SMBH連星の合体過程で放射される重力波の電磁波対応天体としての潮汐破壊現象（TDE）

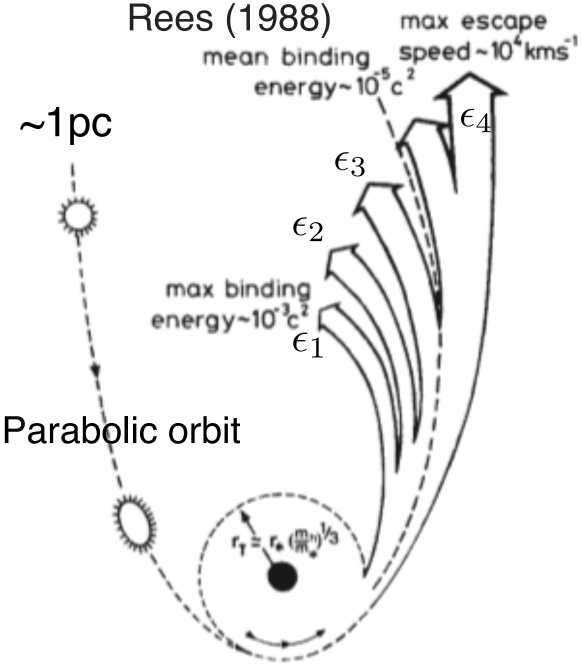
早崎公威

Chungbuk National University (Korea)

BH大研究会@御殿場高原 on 2/Mar/2024

Overview of the TDE theory

Rees (1988)



- Specific binding energy

$$\epsilon = 0 \rightarrow \epsilon \pm \Delta\epsilon$$

Star　　　　Stellar debris

- Tidal disruption radius

$$r_{\rm t} = \left(M_{\rm bh}/m_*\right)^{1/3} r_*$$
$$\sim 25\, r_{\rm S}\, M_6^{-2/3}\, m_{*,1}^{-1/3} r_{*,1}$$

- Debris spread energy

$$\frac{m_* \Delta\epsilon}{m_* c^2} \approx \frac{GM}{r_{\rm t} c^2}\frac{r_*}{r_{\rm t}} \sim 2\times 10^{-4}\, M_6^{1/3} m_{*,1}^{2/3}\, r_{*,1}^{-1}$$

- Fallback time of most tightly bound debris

$$t_{\rm mtb} \sim 0.1 {\rm yr}\; M_6^{1/2} m_{*,1}^{-1}\, r_{*,1}^{2/3}$$

- Mass fallback rate at the peak

$$\dot{M}_{\rm fb,pk} = \frac{1}{3}\frac{m_*}{t_{\rm mtb}} \sim 2\times 10^{25}\,{\rm g\,s^{-1}}\, M_6^{-1/2}\, m_{*,1}^{2}\, r_{*,1}^{-3/2} \gg \dot{M}_{\rm Edd}$$

- Time dependence of mass fallback rate

$$\dot{M}_{\rm fb} \propto t^{-n}$$

Power-law index: $n = \begin{cases} 5/3 & \text{w/o stellar internal structure} \\ < 5/3 & \text{w/ stellar internal structure} \\ > 5/3 & \text{others (partial or bound TDEs)} \end{cases}$

Fiducial normalized parameters

$$M_6 = M_{\rm bh}/10^6\, M_\odot$$
$$r_{*,1} = r_*/R_\odot$$
$$m_{*,1} = m_*/M_\odot$$

Debris circularization, disk size and evolution

1. Debris is circularized at $r_{\rm circ}$ by stream-stream collision over the circularization time: $t_{\rm circ}$

$$r_{\rm circ} = l^2/GM = 2r_{\rm t}$$
$$\sim 50\, r_{\rm S}\, M_6^{-2/3}\, m_{*,1}^{-1/3} r_{*,1}$$

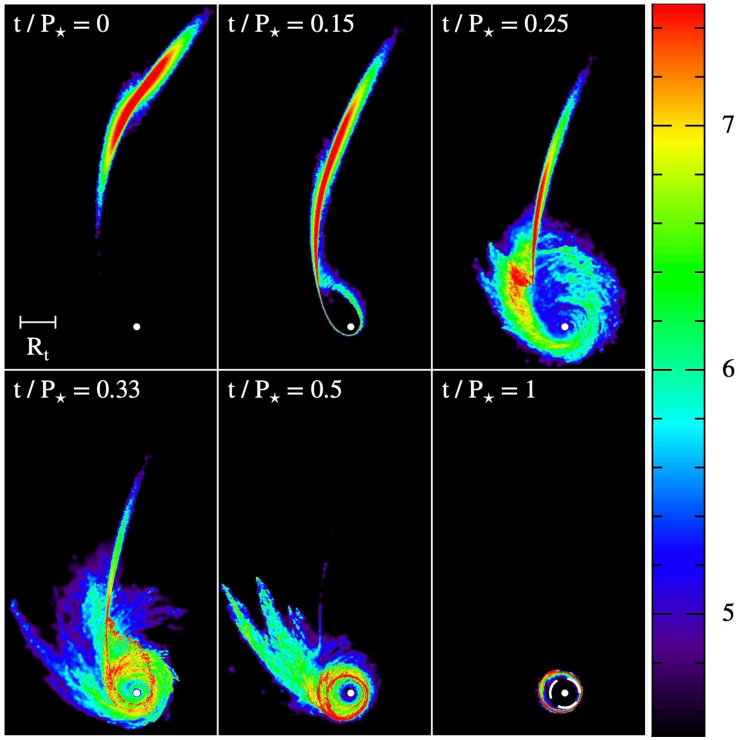
$$t_{\rm circ} \sim t_{\rm acc} \rightarrow \dot{M}_{\rm fb} \approx \dot{M}_{\rm acc}$$
$$t_{\rm circ} \ll t_{\rm acc} \rightarrow \dot{M}_{\rm fb} \neq \dot{M}_{\rm acc}$$

(Cannizzo et al. 1990; Balbus 2017; Mummery & Balbus 2020; Magesh and Hayasaki 2023)

2. liberated energy due to stream-stream collision:

$$E_{\rm ssc} = GMm_*/4a_{\rm mtb}$$
$$\sim 1.1 \times 10^{50}\,{\rm erg}\, M_6^{1/3}\, m_{*,1}^{5/3}\, r_{*,1}^{-1}$$
$$(\, a_{\rm mtb} \sim 6 \times 10^{14}{\rm cm}\ M_6^{2/3} m_{*,1}^{-2/3}\,)$$

