Revisit the rate of tidal disruption: the role of partial tidal disruption event

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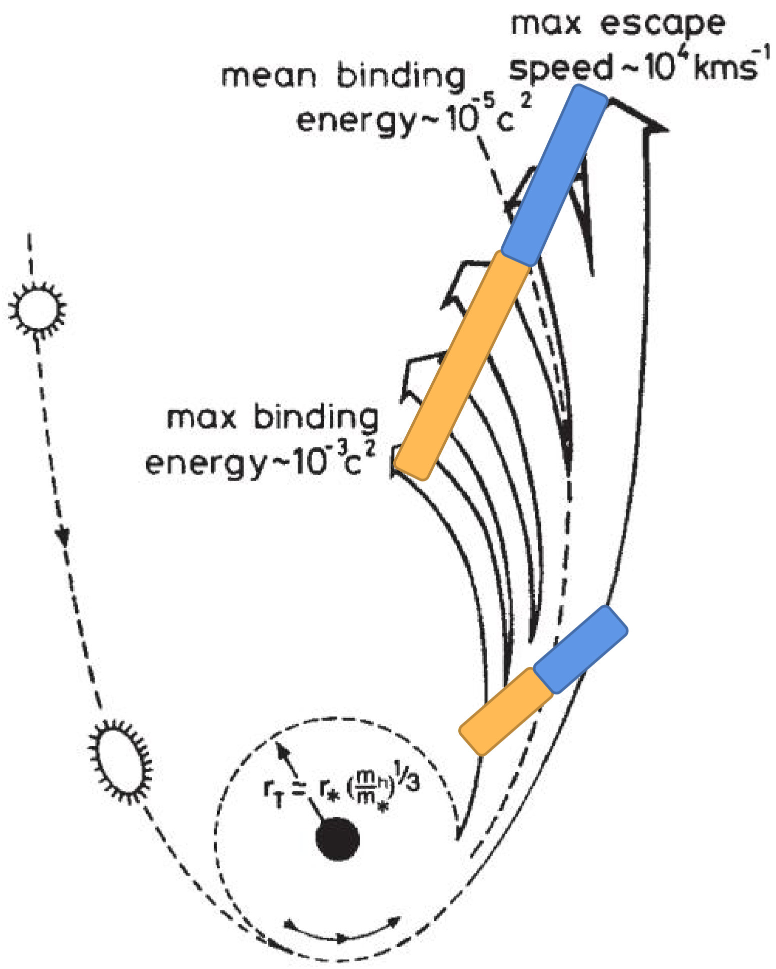
Outline

- Introduction to TDE (full and partial)
- The event rate
- N-body simulation and results

What is a (full) tidal disruption event (FTDE)?



Rees (1988)

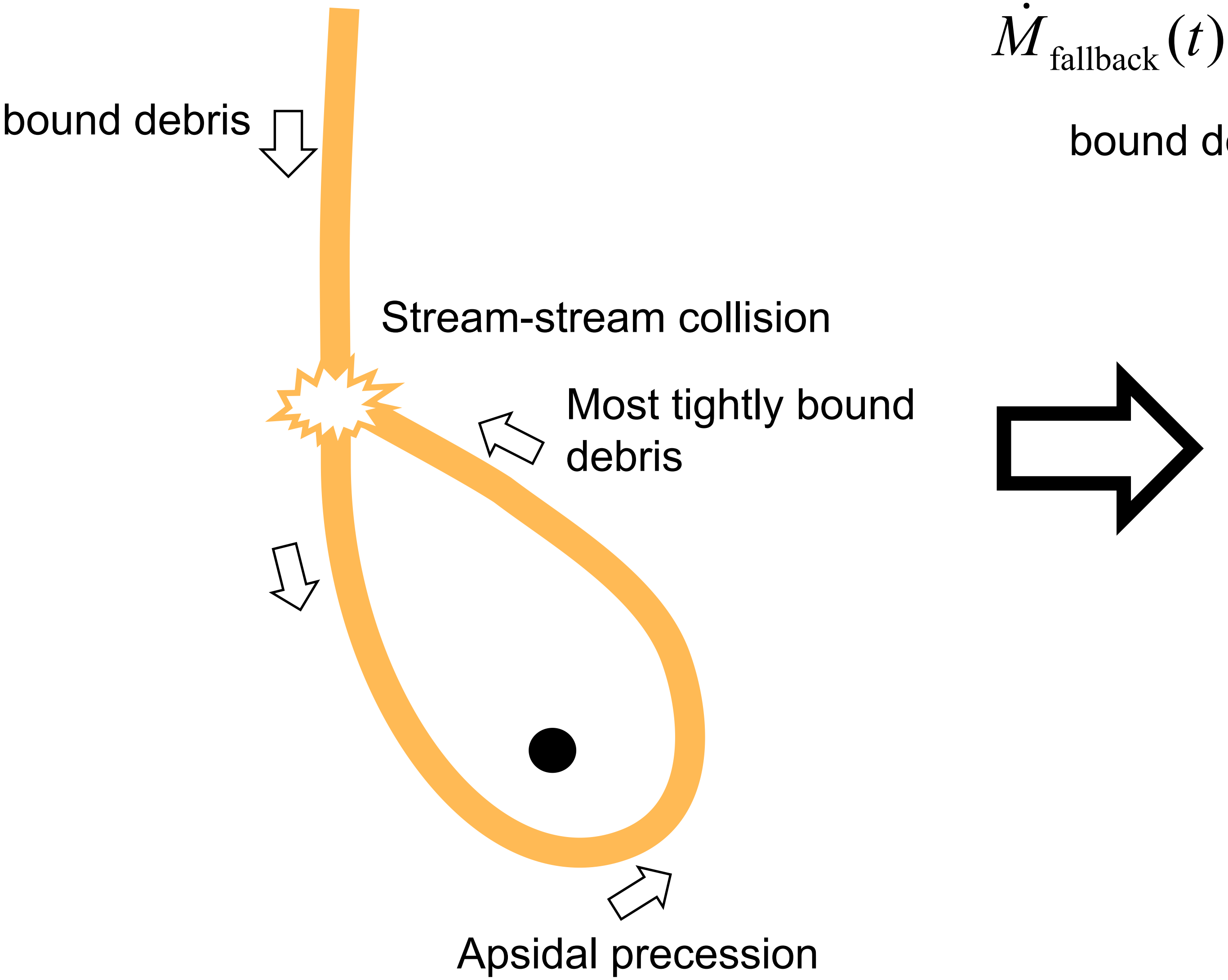
- When a star's distance to the SMBH becomes less than the tidal radius (r_t), the tidal force of the SMBH will tear the star apart, causing a TDE.
- In the classic picture of TDE, the star approaches the SMBH on **a parabolic orbit** with **pericentric distance $r_p = r_t$** (Rees, 1988)

