Dynamical evolution of globular clusters using N-body simulation

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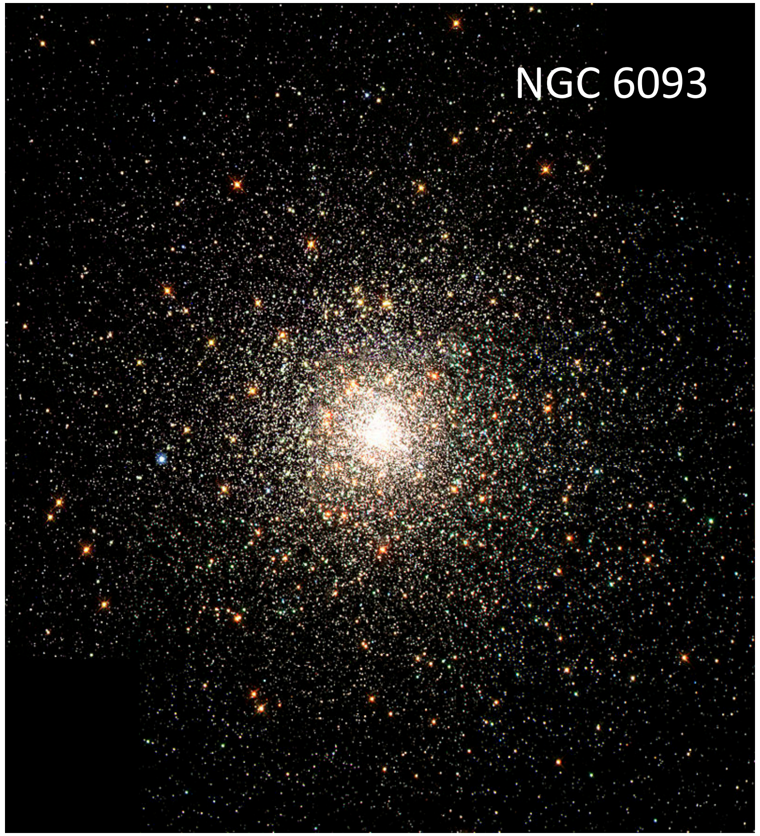
Introduction

Globular cluster

- Star : 10^5 - 10^6
- Size : 1 - 10 pc
- Age : 10 Gyr
- Shape : Nearly spherical
- 150 globular clusters in our Galaxy

They are very closely related to the formation of galaxies, but their formation process is still unclear.



Introduction

Gravothermal dynamics of star clusters

- Core collapse increases the core density
- Massive stars concentrate on the cluster core due to the energy equipartition
- Binaries are formed because of three-body encounter
- Formation of hard binary halts the collapse

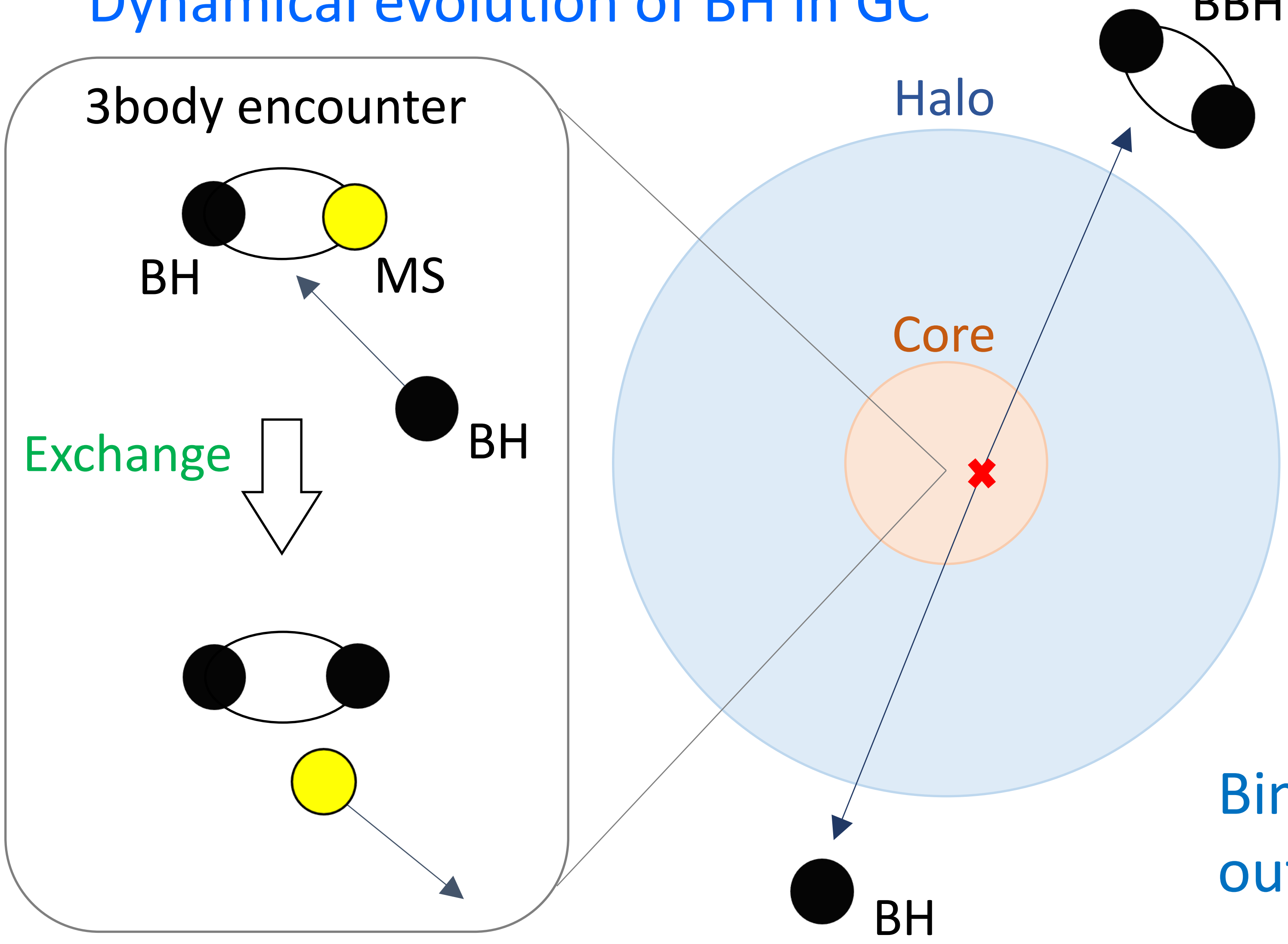
Binary star systems can provide an important source of energy for globular clusters

