August 22, 2024

神戸大学

The disintegration process and orbital evolution of equal-mass hierarchical triple systems

R. Iwakura[1], Y. Funato[2] and J. Makino[1]

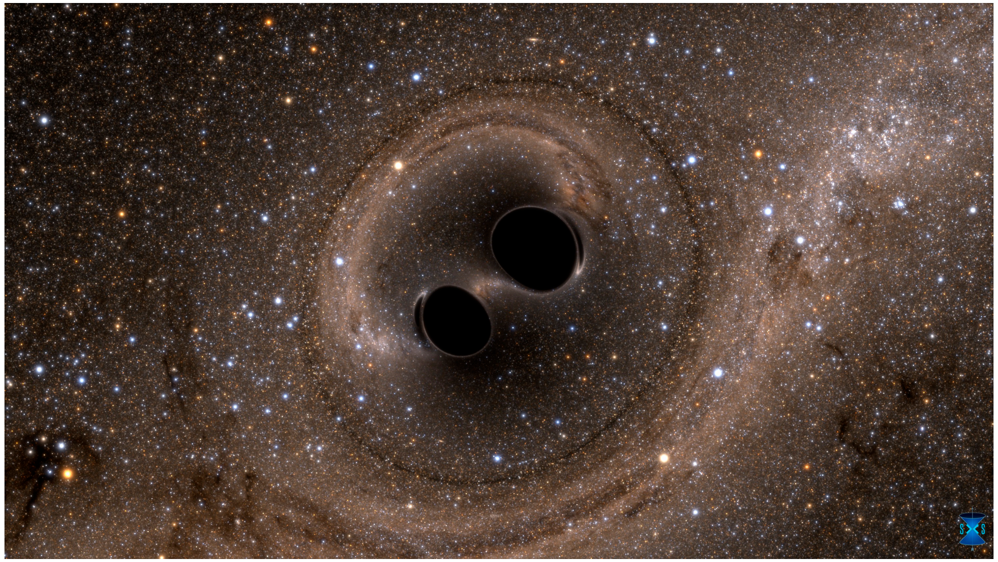
[1] Kobe University [2] University of Tokyo

Summary

- We need more efficient hierarchical triple integration method for globular cluster simulations.
- Current stability criteria for hierarchical triple systems are not sufficient. The parameter $Q = a_{\rm out}(1 - e_{\rm out})/a_{\rm in}$ is used, but even with the same Q, there are systems that stabilize and that become unstable.
- By analyzing the Fourier components of orbital evolutions, we find that there are obvious difference between stable systems and unstable systems.
- Stable systems have evenly spaced peaks in the frequency domain and do not change significantly with time evolution.
- First several thousands period Fourier components may makes us possible to predict the stability of hierarchical triple systems.

