Few-body modes of binary formation during core collapse

Ataru Tanikawa (The University of Tokyo)

The BH Dynamics Workshop

Nov. 24th, 2017

Tanikawa, Hut, Makino (2012)

Tanikawa, Heggie, Hut Makino (2013)

Contents

- Conventional picture & our motivation
- N-body simulation
- Analysis for few-body interactions
- Implication for dynamical BH-BHs

Binary formation

- A cluster core gets high density due to core collapse driven by two-body relaxation.
- Many soft binaries are formed through 3-body encounters under such high density environment.
- A few binaries survive by chance despite of many destructive encounters.
- The surviving binaries become harder and harder.
- (Aarseth 1971; Heggie 1975; Hut 1985; Goodman, Hut 1993)

Our study

- We assess the conventional picture that the first hard binary is formed through 3-body encounters.
- For this purpose, we perform N-body simulation, and capture the moment of the formation of the first hard binary.
- We analyze the formation mechanism of the first hard binary.

N-body simulation

- N=1k, 4k, 16k (1k=1024)
- Plummer model
- Equal-mass stars
- No primordial binary
- GORILLA code (Tanikawa, Fukushige 2009)
  - 4th-order Hermite scheme (Makino, Aarseth 1992)
  - Approximation of hard binary orbits as Kepler orbits

Units

- Time scaled by current crossing time in the core

$$\tau = \int \frac{dt}{t_{\rm cr,c}} \quad \left(t_{\rm cr,c} = \frac{r_{\rm c}}{v_{\rm c}} \right)$$

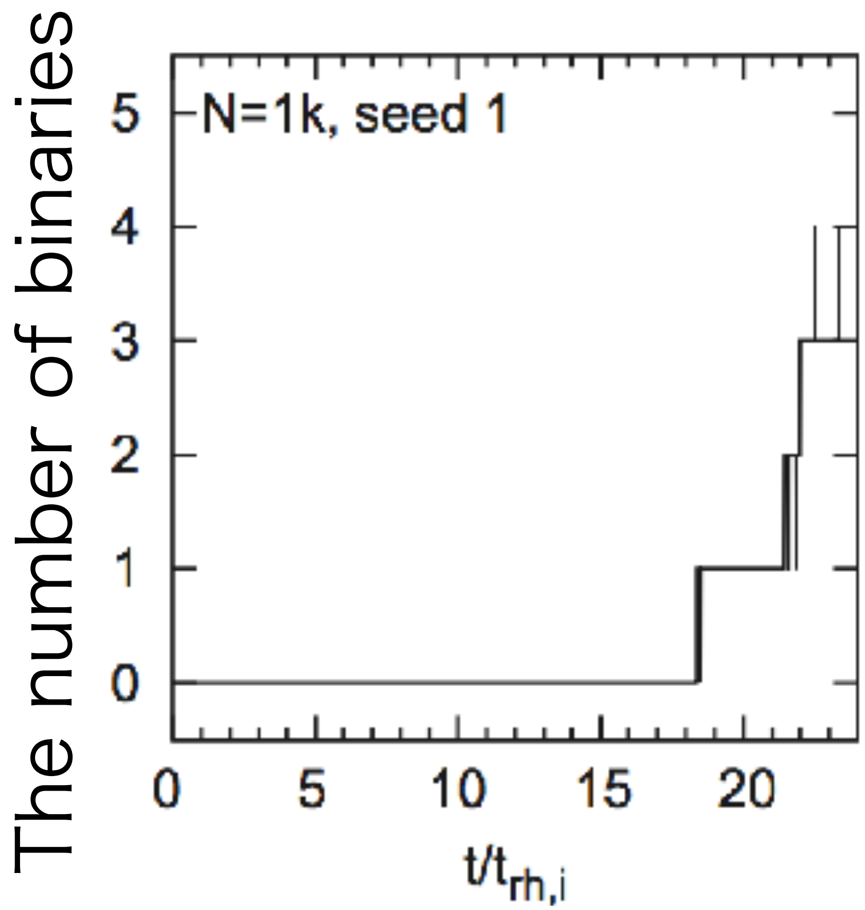
- Energy scaled by average 1D kinetic energy in the cluster

$$e = \frac{E}{kT} \quad \left(kT = \frac{1}{6N} \frac{GM^2}{r_{\rm v}} \right)$$

