Tidal Disruption Flares From Stars on Bound Orbits

Hayasaki, Stone & Loeb., MNRAS, 2013, v434, p909

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23/Jan/2015 the first KNAG meeting@KASI

Outline

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   b. Standard theory and past observations
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2. **Our model**
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   b. Simple general relativistic (GR) treatment: pseudo-Newtonian potential approach
3. **Results**
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   b. Accretion disk formation
4. **Summary**

Introduction

Scientific motivations for tidal disruption events (TDEs)

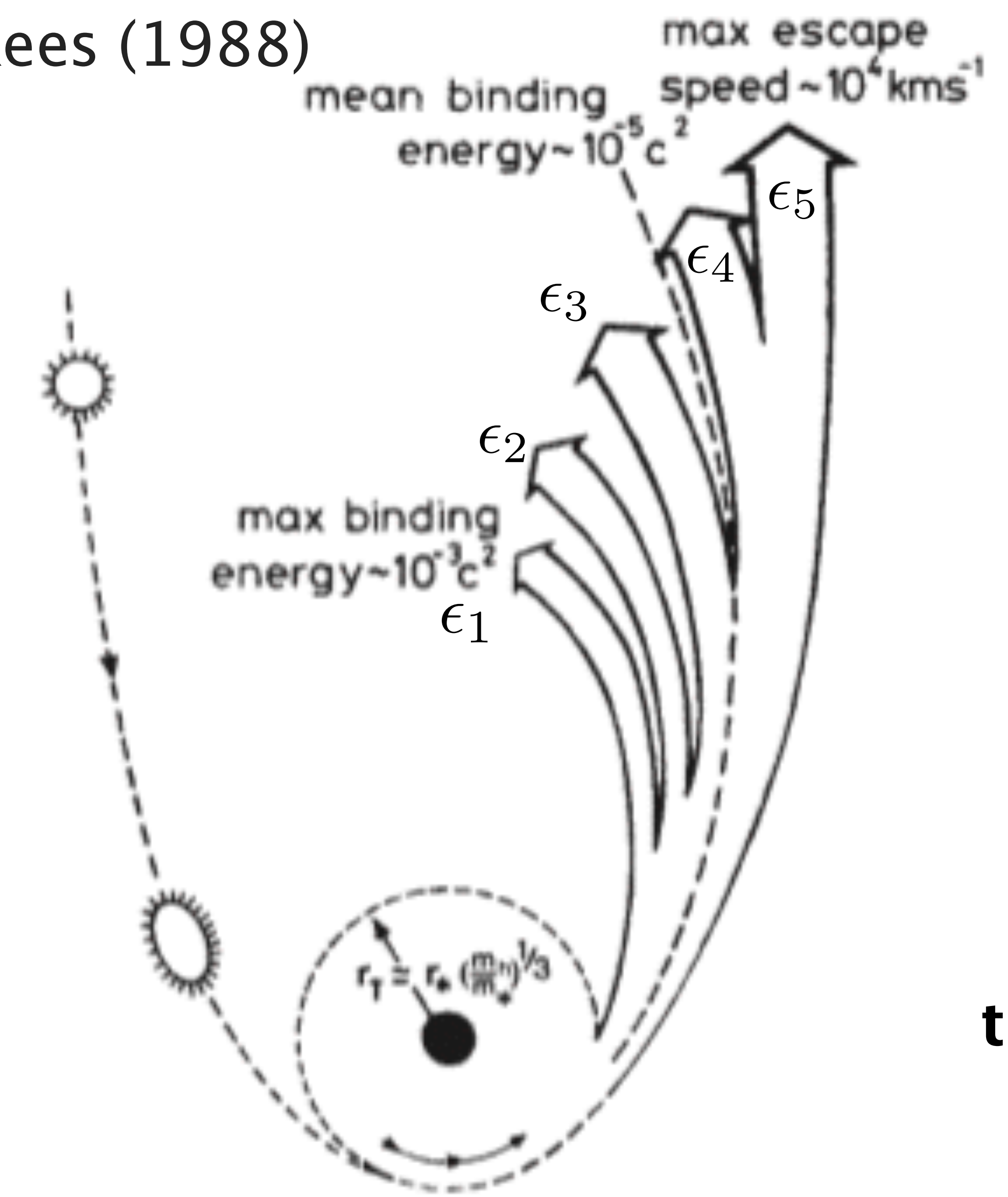
1. Probe of quiescent supermassive black holes
2. Contribution to black hole growth (tidal disruption rate)
3. Laboratory for super-Eddington accretion/Jet physics
4. One of gravitational wave source candidates (EMRIs)

Good candidate for multi-messenger astronomy

Tidal Disruption of star by SMBH

TDE Standard Picture

Rees (1988)



Δε: Spread in debris energy by tidal force

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

ε: Debris specific 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

t: Fallback time for most tightly bound debris

$$t_{\rm fall} \sim 0.1\,{\rm yr}\left(\frac{r_*}{R_\odot}\right)^{3/2}\left(\frac{m_*}{M_\odot}\right)^{-1}\left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{1/2}$$

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

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

What is the rate of mass fallback?

Mass fallback rate I.

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

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

Its time derivative:

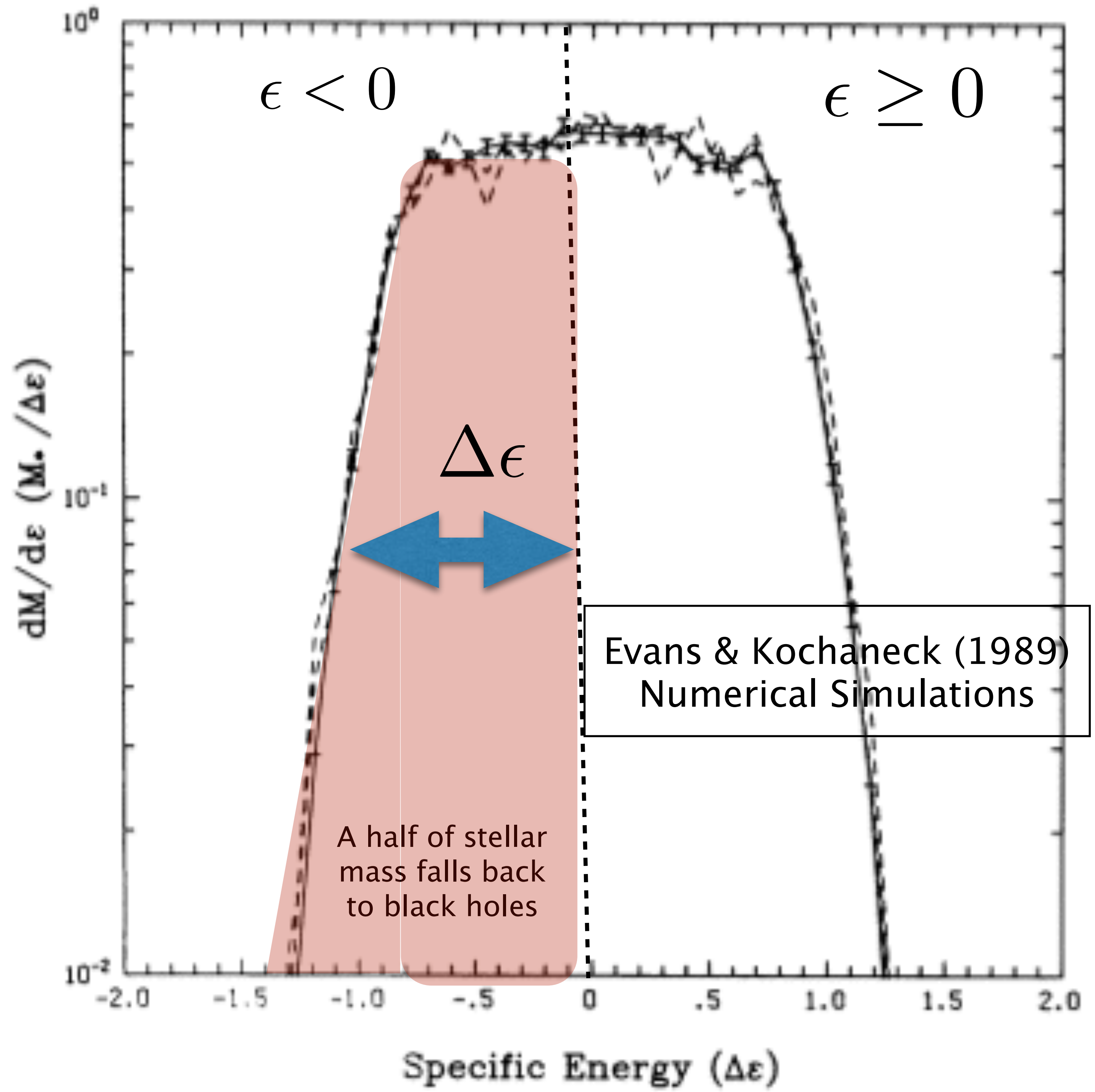
$$\frac{d\epsilon}{dt} = -\frac{1}{3}(2\pi GM_{\rm BH})^{2/3}t^{-5/3}$$

(by using Keplerian third law)

