

LETTER TO THE EDITOR

# Measuring the dark matter velocity anisotropy in galaxy clusters

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## ABSTRACT

**Aims.** The Universe contains approximately 6 times more dark matter than normal baryonic matter, and directly observed fundamental difference between dark matter and baryons would both be significant for our understanding of dark matter structures and provide us with information about the basic characteristics of the dark matter particle. We discuss one distinctive feature of dark matter structures in equilibrium, namely the property that a local dark matter temperature may depend on direction. This is in stark contrast to baryonic gases.

**Methods.** We used X-ray observations of two nearby, relaxed galaxy clusters, under the assumptions of hydrostatic equilibrium and identical dark matter and gas temperatures in the outer cluster region, to measure this dark matter temperature anisotropy  $\beta_{\text{dm}}$ , with non-parametric Monte Carlo methods.

**Results.** We find that  $\beta_{\text{dm}}$  is greater than the value predicted for baryonic gases,  $\beta_{\text{gas}} = 0$ , at more than  $3\sigma$  confidence. The observed value of the temperature anisotropy is in fair agreement with the results of cosmological  $N$ -body simulations and shows that the equilibration of the dark matter particles is not governed by local point-like interactions in contrast to baryonic gases.

**Key words.** cosmology: dark matter – galaxies: clusters: general – galaxies: clusters: individual: A2052 – galaxies: clusters: individual: Sersic 159-03

## 1. Introduction

The possibility that the temperature of the dark matter depends on direction is usually expressed through the velocity anisotropy

$$\beta_{\text{dm}} \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2}, \quad (1)$$

where  $\sigma_t^2$  and  $\sigma_r^2$  are the 1-dimensional tangential and radial velocity dispersions in a spherical system (Binney & Tremaine 1987). Our intuition from classical gases leads us to loosely refer to these dispersions as the dark matter temperatures in the tangential and radial directions with respect to the centre of the galaxy cluster. If most dark matter particles in an equilibrated structure were purely on radial orbits, then  $\beta_{\text{dm}}$  could be as large as 1 and, for mainly tangential orbits  $\beta_{\text{dm}}$  could be arbitrarily large and negative.

The temperature of a baryonic gas is only well-defined when the gas is locally in thermal equilibrium, and this gas equilibration is achieved through point-like interactions. In that case the gas temperature is independent of direction, which is expressed as  $\beta_{\text{gas}} = 0$ . This is because the mean free path, typically in the tens of kpc (Sarazin 1986), is much shorter than the cluster scale of Mpc. If dark matter was collisional and hence achieved equilibration through collisions, then one would also have  $\beta_{\text{dm}} = 0$ .

Numerical  $N$ -body simulations of collision-less dark matter particles show that the dark matter temperature anisotropy is different from zero, and for galaxy clusters these simulations show that  $\beta_{\text{dm}}$  goes from zero in the central region to 0.4–0.6 towards the outer region (Cole & Lacey 1996; Carlberg et al. 1997; Hansen & Moore 2006; Hansen & Stadel 2006). A mass-averaged  $\beta_{\text{dm}}$  is close to 0.3.

During the assembly of galaxy clusters, the baryonic gas is shock-heated and eventually achieves energy equipartition with the gravitationally dominating dark matter at a temperature that is directly related to the temperature of the dark matter. This is true as long as radiation and similar non-gravitational effects are negligible. The most sensible definition of dark matter temperature is by averaging over the 3 directions

$$T_{\text{dm}} \frac{k_{\text{B}}}{\mu m_{\text{p}}} \equiv \frac{1}{3} (\sigma_r^2 + 2\sigma_t^2) = \sigma_r^2 \left( 1 - \frac{2}{3}\beta_{\text{dm}} \right) \quad (2)$$

and we describe in the next section how to derive this dark matter temperature from X-ray observations of the gas. Here  $k_{\text{B}}$  is the Boltzmann constant,  $m_{\text{p}}$  the proton mass, and  $\mu$  the mean molecular weight (we assume  $\mu = 0.61$ ). We later discuss to what extent the assumption of equality between gas and dark matter temperatures is supported by numerical simulations (from an average over a large set of simulated clusters, some of which are significantly more perturbed than the ones considered here), and estimate the possible effect on  $\beta_{\text{dm}}$ .

