Non-Linear Structure in Early Dark Energy Cosmology

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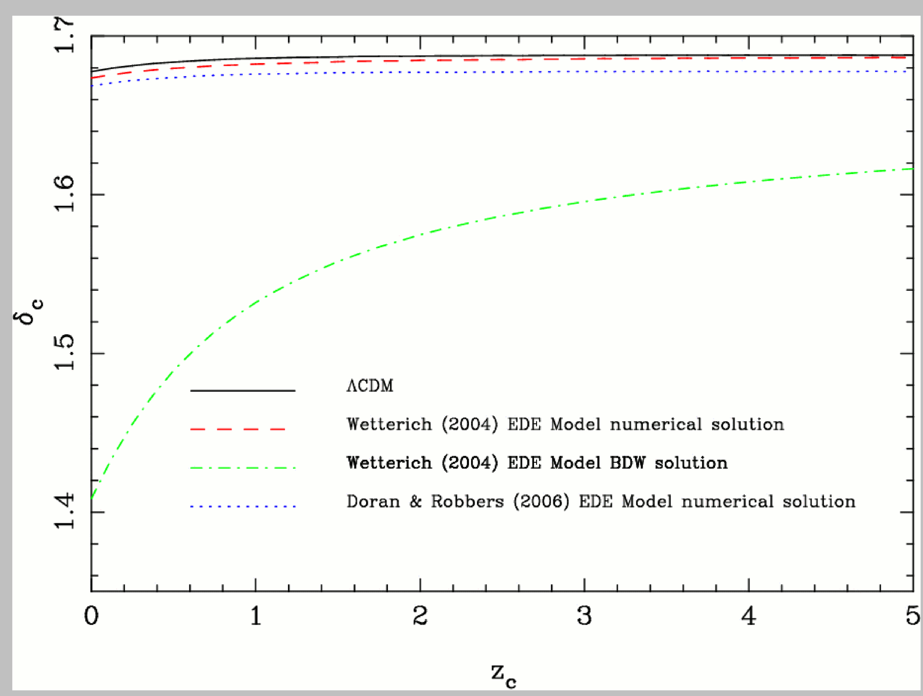
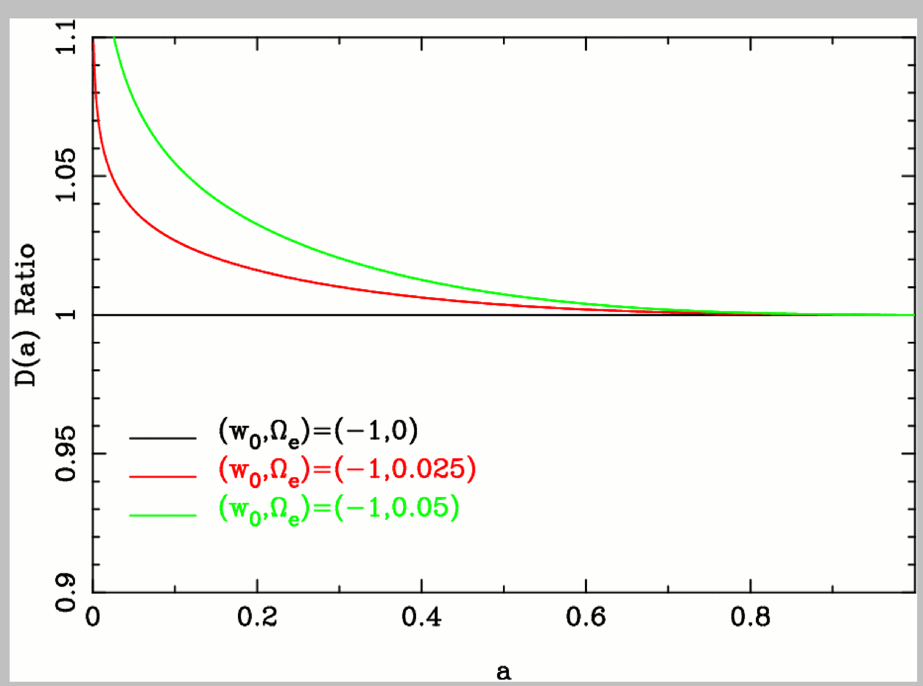
We investigate the formation of non-linear structure in cosmologies with early dark energy using cosmological N-body simulations. We find that standard approaches for predicting the power spectrum and the halo mass function in ΛCDM show good agreement with our simulation data. Earlier work suggested that the extended Press-Schechter approach fails for early dark energy, however we demonstrate an improved calculation of the linear density contrast at collapse, δ_c, that preserves both the function form and physical motivation of this approach.

