Evolution of SMBH-SMBH and SMBH-IMBH Binaries: Effect of Large Mass Ratio

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Main points

If we consider stellar dynamics only (no gas),

- **SMBH-SMBH binary would not merge**
- **SMBH-IMBH binary (or MBH binary with large mass ratio) do merge**

Talk structure

1. **SMBH-SMBH binary**
    - **Summary recent results**
2. **SMBH-IMBH binary**
    - **Why we consider SMBH-IMBH binary**
    - **Simulation result**
3. **Summary**

SMBH-SMBH binary

Many more talks on this subject...

- **Formed by merger of two galaxies with SMBHs**
- **“Last parsec problem”**

Last parsec problem

- (If there is not much gas) BHB evolves (hardens) through interaction with nearby stars.
- As it hardens, it becomes more compact and number of stars that can interact with BHB becomes smaller.
- At some point, BHB would kick out all stars it can interact (loss-cone depletion) , and stars will be only slowly supplied through two-body relaxation.
- Orbital evolution becomes very slow.

This problem has been known for many years (e.g., Begelman, Blandford and Rees 1980).

N-body simulations on loss-cone depletion

Theoretical prediction: growth timescale $\sim$ relaxation time $\sim N$ (number of particles)

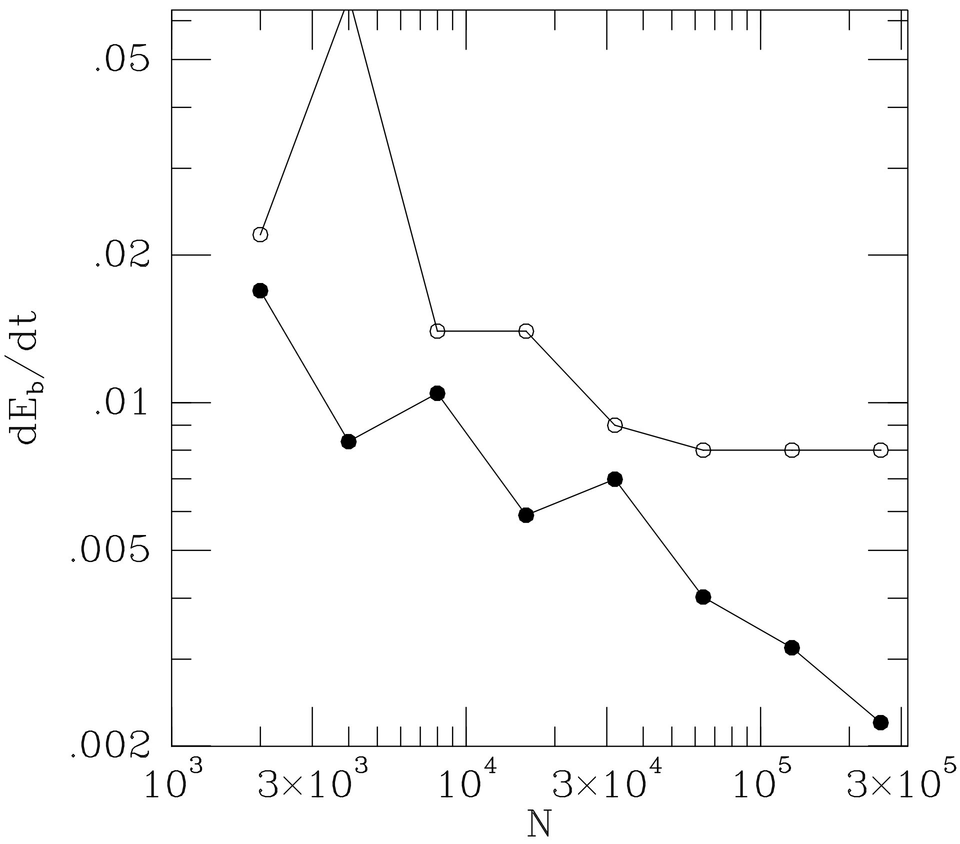
- **Before 2003 — Total Confusion**
- **After 2003 — Begin to converge (but...)**

Before 2003

- JM 1997
- Quinlan 1997
- Milosavljević & Merritt 2001 (also 2003)
- Chatterjee, Hernquist & Loeb 2003

Results are not quite consistent with each other or with the loss-cone argument.

