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

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# Outline

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

# K-essence models

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

## Perfect Fluid Correspondence

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

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

## Linear solutions in EdS

$$c_s^2 \simeq 1 \qquad c_s^2 \to 0$$

$$\delta_{de} = -\frac{1+w}{c_s^2} \phi \qquad \delta_{de} = \frac{1+w}{1-3w} \delta_m$$

**Homogeneous DE** **Clustering DE**

# Spherical Collapse Model

Gunn & Gott 1972

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

**Analytical solutions in EdS:**

**Linear collapse threshold**

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

**Virialization**

$$U = -2K \qquad R_{\rm v} = R_{\rm max}/2 \qquad \Delta = \frac{\rho_m(z_{\rm v})}{\bar{\rho}_m(z_c)} \simeq 177.7$$

**Homogeneous DE Models:**

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

# 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.**

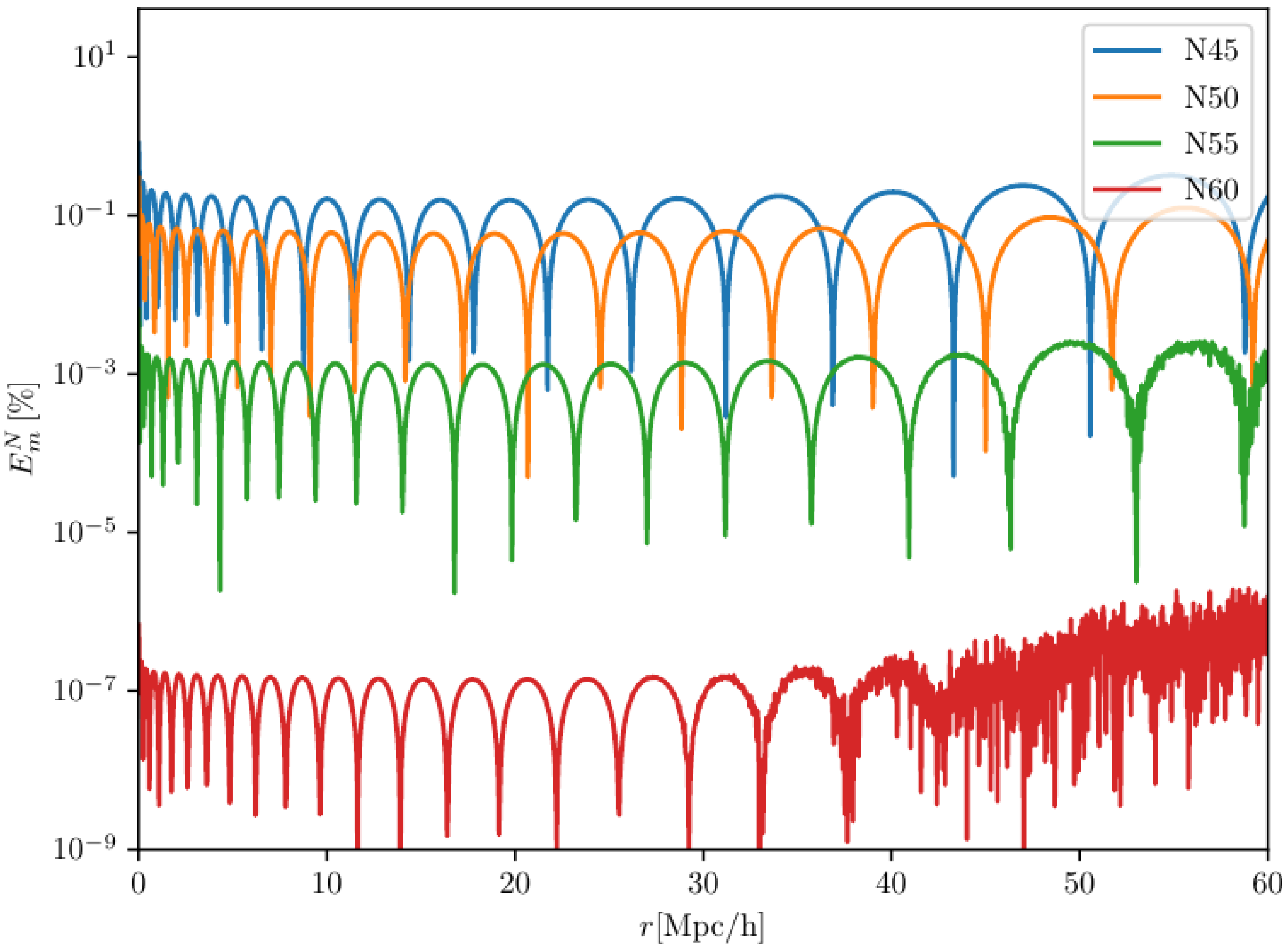
**For more applications and discusions see “A short review on Clustering Dark Energy” Universe 8 (2021), arXiv:2204.12341**