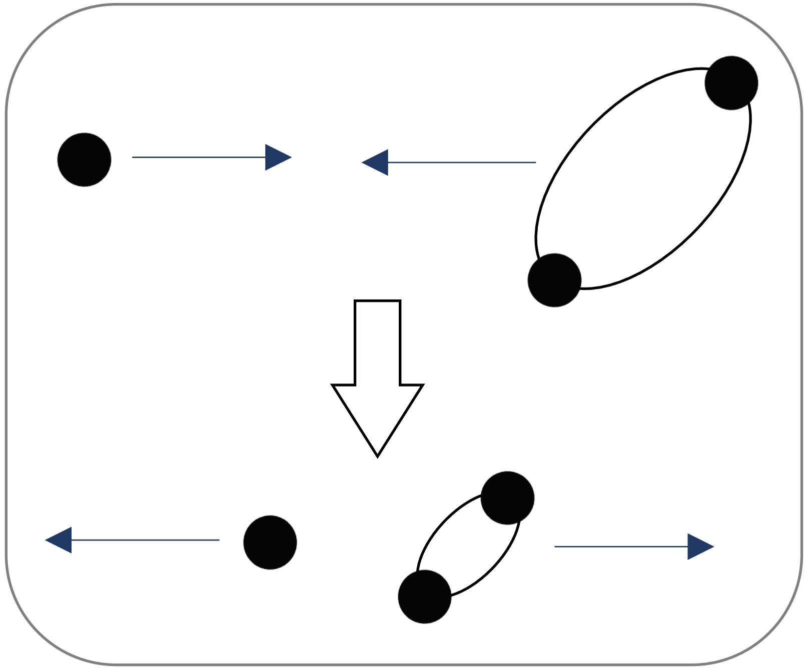
These proceed on the relaxation timescale

$$t_{\mathrm{rh}} = \frac{N r_{\mathrm{h}}^{3/2}}{M^{1/2} G^{1/2} \ln(0.1N)} \sim 2\times10^{8}\ \mathrm{year} \left(\frac{r_{\mathrm{h}}}{1\mathrm{pc}}\right)^{3/2} \left(\frac{M}{10^{6}\mathrm{M}_{\odot}}\right)^{1/2} \left(\frac{\langle m\rangle}{\mathrm{M}_{\odot}}\right)^{-1}$$