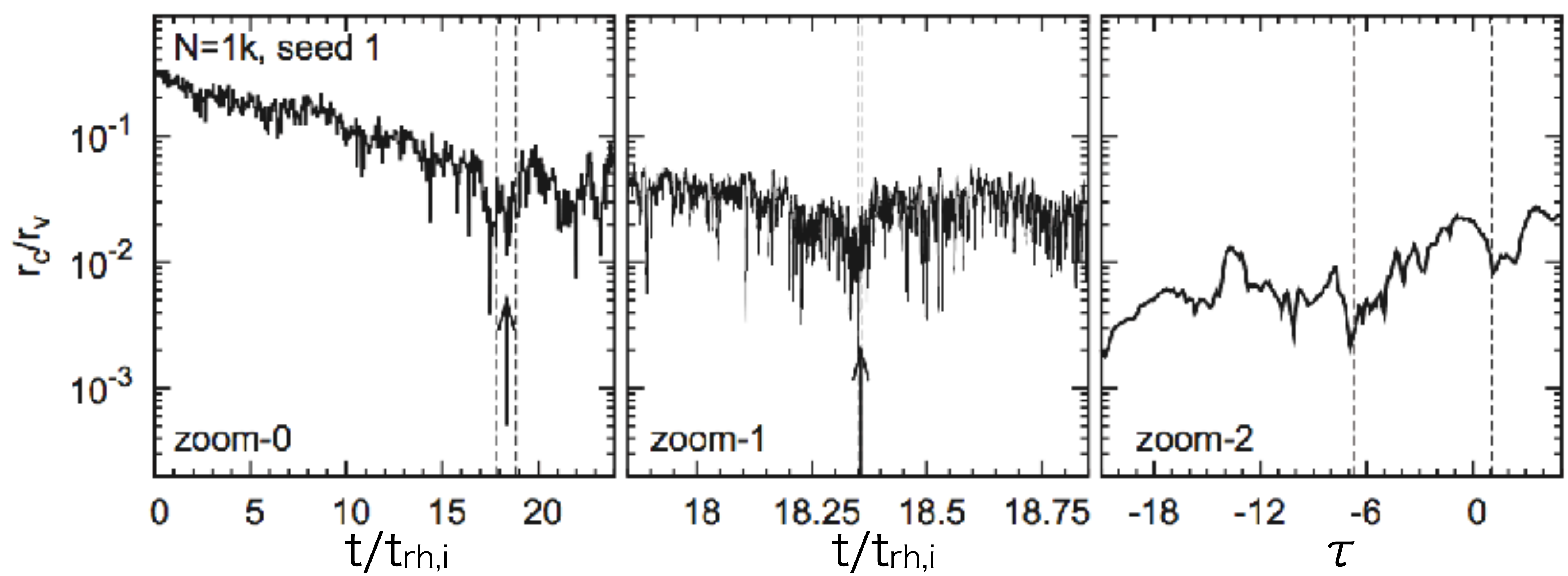
- Length scaled by semi-major axis of 1kT binary