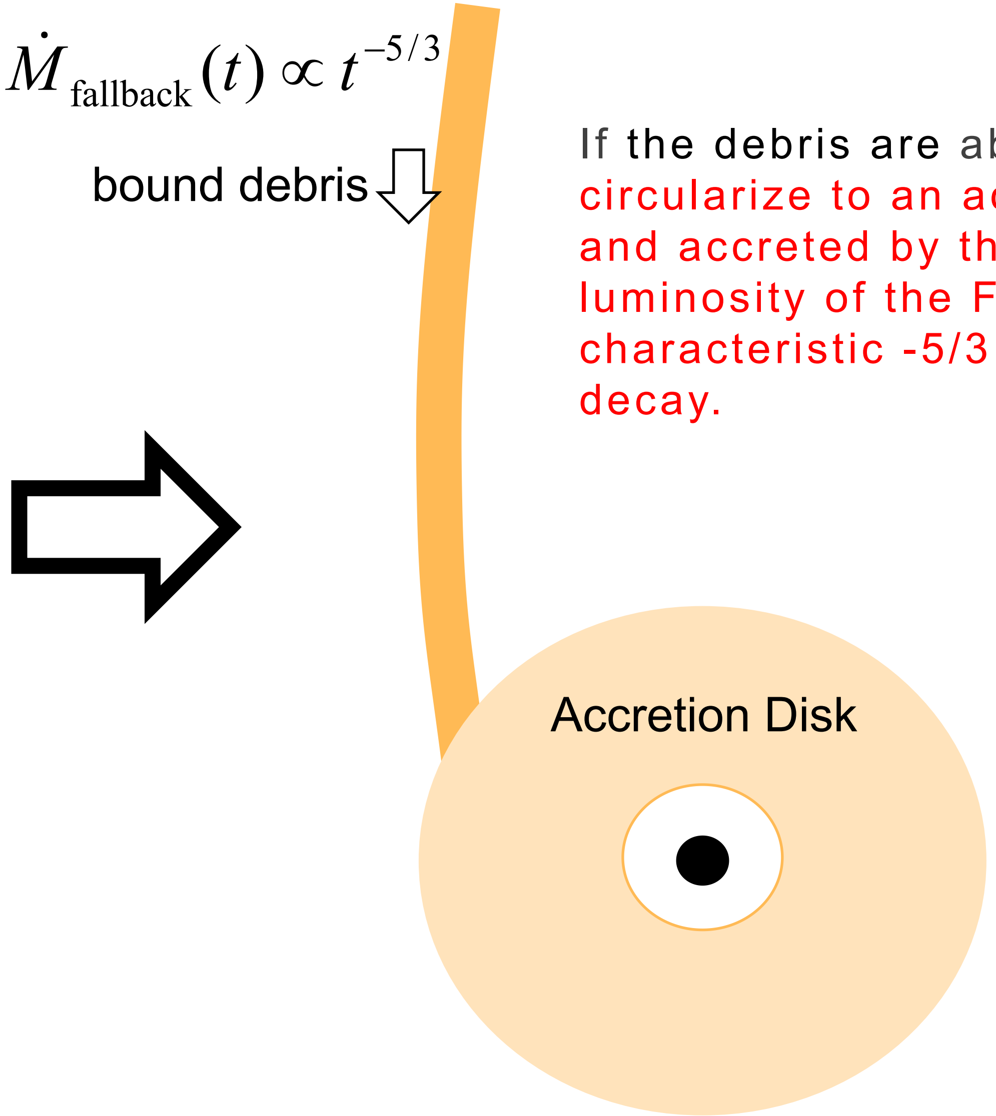
$$r_t = r_s \left(\frac{M_{BH}}{m_s} \right)^{\frac{1}{3}}$$

After the disruption, half of the debris (yellow part) are bound to the SMBH and will return to the pericenter roughly one month later, with a mass fall back rate:

$$\dot{M}(t) = \frac{dM}{dE}\frac{dE}{dt} = \frac{2\pi}{3}(GM_{\rm h})^{2/3}\frac{dM}{dE}t^{-5/3}.$$

~1 month after the breakup of the star

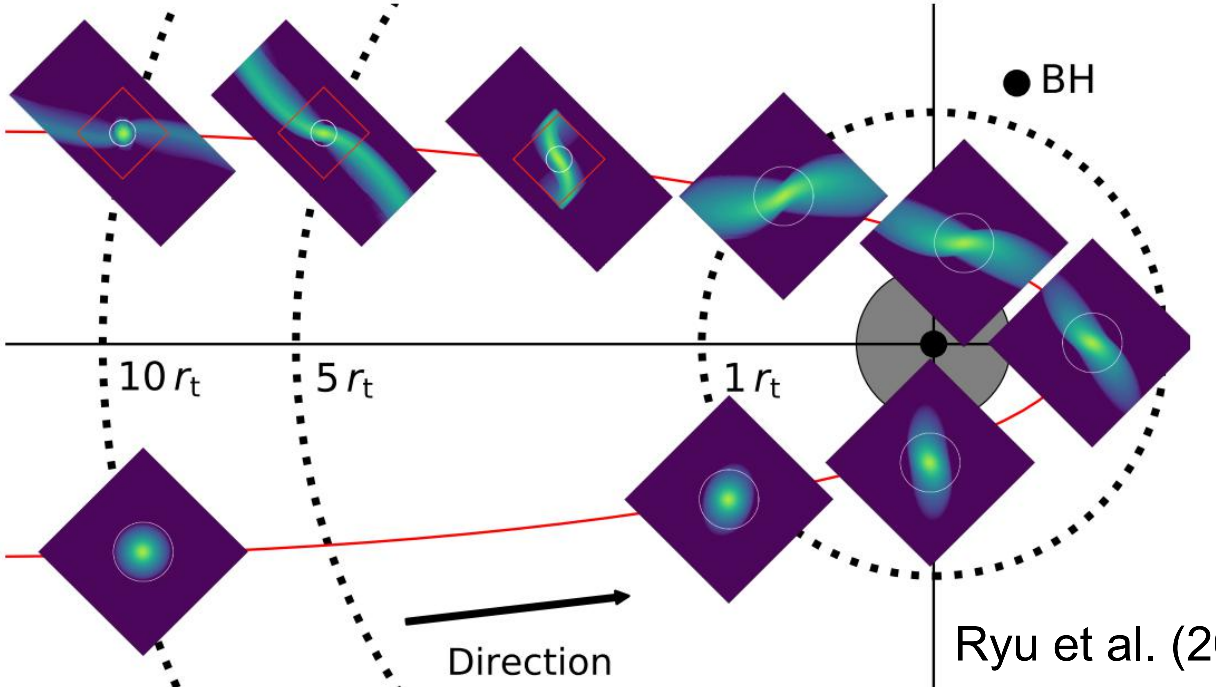




If the debris are able to quickly circularize to an accretion disk and accreted by the SMBH, the luminosity of the FTDE has a characteristic -5/3 power law decay.

Partial tidal disruption event (PTDE)

- A star passing by the SMBH with pericentric distance r_p slightly larger than r_t could also cede part of its mass to the SMBH, producing a partial tidal disruption event.
- Key difference between PTDE and FTDE: A remnant core will survive (we call it the "leftover star" in this work) and could produce many more PTDEs or end its life in FTDE.



Ryu et al. (2020)

Key Questions about TDE

1. *How often does this event happen?*

Event rate: dynamical co-evolution between the SMBH and the host star cluster.

