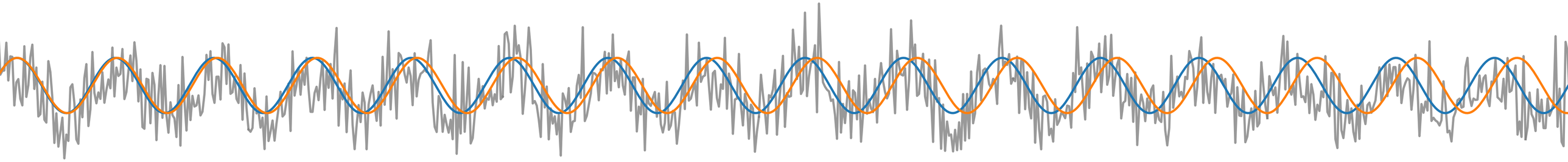

Environmental Effects of Dark Matter Spikes on EMRIs

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Outline of this talk

1. Introduction to **dark matter spikes**.
    A. What is dark matter?
    B. How do dark matter spikes form?
    C. What can we learn from dark matter spikes?
2. **Modelling environmental effects** from dark matter.
    A. The main effects.
    B. Impact of phase space distribution.
3. **Fully relativistic treatment** of EMRI-spike interactions.

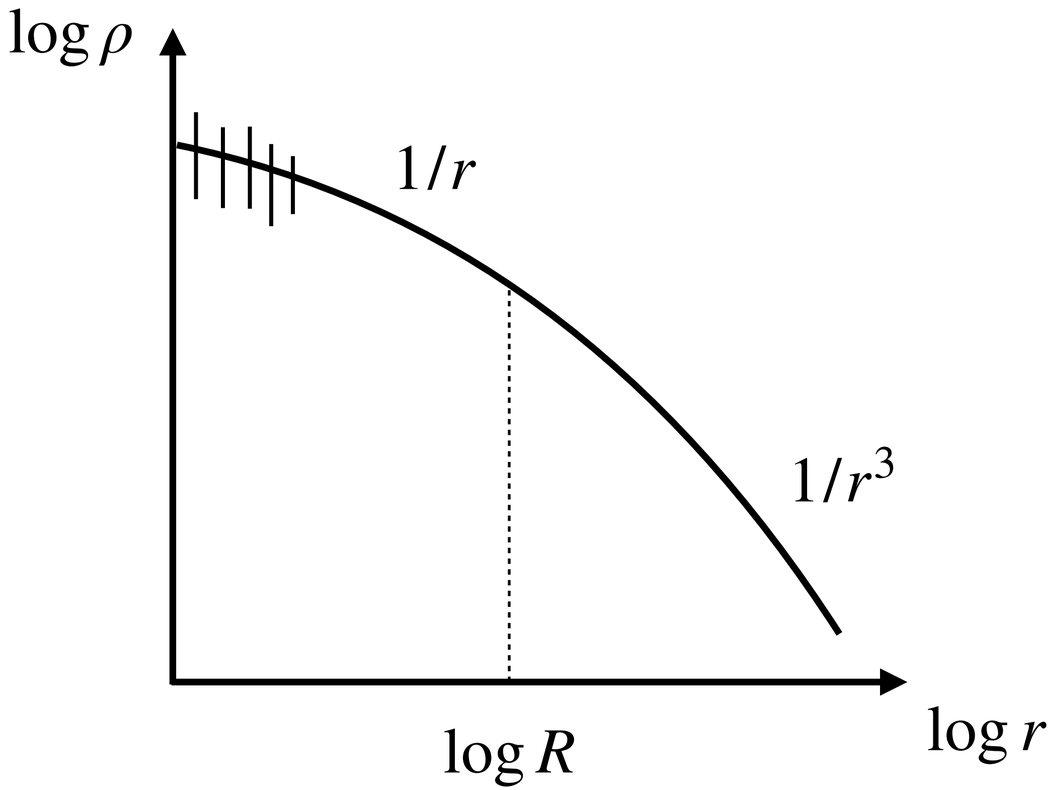
What is dark matter?

