Three body systems in Strong Gravity Regime

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◉ ***Tidal deformations of a binary system induced by an external Kerr black hole***

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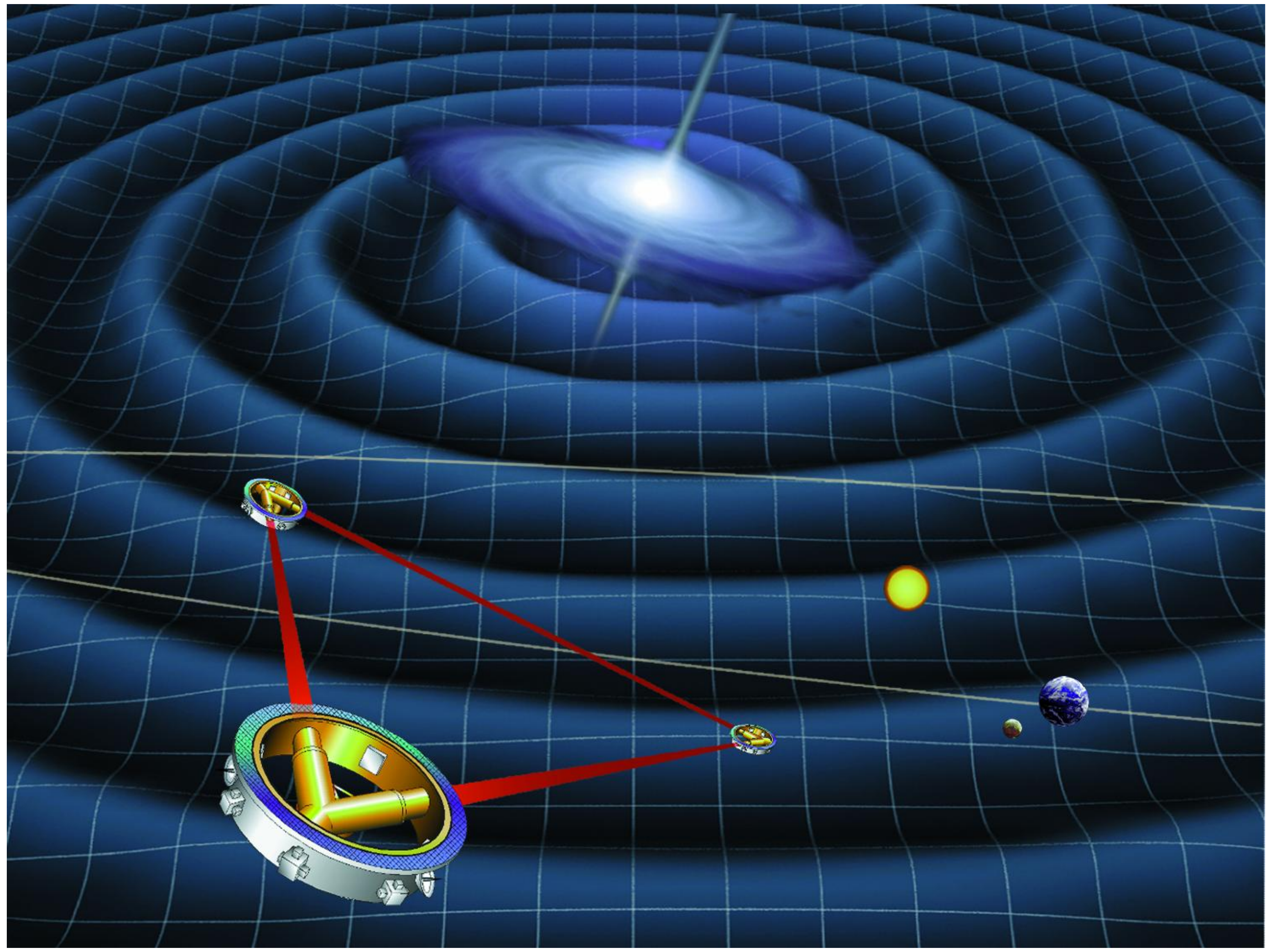
◉ ***Binary mergers in strong gravity background of Kerr black hole***

In preparation - [F. Camilloni, G.Grignani, T. Harmark, M. Orselli, D. Pica]

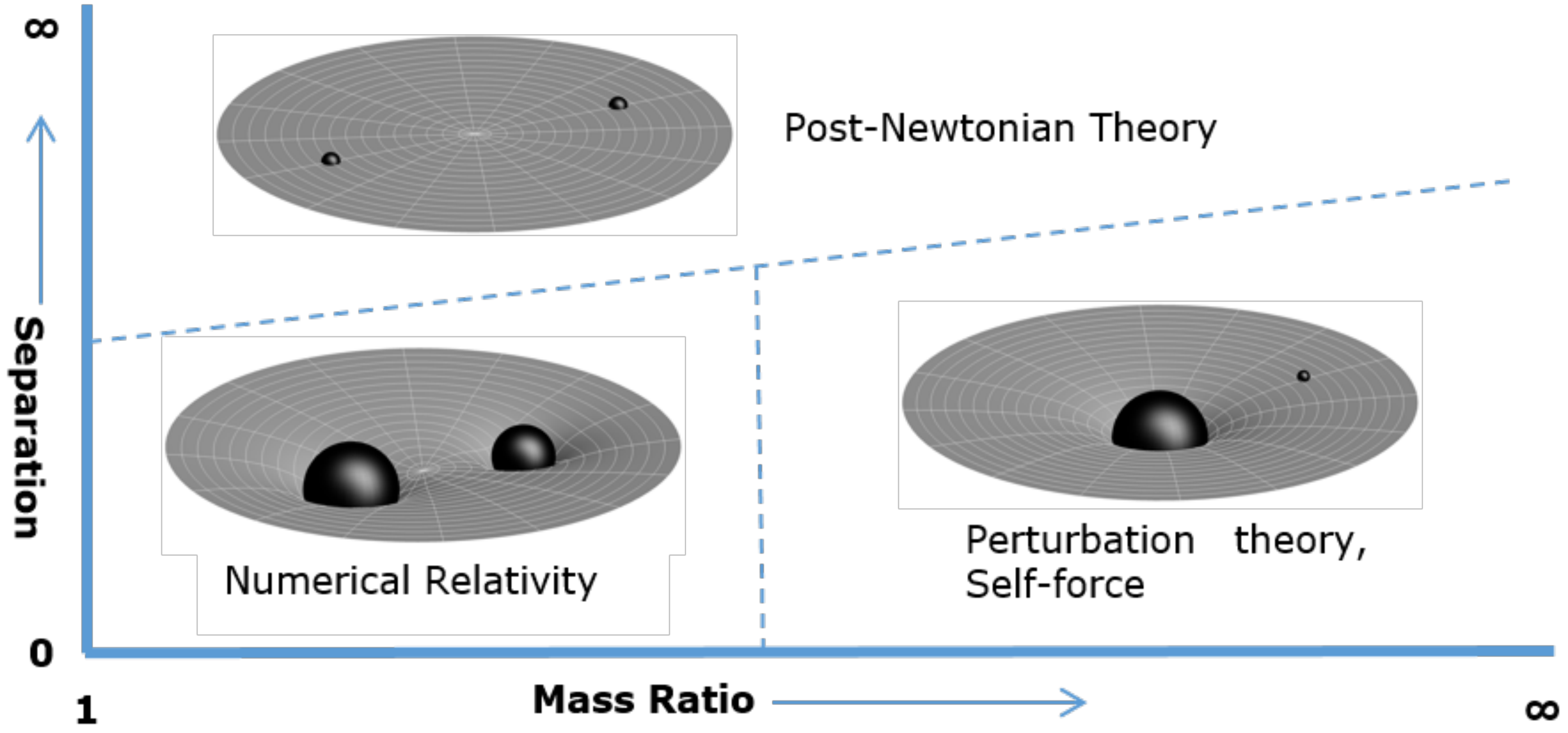
Why Three Body Systems?