$$r = \frac{R}{a_0} \quad \left(a_0 = \frac{3}{N} r_{\rm v} \right)$$

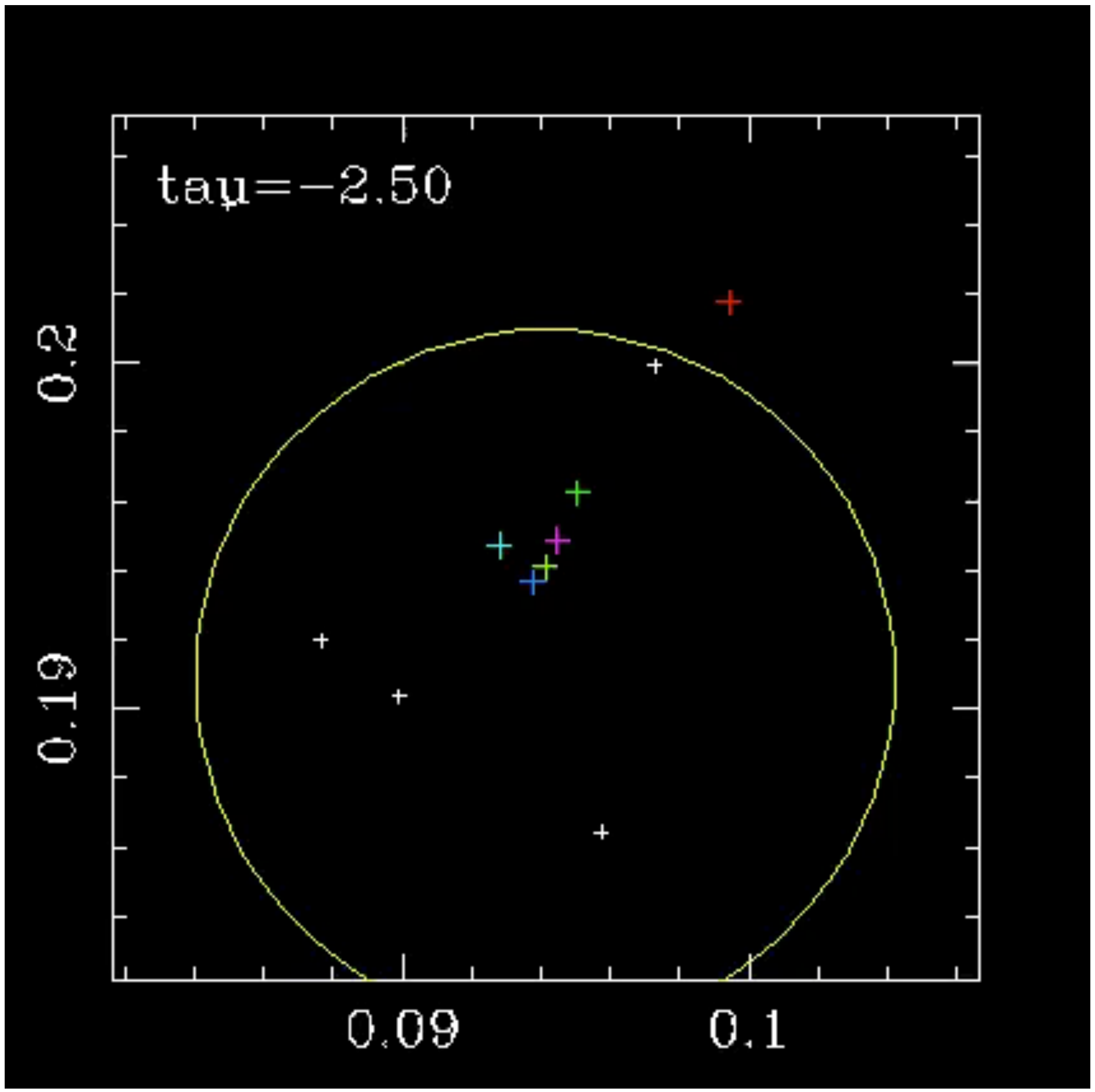
Search for the first binary



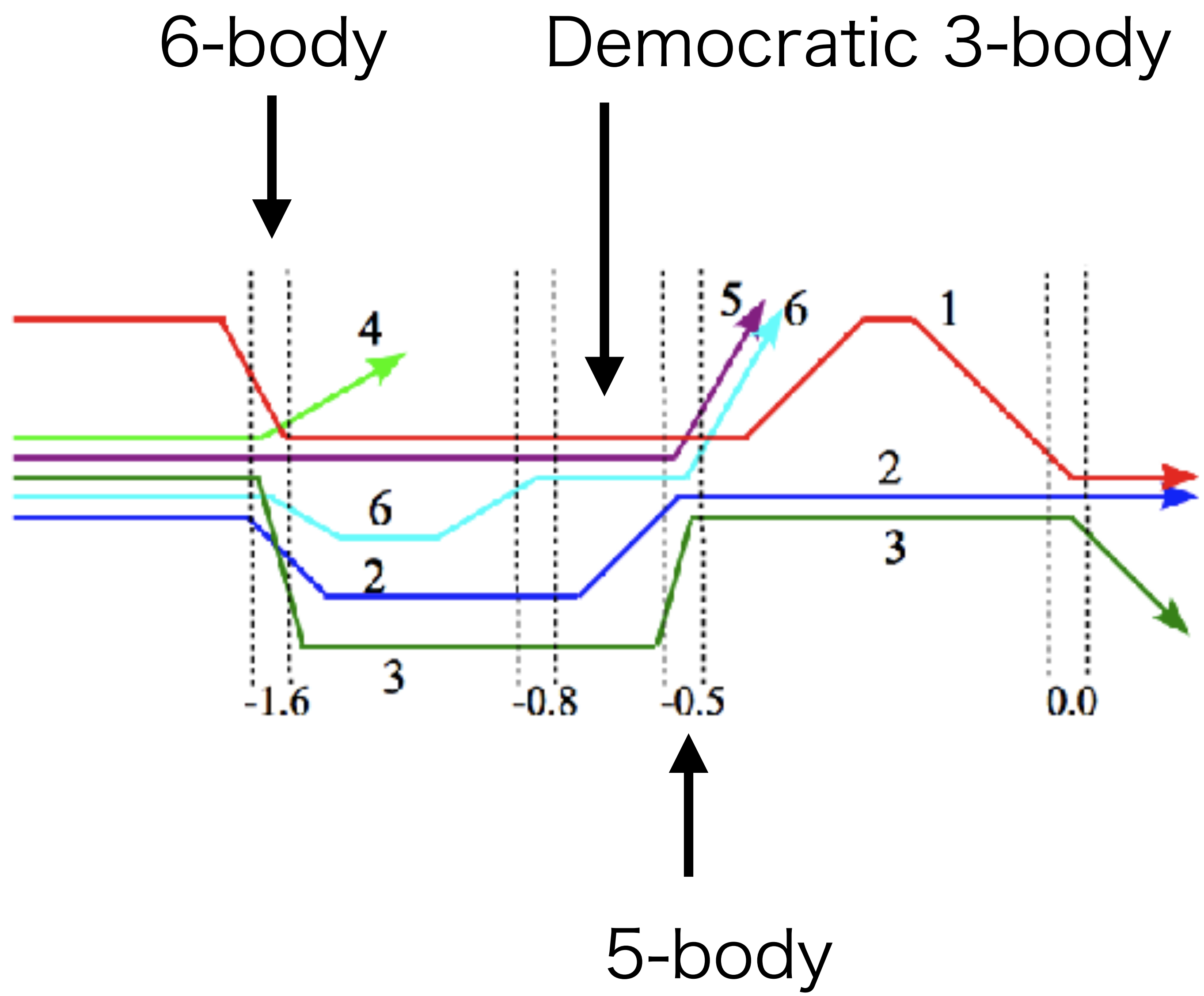
- Simulate the overall evolution
- Find the moment when the first binary is formed
- Resimulate the overall evolution, and record orbits of particles around at the moment.