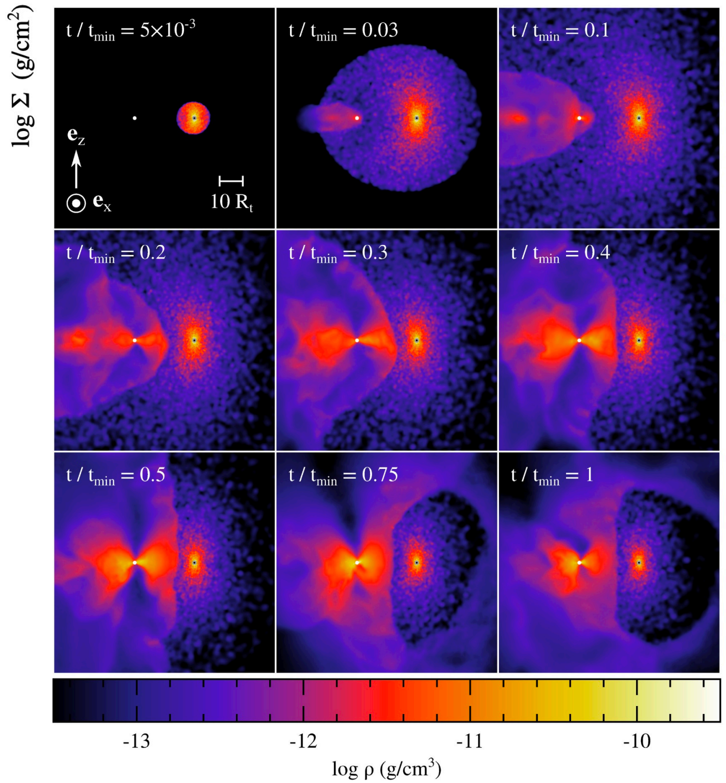
Optically thin case



Bonnerot et al. (2016); see also Hayasaki et al. (2013, 2016)

Optically thick case

Lu and Bonnerot (2020); Bonnerot and Lu (2020)



$$t_{\rm min} = (\pi/\sqrt{2}\Omega_*)(M_{\rm bh}/m_*)^{1/2} \approx 0.11\, M_{\rm bh,6}^{1/2}\, m_{*,1}^{-1}\, r_{*,1}^{3/2}\ {\rm yr}$$

In this talk, we assume that $\dot{M}_{\rm fb} \approx \dot{M}_{\rm acc}$ ➡ $L \propto \dot{M}_{\rm fb} c^2$

Summary for TDE observations

- TDE candidates

$$\gtrsim 100$$

- Event rate

1. Non-jetted/thermal TDEs

$$\sim 10^{-7}\,/\mathrm{yr}/\mathrm{Mpc}^3$$

2. Jetted TDEs (4 on-axis jets)

$$\sim 3 \times 10^{-11}\,/\mathrm{yr}/\mathrm{Mpc}^3$$

Donley et al. (2002); van Velzen et al. (2014); Leaven et al. (2015); Hung et al. (2018)

- Diversity of observed TDEs

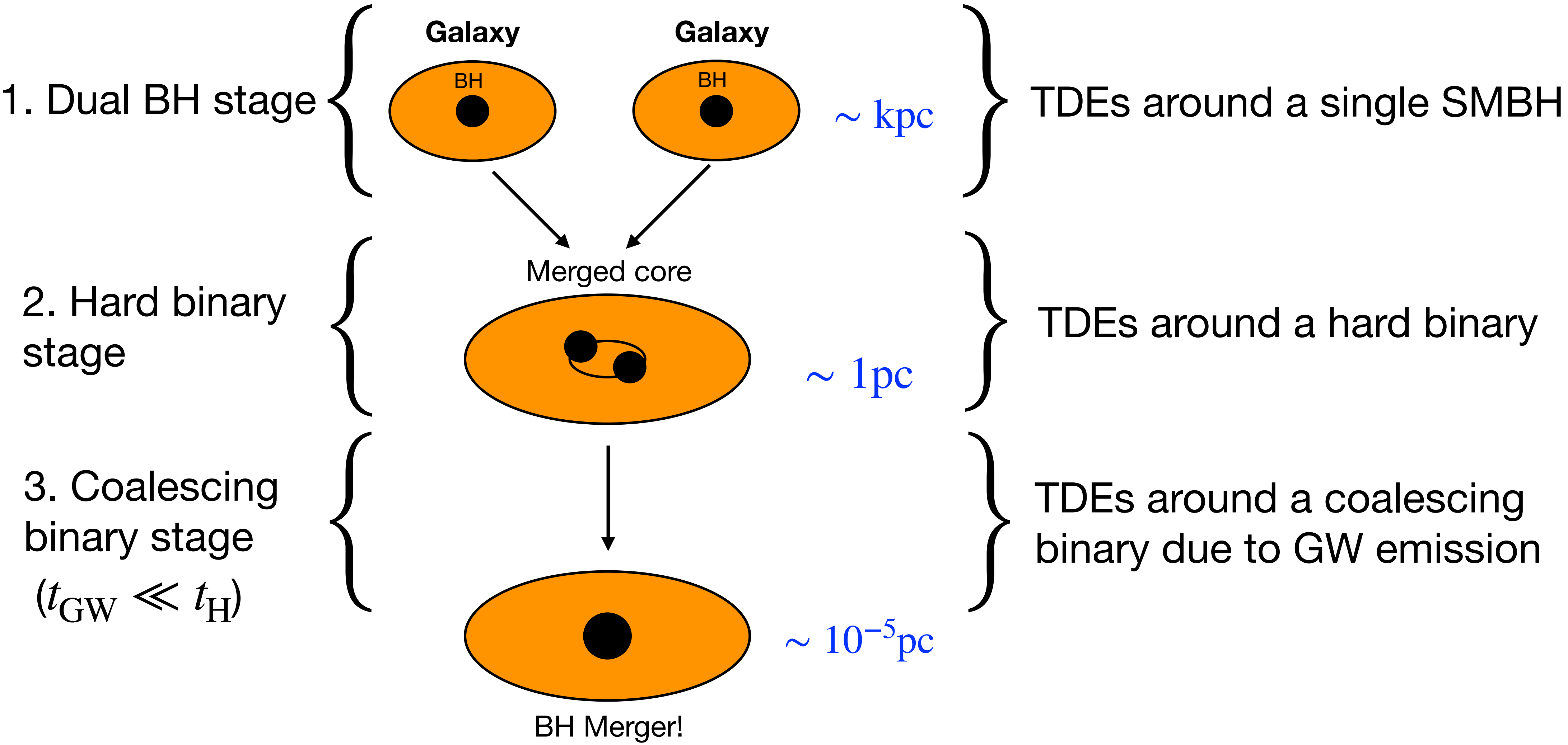
1. Thermal comp. **dominant** (non-jetted TDEs)
   #1 thermal origin: soft-X-rays to optical/UV
   #2 thermal origin: optical/UV only
   # 1 and/or 2 + IR echo
   # 1 and/or 2 + Radio
   # 1 and/or 2 + Hard X-ray
   # 1 and/or 2 + IR echo + Radio
2. Non-thermal comp. **dominant** (Jetted TDEs)
   # Gamma-ray, hard X-ray, and radio + thermal emissions