Dark matter halos

NFW profile arising from cosmological simulations

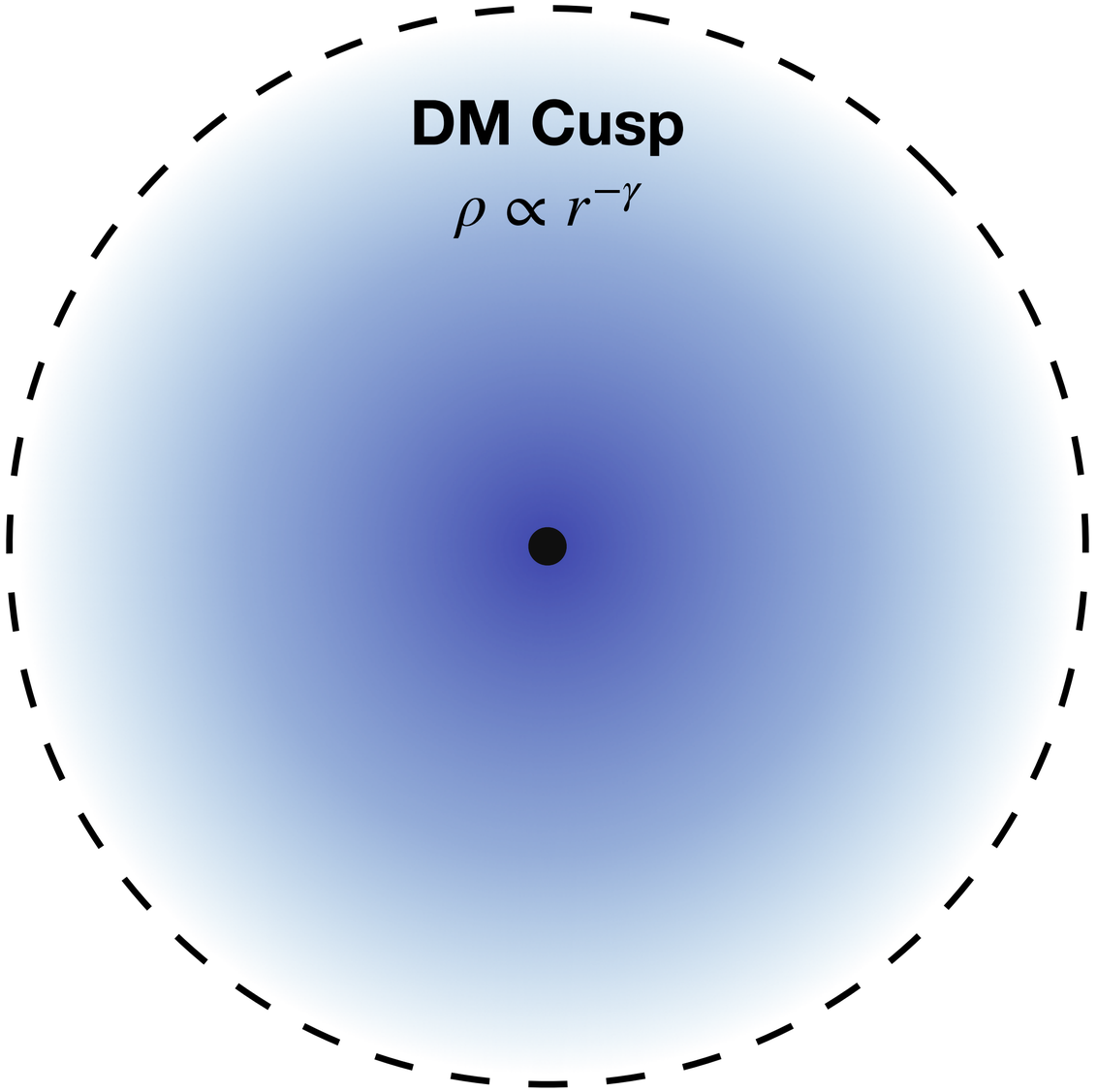
$$\rho(r) \propto \frac{1}{r\,(R+r)^2}$$

