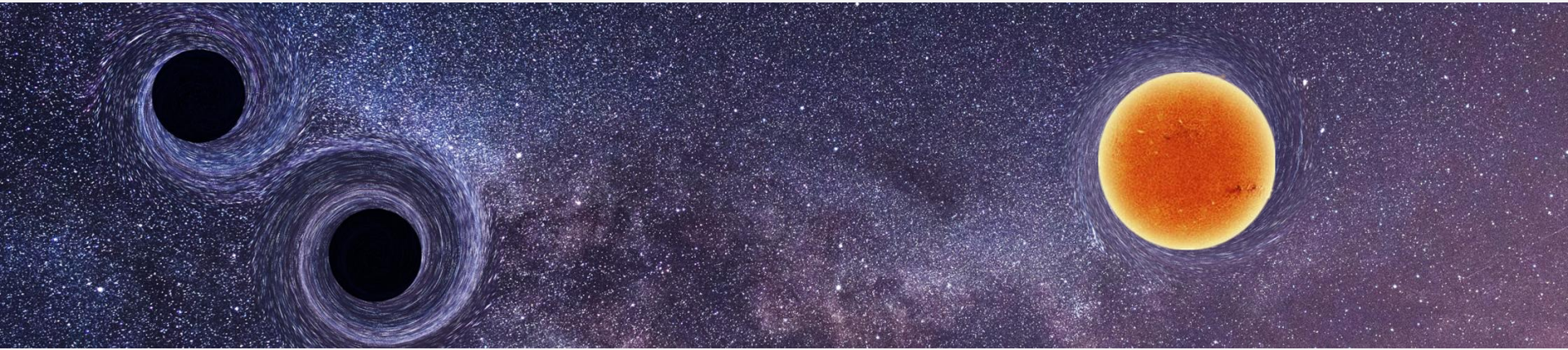


# Extreme resonant eccentricity excitation of stars around merging BH binary

Apsidal Precession Resonance

**Bin Liu**

Transient Phenomena and Physical Processes Around SMBHs Conference @ TDLI | Oct 17th 2024

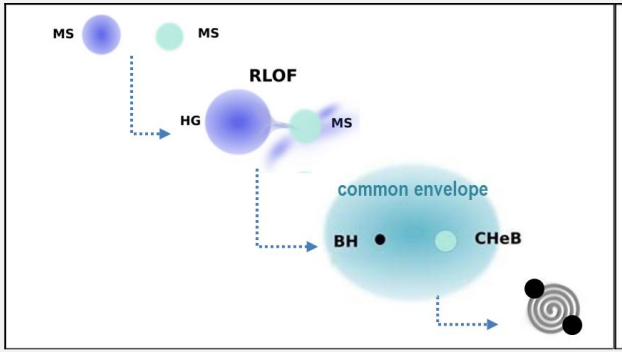
liubin23@zju.edu.cn

浙江大学 ZHEJIANG UNIVERSITY

李政道研究所 TSUNG-DAO LEE INSTITUTE

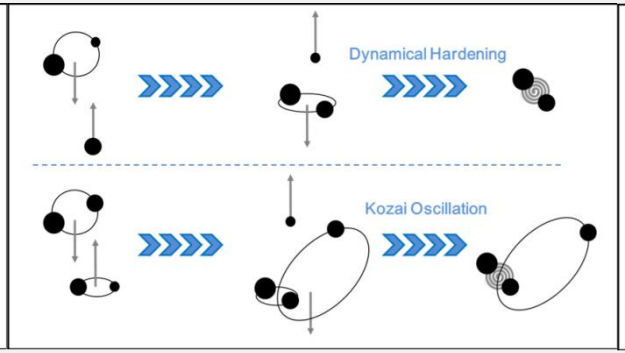
# Formation Channels of LIGO events

## Isolated Binary Evolution




e.g., Lipunov + 1997, 2017;
Podsiadlowski + 2003;
Belczynski + 2010, 2016;
Dominik + 2012;
Han + 2020;
Shao & Li 2019-2022;
etc

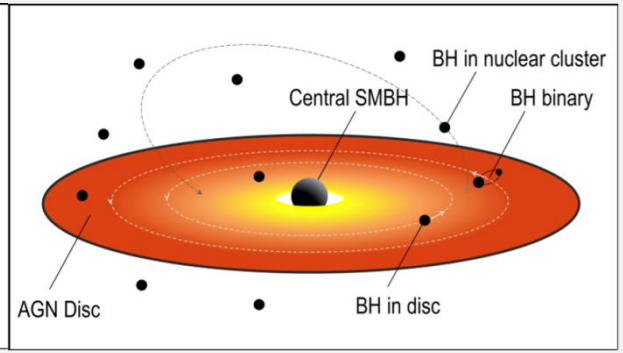
## Dynamical Formation




--- **"Strong" Scatterings:**
e.g., Portegies Zwart & McMillan 2000;
Miller & Lauburg 2009;
Rodriguez + 2015, 2018;
Samsing + 2017, 2018; etc

--- **"Gentle" Tertiary-Induced:**
e.g., Silsbee & Tremaine 2017;
Antonini + 2017;
Hamers + 2018, 2019;
**Liu & Lai 2017-2021;**

## AGN disk Channel

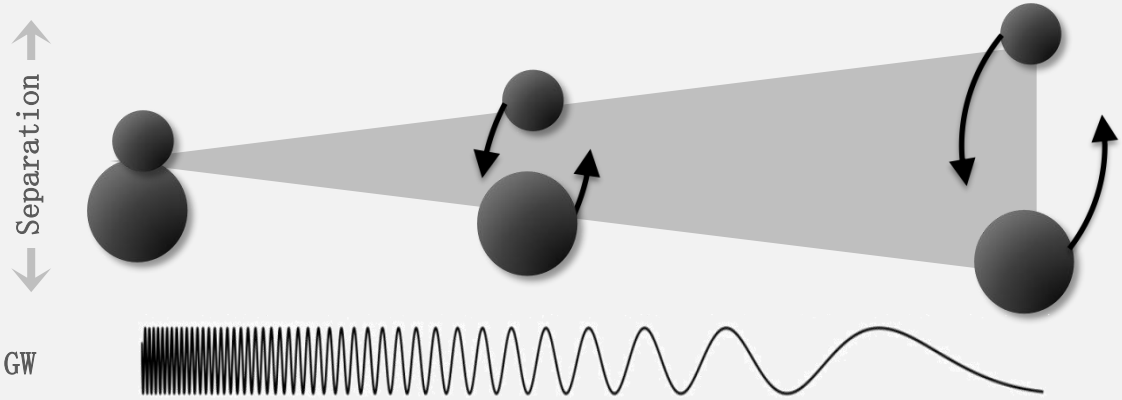



...

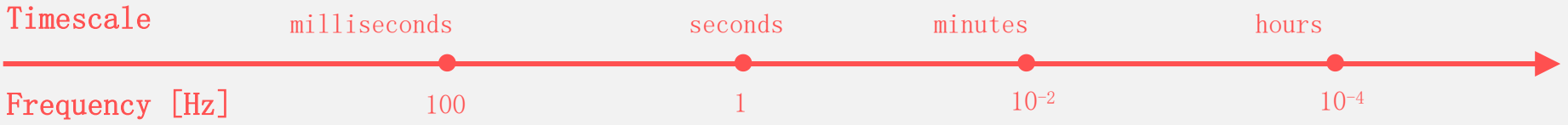
e.g., Cheng & Wang 1999;
Tagawa + 2020, 2021;
Wang J. M. + 2021;
Pan Z. + 2021;
Samsing + 2022;
Li Y. P. + 2021, 2022;
Li R. X. & Lai D. 2022a, 2022b;
Li J. R. + 2022a, 2022b;
Chen K. + 2023;
Wang M. Y. + 2023; etc.

# GW Sources

LIGO Merger rate → ~$10^{-4}$ galaxy$^{-1}$yr$^{-1}$ → ~$10^{2}$ BHBs galaxy$^{-1}$




constrain formation channel



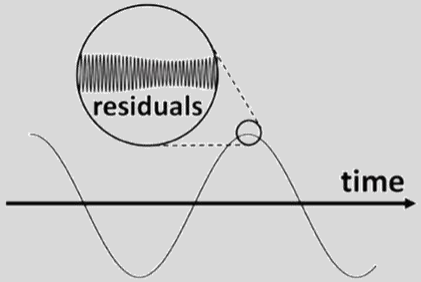

How to find the BHB that is far from merger?


