Tidal Disruption Flares from Stars on Bound Orbits

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Outline

1. **Introduction**

   Tidal disruption events (TDEs)
   Standard theory and past observations
   Our scenario (Eccentric TDEs)

2. **Our model**

   1. Numerical modeling of a star-black hole system
   2. Simple General relativistic (GR) precession treatment

3. **Result**

   1. Mass fall-back rate in eccentric TDEs
   2. Accretion disk formation

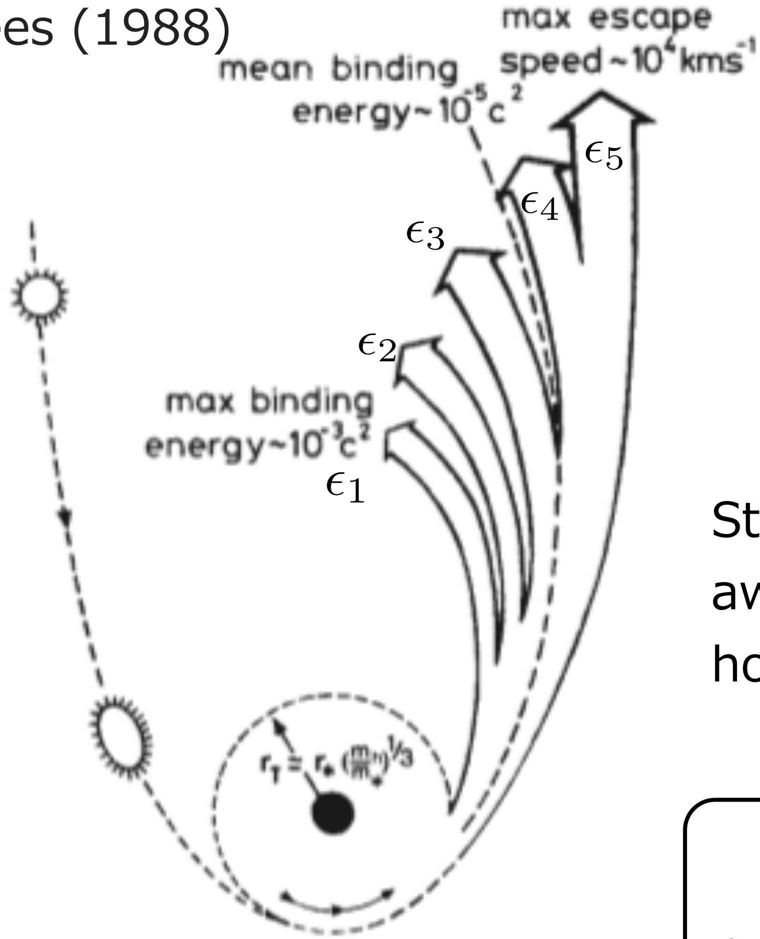
4. **Summary & Discussion**

Introduction

Tidal disruption events

Standard picture of tidal disruption events

Rees (1988)



ε = kinetic energy + potential energy + thermal energy
~ kinetic energy + potential energy

if ε>=0

Stellar debris flies away from the black hole

if ε< 0

Stellar debris is bounded by the black hole's gravity and falls back to black hole

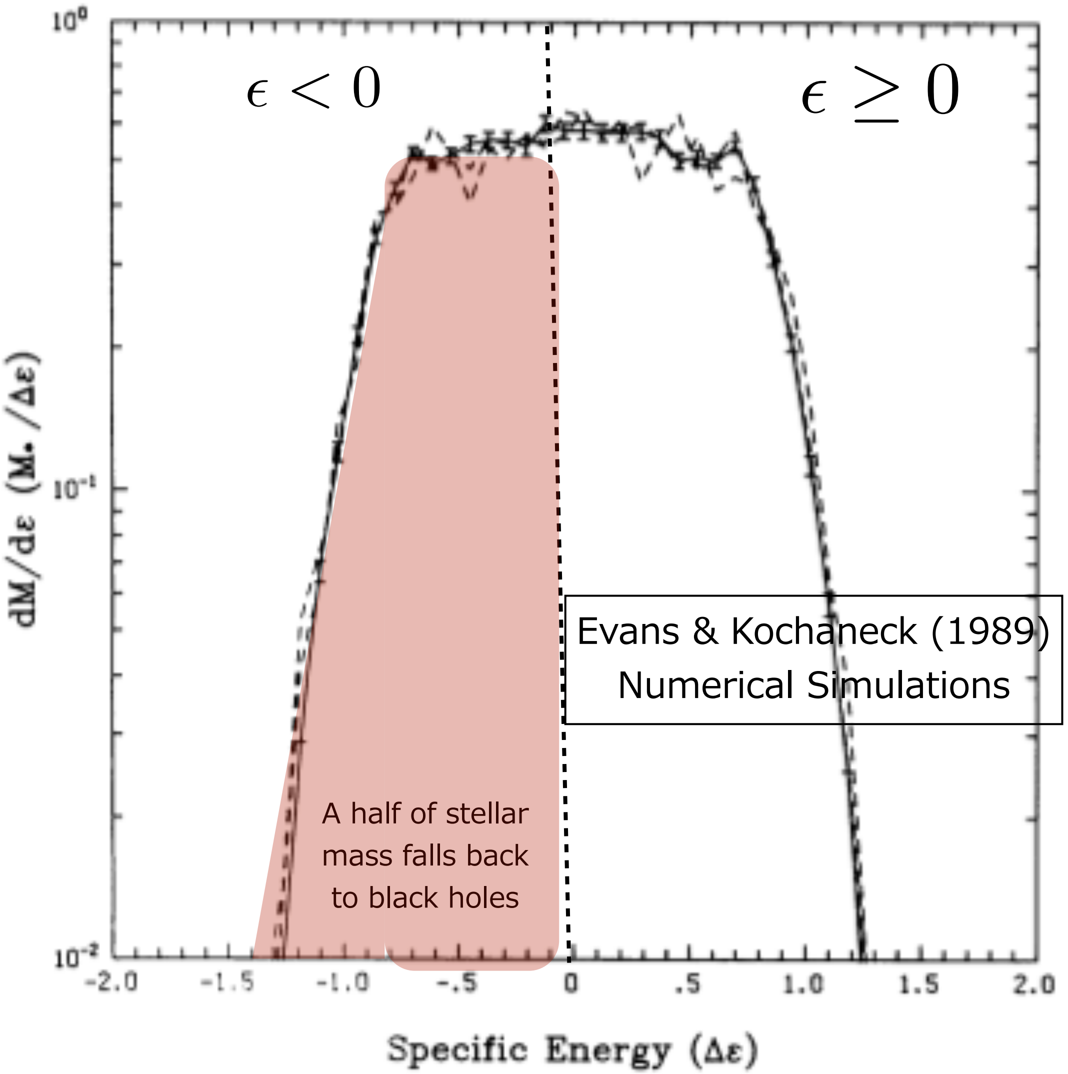
Tidal disruption radius
(self-gravity force=tidal force):

$$r_{\rm t} = \left(\frac{M_{\rm BH}}{m_*}\right)^{1/3} r_*$$

Scientific motivation

1. Evidence for quiescent supermassive black holes
2. Contribution to black hole growth
3. One of gravitational wave source candidates (EMRIs)

Differential mass-energy distribution of stellar debris



Mass fallback rate

$$\frac{dM}{dt} = \frac{dM(\epsilon)}{d\epsilon}\left|\frac{d\epsilon}{dt}\right| \quad (\epsilon < 0)$$

Specific energy: $\epsilon \approx -\frac{GM_{\rm BH}}{2a}$

Its time derivative:

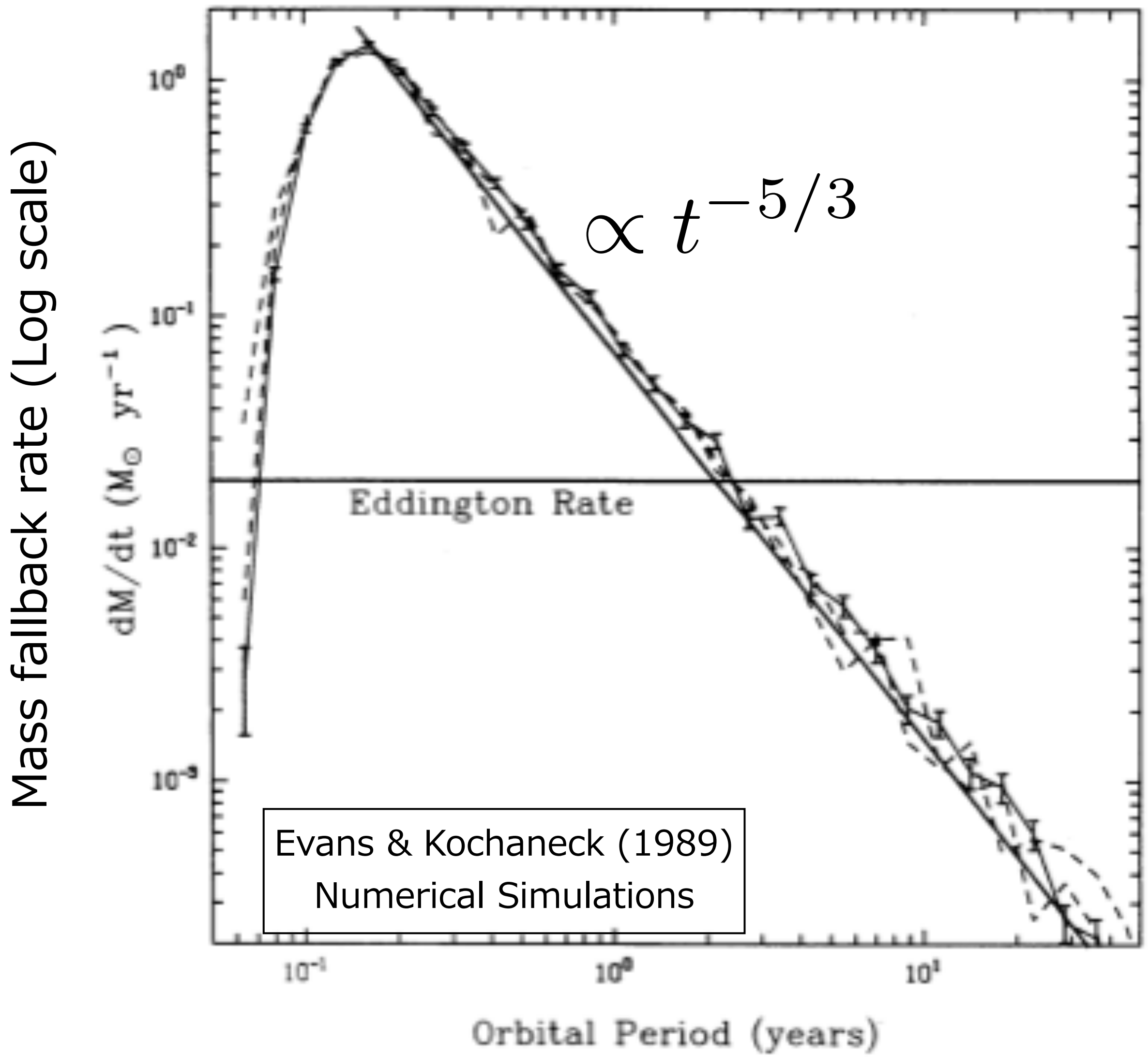
$$\frac{d\epsilon}{dt} = -\frac{1}{3}(2\pi G M_{\rm BH})^{2/3} t^{-5/3}$$

(by using Keplerian third law)

$$\frac{dM}{dt} \propto t^{-5/3}$$

Rees's conjecture (1988)

Mass fallback rate



Rees's conjecture is consistent with numerical simulations

cf. Guillechon et al. (2011,2012,2013)

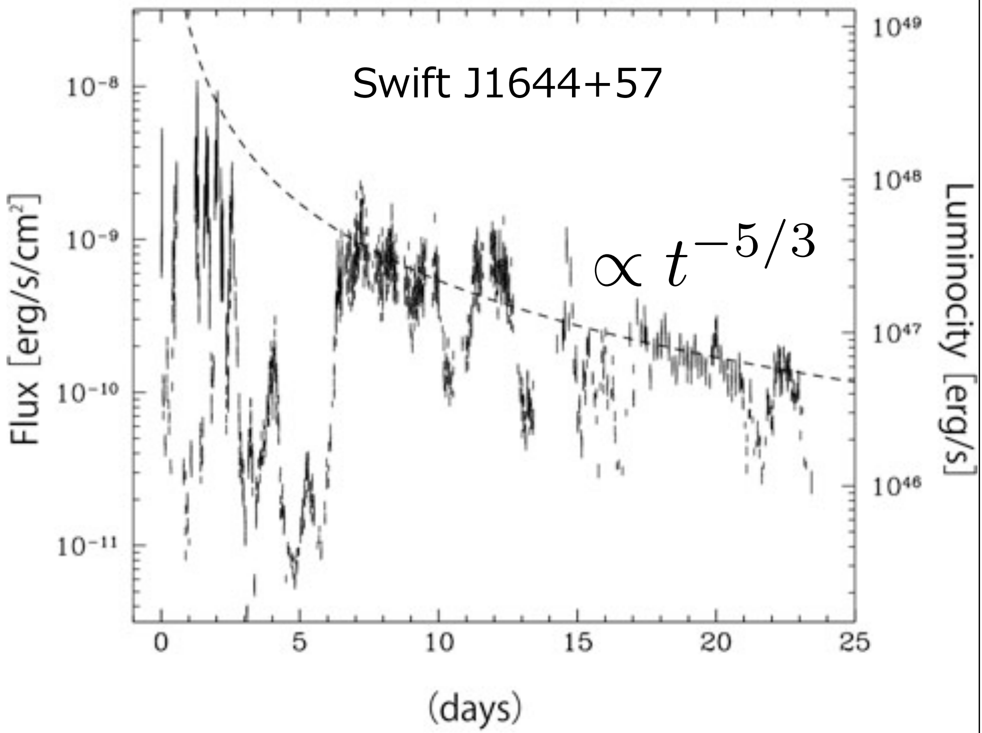
Past Observations

- 15 Tidal disruption event (TDE) candidates
  (cf. Maksym +2010; Burrows +2011)

- Some observed light curves match theoretical expectations proposed by Rees (1998).

- Event rate: 10^{-4}~10^{-5} per galaxy [1/year]
  (Donley + 2002)

Burrows+(2011)



Approaching stars are on parabolic orbits?

- Historically, TDE theory considers parabolic orbits:

  Well-motivated for 2-body scattering (bulge), large-scale triaxiality (galaxy)

- More exotic contributions to TDE rate have been proposed recently:

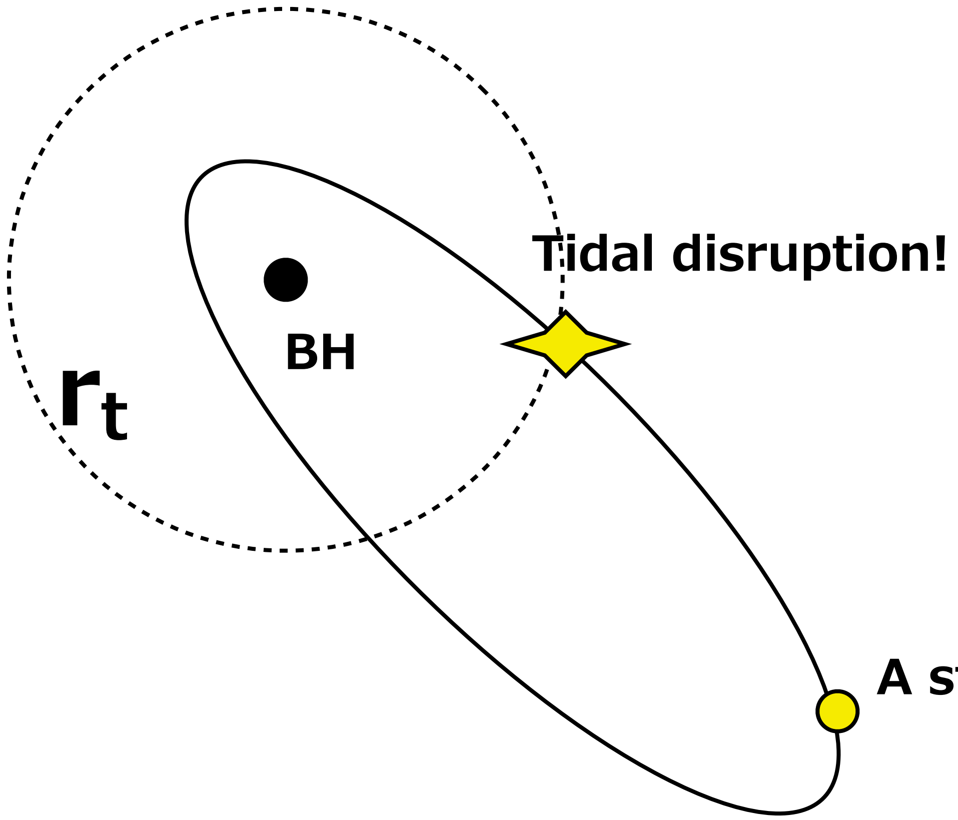
  - Binary star separation (Amaro-Seoane+2012, Bromley+ 2012)
  - Recoiling SMBH (Stone & Loeb 2011)
  - Binary SMBHs (Chen+2009,2012; Seto & Muto 2010,2011)

- These mechanism makes smaller eccentricities possible than $e=1$.