The moment

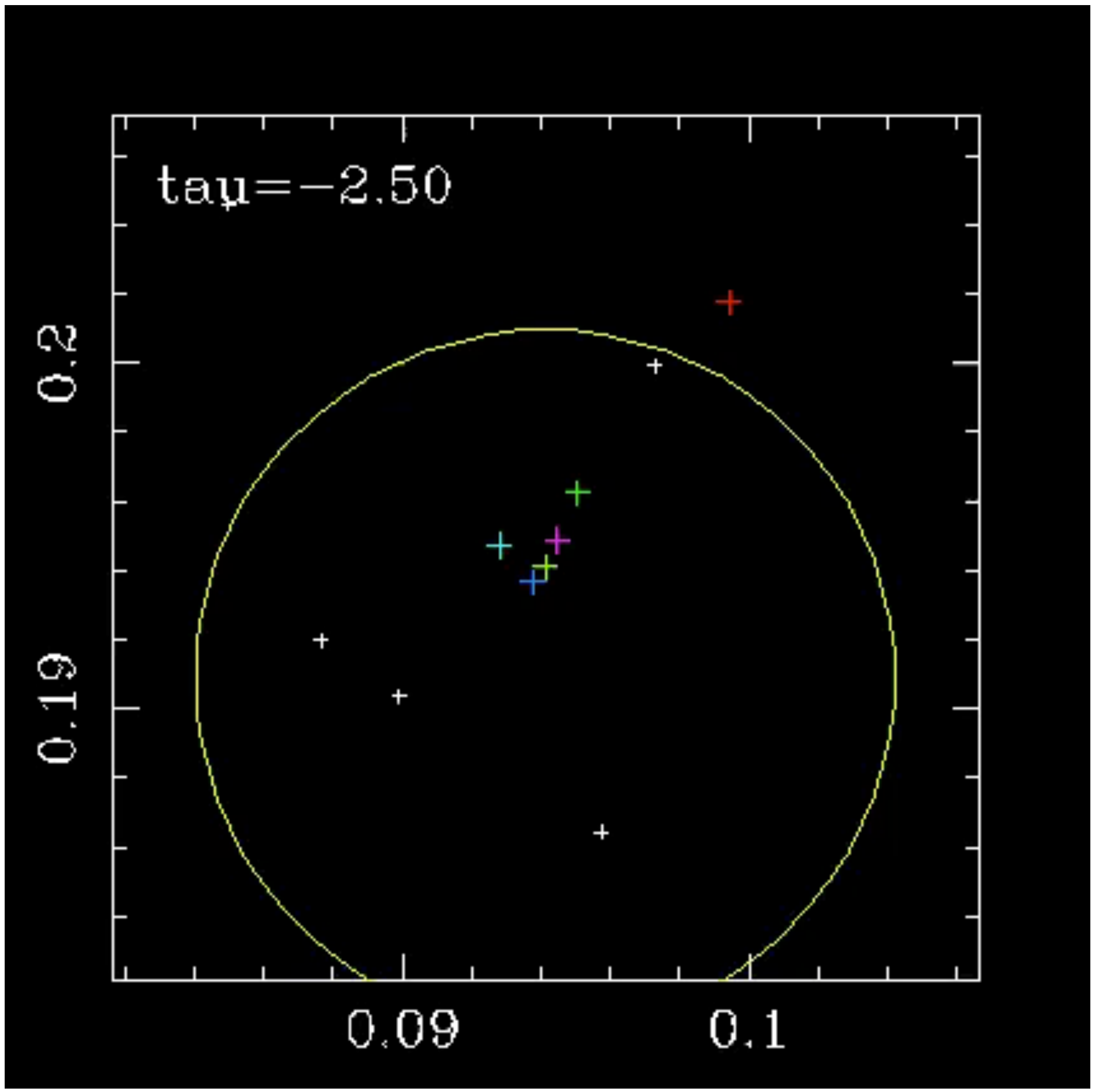


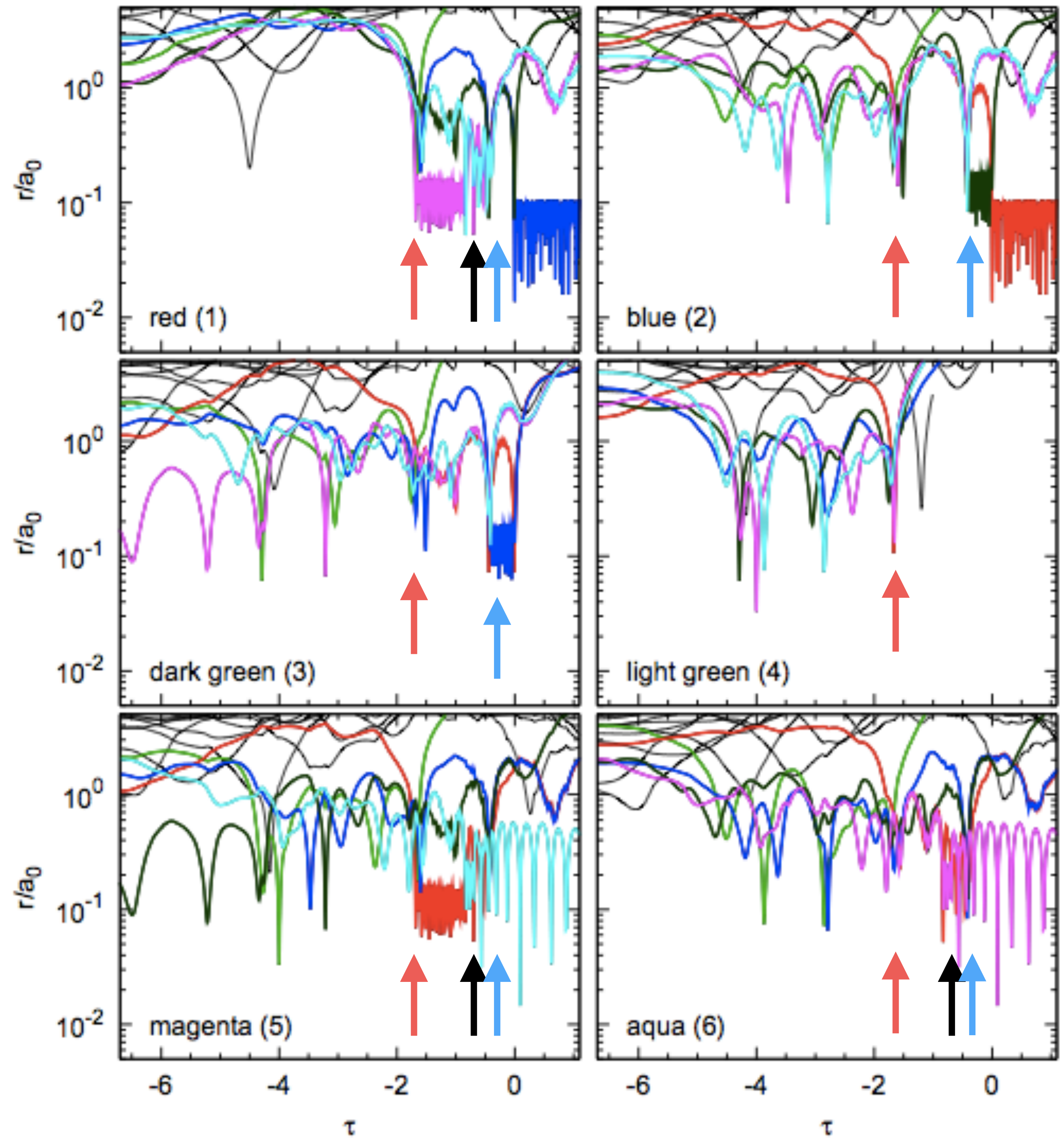
tau=-2.50
0.2
0.19
0.09
