Ministero dell'Università e della Ricerca
Università di Trento
Università degli Studi di Milano Bicocca
PhD SST Space Science and Technology
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Cliffhanger EMRIs

local two-body relaxation and post-Newtonian dynamics

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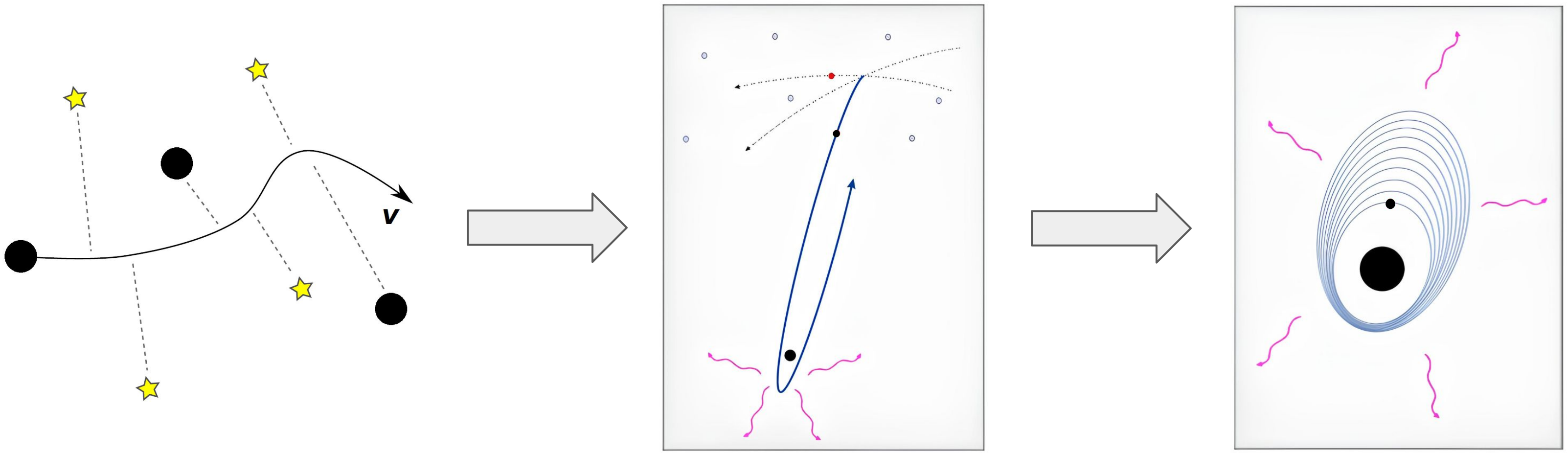
EMRIs and two-body relaxation

- In **nuclear stellar clusters**, compact objects can be scattered onto **tight and eccentric orbits** around the central massive black hole (MBH) via **two-body interactions**

two-body relaxation — GWs emitted at pericentre — slow inspiral

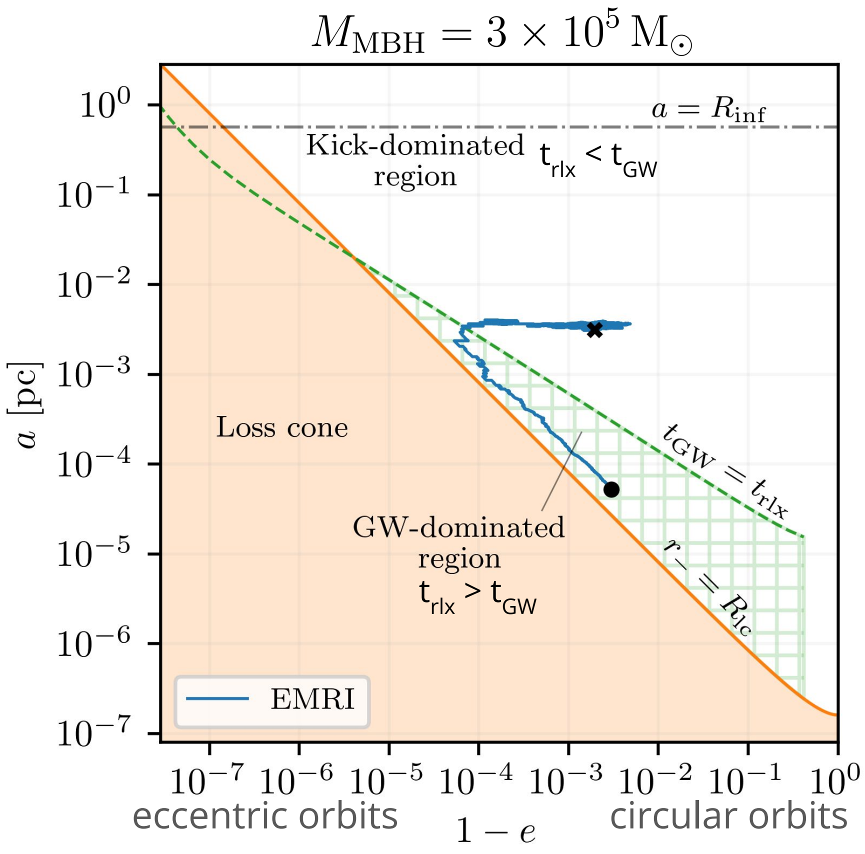


L. Barack

EMRIs and two-body relaxation

t_{GW} time needed for **GWs** to significantly change the orbital elements

t_{rlx} time needed for **two-body relaxation** to significantly change the orbital elements