See Space Sci Rev Series X et al. (2020)

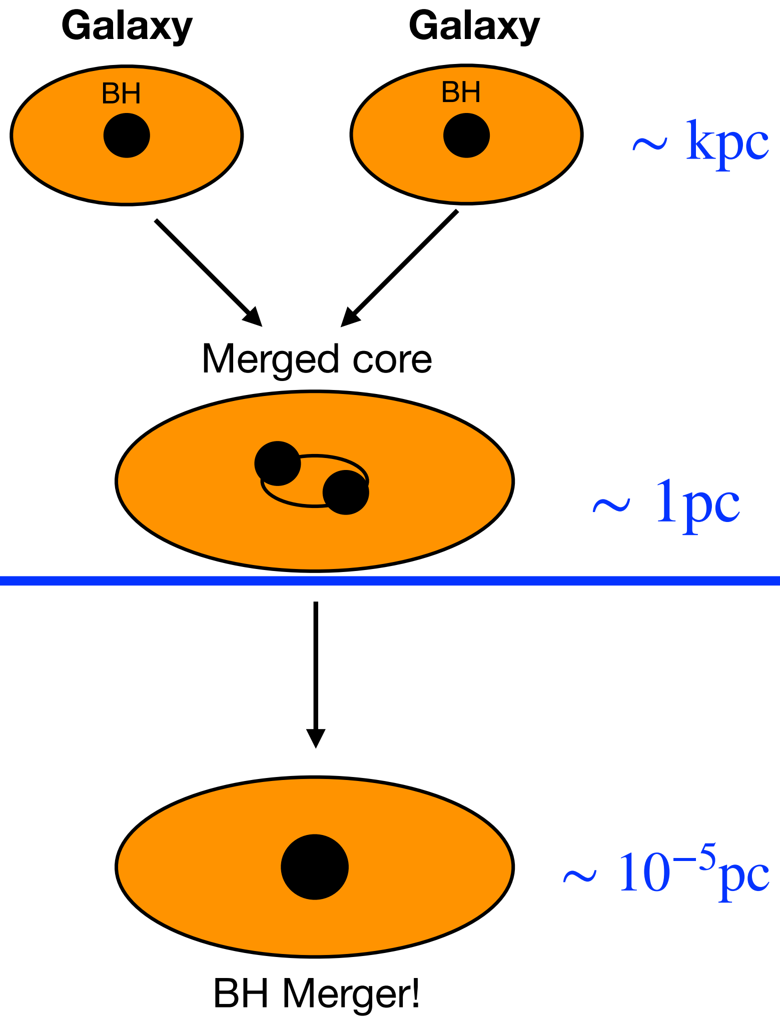
What made the observed diversity of TDEs?

1. Accretion disk
2. Stream-stream collision
3. Reprocessing from them

Hierarchical evolution of two SMBHs in a galaxy merger



Mass fallback rate on each stage



1. Dual BH stage

$\dot{M}_{\rm fb} \propto t^{-5/3}$

Rees(1988); Evans & Kochaneck (1989); Enrico&Rosswog (2009); Rossi et al. (2021) for a review

2. Hard binary stage

$\dot{M}_{\rm fb} \propto t^{-5/3}$ with dips

Liu et al. (2009, 2014); Ricarte et al. (2016); Coughlin et al. (2017)

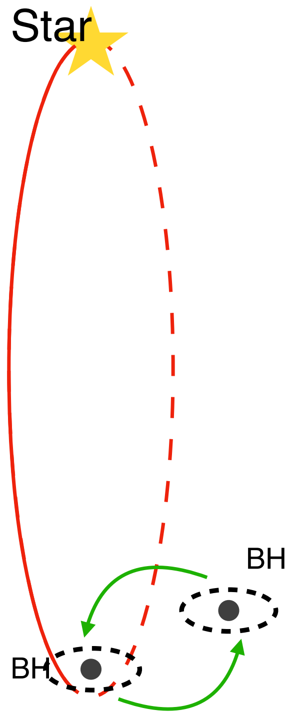
3. Coalescing binary stage ($t_{\rm GW} \ll t_{\rm H}$)

?

Hayasaki & Loeb (2016)

How to supply stars to a SMBH binary

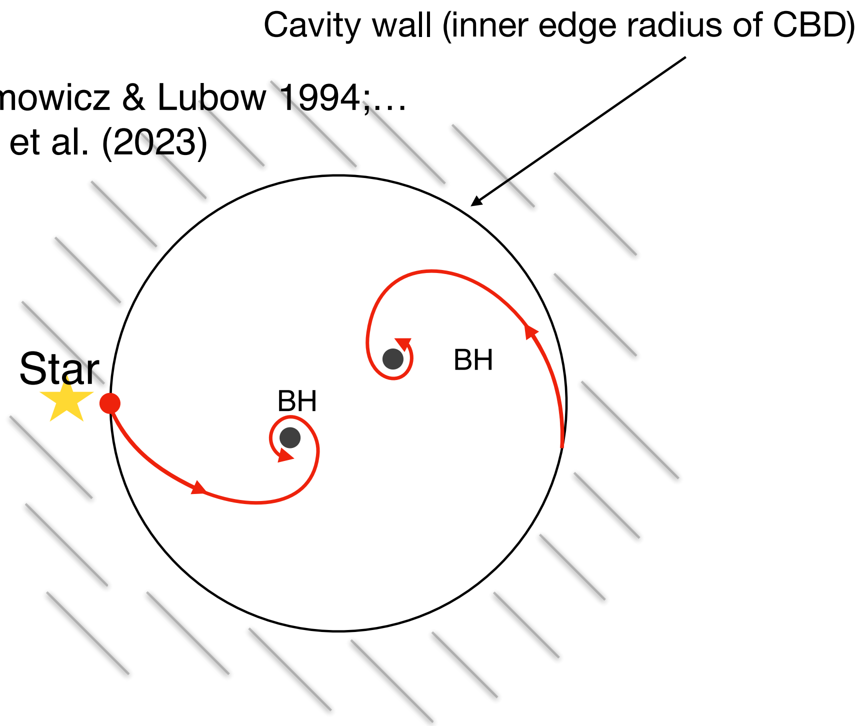
① Nearly radial stellar orbit



Less bound (parabolic) TDEs
(Similar to the standard TDE case)

