A semi-analytic model of self-interacting dark matter substructures

Based on Shirasaki, Okamoto, Ando (2022) MNRAS, 516, 3

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March 8, 2023 "What is dark matter? - Comprehensive study of the huge discovery space in dark matter"

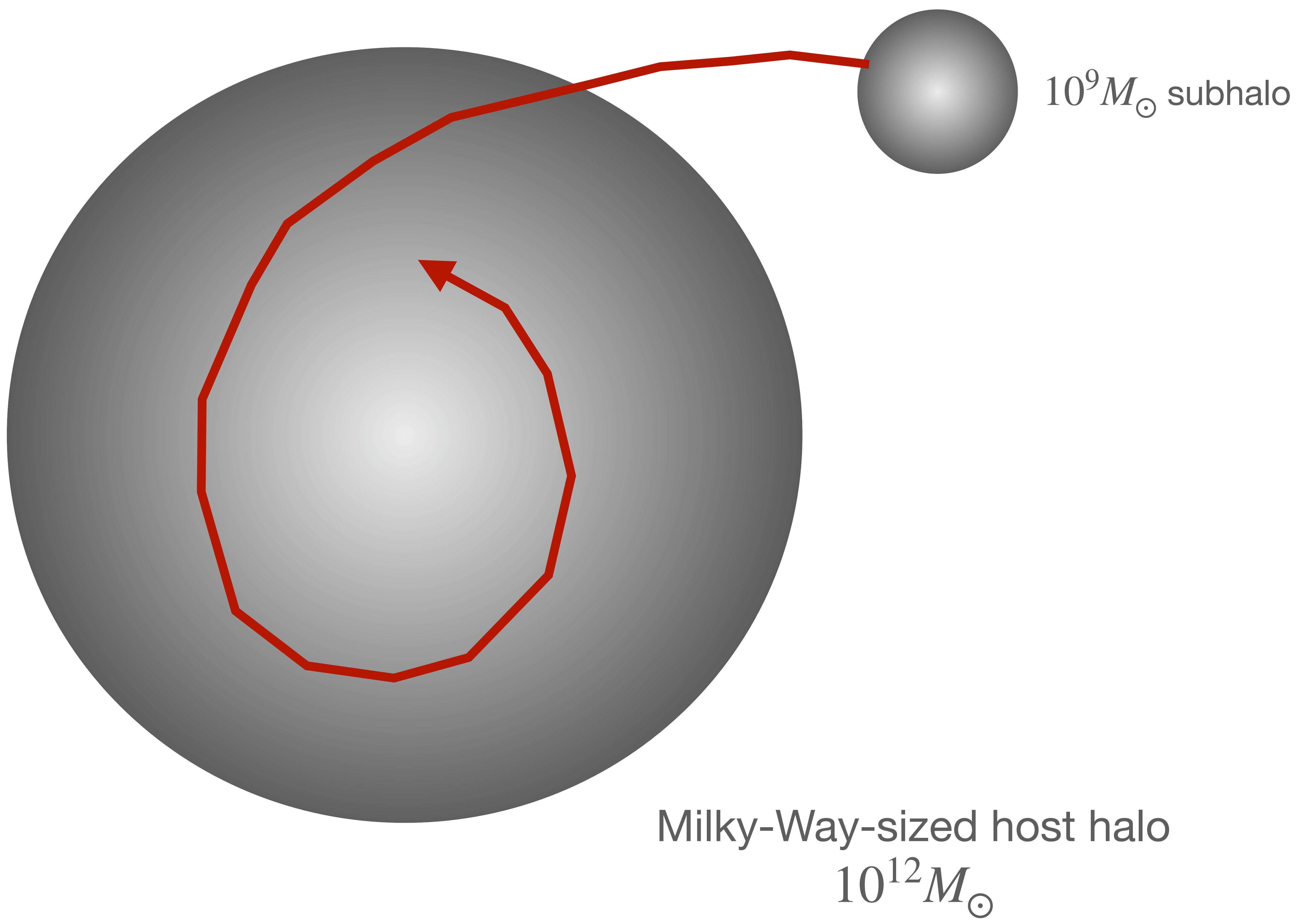
Self-interacting dark matter (SIDM)

- Self-interacting dark matter particles with their scattering cross section of $\sigma/m \sim O(1)\,\mathrm{cm^2/g}$ can be a good candidate for cosmic dark matter
  - A typical mean free path can be ~1 Mpc in a galaxy if the SIDM particle mass is set to ~1 GeV (e.g. Spergel & Steinhardt 2000)
  - Any SIDM signatures may be found in small scale structures on scales of <1Mpc
- In practice, MW satellites are the best target to examine the nature of dark matter because they are a DM-dominated system
- Let us develop a model of SIDM subhalos with the help of simulation data.

