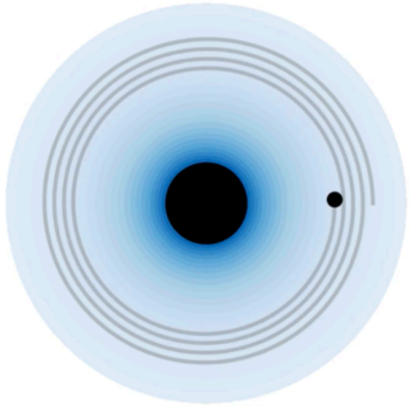
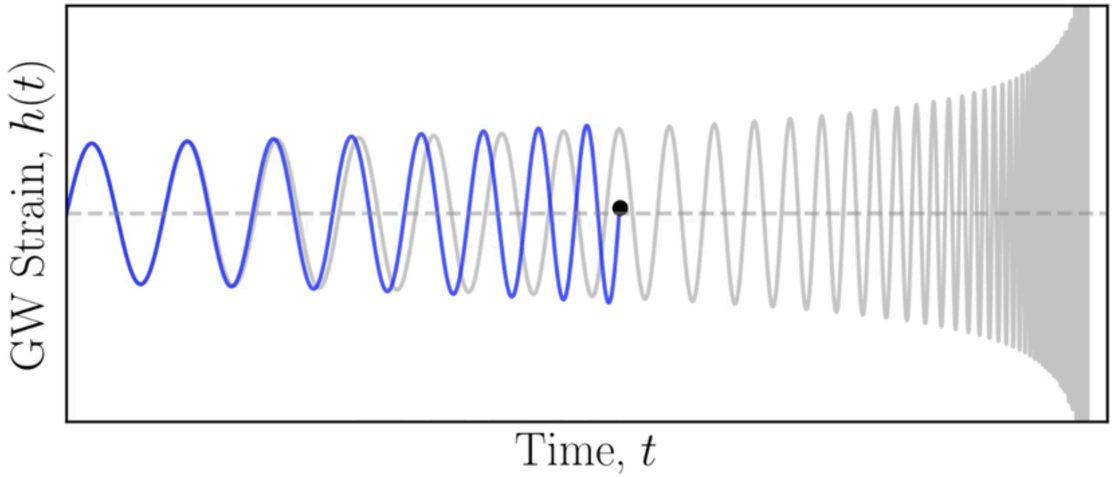




Feedback on Dark Matter Spikes (Interactions with Stars/SBHs)

Bradley J Kavanagh [he/him]

kavanagh@ifca.es

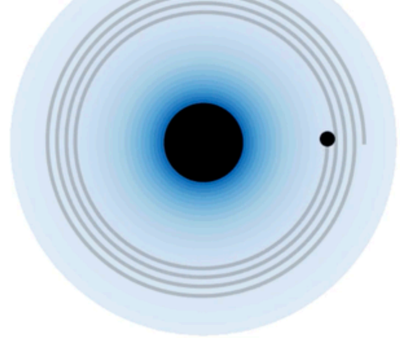
Instituto de Física de Cantabria (CSIC-UC)

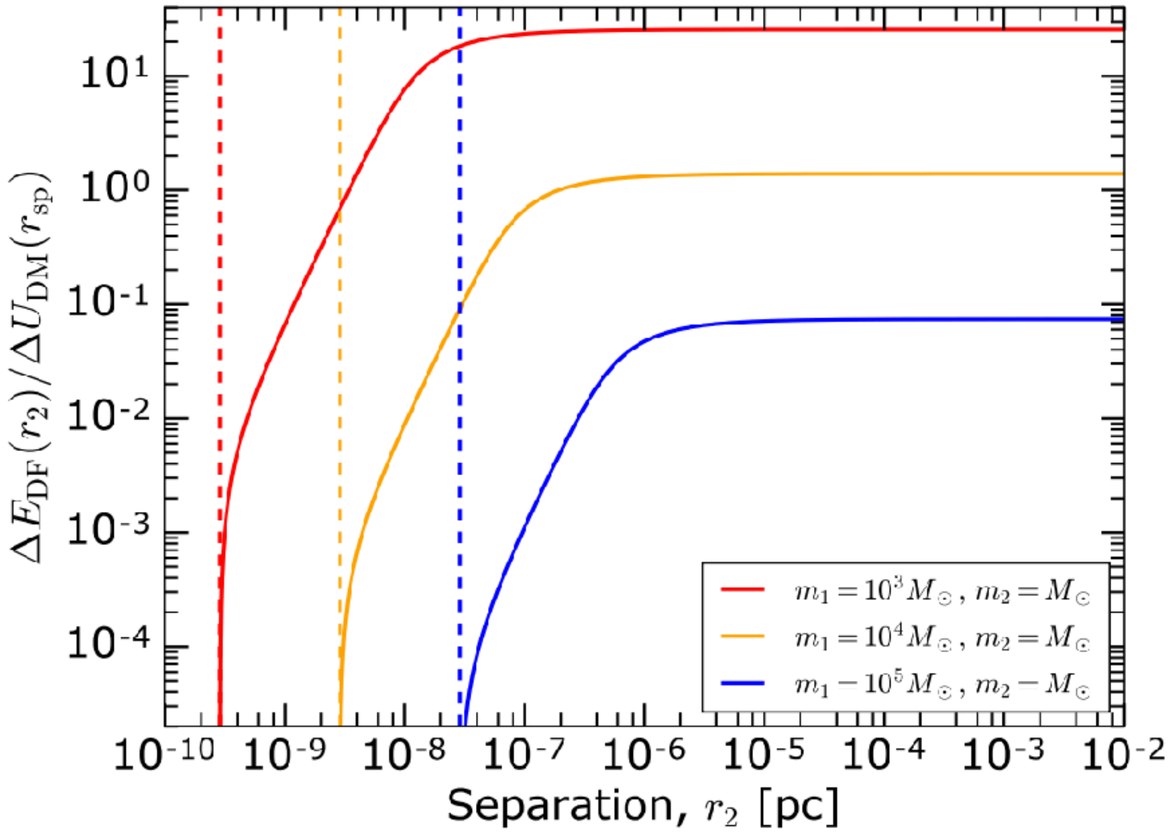
De Tenebris Kick-off Meeting

11 November 2026

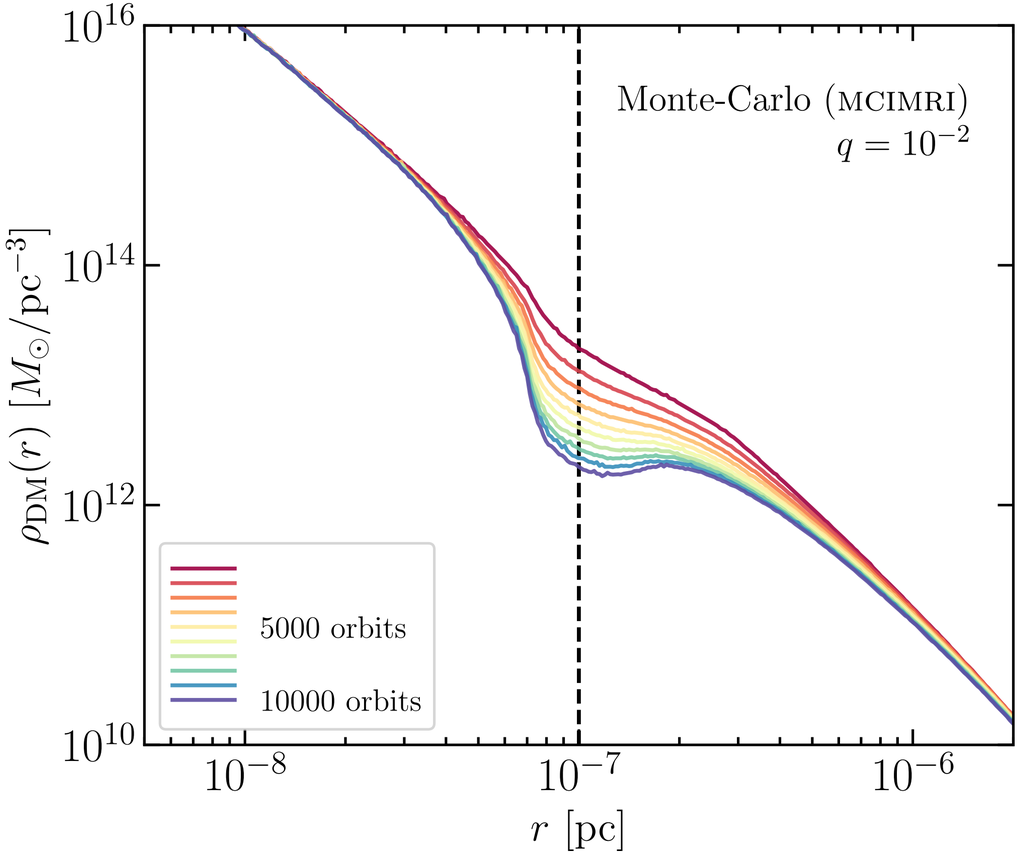
IFCA Instituto de Física de Cantabria | UC Universidad de Cantabria | CSIC Consejo Superior de Investigaciones Científicas | Excelencia María de Maeztu | Gobierno de España | Ministerio de Ciencia, Innovación y Universidades | Unión Europea Fondo Europeo de Desarrollo Regional | Agencia Estatal de Investigación

Energy Conservation and Depletion





[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

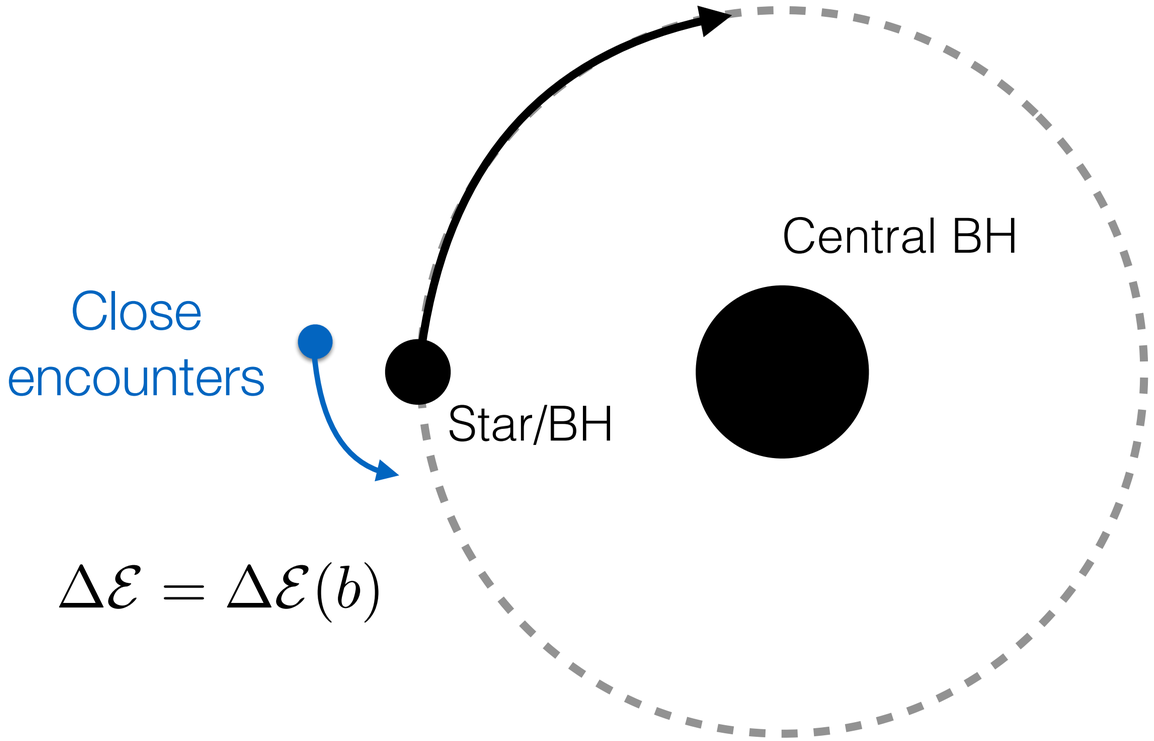


[Scarcella & **BJK**, 2611.XXXXX]

Orbiting objects will inject (specific) energy $\mathscr{E}$ and angular momentum L into the DM distribution

Sources of feedback/depletion

Close encounters (‘dynamical friction’)

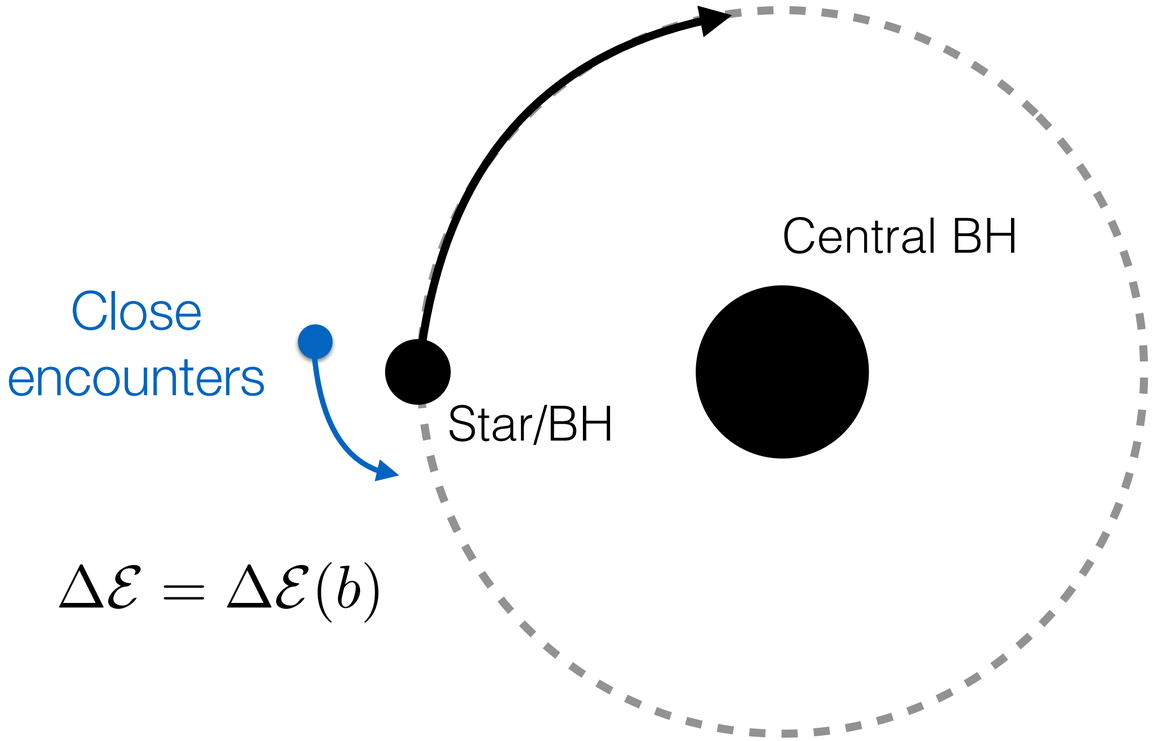


$$\Delta\mathcal{E} = \Delta\mathcal{E}(b)$$

Sources of feedback/depletion

Close encounters (‘dynamical friction’)

3-body interactions (‘stirring’)

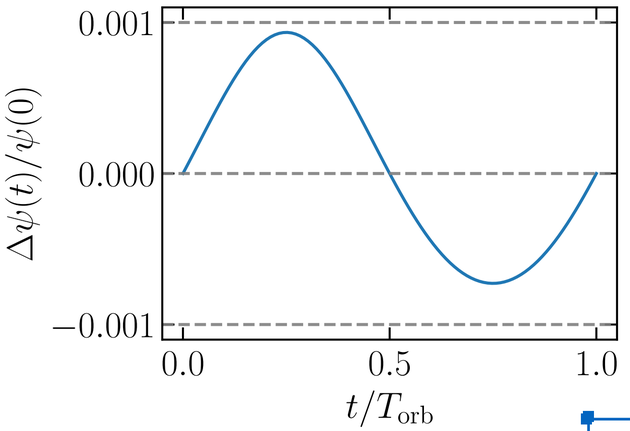


$$\Delta\mathcal{E} = \Delta\mathcal{E}(b)$$



3-body ‘stirring’

$$\Delta\mathcal{E} = \int_0^{\Delta t} \frac{\partial\psi}{\partial t}\,\mathrm{d}t$$

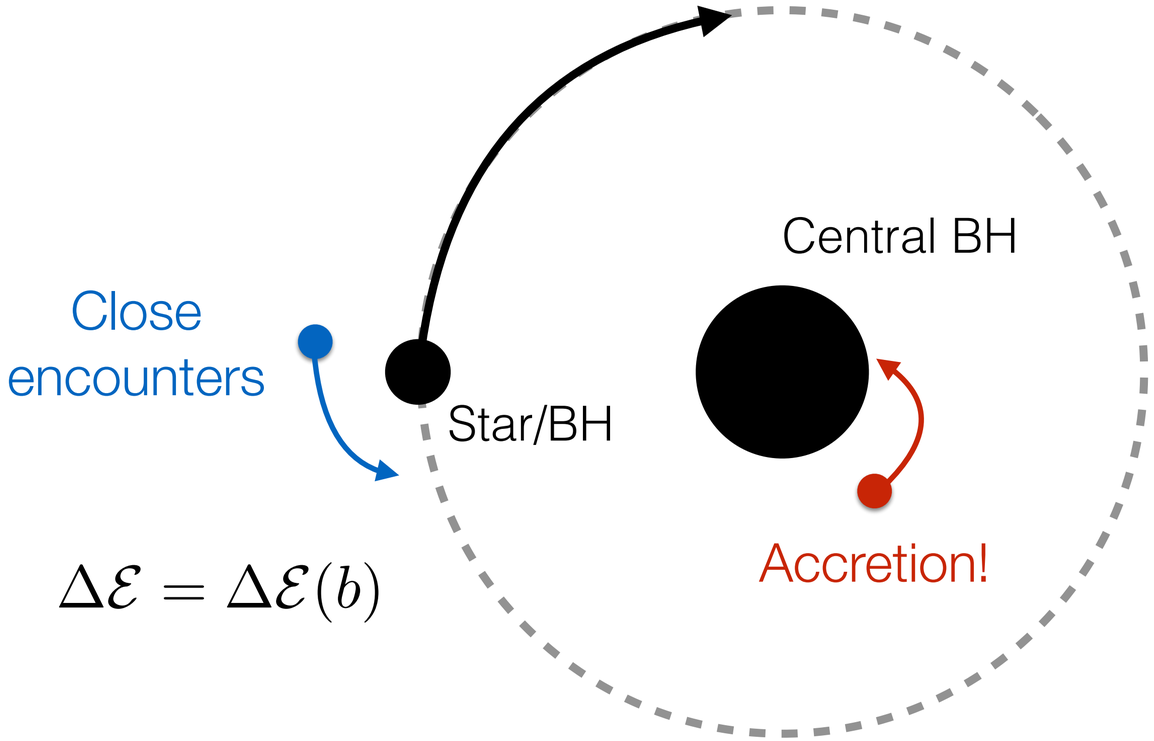


Sources of feedback/depletion

Close encounters (‘dynamical friction’)

3-body interactions (‘stirring’)

Accretion by the central BH

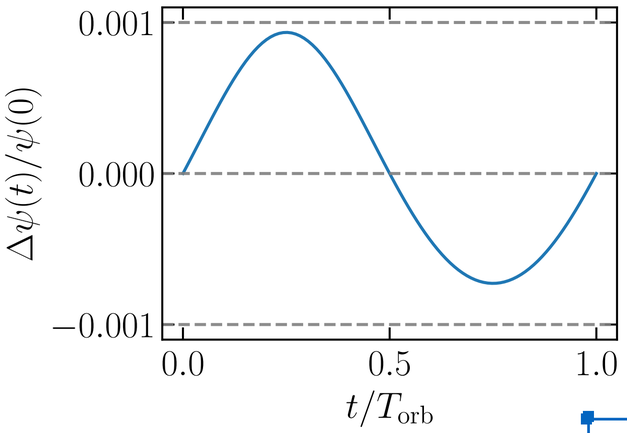


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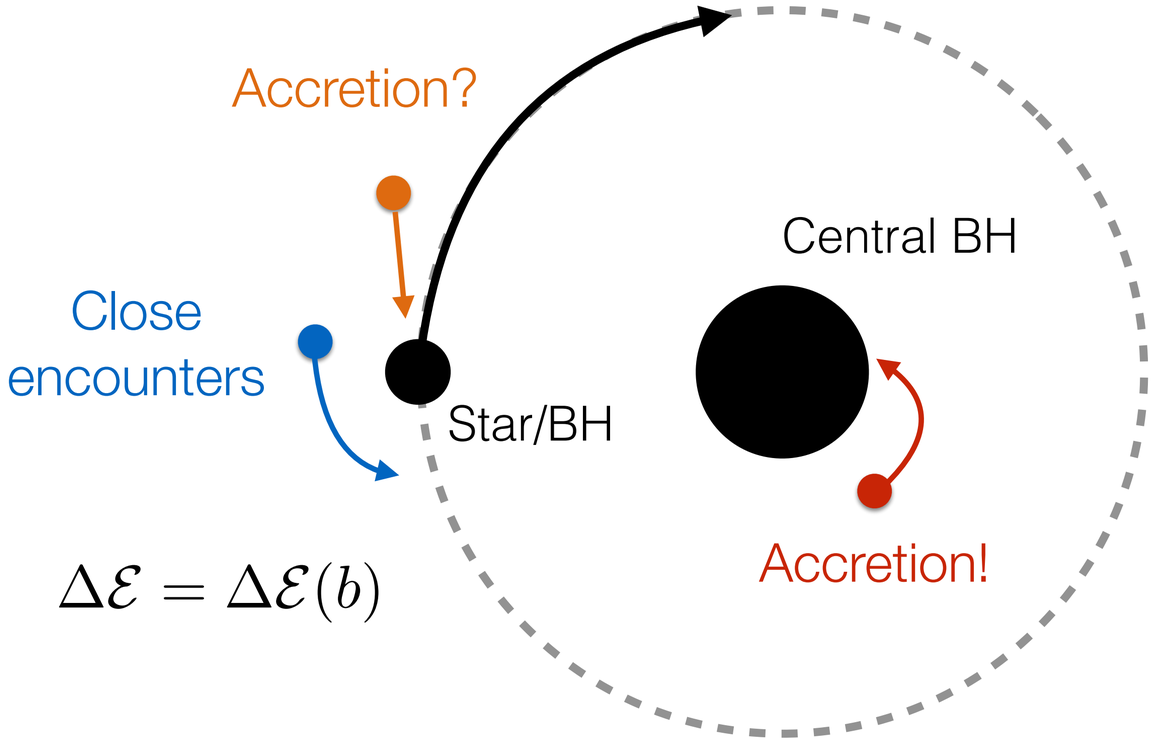
Sources of feedback/depletion

Close encounters (‘dynamical friction’)

3-body interactions (‘stirring’)

Accretion by the central BH

Accretion by the secondary BH?