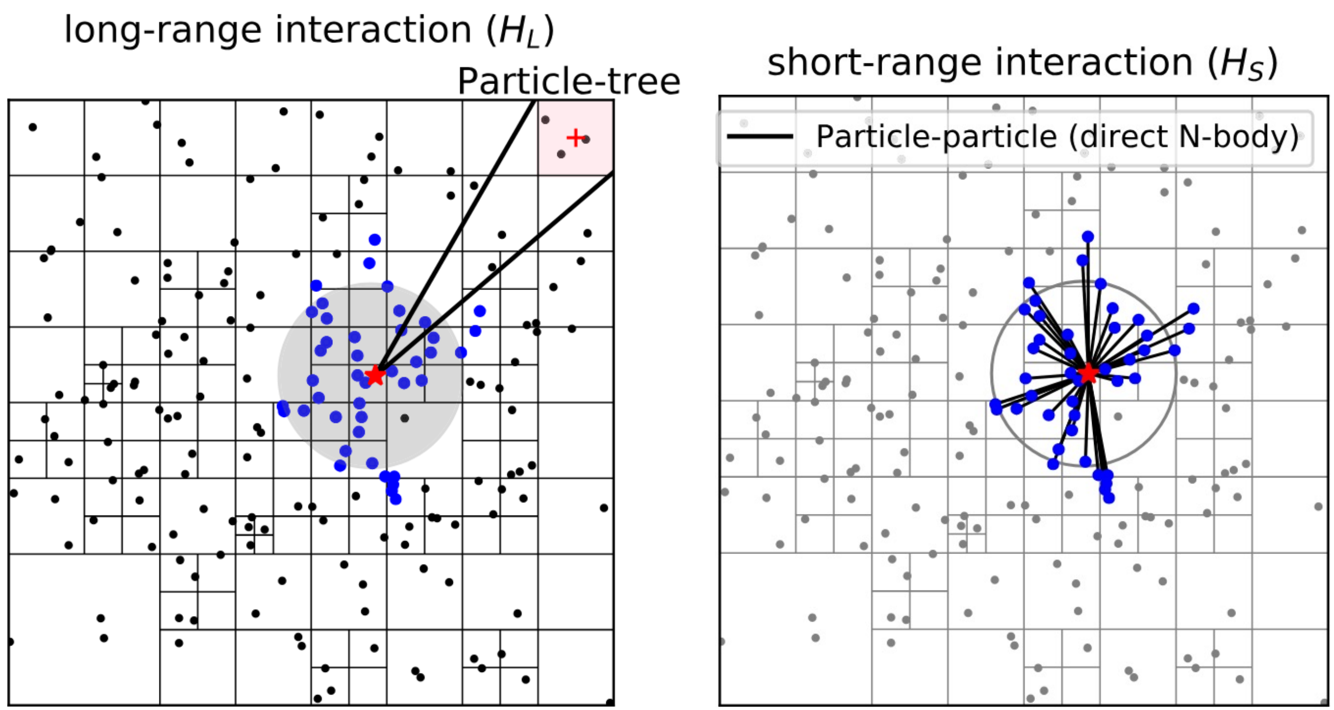
Introduction

- Gravitational-wave astronomy since GW150914 in 2015
- Where are BBHs that merge within Hubble time formed?
  - Pop III stars?
  - Globular clusters? ← Our interest



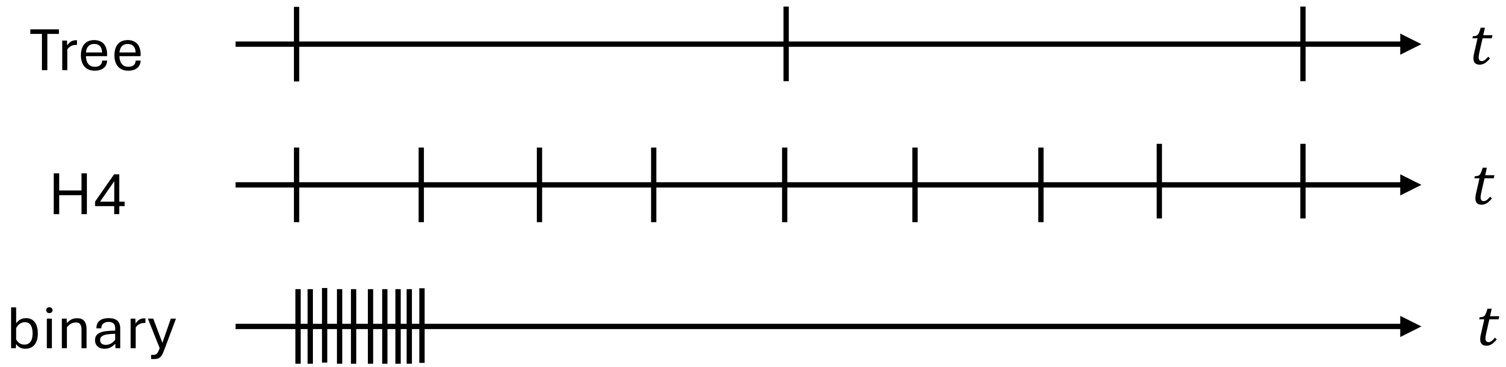
Direct N-body simulation of GCs

- Example of `PETAR` (Wang+2020a)
- Hamiltonian splitting: $H = H_{\mathrm{soft}} + H_{\mathrm{hard}}$