0.1



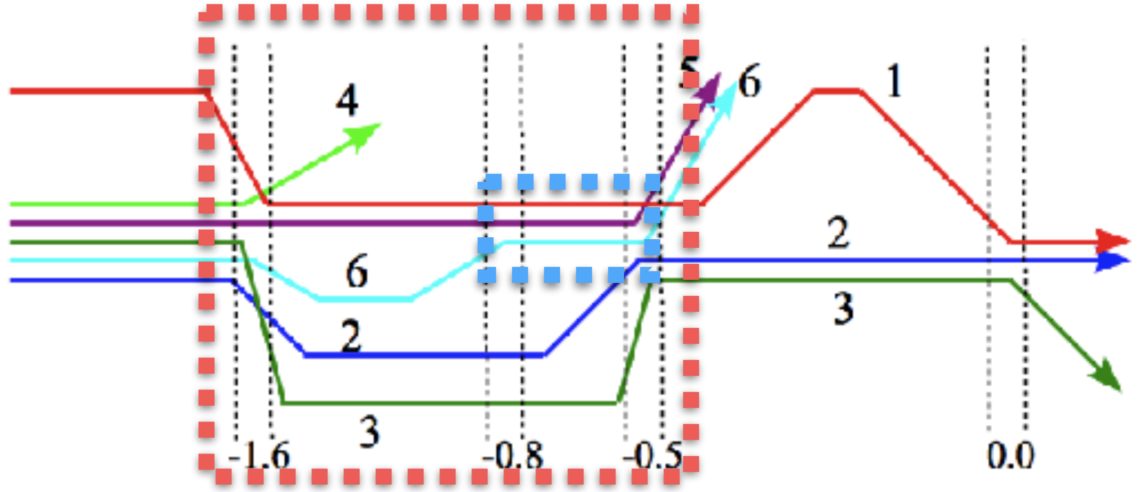
6-body
Democratic 3-body
5-body
4
5
6
1
2
3
6
2
3
-1.6
-0.8
-0.5
0.0