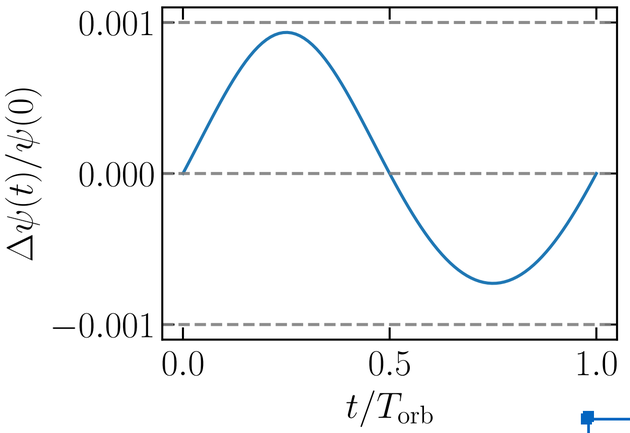


$$\Delta\mathcal{E} = \Delta\mathcal{E}(b)$$



3-body ‘stirring’

$$\Delta\mathcal{E} = \int_0^{\Delta t} \frac{\partial\psi}{\partial t}\,\mathrm{d}t$$



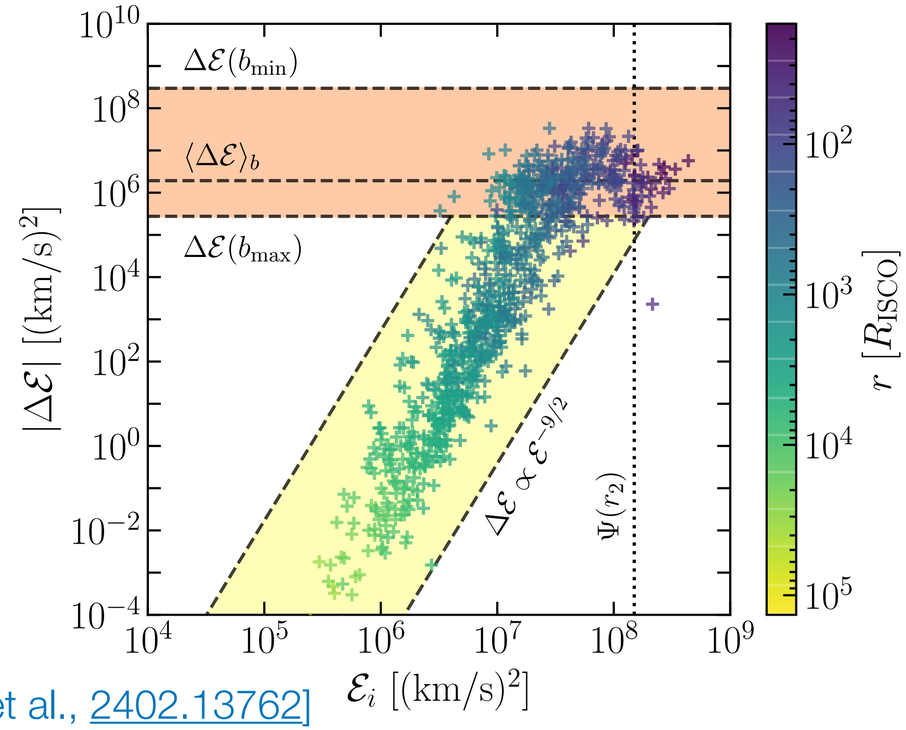
Sources of feedback/depletion

Close encounters (‘dynamical friction’)

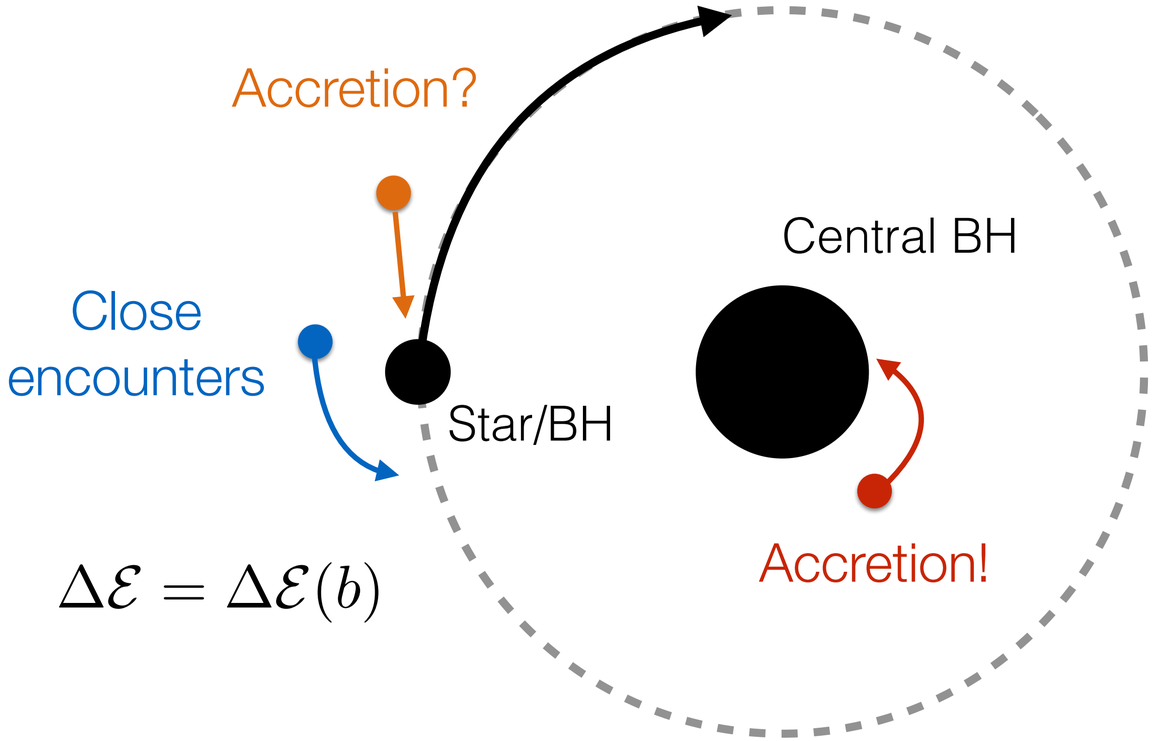
3-body interactions (‘stirring’)

Accretion by the central BH

Accretion by the secondary BH?



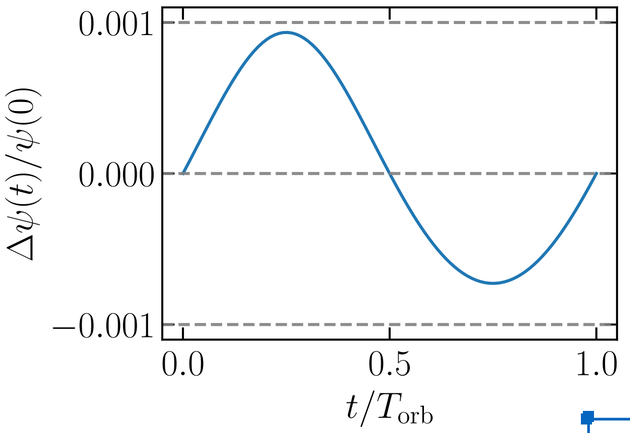
[**BJK** et al., 2402.13762]



$$\Delta\mathcal{E} = \Delta\mathcal{E}(b)$$

3-body ‘stirring’

$$\Delta\mathcal{E} = \int_0^{\Delta t} \frac{\partial\psi}{\partial t}\,{\rm d}t$$



Depletion Timescales

*Newtonian simulations, neglecting accretion

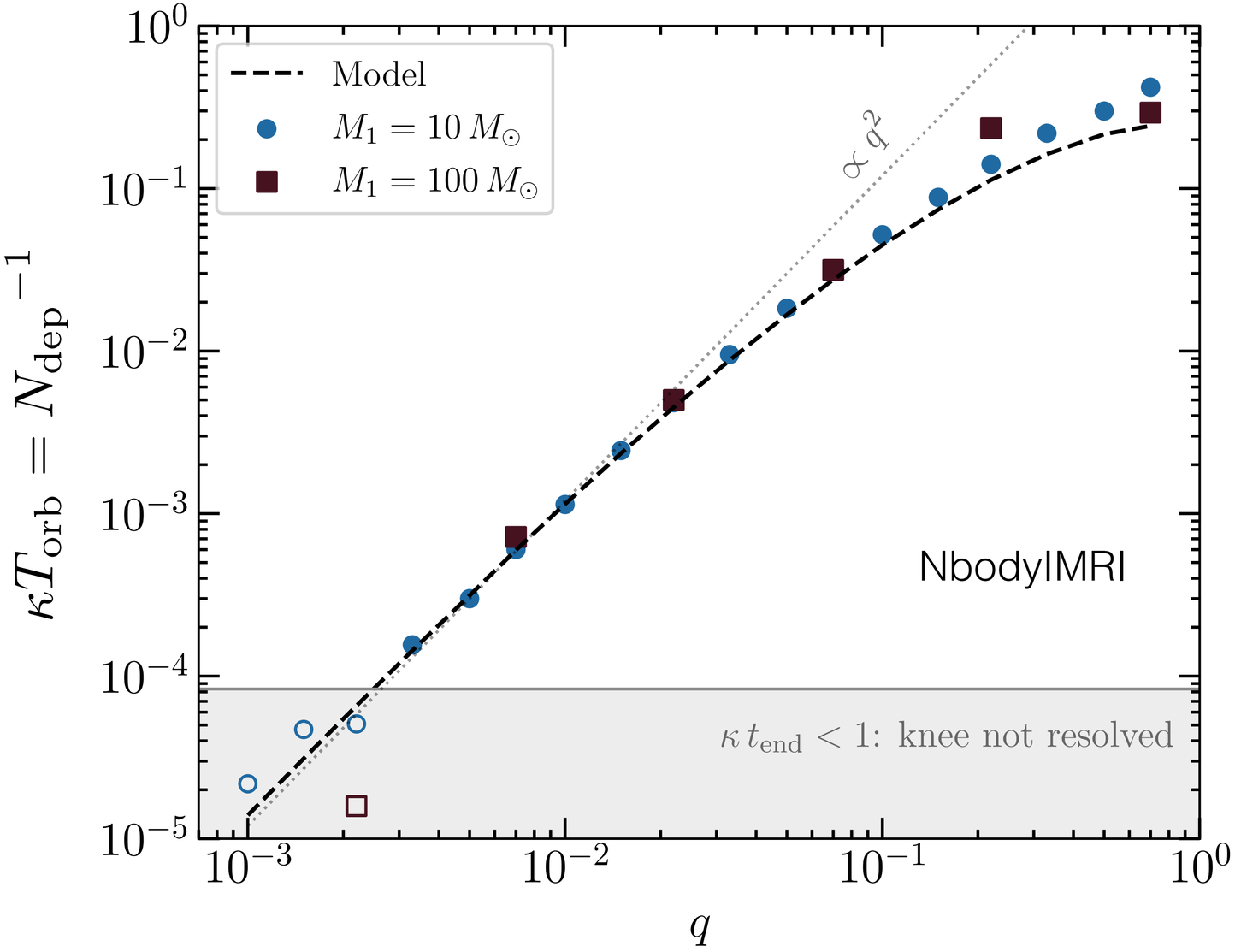
Depletion timescale $N_{\rm dep}$ is independent of orbital radius and primary mass

Rate of depletion scales roughly as $q^2 = (m_2/m_1)^2$

Impact of stars and stellar-mass BHs on SMBHs ($q \ll 1$) is small (but cumulative!)



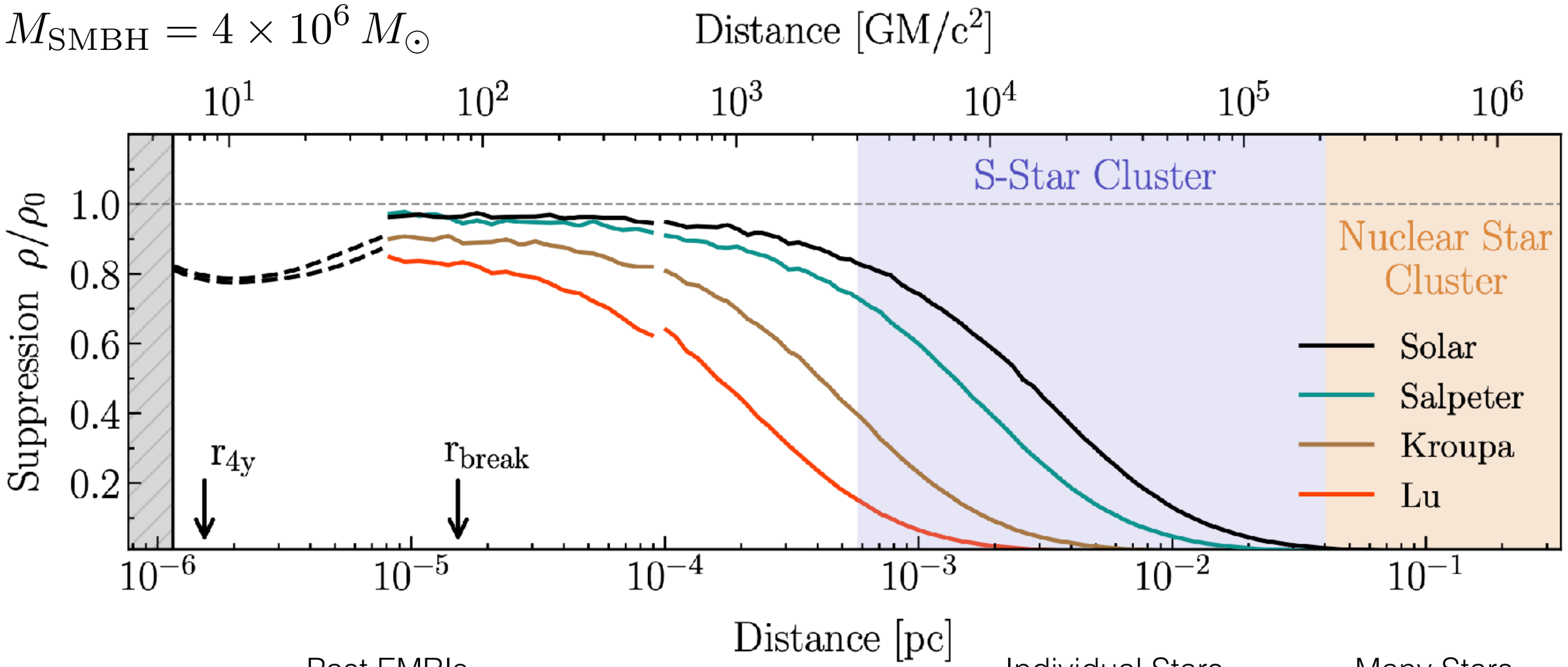
Many of the simulation results presented here were performed by Francesca Scarcella



[Scarcella & **BJK**, 2611.XXXXX]

DM around Sgr A*

[Karydas, Scarcella, **BJK**, Bertone, 2606.13761]



Past EMRIs → Depletion (with inspiral)

Individual Stars → Depletion (in the static limit)

Many Stars → Fokker Planck

Stellar Depletion (Fokker Planck)

The motion of stars is well-known to dynamically 'heat' the DM distribution.

Diffusion in energy and angular momentum depends on average rate of kicks from stars $\langle \Delta \mathscr{E} \rangle_t$, $\langle \Delta \mathscr{E} \Delta L \rangle_t$, etc:

$$\frac{\partial N(\mathcal{E}, L)}{\partial t} = -\frac{\partial F_{\mathcal{E}}}{\partial \mathcal{E}} - \frac{\partial F_L}{\partial L}$$

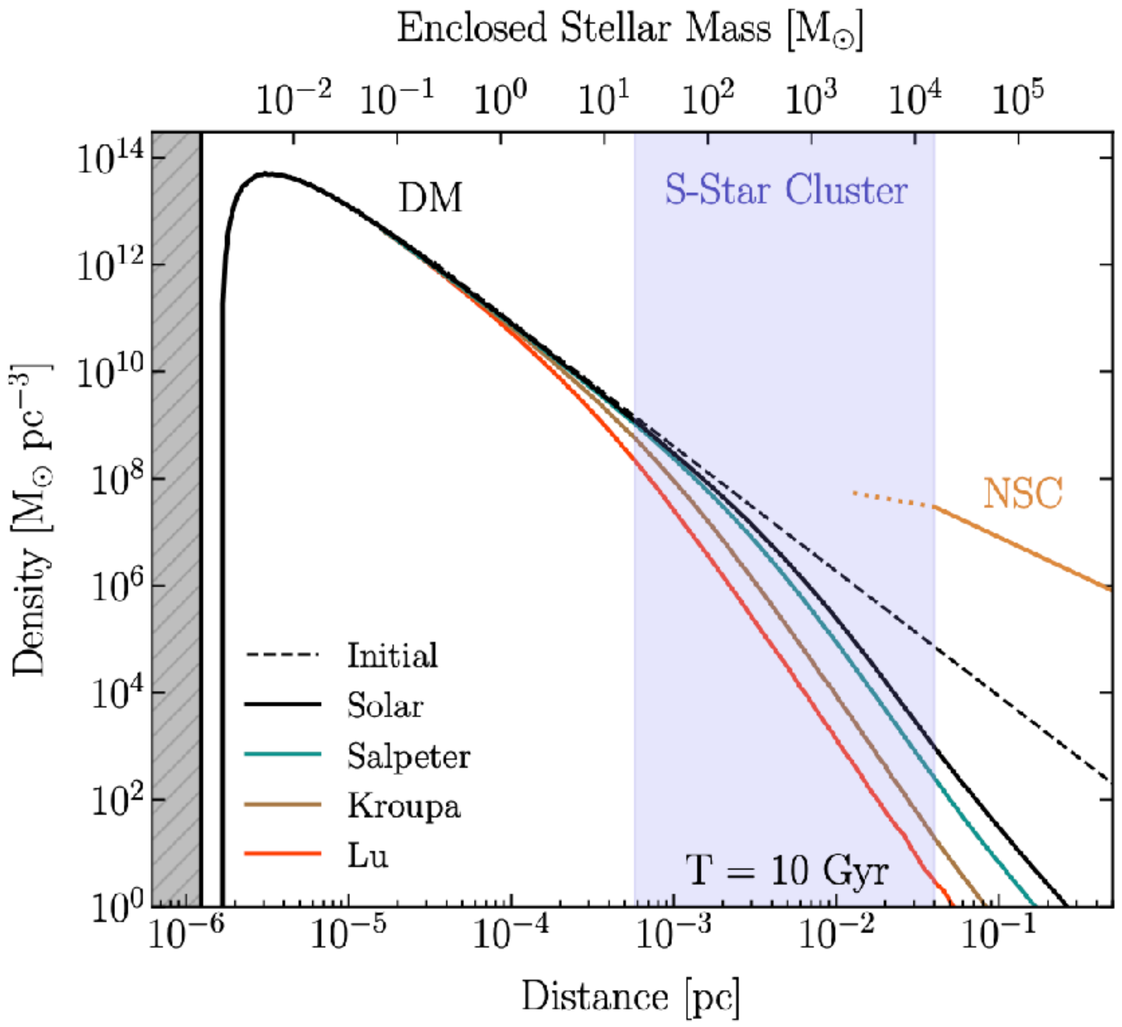
But, formalism cannot be trivially extended to $r \to 0$, as number of enclosed stars drops below $\mathcal{O}(1)$!