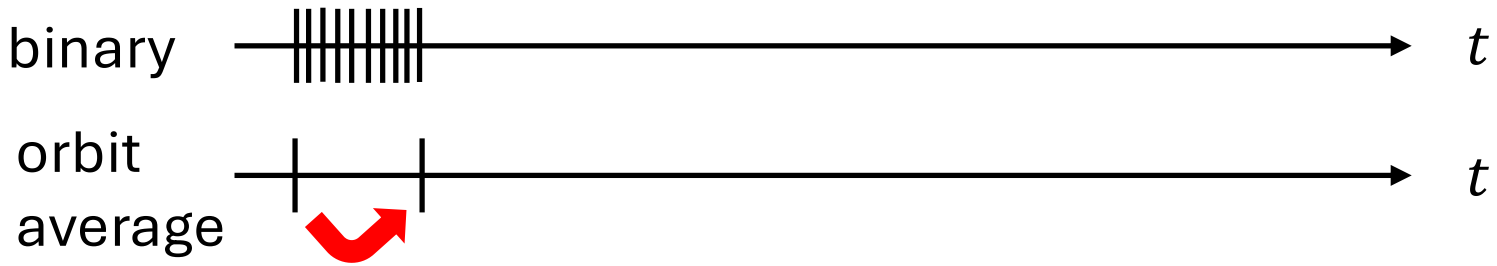


- Tree(soft) + 4th Hermite(hard)
- Slow-down & TSI for binary (SDAR; Wang+2020b)

- Calculating binary or triples directly is too time consuming.

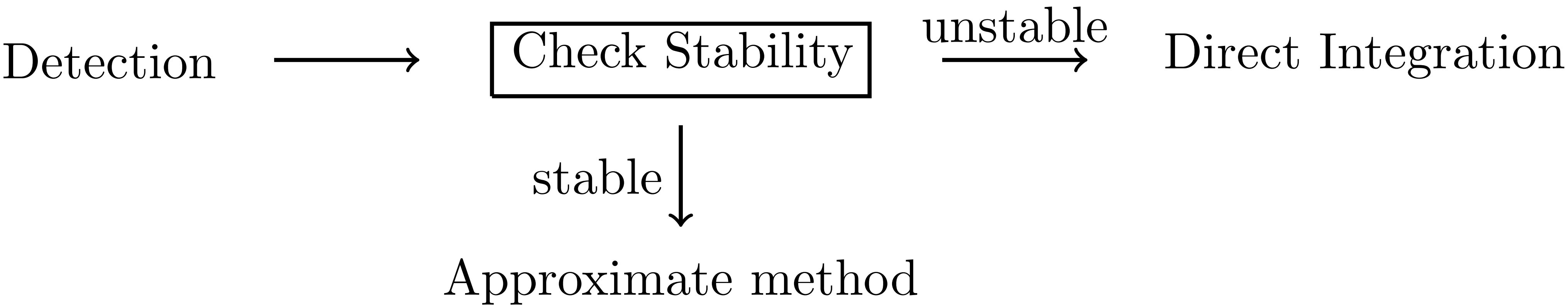


- Binary period ($\sim$ days) $\ll$ typical crossing time t_{cross}($\sim 10^6$ yr)
- For stable systems, we can use proper method such as orbit averaged method.