Introduction

Dynamical evolution of BH in GC





Hard binary star becomes harder due to encounters

Binary star systems escape outside the cluster

Introduction

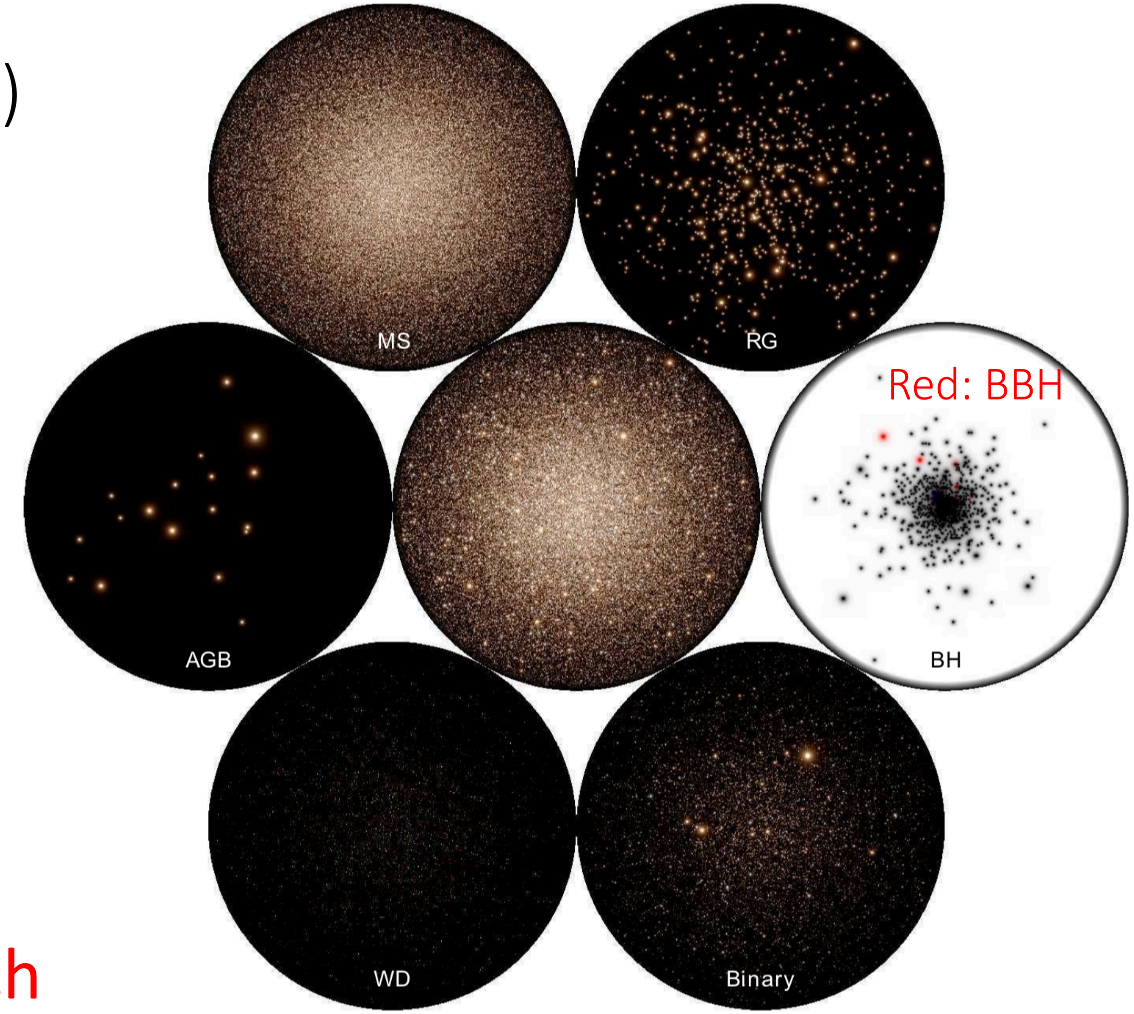
Recent N-body simulation

Dragon simulation (Wang et al. 2016)
NBODY6++GPU

- Star : 10^6
- Age : 12 Gyr
- King model
- Direct integration
- (KS) Regularization

BUT, the cluster density is relatively low

⇨ BBHs were not formed much



Problems

Our targets

- Simulation of binary stars in the globular cluster
- Investigation of the formation rate of BBHs (Detection of GW)

Difficulties

- When the distance between two stars becomes extremely close, the calculation breaks down.
- Direct calculation cost $O(N^2)$ ⇨ Compute-intensive!
- Binary stars have short orbital period (days), but globular cluster life time is more than 10Gyr.

It is difficult to simulate the evolution of globular clusters.

PENTACLE

(Parallelized Particle-Particle Particle-Tree code for Planet formation)

