The impact of baryonic potentials on the gravothermal evolution of self-interacting dark matter haloes

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w/ D. Yang, H.-B. Yu [arXiv:2306.08028]

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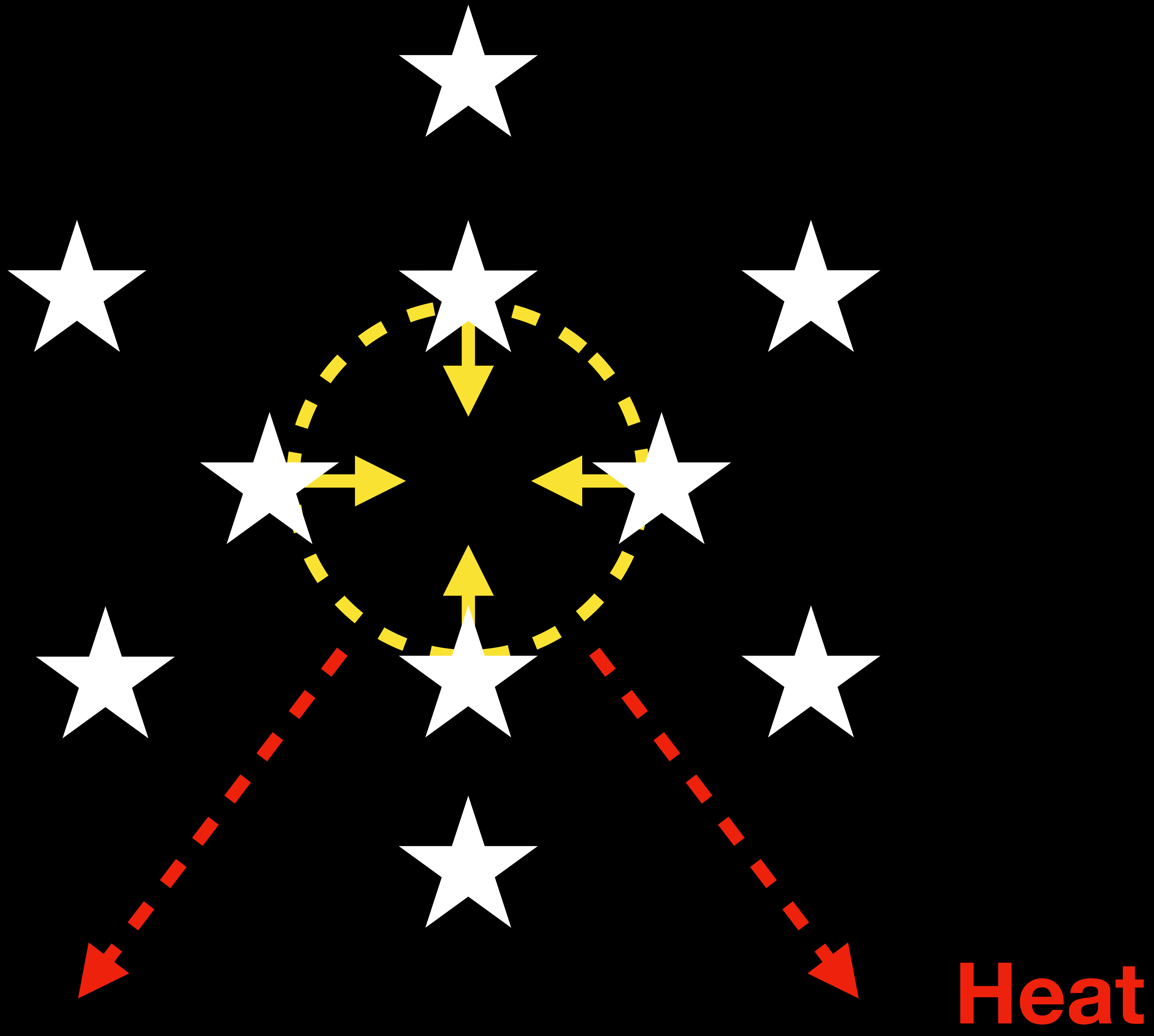
Outline

- Introduction
- Simulations for Self-interacting dark matter (SIDM) halos + central baryonic component
    - The accelerated evolution
    - The quasi-universal behavior
- Summary

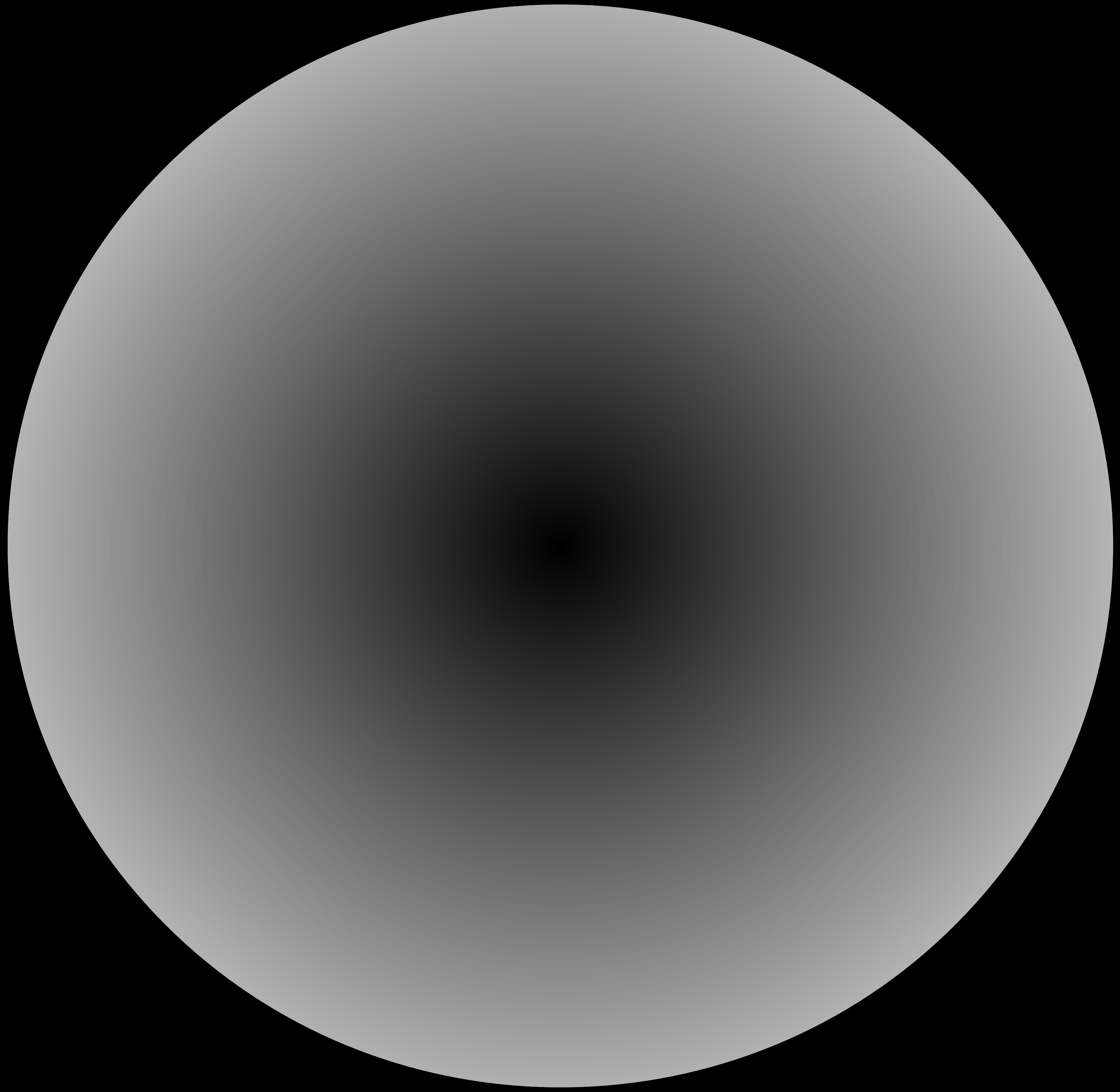
Globular cluster (GC)

