

# Spherical collapse of non-top-hat profiles in the presence of dark energy with arbitrary sound speed

**Ronaldo Carlotto Batista**

Escola de Ciências e Tecnologia, UFRN  
Instituto de Física, USP

**Henrique Pereira de Oliveira**

Universidade Estadual do Rio de Janeiro

**Luís Raul Weber Abramo**

Instituto de Física, USP

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# Outline

- ♦ **Context: K-essence and SC Model**
- ♦ **Numerical method**
- ♦ **SC with arbitrary DE sound speed**
- ♦ **Summary**

# K-essence models

$$S = \int d^4x \sqrt{-g} \left( \frac{R}{2} + \mathcal{L}_m + \mathcal{L}_K \right) \quad \mathcal{L}_K = K(X, \varphi) \quad X = \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

## Perfect Fluid Correspondence

**Equation of State**  $p = w\rho$   $w = \frac{K}{2XK_{,X} - K}$

**Sound Speed**  $c_s^2 = \left( \frac{\delta p}{\delta \rho} \right)_{\text{rest}}$   $c_s^2 = \frac{K_{,X}}{K_{,X} + 2XK_{,XX}}$

## Linear solutions in EdS

$$c_s^2 \simeq 1 \quad c_s^2 \rightarrow 0$$

$$\delta_{de} = -\frac{1+w}{c_s^2} \phi$$

**Homogeneous DE**

$$\delta_{de} = \frac{1+w}{1-3w} \delta_m$$

**Clustering DE**

# Spherical Collapse Model

Gunn & Gott  
1972

$$\ddot{R} = -\frac{GM}{R^2} \quad M = \frac{4\pi}{3} R^3 \bar{\rho}_m (1 + \delta_m(t)) = \text{const}$$

**Analytical solutions in Eds:**

**Linear collapse threshold**

$$\delta_c = \delta_m^L(R \rightarrow 0) = \frac{3}{5} \left( \frac{3\pi}{2} \right)^{(2/3)} \simeq 1.686$$

**Virialization**

$$U = -2K \quad R_v = R_{\text{max}}/2 \quad \Delta = \frac{\rho_m(z_v)}{\bar{\rho}_m(z_c)} \simeq 177.7$$

**Homogeneous DE Models:**

$$M \rightarrow M = \frac{4\pi}{3} R^3 [\bar{\rho}_m (1 + \delta_m) + \bar{\rho}_{de} (1 + 3w)]$$

# Spherical Collapse Model from Pseudo-Newtonian Cosmology

$$\dot{\rho} + \vec{\nabla} \cdot (\vec{u}\rho) + \frac{p}{c^2} \vec{\nabla} \cdot \vec{u} = 0$$

Abramo, RCB,  
Liberato & Rosenfeld  
0707.2882  
0806.3461

$$\dot{\vec{u}} + \left( \vec{u} \cdot \vec{\nabla} \right) \vec{u} = -\vec{\nabla} \Phi - \frac{\vec{\nabla} p}{\rho + p/c^2}$$

Good agreement  
with relativistic  
perturbations.

$$\nabla^2 \Phi = 4\pi G \left( \rho + 3\frac{p}{c^2} \right)$$

Spherical Collapse  
Approximation

$$\vec{v} = f(t)\vec{x}$$

All fluids flow with the same  
velocity.

$$c_s^2 \vec{\nabla} \delta = 0$$

No pressure gradients.

