Supermassive Black Holes and their Environment

A numerical Challenge

PhD Halftime Review
Marcel Zemp
ETH Astro Lunch
26. November 2004

Content

- Introduction
- Technical Problems
  Spatial Resolution
  Time Steps
- Outlook

Introduction

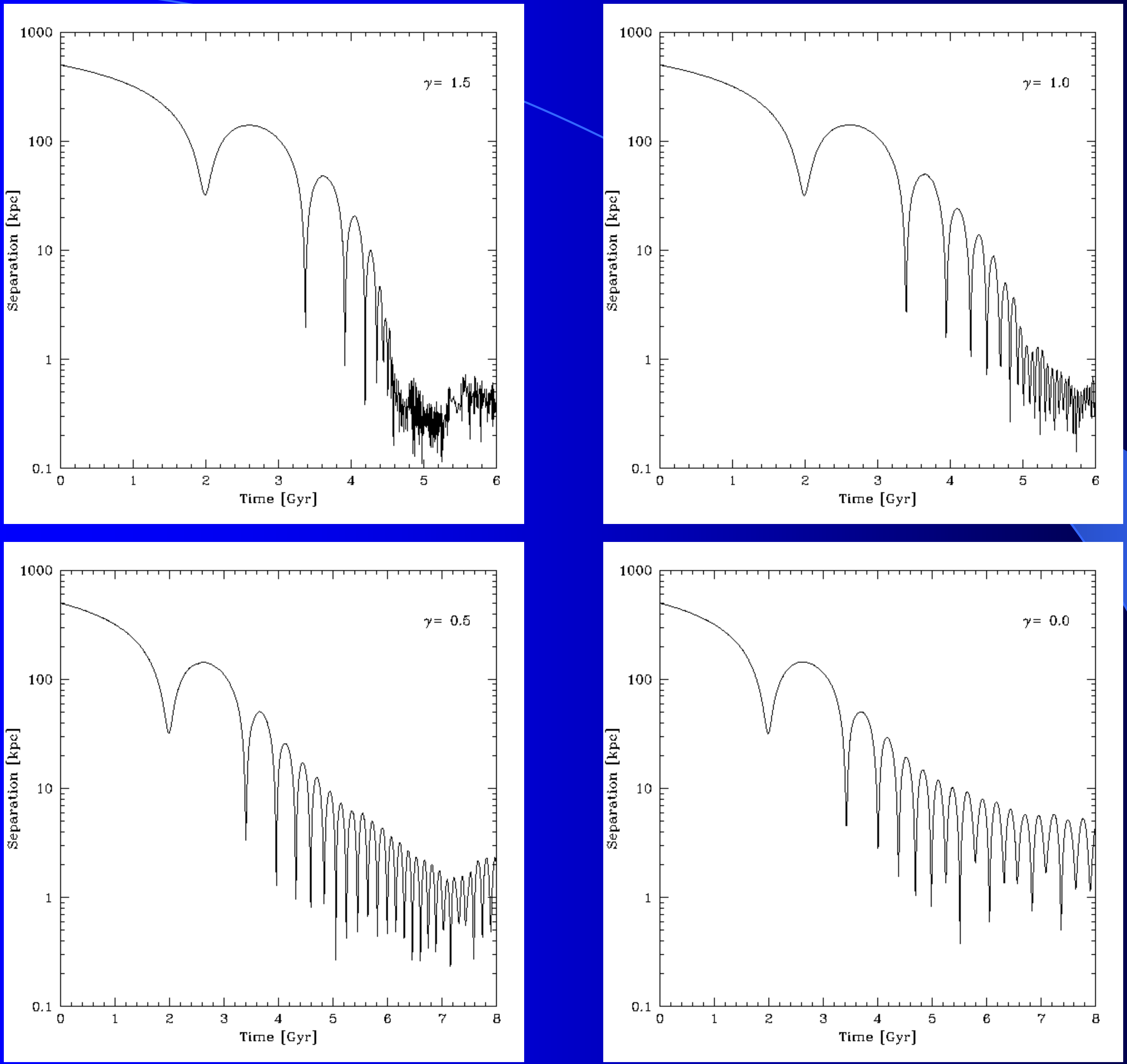
- SBHs with masses from 10^6 – $10^{9.5}$ $M_\odot$ are omnipresent in galactic nuclei
- Current paradigm of galaxy formation: larger galaxies grow through mergers with other galaxies