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P³T scheme

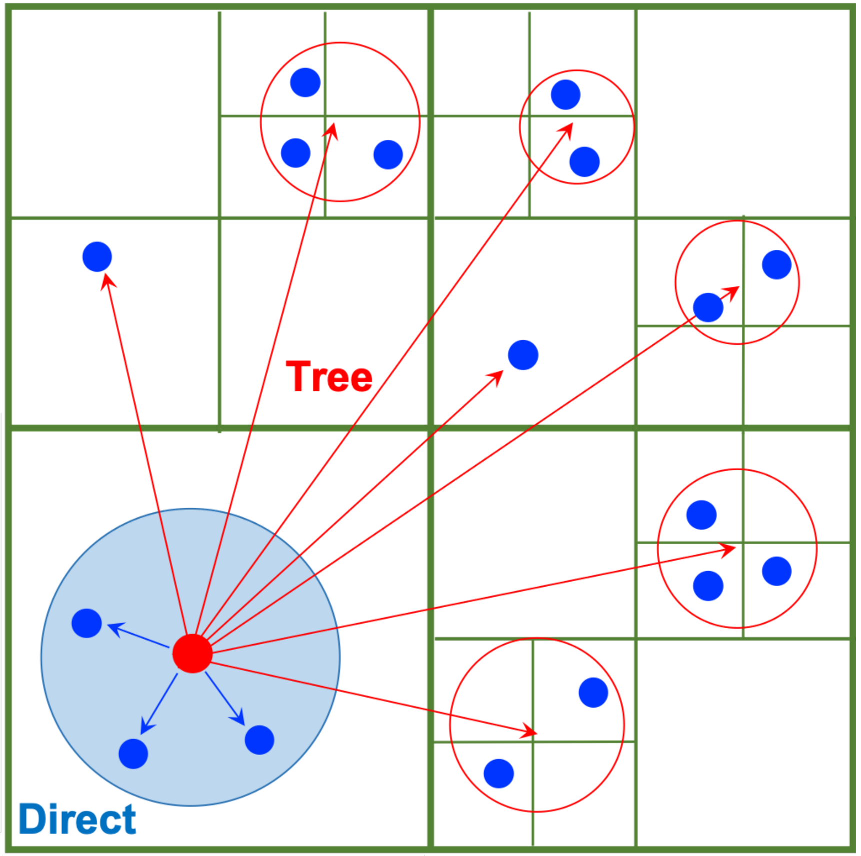
Oshino et al.(2011), Iwasawa et al.(2015)

- Open-source library designed for full automatic parallelization
- New hybrid algorithm for the time integration
- For Collisional N-body system

Short-range : Direct integration + Hermite method (Individual timestep)

Long-range : Tree method + Leap-Frog integrator (Block timestep)

Calculation cost : $O(N\log N)$



Method of P³T

Algorithm

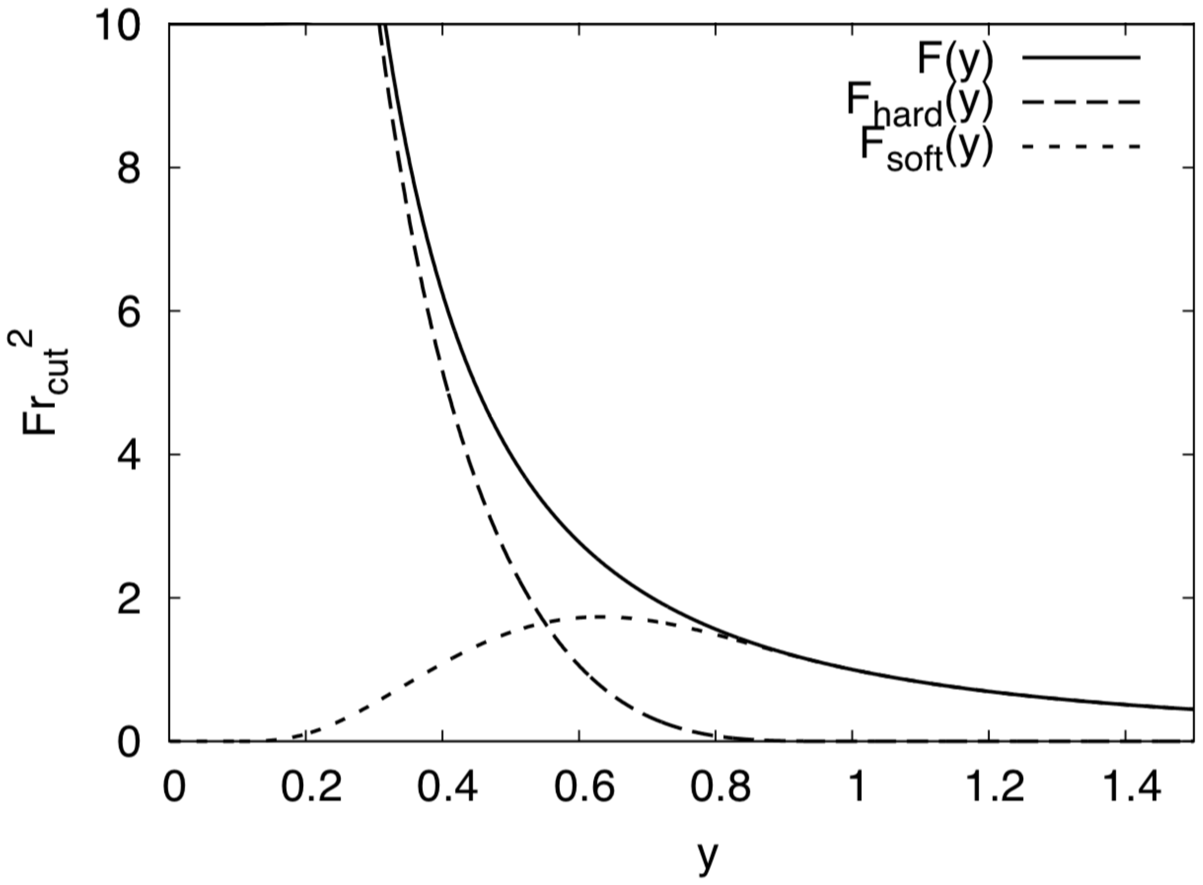
The cutoff function $K(r_{ij})$ splits the gravitational force between particles to contribution of close encounters and others

