average procedure). X-ray values come from Akamatsu et al. (2011), weak lensing (WL) from Umetsu et al. (2009). Both for X-ray and WL we had the values and the errors of the virial radius and the concentration: we have symmetrized these errors and propagated them to obtain the estimates of the errors on the scale radii.

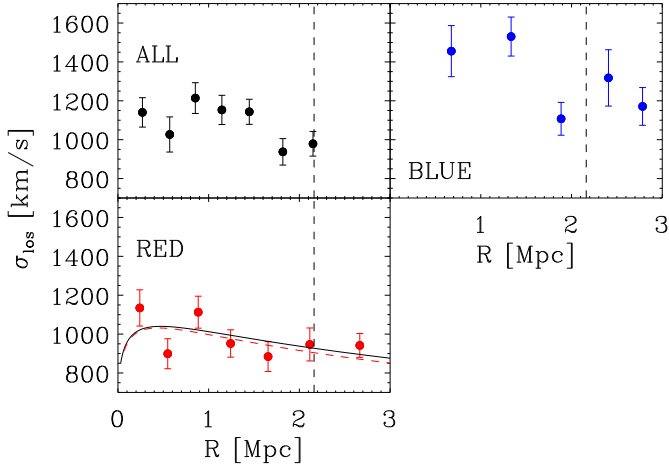


Fig. 4. Velocity dispersion profiles for the ALL, RED and BLUE sample. For the RED sample we also show the best-fit profile coming from the DK analysis (black), and the profile computed after the MAMPOSSt analysis (dashed red). The dashed vertical line locates the virial radius of the concordance model (see Sect. 4).

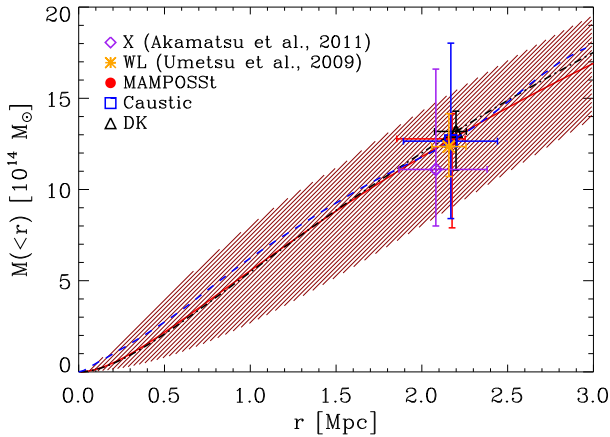


Fig. 6. Mass profiles computed from the different methods. The black dash-dotted line and the triangle with error bars refer to DK technique, the dashed blue line and blue square to the caustic method, the solid red line and red point to MAMPOSSt. The symbols with error bars refer to the virial mass and radius. The purple diamond with error bars is the result of the X-ray analysis, while the orange star is the one coming from weak lensing analysis. The shaded area is the 1σ confidence region of the mass profile according to the MAMPOSSt results.

the average. In fact, the usual error on the weighted average decreases like the square root of the number of values.

The mean value and its error are shown as solid and dashed lines in the left panels of Fig. 7. In the right panels of Fig. 7, we plot the values of scale and virial radius obtained from the three independent methods: kinematics, X-ray and WL. The average error-weighted value and its error, this time computed without multiplication factor (since the three measures are independent), are $r_{200} = 2.16 \pm 0.08$, $r_s = 0.54 \pm 0.07$.

5. Velocity anisotropy profiles

The Jeans equation can be solved for $\beta(r)$ to obtain information about the anisotropy of the orbits of the system. The Jeans equation contains 4 unknown quantities, therefore to solve it we need