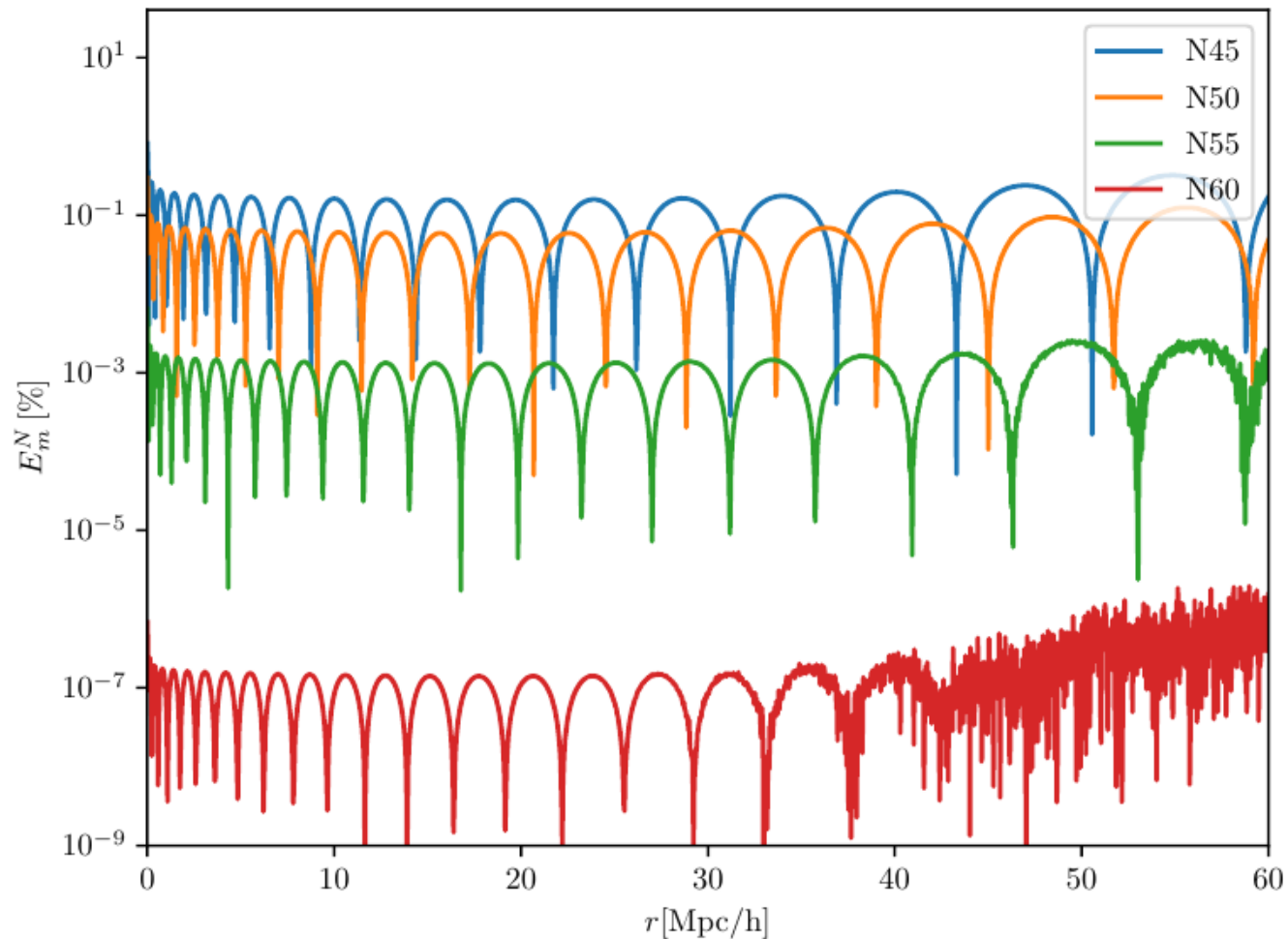
For more applications and discussions see  
“A short review on Clustering Dark Energy”  
2204.12341