$$\boldsymbol{F}_{\mathrm{hard},i} = -\sum_{i\neq j}^{N} \frac{Gm_i m_j}{r_{ij}^3} K(r_{ij})\boldsymbol{x}_{ij}$$

$$\boldsymbol{F}_{\mathrm{soft},i} = -\sum_{i\neq j}^{N} \frac{Gm_i m_j}{r_{ij}^3} [1 - K(r_{ij})]\boldsymbol{x}_{ij}$$

$$x = \frac{y-\gamma}{1-\gamma}, \quad y = \frac{r_{ij}}{r_{\mathrm{cut}}}, \quad \gamma = \frac{r_{\mathrm{in}}}{r_{\mathrm{cut}}}$$

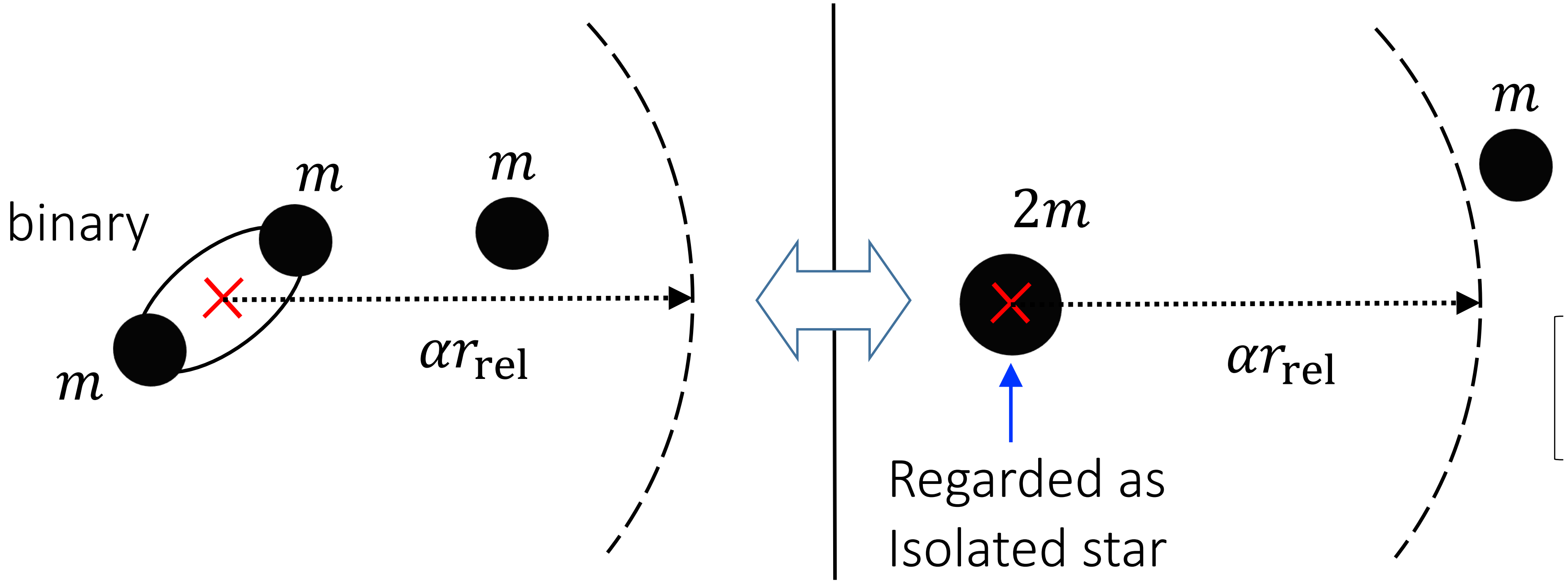
(r_{in} : inner cutoff radius
r_{cut} : outer cutoff radius)



GORILLA

GORILLA (Tanikawa & Fukushige 2009)

- N-body simulation code for star clusters
- Forth-order Hermite scheme with individual timestep
  Calculation cost : $O(N^2)$
- Tight Binaries are approximated as Kepler motions.