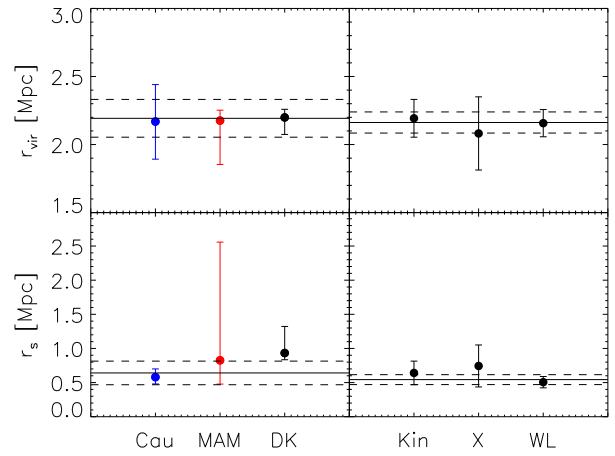


Fig. 7. Virial (top panels) and scale (bottom panels) radius for all the methods. *Left panels:* blue diamonds are values obtained from the caustic technique, red ones for MAMPOSSt, and black ones for DK (from left to right, respectively). The average value and its error are the solid and dashed lines, respectively. See the text for the computation of the error. *Right panels:* values obtained from the kinematical analysis, X-ray and WL (from left to right, respectively). The average value and its error are the solid and dashed lines, respectively.

other 3 relations, namely the Abell integrals to relate the projected number density and velocity dispersion to the real ones and assume a mass profile for the cluster. This *anisotropy inversion* was first solved by Binney & Mamon (1982), but several other authors have provided simpler algorithms. We follow the approach of Solanes & Salvador-Sole (1990), and we test the results by comparing them with those obtained following the approach of Dejonghe & Merritt (1992). Once the mass profile is specified, this procedure is fully non parametric. In fact, instead of fitting the number density profile, we bin and smooth it with the LOWESS technique (see, e.g. Gebhardt et al. 1994). We then obtain the 3D number density profile by using Abel's equation (e.g., Binney & Mamon 1982). In the same way, we smooth the binned σ_{los} profile. This procedure requires the solution of integrals up to infinity. Mamon et al. (2010) showed that a 3σ clipping removes all the interlopers beyond 19 virial radii. Therefore, an extrapolation up to such a distance is enough to solve the integrals having infinity as limit of integration. We use 30 Mpc as the maximum radius of integration, and extrapolate the smoothed profiles up to this limit. A factor 2 change of the upper limit of integration does not affect our results in a significant way.

The result of the anisotropy inversion is shown in Fig. 8. The confidence levels are obtained by estimating two error contributions. One contribution comes from the uncertainties in the number density and σ_{los} profiles. Since the number density profile is affected by much smaller uncertainties than the σ_{los} profile, we only consider the error contribution from the latter. It is virtually impossible to propagate the errors on the observed σ_{los} through the Jeans inversion equations to infer the uncertainties on the β profile solution. We then proceed to estimate these uncertainties the other way round. We modify the β profile in two different ways: 1) $\beta(r) \rightarrow \beta(r) + S + T r$, and 2) $\beta(r) \rightarrow J\beta(r) + Y$, using a wide grid of values for the constants, respectively (S, T) and (J, Y). Using the mass and anisotropy profiles, it is then possible to determine $\sigma_r(r)$ and then the σ_{los} profile (e.g., Mamon & Łokas 2005b). The range of acceptable β profiles is deter-

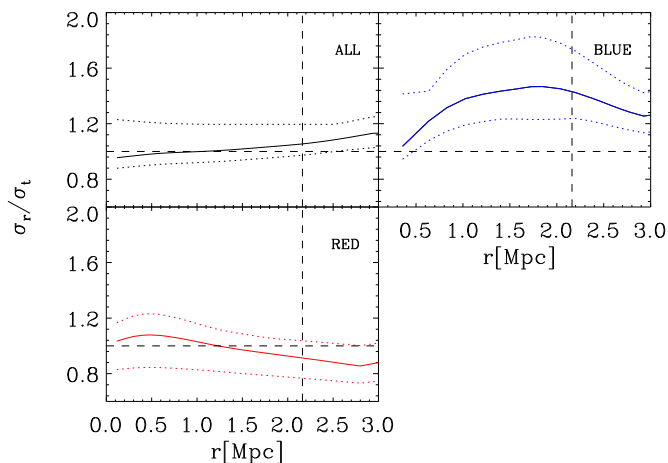


Fig. 8. Velocity anisotropy profile for the ALL, RED and BLUE samples. The solid line is the result of the inversion of the Jeans equation, while the dotted lines are the 1σ confidence intervals. The vertical dashed line locates the virial radius.

mined by a χ^2 comparison of the resulting σ_{los} profiles with the observed one.