Our approach does not make any assumptions about the parametric form of mass or dispersion profiles in contrast to earlier related studies (Natarajan & Kneib 1996; Ikebe et al. 2004). We later demand that the reconstructed dark matter temperature and the observed gas temperature must be equal in equilibrated regions that are not affected by radiative processes. This is a fair assumption since it only relies on the principle of equipartition between the dark matter and the gas. However, we emphasise that this is an assumption to be tested in the near future on high-resolution numerical simulations.

## 2. Finding the dark matter temperature

For relaxed and spherically symmetric galaxy clusters, one can use X-ray observations of the hot, ionized gas to deduce the de-projected gas temperature and gas density as functions of radius. These are needed in the equation of hydrostatic equilibrium (Fabricant et al. 1980; Sarazin 1986), which for spherical structures relates the total mass of gravitating matter at a given radius to the radial dependence of gas temperature and density

$$M(r) = -\frac{k_B T_e(r) r}{\mu m_p G} \left( \frac{d \ln n_e}{d \ln r} + \frac{d \ln T_e}{d \ln r} \right), \quad (3)$$

where  $G$  is the gravitational constant. We here assume that turbulence is negligible, which will have to be tested in the future e.g. by using line-broadening in metal lines (Sunyaev et al. 2003).

We consider two highly relaxed clusters, which are likely to have only very little turbulence. That equilibrated structures have reliably reconstructed mass (i.e. obey the hydrostatic equilibrium) was supported in the comparison between lensing and X-ray observations (Allen 1998). We also assume that non-gravitational entropy injection into the baryonic gas (e.g. from a central AGN) can be ignored in the region we consider. Radio cavities are typically located within much smaller cluster-centric distances than those excised in our analysis (e.g. Bîrzan et al. 2004). We thus have both the total mass and the baryonic mass (since the cluster plasma is optically thin); since the stellar component is negligible (Fukugita et al. 1998), we can easily get the dark matter mass and dark matter density as functions of radius.

To make the connection with the dark matter temperature, we must consider the Jeans equation (Binney & Tremaine 1987), which relates the dark matter density and velocity dispersions with the total gravitating mass:

$$M(r) = -\frac{\sigma_r^2 r}{G} \left( \frac{d \ln \rho}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta_{\text{dm}} \right). \quad (4)$$

We are assuming that the Jeans equation for spherical structures is accurate for dark matter, which has been shown to be a good assumption by numerical simulations (Rasia et al. 2004). Equation (4) can be integrated to give

$$\sigma_r^2(R) = \frac{G}{\tilde{\rho}(R)} \int_R^\infty \frac{M(r) \tilde{\rho}(r)}{r^2} dr, \quad (5)$$

where  $\tilde{\rho}$  is defined from the dark matter density and anisotropy

$$\frac{d \ln \tilde{\rho}}{d \ln r} = \frac{d \ln \rho_{\text{dm}}}{d \ln r} + 2\beta_{\text{dm}}. \quad (6)$$

Equations (3)–(6) provide all the tools needed to use the observed gas density and gas temperature to derive the dark matter temperature. The only free parameter is the dark matter anisotropy,  $\beta_{\text{dm}}$ . We assume for simplicity that  $\beta_{\text{dm}}$  can be treated as a constant throughout the observed part of the galaxy cluster, a simplification that future data clearly will be able to lift. Thus, for any given value of  $\beta_{\text{dm}}$ , we can calculate the DM temperature, which can then be compared with the gas temperature. This gives us the possibility of comparing different values of  $\beta_{\text{dm}}$  by standard statistical means.