Smoothly cut off stellar density at low r, and allow DM to diffuse in both $(\mathscr{E}, L)$ - inner density is preserved!

[Karydas, Scarcella, **BJK**, Bertone, 2606.13761]

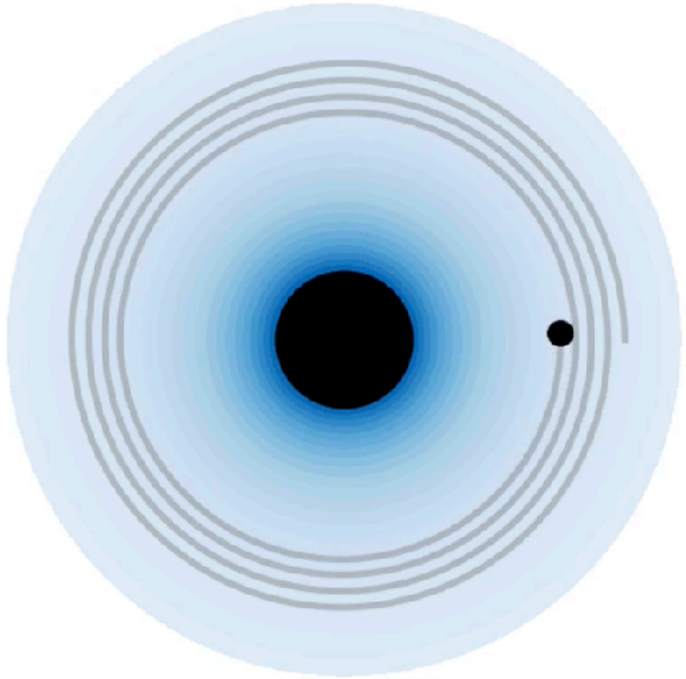
Including a time-dependent stellar population doesn't change much

[Herrera et al., 2605.01023]



‘Individual’ Depletion

HaloFeedback NbodyIMRI MCIMRI



‘Individual’ Depletion

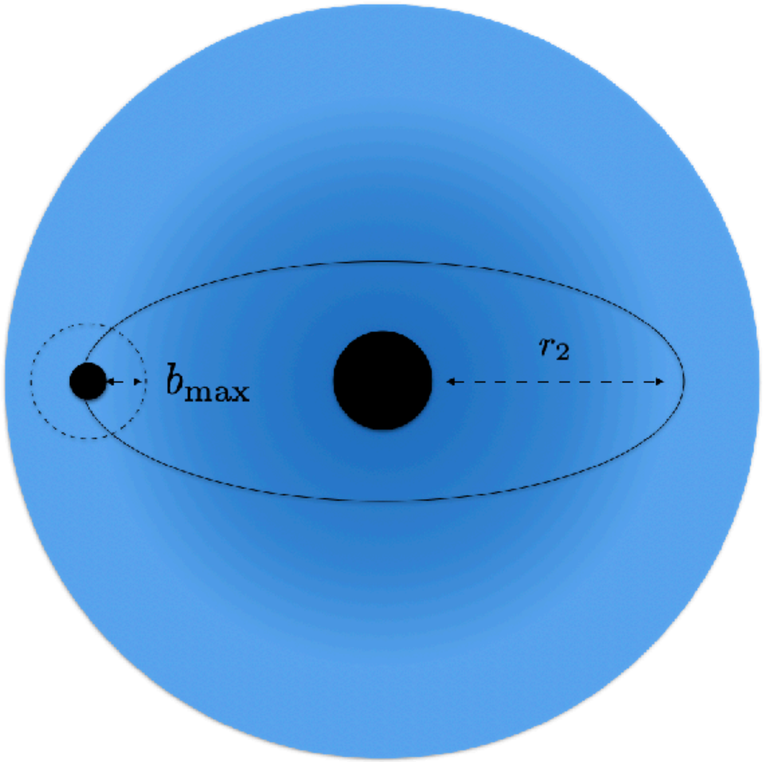
Follow semi-analytically the phase space distribution of DM (assuming isotropy and spherical symmetry):

$$f = \frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{r}\,\mathrm{d}^3\mathbf{v}} \equiv f(\mathcal{E}) \qquad \mathcal{E} = \Psi(r) - \frac{1}{2}v^2$$

Compact object scatters with all DM particles within ‘torus’ of influence over one orbit, receiving a ‘kick’ $\Delta\mathscr{E}$ with probability $P_{\mathscr{E}}(\Delta\mathscr{E})$:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{1}{T_s}\left(\Delta_+ f - f\int P_{\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}\right)$$

$$\Delta_+ f = \int \left(\frac{\mathcal{E}}{\mathcal{E}-\Delta\mathcal{E}}\right)^{5/2} f(\mathcal{E}-\Delta\mathcal{E}) P_{\mathcal{E}-\Delta\mathcal{E}}(\Delta\mathcal{E})\,\mathrm{d}\Delta\mathcal{E}$$

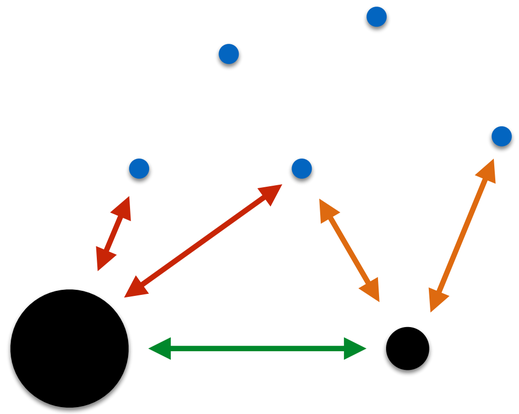


[**BJK**, Nichols, Gaggero, Bertone, 2002.12811]

[Code available online: github.com/bradkav/HaloFeedback]

‘Individual’ Depletion

Newtonian N-body solver tailored to DM spikes:



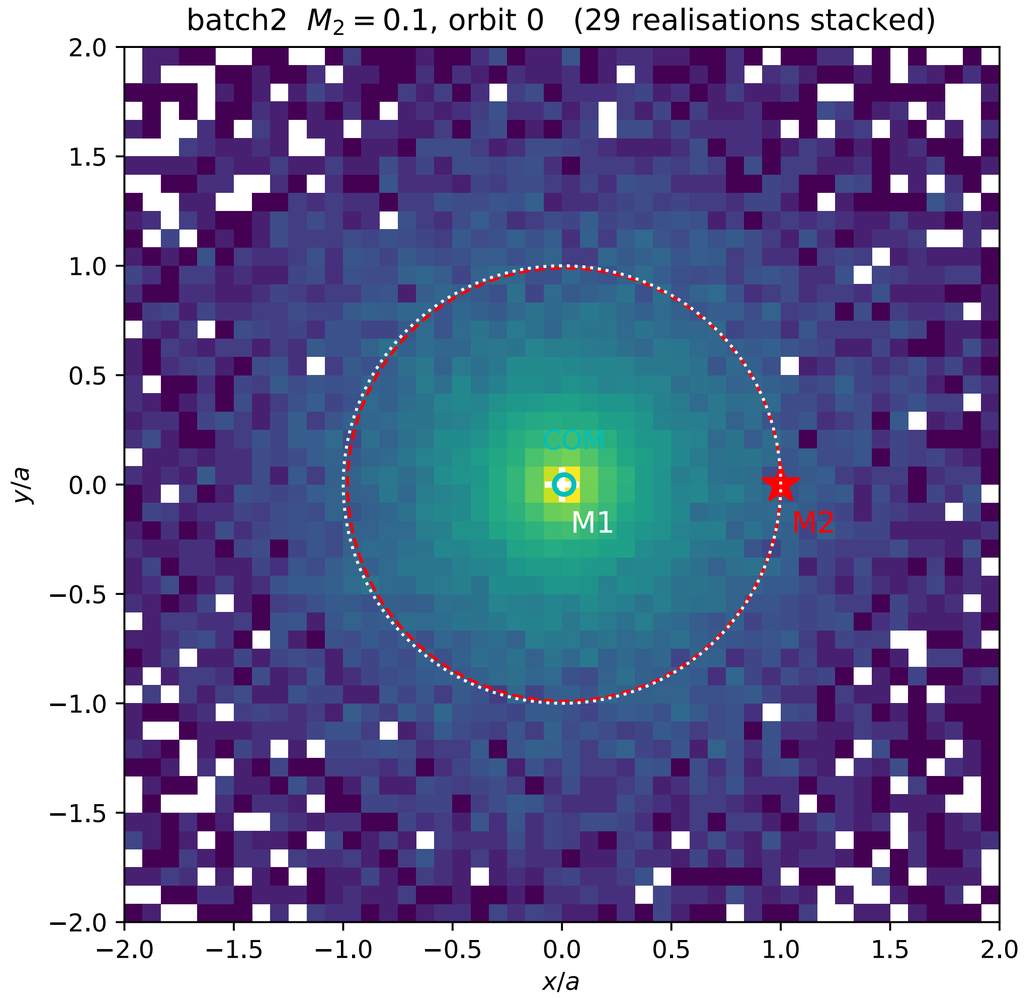
Neglect GW emission and *ignore DM-DM interparticle forces (valid in inner spike)*

Can be used to check strength of DF force, and study feedback

Can include accretion by central BH (though we haven’t used it that way yet)

[**BJK** et al., 2402.13762]

[Code here: github.com/bradkav/NbodyIMRI]

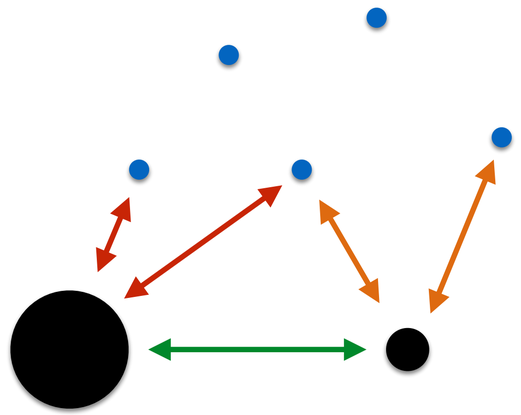


[Scarcella & **BJK**, 2611.XXXXX]

[See also Mukherjee et al., 2312.02275]

‘Individual’ Depletion

Newtonian N-body solver tailored to DM spikes:



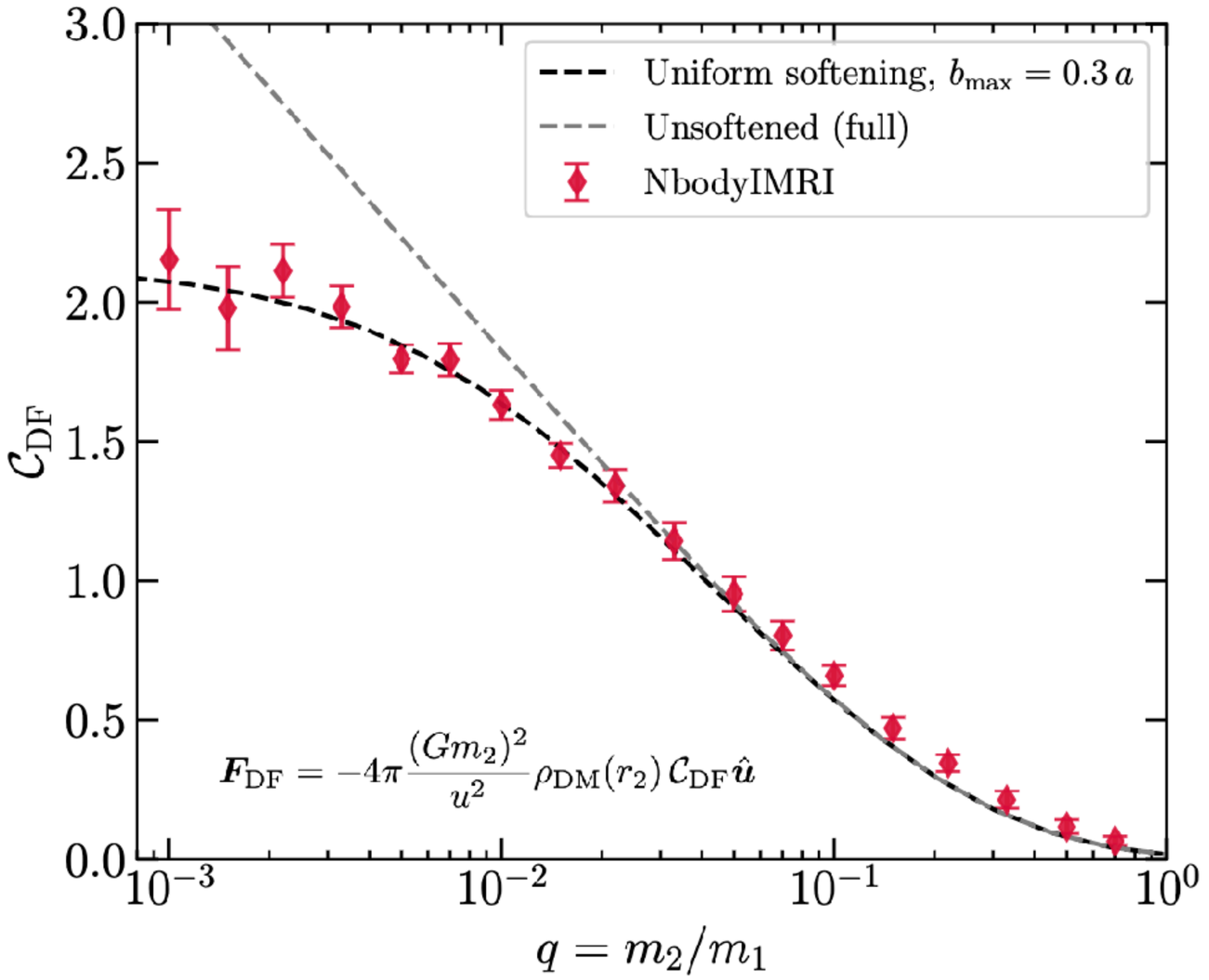
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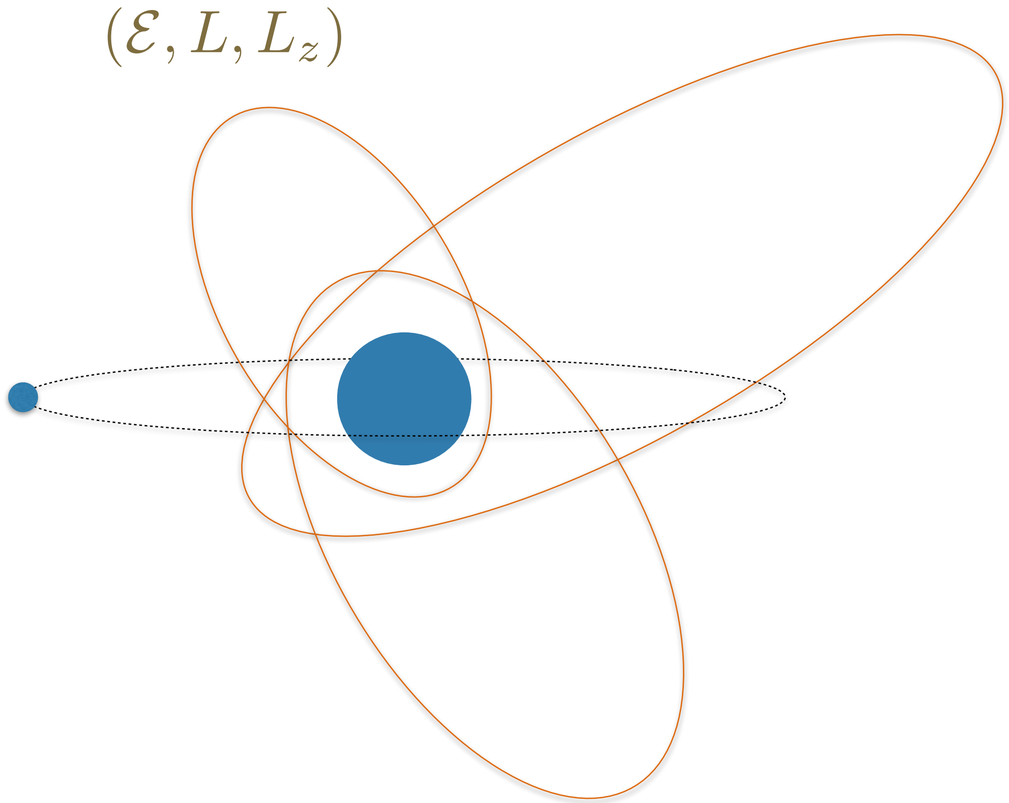
‘Individual’ Depletion

Newtonian phase-space Monte Carlo simulations, in which we track integrals of motion of DM particles $(\mathscr{E}, L, L_z)$.

At each orbit of the binary, we apply a kick $(\Delta\mathscr{E}, \Delta L, \Delta L_z)$ due to close encounters (‘dynamical friction’) and due to 3-body effects (‘stirring’).

Different physics can be ‘switched’ on and off (close encounters, stirring, loss cone capture, etc). Can also be used to measure the DF force as the spike depletes.

Much faster than NbodyIMRI (can simulate 1000s of orbits per minute), but currently only quasi-circular inspirals

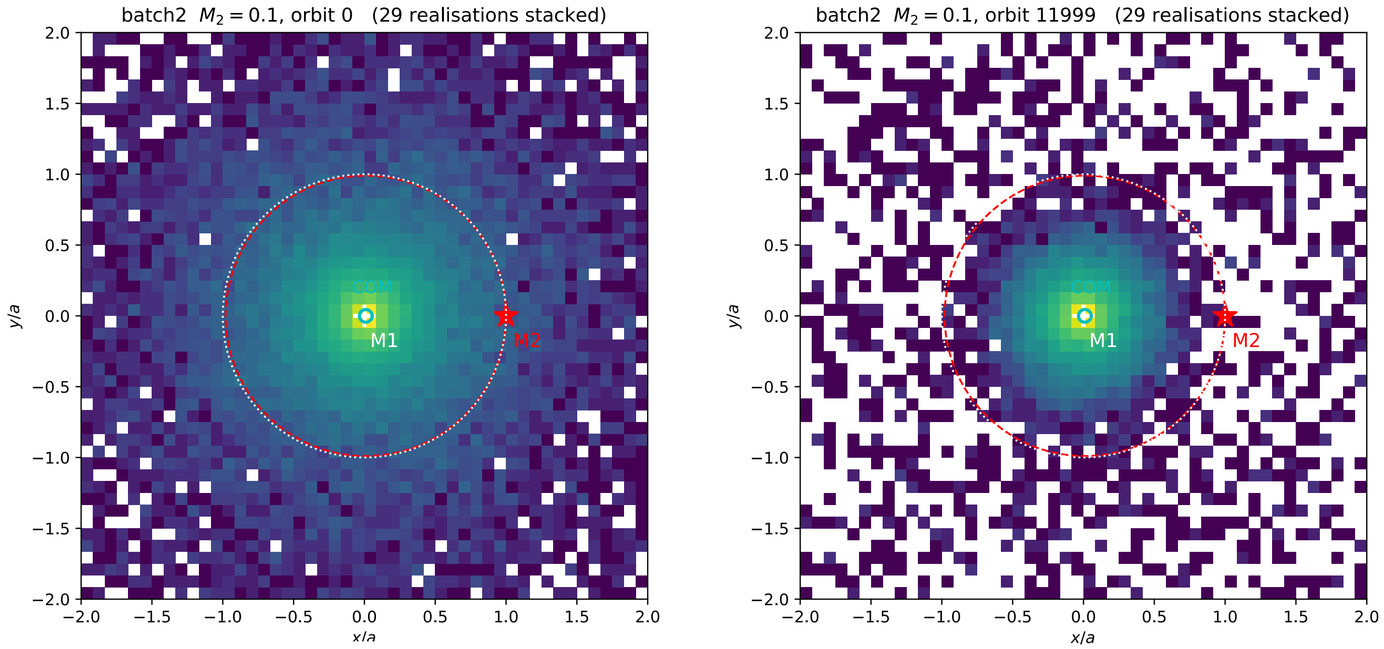


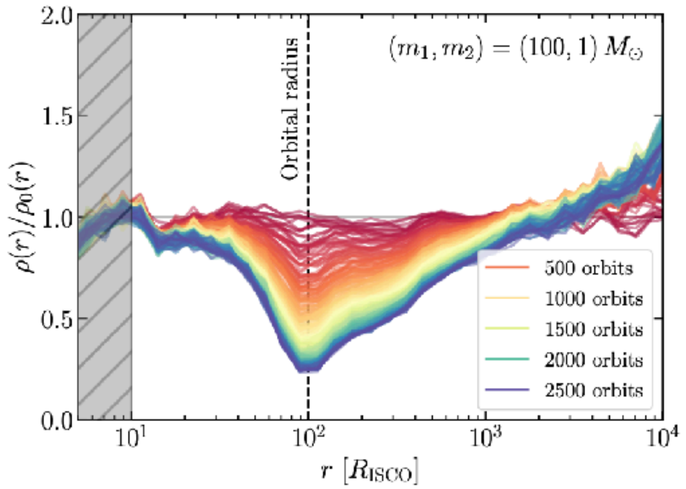
[Scarcella & **BJK**, 2611.XXXXX]