In addition, another source of uncertainty on the β profile solution comes from the uncertainty in the mass profile. This is estimated by running the anisotropy inversion for four different mass profiles corresponding to the combination of allowed values of virial and scale radii within 1σ . The profiles obtained modifying the mass profile (not shown) lie within the confidence interval of the main result, hence the confidence interval represents well the uncertainty on the anisotropy profile.

The ALL sample $\beta(r)$ depends weakly on radius: the innermost region is compatible with isotropy, while the anisotropy is increasingly radial at large radii. The RED sample is compatible with isotropy at almost all radii. The difference between the two samples is almost entirely due to the BLUE galaxies, the anisotropy of which is compatible with isotropy in the center, then becomes rapidly radially anisotropic and finally flattens at radii $> 1\text{Mpc}$.

As a check, we compare the values of β obtained from the anisotropy inversion with the best-fit results of DK and MAMPOSSt. In these techniques, we assumed a constant value of the anisotropy for the RED sample, which appears to be a good assumption given the results of β after the inversion. The value estimated by both DK and MAMPOSSt is $\beta = 0.0$, consistent within the uncertainties with the β profile shown in Fig. 8.

6. $Q(r)$ and $\beta - \gamma$ relations

We can take advantage of the results just found for the galaxy populations of A2142 to test the PPSD profile and the relation linking the logarithmic slope of the density profile and the anisotropy $\beta(r)$.

The mass is dominated by dark matter, which is not an observable, so we use the galaxies as tracers of the total matter dynamics. We thus consider the radial velocity dispersion and velocity anisotropy that we measured (using our concordance mass profile) for the galaxies (see Sect. 5), instead of those of the dominant DM, which we cannot directly measure. We still have a choice for the density profile in both the PPSD and the $\beta - \gamma$ relation: it could be either the total density profile or the

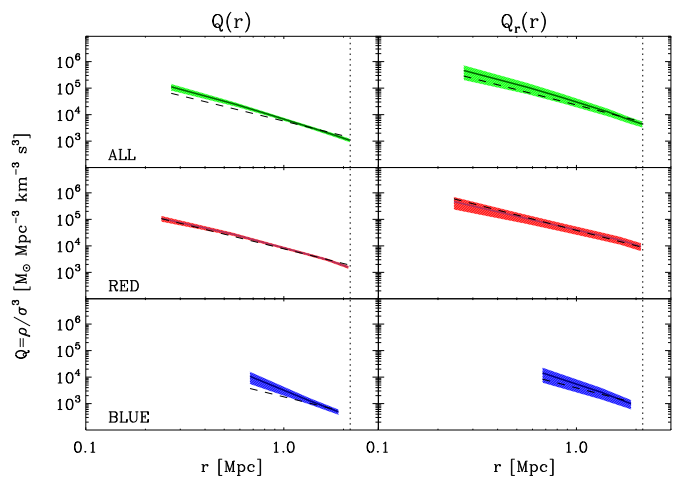


Fig. 9. Radial profiles of Q (left columns) and Q_r (right columns) within the virial radius, and the 1σ confidence regions (shaded areas), for different types of member tracers: green for the ALL sample (top panels), red for the RED sample (middle panels) and blue for the BLUE sample. The shaded areas represent the propagation of the errors associated with ρ , σ and σ_r . The dashed lines are the power-law relations $Q(r) \propto r^{-1.84}$ and $Q_r(r) \propto r^{-1.92}$ found by Dehnen & McLaughlin (2005) on numerically simulated haloes. The vertical dotted lines locate the virial radius of the concordance model (see Sect. 4).

density profile of the tracer for which we compute the radial velocity dispersion and the anisotropy.

6.1. Use of the total matter density profile

We begin by adopting the total density profile $\rho(r)$. We compute both the PPSD profile $Q(r) = \rho/\sigma^3$ and its radial counterpart $Q_r(r) = \rho/\sigma_r^3$. In the top panels of Fig. 9, we show, for the different tracers (ALL, RED, BLUE), the radial profile of $Q(r)$ (left panels) and $Q_r(r)$ (right panels) within the virial radius. In order to compute the errors on the best-fit slope parameters, we have assumed the number of independent Q and Q_r values to be the same as those of the observed velocity dispersion profile (see Fig. 4).