# Numerical Method

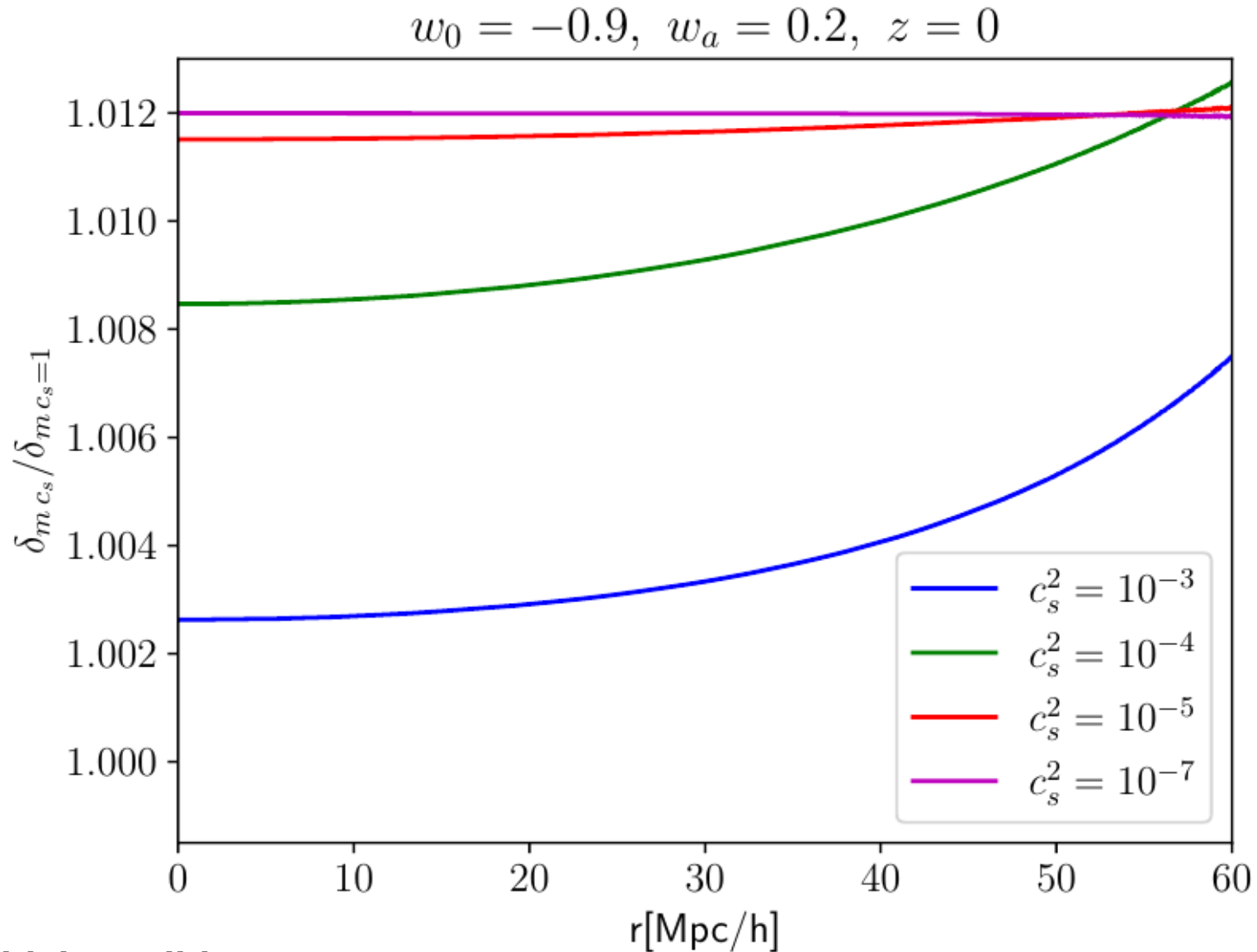
**Galerkin-Collocation  
method**

$$\delta_m(t, r_j) = \sum_{k=0}^N a_k(t) \psi_k(r_j) \equiv \delta_{m[j]}^{(\text{exact})}(t)$$

$$\delta_m(a_i, r) = A \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad \sigma = 30\text{Mpc/h}$$



