HALO PROPERTIES IN MODELS WITH DYNAMICAL DARK ENERGY

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ABSTRACT

We study the properties of dark matter (DM) halos in several models in which we have included dark energy (DE). We consider both dynamical DE, due to a scalar field self-interacting through Ratra-Peebles or supergravity potentials, and DE with constant negative \( w = p/\rho < -1 \). We find that at zero redshift, both the nonlinear power spectrum of DM and the mass function of halos do not depend appreciably on the state equation of DE, which implies that both statistics are almost indistinguishable from those of \( \Lambda \)-dominated cold dark matter (\( \Lambda \)CDM). This result is consistent with the nonlinear treatment in the accompanying paper and is also a welcome feature, because \( \Lambda \)CDM fits a large variety of data. On the other hand, DE halos differ from \( \Lambda \)CDM halos in that they are denser in their central parts, because DE halos collapsed earlier. Nevertheless, such differences are not so large. For example, the density at 10 kpc of a ~10^{13} M_\odot DE halo is only 50% denser than the \( \Lambda \)CDM halo. This means that DE does not ease the problem with cuspy DM profiles.

Addressing another cosmological problem, the abundance of subhalos, we find that the number of satellites of halos in various DE models does not change with respect to \( \Lambda \)CDM when normalized to the same circular velocity as the parent halo. Most of the above similarities are related to choosing for all models the same normalization factor \( \sigma_8 \) at \( z = 0 \). At high redshifts, different DE and \( \Lambda \)CDM models have different amplitudes of fluctuations, which causes substantial deviations of halo properties to occur. Therefore, the way to find which DE equation of state gives the best fit to the observed universe is to look at the evolution of halo properties. For example, the abundance of galaxy groups with mass larger than 10^{13} h^{-1} M_\odot at \( z \geq 2 \) can be used to discriminate between the models and thus to constrain the nature of DE.

Subject headings: cosmology: theory — dark matter — galaxies: clusters: general — galaxies: halos — methods: analytical — methods: numerical

On-line material: color figures

1. INTRODUCTION

The mounting observational evidence for the existence of dark energy (DE), which probably accounts for ~70% of the critical density of the universe (Perlmutter et al. 1999; Riess et al. 1998; Tegmark, Zaldarriaga, & Hamilton 2001; Netterfield et al. 2002; Pogosyan, Bond, & Contaldi 2003; Efstathiou et al. 2002; Pércaivl et al. 2002; Spergel et al. 2003), raises a number of questions concerning galaxy formation. The nature of DE is suitably described by the parameter \( w = p/\rho \), which characterizes its equation of state. The \( \Lambda \)-dominated cold dark matter (\( \Lambda \)CDM) model (\( w = -1 \)) was extensively studied during the last decade. On the other hand, models with a constant negative \( w > -1 \) were mostly ignored. Even less attention was given to physically motivated models with variable \( w \) (Mainini, Macciò, & Bonometto 2003a; Mainini et al. 2003b), for which no \( N \)-body simulations have been performed yet. Observations (Spergel et al. 2003; Schuecker et al. 2003a) limit the present-day value to \( w \lesssim -0.8 \), although this limit has been derived assuming constant-\( w \) models only.

In the accompanying paper (Mainini et al. 2003b) we performed the nonlinear treatment of density fluctuations for models in which DE is produced by a self-interacting scalar field (dynamical DE). This analysis gives us approximations for various quantities, which are used in this paper to both perform \( N \)-body simulations and analyze them. For the sake of completeness, we simulate models with constant \( w = -0.6 \) and 0.8 as well as dynamical DE models.

Models with varying \( w \) arise from physically motivated potentials that admit tracker solutions. In particular, we focus on the two most popular variants of dynamical DE (Wetterich 1988, 1995; Ratra & Peebles 1988, hereafter RP). The first model was proposed by RP, and it yields a rather slow evolution of \( w \). The second model (Brax & Martin 1999; Brax, Martin, & Riazuelo 2000; Brax & Martin 2000) is based on potentials found in supergravity (SUGRA), and it results in a much faster evolving \( w \). Hence, RP and SUGRA potentials cover a large spectrum of evolving \( w \). These potentials are written as

\[
V(\phi) = \frac{\Lambda^{4+\alpha}}{\phi^{4\alpha}} \quad \text{(RP)},
\]

\[
V(\phi) = \frac{\Lambda^{4+\alpha}}{\phi^{4\alpha}} \exp(4\pi G \phi^2) \quad \text{(SUGRA)}.
\]