Inner region is poorly resolved



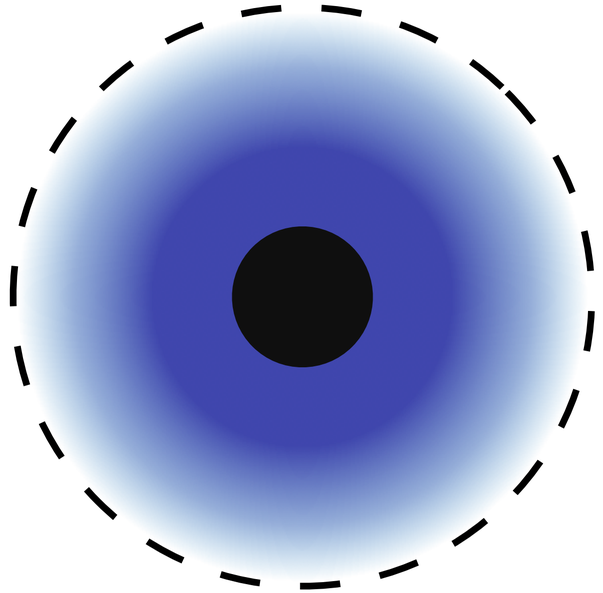
JFN, CSF, SDMW, et al. Astrophys. J. 490 (1997)

Dark matter distribution near black holes



Adiabatic BH Growth

$$L = L'$$
$$I_r = I'_r$$



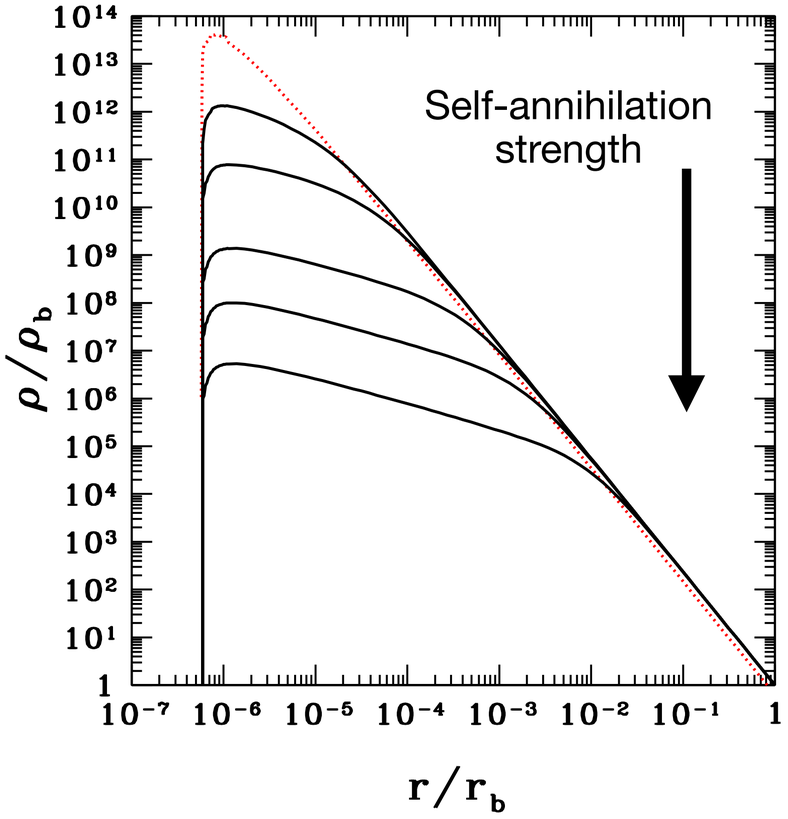
$$\gamma_{\rm sp} = \frac{9 - 2\gamma}{4 - \gamma}$$

