Binary Stars Approaching SMBH:

Tidal Break-up, Double Stellar Disruptions and Stellar Collision

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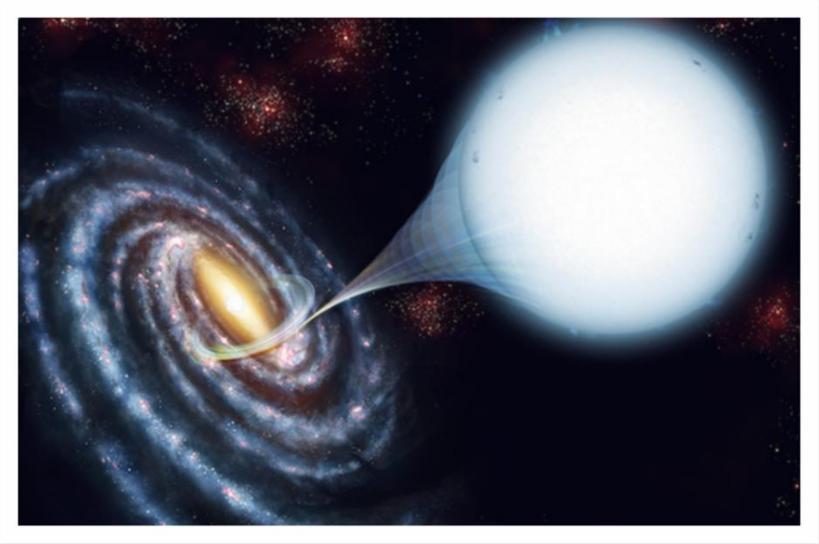
Tidal Disruption

Stellar Tidal Disruption

$$r_p \sim r_{tide}^{\star} = R_{\star}\left(\frac{M}{m_{\star}}\right)^{\frac{1}{3}}$$

Binary Tidal Break-up (Hills mechanism)
Bound star (S stars) + Hyper velocity stars

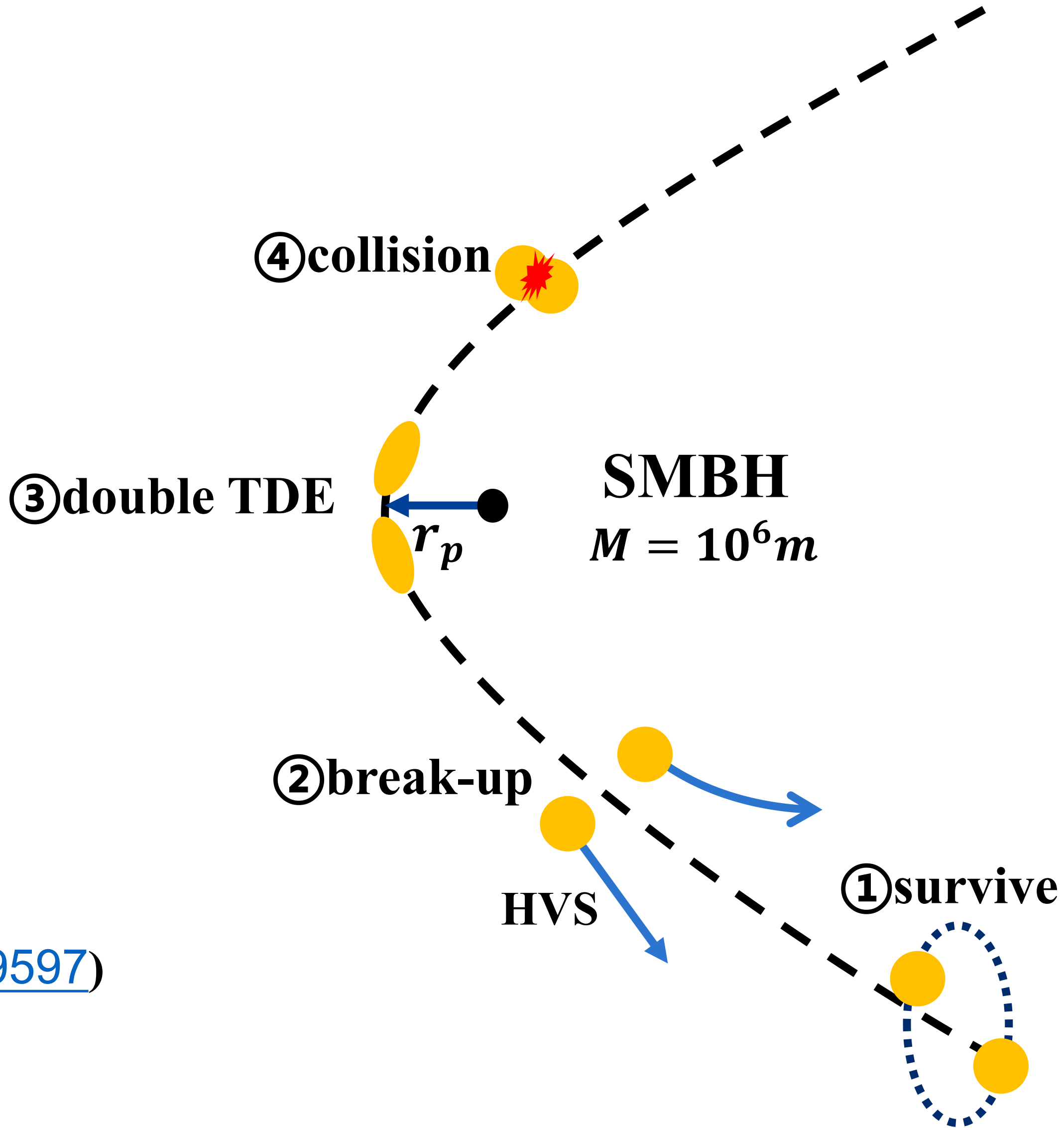
$$r_p \sim r_{tide}^{b} = a_b\left(\frac{M}{m_b}\right)^{\frac{1}{3}}$$



Binary-SMBH

Different outcomes:

0. **Binary survived**
1. **Binary tidal break-up**
2. **Double stellar disruptions**
3. **Stellar collision**



Based on
Yu & Lai 2024a (submitted, arxiv.org/abs/2409.09597)
Yu & Lai 2024b (in prep)