Eccentricity of disrupted stars could be widely distributed over $0.1 < e < 1$.

Our Goal

A schematic picture of "**Eccentric TDEs**"

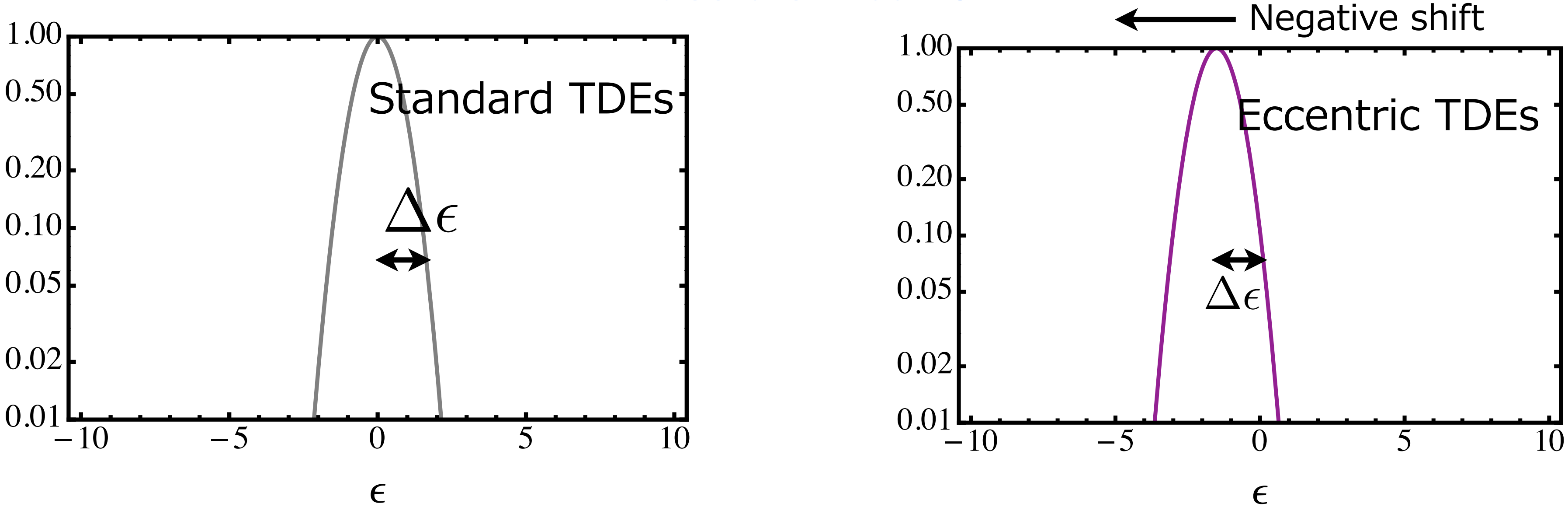


To find differences between standard TDEs and TDEs of stars on eccentric orbits

Our *original* theoretical expectation

All of stellar debris are bounded by black hole even after the tidal disruption, when $\Delta\varepsilon =< \varepsilon_{orb}$

mass distribution



All of disrupted mass can fall back to black hole

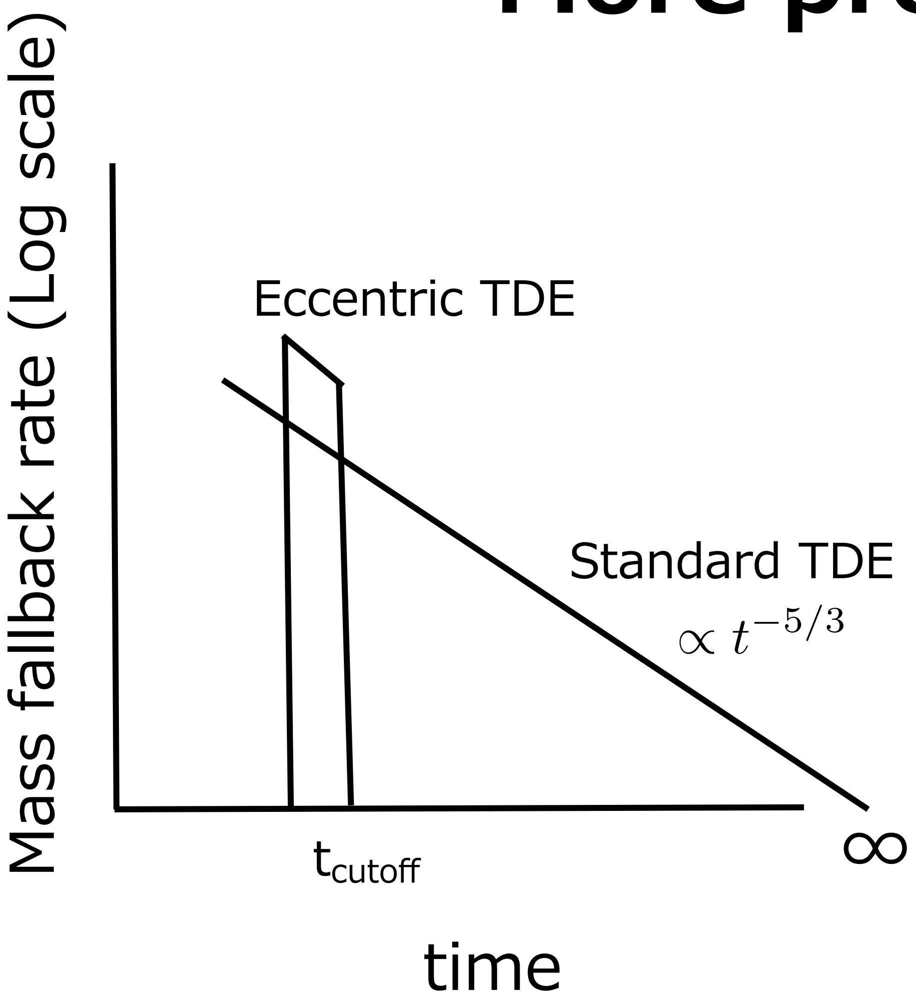
if e < $e_{crit.}$

$$\Delta\epsilon = \frac{GM_{\rm BH}}{r_{\rm t}^2} r_*$$

$$\epsilon_{\rm orb} \approx -\frac{GM_{\rm BH}}{2r_{\rm t}}\beta(1-e_*)$$

$$e_{\rm crit} \approx 1 - \frac{2}{\beta}\left(\frac{M_{\rm BH}}{m_*}\right)^{-1/3}$$

More predictions



1. There is a cut-off time in mass fallback rate, because all of stellar masses fall back to the black hole.

2. Mass fallback rate is bigger than that of standard TDE, because the fallback time is shorter. $t \propto \epsilon^{-3/2}$

Finite and more intense accretion

Next, we test them by numerical simulations

Numerical Model

Smoothed Particle Hydrodynamics (SPH)