JM 1997 — Hardening rate



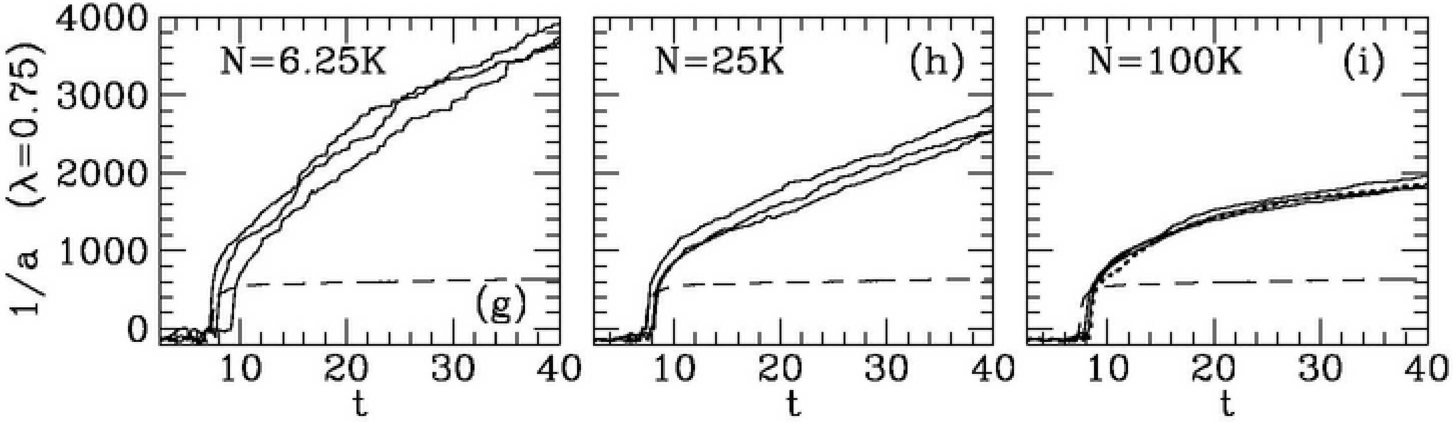
N up to 256K

Upper: $E_b \sim 1/160$
Lower: $E_b \sim 1/10$

Late phase: Slope depends on N, but too weak (around $-1/3$)

Not consistent with thermal relaxation argument

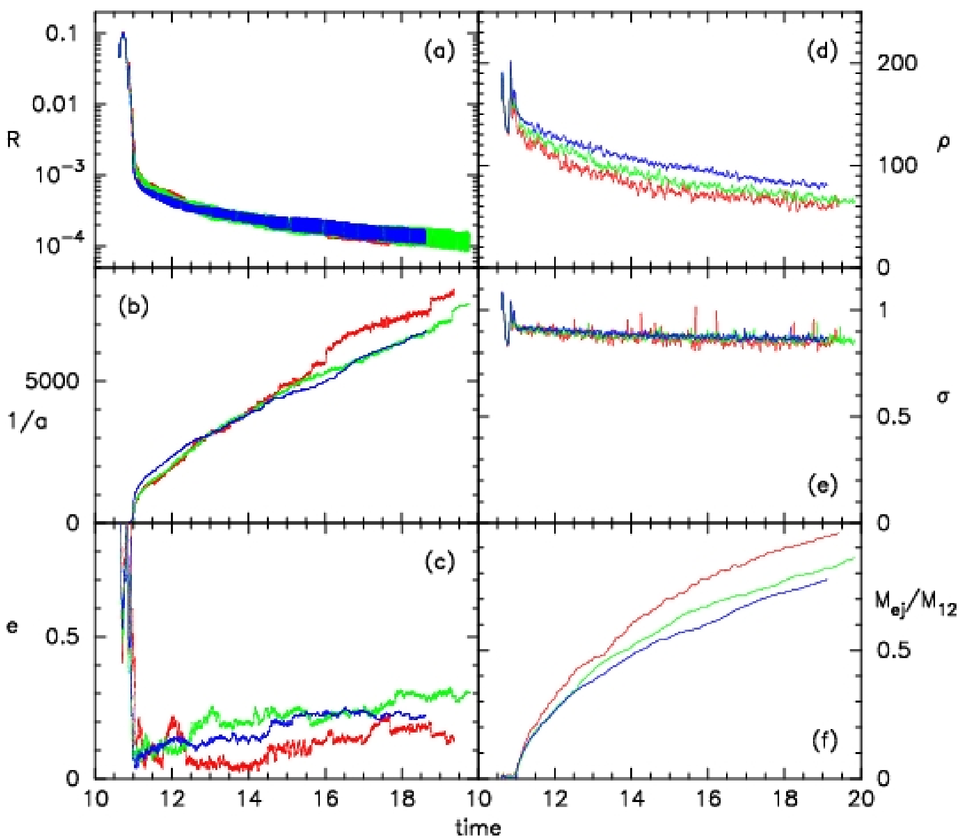
Quinlan 1997



N up to 200K (One of the curves in "N=100K" panel is for N=200K)

Hardening rate **independent of N for $N > 100K$**

Milosavljević & Merritt 2001



***N* up to 32k**
Hardening rate independent of *N*

Argued that they could not see *N* dependence because *N* was too small (quite reasonable).

The state of the art in 2003

No agreement at all...

- $N \leq 256\mathrm{K}$
- **No agreement between different people.**
- **No result consistent with the loss cone depletion argument.**

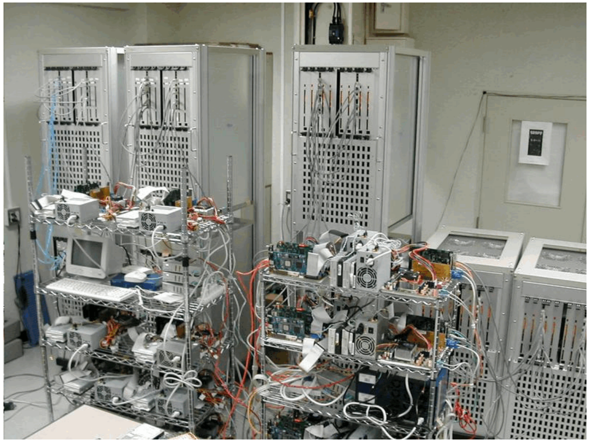
"numerical N-body experiments are not well suited to probe these mechanisms over long times due to spurious relaxation."
(Milosavljvić and Merritt 2003)