Assuming a power-law behaviour of the PPSD profile, as suggested by Dehnen & McLaughlin (2005), we fit the profiles of both $Q(r)$ and $Q_r(r)$ in two ways: either keeping the exponent fixed to the values found for haloes in ΛCDM simulations by Dehnen & McLaughlin (2005) or considering it as a free parameter. In Table 4 the results of such fits are shown. The $Q(r)$ profile for the RED sample is in good agreement with the $r^{-1.84}$ relation by Dehnen & McLaughlin (2005), the latter being almost always within the confidence interval of our results. The fit of the profile with a linear relation in the log-log plane is compatible with the theoretical value -1.84 within 1.7σ . On the other hand, for the BLUE sample, the slope of the PPSD is steeper than the theoretical expectation.

The $Q_r(r)$ profiles of all 3 samples are in good agreement with the relation that Dehnen & McLaughlin (2005) found for simulated ΛCDM haloes, $r^{-1.92}$. The better agreement for the BLUE sample is due to the relatively larger uncertainty that we have on σ_r with respect to σ , because of the large uncertainties that affect $\beta(r)$. The profile for the RED sample is in agreement with the theoretical relation within 0.3σ .

Table 4. Best-fit parameters of the PPSD profile

	$Q(r)$		$Q_r(r)$	
	A	B	A	B
	[$M_\odot \text{ Mpc}^{-3} \text{ km}^{-3} \text{ s}^3$]		[$M_\odot \text{ Mpc}^{-3} \text{ km}^{-3} \text{ s}^3$]	
Fixed slope				
ALL	5534 ± 314	-1.84	25071 ± 3341	-1.92
RED	7727 ± 391	-1.84	38484 ± 5622	-1.92
BLUE	1753 ± 294	-1.84	3998 ± 1084	-1.92
Free slope				
ALL	6342 ± 367	-2.28 ± 0.11	29175 ± 4223	-2.27 ± 0.24
RED	8034 ± 411	-2.00 ± 0.09	38881 ± 5665	-1.77 ± 0.23
BLUE	3121 ± 793	-2.97 ± 0.50	5413 ± 1810	-2.60 ± 0.67

	$Q(r) \text{ GAL}$		$Q_r(r) \text{ GAL}$	
	A	B	A	B
	[$10^{-9} \text{ Mpc}^{-3} \text{ km}^{-3} \text{ s}^3$]		[$10^{-9} \text{ Mpc}^{-3} \text{ km}^{-3} \text{ s}^3$]	
Fixed slope				
ALL	6.82 ± 0.68	-1.84	28.49 ± 5.37	-1.92
RED	3.62 ± 0.46	-1.84	13.23 ± 3.21	-1.92
BLUE	0.98 ± 0.23	-1.84	1.30 ± 0.47	-1.92
Free slope				
ALL	10.19 ± 25.60	-1.09 ± 0.15	46.94 ± 7.34	-1.09 ± 0.26
RED	8.21 ± 17.01	-0.90 ± 0.14	40.48 ± 6.69	-0.71 ± 0.25
BLUE	0.88 ± 1.81	-0.90 ± 0.61	1.52 ± 0.55	-0.52 ± 0.74

Notes. The PPSD profile is parametrized as $Q(r) = A \cdot r^B$. The first panel at the top shows the results of the fit of $Q(r)$ and $Q_r(r)$ for the different samples, both when keeping fixed the exponent to the values suggested by Dehnen & McLaughlin (2005), and when considering the exponent as a free parameter. In the bottom panel, the one identified by $Q(r) \text{ GAL}$ and $Q_r(r) \text{ GAL}$, the same quantities are shown, but referred to the PPSD computed using the galaxy number density profile instead of the total matter density profile.

Ludlow et al. (2010) warn against fitting the pseudo phase space density profile outside the scale radius, because of the upturn they find in the $Q(r)$ profile in the outer regions. However, for our 3 samples, none of the $Q(r)$ and $Q_r(r)$ profiles show significant curvature in log-log space.

In Fig. 10, we show the $\beta(r) - \gamma(r)$ relation. The $\beta - \gamma$ relation of the ALL sample matches well that found by Hansen & Moore (2006) on single-component dissipationless simulations (cosmological and academic). However, the $\beta - \gamma$ relation for the RED sample shows curvature, with lower values of β at the steeper slopes (larger radii) than found in simulations by Hansen & Moore (2006).

6.2. Use of the tracer density profile

We now repeat our analyses of the PPSD and the $\beta - \gamma$ relations, replacing the total mass density with the number density of the tracer of the sample.