P. Young, AJ 242:1232 (1980)
P. Gondola, J Silk, PRL 83:1719 (1999)
L. Sadeghian, et al. PRD 88:063522 (2013)

Spikes are sensitive to dark matter properties

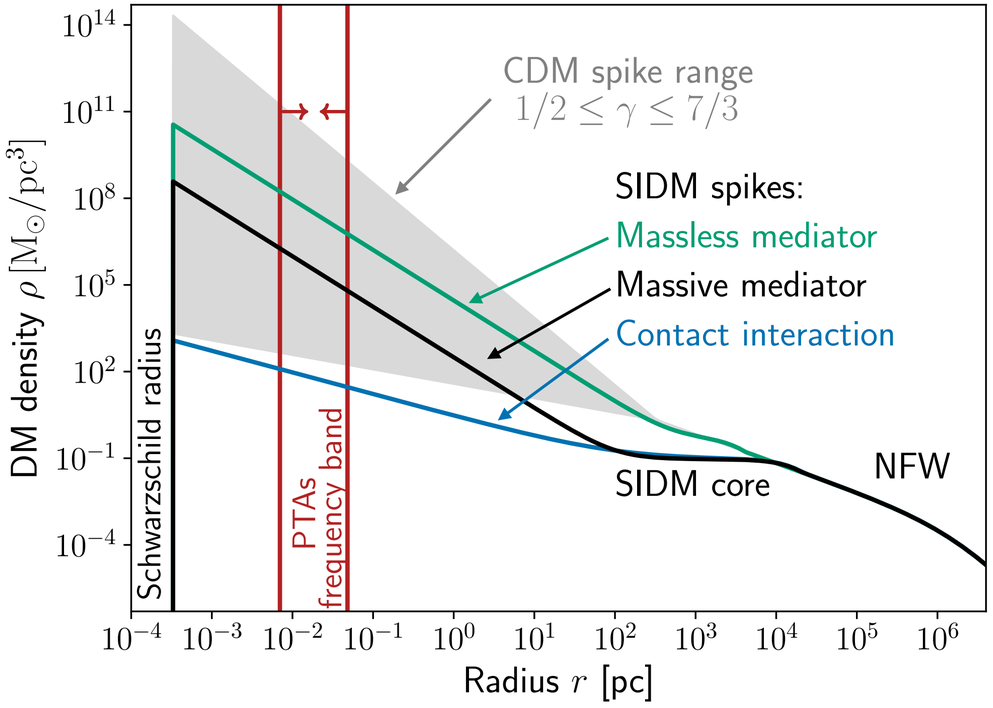
WIMPs / Self-annihilation

SL Shapiro, J Shelton PRD (2016)



