Distribution of Baryonic Matter in Dark Matter Halos: Effect of Dynamical Friction

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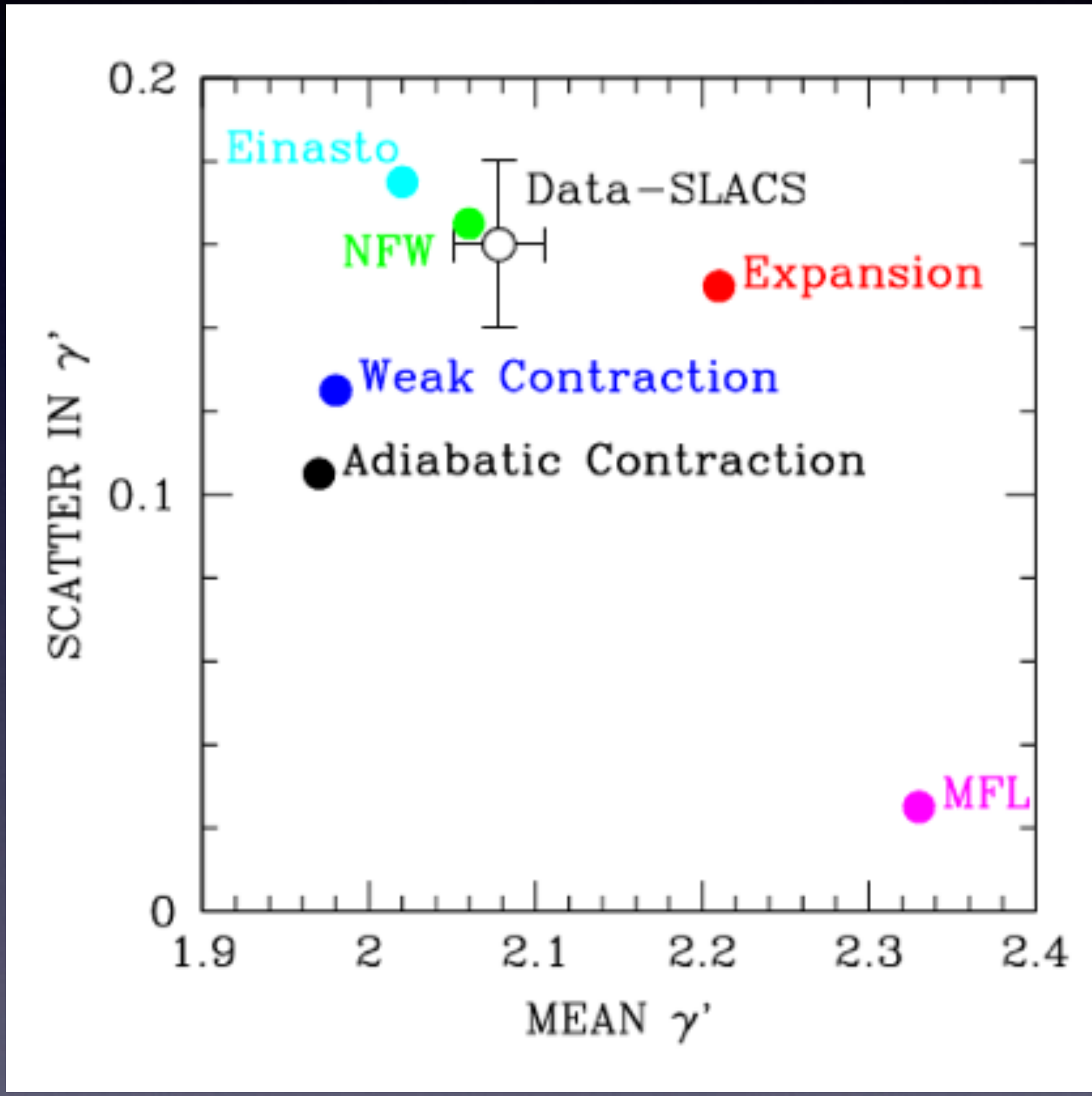
Issues

- The distribution of dark matter particles: NFW Profile (or some variation, Jing & Suto 2000, Mamon & Lokas 2005)
- Distribution of ‘Light” (baryons): Hubble, de Vaucouleurs or Sersic profiles
- Why the central parts of the galaxies are so distinct?
  - Origin of M_{BH}–M_{total} relation?

Dark matter and baryons

- Dark matter: collisions
- Baryons: dissipation
    - Contraction
    - Expansion
- Response of dark matter depends on baryonic process
- Here we consider dynamical friction on baryonic matter conglomerates by dark matter particles



Dutton & Treu (2014)

$$\gamma' = 3 - \frac{d\log M}{d\log r}$$

Assumptions

- Spherical systems
  - We do not consider disk galaxies
  - We do not consider rotation, but could be easily extended if the rotation is mild
- No velocity anisotropy
- Galaxies are composed of only two types of particles
  - Dark matter (m_{dm}, M_{dm})
  - Baryons, but in the form of massive conglomerates ($m_b \gg M_{sun}$, $M_b < M_{dm}$)
- Initially, these two components follow the same density profile of NFW.