Gravothermal collapse in GCs

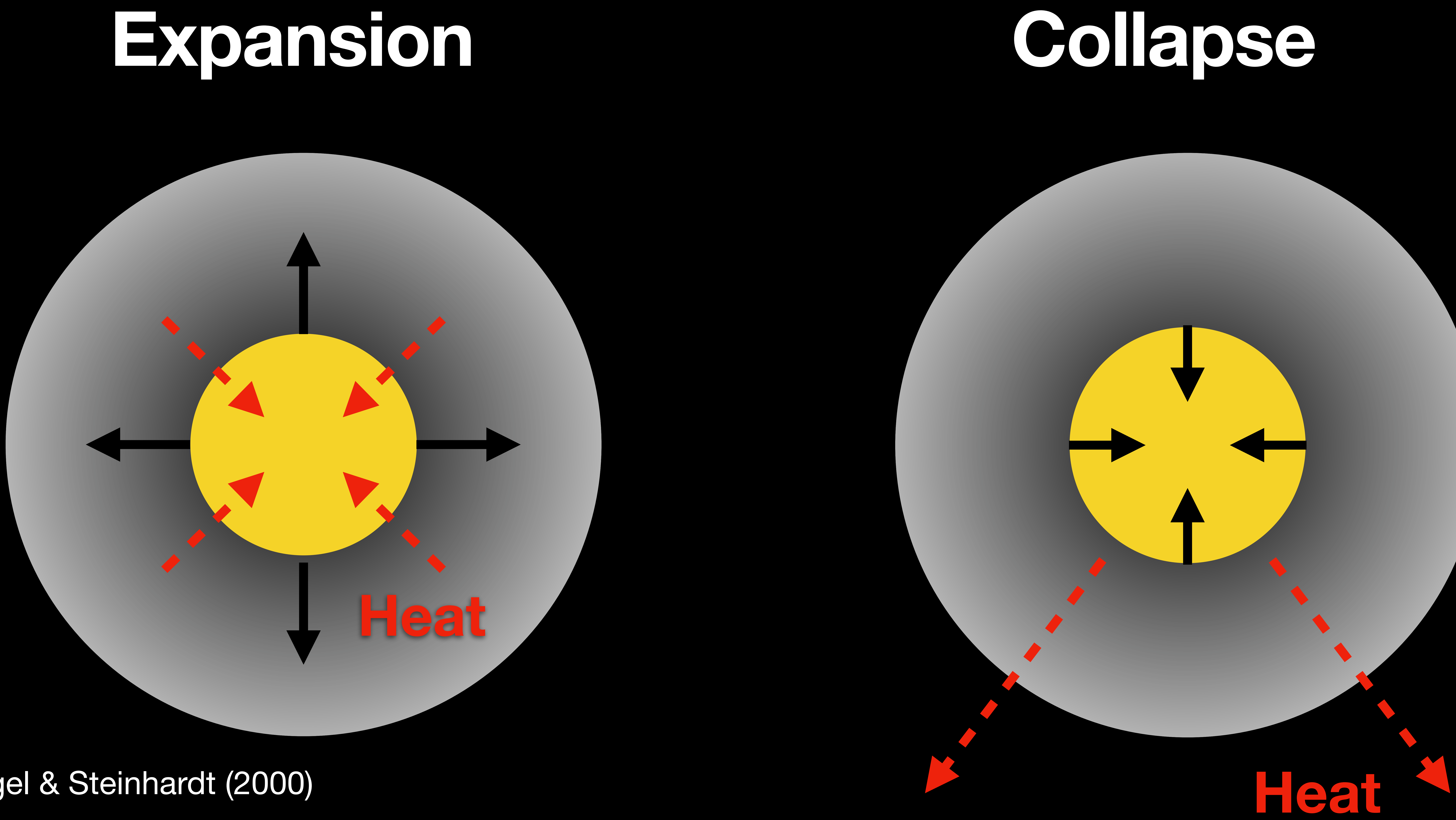
See Spitzer (1987)



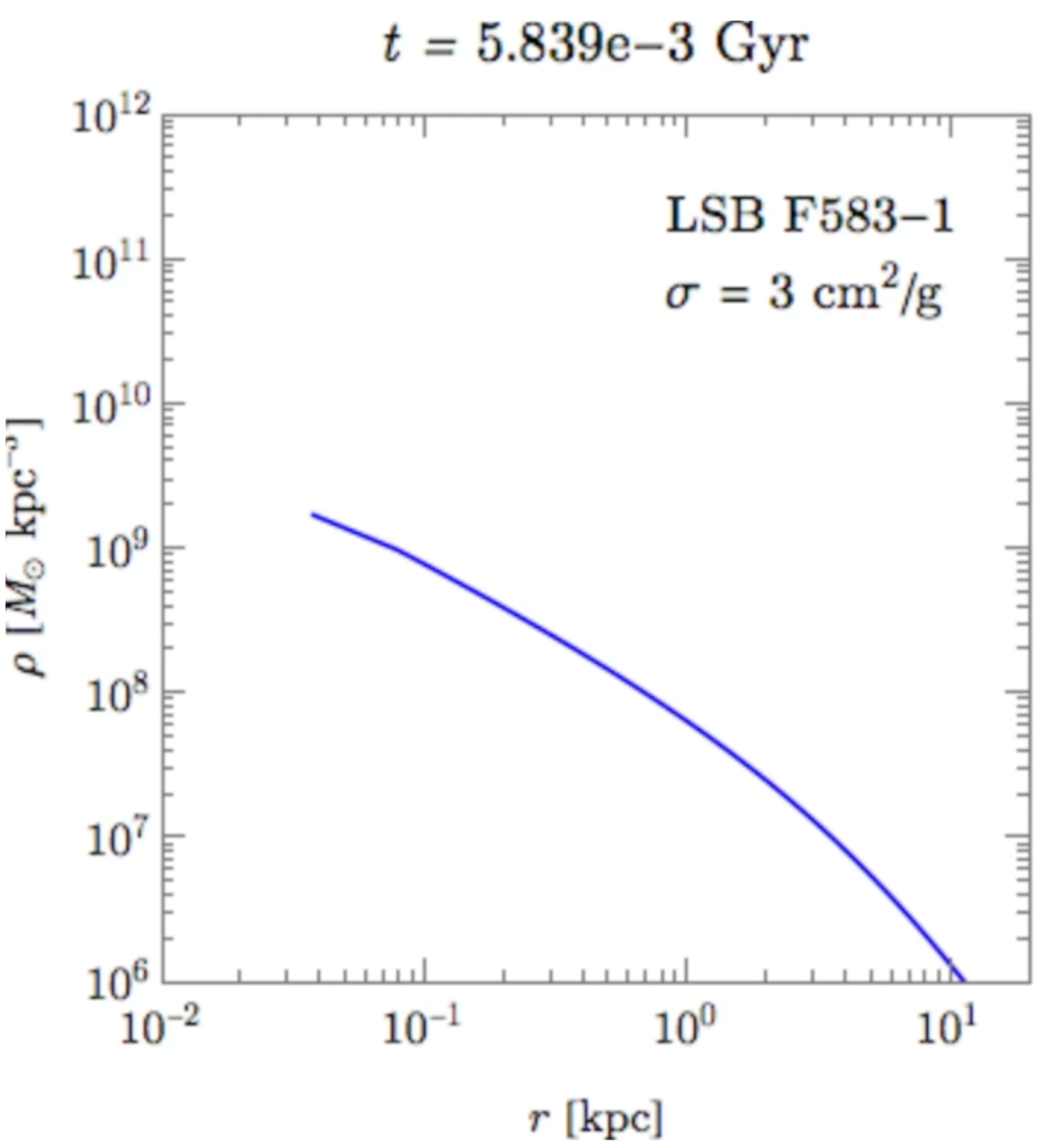
Gravothermal collapse in SIDM halos



Spergel & Steinhardt (2000)



Spergel & Steinhardt (2000)



t = 5.839e−3 Gyr
LSB F583−1
σ = 3 cm²/g
ρ [M⊙ kpc⁻³]
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁻²
10⁻¹
10⁰
10¹
r [kpc]

Tools	Gravo. Expansion	Gravo. Collapse
N-body model	✔	✔
Fluid model	✔	✔
Isothermal model	✔	✔
Parametric model	✔	✔