DM+ 2024, submitted

EMRIs and two-body relaxation

t_{GW} time needed for **GWs** to significantly change the orbital elements

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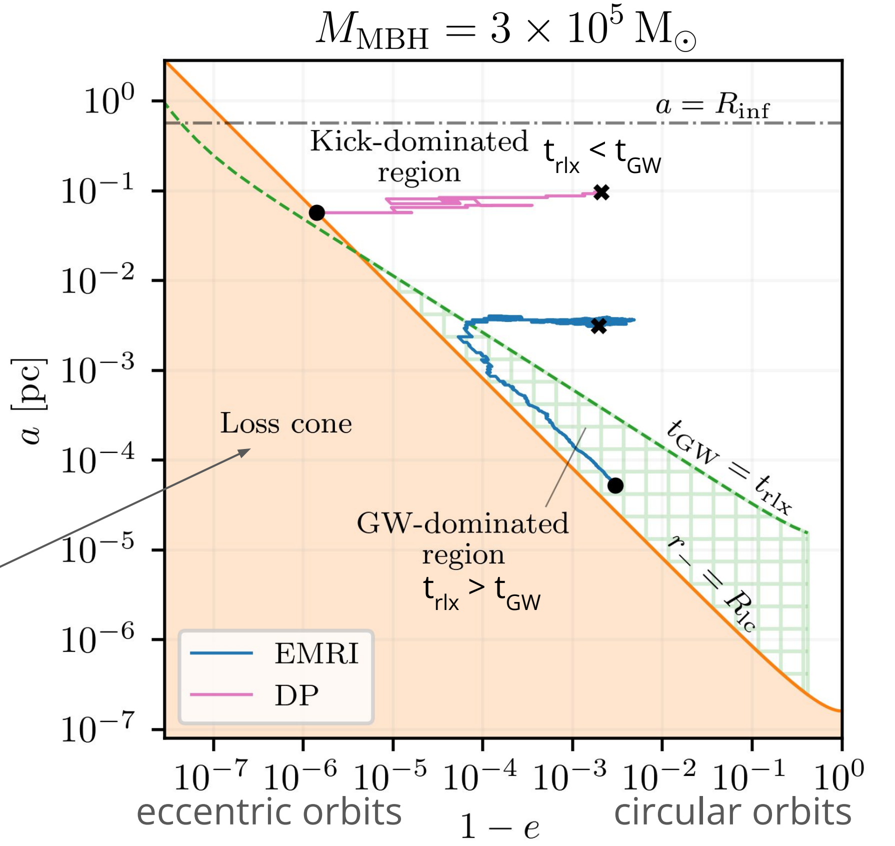
Direct plunges (DPs)



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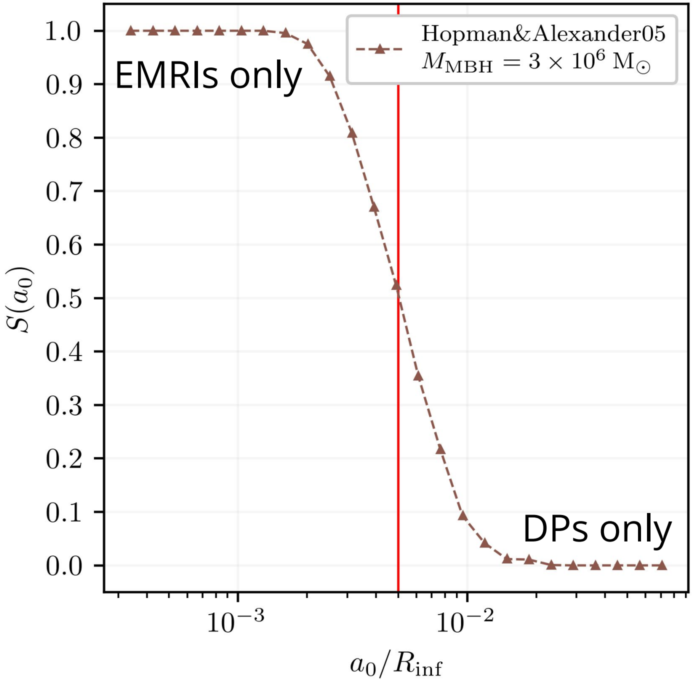
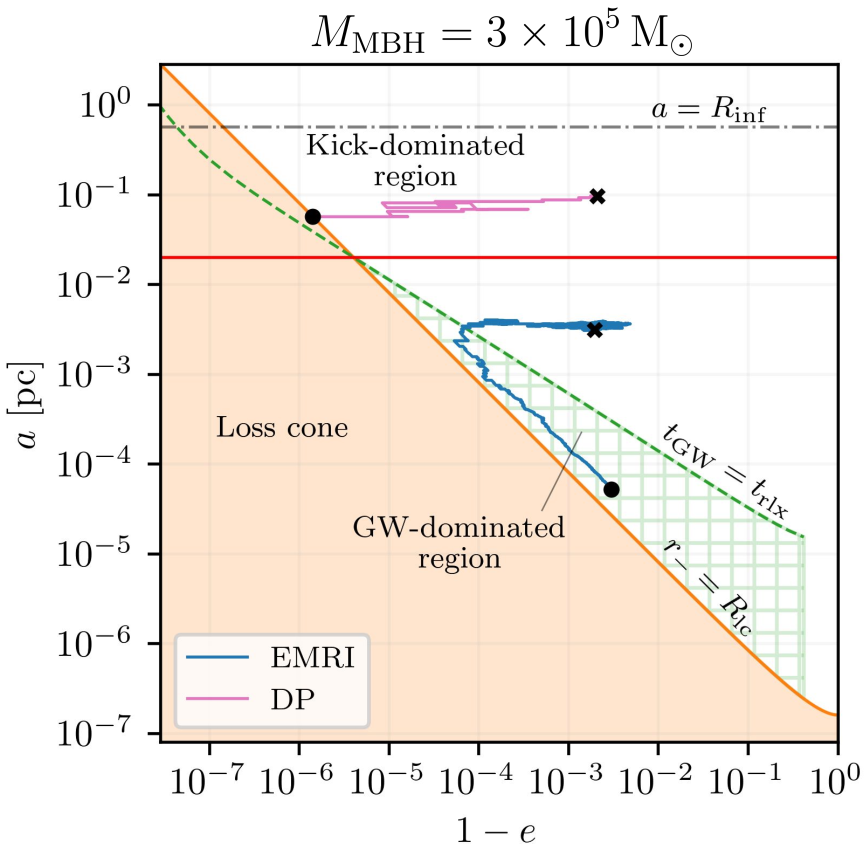
EMRI-to-plunge ratio