Semi-analytic model of SIDM subhaloes

Calibration with ideal N-body simulations of minor mergers

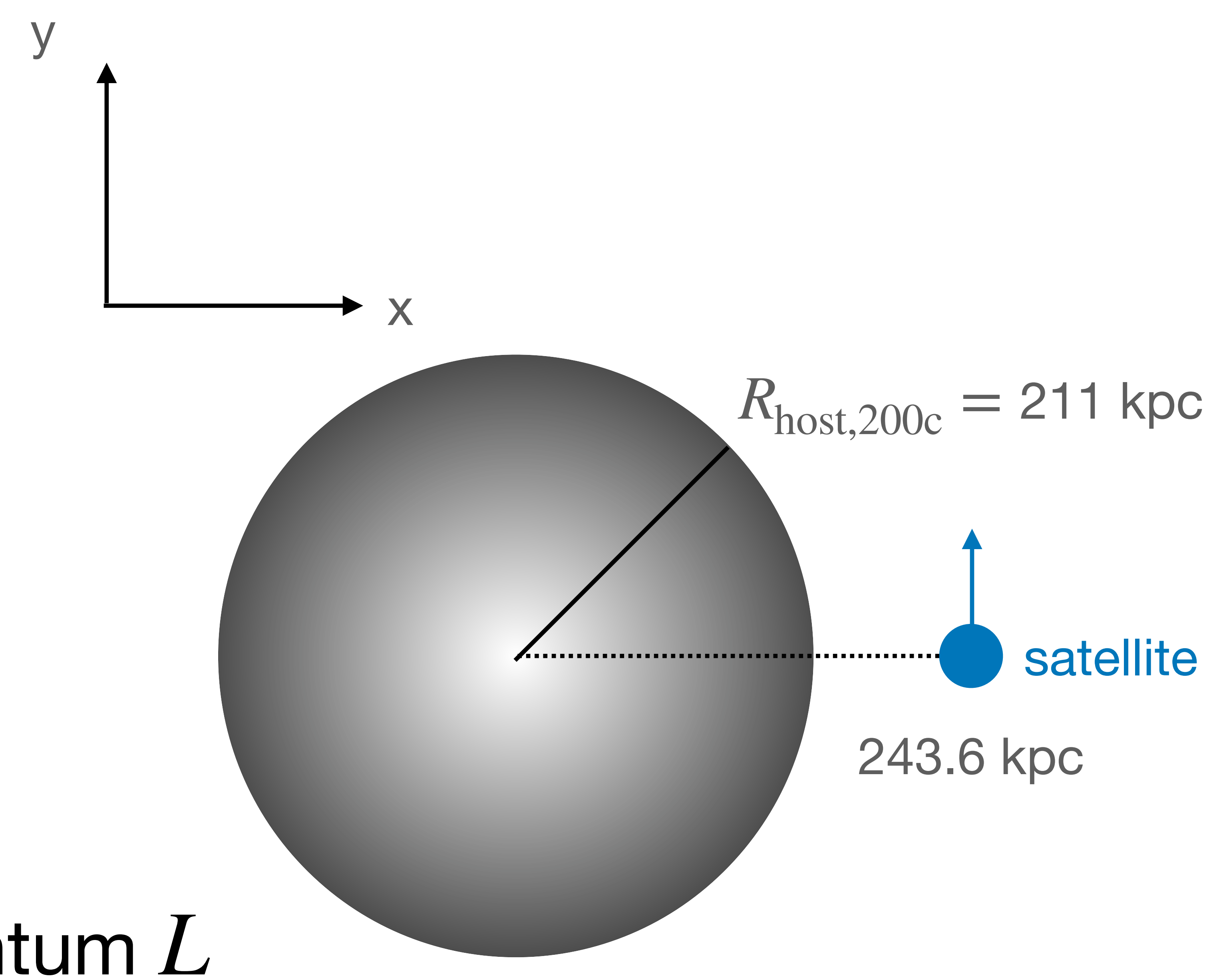
- Testing self-interactions of DM particles would require a precise modeling of
  - thermalization of SIDM halo/subhalo
  - Tidal stripping / Ram pressure
- Develop a semi-analytic model of infalling subhalos to a MW-sized halo and calibrate it with (isolated) N-body sims