## 3. Two quiet clusters

We used X-ray data from *XMM-Newton* of the two nearby galaxy clusters A 2052 and Sérsic 159–03 (also known as Abell S1101). These are highly relaxed clusters, where a temperature decrement in the central region is clearly identified in the de-projected

data (Kaastra et al. 2004; Piffaretti et al. 2005). These two clusters were chosen for three reasons. First of all, to extract the dark matter temperature non-parametrically one needs data at large radii. Secondly, the cluster surface-brightness map must be highly circular, with no evidence of a substructure, and the visual inspection of the de-projected temperature must show a smooth behaviour, indicating a fully relaxed cluster. Finally, the de-projected gas temperature must be robustly observed. These clusters were analysed assuming the standard cosmological  $\Lambda$ CDM model by Piffaretti et al. (2005), who show that the outer temperature decreases by approximately 30% from the maximum temperature. These authors also show that a one-component gas temperature gives an excellent fit to the observed spectra. Even though the gas temperature profiles of these two clusters are slightly different, they both appear to provide a fair fit to a universal temperature profile (Piffaretti et al. 2005).

## 4. Non-parametric analysis

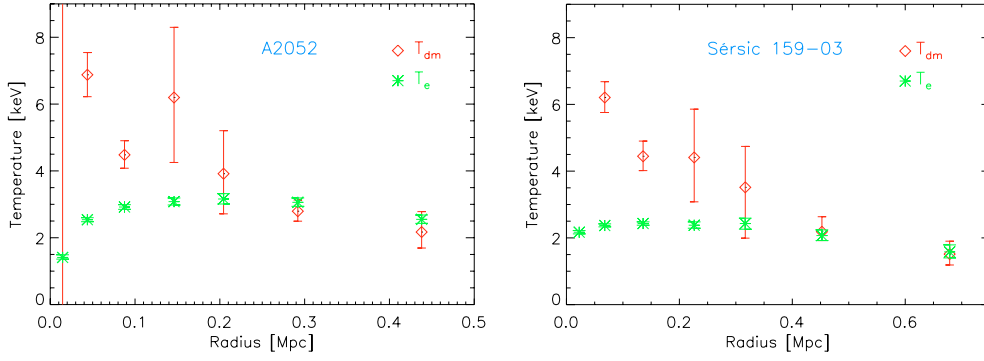
We treat the data in an entirely non-parametric way by Monte Carlo methods. The input data is a set of 7 radial values for the de-projected gas temperature and density and their corresponding error bars. These are determined from de-projected, spatially resolved spectra. A detailed description of the de-projection technique is given in Kaastra et al. (2004).

For each radial bin, we select randomly a temperature and density with a Gaussian-distributed value around the observed number and a width corresponding to the observed error bars. We then use the equation of hydrostatic equilibrium (Eq. (3)) to derive the total mass as function of radius. This total mass extends only to a radius of 0.5–0.8 Mpc, so we select a random number between  $-4$  and  $-2$  for the logarithmic dark matter density slope at larger radii, which is a larger range than expectations from both simulation and theory (e.g. Diemand et al. 2004). The gas mass is already negligible beyond the outermost bin. We checked that varying these assumptions has virtually no influence on the results.

We can now subtract the gas mass from the total mass. Having both the total mass and the dark matter density as functions of radius, as well as the assumed value for  $\beta_{\text{dm}}$ , allows us to integrate Eq. (5) and hence get the dark matter temperature from Eq. (2). At no point do we make any assumption about the form of the dark matter or gas profiles, nor about boundary conditions. This is in contrast to earlier related studies (Natarajan & Kneib 1996; Ikebe et al. 2004).