② Massive circumbinary disk (CBD)

e.g., Artymowicz & Lubow 1994;…
;Dittmann et al. (2023)

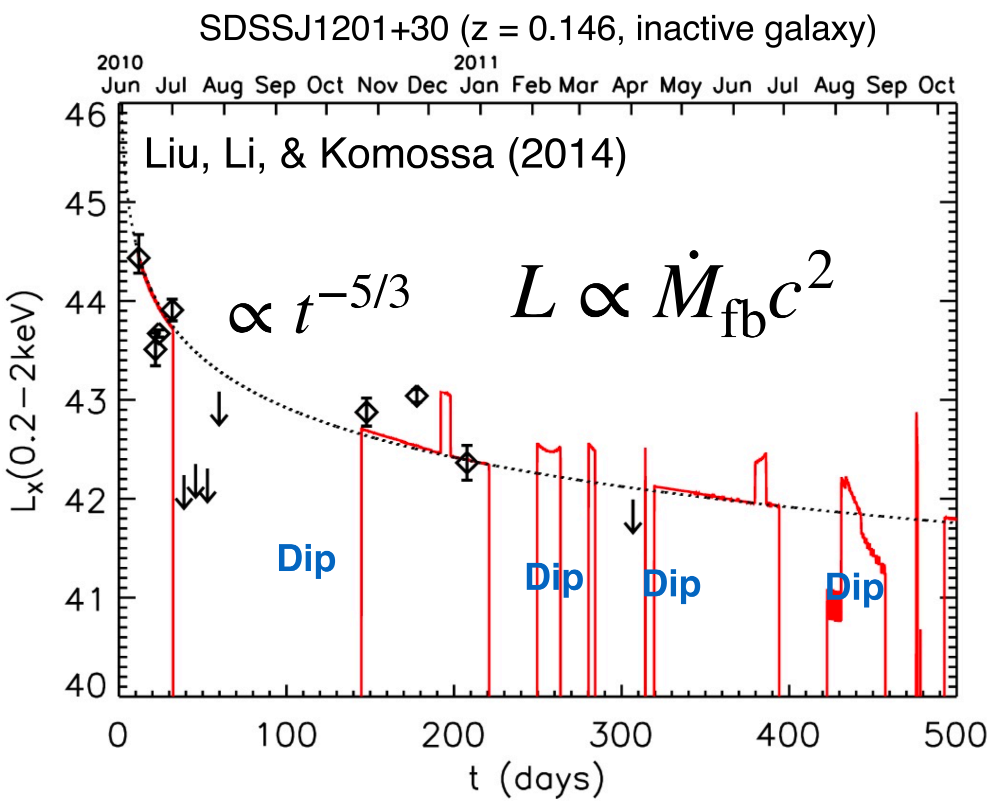


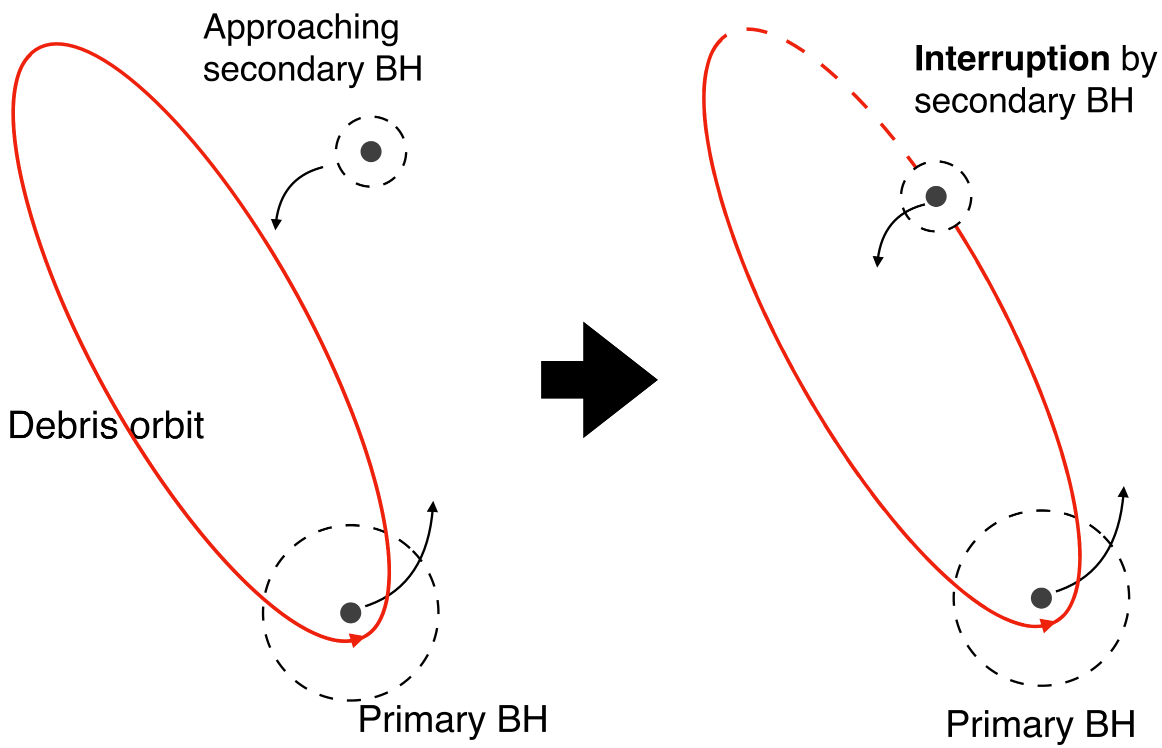
Bound TDEs

Hayasaki et al.(2013, 2016, 2018)
and Park & Hayasaki (2020)

Less bound TDE case

Liu et al. (2009); Ricarte et al. (2016)