Others include
TianQin,
TaiJi
DECIGO,
etc

# Solar type Star Near a Massive BH Binary

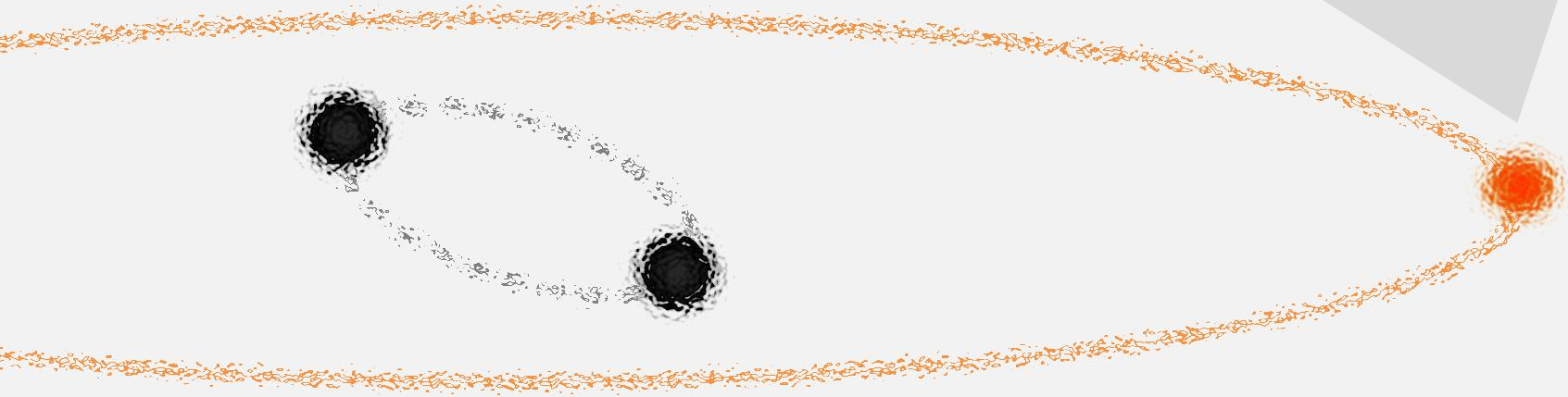
- **Short-term Evolution**

*Hayashi + 2019, 2020*

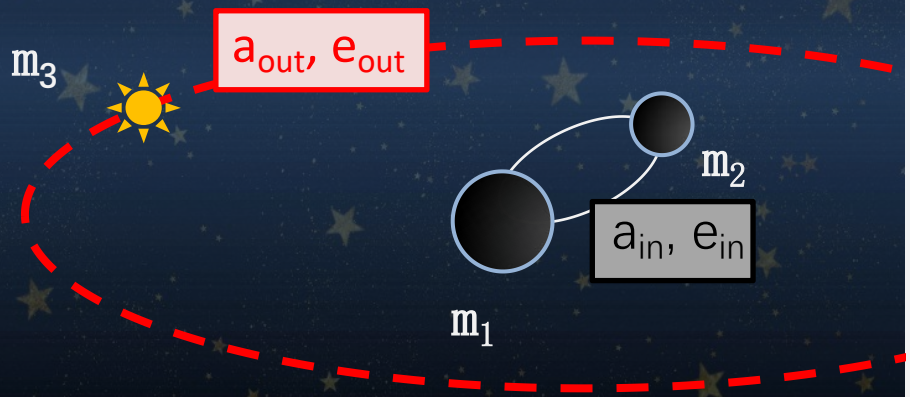



RV curve for $m_*$

short-term RV variations due to BHB period: ~ $P_{in}/2$

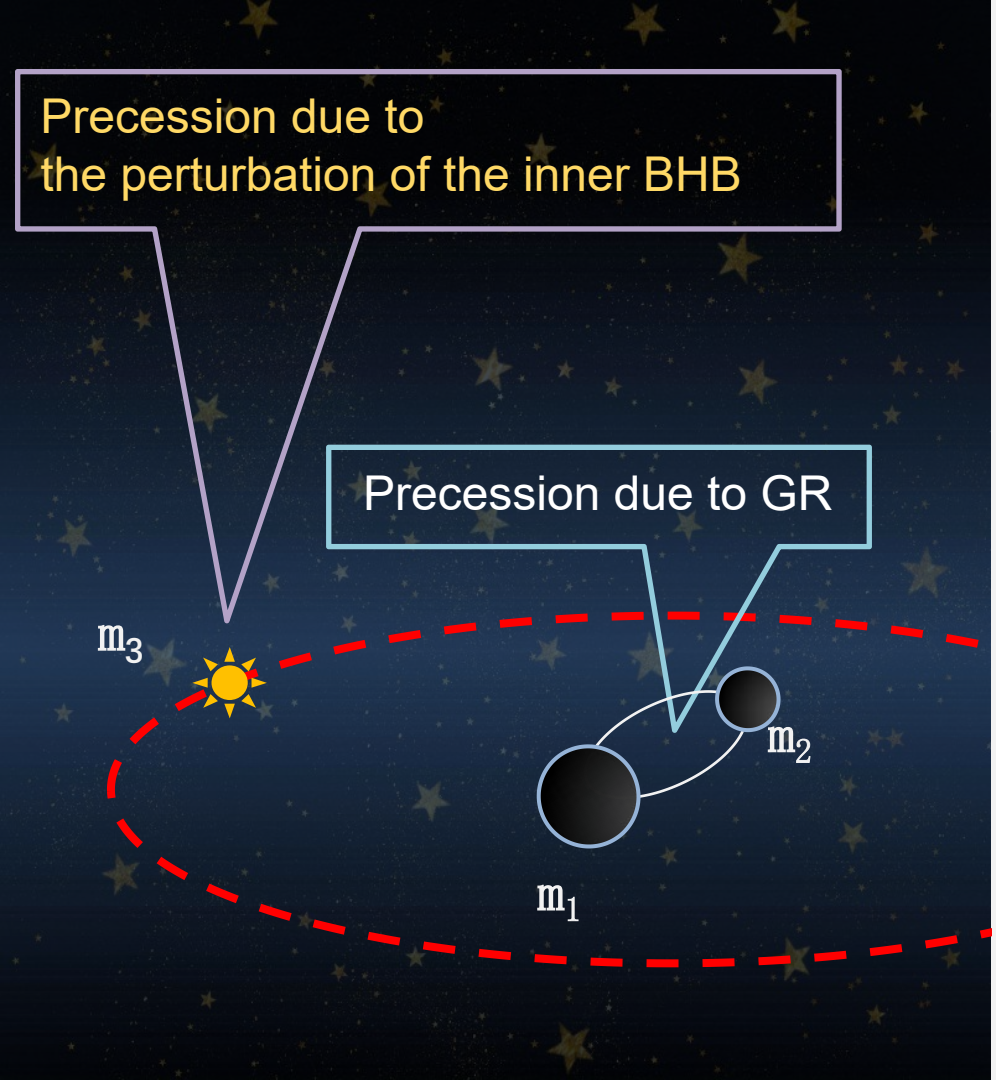


# A solar type star orbiting around a BHB

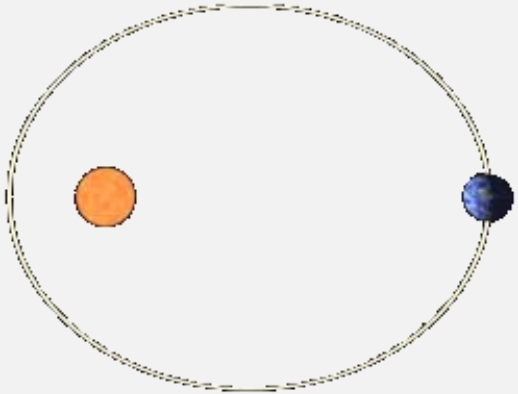



## Focus on:

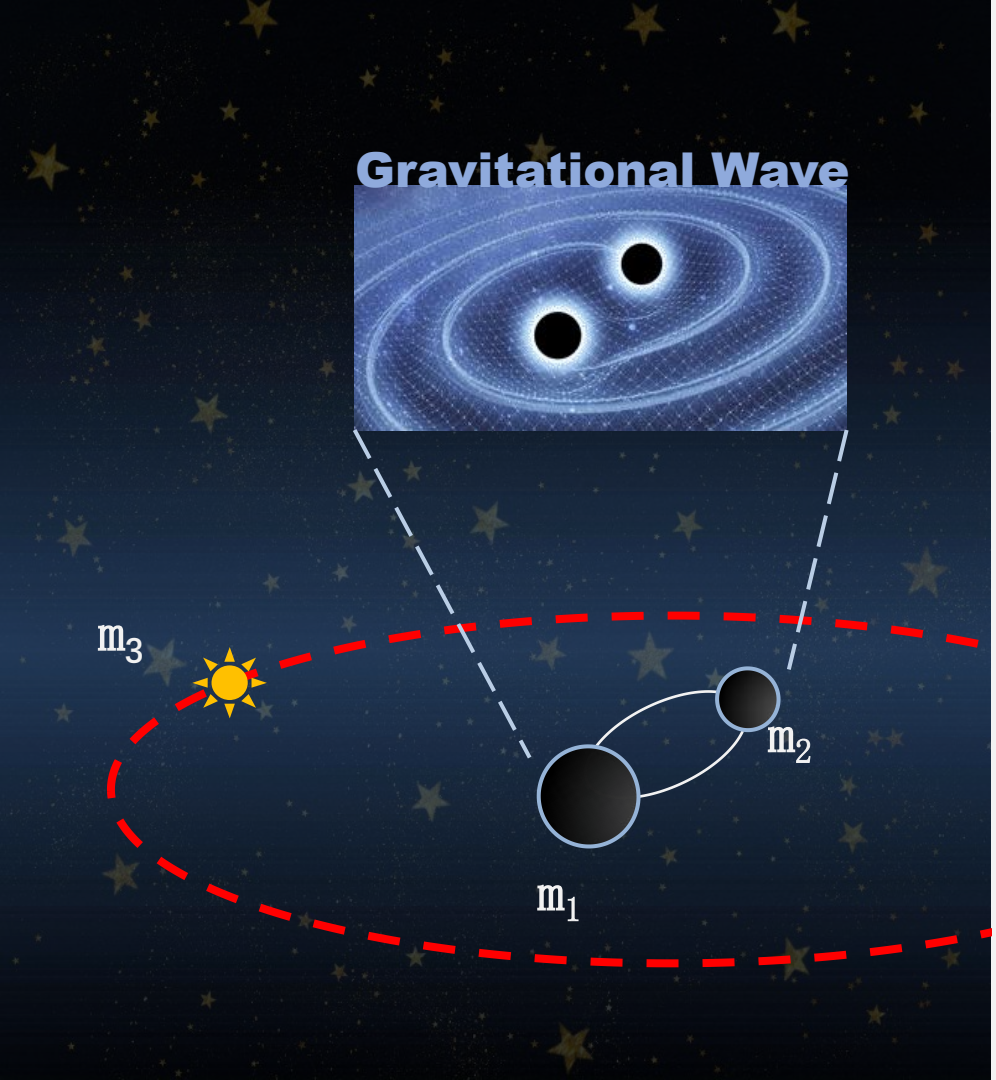
- $m_1 + m_2 \gg m_3$
- $a_{out} \gg a_{in}$ (hierarchical system)
- Secular approximation (Orbital averaging)
- Coplanar configuration




- Apsidal precession in a binary



Liu, et al, 2022, PRD




# System Setup:

Black hole binary (eccentric)
+
Tertiary star (quasi-circular)