Dominant Dynamical Processes

- Equilibrium distribution of dark matter particles would remain almost static since the relaxation time scale is extremely large
- Interaction between massive and less massive particles lead to dynamical friction.
  - Orbital decay and inspiral toward the central parts.
  - Redistribution of massive component
- Further collapse of the central core through gravothermal catastrophe

Time Scales

- Dynamical Friction ($m_{dm} << m_b$): Chandrasekhar’s formula

$$t_{fric} = \frac{1.17}{\ln\Lambda}\frac{r_i^2 v_c}{G m_b} = 2.6\times10^9\text{years}\left(\frac{10}{\ln\Lambda}\right)\left(\frac{r_i^2}{1\text{kpc}}\right)^2\left(\frac{v_c}{100\text{km/s}}\right)\left(\frac{10^6\text{M}_\odot}{m_b}\right)$$

(Binney & Tremaine 2008)

- Two-body Relaxation: could become important in the center.

$$t_{relax} = \frac{v^3}{8\pi G^2 m^2 n \ln\Lambda}$$

Numerical Method

- Isotropic Fokker-Planck Equation for self-gravitating system

$$4\pi^2 p(E)\frac{\partial f_i(E)}{\partial t} = -\frac{\partial}{\partial E}\left(-D_E f_i(E) - D_{EE}\frac{\partial f_i(E)}{\partial E}\right)$$

$$E = \frac{1}{2}v^2 + \phi(r)$$

$$\nabla^2\phi(r) = 4\pi G\rho(r)$$

- $f_i(E)$: Phase space distribution function of the i-th component
- $p(E)$, D_E, D_{EE}: statistical weight, first and second-order Fokker-Planck coefficients

Initial Models

- Navarro-Frenk-White Density Distribution (Lokas 2001)

$$\rho(r) = \frac{g(c)}{4\pi}\frac{1}{r(1+r^2)}$$

$$\phi(r) = -g(c)\frac{\ln(1+r)}{r}$$

$$g(c) = \frac{1}{\ln(1+c) - c/(1+c)}$$

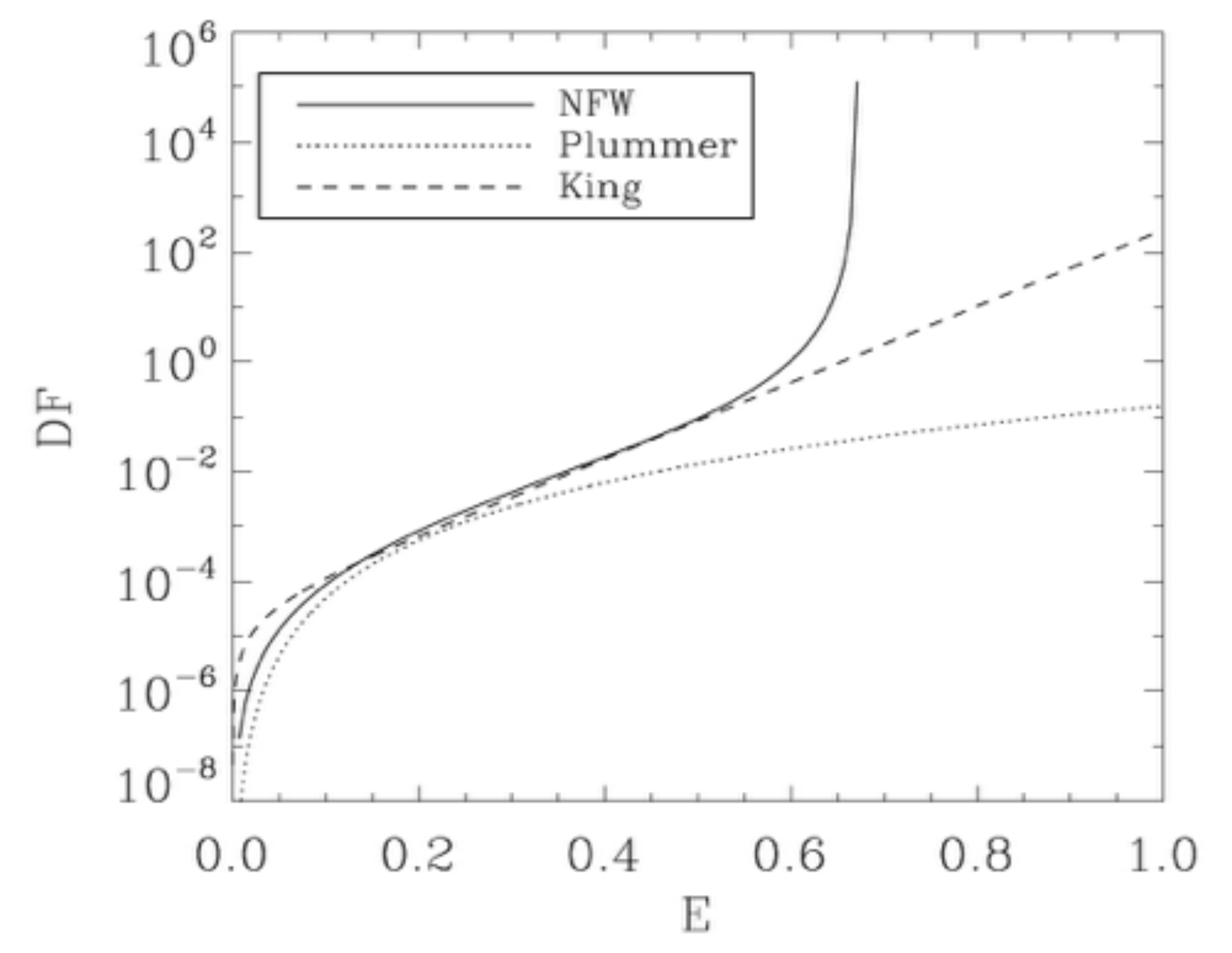
c: concentration parameter (~10 for bright galaxies, Lockas & Mamon 2001)