For each radial bin we now generate 10 000 models, and we can proceed with a frequentists statistical analysis. We calculate the median value of all the derived model temperatures, and we select the range covered by the central 70–75% of these models as representative of the error bars of the reconstructed dark matter temperature,  $\Delta T_{\text{dm}}$ . This number of central models is chosen to make the best  $\chi^2$  per degree of freedom of order unity. We are being conservative since we are including more than the normal 68% of the models, corresponding to 1 standard deviation for a Gaussian probability distribution. As total error bar we use the quadratic sum of this reconstructed error and the observed temperature error bars,  $\Delta T_e$  (which is anyway much smaller). It is worthwhile to mention that a few of the produced models are non-physical in the sense that they may have decreasing mass locally; however, we choose the most conservative approach and keep all models, hence slightly increasing the error bars while only very mildly shifting the median.

In Fig. 1 we show the observed gas and reconstructed dark matter temperatures for A 2052 (top-panel) and Sérsic 159–03



**Fig. 1.** Observed baryonic (green stars) and reconstructed dark matter (red diamonds) temperatures with error bars for A 2052 (*top*) and Sérsic 159–03 (*bottom*), as function of radius. A dark matter velocity anisotropy of  $\beta_{\text{dm}} = 0.6$  is assumed in both plots, because it gives a reasonable fit to the outer region. The radiative cooling is prominent in the central dense region, and in the analysis we include only the 4 outermost temperature bins.

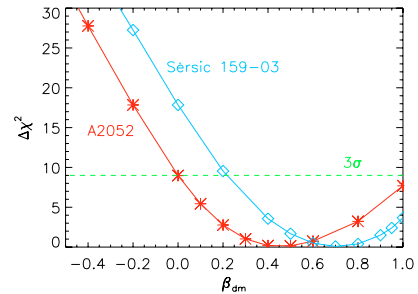
(bottom panel), with their corresponding error bars, for the case of  $\beta_{\text{dm}} = 0.6$ . We see from Fig. 1 that the gas and dark matter temperatures are in good agreement in the outer region. This value of  $\beta$  was chosen because it leads to reasonable agreement between the dark matter and gas temperatures. For a different value of  $\beta$ , the reconstructed DM temperature will be different according to Eqs. (2), (5). The main effect comes from Eq. (2) and shows that a smaller (or negative)  $\beta$  will imply a higher reconstructed temperature.

There are large radial variations due to the non-parametric treatment: small non-monotonous variations in the measured gas temperature and density imply non-trivial variation in the reconstructed dark matter temperature. Similarly, the error bars of the reconstructed dark matter temperature directly reflect the error bars of the measured gas density and especially temperature.

The central region of the cluster is very dense, and the gas temperature is most likely governed by radiative and conductive processes (e.g. Sarazin 1986), so we expect the dark matter and gas temperatures to agree only in the outer part. The corresponding radius where radiative processes become important is roughly where the temperature starts decreasing as one approaches the centre. In particular, the central dark matter temperatures appear to have a quite different radial behaviour from the shape expected from numerical simulations (e.g. Eke et al. 1998; Rasia et al. 2004). This is clearly related to these being derived directly from the gas profile, which is strongly affected in the central region by non-gravitational processes. The most recent numerical simulations show good agreement between the simulated and observed gas temperatures in the outer region (Pratt et al. 2007), whereas the central region still allows for improvements in the simulations to reach agreement with observations.

We have discussed how to reconstruct the dark matter temperature for a given assumed velocity anisotropy above. We therefore proceed and reconstruct the DM temperature for a range of different velocity anisotropies, and then compare them.

We assume that gas and DM temperatures in the 4 outer-most radial bins must agree and do thus not include the region dominated by radiative processes. This allows us to perform a  $\chi^2$  comparison between the reconstructed model and the observed temperature. We show the resulting figure of  $\Delta\chi^2$  as a function of  $\beta_{\text{dm}}$  in Fig. 2. One finds that a positive and non-zero dark matter anisotropy is preferred, with  $\beta_{\text{dm}} > 0.2$  for Sérsic 159–03 (and  $\beta_{\text{dm}} > 0$  for A 2052) at  $\Delta\chi^2 = 9$ , corresponding to  $3\sigma$  confidence. The two structures have  $\beta_{\text{dm}} < 1$  only at  $\Delta\chi^2 = 3(7)$ . This is the first time the dark matter temperature anisotropy has been