Covergent

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N-body model	✔	✔
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Isothermal model	✔ Kaplinghat, Tulin & Yu (2016)	✔
Parametric model	✔	✔

Yang+ [YZ incl] (2023) arXiv: 2305. 05067; See Jiang's talk

Yang+ [YZ incl] (2023) arXiv:2305.16176 ; See Nadler's talk

This talk

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Simulations for SIDM halos
+
central baryonic component

Setup

- An isolated SIDM halo (M=1.2e11 $M_\odot$, c=15, NFW @ t = 0)
- Const. & Rutherford self-interactions
- SIDM-only, SIDM + 3 types of central baryonic potentials
  - Median
  - Diffuse
  - Compact

Setup

	NFW		Hernquist			Effective xsec.	Central potent.
Name	ρ_s [$M_\odot/kpc^3$]	r_s [kpc]	$M_{b,tot}$ [$M_\odot$]	ρ_h [$M_\odot/kpc^3$]	r_h [kpc]	σ_m^{eff} [cm^2/g]	Φ_c [km^2/s^2]
SIDM10-only	6.9×10^6	9.1	0	–	–	10	-3.1×10^4
SIDM10+baryonM	6.9×10^6	9.1	1.0×10^9	3.6×10^8	0.77	10	-3.6×10^4
SIDM10+baryonD	6.9×10^6	9.1	1.0×10^9	9.0×10^7	1.2	10	-3.4×10^4
SIDM10+baryonC	6.9×10^6	9.1	2.0×10^9	5.3×10^8	0.85	10	-4.1×10^4
SIDM100+baryonM	6.9×10^6	9.1	1.0×10^9	3.6×10^8	0.77	100	-3.6×10^4
vdSIDM-only	6.9×10^6	9.1	0	–	–	9.7	-3.1×10^4
vdSIDM+baryonM	6.9×10^6	9.1	1.0×10^9	3.6×10^8	0.77	8.6	-3.6×10^4

t = 0

Methods

- N-body model (Gadget 2)
- Fluid model

1. Mass conservation

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

2. Hydrostatic equilibrium

$$\frac{\partial p}{\partial r} = -\rho \nabla \Phi$$

3. First-law of thermal dynamics

$$dw = T ds + V dp$$

4. Heat conduction

$$F = -\kappa \frac{\partial T}{\partial r}$$

Self-interaction enters → κ

See Slone's talk

More on fluid model

$$\rho \to \hat{\rho} = \frac{\rho}{\rho_s}, \quad r \to \hat{r} = \frac{r}{r_s}, \quad \sigma \to \hat{\sigma} = \sigma \rho_s r_s, \quad \nu \to \hat{\nu} = \frac{\nu}{\sqrt{4\pi G \rho_s r_s}}, \cdots$$

↓

$$\frac{\partial \hat{M}_\chi}{\partial \hat{r}} = \hat{r}^2 \hat{\rho}_\chi, \quad \frac{\partial (\hat{\rho}_\chi \hat{\nu}_\chi^2)}{\partial \hat{r}} = -\frac{(\hat{M}_\chi + \hat{M}_b)\hat{\rho}_\chi}{\hat{r}^2},$$

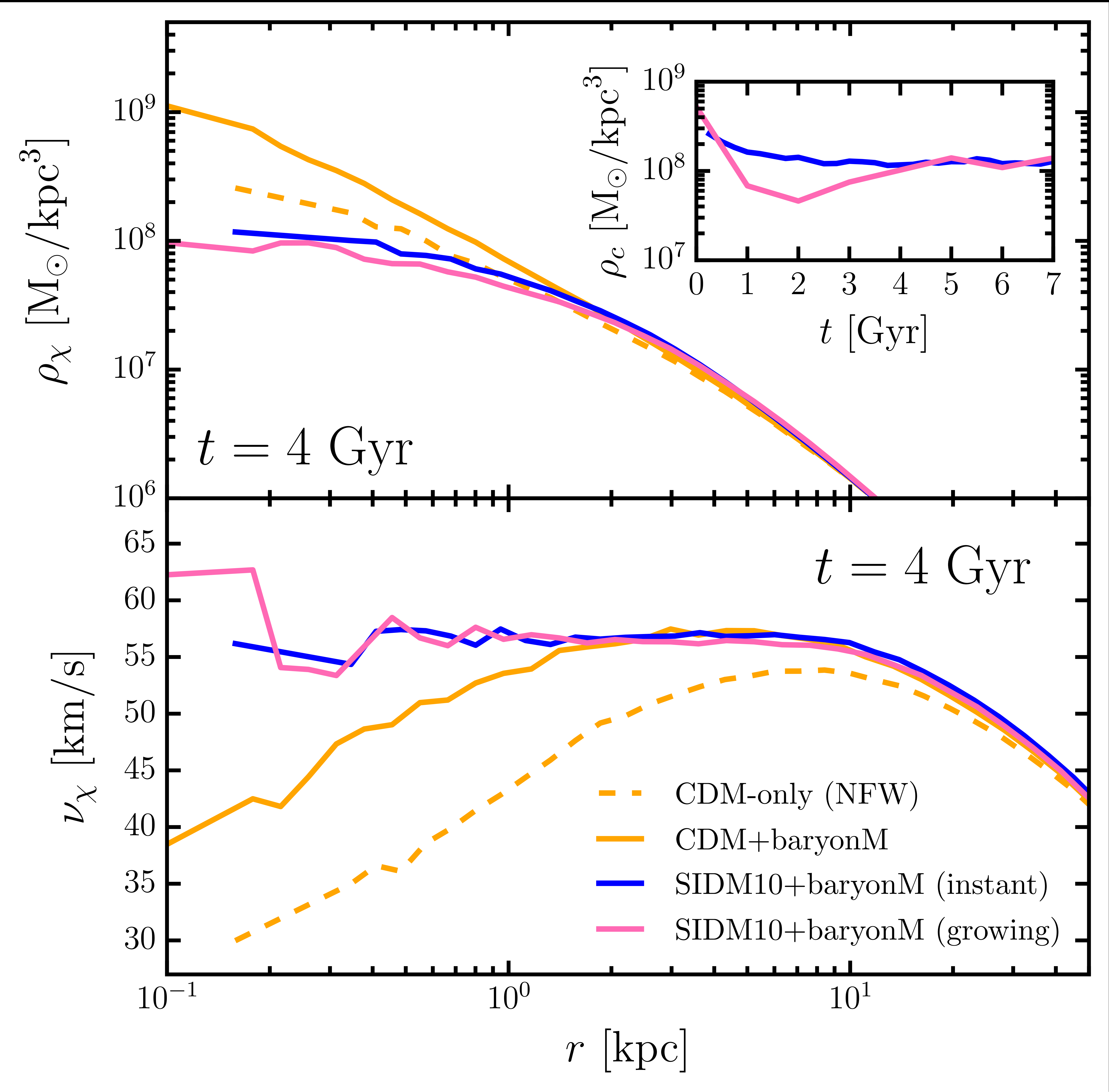
$$\frac{\partial \hat{L}_\chi}{\partial \hat{r}} = -\hat{\rho}_\chi \hat{r}^2 \hat{\nu}_\chi^2 D_{\hat{t}} \ln \frac{\hat{\nu}_\chi^3}{\hat{\rho}_\chi},$$

$$\frac{\hat{L}_\chi}{\hat{r}^2} = -\left[(3.4\beta \hat{\rho}_\chi \hat{\nu}^3 \hat{\sigma}_m)^{-1} + \left(\frac{2.1\hat{\nu}}{\hat{\sigma}_m} \right)^{-1} \right]^{-1} \frac{\partial \hat{\nu}_\chi^2}{\partial \hat{r}}.$$