Density-Distribution Function Pair

- Eddington's Formula for isotropic distribution

$$f(\varepsilon) = \frac{1}{\sqrt{8}\pi^2} \frac{d}{d\varepsilon} \int_0^{\Psi} \frac{d\Psi}{\sqrt{\varepsilon - \Psi}} \frac{d\rho}{d\Psi}$$

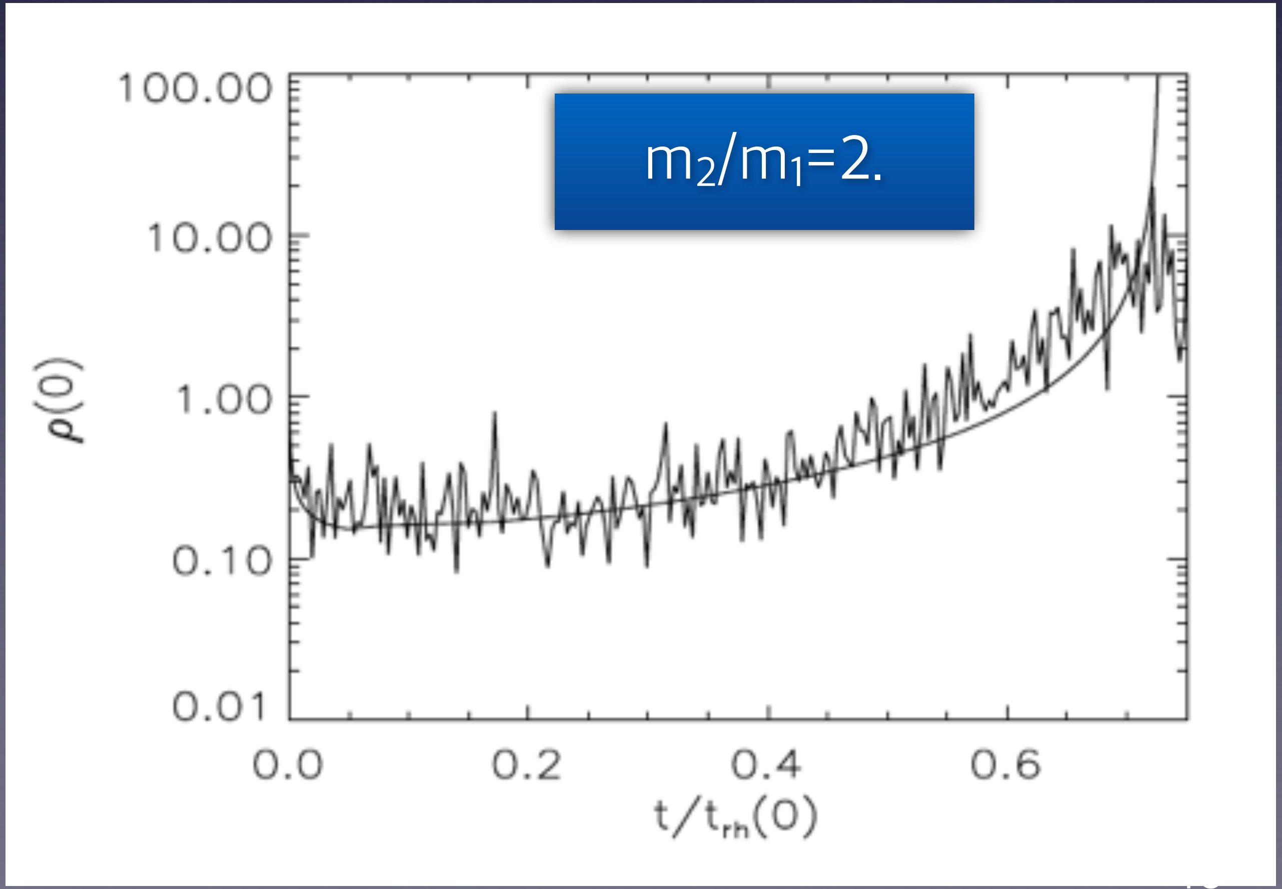
- Both dark matter and baryonic conglomerates are assumed to follow the same density distribution initially