Isolated N-body halos

Initial condition in our simulations

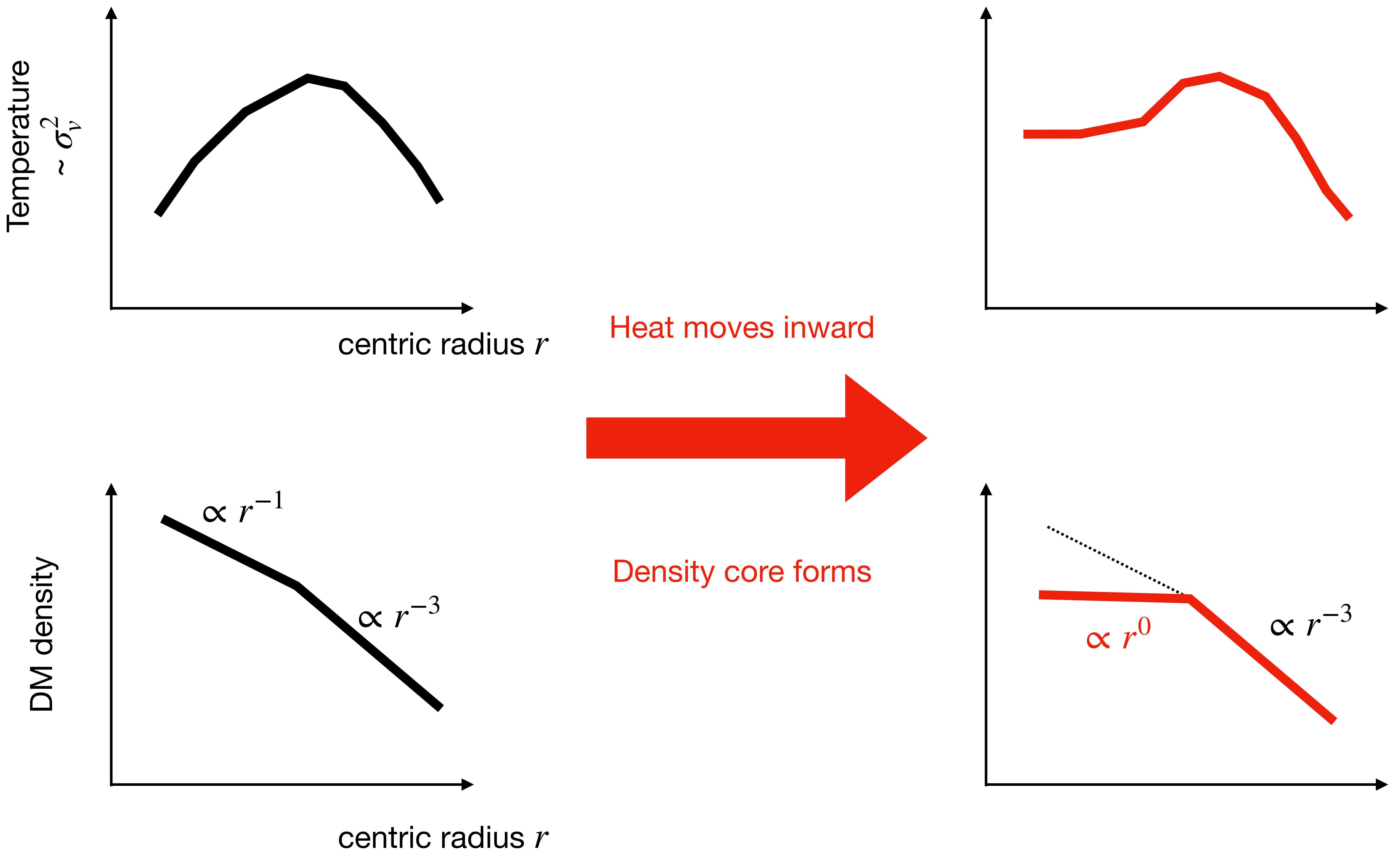
- Host: NFW halo ($M_{200c} = 10^{12}\,M_\odot, c = 10, r_s = 21.1\,\mathrm{kpc}$)
- Satellite: NFW halo ($M_{200c} = 10^{9}\,M_\odot, c = 6, r_s = 1.68\,\mathrm{kpc}$)
- MAGI: Generator of spherical N-body halos in dynamical equilibrium
  - https://bitbucket.org/ymiki/magi/src/master/
  - No disc components for now
- Set the initial condition of the satellite with its energy E and angular momentum L
  - $E = \frac{1}{2}V_c^2 + \Phi_{\mathrm{NFW-host}}(R_c), L = \eta R_c V_c$ where $V_c = (GM_{\mathrm{host}}/R_c)^{1/2}$
  - $x_c = R_c/R_{\mathrm{host,200c}} = 0.5, \eta = 0.6$ → apocenter = 243.6 kpc