- **Abundance of sources**: the density of stars in galactic nuclei can be 10^6 times the one in our solar system neighborhood $\left(0.1\text{stars/pc}^3\right)$



- Primary targets for **future GWs observations**
  - $\omega \sim 10^{-2} - 10$ **kHz** $\rightarrow$ **LIGO/VIRGO**
  - $\omega \sim 0.1 - 100$ **mHz** $\rightarrow$ **LISA**
- **Kozai-Lidov Mechanism** $\rightarrow$ very short merger timescale!
  - A circular binary of two $10M_\odot$ black holes orbiting a SMBH, with a separation of 1AU it would take 10^{14}years to merge.
  - A binary of two $10M_\odot$ black holes with eccentricity $e = 0.9995$ orbiting a SMBH, with a separation of 1AU it would take 4×10^3years to merge.

Strong Gravity Regime

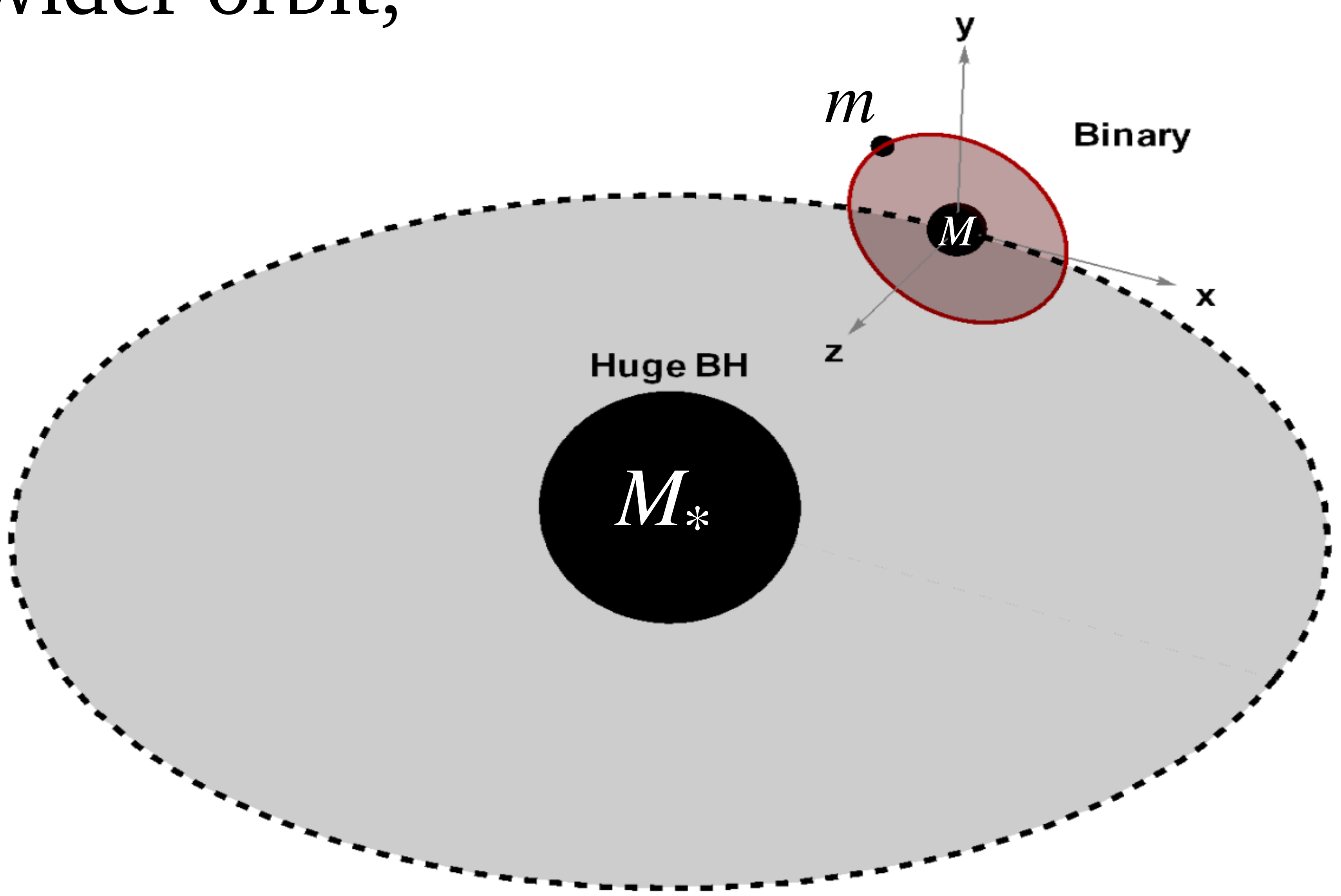


- **Strong Gravity:** when GR effects become relevant
- **Small-tide approximation:** when the characteristic scale of the binary is much smaller than the radius of the curvature generated by the third body evaluated in the position of the binary system
  - *Weak-field approximation* → the orbital velocity of the binary system must be small→ binary system far away from the perturber.
  - *Small-hole approximation* → dimension of the binary system is assumed to be much smaller than the external mass → the binary system can be close to the source of the tidal fields.
- Three body systems are usually studied as point particles in the weak-field approximation

Tidal deformation of a binary system induced by a Kerr black hole

[F. Camilloni, G.Grignani, T. Harmark, R. Oliveri, M. Orselli, D. Pica]

- **Hierarchical three body system**: a binary system under the gravitational interaction of another massive astrophysical object.