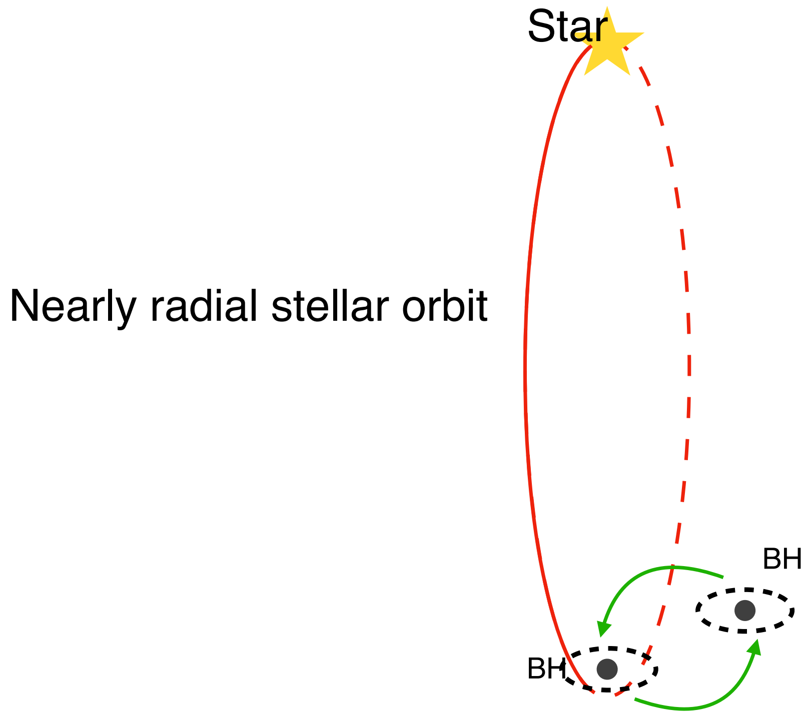




The bolometric luminosity follows $t^{-5/3}$ law with dips and aperiodic

How to supply stars to a SMBH binary

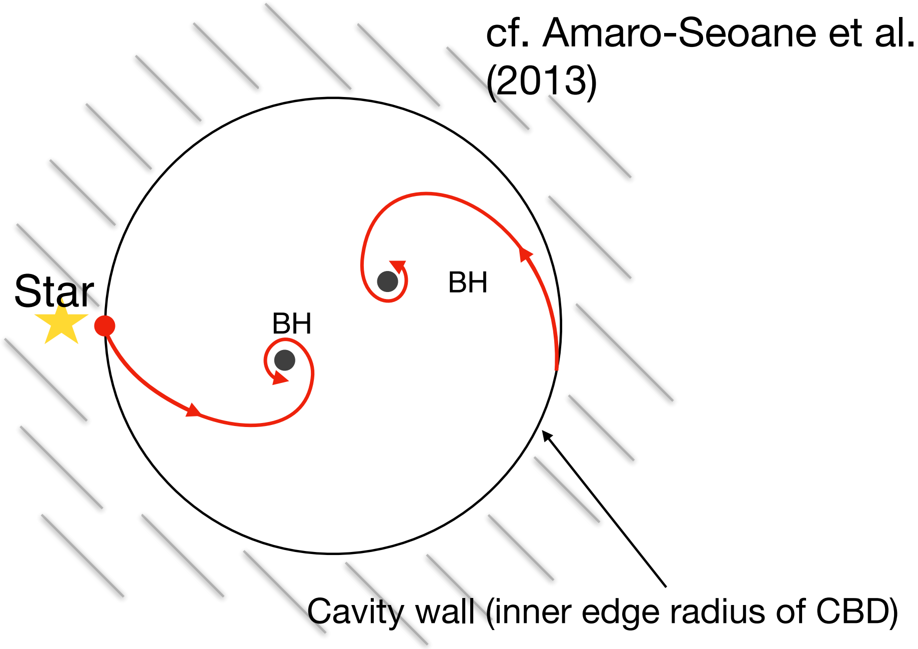
① Less bound (parabolic) TDEs



$\dot{M}_{\rm fb} \propto t^{-5/3}$ with dips

② Bound TDEs

Massive circumbinary disk (CBD)



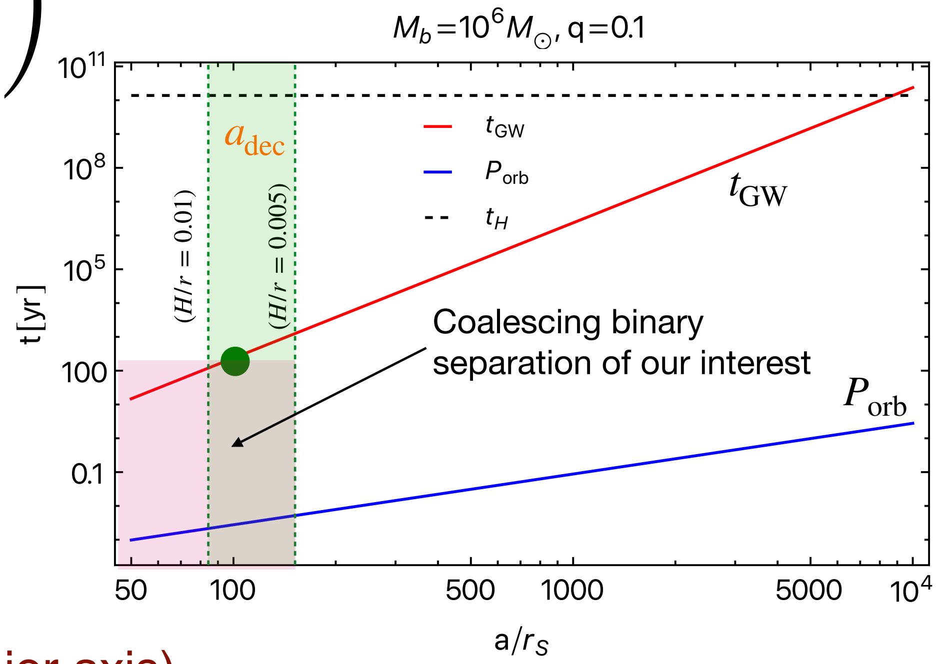
Once stars are injected inside the Roche lobe, they are bound by binary gravity, making it hard to predict the stellar orbit.

Characteristic timescales and sizes of coalescing SMBH binary

• Orbital decay timescale for a circular binary (Peters 1964):

$$t_{\rm GW} = \frac{5}{8}\frac{(1+q)^2}{q}\frac{r_{\rm S}}{c}\left(\frac{a}{r_{\rm S}}\right)^4$$