# Numerical Method

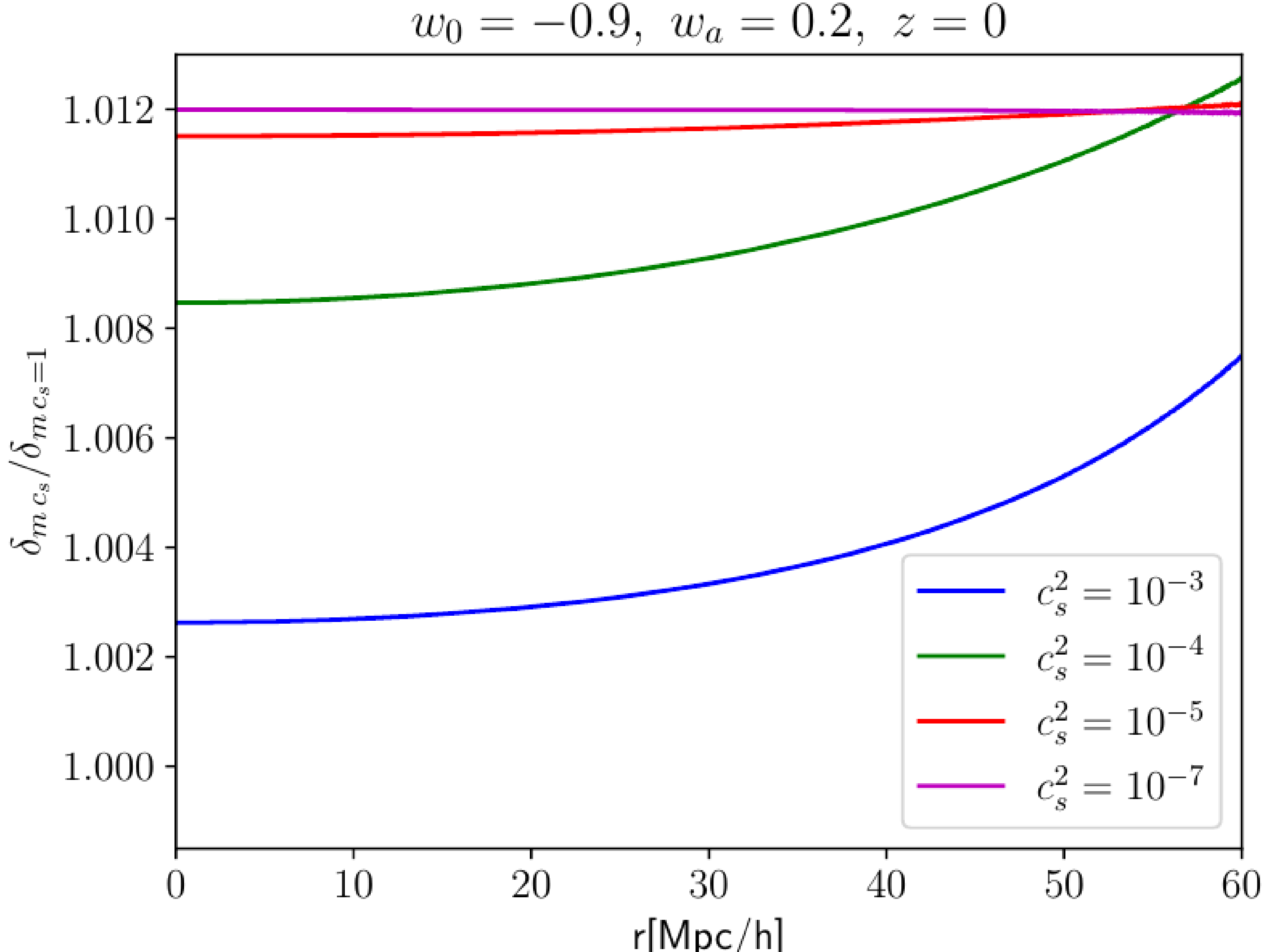
**Galerkin-Collocation method**

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

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