In Fig 11, we show the PPSD computed using the galaxy number density profile instead of the total matter density one. For all three samples, both $Q(r)$ and $Q_r(r)$ remain as power laws,

but are considerably shallower than the relation found by Dehnen & McLaughlin (2005) on simulated Λ CDM halos.

In Fig. 12, we show the $\beta - \gamma$ relation computed using the galaxy number density profile instead of the total matter density one. The behaviour does not change significantly from the case of the $\beta - \gamma$ relation computed using the total matter density profile: the global shapes of the profiles are similar but the BLUE sample now presents a noisier profile, while ALL and RED profiles are shifted toward higher values of γ , reflecting the shallower trend of the galaxy number density profile with respect to the matter density one.

7. Conclusions and Discussion

We have computed the mass and velocity anisotropy profiles of A2142, a nearby ($z = 0.09$) cluster, using the kinematics of cluster galaxies. After a membership algorithm was applied, we considered the sample made of all members (ALL sample), as well as two subsamples, consisting in blue member galaxies (BLUE sample) and in red member galaxies that do not belong to substructures (RED sample).

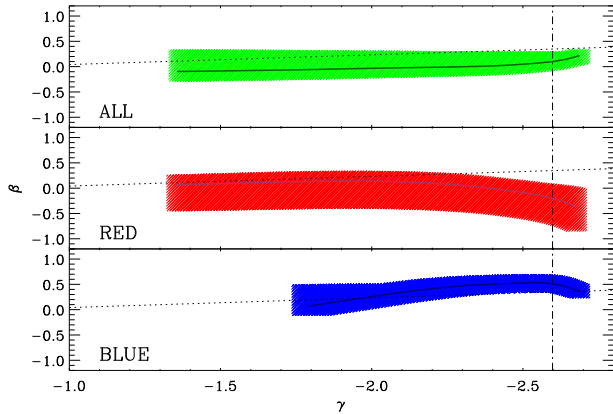


Fig. 10. Velocity anisotropy versus logarithmic slope of the total density profile. The samples are ALL galaxies (top), RED (middle) and BLUE galaxies (bottom panel). The dashed areas are the 1σ confidence regions. The β – γ relation found by Hansen & Moore (2006) for single-component dissipationless simulations is shown as the dotted lines. The vertical dot-dashed line locates the value of γ relative to the virial radius.

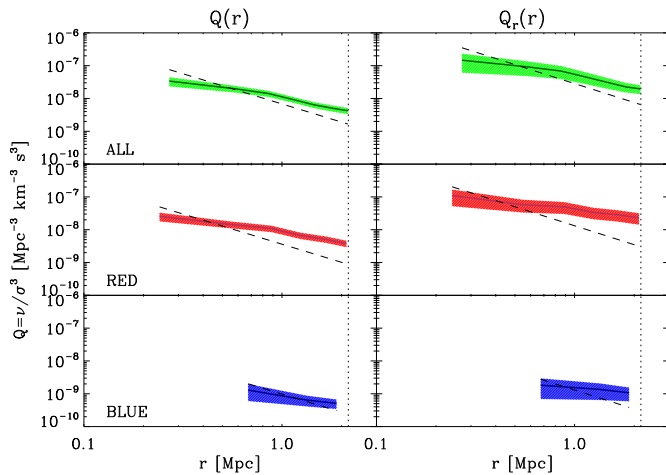


Fig. 11. Same as Fig. 9, but now using the radial profiles of galaxy number density instead of total mass density to estimate the PPSD.

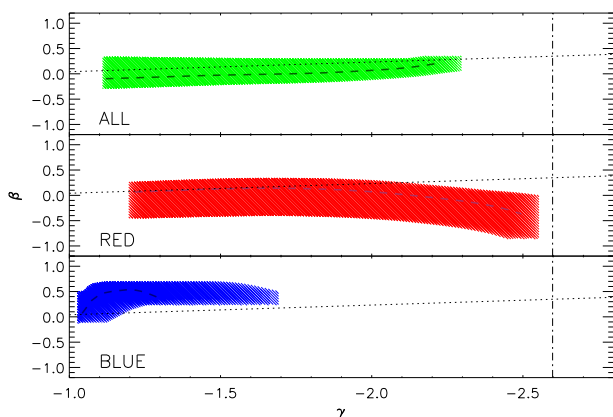


Fig. 12. Same as Fig. 10, but now using the radial profiles of galaxy number density of the three samples instead of total mass density to estimate the slope.

