EVOLUTION OF DARK-MATTER HALOES IN A VARIETY OF DARK-ENERGY COSMOLOGIES

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ABSTRACT

High-resolution, numerical simulations of 17 cluster-sized dark-matter haloes in eight different cosmologies with and without dynamical dark energy confirm the picture that core halo densities are imprinted early during their formation by the mean cosmological density. Quite independent of cosmology, halo concentrations have a log-normal distribution with a scatter of $\sim 0.2$ about the mean. We propose a simple scaling relation for halo concentrations in dark-energy cosmologies.

1. Introduction

Having to accept that the expansion of the Universe is accelerated today and that only $\sim 30\%$ of its content is contributed by matter, we need to search for what may be driving the accelerated expansion. Friedmann’s equations require the dominant form of matter to have a pressure $p = -\rho c^2/3$, where $\rho$ is its density and $c$ is the speed of light. The cosmological constant has $p = -\rho$. Generalising this, the equation of state is modified to $p = w\rho c^2$, with $w < -1/3$. In the simplest of these models, $w$ is constant, but it is more natural to assume that $w$ is a function of time, scale factor or redshift. One possible, admittedly hypothetical form of matter with such an equation of state is a self-interacting scalar field with an interaction potential which is sufficiently larger than its kinetic energy (e.g., Wetterich 1988; Ratra and Peebles 1988; Peebles and Ratra 2002).

Replacing the cosmological constant by such a hypothetical “dark energy” has consequences for structure growth and the properties of dark-matter haloes (Bartelmann et al. 2002; Weinberg and Kamionkowski 2003; Klypin et al. 2003). We report here on our studies of how halo concentrations change in a variety of dark-energy models (Dolag et al. 2004). This leads us to suggest a remarkably simple scaling of halo concentrations with the linear growth factor in dark-energy models. We indicate consequences for strong lensing by galaxy clusters, which offer one possibility for constraining dark-energy models. Throughout, we use present-day matter and dark-energy density parameters of $\Omega_{\text{m0}} = 0.3$ and $\Omega_{\text{\Lambda0}} = 0.7$, and a Hubble constant of $h = 0.7$ in units of 100 km s$^{-1}$ Mpc$^{-1}$.

2. Dark-Energy Models

The continuity equation requires that the density of dark energy changes with the scale factor $a$ as

$$\frac{\dot{\Omega}_{\text{\Lambda}}(a)}{\Omega_{\text{\Lambda0}}} = -3\int_a^1 [1 + w(a')] \text{d} \ln a', \quad (1)$$

This term replaces the usual cosmological-constant term in Friedmann’s equation. For $w = \text{const.} = -1$, the cosmological-constant behaviour is retained. For $w = \text{const.}$, the scale-factor dependence simplifies to

$$\Omega_{\text{\Lambda}}(a) = \Omega_{\text{\Lambda0}} a^{-3(1+w)}. \quad (2)$$

If $w = -1/3$, the model behaves like an open CDM model without cosmological constant because then $\Omega_{\text{\Lambda}}$ mimics the curvature term in Friedmann’s equation.

We use one model with $w = -0.6 = \text{const.}$ for reference, and two models with time-varying $w$. These are the Ratra-Peebles model (Ratra and Peebles 1988) in which the scalar-field potential is a power law, and the SUGRA model (Brax and Martin 2000) which has an additional exponential factor in the potential. Both are normalised such that $w_0 = -0.83$ at $a = 1$. While $w$ is almost constant for the Ratra-Peebles model in the relevant redshift range, it increases from $-0.83$ to $-0.4$ between redshifts 0 and 2 in the SUGRA model.

If normalised to its amplitude today, structure grows earlier in dark-energy compared to cosmological constant models. Since numerical simulations demonstrate that dark-matter haloes keep a memory in their cores of the mean cosmic density at their formation times (Navarro et al. 1997), haloes forming earlier are expected to have higher core densities. Thus, at fixed mass and redshift, haloes are expected to be more concentrated in dark-energy than in cosmological-constant models. This was expected from analytic considerations. The work reported here aims at testing this expectation with numerical simulations.

3. Numerical Simulations

Using the Gadget code (Springel et al. 2001), we ran a large-scale cosmological simulation of the CDM model, identified massive haloes within it, identified their Lagrangian volumes at the initial redshift, added small-scale power and re-simulated them at much increased resolution (Tormen et al. 1997). The particle mass is $5 \times 10^9 h^{-1} M_{\odot}$. We thus created a sample of 70 clusters with final masses between $3 \times 10^{14}$ and $2 \times 10^{15} h^{-1} M_{\odot}$. The CDM simulation was normalised to $\sigma_8 = 0.9$.

We then re-simulated this same cluster sample in dark-energy cosmologies. For doing so, we shifted the initial redshift of the simulation to higher values such that the earlier structure growth in the dark-energy models was compensated. For achieving the same density-fluctuation normalisation today, the initial redshift $z_{\text{ini}}$ of the dark-energy simulations needs to satisfy

$$\frac{D_s(z_{\text{ini}})}{D_s(0)} = \frac{D_{s,\Lambda CDM}(z_{\text{ACDM}})}{D_{s,\Lambda CDM}(0)}, \quad (3)$$

where $D_s(z)$ is the linear growth factor as a function of redshift,
and $z_{\text{coll}}^{\text{ini}}$ is the initial redshift of the $\Lambda$CDM simulation. It is important to also rescale the initial velocities of the simulation particles to the higher initial redshift.

