TDE rates under the magnifying glass

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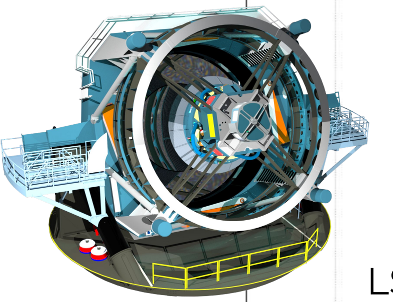
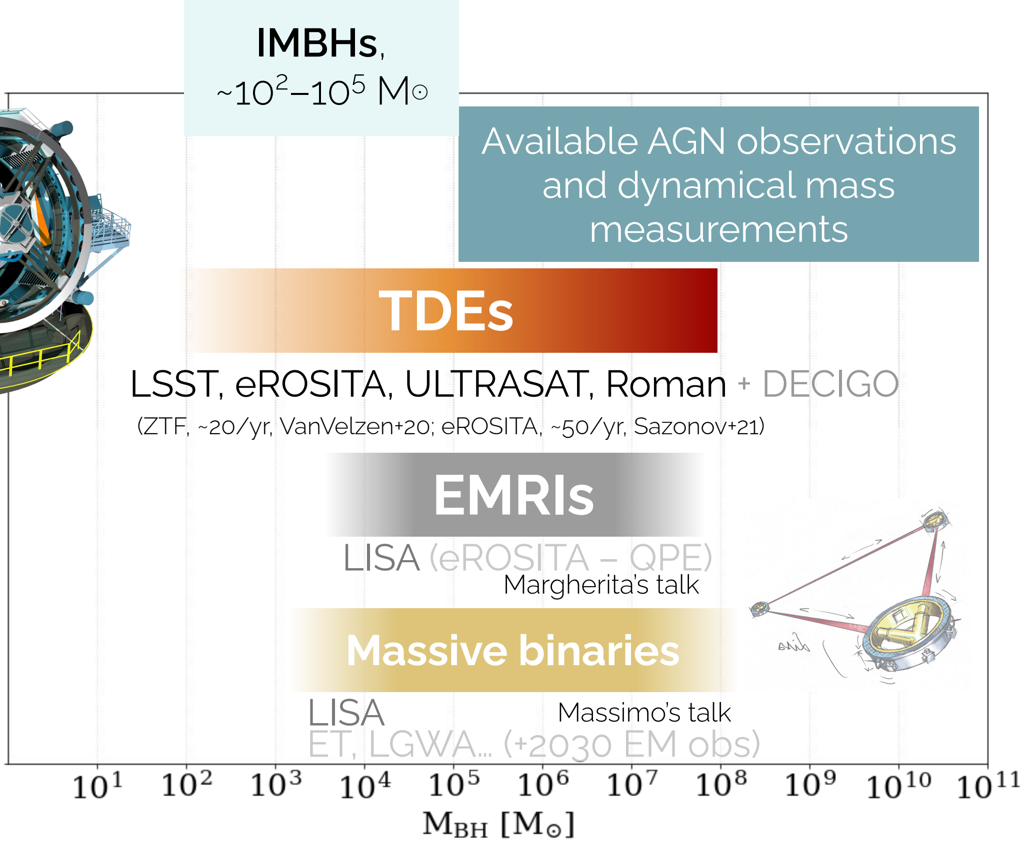
Tidal disruption events

$$R_{TDE} \approx \left(\frac{M_{BH}}{m_\star}\right)^{1/3} R_\star = 3.6 \times 10^{-6}\,\mathrm{pc}\left(\frac{M_{BH}}{4\times10^6\,M_\odot}\right)^{1/3}$$





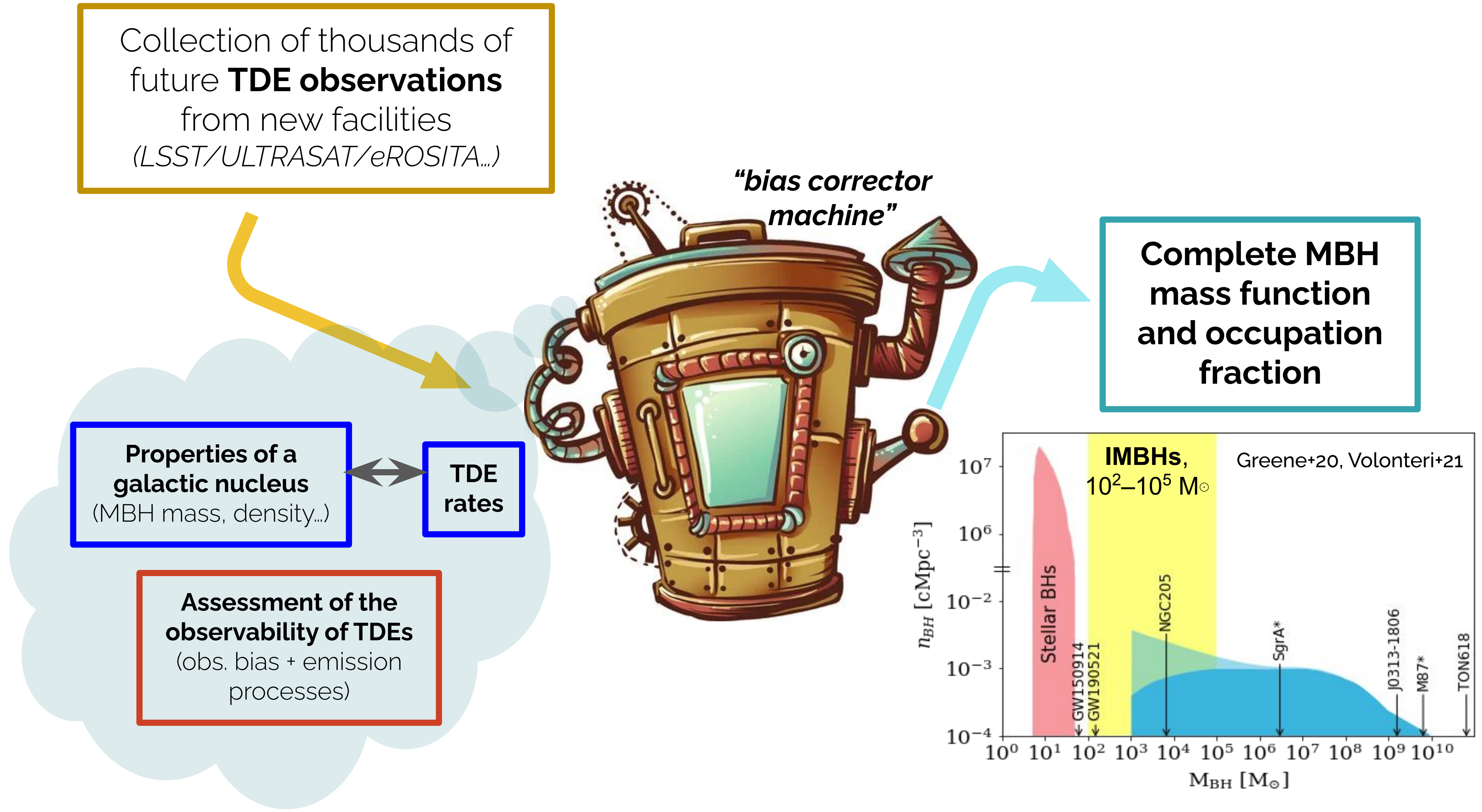
- Luminosities of ~$10^{43\text{-}44}$ erg/s
- Transients: steep rise of the (*characteristic*) lightcurve that then declines over months to years
- Multiwavelength! (multiband)

Rees88, Phinney89, Lodato&Rossi11, Rossi+21

Ideal to unveil otherwise quiescent (I)MBHs and measure their masses

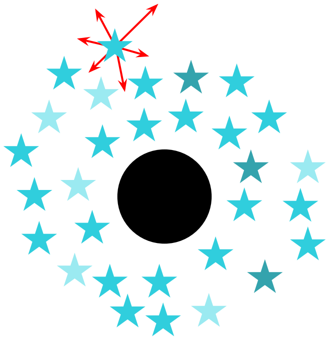
Guillochon+17, Mockler+19; Ryu+20; Mummery+23

See e.g. Sjoert's talk


Collection of thousands of future **TDE observations** from new facilities
(LSST/ULTRASAT/eROSITA…)
Properties of a galactic nucleus
(MBH mass, density…)
TDE rates
Assessment of the observability of TDEs
(obs. bias + emission processes)
"bias corrector machine"
Complete MBH mass function and occupation fraction
IMBHs,
10^2–10^5 M⊙
Greene+20, Volonteri+21
Stellar BHs
GW150914
GW190521
NGC205
SgrA*
J0313-1806
M87*
TON618
n_{BH} [cMpc^{-3}]
M_{BH} [M⊙]
10^7
10^6
10^{-2}
10^{-3}
10^{-4}
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}

Predicting TDE rates

Ubiquitous production mechanism: two-body relaxation



Two-body relaxation between stellar objects slowly perturbs stellar orbits → statistically, at some point, a star can reach a *deadly* orbit and get disrupted

Predicting TDE rates

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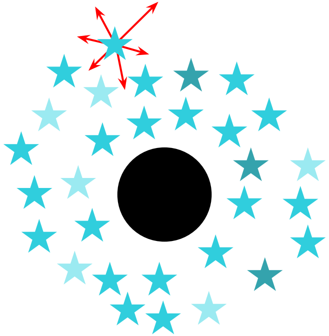