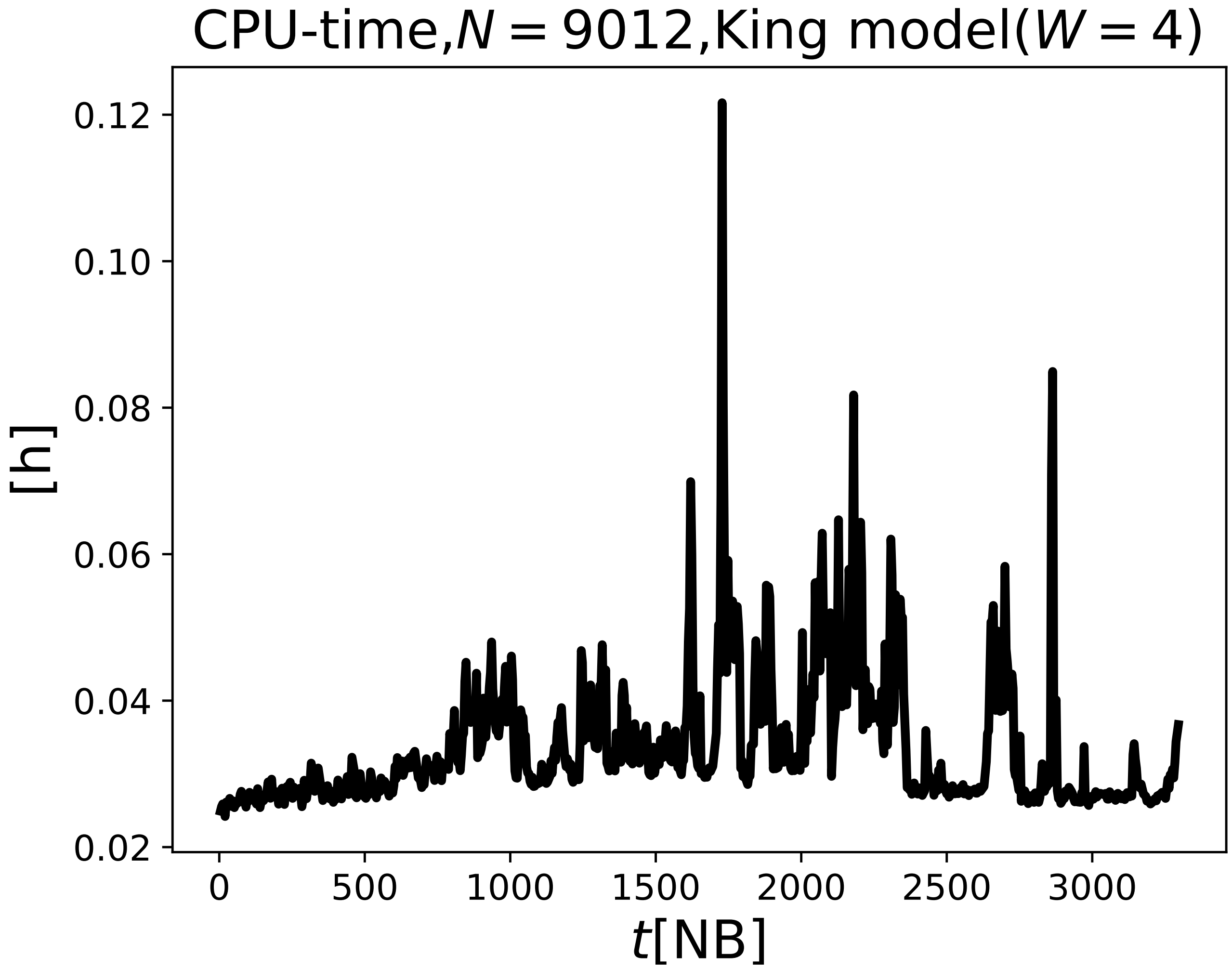
The treatment of binaries in real simulation

1. Detect binary systems.
2. Predict stability of binary systems.
3. If stable, calculate orbit by approximate method.
4. If unstable, calculate orbit by direct calculation.



- The efficiency depends on stablity criterion's precision.
- 3-body stability is only studied by numerically.

- If a stable system regarded as unstable, it costs a lot of time...