3 Phases Scenario of BH evolution

- Dynamical friction
- Gravitational slingshot interactions
- Gravitational radiation

1. Phase: Dynamical Friction

- BHs sink to the center until they form a binary
- Dynamical friction time depends strongly on profile


γ= 1.5
γ= 1.0
γ= 0.5
γ= 0.0
Separation [kpc]
Time [Gyr]
1000
100
10
1
0.1

2. Phase: Graviatational slingshot interactions

- When BH binary becomes hard

$\Rightarrow$ strong interactions with surrounding particles

$\Rightarrow$ slingshot effect!

$\Rightarrow$ particles ejected with $\approx v_{binary}$

What is a hard BH binary?

Kepler Orbit $\Rightarrow$ Binding energy E_B

$$E_B = G\frac{m_1 m_2}{2a} = G\frac{\mu M_{12}}{2a}$$

Hard binary $\equiv E_B/M_{12} \approx \sigma^2(r)$

$$a_h \equiv \frac{G\mu}{4\sigma^2(r)} \quad \text{or} \quad a_h \equiv \frac{GM_{12}}{8\sigma^2(r)}$$

Example: Milky Way

- $M_{BH} \approx 3\times10^6\ M_\odot$
- Dark Matter Halo / NFW Profile
  $M_{Halo} \approx 10^{12}\ M_\odot$ / spherical / isotropic
- Spherical Jeans equation $\Rightarrow \sigma(r)$

$$\Rightarrow a_h \approx 10 - 15 \text{ pc}$$

3. Phase: Gravitational radiation

- If the BH separation shrinks enough
  $\Rightarrow$ Emission of gravitational radiation