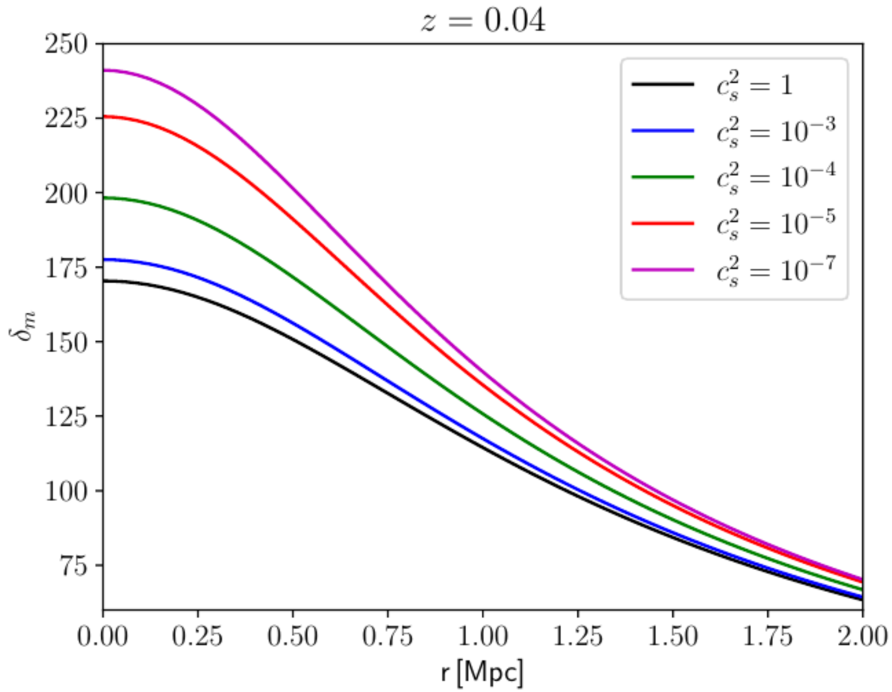
# Scale-dependent growth

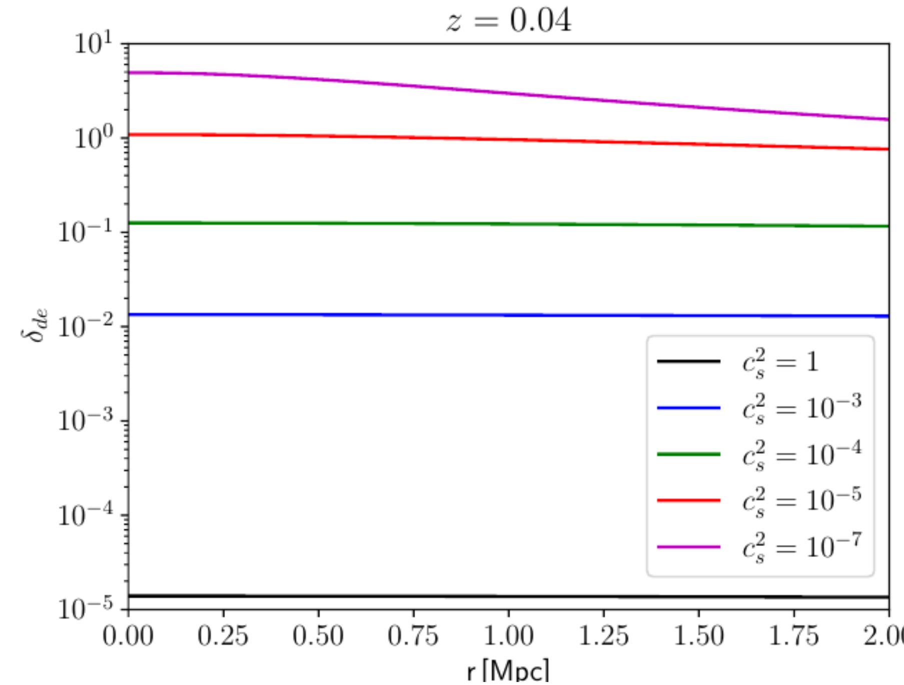


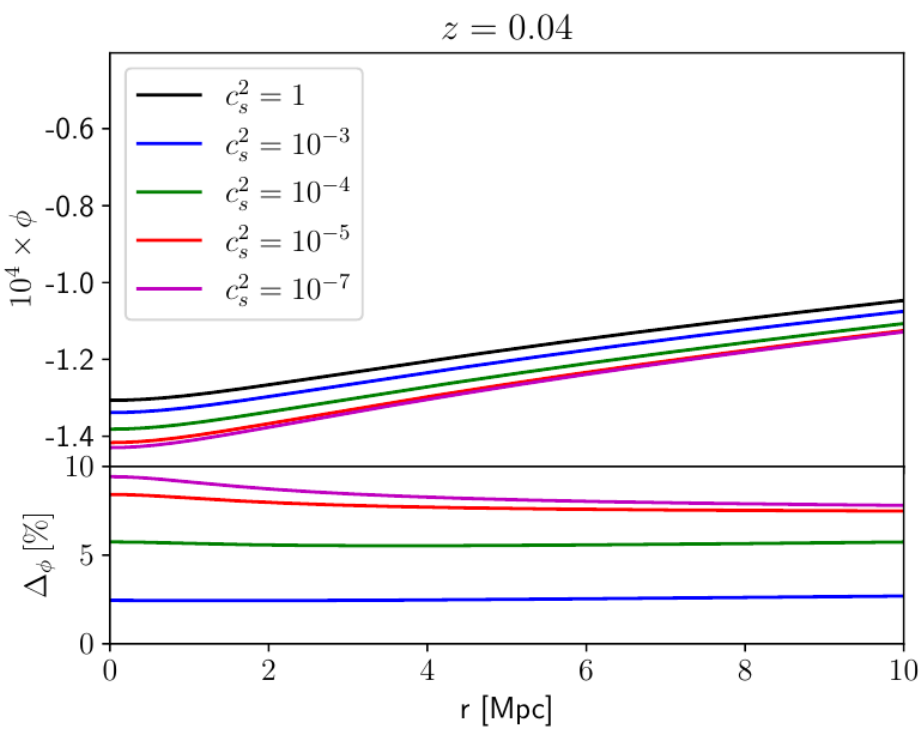