GRAPE-6

- **Special-purpose computer for Gravitational N-body problem**
- **Completed in 2002**
- **32Gflops, 10W/chip**
- **Largest configuration 64 Tflops (2048 chips)**
- **Many copies have been built and used at more than 30 institutes**
- **Made direct simulations with $\geq 10^6$ particles practical**

Some of largest GRAPE-6 setups

Tokyo (64TF)



Heidelberg (4TF)

Rochester (4TF)

Tsukuba (8+30TF)

GRAPE-DR — Next generation

5-year grant FY2004-2008, 2-Petaflops peak

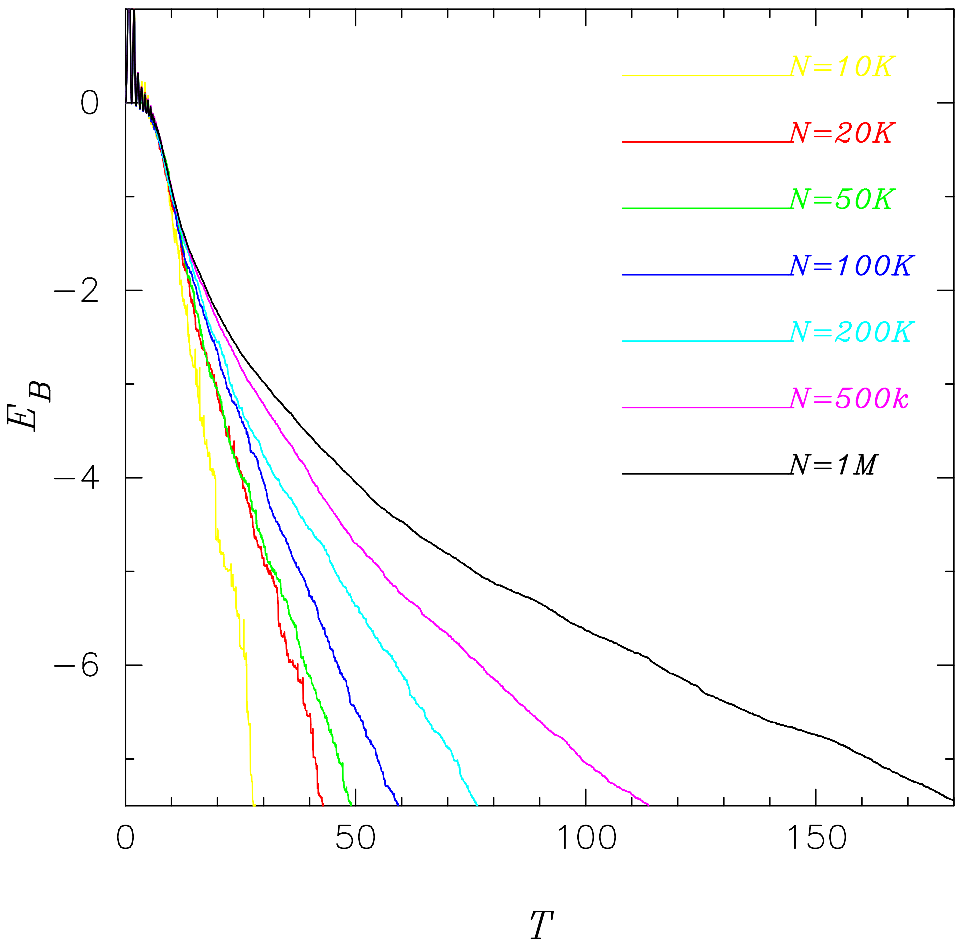
First sample chip and board arrived May 2006

Currently being tested (no serious error found yet)

