THE TEMPERATURE OF HOT GAS IN GALAXIES AND CLUSTERS: BARYONS DANCING TO THE TUNE OF DARK MATTER

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ABSTRACT

The temperature profile of hot gas in galaxies and galaxy clusters is largely determined by the depth of the total gravitational potential and thereby by the dark matter (DM) distribution. We use high-resolution hydrodynamical simulations of galaxy formation to derive a surprisingly simple relation between the gas temperature and DM properties. We show that this relation holds not just for galaxy clusters but also for equilibrated and relaxed galaxies at radii beyond the central stellar-dominated region of typically a few kpc. It is then clarified how a measurement of the temperature and density of the hot gas component can lead to an indirect measurement of the DM velocity anisotropy in galaxies. We also study the temperature relation for galaxy clusters in the presence of self-regulated, recurrent active galactic nuclei (AGNs), and demonstrate that this temperature relation even holds outside the inner region of ≈30 kpc in clusters with an active AGN.

Key words: galaxies: clusters: intracluster medium – galaxies: evolution – galaxies: fundamental parameters – methods: numerical

Online-only material: color figures

1. INTRODUCTION

Dark matter (DM)-dominated cosmological structures are a direct outcome of hierarchical structure formation with a subdominant baryon fraction. The baryons can either cool fast to form stars or end up as a hot virialized gas (Rees & Ostriker 1977; Silk 1977; Birnboim & Dekel 2003; Kereš et al. 2005). This hot gas is customarily observed in galaxies and galaxy clusters (Sarazin 1986), and can be heated through adiabatic compression, shock heating, or non-gravitational processes, and cooled through radiative processes.

The ability of the hot gas to shock heat to the virial temperature opens the possibility that one can combine the equations governing the dynamics of the gas and the DM, namely the equation of hydrostatic equilibrium and the Jeans equation. The simultaneous solution to these equations can, in principle, allow us to determine the DM velocity dispersion anisotropy, which holds information about the fundamental difference in the way DM and baryons equilibrate in cosmological structures. In fact, such a method has already been applied to galaxy clusters, where numerical simulations of cluster formation and evolution have been used to confirm that the gas equilibrium temperature is determined through the averaged velocity dispersion of the DM (Hansen & Piffaretti 2007; Host et al. 2009). The resolution of these simulations, however, did not allow us to probe radii smaller than a few hundred kpc. The temperature of the cooling gas remains to be determined at smaller radii and in the presence of an active AGN. Furthermore, it remains unknown if the gas temperature in galaxies will obey a similar simple relation.

In this paper, we conduct a dedicated comparison between the gas and DM in a range of simulated cosmological objects. The structure of the paper is as follows: first we discuss the relationship between the gas temperature and the DM velocity dispersion. In Section 3, we present the results of numerical simulations of galaxy formation, and confirm that the gas temperature in galaxies exhibits a bimodal distribution—the hot gas resides at the DM temperature and the cold gas cools below 10^4 K and forms stars. In Section 4, we present the results of numerical simulations of AGN outflows, which demonstrate that even when the gas is heated episodically by a self-regulated AGN, it still moves toward the DM temperature, which it succeeds in reaching already beyond ≈30 kpc. Finally, in Section 5 we explain how our findings open up the possibility of measuring the DM velocity anisotropy in galaxies, and in Section 6 we briefly offer our conclusions.