Self-Interaction Models

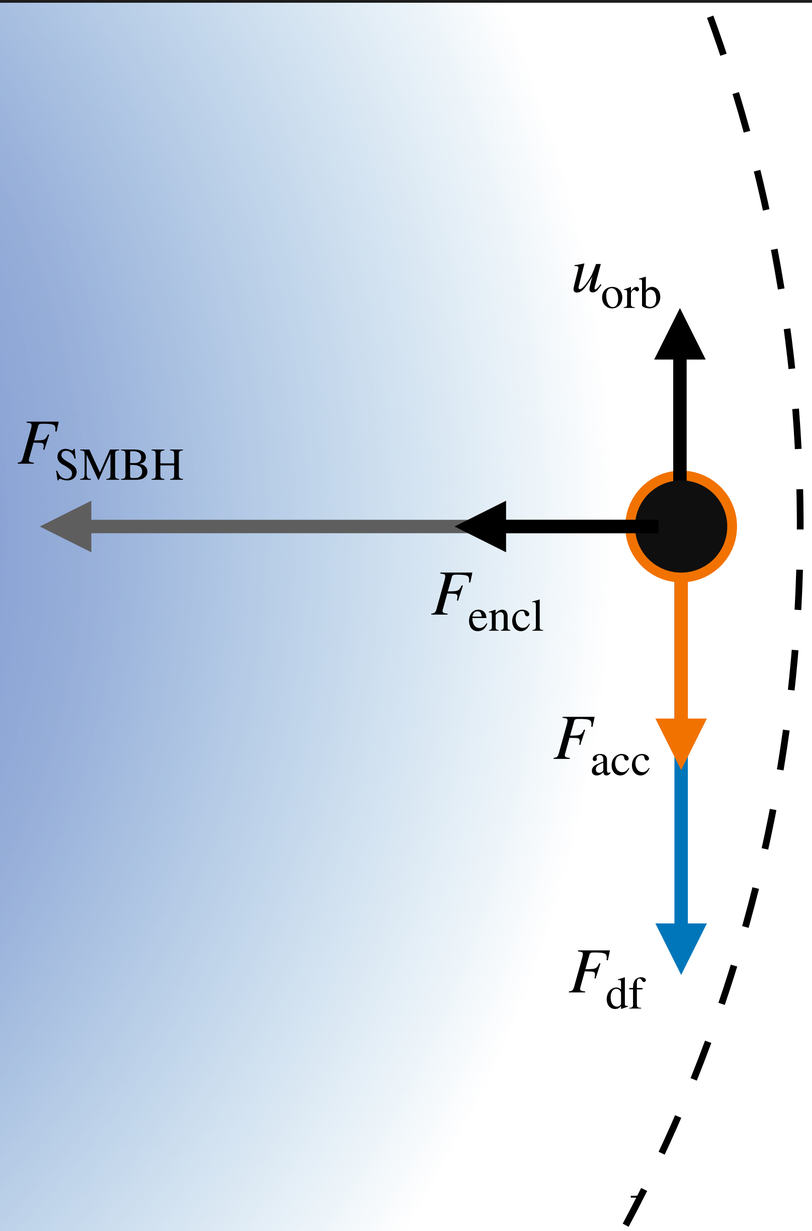
G. Álvarez, et al. PRL (2024)



Fermionic and more:

OA Hannuksela, et al. PRD 102 (2020)
V Crespi, et al. (2024)

Environmental effects on inspirals



1. Enclosed Mass

Negligible

Perturbed metric /
Additional gravitational force

2. Mass Accretion

$q \gtrsim 10^{-4}$

Varies the mass-ratio and
brings in momentum

3. Dynamical Friction

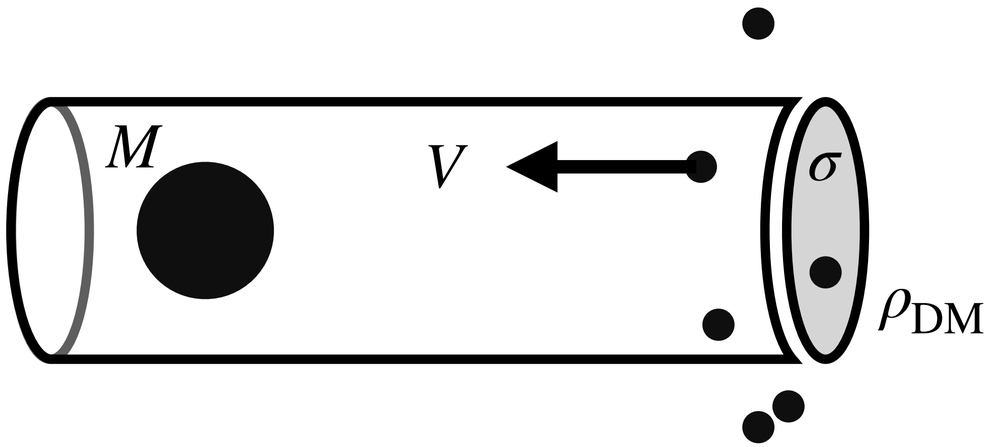
Dominant

Long-range slingshots

TK, PRD 111, 063070 (2025)
BJK, et al. PRD 102, 083006 (2020)

First principles vs plugging by hand

How do you construct the equations?