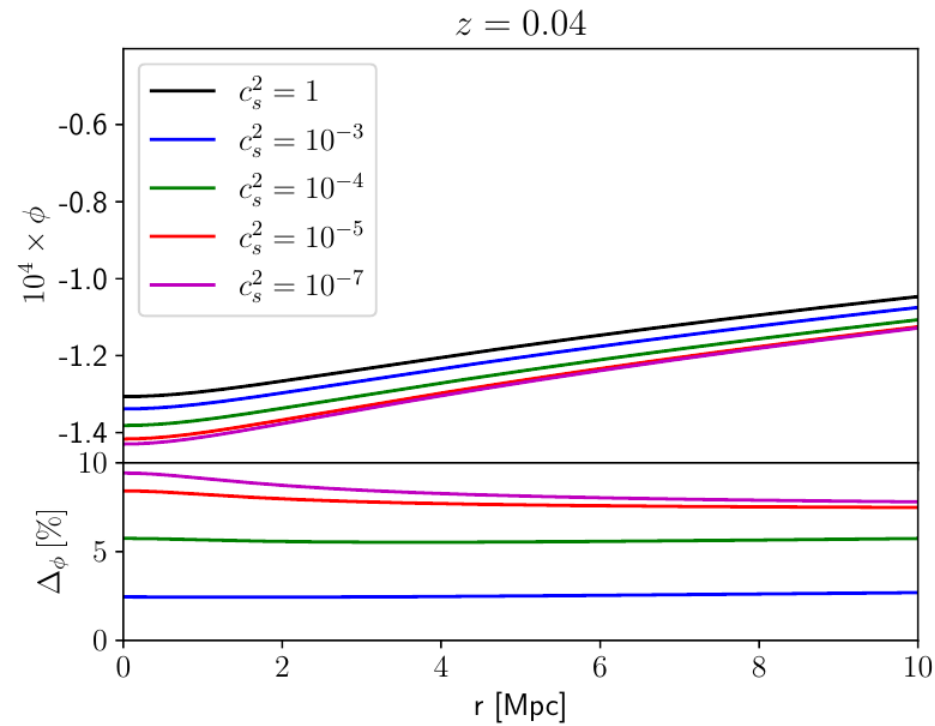
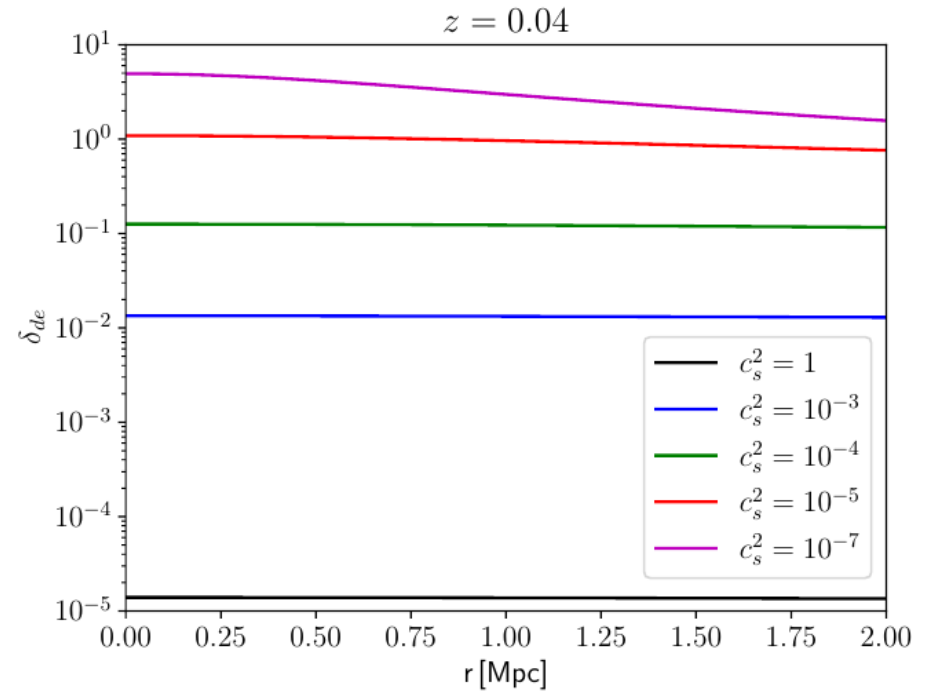
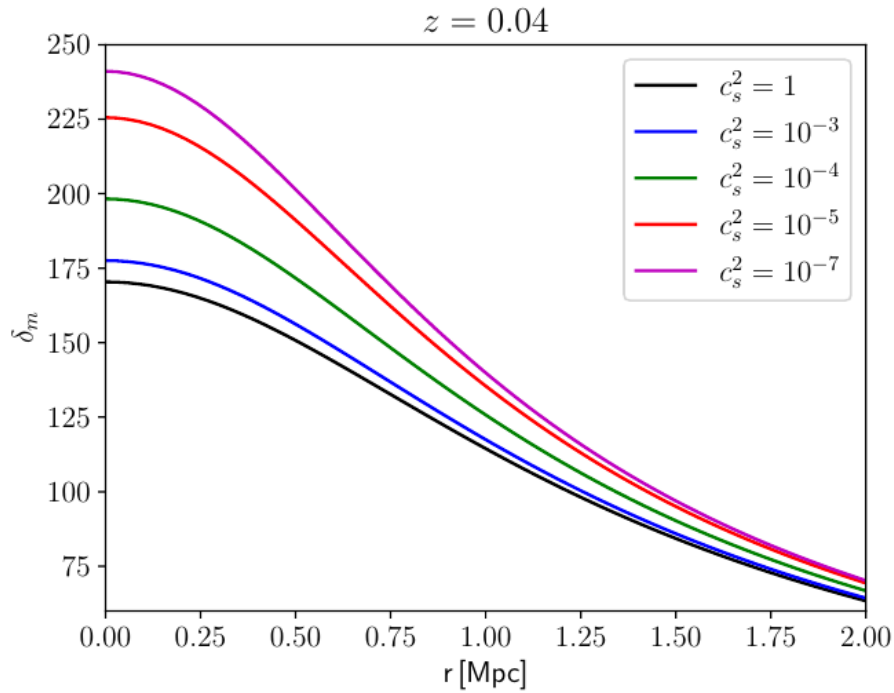
# Scale-dependent growth