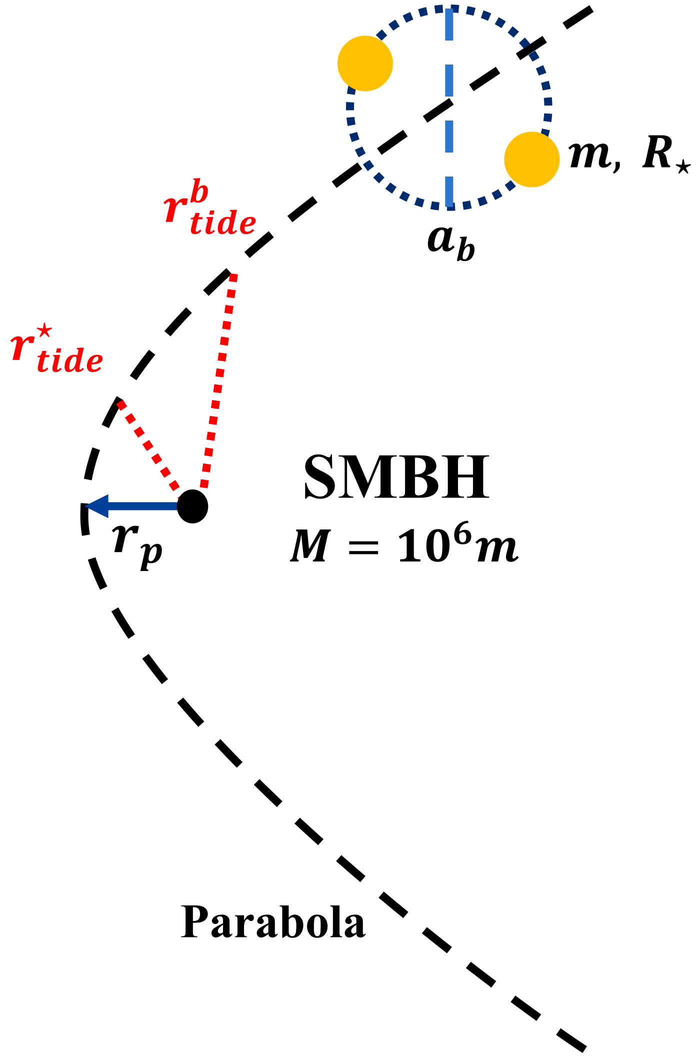
Binary-SMBH

Key dimensionless parameters:

$$r_{tide}^{b} \equiv a_b \left(\frac{M}{m_{tot}}\right)^{\frac{1}{3}},\ \beta_b \equiv \frac{r_{tide}^{b}}{r_p};$$

$$r_{tide}^{\star} \equiv R_\star \left(\frac{M}{m}\right)^{\frac{1}{3}},\ \beta_\star \equiv \frac{r_{tide}^{\star}}{r_p};$$

$$\alpha \equiv \frac{a_b}{R_{col}} \approx \frac{a_b}{2R_\star};$$



Tidal Break-up

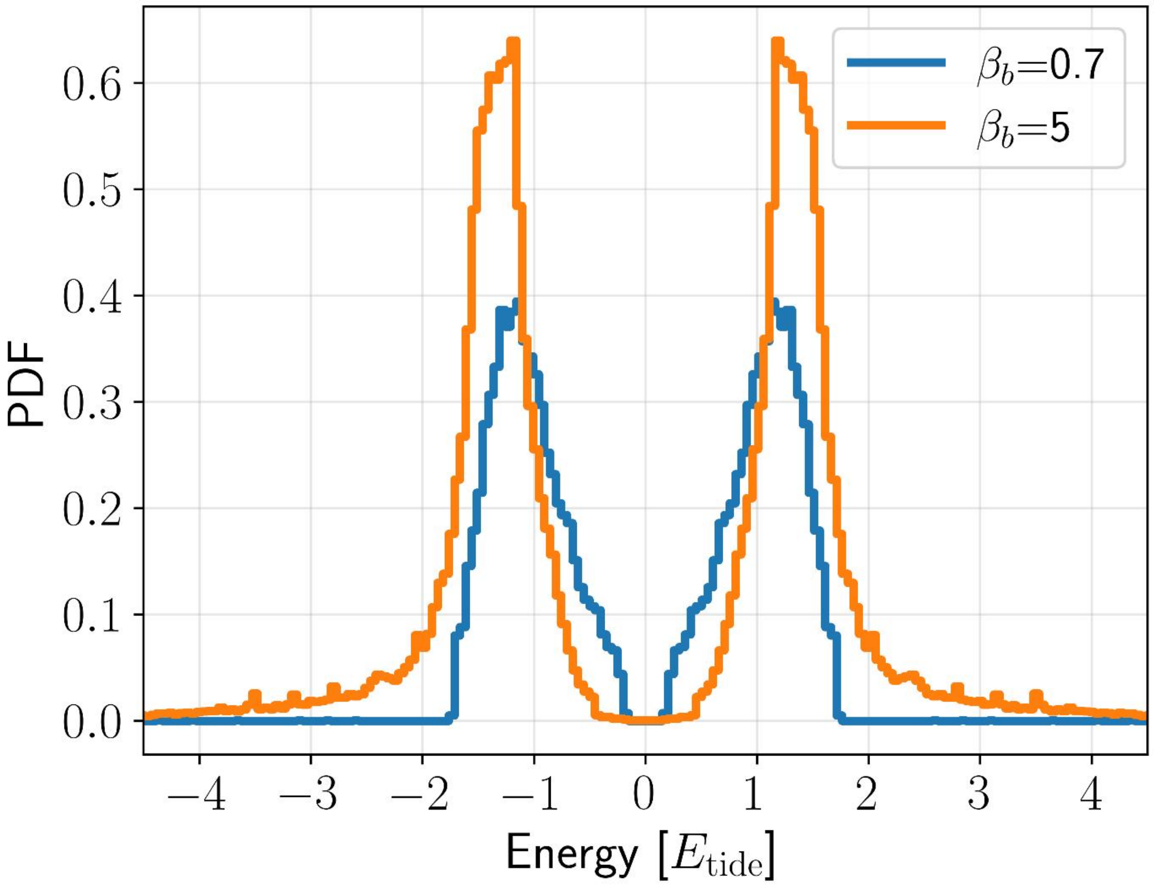
Gentle encounter: $\beta_b \equiv \frac{r_{tide}^b}{r_p} < 1$

Deep encounter: $\beta_b \equiv \frac{r_{tide}^b}{r_p} > 1$

Hills mechanism: $E_{tide} = \frac{GMm}{{r_{tide}^b}^2} a_b$

Peak value: no dependence on β_b

Distribution: Truncation (gentle) vs. long tail (deep)



