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Observational tests of the δ_c–M_{vir} relation in hierarchical clustering models

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Abstract. Observational determinations of the correlation between the characteristic density δ_c and the virial mass M_{vir} of dark halos constitute a critical test for models of hierarchical structure formation. Using the dynamical properties of dark halos reconstructed from the galaxy distributions in massive systems (groups/clusters) and the rotation curves in less massive systems (dwarf, low surface brightness and spiral galaxies) drawn from the literature, we confirm the existence of the δ_c-M_{vir} relation over a broad mass range from 10^{10} $M_\odot$ to 10^{15} $M_\odot$, which is in gross consistency with the prediction of a flat cosmological model with $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. It is pointed out that previous analyses based on the measurements of X-ray emitting gas and the hydrostatic equilibrium hypothesis, which claimed a shallower scale-free spectrum of $n \approx -1$ for initial density fluctuations, may suffer from nongravitational heating influence especially in low-mass systems.

Key words. cosmology: observations – dark matter – galaxies: formation

1. Introduction

In hierarchical clustering models, low-mass halos (e.g. galaxies) are denser and have higher collapse redshift than massive halos (e.g. clusters), while the latter form by the gravitational aggregation of individual low-mass objects. For a halo density profile of the form $\rho_{DM}(r) = \delta_c\rho_c\overline{\rho}(r/r_s)$ where ρ_c is the critical density of the universe, δ_c and r_s are the characteristic density and length, respectively, the above scenario implies that the characteristic density δ_c of virialized dark halos should correlate with virial mass M_{vir}. Indeed, the existence of such a δ_c-M_{vir} relation has been confirmed by a number of high-resolution N-body simulations in various cosmological models (SCDM, LCDM and OCDM) with different power spectra (e.g. Navarro et al. 1997; Salvador-Solé et al. 1998).

On the observational side, several attempts have been recently made to test the δ_c-M_{vir} relation and hence, to constrain the scale-free power spectrum ($P(k) \propto k^n$) for primordial density fluctuations on relevant scales. By fitting the X-ray surface brightness profiles of clusters predicted by the universal density profile (Navarro et al. 1995; NFW) to the ones for 63 rich clusters observed with ROSAT, Wu & Xue (2000) found that $\delta_c \propto M_{vir}^{-1.2}$, indicating $n \approx -0.7$. This result was subsequently confirmed by Sato et al. (2000) based on an analysis of the mass profiles of 83 ASCA X-ray objects over a wider mass range from $M_{vir} = 10^{12}$ $M_\odot$ to 10^{15} $M_\odot$, which gives $n = -1.2 \pm 0.3$ (90% confidence level). It appears that while the presence of good correlation between δ_c and M_{vir} has been observationally established, the resulting power spectra are somewhat shallower than the value ($n \approx -2$) expected for typical CDM, scale-free cosmologies on cluster scales. Possible reasons for this conflict have been outlined in Mahdavi (1999) and Wu & Xue (2000). Basically, the above observational tests of the δ_c-M_{vir} relation based on X-ray observations of the intragroup/intracluster gas may suffer from the influences of preheating, cooling flows, non-thermal pressure and hydrostatic equilibrium hypothesis. Among these, preheating by supernovae and AGNs in the early phase of structure formation may lead the intragroup/intracluster gas to extend out to larger radii (e.g. Kaiser 1991; David et al. 1991; Ponman et al. 1999; Bower et al. 2001), which can significantly affect our mass estimates from the X-ray observed surface brightness profiles especially for galaxies and groups when incorporated with the hydrostatic equilibrium hypothesis.

Unlike intracluster gas, galaxies in groups and clusters are essentially unaffected by the presence of preheating, cooling flows and non-thermal pressure and can, therefore, be regarded as better tracers of underlying gravitational potentials. In less massive systems such as the dark matter dominated dwarf galaxies or low surface brightness galaxies, one is able to recover the dark matter profiles from the

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well-measured rotation curves (e.g. Carignan & Beaulieu 1989). Dynamical properties of dark halos derived from the distributions of galaxies in groups/clusters and the rotation curves of dwarf, low surface brightness and spiral galaxies, which spans several decades in mass, have already been available in the literature. It thus becomes possible and also timely to have a close examination of the δ_c-M_{vir} relation motivated by hierarchical clustering models. We attempt to fulfill the task in this paper, and compare our new determination with the results given by X-ray observations and theoretical expectations. Throughout this paper, we assume $H_0 = 100$ km s^{-1} Mpc^{-1} and a flat cosmological model of $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. The shape of the δ_c-M_{vir} relation is roughly unaffected by this choice (Wu & Xue 2000; Sato et al. 2000).