Same initial conditions

# Halos

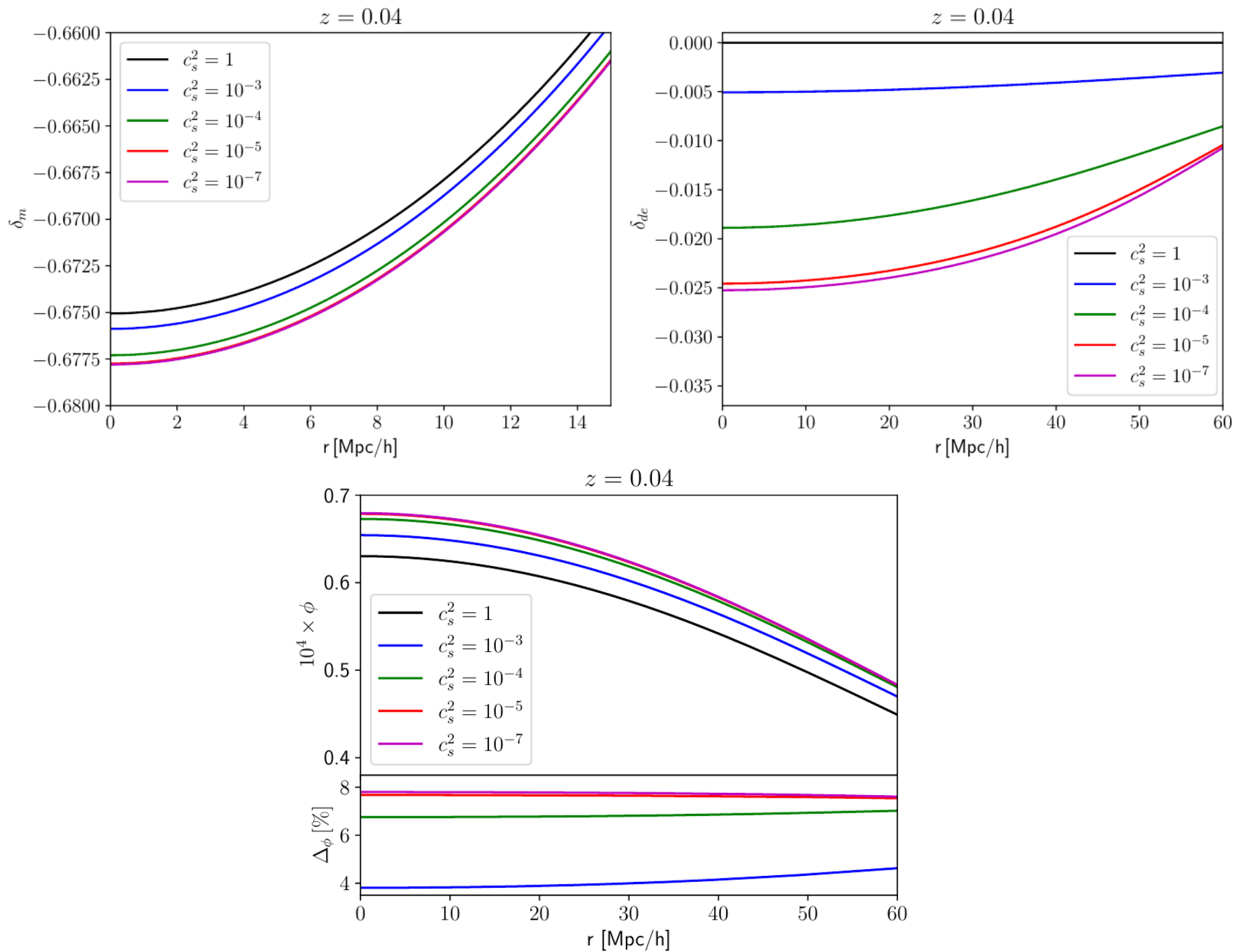
$$w_0 = -0.9, w_a = 0.2$$