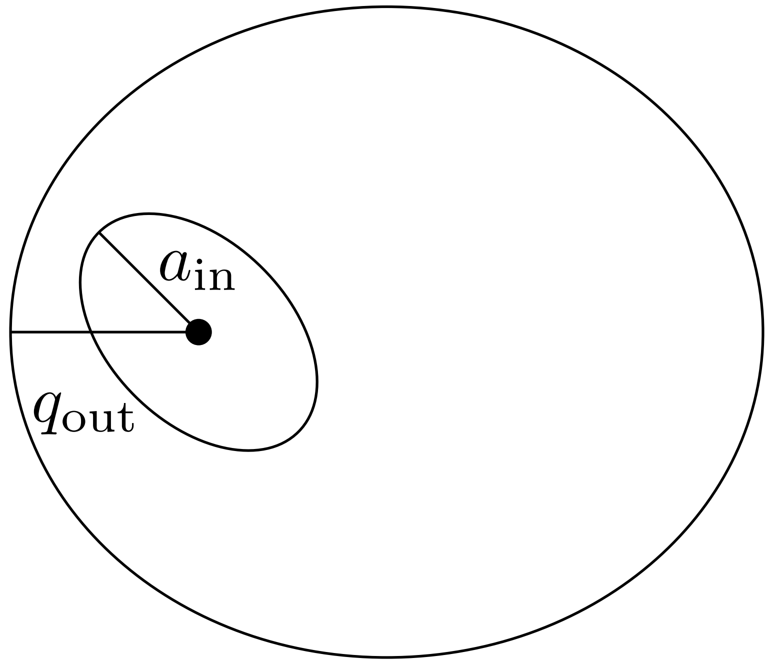


- There is a something wrong within stability criterion...

The traditional 3-body stability criterion

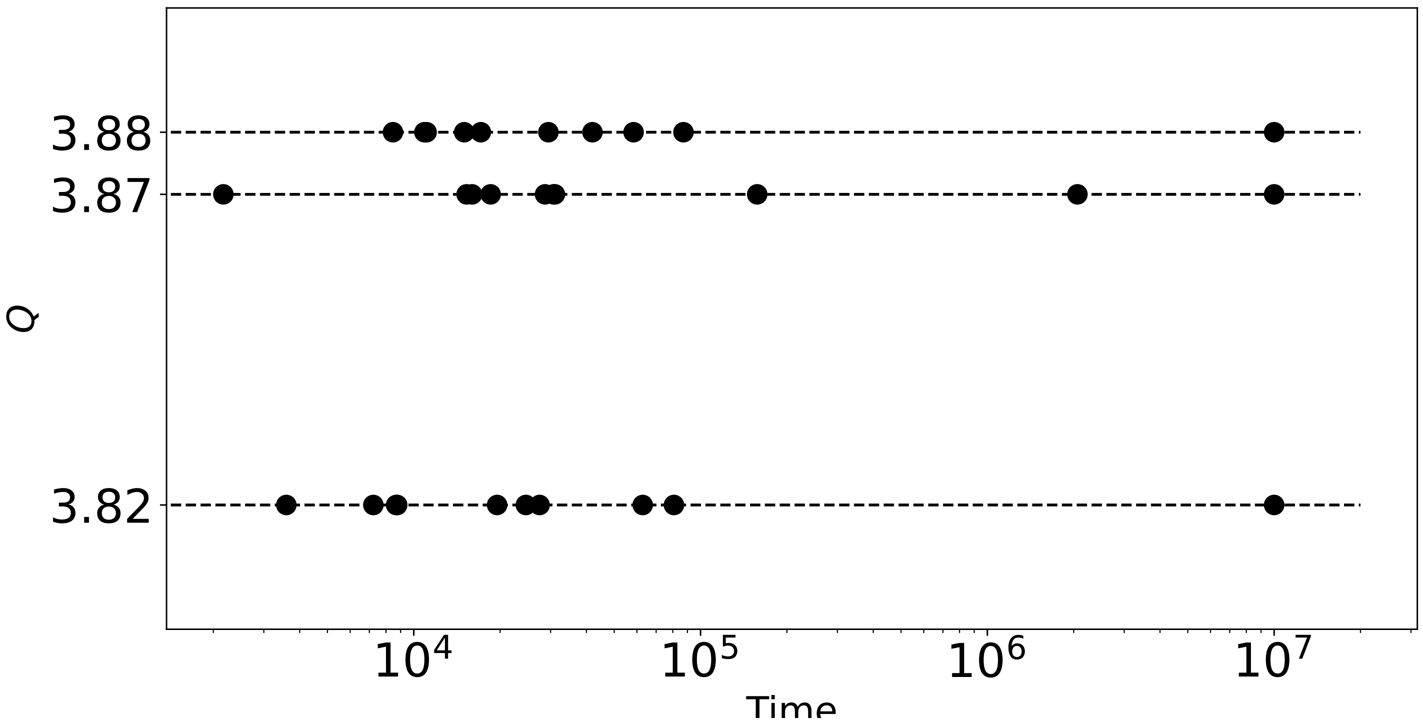
- The traditional parameter Q (Harrington 1972):

$$Q \equiv \frac{q_{\rm out}}{a_{\rm in}} = \frac{a_{\rm out}(1 - e_{\rm out})}{a_{\rm in}}.$$



- This value is not conservative.