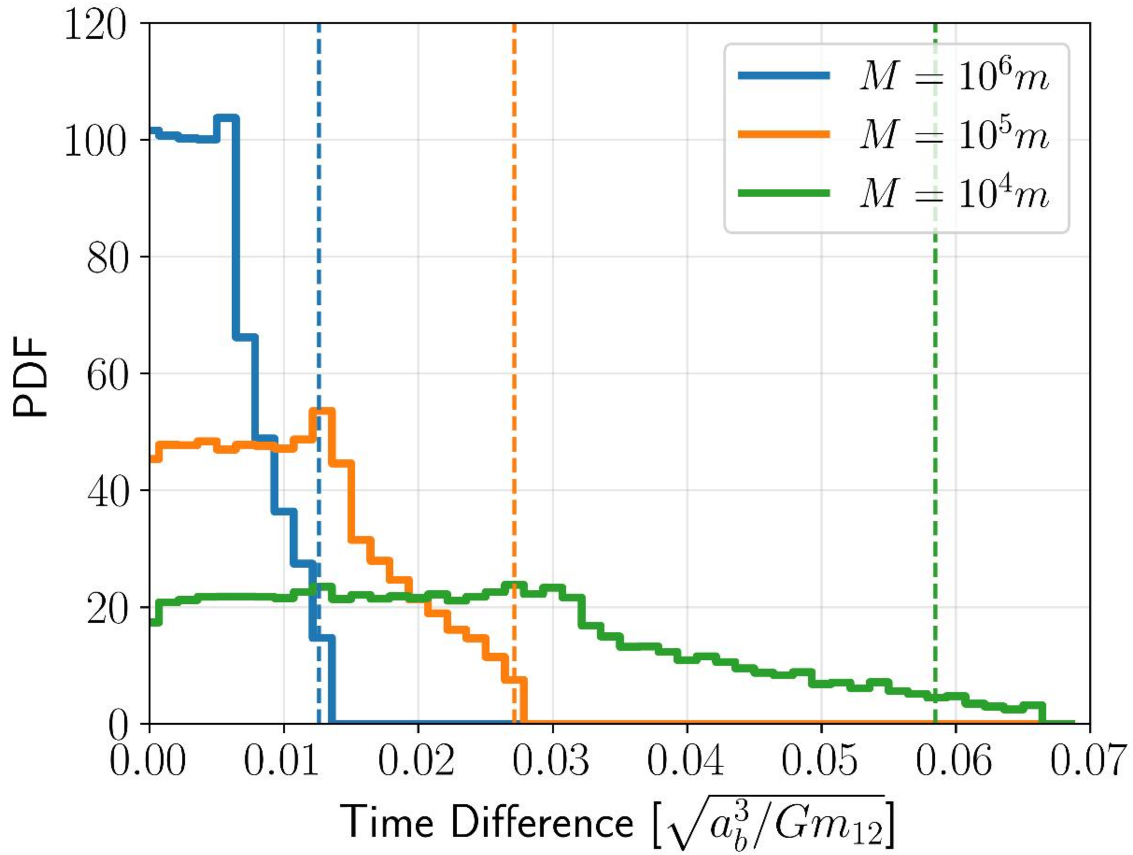
Double Stellar Disruption

Very deep encounter: $\beta_\star \equiv \frac{r^\star_{tide}}{r_p} > 1$

Fraction and probability have been discussed by Mendel & Levin 2015.

Here we focused on the time interval.

$$(\Delta T_{DD})_{\max} \sim \frac{a_b}{\sqrt{\frac{GM_{BH}}{r_t^{(b)}}}} \sim \left(\frac{m_{12}}{M}\right)^{\frac{1}{3}} \sqrt{\frac{a_b^3}{Gm_{12}}}$$ (dashed line)



For most bound debris: $t_{min} \sim \frac{\pi G M}{\sqrt{2}} \left(\frac{GMR_\star}{r_t^2}\right)^{-\frac{3}{2}} \sim \left(\frac{M}{m_{12}}\right)^{\frac{1}{2}} \left(\frac{R_\star}{a_b}\right)^{\frac{3}{2}} \sqrt{\frac{a_b^3}{Gm_{12}}}$

Stellar Collision

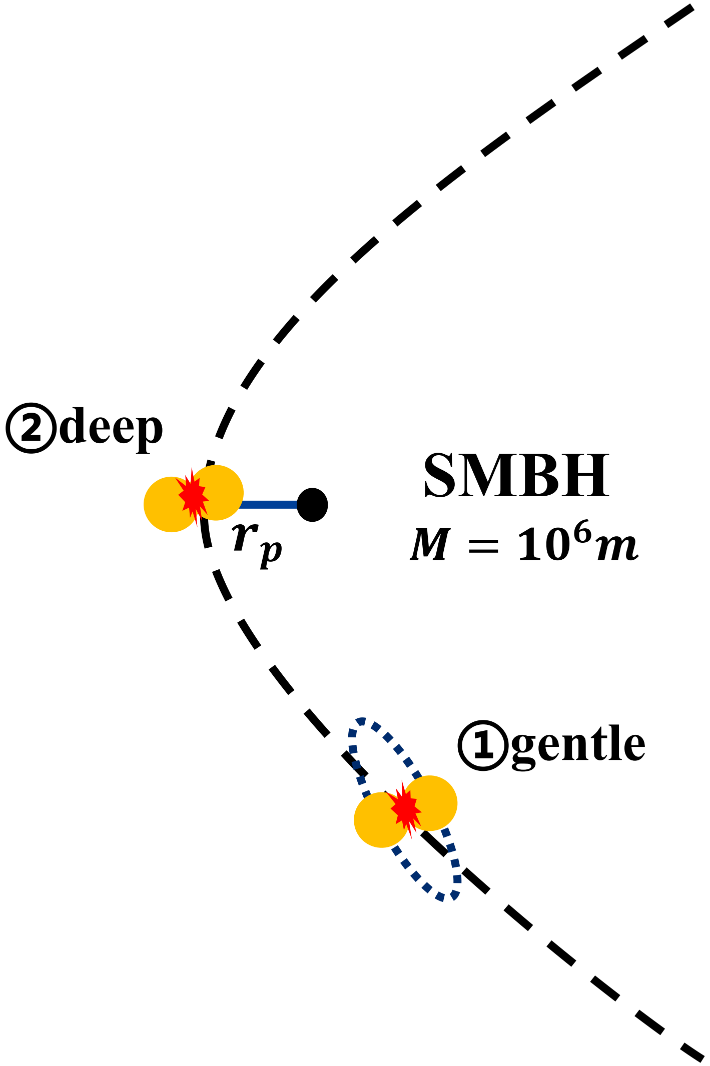
Two collision channel:

① **Gentle encounter: $\boldsymbol{\beta_b < 1}$, survived but high $\boldsymbol{e}$**