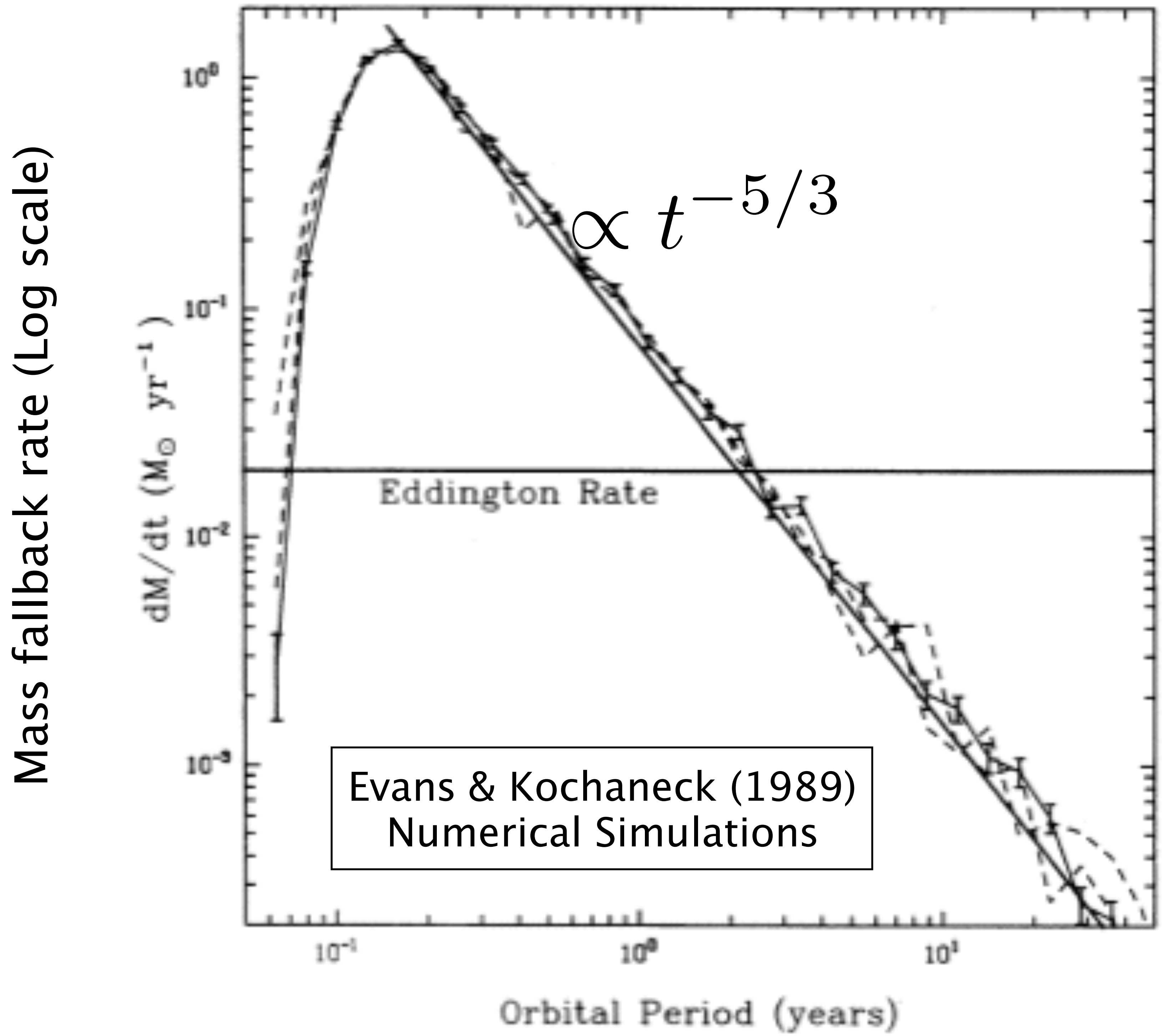
$$\frac{dM}{dt} \propto t^{-5/3}$$

Rees's conjecture (1988)

Differential mass-energy distribution of stellar debris



Mass fallback rate II.



Rees's conjecture is consistent with numerical simulations

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

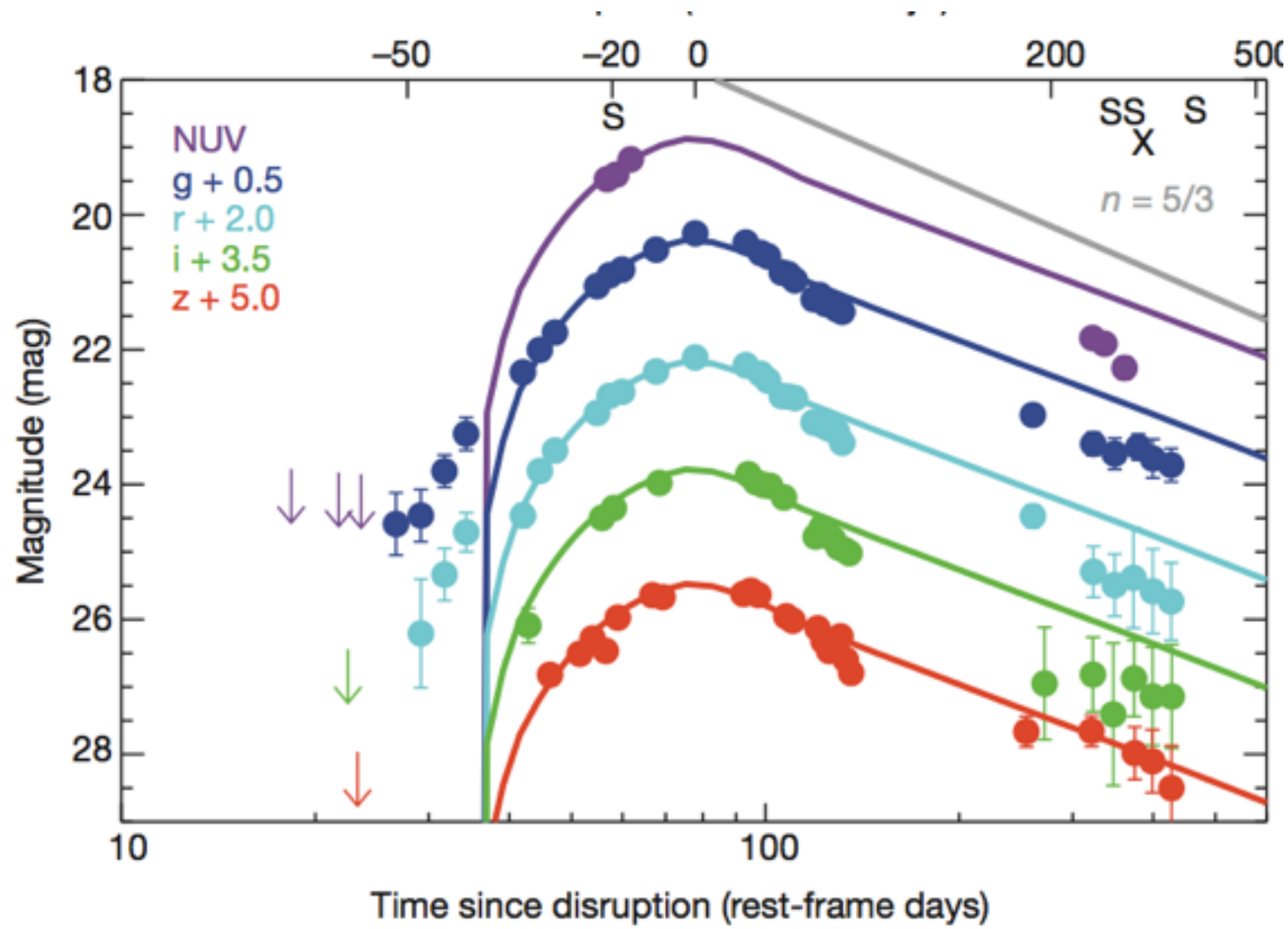
Past Observations

- ~20 TDE candidates (Komossa&Bode 1999; Maksym et al.2010; Burrows et al. 2011; Arcavi et al. 2014; Holoien et al 2014; Vinko et al.2015, and more)

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

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

Gezari et al. (Nature, 2012)



Approaching stars are on parabolic orbits?

- Historically, TDE theory considers parabolic orbits:

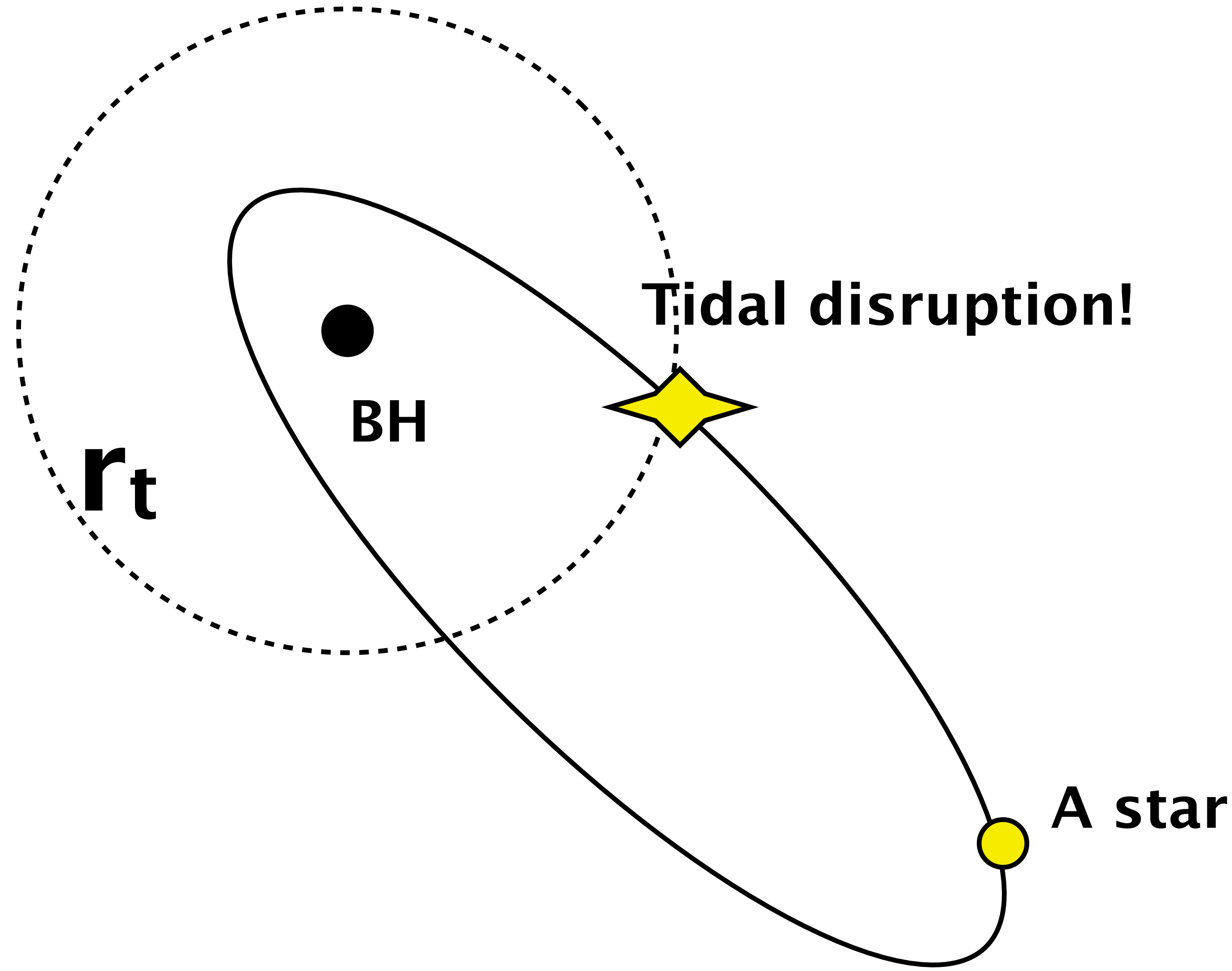
  Well-motivated for 2-body scattering (bulge), large-scale triaxiality (galaxy)

- 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 parabolic TDEs and TDEs of stars on eccentric orbits:

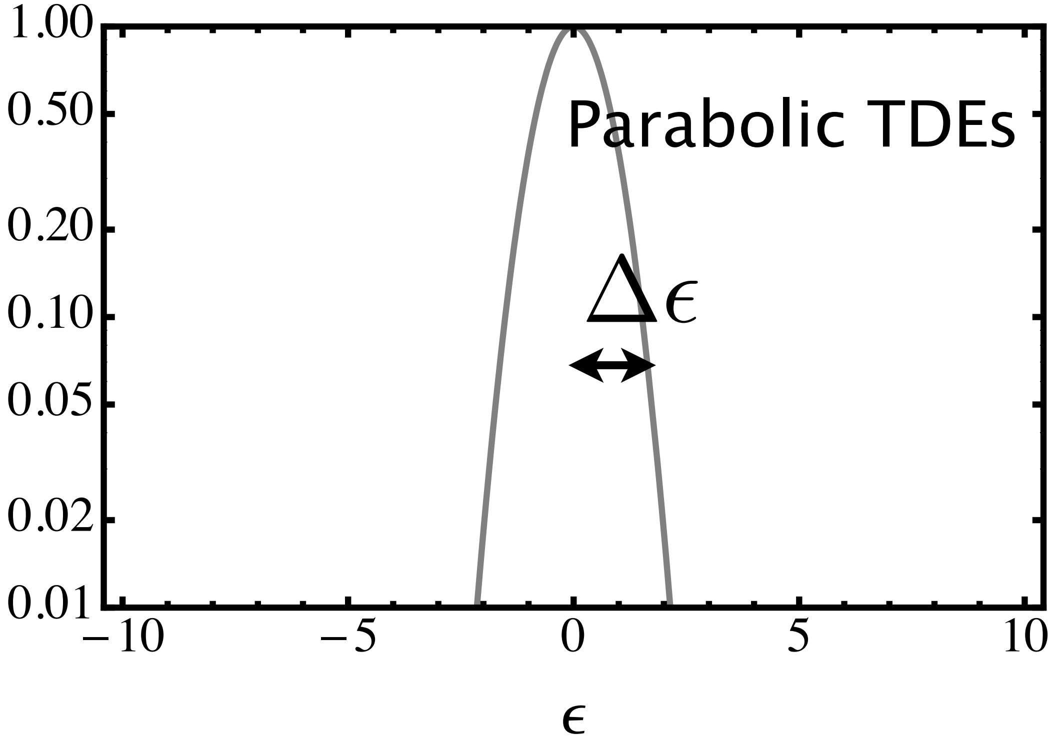
1. Mass fall back rate
2. Accretion disk formation

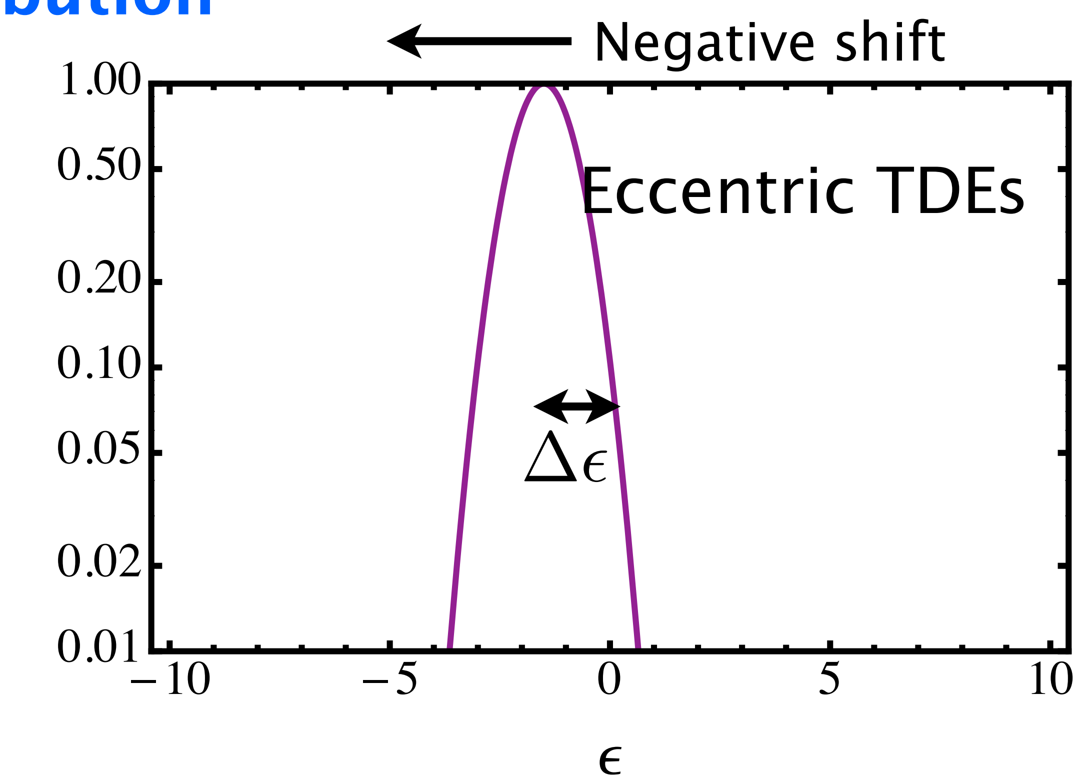
Our theoretical expectation

Hayasaki et al. (2013)

All of stellar debris are bounded by black hole even after the tidal disruption, when $\Delta\epsilon \leq |\epsilon_{\rm orb}|$

