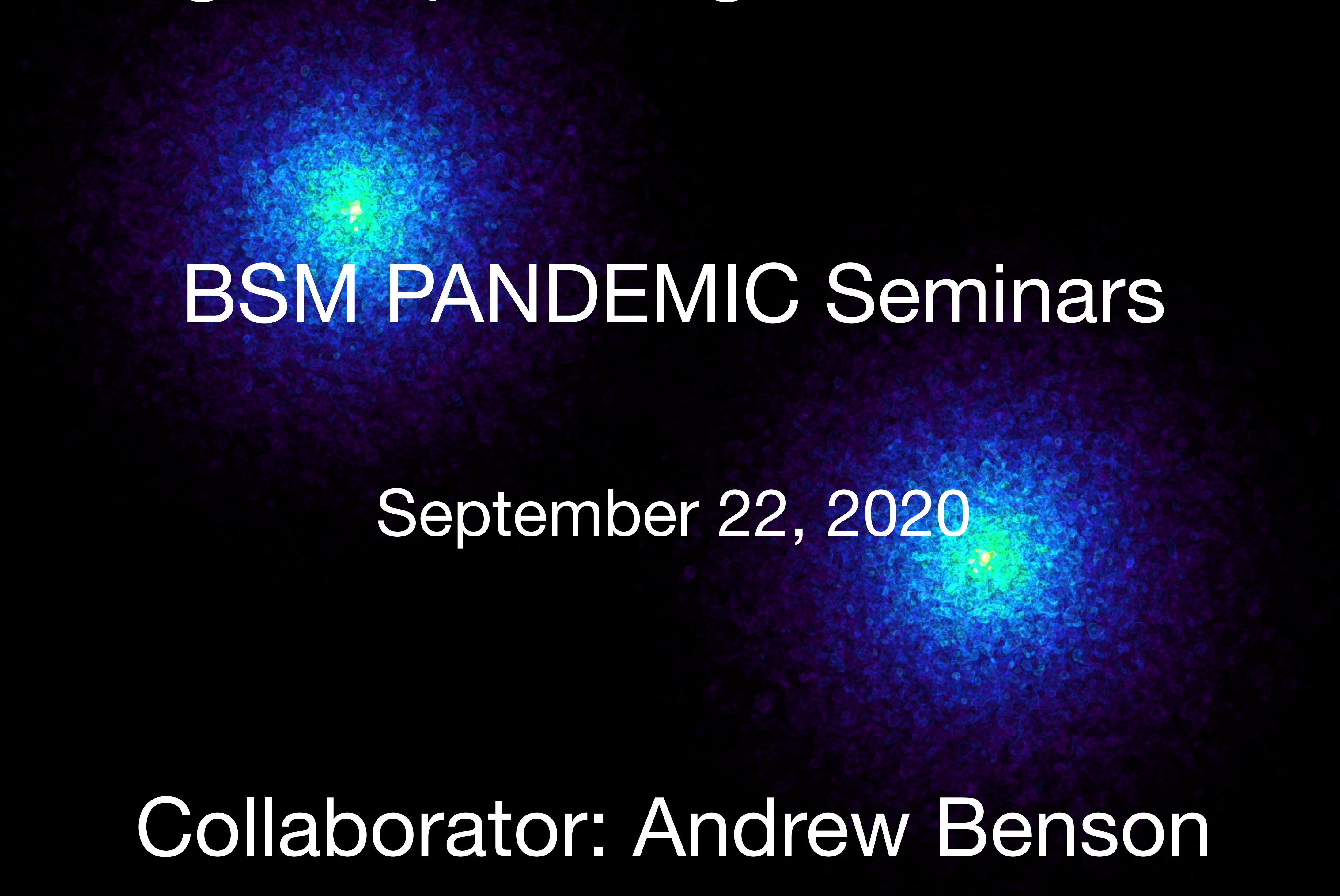
Carnegie Science Observatories

Collison of Fuzzy Dark Matter Halos

Xiaolong Du (Carnegie Observatories)

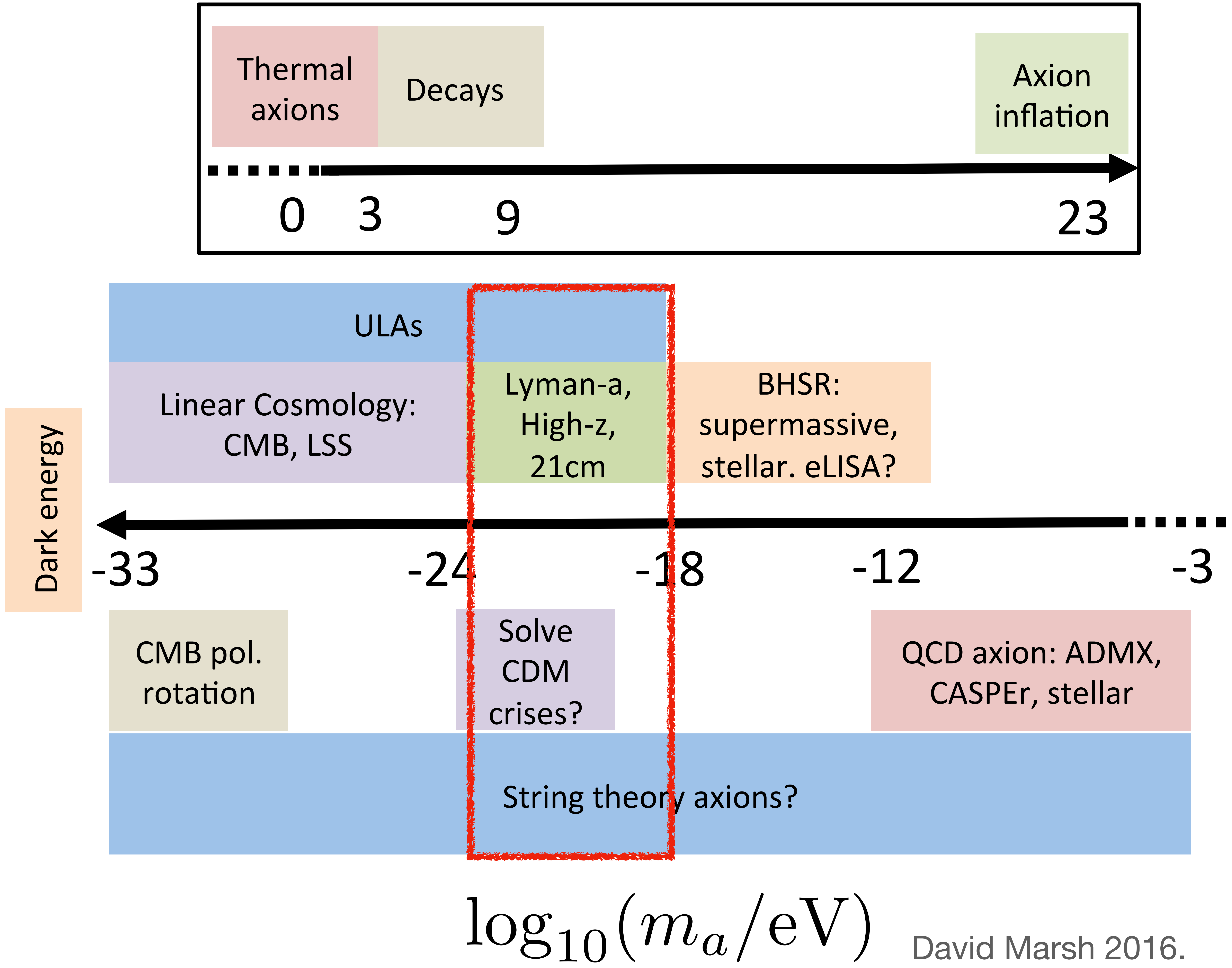


BSM PANDEMIC Seminars

September 22, 2020

Collaborator: Andrew Benson

Axion-like particles



David Marsh 2016.