**Same initial conditions**

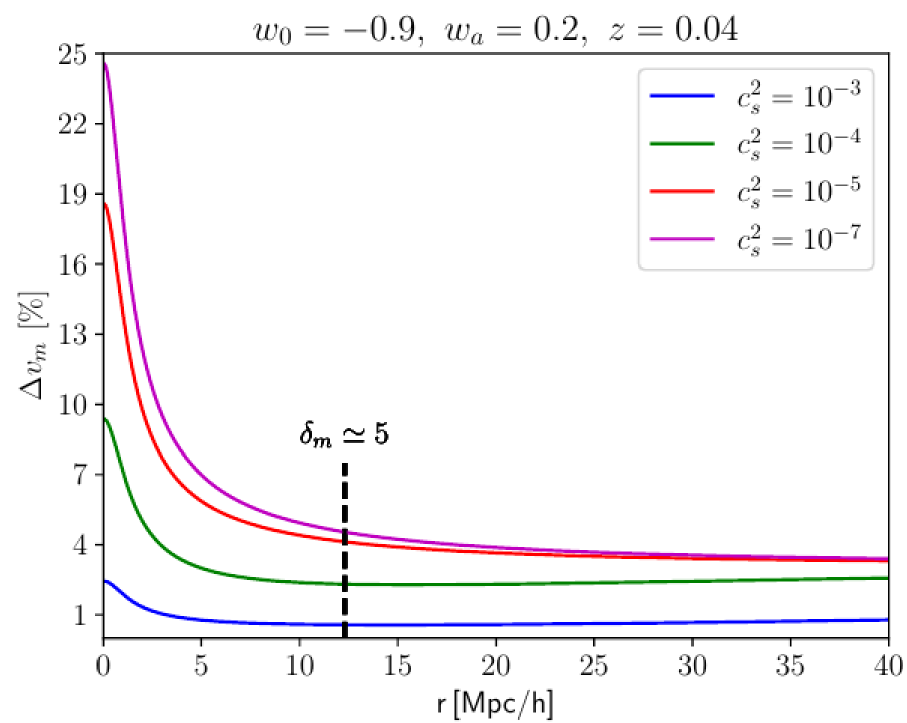
# Halos

$w_0 = -0.9,\ w_a = 0.2$

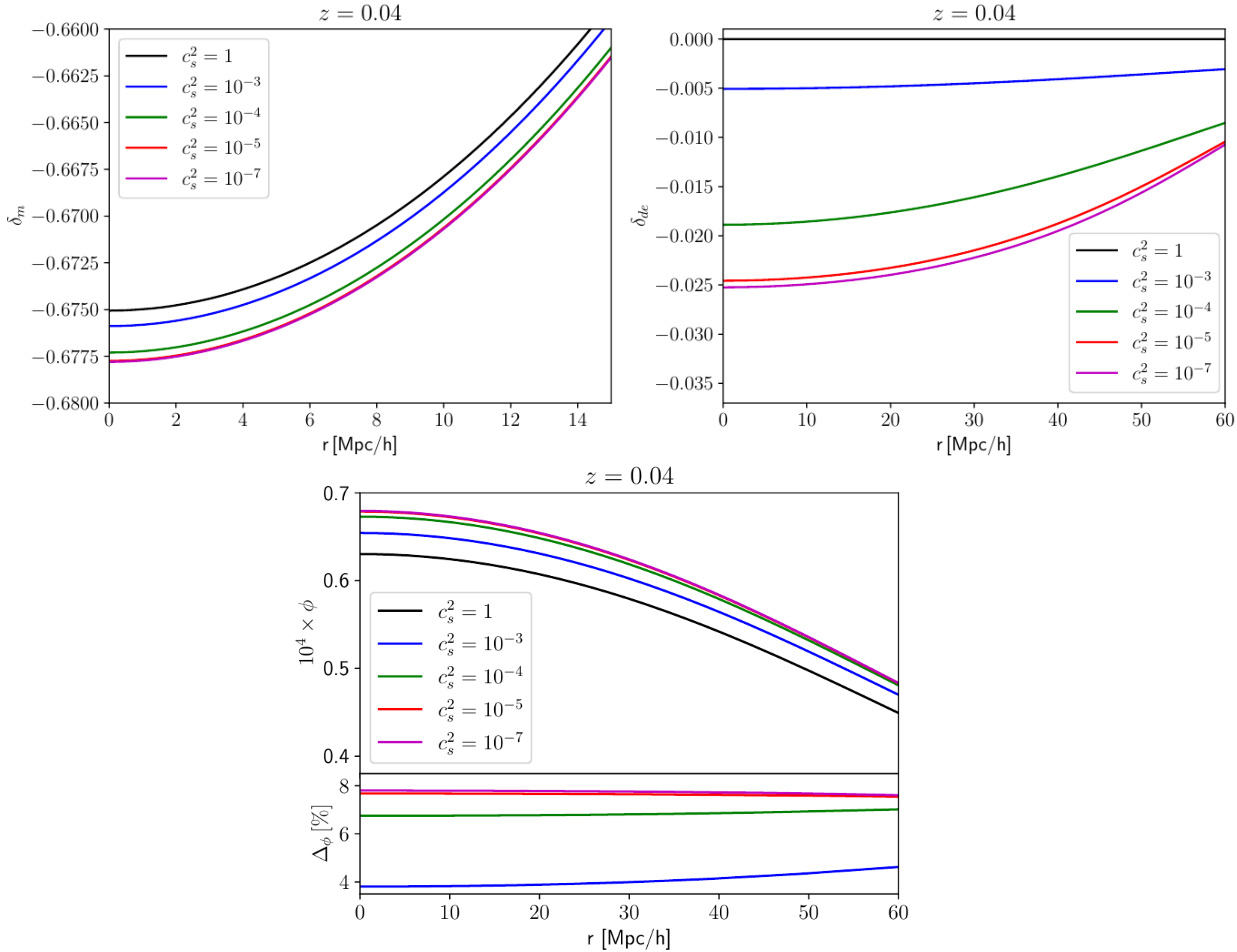


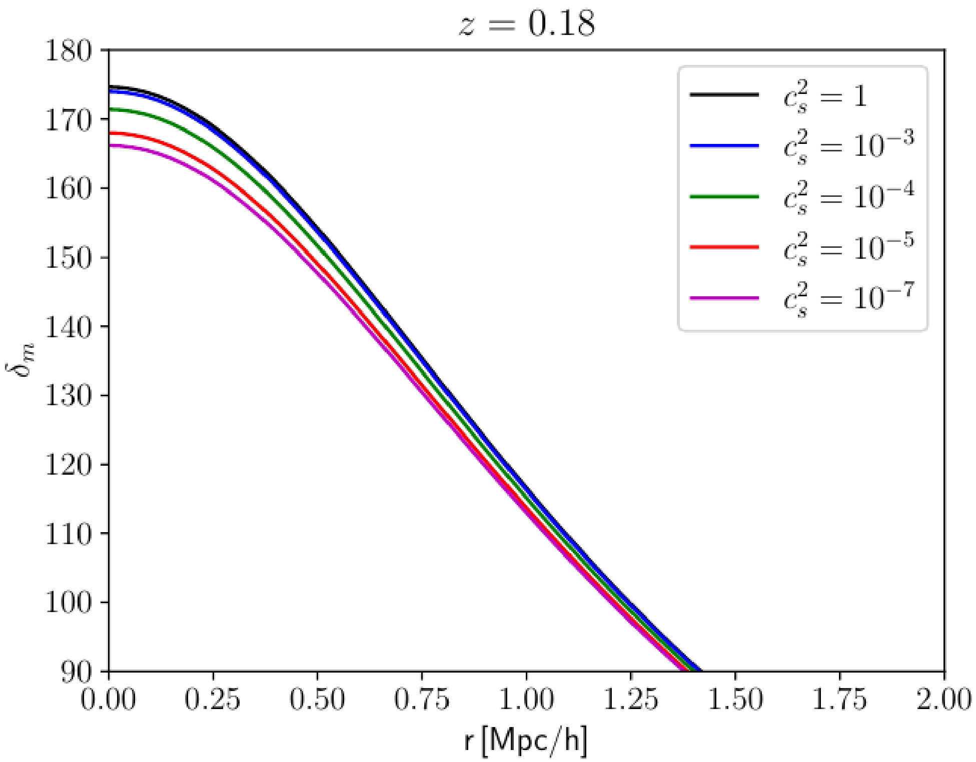