Let's consider

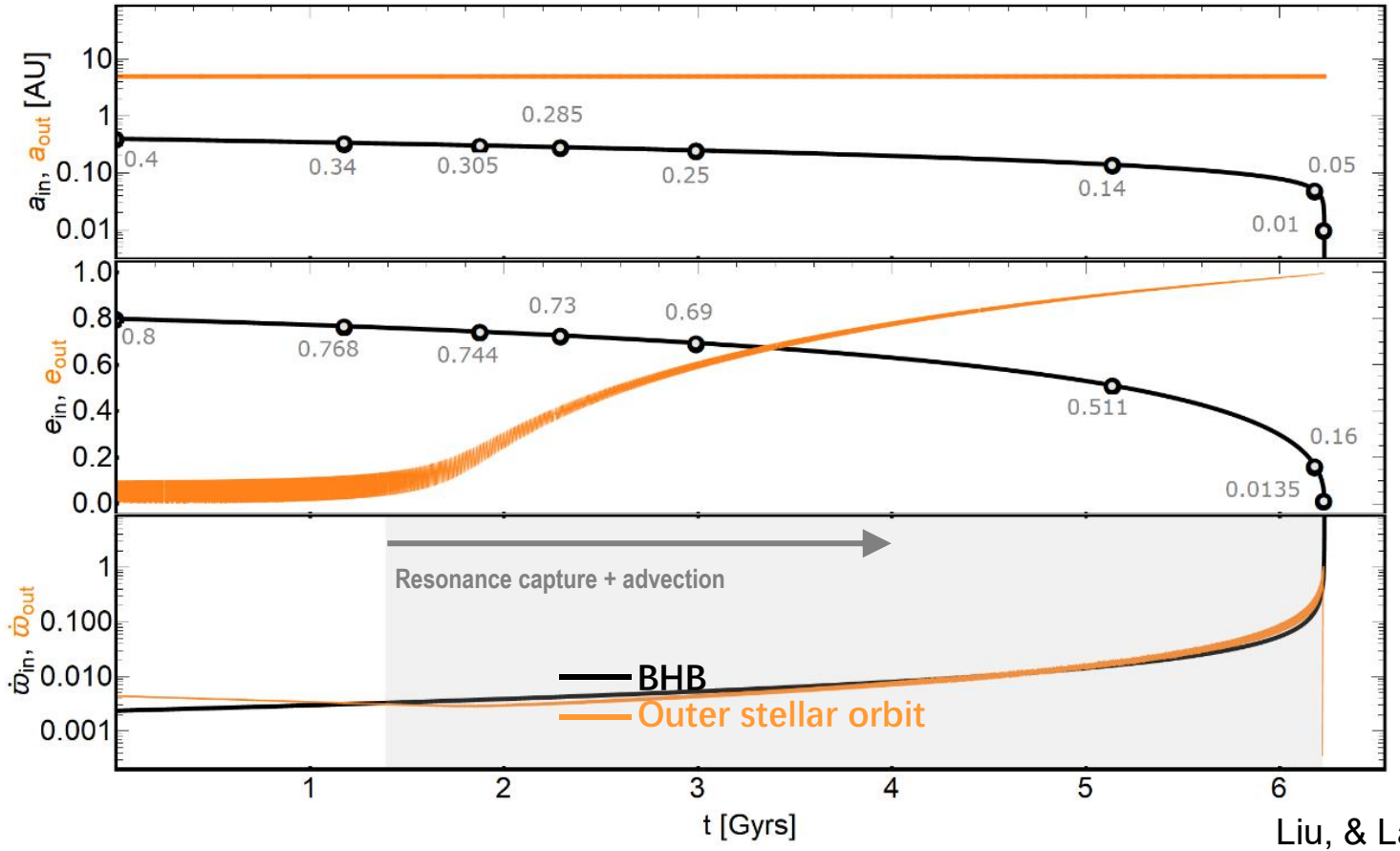
orbital decay of the BHB

To see

what happen to $e_{out}$ ?

# Example of orbital evolution

$m_1 = 46\ M_\odot$, $m_2 = 14\ M_\odot$, $m_3 \sim$ TP ; $e_{in,0} = 0.8$, $e_{out,0} = 0.1$




Liu, & Lai, PRL, 2024

# Phase space diagram

- **Dynamics can be understood analytically for coplanar triples**

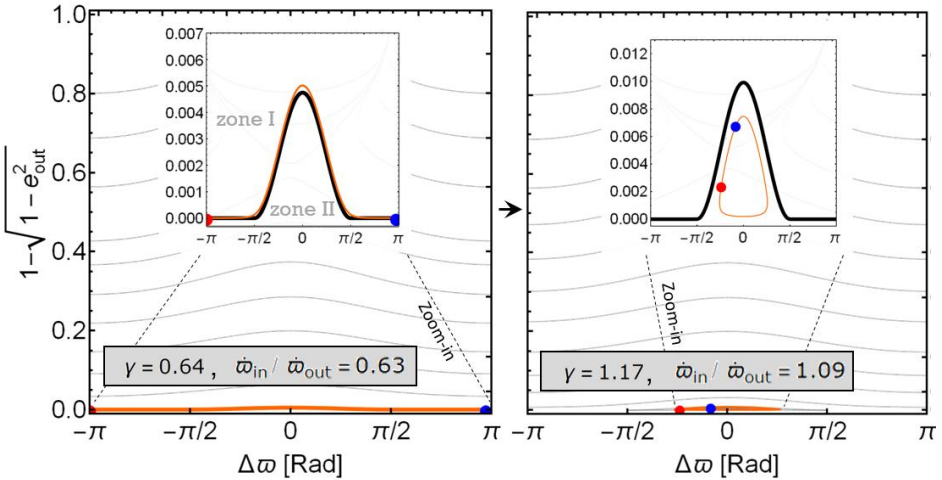
$$\gamma \equiv \frac{\dot{\varpi}_{\rm in}}{\dot{\varpi}'_{\rm out}}$$

Dimensionless Hamiltonian:

$$\overline{\mathcal{H}} = A\left[\frac{B + C\frac{e_{\rm out}}{1-e_{\rm out}^2}\cos\Delta\varpi}{6(1-e_{\rm out}^2)^{3/2}} - \gamma\sqrt{1-e_{\rm out}^2}\right]$$

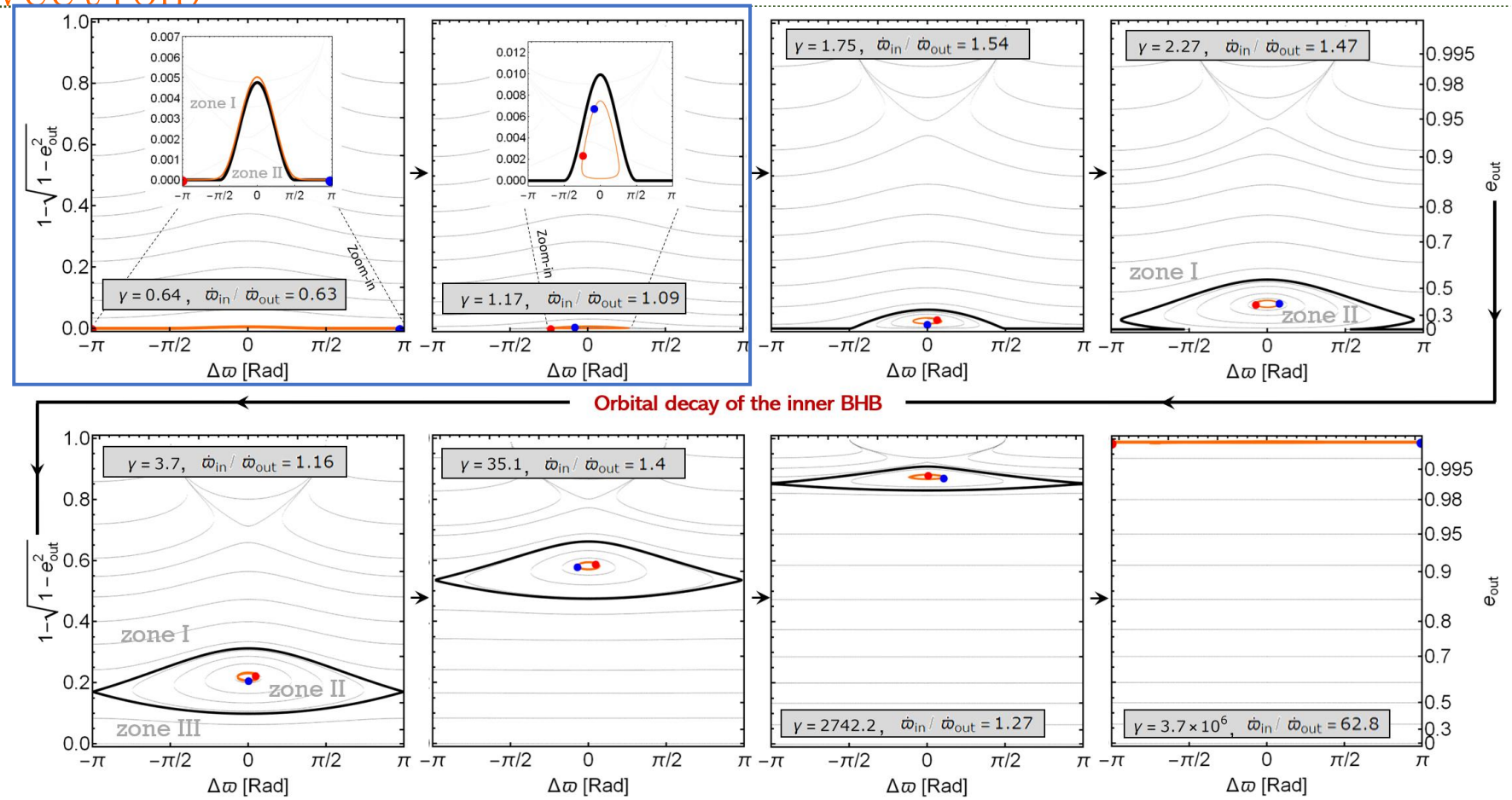
$$\begin{cases} A \equiv \left(\dfrac{a_{\rm in}}{a_{\rm in,0}}\right)^2, \\ B \equiv -2 - 3e_{\rm in}^2, \\ C \equiv \dfrac{15}{8}\dfrac{m_1 - m_2}{m_1 + m_2}\dfrac{a_{\rm in}}{a_{\rm out}}e_{\rm in}(4 + 3e_{\rm in}^2), \end{cases}$$

Phase space diagram:

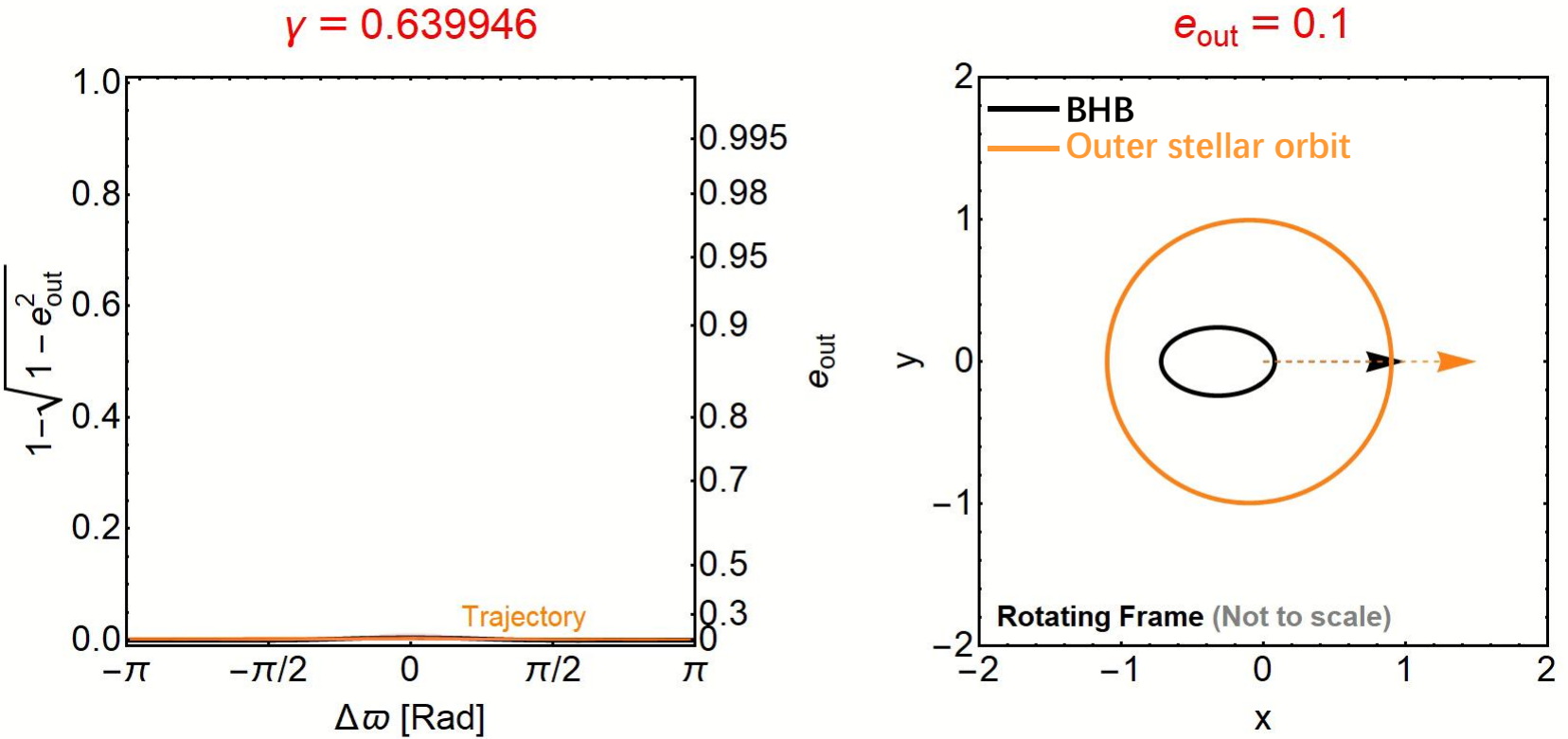



Resonance Capture (Separatrix crossing)