$$S(a_0) = \frac{N_{\rm EMRI}(a_0)}{N_{\rm EMRI}(a_0) + N_{\rm DP}(a_0)}$$





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Cliffhanger EMRIs

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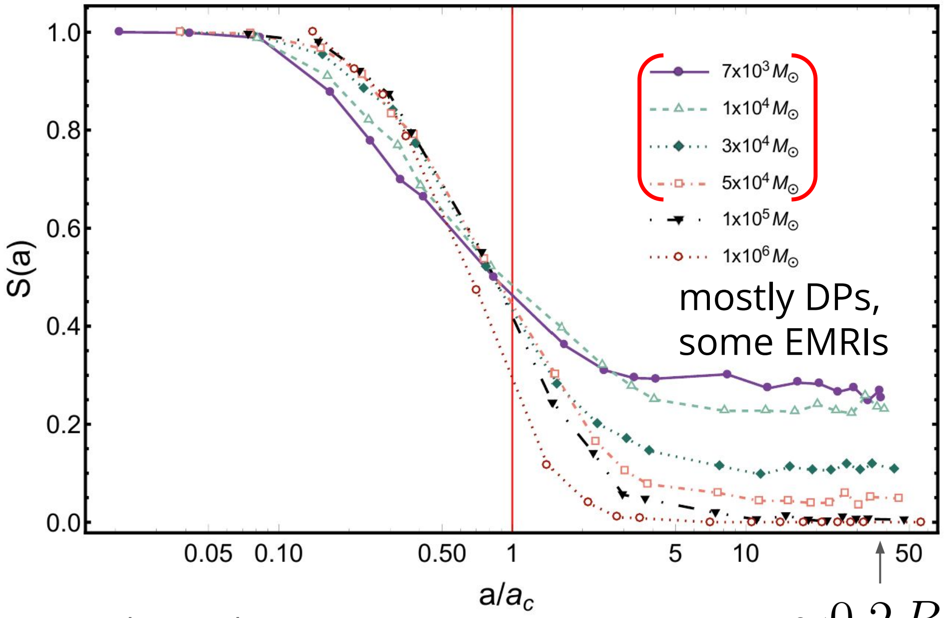
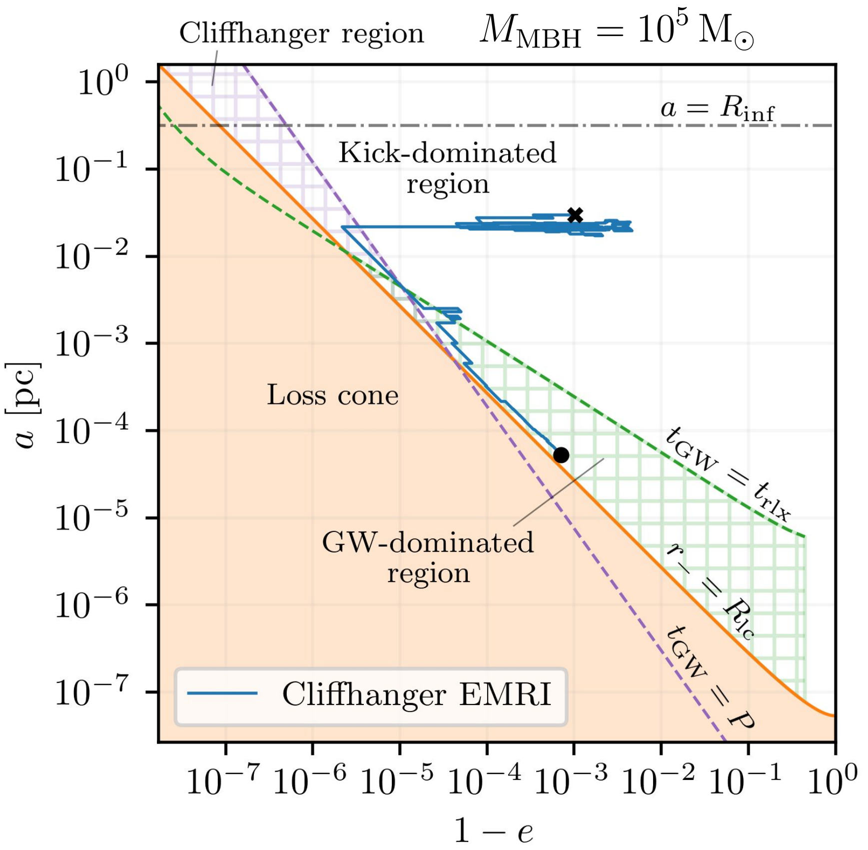


$\sim 0.2\, R_{\rm inf}$

Qunbar and Stone, 2024



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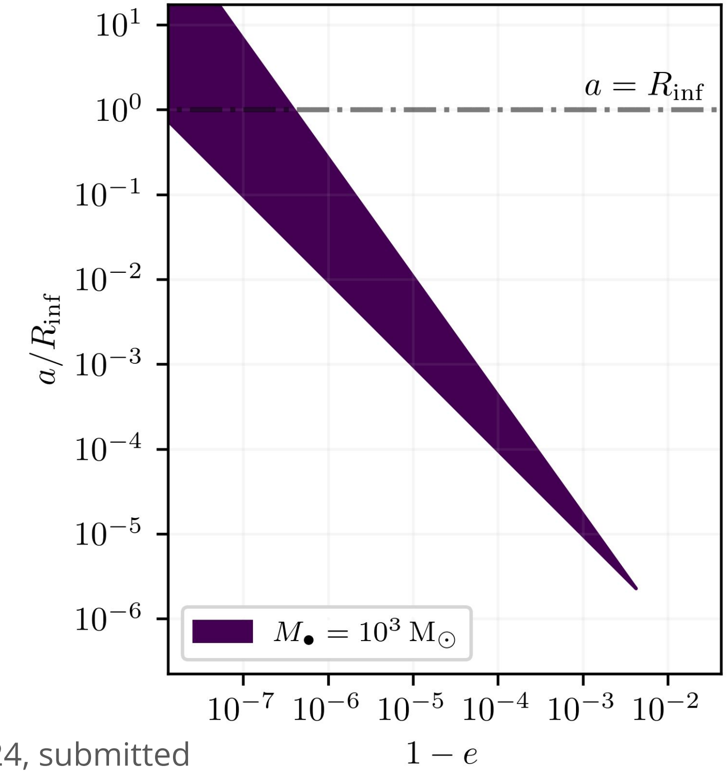
Cliffhanger EMRIs