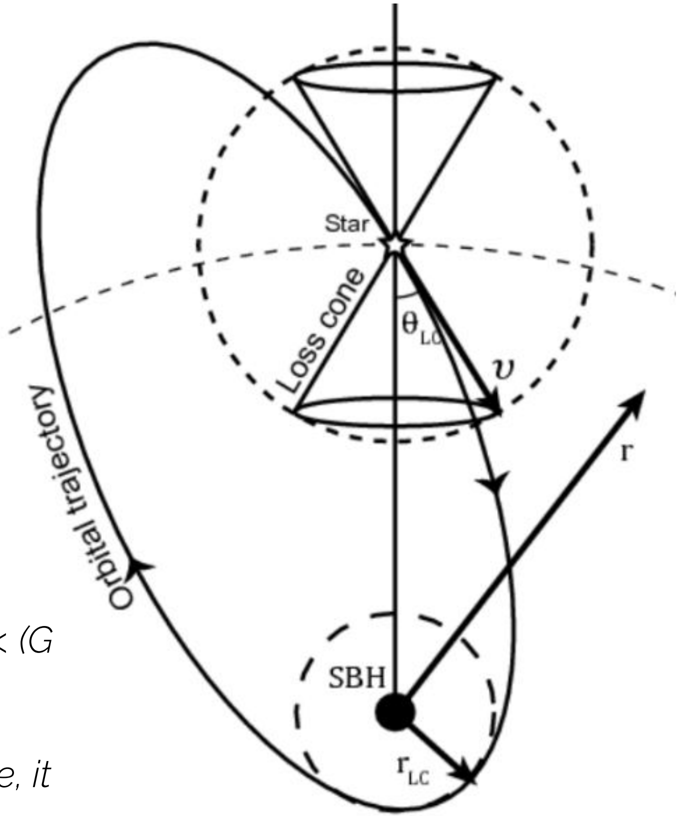
Two-body relaxation between stellar objects slowly perturbs stellar orbits → statistically, at some point, a star can reach a *deadly* orbit and get disrupted

LOSS CONE THEORY to compute TDE rates

Lightman&Shapiro77, Cohn&Kulsrud78

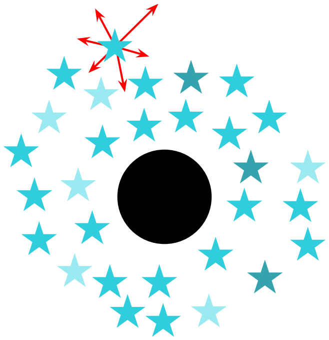
Loss cone = region of phase space containing stars with <u>instantaneous</u> pericentre smaller than r_t – or equivalently $j < (G M_{BH} r_t)^{1/2}$

*If a star <u>reaches the pericentre</u> when its orbit is in the loss cone, it "**disappears**" from the system (eaten by the MBH).*



Predicting TDE rates

Ubiquitous production mechanism: two-body relaxation



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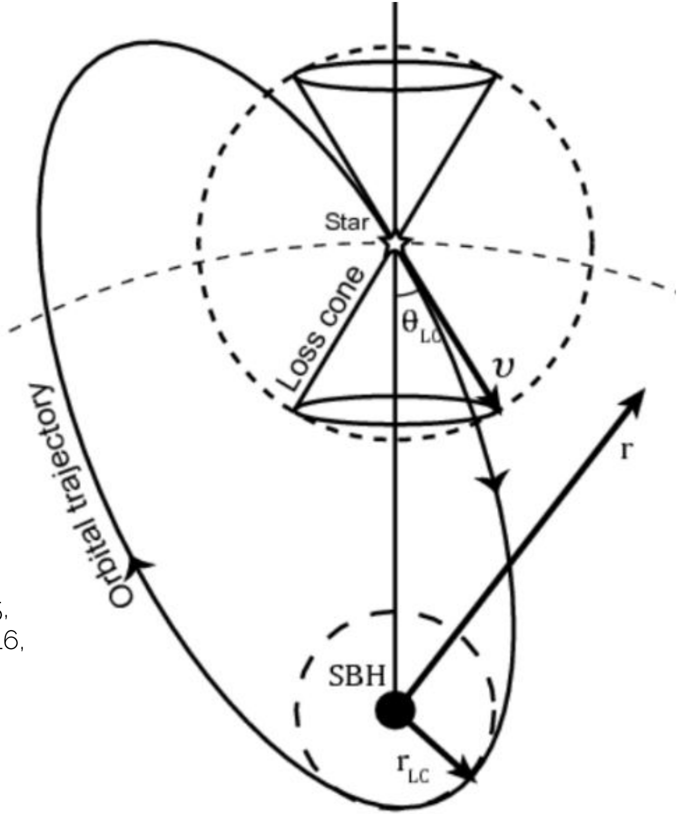


LOSS CONE THEORY to compute TDE rates
Lightman&Shapiro77, Cohn&Kulsrud78

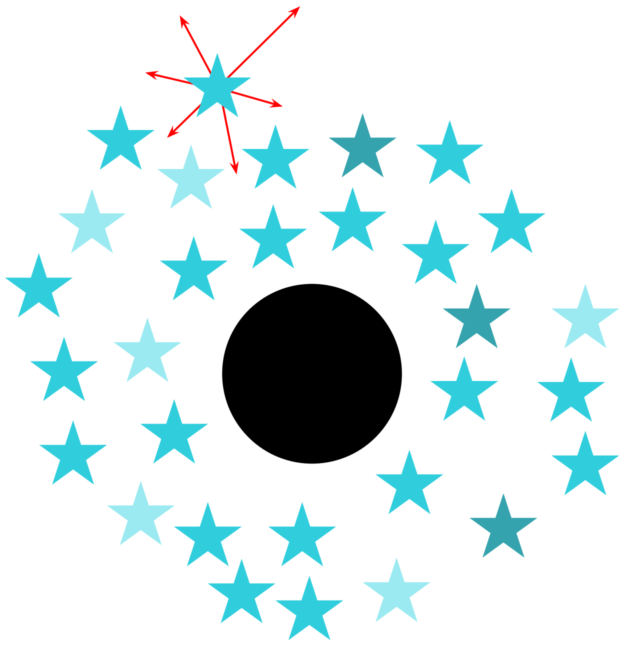
OPEN PROBLEMS:

Predicted TDE rates ~ a few x 10^{-4} /galaxy/year — Wang&Merritt05, Stone&Metzger16, Stone+20

Observed TDE rates ~ 10^{-5} galaxy/year — VanVelzen+18, Yao+23

Estimates on TDE rates suffer from **many simplifications**

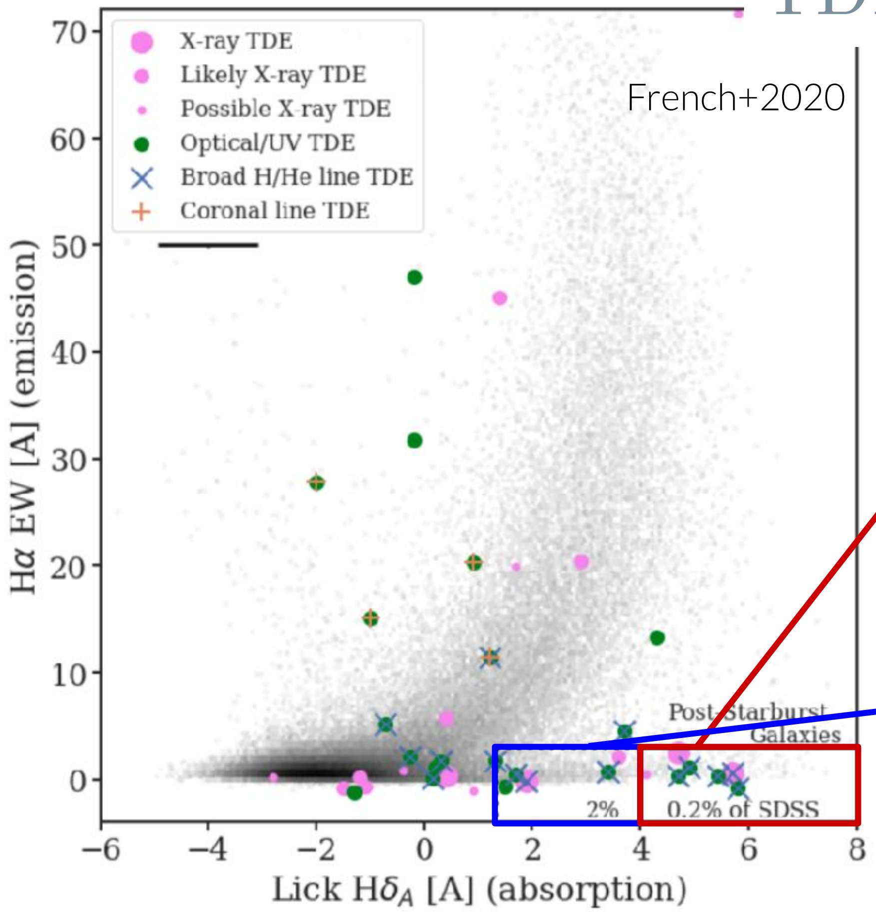
Predicting TDE rates



1. **Stellar mass function**
2. **Time-dependent rates**
3. **Partial vs total disruptions**

A complete stellar mass function (+time dep. rates)

TDEs post-starburst preference



TDEs are more likely to occur in rare galaxies that just forged a large fraction of their stellar mass

–

Overrepresentation: ~20

E+A galaxies: recent starburst (<1 Gyr old) created >3% of their current stellar mass over 25-200 Myr

Overrepresentation:
factor ~20-30
(Law-Smith+17, Hammerstein+21)