# Phase space diagram (Resonance capture + advection)



# Phase space diagram

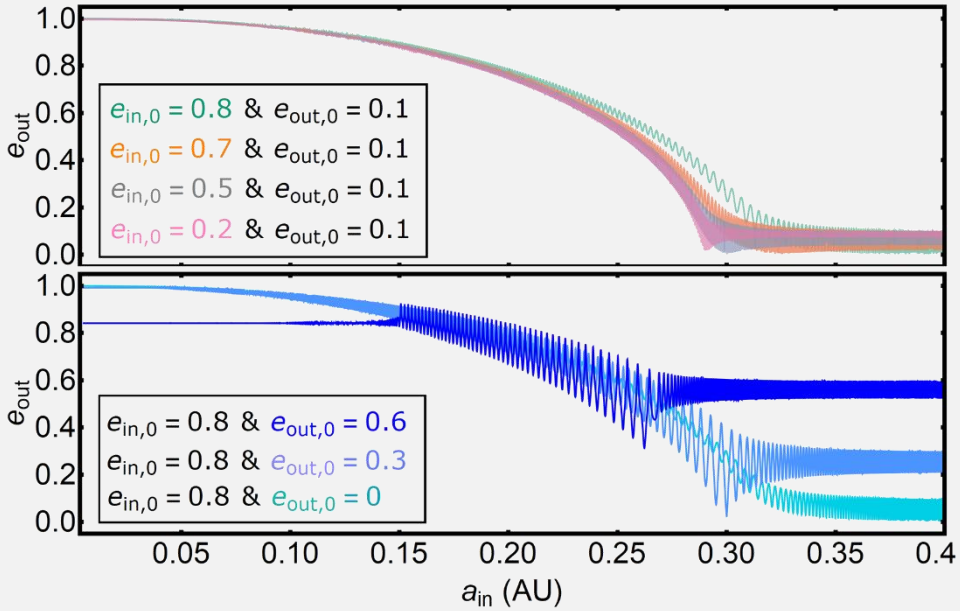



Liu, & Lai, PRL, 2024

# Resonance capture and advection

*See also: Heppenheimer 1980; Ward 1981; Nagasawa + 2003*

- **Dependence on the initial eccentricities**

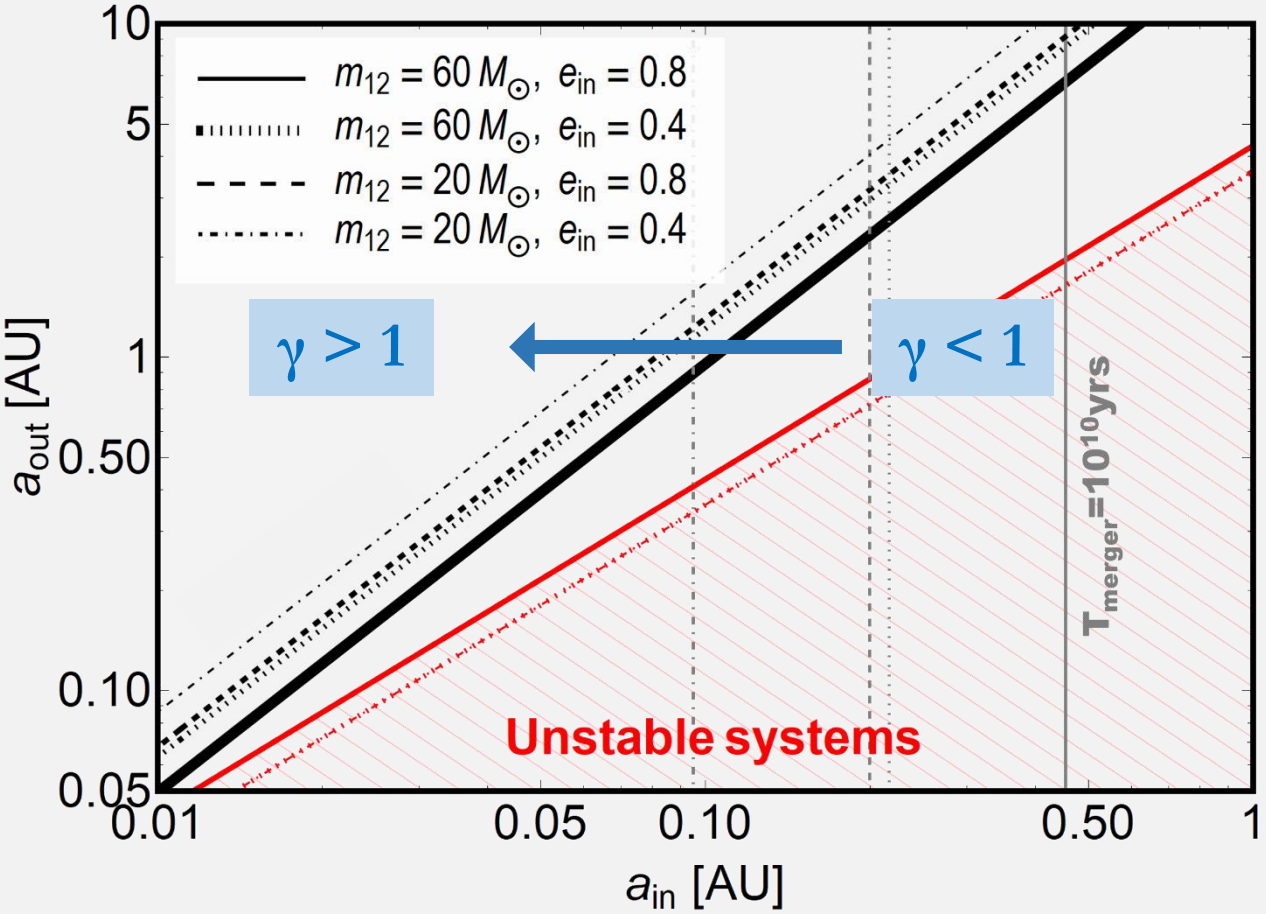



- **Requirements for the system to end up captured into resonance advection have to be satisfied**

I. Adiabatic evolution
II. Specific direction of time-varying $\gamma$
III. Sufficiently small initial eccentricity : $e_{\rm out,0} \simeq \frac{15}{8}\frac{m_1-m_2}{m_1+m_2}\frac{a_{\rm in}}{a_{\rm out}}e_{\rm in}(4+3e_{\rm in}^2)$ (at $\gamma \sim 1$)