2. THE TEMPERATURE RELATION

It has been known for years that baryons in a DM-dominated potential will heat up to a temperature that is determined by the properties of the DM mass profile (Rees & Ostriker 1977; Cavaliere & Fusco-Femiano 1978, 1981; Sarazin 1986; Cavaliere et al. 2009). This is easily seen when considering the similarity between the equation of hydrostatic equilibrium (Sarazin 1986) and the Jeans equation (Binney & Tremaine 1987). The former depends on the gas temperature, $T$, and through its equation of state on the density, $\rho_{\text{gas}}$, while the latter depends on the DM density, $\rho_{\text{DM}}$, its radial and tangential velocity dispersions, $\sigma_r^2$, and $\sigma_t^2$, and the velocity anisotropy

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8 The corresponding stellar velocity dispersion will also be of the same magnitude as the DM velocity dispersion. However, there is no theoretical reason why the anisotropies of the galaxies should be the same as that of the DM (Lokas & Mamon 2003; Wojtak et al. 2009).
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\[ \beta = 1 - \frac{\sigma_t^2}{\sigma_r^2}; \]

\[ \frac{GM_{\text{tot}}}{r} = - \frac{T k_B}{\mu m_p} \left[ \frac{d\log \rho_{\text{gas}}}{d\log r} + \frac{d\log T}{d\log r} \right] \]  \hspace{1cm} (1)

\[ \frac{GM_{\text{tot}}}{r} = - \sigma_r^2 \left[ \frac{d\log \rho_{\text{DM}}}{d\log r} + \frac{d\log \sigma_r^2}{d\log r} + 2\beta \right], \]  \hspace{1cm} (2)

where \( \mu m_p \) is the averaged mass of the gas particles. For a given total mass profile, the hydrostatic equilibrium equation, Equation (1), has a wide range of possible solutions: basically any radial gas temperature profile is allowed (in principle) since a gas density profile can always be constructed to fulfill the equation. Furthermore, there is a priori no theoretical connection between the gas temperature and the DM dispersions, except that the particles are sitting in the same gravitational potential. One can, however, use the DM dispersions to define a “DM temperature” by

\[ \frac{T_{\text{DM}}}{k_B} = \frac{1}{3} \left( \frac{\sigma_t^2 + \sigma_r^2 + \sigma_\phi^2}{\mu m_p} \right), \]  \hspace{1cm} (3)

where \( \sigma_t \) and \( \sigma_r \) are the DM tangential dispersion velocities. We emphasize that there is no fundamental reason why the temperature of the gas, \( T \), should be identical to the DM temperature (in praxis the DM only sets an upper limit to the gas temperature). We will, however, consider the ratio between the gas temperature and the temperature derived from the DM dispersions, namely,

\[ \kappa(r) \equiv \frac{T k_B}{\mu m_p} \frac{3}{\sigma_t^2 + \sigma_r^2 + \sigma_\phi^2}, \]  \hspace{1cm} (4)

and we will discuss a possible universality of this ratio. There is, to our knowledge, no simple dynamical argument why this ratio should be close to unity, or why it should have a universal radial behavior. For instance, in the adiabatic simulations presented in Faltenbacher et al. (2007) it was found that \( \kappa \) decreases with radius in the inner region. We will here address this question using galaxy formation including cooling, heating, and feedback.

Naturally, gravity does not care about the masses of the individual (collisionless) particles, which is why their velocity dispersions are equal, and not their temperatures. The standard definition of the temperature is written in terms of the average kinetic energy of particles and describes a system in thermodynamic equilibrium. This thermodynamic limit is not achieved for most particle systems with long-range forces, such as gravitational structures for which this steady state is normally not described by simple distribution functions, e.g., Maxwell–Boltzmann statistics. Thus, the DM is not in thermal equilibrium, and technically it does not have a “temperature,” however, the use of this word should not cause any confusion.

An important point is that the DM temperature, as defined in Equation (3), is not only a function of the mass profile or potential of the DM but also depends on the dynamical state of the DM through its velocity anisotropy, \( \beta(r) \). The velocity anisotropy is much harder to observationally determine than the mass profile. Hence for a nonvanishing velocity dispersion anisotropy in the DM, the DM temperature is not identical to the velocity dispersion of the DM along any random direction, such as the radial direction, but only to their spatial average.