# Voids $w_0 = -0.9,\ w_a = 0.2$

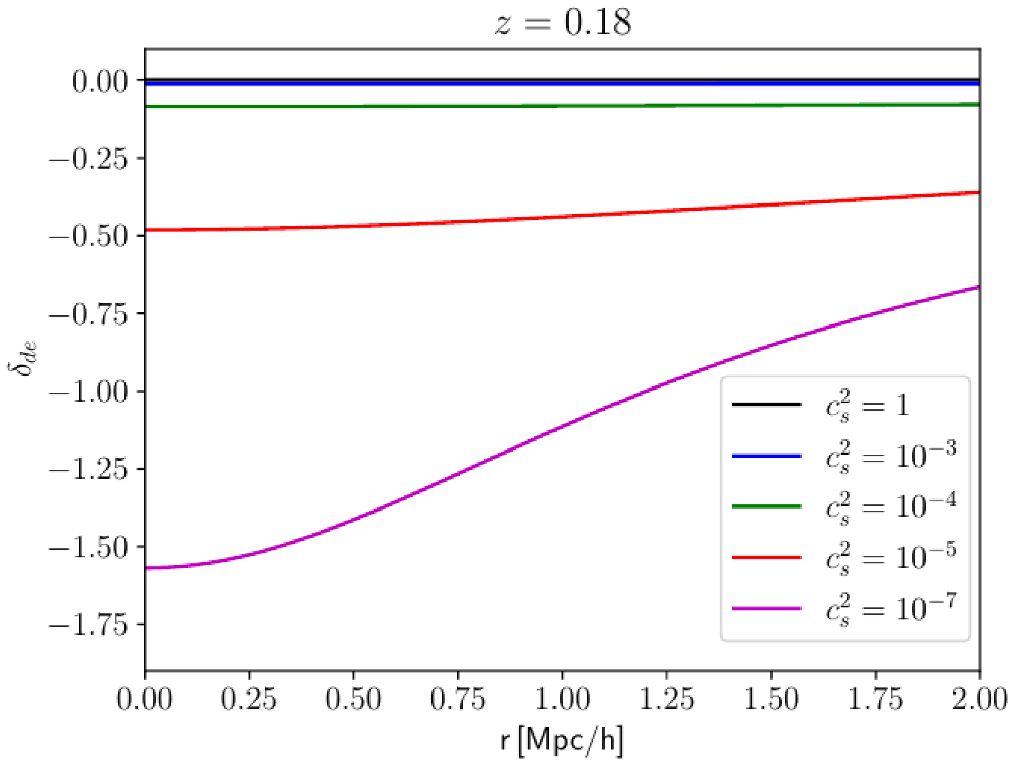


# Phanton Pathology

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