On the purple line, the semi-major axis is halved in a period



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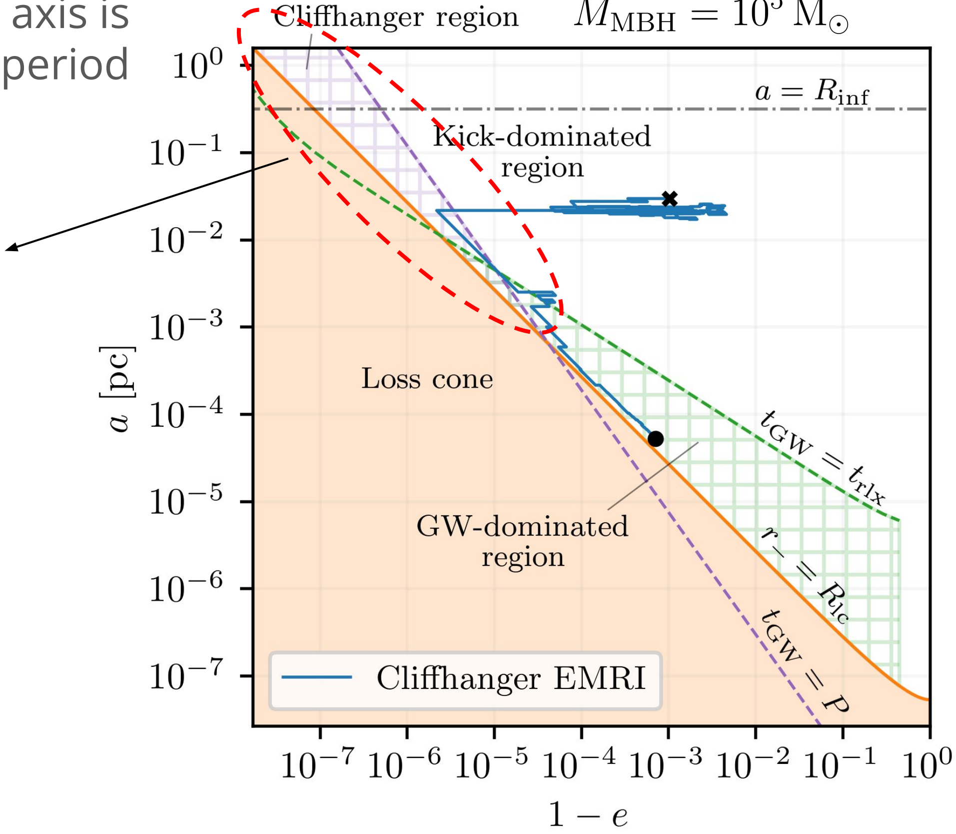

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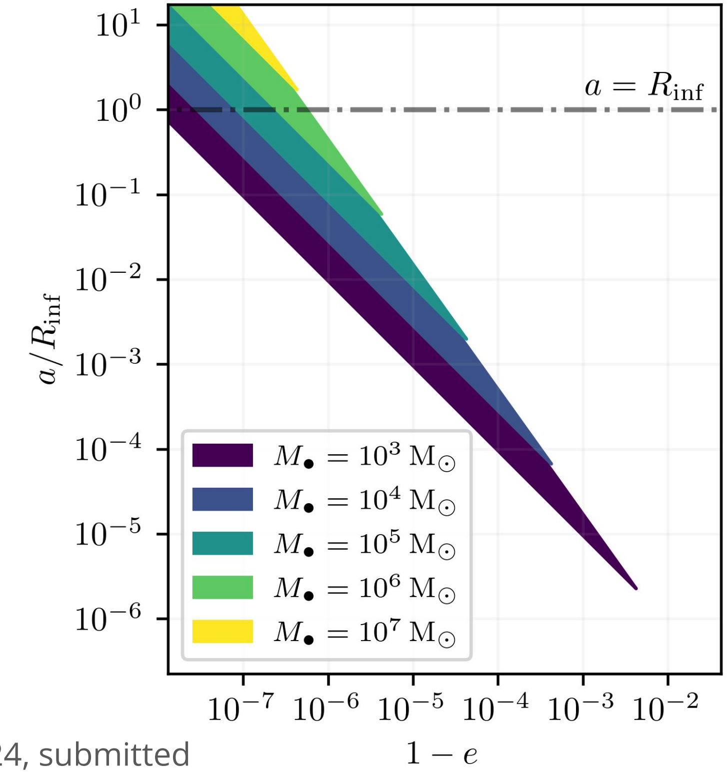

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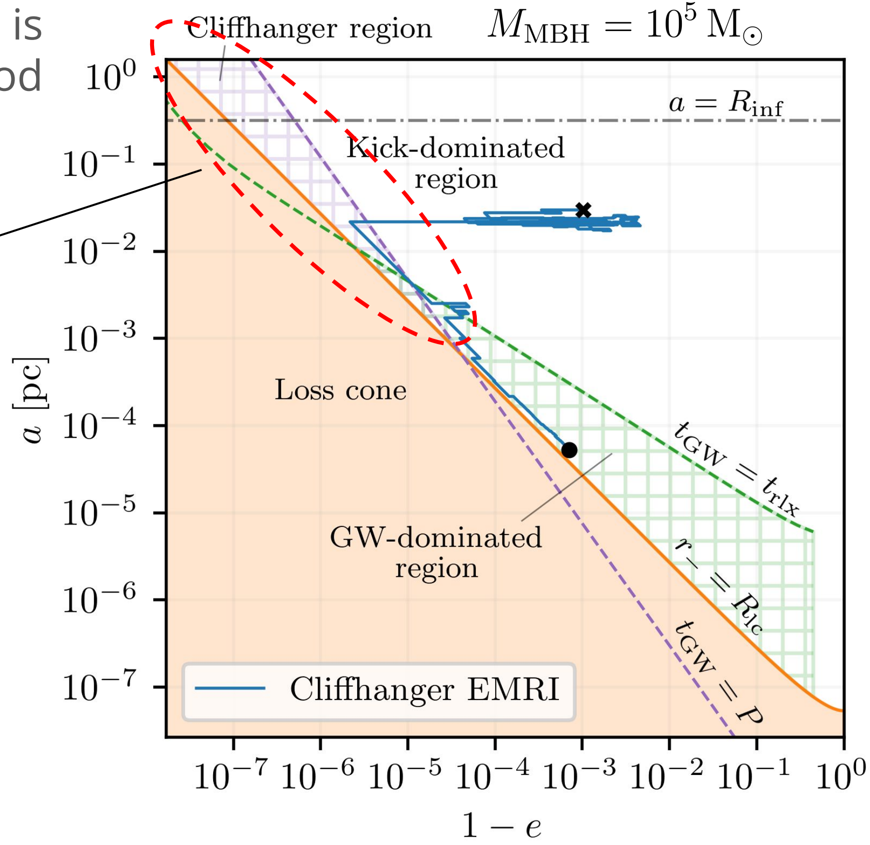