# Voids

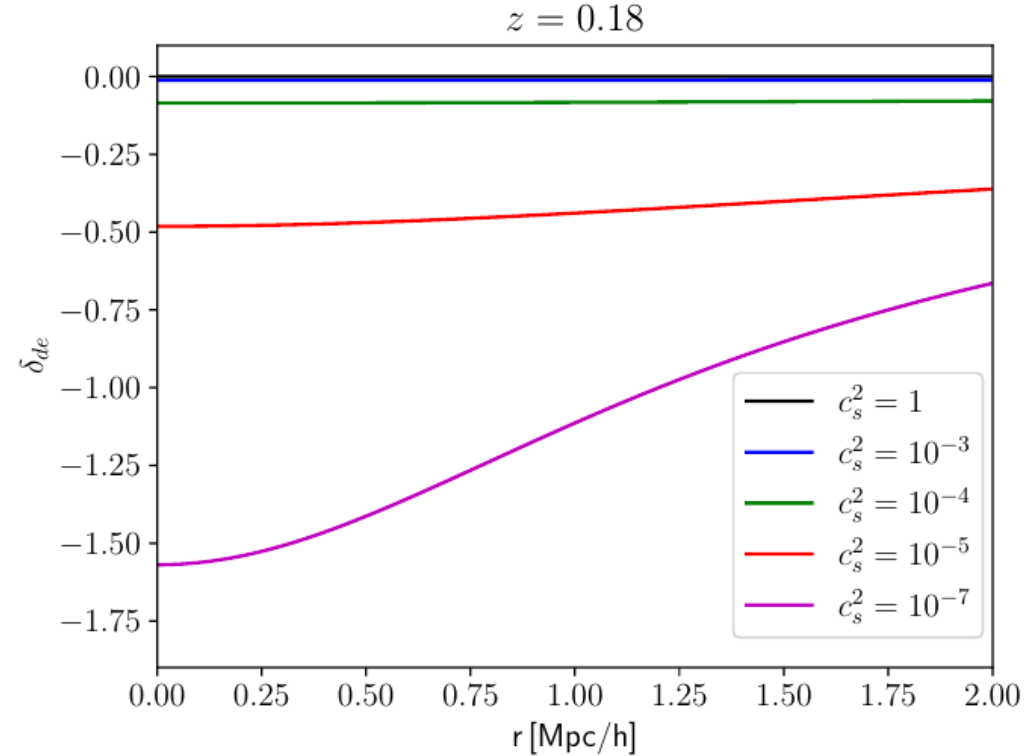
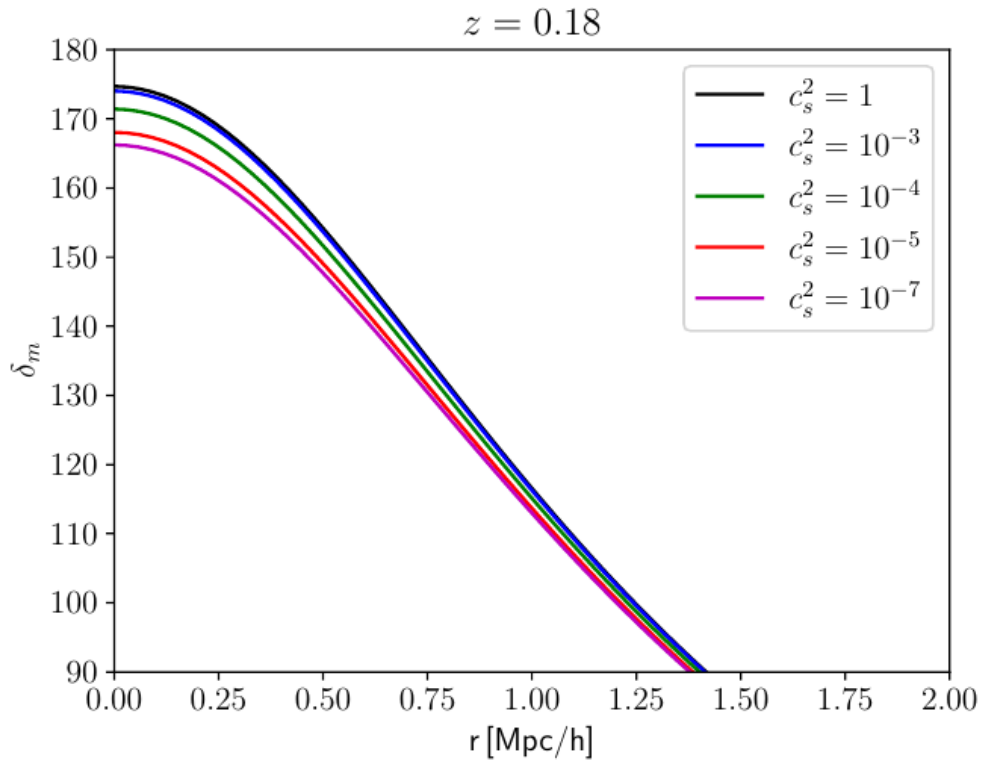
$$w_0 = -0.9, w_a = 0.2$$