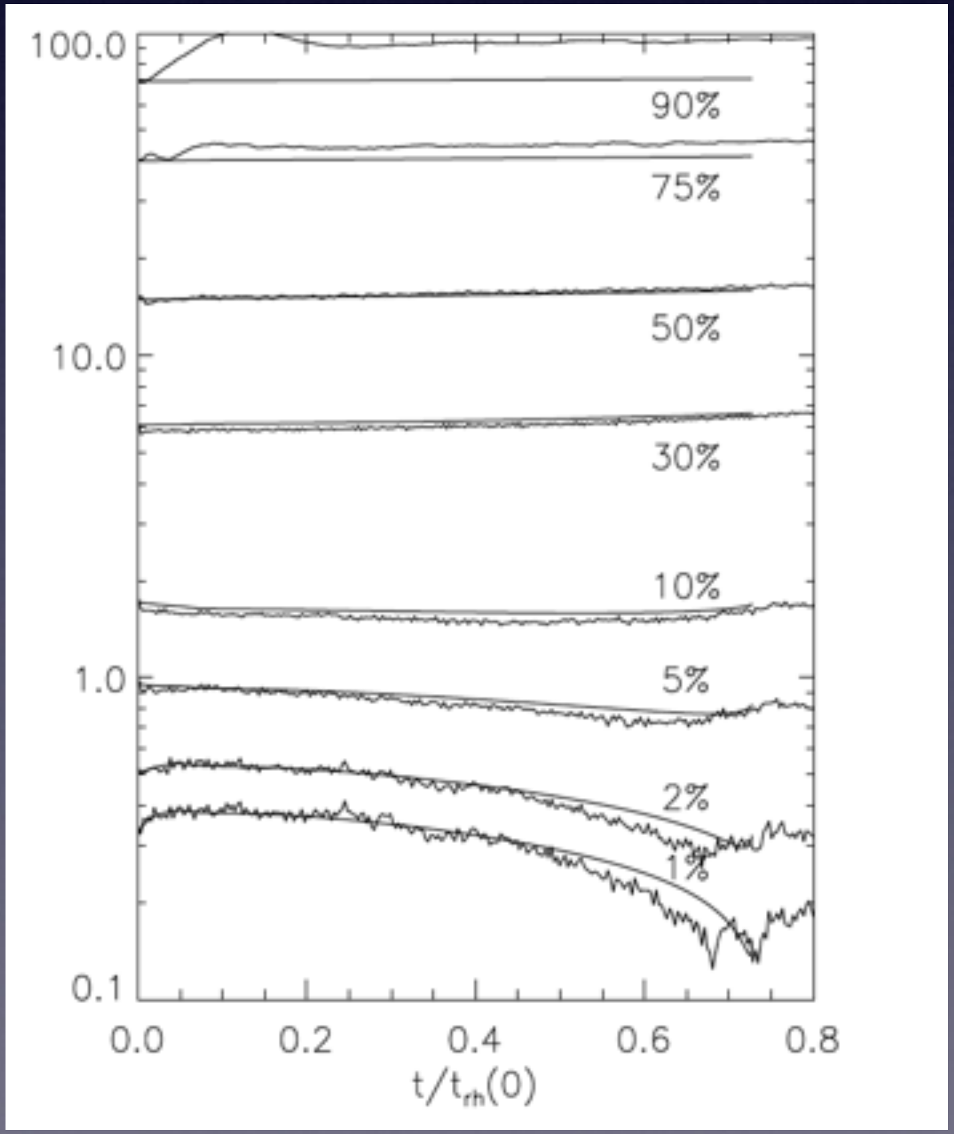
Test of Fokker-Planck against N-body

- F-P is known to work very well for initial models with flat core (i.e., King models, Plummer model, etc.)

- Since we applied F-P equation for cuspy initial models for the first time, we need to check against the N-body: good agreement with NBODY6