Simulation

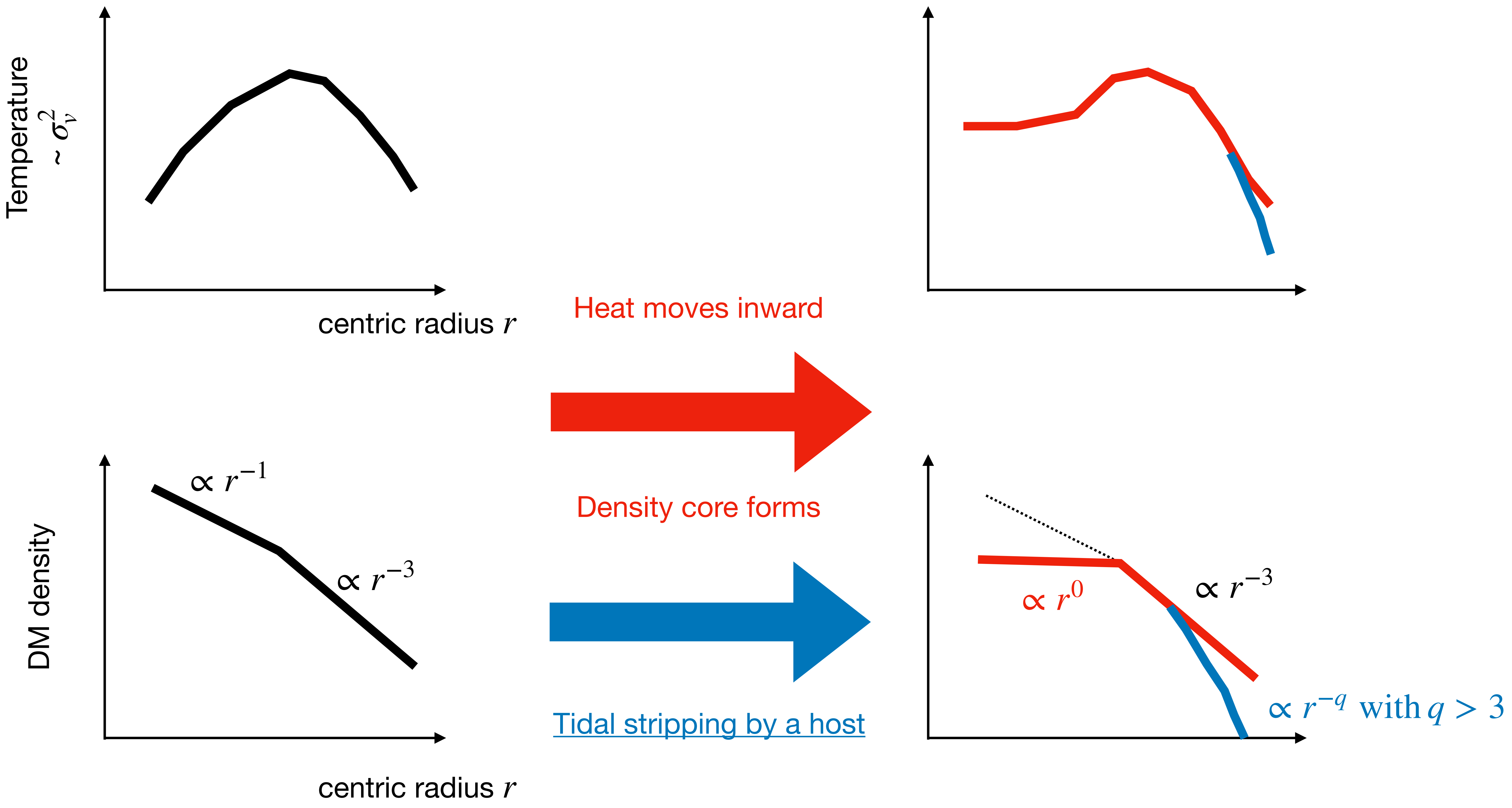
- Set the number of N-body particles to $(N_{\mathrm{host}}, N_{\mathrm{sat}}) = (10^7, 10^4)$
- N-body simulation code : GIZMO+ SIDM (Hopkins 2015)
- velocity independent, isotropic scattering with $\sigma/m\,(\mathrm{cm}^2/\mathrm{g}) = 0,1,3$
- Softening length = $0.05\,(N_{\mathrm{sat}}/10^5)^{-1/3}\,r_{s,\mathrm{sub}}$ (van den Bosch and Ogiya 2018)
- Maximum time step = 0.03 Gyr ~ 1% of the dynamical time for a MW-like halo
- 100 snapshots with the equal-space time interval until t < 10 Gyr
- Confirmed that our simulations provide converged results of subhalo profiles at $r > 0.3\,\mathrm{kpc}$ (equivalent to $r/r_{\mathrm{s,sub}} > 0.2$)