Fuzzy Dark Matter $(10^{-19} \sim 10^{-22}\mathrm{eV})$

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{g}{4!}\phi^4 + \ldots$$

$$\phi = \mathrm{Re}(\psi e^{imt})$$

Schrödinger-Poisson Equations (non-relativistic limit)

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{x},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{x},t) + m\Phi(\mathbf{x})\psi(\mathbf{x},t)$$

$$\nabla^2\Phi(\mathbf{x},t) = 4\pi G|\psi(\mathbf{x},t)|^2$$

Wave Equation

$$\psi = \sqrt{\rho}e^{iS} \quad , v = \frac{\hbar}{m}\nabla S$$

$$\dot{\rho} + \nabla\cdot(\rho v) = 0$$

$$\dot{v} + v\cdot\nabla v = -\nabla\Phi + \frac{1}{2m^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

Fluid Equation

Simulations of Cosmic Structure Formation

1. Solve the wave equation

   (1) Finte difference: Schive et al. 2014a, Bodo et al. 2016
   (2) Pseudo-spectral method: Woo et al. 2009, Mocz et al. 2017, Du et al. 2018, Mocz et al. 2019

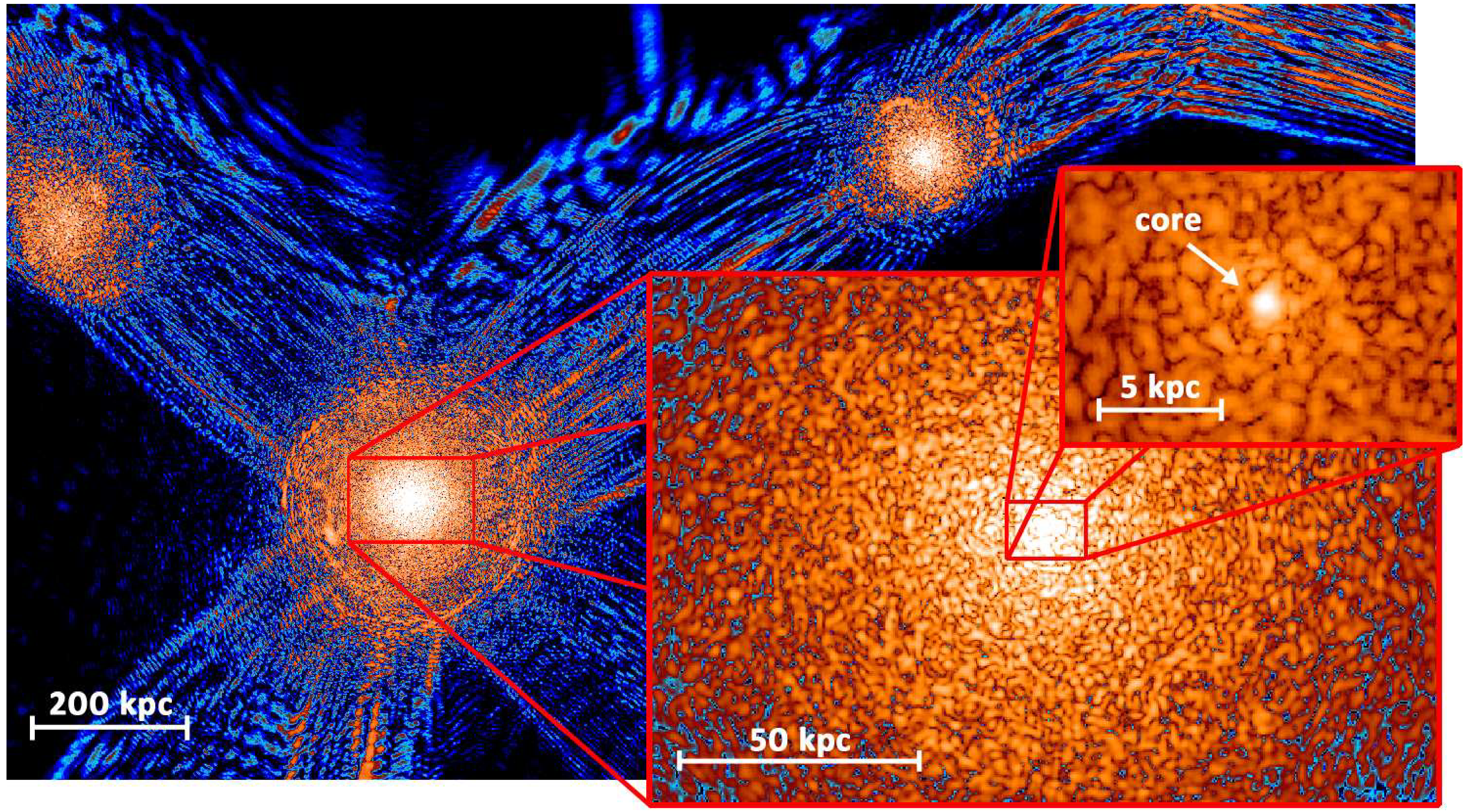
2. N-body+quantum pressure

   Mocz et al. 2015, Veltmaat et al. 2016, Nori et al. 2018

3. Hybrid Method

   Veltmaat et al. 2018, 2020

Schive et al. 2014a



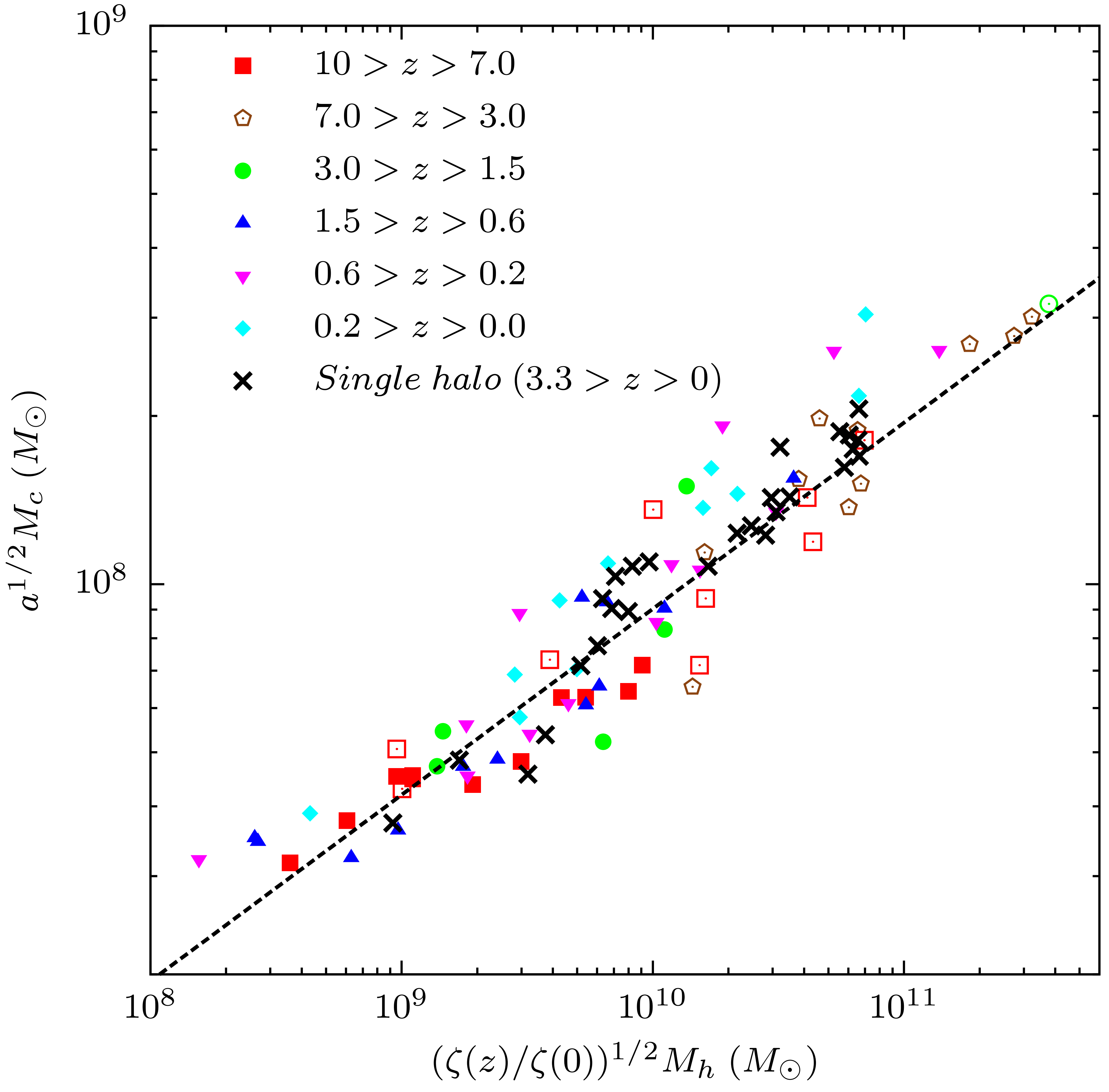
Suppression of small-scale structure

$$m = 10^{-22} eV \rightarrow M_h < 10^9 M_\odot$$

Flat halo core

Soliton solution + NFW envelope

Core-halo Mass Relation



Schive et al. 2014b

Soliton (core) density

$$\rho_c(r) = \frac{1.9 a^{-1} (m/10^{-23}\mathrm{eV})^{-2} (r_c/\mathrm{kpc})^{-4}}{[1 + 9.1 \times 10^{-2} (r/r_c)^2]^8} M_\odot \mathrm{pc}^{-3}$$

Core mass - halo mass

$$M_c \propto a^{-1/2} \left(\frac{\xi(z)}{\xi(0)} \right)^{1/6} M_h^{1/3}$$

Uncertainty principle

$$r_c \sigma_h \sim 1 \longrightarrow r_c M_h^{1/3} \sim 1 \xrightarrow{r_c \sim M_c^{-1}} M_c^{-1} M_h^{1/3} \sim 1$$