> Theoretical study : loss cone theory
> Numerical study: Fokker-Planck, Monte Carlo, gaseous model, N-body

2. *How does the event look like?*

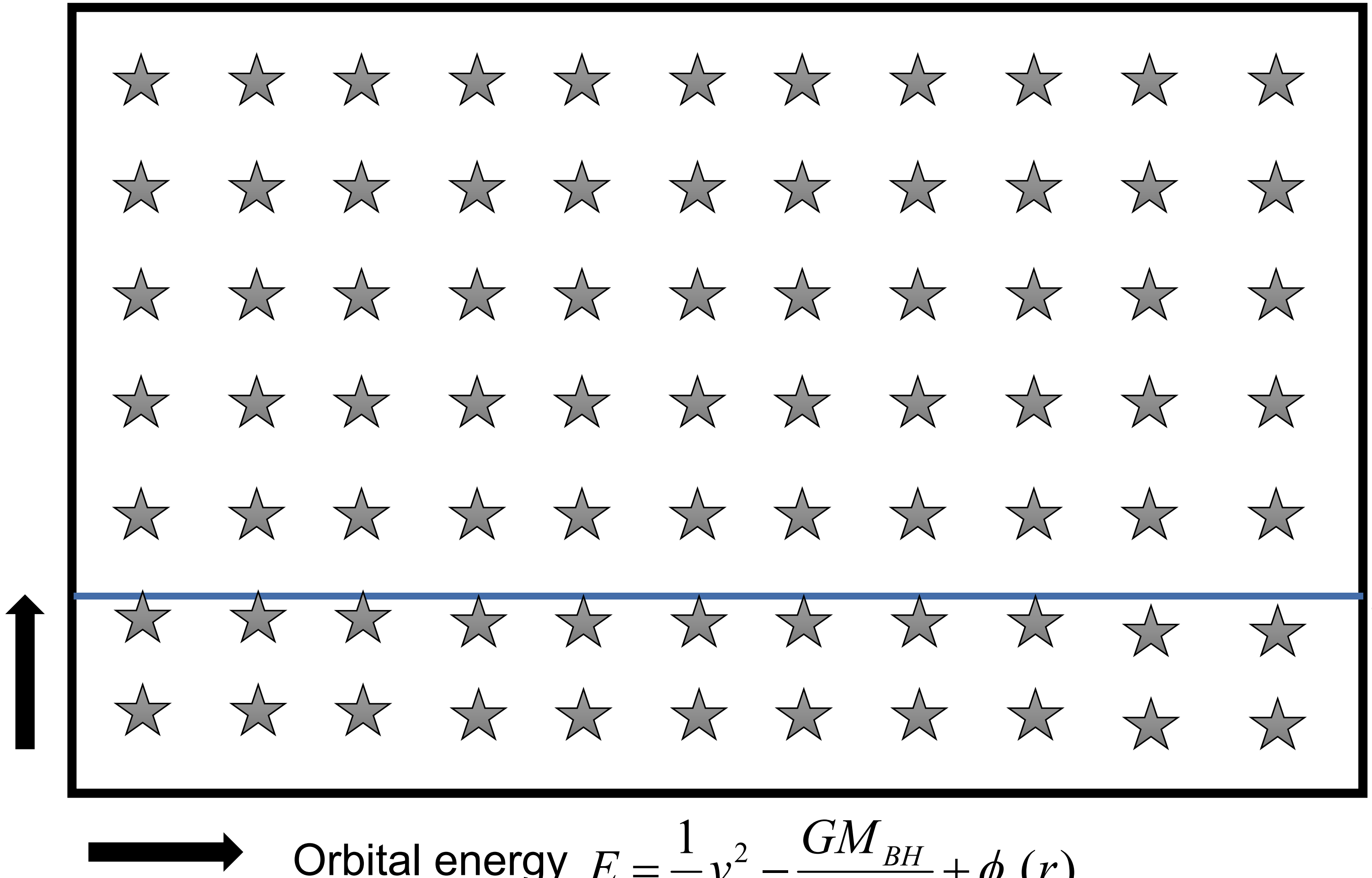
Light curve & spectrum: mass fall back rate, accretion physics, radiation transfer, stellar types.

Part 2 The event rate

The rate of (full) TDEs

- Computed in phase space, based on the Loss Cone theory (Frank & Rees, 1976) ...