- Hierarchical in scale, a tight inner binary orbited by a tertiary on a wider orbit, forming the outer binary: $m << M << M_*$
- m is a test particle, M is a Schwarzschild black hole, M_* is a Kerr black hole
- In the limit $m \to 0$, extreme mass ratio (**EMR**)



- $\mu = \dfrac{m}{M} \ll 1 \Rightarrow$ Natural perturbative approach to include all possible GR effects!

Tidal deformation of a binary system induced by a Kerr black hole

- **Two different length scales**: the mass of the intermediate black hole M and the radius of the curvature generated by the third body evaluated in the position of the binary system $\mathscr{R}$

- *Small-hole approximation* $\rightarrow$ black hole mass is assumed to be much smaller then the external mass, $M \ll M_*$ $\rightarrow$ the binary system can be close to the source of the tidal fields.

- <u>*Small-hole approximation*</u> $\rightarrow$ EMR could be on the Innermost Stable Circular Orbit (**ISCO**) of the Kerr black hole $\rightarrow$ "migration trap"!

- **Tidally deformed metric:** $ds^2 \simeq -\left(1-\frac{2M}{r}\right)dt^2 + \left(1-\frac{2M}{r}\right)^{-1}dr^2 + r^2\left(d\theta^2+\sin^2\theta d\phi^2\right) + h_{\mu\nu}dx^\mu dx^\nu + \mathcal{O}(r^3/\mathscr{R}^3)$

- At leading order the Tidal Environment is specified by **Quadrupole Tidal Moments**

- We neglect the motion of the binary system around the SMBH

Tidal deformation of a binary system induced by a Kerr black hole

- Tidal fields generated by the outer body deform the orbits of the unperturbed Schwarzschild metric

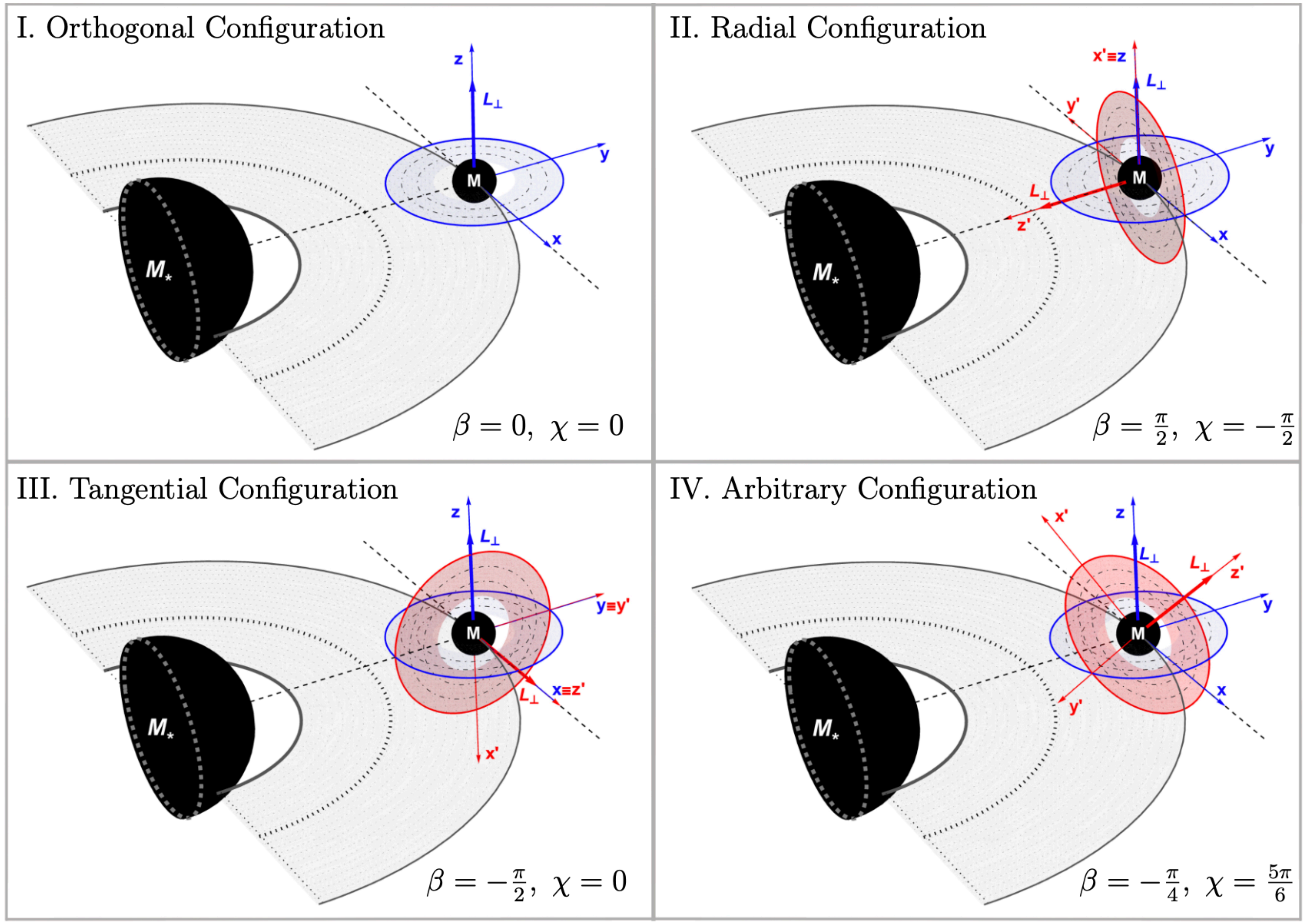
- **Secular dynamics** → integrate over one orbit of the test particle