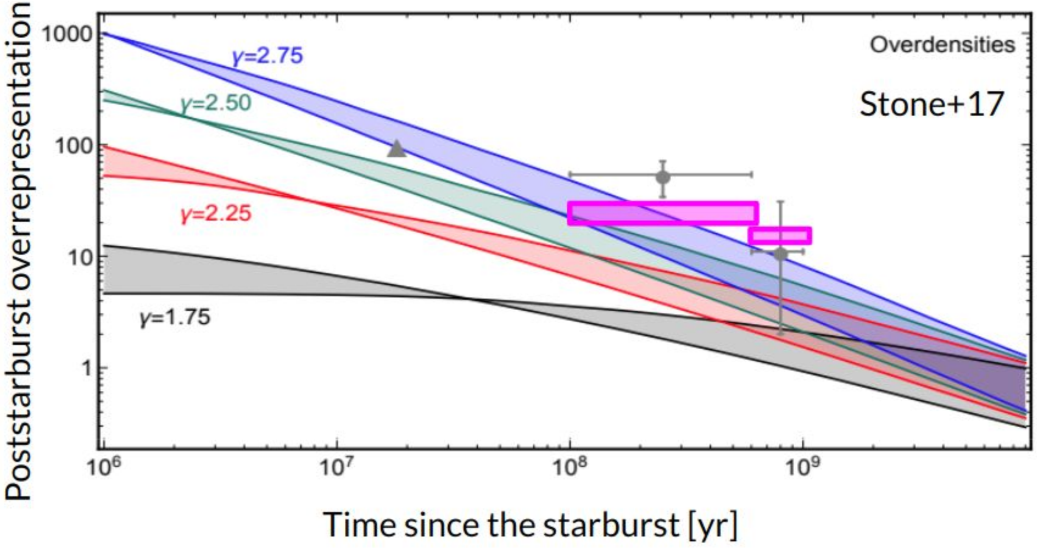
Quiescent Balmer-strong galaxies: recent starburst (<1 Gyr old) created >0.1% of their current stellar mass over 25-1000 Myr

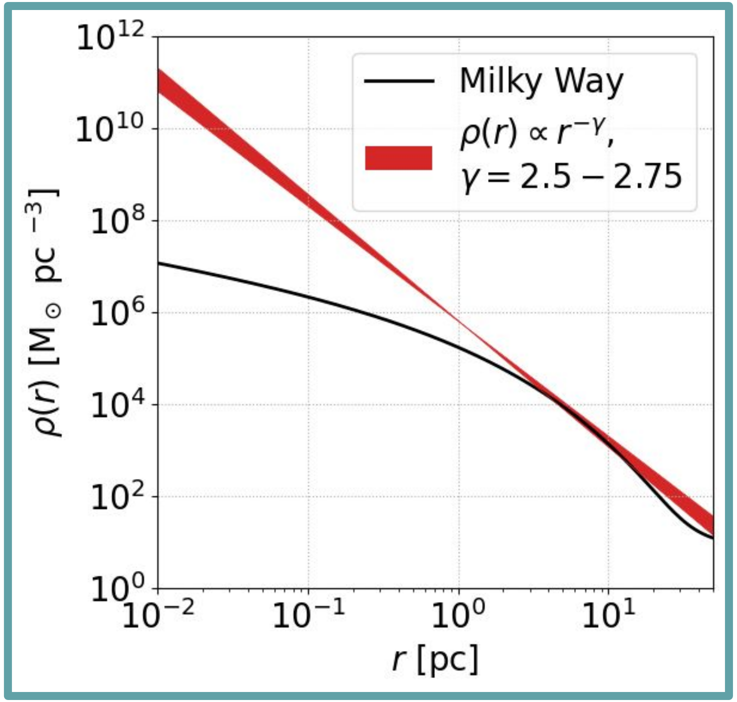
Overrepresentation:
Factor ~15-17
(French+16, Graur+18, Hammerstein+21)

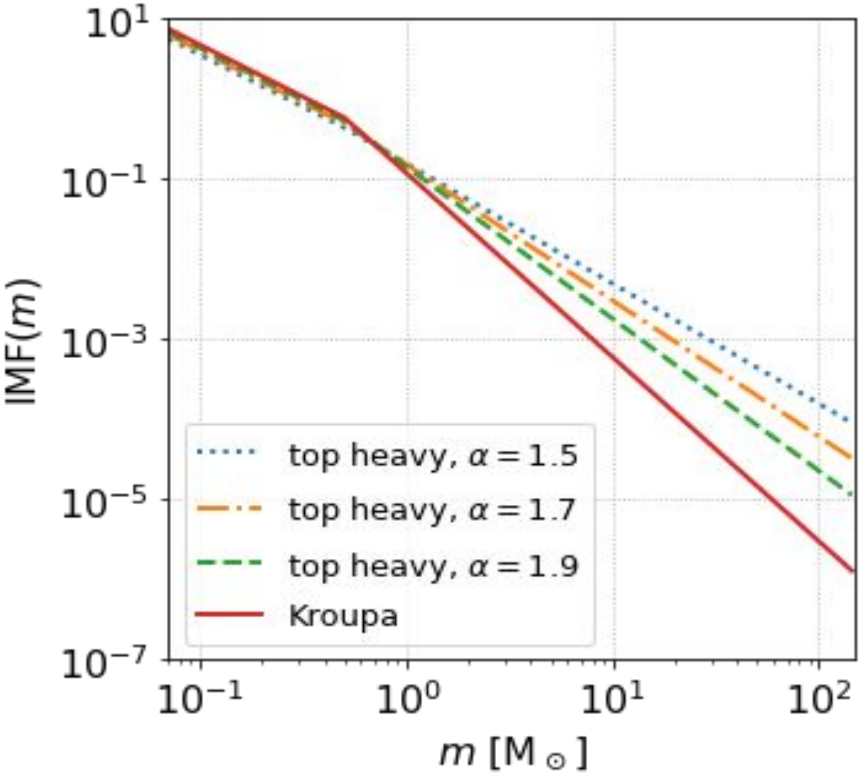
An explanation for the post-starburst preference

If starbursting galaxies yield very large central stellar densities *the poststarburst preference can be explained*

(Stone+17)







Monochromatic *vs* complete stellar mass function

Almost all TDE rate estimates assume the system to be composed by 1 Mo, 1 Ro stars but galaxies feature broad mass functions that evolve with time

→

Considering a non-monochromatic mass function can substantially affect the time evolution of TDE rates!

- **Relaxation effects (→ TDE rates) depend on <m²>**, that can be much larger than 1 M☉ for a young population (Merritt2013)

$$\langle m^2 \rangle = \int_{m_{\rm min}}^{m_{\rm max}} {\rm IMF}(m)\, m^2(t)\, dm$$

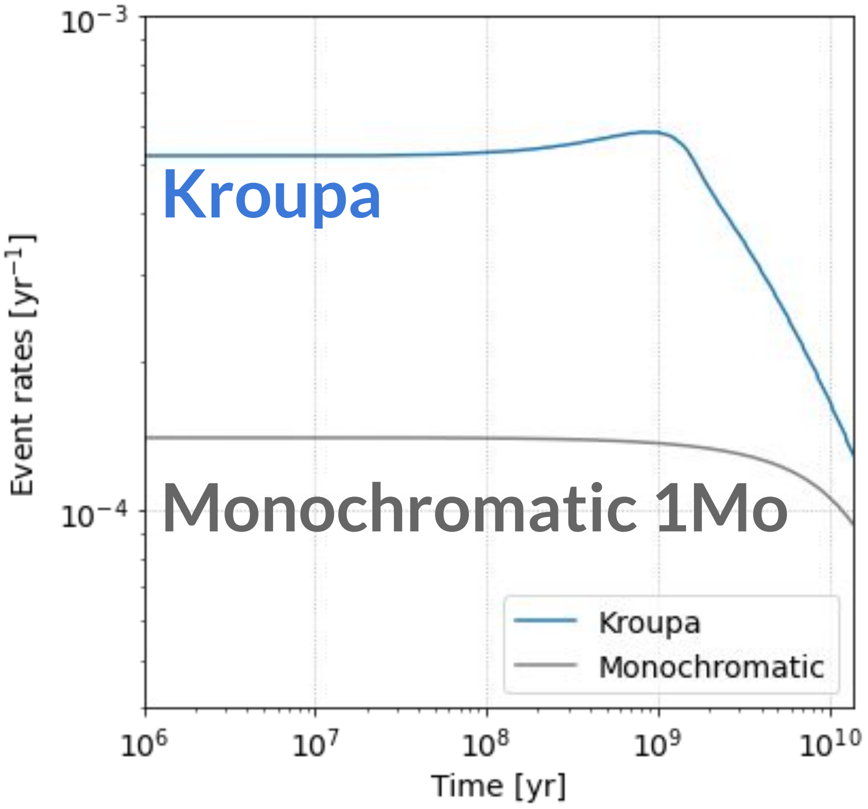
- **Heavy stellar objects undergo mass segregation**

$$t_{\rm mass\ segr.} \approx \frac{0.0814 v_{\rm rms}^3}{G^2 \tilde{m}_\star \rho_\star \ln \Lambda}$$

- **Starbursting galaxies might have top-heavy initial mass functions** (Zhang+2018, Lu+13)

The time evolution of TDE rates

Evolved with the Fokker-Plank 1-D code ***Phaseflow*** (Vasiliev17)