Q is inappropripate parameter for stability criterion!



- The stability depends on not only Q but also other parameters.
- Sometimes, the system that has lower Q than stable limit survives for long periods.

Aim and method

- AIM:
  - Understand the bihavior of triple systems and consider the predictability of hierarchical triples' stability.

- While former studies mainly focused on triple's lifespan, we focused on how triples breaks (how instability occurs).

- METHOD:
  - 3-body simulation of coplanar equal-mass hierarhical triple systems on the stable/unstable boundary.
  - The value of Q is varied from
    - from 3.5 to 4.1 (prograde)
    - from 2.3 to 3.1 (retrograde)

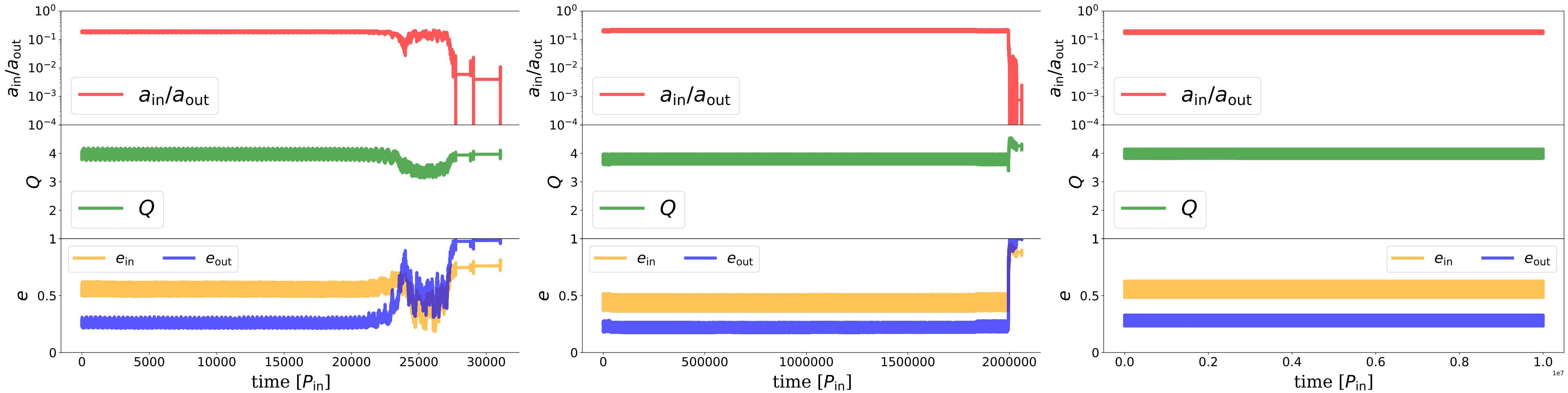
    in increments of 0.01
  - We prepared 10 initial condition for each Q.
  - Eccentricity is set to $e_{\text{in}} = 0.5$, $e_{\text{out}} = 0.25$.
  - Numerical integration up to $10^7 P_{\text{in}}$.
- We compared cases with the same Q but with significantly different survival times.

- NUMERICAL METHOD:
  - Algorithmic regularization

    (Mikkola & Aarseth 1999; Preto & Tremaine 1999)
  - `TSUNAMI` code (Spera & Trani 2022)
  - time-transformed, conserve E & $\mathbf{L}$ well.
  - Our result does not depend on integrators.

Result

- Prograde case $Q = 3.87$, ω and phase are different.