- Coalescence in Hubble time 10^{10} yr

$$\Rightarrow a_{gr} \approx 0.05 - 0.15\ a_h$$

Scenario

- What happens if you merge two galaxies like the Milky Way?
- Spacial scales

  Virial Radius $r_{vir} \approx 300$ kpc

  Scale Radius $r_s \approx 30$ kpc

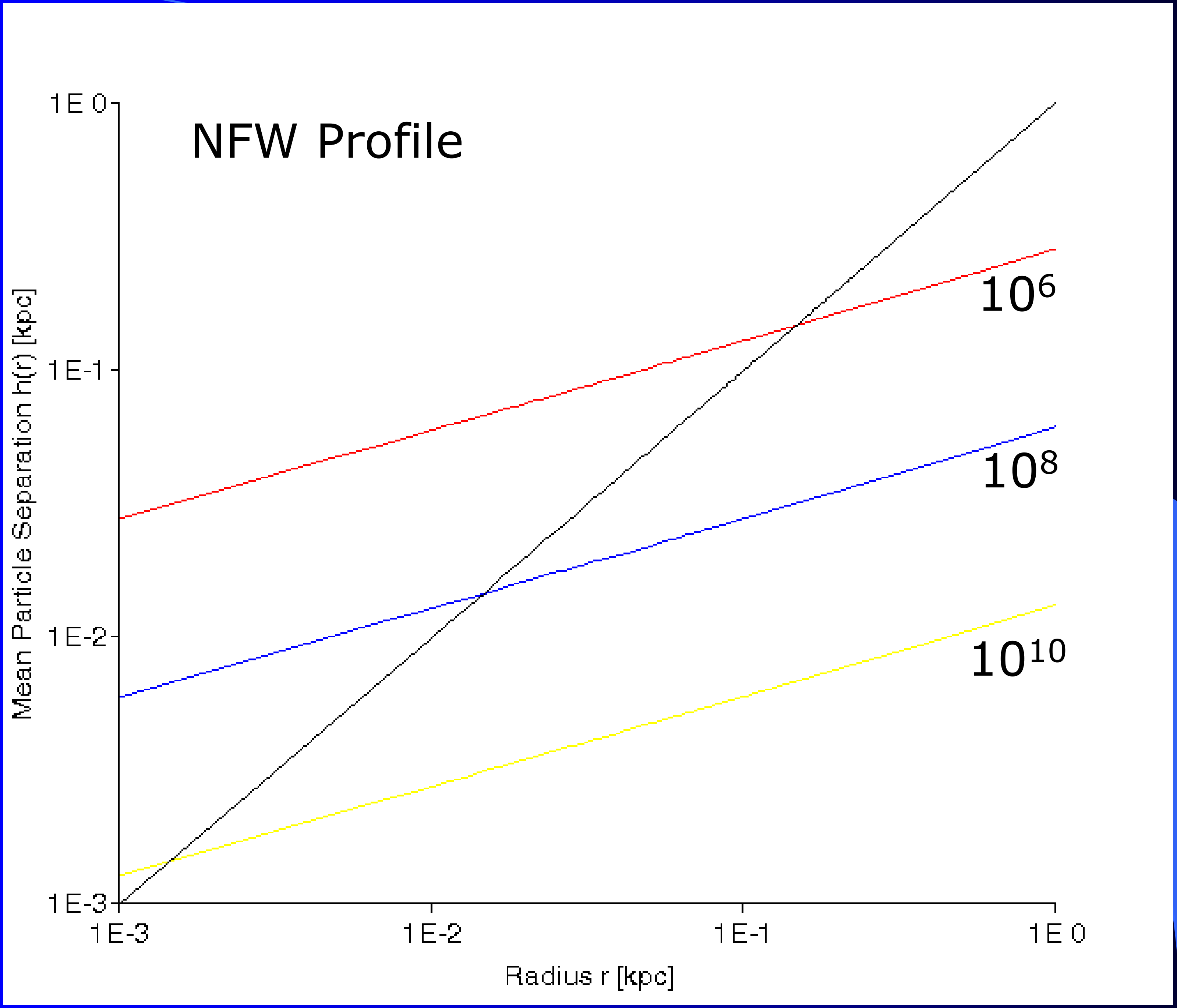
  Hard Binary $a_h \approx 10$ pc

  GR $a_{gr} \approx 1$ pc
- 300 kpc / 1 pc $\approx 10^{5.5}$!

Spatial Resolution

- How many particles do you need in order to resolve a spatial scale of $10^{5.5}$?
- Mean particle separation

$$h(r) \equiv \left(\frac{M/N}{\rho(r)} \right)^{1/3}$$



NFW Profile
10^6
10^8
10^10
1E 0
1E-1
1E-2
1E-3
Mean Particle Separation h(r) [kpc]
1E-3
1E-2
1E-1
1E 0
Radius r [kpc]

Use shells with different mass resolution!!