2. Sample

We model the virialized dark halos by the NFW universal density profile: $\rho_{DM}(r) = \delta_c\rho_c/[(r/r_s)(1+r/r_s)^2]$, where the critical density of the universe reads $\rho_c = (3H_0^2/8\pi G)E^2(z)$ and $E^2(z) = (1+z)^2\{1+z\Omega_M + [(1+z)^{-2}-1]\Omega_\Lambda\}$. The virial mass M_{vir} is defined by $M_{vir} = 4\pi r_{vir}^3\Delta_c\rho_c/3$, so that $\delta_c = (\Delta_c/3)\{c^3/[\ln(1+c) - c/(1+c)]\}$, where Δ_c is the overdensity of dark matter with respect to the critical value ρ_c and can be approximated by $\Delta_c = 178\Omega_M(z)^{0.45}$ (Eke et al. 1998), and $c = r_{vir}/r_s$ is called the concentration parameter.

Assuming that galaxies in groups and clusters trace mass, we are able to fix the free parameter r_s by straightforwardly fitting the observed surface number density profiles of galaxies to the projection of the NFW profile. In order to obtain δ_c, we also need to have an independent estimate of the virial radius r_{vir} or the concentration parameter c. An approximate approach to the problem is to employ virial theorem: $M_{vir} = 3\sigma_p^2 r_{vir}/G$, which yields $r_{vir} = (6/\Delta_c)^{1/2}[\sigma_p/H_0E(z)]$, where σ_p is the global line-of-sight velocity dispersion. However, this expression holds true only for clusters with an isotropic distribution of galaxies, and their velocity dispersion can be reliably measured out to virial radii. Recall that the velocity dispersion of galaxies varies with radius if galaxies are assumed to trace mass (Cole & Lacey 1996). We have thus checked the accuracy of the estimated virial radii using a sample of 158 nearby clusters of Girardi et al. (1998), in which the virial radii have been given by dynamical analysis, and found that there is good agreement between the two methods. This technique has been applied to an ensemble of rich systems of galaxies by CNOC (Carlberg et al. 1997), and poor systems of galaxies (PSG) by Mahdavi et al. (1999). Their averaged, best-fit parameters are summarized in Table 1. For PSG we adopt the results of the sample D [PSG(D)] and eight groups with $\sigma_p > 350$ km s^{-1} [PSG(H)] but exclude the result for the nine groups with $\sigma_p < 350$ km s^{-1} due to the failure of the NFW fit. The third data set is taken from the ENACS cluster sample fitted by Adami et al. (1998). These authors used a similar technique but a pseudo NFW profile. We adopt their average value of $r_s = 0.26$ Mpc among the 41 clusters whose velocity dispersions are observationally determined. The recent work based on a sample of 77 composite ENACS clusters gives the similar result, $r_s = 0.318$ Mpc (Adami et al. 2001).

For less massive systems, the two free parameters in the NFW profile can be determined by utilizing the high-quality rotation curves. Van den Bosch & Swaters (2001) have recently obtained the concentration parameters c_{200} and the circular velocities V_{200} at r_{200} for a sample of 20 dwarf galaxies by properly subtracting the contributions of the thin gas disk and the thick stellar disk to the rotation curves. We take the mean values of their best-fit c_{200} and V_{200} for the 15 dwarf galaxies (DWG) that satisfy $c_{200} > 1$ and convert c_{200} and r_{200} into c and r_{vir} in terms of the NFW profile and our definitions of c and r_{vir}. The major uncertainty in their fittings arises probably from the constant mass-to-light ratio M/L assumed for the stellar disk components. In order to demonstrate this uncertainty, we adopt both the result for $M/L = 1(M/L)_\odot$ (DWG1) and the one for $M/L = 0$ (DWG0). Another sample we have used is the 9 low-luminosity disk galaxies (DIG) studied by Borriello & Salucci (2001). These authors have worked out the c and r_s parameters based on the fitting of the rotation curves to the stellar disk plus dark halo models, in which the mass-to-light ratio M/L for the stellar disk is treated as a free parameter. However, they found that good fits in DIG sample are obtained only for unreasonably large virial velocities and masses. To overcome the inadequacy, they imposed an upper limit of 2×10^{12} $M_\odot$ on M_{vir} in their fitting. We use their average values of c and r_s after the cosmological model correction is properly made. We have also performed the fitting of the rotation curves predicted by the NFW halo plus thin stellar disk model to a sample of 30 spiral galaxies in the Ursa Major (UMA) cluster analyzed by Sanders & Verheijen (1998). However, the models are not well constrained for majority of galaxies due to the sparse data points of the rotation curve if the mass-to-light ratio of stellar components is treated as a free parameter and no upper limit is imposed on the virial masses of dark halos. We have only used the results of 13 galaxies that satisfy $c > 1$, and their best-fit parameters are listed in Table 1.