mass distribution





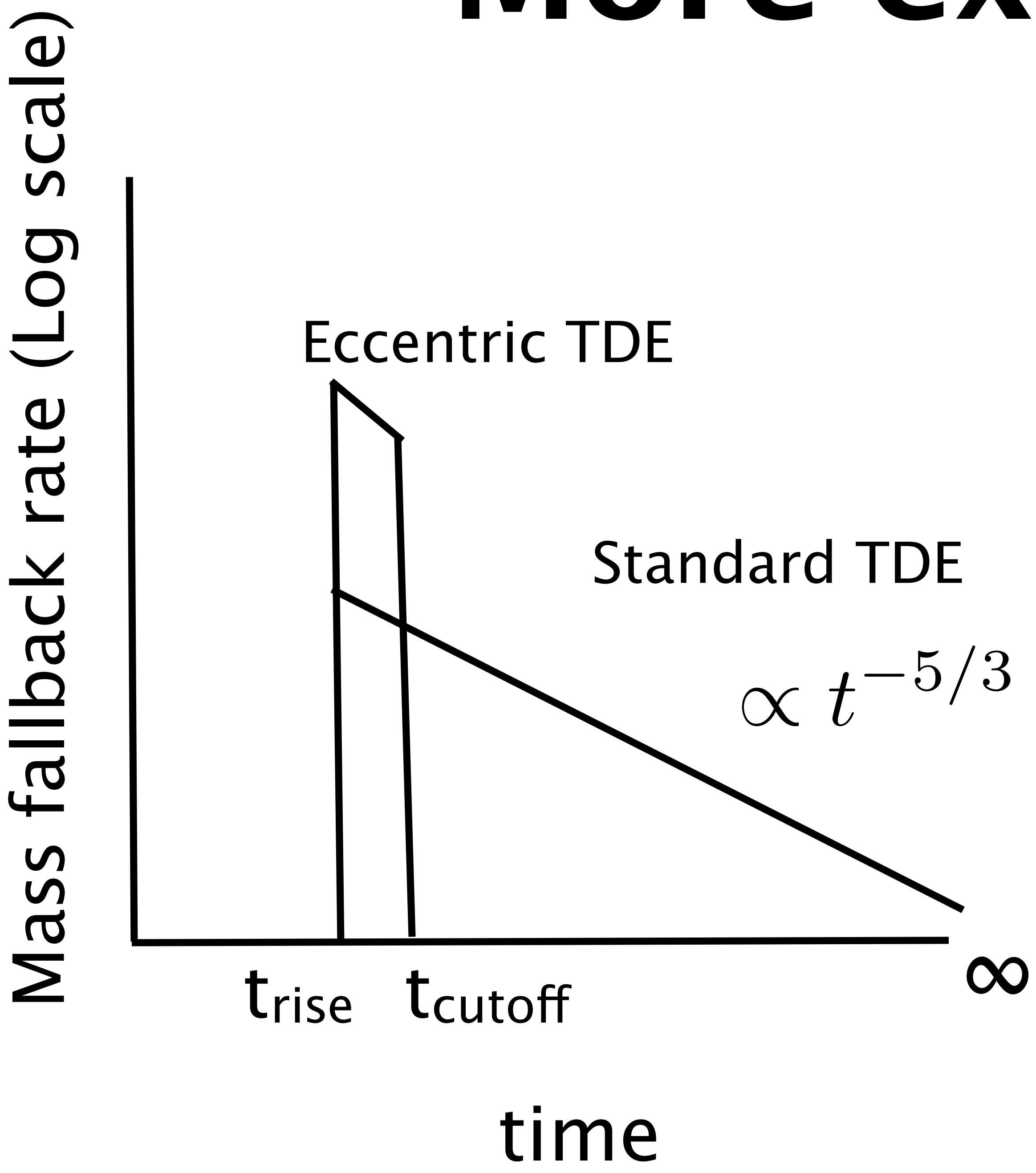
All of disrupted mass can fall back to black hole if e < e$_{\rm crit.}$

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

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

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

More expectation



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 parabolic TDE, because the fallback time is shorter.

$$t \propto \epsilon^{-3/2}$$

Finite and more intense accretion!

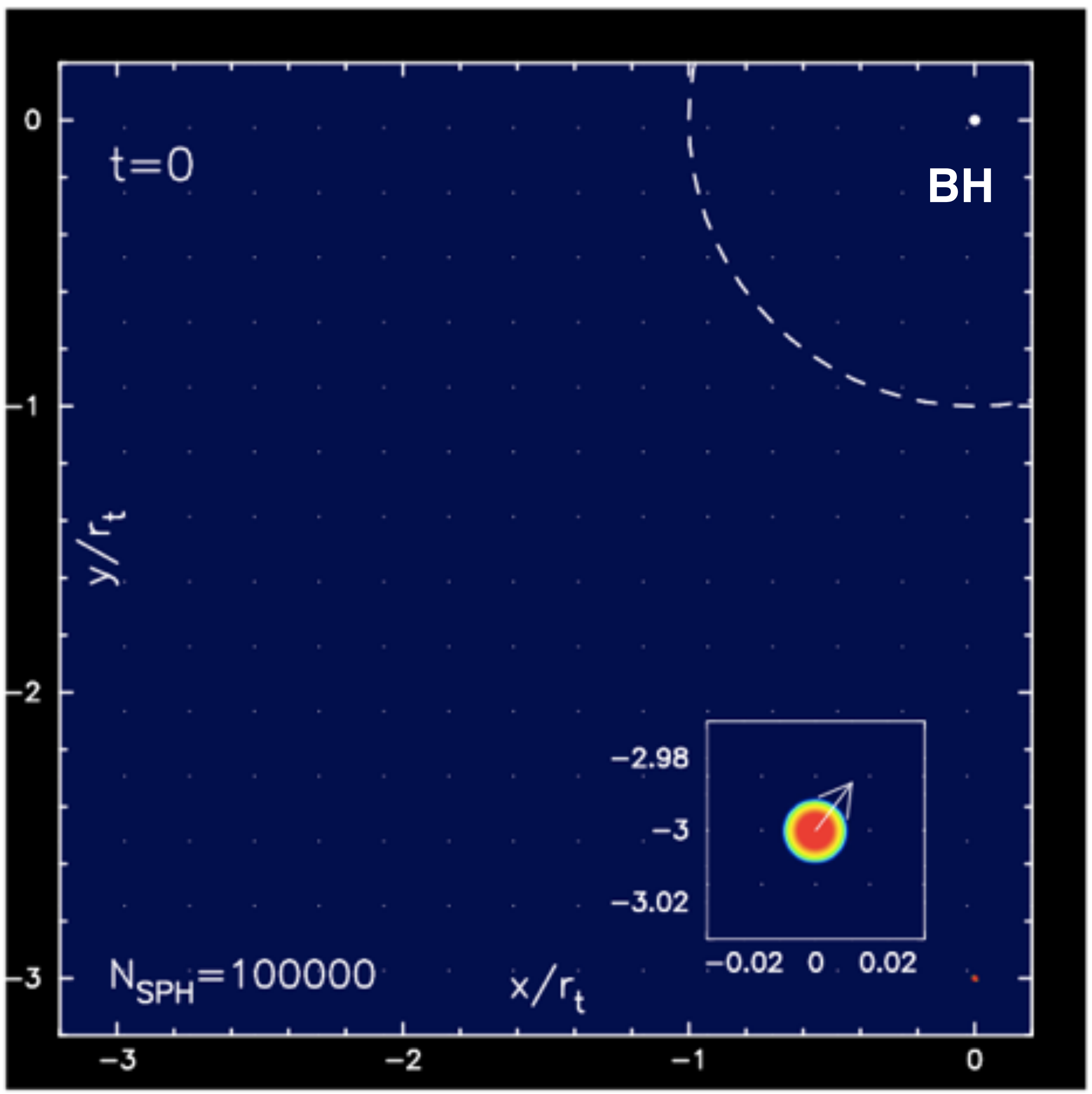
Next, we test these theoretical expectations by numerical simulations

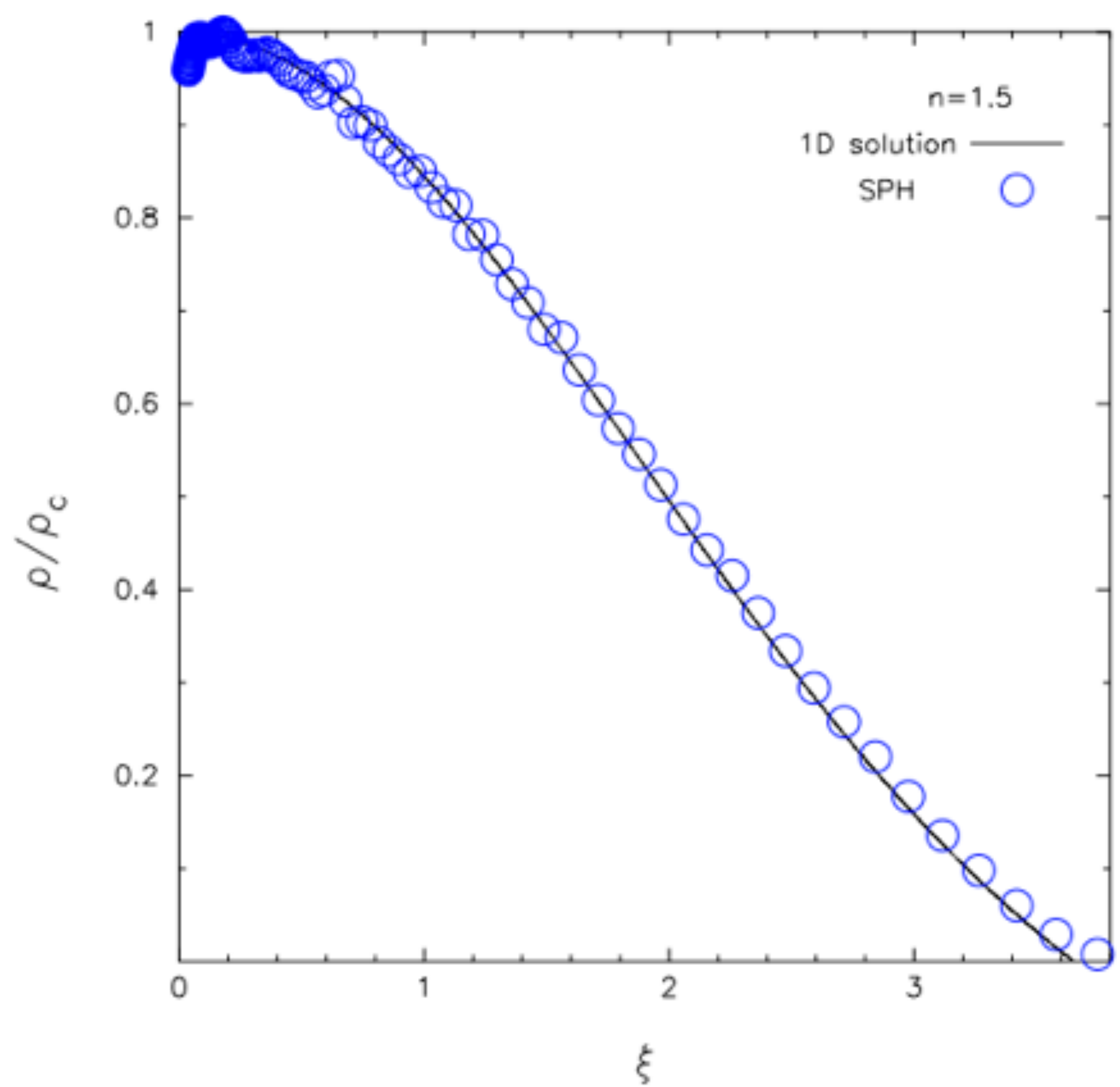
Numerical Model

Method

1. Modeling a star by SPH (Benz(1990); Bate et al.(1995))
2. Modeling a star-black hole system
3. Performing SPH simulations with relativistic apsidal precession