Scale density & radius free

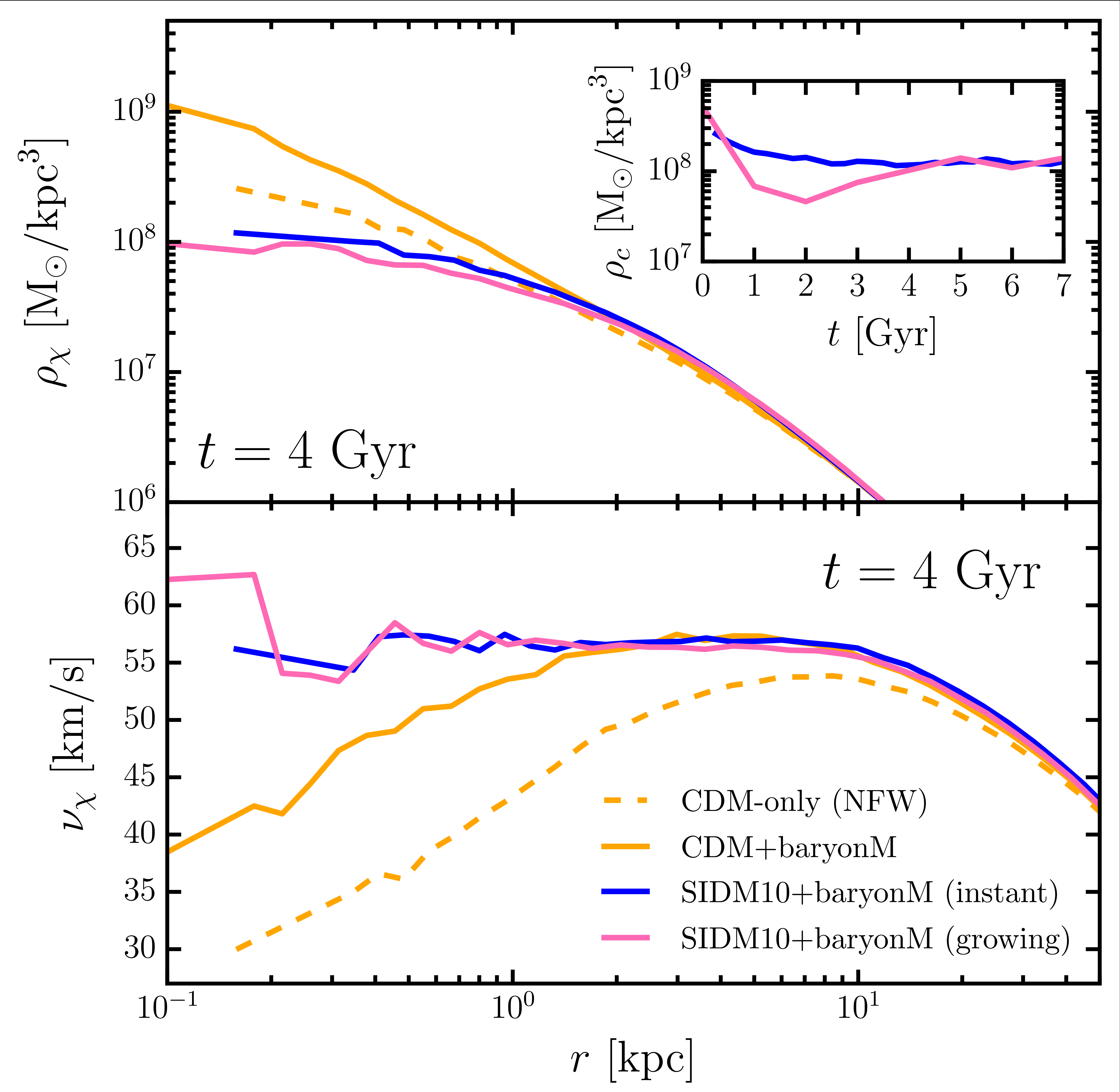
Insert baryons

- Instant baryonic potential
- Growing baryonic potential
- No big difference if thermalization is rapid



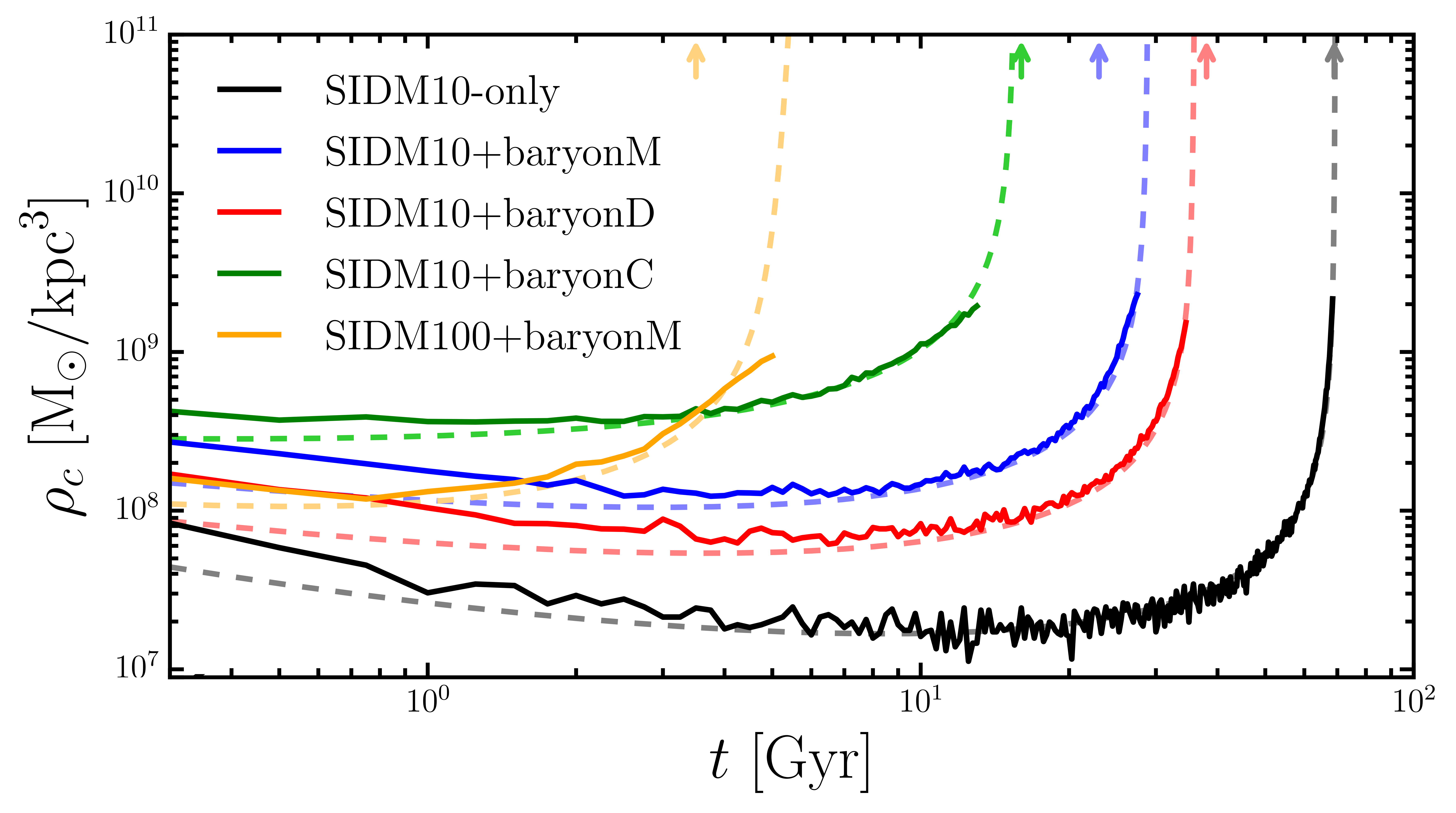
Effects of central baryons

- Increase the central velocity dispersion
- Shorten the time for core expansion
- Shorten the time for core collapse