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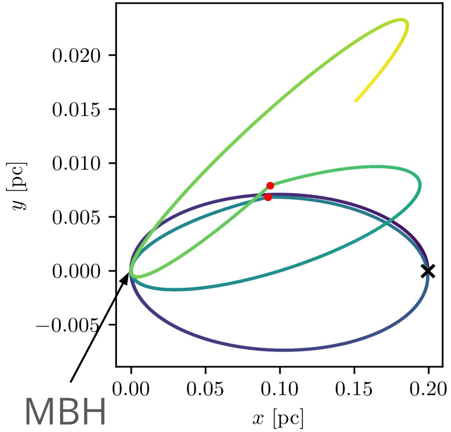
Orbit-averaged approximation

- Two-body relaxation is treated via **diffusion coefficients D[X]**, which give the expected change of X per unit of time
- In the usual Monte Carlo or Fokker-Planck approaches, the effects of two-body relaxation are **orbit-averaged**



$$\langle \mathrm{D}[\Delta E] \rangle_P = \frac{2}{P} \int_{r_{\mathrm{apo}}}^{r_{\mathrm{peri}}} \mathrm{D}[\Delta E] \frac{\mathrm{d}r}{v_{\mathrm{r}}}$$

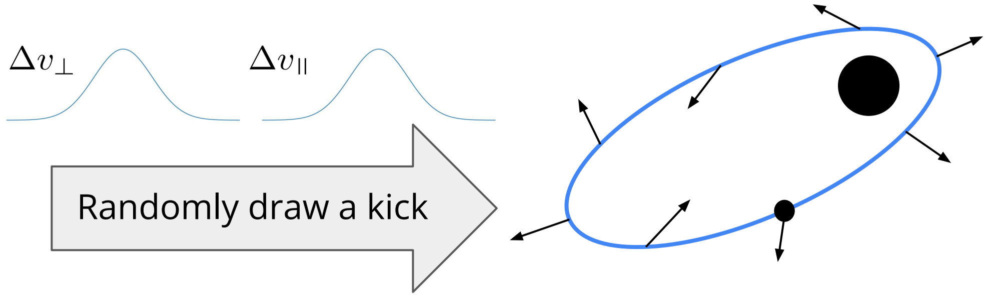
$$\langle \mathrm{D}[\Delta J] \rangle_P = \frac{2}{P} \int_{r_{\mathrm{apo}}}^{r_{\mathrm{peri}}} \mathrm{D}[\Delta J] \frac{\mathrm{d}r}{v_{\mathrm{r}}}$$

Local two-body relaxation

- We integrate the orbit of a stellar-mass BH around a **non-spinning MBH** with post-Newtonian dynamics up to the **2.5PN** term
- At each time step, we **kick** the stellar-mass BH to mimic two-body interactions during the last Δt

$$\mu_\perp = 0 \qquad \mu_{||} = \mathrm{D}[\Delta v_{||}]\Delta t$$

$$\sigma_\perp^2 = \mathrm{D}\left[(\Delta v_\perp)^2\right]\Delta t \qquad \sigma_{||}^2 = \mathrm{D}\left[(\Delta v_{||})^2\right]\Delta t - \left(\mathrm{D}[\Delta v_{||}]\Delta t\right)^2$$



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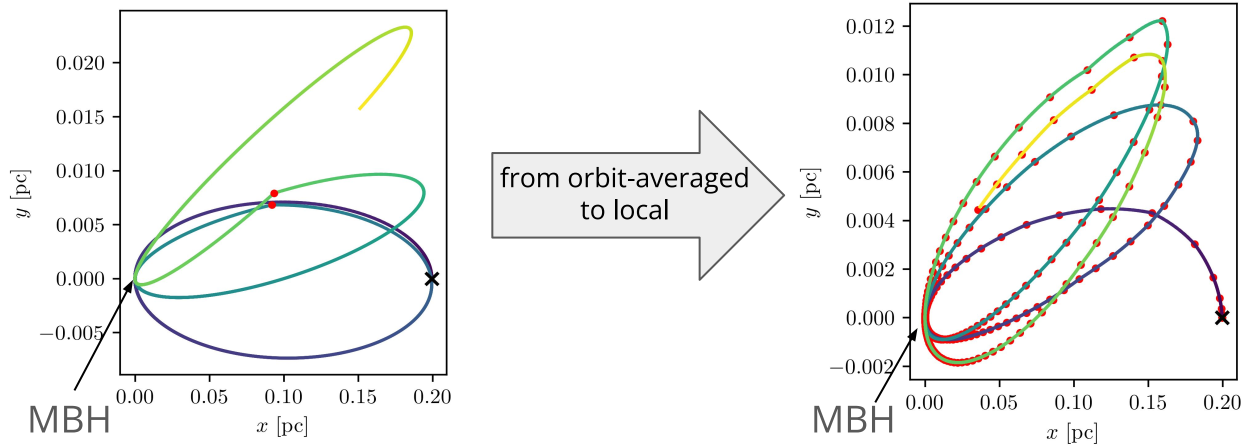