New simulations

- **JM and Funato 2004**
- **Berczik, Merritt, and Spurzem 2005**

JM and Funato 2004

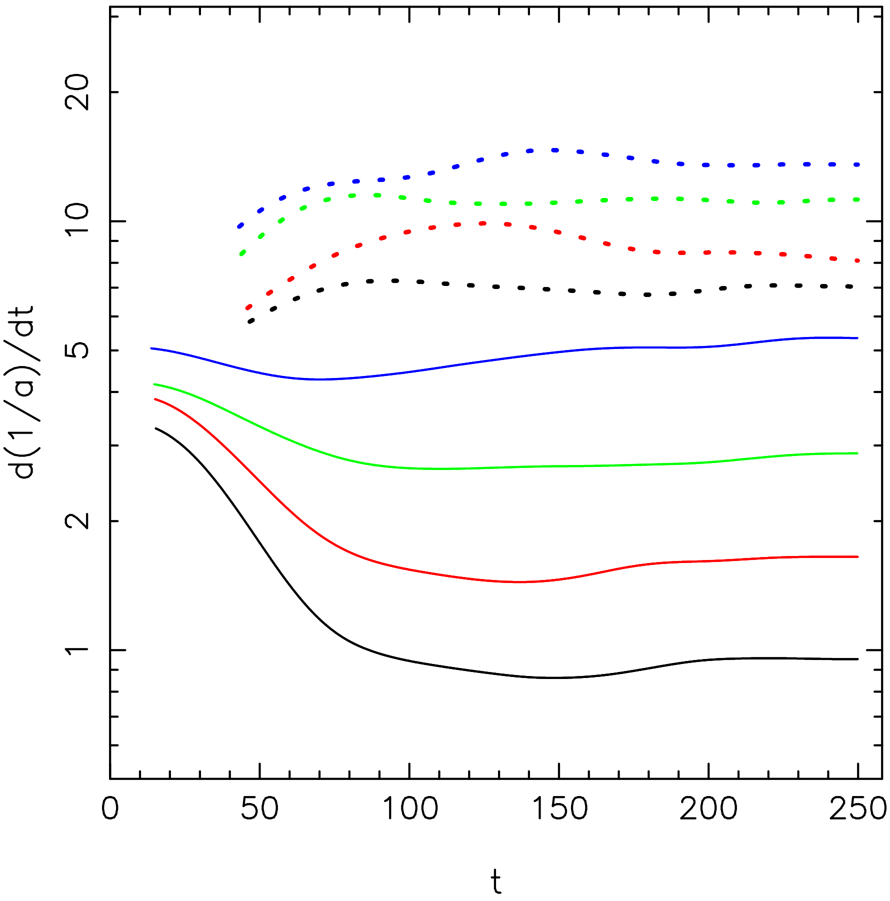


N up to 1M.
Hardening rate β depends on N.

If we write $\beta \propto N^{-\gamma}$, γ approaching to 1 for late phase

Not inconsistent with asymptotic value being 1.

Berczik et al 2005



N up to 0.4M

Simulation significantly longer than JM and F 2004.

N dependence

$\sim N^{0.8}$ ($M_{bh} = 0.02$)

$\sim N^{0.33}$??

($M_{bh} = 0.005$)

Summary of BHB N-body simulations

- N much larger than old simulations
- Duration also longer
- Growth rate shows clear dependence on N
- Results not converged yet...
- "Last parsec problem" is there.

SMBH-IMBH binary

- **IMBHs might exist in some young and compact clusters (Matsumoto et al. 2001, Kaaret et al 2001)**
- **They might exist near Galactic center (IRS13E, Maillard et al. 2004)**

Much controversy on both topics...

Evolution of SMBH-IMBH binary

SMBH potential dominates over background.

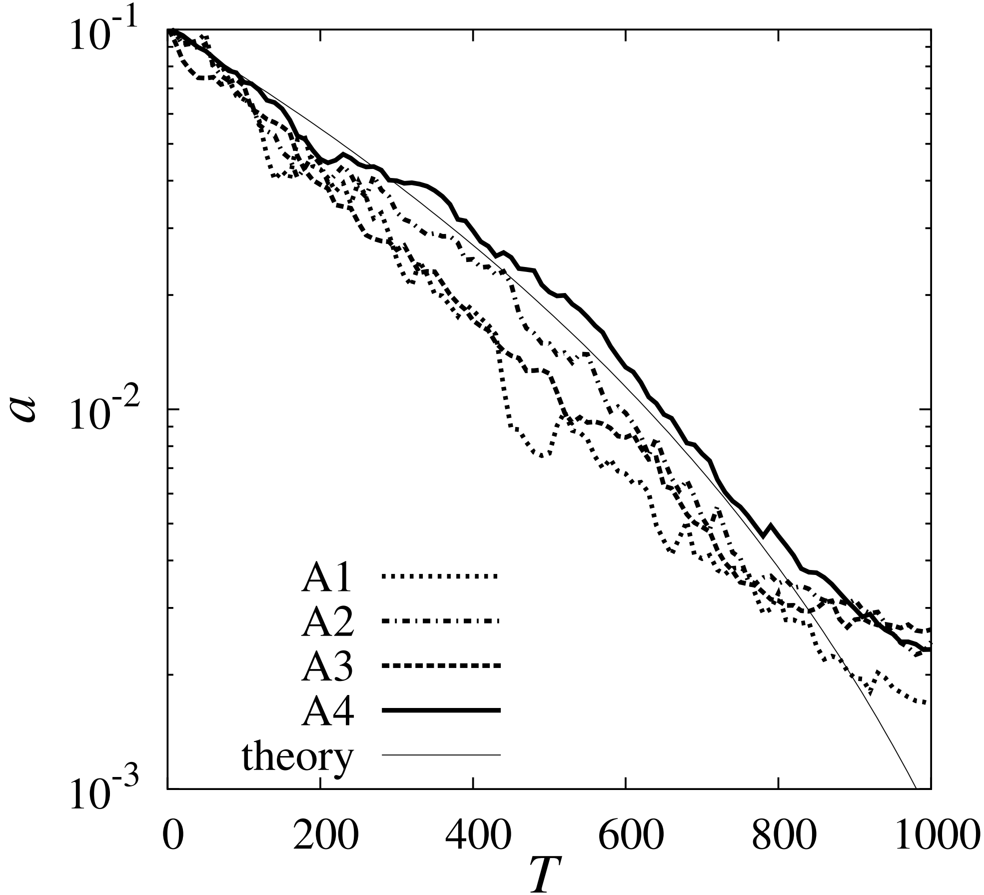
- **Scaled-down version of SMBH binary?**
- **Any effect of large mass ratio?**