Bortolas 2022, MNRAS 511, 2885

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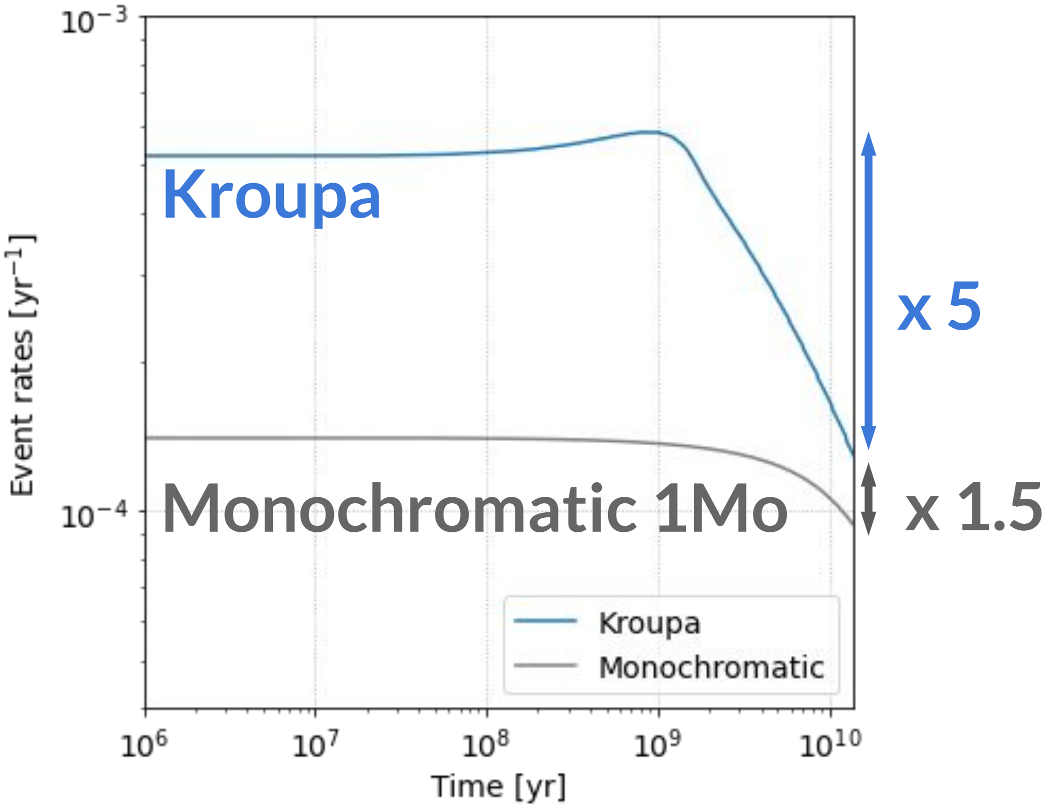


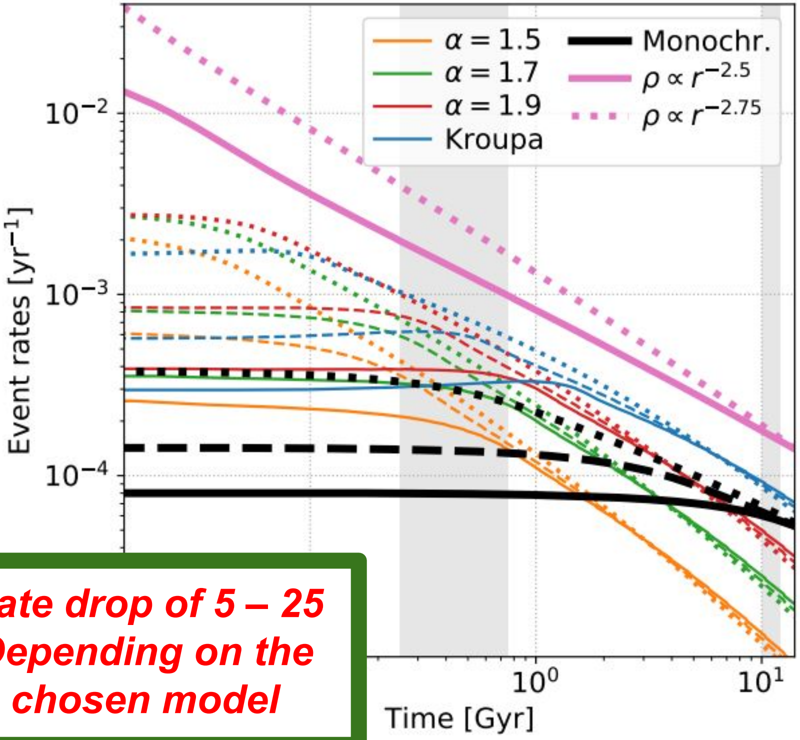
Caveat: forget about the normalization of the curves, focus on rate drops!

Bortolas 2022, MNRAS 511, 2885

Varying the NSC compactness and IMF

Evolved with the Fokker-Plank 1-D code ***Phaseflow*** (Vasiliev17)

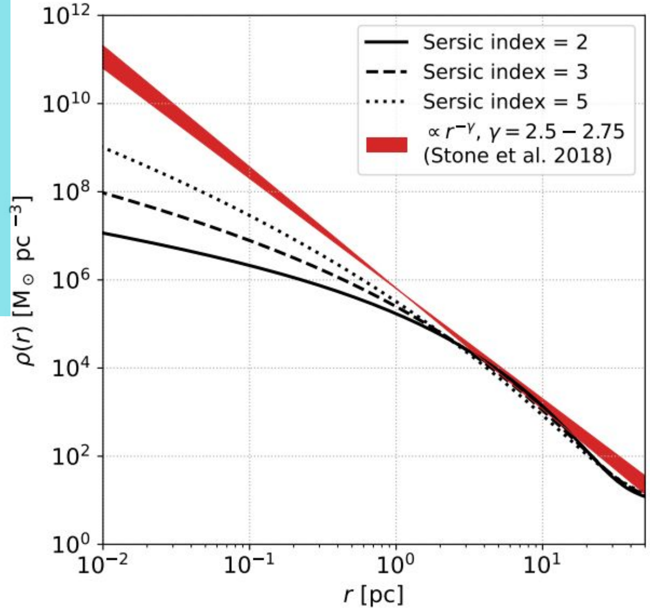
The post-starburst preference can be explained considering rate drops if the IMF is not monochromatic



Rate drop of 5 – 25 Depending on the chosen model

More concentrated systems and more top-heavy IMFs yield even more dramatic rate drops

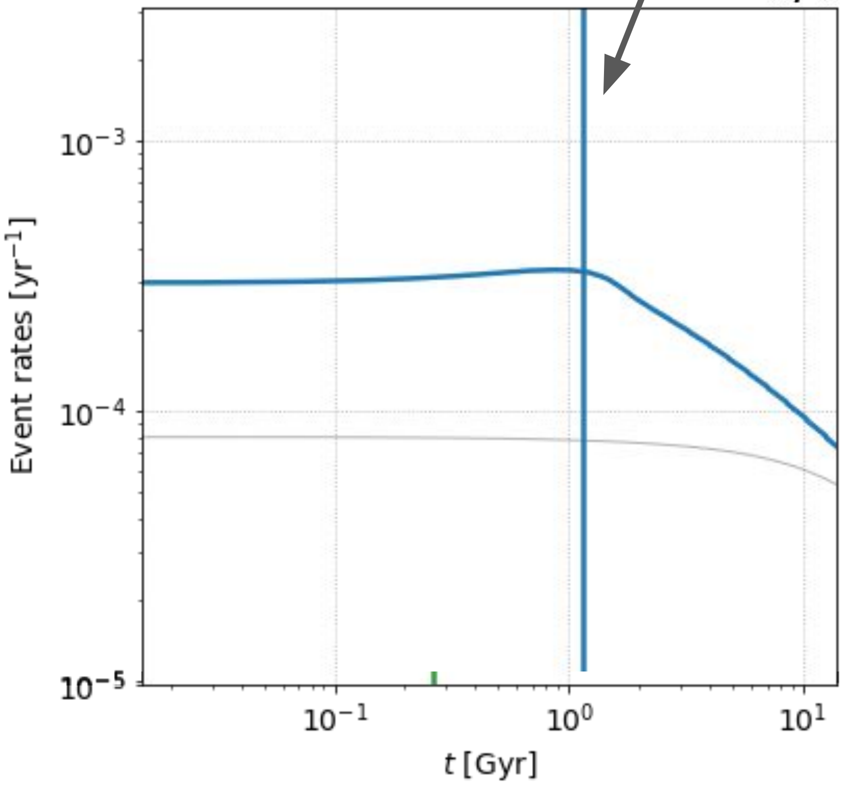
Rate drop in the equivalent ultrasteep cusp proposed by Stone+ is about 8 – 14



Bortolas 2022, MNRAS 511, 2885

Interpretation

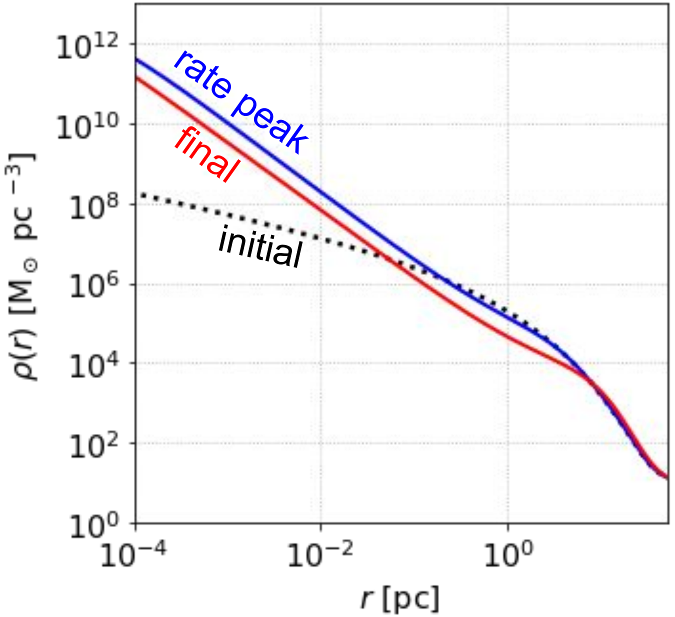
$$t_{\text{mass segr.}} \approx \frac{0.0814 v_{\text{rms}}^3}{G^2 \tilde{m}_\star \rho_\star \ln \Lambda}$$



It is an outcome of two-body relaxation!