Spherical star cluster



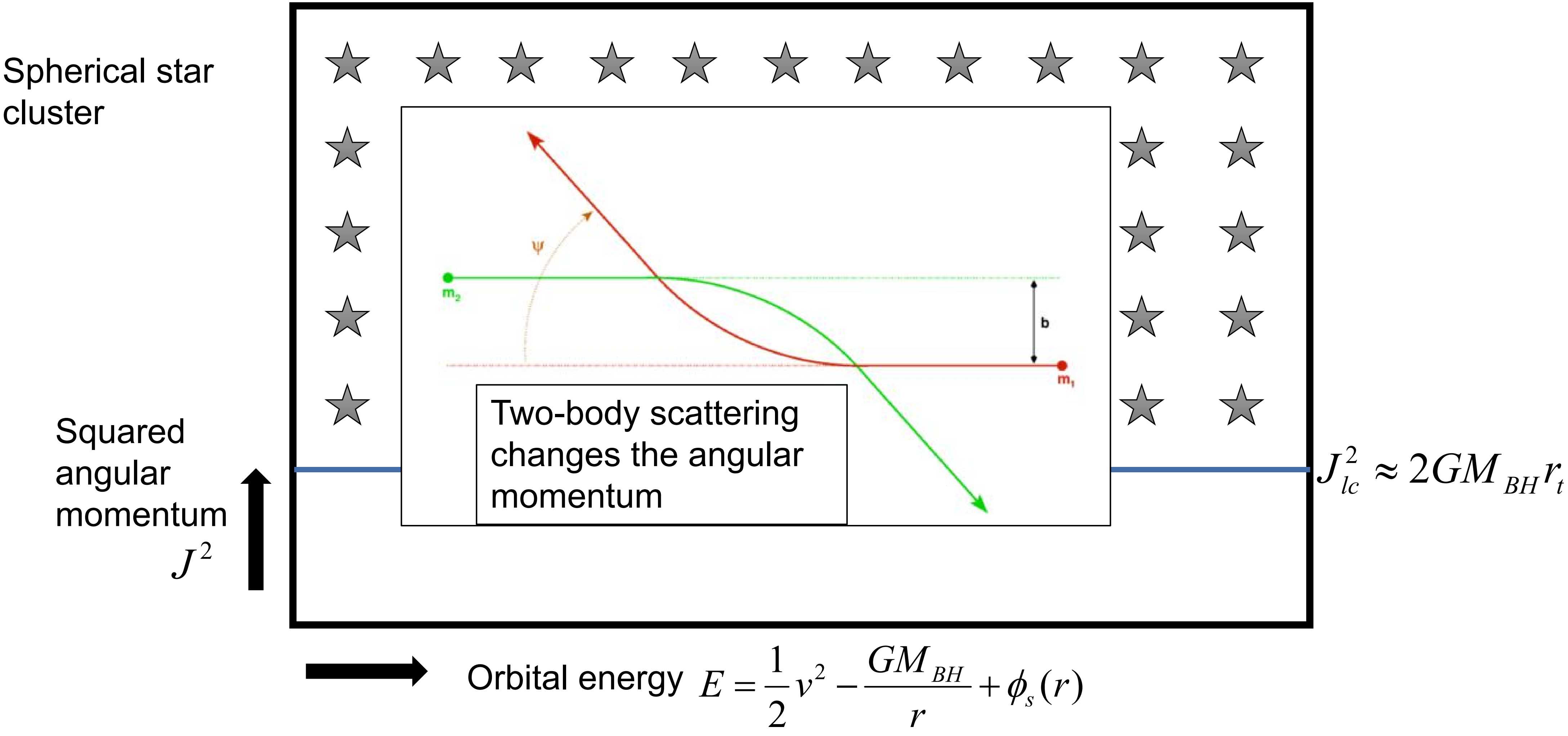
Squared angular momentum J^2

$J_{lc}^2 \approx 2GM_{BH}r_t$

Orbital energy $E = \frac{1}{2}v^2 - \frac{GM_{BH}}{r} + \phi_s(r)$

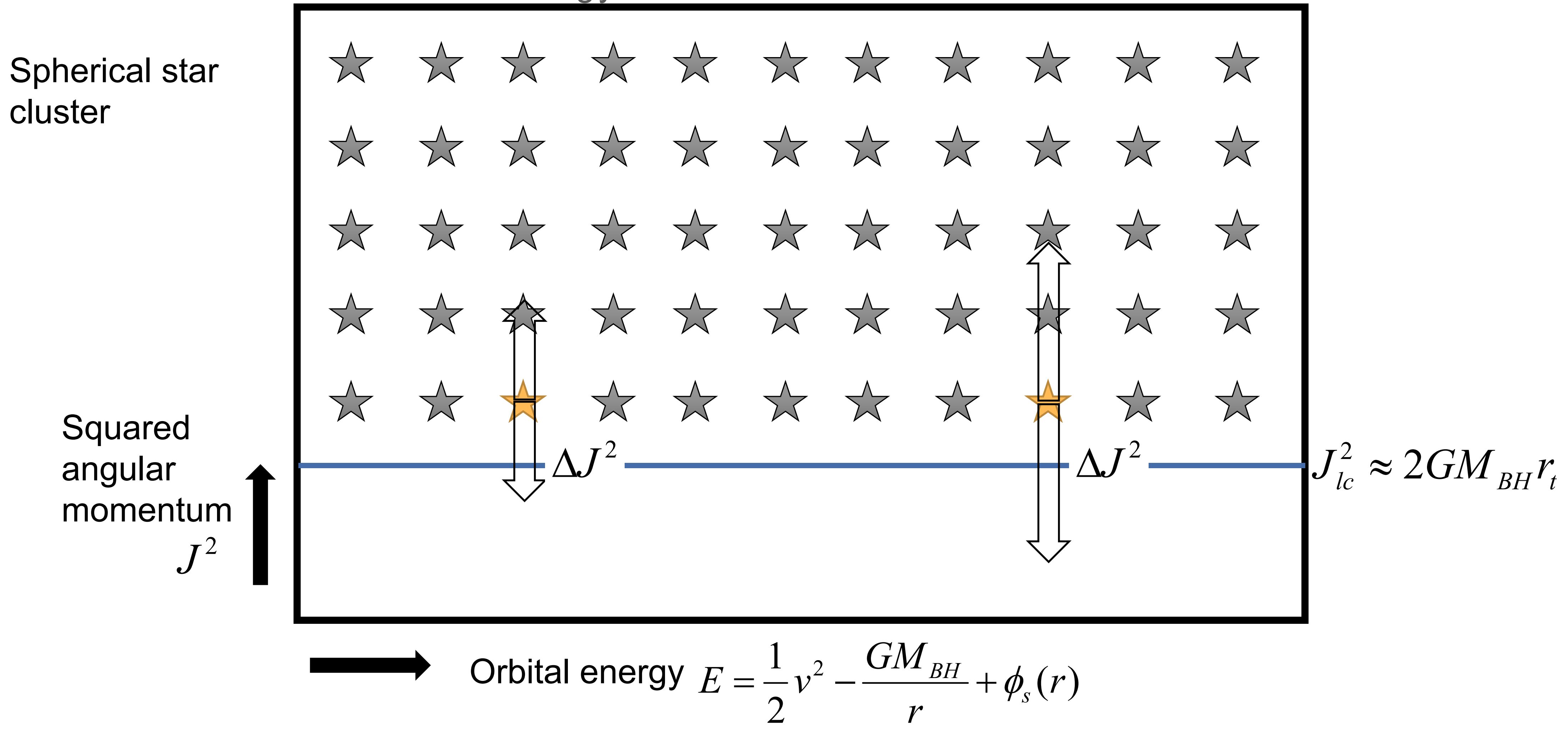
The rate of FTDEs

- Two-body scattering changes the angular momentum, can refill the loss cone



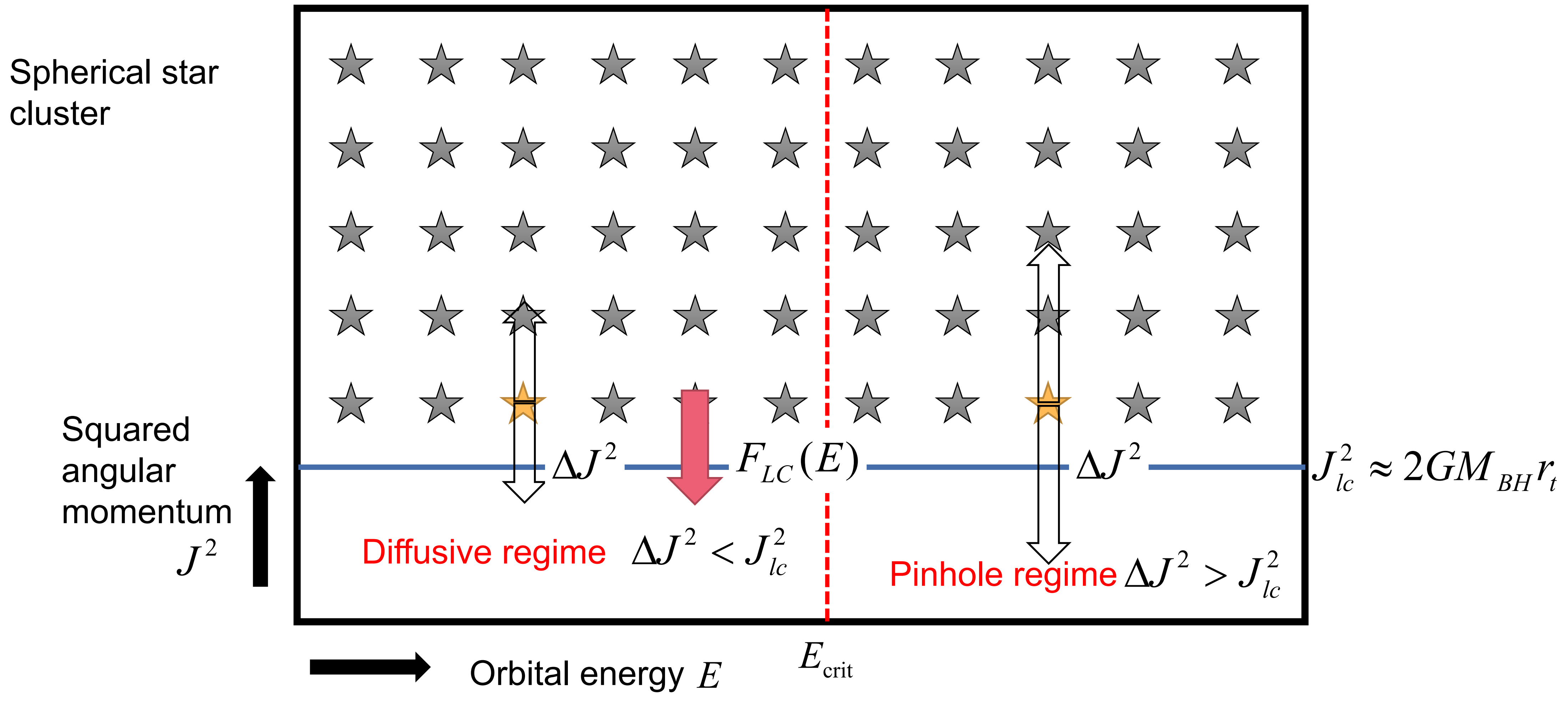
The rate of FTDEs

- From the relaxation theory, ΔJ^2 (variation of the squared angular momentum per orbit) increases with the orbital energy