Valid only for relaxed halos

Collison of Two Halos

1. Initial conditions

$$\psi(x,t) = \sum \sqrt{f(E)}\,\psi_E(x)e^{-iEt/\hbar}$$

$$f(E) = A\left[e^{-\beta(E-E_c)} - 1\right], \quad E \le E_c$$

$$f(E) = 0, \quad E > E_c$$

(King model, Lin et al. 2018)

2. Pseudo-spectral method

$$\psi(x, t+\Delta t) = e^{-i\hat{H}\Delta t}\psi(x,t)$$

$$\exp(-i\hat{H}\Delta t) = \prod_i e^{-it_i K\Delta t}e^{-iv_i W\Delta t}$$

An example (kick-drift-kick, 2-order)

a. gravitation potential

$$\Phi = -\,\mathrm{iFFT}\left[\frac{4\pi G}{k^2}\,\mathrm{FFT}\,[\rho]\right]$$

b. Wave function

Kick: $\psi(x) \leftarrow e^{-\frac{i}{2}\Phi\Delta t}\psi(x)$

↓

Drift: $\psi(k) = \mathrm{FFT}[\psi(x)]$

$\psi(k) \leftarrow e^{-ik^2\Delta t}\psi(k)$

$\psi(x) = \mathrm{iFFT}[\psi(k)]$

↓

Kick: $\psi(x) \leftarrow e^{-\frac{i}{2}\Phi\Delta t}\psi(x)$

Higher oder: **fourth-oder time integration**

Two halos with initial velocities v1 and v2

$$\psi_{\rm ini}(x) = \psi_1(x - x_1)e^{\frac{imv_1}{\hbar}x + S_1} + \psi_2(x - x_2)e^{\frac{imv_2}{\hbar}x + S_2}$$

$$\Delta S = S_1 - S_2$$

Consider two halos with equal mass

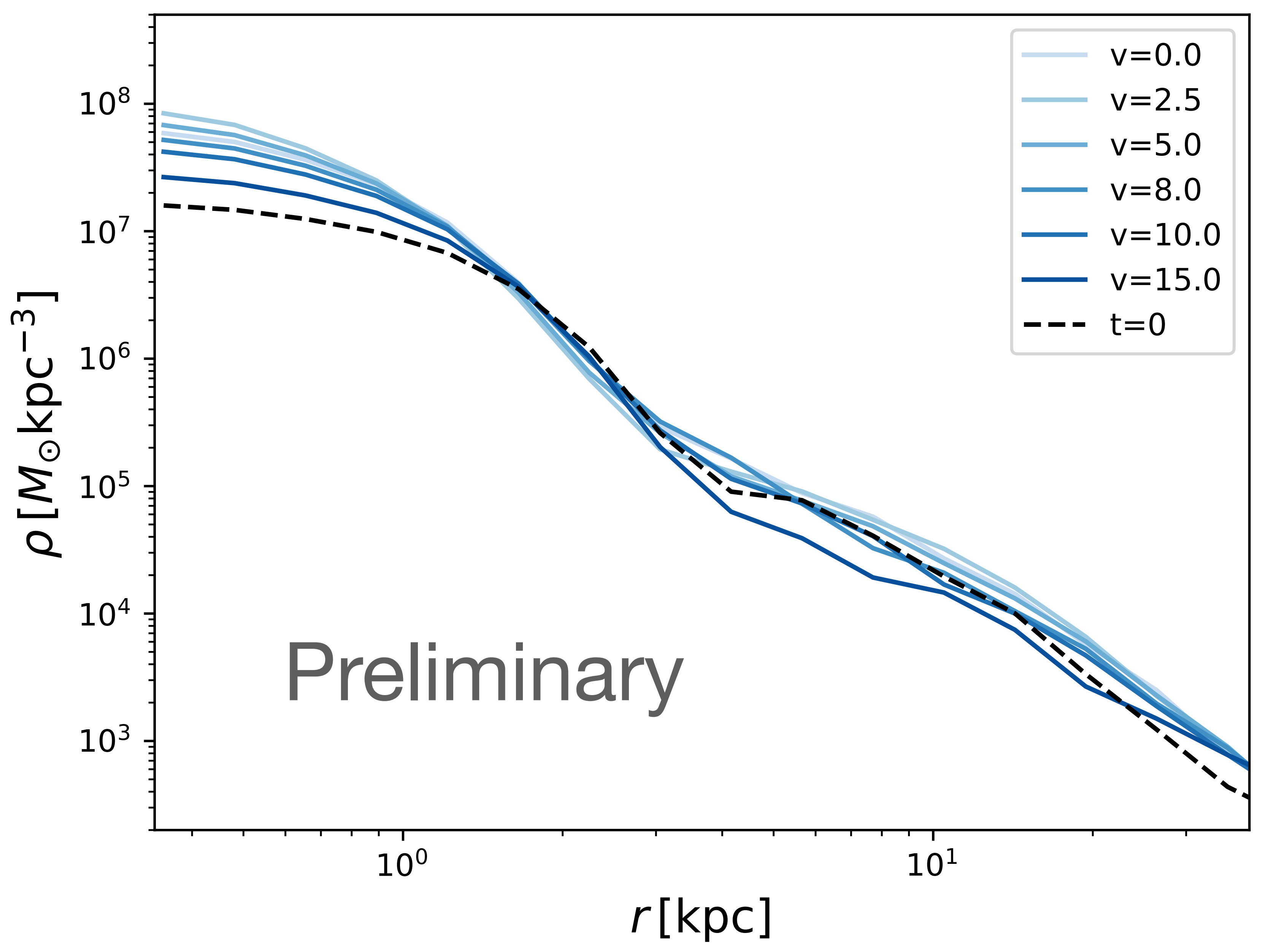
Escape velocity

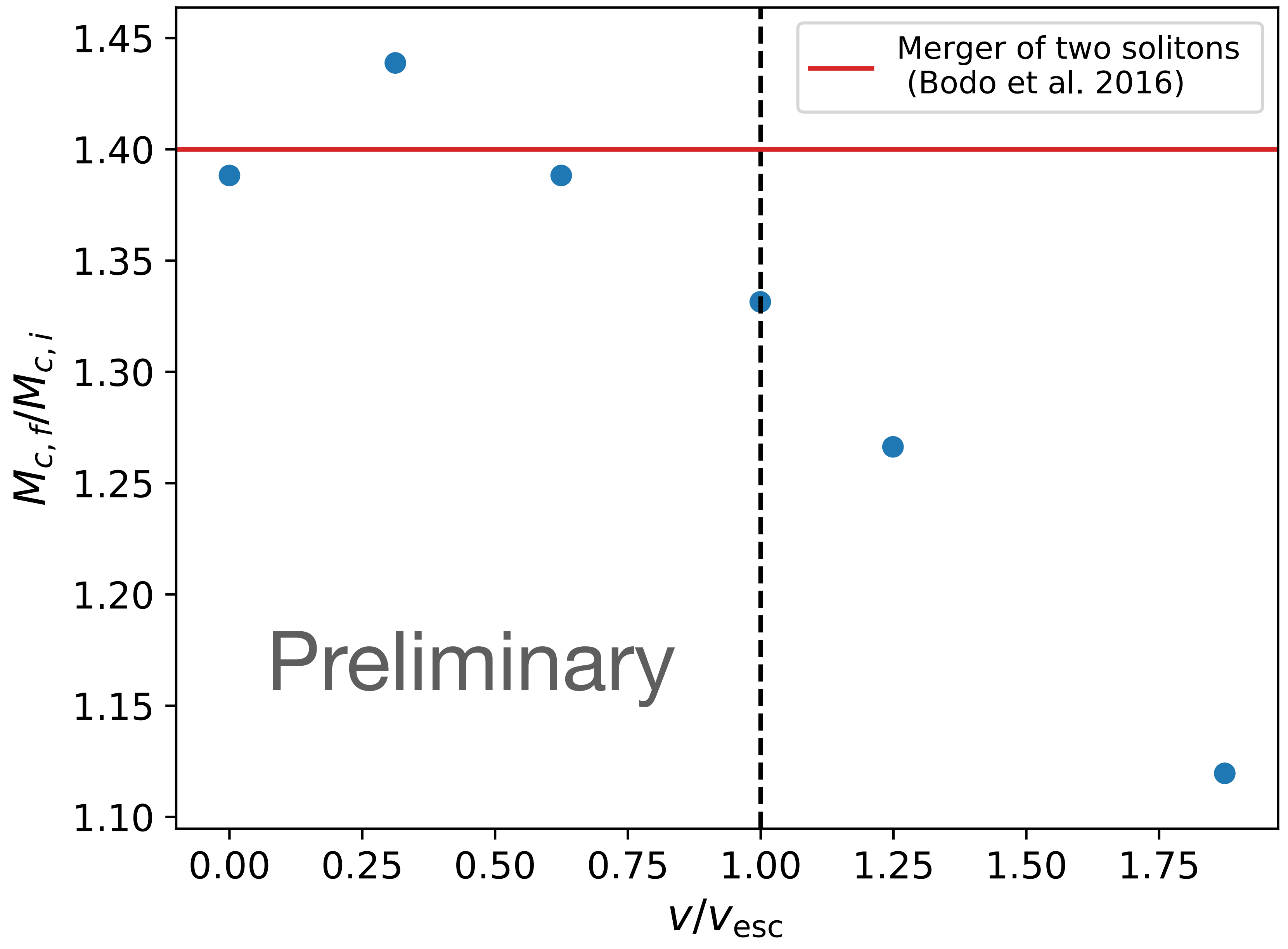
$$v_{\rm esc} = \sqrt{GM_h/R_{\rm ini}}$$