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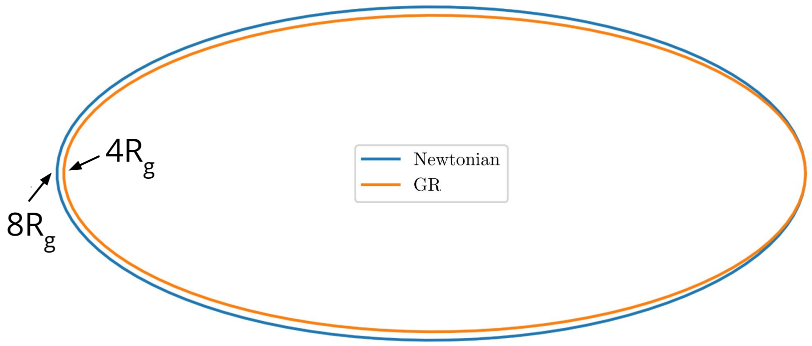
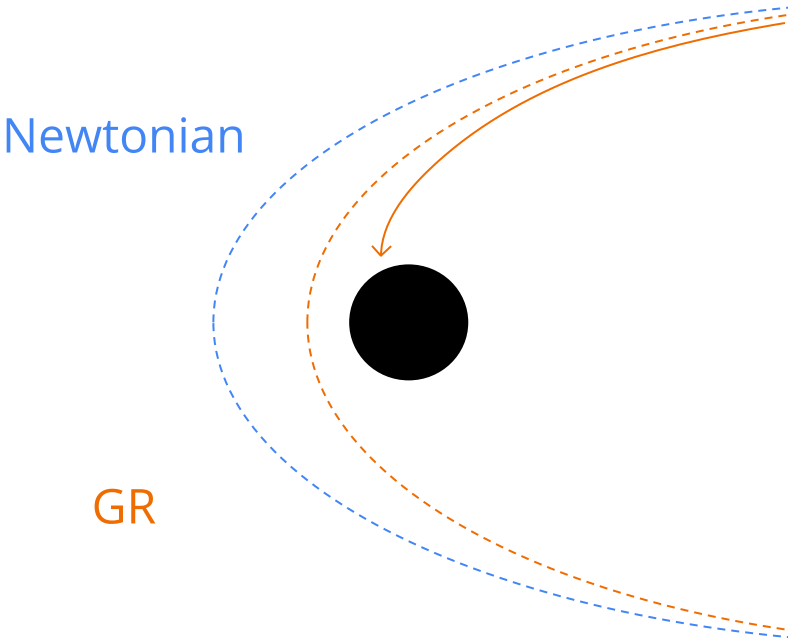
Loss cone definition in PN dynamics

Plunging orbits:





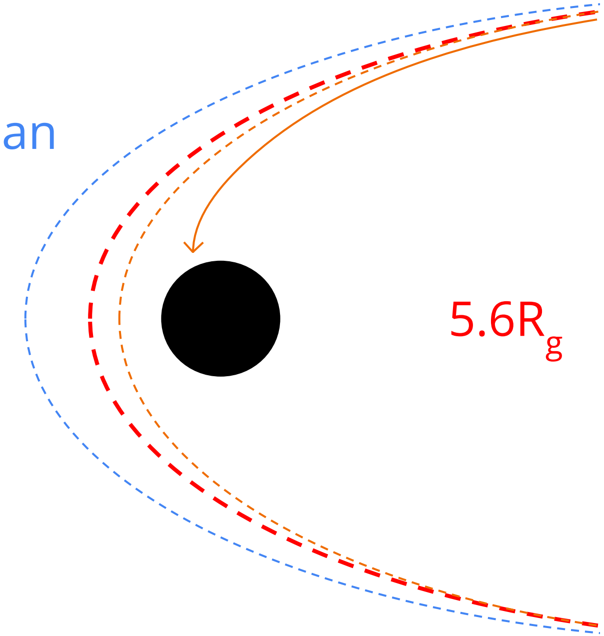
Loss cone definition in PN dynamics

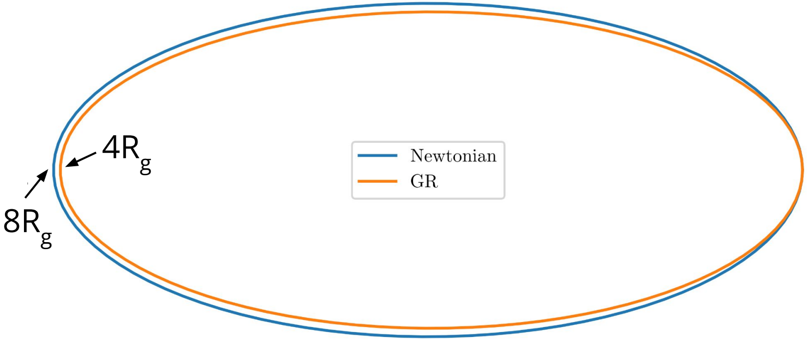
Plunging orbits:

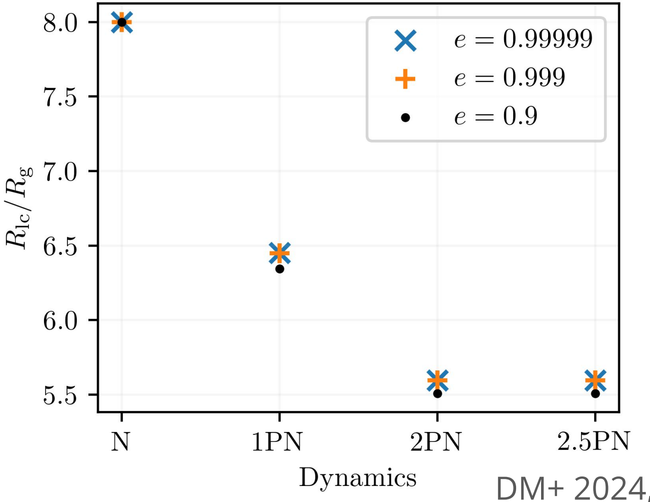
Newtonian

2PN

GR







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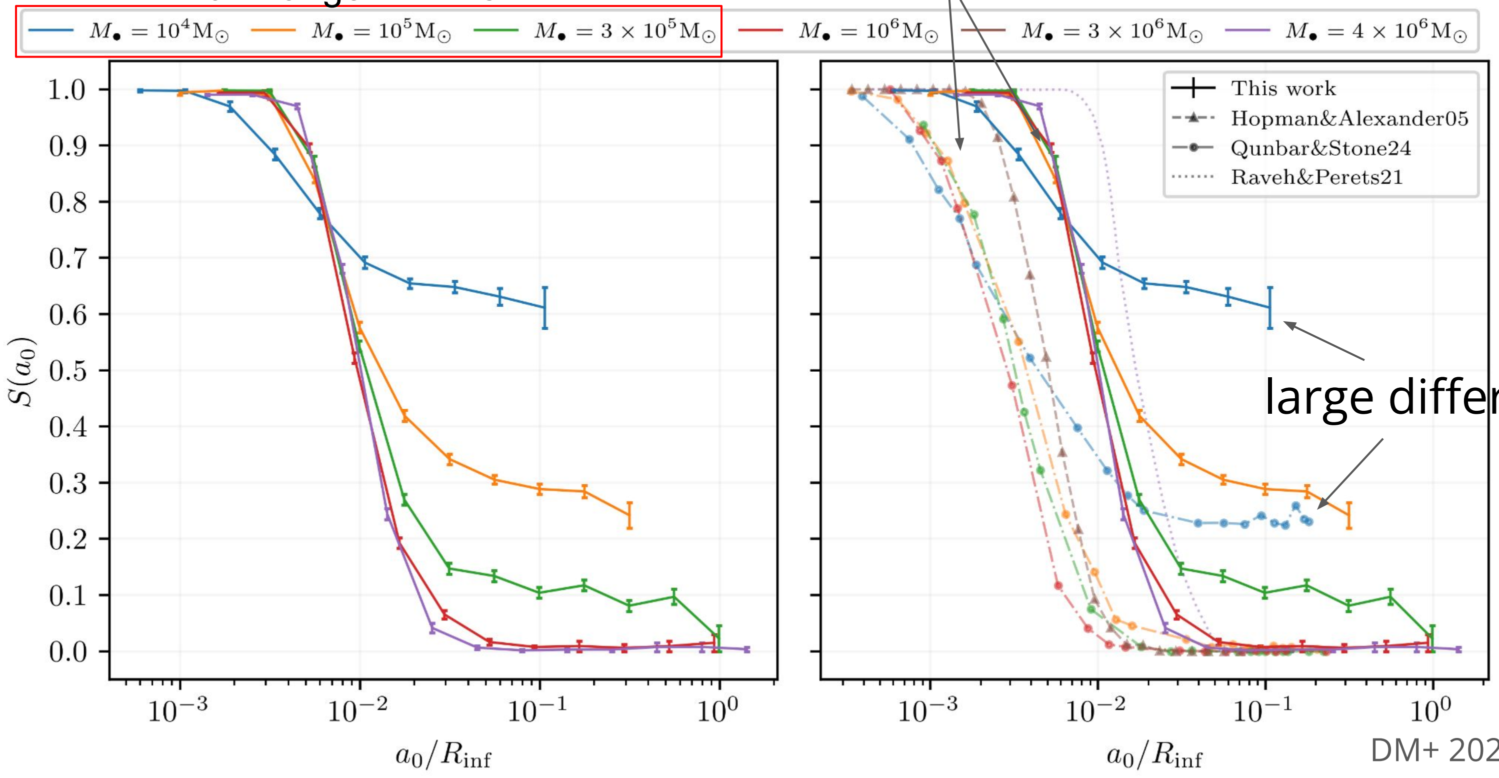
EMRI-to-plunge ratio

PN terms shift S(a) to the right

$$S(a_0) = \frac{N_{\rm EMRI}(a_0)}{N_{\rm EMRI}(a_0) + N_{\rm DP}(a_0)}$$

cliffhanger EMRIs!



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Comparison with Qunbar&Stone24

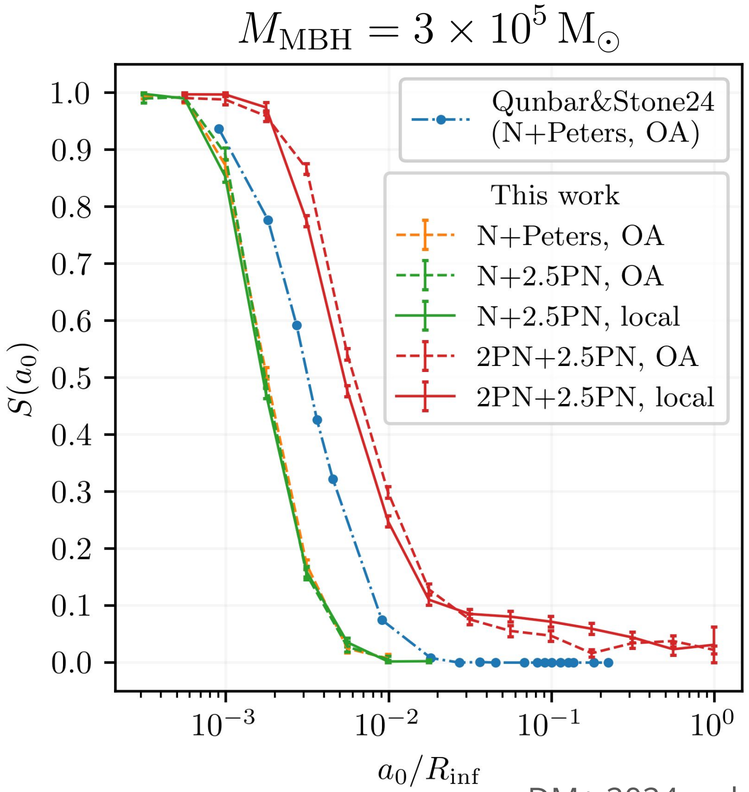
We could not exactly reproduce their result employing similar techniques

Qunbar and Stone 2024

- Two-body relaxation is orbit-averaged
- Newtonian dynamics
- Only stellar population around the MBH
- Stellar potential is ignored

This work

- Two-body relaxation is local
- 2.5PN dynamics
- Stars and stellar-mass BHs around the MBH
- Stellar and BHs potential accounted for