BH mass : $M_{\rm bh} = 10^6 M_\odot$ **Stellar mass :** $M_{\rm star} = 1 M_\odot$ **polytropic index : n=1.5**

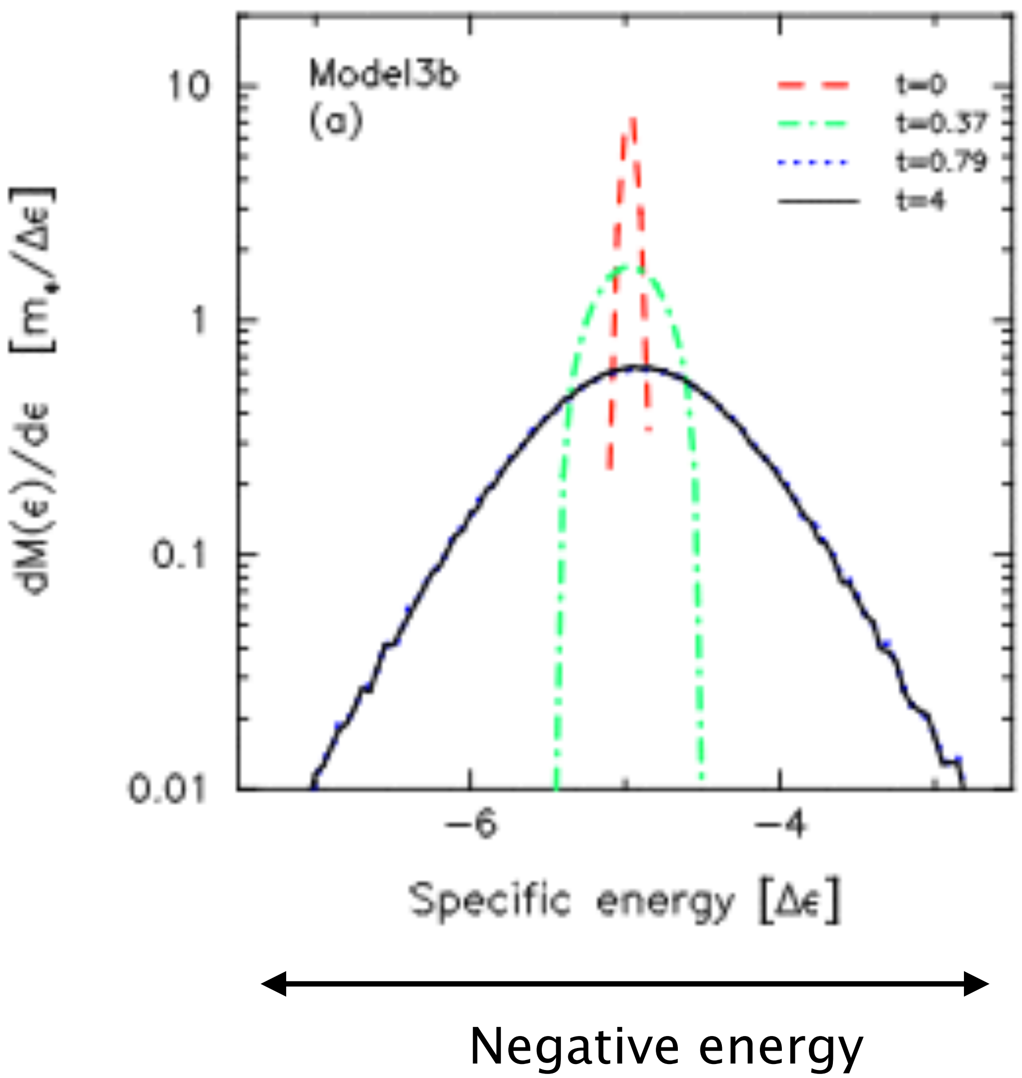




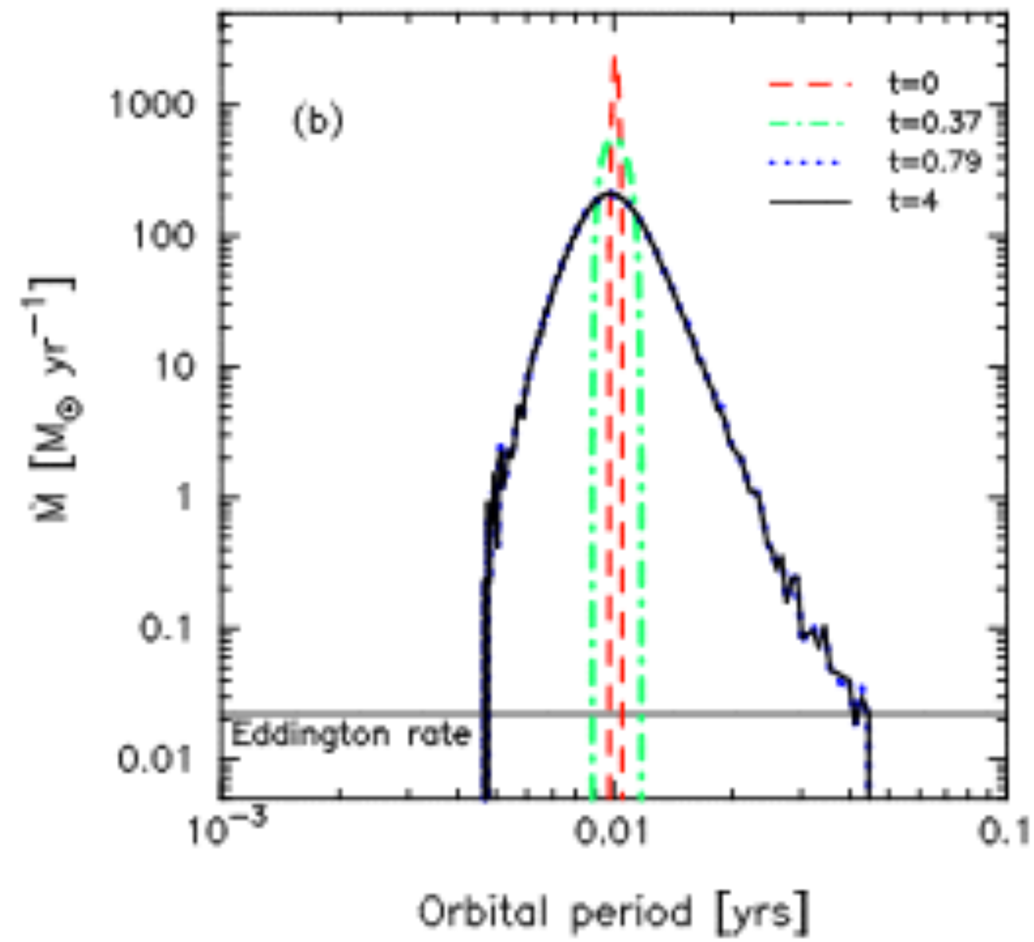
Eccentric TDE: e=0.98 and β=5

Critical eccentricity: e_{crit}=0.996

Mass distribution



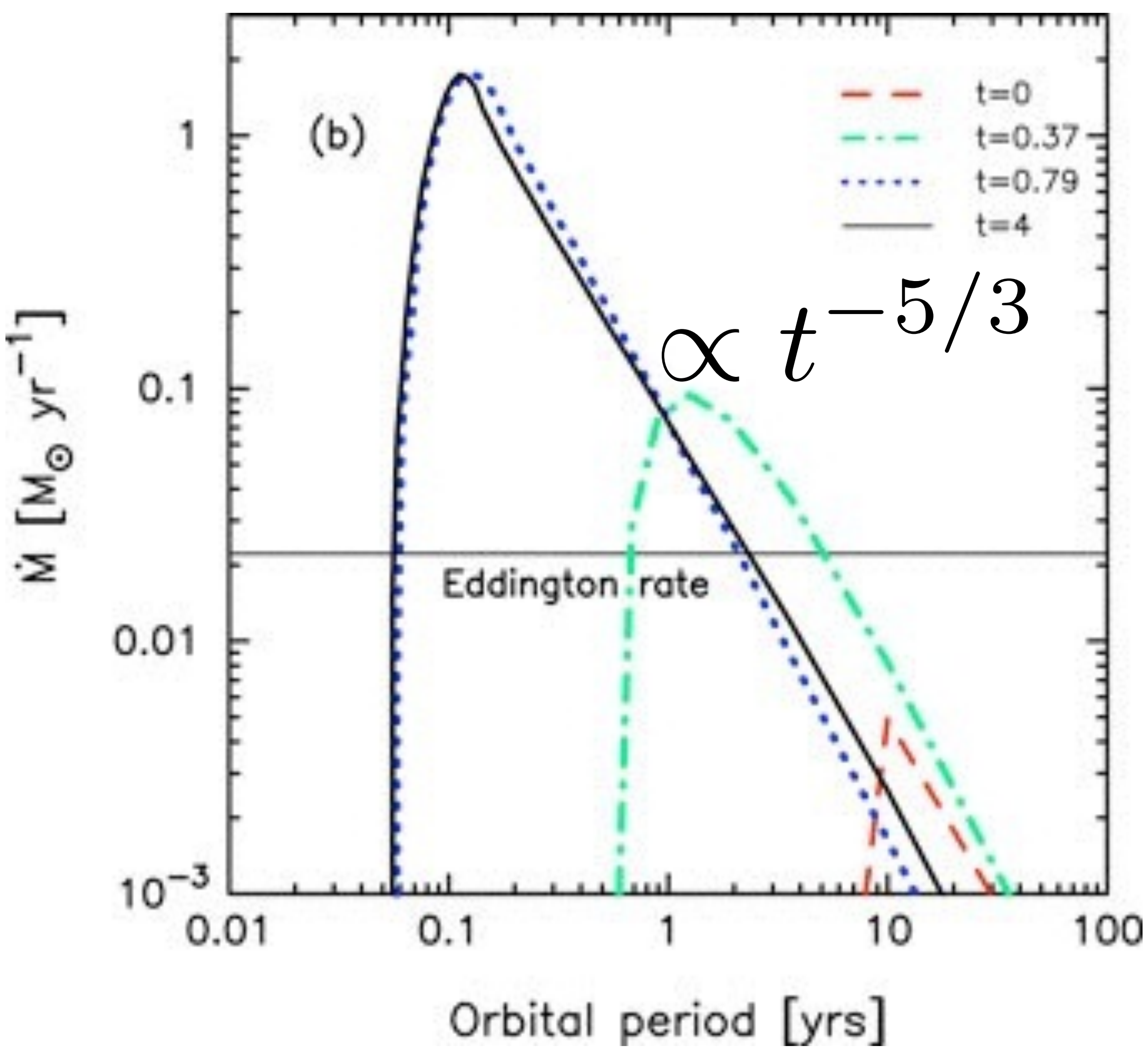
Mass fallback rate



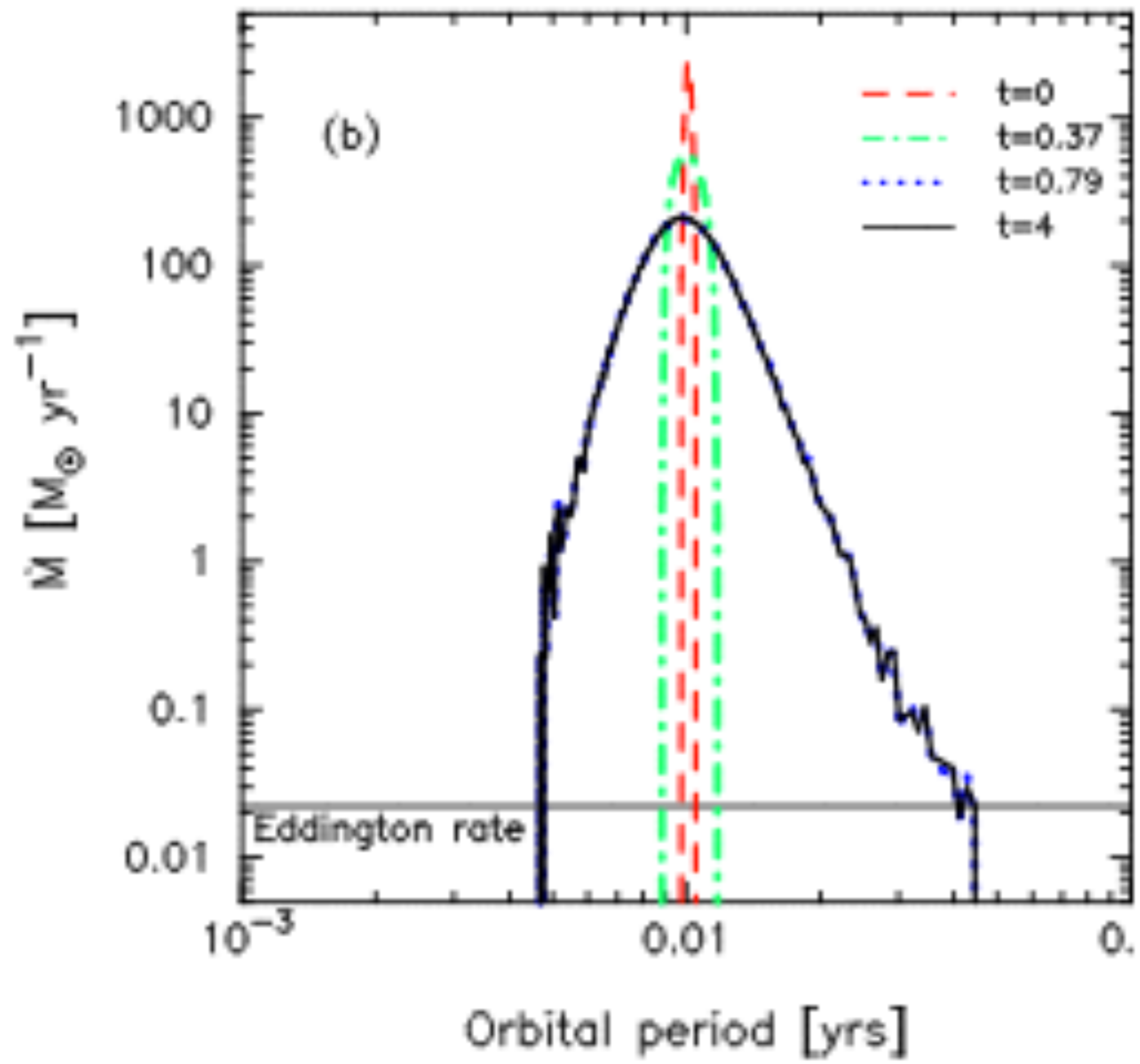
1. e < e_{crit} leads that mass is distributed in a range of negative energy
2. Mass fallback rate has clearly a finite cut-off time and is ~200 times larger than that of standard TDEs.

Comparison between Eccentric TDE and standard, parabolic TDE cases

Parabolic (Standard) TDE



Eccentric TDE



Summary I.

- In parabolic TDEs, mass fallback rate is consistent with $t^{-5/3}$ law.
- Eccentric TDEs have critical value of eccentricity, below which all mass is bounded by black hole. Since fallback time is finite when $e < e_{crit}$, fallback rate substantially exceeds Eddington rate.

Accretion Disk Formation

There are arguments whether/how an accretion disk is formed around the black hole after stellar debris falls back (Rees 1988, Cannizzo 1990, Kochenck 1994): What causes strong shock to thermalize debris orbital energy, leading to debris circularization?

1. Tidal compression at the periastron (Carter & Luminet 1982; Ramirez-Ruiz & Rosswog 2009; Guillochon et al. 2013)

2. **Debris crossings due to relativistic perihelion shift (Rees 1988; Hayasaki et al.2013; Hayasaki et at. 2015, arXiv: 1501.05207)**

GR Effects (Schwarzschild space-time)

Hayasaki+(2013)

● Why do we consider GR effects?

Apsidal 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):