(1) Head on collision $\Delta S = 0$

$$M_h = 10^9 M_\odot,\ R_{\rm vir} = 12.8\,{\rm kpc}$$

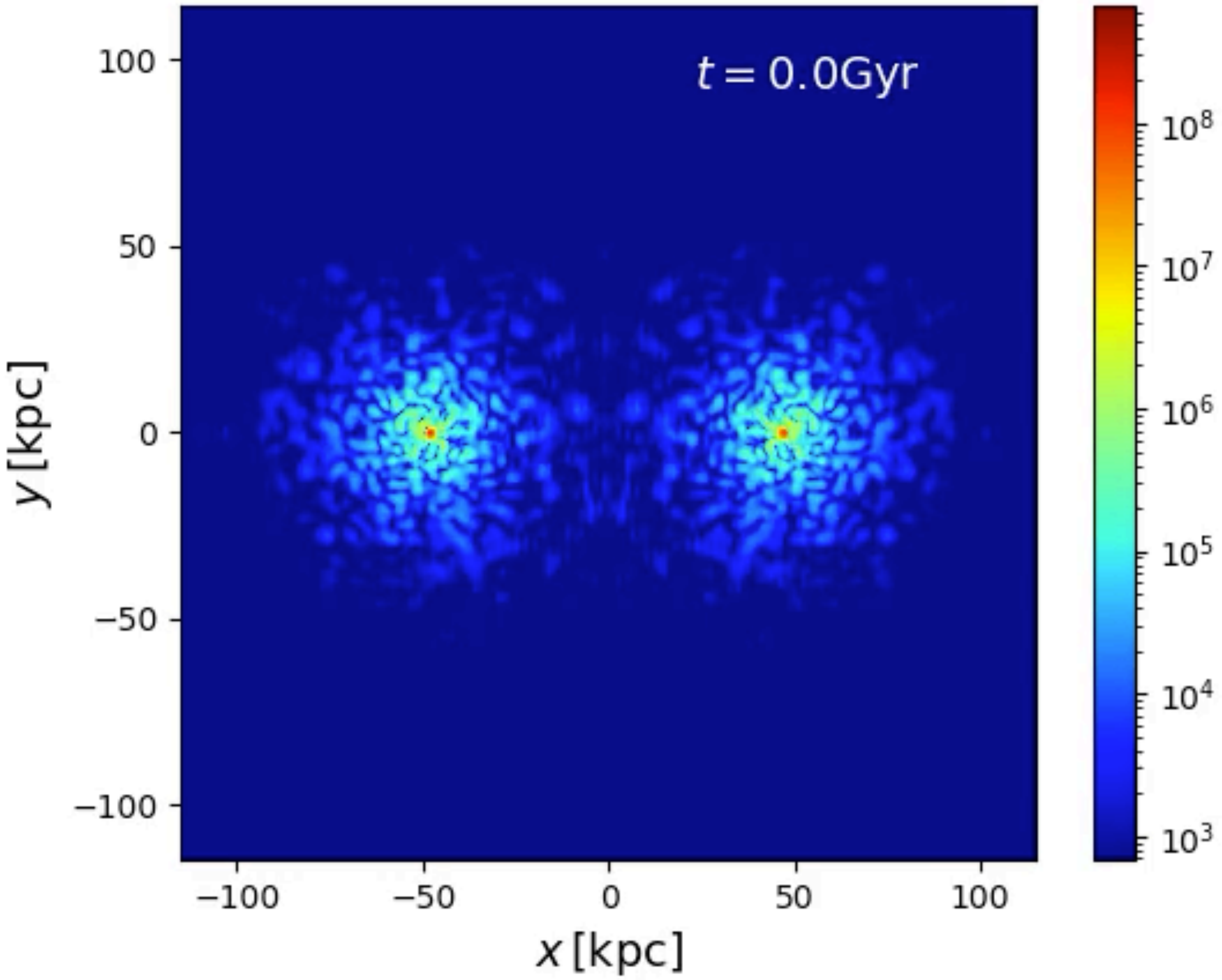
$$M_{c,i} = 5.3 \times 10^7 M_\odot$$



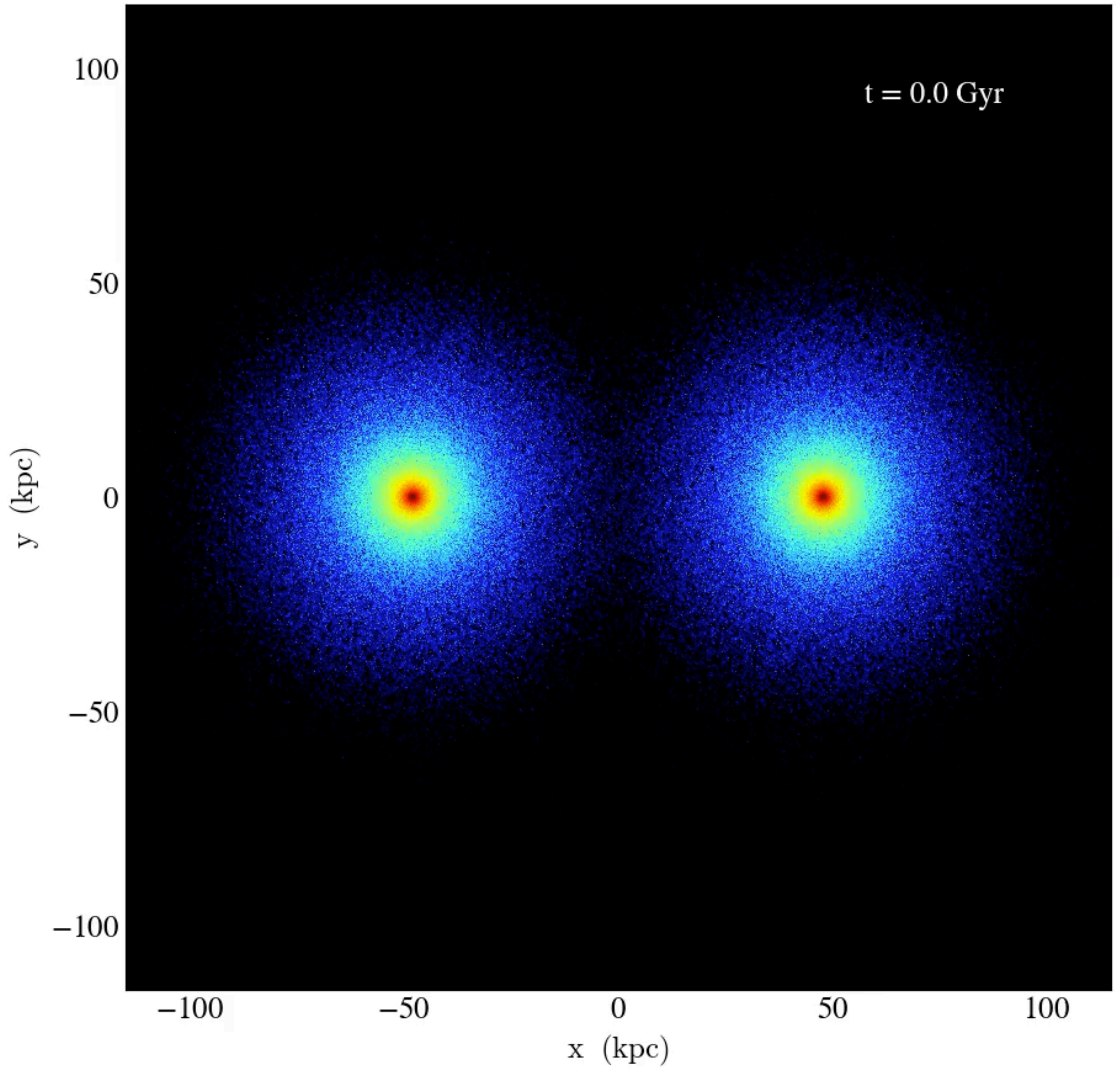


$$M_h = 10^{9.5} M_\odot \, , \; v_{\rm ini} = 1.68 v_{\rm esc}$$

Fuzzy DM