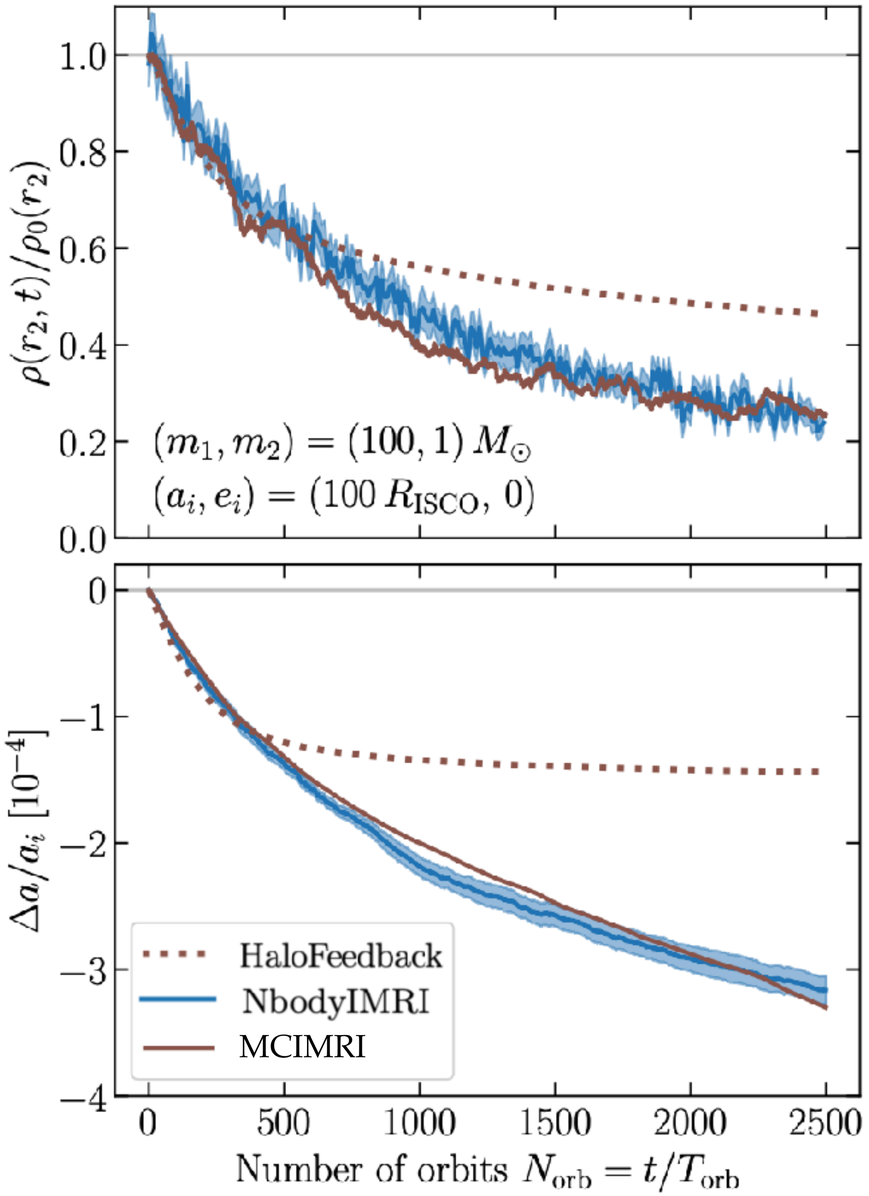
[Code available online: github.com/bradkav/MCIMRI]

‘Individual’ Depletion

HaloFeedback NbodyIMRI MCIMRI

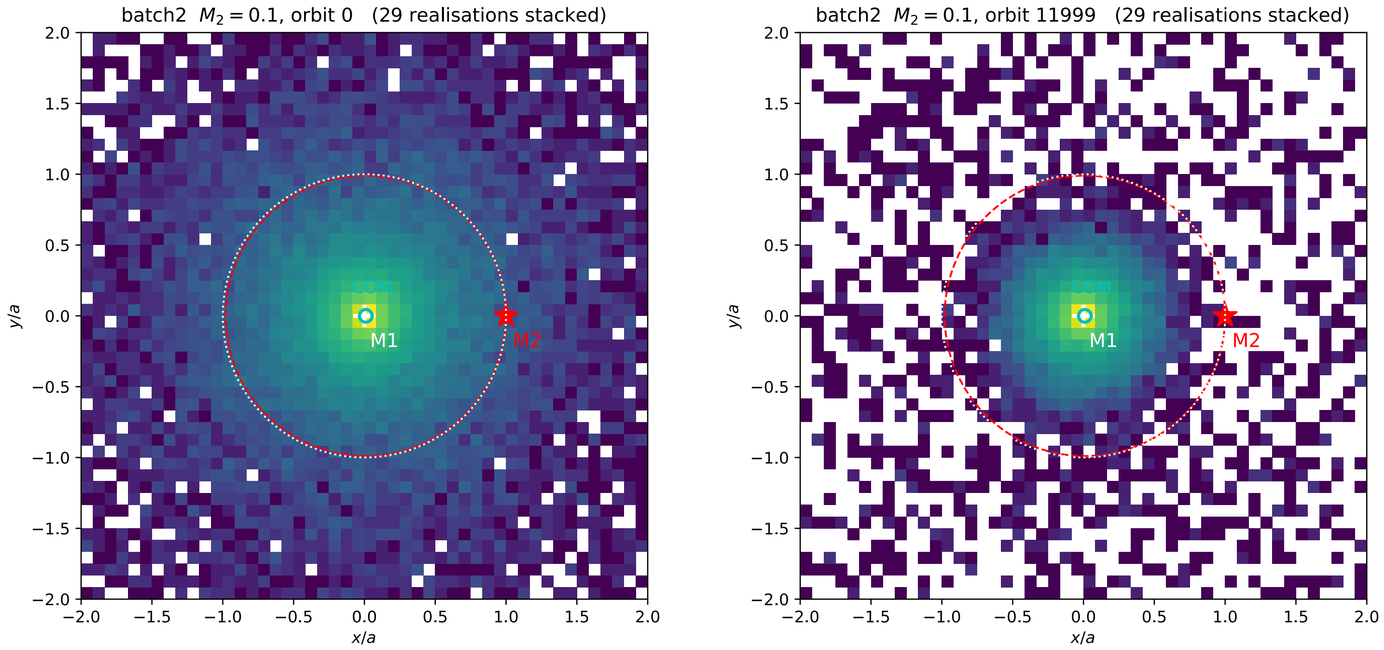


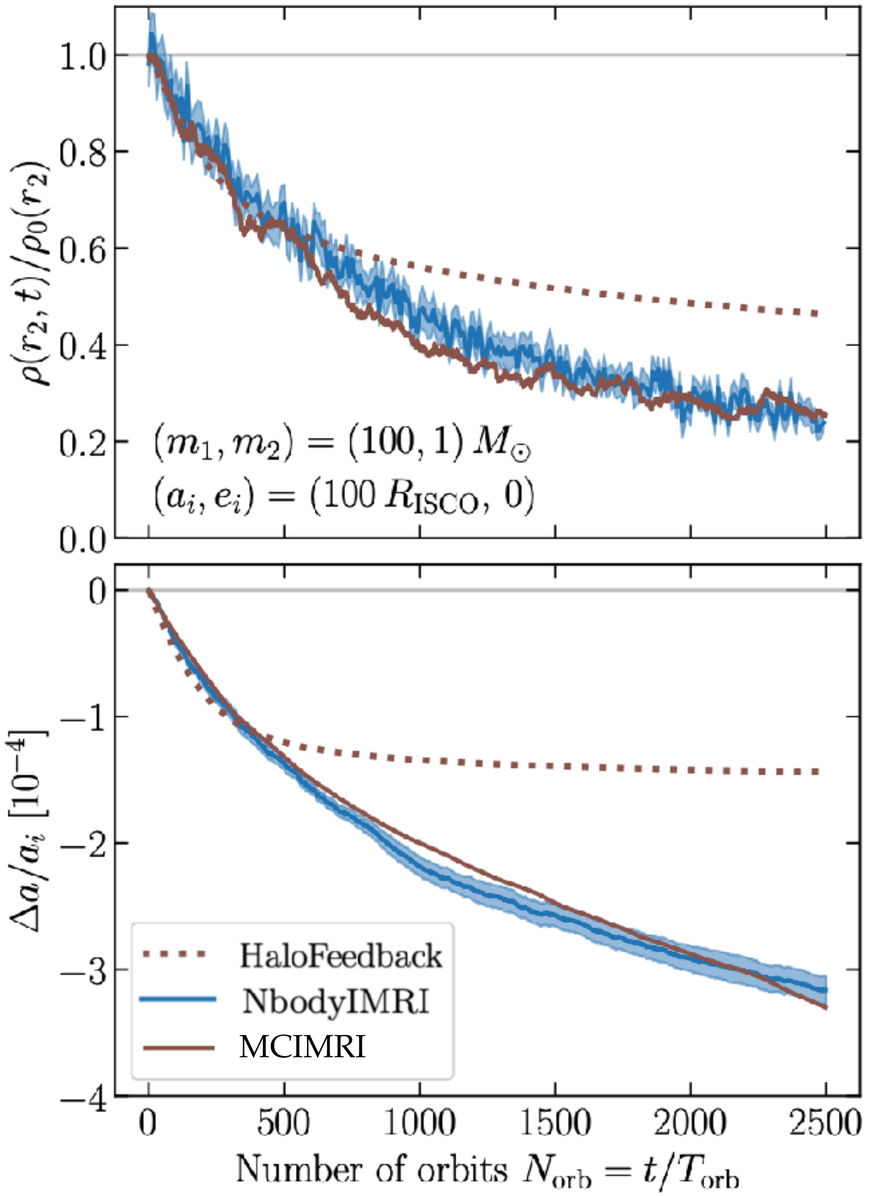




‘Individual’ Depletion

HaloFeedback NbodyIMRI MCIMRI





The three approaches agree in the early stages of evolution.

Treating individual stars in the S-cluster,
find minimal depletion:

$$\frac{\Delta\rho}{\rho_0} \approx 2.2 \times 10^{-5} \left(\frac{t}{\mathrm{Myr}}\right)$$

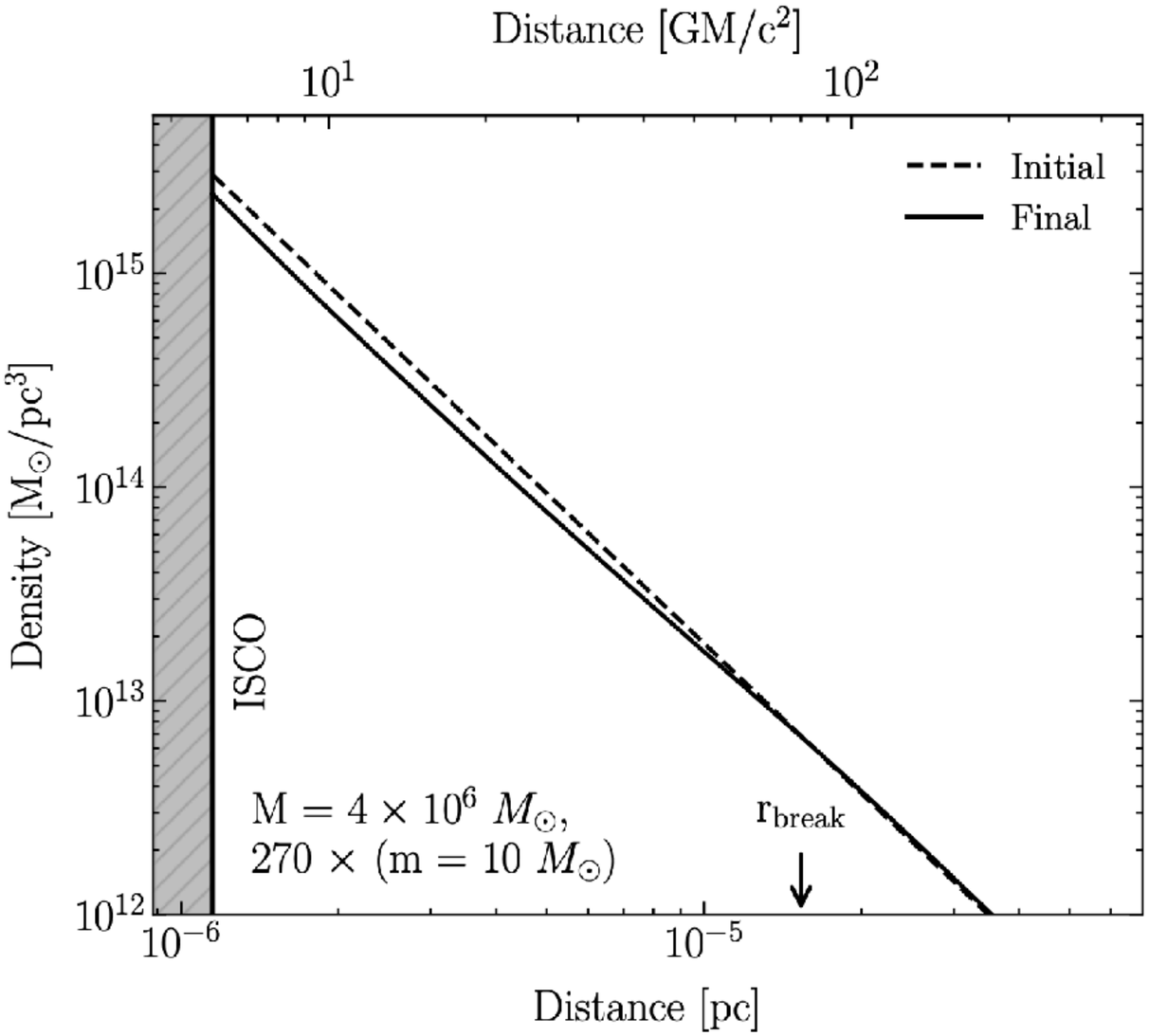
Repeated Depletion

Use HaloFeedback to simulate repeated inspirals of stellar mass BHs:

At most ~18% suppression after 270 EMRIs

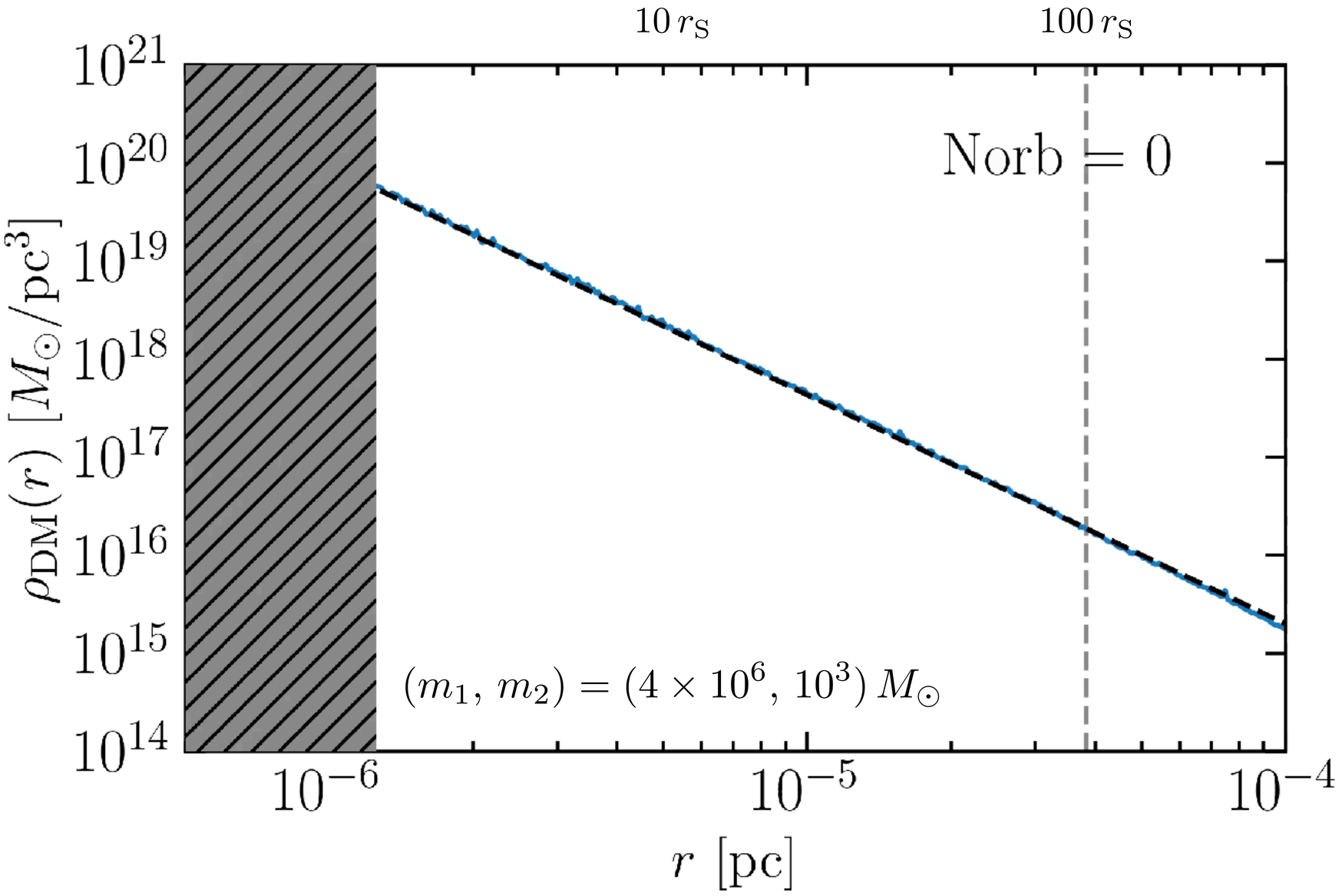
Depends a lot on secondary masses, eccentricity distributions and IMRI rate!

NB: Per orbit depletion scales as q^2, number of orbits to merger scales as q

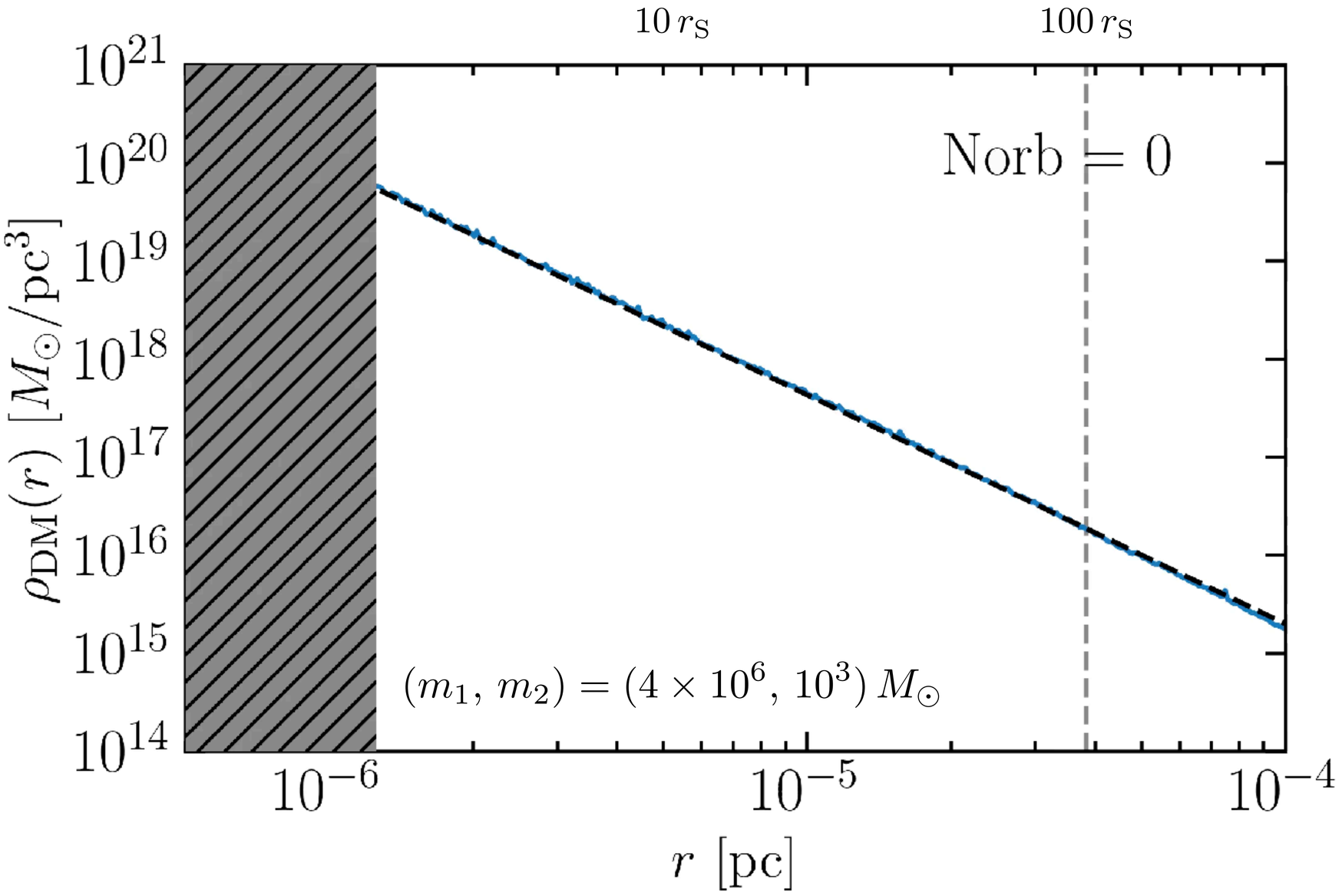


How does this compare with MCMRI?