$(M_{\rm b} = M_1 + M_2, q = M_2/M_1)$



• Orbital period

$$P_{\rm orb} = 2\pi\sqrt{a^3/GM_{\rm b}}$$

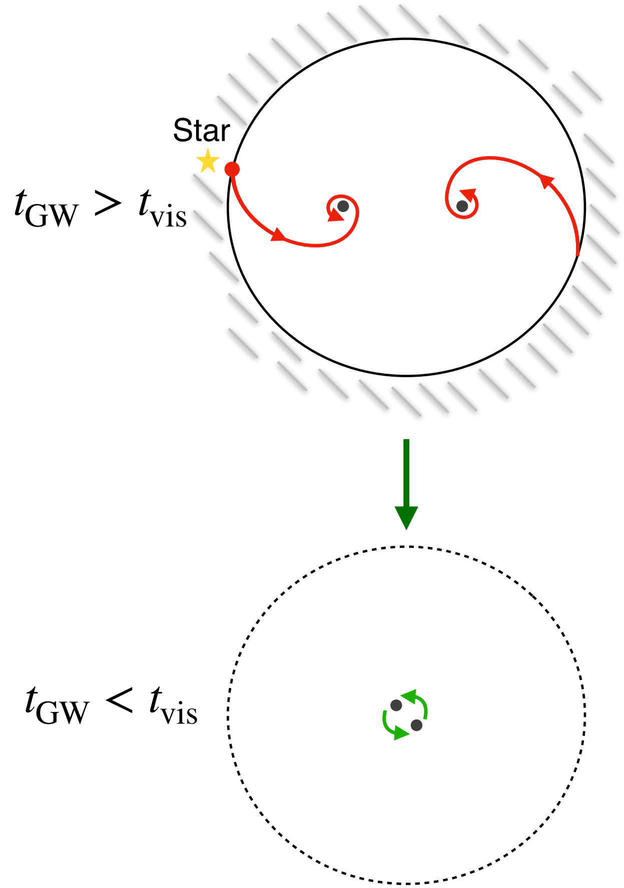
• Fiducial semi-major axis

$$a_0 = 100\, r_{\rm S}$$

• Decoupling radius (semi-major axis)

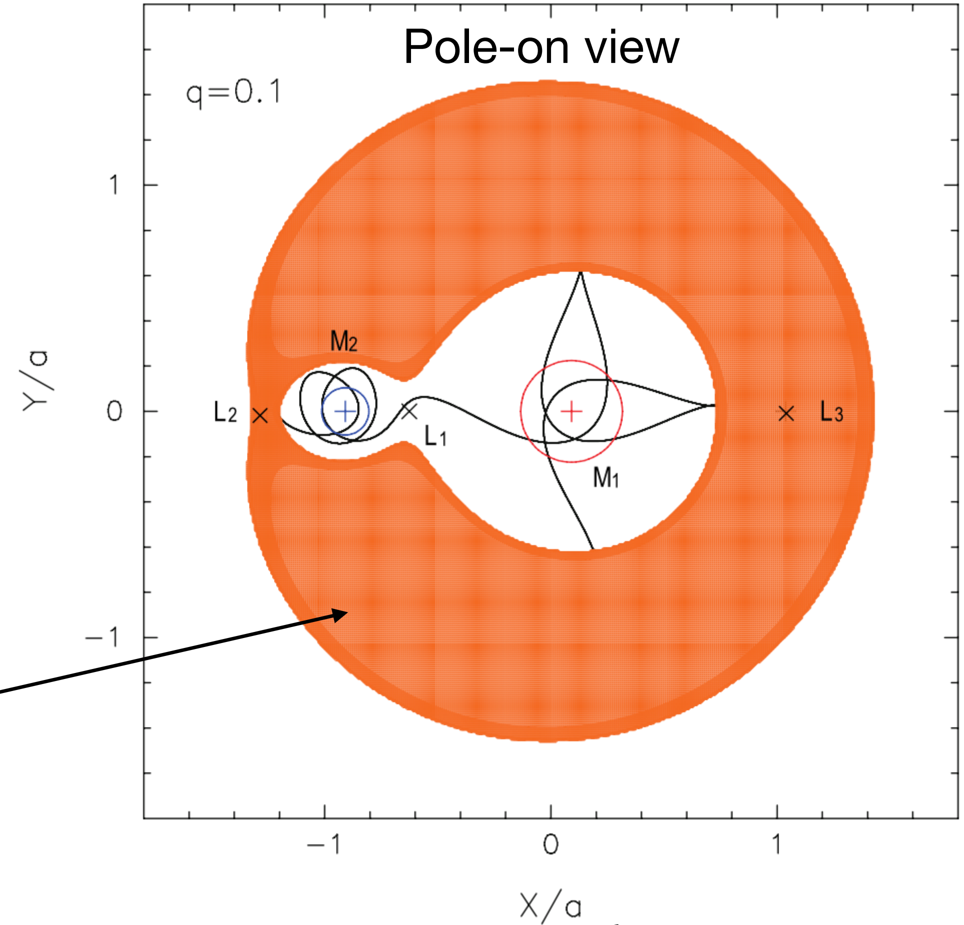
$$t_{\rm GW} = t_{\rm vis}(r_{\rm in}) \quad (r_{\rm in} \sim 2a) \quad \Rightarrow \quad \frac{a_{\rm dec}}{r_{\rm S}} = \left(\frac{128}{25}\right)^{1/5}\frac{1}{\alpha_{\rm SS}^{2/5}}\left(\frac{H}{r_{\rm in}}\right)^{-4/5}\frac{q^{2/5}}{(1+q)^{4/5}}$$

Decoupling from CBD



Simple test particle simulations

Hayasaki & Loeb (2016)



Evanescent region
(Zero-velocity surfaces)

* A star is a solar-type

* The star starts moving from the L_2 point in the binary orbital plane

* Two circles shows respective tidal radii

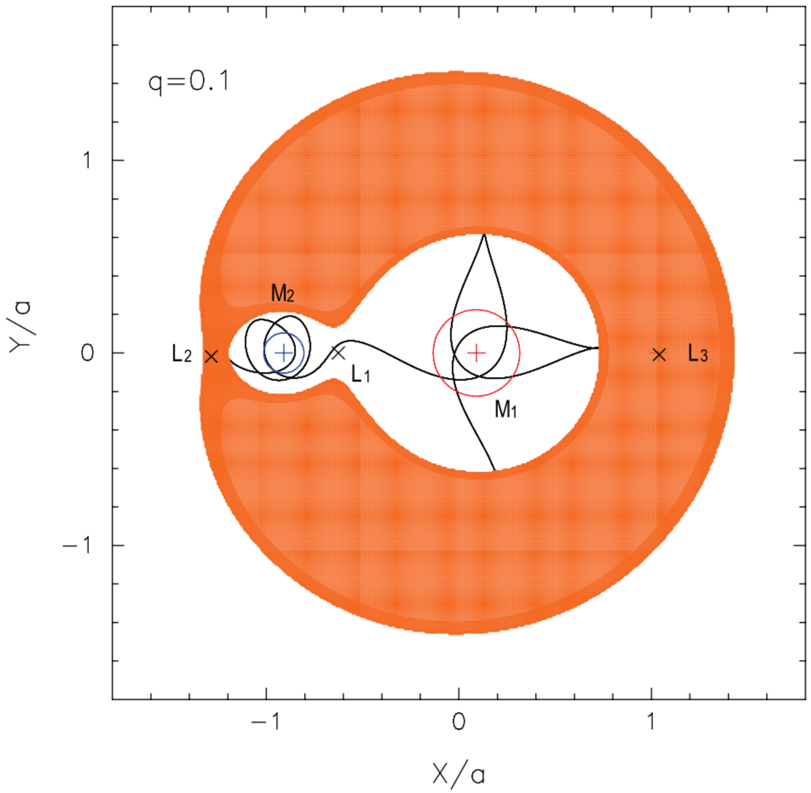
* GR effects of respective BHs are not included