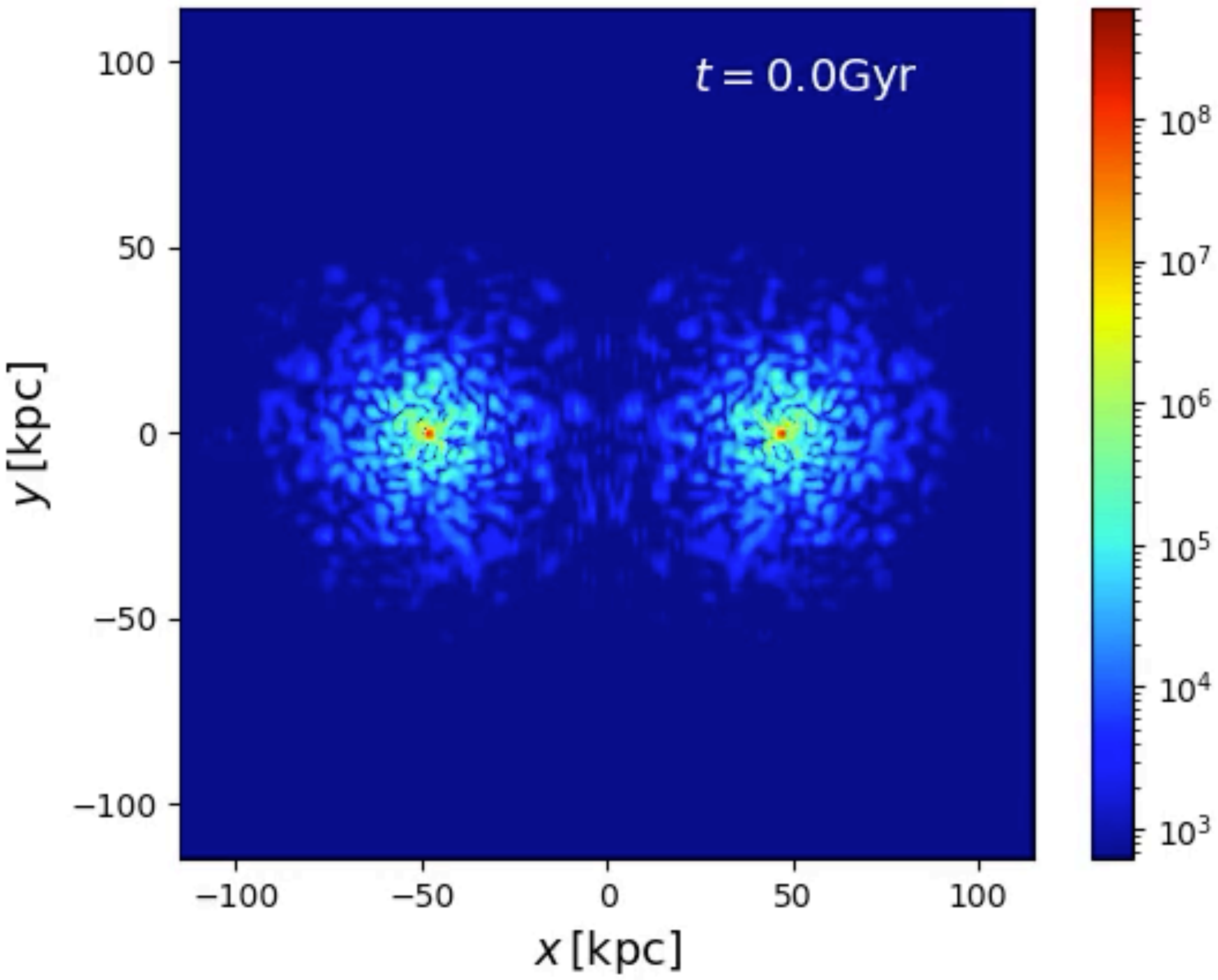
Collisionless Cold DM



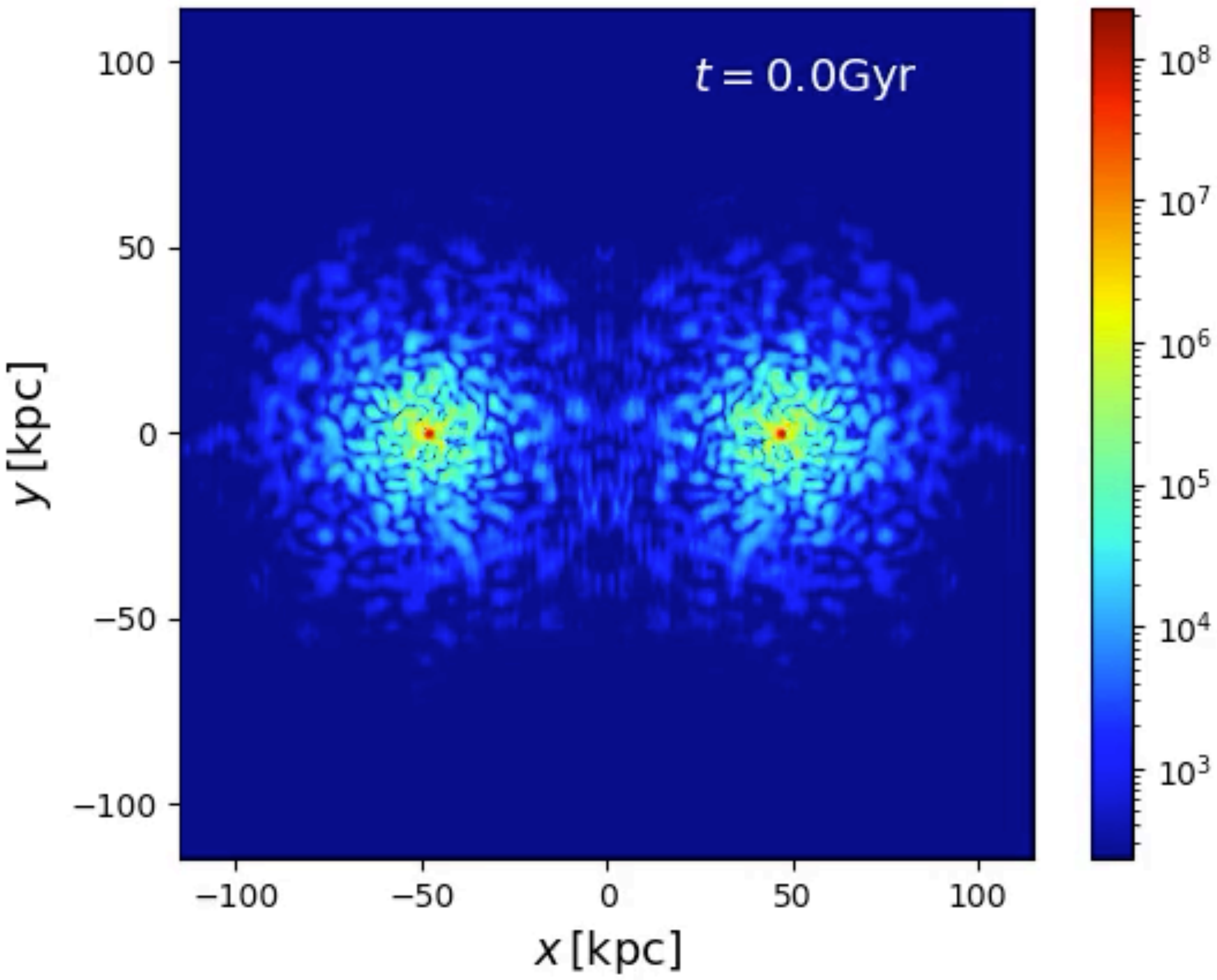
Core stays at the center

(2) Head on collision $\Delta S \neq 0$

$\Delta S = \frac{\pi}{2}$

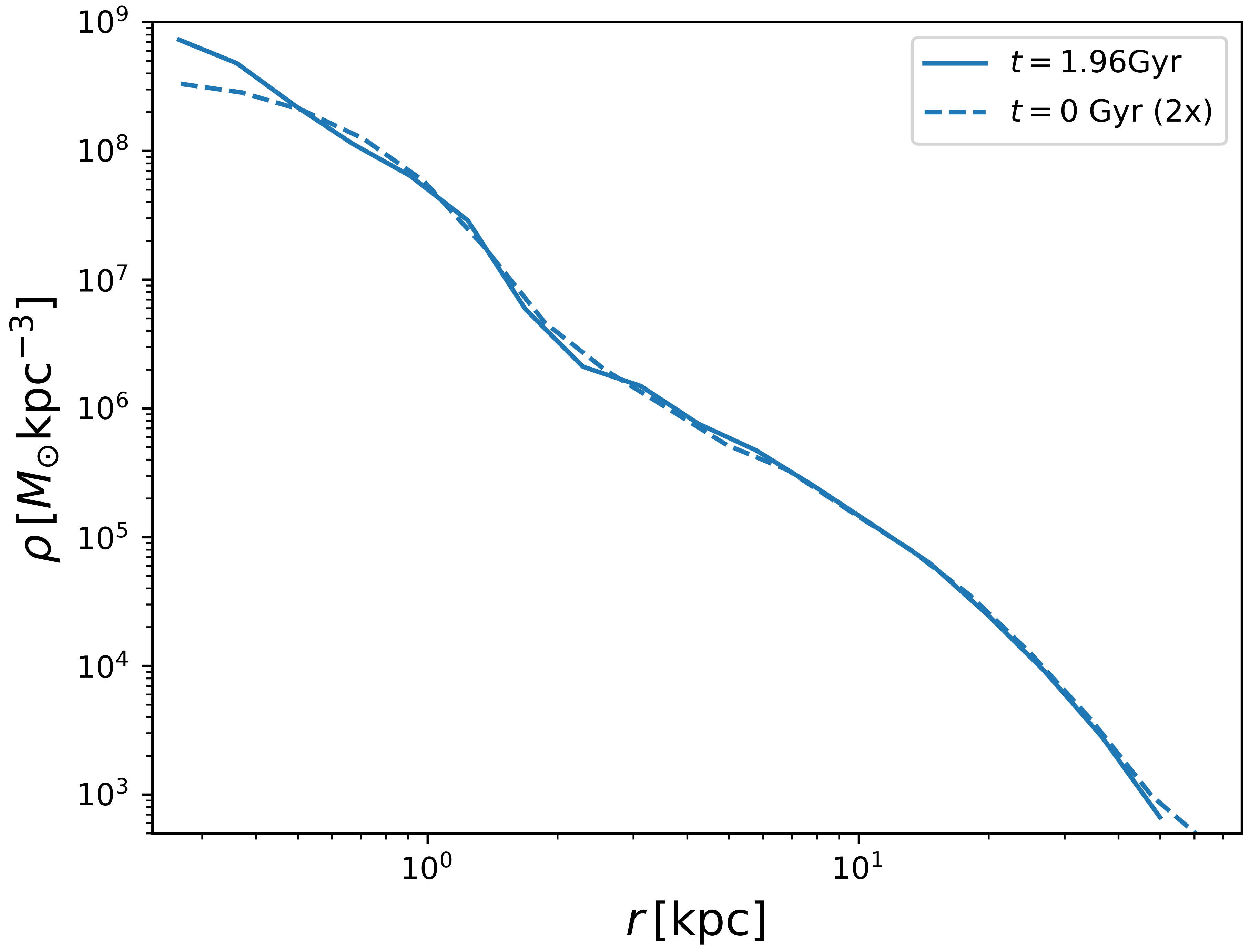


$\Delta S = \pi$

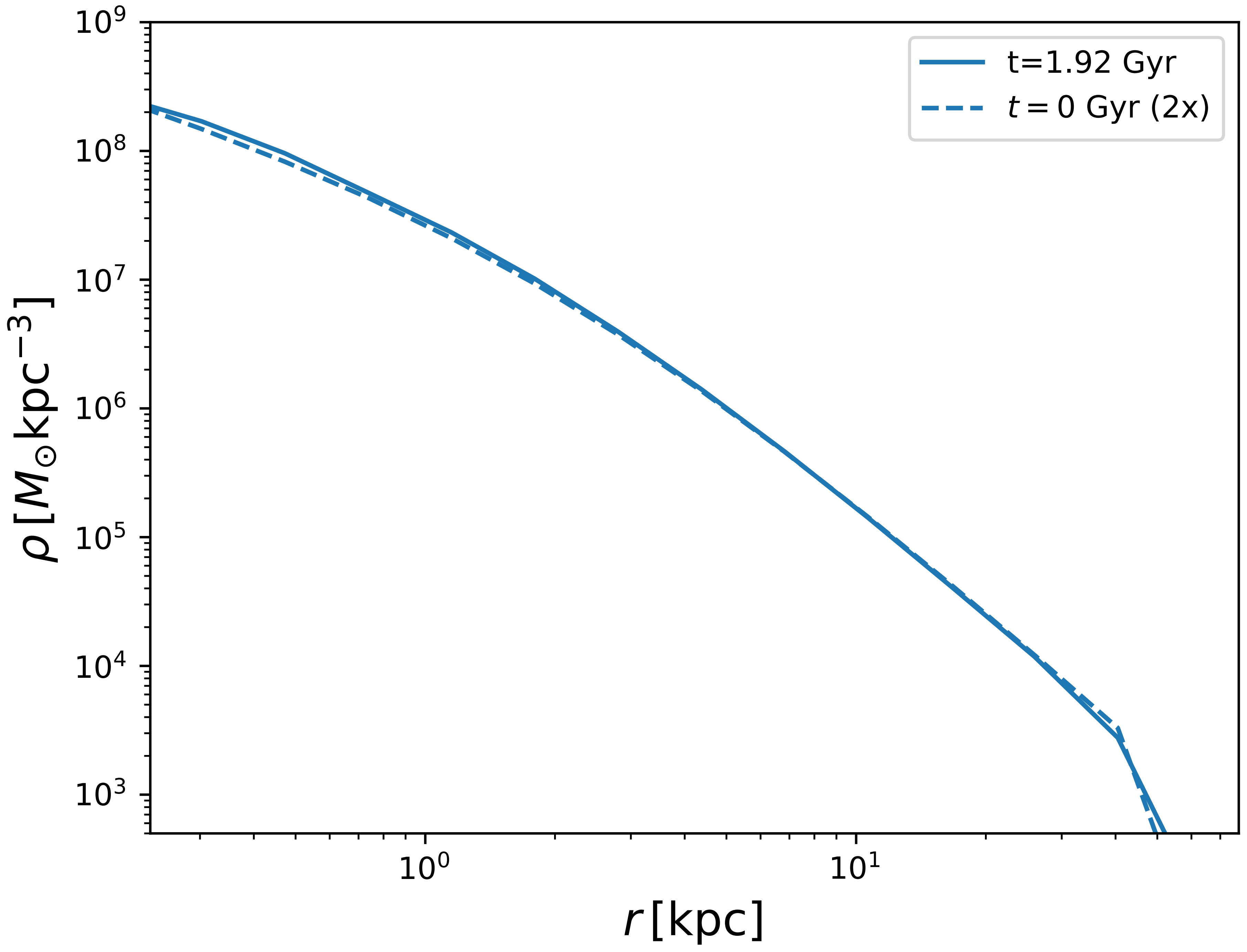