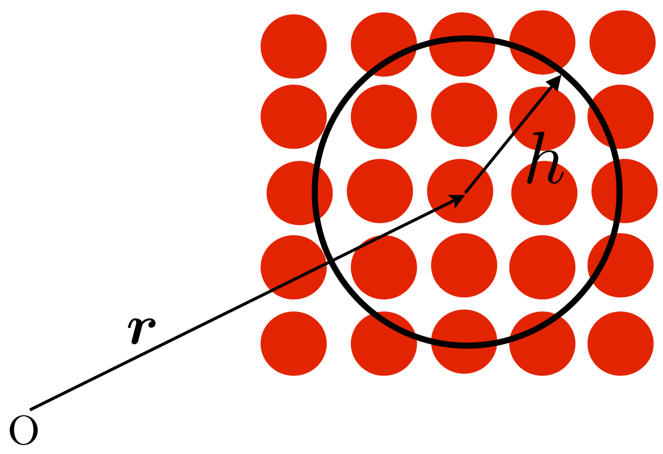
Lucy (1977); Monaghan & Gingold (1977)

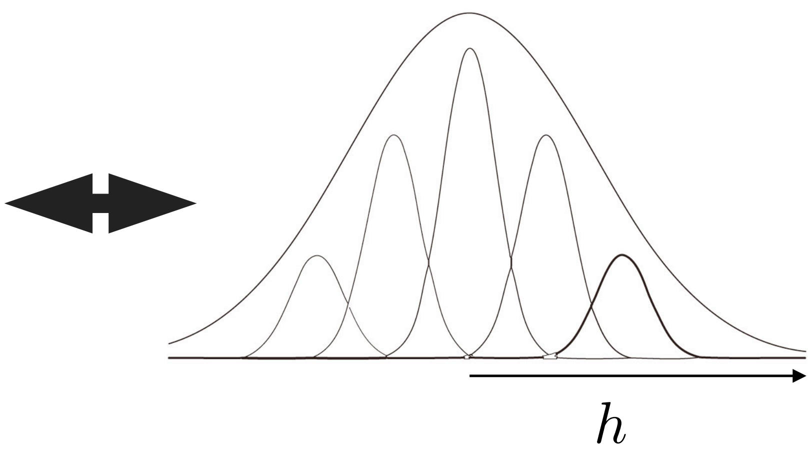
1. Mesh-free Lagrangian methods in Computational Fluid Hydrodynamics
2. Treating fluid as ensemble of discrete elements (SPH particles)
3. Each SPH particles satisfies conservation laws.

A physical quantity in SPH: $$\langle f(\boldsymbol{r})\rangle = \sum_j m_j \frac{f_j}{\rho_j} W(|\boldsymbol{r}-\boldsymbol{r}_j|, h)$$

m_j : SPH particle mass; ρ_j : Density of SPH particle; W : Kernel function

●: SPH particle h : Smoothing length



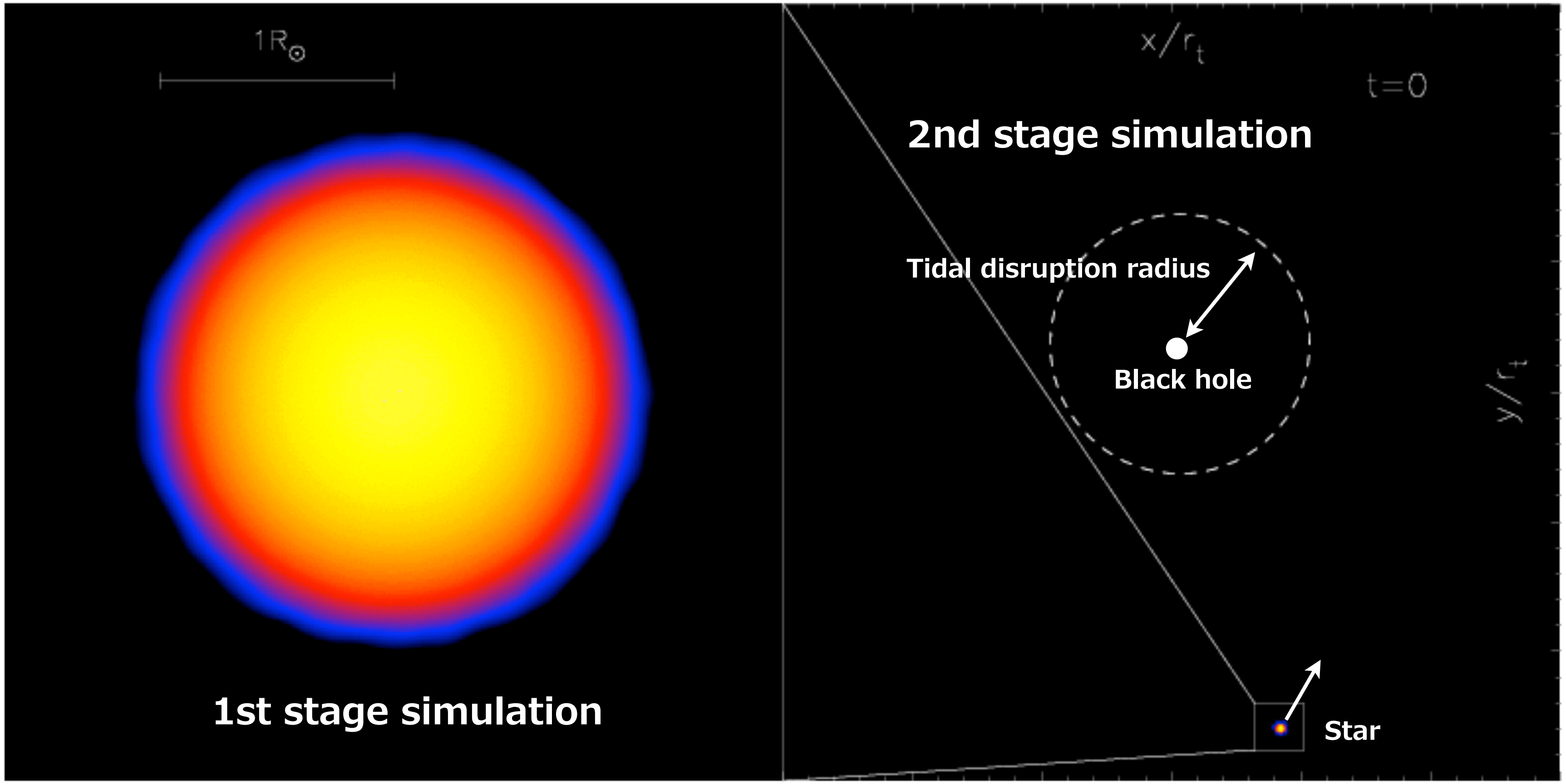


Method

1. Modeling a star by SPH (Benz(1990); Bate et al.(1995))
2. Simulating a star-black hole system
3. Incorporating Pseudo-Newtonian potential (Wegg 2012) into SPH code to treat general relativistic (GR) effect

BH mass : $M_{\rm bh} = 10^6 M_\odot$ **β=r_t /r_p= 1, 5** **polytropic index : n=1.5**

Stellar mass : $M_{\rm star} = 1 M_\odot$ **Stellar Orbital eccentricity: e=1, 0.98, 0.8**



We will show simulation results with N_{SPH}=10^5

GR Effects (Schwarzschild space-time)

● Why do we consider GR effects?

GR precession is strong for small periastron distances.
We expect that it can cause the orbital crossing of the stellar debris.

● How do we model GR effects?