We will now proceed to analyze the ratio between the local gas and DM temperatures defined in Equation (4), and use numerical simulations of galaxy clusters or galaxies to test if \( \kappa \) is of order unity. Considering the results of two different numerical codes (Kay et al. 2007; Valdarnini 2006) simulating both DM and baryonic physics, Host et al. (2009) demonstrated that \( \kappa = 1 \) within 20% for relaxed galaxy clusters. The gas in galaxies is much denser, and the cooling times are, therefore, much shorter, and one might have expected that \( \kappa \) might have a much more complicated profile. We demonstrate below that indeed the hot gas in galaxies does have virtually universal temperature ratios, with \( \kappa \approx 1 \).

3. NUMERICAL SIMULATIONS

The hydrodynamical simulations were performed with GASOLINE (Wadsley et al. 2004; see Governato et al. 2007 or Stinson et al. 2010 for a more detailed description)—a multi-stepping, parallel TreeSPH N-body code. We include radiative and Compton cooling for a primordial mixture of hydrogen and helium. The star formation (SF) algorithm is based on a Jeans instability criteria (Katz 1992), where gas particles in dense, unstable regions and in convergent flows spawn star particles at a rate proportional to the local dynamical time (see Governato et al. 2004). The SF efficiency was set to 0.05, but in the adopted scheme its precise value has only a minor effect on the SF rate (Katz 1992). The code also includes supernova feedback (Stinson et al. 2006) and a UV background (Haardt & Madau 1996). Additional simulations using the FTM 4.5 code (Heller & Shlosman 1994) are described in Section 3.1.

For the simulations with GASOLINE, we selected three candidate haloes with masses similar to the mass of the Milky Way (\( M \approx 10^{12} M_\odot \)) from an existing low-resolution DM simulation (300^3 particles within 90 Mpc) and re-simulated them at higher resolution. These high-resolution runs are 8^3 times more resolved in mass than the initial ones and included a gaseous wind (Katz 1992). The code also includes supernova feedback (Stinson et al. 2006) and a UV background (Haardt & Madau 1996). Additional simulations using the FTM 4.5 code (Heller & Shlosman 1994) are described in Section 3.1.

In Figure 1, we show contours over the temperature and local density of all the gas particles in one of the three galaxies (the others look essentially identical). In Figure 2, we show histograms over the individual gas particle temperatures in the three selected galaxies, which is a projection of Figure 1. The gas temperature exhibits a bimodal distribution: it either cools down to the floor of atomic cooling about 10^4 K in dense clumps (central disk/bulge or satellite cores) or stays at the DM temperature in the larger and less dense regions. This is largely caused by the significantly shorter cooling time around 10^5 K (see, e.g., Kereš et al. 2005). When we discuss the gas temperature from the simulations using GASOLINE we refer to the second (large) bump. Practically, we calculate a mass-averaged

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Galaxy & Mass & \( R_{200} \) & \( V_{\text{circ}} \) \\
\hline
G0 & 0.74 & 188 & 178 \\
G1 & 0.89 & 199 & 188 \\
G2 & 0.93 & 202 & 203 \\
\hline
\end{tabular}
\caption{Galaxies’ Parameters}
\end{table}
The gas particles either cool down to the floor of the atomic cooling, $10^4$ K or stay at the DM temperature around $10^6$ K.

(a color version of this figure is available in the online journal.)

Making a mass average over all particles (including the cold ones) makes a negligible difference at most times. There is no metal cooling in this simulation, which is the reason for the floor at $10^4$ K. The galaxies are typical field galaxies, and have been selected to have a quiet merger history (except G1, which had a major merger at $z = 0.8$).

When re-simulating only three halos, one could wonder if selection effect biases have an effect on our findings (Ricotti 2003). First, the chosen haloes have rather different formation history, and second, we will later compare the finding with an independent suite of simulations, confirming that selection bias is not an issue here.

While simulations of viscous accretion disks may suffer from kernel issues (Lanzafame 2010), no such problems are expected in cosmological simulations.