Simulation

Matsubayashi et al. 2005 (astro-ph/0511782)

- **Bahcall-Wolf cusp around SMBH**
- **SMBH $3 \times 10^6 M_\odot$**
- **IMBH $3 \times 10^3 M_\odot$**
- **1 length unit $\sim$ 1pc, 1 time unit $\sim$4600 year**
- **Lowest star mass $\sim 3M_\odot$**
- **IMBH placed at 0.1pc (runs A) or 0.01pc (runs B)**

IMBH orbital evolution (runs A)

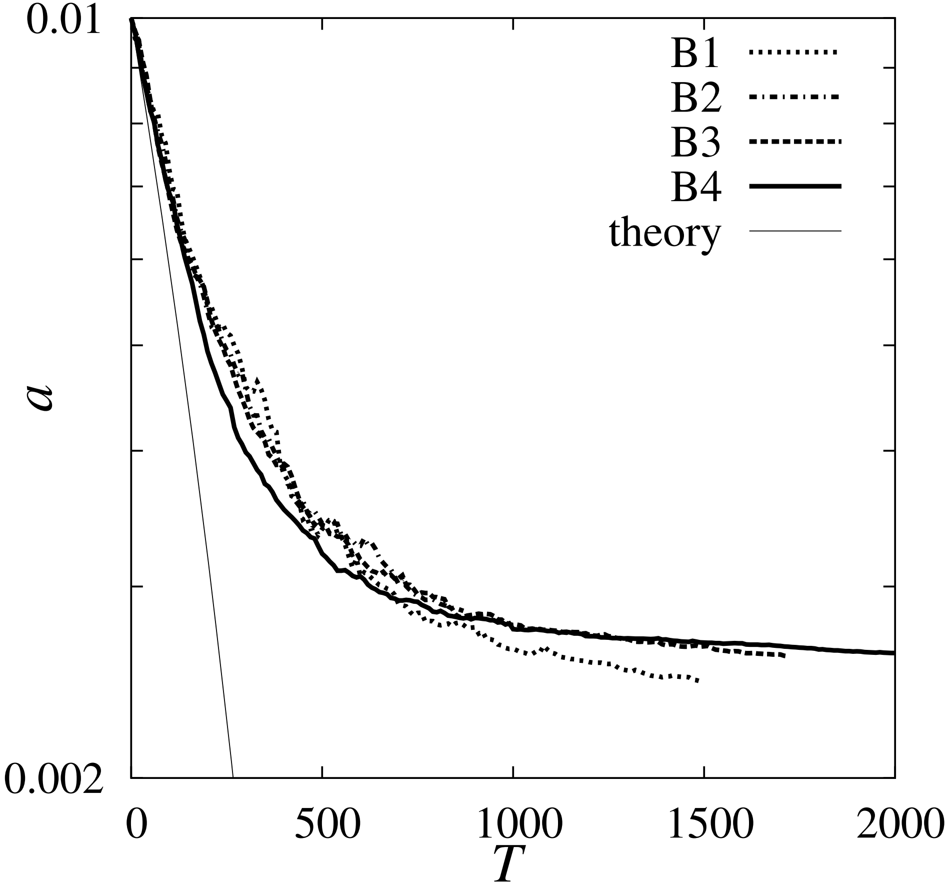


Slows down at late phase.

Not much dependence on N

(A1-A4 are for different N)

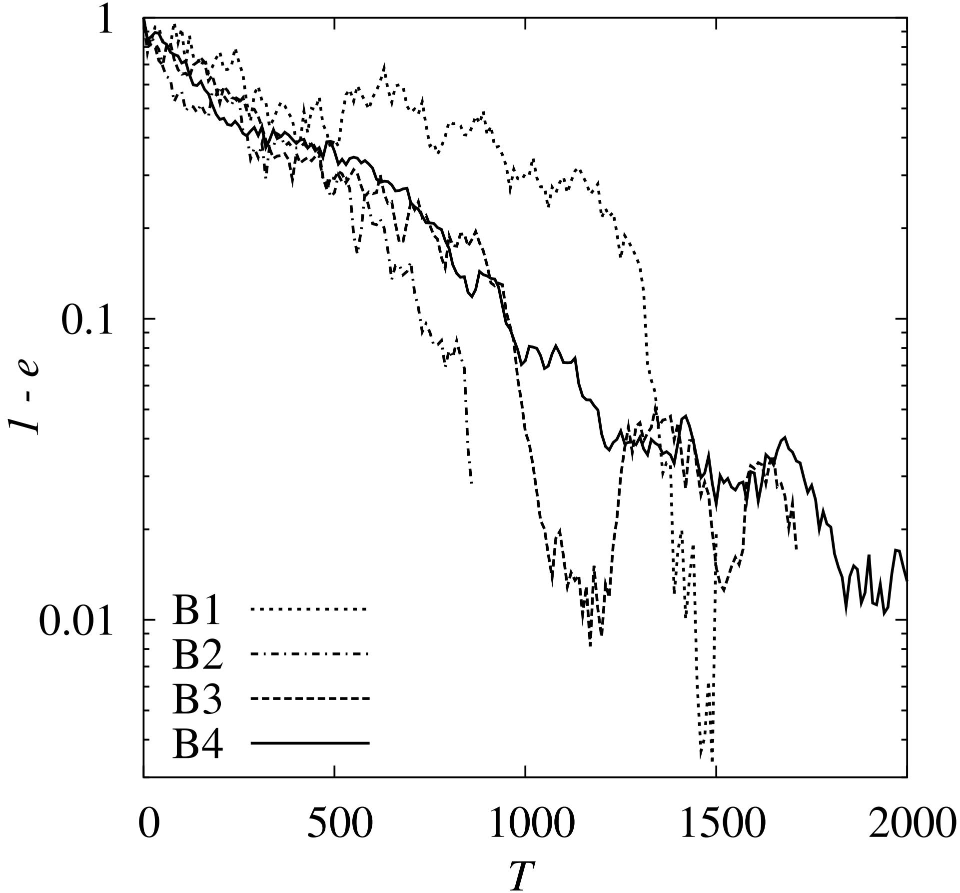
IMBH orbital evolution (runs B)