Mass segregation and the related efficient relaxation **is the drivers for the initial TDE burst**

At later times, **the system expands in time** → rate drop



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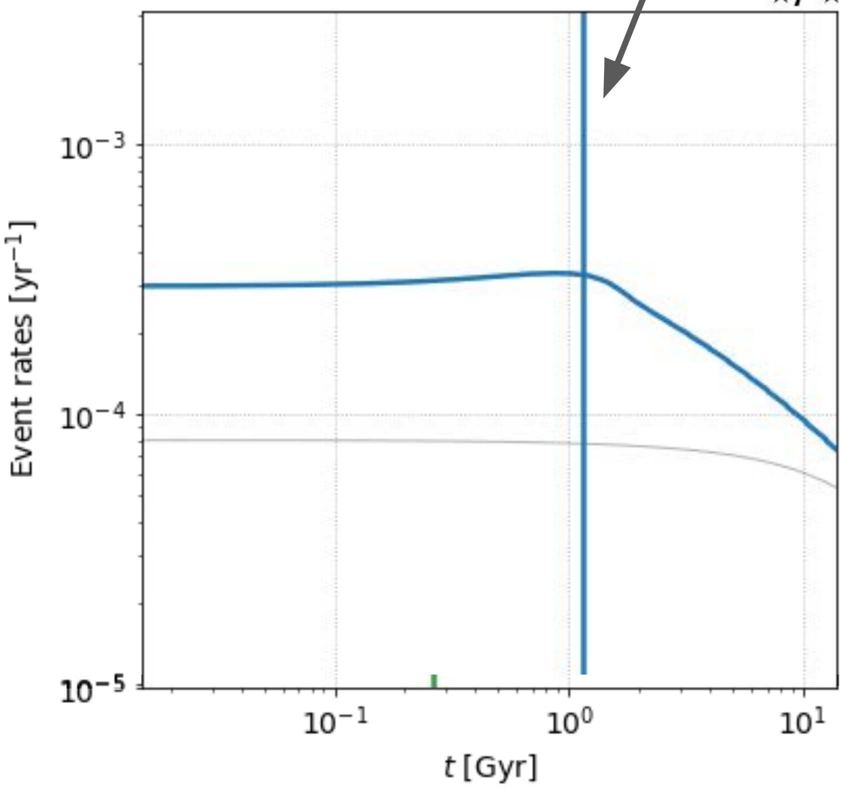

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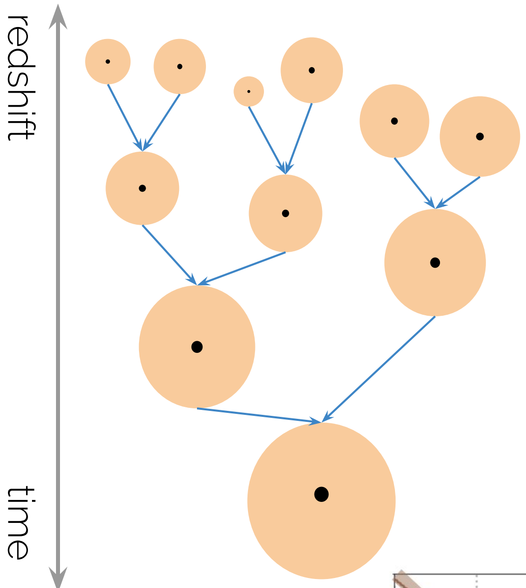
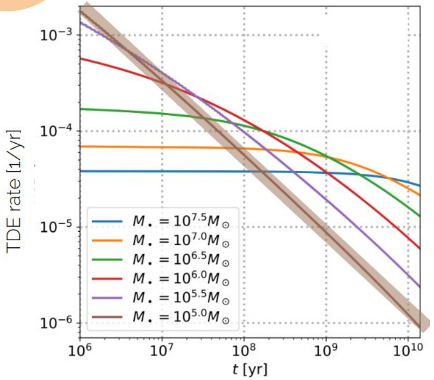
Important considerations:

1. **When does the clock for the "TDE burst" start?** Every time there is an event violent enough to completely reshuffle the stellar distribution in the center (**star formation burst, galaxy merger**, infall of stellar cluster…)
2. **The fact that stars slowly evolve** and become white dwarfs, neutron stars, black holes **has a negligible impact on the drop of TDE rates!**
3. One does not need a complete IMF to recover the rate drop. Already **including stellar BHs does most of the job.**

Preliminary work with a semi-analytical model

Semianalytical model (gal. evolution) to estimate TDE rates

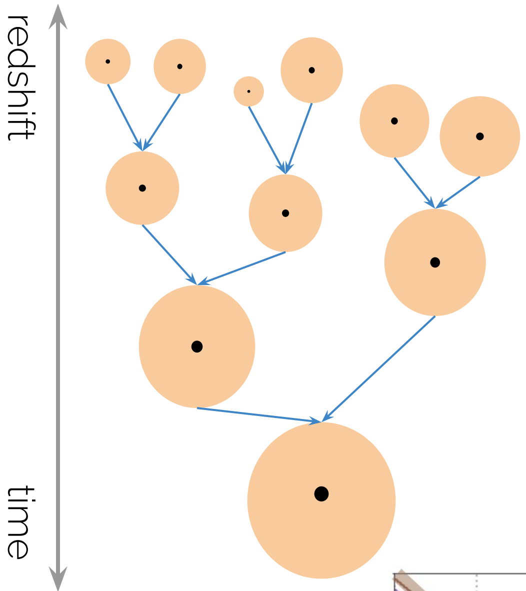


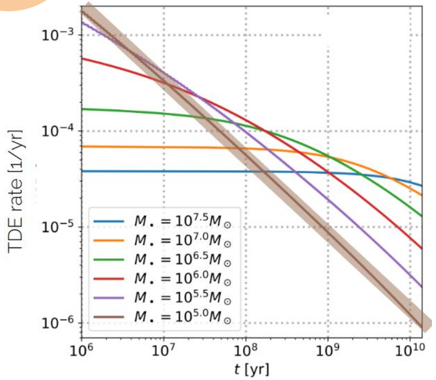


L-galaxies SAM [Henriques+15]

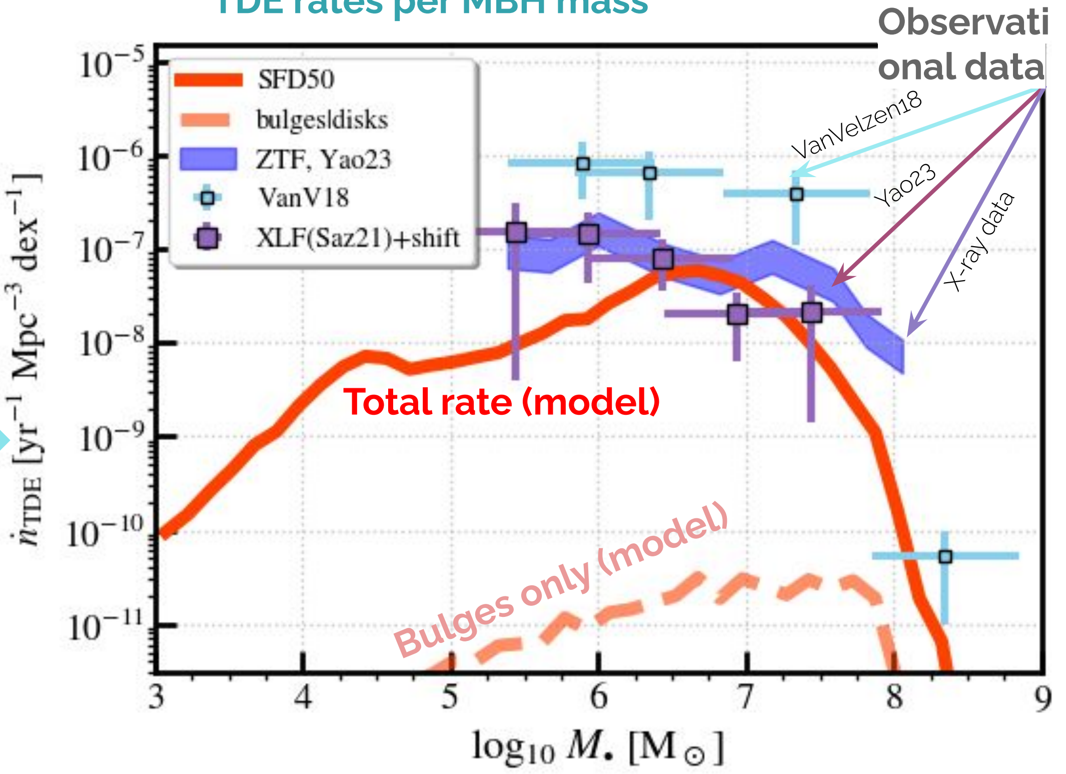
Semianalytical model (gal. evolution) to estimate TDE rates