Shell Model Halos

- Halo is represented by shells with different particle masses

$\Rightarrow$ light particles in the center

$\Rightarrow$ heavy particles in the outskirts

Possible Problems

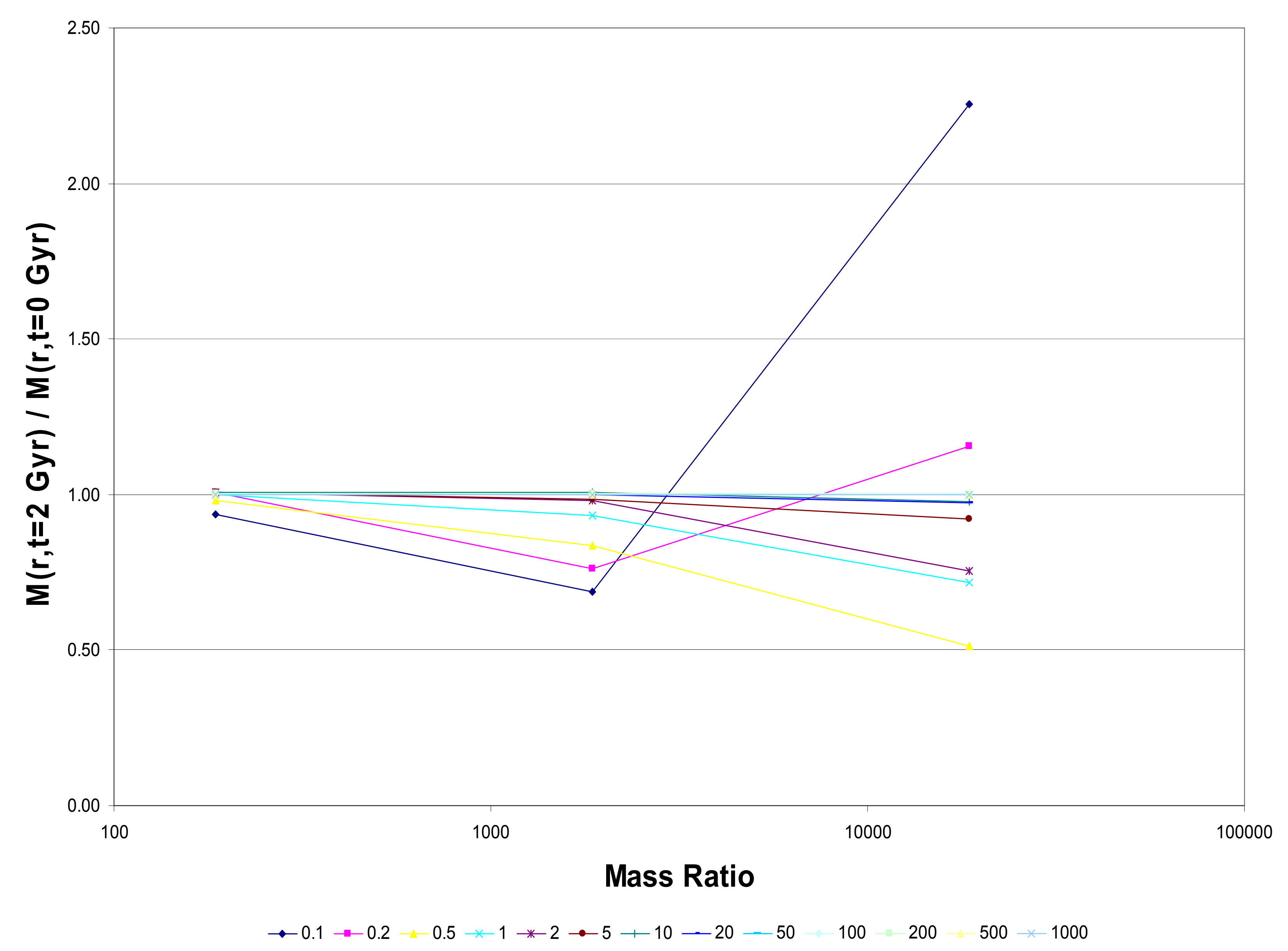
- Heating
  The heavy particles will heat the light ones!