IMBH placed at 0.01pc
Field star mass smaller than that in runs A

Loss-cone depletion effect clearly visible

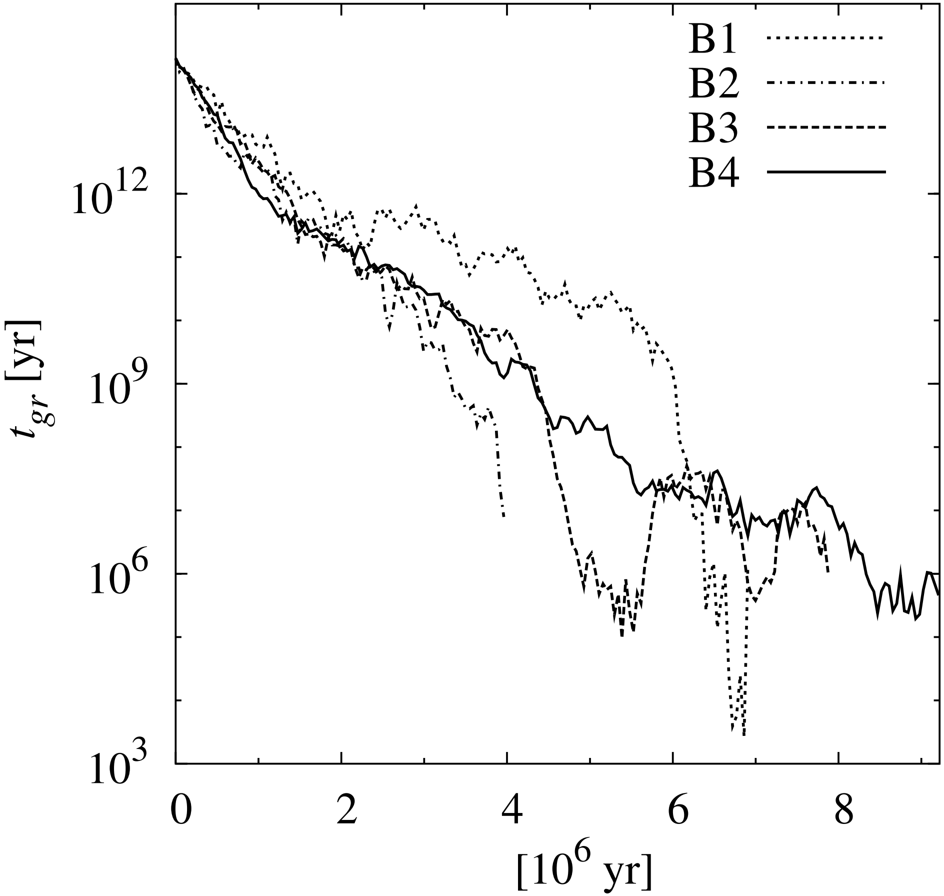
Eccentricity



Eccentricity grows quickly after separation evolution stalled

Different from SMBH-SMBH binary

Gravitational Wave timescale



Can become very short ($<< 10^6 yrs$)

Why does eccentricity grow?

Simple explanation:

There are practically no stars within the IMBH orbit.