Density profile when two halos overlap

Fuzzy DM



Collisionless Cold DM



Semi-analytic Model

1. Build merger trees (extended Press-Schechter formalism)

2. Models for the core evolution

    (a) core growth by major mergers

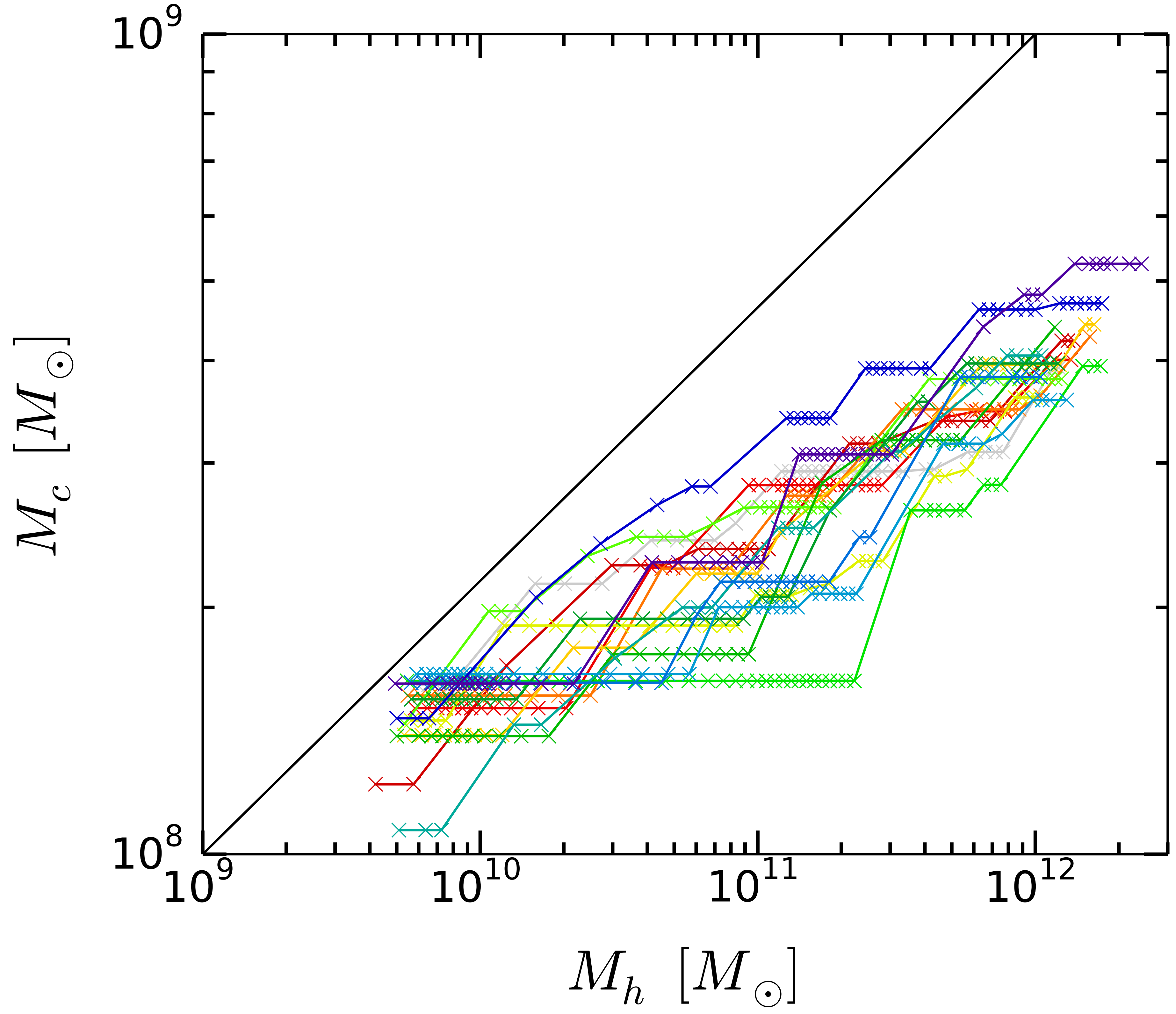
    (b) core mass loss due to tidal stripping