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



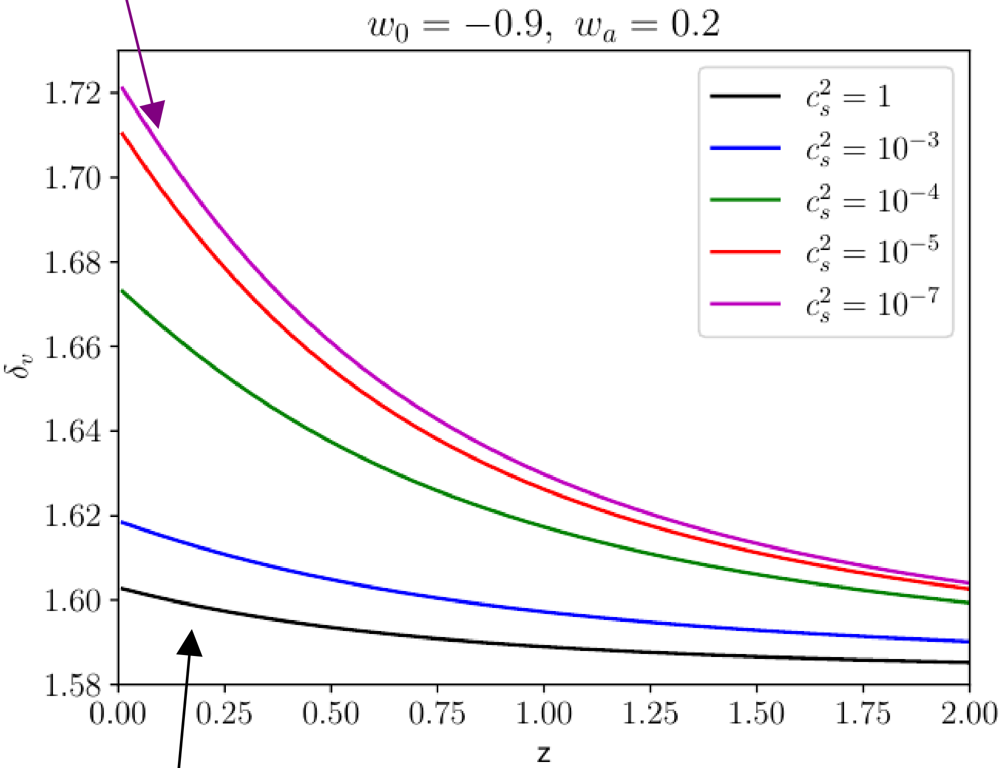

$$\ddot{\delta}_{de} \propto \left(1 + w + (1 + c_s^2)\delta_{de}\right)\nabla^2\phi$$