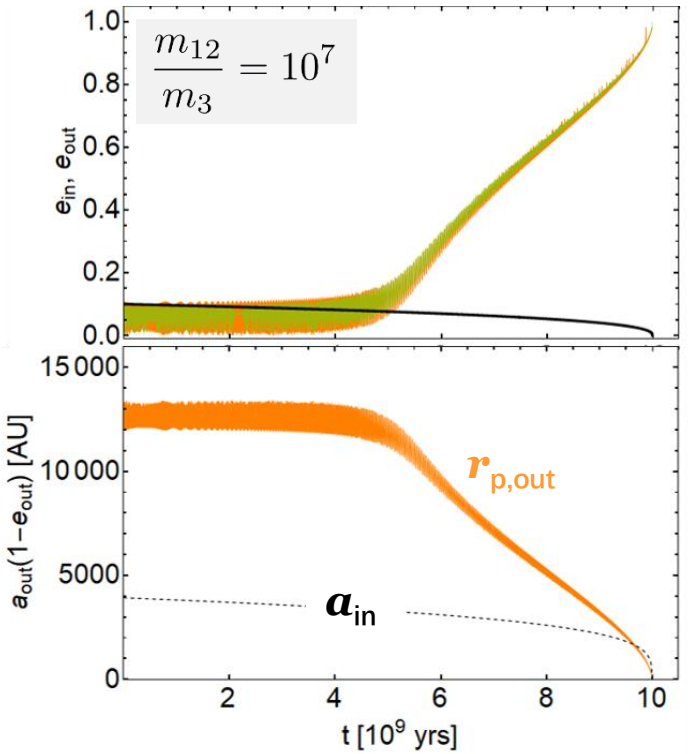
Liu, & Lai, PRL, 2024

# Parameter Space

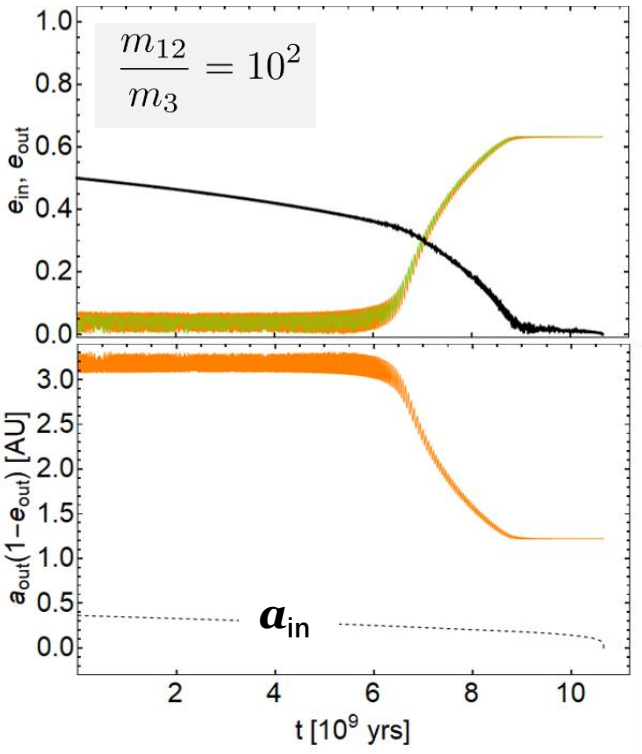


# Eccentricity excitation of the outer binary

SMBH binary + Star

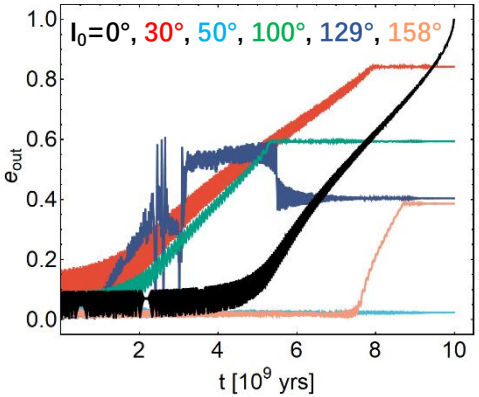


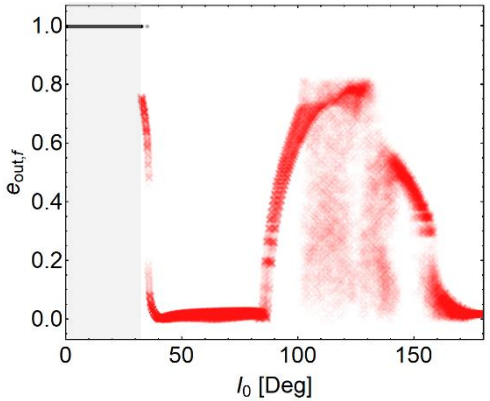

Massive BH binary + Star



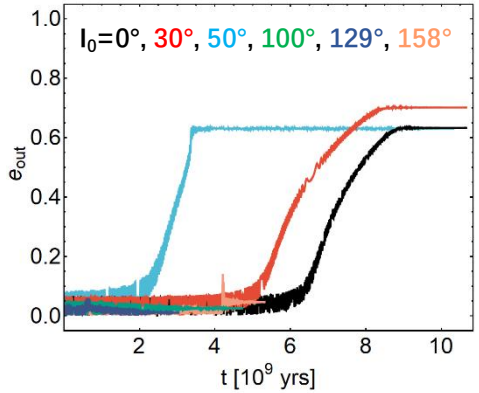
# Inclined systems

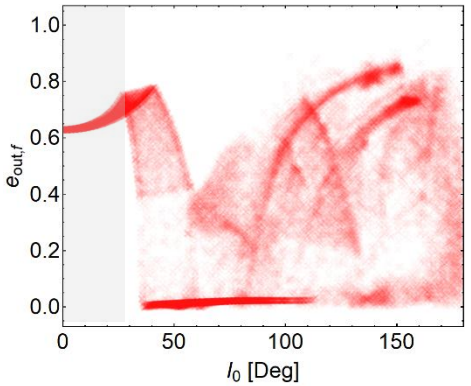
**SMBH binary**
**+**
**Star**



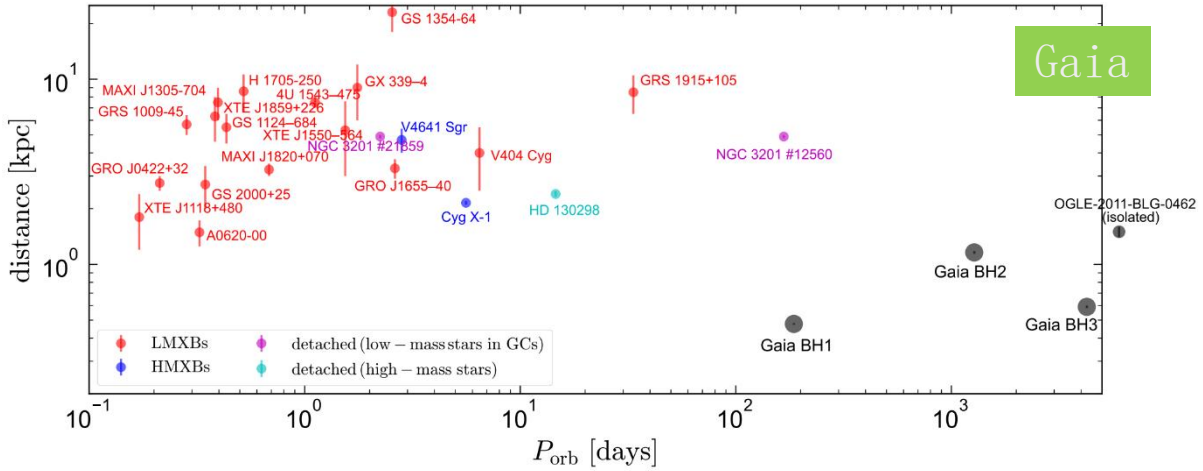




**Massive BH binary**
**+**
**Star**



# Binary with a unseen companion



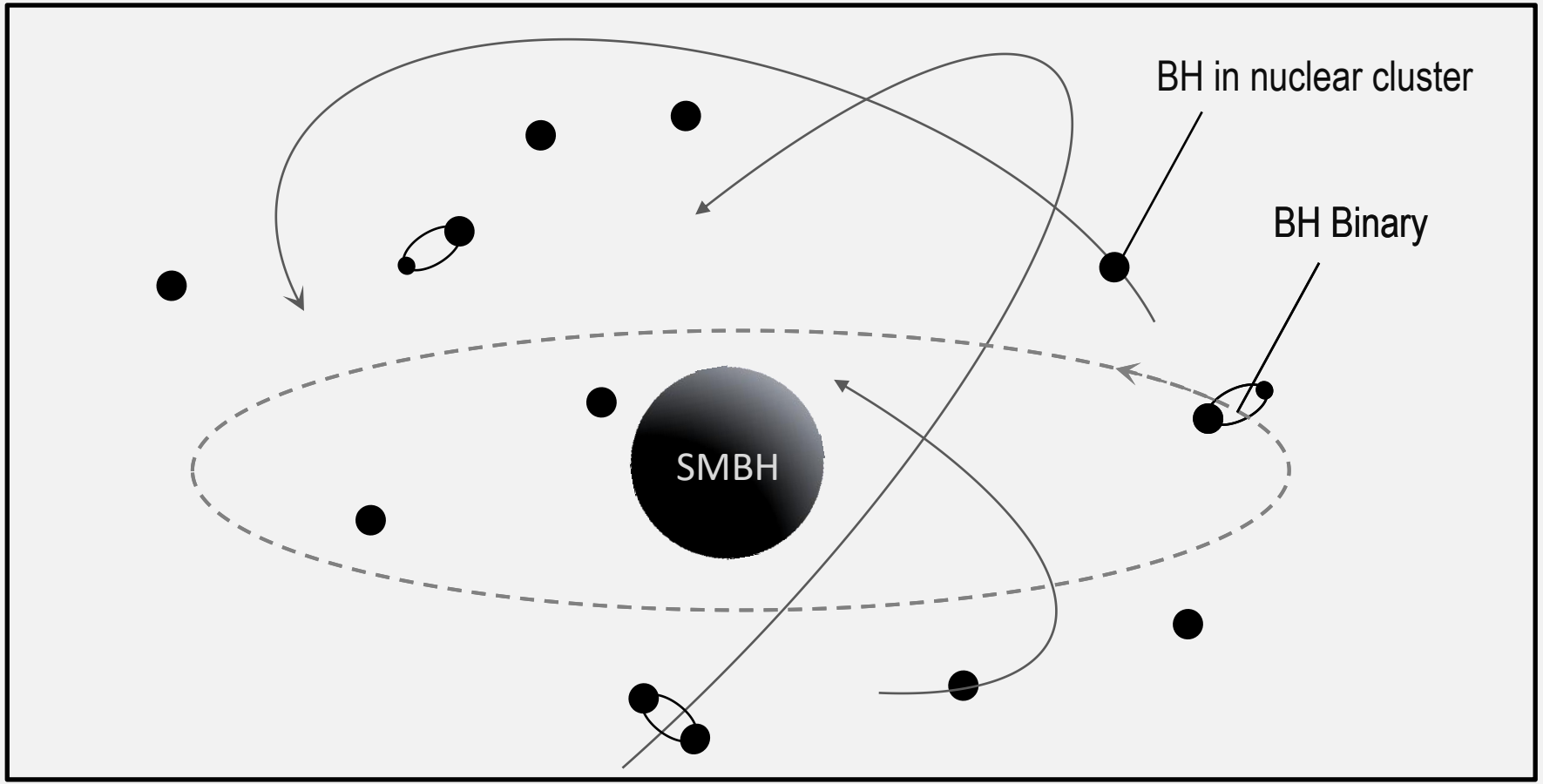

Gaia

El-Badry K., 2024, NewAR

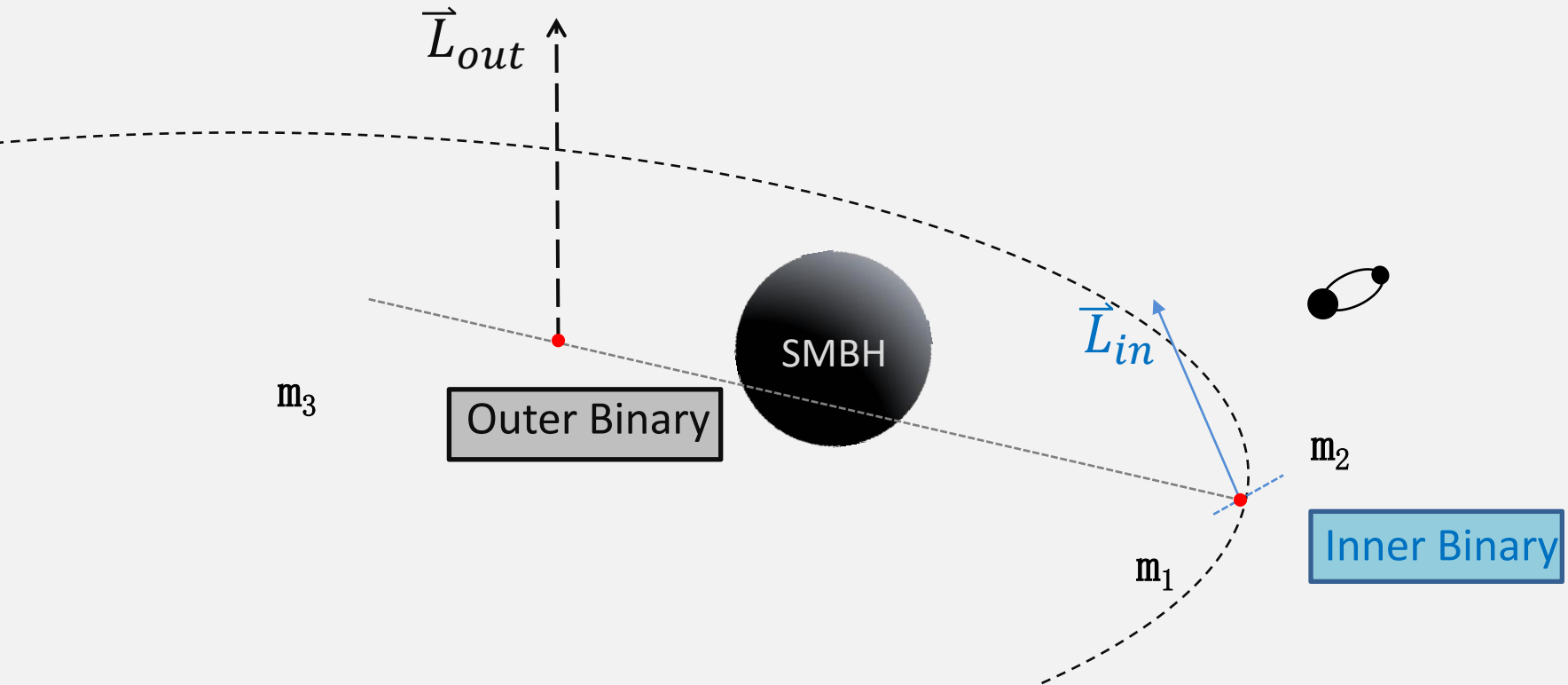
| Gaia BH1 | Gaia BH2 | Gaia BH3 |
|---|---|---|
| D ~ 478 pc | D ~ 1160 pc | D ~ 590 pc |
| $m_{BH} \sim 10\ M_\odot$ | $m_{BH} \sim 9\ M_\odot$ | $m_{BH} \sim 33\ M_\odot$ |
| $m_* \sim 1\ M_\odot$ | $m_* \sim 1\ M_\odot$ | $m_* \sim 0.8\ M_\odot$ |
| $P_* \sim 185$ days | $P_* \sim 3.5$ yrs | $P_* \sim 11.6$ yrs |
| $e_* \sim 0.45$ | $e_* \sim 0.51$ | $e_* \sim 0.7$ |

...