3. Models for the evolution of halos

    (a) dynamical friction

    (b) tidal effects

    (c) dynamical heating



Du et al. 2016

Summary

The collision of Fuzzy Dark Matter halos behaves differently on small scales

- Interference pattern in the density

$$\rho = |\psi_1|^2 + |\psi_2|^2 + \psi_1^* \psi_2 + \psi_1 \psi_2^*$$

Observational features in merging galaxies? (Paredes et al. 2016)

- The solitonic cores are easier to merge

Orphan cores?

Build a well-calibrated semi-analytic model

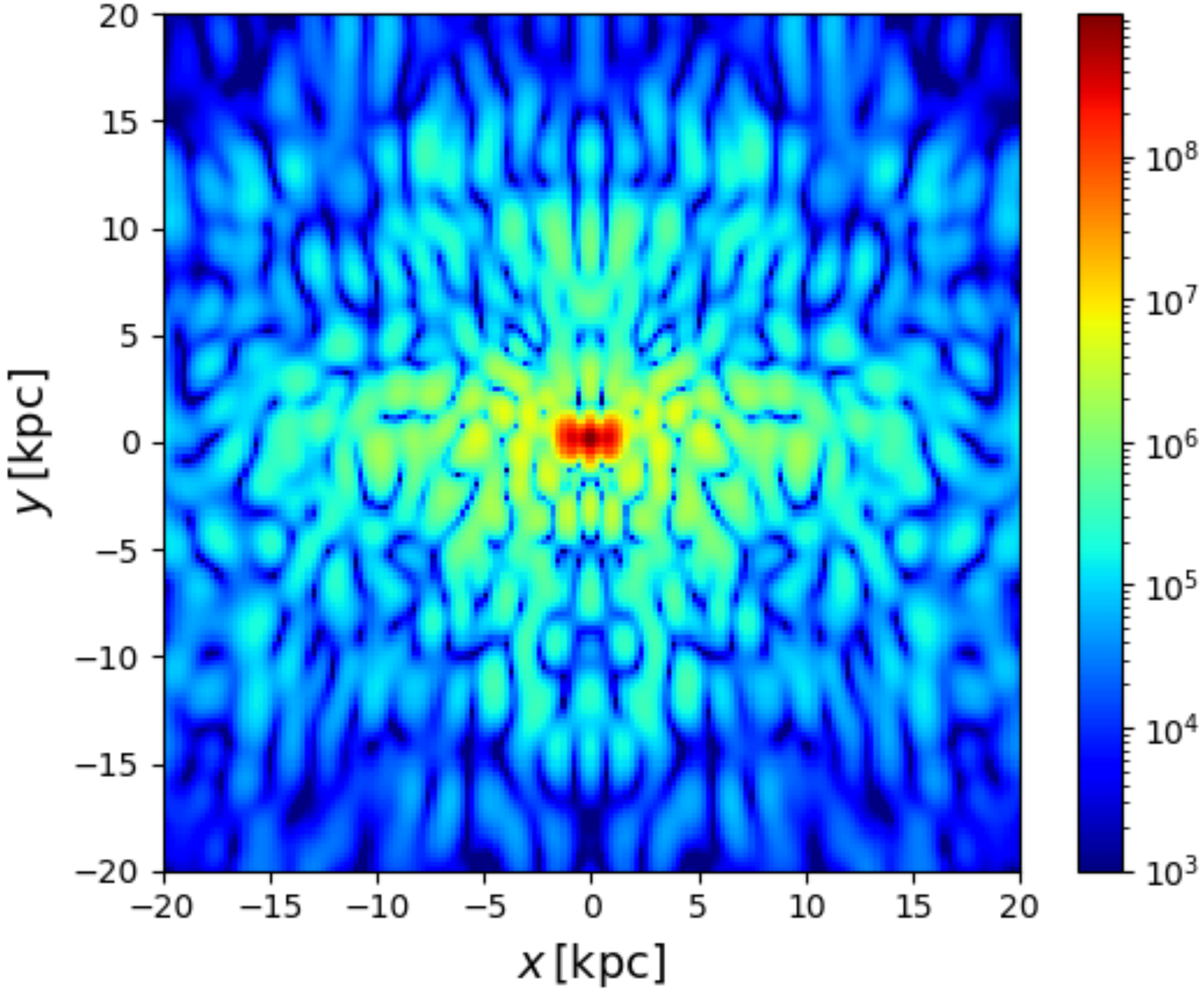
Gravitational lensing, a large number of realizations needed

Milky May-size halos (currently can not be simulated directly)

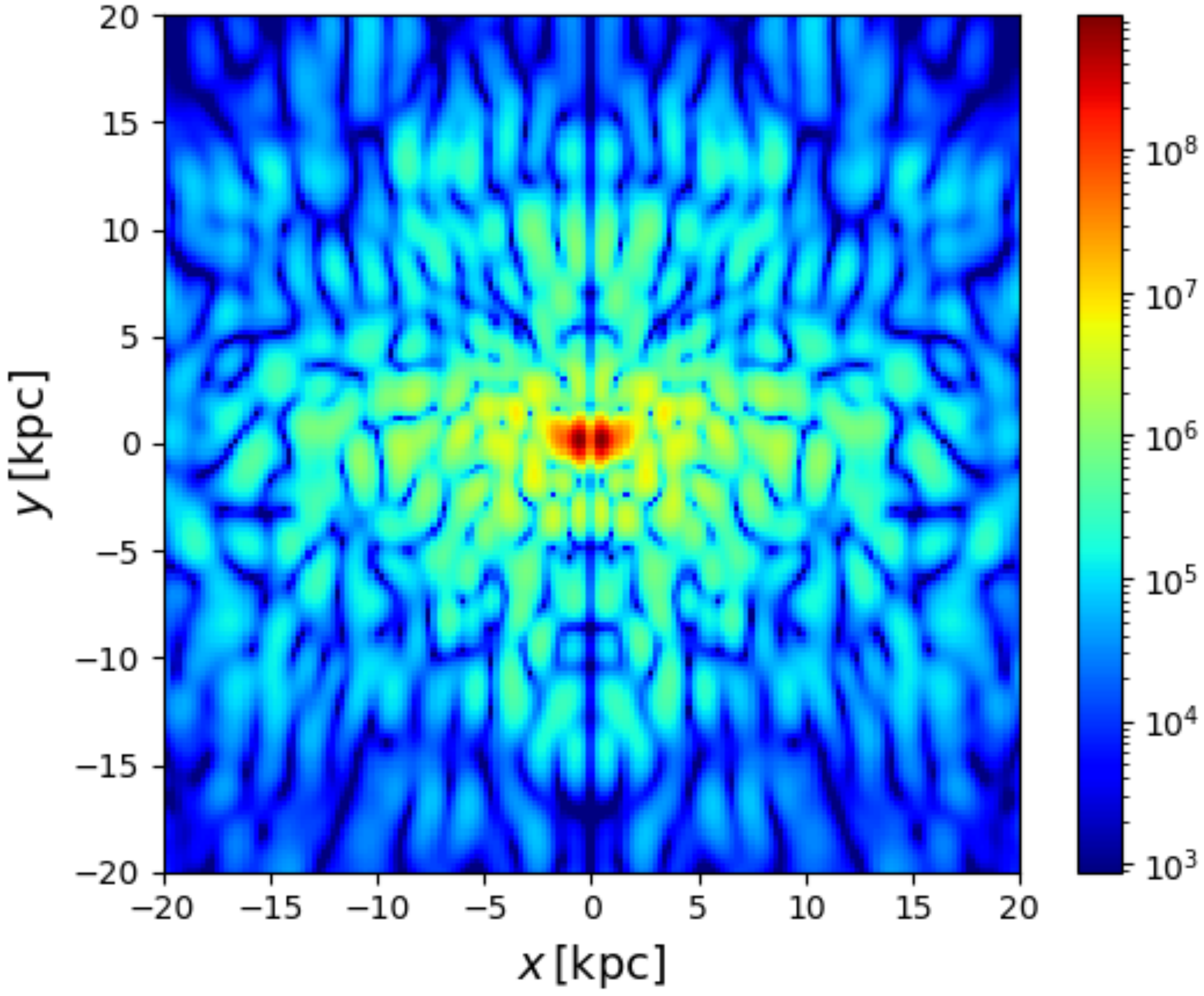
Thanks!