Here \( \Lambda \) is an energy scale, currently set in the range \( 10^2 \text{--} 10^{10} \) GeV, relevant for the physics of fundamental interactions. The potentials depend also on the exponent \( \alpha \). The parameters \( \Lambda \) and \( \alpha \) define the DE density parameter \( \Omega_{DE} \). However, we prefer to use \( \Lambda \) and \( \Omega_{DE} \) as independent parameters. Figure 10 in Mainini et al. (2003b) gives...
examples of $w$ evolution for RP and SUGRA models. The RP model considered in this paper has $\Lambda = 10^3$ GeV. At redshift $z = 0$ it has $w = -0.5$. The value of $w$ gradually changes with the redshift: at $z = 5$ it is close to $-0.4$. The SUGRA model has $w = -0.85$ at $z = 0$, but $w$ drastically changes with redshift: $w \approx -0.4$ at $z = 5$. Although the $w$ interval spanned by the RP model covers values significantly above $-0.8$ (not observed by observations), this case is still important both as a limiting reference case and to emphasize that models with constant $w$ and models with variable $w$ produce different results even if the average values of $w$ are not so different. Such constant-$w$ models have no physical motivation and can only be justified as toy models to explore the parameter space. The typical values of $w$ observed in dynamical DE models, however, suggest the use of $w = -0.8$ and 0.6 for models with constant $w$.

2. SIMULATIONS

The Adaptive Refinement Tree (ART) code (Kravtsov, Klypin, & Khokhlov 1997) was used to run the simulations. The ART code starts with a uniform grid that covers the whole computational box. This grid defines the lowest (zeroth) level of resolution of the simulation. The standard multiparticle-mesh algorithms are used to compute density and gravitational potential on the zeroth-level mesh. The ART code reaches high force resolution by refining all high-density regions using an automated refinement algorithm. The refinements are recursive: the refined regions can also be refined, each subsequent refinement having half of the previous level’s cell size. This creates a hierarchy of refinement meshes of different resolution, size, and geometry covering the regions of interest. Because each individual cubic cell can be refined, the shape of the refinement mesh can be arbitrary and effectively match the geometry of the region of interest.

The criterion for refinement is the local density of particles: if the number of particles in a mesh cell (as estimated by the cloud-in-cell method) exceeds the level $n_{\text{thresh}}$, the cell is split (“refined”) into eight cells of the next refinement level. The refinement threshold depends on the refinement level. For the zeroth level it is $n_{\text{thresh}} = 2$. For the higher levels it is set to $n_{\text{thresh}} = 4$. The code uses the expansion parameter $a$ as the time variable. During the integration, spatial refinement is accompanied by temporal refinement. Namely, each level of refinement $l$ is integrated with its own time step $\Delta t_l = \Delta t_0/2^l$, where $\Delta t_0 = 3 \times 10^{-3}$ is the global time step of the zeroth refinement level. This variable time stepping is very important for the accuracy of the results. As the force resolution increases, more steps are needed to integrate the trajectories accurately. Extensive tests of the code and comparisons with other numerical $N$-body codes can be found in Kravtsov et al. (1997) and Knebe et al. (2000). The code was modified to handle DE of different types [e.g., $w(\tau)$].

We find halos using the Bound Density Maxima (BDM) code described in Klypin et al. (1999a). The BDM code finds local density maxima, places spherical shells around each maximum, and removes unbound particles. It identifies both isolated halos and subhalos. This code was extensively tested and used during the last few years.

A large number of simulations were performed. The simulations have different sizes of computational box, as well as different force and mass resolutions. Table 1 lists the parameters of all our simulations. This large set of simulations allows us to study properties of halos ranging from dwarf satellites to clusters of galaxies. Most of the simulations were run until $z = 0$. Only the models in the 160 $h^{-1}$ Mpc box were run until $z = 2$.

All simulations were extensively studied. In all cases we find that the results are bracketed by $\Lambda$CDM and RP models. Often, differences between models are not very large. In order to avoid overly crowded plots, in several figures we show the results for these two models only.