# **INVERSE CASE**: Binary Near a Supermassive BH

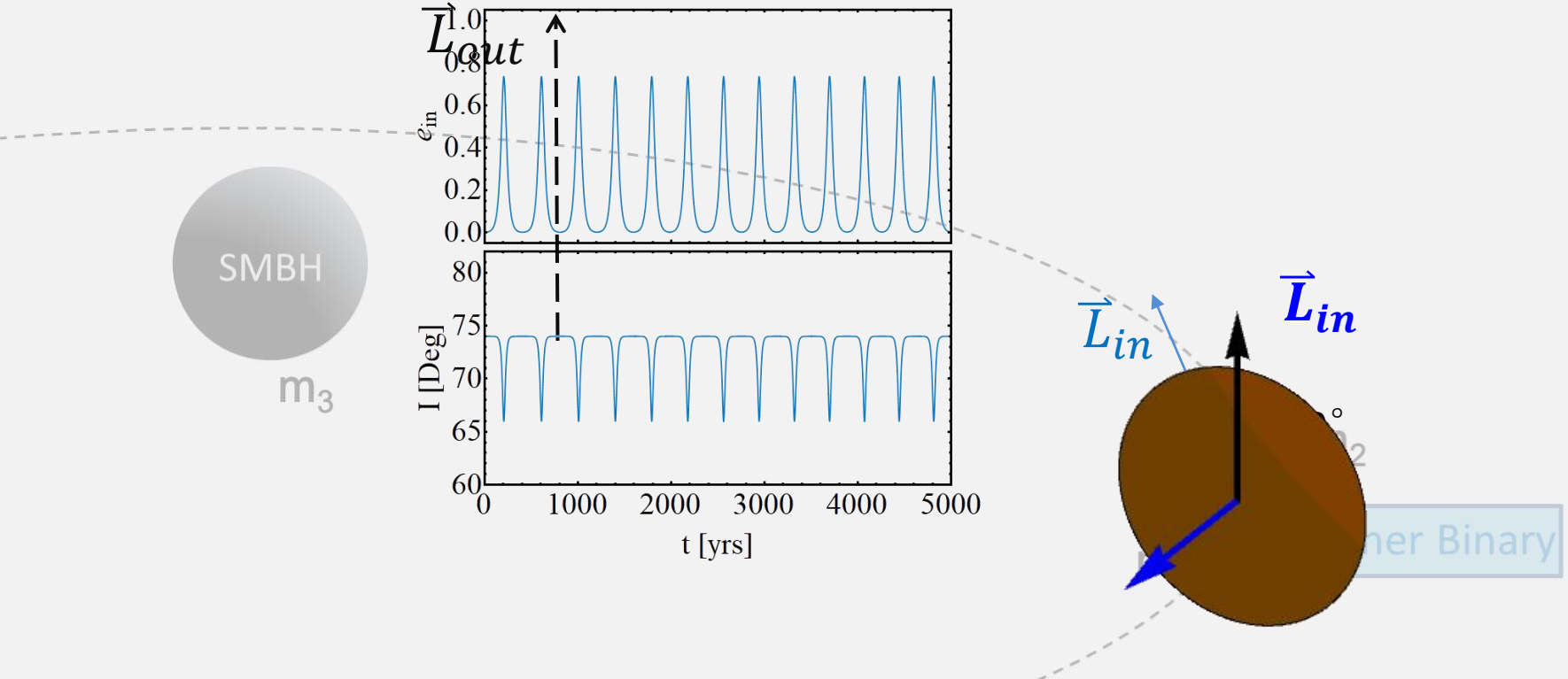


# Binary - SMBH Interaction



# Binary - SMBH Interaction

--- Newtonian Effect: Lidov-Kozai Oscillations

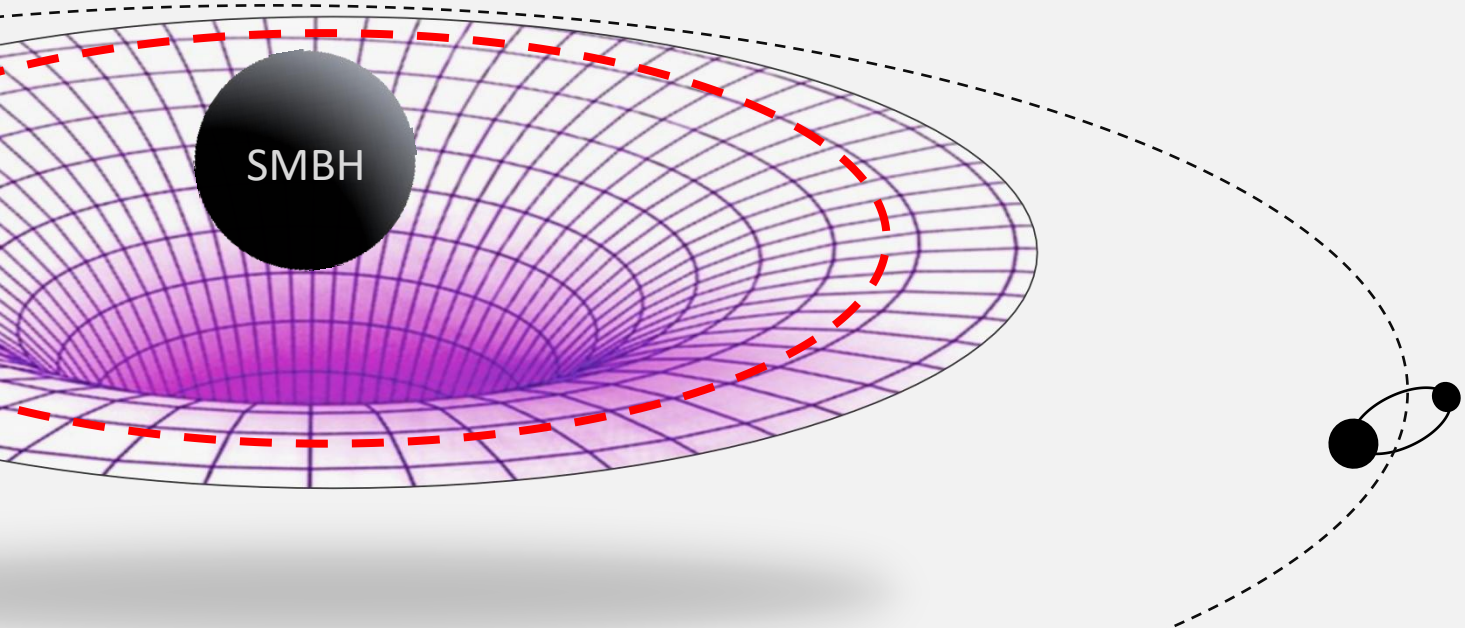


# Binary Dynamics Near a Supermassive BH

--- Newtonian Effect: Kozai Oscillations

--- GR Effect involving SMBH Tertiary

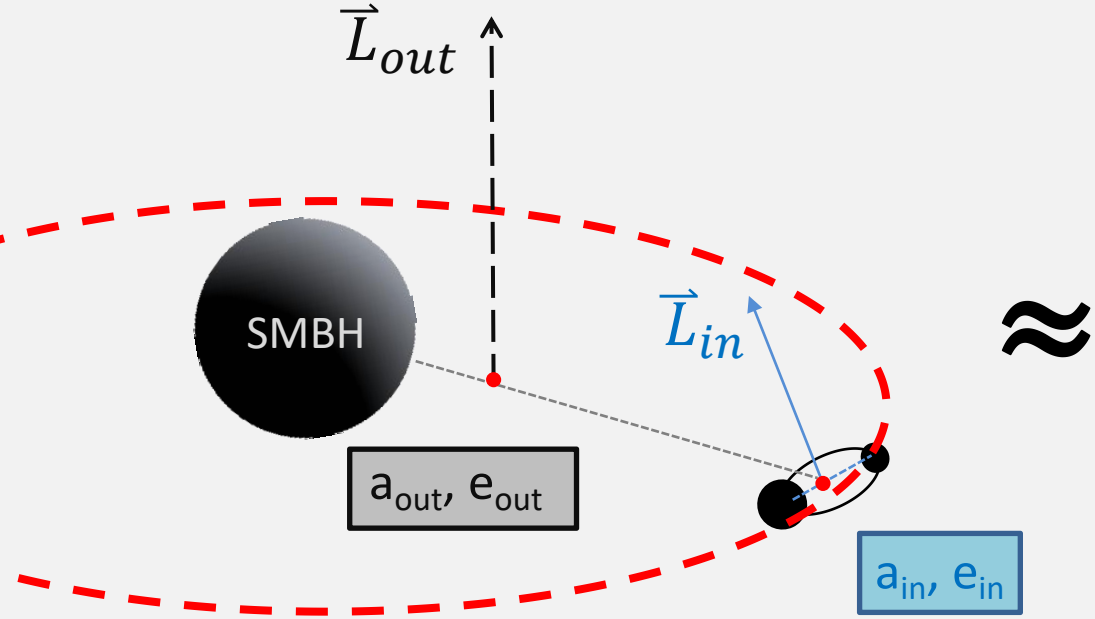
**Strong GR effect induced by the SMBH**