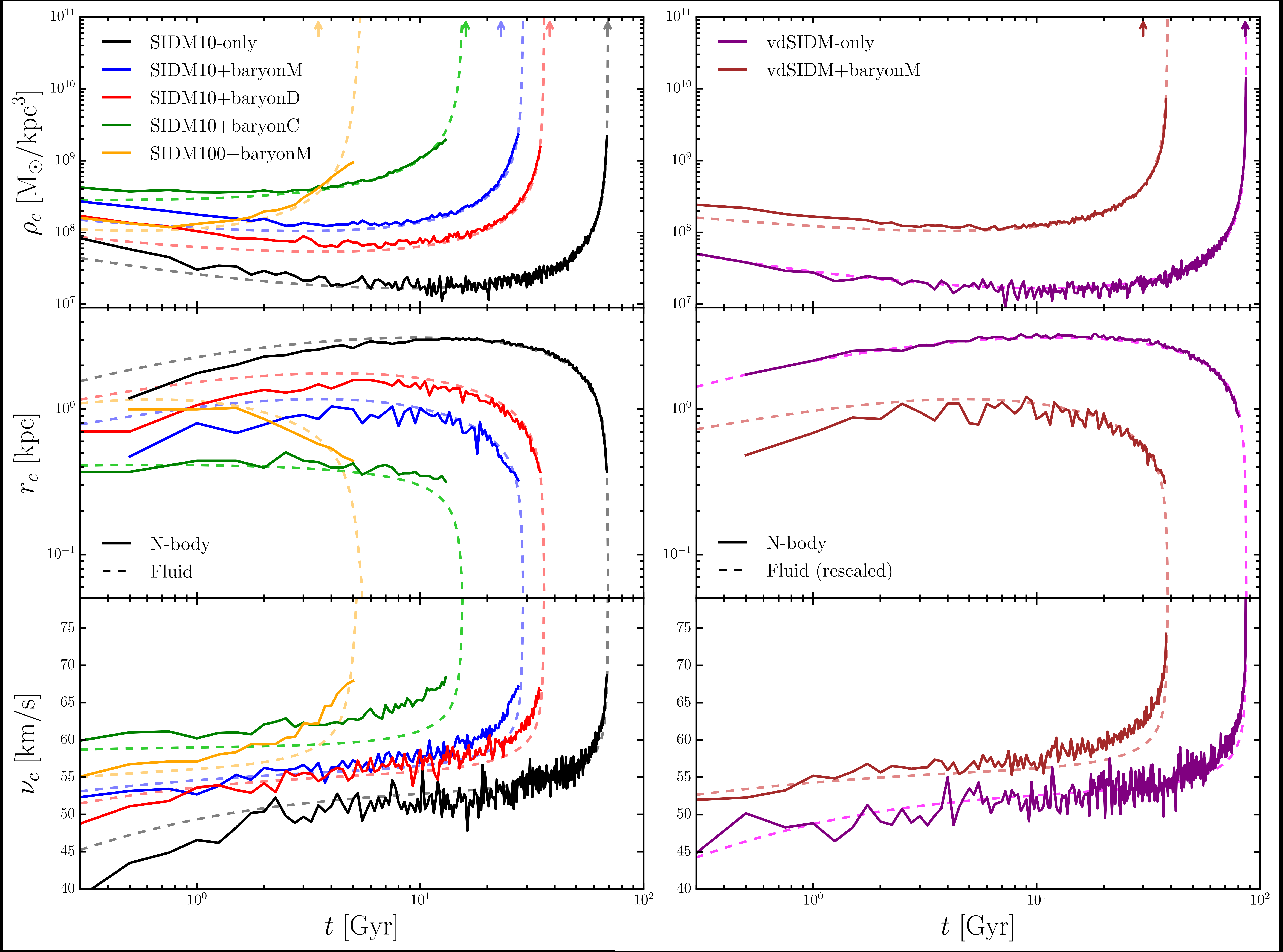


Accelerated evolution

Central density evolution



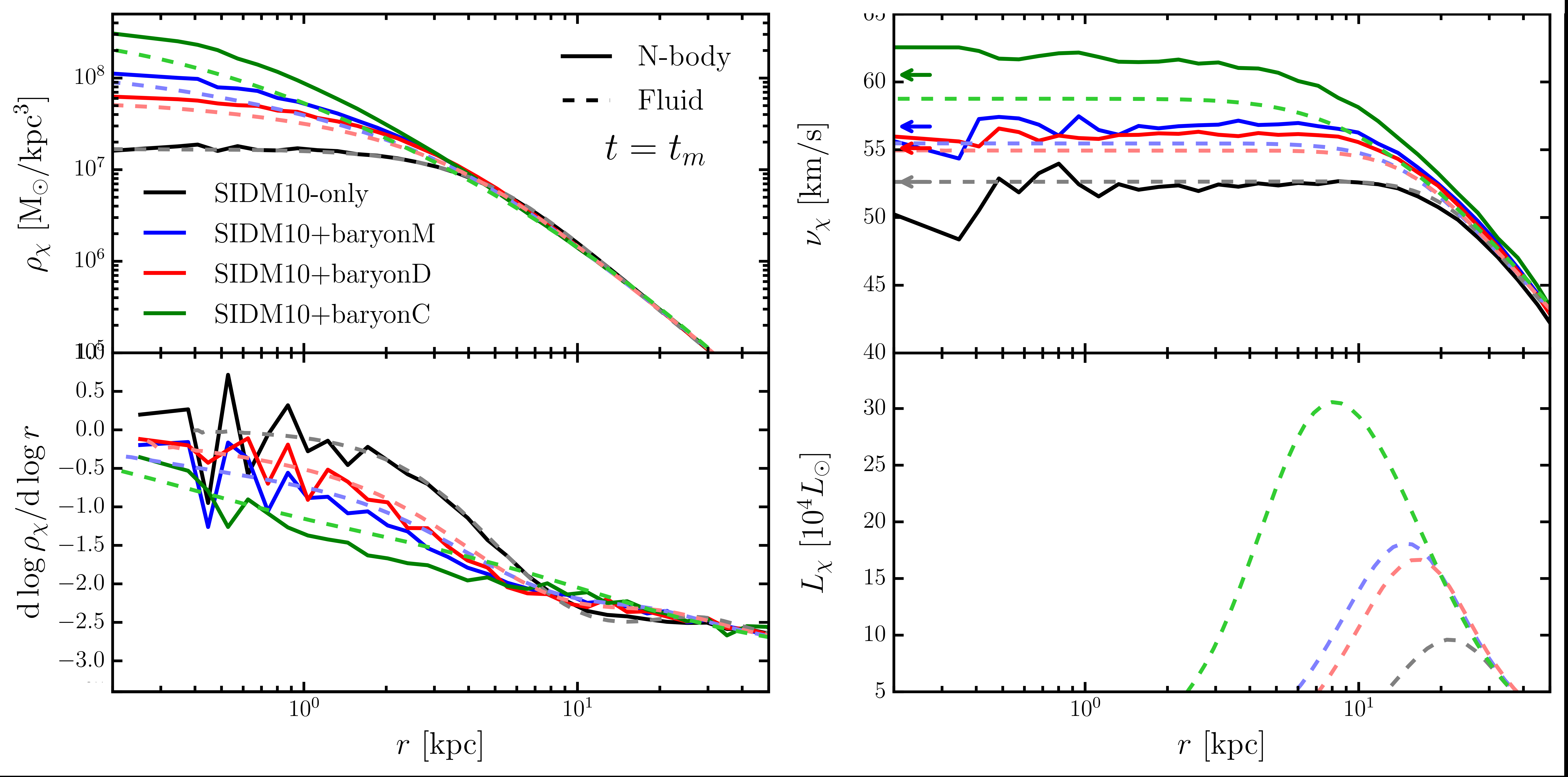
Constant Self-interaction



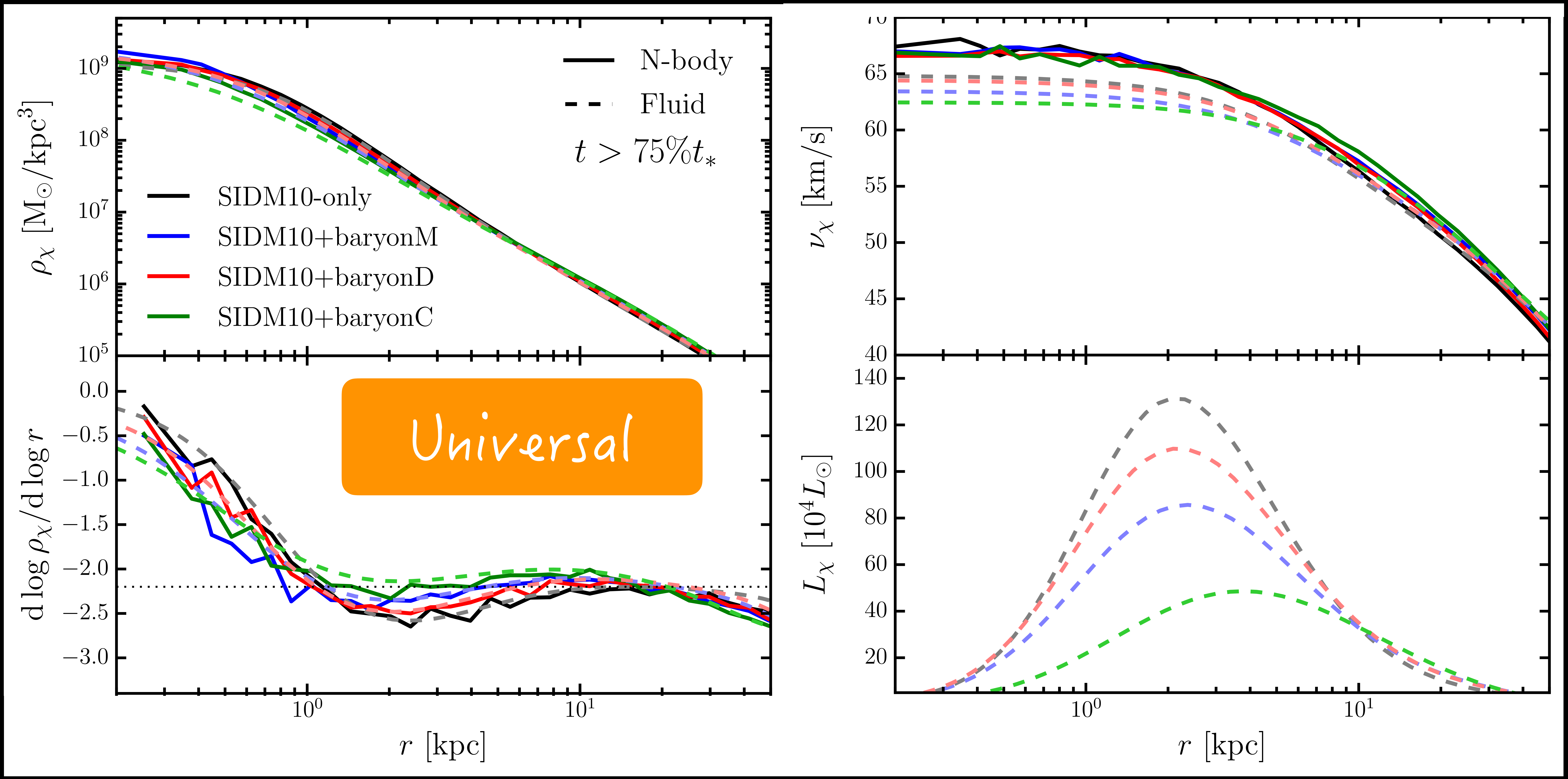
Rutherford Self-interaction

Max core expansion

$$\nu_c(t_m) \propto \sqrt{|\Phi_c(t=0)|}$$



Deep in the core collapse regime



Collapse time

- SIDM-only

Balberg+ (2002); Koda & Shapiro (2011); Essig+ [YZ included] (2019)

$$t_* = \frac{150}{\beta \sigma_m} \frac{1}{\rho_s r_s} \frac{1}{\sqrt{4\pi G \rho_s}} = \frac{150}{\beta \sigma_m} \frac{1}{\rho_s \sqrt{|\Phi_\chi(0)|}|_{t=0}}$$