Binary parameters: $M_{\rm b} = M_1 + M_2 = 10^6 M_\odot,\ a = 100\, r_{\rm S},\ q = 0.1,\ e = 0.0$

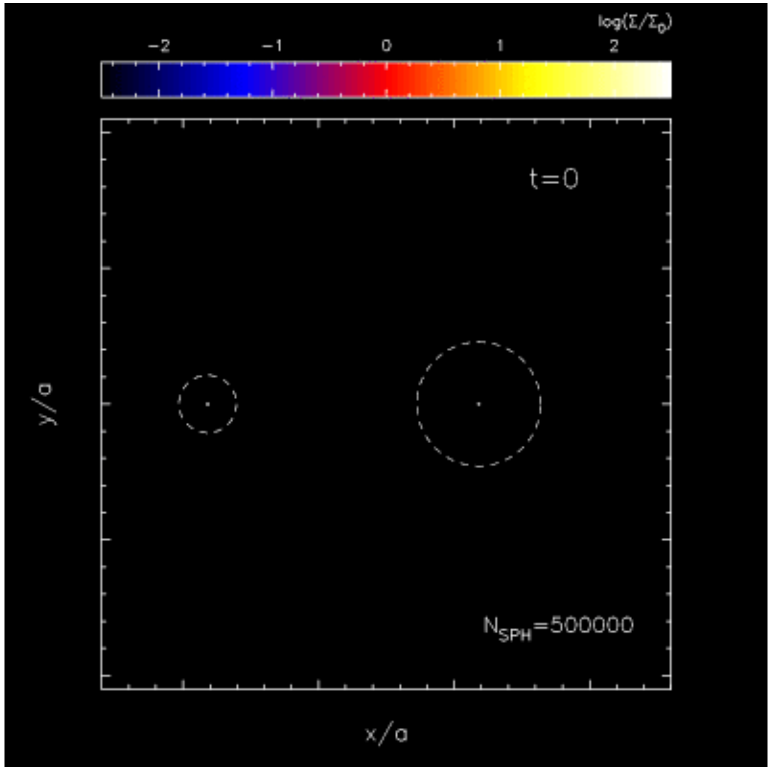
SPH simulations of tidal disruption of a star by a SMBH binary: rotating frame

Hayasaki & Loeb (2016)

Test particle simulation

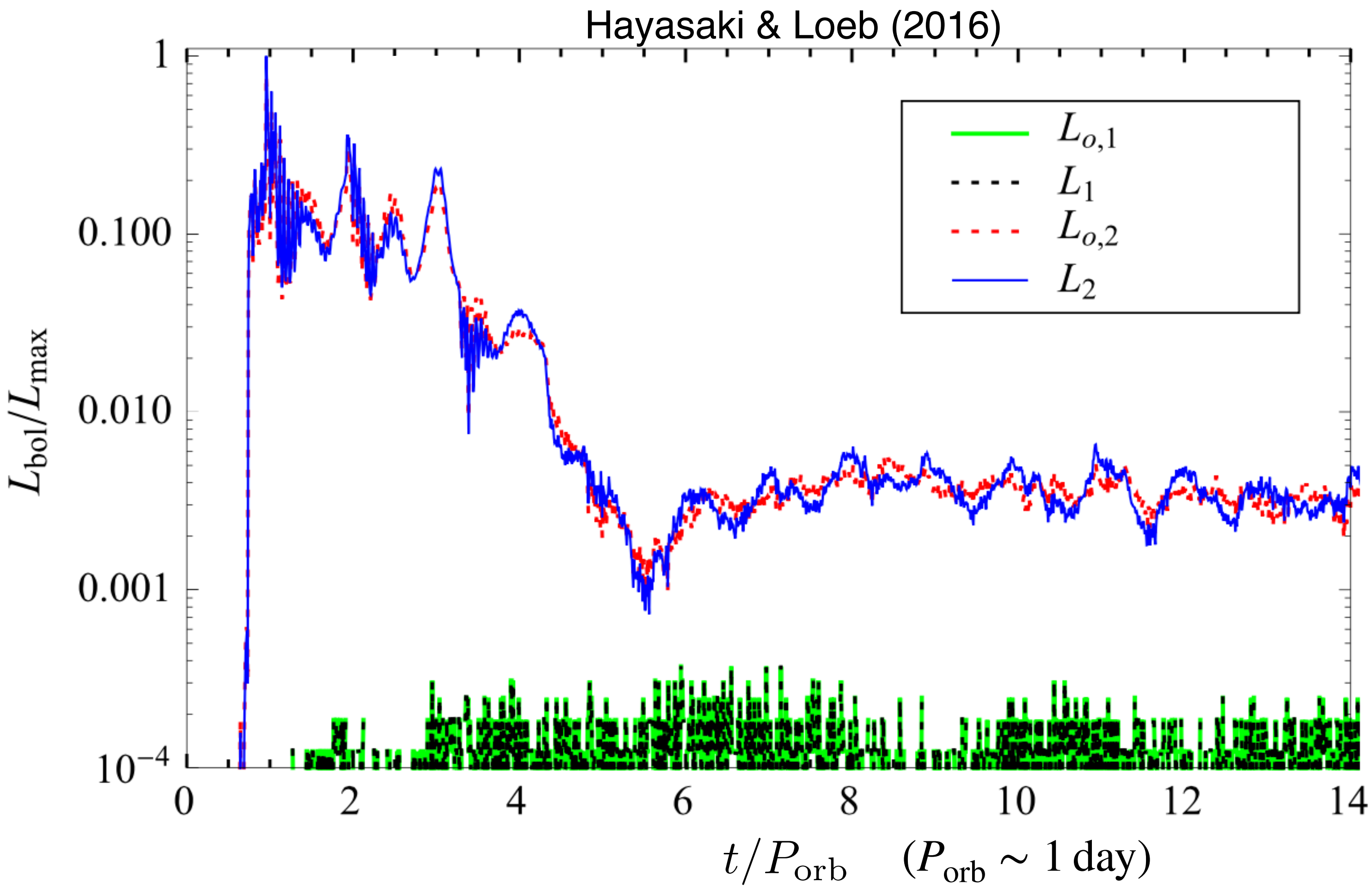


SPH simulation



Binary parameters: $M_b = M_1 + M_2 = 10^6 M_\odot$, $a = 100\, r_S$, $q = 0.1$, $e = 0.0$