**Fig. 2.**  $\Delta\chi^2$  as a function of  $\beta_{\text{dm}}$ . Both galaxy clusters have a preference for radial dark matter velocity anisotropy, with best-fit values at 0.45 (A 2052, red stars) and 0.7 (Sérsic 159–03, blue diamonds). The  $3\sigma$  confidence level is shown with the horizontal (green dashed) line. A vanishing  $\beta_{\text{dm}}$  is ruled out at  $\Delta\chi^2$  of 9 and 18.

measured, and it is comforting that it agrees fairly well with cosmological  $N$ -body simulations, which find  $\beta_{\text{dm}} \sim 0.3$ . We emphasise that we do not claim that the clusters have anisotropies of 0.45 or 0.7 (which naturally would disagree with numerical simulations), but are merely stating that the anisotropies are greater than zero and consistent with numerical simulations.

For robustness we checked that keeping 68% of the models gives  $\chi^2$  per degree of freedom of 1.5 for A 2052 (and 1.1 for Sérsic 159–03), while keeping the best-fit points for  $\beta_{\text{dm}}$  virtually unchanged. In this case the resulting error bars of  $\beta_{\text{dm}}$  become slightly more stringent.

We performed the same study using only the outermost 3 bins in the statistical analysis, and the central values for  $\beta_{\text{dm}}$  were found to be near 0.4 for A 2052 and at 0.7 for Sérsic 159–03, in excellent agreement with the results above. In this case one only keeps 40% of the models in order to get  $\chi^2/\text{d.o.f.}$  close to unity, so we do not trust the resulting (slightly more restrictive) confidence interval for  $\beta_{\text{dm}}$  in that case.

## 5. Discussion

The selected clusters appear to be fully relaxed; however, as noted above, the possibility of bulk motion in the gas still exists. Such a bulk motion implies that the reconstructed total mass is underestimated since there will then be an extra term on the r.h.s. of Eq. (3). Numerical simulations, including both gas and DM, have shown that for equilibrated structures this underestimation in the reconstructed mass is less than 15% (Rasia et al. 2004).

This implies that  $\sigma_r^2$  is underestimated by at most 15% (Eq. (5)). In addition, the dark matter temperature will be underestimated, since the energy of the gas also contains a term from the bulk motion. This underestimate is also at most 15% (Rasia et al. 2004) in the region considered. These two effects partially (possibly almost totally) cancel out in the determination of the velocity anisotropy. Therefore  $\beta_{\text{dm}}$  is accurately determined, and the error from a possible bulk motion in the gas is significantly smaller than 20% (see Eq. (2))<sup>1</sup>.

We have here considered two clusters that both have a central temperature decrement, and we see that the reconstructed dark matter temperature is very different from the gas temperature in the central region. There is growing evidence that clusters separate into two distinct classes, where one class has decreasing central temperature, the so-called cool-core clusters like the two structures considered here, and the second class has a roughly constant temperature in the central region (e.g. Sanderson et al. 2006). It will be very interesting to perform another study similar to the one made here, to see if these non-cool-core clusters have dark matter temperatures that may even agree in the central region.

It is worth mentioning that the temperature anisotropy can be measured in principle in an underground directional sensitive detector; however, it will require a large dedicated experimental programme (Host & Hansen 2007).

Studies of highly non-equilibrated merging clusters (e.g. Clowe et al. 2006) have shown that the dark matter has a much smaller scattering cross section than baryonic gas. We have here extended our understanding of dark matter to show that the equilibration of dark matter structures is not governed by point-like collisions. This demonstrates that dark matter behaviour is fundamentally different from baryons. This is particularly important

for understanding what drives structure formation and the evolution of cosmological structures. The standard theory of structure formation is based on the one basic assumption that dark matter is indeed collisionless, and we here provide observational evidence that this is a correct assumption.

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<sup>1</sup> We are in the process of quantifying these estimates through high resolution numerical simulations, and the results will be presented elsewhere.