- **3 Euler angles** → All possible orientation for the binary system

- **ISCO shifts!**

$$r = r_{ISCO} + \eta\ r_1,$$
$$E = E_{ISCO} + \eta\ E_1,$$
$$L = L_{ISCO} + \eta\ L_1,$$
$$\Omega = \Omega_{ISCO} + \eta\ \Omega_1$$

$$\eta = -\frac{M^2}{2}\langle \mathcal{E}^q \rangle$$



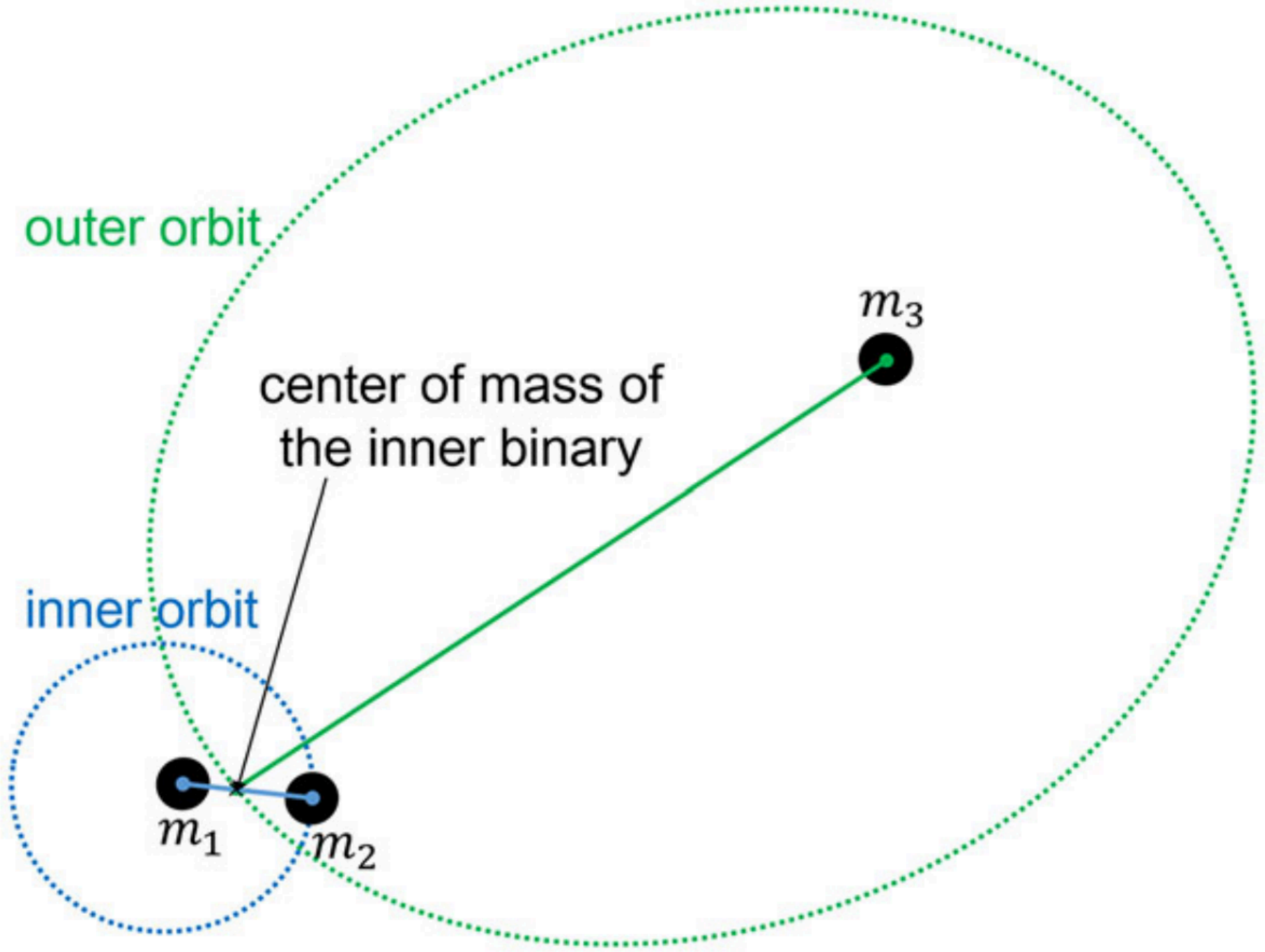
- **Effective perturbative parameter** η

Binary mergers in strong gravity background of Kerr black hole

[F. Camilloni, G.Grignani, T. Harmark, M. Orselli, D. Pica]

- Binary system of two black holes m_1 and m_2 moving along a geodesic around a SM Kerr BH m_3
  - *Inner orbit*
  - *Outer orbit*
- a semi-major axis of the binary, $\hat{r}$ distance between the binary and the SMBH

- **Two approximations**:
  - *Tidal Limit* $\rightarrow a \ll \dfrac{Gm_3}{c^2}$
  - *Point Particle Limit* $\rightarrow \dfrac{Gm_{1,2}}{c^2} \ll a$