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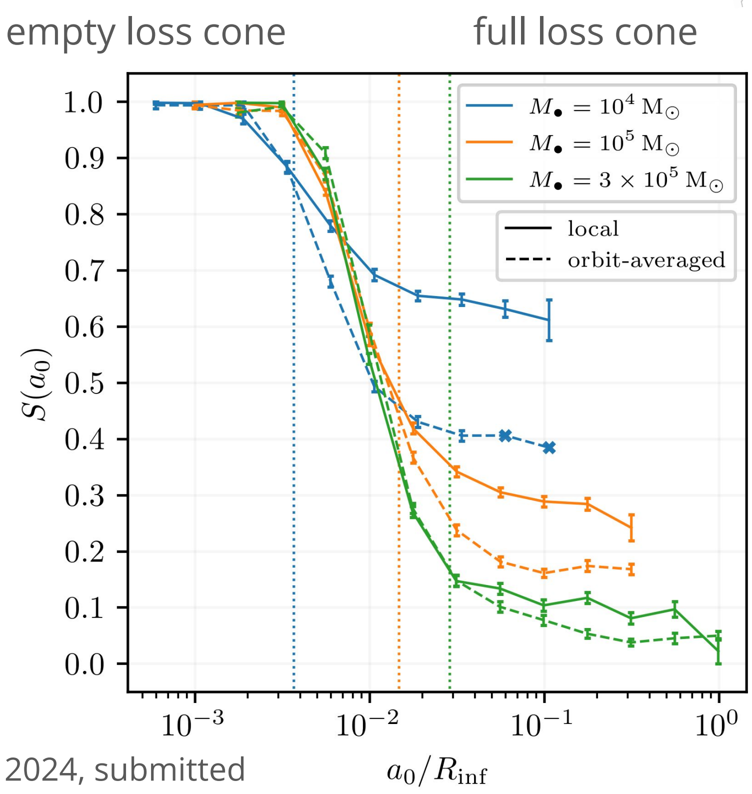
Local vs orbit-averaged



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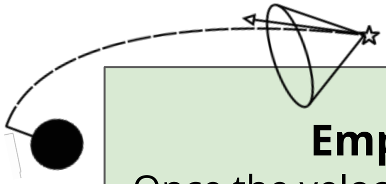


Empty loss cone regime

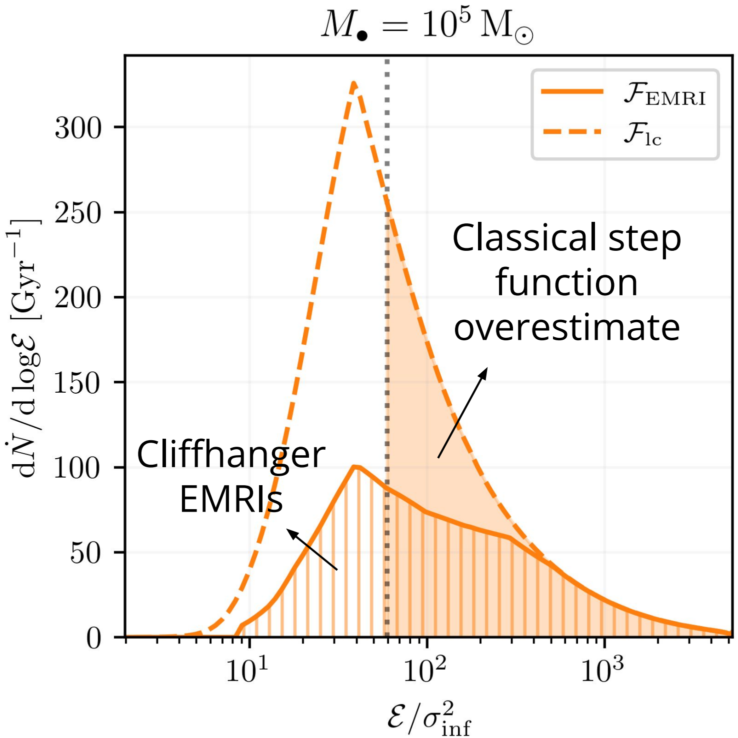
Once the velocity vector falls inside the loss cone, **the object WILL reach the pericentre** and fall into the MBH

Full loss cone regime

Two-body encounters can still happen inside the loss cone: **the object can leave the loss cone before reaching the pericentre** and avoid plunging

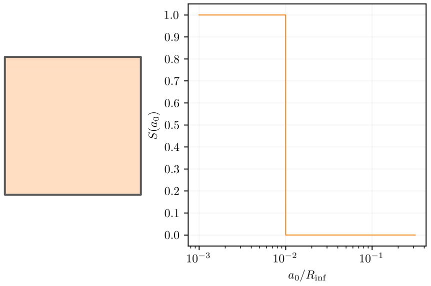
You cannot describe the full loss cone regime if you keep the shape of the orbit frozen for a full period!

EMRI and plunge rates

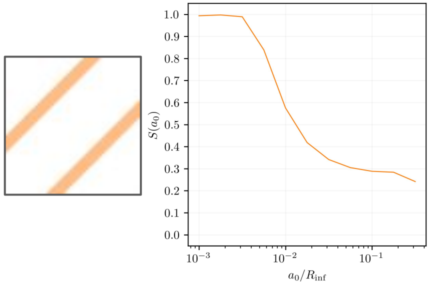


increasing a

DM+ 2024, submitted



Usually people assume a step function based on Hopman&Alexander2005



In reality:
- S(a) is smooth
- S(a) does not go to zero

Conclusions

arXiv:2409.09122

1. Cliffhanger EMRIs break the classical EMRI-to-plunge ratio picture: EMRIs can form from initially wide orbits around MBHs smaller than $10^6\ M_{sun}$
2. More EMRIs are formed by locally accounting for two-body relaxation and using PN dynamics
3. The orbit-averaged approximation fails in predicting the EMRI-to-plunge ratio in the full loss cone regime
4. Cliffhanger EMRIs can contribute to a large fraction of the total EMRI rate. The total rate is overestimated if S(a) is approximated to a step function

Thank you for the attention!