The rate of FTDEs $= \int F_{LC}(E)\mathrm{d}E$

- The **diffusive and pinhole regimes**



Notes about the FTDEs

- Event rate
  - the pinhole regime contributes a lot
  - diffusive regime's contribution is small.
- The stars are disrupted on highly radial orbits (eccentricity very close to 1), and the squared angular momentum $J^2 \approx 2GM_{BH}r_p$
- TDEs in the diffusive regime: J^2 is only a little bit smaller than J_{lc}^2
- TDEs in the pinhole regime: J^2 could be much less than J_{lc}^2

What's new for PTDEs?

The leftover stars

Features of the leftover star: varying stellar mass and radius

The leftover star could continue its orbit in the star cluster and produce further PTDEs and FTDE, but with a different tidal radius:

$$r_{\rm t} = r_{\rm t,0} \times \left(\frac{r_{\rm s}}{r_{\rm s,0}}\right)\left(\frac{m_{\rm s}}{m_{\rm s,0}}\right)^{-1/3}$$

The changes in tidal radius would affect the event rate ($\propto r_t^{4/9}$, Baumgardt et al. 2004) of both PTDE and FTDE

Features of the leftover star: varying stellar mass and radius

The leftover star's new stellar mass:

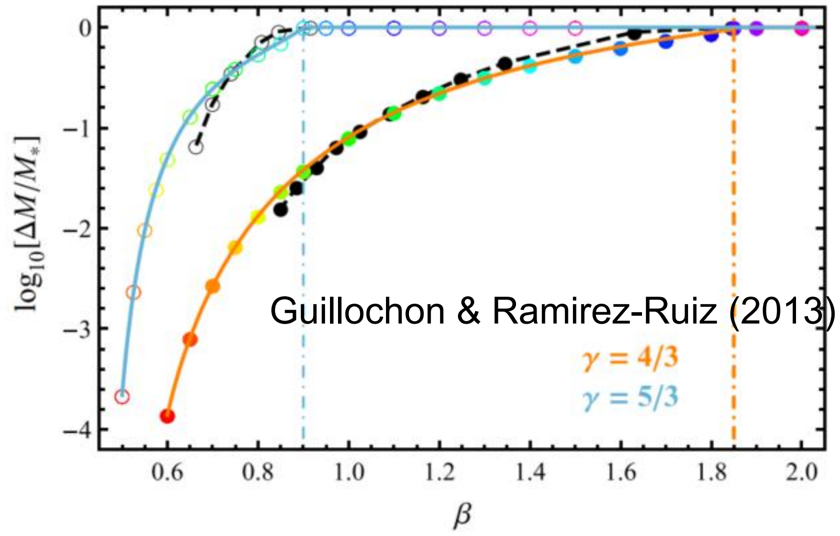
The amount of the stripped mass (Δm) is resulted from the competition between

The strength of tidal force from the SMBH:
related to the penetration factor

$$\beta = r_t / r_p$$

The self-gravity of the star: determined by the internal structure of the star:

- polytropes (characterized by γ)
- real stellar model (e.g. generated by MESA)

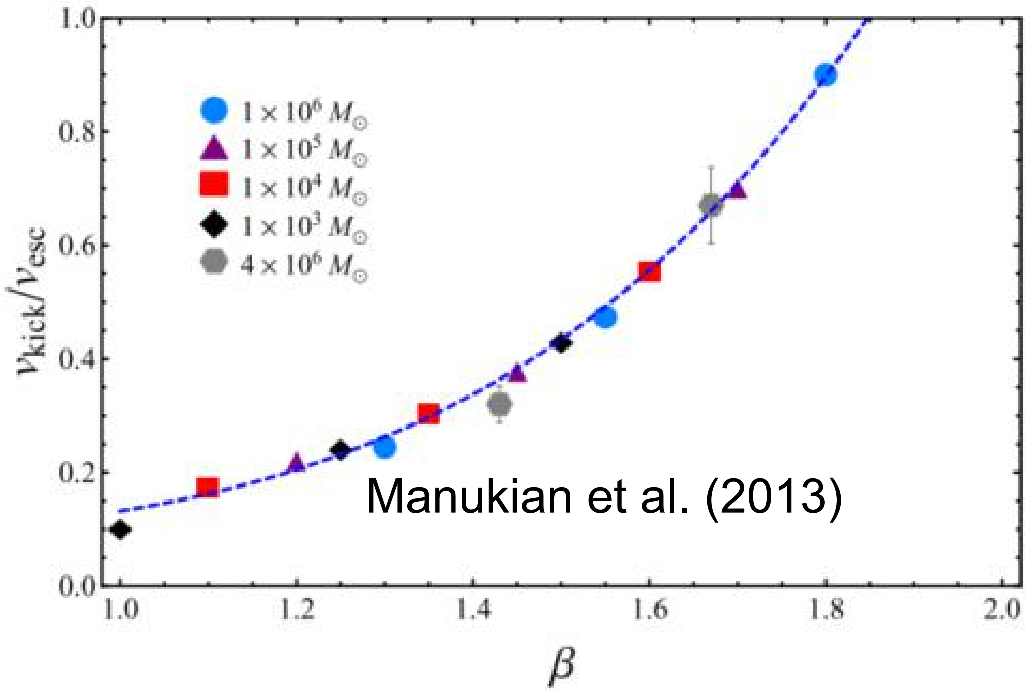


Guillochon & Ramirez-Ruiz (2013)

The stellar radius is obtained through the mass-radius relation.

Features of the leftover star: increase of the orbital energy

The leftover star **receives a velocity kick** during the PTDE (Manukian et al. 2013; Gafton et al. 2015)



Manukian et al. (2013)