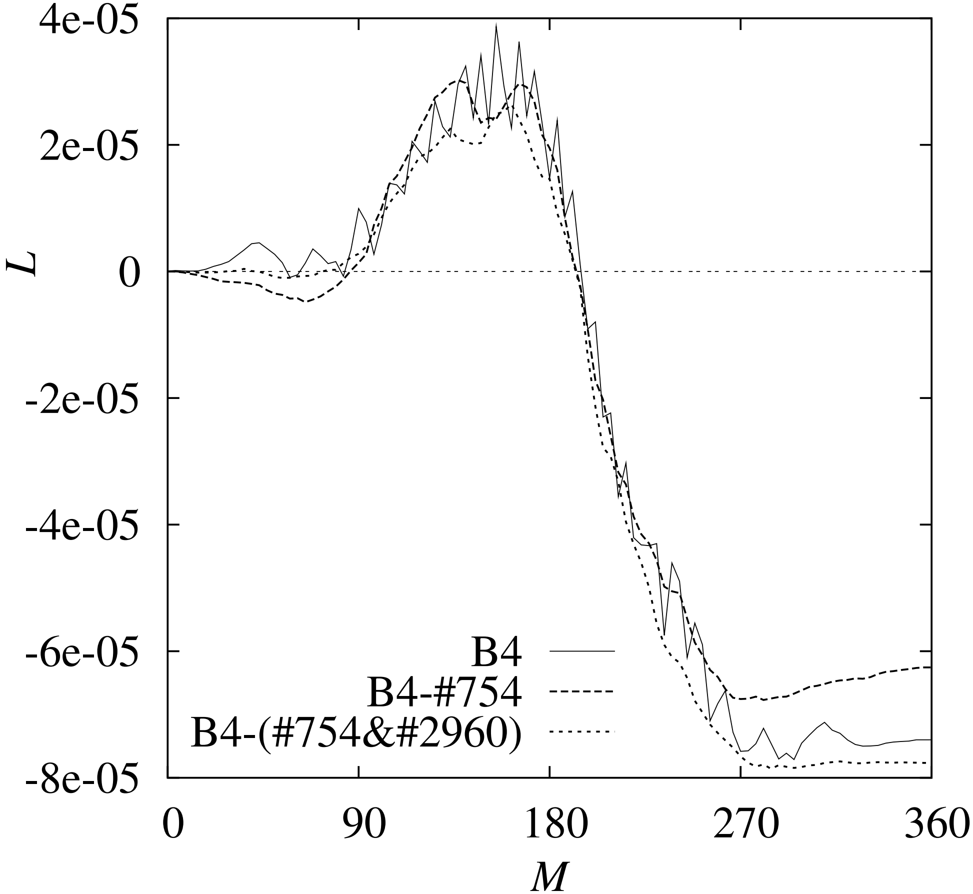
$\downarrow$

If the IMBH interacts with other stars, the interaction most likely occurs at the apocenter of IMBH orbit.

$\downarrow$

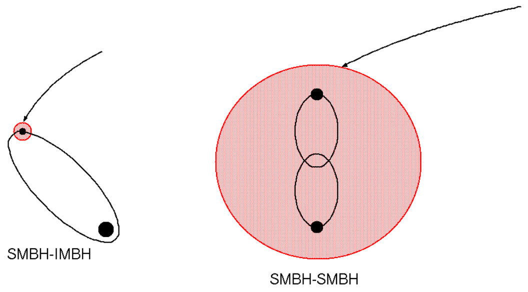
Therefore the IMBH loses angular momentum more efficiently.

Change of L in one orbit



- **Averaged over multiple orbits**
- **M: mean(?) anomaly, 180: apocenter**
- **Spikes due to two stars strongly bound to SMBH**
- **IMBH loses L around and after apocenter**

Why SMBH binaries do not become eccentric?



- In order to interact with IMBH, field stars need to come close to IMBH
- For SMBH-SMBH binary, anywhere with distance order of BH separation is OK.

$$t_{interaction} \begin{cases} << t_{orbit} & \text{(IMBH)} \\ \sim t_{orbit} & \text{(SMBH)} \end{cases}$$

Mass ratio makes difference

Summary

- **SMBH binaries would not merge if there is not much gas**
- **SMBH-IMBH binaries do merge, even if there is no gas**
- **Main difference:**
  eccentricity of SMBH-IMBH binary increases, while that of SMBH-SMBH binary does not

Some comments

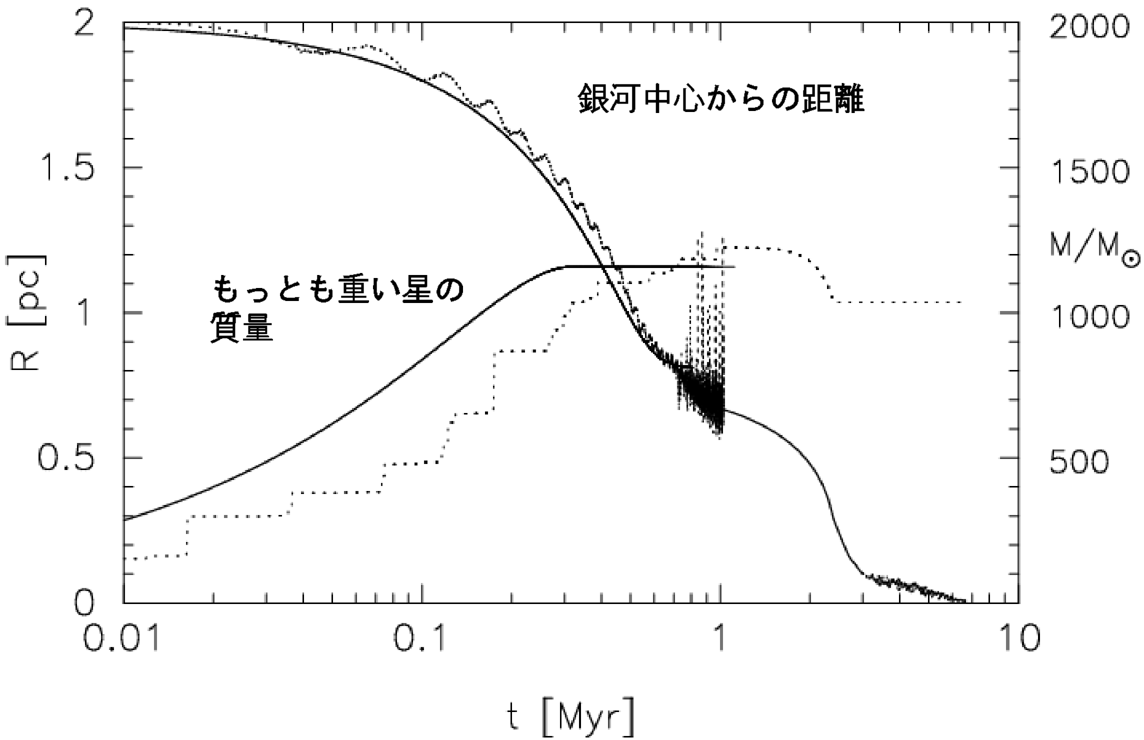
- N-body simulation results are in many cases over-interpreted.
- Larger and more reliable simulations do help resolving fundamental issues.