We have made use of three methods based on the kinematics of galaxies in spherical clusters: DK, MAMPOSSt and Caustic (see Sect. 3). The mass profiles, as well as the virial values of the mass and the radius, are consistent among the different methods, and in agreement with the results coming from the X-ray (Akamatsu et al. 2011) and the weak lensing (Umetsu et al. 2009) analyses. Serra et al. (2011) found that the caustic technique tends to overestimate the value of mass in the central region of a cluster. Our results appear consistent with this finding, the caustic mass profile increasing more rapidly with radius in the inner part with respect to the profiles coming from DK and MAMPOSSt.

Munari et al. (2013) report the scaling relation between the virial mass of clusters and the velocity dispersion of the member galaxies within the virial sphere. Using the most realistic (“AGN”) hydrodynamical simulation at their disposal, they find $\sigma_{1D} = 1177 [h(z) M_{200}/10^{15} M_{\odot}]^{0.364}$ for the galaxies within the virial sphere, where σ_{1D} is the total 3D velocity dispersion within r_{200} , divided by $\sqrt{3}$. The analysis was carried out in the 6D phase space, hence is immune to projection effects. Nevertheless, because of the statistical nature of the relation they find, it provides a relation which is likely to hold for real, observed systems in a relaxed state. As a test, we check the consistency of the velocity dispersion – mass relation found by Munari et al. (2013) with our findings for A2142. The values of virial mass obtained with this relation are as follows: $1.42 \times 10^{15} M_{\odot}$ for the ALL sample, $1.07 \times 10^{15} M_{\odot}$ for the RED sample and $2.50 \times 10^{15} M_{\odot}$ for the BLUE sample. The values obtained for the ALL and RED samples are in agreement, within the uncertainties, with the concordance value of the mass of A2142. This seems to indicate that RED cluster members are in, or very close to, equilibrium. The large difference obtained for the BLUE cluster members warns against using the blue galaxy los velocity dispersion as a proxy for the cluster mass.

A glance at Table 3 indicates that our different estimates of the mass concentrations are bimodal: the caustic and weak lensing have values ≈ 4 , while those for the DK, MAMPOSSt and X-ray methods are < 3 .

Could these lower mass concentrations found by methods based upon internal kinematics be a sign that A2142 is out of dynamical equilibrium? The substructures found by Owers et al. (2011) and the results by Rossetti et al. (2013) on the importance of the mergers undergone by A2142 suggest that full relaxation is to be excluded. On the other hand, the agreement on the virial radius among the different method and with the results from X-ray and lensing (the latter of which does not require equilibrium) suggests that A2142 is not far from dynamical equilibrium. This allows us to assume a concordance model for the mass profile, with $M_{200} = (1.25 \pm 0.13) \times 10^{15} M_{\odot}$ and $c = 4.0 \pm 0.5$.

Previous studies based on the kinematics of galaxies in clusters have shown that galaxy populations have similar concentrations to those of the total matter, or slightly smaller, blue galaxies being instead much less concentrated (see, e.g., Biviano & Girardi 2003; Katgert et al. 2004). On the other hand, Biviano & Poggianti (2009) found in the ENACS clusters that the red galaxy population has a concentration that is as much as 1.7 times lower than that of the total matter density profile. Here, we find that the scale radius for the RED galaxy number density profile (0.95 kpc) is 1.8 times greater than that of the total mass density profile from our concordance model, which is in agreement with the ENACS result.

The scale radius of the BLUE population in Abell 2142 appears unusually high, leading to a concentration (using our concordance virial radius) of 0.16 (best) or 0.39 (+1 σ), which are

much lower than expected from previous studies. Blue galaxies within the virial cones of clusters are more prone to projection effects than red galaxies: Mahajan et al. (2011) analysed clusters and their member galaxies in the SDSS, using los velocities and cosmological simulations to quantify the projection effects. They conclude that $44 \pm 2\%$ of galaxies with recent (or ongoing) starbursts that are within the virial cone are outside the virial sphere. Since galaxies with recent star formation have blue colours, our BLUE sample includes this recent-starburst subsample, plus perhaps some more galaxies with more moderate recent star formation. Moreover, an analysis of cosmological simulations by Mamon et al. (2010) indicates that there is a high cosmic variance in the fraction of interlopers within the DM particles inside the virial cone. This suggests that the unusually low concentration of the blue galaxy sample could be a sign of an unusually high level of velocity interlopers with low rest frame velocities in front and behind Abell 2142.