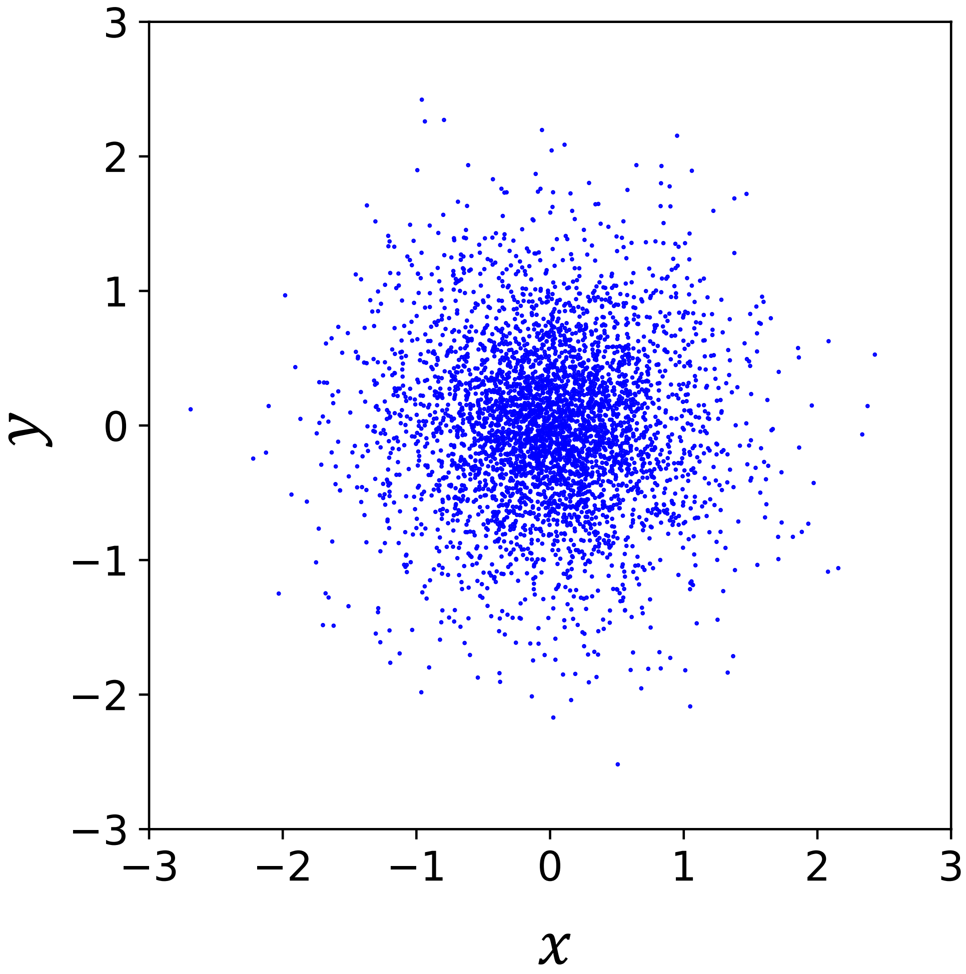


$r_{\rm rel}$: separation of binary
α : constant

Initial condition

- Unit : N-body unit
  (G = 1, M = 1, E = -1/4)
- Distribution : King model
- Particle : N = 4096
  (equal-mass particles)