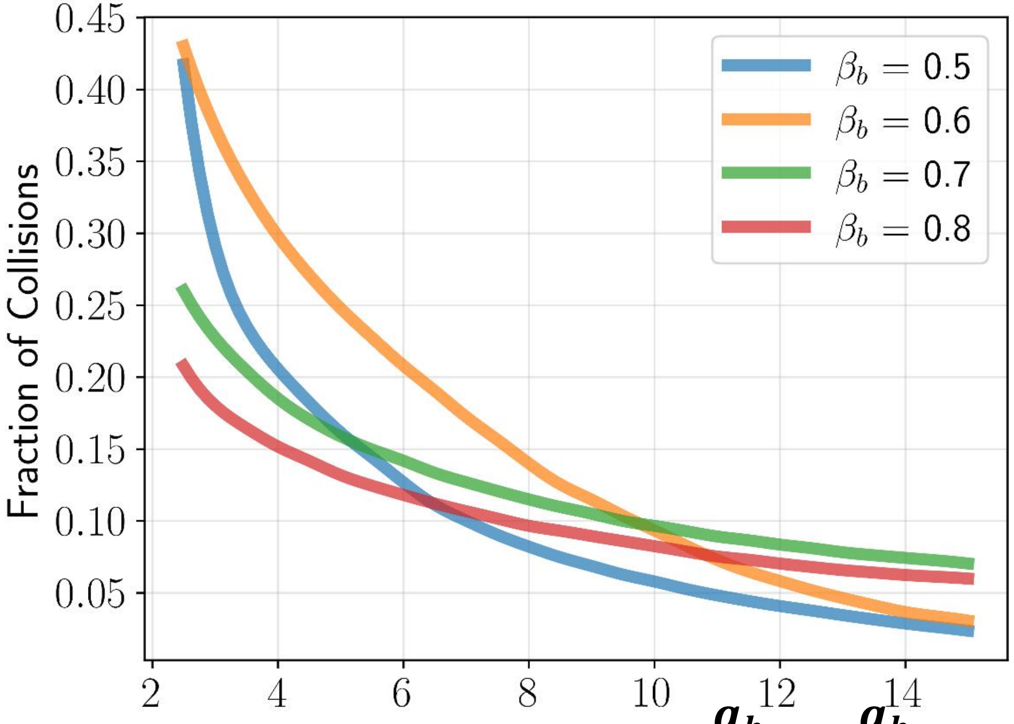
② **Deep encounter: $\boldsymbol{\beta_b > 1}$, randomly at $\boldsymbol{r_p}$**

Difference:

Collision fraction, collision velocity, orbit of the remnant.

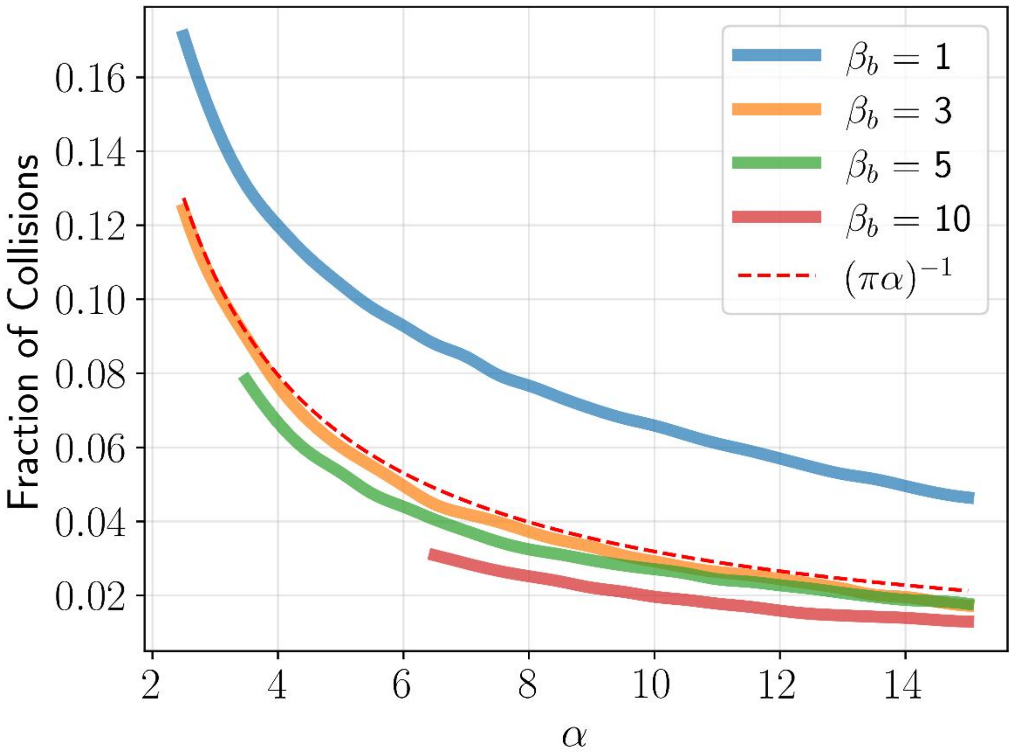


Stellar Collision - fraction



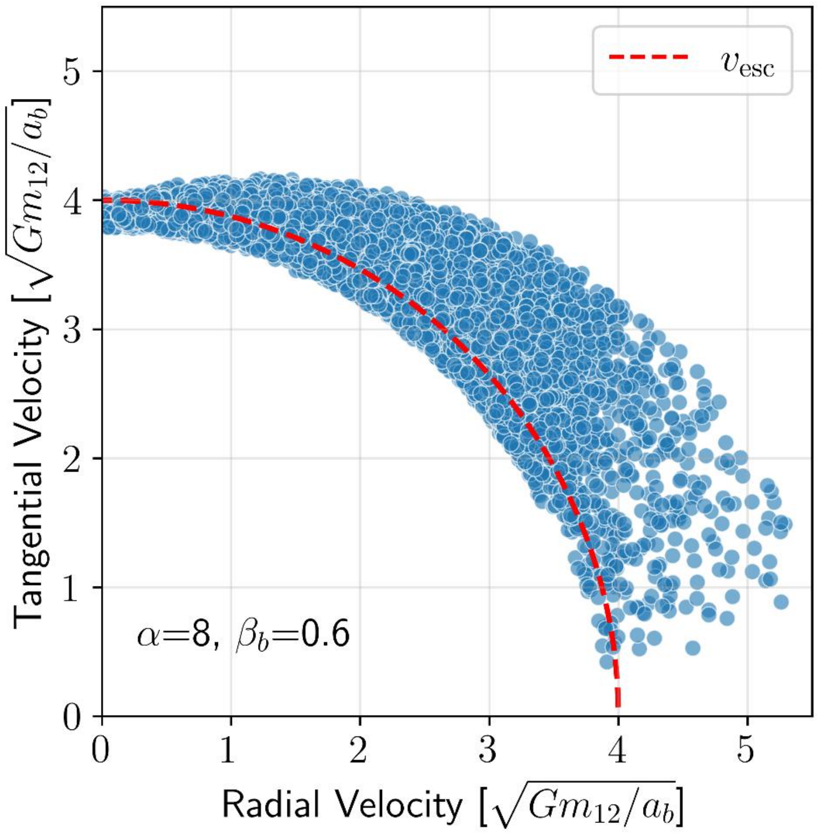
$$\alpha \equiv \frac{a_b}{R_{col}} \approx \frac{a_b}{2R_\star}$$