# Binary Dynamics Near a Supermassive BH

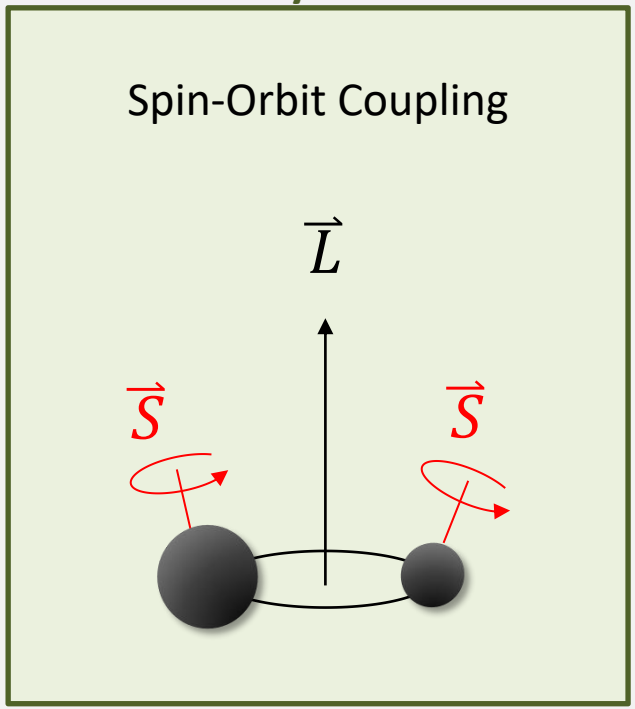
--- Newtonian Effect: Lidov-Kozai Oscillations

--- GR Effect: Precession of $L_{in}$ around $L_{out}$ (1.5 PN)




≈

**Isolated Binary**

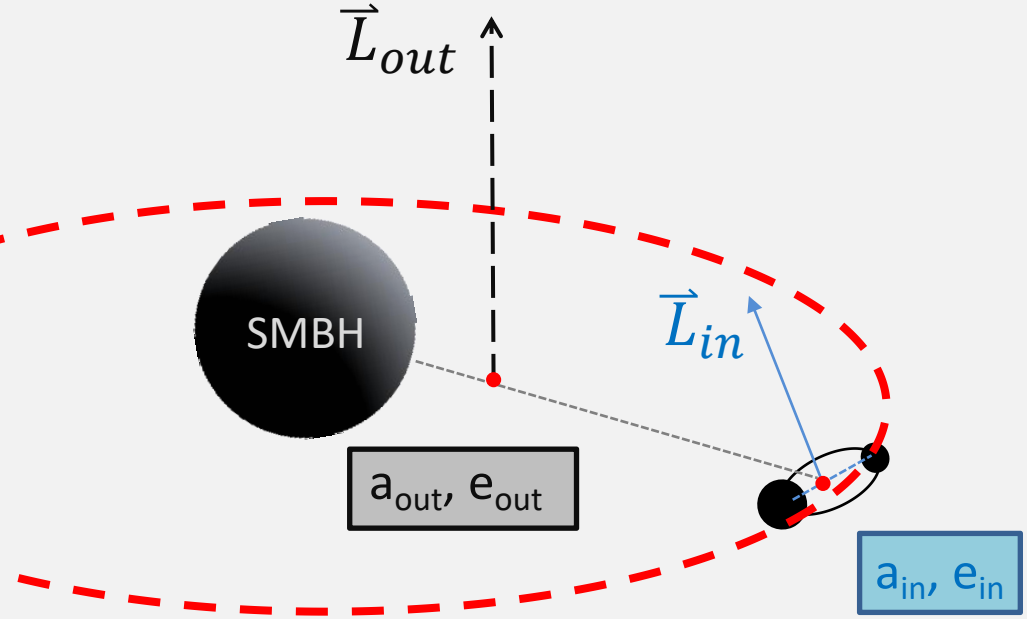


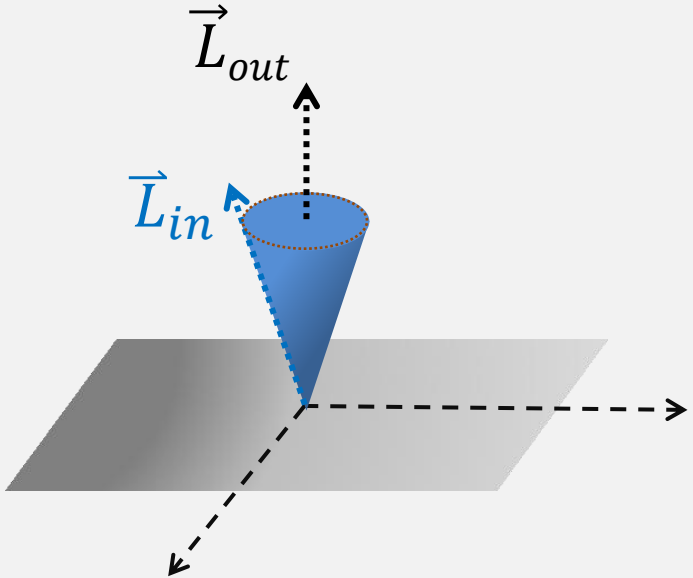

*Liu & Lai ApJL 2019*

# Binary Dynamics Near a Supermassive BH

--- Newtonian Effect: Lidov-Kozai Oscillations

--- GR Effect: Precession of $L_{in}$ around $L_{out}$ (1.5 PN)



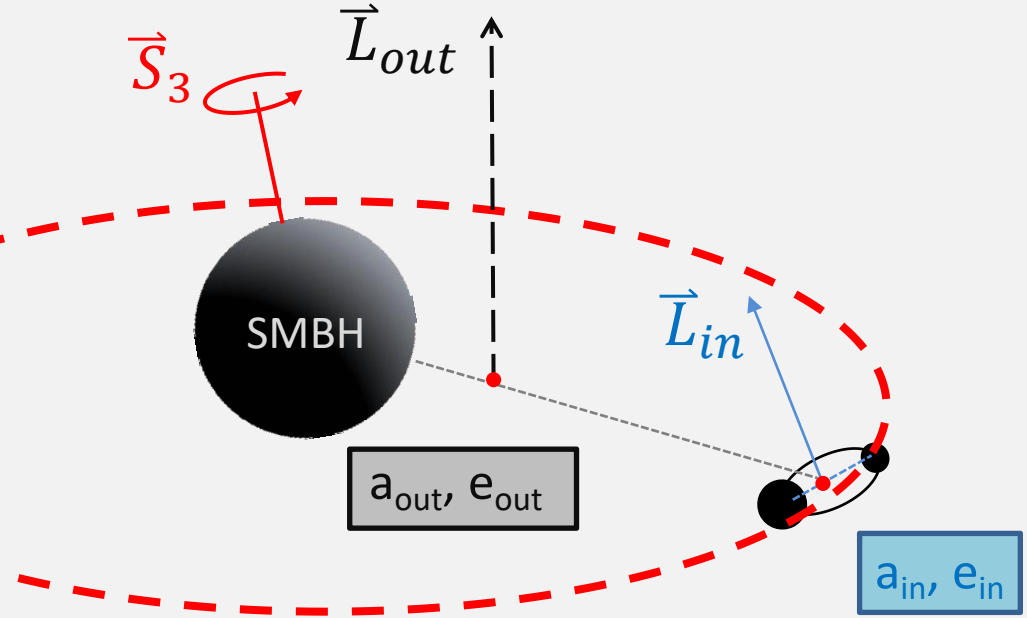



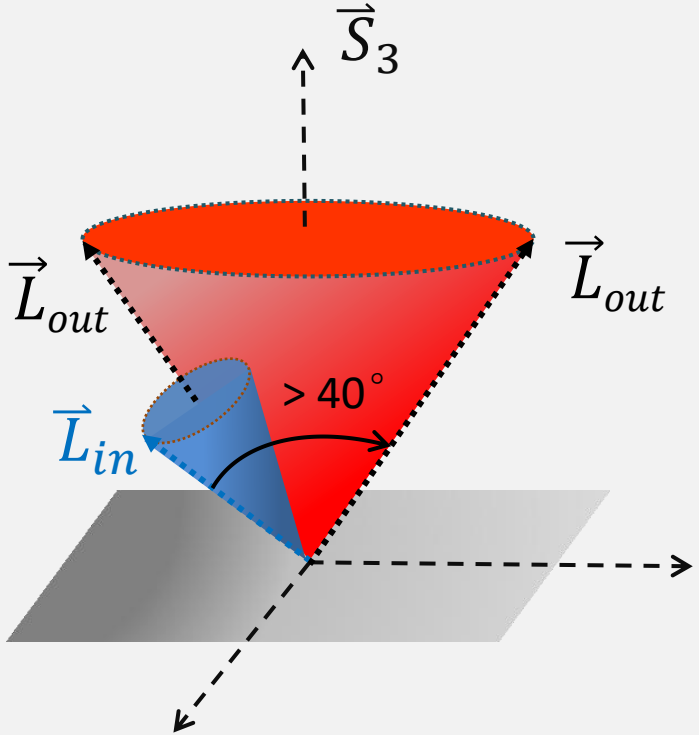

*Liu & Lai ApJL 2019*

# Binary Dynamics Near a Supermassive BH

--- Newtonian Effect: Lidov-Kozai Oscillations

--- GR Effect: Precession of $\boldsymbol{L_{out}}$ around $\boldsymbol{S_3}$ **(1.5 PN)**



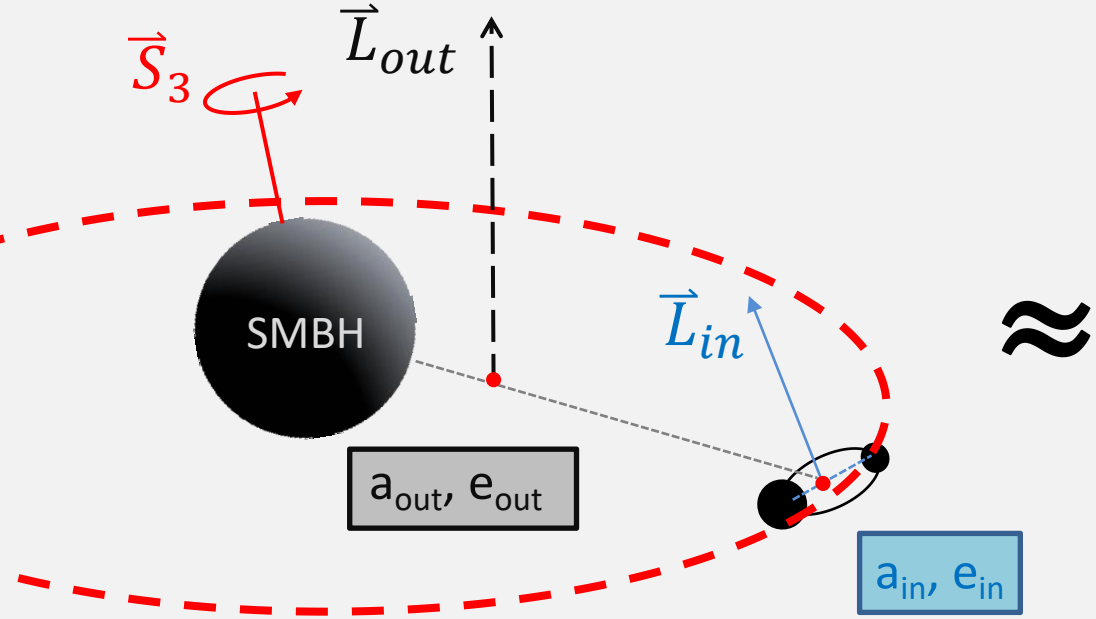




*Liu & Lai ApJL 2019*

# Binary Dynamics Near a Supermassive BH

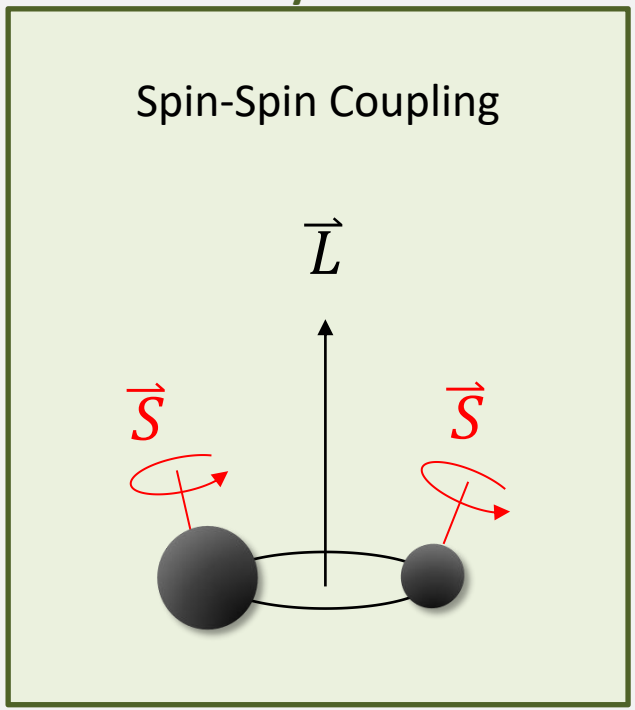
--- Newtonian Effect: Lidov-Kozai Oscillations