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

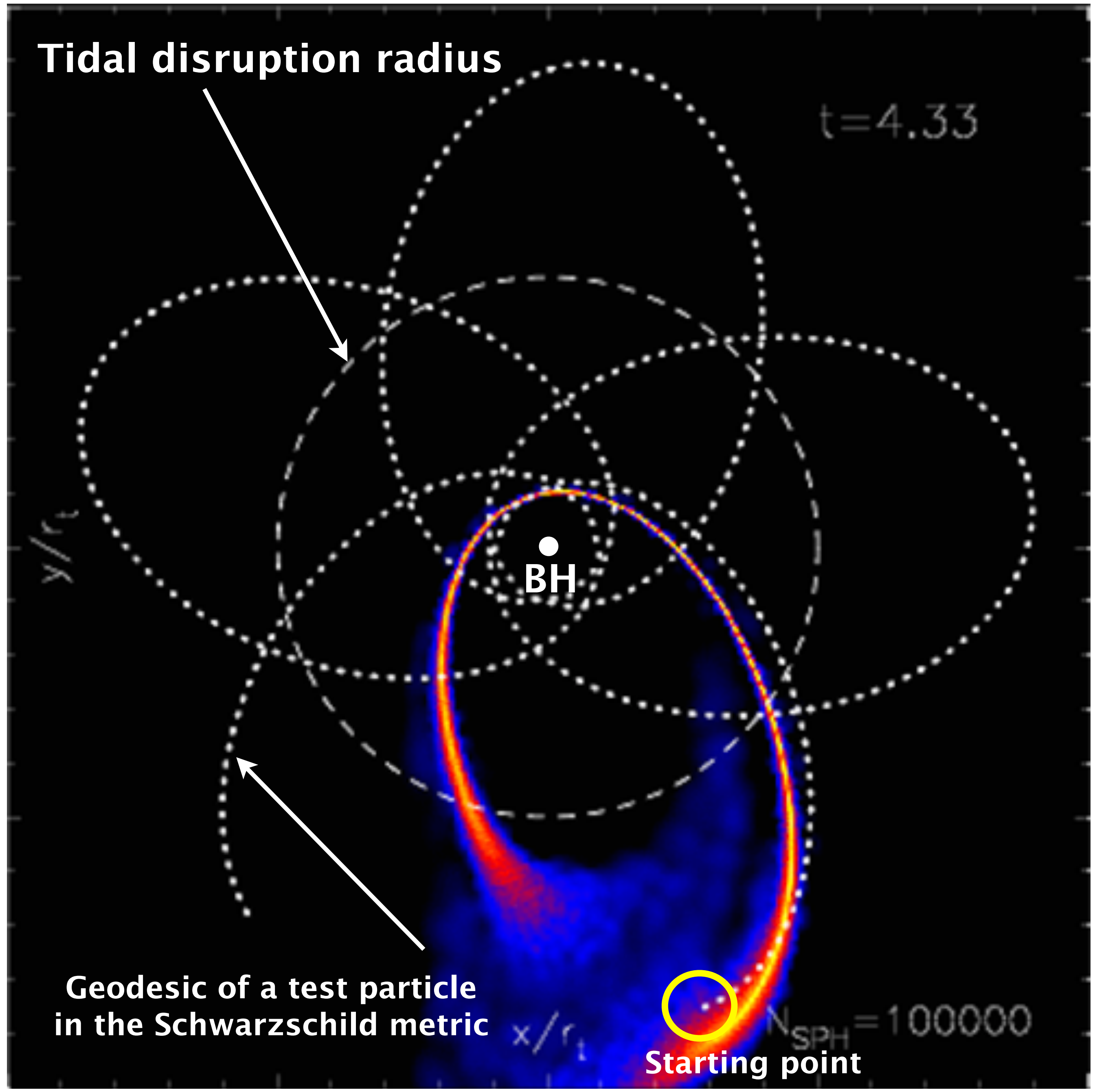
where c1=-(4/3)(2+$6^{1/2}$), c2=4*$6^{1/2}$-9, c3=-(4/3)(2*$6^{1/2}$-3)

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.