Gentle encounter

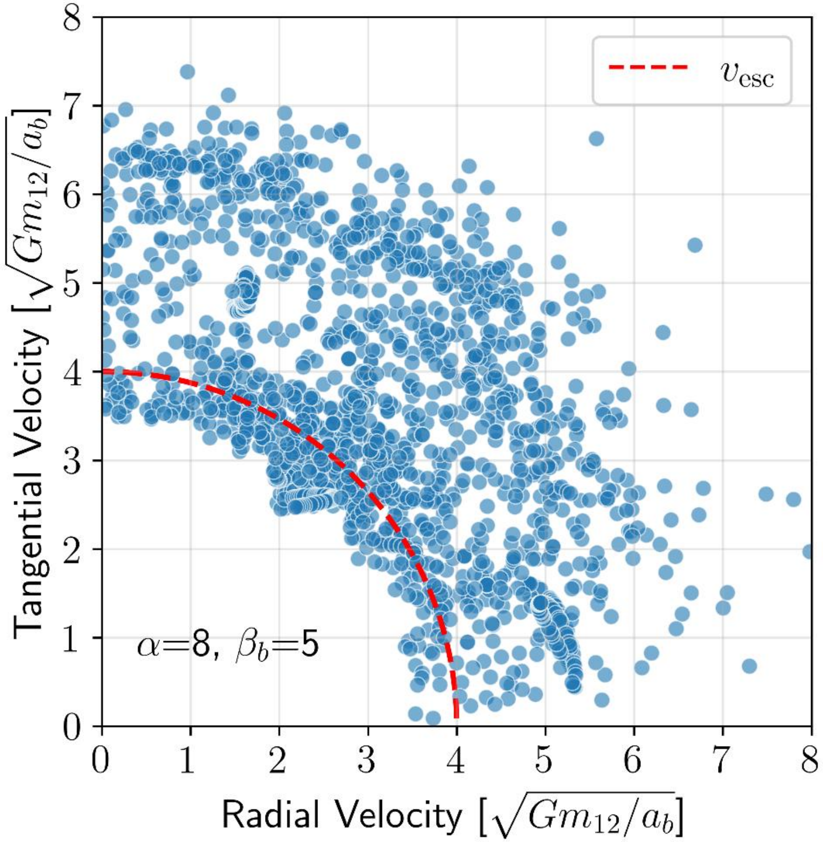


Deep encounter

Stellar Collision - velocity



Gentle encounter



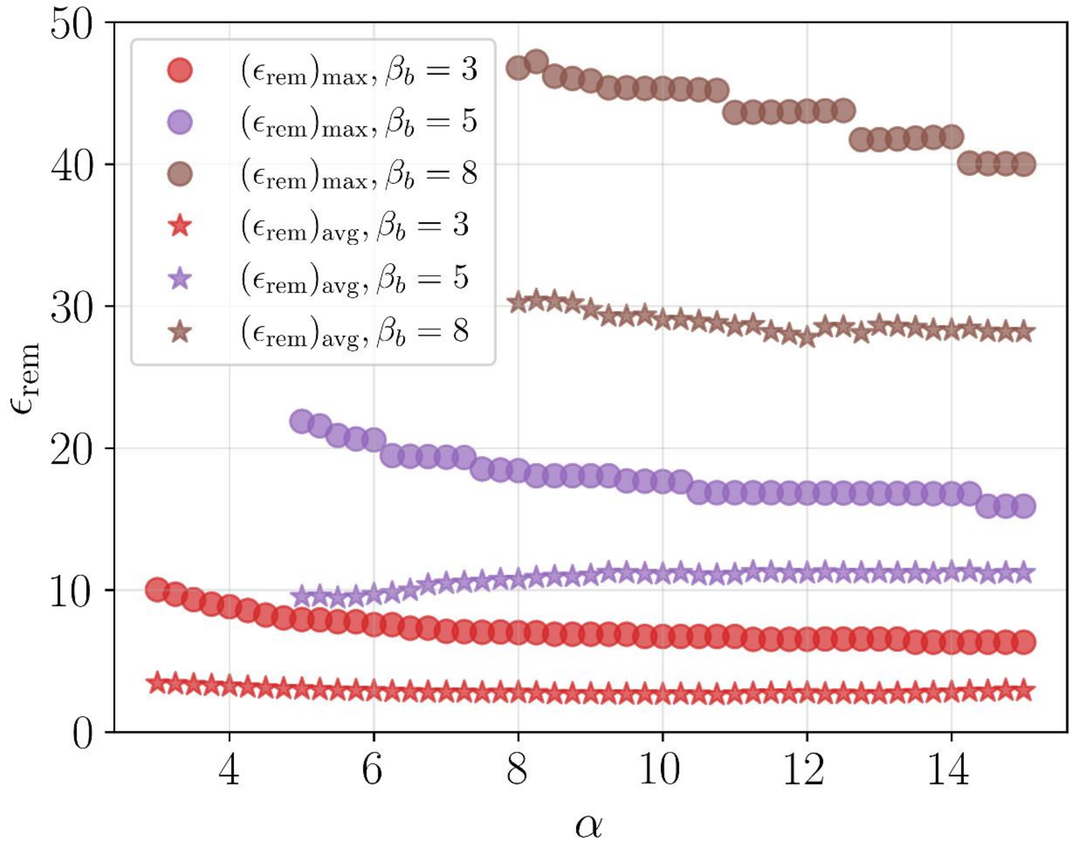
Deep encounter

$$v_{esc} \equiv \sqrt{\frac{2Gm}{R_\star}}$$

Collision velocity larger than escape velocity of the star (up to 2 times) →Mass loss

Stellar Collision - remnant

Assume an inelastic collision (momentum is conserved but kinetic energy is not)



Orbital energy of merger remnant

$$E_{rem} = -\epsilon_{rem}\frac{Gm_1m_2}{a_b}$$

$$P_{rem} = \left(\frac{m_{12}}{2\epsilon_{rem}\mu_{12}}\right)^{\frac{3}{2}}\left(\frac{M}{m_{12}}\right)P_b$$

Stellar Collision - remnant

For example: for $\alpha \equiv \frac{a_b}{2R_\star} = 10,\ \beta_b = 8, \frac{M}{m} = 10^6$:

$P_{rem}\sim$ 10 years for main-sequence binaries ($m = M_\odot$)

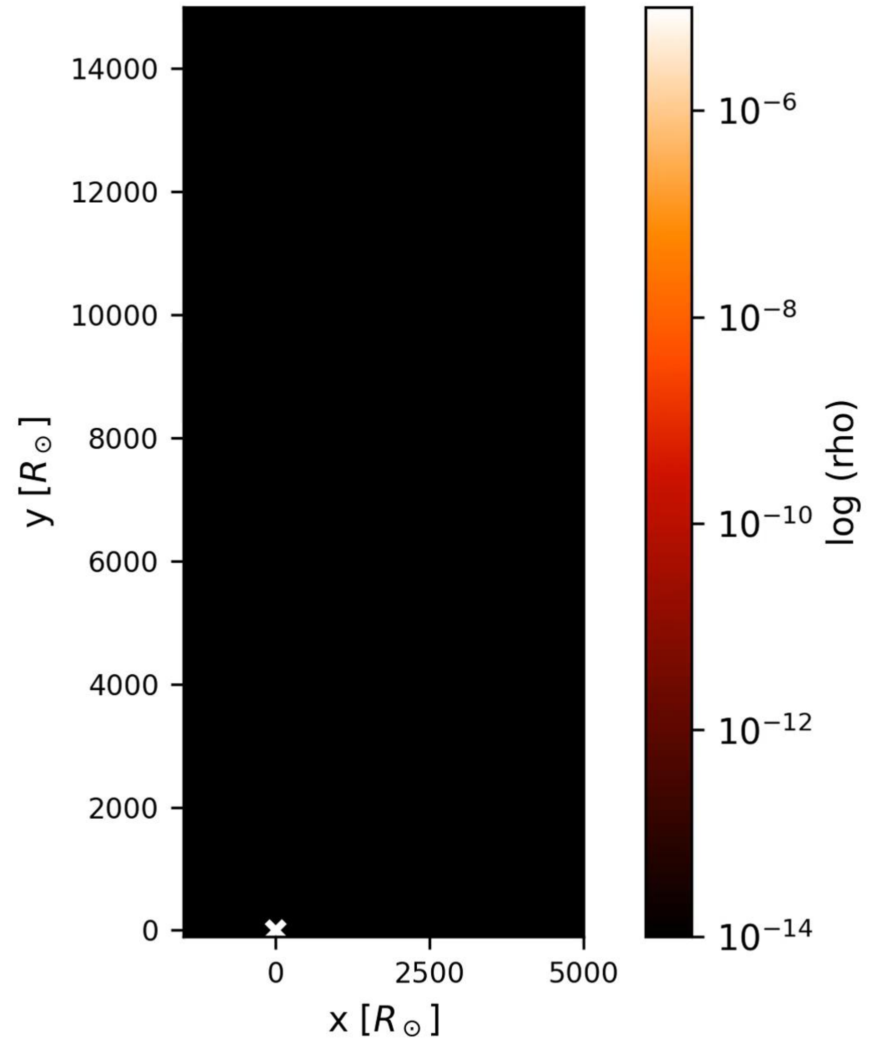
Remnant coming back may suffer partial tidal disruption?

Puffier
Envelope may be disrupted

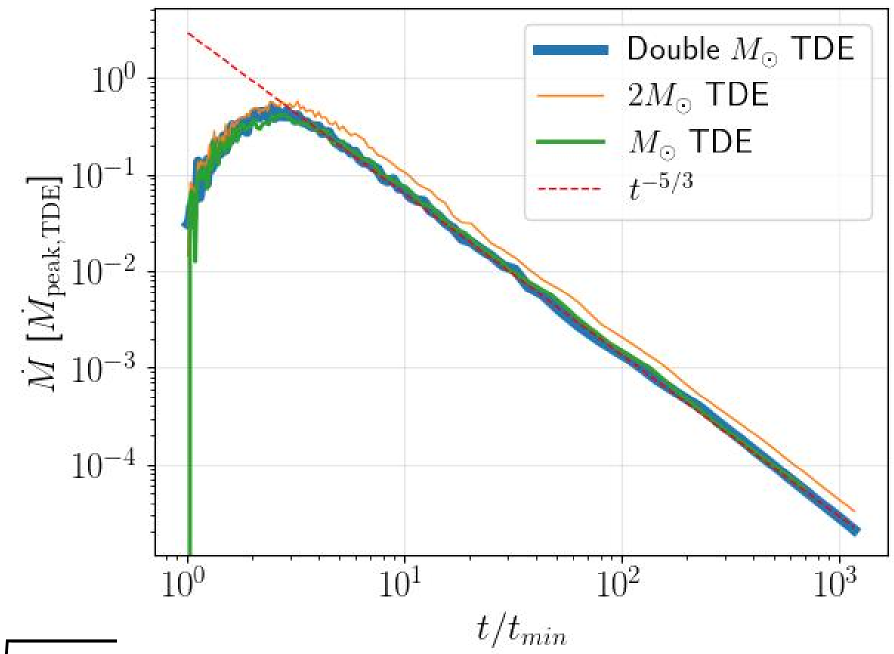
Repeated pTDE?

Hydrodynamics Simulation: Preliminary Results

Hydrodynamics simulation – double TDE



$$\dot{M} = \frac{\mathrm{d}M}{\mathrm{d}\epsilon}\left|\frac{\mathrm{d}\epsilon}{\mathrm{d}t}\right|$$