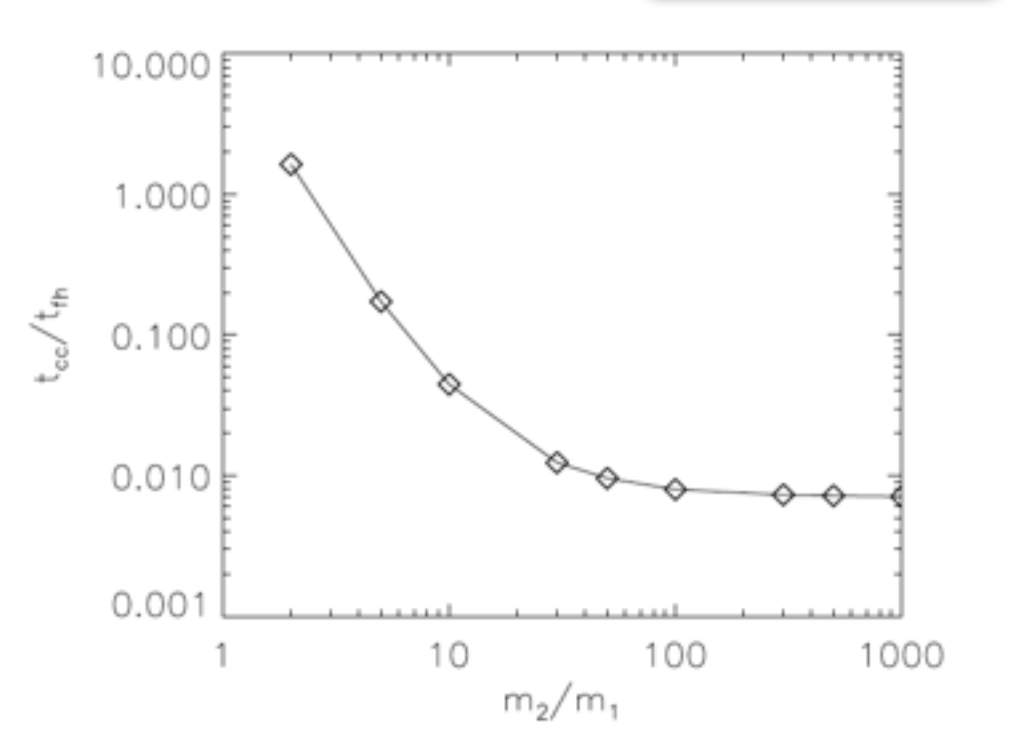


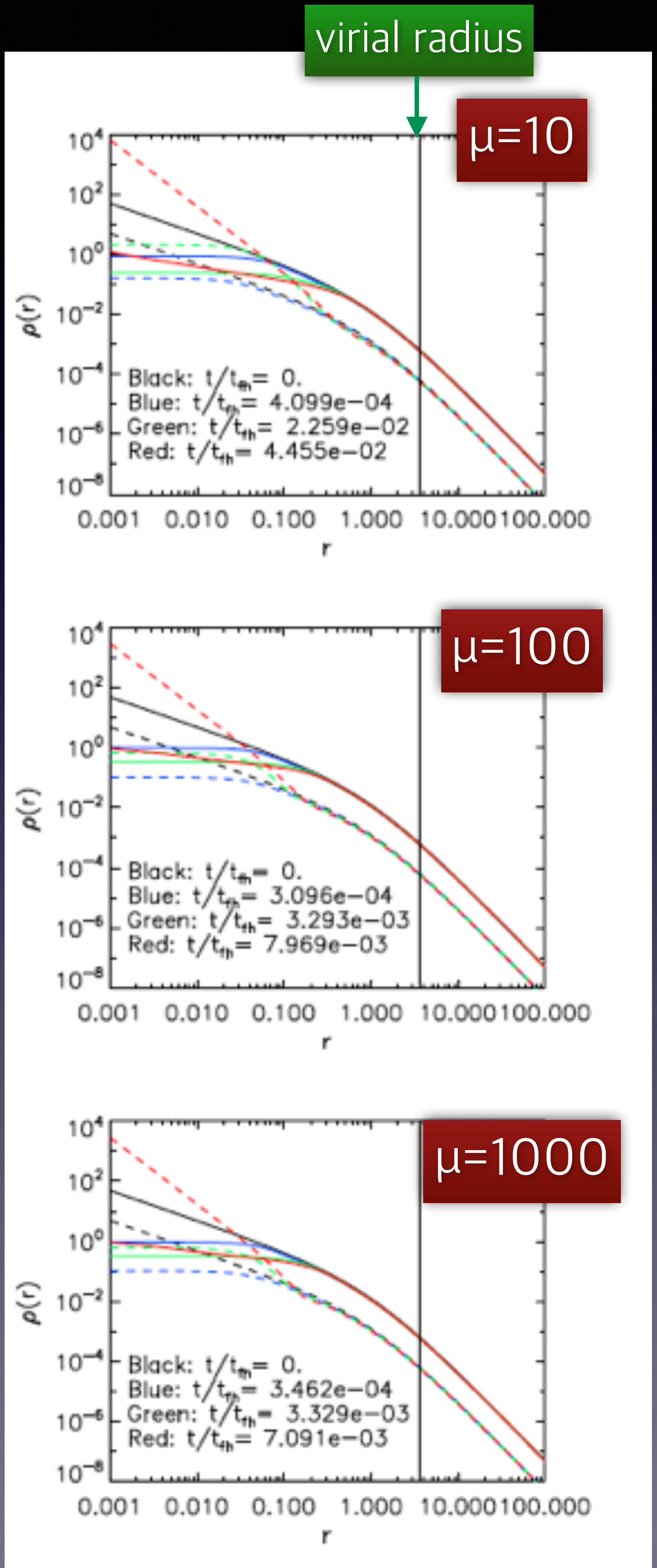
$m_2/m_1=2.$



Convergence Test

- The evolution depends on μ=m_b/m_{dm}.
- One cannot have arbitrarily large value for μ.
- The evolution, measured by ($t_{cc}/t_{fh} \rightarrow 7.1 \times 10^{-3}$) becomes independent of μ for large μ>1000. The distinct core develops in short time!