Wojtak & Łokas (2010) found a virial radius that corresponds to $r_{200} = 2.15^{+0.10}_{-0.12}$ Mpc, in excellent agreement with our different estimates of the virial radius (Table 3). On the other hand, they find a scale radius $r_s = 1.0^{+0.3}_{-0.2}$ Mpc not compatible with our value of the concordance model, although in agreement with the results of the DK, MAMPOSSt and X-ray analyses. Note that Wojtak & Łokas assumed that the DM and galaxy scale radii were equal. Such an unverified assumption may have biased high their scale radius for the mass distribution. On the other hand, the values of the DM scale radii that we found from DK and MAMPOSSt (0.93 and 0.83 Mpc, respectively, see Table 3) are quite close to that of the RED galaxy population used as the tracer (0.95 Mpc).

The parameters describing the mass profile are then used to invert the Jeans equation and compute the velocity anisotropy for the three different samples considered. Despite large uncertainties, the $\beta(r)$ profile for the full set of cluster members is compatible with isotropy, becoming weakly radially anisotropic in the outer regions. The behaviour of the RED sample is different. Although compatible within 1σ with isotropy at all radii within r_{200} , it has a marginally significant decreasing slope, starting slightly radially anisotropic in the center and becoming slightly tangentially anisotropic at large radii. The difference between the $\beta(r)$ profiles for the ALL sample and the RED sample is mainly due to the behaviour of the BLUE sample, which shows radial anisotropy at all radii except in the center where it is isotropic.

The velocity anisotropy profile for the ALL sample in the center is compatible with that found by Wojtak & Łokas (2010). In the outer part, at ≈ 3 Mpc, the value of σ_r/σ_θ found by Wojtak & Łokas (2010) is higher and 1.4σ distant from ours. Analysing a stacked sample of 107 ENACS clusters, Biviano & Katgert (2004) found the orbits of ellipticals and S0s (hence red) galaxies to be compatible with isotropy and those of early and late-type spirals to have radial anisotropy. The velocity anisotropy profile for our BLUE sample presents a behaviour that lies in between the profiles found in Biviano & Katgert for the early spirals and the late spirals together with emission line galaxies, suggesting agreement between their findings and ours. The anisotropy profiles we found for the ALL sample appears to be consistent with that measured in simulated Λ CDM haloes by Lemze et al. (2012). The scatter in the anisotropy profiles is considerable in the above-mentioned papers and this reflects the variety of configurations of galaxy clusters. In this sense, the behaviour of the anisotropy of A2142 does not present strong deviations from the general trend.

With the information obtained on A2142, we are able to test some theoretical relations regarding the interplay between the mass distribution and the internal kinematics of a cluster. We investigated the radial profile of the pseudo phase space density $Q(r)$, as well as its radial counterpart $Q_r(r)$. When we consider the total density profile to compute Q and Q_r , we find that the profiles for A2142 are weakly consistent with the theoretical expectations (Dehnen & McLaughlin 2005; Ludlow et al. 2010) when considering the ALL sample, but a good agreement is observed in the RED sample. This strengthens the scenario of blue galaxies being a population of galaxies recently fallen into clusters, that have had no time to reach an equilibrium configuration yet, or are heavily contaminated by interlopers.

Biviano et al. (2013) have performed a similar analysis on MACS1206, a cluster at $z = 0.44$. They find a $Q(r)$ profile with a slope for the blue galaxies in agreement with the predictions of Dehnen & McLaughlin (2005). We speculate that this different behaviour might provide a hint on the dynamical history of clusters. In fact, a cluster that has undergone the phase of violent relaxation only recently might present a population of blue galaxies in equilibrium. On the other hand, a cluster that has undergone the violent relaxation phase since long, should have had time to transform its blue galaxies into red ones. Therefore the blue galaxy population would be mainly composed of only recently accreted galaxies, hence not in dynamical equilibrium.