3. STATISTICS OF HALOS: POWER SPECTRUM, MASS, AND VELOCITY FUNCTIONS

Figure 1 shows the mass function for isolated halos in RP and $\Lambda$CDM models. The simulations have the same initial phases and the same value $\sigma_8 = 0.75$. Thus, the differences between models are only due to different $w(\tau)$. Remarkably, at $z = 0$ the mass functions are practically indistinguishable: a mass function has no “memory” of the past evolution. In this figure we show only two models, but all the other

| Model | $\sigma_8$ | Box Size ($h^{-1}$ Mpc) | Number of Particles | Mass Resolution ($h^{-1} M_\odot$) | Force Resolution ($h^{-1}$ kpc) |
|-------|------------|------------------------|---------------------|----------------------------------|-------------------------------|
| $w = -0.6$         | 0.75       | 80                     | $128^3$            | $2.0 \times 10^{10}$              | 5                            |
| $w = -0.8$         | 0.75       | 80                     | $128^3$            | $2.0 \times 10^{10}$              | 5                            |
| RP1          | 0.75       | 60                     | $128^3$            | $8.4 \times 10^9$                | 5                            |
| RP2          | 0.75       | 80                     | $128^3$            | $2.0 \times 10^{10}$              | 5                            |
| RP3          | 0.75       | 160                    | $256^3$            | $2.0 \times 10^{10}$              | 10                           |
| RP4          | 0.75       | 80                     | $7.32 \times 10^3$ | $3.1 \times 10^6$                | 1.2                          |
| RP5          | 1.00       | 60                     | $7.32 \times 10^3$ | $1.3 \times 10^6$                | 0.9                          |
| SUGRA1       | 0.75       | 60                     | $128^3$            | $8.4 \times 10^9$                | 5                            |
| SUGRA2       | 0.75       | 80                     | $128^3$            | $2.0 \times 10^{10}$              | 5                            |
| SUGRA3       | 0.75       | 160                    | $256^3$            | $2.0 \times 10^{10}$              | 5                            |
| SUGRA4       | 0.75       | 80                     | $7.32 \times 10^3$ | $3.1 \times 10^6$                | 1.2                          |
| $\Lambda$CDM1 | 0.75       | 60                     | $128^3$            | $8.4 \times 10^9$                | 5                            |
| $\Lambda$CDM2 | 0.75       | 80                     | $128^3$            | $2.0 \times 10^{10}$              | 5                            |
| $\Lambda$CDM3 | 0.75       | 160                    | $256^3$            | $2.0 \times 10^{10}$              | 20                           |
| $\Lambda$CDM4 | 0.75       | 80                     | $7.32 \times 10^3$ | $3.1 \times 10^6$                | 1.2                          |
| $\Lambda$CDM5 | 1.00       | 60                     | $7.32 \times 10^3$ | $1.3 \times 10^6$                | 0.9                          |
models have the same halo mass function at $z = 0$. This mass function is well fitted by the approximation provided by Sheth & Tormen (Sheth & Tormen 1999, 2002, hereafter ST; Sheth, Mo, & Tormen 2001).

At higher redshifts the situation is different: the halo mass functions deviate substantially. Figure 1 (bottom) clearly shows this point: the number of halos with mass exceeding $M > 10^{13} h^{-1} M_{\odot}$ is almost 10 times larger in the RP simulation. The differences depend on the mass scale. They are greater for massive clusters and much smaller for less massive halos. For galaxy-size halos, with mass $10^{12} h^{-1} M_{\odot}$, the differences reduce to about 20%, and this would be difficult to detect observationally.

The dependence of halo abundance on redshift is further illustrated in Figure 2, in which we study halos with masses ranging on the scales of galaxy groups. On such scales, there is almost no way to discriminate among models if we look at recent times ($z < 1$), but at $z \simeq 2–3$, differences become significant. We note that the observational detection of group-size halos at high redshift is difficult but feasible. We know how these objects should look: almost the same as nearby groups. A group at high redshift should be more compact than a group at $z = 0$, and it should consist of 3–10 Milky Way–size galaxies. Galaxies are expected to be distorted by interactions with other galaxies. A sample including a few thousands of galaxies is suitable to count the number of groups. A comparison with the number of groups at $z = 0$ could then discriminate between different models of DE. Our conclusions regarding the mass function at low redshift were confirmed in a later paper by Linder & Jenkins (2003), who used one large-volume low-resolution simulation to estimate the cluster mass function in a SUGRA model.