We can now consider radial bins for each galaxy at $z = 0$, and in each bin we calculate the mass-averaged gas temperature and the mass-averaged DM velocity dispersion. Their ratios as in Equation (4) are shown in Figure 3. From this figure we can see that outside the range of the disk, i.e., beyond $\approx 6$ kpc, these ratios remain close to unity. Beyond 20 kpc, where the gas density is lower and hence the cooling time longer, the gas temperature is slightly above the DM dispersion velocities by 10%–20%. The velocity anisotropy is nearly constant, $\beta(r) \approx 0.2$ outside 2 kpc, slowly increasing to about 0.3 near 100 kpc. We thus confirm that indeed there remains a substantial component of the hot gas at the DM temperatures, even in dense environments of galaxies.

### 3.1. History of Hot and Cold Particles

In order to better understand the origin of the above bimodal distribution of gas temperatures, we tracked the evolution of various properties of individual particles. Each gas particle has its own unique thermal history, however, it appears that we as a first approximation can split the particles into four groups.

1. Hot particles, which are shock heated to roughly $10^6$ K, and then retain that temperature.
2. Warm particles, which are shock heated to roughly $10^6$ K, and then slowly cooled down somewhat. These constitute less than 15% of the particles with $T > 10^{4.5}$ K.
3. Cold particles close to the center \((r < 15 \text{ kpc})\). These are shock heated, and then they cooled down very quickly. These may have experienced several episodes of heating and cooling.

4. Cold particles which are never shock heated. These particles come through the cold accretion phase. The two cold modes (3 and 4 above) were discussed in detail in Kereš et al. (2005) and Macciò et al. (2006).

In Figures 4 and 5, we present the entropy, local density near the particle, and temperature as functions of the expansion factor. In Figure 4, we present the history of two particles that are hot today. The first particle (Hot 1) only has one period of heating as it enters the final halo. The second gas particle (Hot 2) has one episode of heating followed by rapid cooling in its first subhalo, followed by heating when it enters the final halo. In Figure 5, we present the history of two particles that are cold today. The first (Cold 1) has been accreted cold, and it never experienced any shock heating. The second particle (Cold 2) had two periods of heating followed by rapid cooling, which is clearly seen to happen when the particle enters the high density region.

### 3.2. Evolution of \(\kappa\) with Redshift

In order to test the generality of the above results, that \(\kappa(r) \approx 1\), we present results from independent simulations of Romano-Díaz et al. (2008a, 2008b, 2009) using the parallel version of the hybrid SPH/N-body FTM 4.5 code (Heller & Shlosman 1994; Heller et al. 2007). The gravitational forces are computed using the falcON routine (Dehnen 2002) which scales as \(O(N)\). The tolerance parameter \(\theta\) is fixed at 0.55. The gravitational softening applied is \(\epsilon = 500 \text{ pc}\) for the DM, stars, and gas. The vacuum boundary conditions are used and the simulations are performed with physical coordinates. The cosmological constant is introduced by an explicit term in the acceleration equation. The conservation of the total angular momentum and energy within the computational sphere in the collisionless models is within \(\sim 0.01\%\) and \(\sim 1\%\), respectively. The evolution of various parameters characterizing the DM and baryons is followed in 1000 snapshots, linearly spaced in the cosmological expansion parameter \(a\).

The modeling of SF processes and associated feedback are described in Heller & Shlosman (1994) and Heller et al. (2007), which should be consulted for details. Feedback from OB stellar winds and supernovae (SNe) Type II is also included. A fraction of this energy is thermalized and deposited in the gas in the form of thermal energy, then converted to kinetic energy through the equations of motion. This method is preferable over injecting a fraction of the stellar energy directly in the form of kinetic energy (Heller et al. 2007).

Multiple generations of stars are allowed to form from each gas particle. The evolution of gas metallicity is followed and the fraction of massive stars that lead to the OB stellar winds and SNe is calculated from the Salpeter IMF.