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

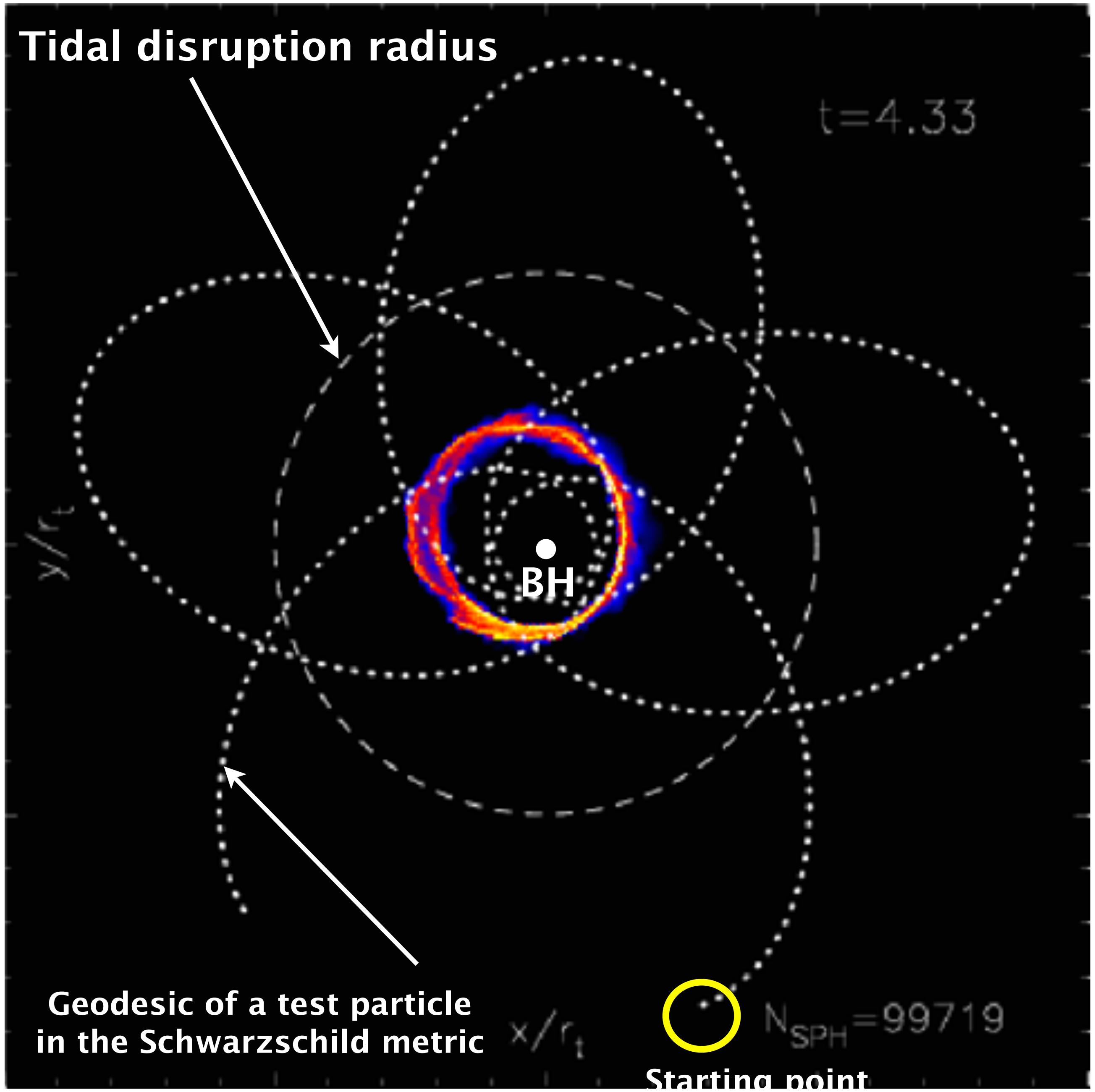


$$\beta = \frac{r_\mathrm{t}}{r_\mathrm{p}}$$

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

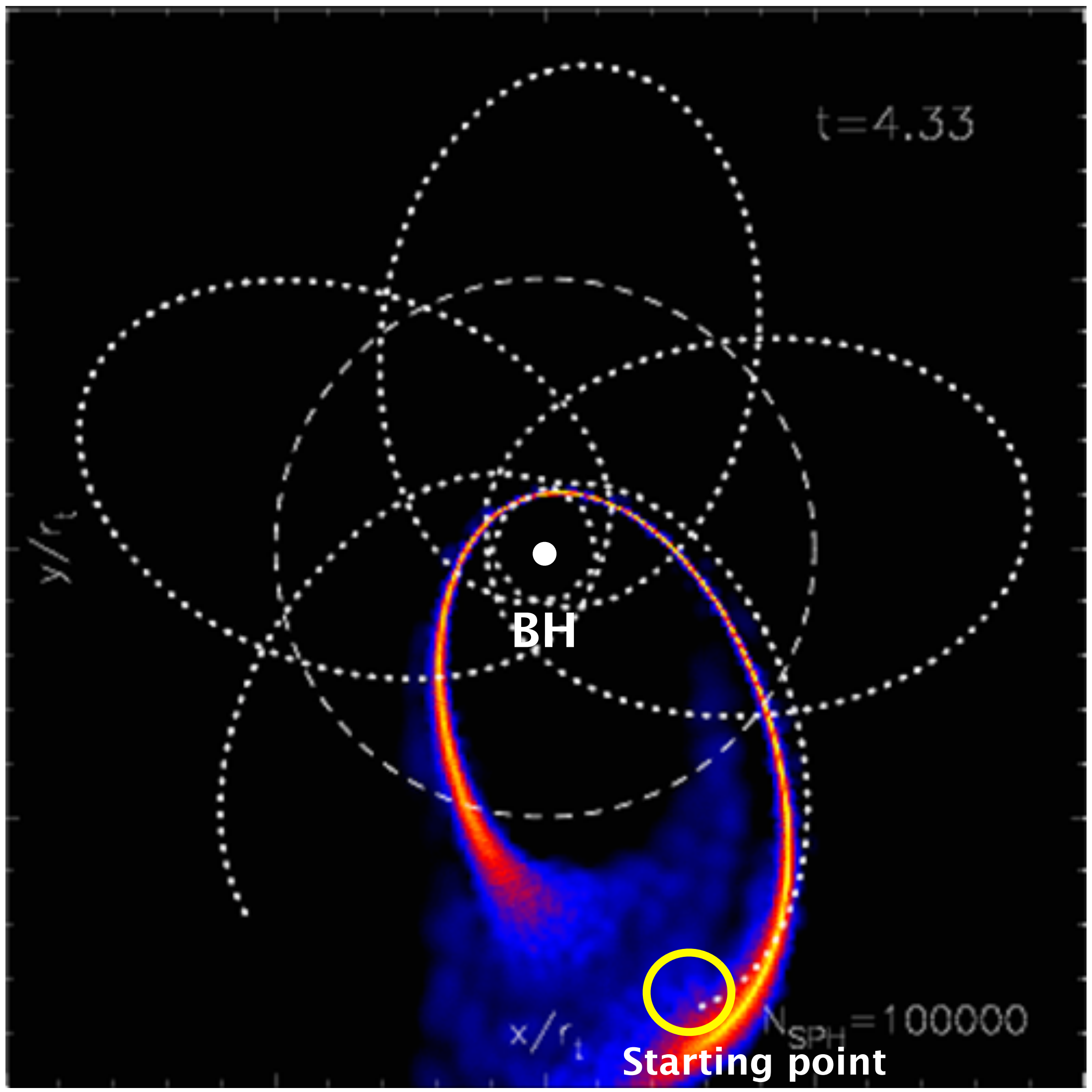


$$\beta = \frac{r_{\rm t}}{r_{\rm p}}$$

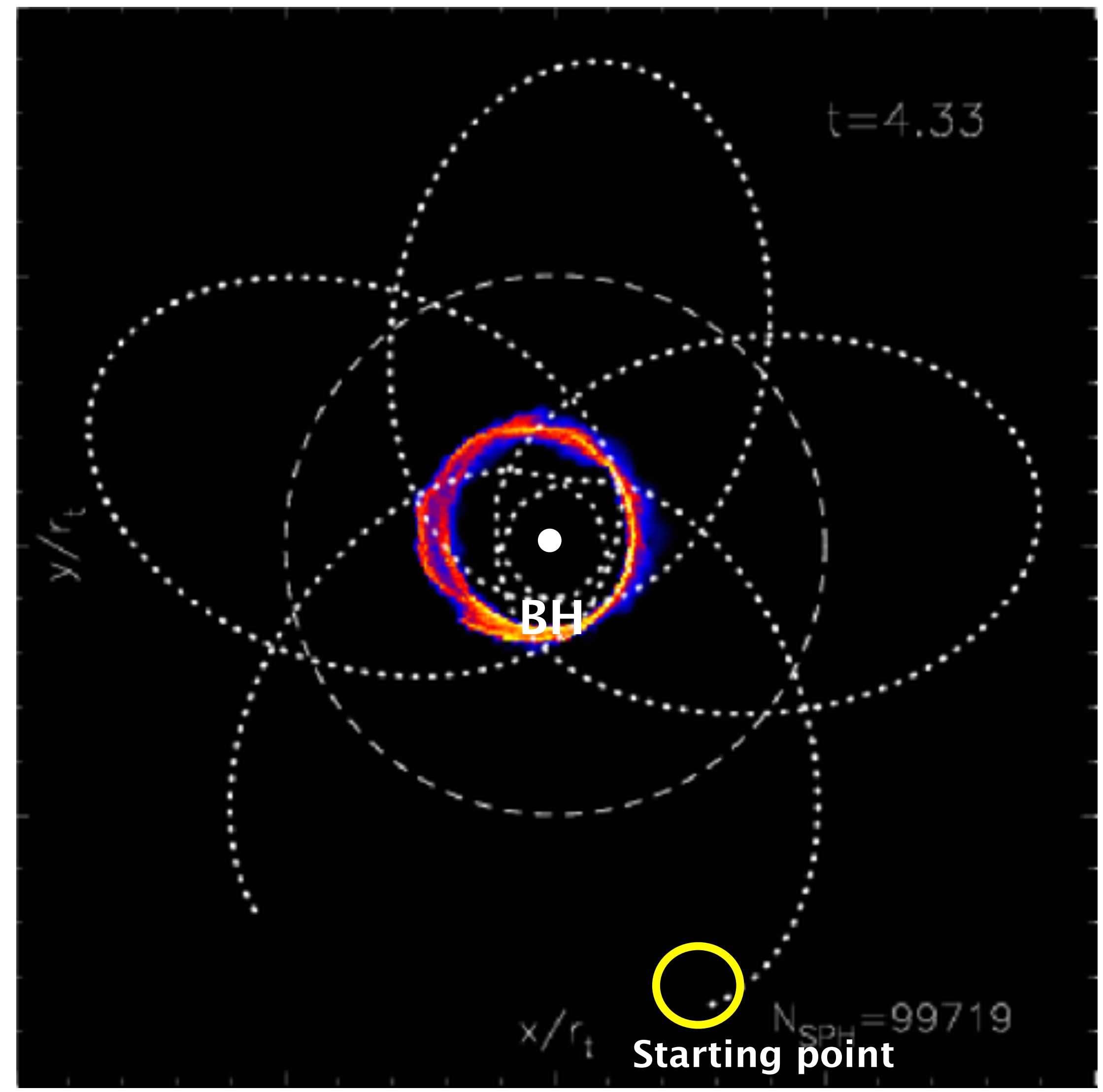
Accretion disk is formed around the black hole due to shock energy dissipation of orbital crossings induced by GR precession

Comparison of two animations

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

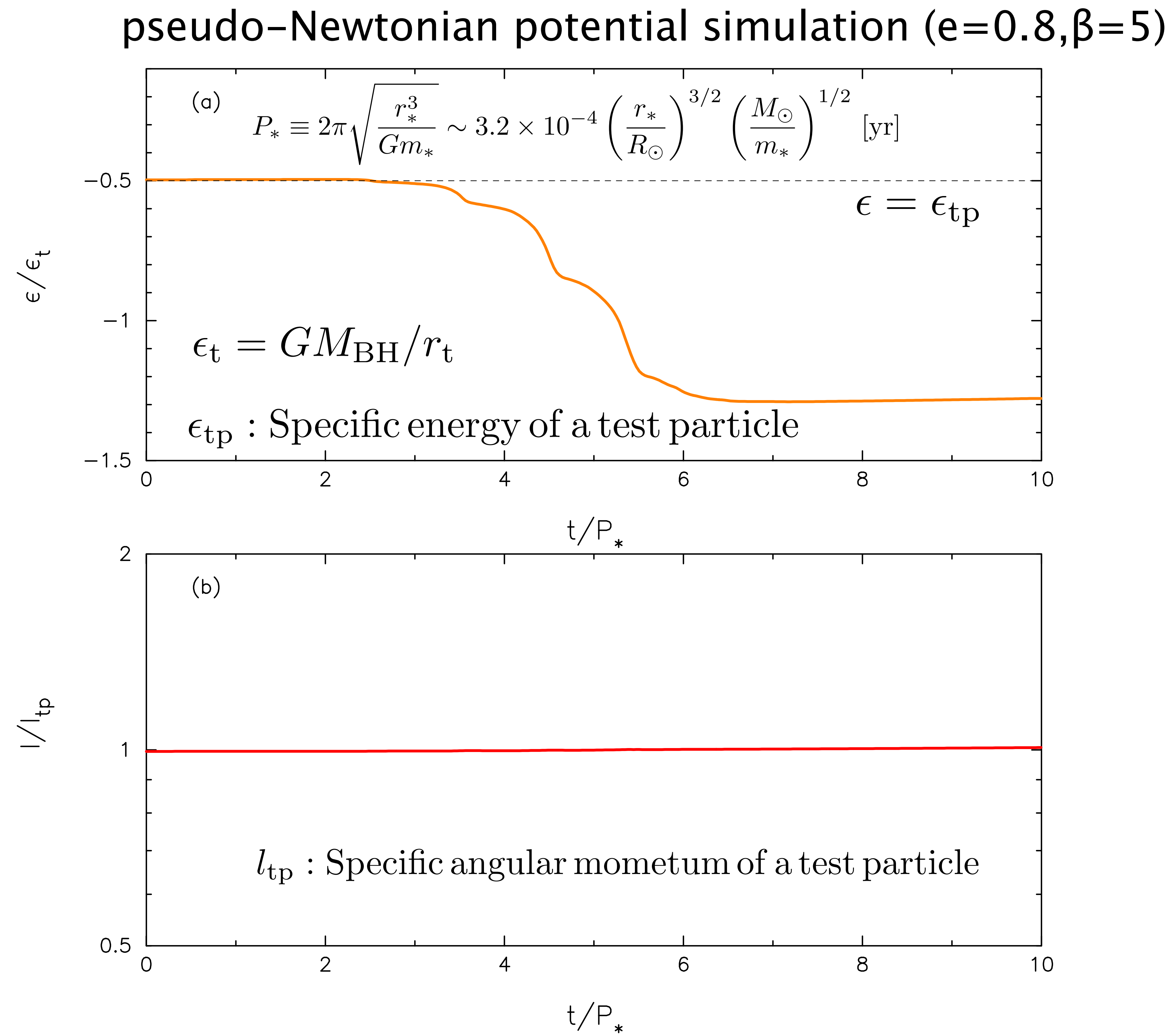


Pseudo-Newtonian potential
simulation (e=0.8,β=5)



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

Averaged specific energy and angular momentum



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

Summary & Discussion

- GR (perihelion shift) plays an important role in accretion disk formation via circularization of stellar debris from stars on moderately eccentric orbits.
- Energy dissipation rate ($\varepsilon_{end}-\varepsilon_{ini}/\varepsilon_{ini}$): 0.4% for Newtonian case, more than 100% for GR case): Tidal compression is not important?
- Angular momentum is conserved from pre-tidal disruption to post-tidal disruption via debris circularization in Eccentric TDEs.
- 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. (at Next or the third meeting?) (Hayasaki, et al. 2015, arXiv:1501.05207)