A schematic picture of time evolution of SIDM haloes



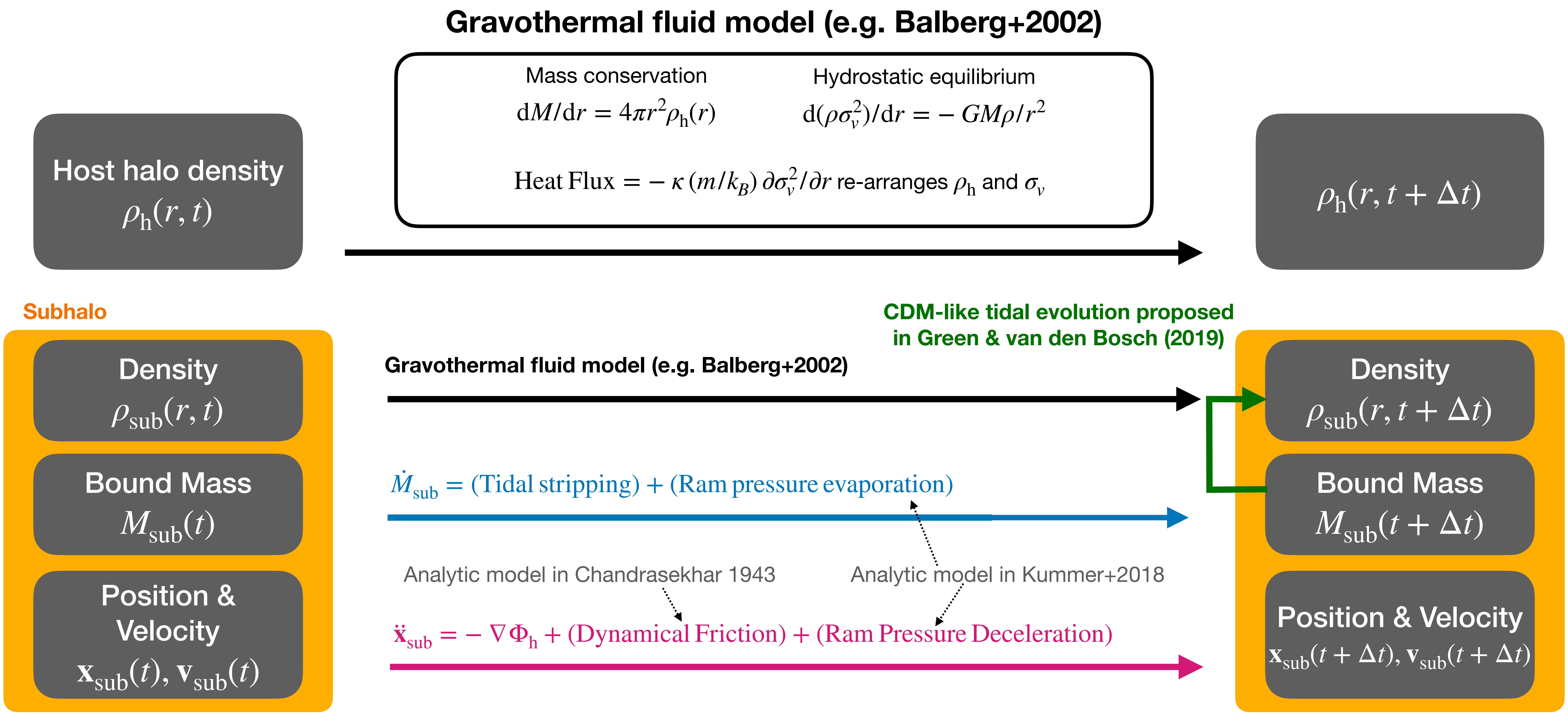
Initial state is assumed to be NFW

A schematic picture of time evolution of SIDM subhaloes