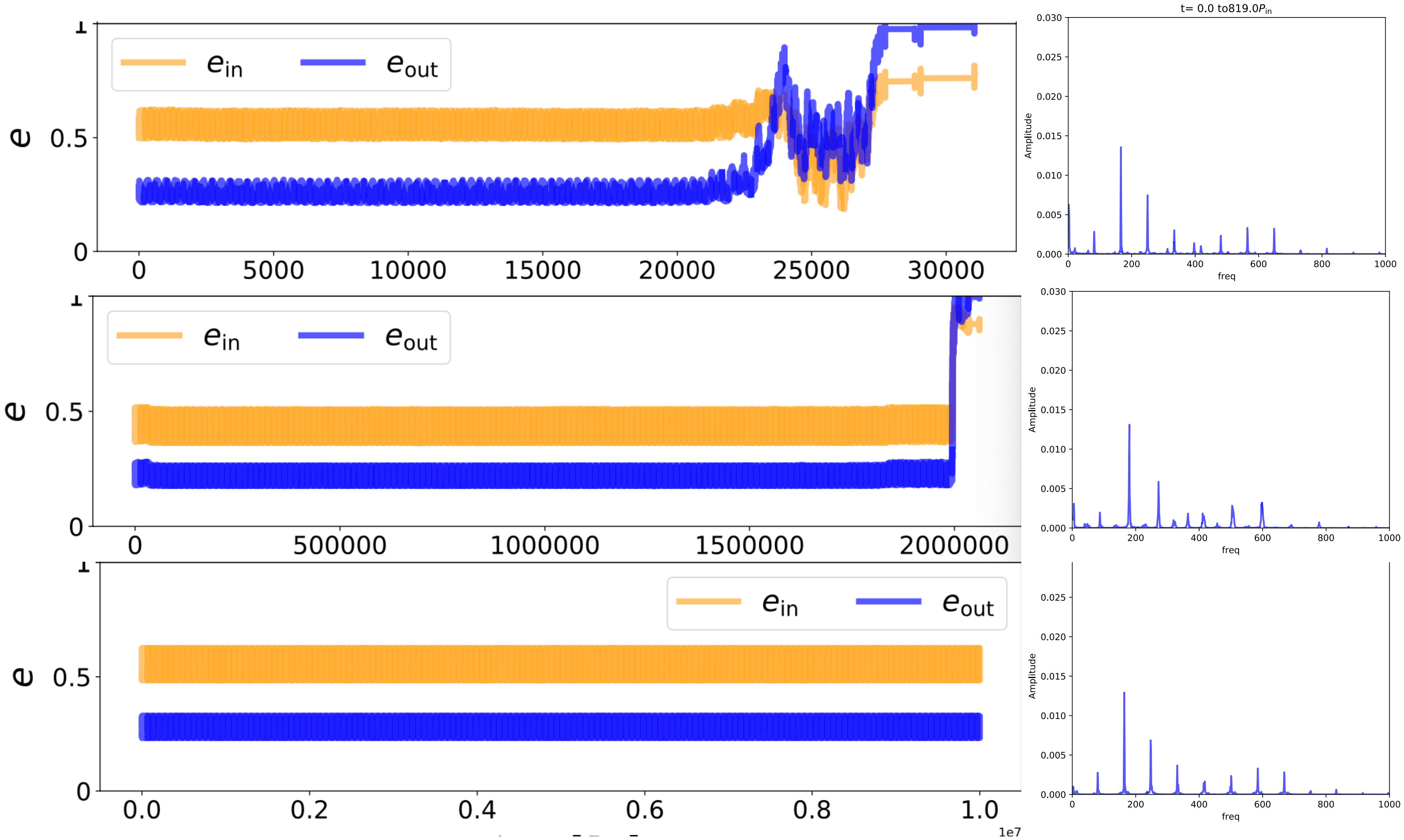


$\sim 10^4 P_{in}$ $\sim 10^6 P_{in}$ $\sim 10^7 P_{in}$

- POINT: We cannot tell them apart form initial Q.