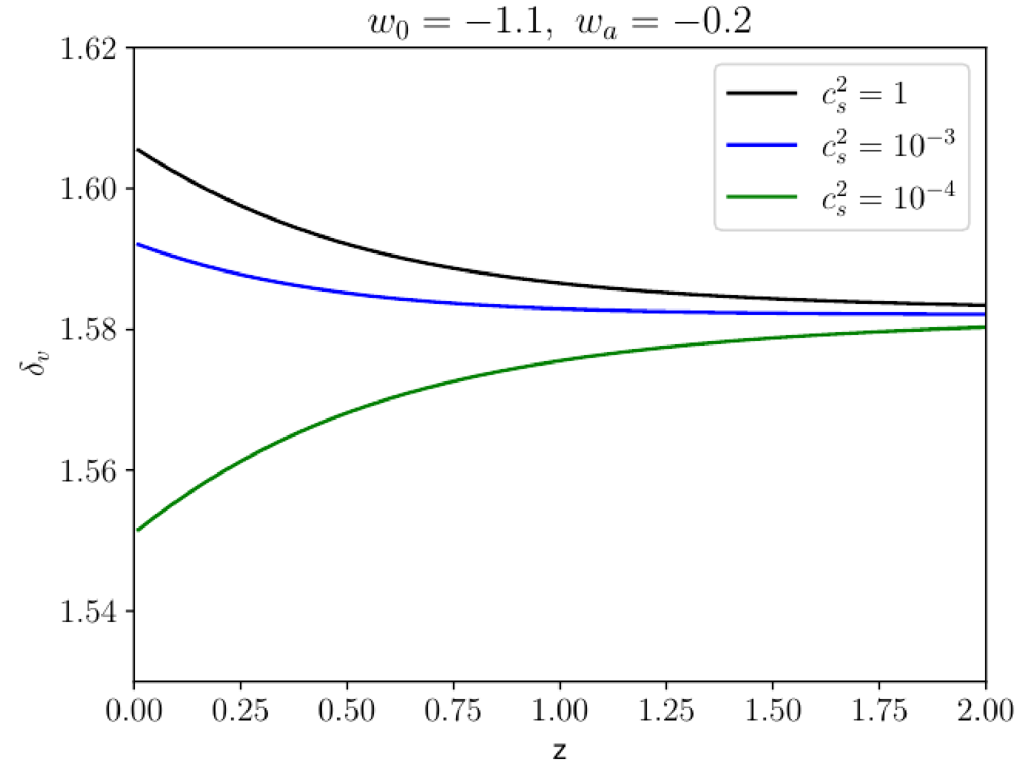
# Virialization threshold

$$\delta_{\rm v}^{\rm EdS} = \delta_m^L(z_{\rm v}) \simeq 1.583$$

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

**Clustering DE**




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