Initial state is assumed to be NFW

A brief summary of our model

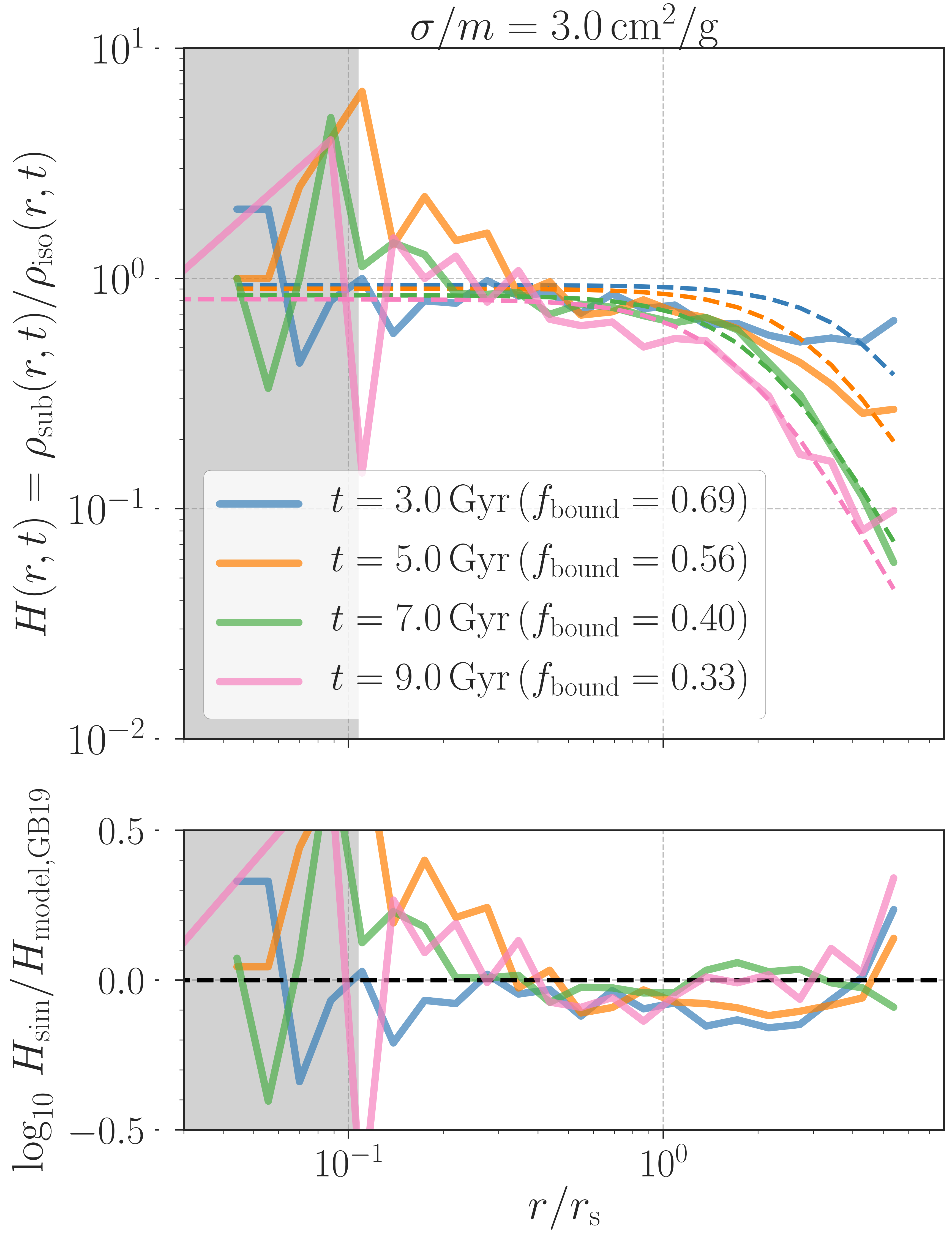


Note: We ignore possible changes of subhalo density profiles due to ram pressure effects