Feedback with MCIMRI

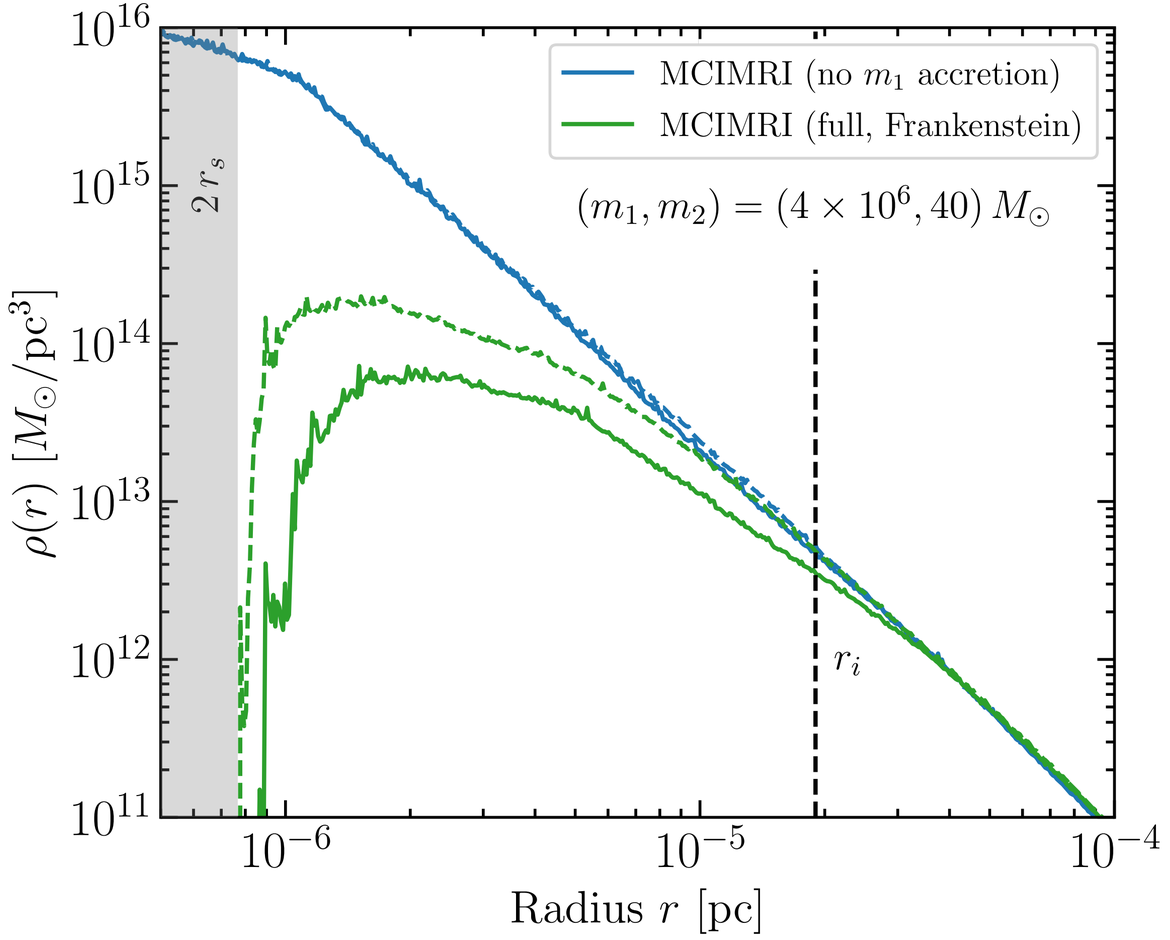


Feedback with MCIMRI



Final Density profile

After a single $q = 10^{-5}$ inspiral ($\sim 10^7$ orbits):
(Dashed blue and green lines are initial densities)



Frankenstein Prescription!

Newtonian distribution function, but reconstruct density using Schwarzschild radial velocity:

$$\tilde{v}_r^2 = c^2 - 2\mathcal{E} - \left(c^2 - \frac{2GM_{\rm BH}}{r}\right)\left(1 + \frac{L^2}{r^2 c^2}\right)$$

And don't include in density calculation DM particles with:

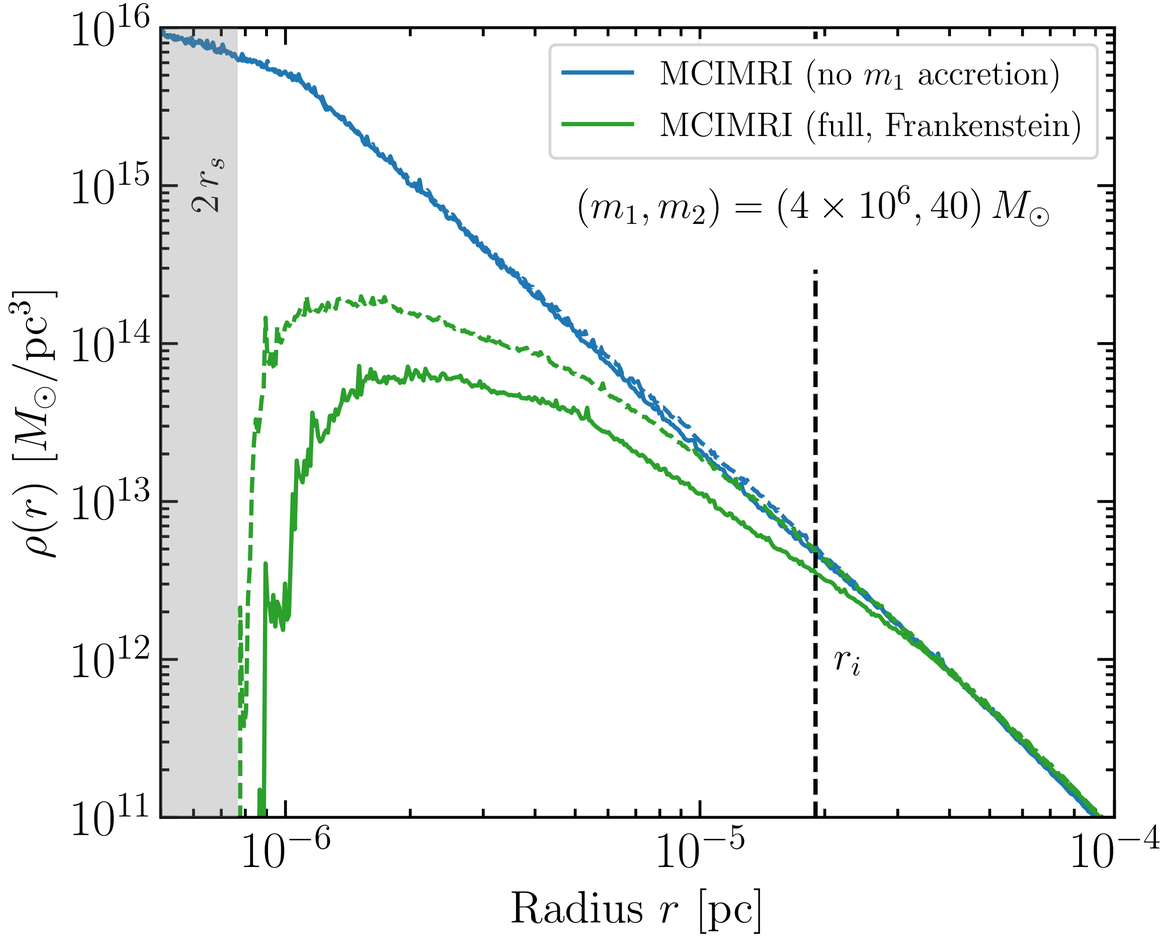
$$L < L_c \equiv 2 r_s c \left(1 - \frac{4\mathcal{E}}{c^2}\right)^{1/2}$$

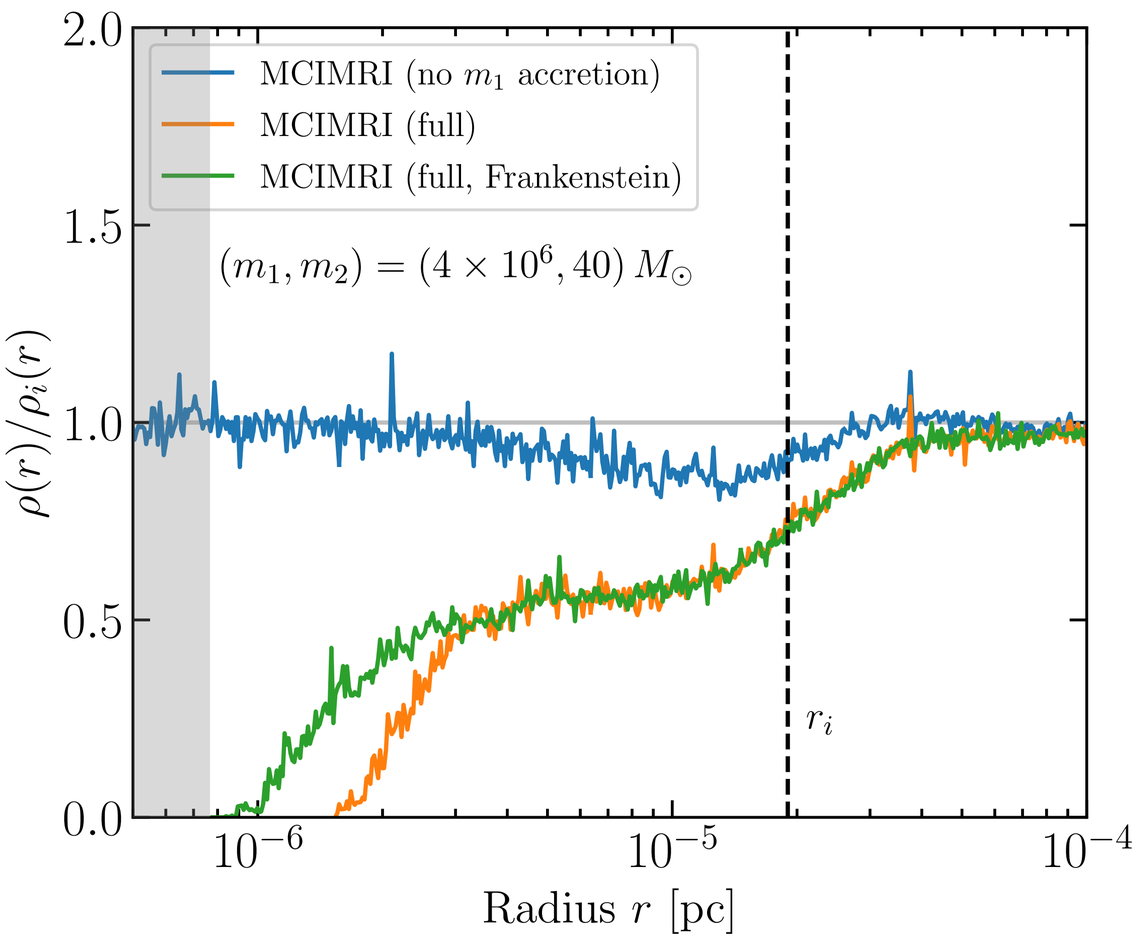
$$\mathcal{E} > \mathcal{E}_c \equiv \frac{c^2}{2} \frac{r_s (r - 2r_s)}{(r^2 + 2 r r_s - 4 r_s^2)}$$

[Bertone, Wierda, Gaggero, **BJK**, Volonteri & Yoshida, 2404.08731]

Final Density profile

After a single $q = 10^{-5}$ inspiral ($\sim 10^7$ orbits):
(Dashed blue and green lines are initial densities)





Blue curve (no accretion) seems consistent with HaloFeedback. But accretion seems to have a big effect!

The Oxford Group!

Why are these titles all so similar?
It's very hard to remember which paper is which…

The Depletion of Collisionless Dark Matter Spikes

Charlie Sharpe,[1,*] Yonadav Barry Ginat,[1,†] Thomas F. M. Spieksma,[1,‡] Alexander Heger,[2,§] and Bence Kocsis[1,3,4,¶]

[1] *Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[2] *School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia*
[3] *St. Hugh's College, University of Oxford, St. Margaret's Road, Oxford OX2 6LE, United Kingdom*
[4] *Institute of Physics, Eötvös University, Pázmány P. s. 1/A, Budapest 1117, Hungary*

(Dated: September 30, 2026)

Dense concentrations of dark matter surrounding black holes provide a compelling opportunity to probe the nature of dark matter. In the classic Gondolo–Silk model, the adiabatic growth of a massive black hole in a dark matter cusp produces a steep density spike ($\rho \propto r^{-7/3}$), potentially

[Sharpe et al., 2603.28866]

The Irreversible Depletion of Dark Matter Spikes by Extreme-Mass-Ratio Inspirals

Charlie Sharpe,[1,*] Yonadav Barry Ginat,[1] Thomas F. M. Spieksma,[1] Alexander Heger,[2] and Bence Kocsis[1,3,4]

[1] *Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*
[2] *School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia*
[3] *St. Hugh's College, University of Oxford, St. Margaret's Road, Oxford OX2 6LE, United Kingdom*
[4] *Institute of Physics, Eötvös University, Pázmány P. s. 1/A, Budapest 1117, Hungary*

(Dated: September 30, 2026)

Dense dark matter spikes around massive black holes (MBHs) have been widely predicted to produce gravitational-wave dephasing in extreme-mass-ratio inspirals (EMRIs) that are potentially observable by LISA. We show that EMRIs, the very objects used to probe these spikes, also destroy them. Combining Fokker-Planck models of nuclear star clusters with post-Newtonian three-body

[Sharpe et al., 2609.37234]

Depletion of Dark Matter Spikes by Massive Black Hole Mergers

Charlie Sharpe,[1*] Thomas F. M. Spieksma,[1,2] Yonadav Barry Ginat,[1] Ricarda S. Beckmann,[3] Alexander Heger[4] and Bence Kocsis[1,5,6†]

[1] *Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, United Kingdom*
[2] *School of Natural Sciences, Institute for Advanced Study, 1 Einstein Drive, Princeton, NJ 08540, USA*
[3] *Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, United Kingdom*
[4] *School of Physics and Astronomy, Monash University, 19 College Walk, Melbourne, Victoria 3800, Australia*
[5] *St. Hugh's College, University of Oxford, St. Margaret's Road, Oxford, OX2 6LE, United Kingdom*
[6] *Institute of Physics, Eötvös University, Pázmány P. s. 1/A, Budapest 1117, Hungary*

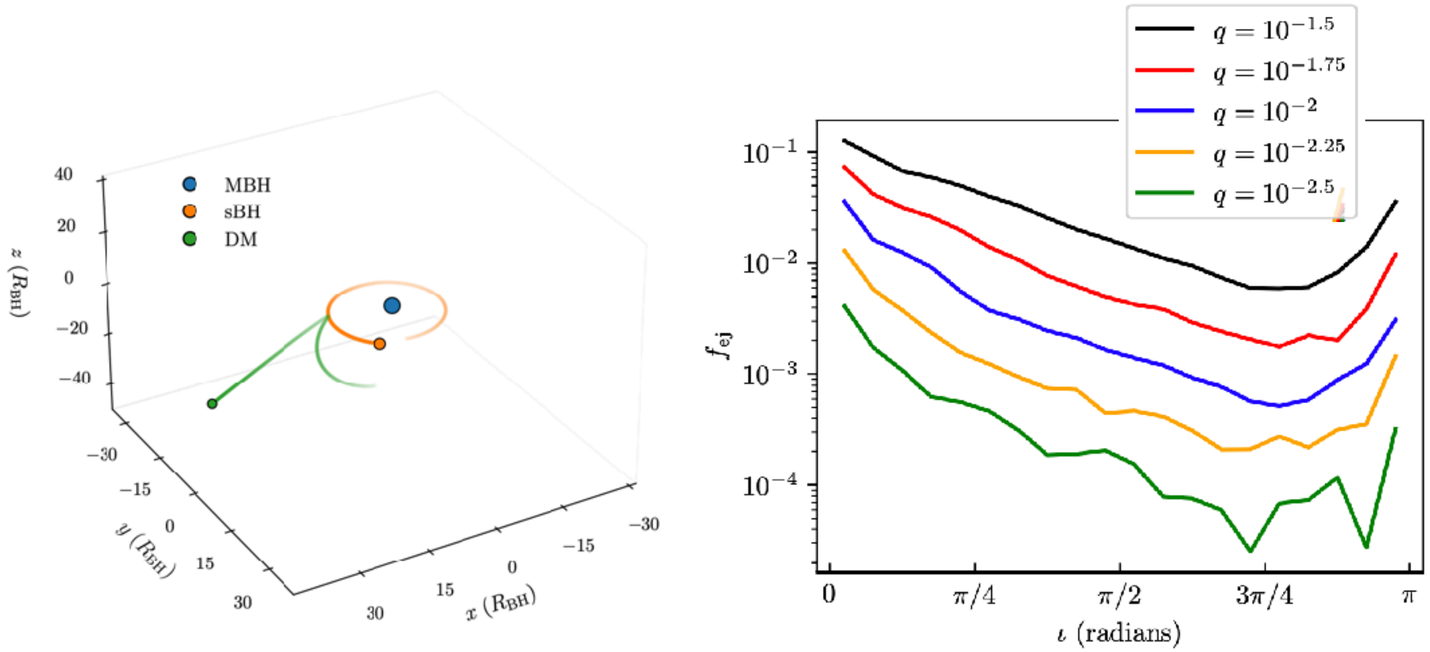
Accepted XXX. Received YYY; in original form ZZZ

[Sharpe et al., 2611.13170]

3-body Toy Simulations

[Sharpe et al., 2603.28866]

Use PN 3-body simulations to estimate probability of ejection (or accretion by primary) per binary orbit $f_{\rm ej}$:



Repeat for a grid of orbital and DM parameters, and then evolve the system 'removing' particles according to $f_{\rm ej}$

Ignores 'diffusion' and replenishment of particles in phase space.

Find a factor of 2-3 more depletion for Sgr A*

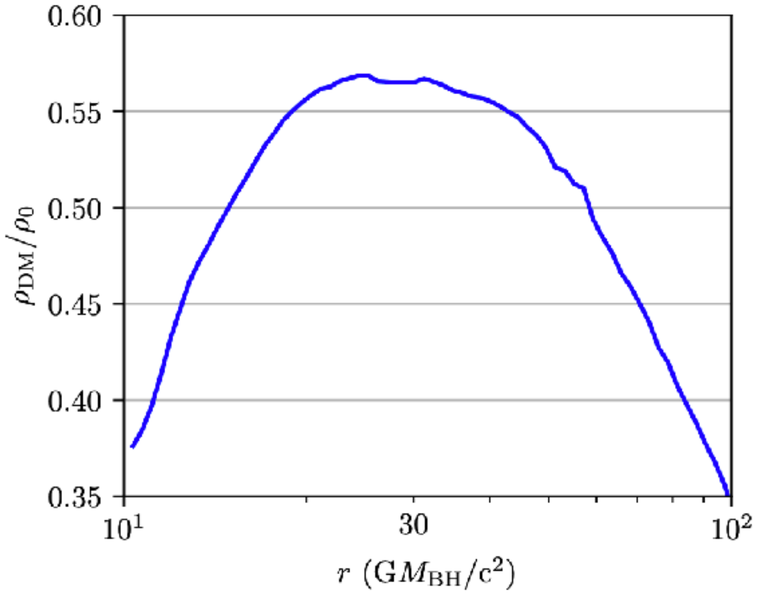


FIG. 14. The fractional reduction in DM density as a function of radius for $M_{\rm BH} = 4 \times 10^6\,{\rm M}_\odot$ after 270 EMRIs. Our calculation predicts a density reduction of $\sim 50\%$ over the radii shown, whereas Karydas *et al.* [179] report a maximum reduction of approximately 18%. This discrepancy is most likely attributable to the use of different distributions for EMRI periapsides and eccentricities.