For each halo we find the density profile and estimate the maximum circular velocity $V_{\text{circ}} = \left[ GM(r)/r \right]^{1/2}$. We then construct the circular velocity function of the halos: the number density of halos with a given $V_{\text{circ}}$. The velocity function is akin to the mass function, but it probes deeper inside halos. For a typical halo discussed here, with a concentration $C \approx 10$, the radius of the maximum circular velocity is about 5 times smaller than the virial radius. Figure 3 shows the velocity function at $z = 2$ for the RP and $\Lambda$CDM models. Just as in the case of the mass function, the
differences between models are larger at high redshift. At a given redshift the differences are also larger for massive halos. Still, the velocity function brings new results. In fact, even at \(z = 2\), the mass functions of different models are very close for low-mass halos with virial masses of \(\approx 10^{12} \, h^{-1} M_\odot\). These halos have \(V_{\text{circ}} \approx 200 \, \text{km s}^{-1}\). On the other hand, the velocity functions at such \(V_{\text{circ}}\) are visibly different: the RP model has about 1.5 times as many halos. The only way to explain this is to have more concentrated halos in the RP model. In §4 we explore this point in detail.

Figure 4 shows the evolution of the power spectrum \(P(k)\) for DM fluctuations. The power spectrum basically follows the same pattern as the mass function: relatively large differences at high redshift, which become smaller when approaching \(z = 0\). At \(z = 0\), modest deviations remain only on small scales \((k > 2)\).

4. HALO STRUCTURE

We start our study of halo profiles by performing high-resolution simulations of the same halo in different models. The halo was initially identified in a low-resolution run. Short waves were added to the spectrum of initial perturbations, and the halo was simulated again using more particles, \(\approx 2 \times 10^5\). In the \(\Lambda\)CDM model the halo has virial mass \(5 \times 10^{13} \, h^{-1} M_\odot\) and virial radius \(730 \, h^{-1} \text{kpc}\). It is accurately fitted by an NFW profile (Navarro, Frenk, & White 1997) with concentration \(C_{\text{vir}} = 7.2\). In the RP model the virial radius is \(680 \, h^{-1} \text{kpc}\), visibly smaller than for the \(\Lambda\)CDM halo. The RP halo also has a larger maximum circular velocity as compared to the \(\Lambda\)CDM halo. Figure 5 shows profiles of the halo in the \(\Lambda\)CDM, RP, and SUGRA models. In spite of the fact that the virial radii for all the models are different, the density profiles in the outer part of the halo \((R > 100 \, h^{-1} \text{kpc})\) are practically coincident: from 100 to 700 \(h^{-1} \text{kpc}\) the differences are less than \(10\%\). At the same time, halos in the central region \((R < 100 \, h^{-1} \text{kpc})\) differ. In particular, the RP halo is clearly denser and more concentrated than the \(\Lambda\)CDM halo, while the SUGRA halo lies in between. In principle, this difference could be used to discriminate between the models. However, this will not be easy, because the differences are relatively small: a factor of 1.5 at \(10 \, h^{-1} \text{kpc}\).

The RP halo has a smaller virial radius because for the RP model, the top-hat model of halo collapse (Mainini et al. 2003b) predicts a larger virial overdensity \((\Delta_{\text{vir,RP}} = 149.8\rho_c)\). The differences in virial radii complicate the comparison of density profiles and concentrations in different DE models. For example, a halo with exactly the same profile in different DE models has different virial radii and thus different concentrations. In order to make the comparison of density profiles less ambiguous, we decided to measure the halo concentration as the ratio of the radius at the overdensity of the \(\Lambda\)CDM model \(103\times\) the critical density) to the characteristic (“core”) radius of the NFW profile. The effect of using the radius at the constant overdensity instead of the virial radius is relatively small. For a typical RP halo with virial mass \(\sim 10^{12} \, h^{-1} M_\odot\), the virial radius is \(\sim 15\%\) smaller than the constant overdensity radius.

We also study profiles of hundreds of halos in simulations with lower resolution. Figure 6 shows the dependence of the halo concentration on the mass of halos, in simulations with an \(80 \, h^{-1} \text{Mpc}^3\) box and \(\sigma_8 = 0.75\). This plot shows the same tendency that we had found for the high-resolution halo: models with dynamical DE produce more concentrated halos. Figure 7 shows the distribution of halo concentrations for halos in the mass range \((5–10) \times 10^{13} \, h^{-1} M_\odot\).
When making this plot, we preferred not to consider halos with large deviations from NFW fits: halos with an rms relative deviation larger than 0.5 were therefore excluded. The number of rejected halos is relatively small: 10%. The spread of concentrations that we find in the \( \Lambda \)CDM model is about twice as small as in Bullock et al. (2001a). This disagreement arises from the fact that we use only halos that are relaxed. We consider this a more accurate way of treating halo profiles, because when halo concentrations are used for predictions of densities and circular velocities, the NFW profile is assumed.

