The structure of dark matter haloes in coupled dark energy cosmologies

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Coupled dark energy: Theory

Coupled dark energy models - Theory

- Scalar fields (quintessence) could explain dark energy and are predicted in particle physics theories
- Interacting dark sector may explain coincidence and fine tuning problem. Unified dark sector theoretically appealing
- General dark sector lagrangian density can be written as:

$$\mathcal{L} = \mathcal{L}_{SM+DM} + \frac{1}{2}\dot{\phi}^2 + m(\phi)\psi_{DM}\bar{\psi}_{DM} + V(\phi)$$

Coupled dark energy models - Theory

- Ratra-Peebles potential:

$$V(\phi) = V_0 \left(\frac{\phi}{M_p} \right)^{\alpha}$$

- Interaction through varying mass term:

$$m(\phi) = m_0 e^{-\beta(\phi) \frac{\phi}{M_p}}$$

- $\beta > 0 \rightarrow$ energy transfered from DM to DE, in general $\beta = \beta(\phi)$ or $\beta =$constant.

Coupled dark energy models - Theory

- For uncoupled models, best fit values for Ratra-Peebles potential are: $V_0 = 1.3 \times 10^{-7} M_p^4$, $\alpha = -0.143$
- Degeneracy between coupling, initial ϕ_0 and potential, loose observational constraints.
- Fixing Ratra-Peebles to free ϕ values, coupling $\beta < 0.15$ from combined observations (SNeIa, CMB, BAO)

Coupled dark energy models - Theory

- Solving the perturbation equations, we find a new gravitational potential for CDM. DM particles feel the effective gravitational constant:

$$\tilde{G} = G_N(1 + 2\beta^2)$$

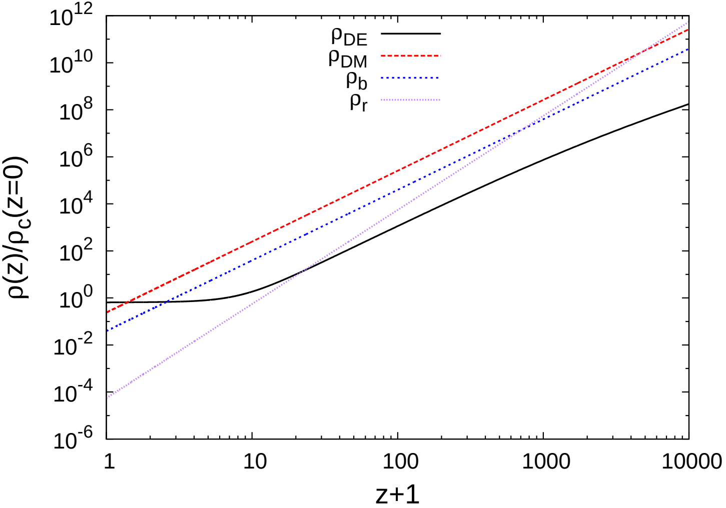
- Solving Euler equation we find that particles' velocities obey the new law:

$$\dot{v}_c = -\tilde{H} v_c - \nabla \frac{\tilde{G}\tilde{M}}{r}$$

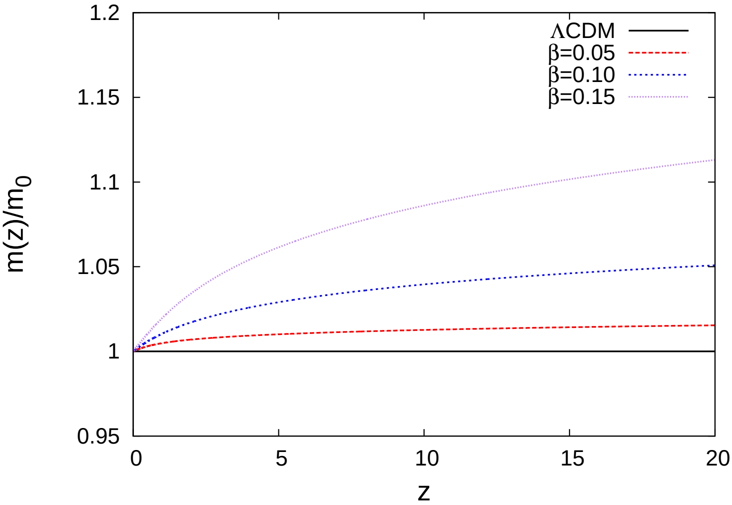
- Additional cosmic friction term:

$$\tilde{H} = H\left[1 - \frac{\beta\phi}{M_p H}\right]$$

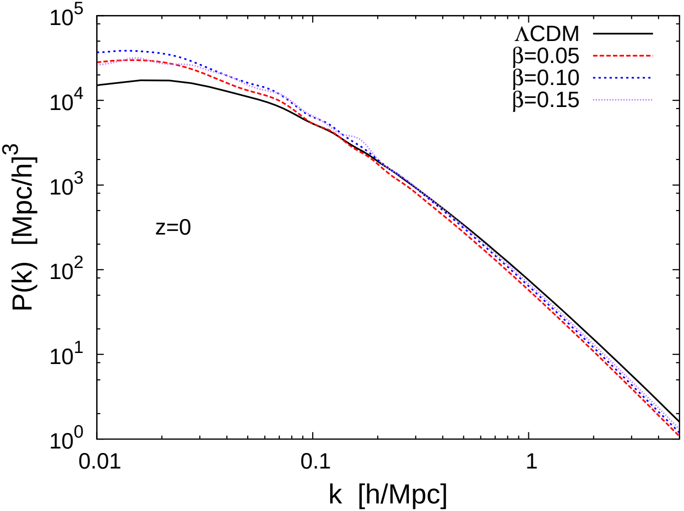
Energy densities for RP, $\beta = 0.1$



Mass variation



Power spectra



N-Body Simulations

N-body simulations

- GADGET-2: Tree-PM code [1] modified for cDE
- Several effects to be taken into account [2]:
  - background expansion
  - varying particle mass
  - cosmic friction
  - fifth force
  - initial conditions
- Input tables computed with CMBEASY [3] (C++ Boltzmann code)

[1] **V. Springel '05**
[2] **M. Baldi '10**
[3] **M. Doran, M. Mueller, G. Robbers '03**

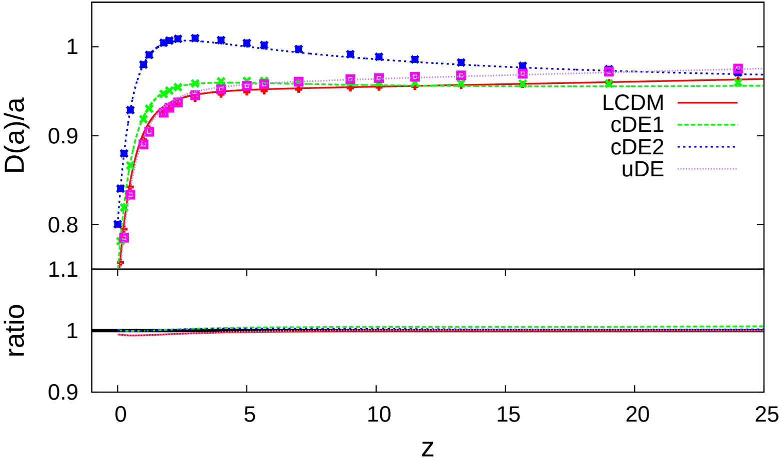
Model parameters

Model	Ω_M	Ω_{DE}	σ_8	h	β	α
ΛCDM	0.27	0.73	0.8	0.7	-	-
uDE	0.27	0.73	0.8	0.7	-	0.143
cDE1	0.27	0.73	0.8	0.7	0.05	0.143
cDE2	0.27	0.73	0.8	0.7	0.10	0.143

Simulation settings

- Box size: $50 Mpc/h$
- $N = 512^3$ particles
- DM only, $m = 6.9 \times 10^7 M_\odot/h$
- $z_{start} = 60$

Code testing



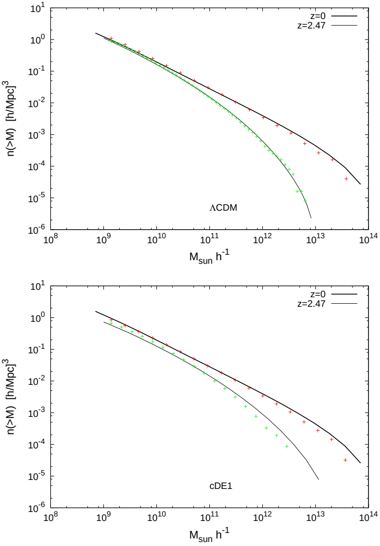
First results

Halo finding

- Amiga Halo Finder v. 1.0 [4]
- $M_{vir} = \Delta \rho_{crit} \frac{4\pi R_{vir}^3}{3}$,
- $\Delta = \frac{\rho(R_{vir})}{\rho_c} = 200$
- $\rho_c = \frac{3H^2}{8\pi G}$, H(z) is model dependent.