Polkas+, in prep





TDE rates per MBH mass



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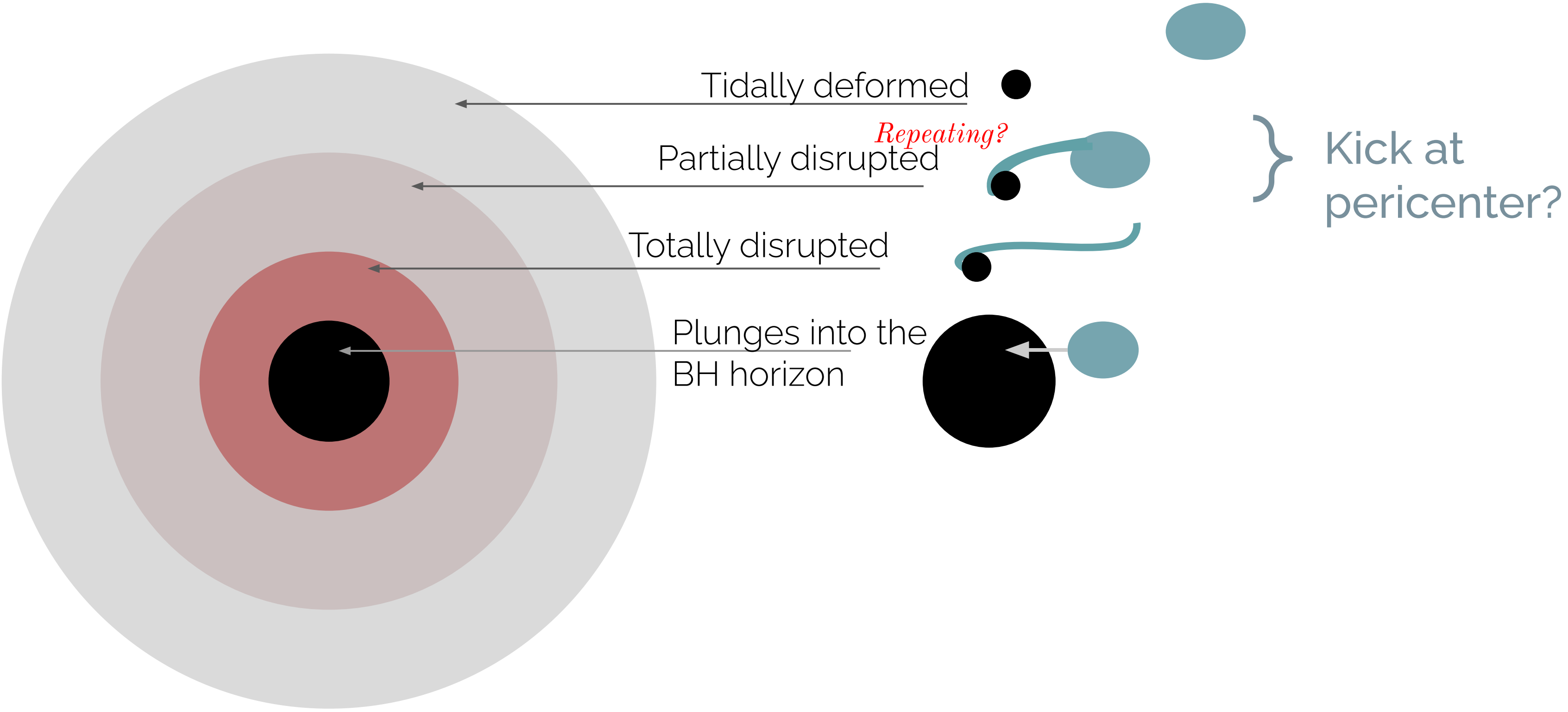
Partial tidal disruption events

Partial *vs* total tidal disruption events

Stars getting close to, but not crossing the tidal disruption radius can get ***partially disrupted***

What is the largest pericentre passage that guarantees a partial disruption?



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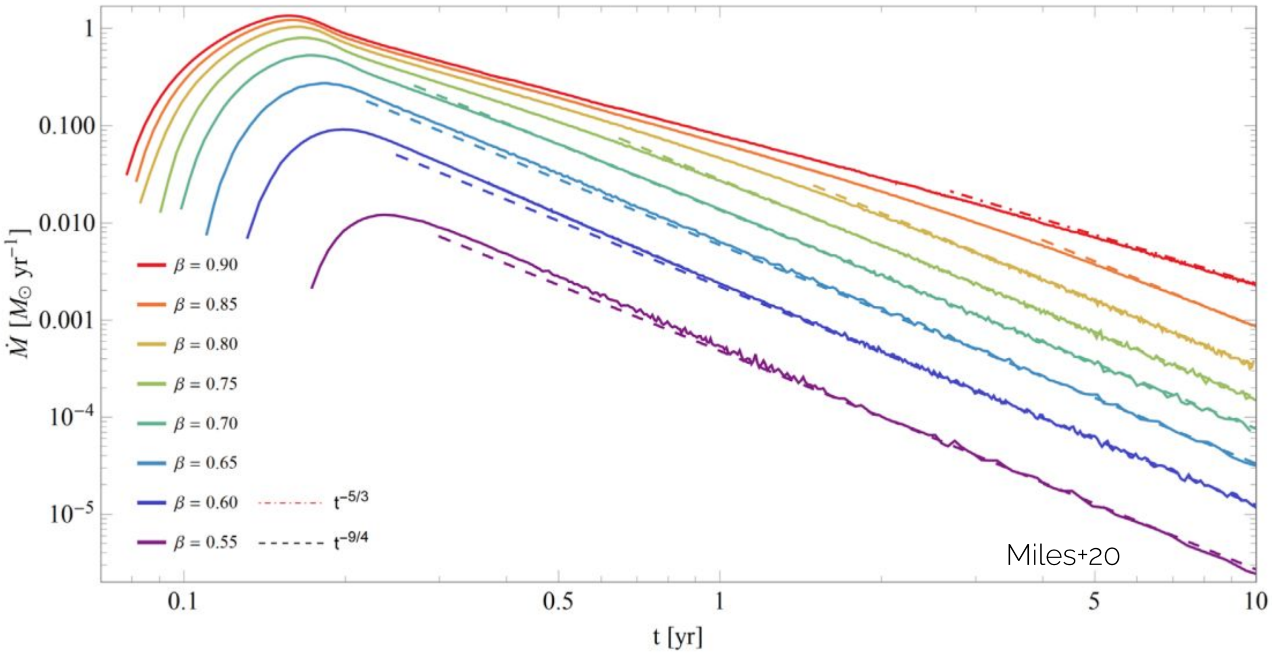


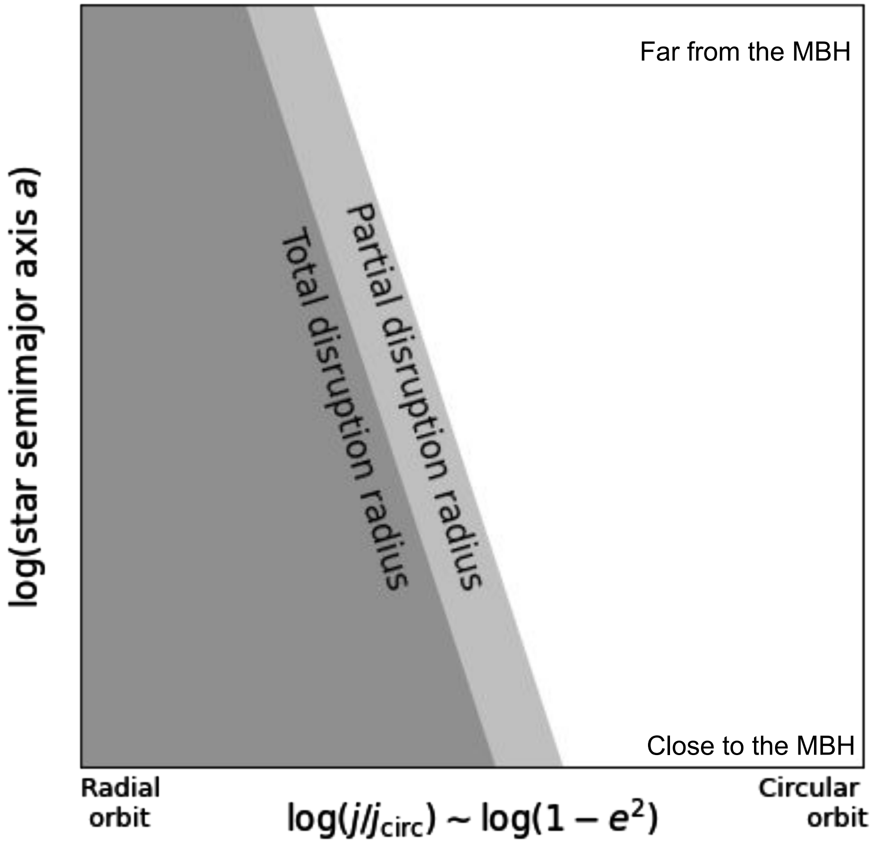
Less mass available for disruption
→ **less luminous flares**

The characteristic light-curve of partial disruptions declines as $t^{-9/4}$ at late times (Coughlin&Nixon19)

Relatively little literature work focussing on partial tidal disruption event ***rates***!

A few candidates *(Payne+21, Liu+23, Wevers+23)*

Towards a new definition of loss cone



Bortolas+23

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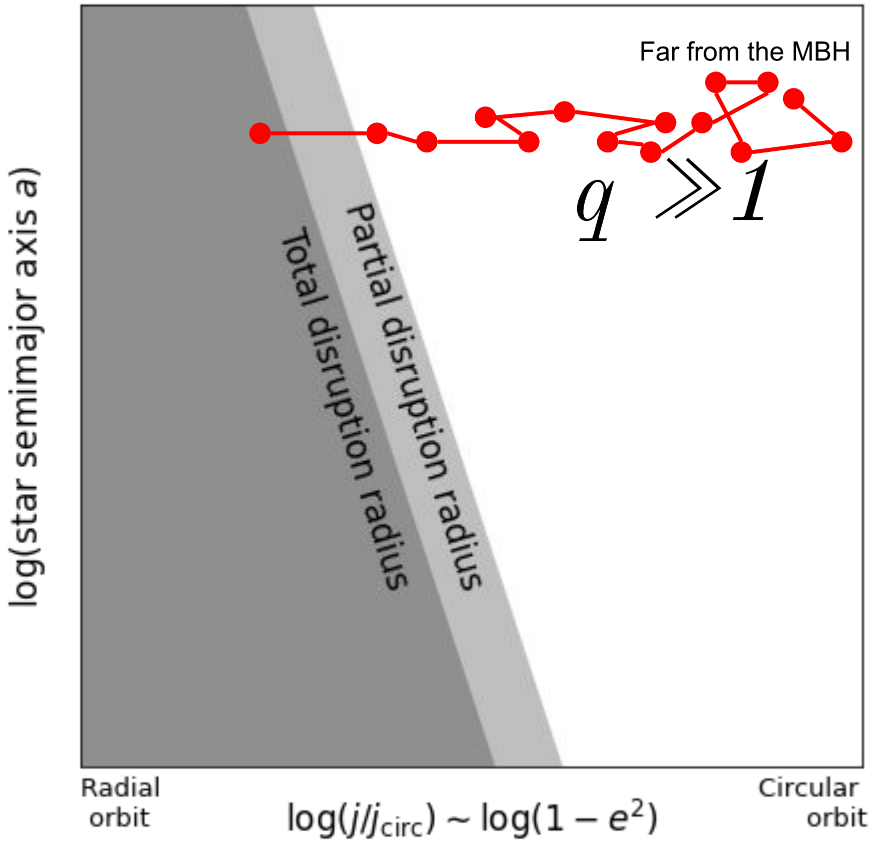