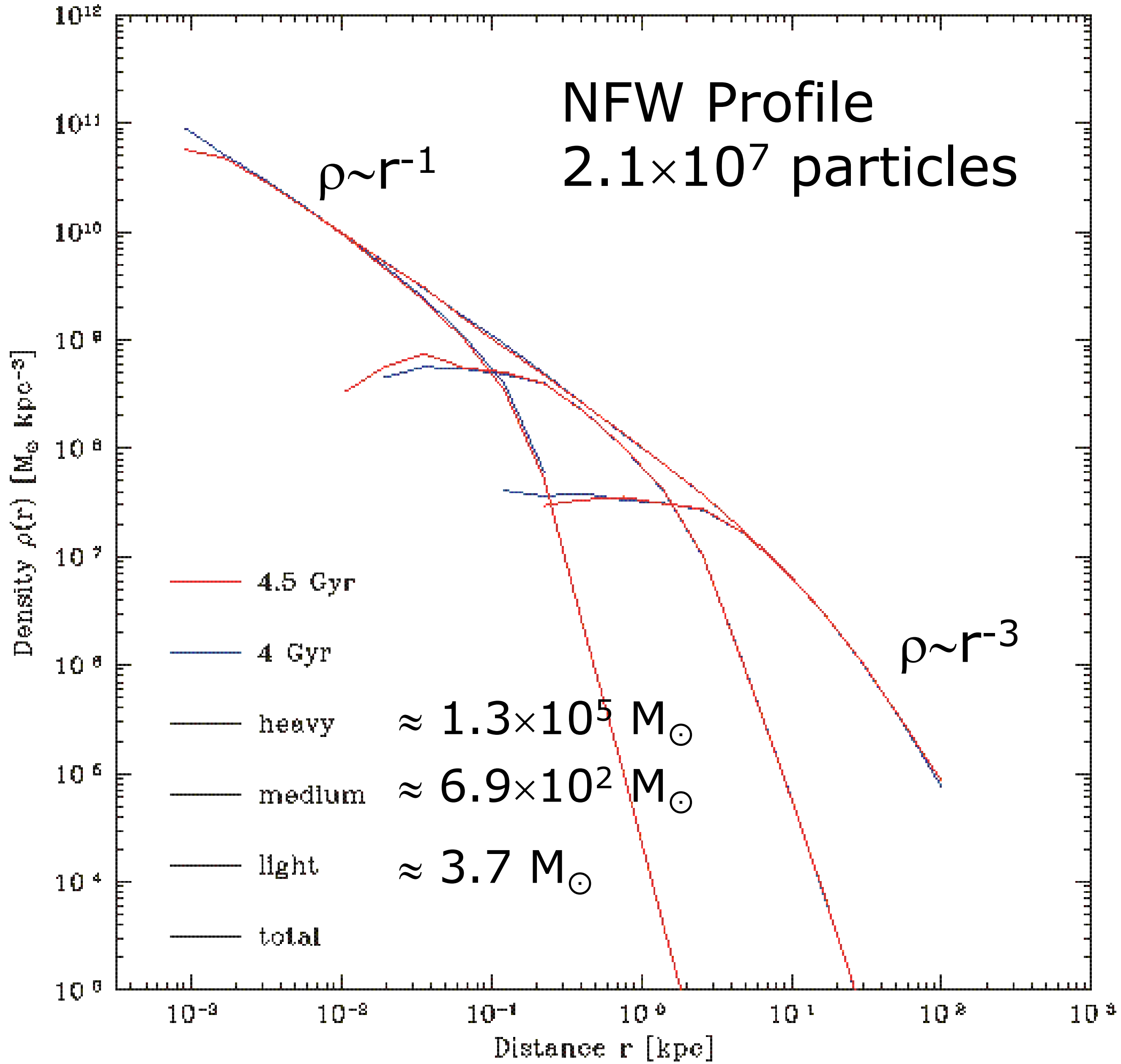
- Mass segregation
  The heavy particles will sink to the center!

Solutions

- Heating
  Do not choose too big mass ratios!

- Mass segregation
  Choose a good softening!


2.50
2.00
1.50
1.00
0.50
0.00
M(r,t=2 Gyr) / M(r,t=0 Gyr)
100
1000
10000
100000
Mass Ratio
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1000



NFW Profile
2.1×10^7 particles
$\rho\sim r^{-1}$
$\rho\sim r^{-3}$
4.5 Gyr
4 Gyr
heavy $\approx 1.3\times10^5\ M_\odot$
medium $\approx 6.9\times10^2\ M_\odot$
light $\approx 3.7\ M_\odot$
total
Density $\rho(r)$ $[M_\odot\ kpc^{-3}]$
Distance r [kpc]

Time Steps

- PKDGRAV is a Treecode that allows adaptive time steps for each particle

$$T_i = \frac{\Delta T}{2^{n_i}}$$

- How does one choose T_i?

The local dynamical time!