- SIDM+baryon

$$t_*^{\rm est} = \frac{150}{\beta \sigma_m^{\rm eff}} \frac{1}{\rho_{\rm eff} \sqrt{|\Phi_\chi(0)| + |\Phi_b(0)|}|_{t=0}}$$

$$\rho_{\rm eff} \approx \rho_s + 0.064 \frac{M_{b,{\rm tot}}}{r_s r_h^2}$$

Quasi-universal behavior

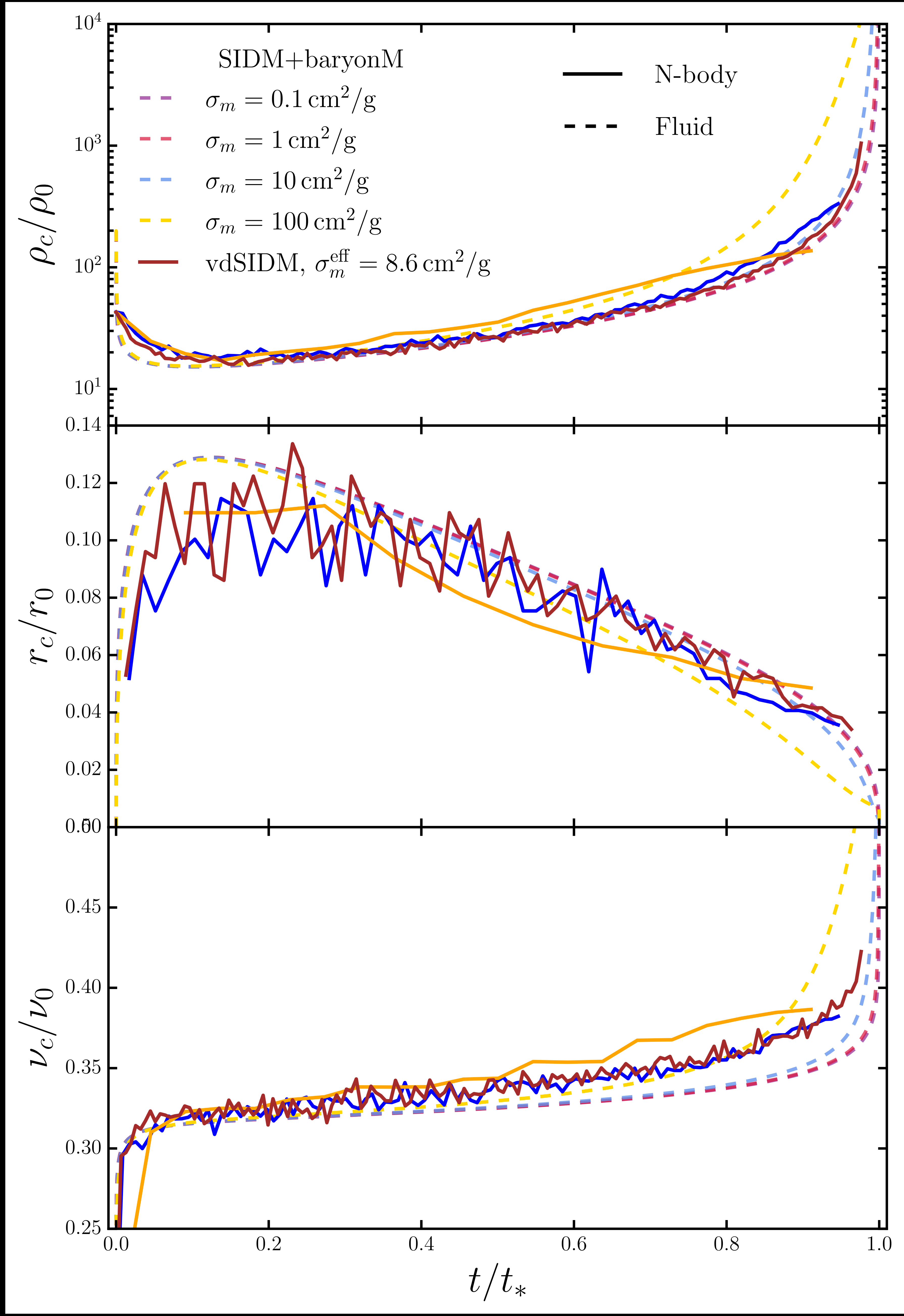
The evolution curves of halo properties largely overlap with each other after rescaling

Universality 1: same baryon pot., different xsec.

$$t \to \frac{t}{t_*}, \quad \rho_c \to \frac{\rho_c}{\rho_s}$$

$$\nu_c \to \frac{\nu_c}{\sqrt{4\pi G \rho_s} r_s}, \quad r_c \to \frac{r_c}{r_s}$$