Calculation of δ_c

Bartelmann, Doran & Wetterich (2006; BDW) calculated that the linear density contrast at collapse time, δ_c, is significantly altered in early dark energy cosmologies compared to ΛCDM. δ_c is a key element in the extended Press-Schechter mass function approach [such as Sheth & Tormen (1999)] and using this approach, BDW predicted a significant increase in the abundance of dark matter halos in early dark energy cosmologies compared to ΛCDM. In Francis, Lewis & Linder (2008a) we found that this result disagreed strongly with N-body simulation results, suggesting that the Press-Schechter approach fails for early dark energy. However, in Francis, Lewis & Linder (2008b), we examined the calculation of δ_c and find it to be little altered compared to ΛCDM, in contrast to previous calculations. Sheth-Tormen mass functions using our values agree with the simulation data preserving the form and physical motivation of the Sheth-Tormen mass function.



Comparison of δ_c values from Bartelmann, Doran & Wetterich (2006) and our results from Francis, Lewis & Linder (2008b). We find that early dark energy has little effect on δ_c using a numerical solution rather than the analytic approximation of Bartelmann, Doran & Wetterich (2006) that predicts a significant difference.



Comparison between the linear growth factor, D(a), of early dark energy and ΛCDM. When normalised to the same value today, the growth factor is higher in the early universe in early dark energy. This is due to a slowing of the early universe growth rate.

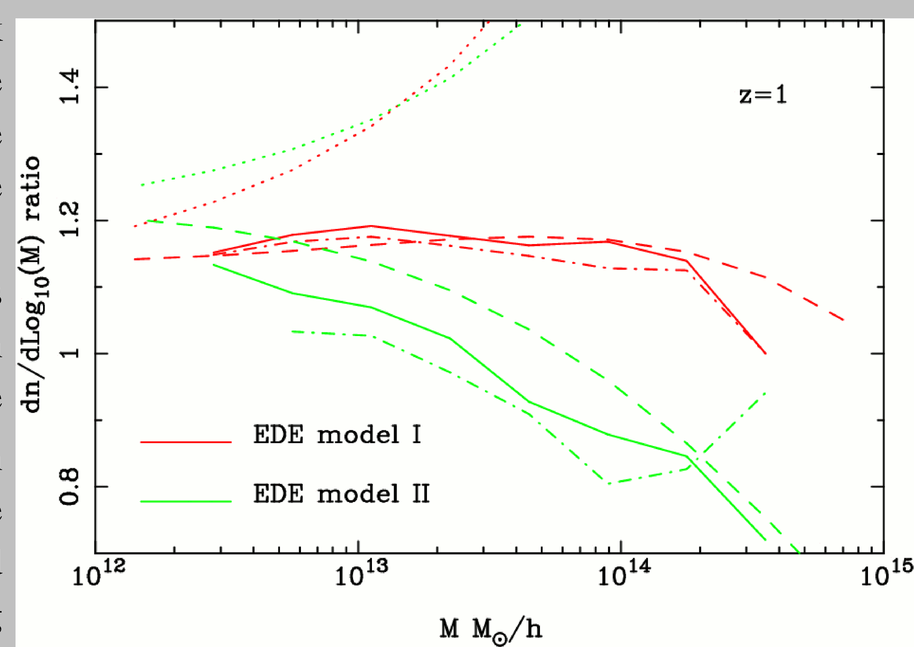
Halo Mass Function

The slower rate of structure growth in early dark energy cosmologies compared with ΛCDM means that in order to reach the same overall level of structure today (the same σ_8), the amount of structure in the past must have been greater assuming the rest of the cosmology is fixed. Our N-body simulations do show an enhanced number of dark matter halos at high redshift for early dark energy compared to ΛCDM, however the difference is minor and occurs only for the most massive halos. We find that the relative mass functions of early dark energy and ΛCDM are fit well by universal mass functions such as the Jenkins *et al.* (2001) and Warren *et al.* (2006) formulas, as well as the extended Press-Schechter approach of Sheth & Tormen (1999) as long as the correct linear density contrast at collapse time, δ_c, is used in the early dark energy case. The prospects for detecting early dark energy through halo abundance are not as great as previously thought, however a detectable difference should occur at sufficiently high redshift for massive clusters.