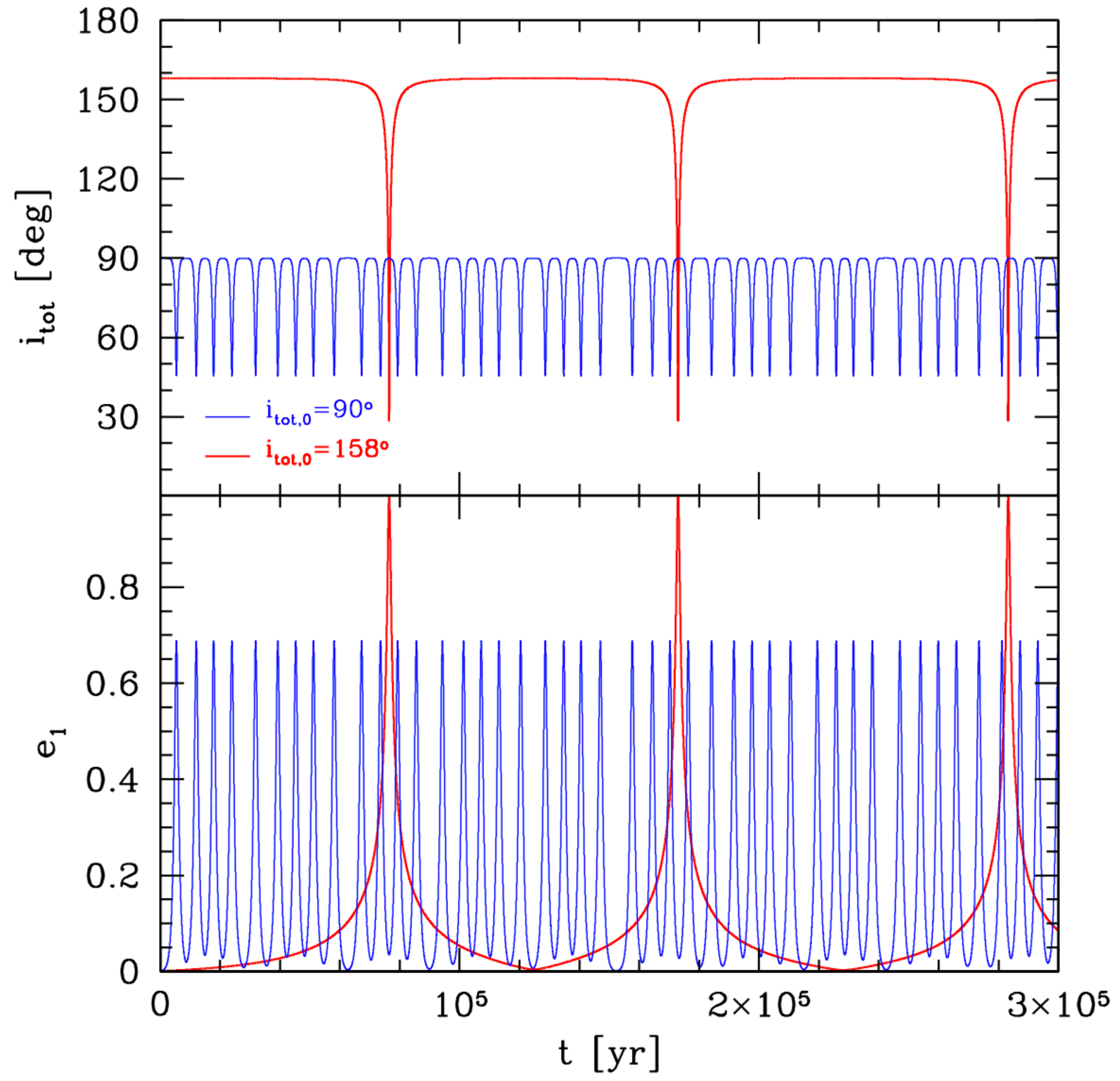
Kozai-Lidov Mechanism - Point Particle Approximation

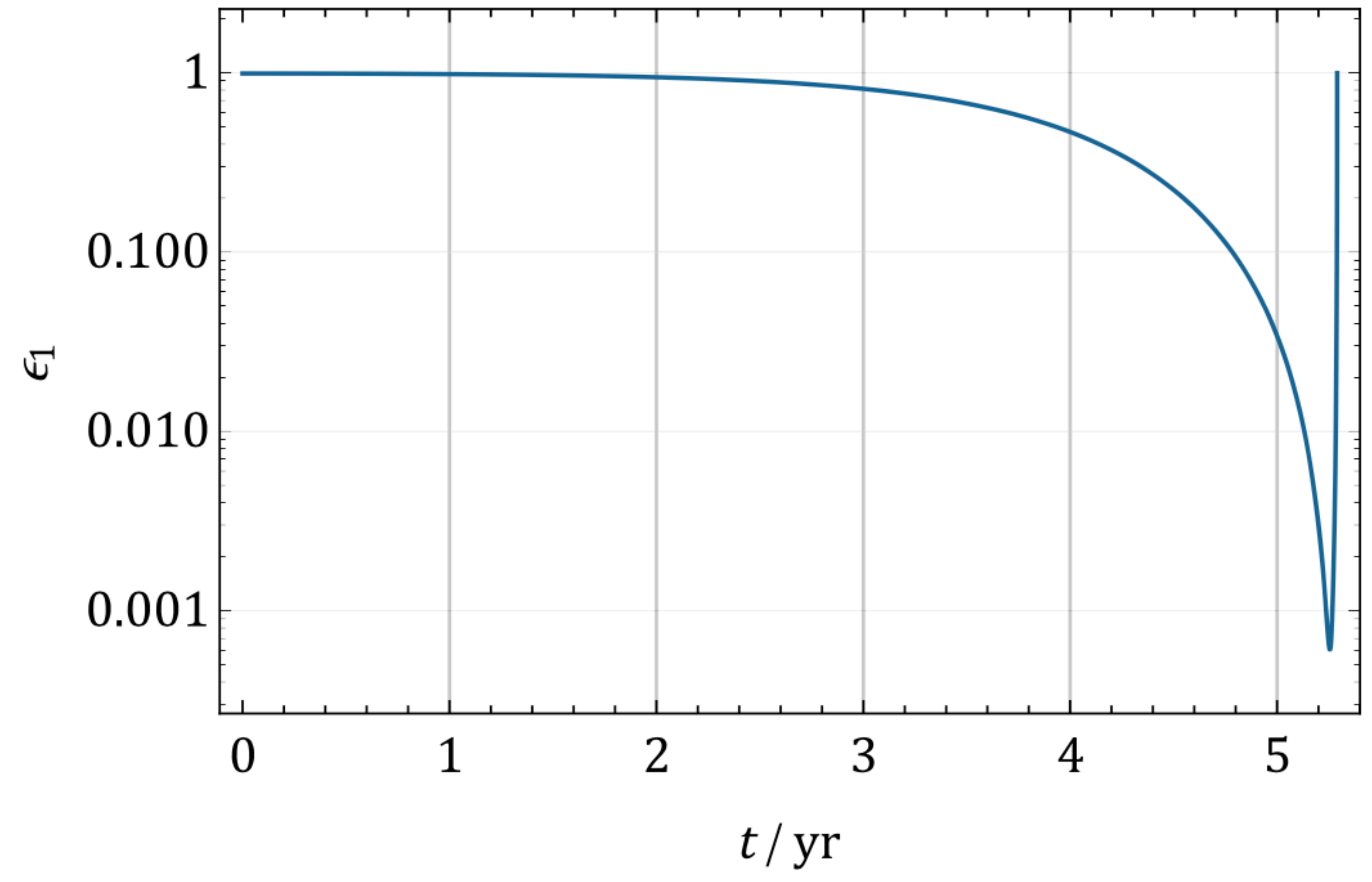
- When the binary system has a high relative inclination to its orbit around the SMBH it will evolve over many orbits trading eccentricity for inclination in a periodic fashion