Figure 6 displays the redshift evolution of the radial profiles of the temperature ratio, \(\kappa\). All the gas particles (both hot and cold) are included in the averages here, and therefore different aspects of the time evolution of \(\kappa(r)\) can be followed. At higher redshifts, \(z \geq 2\), when the disk is being assembled from the cold gas supplied by the filaments, and which is converted into stars, the temperature ratio drops below unity in the disk region. For \(z < 1\), when the SF feedback by SNe and stellar winds (Romano-Díaz et al. 2008a, 2009) consume a large fraction of this gas, the temperature ratio rises to unity, as the heated gas tends to the DM temperature. After \(z \approx 1\), we observe an influx of subhalos along the filaments which ablate the cold gas from the disk nearly completely. Two independent parameters verify the overall evolution of the model from a late-type to the early-type: the fraction of the gas-to-disk mass ratio, and the ratio of a spheroidal-to-disk mass ratio (within the disk radius). At \(z = 0\), we find a temperature ratio which is slightly below unity in the central region and rises to slightly above unity toward the virial radius.
Hence, we see that the gas-to-DM temperature ratio approaches unity for the evolved and relaxed galaxies. Of course, the actual evolution of the ratio does depend on the particular history of the galaxy, but the important point here is that for equilibrated galaxies today, the temperature ratio is close to unity.

As a sidenote we point out that the stellar dispersion does not agree with the DM dispersion for these galaxies. We can therefore not use the stellar velocities in the same way to extract information about the DM, and we cannot assume that the stellar velocity dispersion anisotropy should equal that of the DM.

As we have seen above, despite the short cooling time in galaxies the hot gas component is strongly linked with the DM dispersion. It will be very interesting in future numerical simulations to see if a similar simple relation will hold for the hot gas component in dwarf galaxies, with gas temperatures an order of magnitude smaller than in galaxies.

4. AGN OUTFLOWS

The simple relation between the gas and DM velocity dispersions in Equation (3) has been demonstrated using numerical simulations for galaxy clusters in Host et al. (2009). Those simulations had sufficient resolution to probe a region outside of roughly 100–200 kpc. It remains unknown if this simple relation still holds further toward the central region, where cooling may be faster, or where a central AGN may pump energy into the intracluster gas.

To address this question, we present results of a simulation of a three-dimensional model of AGN self-regulation in a cool-core cluster (Brüggen & Scannapieco 2009). This simulation was performed with FLASH version 3.0 (Fryxell et al. 2000), a multidimensional adaptive mesh refinement hydrodynamics code, which solves the Riemann problem on a Cartesian grid using a directionally split piecewise-parabolic method (PPM) solver. In this simulation the cluster properties, such as the density and temperature profiles have been chosen to resemble the best-studied cluster, the Perseus cluster. The gravitational potential is taken to be static, and initially the gas is set up in hydrostatic equilibrium. The gas physics includes radiative cooling, heating through AGN feedback, and a subgrid model for Rayleigh–Taylor-driven turbulence, as described in Brüggen & Scannapieco (2009).

Figure 7 demonstrates that outside the central region (≈30 kpc, where the recent AGN burst has heated the gas temperature much above the DM temperature) the ratio $\kappa (r) = \sigma_{\text{gas}}^2 / \langle \sigma_{\text{DM}}^2 \rangle$ is unity within 10%. The dashed line shows the results from an extreme case of AGN feedback, where strong outflows occur every 50 Myr (Scannapieco & Brüggen 2008).
non-self-regulated, and somewhat less physically motivated case, the dashed line in Figure 7 shows that, as long as we consider radii outside of 70–100 kpc region, the velocity dispersion ratio stays within 10% of unity.

5. IMPLICATIONS FOR THE VELOCITY ANISOTROPY

For the self-regulated AGN, the simple temperature relation $\kappa(r) \approx 1$ holds outside the inner region of $r \approx 30$ kpc, as we have shown in Section 4. For the observed X-ray clusters studied in Host et al. (2009), this radius corresponds roughly to the center of the innermost bin. This shows that one can trust the inference of the DM velocity anisotropy in galaxy clusters down to radii as small as $\approx 50$ kpc.