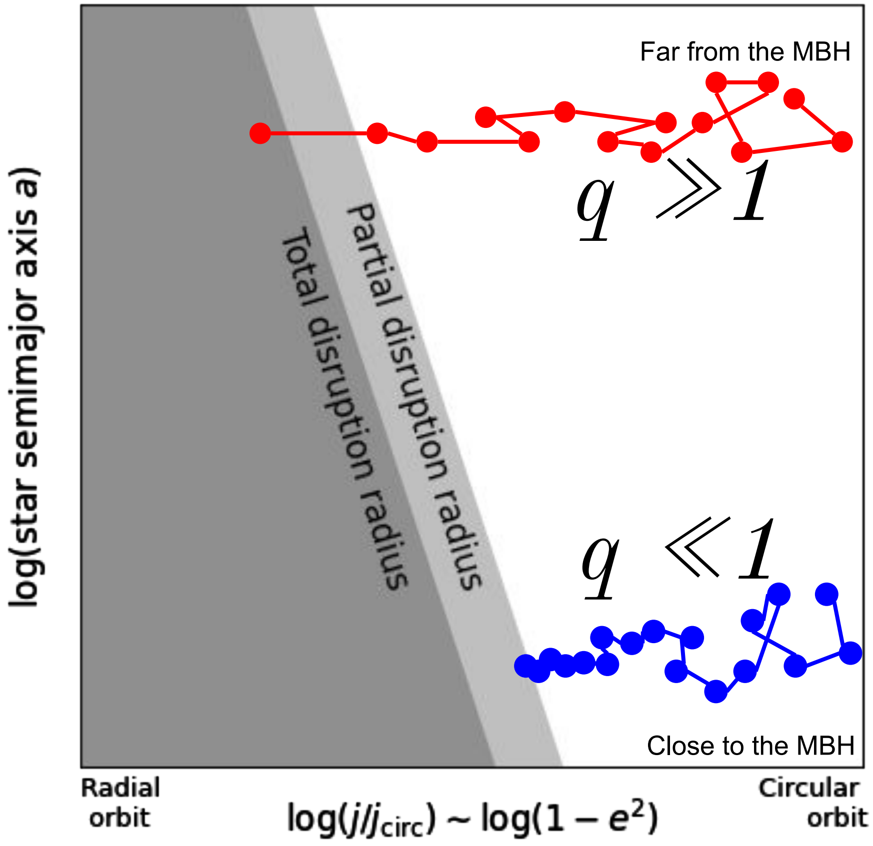
Very eccentric orbits: easily deflected *out of the loss cone*

Here partial disruptions cannot repeat

$$q = \frac{\textit{orbital time}}{\textit{relaxation time for an orbit near the loss cone}}$$

Bortolas+23

Towards a new definition of loss cone



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Less eccentric orbits: relaxation is inefficient within an orbital period

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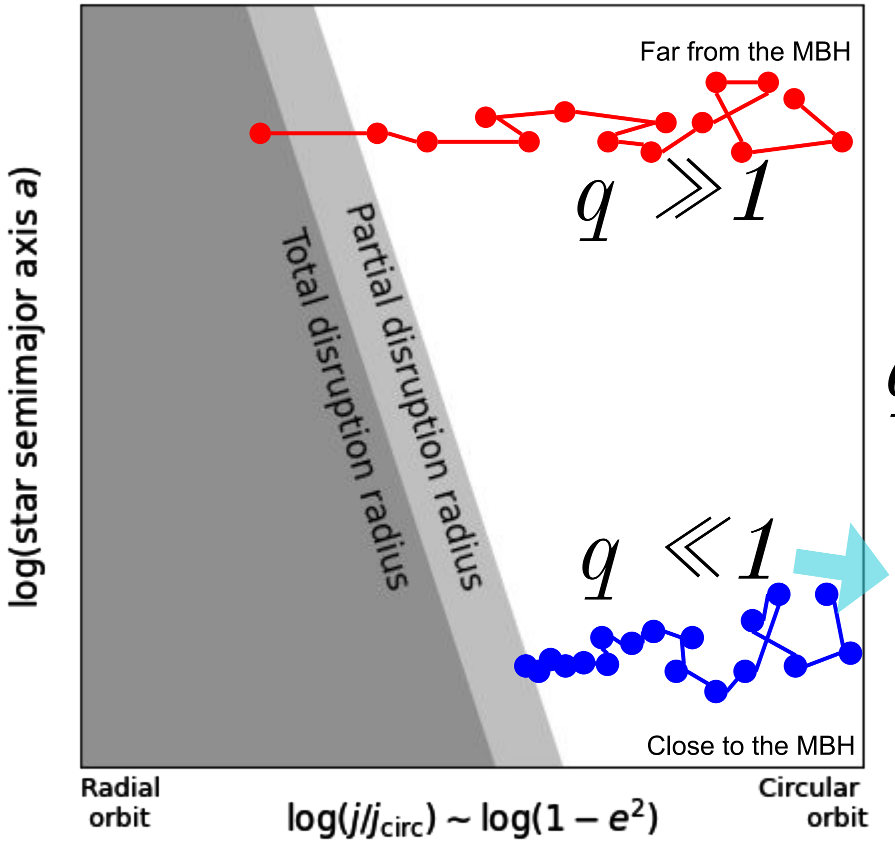
A new definition of loss cone



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Less eccentric orbits: relaxation is inefficient within an orbital period

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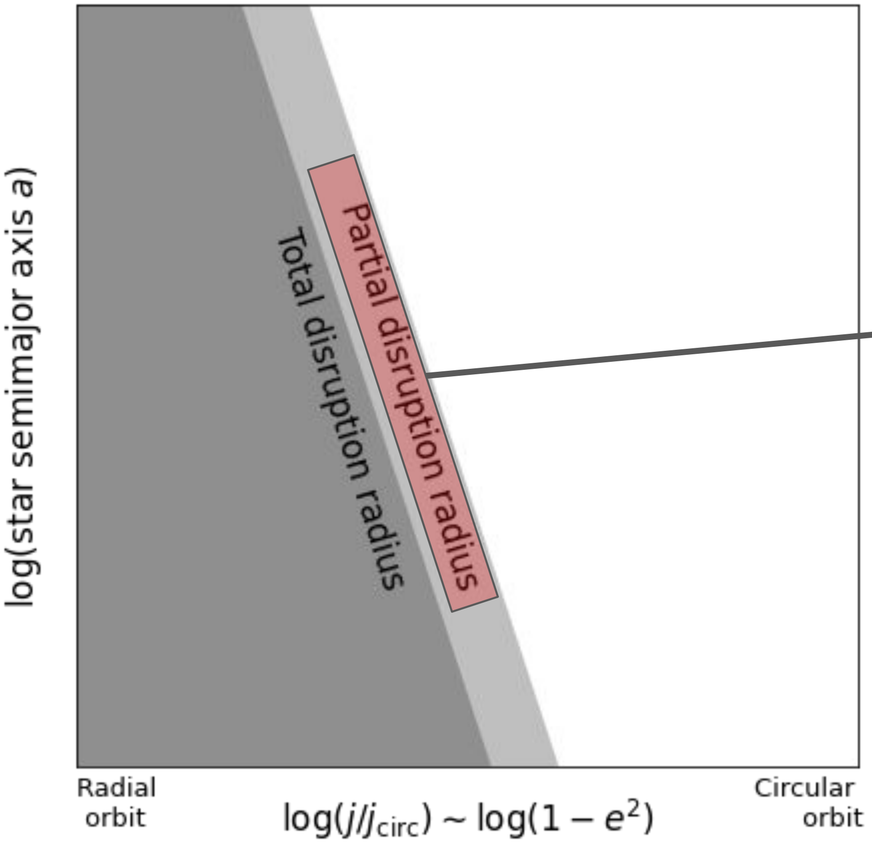
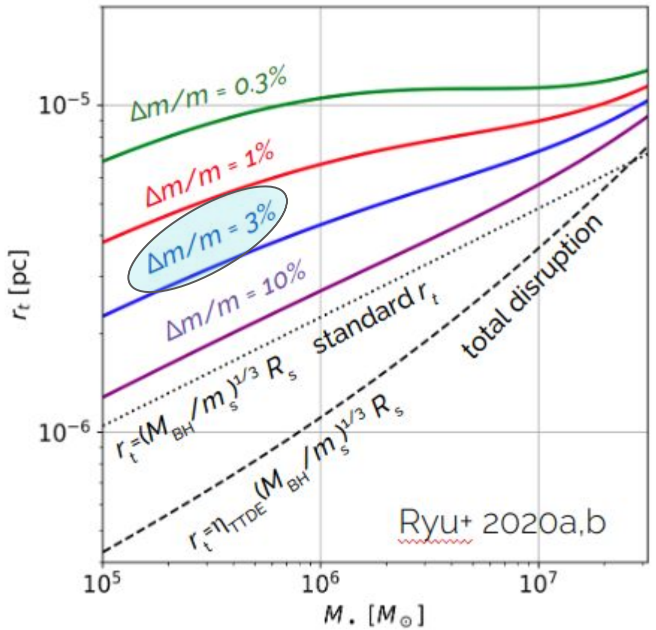
IN THIS LIMIT, ALL THE FIRST TDES EXPERIENCED BY A STAR ARE PARTIAL!

Bortolas+23

What is the *partial* tidal disruption radius?