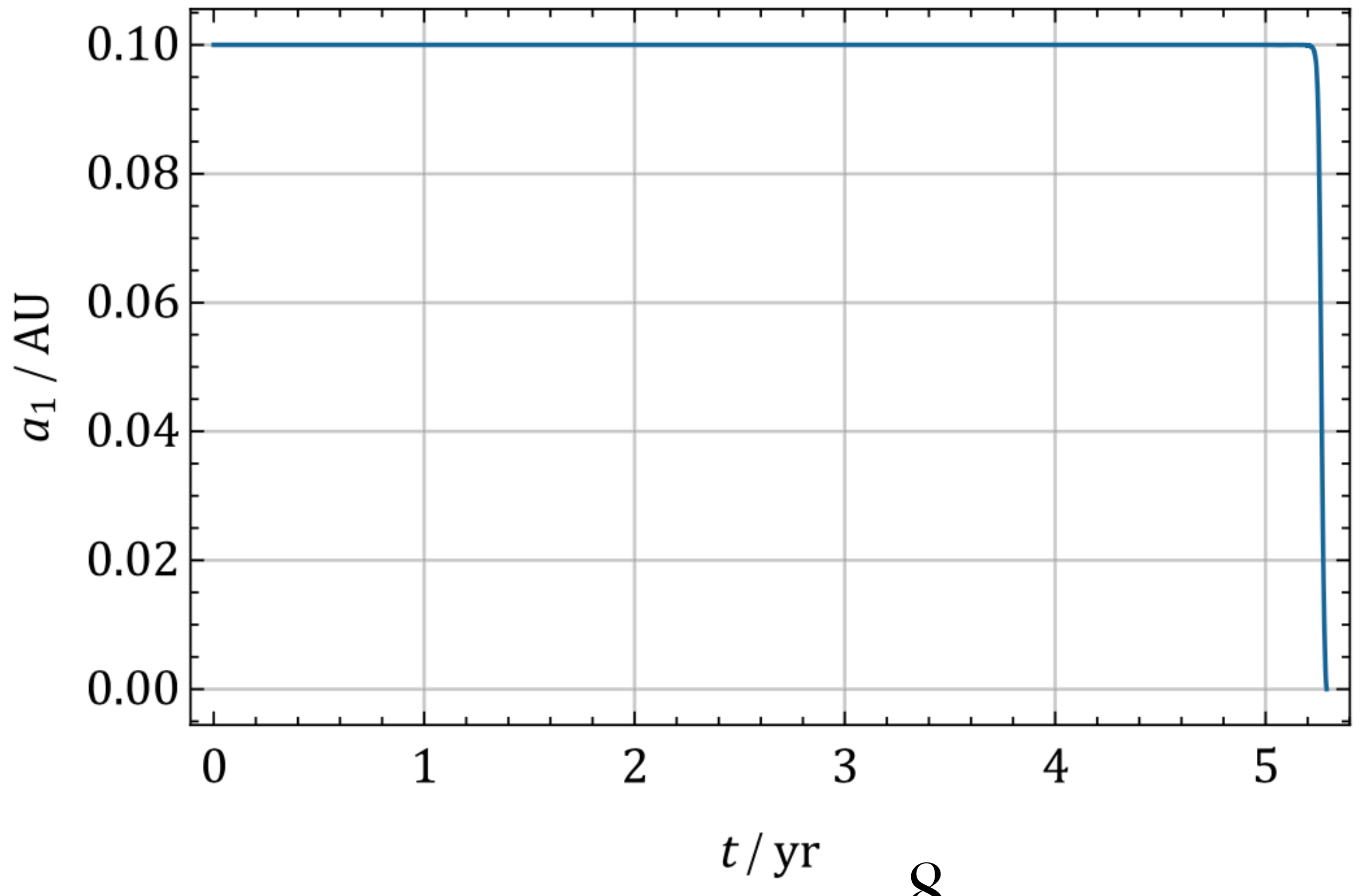
- Secular average over both the inner and outer orbit → Long timescale

- The BHB can reach eccentricity close to 1 → $e \sim 1$

- When including the emission of GW from the BHB the KL mechanism can speed up the merger!