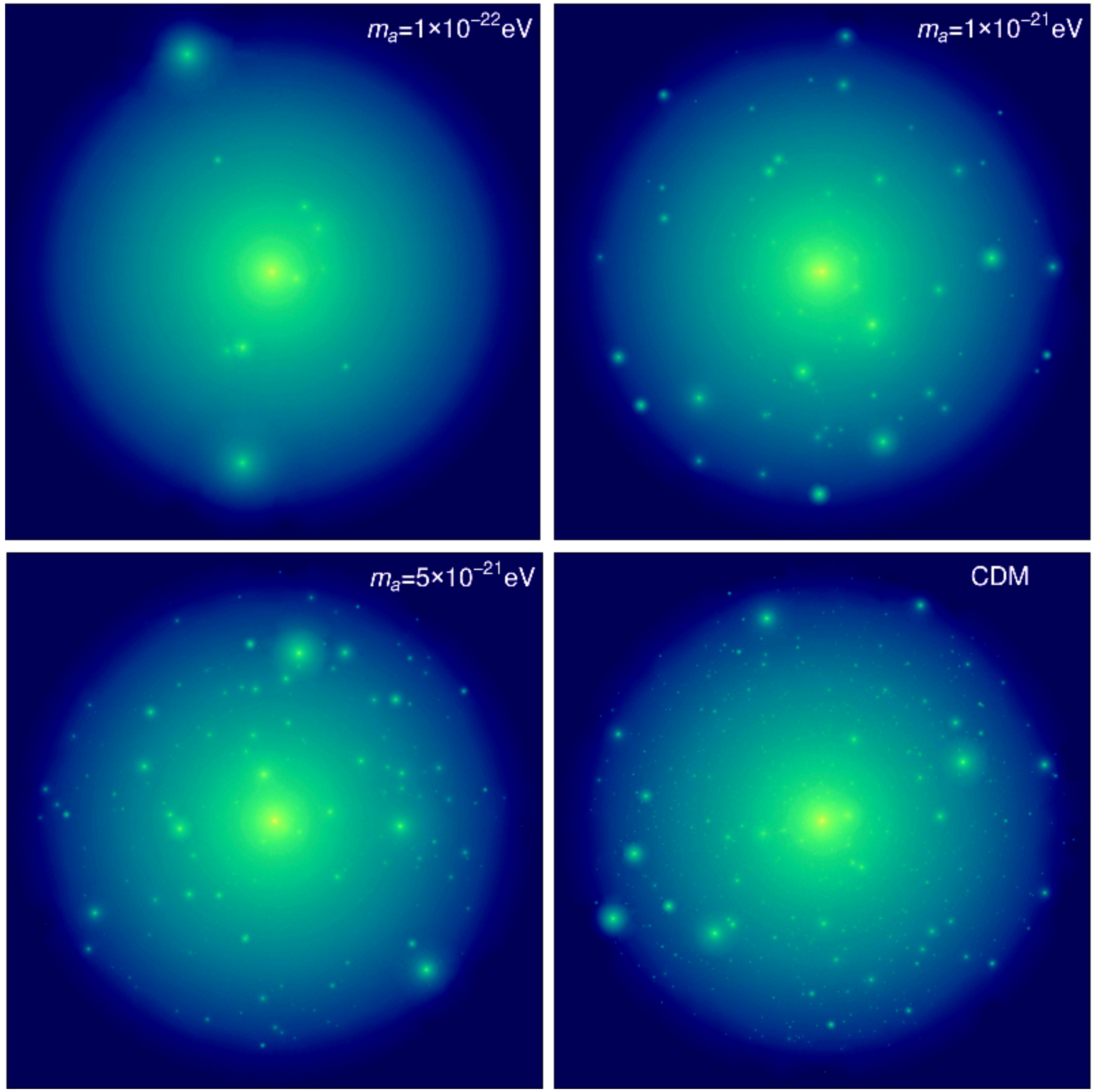
Backup slides

$\Delta S = 0$



$\Delta S = \pi$



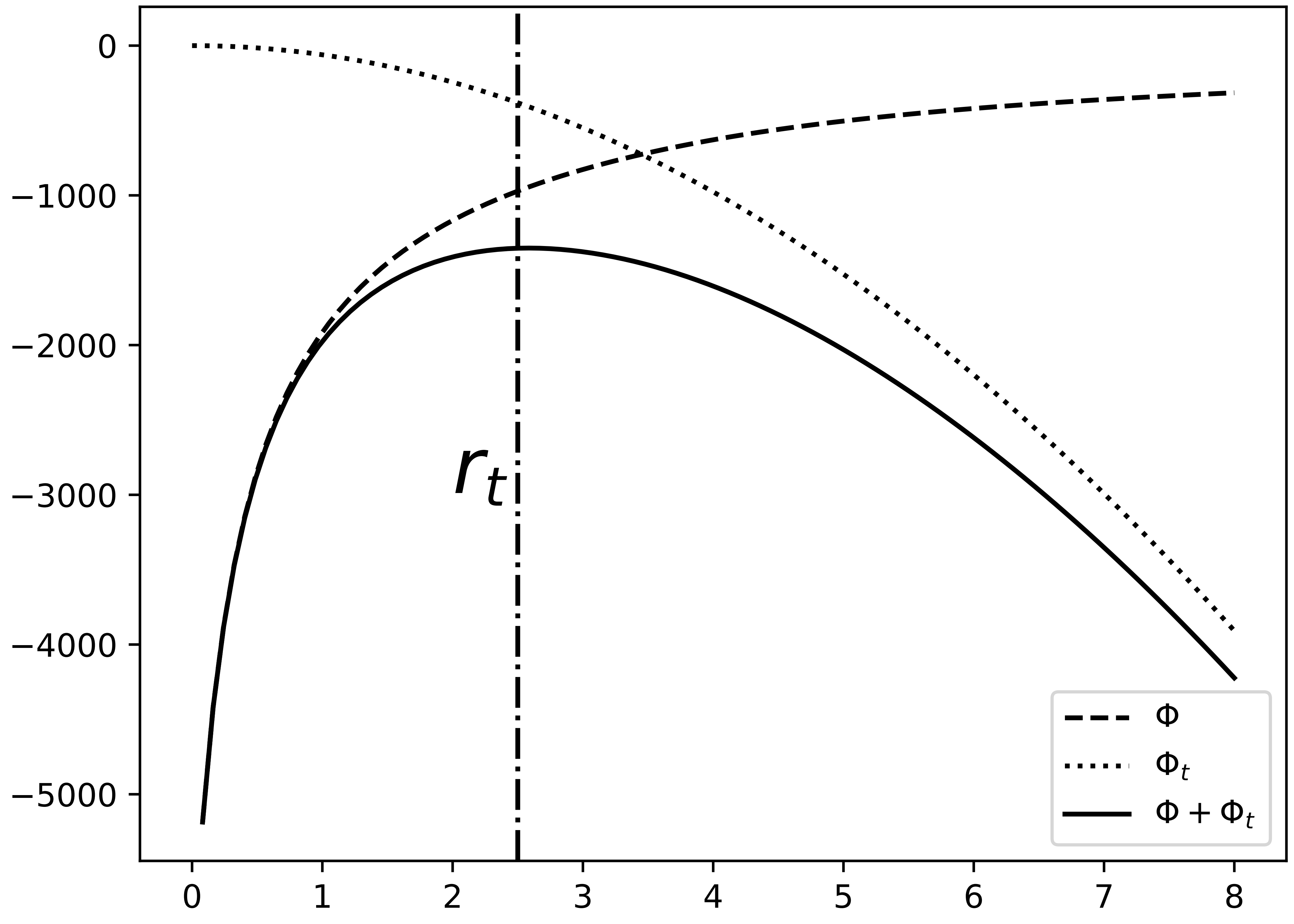


Milky Way-sized halos from Semi-analytic models

Evolution in tidal field (subhalos)

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{x},t) = -\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{x},t) + m[\Phi(\mathbf{x}) + \Phi_t(\mathbf{x})]\psi(\mathbf{x},t)$$

$$\Phi_t(r) = -\frac{GM_h(R)}{R^3}r^2$$



Tunneling effects

(Hui et al. 2017, Du et al. 2018)