As a comparison, we turn to the best-fit values of r_s and c from the X-ray measurements of 63 rich clusters observed with ROSAT (Wu & Xue 2000) and 83 objects observed with ASCA (Sato et al. 2000). While these two groups both assumed hydrostatic equilibrium for X-ray emitting gas, they used very different methods in the determinations of r_s and c: Wu & Xue (2000) directly fitted the theoretically predicted X-ray surface brightness profiles $S_X(r)$ from the NFW profile via isothermality (Makino et al. 1998) to the ROSAT observed $S_X(r)$; Sato et al. (2000) first derived the mass distributions of groups/clusters from the X-ray observed surface brightness profiles characterized by conventional β model and the temperature profiles. They then calculated δ_c and r_s

by fitting the NFW model to the mass profiles. For our analysis below, we use 3 and 4 bins according to virial mass for the ROSAT and ASCA samples, respectively (see Table 1).

3. Analysis and results

Figure 1 shows the δ_c-$M_{\rm vir}$ relation over a broad mass range from 10^{10} $M_\odot$ to 10^{15} $M_\odot$, in which the data points from X-ray emitting gas and those from distributions and rotation curves of galaxies are clearly marked. All the quoted error bars are 95% confidence limits. Also plotted in Fig. 1 is the corresponding c-$M_{\rm vir}$ relation for the purpose of easier comparison with numerical results (e.g. Navarro et al. 1997). It can be seen that the two data sets (galaxies and X-ray gas) are essentially consistent with each other on large mass scales $M_{\rm vir} > 10^{14}$ $M_\odot$, but differ significantly at low-mass end. The best-fit relations based on the X-ray sample alone are

$$\delta_c = 10^{19.44\pm2.65}(M_{\rm vir}/M_\odot)^{-1.06\pm0.17}; \quad (1)$$

$$c = 10^{7.34\pm1.10}(M_{\rm vir}/M_\odot)^{-0.45\pm0.07}. \quad (2)$$

In order to compare with theoretical predictions in hierarchical clustering models, we compute the collapse redshift $z_{\rm coll}$ for halo of mass $M_{\rm vir}$ identified at redshift $z = 0$ in terms of the extended Press-Schechter formalism (Lacey & Cole 1993; Navarro et al. 1997):

$$\delta_{\rm crit}(z_{\rm coll}) = \delta_{\rm crit}(0) + 0.477\sqrt{2[\sigma^2(fM_{\rm vir}) - \sigma^2(M_{\rm vir})]}, \quad (3)$$

where $f \approx 0.01$, $\delta_{\rm crit}(z) = \delta_{\rm crit}(0)/D(z, \Omega_{\rm M}, \Omega_\Lambda)$ is the density threshold for spherical collapse at z with D being the linear grow factor and $\delta_{\rm crit}(0) \approx 1.69$, and $\sigma(M_{\rm vir})$ is the rms linear density fluctuation at mass scale $M_{\rm vir} = (4\pi/3)\rho_c\Omega_{\rm M}R^3$, which is related to the fluctuation power spectrum by

$$\sigma^2(M_{\rm vir}) = \frac{1}{2\pi^2}\int_0^\infty {\rm d}k k^2 P(k) W^2(kR). \quad (4)$$

We use the standard top hat window function and parameterize the fluctuation power spectrum by $P(k) = Ak^nT^2(k)$, in which the transfer function $T(k)$ is taken from an adiabatic CDM model given by Bardeen et al. (1986) for the shape parameter $\Gamma = 0.25$ and the Harrison-Zeldovich spectrum $n = 1$. Furthermore, we assume that the rms fluctuation amplitude within a sphere of $R = 8$ Mpc is $\sigma_8 = 0.85$.