$$v_{\rm kick} = (0.0745 + 0.0571\beta^{4.539})v_{\rm esc}$$

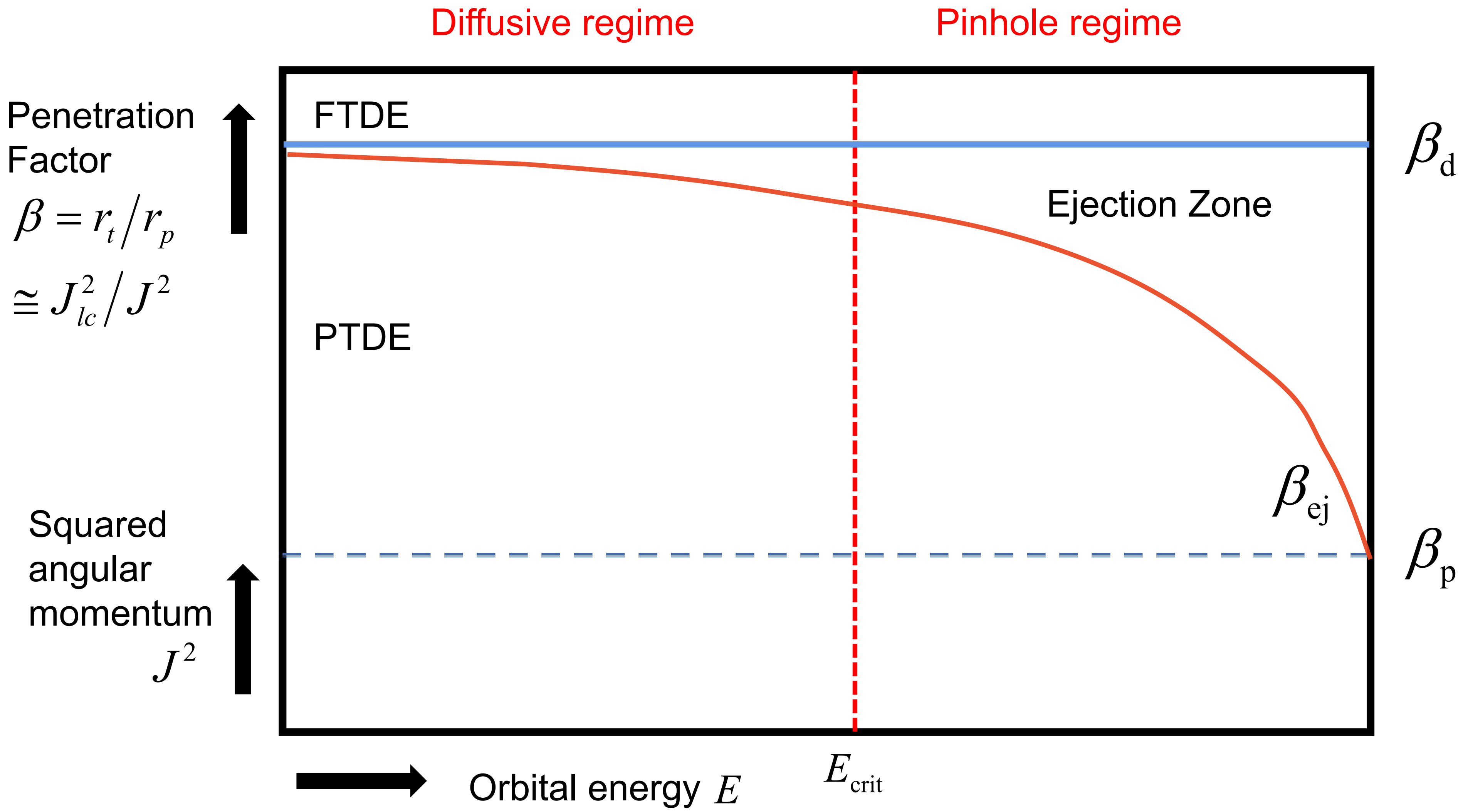
where v_{esc} is the escape velocity at the surface of the star.

Accordingly, we could define the quantity $\beta_{\rm ej}$, above which the star will be ejected from the cluster, by solving the following equation

$$|E| = \frac{1}{2}v_{kick}^2(\beta_{\rm ej})$$

Note, the velocity kick do not change the oribtal angular momentum of the leftover star. (Ryu et al. 2020)

The loss cone filling process, taking into account the novel features of PTDE



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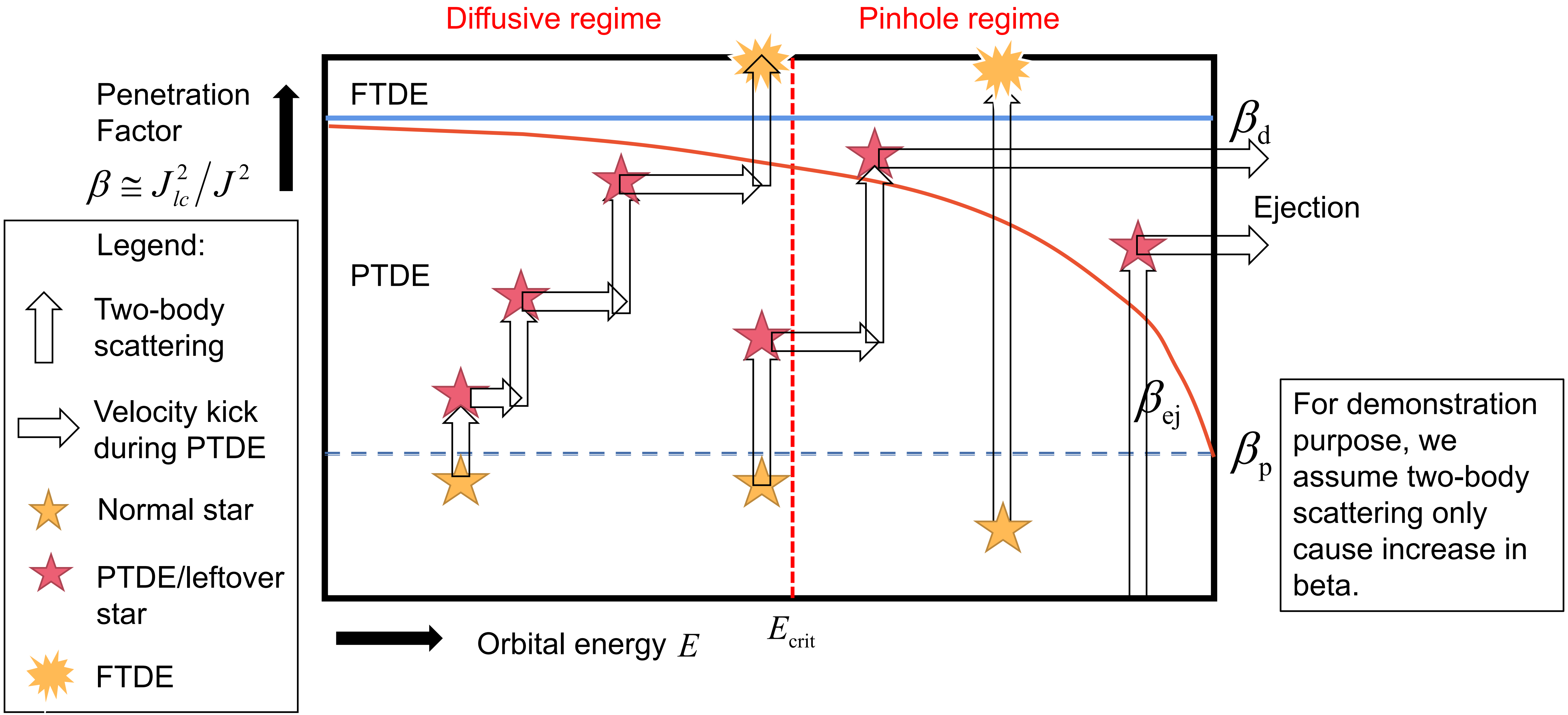


In short summary ...

- A single star could produce multiple PTDEs (especially in the diffusive regime), hence raises the event rate of PTDEs.
- Ejection of the leftover stars shall reduce the event rate of both PTDE and FTDE.

The problem is:
How to estimate the amount of enhancement in PTDEs and the reduction in FTDE/PTDEs.