In the case of galaxies, we have demonstrated that the simple temperature relation holds for relaxed and equilibrated structures, when applied to radii beyond the regions dominated by the stellar component. This opens for the possibility of indirectly determining the DM velocity anisotropy in galaxies in the following way. By measuring the temperature and the density of the hot X-ray-emitting gas, one may use the equation of hydrostatic equilibrium, Equation (1), to measure the total gravitating mass. Now, considering the Jeans equation, Equation (2), we see that it contains the total mass on the left-hand side, and three unknown quantities on the right-hand side ($\rho_{\text{DM}}, \sigma^2, \beta$). First, combining the total mass measurement from X-ray with spectral determination of the stellar mass allows one to determine the DM density profile:

$$\rho_{\text{DM}}(r) = f_1(T_e(r), \rho_g(r), \rho_{\text{gas}}(r)).$$  \hspace{1cm} (5)

We are thus left with two unknowns on the right-hand side of the Jeans equation, Equation (2), namely, the radial dispersion and the velocity anisotropy, $\beta$. Using the temperature relation, Equation (3), together with the X-ray-determined gas temperature, we get rid of one of these, and hence get an indirect measurement of the DM velocity anisotropy:

$$\beta(r) = f_2(\kappa(r), T_e(r), \rho_g(r), \rho_{\text{gas}}(r)).$$  \hspace{1cm} (6)

Such observation has only very recently become possible for X-ray-bright galaxy cluster (Hansen & Piffaretti 2007; Morandi & Ettori 2007; Host et al. 2009), and it is clear that such indirect observations in galaxies most likely will require improved X-ray satellites. The simplest possibility would be if $\kappa(r) = 1$ everywhere, however, the method to infer the DM velocity anisotropy as described above works as long as the radial form of $\kappa(r)$ is known (Host et al. 2009). This is exactly one of the points of this paper, that the form of $\kappa(r)$ appears to be universal for galaxies (see Figure 3).

A direct measurement of this velocity anisotropy is expected to be virtually impossible in terrestrial experiments (Host & Hansen 2007). Measuring $\beta$ of the DM in galaxies, as described above, can provide an independent confirmation to virtually every numerical modeling of DM halo formation in the cosmological context, and to the suggestion that a non-zero $\beta$ is a fundamental property of galactic DM halos, even in equilibrium (Hansen 2009; Hansen et al. 2010). Furthermore, a non-zero $\beta$ has an effect on the underground direct detection experiments (Vergados 2000; Evans et al. 2000; Vergados et al. 2008). A detection through the method laid out above would therefore decrease the systematic error bars in terrestrial DM detection experiments.

6. CONCLUSIONS

In summary, we have found a very simple relation between the temperature of the hot gas and the averaged dispersion of the DM, namely, that their ratio is close to unity, $\kappa \approx 1$. We have demonstrated that this near equality of the gas and DM temperatures holds in the case of equilibrated and relaxed galaxies.

This relation is not only conceptually important, but it will also allow an indirect determination of the DM velocity anisotropy in galaxies. Such an observation will provide an important and independent confirmation of all cosmological DM halo formation simulations.

We have also studied this relation in galaxy clusters containing an active AGN, and our results confirm that one can indeed use galaxy clusters to infer the DM velocity anisotropy.