In terms of the prescription of Navarro et al. (1997), the characteristic density δ_c of a virialized dark matter halo $M_{\rm vir}$ is proportional to the mean density of the universe at the corresponding collapse redshift $z_{\rm coll}$

$$\delta_c = C\Omega_{\rm M}[1 + z_{\rm coll}(M_{\rm vir})]^3, \quad (5)$$

where C is the proportionality constant and can be approximately taken to be $C = 3000$ for our choice of cosmological parameters. In particular, for a power-law spectrum of primordial density fluctuations, the above

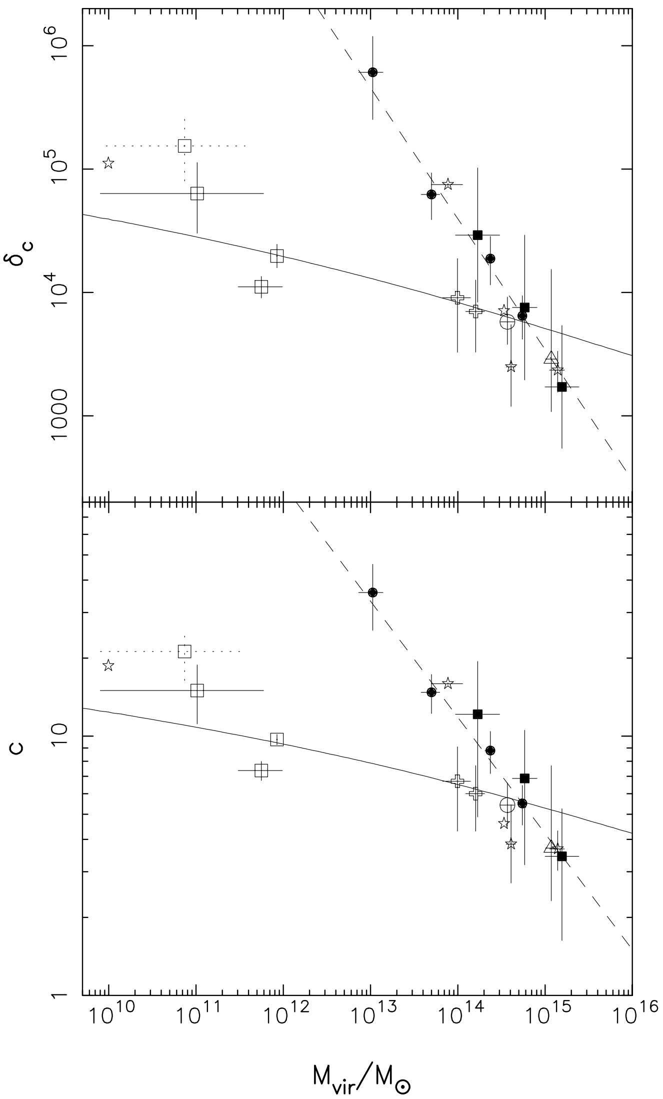

Fig. 1. The observationally determined δ_c–$M_{\rm vir}$ (upper panel) and c-$M_{\rm vir}$ (lower panel) relations for two samples: (1) galaxies – CNOC (open triangle), ENACS (open circle), PSG (open cross), DWG0, DWG1, DIG and UMA (open squares from left to right); (2) X-ray gas – ROSAT (fitted square) and ASCA (filled circle). The asterisks from left to right denote the results for five individual objects: DDO 154 from the measurement of HI rotation curve (Carignan & Purton 1998; Burkert & Silk 1999), the Hydra A cluster observed recently with Chandra (David et al. 2000), the poor cluster AWM 7 from the NFW fit to the radial profiles of galaxies and their velocity dispersion (Koranyi & Geller 2000), the nearest cluster Virgo from a combined analysis of optical and X-ray observations (McLaughlin 1999), and the cluster Abell 576 from the measurement of galaxy distribution out to the infall region (Rines et al. 2000). Dashed line is the best-fit relation to the X-ray data. Solid line is the theoretical expectation for a flat cosmological model of $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ with $\Gamma = 0.25$, $\sigma_8 = 0.85$ and $n = 1$.