[4] **S.Gill, A.Knebe '04; S.Knollmann, A.Knebe '09**

LSS: Cumulative mass functions vs. Tinker



Halo sample

- $M > 3 \times 10^{10}\ h^{-1} M_{\odot}$, $\gtrsim$ 500 particles per halo
- Virialization [5]:

$$\left|\frac{2E_{kin}}{E_{pot}}\right| < 1.5$$

- Spin [5]:

$$\lambda < 0.15$$

- Total halo sample $\approx 10^4$

[5] **Maccio et al '08**

Basic halo properties

- Spin:

$$\lambda = \frac{L_{200}}{\sqrt{2} M_{200} V_{200} R_{200}}$$

- Concentration:

$$c = \frac{r_{200}}{r_s^{NFW}}$$

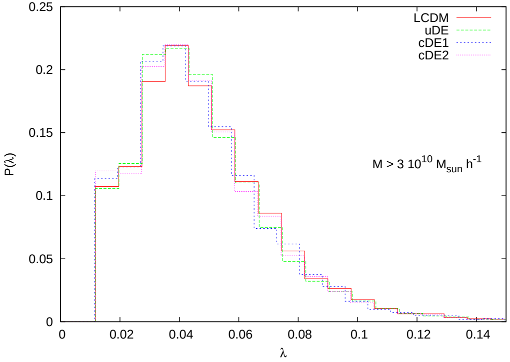
- Triaxiality (halo axes $a > b > c$):

$$T = \frac{a^2 - c^2}{a^2 - b^2}$$

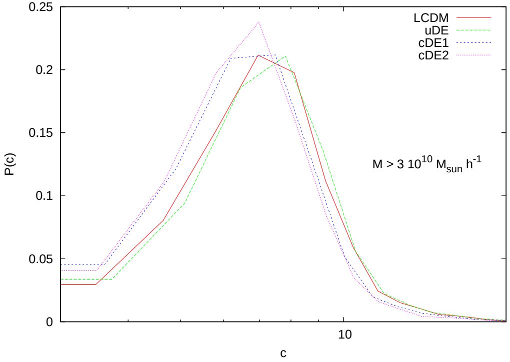
- Shape:

$$s = \frac{c}{a}$$

Spin parameter



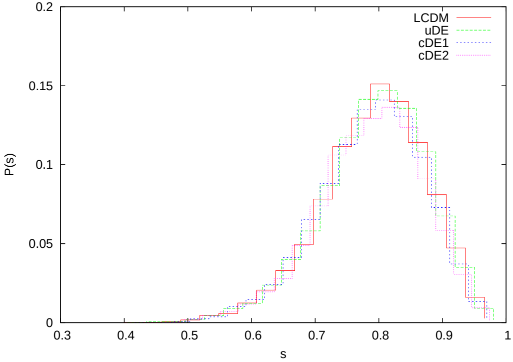
Best fit log norm $\lambda_0 \simeq 0.036$ for all models



Average c:

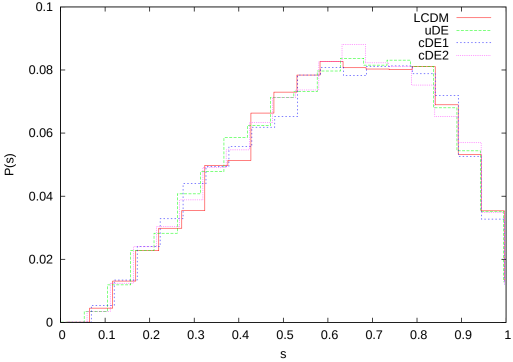
$$c_{\Lambda CDM} = 7.3; \quad c_{uDE} = 7.2; \quad c_{cDE1} = 6.9; \quad c_{cDE2} = 6.8;$$

Triaxiality



Average triaxiality $T_0 \simeq 0.79$ for all models

Shape parameter



Average shape $s_0 \simeq 0.68$ for all models

Substructure

- Largest halo $M_{200} \approx 1.3 \times 10^{14} M_\odot/h$; N of subhalos:

$$N_{\Lambda CDM} \approx 340, N_{uDE} \approx 280, N_{cDE} \approx 240$$

- 38 halos with $M_{200} > 10^{13} M_\odot/h$, average N subhalos

$$< N_{\Lambda CDM} >\approx 70, < N_{uDE} >\approx 60, < N_{cDE} >\approx 50$$

- Larger sample needed to improve statistics

Conclusions

- N-body code to simulate interacting coupled DE-DM models
- First results on basic halo properties do not show many differences between models
- Substructure may reveal interesting differences between cosmologies
- New simulations 1024^3 particles in 75 h^{-1}Mpc box to study substructure