N-body simulation

Portegies Zwart et al 2005

- 64K stars, Salpeter IMF (lower cutoff: $0.2 M_\odot$)
- 2pc from GC, circular orbit
- Roche-lobe filling King model ($W_c = 9$)

Result



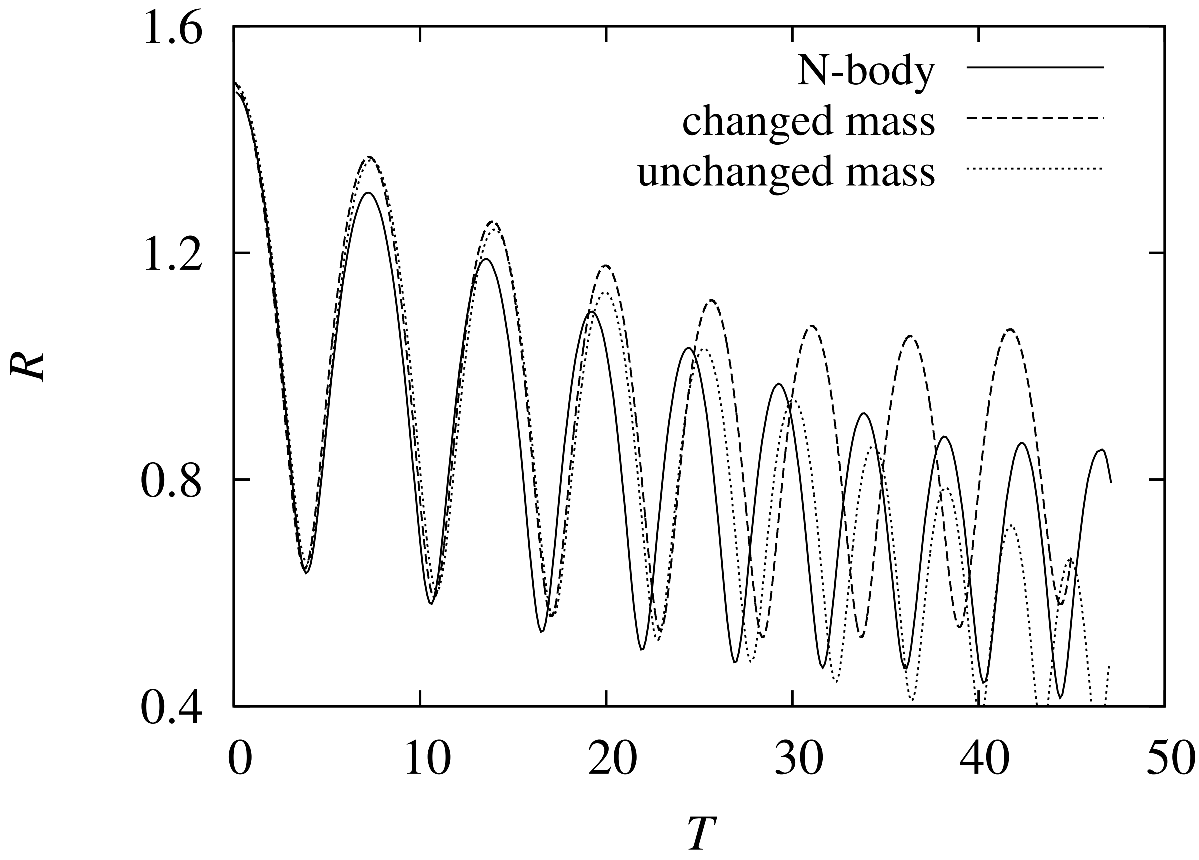
銀河中心からの距離
もっとも重い星の
質量
R [pc]
M/M⊙
t [Myr]
2
1.5
1
0.5
0
2000
1500
1000
500
0.01
0.1
1
10

Result

- **Cluster at 2pc, mass $10^4 M_\odot$: DF timescale=a few Myrs**
- **Cluster at 5-10 pc must be more massive**

Orbital evolution of cluster with DF

Fujii et al. 2006: Satellite galaxy N-body simulation



In full-nbody simulation, satellite falls faster.

Why?

- **Satellite gives angular momentum to escaped stars**
- **escaped stars, while remaining close to the satellite, enhance the dynamical friction**

Circular orbit?

We do not know how young clusters are formed

Not much reason to assume a circular orbit

If initially in eccentric orbit, DF timescale can be much shorter