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REFERENCES

Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton, NJ: Princeton Univ. Press)

Brinboim, Y., & Dekel, A. 2003, MNRAS, 345, 349

Bürggen, M., & Scannapieco, E. 2009, MNRAS, 398, 548

Bürggen, M., Scannapieco, E., & Heinz, S. 2009, MNRAS, 395, 2210

Cavaliere, A., & Fusco-Femiano, R. 1978, A&A, 70, 677

Cavaliere, A., & Fusco-Femiano, R. 1981, A&A, 100, 194

Cavaliere, A., Lapi, A., & Fusco-Femiano, R. 2009, ApJ, 698, 580

Dehnen, W. 2002, J. Comput. Phys., 179, 27

Evans, N. W., Carollo, C. M., & de Zeeuw, P. T. 2000, MNRAS, 318, 1131

Faltenbacher, A., Hoffmann, Y., Gottlöber, S., & Yepes, G. 2007, MNRAS, 376, 1327

Fryxell, B., et al. 2000, ApJS, 131, 273

Governato, F., Willman, B., Mayer, L., Brooks, A., Stinson, G., Valenzuela, O., Wadsley, J., & Quinn, T. 2007, MNRAS, 374, 1479

Governato, F., et al. 2004, ApJ, 607, 688

Haardt, F., & Madau, P. 1996, ApJ, 461, 20

Hansen, S. H. 2009, ApJ, 694, 1250

Hansen, S. H., Juncher, D., & Sperre, M. 2010, ApJ, 718, L68

Hansen, S. H., & Piffaretti, R. 2007, A&A, 476, L37

Heller, C. H., & Shlosman, I. 1994, ApJ, 424, 84

Heller, C. H., Shlosman, I., & Athanassoula, E. 2007, ApJ, 671, 226

Host, O., & Hansen, S. H. 2007, J. Cosmol. Astropart. Phys., JCAP06(2007)016

Host, O., Hansen, S. H., Piffaretti, R., Morandi, A., Ettori, S., Kay, S. T., & Valdarnini, R. 2009, ApJ, 690, 358

Katz, N. 1992, ApJ, 391, 502

Kay, S. T., da Silva, A. C., Aghanim, N., Blanchard, A., Liddle, A. R., & Matarrese, S. 2005, MNRAS, 363, 2

Lanzafame, G. 2010, MNRAS, 408, 1551

Lokas, E. L., & Mann, G. A. 2003, MNRAS, 343, 401

Maccio, A. V., Moore, B., & Stadel, J. 2006, ApJ, 636, L25

Morandi, A., & Ettori, S. 2007, MNRAS, 380, 1521

Rees, M. J., & Ostriker, J. P. 1977, MNRAS, 179, 541

Ricotti, M. 2003, MNRAS, 344, 1237

Romano-Díaz, E., Shlosman, I., Heller, C., & Hoffman, Y. 2008a, ApJ, 685, L13

Romano-Díaz, E., Shlosman, I., Heller, C., & Hoffman, Y. 2009, ApJ, 702, 1250

Romano-Díaz, E., Shlosman, I., Heller, C., & Hoffman, Y. 2009a, ApJ, 685, L13
Romano-Díaz, E., Shlosman, I., Hoffman, Y., & Heller, C. 2008b, ApJ, 685, L105
Sarazin, C. L. 1986, Rev. Mod. Phys., 58, 1
Scannapieco, E., & Brüggen, M. 2008, ApJ, 686, 927
Schewtschenko, J., & Macciò, A. 2011, MNRAS, 413, 878
Silk, J. 1977, ApJ, 211, 638
Stinson, G., Seth, A., Katz, N., Wadsley, J., Governato, F., & Quinn, T. 2006, MNRAS, 373, 1074

Stinson, G. S., Bailin, J., Couchman, H., Wadsley, J., Shen, S., Nickerson, S., Brook, C., & Quinn, T. 2010, MNRAS, 408, 812
Valdarnini, R. 2006, New Astron., 12, 71
Vergados, J. D. 2000, Phys. Rev. D, 62, 023519
Vergados, J. D., Hansen, S. H., & Host, O. 2008, Phys. Rev. D, 77, 023509
Wadsley, J. W., Stadel, J., & Quinn, T. 2004, New Astron., 9, 137
Wojtak, R., Łokas, E. L., Mamon, G. A., & Gottlüber, S. 2009, MNRAS, 399, 812