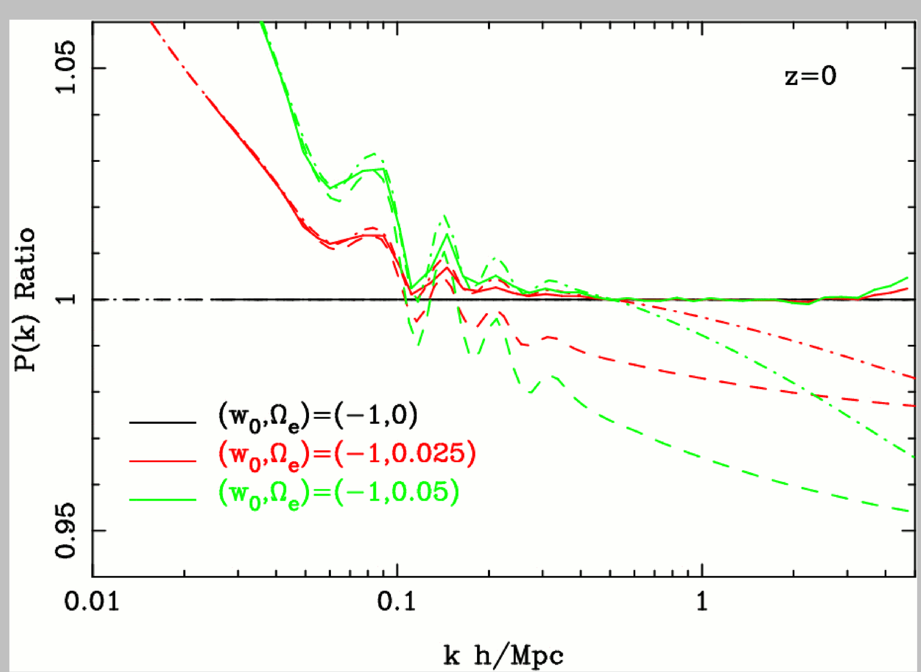
Non-Linear Power Spectrum

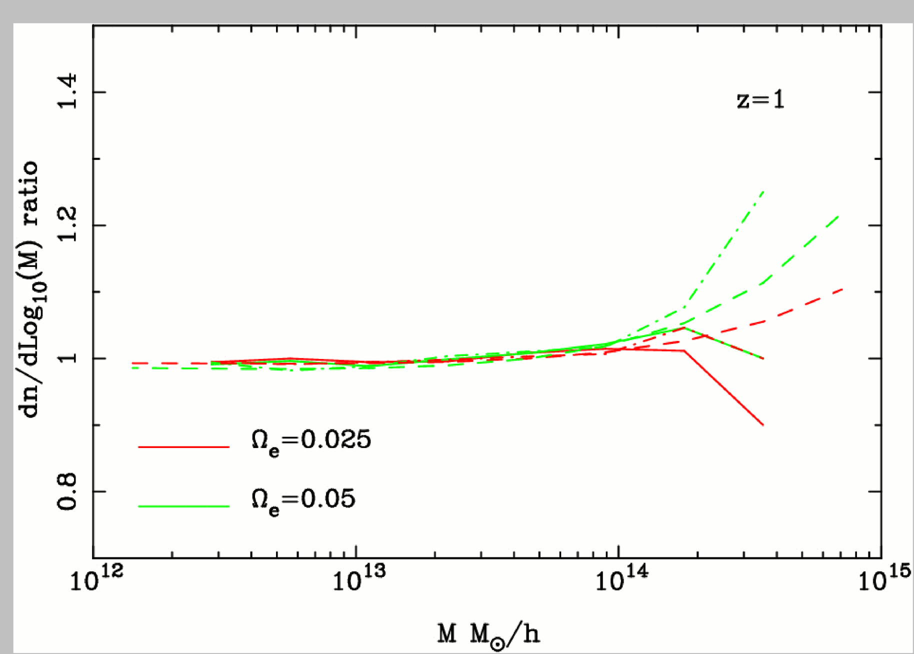
The non-linear dark matter power spectrum, P(k), is fit well in ΛCDM by the Halofit (Smith *et al.* 2003) formula. The presence of early dark energy changes the effective slope of the linear matter power spectrum for a fixed primordial spectral index, *n*, relative to ΛCDM. It also changes the linear growth factor, D(a). Both of these changes can be incorporated into the Halofit formula, by calculating the early dark energy growth factor and the linear power spectrum using a CMB package, in our case Cmbeasy (Doran 2005). However, while the Halofit formula can be modified for the instantaneous growth factor, it does not see the altered growth *history* compared to ΛCDM. We find that for large and intermediate scales, the Halofit formula works well, but at small scales where the one halo term dominates, the non-linear power is enhanced in early dark energy models; this is consistent with the higher halo concentrations found in Grossi & Springel (2008).

Halo mass function ratios of early dark energy and ΛCDM. The solid lines are simulation results for FOF halos, the dot dashed lines are SO halos, the dashed lines are the Jenkins *et al.* (2001) formula, which also agrees closely with the Sheth & Tormen (1999) formula using our δ_c and the dotted lines are the Bartelmann, Doran & Wetterich (2006) prediction. The EDE models in this case are picked from a Monte Carlo chain fitting current data.



The non-linear power spectrum ratio for two early dark energy models using the Doran & Robbers (2006) model. All other cosmological parameters are held fixed and the linear power spectra are normalised to the same σ_8 today. The linear power spectrum ratios are shown with dashed lines and the measured non-linear ratios with solid lines. The modified Halofit formula predictions are shown with dot-dashed lines.





To investigate the effects of early dark energy alone, here we hold the cosmology fixed apart from Ω_e, the parameter quantifying the dimensionless energy density of dark energy at early times. Line styles are the same as above. In this case we see that early dark energy makes a small difference to the halo abundance relative to ΛCDM and only at the high mass end.

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