Follow the evolution of the system up to the moment of the core collapse



Comparison

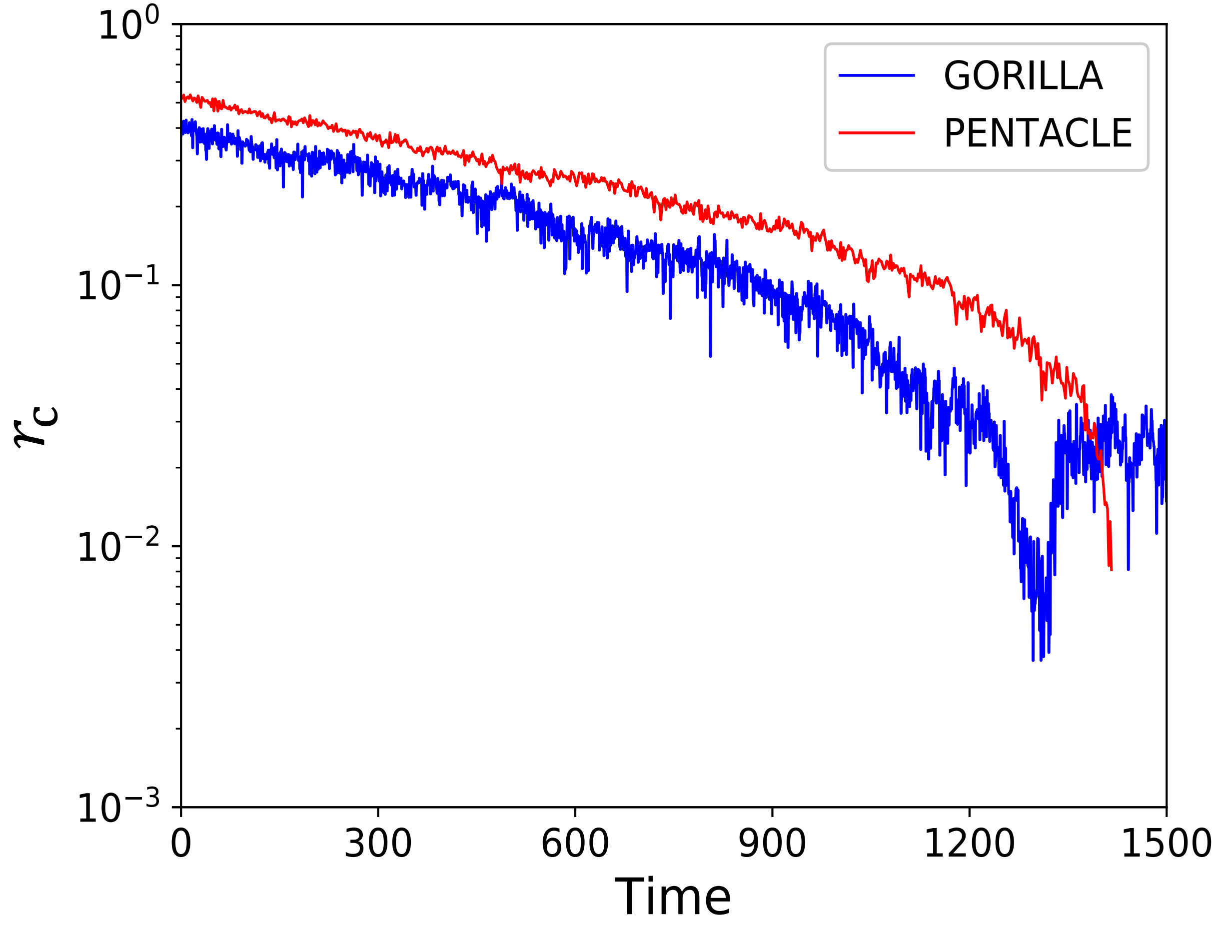
Core radius

$$r_c = \sqrt{\frac{9v_c^2}{4\pi G\rho_c}}$$

[v_c : central velocity dispersion
ρ_c : central density]

Core radius becomes smaller gradually.

PENTACLE breaks down when the cluster core contracts enough.