Part 3 : N-body simulation and results

Our solution: N-body simulation

- General setting of the models
  - N=128K, initially Plummer model
  - $r_{t,0}$ = 5.94e-5 [L]
  - M_{BH} = 0.075 [M]

  Can be scaled to star cluster with 10^6 M_{sol} SMBH
- Implementation of the PTDE routine
  - Assuming all the stars are solar type, hence $\beta_p = 0.6$ $\beta_d = 1.85$
  - The normal and leftover star share the same recipes
    - Mass stripping uses the fitting formula of Guillochon & Ramirez-Ruiz (2013)
    - Velocity kick uses the fitting formula of Manukian et al. (2013)
    - Stellar mass-radius relation, $r_s \propto m_s^{0.8}$ (Kippenhahn & Weigert, 1994)
- Fiducial model and control model, each with 5 realizations.

Simulations performed with Nbody6++GPU

Results: Reduction of FTDE

Number of events recorded in the fiducial model, simulated for 1000 [T].

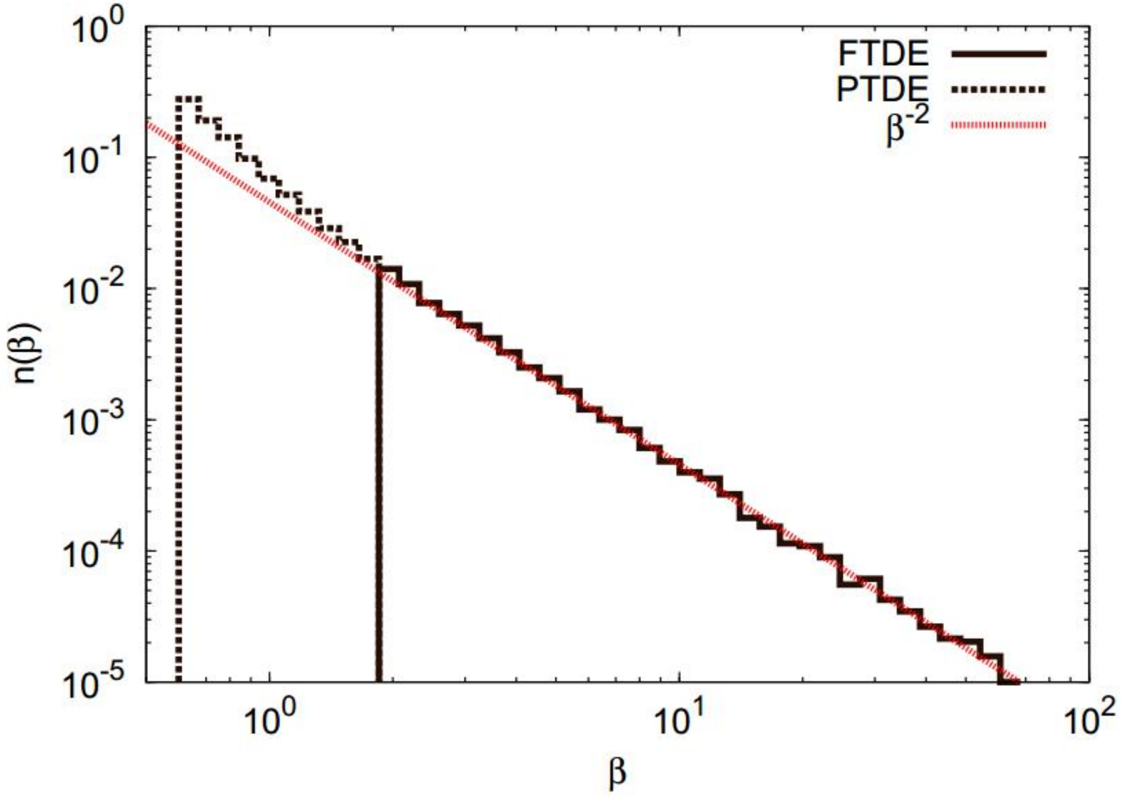
Type	Normal star	Leftover star	Total
FTDE	1521	770	2291
PTDE	3989	3900	7889
Total	5510	4670	10180

Compare to control model, the number of FTDEs in the fiducial model is reduced by 28% (2291 vs. 3214).

The reduction is mainly due to the ejection of stars (875) in the pinhole regime.

1/3 of the FTDEs are produced by the leftover stars

Results:Enhancement of PTDE



Stone et al. (2020) has estimated that the event rate of PTDE to FTDE is roughly 2.

By adpoting $n(\beta) \propto \beta^{-2}$ (pinhole regime), and take $\beta_{\mathrm{p}} = 0.6$, and $\beta_{\mathrm{d}} = 1.85$

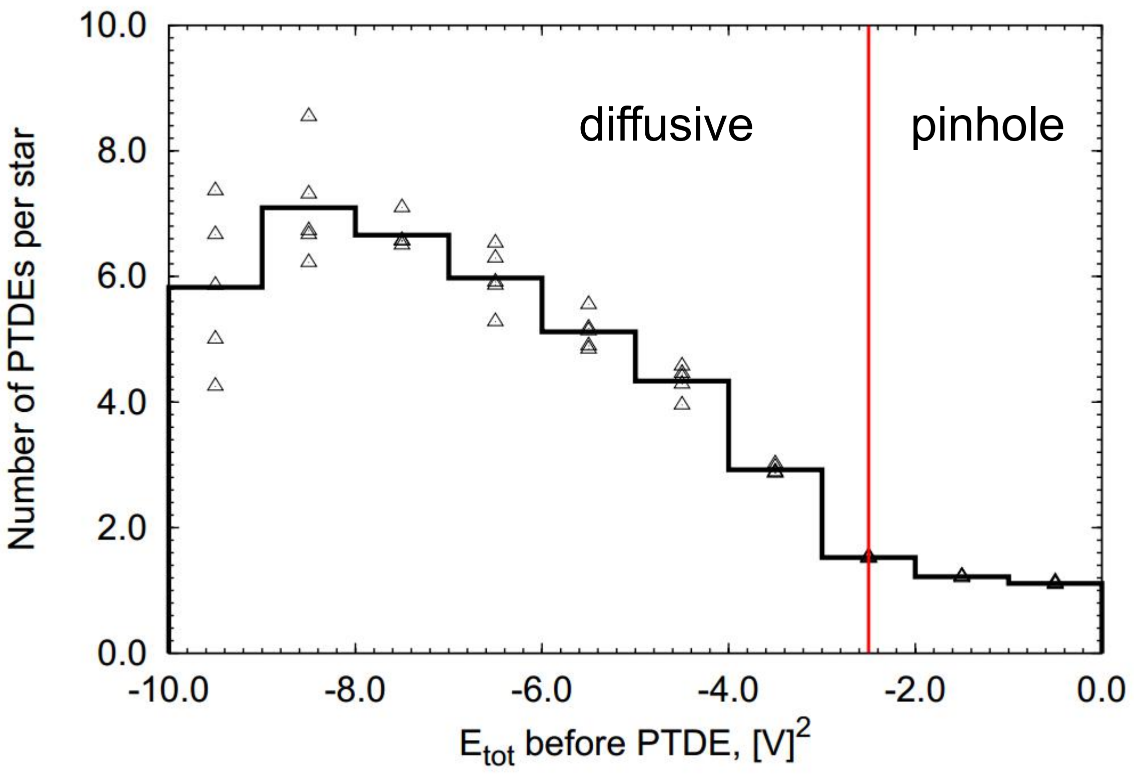
In our simulation, the ratio is 3.5.