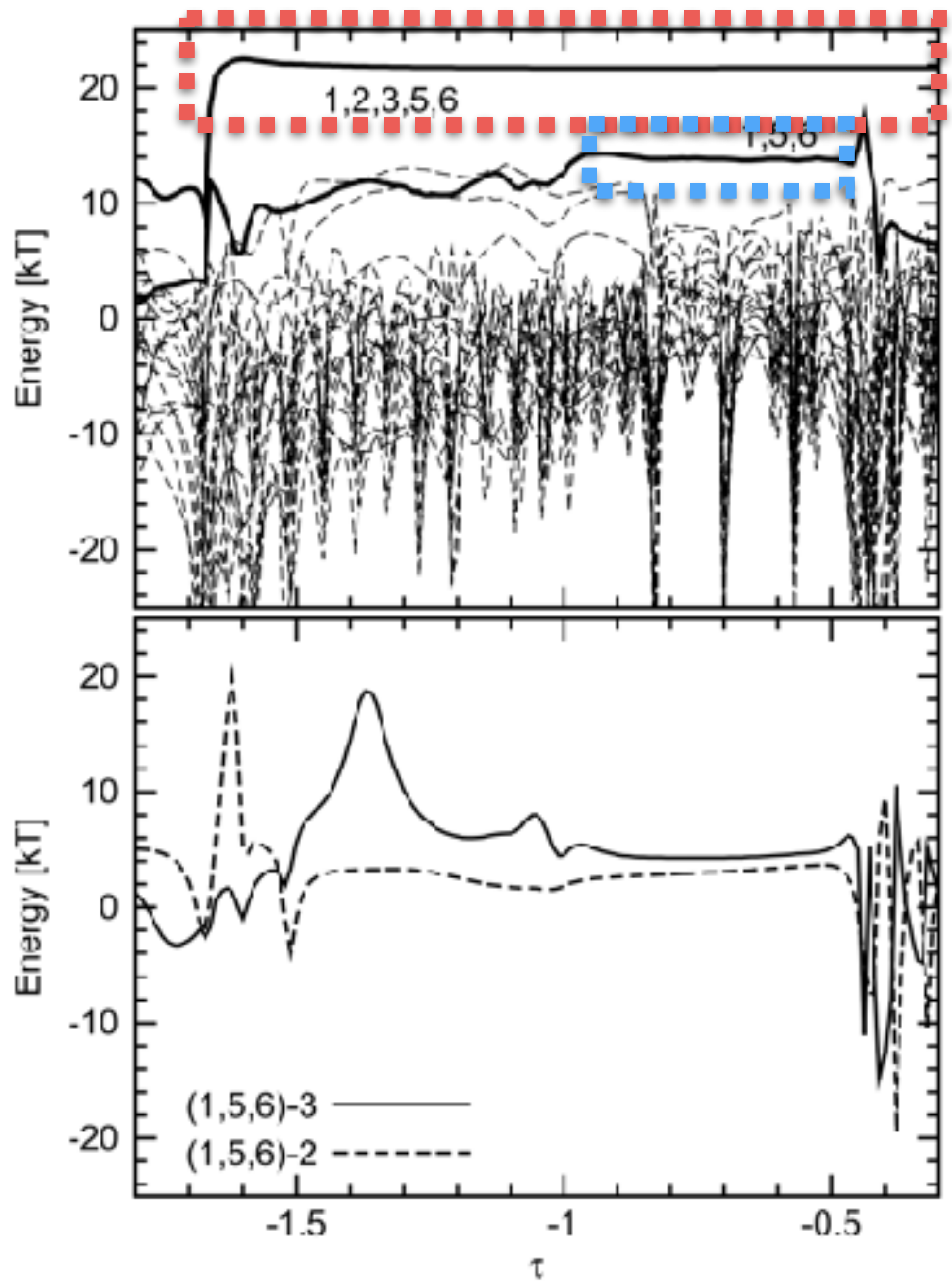
Pairwise distances

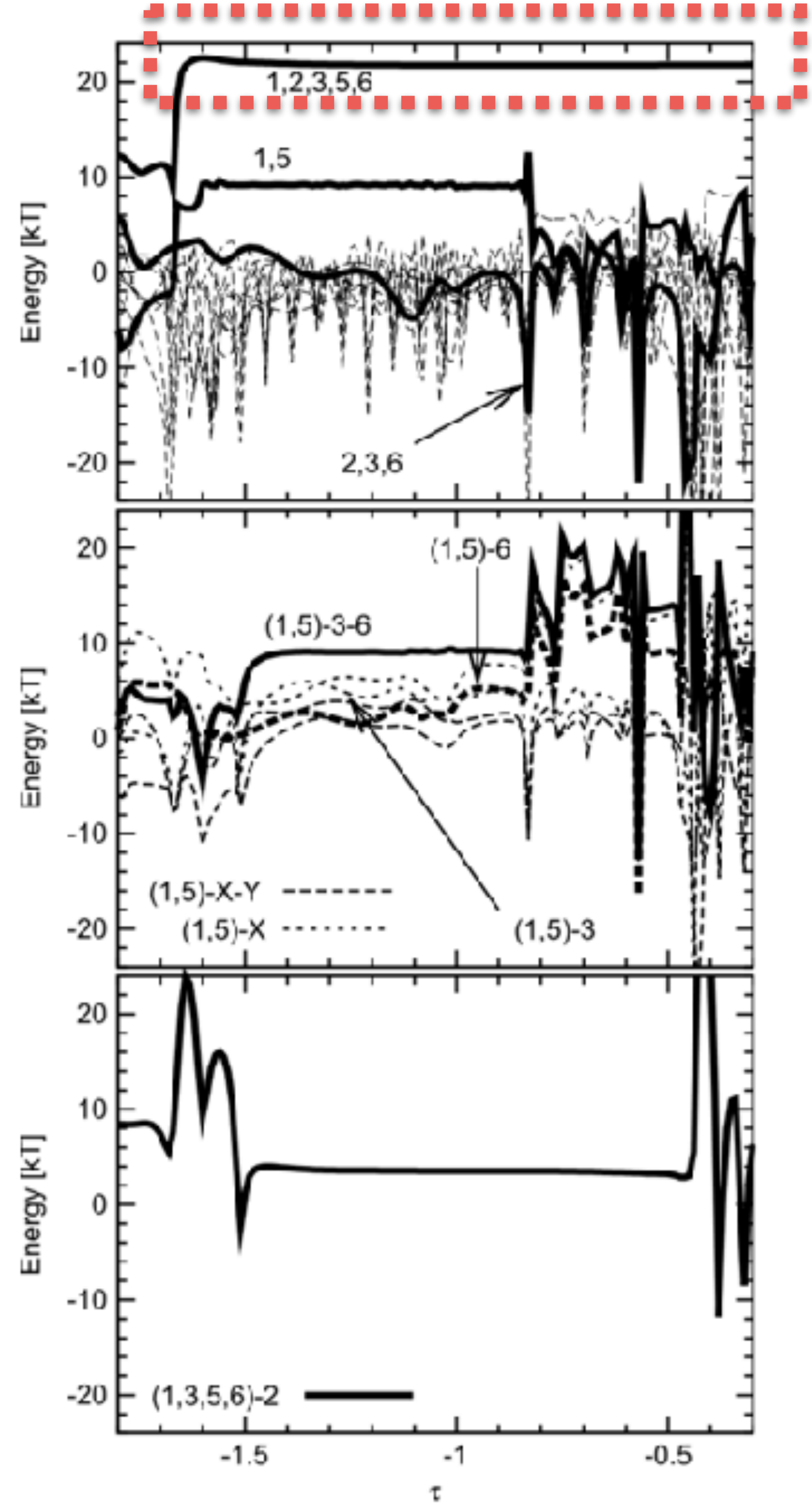




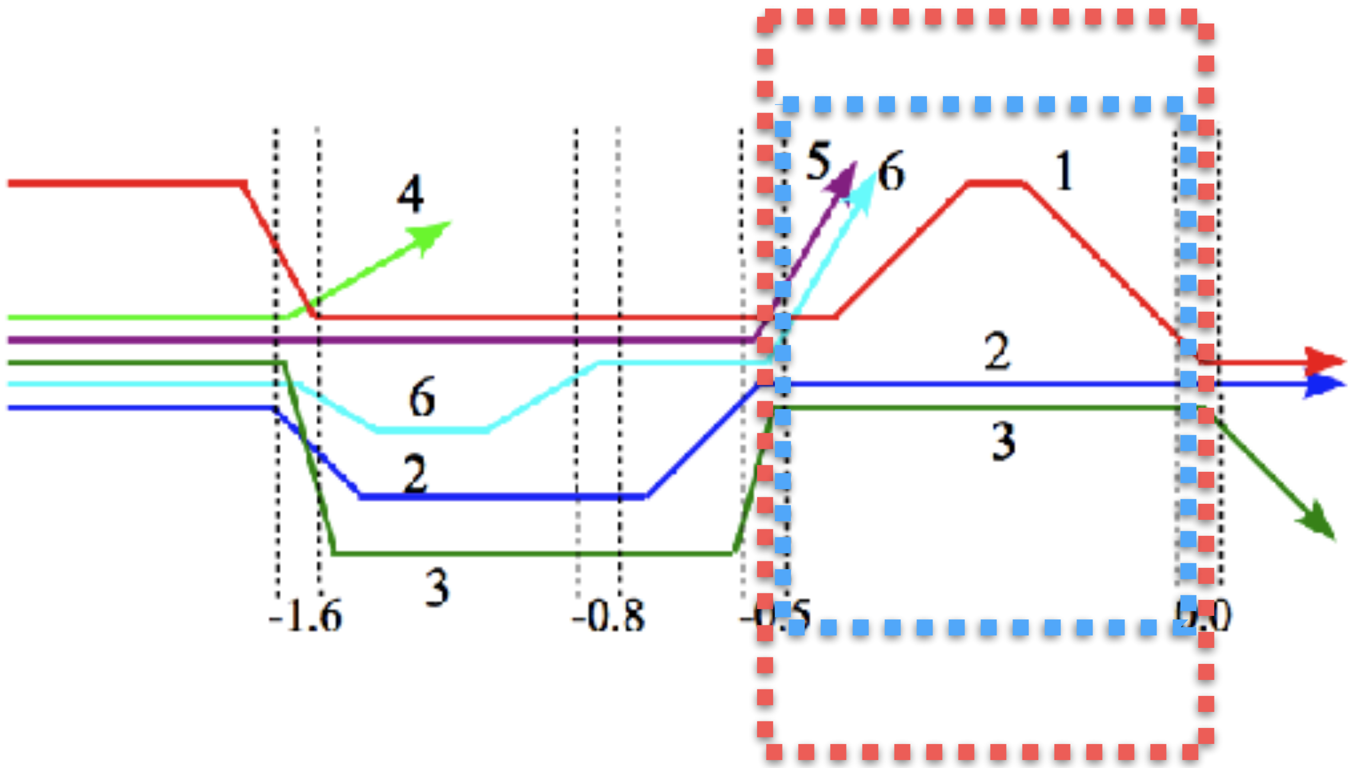
Binary energies of subsystems

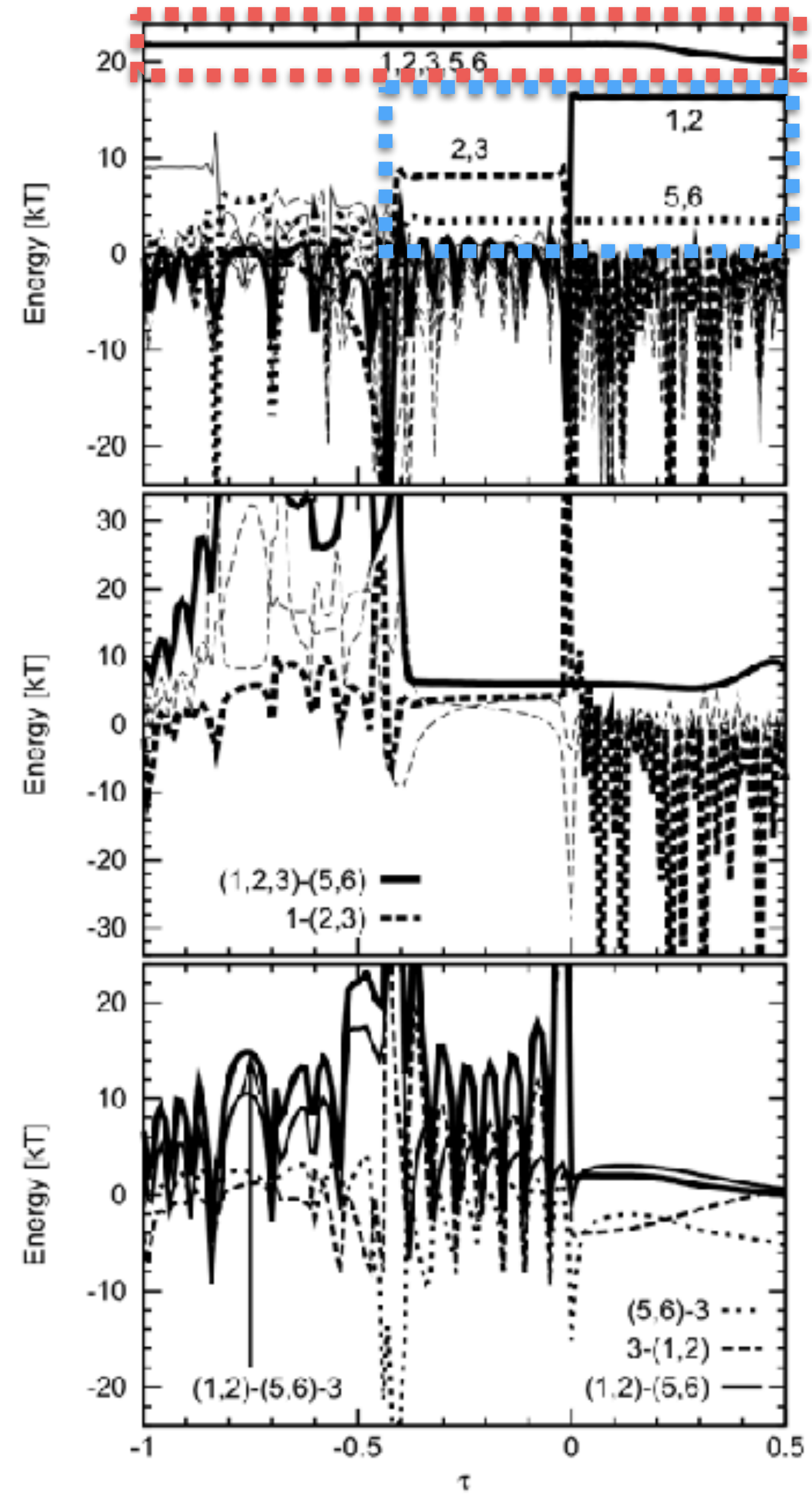






Binary energies of subsystems





- The 5-body system seems to continue to be bound.
- But, hierarchical structures are formed in the 5-body system: a soft binary and hierarchical 3-body system.
- Finally, the 5-body system leaves soft and hard binaries.

Probability of encounter of democratic 3-body system with another star (1)

- Democratic 3-body system is a seed of a dynamical binary in the conventional picture.
- How is the seed perturbed frequently?
- Probability: $P = n_c \Sigma_{3b} \left(\sqrt{3} \sigma_c \right) t_{3b}$
  - n_c: Stellar number density in the core
  - Σ_{3b}: Cross section of the 3-body system
  - σ_c: 1D velocity dispersion in the core