Test 1: CDM-like tidal stripping model can work or not

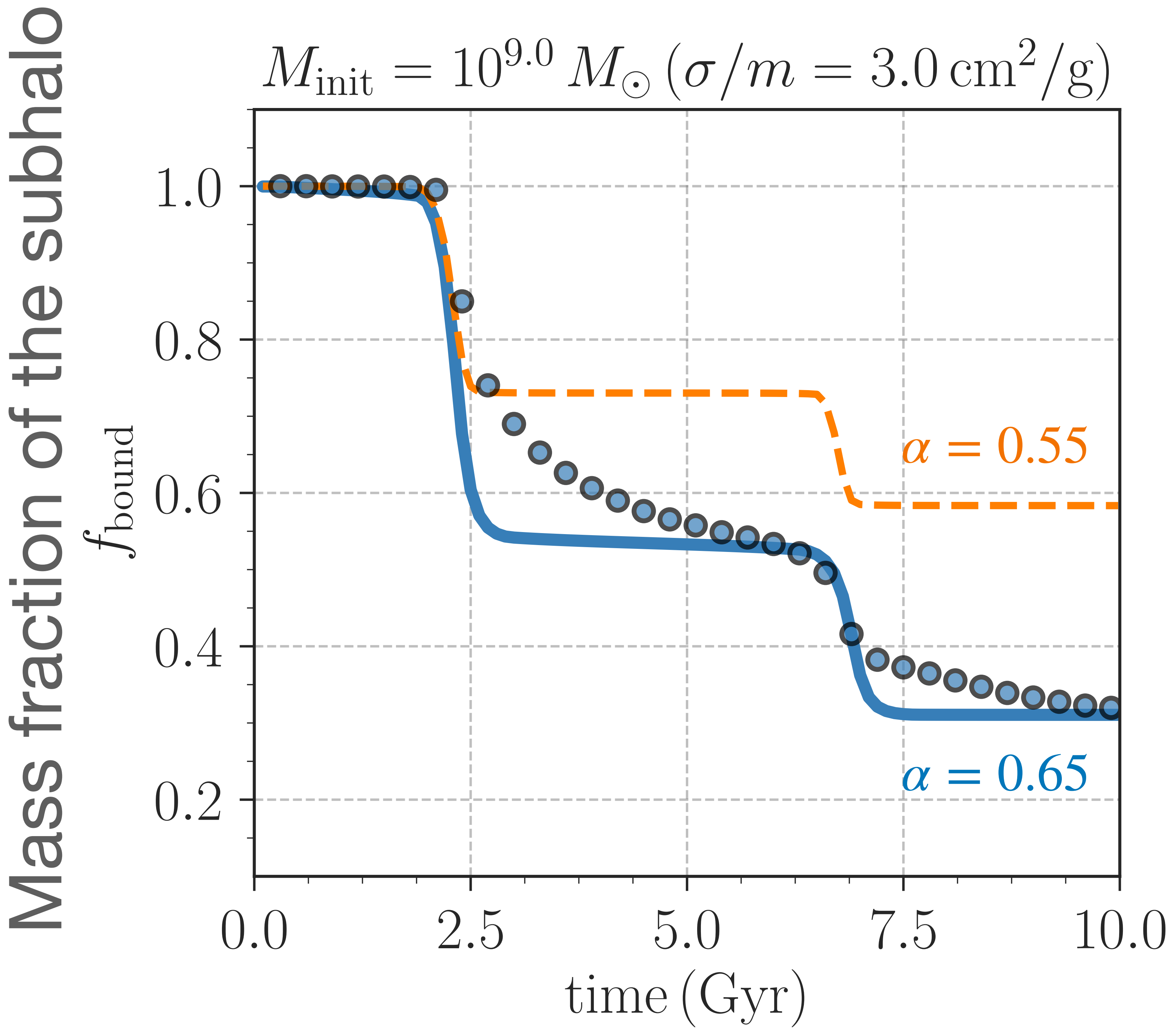
- Green and van den Bosch (2019) have found that the tidal stripping effect in CDM subhaloes can be expressed as
  - $\rho_{\rm sat}(r,t) = H_{\rm GB19}(r, f_b(t))\,\rho_{\rm NFW}(r)$

    Mass fraction of subhaloes at t
- In the SIDM case, we naively expect that
  - $\rho_{\rm SIDM,sat}(r,t) = H_{\rm GB19}(r, f_b(t))\,\rho_{\rm SIDM,iso}(r,t)$
- We evolved isolated haloes with the same mass as the subhalo at initial states and then compute
  - $H_{\rm sim}(r,t) = \dfrac{\rho_{\rm sat}(r,t)}{\rho_{\rm iso}(r,t)}$
- Confirmed $H_{\rm sim} \simeq H_{\rm GB19}$ in our simulations