M_B/M_{tot} =0.1

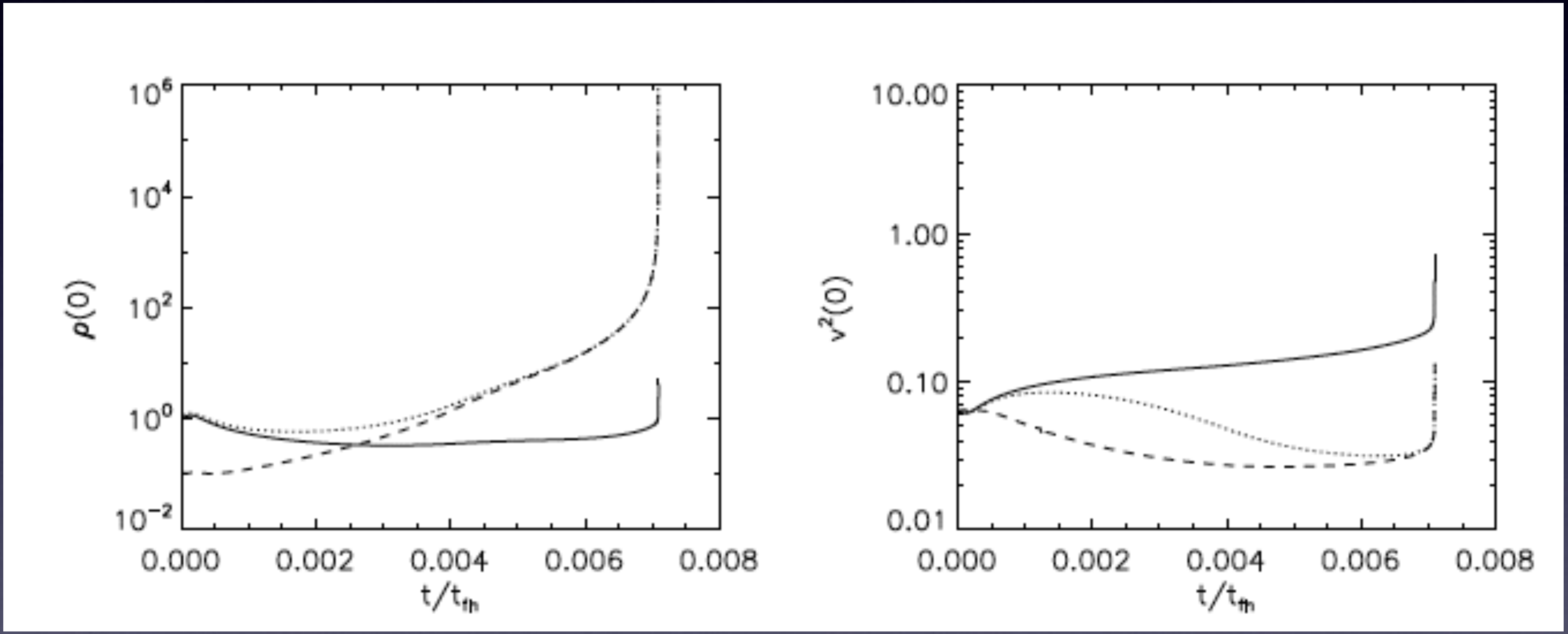

virial radius

μ=10

μ=100

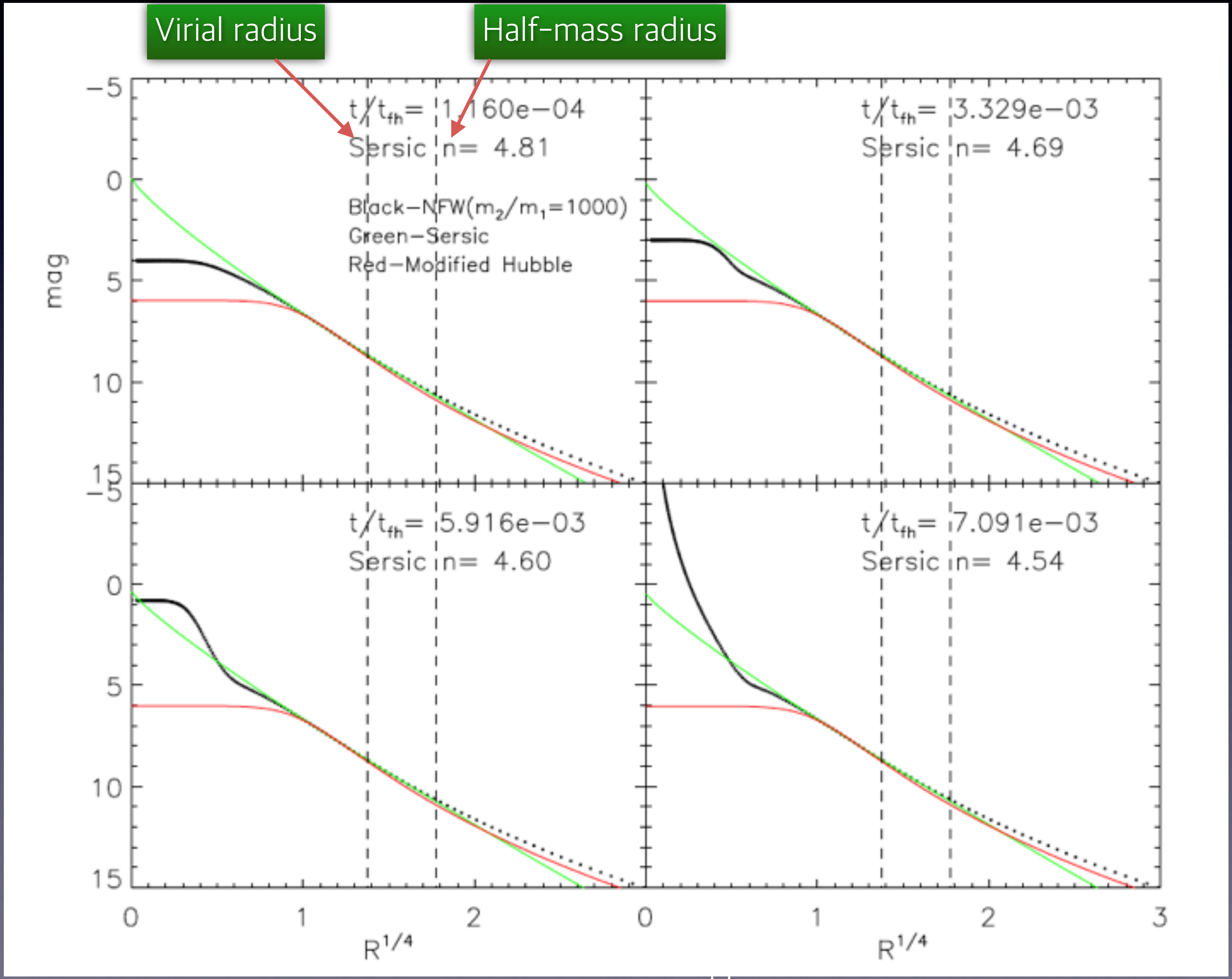
μ=1000

Evolution of the central density and velocity dispersion



solid: low mass (dark matter)
broken: (baryon)
dotted: total

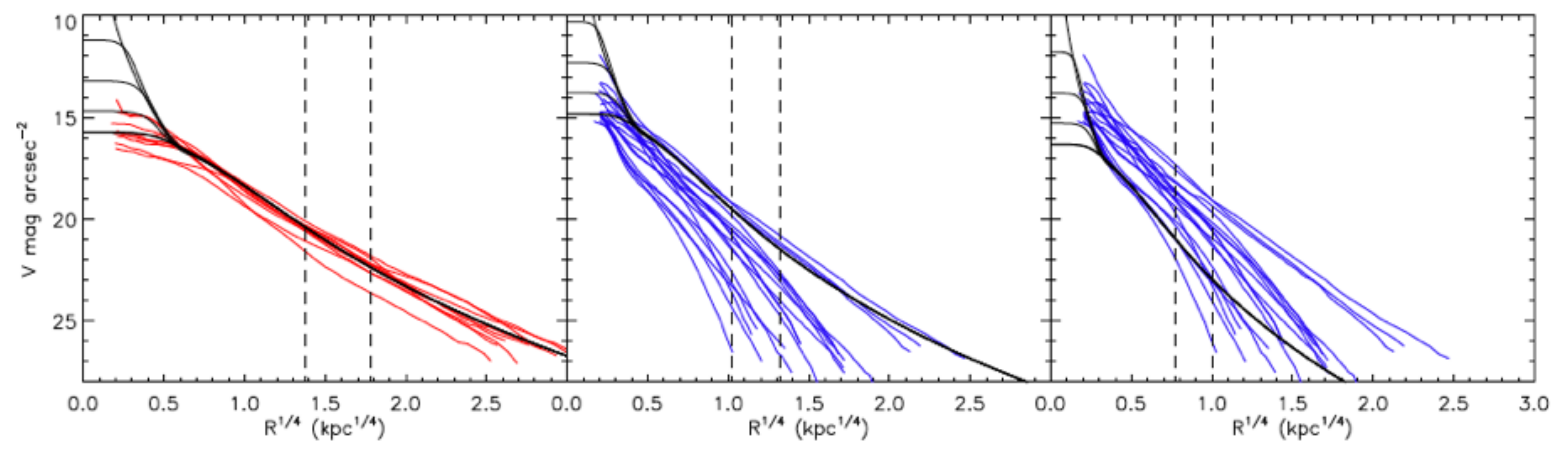
Density Profiles



Virial radius

Half-mass radius

Comparison with Observed Surface Brightness Distributions

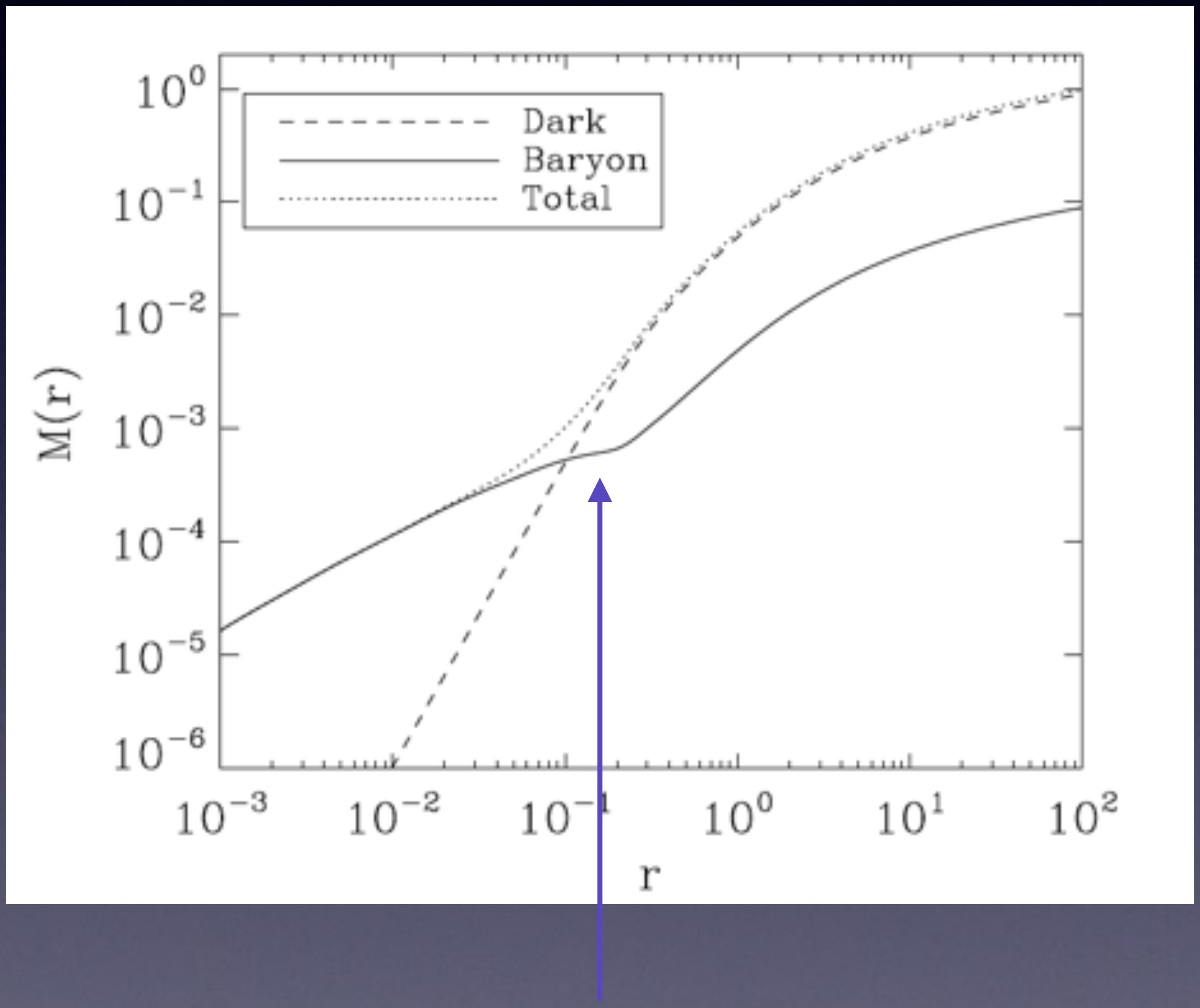


Red: Core elliptical galaxies
Blue: Coreless

Data: Kormendy et al. (2009)

Inner concentration of the baryonic matter

- Formation of distinctive core composed of baryonic conglomerate through the core collapse.
- Total mass in this central concentration typically becomes ~ a few 10^{-3} of the baryonic mass: close to SMBH?



Extent of Central Core

Limitations of the current calculations

- Initial models are limited to the NFW profile only. General results and trends would be independent of the initial profiles.

- No further evolution of after the core-collapse: extension is possible by artificially adding an energy source to stop the collapse

- Velocity distribution is isotropic. If substantial radial anisotropy among the baryonic conglomerates develops, the radial density profile could be modified

    - Core-Halo structure (Spitzer 1987)

$$\rho_{halo} \propto r^{-3.5}$$

Summary

- Dynamical friction could be effective if the early stars are preferentially formed in the form of massive clusters
- The centrally concentrated systems can form quite rapidly (~0.01 t_{fh})
- The radial velocity anisotropy could modify the density profile in the outer parts.
- Mild rotation could be easily be incorporated, but may not change the results significantly.