expression reduces to $\delta_c \propto M_{\rm vir}^{-(n+3)/2}$ when combined with Eq. (3). Therefore, the best-fit δ_c-$M_{\rm vir}$ relation Eq. (1) from the X-ray data indicates $n = -0.88 \pm 0.24$, which is simply the combined result of Wu & Xue (2000) and Sato et al. (2000). The theoretically predicted

Table 1. Sample.

sample	No	redshift	σ_p (km s^{-1})	kT (keV)	r_s (Mpc)	c	M_{vir} (10^{14} $M_\odot$)	δ_c (10^4)	ref.
CNOC	14	0.313 ± 0.120	972 ± 48	...	$0.48^{+0.32}_{-0.26}$	$3.70^{+3.99}_{-1.38}$	$11.76^{+1.82}_{-1.65}$	$0.29^{+1.25}_{-0.18}$	1
ENACS	41	0.073 ± 0.027	617 ± 38	...	0.26 ± 0.03	$5.42^{+1.19}_{-0.92}$	$3.70^{+0.73}_{-0.65}$	$0.58^{+0.34}_{-0.20}$	2
PSG(H)	8	0.025 ± 0.000	460 ± 38	...	0.17 ± 0.05	6.00 ± 1.70	$1.60^{+0.43}_{-0.37}$	$0.70^{+0.56}_{-0.37}$	3
PSG(D)	5	0.024 ± 0.000	392 ± 48	...	0.117 ± 0.043	6.70 ± 2.40	$0.99^{+0.41}_{-0.32}$	$0.91^{+0.98}_{-0.58}$	3
UMA	13	0.004	...	...	0.022 ± 0.002	9.71 ± 0.45	$8.46^{+0.09}_{-0.09} \times 10^{-3}$	$1.97^{+0.48}_{-0.39}$	5
DIG	9	$\sim$0	...	...	0.023 ± 0.002	7.37 ± 0.62	$5.61^{+4.16}_{-2.57} \times 10^{-3}$	$1.11^{+0.24}_{-0.21}$	4
DWG1	15	$\sim$0	...	...	0.006 ± 0.002	15.0 ± 2.3	$1.03^{+2.16}_{-0.78} \times 10^{-3}$	$6.33^{+2.81}_{-2.19}$	6
DWG0	15	$\sim$0	...	...	0.004 ± 0.001	21.2 ± 2.9	$0.74^{+1.32}_{-0.53} \times 10^{-3}$	$15.4^{+6.1}_{-4.9}$	6
ROSAT	20	0.139 ± 0.042	...	9.23 ± 0.57	1.78 ± 0.21	3.44 ± 1.81	$15.6^{+8.8}_{-5.6}$	$0.17^{+0.37}_{-0.12}$	7
	25	0.107 ± 0.035	...	6.83 ± 0.73	0.66 ± 0.02	6.87 ± 3.68	$5.83^{+2.25}_{-1.62}$	$0.75^{+2.16}_{-0.56}$	7
	18	0.069 ± 0.040	...	3.98 ± 0.23	0.24 ± 0.02	12.2 ± 7.3	$1.69^{+1.33}_{-0.75}$	$2.92^{+7.29}_{-2.08}$	7
ASCA	30	0.178 ± 0.037	...	7.51 ± 0.72	0.281 ± 0.042	5.50 ± 0.96	5.48 ± 0.62	$0.65^{+0.29}_{-0.23}$	8
	30	0.120 ± 0.050	...	5.25 ± 0.76	0.155 ± 0.037	8.80 ± 1.63	2.36 ± 0.31	$1.88^{+0.97}_{-0.73}$	8
	10	0.024 ± 0.013	...	2.72 ± 1.37	0.043 ± 0.009	14.8 ± 2.5	0.50 ± 0.13	$6.23^{+3.08}_{-2.35}$	8
	13	0.012 ± 0.006	...	0.95 ± 0.23	0.014 ± 0.005	35.8 ± 10.2	0.11 ± 0.03	$60.9^{+57.9}_{-35.7}$	8

References: (1) Carlberg et al. (1997); (2) Adami et al. (1998); (3) Mahdavi et al. (1999); (4) Borriello & Salucci (2001); (5) Sanders & Verheijen (1998); (6) van den Bosch & Swaters (2001); (7) Wu & Xue (2000); (8) Sato et al. (2000).