We estimate the PPSD profile of the total matter making the assumption that the galaxy velocity dispersion is a good proxy for the total matter dynamics. When we replace the total mass density by the number density of the tracer for which we compute the velocity dispersion, the PPSDs are shallower power-laws than those found by Dehnen & McLaughlin (2005) in simulated Λ CDM haloes.

The anisotropy configuration of the internal kinematics reflects the formation history of the cluster. Therefore we expect a relation between the anisotropy and the potential of the cluster. A relation linking the $\beta(r)$ profile and $\gamma(r)$, the logarithmic slope of the potential, has been analysed and compared to the theoretical results provided by Hansen & Moore (2006), resulting in a weak agreement. A correlation between the β and γ appears to hold out to $\gamma \approx -2.3$ in the RED sample, corresponding to a radial distance $\approx 0.5 r_{200} \approx 1$ Mpc. Interestingly, cluster-mass simulated Λ CDM haloes also follow the Hansen & Moore relation out to slopes of $\gamma \approx -2.3$ but not beyond (see Fig. 17 of Lemze et al. 2012). Our considerations do not change when we compute the β - γ relation using the logarithmic slope of the number density profile of galaxies instead of the total matter density profile.

This brings the question of what is more relevant for galaxy clusters: the total mass density or the tracer number density? One can argue that the PPSDs found in Λ CDM haloes are the consequence of the global gravitational potential (hence total mass profile), violent relaxation, or more generally the mass assembly of clusters through a combination of a several major mergers and numerous minor mergers. Alternatively, one can argue that it is inconsistent to associate the total density profile to the tracer velocity dispersion profile and that one should instead associate the tracer density profile to the tracer velocity dispersion profile. Similar questions arise for the origin of the NFW model for density profiles on one hand and of the $\beta - \gamma$ relation on the other.

For giant elliptical galaxies, the NFW model must apply to the DM component, while the observed tracer applies for $\beta - \gamma$. Indeed, Mamon & Łokas (2005a) have shown that the observed inner aperture velocity dispersions are too high to be matched by

a single NFW component (while the addition of a stellar Sérsic component matches the observations). Moreover, in the elliptical galaxy remnants of binary mergers of spiral galaxies made of stars, gas and DM, the $\beta - \gamma$ relation is well obeyed by the stellar component (Mamon et al. 2006), but not well with the slope of the total mass density profile (Mamon, unpublished).

So it is surprising that the PPSDs that we measure for Abell 2142 match better the relations found in Λ CDM haloes when the total density profile is used instead of the density profile of the tracer used to estimate the velocity dispersion. Perhaps one should not expect clusters to behave as elliptical galaxies. Indeed, in comparison with the progenitors of elliptical galaxies, the progenitors of clusters (galaxy groups) have deeper gravitational potentials that more effectively prevent cooling and dissipative contraction of gas. Moreover, cluster-mass halos grow relatively faster at $z = 0$ than galaxy-mass halos (e.g., van den Bosch 2002), hence are built by more recent mergers than elliptical galaxies, and these mergers, some major, will mix the inner regions. For this reason, the baryonic and DM mass distributions in clusters are closer than in elliptical galaxies.

At all radii, the RED galaxy sample shows somewhat lower β for given γ (measured with total mass density) than found in simulated haloes. This slight mismatch might be due to the use of galaxies as tracers of the internal kinematics of the cluster. In fact, it has been shown (see e.g. Ludlow et al. 2010; Munari et al. 2013) that galaxies and DM may have different kinematics. Furthermore, the above-mentioned relations have been derived using DM-only simulations, therefore the effect of the presence of baryons is not taken into account. Finally, the $\beta - \gamma$ relation may vary from cluster to cluster (Ludlow et al. 2011).

Before reaching any conclusion, we must keep in mind that the present theoretical studies are lacking the influence of the baryonic physics, as well as the dynamical processes acting on galaxies but not on DM particles. This might induce the differences when comparing the theoretical predictions with the observational results.

When we will have a better control on these properties, the PPSD might provide a powerful tool for the study of structure formation. As an example, the PPSD of the blue galaxies in A2142 appears very different from that found for the blue galaxies in another cluster, MACS J1206.2–0847 at $z = 0.44$ (Biviano et al. 2013). This discrepancy suggests interesting perspectives for the comprehension of the formation of galaxy clusters.

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