Doppler-boosted periodic light curves



* Mass accretion rate is estimated at $3r_{\rm S,i}$

* Each bolometric luminosity:

$$L_1 \propto \dot{M}_1 D_1^4$$

$$L_2 \propto \dot{M}_2 D_2^4$$

D: Doppler factor

The secondary's luminosity is much larger than the primary one

Special Relativistic (SR) doppler boosting effect by binary orbital motion

Observed luminosity

$$L_i = L_{\mathrm{o},i} \left[\frac{1}{\gamma_i (1 - \beta_i \cos\theta)} \right]^4$$

Emitted luminosity

Doppler factor: D_i

$i = 1$: Primary BH

$i = 2$: Secondary BH

Lorenz factor:

$$\gamma_i = 1/\sqrt{1 - \beta_i^2}$$

Orbital velocity:

$$v_{\mathrm{orb}} = \sqrt{GM_{\mathrm{b}}/a}$$

$$\begin{cases} \beta_1 = (v_{\mathrm{orb}}/c)(q/[1+q])\sin(\Omega_{\mathrm{orb}} t) \\ \beta_2 = (v_{\mathrm{orb}}/c)(1/[1+q])\cos(\Omega_{\mathrm{orb}} t) \end{cases}$$

Evaluation of Doppler factor

For $q \ll 1$ and $\theta = 0$, $1 - \beta_1 \approx 1, 1 - \beta_2 \approx 1 - v_{\rm orb}/c$,

$$L_1 \approx L_{\rm o,1} \left(1 + \frac{v_{\rm orb}}{c}\right)^2 \left(1 - \frac{v_{\rm orb}}{c}\right)^2 \longrightarrow L_1/L_{\rm o,1} \sim 1$$

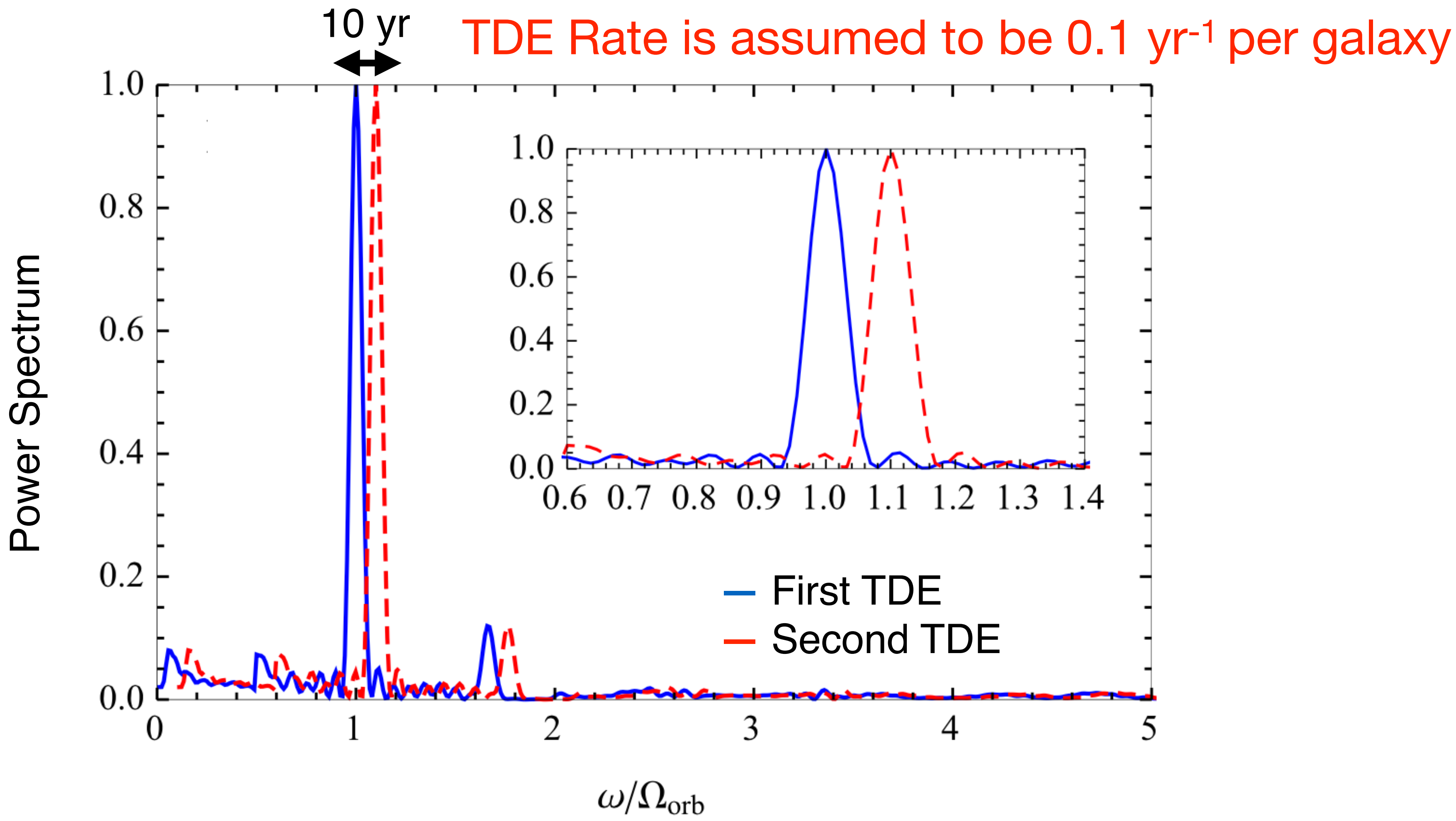
Taylor series

$$L_2 \approx L_{\rm o,2} \left(1 + \frac{v_{\rm orb}}{c}\right)^2 \Bigg/ \left(1 - \frac{v_{\rm orb}}{c}\right)^2 \longrightarrow L_2/L_{\rm o,2} \sim 1.3$$

Here, $v_{\rm orb}/c = \sqrt{GM_{\rm b}/c^2 a} = 1/\sqrt{200} \sim 0.07$

Doppler factor much more efficiently works for L_2 due to small values of (a, q)

Detection of GW emission by two separated TDEs



The frequency deviation between two PS peaks proves orbital decay due to GW emissions

Summary

Tidal disruption of a star by binary SMBHs is a key to understanding the merging process of two SMBHs. If a TDE occurs around a coalescing SMBH binary, the signature could appear in the TDE light curve, giving the EM counterpart of GW emission.

Main differences of light curves between single and binary TDEs are as follows:

1. Bolometric light curves show no power-law decay rate, as expected **bound TDEs**, but vary with a binary orbital motion by **SR Doppler boosting**
2. The frequency deviation between two PS peaks gives evidence for orbital decay due to GW emissions

Thank you for your attention