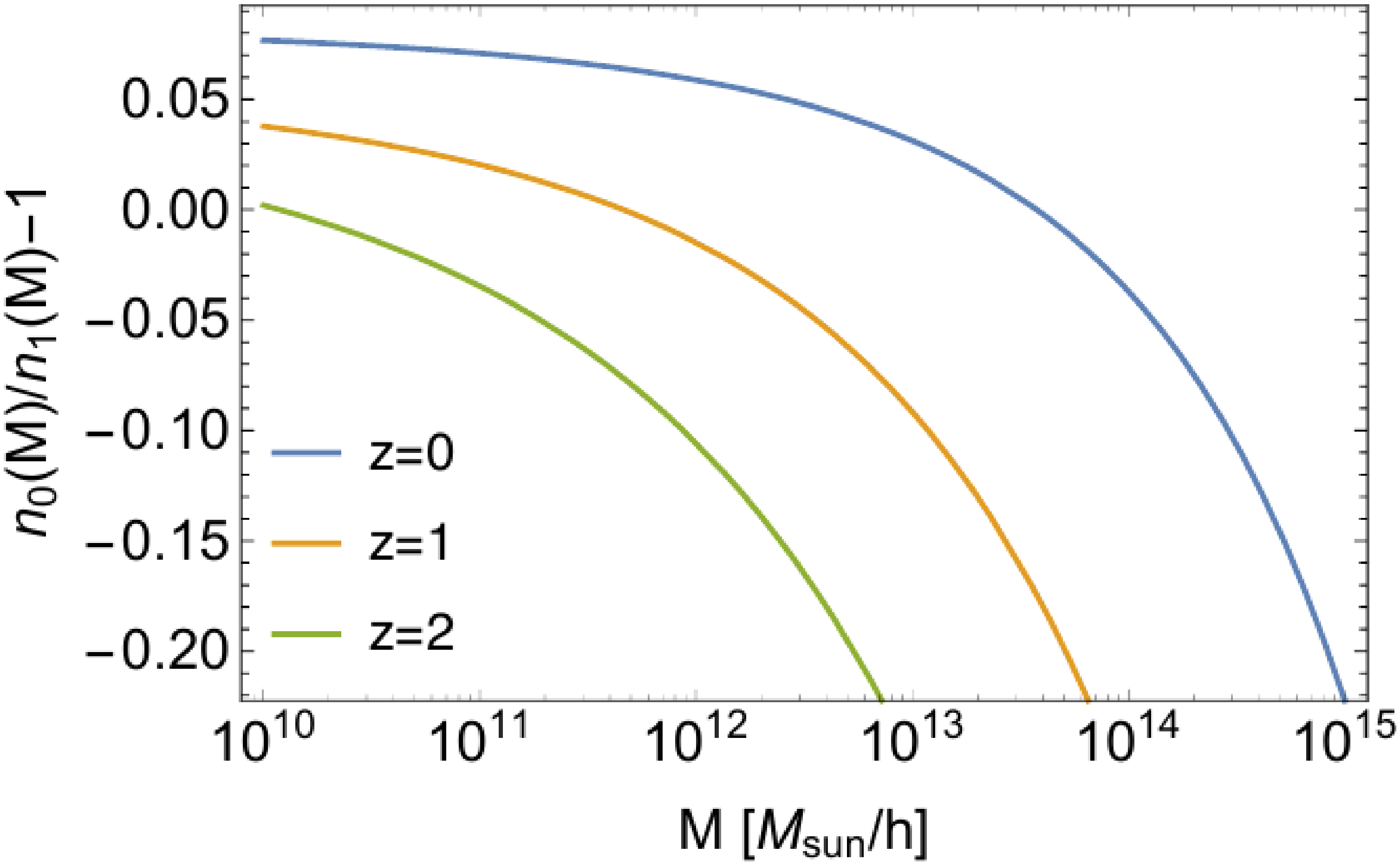
**Homogeneous DE**

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

# 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.**

- **Phatom 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.**