3-body Toy Simulations

[Sharpe et al., 2609.37234]

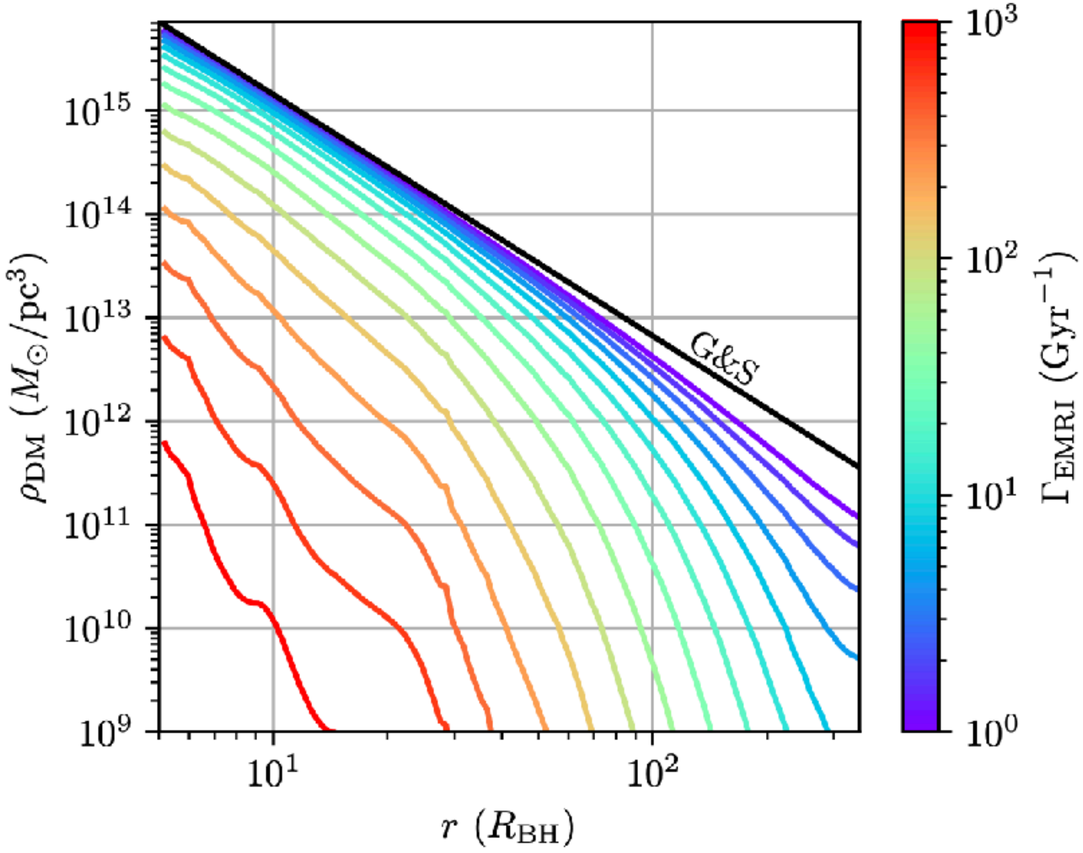


FIG. 3. The DM density profile of an EMRI-depleted DM spike by $z = 3$ (2.14 Gyr) around an MBH with mass $M_{\rm BH} = 10^6 M_\odot$ as a function of EMRI rate, $\Gamma_{\rm EMRI}$. The black line shows the original, undepleted $r^{-7/3}$ Gondolo–Silk profile.

I don't understand this.

Their formalism should include accretion by the primary (I emailed to check)

But their density profiles look like a power-law GS spike down to a few Schwarzschild radii…

Massive BH Mergers

[Sharpe et al., 2611.13170]

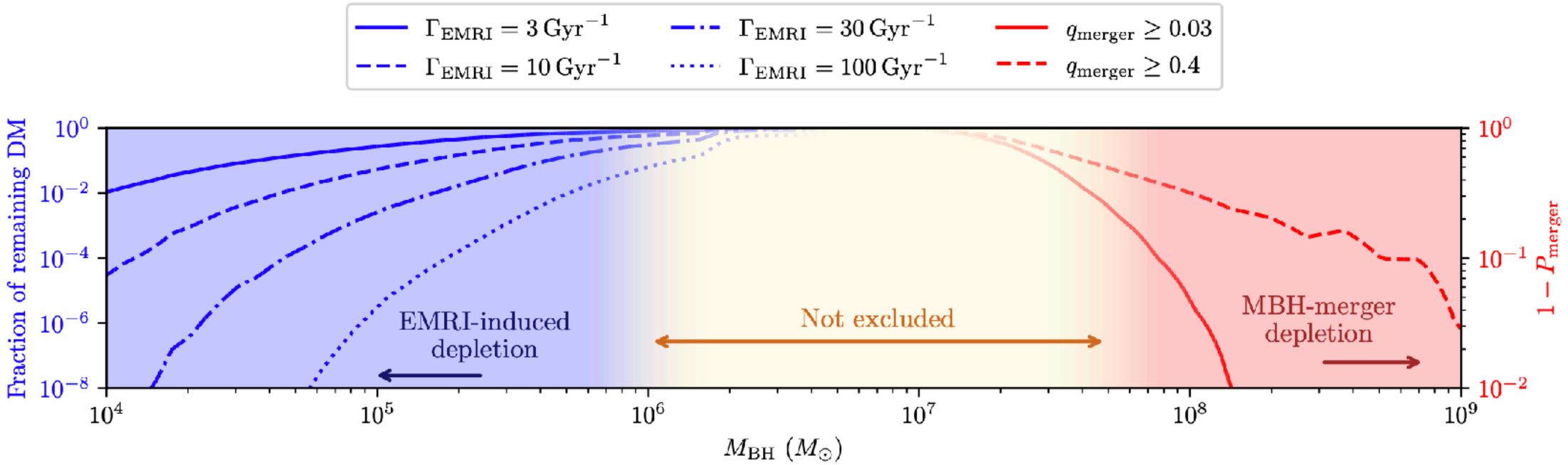


Figure 7. The range of MBH masses that have not been excluded as suitable DM spike hosts by either EMRI-induced or MBH-merger-induced DM depletion. At low masses, we show the fraction of DM density remaining at 10 Schwarzschild radii by $z = 3$, as a function of MBH mass and EMRI rate, $\Gamma_{\rm EMRI}$. At higher masses, the MBH-merger depletion shows the probability that no MBH merger has occurred by $z = 0$ as a function of mass and the merger's mass ratio, which we have labelled $q_{\rm merger}$ for clarity. $P_{\rm merger}$ is the probability that a merger has occurred.

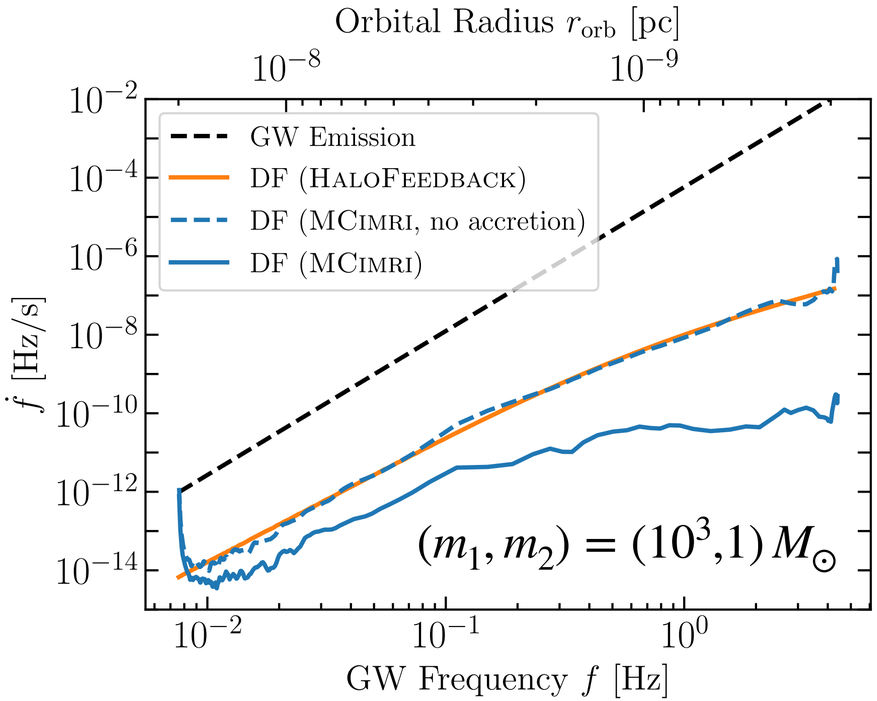
Feedback and Dephasing

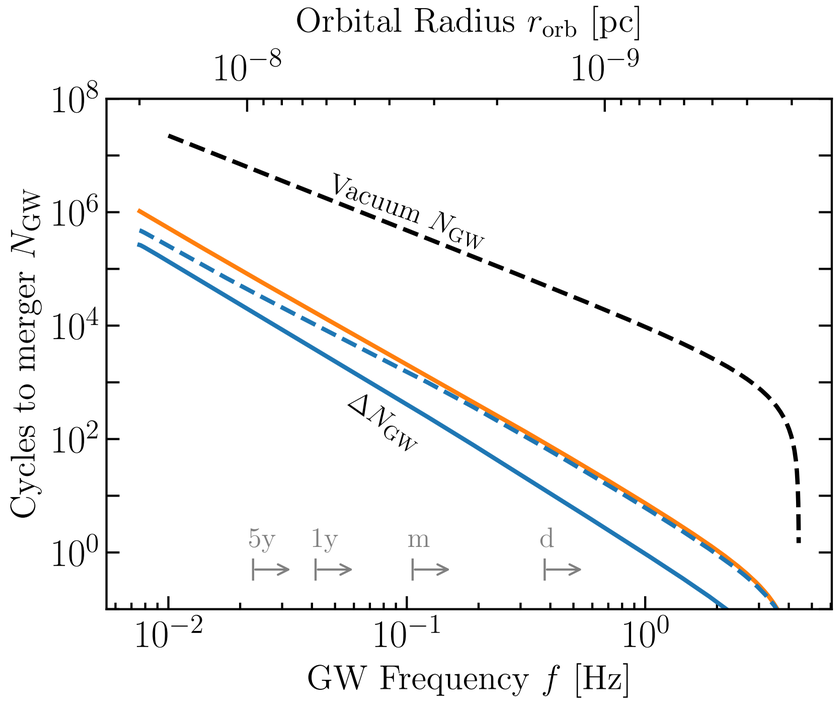
Frequency evolution: $\dot{f} = \frac{3}{2} f \frac{\dot{E}}{E_{\rm orb}}$

MCIMRI results seem to match HaloFeedback (in the absence of accretion)!

Shell Model: $\dot{E}_{\rm DF} \sim \dot{r} \frac{U_{\rm bind}}{{\rm d}r}$

Accretion by the primary seems to reduce the dephasing by ~1 order of magnitude





Open Questions

Galactic History

- Stellar distribution and population
- Are there hidden point masses (SBHs? old stars?)
- EMRI rate, masses and eccentricities
- Possible regrowth?

Relativistic effects

- Relativistic ‘kicks’ from DF
- Relativistic distribution functions

Impact of accretion

- Are these effects real?
- Are we capturing them correctly (Frankenstein approach!)
- Under what circumstances are they important?

Future approaches

- Better (faster) N-body simulations?
- More ‘complete’ semi-analytic formalisms?

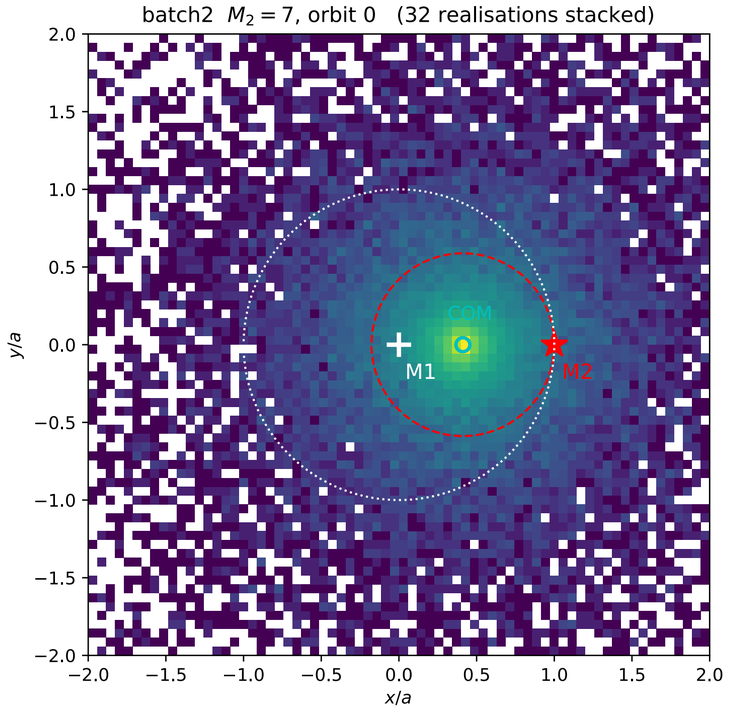
Backup Slides

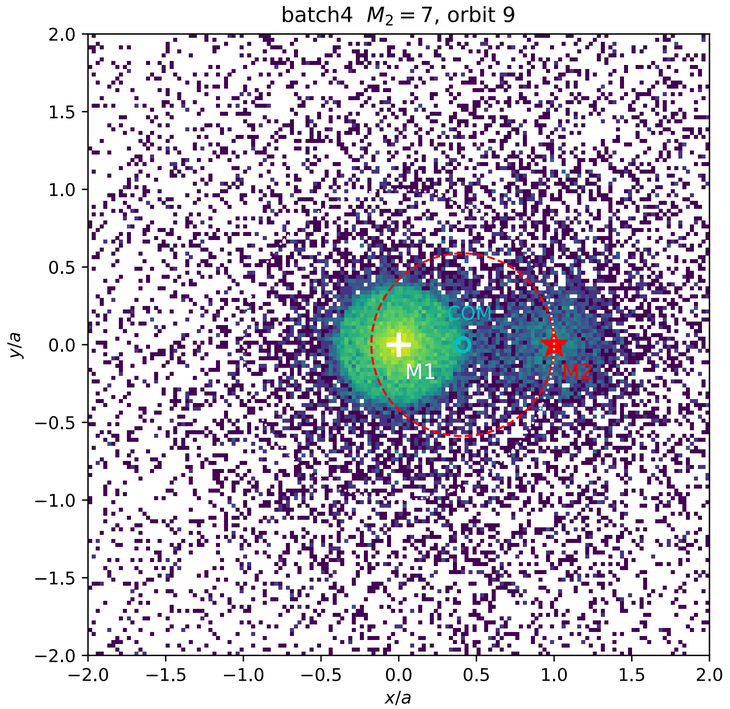
Almost equal masses

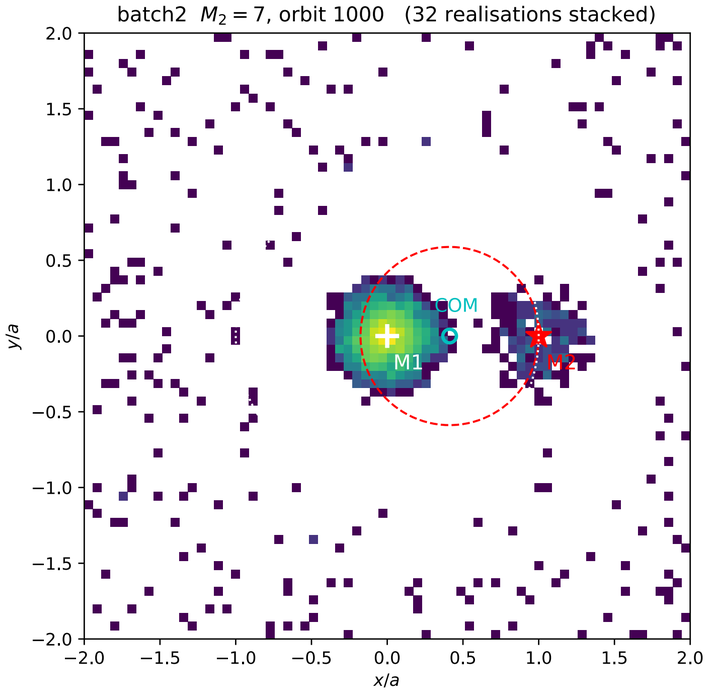
Mass ratio $q = 0.7$

Depletion is rapid!