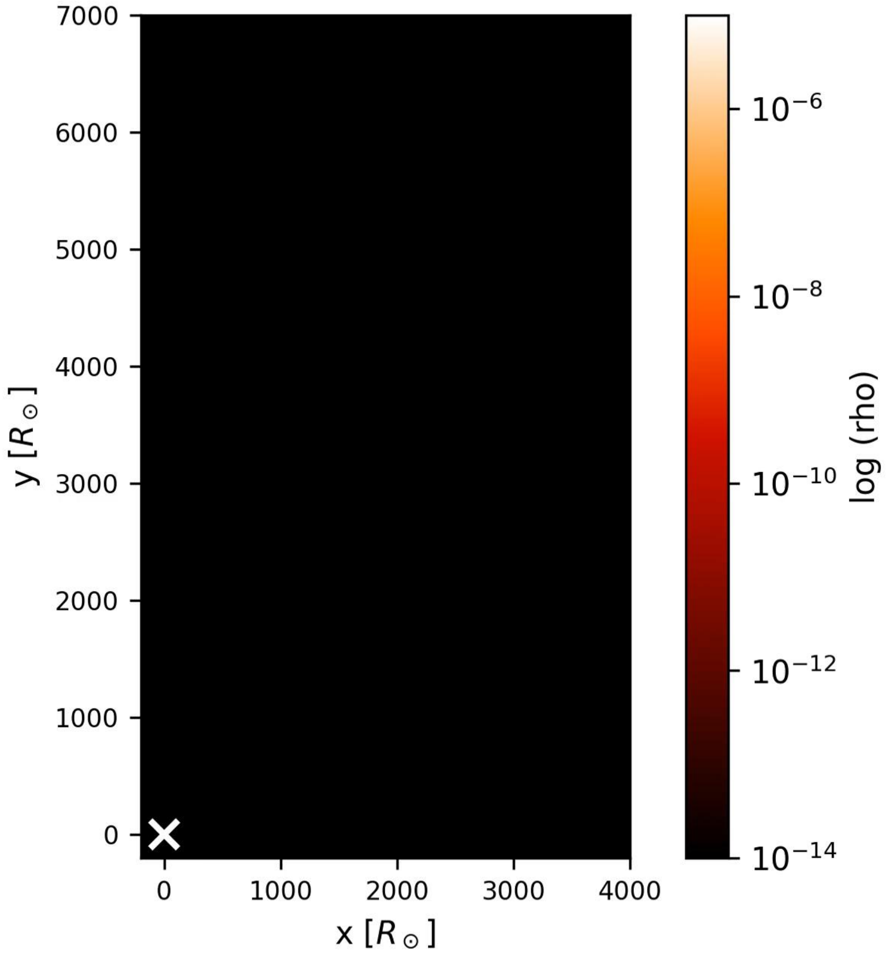
$$\frac{\Delta T_{DD}}{t_{min}} = \frac{\left(\frac{2m}{M}\right)^{\frac{1}{3}}\sqrt{\frac{a_b^3}{2Gm}}}{\frac{\pi GM}{\sqrt{2}}\epsilon_c^{-\frac{3}{2}}{\epsilon_{max}^*}^{-\frac{3}{2}}} = {\epsilon_{max}^*}^{\frac{3}{2}}\frac{2^{\frac{1}{3}}}{\pi}\left(\frac{m}{M}\right)^{\frac{5}{6}}\alpha^{\frac{3}{2}} \sim 10^{-4}$$

$$\alpha \equiv \frac{a_b}{2R_\star} = 8,\ \beta_b \equiv \frac{r_{tide}^b}{r_p} = 25,\ \ \beta_\star \equiv \frac{r_{tide}^\star}{r_p} \simeq 2$$

Stream collision may happen typically for $\frac{\Delta T_{DD}}{t_{min}} > 10^{-2}$, i.e. $\alpha > 10^3$ here (Bonnerot & Rossi 2019)

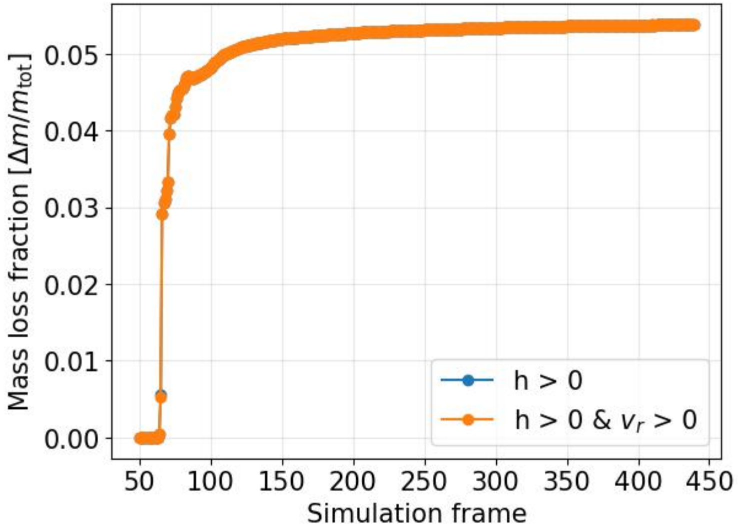
Hydrodynamics simulation – Stellar collision

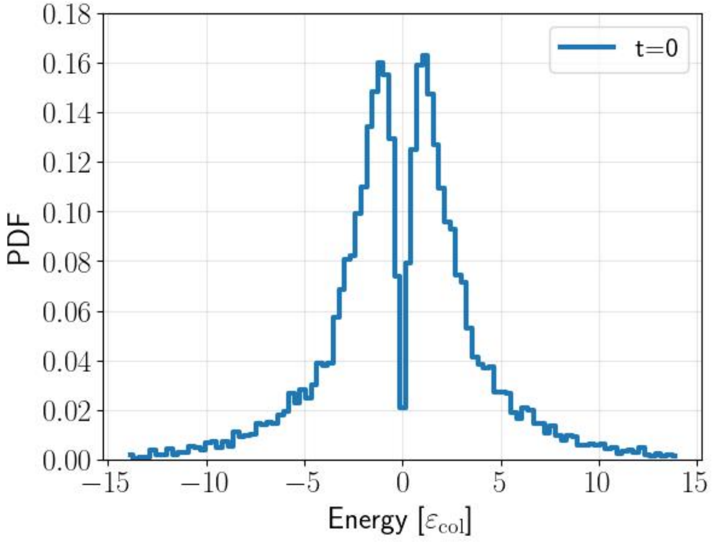
Deep encounter



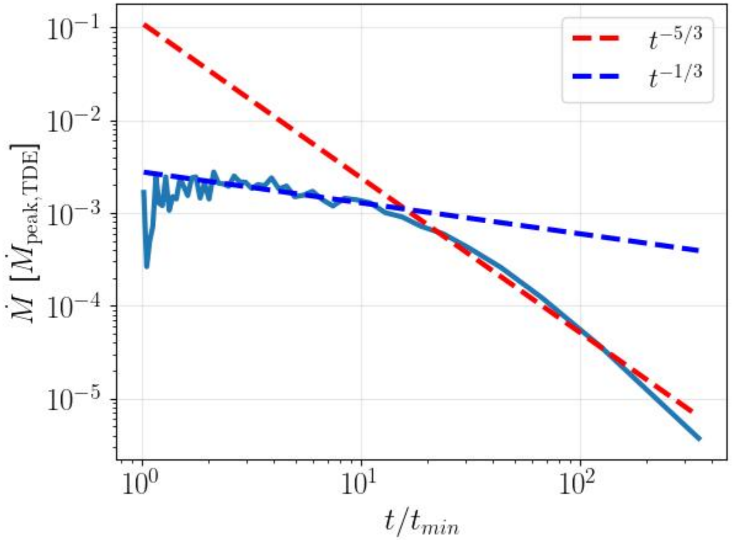
$\beta_b = 5, \alpha = 8$

Mass loss:





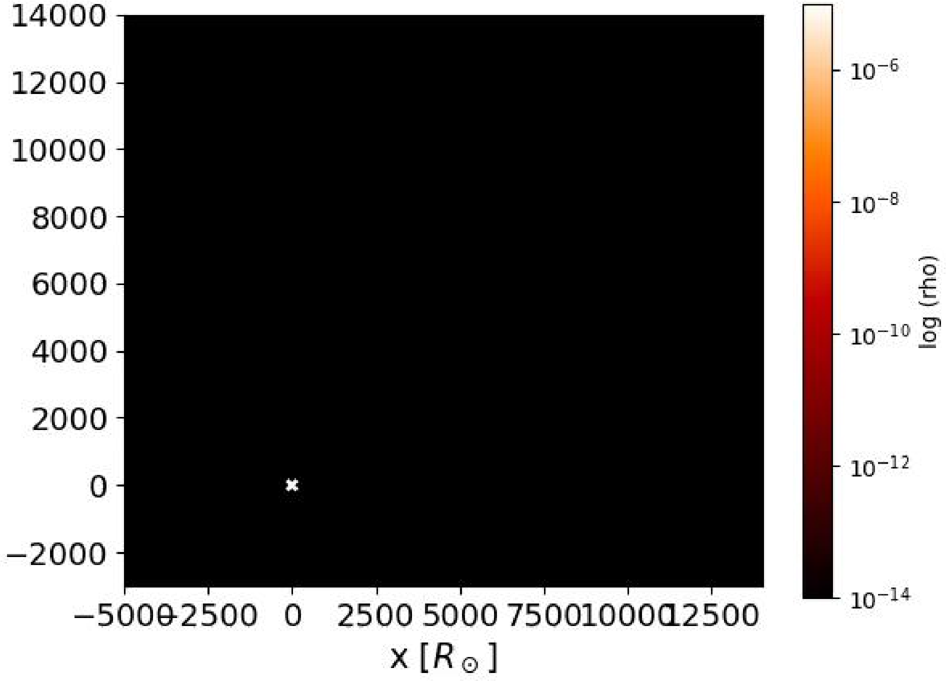
Debris energy distribution



Fall back rate

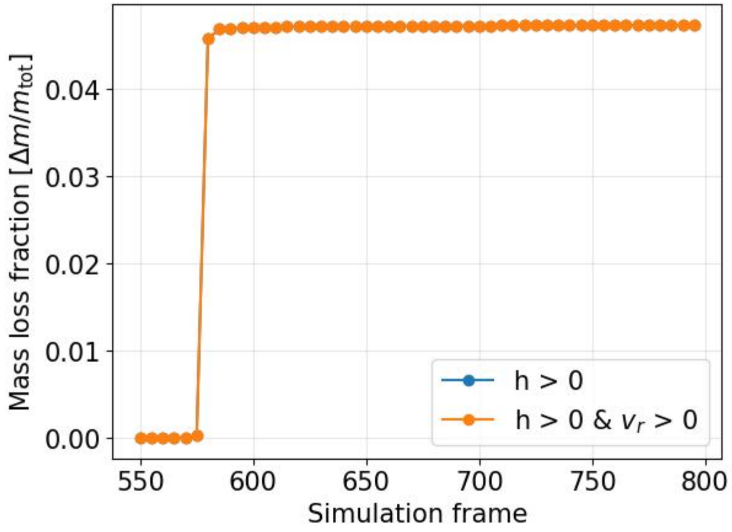
Hydrodynamics simulation – Stellar collision

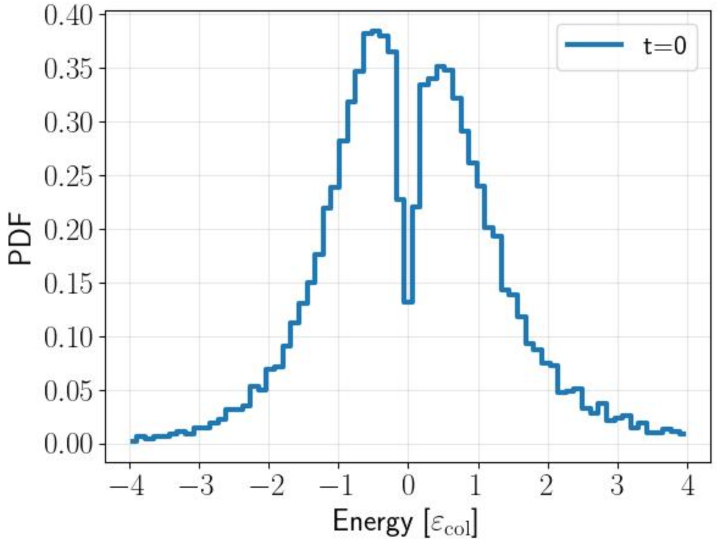
Gentle encounter



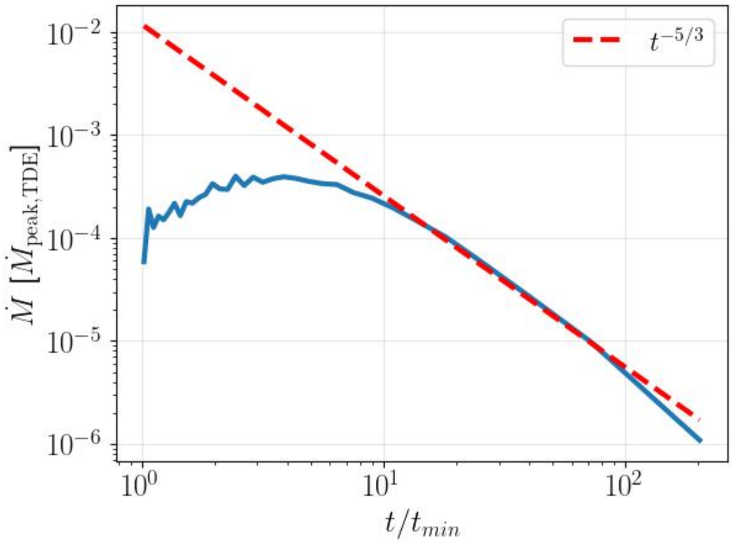
$\boldsymbol{\beta_b = 0.6,\ \alpha = 8}$

Mass loss:





Energy distribution



Fall back rate

Summary

1. The orbital energy distribution of binary components following a binary break-up differs from TDE debris
2. Time interval successive stellar disruptions from a binary is short compared to the binary orbital period
3. Stellar collisions can occur both outside and inside the binary's tidal sphere, typically at roughly the stellar escape velocity, leading to mass loss that may subsequently accrete onto the SMBH
4. The merger remnant can be potentially linked to repeated pTDEs

Thanks!