For simple GR treatment, pseudo Newtonian potentials are incorporated into the SPH code. Wegg (2012):

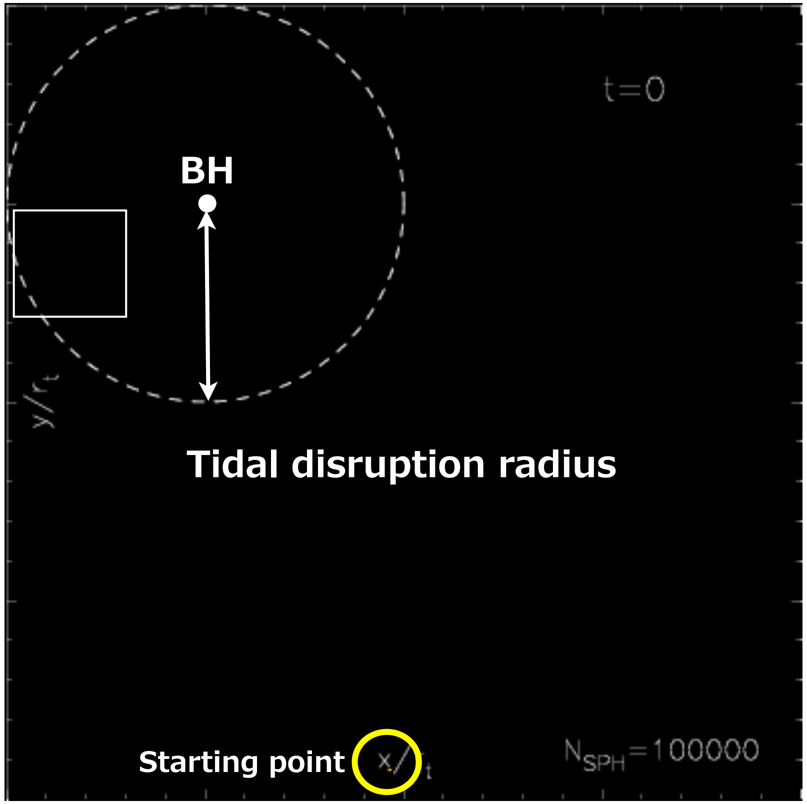
$$U(r) = c_1 \frac{GM_{\rm BH}}{r} - \frac{(1-c_1)GM_{\rm BH}}{r - c_2 r_{\rm g}} - \frac{c_3 GM_{\rm BH}}{r}\frac{r_{\rm g}}{r}$$

where c1=-(4/3)(2+$6^{1/2}$), c2=4*$6^{1/2}$-9, c3=-(4/3)(2*$6^{1/2}$-3)

Newtonian if c1=1, c2=c3=0 : Paczynski-Wiita PN if c1=c3=0, c2=1

We modeled only GR precession effect by incorporating pseudo-Newtonian potential (Wegg 2012) into SPH.

Standard TDE(e=1,β=1) : Density map animation

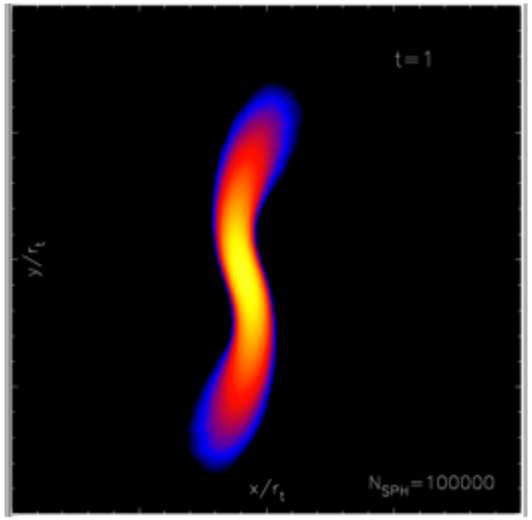


The run time, t, is normalized by

$$P_* \equiv 2\pi\sqrt{\frac{r_*^3}{Gm_*}} \sim 3.2\times10^{-4}\left(\frac{r_*}{R_\odot}\right)^{3/2}\left(\frac{M_\odot}{m_*}\right)^{1/2}\ [\mathrm{yr}]$$

Tidal disruption radius

$$r_\mathrm{t} = 100R\odot\times\left(\frac{M_\mathrm{BH}}{10^6 M_\odot}\right)^{1/3}\left(\frac{1M_\odot}{m_*}\right)^{1/3}\left(\frac{r_*}{R_\odot}\right)$$



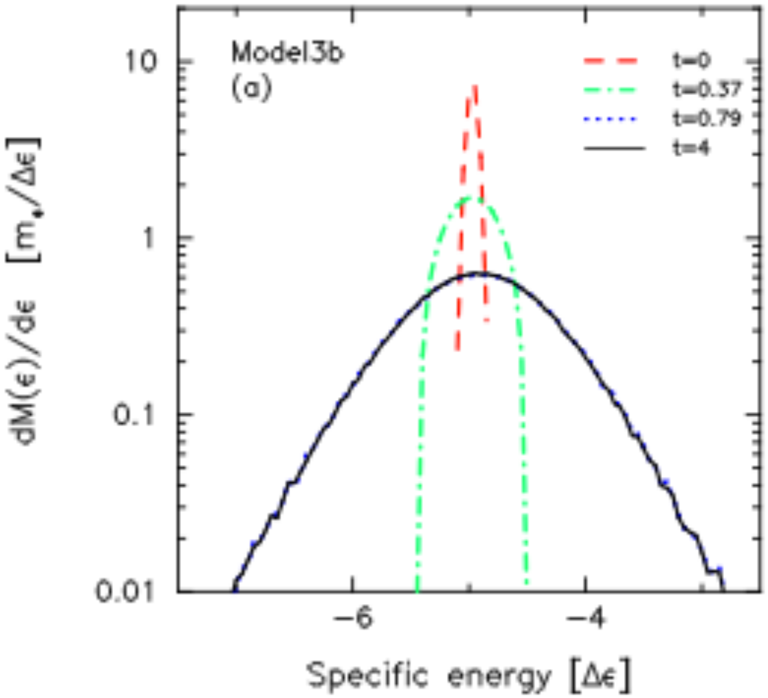
* The star moves in the x-y plane

* The surface density is measured in a range of the seven orders of magnitude in the logarithmic scale