Cross section free

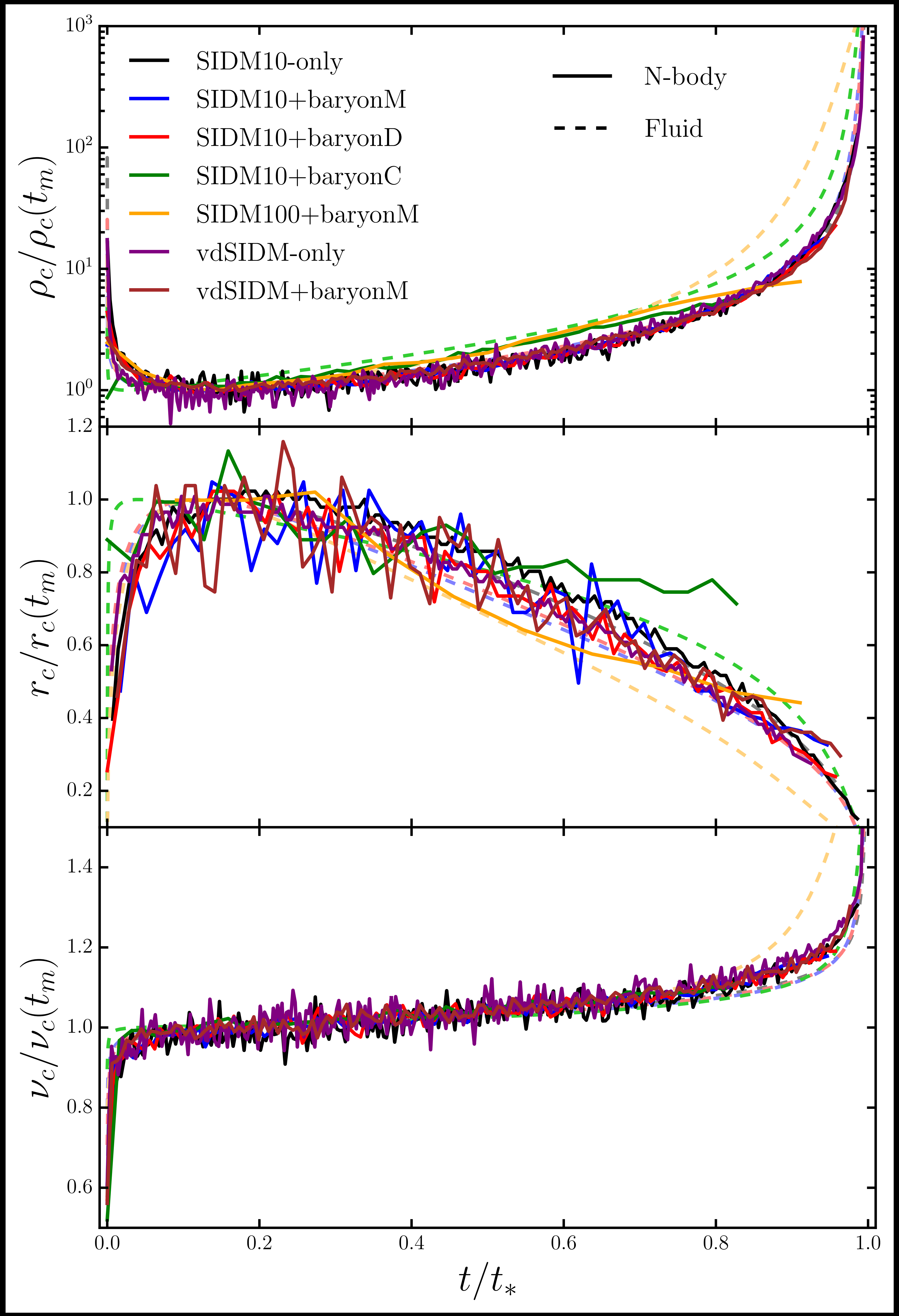


Universality 2: different baryon pot., different xsec.

$$t \to \frac{t}{t_*}, \quad \rho_c \to \frac{\rho_c}{\rho_c(t_m)}$$

$$\nu_c \to \frac{\nu_c}{\nu_c(t_m)}, \quad r_c \to \frac{r_c}{r_c(t_m)}$$

Baryonic potential free



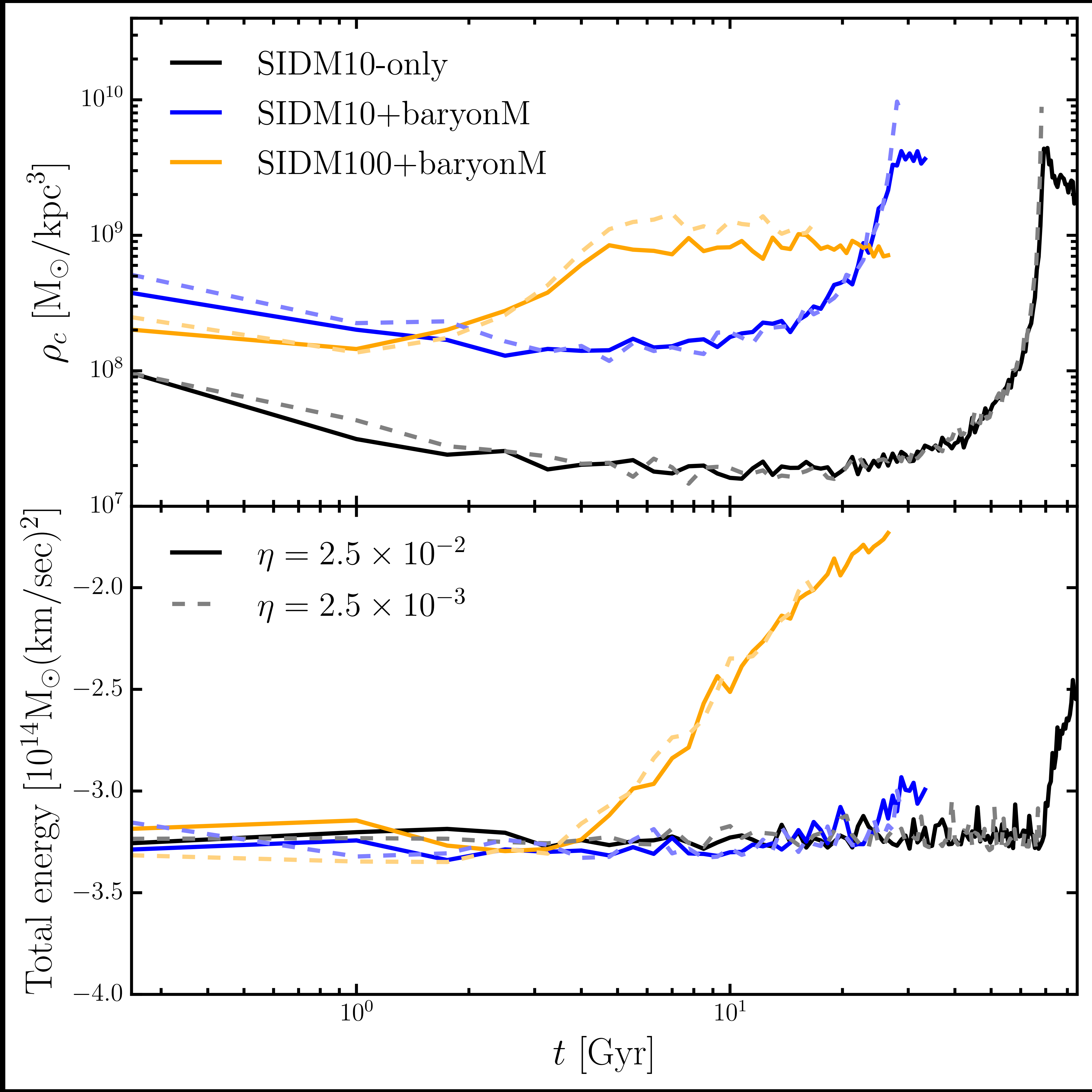
Summary

- Central baryonic potential accelerates gravothermal expansion and collapse.
- Universality is manifested in SIDM+baryon halo evolutions. The evolution are
  - Insensitive to how to insert baryons
  - ``Insensitive” to whether add or not add baryons

Thermalized SIDM halos are “simpler” than the CDM halos.