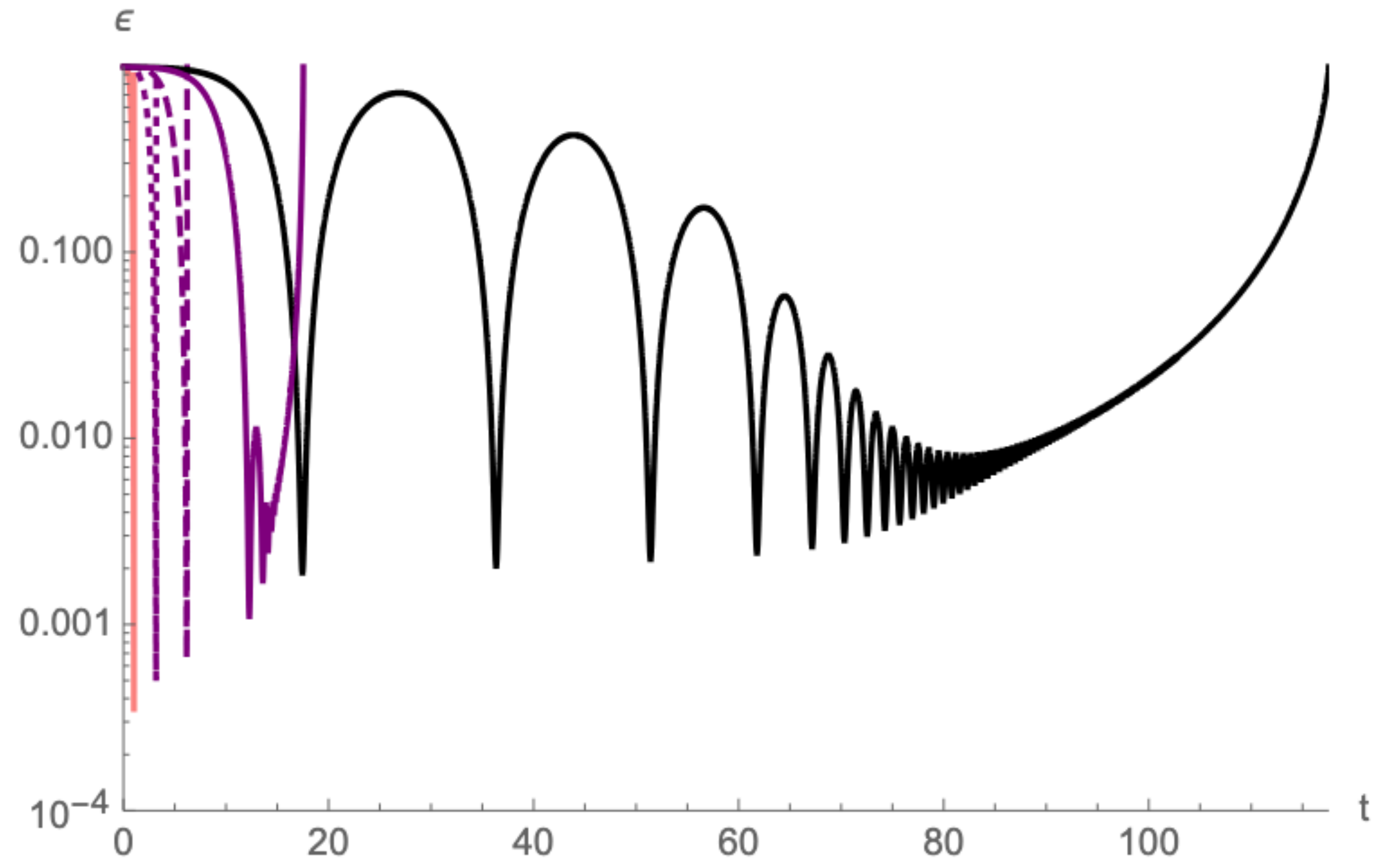


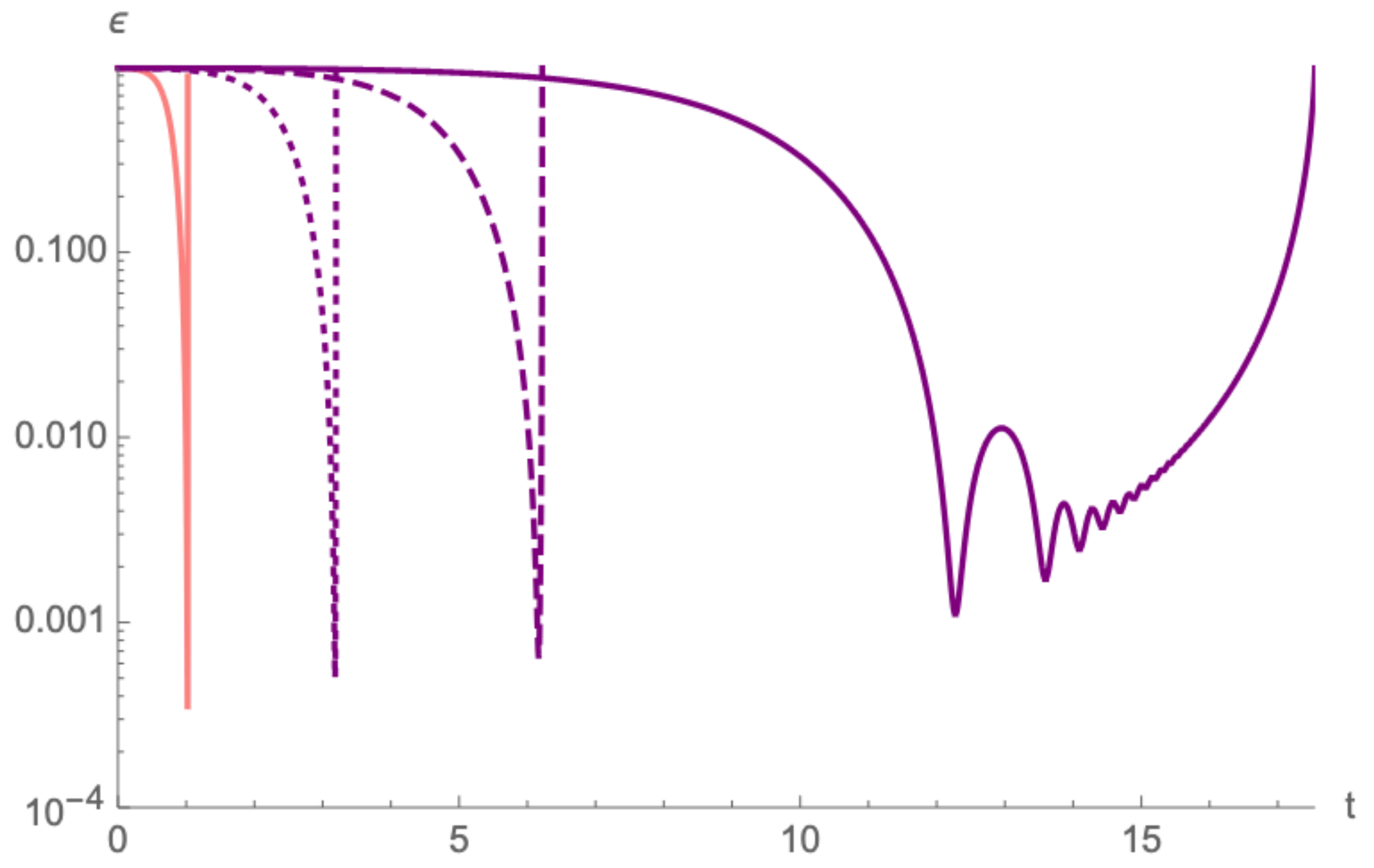




Kozai-Lidov Mechanism - Strong Gravity Regime

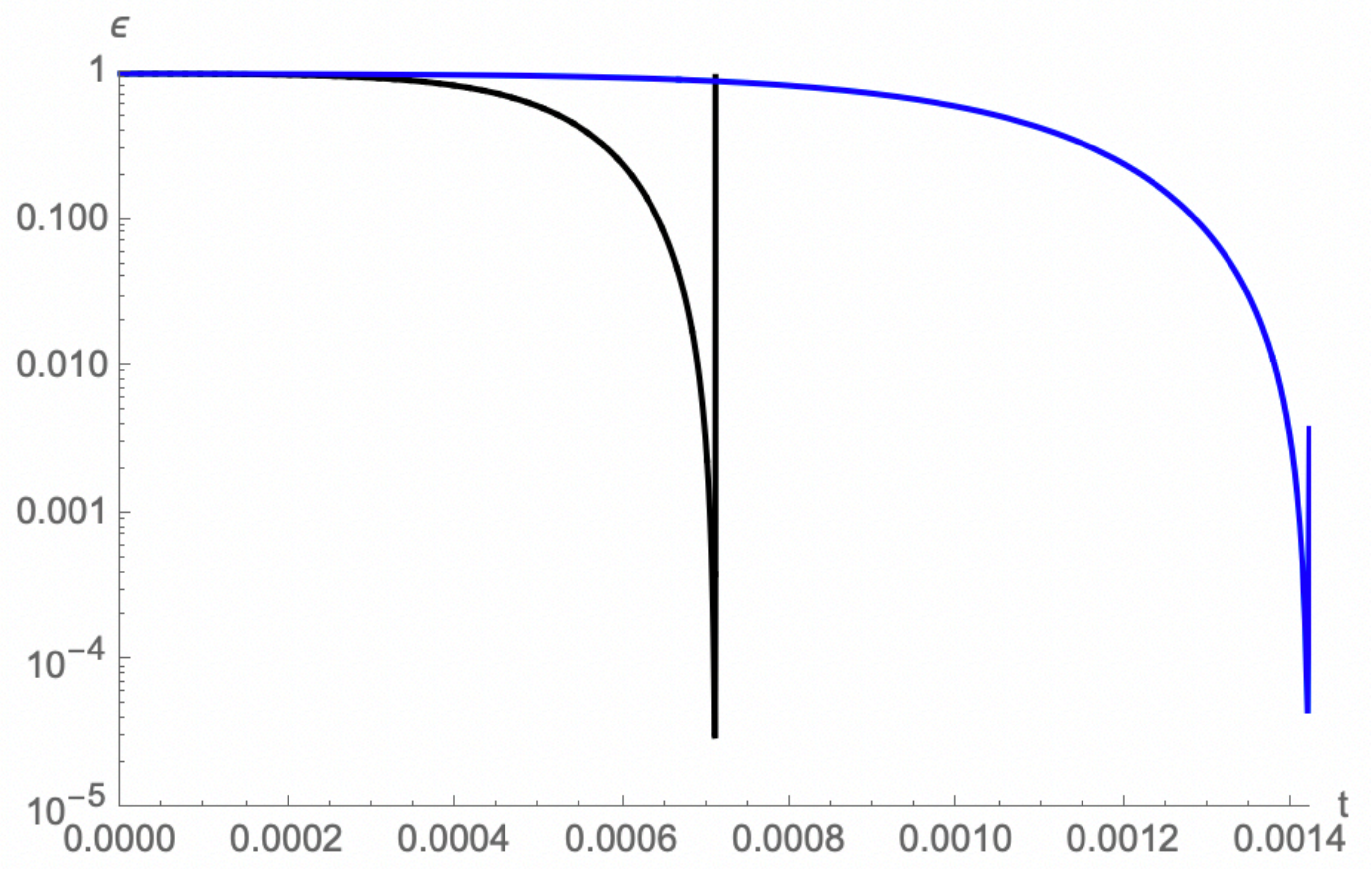
- The black holes in the binary are treated as point particles, the perturber as a rotating black hole
- **How the spin affects the merger**
- $m_3 = 4 \times 10^6 M_\odot, m_1 = m_2 = 10 M_\odot, \hat{r} = 500 r_{ISCO}, a = 0.1\text{AU}$
- As the spin of the SMBH increases
  - Merger time decreases
  - Fewer KL cycles
  - Higher eccentricity
  - **Faster merger!**





Kozai-Lidov Mechanism - Strong Gravity Regime

- The black holes in the binary are treated as point particles, the perturber as a rotating black hole
- Binary close to the supermassive (**ISCO** - **I**nnermost **S**table **C**ircular **O**rbit)
- $m_3 = 4 \times 10^8 M_\odot, m_1 = m_2 = 10 M_\odot, \hat{r} = r_{ISCO}, a = 0.1\text{AU}$
  - Point Particle result → blue line
  - Full GR result → black line



- Point Particle approximation breaks down on the ISCO!
- The spin speed up the merger as expected even on the ISCO