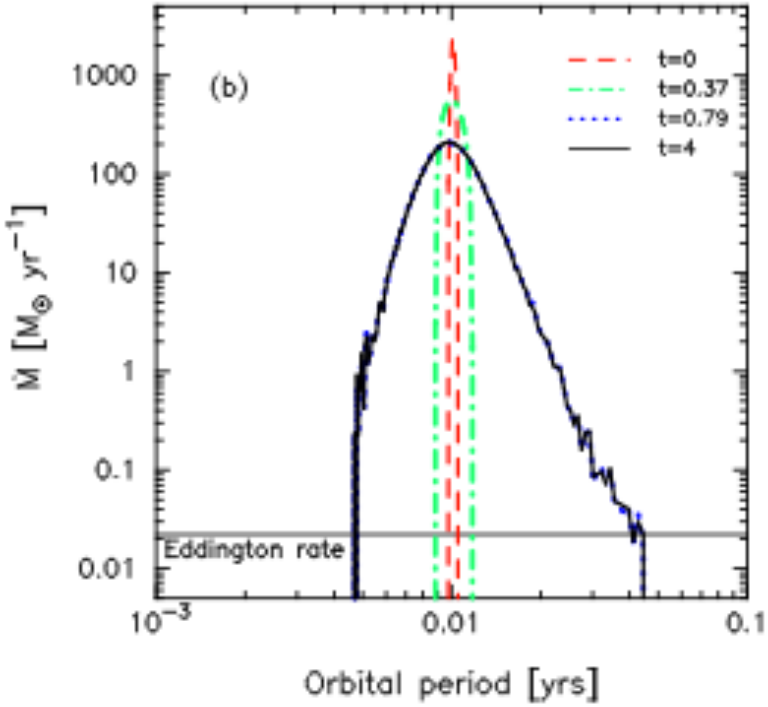
Eccentric TDE: e=0.98 and β=5

Critical eccentricity: e_{crit}=0.996

Mass distribution



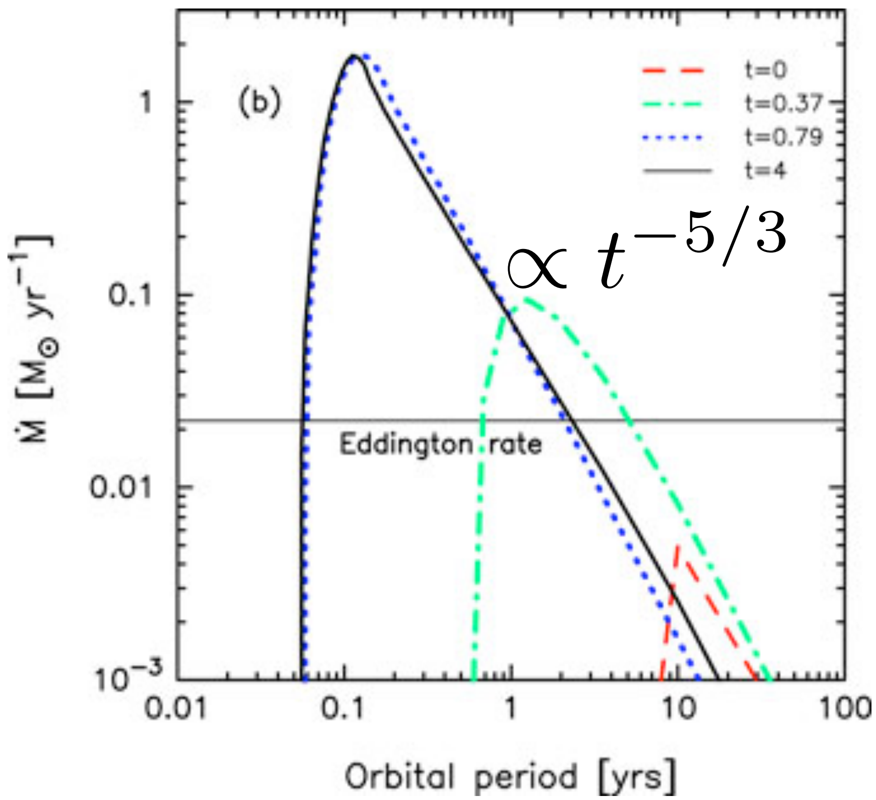
Mass fallback rate



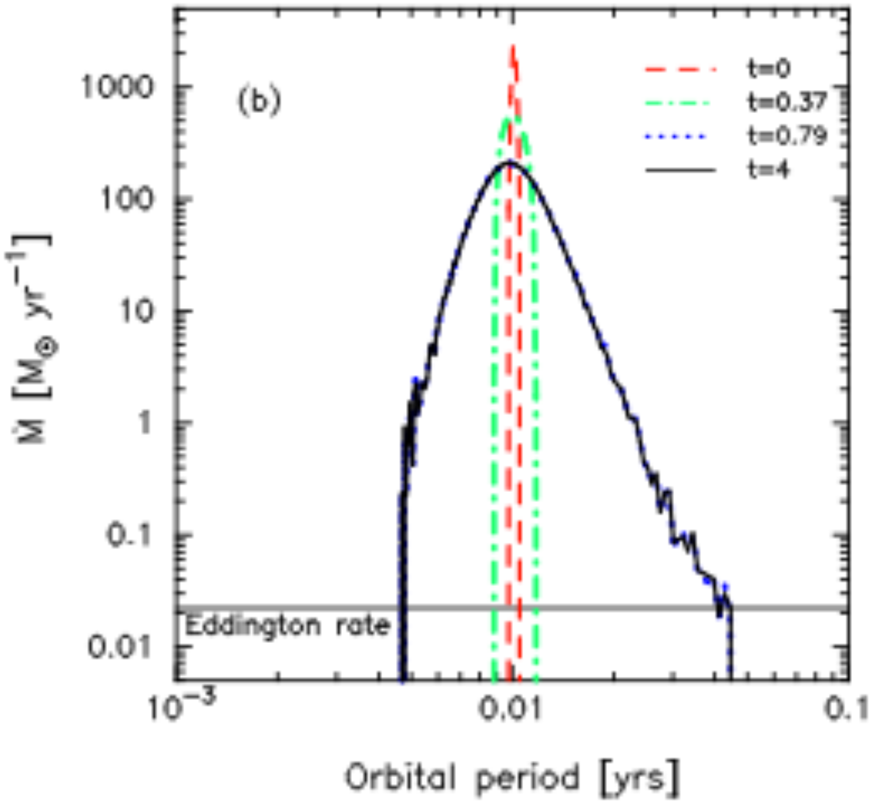
1. **$e < e_{crit}$ leads that mass is distributed in a range of negative energy**
2. **Mass fallback rate has clearly a finite cut-off time and is ~200 times larger than that of standard TDEs.**

Comparison between Eccentric TDE case and p Parabolic TDE case

Parabolic TDE



Eccentric TDE



Summary I.

1. Eccentric TDEs has a critical value of eccentricity, below which all the mass is bounded by the black hole. Since fallback time is finite when $e < e_{crit}$, the fallback rate substantially exceeds the Eddington rate

2. Analytic expectation overestimates e_{crit}, because the energy spread is wider as expected.

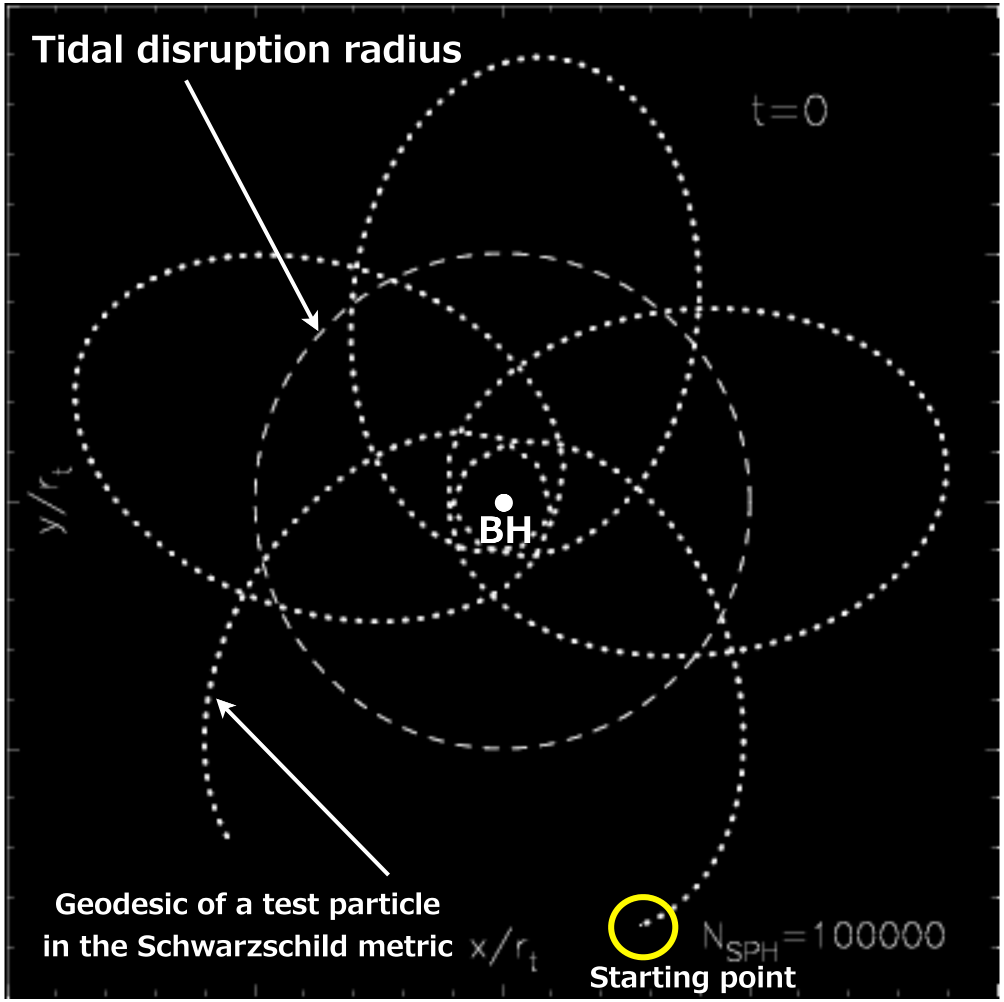
3. In standard TDEs, the mass fallback rate is consistent with $t^{-5/3}$ law.

4. There are arguments whether an accretion disk is formed around the black hole after stellar debris falls back (Rees 1988, Cannizzo 1990, Kochenck 1994). But, there is poorly known how accretion disk is formed around black hole.