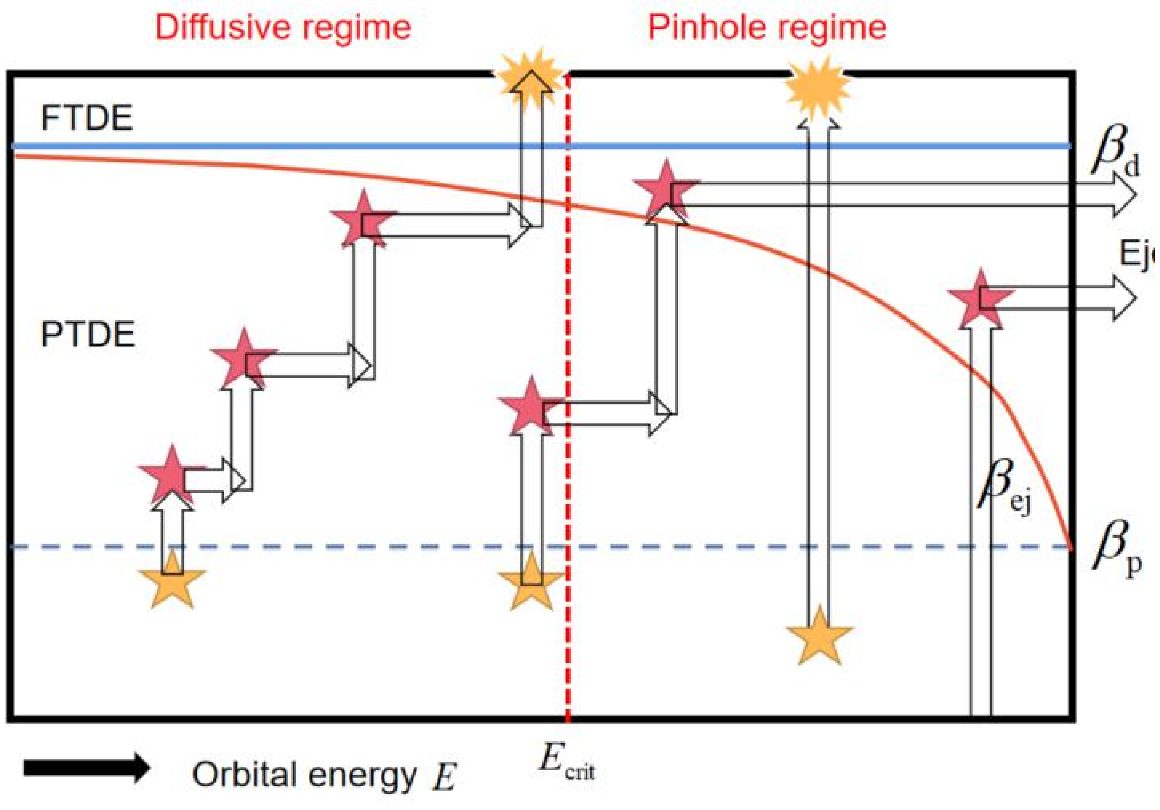
The enhancement is mainly due to the multiple PTDEs produced by stars in the diffusive regime.

Results:Enhancement of PTDE

A single star in the diffusive regime could produce many PTDEs,

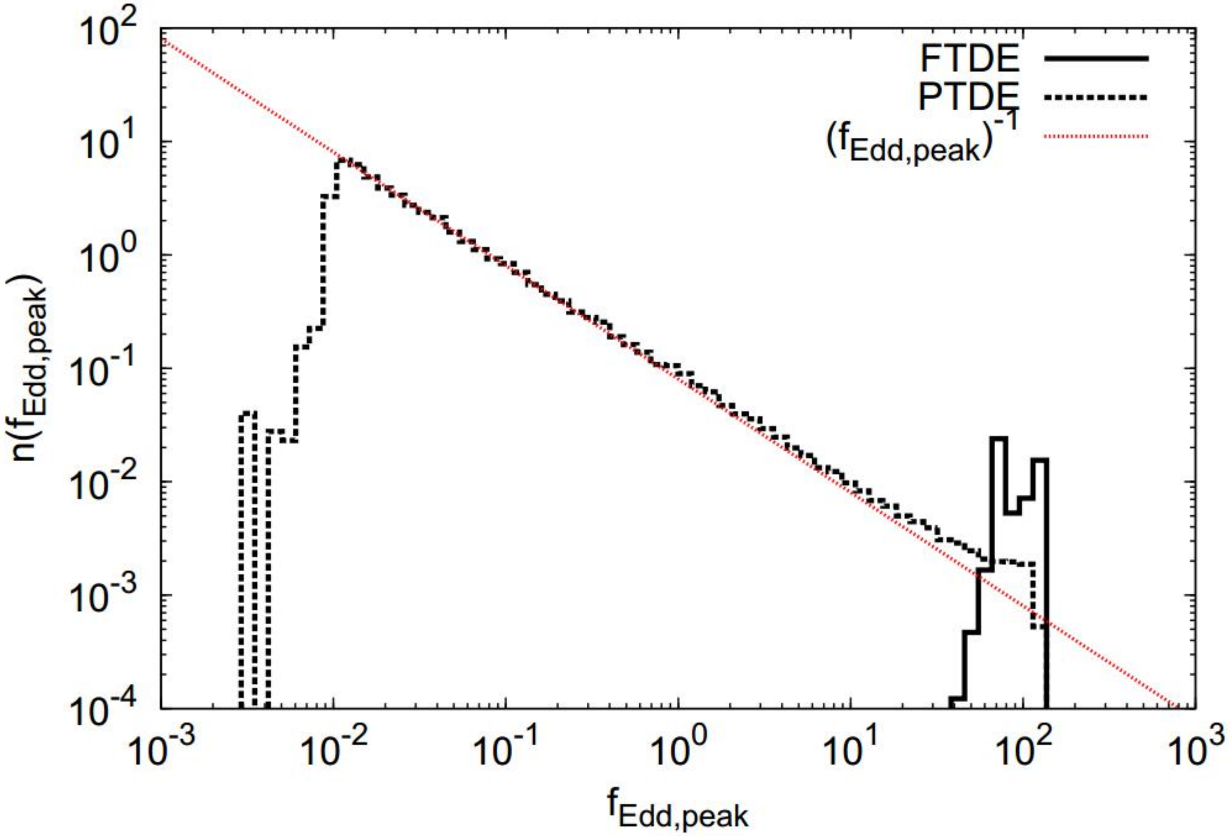
while a single star in the pinhole regime could only produce about 1 PTDE.





Results: observability

Adopting the fitting formula of Guillochon & Ramirez-Ruiz (2013), we compute the peak mass fall back rate for every events, normalized to Eddington accretion rate of 10^6 Msol SMBH.



4597 PTDEs have $f_{Edd,peak} > 1$

If the bolometric luminosity is limited to the Eddington luminosity during the super-Eddington fallback phase, then these PTDEs should be as bright as the FTDEs.

Hence, we expect the ratio of detections to be

$$\frac{N_{\mathrm{PTDE}}(f_{\mathrm{Edd,peak}} > 1)}{N_{\mathrm{FTDE}}} \approx 2.3$$

Summary

- Two novel effects of PTDE are put into the estimation of event rate of both FTDE and PTDE
- The FTDE rate is reduced by 28%, mainly due to the ejection of the leftover stars.
- The PTDE rate is enhanced, mainly due to the multiple PTDEs produced by the stars in the diffusive regime.
- In observations, the expected detections of PTDEs is 2.3 times of FTDEs.