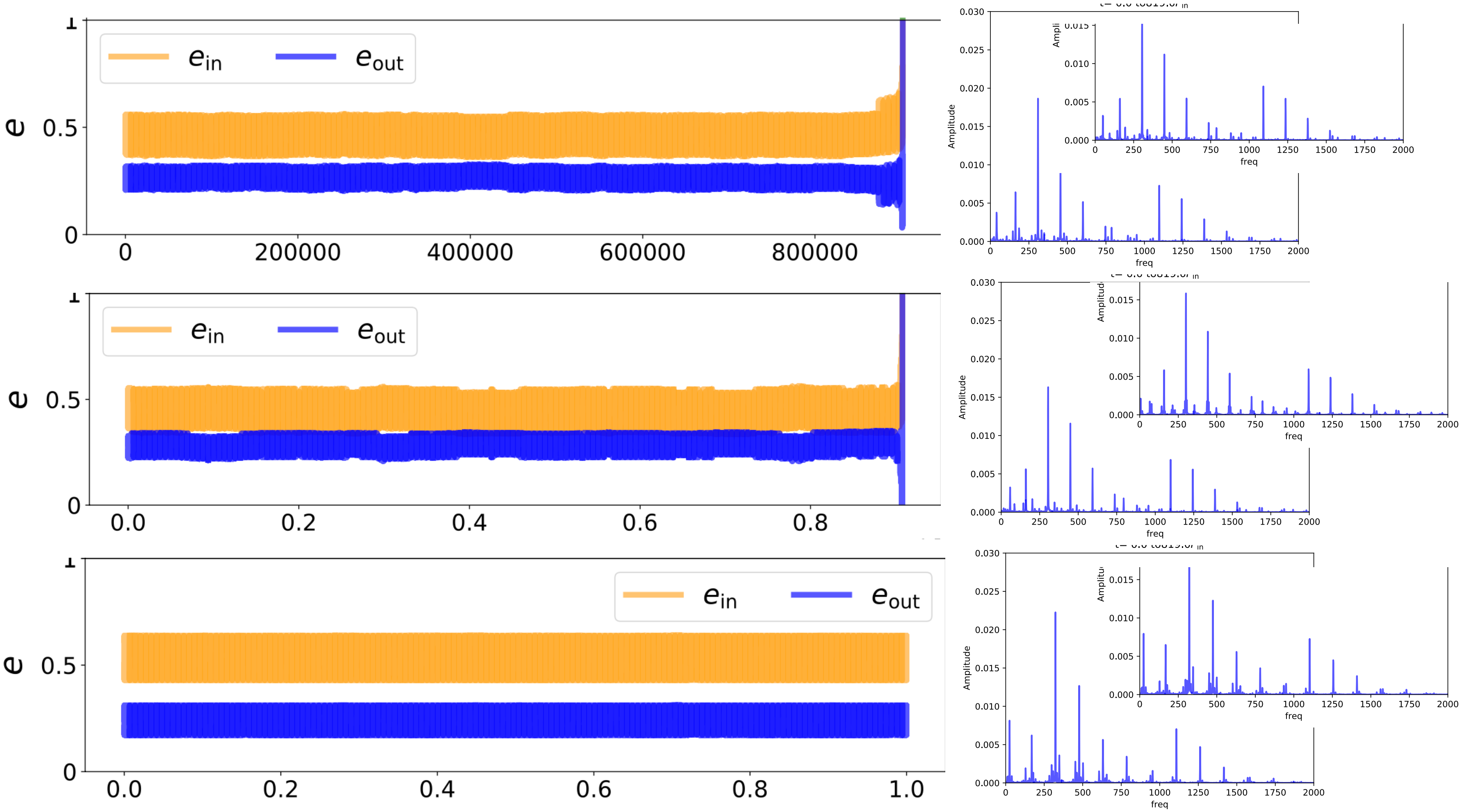
FFT of orbital evolution

- FFT for first $\sim 1000P_{\rm in}$



FFT in retrograde case

- FFT for first $\sim 1000 P_{\rm in}$ and after $10^5 P_{\rm in}$



Causes of instability

- Stable system has stable orbital evolution.
  - In the frequency domain, stable peaks are evenly spaced.
  - Unstable ones have noise between the peaks that shifts, or the paks are not evenly spaced.
- When there are non-periodic components are included in the orbital changes, small changes in the orbit build up over time, eventually leading to close encounters.
- Even within the first $1000P_{\rm in}$, non-periodic components can be observed.

- Is there any room for predictability of the future of hierarchical triple systems?

Conclusion

- We investigated the behavior of hierarchical 3-body systems by numerical integration.
- The traditionally used Q parameter is an inappropriate parameter for stability condition.
- Stable systems exhibit stable orbital evolution.
- In unstable systems, there is an non-periodic orbital evolution, and through this accumulation, the system evolves toward orbital configurations that lead to close encounters (instability).

- We need to investigate the effects of orbital inclination and changes in mass ratios in future.