Backup

Convergence tests of N-body simulations



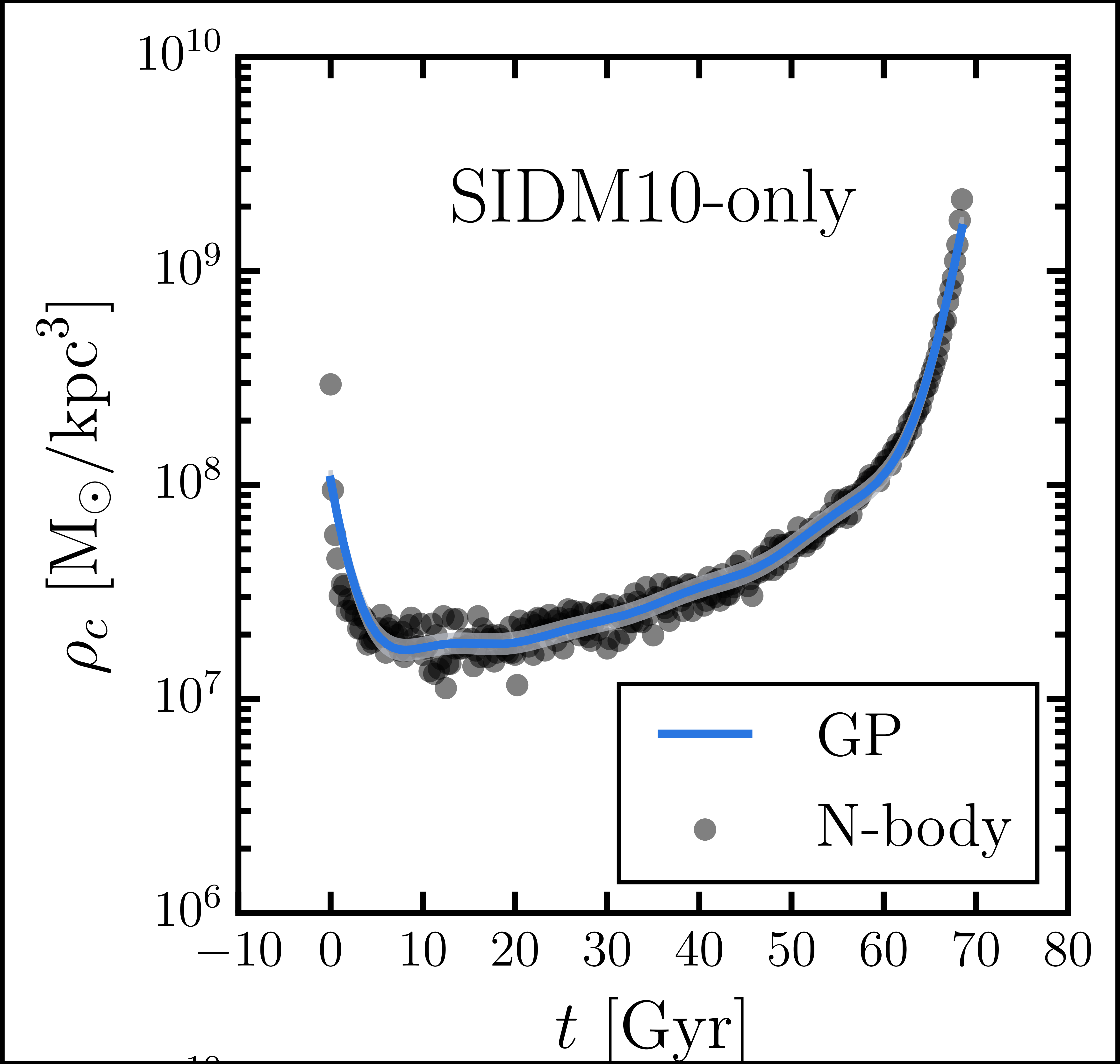
Grav. softening length

$$\Delta t = \sqrt{\frac{2\eta\epsilon}{|\mathbf{a}|}},$$

Time step

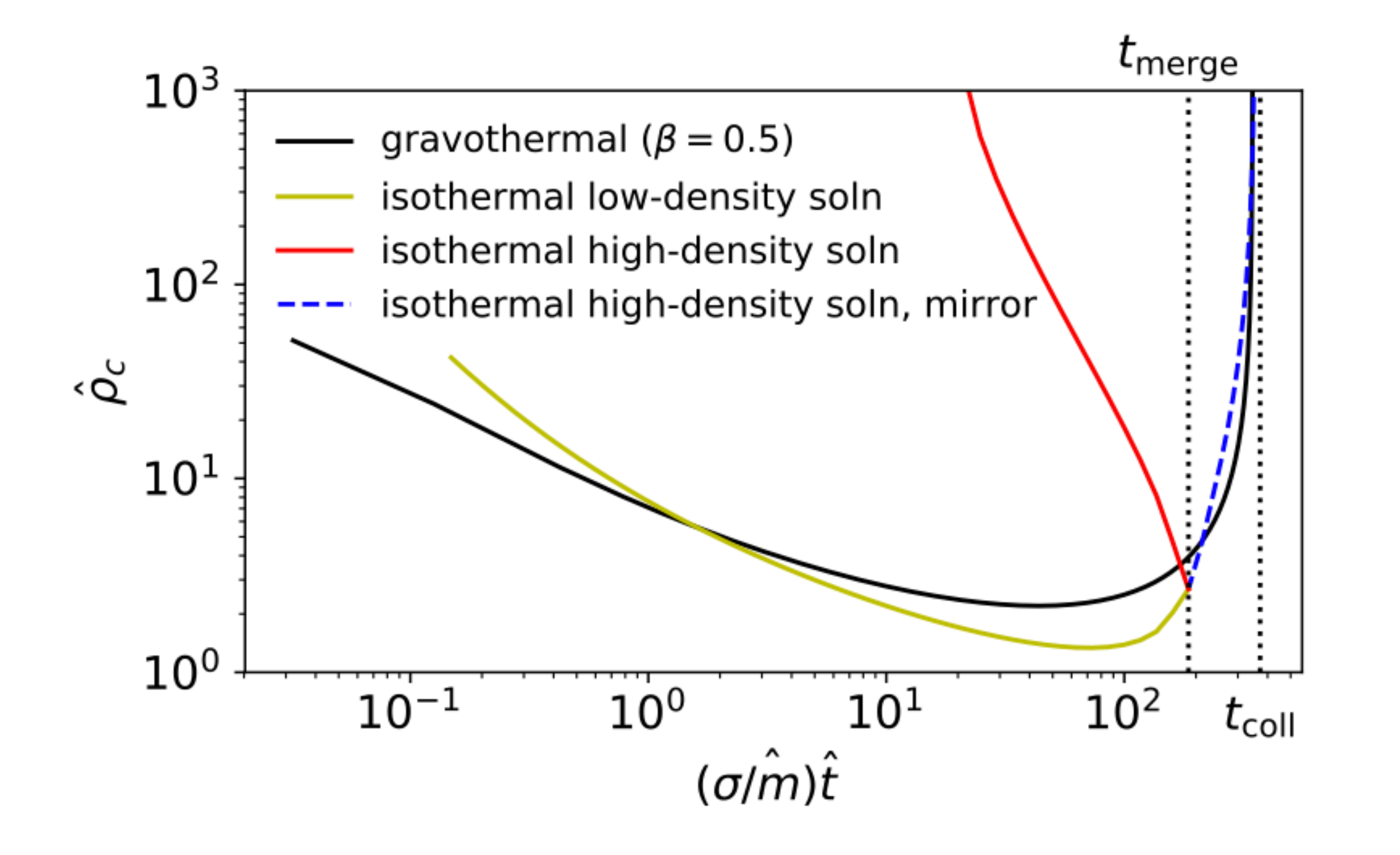
Mag. of one particle acceleration

Gaussian Process Regression



Isothermal to collapsed regime

Yang+ [YZ incl] (2023), arXiv:2305.05067



r_1 condition

$$\frac{4}{\sqrt{\pi}}\rho(r_1)v_{\rm rms}(r_1)\frac{\sigma}{m} = \max\left[\frac{1}{t}, \frac{1}{t_{\rm coll} - t}\right]$$

Fluid vs Isothermal

Yang+ [YZ incl] (2023), arXiv:2305.05067