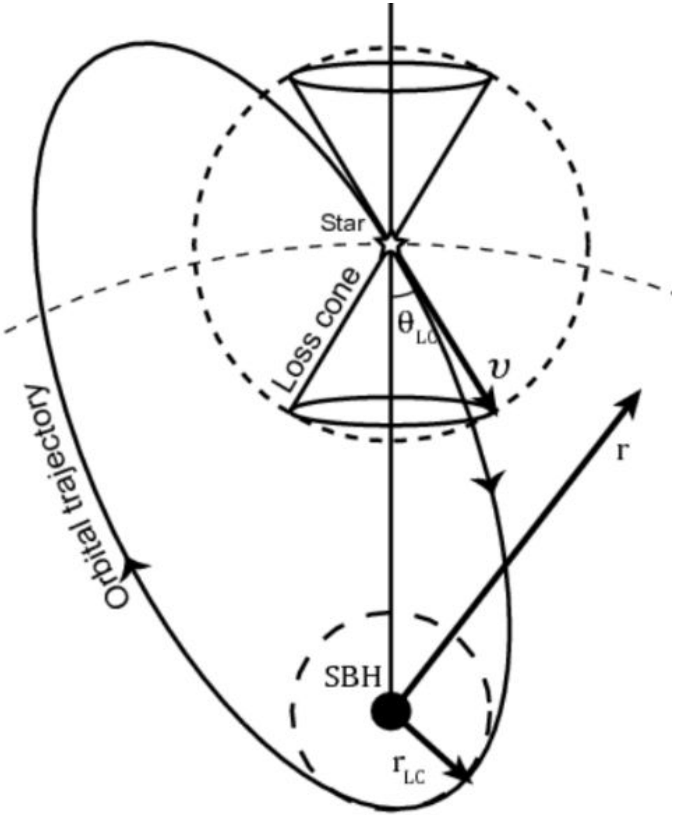




Fits to the GRMHD simulations by Ryu+20a,b

Bortolas+23

Redefining the loss cone in the realm of partial TDEs



LOSS CONE THEORY to compute TDE rates

Loss cone = region of phase space containing stars with instantaneous pericentre smaller than r_t – or equivalently $j < (G M_{BH} r_t)^{1/2}$

*If a star reaches the pericentre when its orbit is in the loss cone, it "**disappears**" from the system (eaten by the MBH).*

The loss cone should be defined as the maximum radius that guarantees a partial disruption

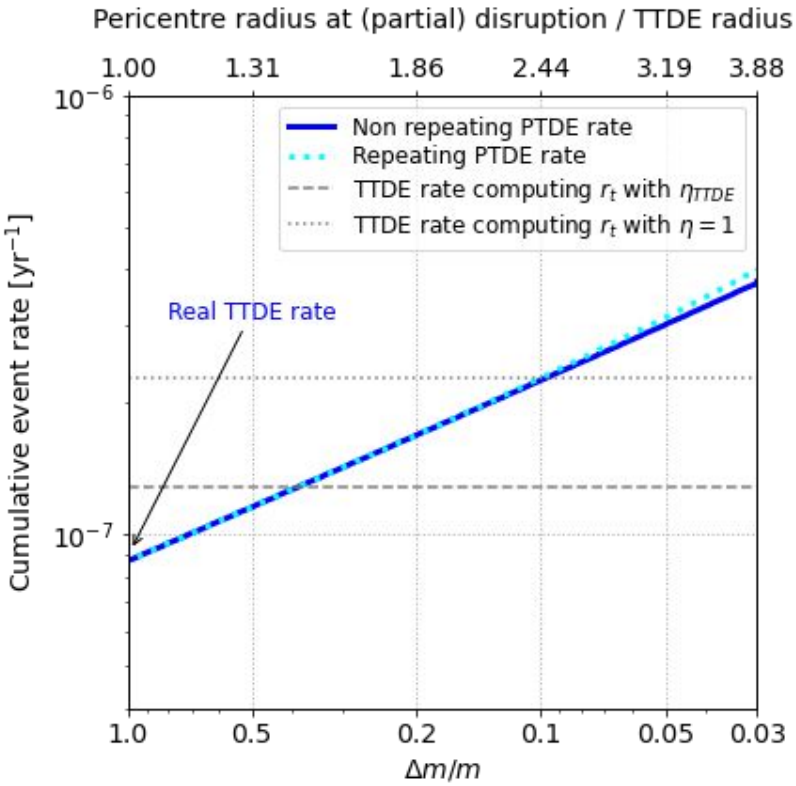
What happens after a partial TDE?

- The star receives a kick and gets far from the loss cone
- The star undergoes a series of events and eventually gets entirely consumed by the MBH

→ ***either way, the star is "lost"***

Bortolas+, 23

A stellar system dominated by the full loss cone (bulge only)



$$q \gg 1$$

MBH of 10^6 Msun

Most of the events come from $q \gg 1$

Little repeating partial disruptions

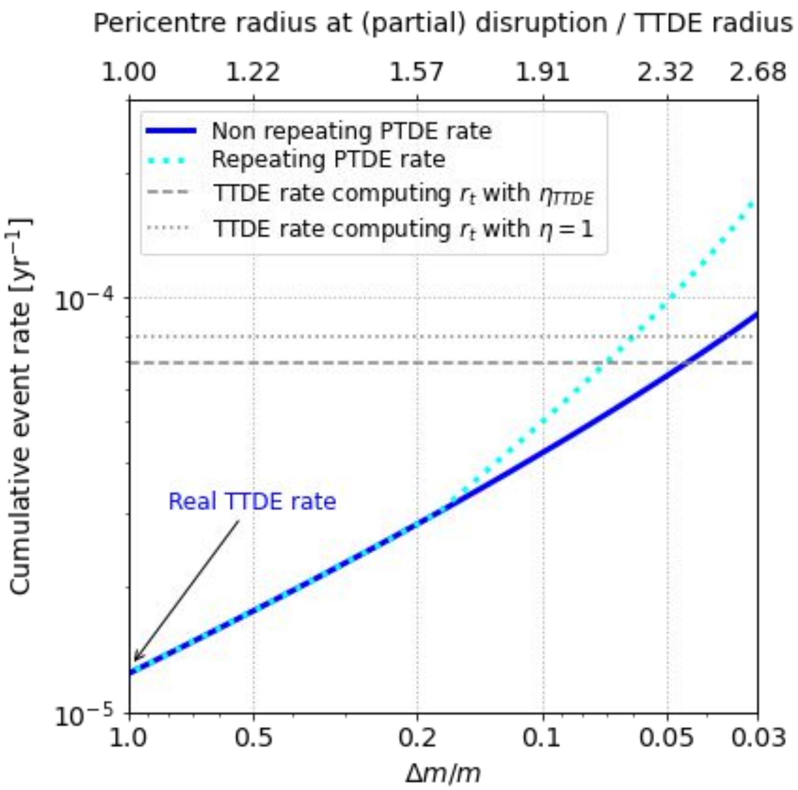
Standard estimates of total TDE rates remain reasonable

Partial TDEs rates are about 50 times more abundant than total TDEs

Results obtained usign the 1-D Fokker-Planck integrator Phaseflow (Vasiliev15)

Bortolas+ 23

Results: a Milky-Way-like nucleus



$$q \ll 1$$

Milky-way like galaxy with a high central density (**features a nuclear star cluster**)

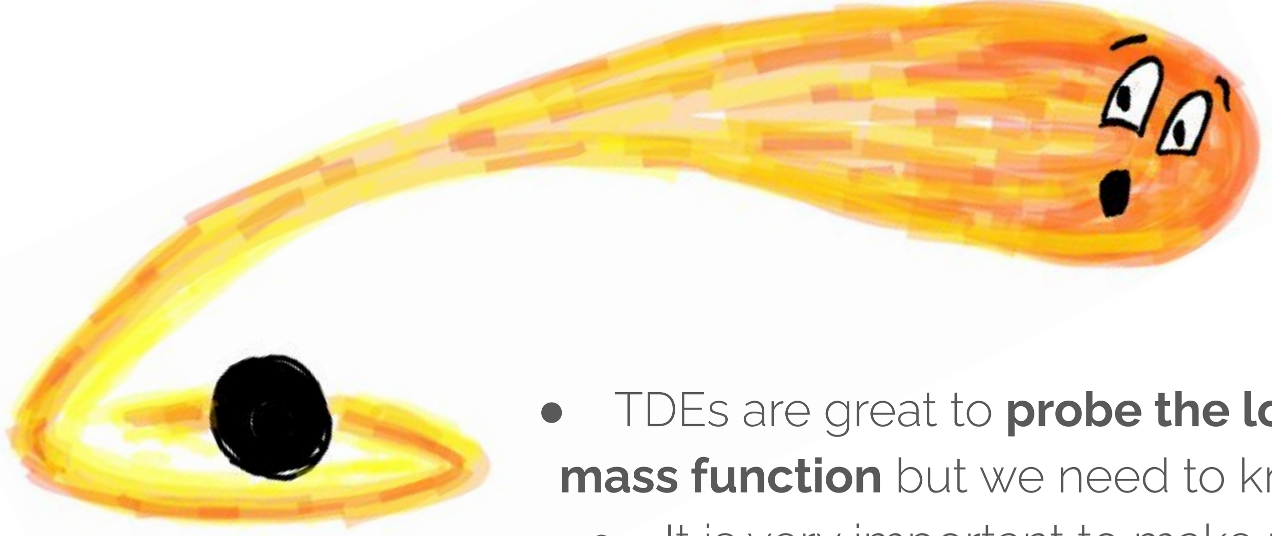
Most of the events come from $q \ll 1$

Many repeating partial disruptions (x2)

<u>Standard rates of total TDE rates are severely overestimated</u> (by ~ 1 order of magnitude)

Partial TDEs rates are about 10-20 times more abundant than total TDEs

Bortolas+23



Conclusions

- TDEs are great to **probe the low-mass end of the MBH mass function** but we need to know well their event rates!
- It is very important to make use of **a time-dependent estimate of TDE rates** to recover the observed event rates

- It is fundamental to consider **stellar populations are not monochromatic** to explain the post-starburst preference of TDEs
- **Partial stellar tidal disruption events** can be very common events (although hard to observe!) and significantly **affect the rates of total TDEs**