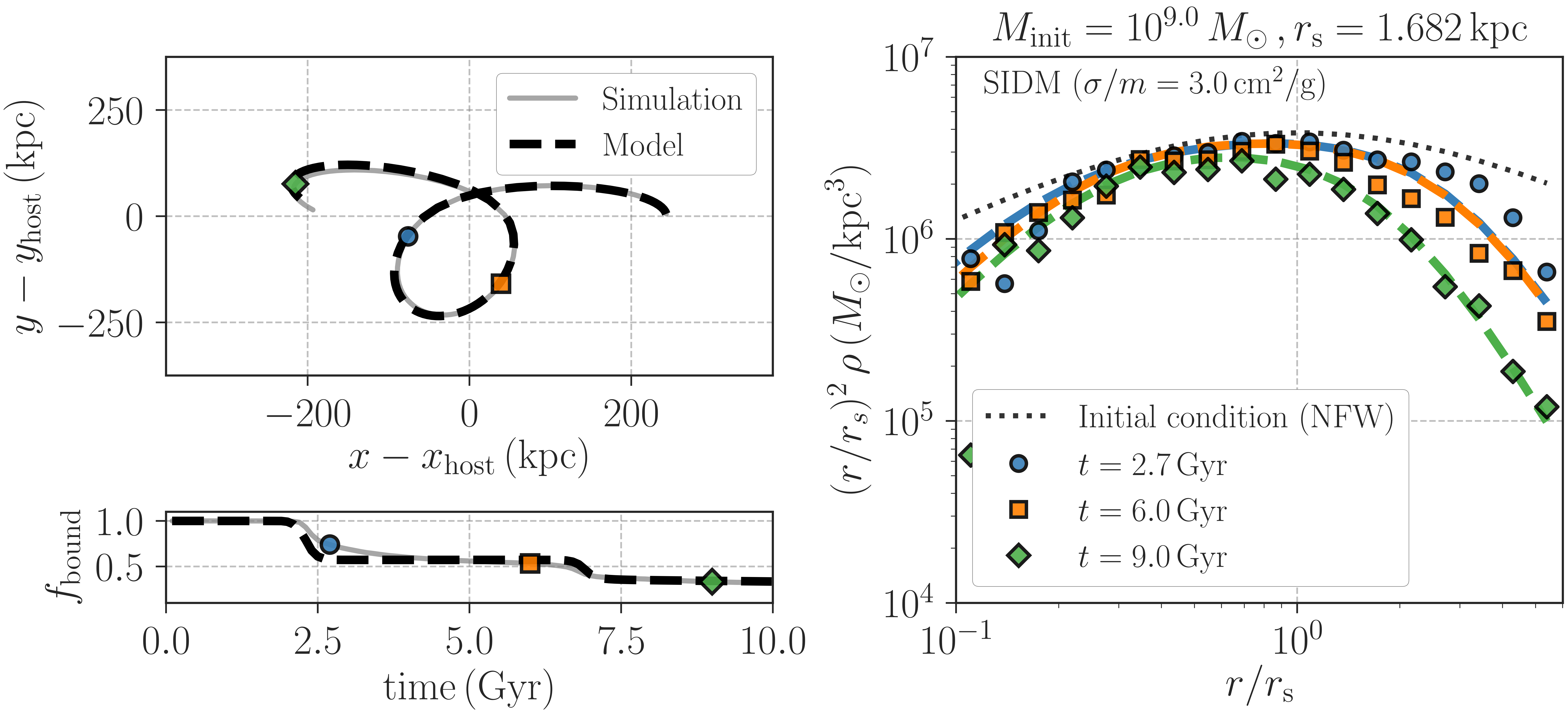
Test 2: Subhalo mass loss rate in SIDM

- The mass loss rate by tidal stripping effects is commonly modeled as
- $$\frac{\mathrm{d}M_{\mathrm{sub}}}{\mathrm{d}t} = -\alpha \frac{M_{\mathrm{sub}}(r > r_t, t)}{\tau_{\mathrm{dyn}}}$$
  tidal radius
  dynamical time
- $\alpha = 0.55$ can explain the CDM simulation results
- Our simulations indicate that α depends on σ/m
- Found that $\alpha \simeq 0.65$ provides a best fit to the simulation results with $\sigma/m = 3\,\mathrm{cm}^2/g$



Comparison with our model and simulations

$\sigma/m = 3\,\mathrm{cm}^2/\mathrm{g}$



Summary and outlook

- MW Satellites are powerful targets for constraining the nature of dark matter
- We developed a semi-analytic model of SIDM subhaloes in a MW-sized host with ideal N-body sims
    1. Found a non-trivial effect in the subhalo mass loss rate for the SIDM scenario
    2. Tested our models with sims in details by varying subhalo orbits, SIDM cross sections, initial subhalo profiles
- Next things to do:
    - Comparisons with our model and *cosmological* sims
    - Include the baryonic disc in a host halo