# Phanton Pathology

$$w_0 = -1.1, w_a = 0$$

$$\rho_{de} = \bar{\rho}_{de} (1 + \delta_{de})$$



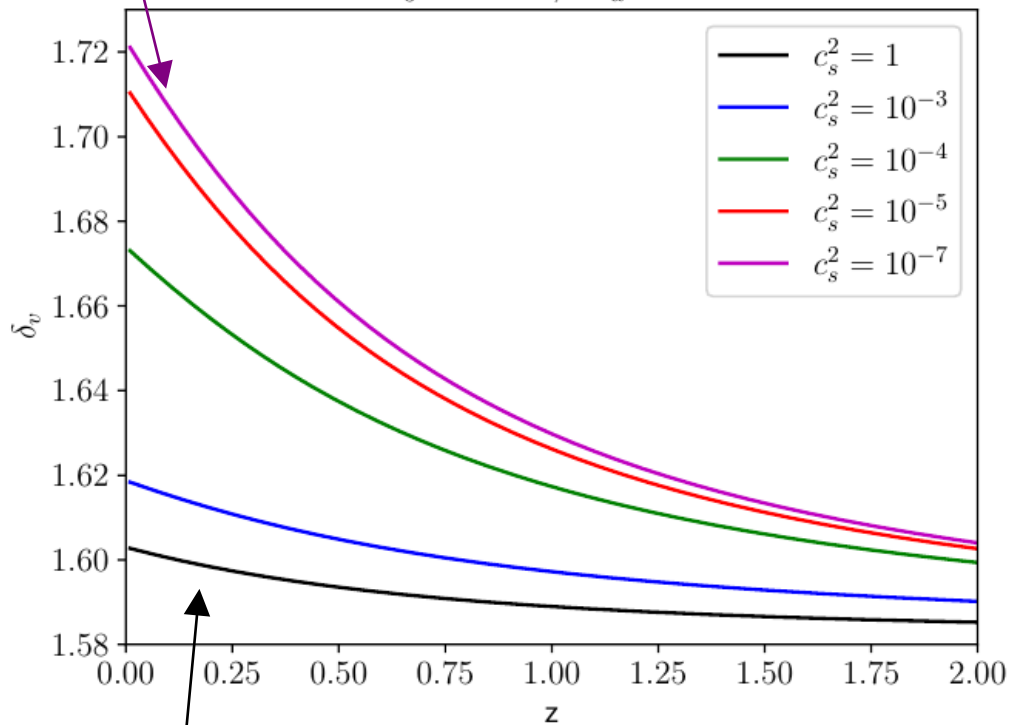
$$\ddot{\delta}_{de} \propto (1 + w + (1 + c_s^2)\delta_{de}) \nabla^2 \phi$$

# Virialization threshold

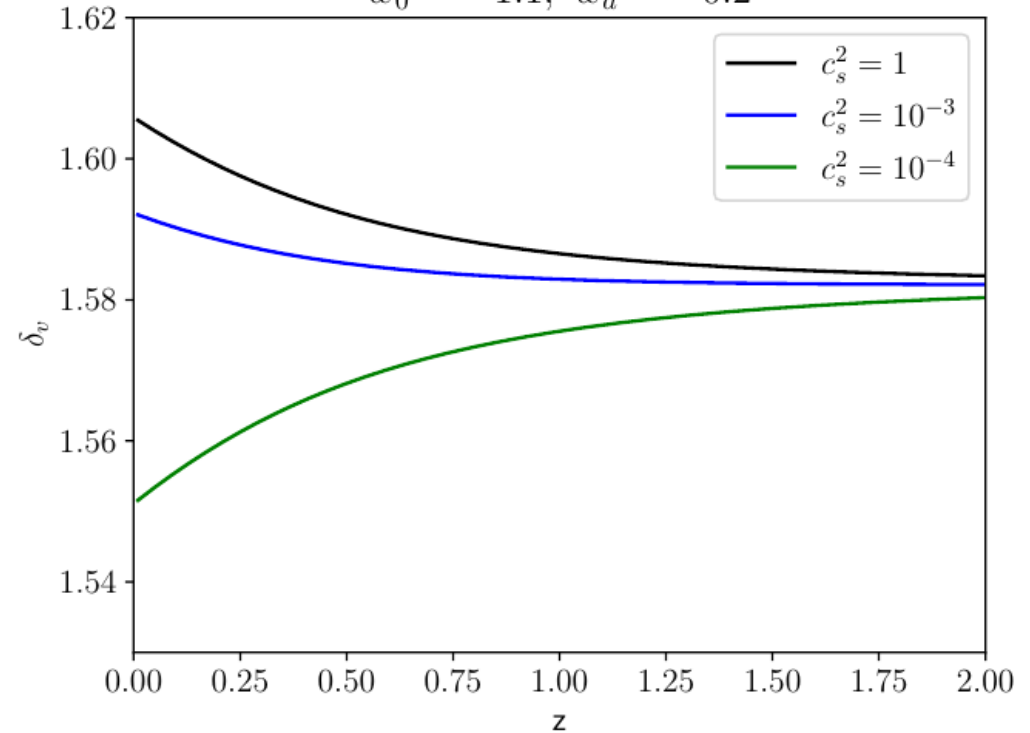
$$\delta_v^{\text{EdS}} = \delta_m^L(z_v) \simeq 1.583$$