Accretion disk formation in eccentric TDEs

Newtonian potential simulation (e=0.8, β=5)

- Dotted line shows the geodesic of a test particle
- Dashed circle shows the tidal disruption radius
- Central point represents the black hole

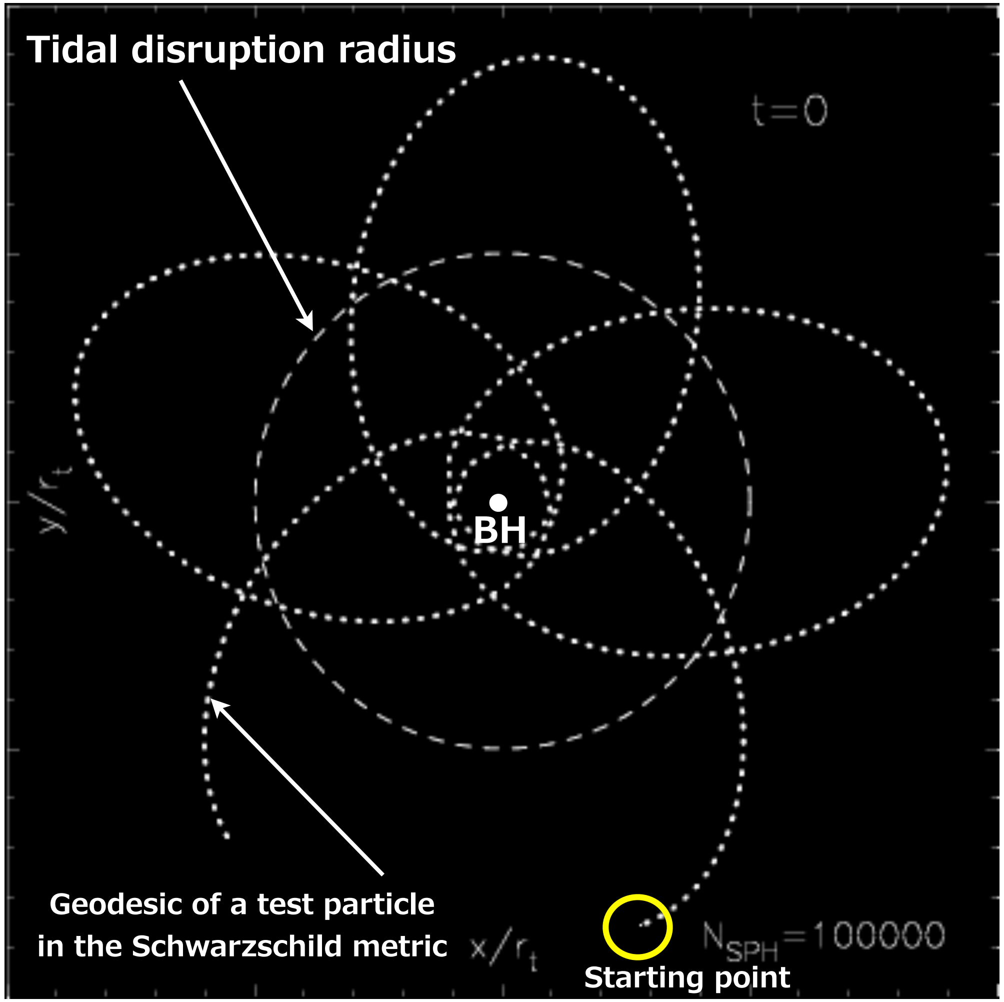


$$\beta = \frac{r_{\mathrm{t}}}{r_{\mathrm{p}}}$$

Stellar debris orbits around the black hole, following the Keplerian third law

Pseudo-newtonian potential simulation (e=0.8,β=5)

- Dotted line shows the geodesic of a test particle
- Dashed circle shows the tidal disruption radius
- Central point represents the black hole

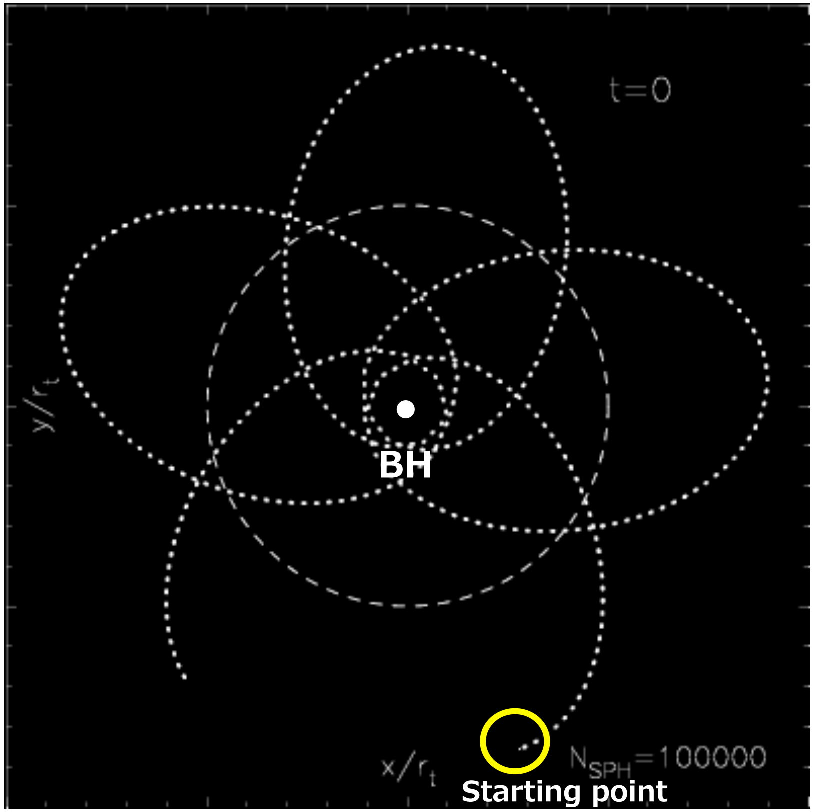


$$\beta = \frac{r_t}{r_p}$$

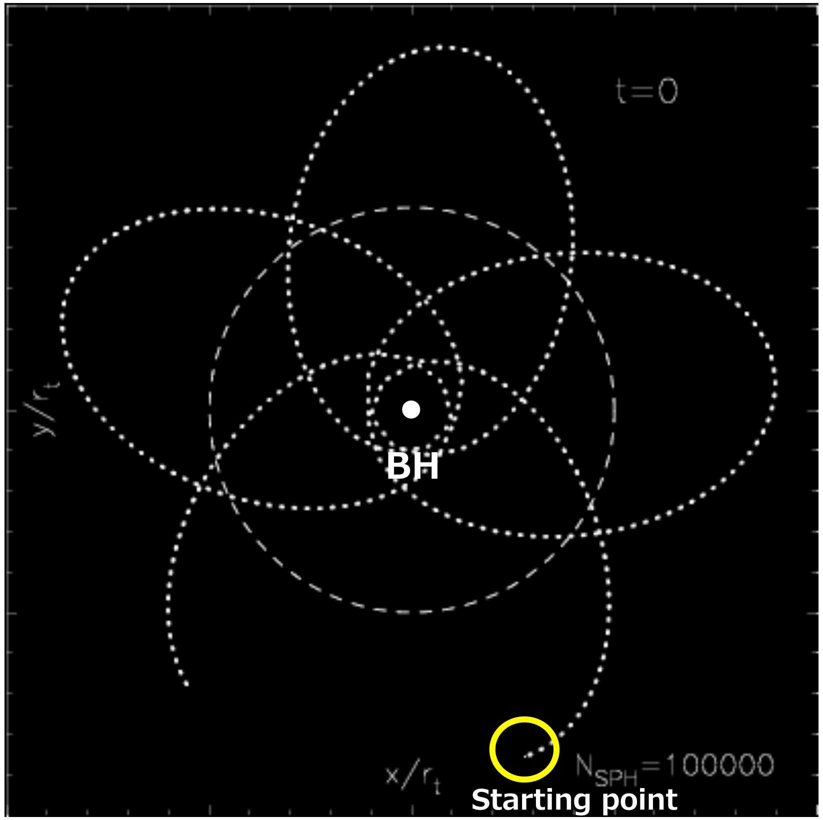
Accretion disk is formed around the black hole due to shock energy dissipation of orbital crossings induced by GR precession

Comparison of two animations

Newtonian potential simulation (e=0.8,β=5)