δ_c-M_{vir} and c-M_{vir} relations from Eq. (5) are illustrated in Fig. 1. It is immediate that the data points of the galaxy sample ($\bar{z} < 0.3$) are roughly consistent with the theoretical prediction.

4. Discussion and conclusions

Using the dynamical properties of dark halos reconstructed from galaxy distributions in massive systems (groups/clusters) and rotation curves in less massive systems (dwarf, low surface brightness and spiral galaxies) drawn from the literature, we have examined the δ_c-M_{vir} relation predicted by hierarchical clustering models. It turns out that the observational data are in gross consistency with the theoretical prediction on a broad mass range from 10^{10} $M_\odot$ to 10^{15} $M_\odot$, although the present analysis still suffers from the sparse data points especially on the low-mass scale of $M < 10^{13}$ $M_\odot$. Indeed, this last point reflects the difficulty in the current determinations of the dark matter profiles of galaxies from their rotation curves. In fact, even if the high-quality rotation curves of HI disks can be traced out to large radii, the unknown mass-to-light ratio of the stellar components can result in ambiguity regarding the determinations of δ_c and r_s in the NFW dark matter profile (e.g. van den Bosch et al. 2000). We have illustrated in Fig. 1 the influence of M/L on the δ_c-M_{vir} and c-M_{vir} relations for DWG sample. We cannot exclude the possibility that the best-fit values of δ_c, r_s and c in other two samples (UMA and DIG) may still contain rather large uncertainties due to the unknown M/L although M/L is allowed to vary in the fitting processes. Recall that good fits in DIG sample are obtained only for unreasonably large virial velocities and masses, while majority of the galaxies in UMA sample simply failed in the fitting of NFW profile. So, more accurate and reliable data of galactic systems will be needed to tighten the constraints on the δ_c-M_{vir} and c-M_{vir} relations on low-mass scales. Alternatively, the assumption that galaxies trace mass has been often used in groups and clusters in order to extract the dynamical properties of dark halos from the optically observed radial profiles of galaxies (e.g. CNOC, ENACS and PSG). A quantitative estimate of the uncertainties in the determinations of the NFW profile from this oversimplification of galaxy distributions should be made in the future.

The newly established δ_c-M_{vir} relation from "galaxies" differs remarkably from previous findings based on X-ray measurements of the hot diffuse gas contained in galaxies, groups and clusters (Wu & Xue 2000; Sato et al. 2000). The latter results in a shallower power-law spectrum ($n \approx -1$) than the expectations of typical CDM models on cluster scales. It is possible that the conflict is associated with nongravitational heating of the X-ray gas in the early phase of structure formation. Such a speculation is supported by the good consistency of the δ_c-M_{vir} (or c-M_{vir}) relations between the two samples (galaxies and gas) in massive systems ($M > 10^{14}$ $M_\odot$) and the remarkable difference on low-mass scales. Note that galaxies are less affected by the possible existence of preheating. This situation is similar to the recent discovery of an entropy floor in the centers of groups and clusters (Ponman et al. 1999) due to the additional heating of the gas from supernovae and/or AGNs. Smaller systems (groups and galaxies) have lower entropies and hence are more affected than clusters. As a result, the present-day saturated configuration of hot/warm gas in less massive systems is shallower than the distributions of dark matter and galaxies. Reconstruction of the dark matter profiles under the assumption of hydrostatic equilibrium without the detailed information about the gas distribution and temperature at large radii may contain large uncertainties. A quantitative analysis will be needed to address whether the departure of the δ_c-M_{vir} relation detected in X-ray observations from those found by rotation curves and distributions of galaxies and predicted by typical CDM models arises from this speculation.

Essentially, it is hoped that the δ_c-M_{vir} and c-M_{vir} relations can be extended to less massive systems below $10^{10}\ M_\odot$. This last point is potentially important for distinction between CDM and warm dark matter models (Eke et al. 2000). Alternatively, the employment of the δ_c-M_{vir} relation established in the present work can allow one to test the different prescriptions of halo formation time (e.g. Navarro et al. 1997; Salvador-Solé et al. 1998; Eke et al. 2000; Bullock et al. 2001), and we will report the result elsewhere.

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