The normalisation of the models is an open issue. The earlier structure growth in dark-energy models increases the integrated Sachs-Wolfe effect and thus the amplitude of large-scale secondary fluctuations in the CMB. A smaller fraction of the observed fluctuations can then be attributed to the primordial CMB, thus the normalisation of the power spectrum should be lowered.

However, we are interested in the properties of dark-matter haloes whose linear scale is much smaller than that of the Sachs-Wolfe tail in the CMB power spectrum. How the large-scale amplitude measured by on CMB translates to small scales depends sensitively on the large-scale slope of the density power spectrum. We argue that weak gravitational lensing directly measures the power-spectrum amplitude at the scales relevant here and should thus develop into the prime method for normalising the power spectrum at small scales. For now, we study two sets of normalisations. One has constant $\sigma_8 = 0.9$ for all cosmological models, the other has reduced $\sigma_8$ such as to take the enhanced ISW effect into account.

In total, we simulate our sample of 17 clusters in eight different cosmologies: $\Lambda$CDM, Ratra-Peebles, SUGRA, and $w = -0.6$, the latter three with two different normalisations each, and an open-CDM model with $\Omega_{\Lambda} = 0$ for comparison.

4. Results

We fit the NFW density profile to all clusters and obtained concentration parameters for all of them at 50 output redshifts between $z = 3$ and today. For all these cluster snapshots, we also compute analytically expected concentrations according to the algorithms proposed by [Navarro et al. (1997), Bullock et al. (2001); Eke et al. (2001)]. These algorithms implement in different ways essentially the same idea: The core halo density is determined by the mean cosmological density at the halo formation redshift, which is typically defined as the redshift when the most massive progenitor of the final halo reaches a certain small fraction of the final halo mass. The factor between the mean cosmological density and the halo core density, and the fraction of the final halo mass used for defining the halo formation redshift, are two free parameters in the algorithms by Navarro et al. (1997) and Bullock et al. (2001). The algorithm by [Eke et al. (2001)] has only one free parameter. We determine these parameters by minimising the squared deviation between the analytic halo concentrations expected for the given halo masses and redshifts, and the numerically-determined halo concentrations.

We find that excellent agreement between the numerical halo concentrations and the predictions by the algorithm of Bullock et al. (2001) can be achieved if haloes are assumed to form very early, or, in other words, if we assume that halo core properties are imprinted when only a very small fraction of the final halo mass is already in place. The results from the algorithm of Eke et al. (2001) agree very well with the numerical concentrations without any parameter adaptation, while the Navarro et al. (1997) algorithm predicts too shallow redshift evolution (cf. Fig. 1).

Our results admit a power-law fit of the form

$$c(M, z) = \left(\frac{M}{10^{14} M_\odot}\right)^{\alpha},$$

where $c_0$ is a constant for each cosmology. The exponent $\alpha \approx -0.1$ for all cosmologies tested, thus the mass-dependence of the halo concentrations is quite shallow for massive haloes. Table 1 summarises the parameters we find.

The scatter among the concentrations is large, but well-described by a log-normal about the mean given by $\mathcal{N}$ (cf. Fig. 2), see also Jing (2000). Quite independent of the cosmological model, the standard deviation of $\ln(c/\bar{c})$ is $\approx 0.22$ (cf. Fig. 2).

Interestingly, it turns out that a simple description can also be given for the cosmology-dependence of the parameter $c_0$. We find $c_0^{\Lambda\text{CDM}} \approx 9.6$, and for the other cosmological models

$$c_0 = c_0^{\Lambda\text{CDM}} \frac{D_z^{\Lambda\text{CDM}}(z_{\text{coll}})}{D_z^{\text{model}}(z_{\text{coll}})},$$

i.e. the concentrations scale in proportion to the linear growth factor, provided that the halo collapse redshift $z_{\text{coll}}$ is chosen high enough; in fact, even $z_{\text{coll}} \to \infty$ produces good agreement with the numerical simulations. This reinforces the impression that halo properties are imprinted at very early times, when only a very small fraction of the final halo mass is already in place.

The higher halo concentrations found in dark-energy cosmologies are expected to have pronounced consequences for strong gravitational lensing by galaxy clusters. This is indicated by an analytic study we have carried out, and demonstrated by a numerical study using the same cluster sample described here (cf. the contribution of Meneghetti et al. to these proceedings).
Fig. 2.—Quite independent of cosmology, the halo concentrations fall on a log-normal distribution with a scatter of \( \approx 0.22 \).

5. Conclusions

Using numerical simulations of 17 cluster-sized haloes in eight different cosmologies, we have tested and confirmed analytic expectations for the dependence of halo concentrations on models for the dark energy. Earlier structure growth in dark-energy models yields more concentrated haloes. If it is assumed that core halo properties are imprinted at very early times, when only a very small fraction of the final halo mass is already in place, the halo-concentration algorithms proposed by Bullock et al. and Eke et al. turn out to work remarkably well. Halo concentrations have a log-normal distribution with a scatter of \( \approx 0.22 \) about their mean values, quite independent of cosmology. For all cosmologies tested, the mean halo concentration at fixed mass and redshift scales in proportion to the linear growth factor at the halo formation time if the latter is defined to be very early.

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