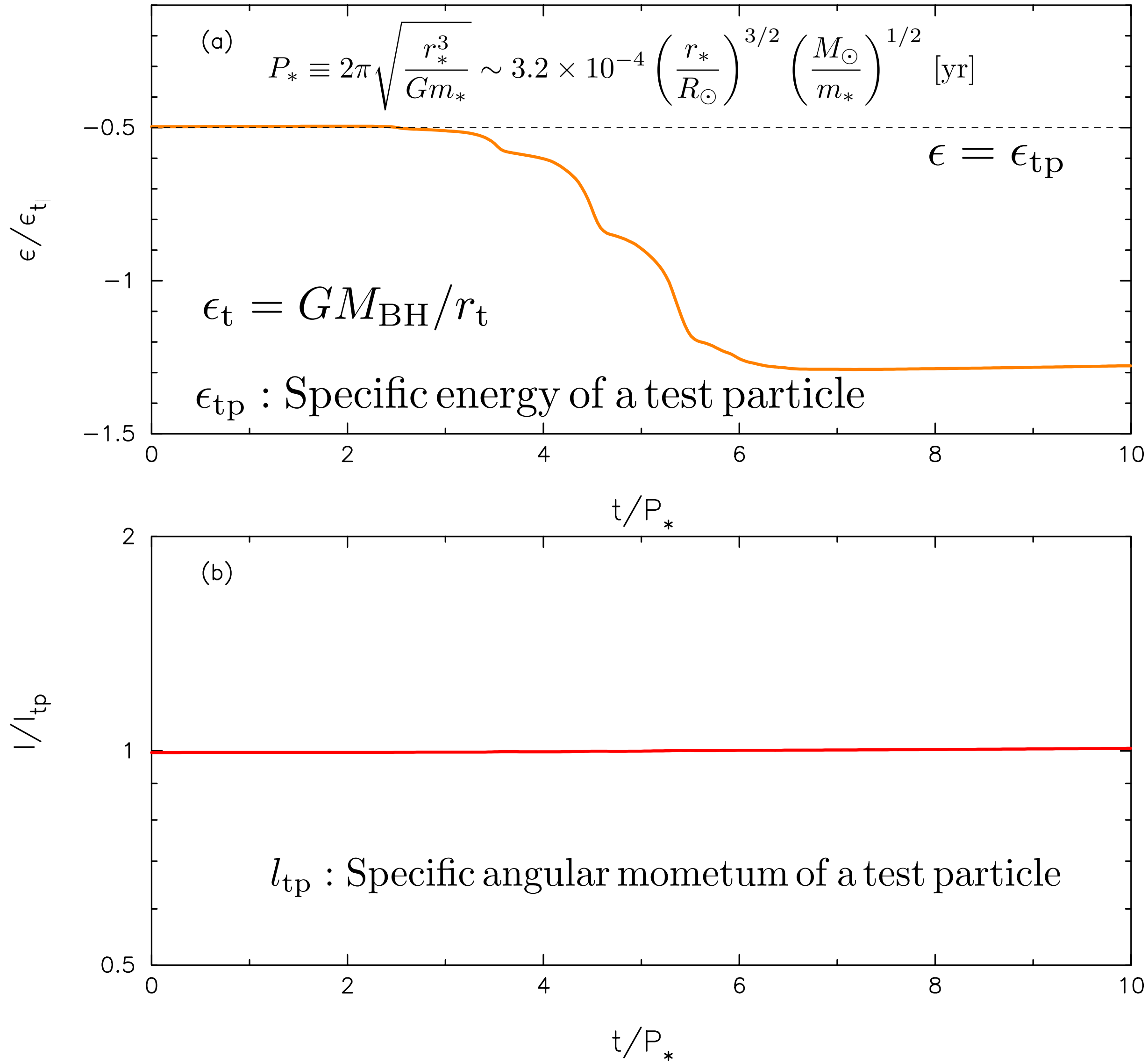
Pseudo-Newtonian potential simulation (e=0.8,β=5)



General relativistic precession plays a crucial role in the accretion disk formation around supermassive black hole

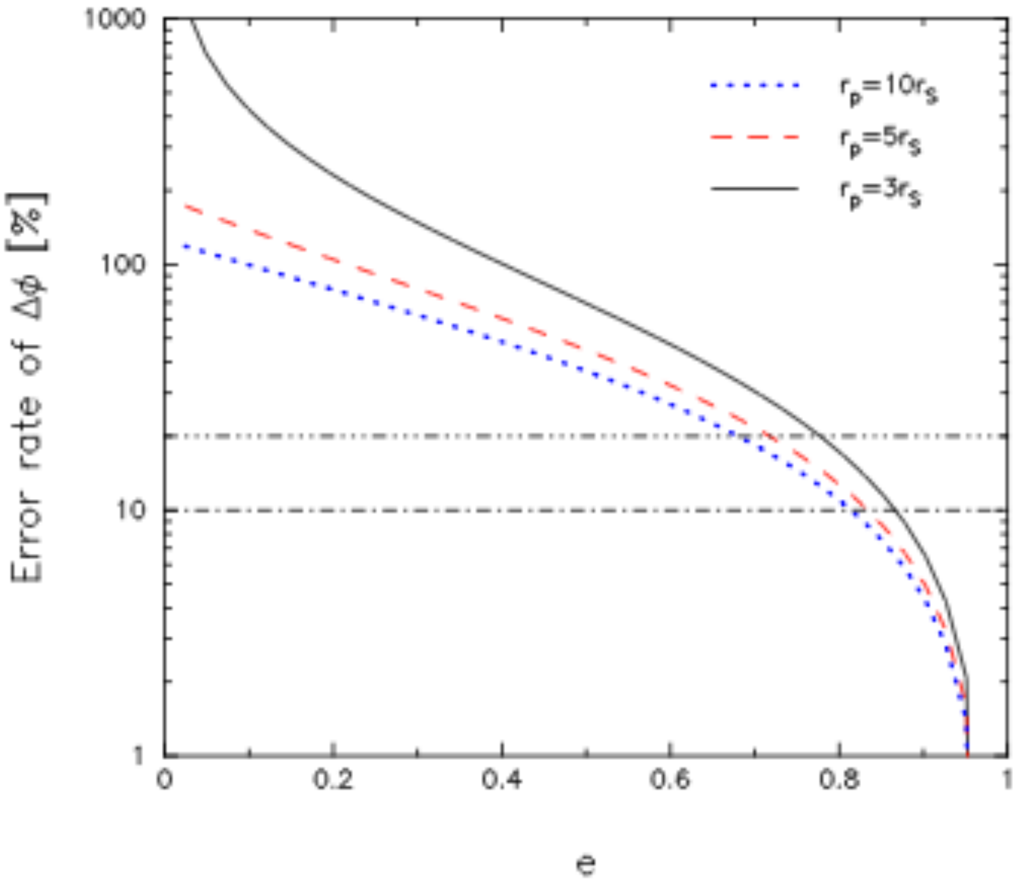
Averaged specific energy and angular momentum

pseudo-Newtonian potential simulation (e=0.8,β=5)



While specific energy is dissipated due to the orbital crossing, specific angular momentum is conserved

Dependence of error rate of precession angle on eccentricity of a test particle under the pseudo-Newtonian potential



$$\text{Error rate}\,[\%] \equiv \frac{\Delta\phi_{\rm GR} - \Delta\phi_{\rm N}}{\Delta\phi_{\rm GR}} \times 100$$

$$\Delta\phi_{\rm GR} = 2\int_{r_-}^{r_+} \left[\frac{(E+1)^2}{h^2} - \left(\frac{1}{h^2}+\frac{1}{r^2}\right)\left(1-\frac{r_{\rm S}}{r}\right)\right]^{-1/2}\frac{dr}{r^2}$$

$$\Delta\phi_{\rm N} = 2\int_{r_-}^{r_+} \left[\frac{E-U(r)}{h^2/2} - \frac{1}{r^2}\right]^{-1/2}\frac{dr}{r^2}$$

r_+ : Apocenter distance

r_- : Pericenter distance

$r_{\rm S}$: Schwarzshild radius

E : Specific energy

h : Specific angular momentum

Error rate increases as e is lower and β is higher

Summary & Discussion

1. GR precession (perihelion shift) plays an important role in accretion disk formation via circularization of stellar debris from stars on moderately eccentric orbits.
   【Energy dissipation rate (ε_{end}-ε_{ini}/ε_{ini}): 0.4% for Newtonian case, more than 100% for GR case)】

2. Angular momentum is conserved from pre-tidal disruption to post-tidal disruption via debris circularization

3. For spin effect of Kerr black hole case, pseudo-Newtonian potential is not available. We need to incorporate Post-Newtonian expansion formula into the SPH code.

Thank you for your attention