Sub-population of DM becomes bound around each BH…

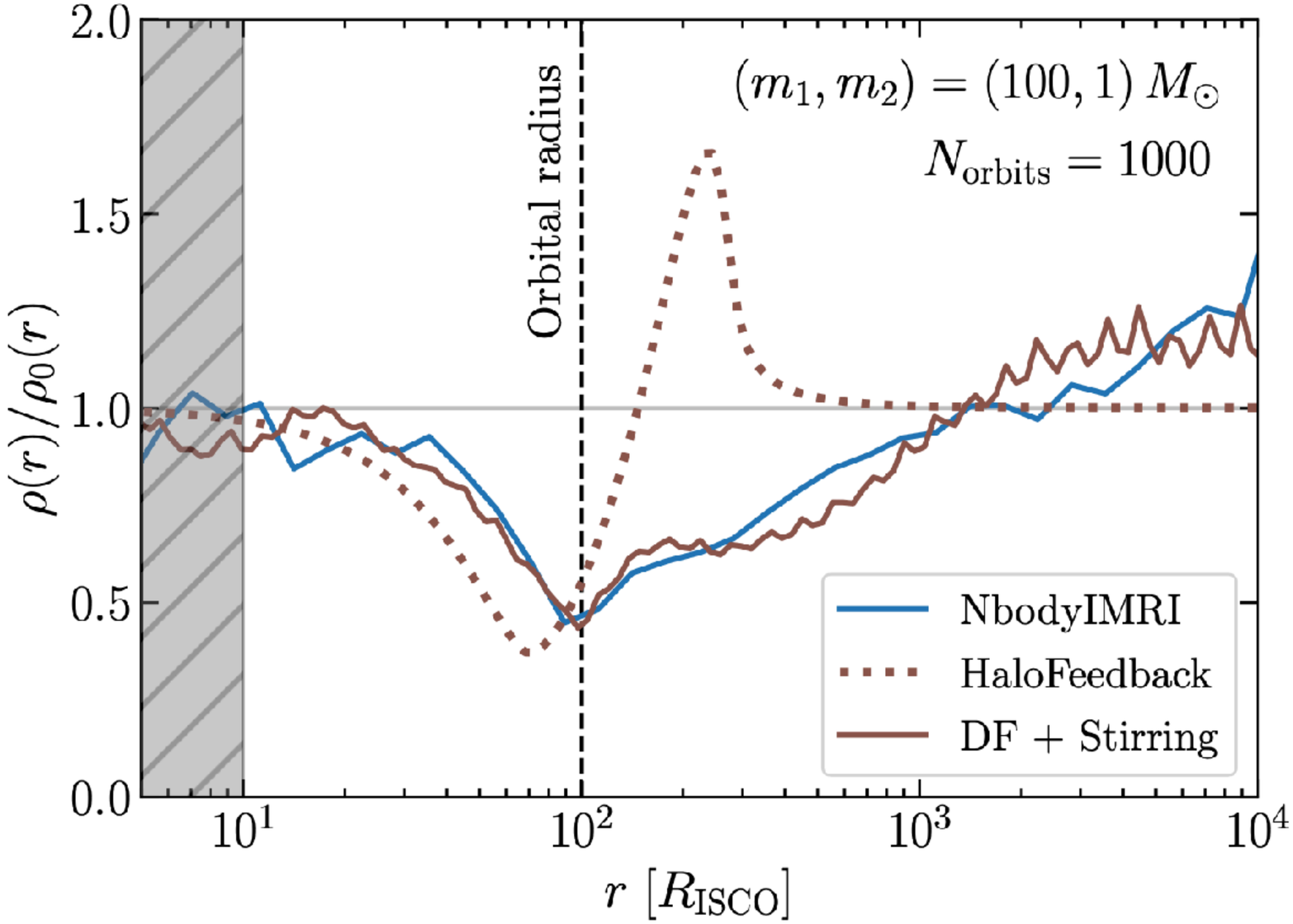




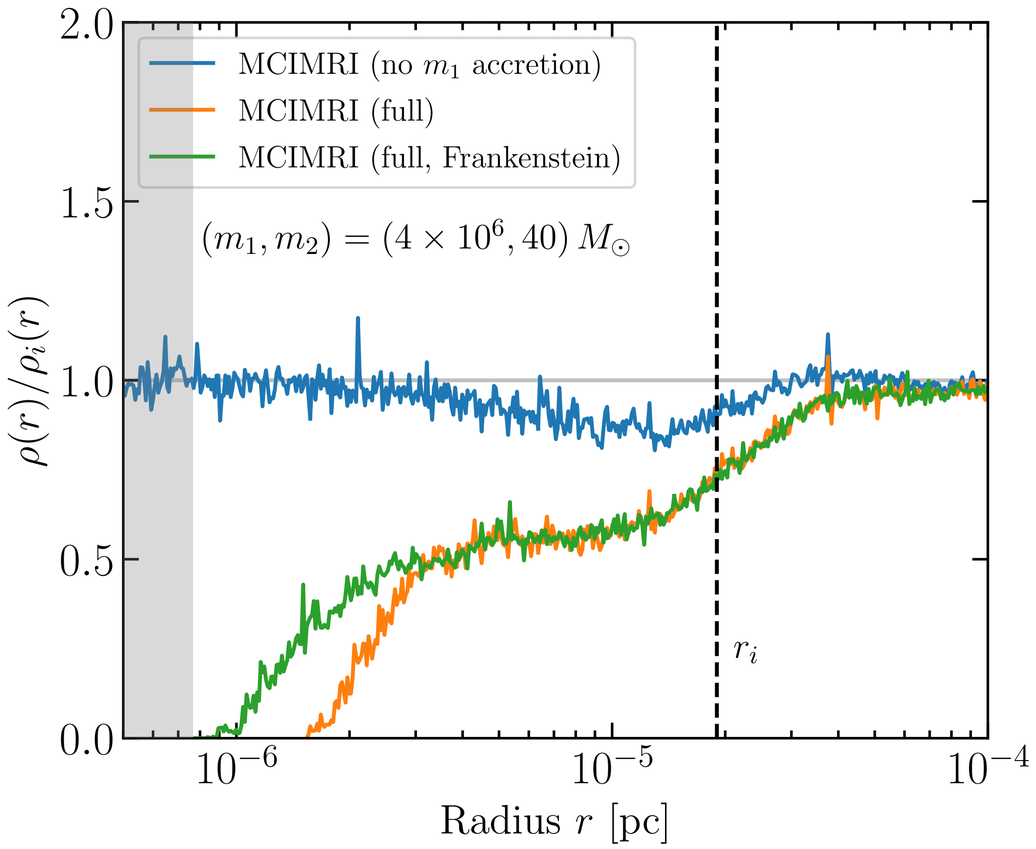


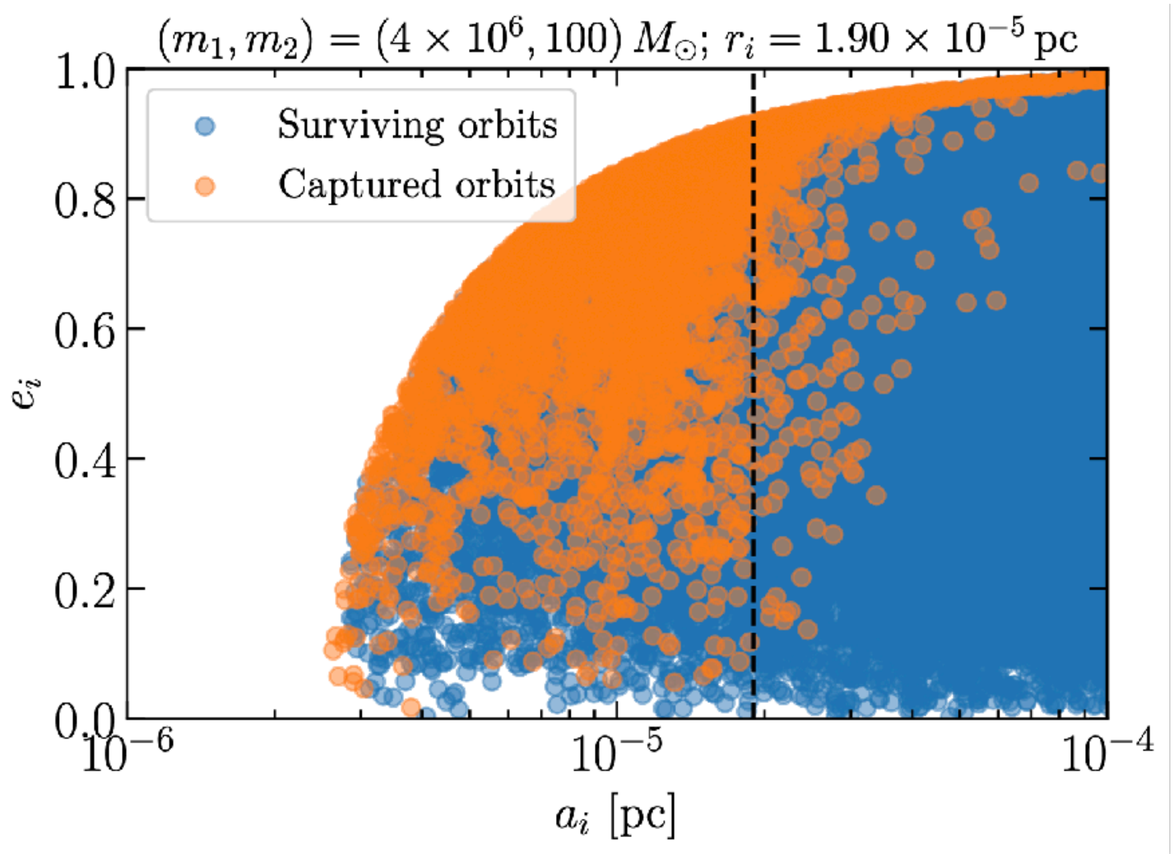
[Scarcella & **BJK**, 2611.XXXXX]

Density Profiles

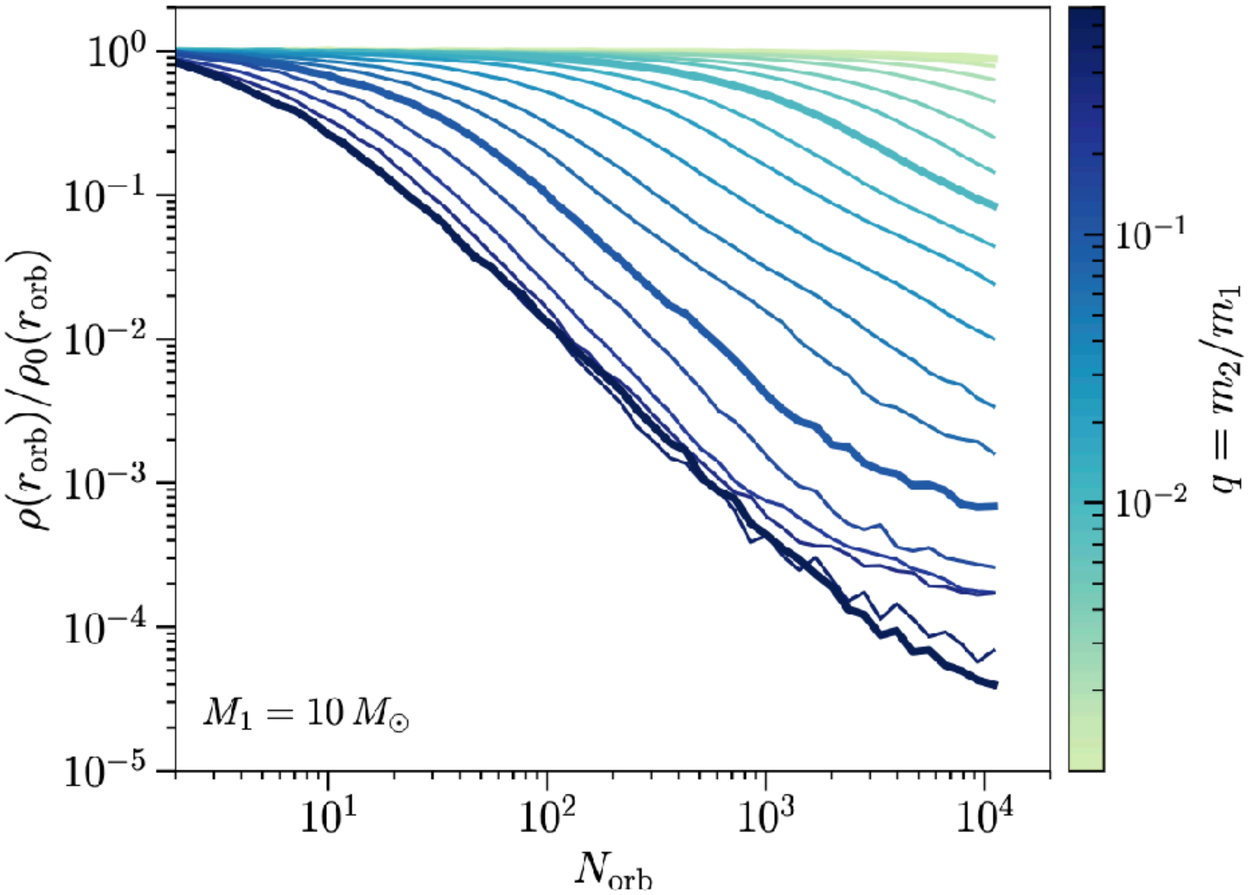


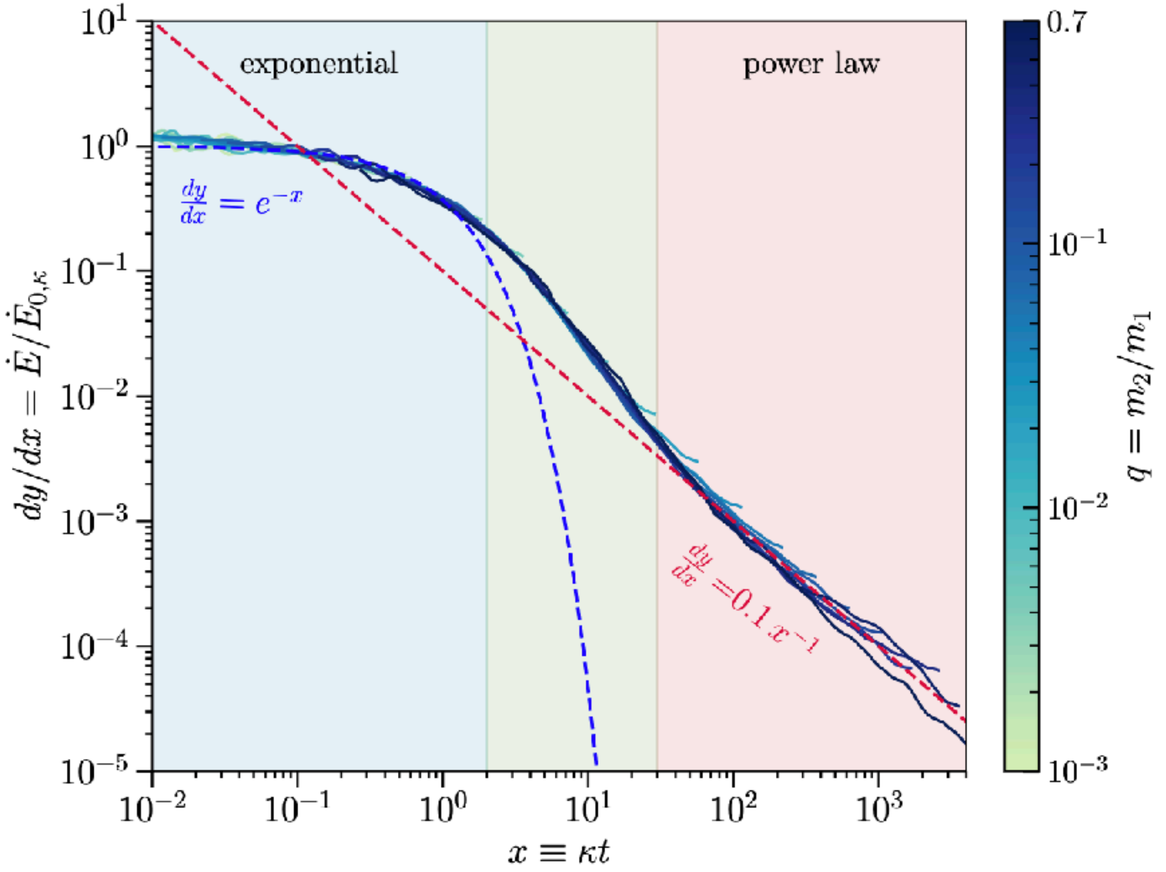
Accretion


MCIMRI (no m_1 accretion)
MCIMRI (full)
MCIMRI (full, Frankenstein)
$(m_1, m_2) = (4 \times 10^6, 40)\, M_\odot$
r_i
$\rho(r)/\rho_i(r)$
Radius r [pc]


$(m_1, m_2) = (4 \times 10^6, 100)\, M_\odot$; $r_i = 1.90 \times 10^{-5}$ pc
Surviving orbits
Captured orbits
e_i
a_i [pc]

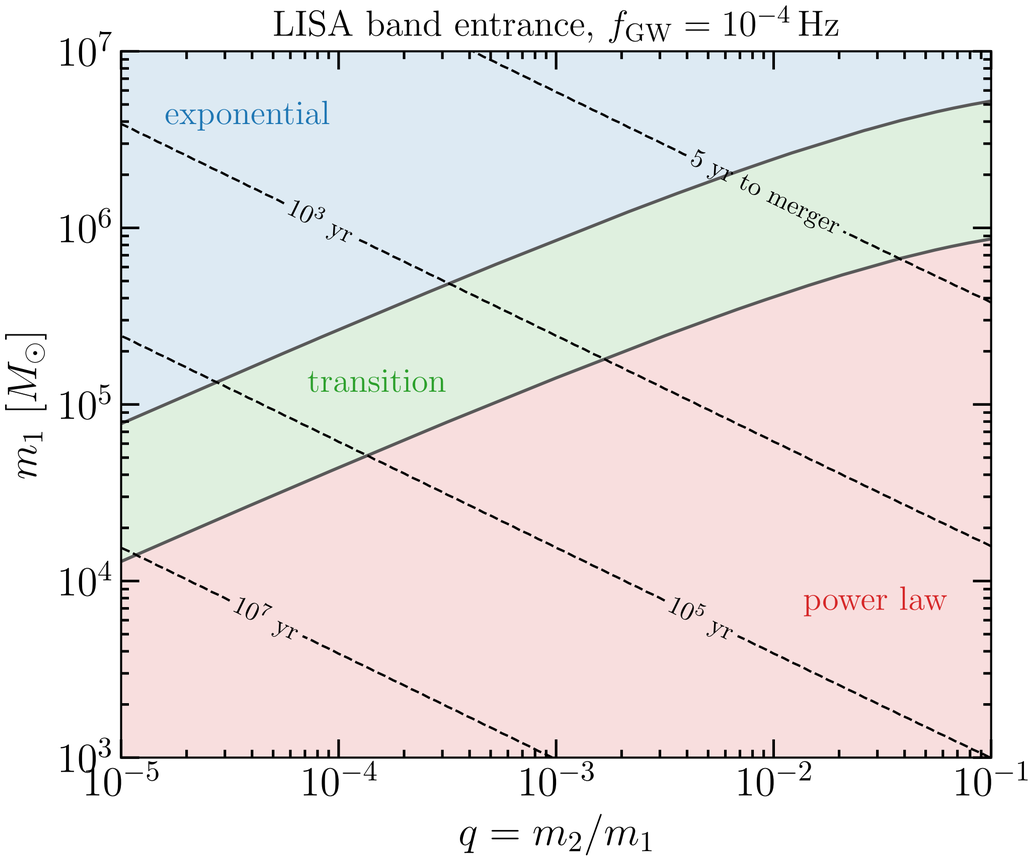
Density Evolution

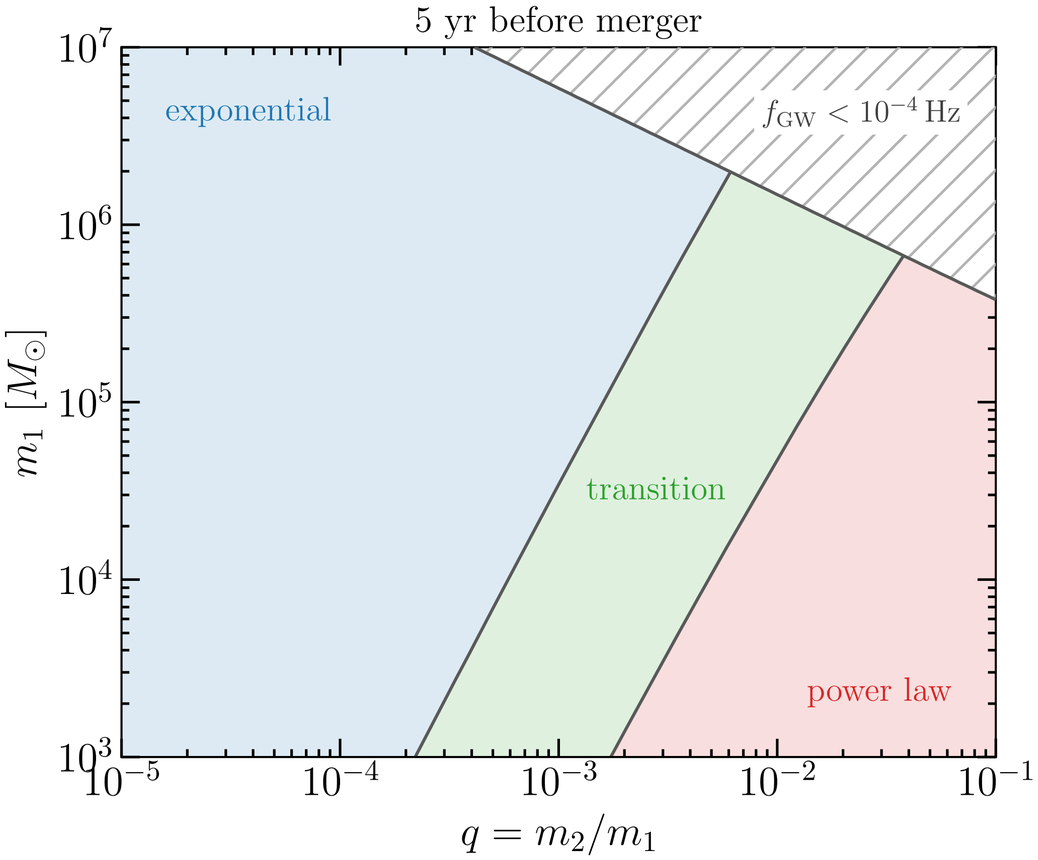




[Scarcella & **BJK**, 2611.XXXXX]

Timescales





[Scarcella & **BJK**, 2611.XXXXX]

Dependence on mass ratio

This scaling matches rough analytic estimates:

$$\dot{E}_{\rm DF} \sim \frac{(m_2)^2}{v_{\rm orb}} \sim \frac{(m_2)^2}{(m_1)^{1/2}}$$

$$U_{\rm bind} \sim m_1$$

$$N_{\rm depl} \sim \frac{U_{\rm bind}}{\dot{E}_{\rm DF} T_{\rm orb}} \sim \frac{(m_1)^2}{(m_2)^2}$$

See more detailed calculation in Appendix A of https://arxiv.org/abs/2108.04154

Putting everything together gives

$$t_{\rm dep}(\mathcal{E}) \sim \frac{m_1^2\, T_{\rm orb}}{32\, m_2^2\, \log(1+m_1/m_2)} \frac{2x-1}{x^{5/2}\sqrt{1-x}}\,, \tag{A17}$$

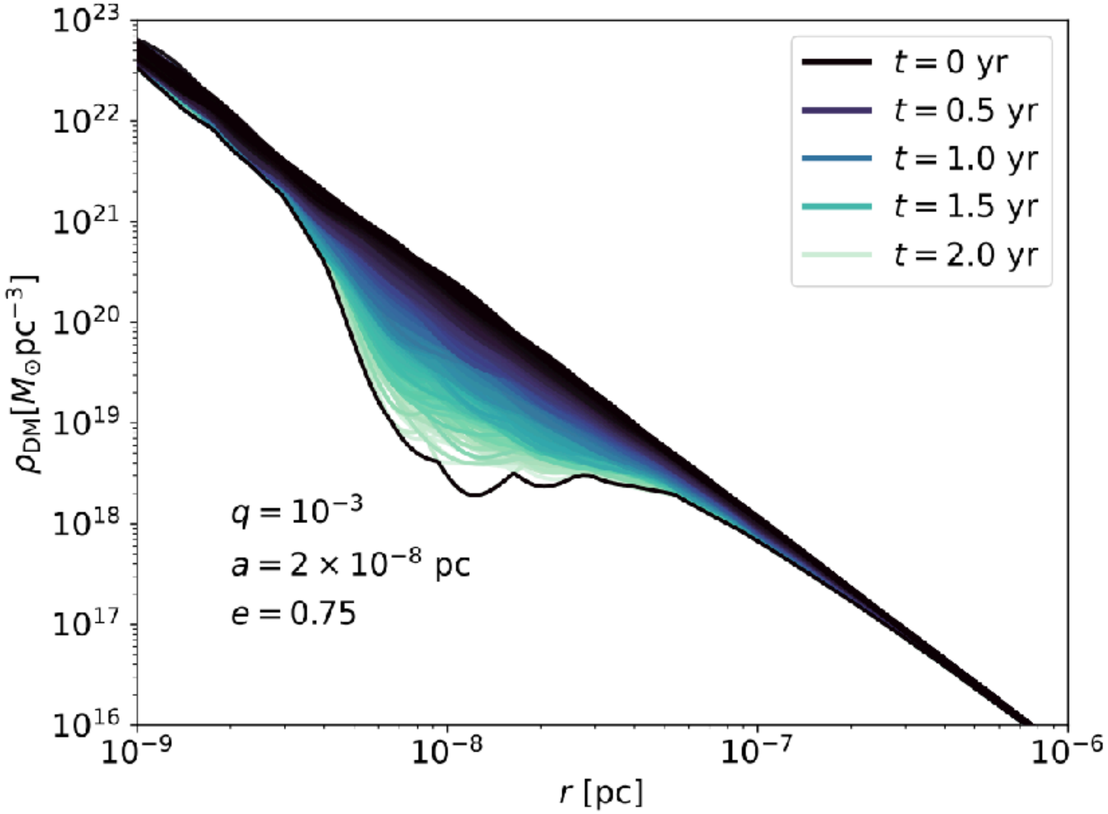
where $x = \mathcal{E}/\Psi(r_2)$ and we remind the reader that $\Psi(r_2) = G_N m_1/r_2$.