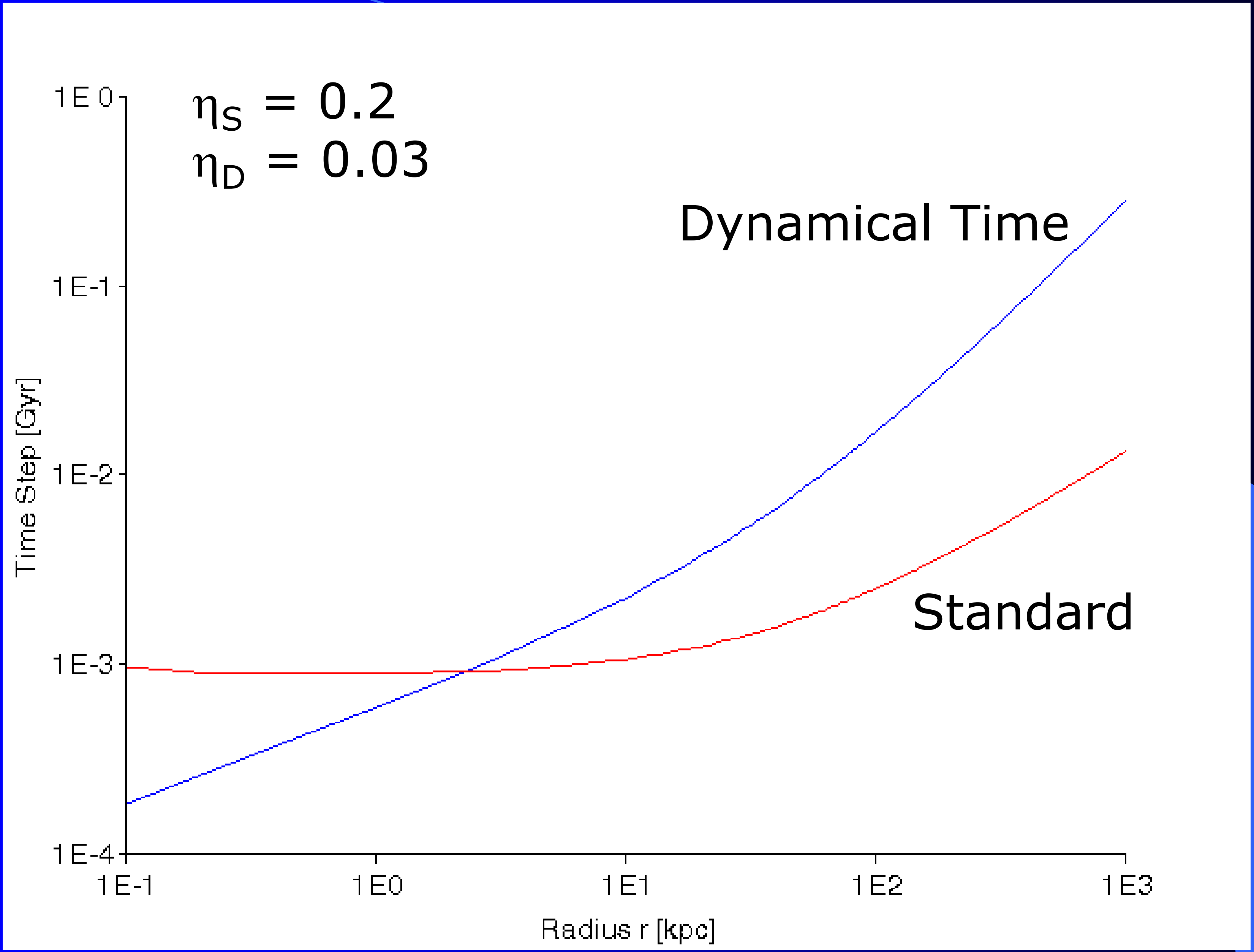
Dynamical Time

- Local dynamical time

$$T_{dyn}(r) = \frac{\alpha}{\sqrt{G\rho_{enc}(r)}}$$

with $\rho_{enc}(r) \equiv M(r)/r^3$

$$\Rightarrow T_i \leq \eta_D \, {}^{1}\!\Big/\!\sqrt{G\rho_{enc}(r)}$$



ηS = 0.2
ηD = 0.03
Dynamical Time
Standard
1E 0
1E-1
1E-2
1E-3
1E-4
Time Step [Gyr]
1E-1
1E0
1E1
1E2
1E3
Radius r [kpc]

Collisions

- We also want to treat the interactions of the particles with the BH in a collisional regime

  $\Rightarrow$ new timestepping criterion is ideal for that!

Problem

- Particles are distributed over an enormous range in time steps!

  Time step range: 1-10^8 yrs

  $\Rightarrow$ Simulations are very slow!

Outlook

- Influence of BH binary dynamics on environment (core formation)
- Study the properties of the ejected particles
- Growth of BH via accretion of dark matter
- Origin of M_{BH}-σ relation