The excessive abundance of subhalos in the \( \Lambda \)CDM model is a known problem (Klypin et al. 1999b; Moore et al. 1999). It is interesting to find where dynamical DE models stand regarding this problem. Because fluctuations in dynamical DE models collapse earlier than in the \( \Lambda \)CDM model, one naively expects the number of subhalos to also be larger. We study the number of subhalos in a high-resolution halo, simulated in RP and \( \Lambda \)CDM models. This halo has a virial mass of \( 2.4 \times 10^{13} \ h^{-1} \ M_{\odot} \) and is resolved with particles of mass \( 1.3 \times 10^8 \ h^{-1} \ M_{\odot} \). The maximum circular velocity of the halo in the \( \Lambda \)CDM and RP models is 522 and 594 km s\(^{-1}\), respectively. The force resolution of \( \approx 1 \ h^{-1} \) kpc allows us to resolve dwarf DM halos with circular velocities larger than 30 km s\(^{-1}\). For each (sub)halo we measure the density profile and estimate the value of the maximum circular velocity.

According to expectations, the number of subhalos in the RP halo is larger than in the \( \Lambda \)CDM halo: inside the radius with a mean overdensity of 103 times the critical density there are 87 satellites in the RP halo and 52 satellites in the \( \Lambda \)CDM halo. Thus, there are a factor of 1.7 more satellites in the RP halo.

Nevertheless, this large difference can be misleading, because the circular velocity of the RP halo is larger by factor of 1.14, and halos with larger circular velocity have a tendency to have more satellites (Klypin et al. 1999b). In Figure 8 we plot the number of satellites as a function of the ratio of the satellite velocity to the halo velocity. Such a plot shows that differences between the models are then very small. It is also interesting to note that the velocity function

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**Figure 6.** Dependence of concentration on halo mass. Halos for models with \( w \neq -1 \) are all more concentrated and thus are denser than the halos in the \( \Lambda \)CDM model. To avoid crowding we show statistical errors only for the \( \Lambda \)CDM model.

**Figure 7.** Distribution of halo concentrations for halos in the mass range \((5-10) \times 10^{13} \ h^{-1} \ M_{\odot}\) for different models. Halos with large deviations from NFW fits (nonrelaxed halos) are not used.

**Figure 8.** Abundance of subhalos in a halo with virial mass \( M_{\text{vir}} = 2.4 \times 10^{13} \ h^{-1} \ M_{\odot} \). When normalized to the circular velocity of the parent halo, the velocity function is the same for both the RP and the \( \Lambda \)CDM models and is well approximated by the power law \( n(>V) \propto V^{-2.75} \). Vertical bars indicate the shot-noise errors. [See the electronic edition of the Journal for a color version of this figure.]
of subhalos is well approximated by a power law $n(> V) \propto V^{-2.75}$. The slope of the power law is the same as for subhalos of Milky Way–size halos (Klypin et al. 1999b). In other words, this indicates that the slope has no dependence on the mass of the halo or on the DE nature.

5. DISCUSSION AND CONCLUSIONS

Models with dynamical DE are in an infant state. We do not know the nature of DE. Thus, the equation of state, $w(t)$, is still uncertain. At first sight it could seem that the situation is hopeless. This paper shows that this is not true: if we accept that $w$ is close to $-1$ at $z = 0$, as many observations suggest, and that $w$ monotonically increases with redshift, dynamical models are useful and can produce definite predictions for properties of halos and galaxies hosted by the halos. At $z = 0$ differences between models are rather small but visible and can be probed with suitable techniques. At higher redshift, not only average $w$-values but also their time evolution might be discriminated.

The main tendency that we find in all DE models is that halos tend to collapse earlier than in the $\Lambda$CDM model with the same normalization of the power spectrum. As a result, halos are more concentrated and denser in their inner parts. Nevertheless, the differences are not so large. For example, the density at 10 kpc of a $\sim 10^{13} M_\odot$ halo in a dynamical DE model deviates from $\Lambda$CDM by no more than 50%. However, this means that DE is not a way to ease the problem with cuspy DM profiles.

Nevertheless, the differences in halo profiles can be exploited. Denser cluster profiles in dynamical DE models can be tested by both weak (Bartelmann, Perrottta, & Baccigalupi 2002) and strong gravitational lensing. Bartelmann et al. (1998) and Meneghetti et al. (2000) argue that arclet statistics favor open CDM models when compared to $\Lambda$CDM. In this respect, dynamical DE models are between the above two models.