  - t_{3b}: Lifetime of the 3-body system

Probability of encounter of democratic 3-body system with another star (2)

- Probability: $P = n_{\rm c}\Sigma_{\rm 3b}\left(\sqrt{3}\sigma_{\rm c}\right)t_{\rm 3b}$

$$n_{\rm c} = \frac{81\sigma_{\rm c}^6}{4\pi G^3 m^3 N_{\rm c}^2} \longleftarrow \begin{array}{l} r_{\rm c} = 3\sigma_{\rm c}/\left(4\pi G m n_{\rm c}\right)^{1/2} \\ N_{\rm c} = 4\pi n_{\rm c} r_{\rm c}^3/3 \end{array}$$

$$\Sigma_{\rm 3b} = \frac{8\pi G m R}{\sqrt{3}\sigma_{\rm c}}$$

(gravitational focusing)

$$\frac{G(3m)^2}{2R} = E_{\rm b}$$

(The binding energy of the 3-body system is equal to that of a new binary.)

Probability of encounter of democratic 3-body system with another star (3)

- Probability: $P = n_{\mathrm{c}} \Sigma_{3\mathrm{b}} \left(\sqrt{3} \sigma_{\mathrm{c}} \right) t_{3\mathrm{b}}$

$$t_{3\mathrm{b}} = \frac{250 G m^{5/2}}{E_{\mathrm{b}}^{3/2}}$$ (Mikkola, K. Tanikawa 2007)

$$P = \frac{4 \times 10^4}{N_{\mathrm{c}}^2} \left(\frac{3 m \sigma_{\mathrm{c}}^2 / 2}{E_{\mathrm{b}}} \right)^{5/2}$$

$N_{\mathrm{c}} \sim 30$ (e.g. Makino 1996)

$E_{\mathrm{b}} \sim 3 m \sigma_{\mathrm{c}}^2 / 2$

The probability can exceed unity.

Implication for dynamical BH-BHs

- A cluster core in simulation with N=1k-16k may be similar to a core of a real globular cluster.
  - BH mass / GC mass ~ 10^{-4}
    - BH mass: ~$10M_\odot$
    - GC mass: ~$10^5M_\odot$
- The Few-body mode may be a dominant process of BH-BH formation.
- BH-BHs formed by few-body encounters can have extremely high eccentricity (e.g. Samsing, Ramirez-Ruiz 2017)

Summary

- We perform N-body simulation with N=1k, 4k, and 16k.
- We observe few-body modes of binary formation.
- We estimate the probability of few-body modes will exceed unity.
- The few-body modes will dominate dynamical BH-BH formation in dense stellar clusters.