Collapse time

$$t_{cc} \sim 20t_{rh}$$
$$\sim 1400\ (N = 4096)$$

Calculation time

PENTACLE : 470m GORILLA : 2000m

Comparison

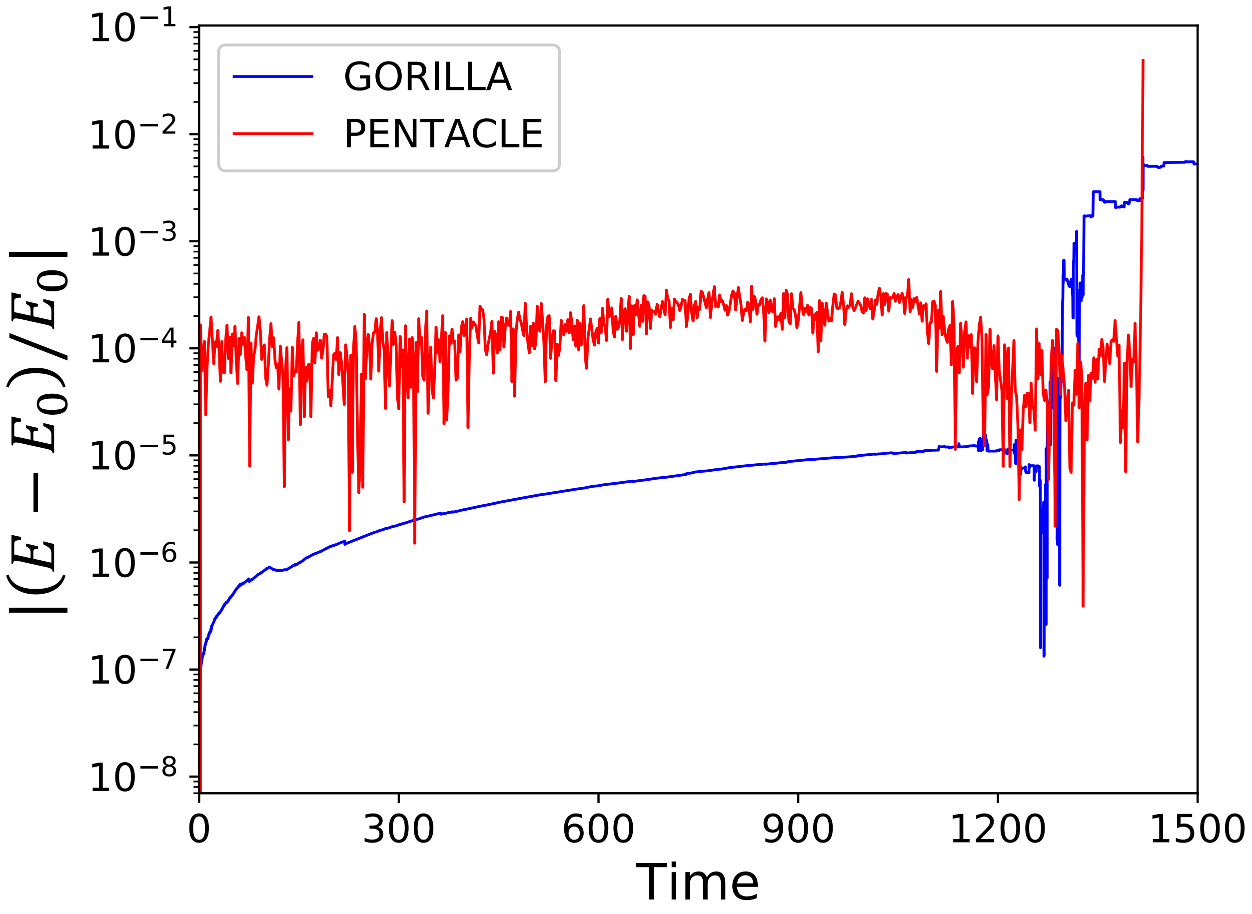
Long term integration

Show the time evolution of the relative energy error until T = 1500.

Growth of energy error is nearly constant during an early stage.

The time that the energy error starts to increase rapidly coincides with the core collapse time t_{cc}.

Hard binaries are formed at the collapse time.



Summary of PENTACLE and GORILLA

Results

- PENTACLE cannot calculate star cluster evolution after core collapse
- Energy conserves until core collapse
- Both of two codes collapsed at the expected time
- Calculation speed of PENTACLE is about 5 times as fast as GORILLA (N=4096)
- Hard binary affects the evolution of whole system

New code

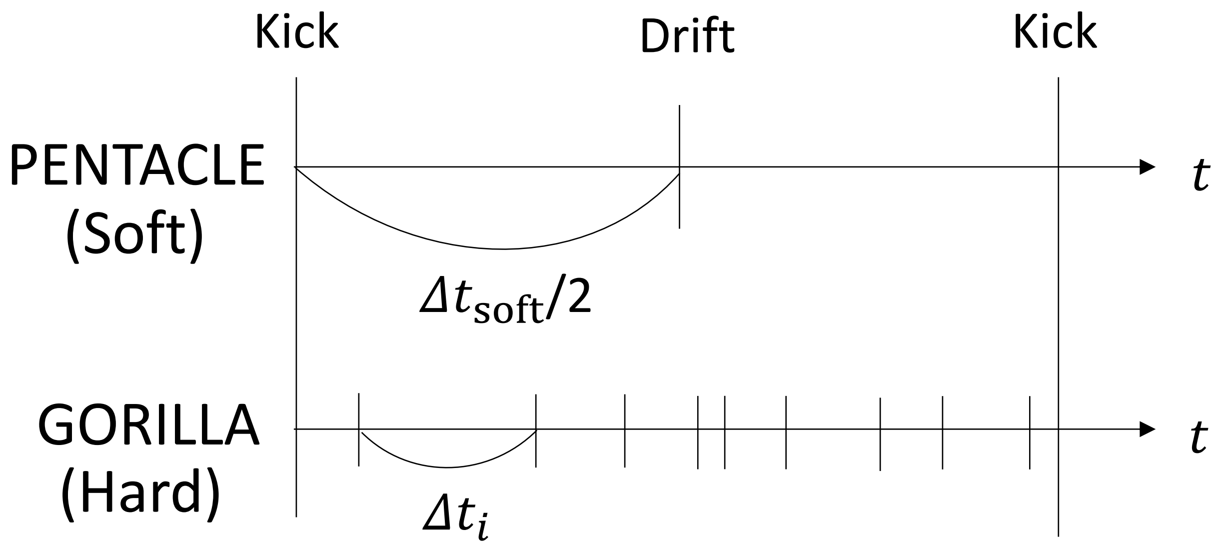
We are developing the new simulation code (PENTACLE + GORILLA)

New code

Expected calculation cost

$\sim O(N\log N)$

Calculate the orbit of binary without regularization



Present situation

- The time that the energy error starts to increase rapidly before core collapse time.
- New code cannot deal with three-body encounter

Summary & Future plans

Summary

- P^3T scheme can reduce the calculation cost of gravitational force
- GORILLA code can calculate star cluster evolution with binaries
- If new hybrid code is developed, the orbits of binaries can be calculated exactly with short time

Future plans

- Implementation of new simulation code
- Application to BBH in globular cluster