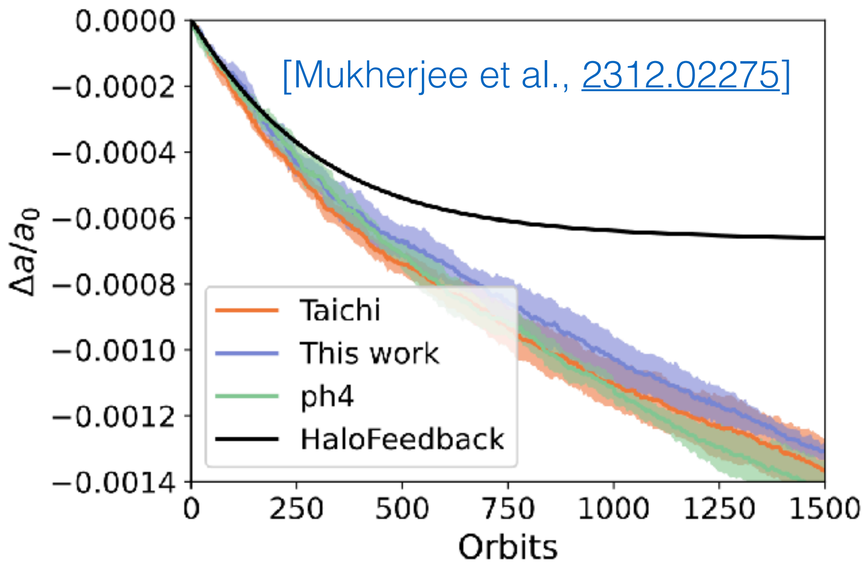
Simulations comparison?

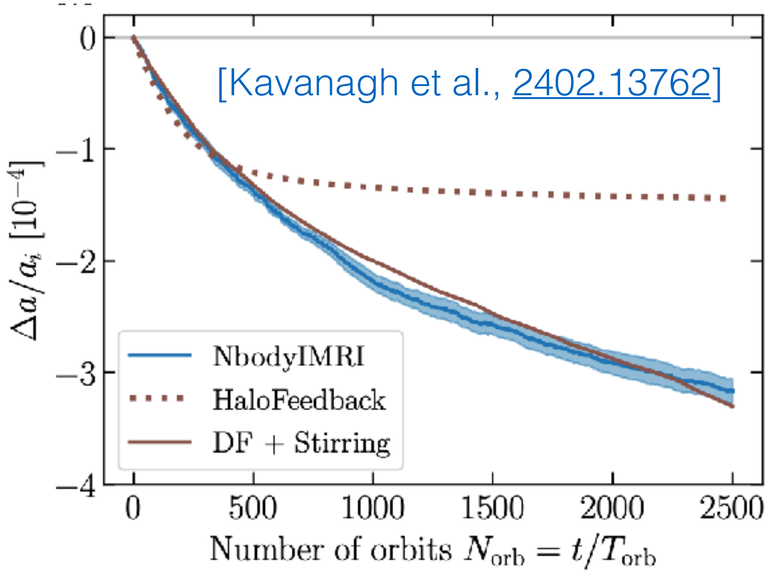
Its not clear whether all codes give the same results

[Mukherjee et al., 2312.02275]

Simulation with Ketju
(much faster than NbodyIMRI)



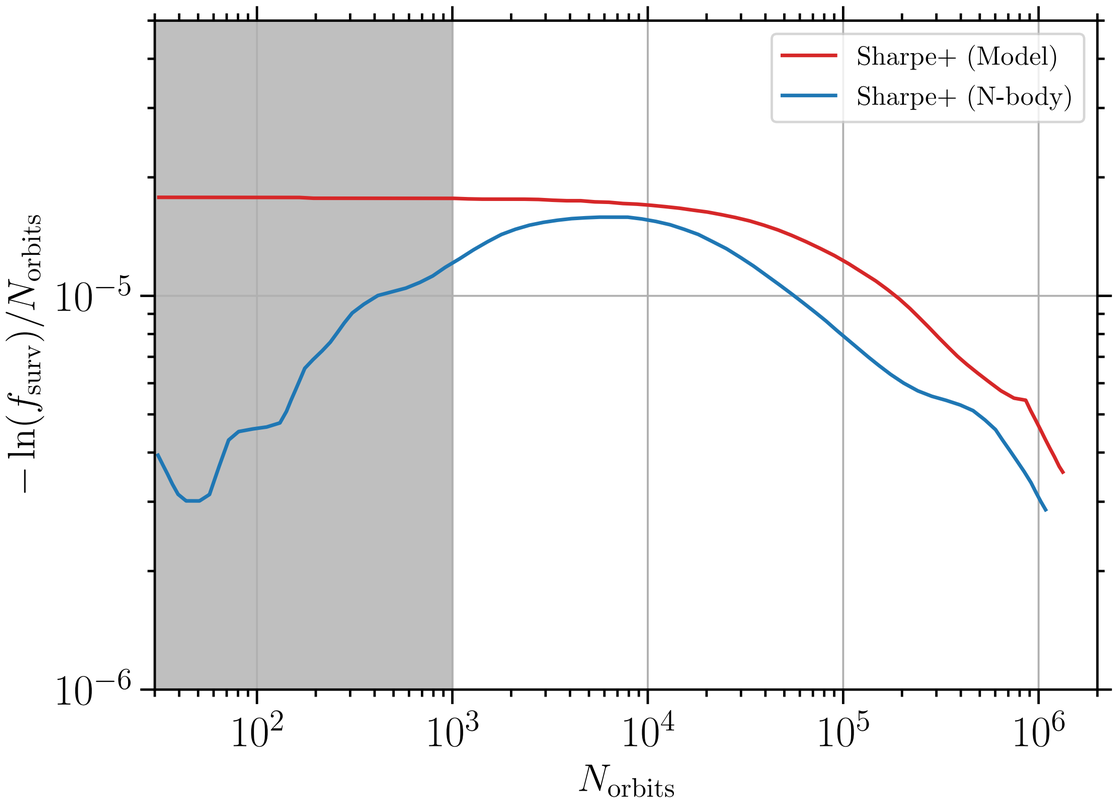


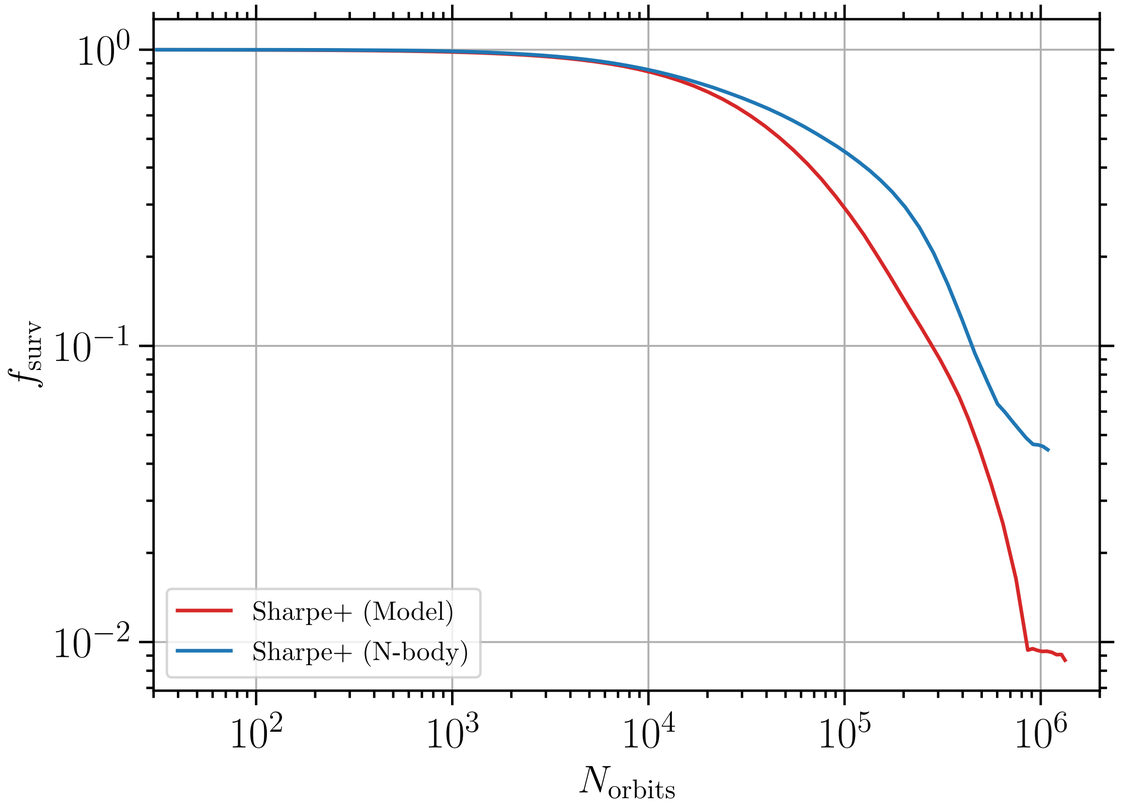


Can we do a direct comparison of different codes?

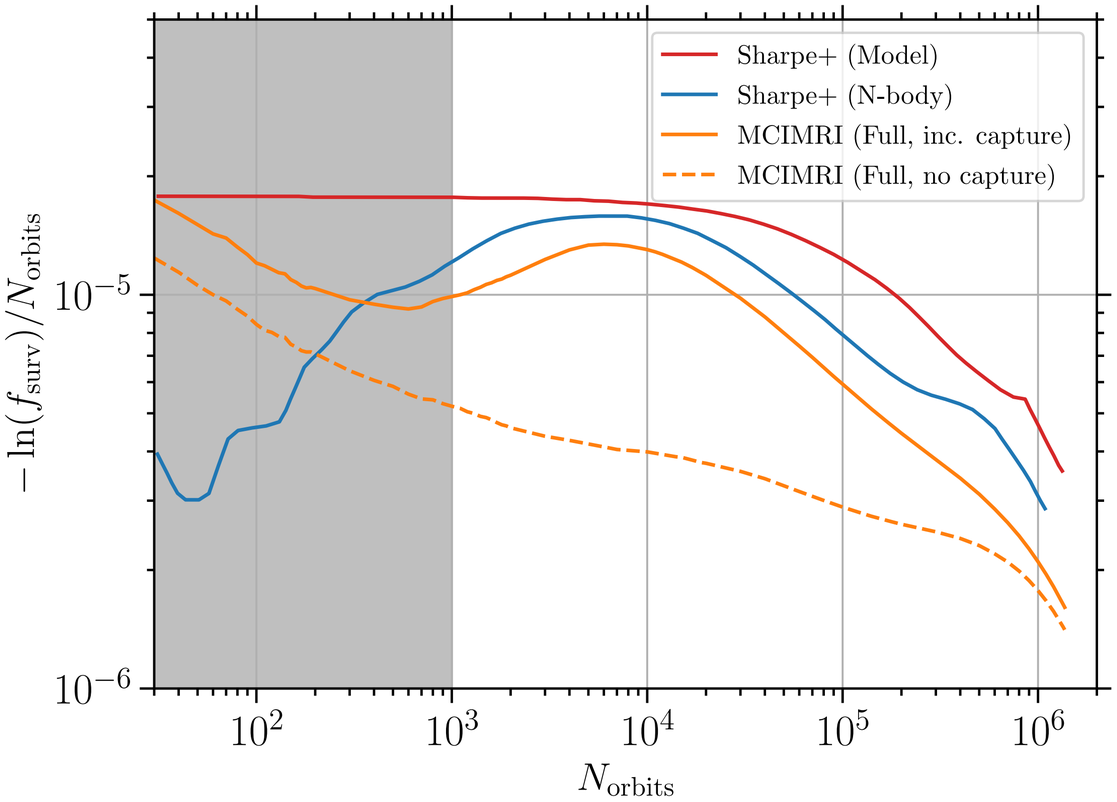
- NbodyIMRI
- Ketju (includes some PN corrections)
- Gadget4

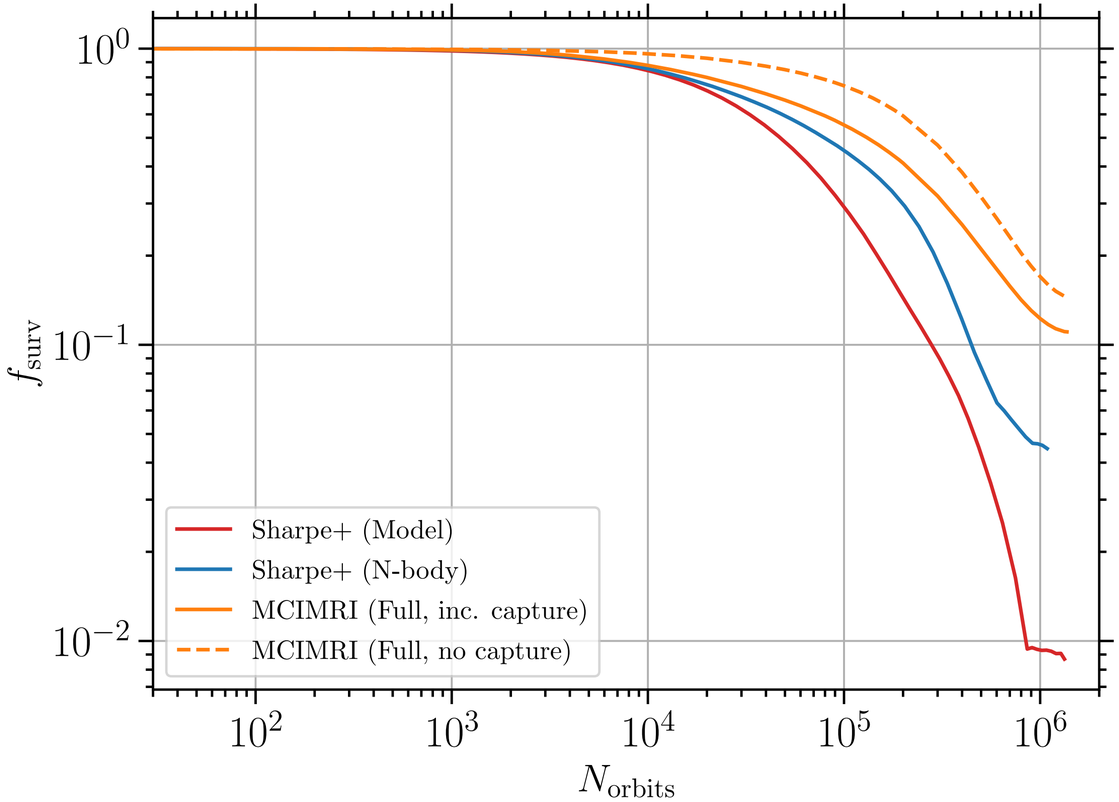
Comparison with Sharpe+





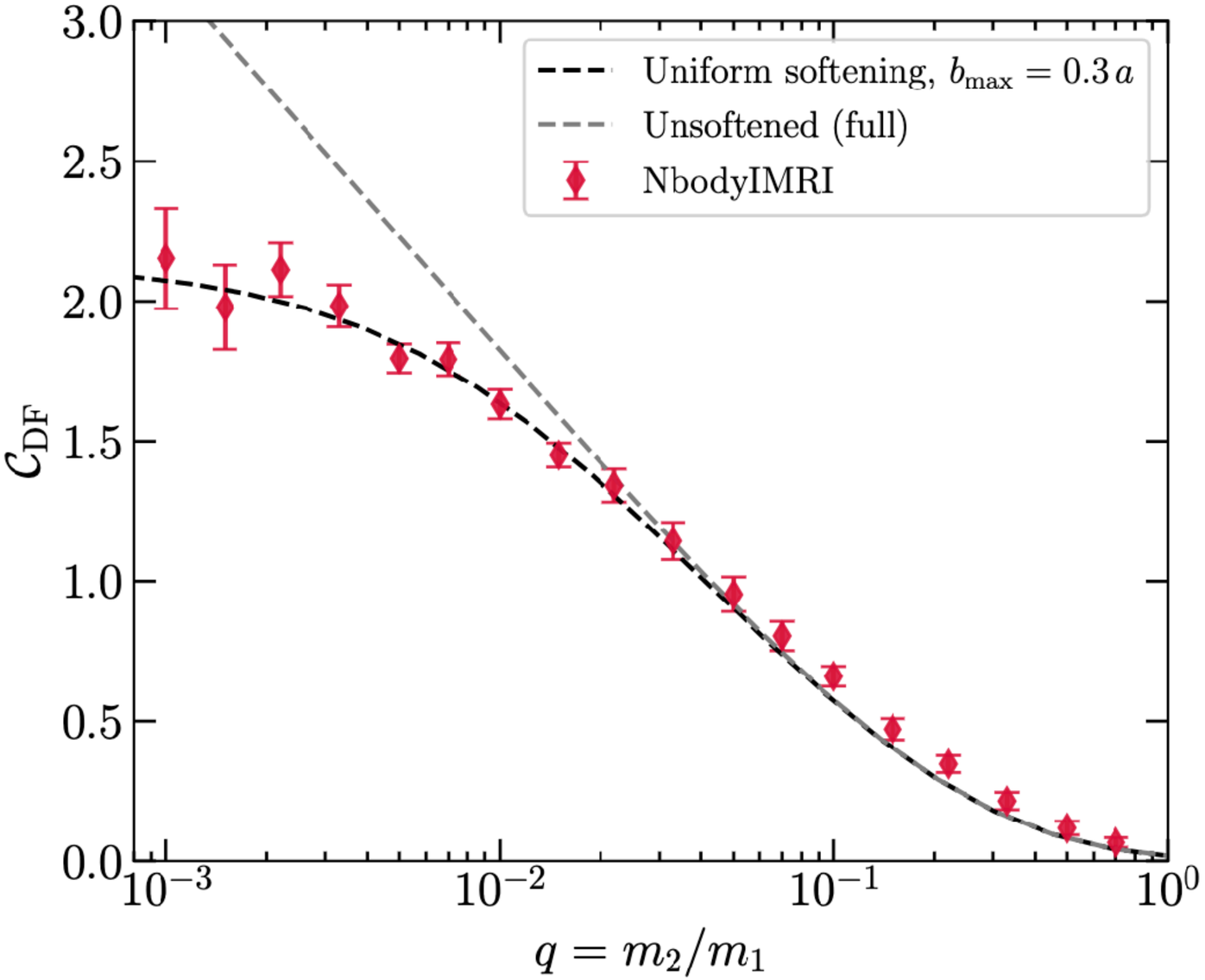
Comparison with Sharpe+





Dynamical Friction

$$\boldsymbol{F}_{\rm DF} = -4\pi \frac{(G m_2)^2}{u^2} \rho_{\rm DM}(r_2)\, \mathcal{C}_{\rm DF} \hat{\boldsymbol{u}}$$



[Scarcella & **BJK**, 2611.XXXXX]