$$\delta_v = \delta_m + \frac{\Omega_{de}}{\Omega_m} \delta_{de}$$

$$w_0 = -0.9, w_a = 0.2$$



$$w_0 = -1.1, w_a = -0.2$$



scales  $< 1\text{Mpc}/h$

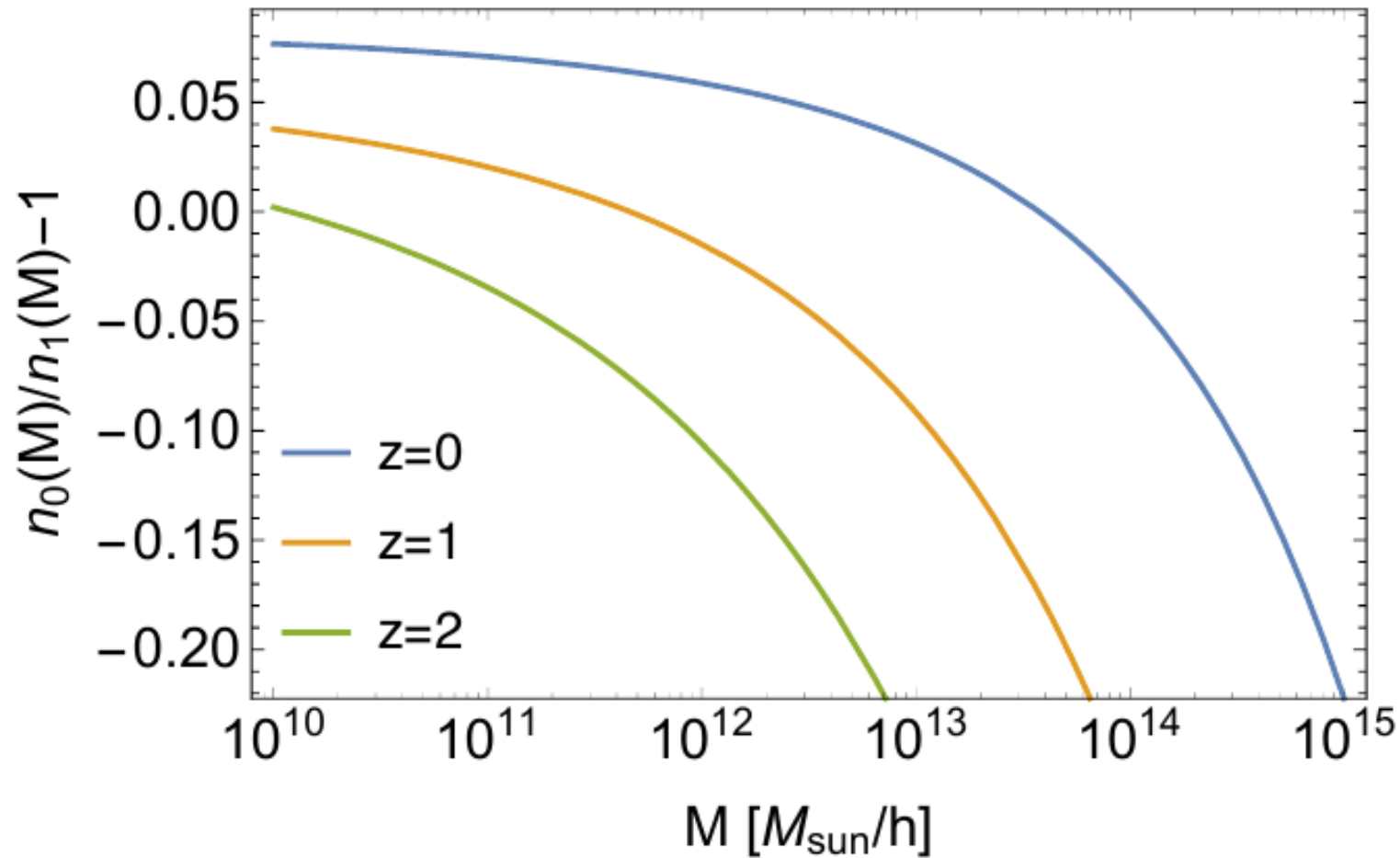
**Homogeneous  
DE**

$$\frac{dn}{d\ln M} = \frac{\bar{\rho}_m}{M} \left| \frac{d\ln\sigma}{d\ln M} \right| f(\sigma, \delta_v), \quad f(\sigma, \delta_v) \propto \exp\left(-\frac{a\delta_v^2}{2\sigma^2}\right)$$

# Cluster Abundances

$$w_0 = -0.9, w_a = 0.2$$

Batista, Marra  
1709.03420



Same  $\sigma_8$

# Summary

- ◆ **K-essence is the simplest generalization of Quintessence.**
- ◆ **Results from SCM for  $cs=0$  and  $cs=1$  recovered.**
- ◆ **Phantom DE can not have  $cs=0$ .**
- ◆  **$cs$  impacts the potential up to 9% in halos and voids. For impact on observables see Hassani et al. (2021).**
- ◆ **Cluster abundances impacted up to 30%.**
- ◆ **The method can be adapted for MG, interacting DM-DE, WDM.**
- ◆ **The method can be used as pathfinder for realistic simulations.**