--- GR Effect: Precession of $L_{in}$ around $S_3$ (2 PN)



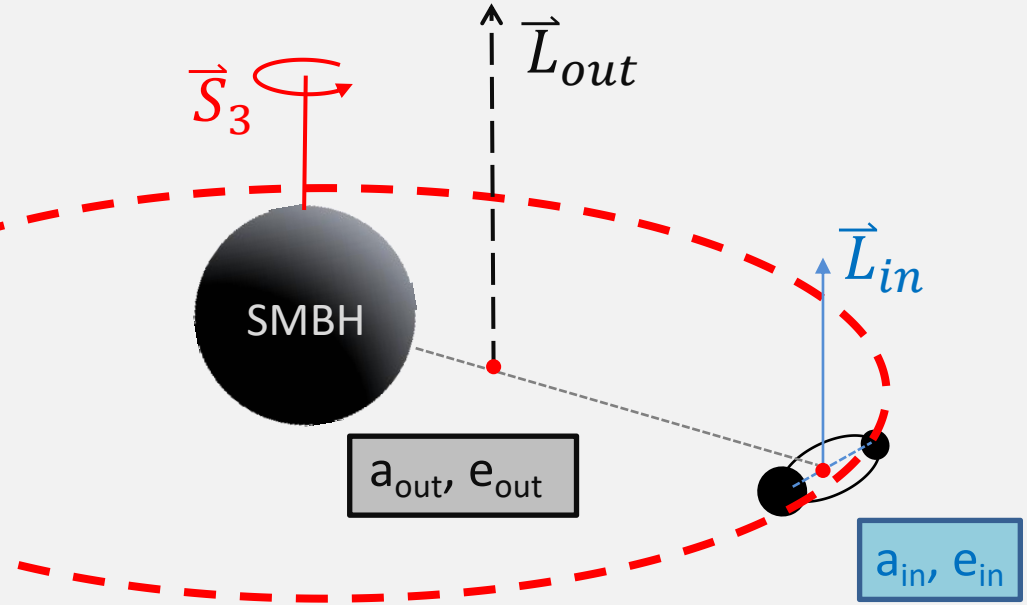

$\approx$

**Isolated Binary**




*Liu & Lai ApJL 2019*

# Binary Dynamics Near a Supermassive BH

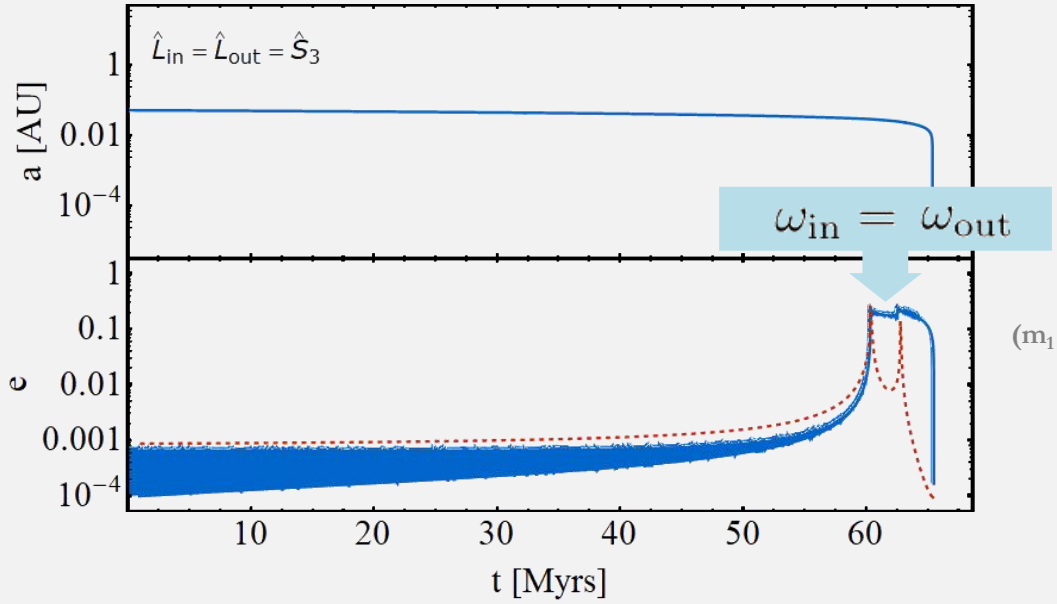



**Coplanar case**

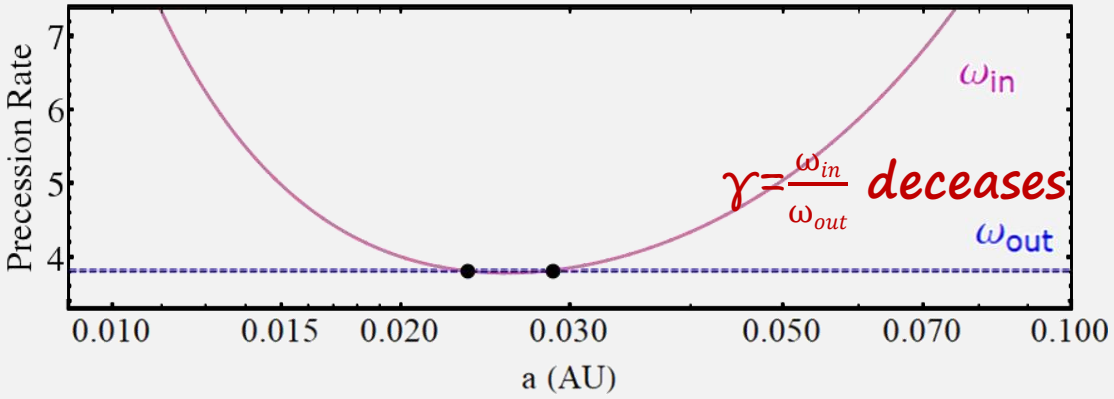
$$\begin{cases} \dfrac{d\hat{L}}{dt} = 0 \\ \dfrac{d\vec{e}}{dt} = \omega\, \hat{L} \times \vec{e} \end{cases}$$

*Liu & Lai PRD 2020*

- **Orbital Evolution:**

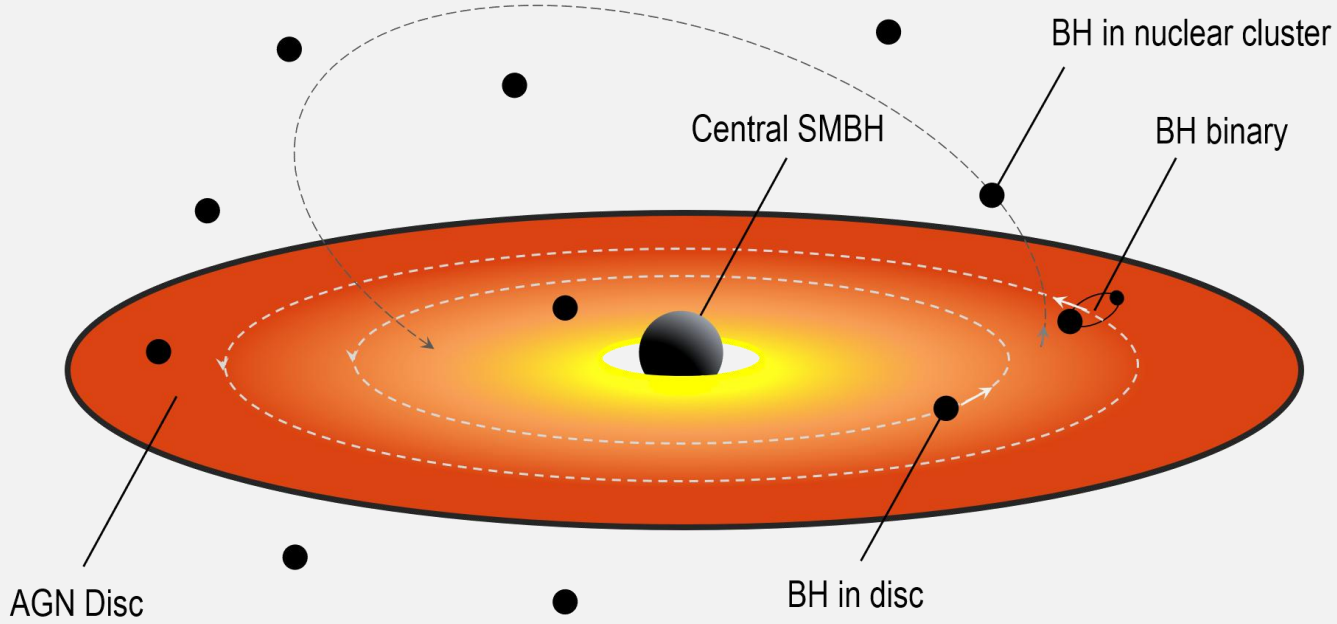



$(m_1, m_2, m_3) = (30, 20, 1\times10^8)\ M_\odot$
$(a_{in,0}, a_{out}) = (0.05, 90)$ AU
$(e_{in,0}, e_{out,0}) = (0.0001, 0.7)$




*Liu & Lai PRD 2020*

# Migration?




*Liu + 2024, in prep*

# Summary

**#1 A novel dynamical effect of the coplanar triple system:**
The outer orbit can encounter an *Apsidal Precession Resonance* during the orbital decay of the inner binary

**#2 Resonance capture and advection:**
The eccentricity of the outer orbit can keep growing

**#3 Applications:**
An independent approach to search for black hole binaries
Trigger the tidal disruption event
Lack of planets around a circumbinary stars ···

**#4 Inverse case:**
It is possible to excite the eccentricity of the inner BHB for coplanar triple

**Thank you for your attention**