We believe that the way to see which DE model fits the observed universe best is to look at the evolution of halo properties. For example, the comparison of low- and high-$z$ ($z \geq 2$) abundances of galaxy groups with mass larger than $10^{13} h^{-1} M_\odot$ can be used to discriminate between models. Potentially, the clustering of galaxies at redshift 2–3 can also be used for this.

In this paper we mostly pay attention to group-size halos, with mass $\sim 10^{13} h^{-1} M_\odot$, at high redshift as a probe for DE. In the accompanying paper (Mainini et al. 2003b) we also argue that the abundance of clusters at intermediate redshifts can be used as a test for DE models. Unfortunately, available cluster samples still have too few objects at intermediate and high redshifts to perform this test.

Deep optical and near-infrared data can be used to identify and study clusters at intermediate redshift. The Las Campanas Distant Cluster Survey (Nelson et al. 2002) or the Red-Sequence Cluster Survey (Gladders & Yee 2000) are examples of this type of catalog. Unfortunately, it is still difficult to take into account selection effects for these catalogs, and the samples currently have only dozens of objects. Selection effects are easier to handle for clusters detected in the X-ray. The ROSAT data were used to compile a number of cluster catalogs (Ebeling et al. 1996, 2000; de Grandi et al. 1999). The most numerous sample of flux-limited clusters (REFLEX; Guzzo et al. 1999; Schuecker et al. 2003a) is also based on the ROSAT observations. It includes 426 objects with redshifts up to $z \sim 0.3$. The XMM survey (Pierre 2000) will add another 500 clusters with redshifts up to $z \sim 1$. Hopefully, follow-up optical programs will provide redshifts for the clusters in the catalogs. While designed for different goals, REFLEX has already been used to constrain many cosmological parameters such as $\sigma_8$, and together with Type Ia supernova data, it provides important constraints on the DE equation of state (Schuecker et al. 2003b).

The Sunyaev-Zeldovich effect (scattering of cosmic microwave background [CMB] photons by the hot intracluster gas) is even more promising for the detection of high-$z$ clusters (La Roque et al. 2003; Weller, Battye, & Kneissl 2002; Hu 2003). The shallow all-sky survey that the Planck experiment will produce will be supplemented by deeper surveys covering a smaller fraction of the sky. These surveys will be using interferometers (One Centimetre Receiver Array: Browne et al. 2000; Sunyaev-Zeldovich Array: Carlstrom et al. 2000; Array for Microwave Background Anisotropy: Lo et al. 2000; Arcminute Microkelvin Imager: Kneissl et al. 2001).

These new cluster catalogs require much more extensive and detailed theoretical modeling. A confrontation of new observational data with theoretical predictions will then be able to discriminate between different DE models.

In our analysis we also address another important issue: the abundance of subhalos. It is well known (Klypin et al. 1999b; Moore et al. 1999) that in the $\Lambda$CDM model, the number of predicted dwarf dark matter satellites significantly exceeds the observed number of satellite galaxies in the Local Group. There are several different possibilities to explain this excess. The most attractive explanation is related to the reionization of the universe resulting in the heating of gas in dwarf halos, which prevents them from becoming galaxies (Bullock, Kravtsov, & Weinberg 2000, 2001b; Somerville 2002; Benson et al. 2002).

We find that the number of satellites of halos, at $z = 0$, in various DE models does not change relative to the $\Lambda$CDM when plotted against the circular velocity of the parent halo. If the reionization of the universe is the solution to the problem, then it is interesting to note that DE models predict an earlier reionization of the universe. This happens because the earlier collapse of dwarf DM halos in DE models requires an earlier reionization to avoid too many satellites at redshift zero. The recent Wilkinson Microwave Anisotropy Probe results (Kogut et al. 2003; Spergel et al. 2003) suggest a large opacity for CMB photons, $\tau \approx 0.17 \pm 0.04$. If true, this requires the reionization to have occurred at a redshift $z_{\rm r} \sim 13–20$, which is too high for the standard $\Lambda$CDM model (Gnedin 2000). If an early reionization occurred in a $\Lambda$CDM model, it would predict too few satellites for the Local Group, because so few dwarf halos collapse that early. DE models with a SUGRA potential seem to be in a better position to fit at the same time the WMAP results and the observed number of satellites, because in this model halos collapse at higher redshifts as compared to a $\Lambda$CDM model.

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