$$\Delta M = \rho_{\rm DM} \times \sigma V \Delta t$$

$$\Delta \vec{p} = \rho_{\rm DM} \times \sigma V \vec{V} \Delta t$$

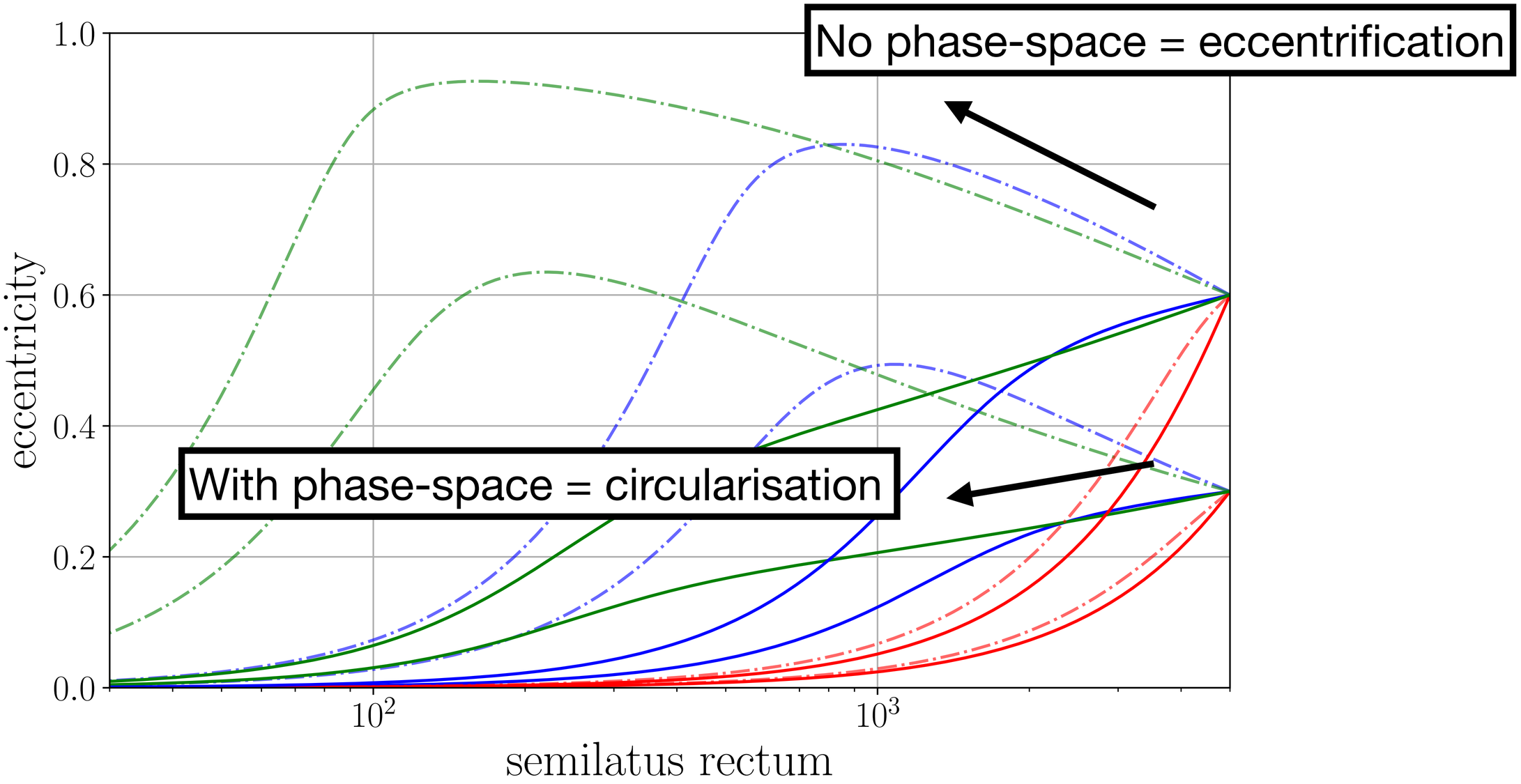
$$\dot{M} = \dot{M} \times C_m \qquad C_m \approx 1.1$$

$$F_{acc} = F_{acc} \times C_{acc} \qquad C_{acc} \approx 1.5$$

$$F_{df} = F_{df} \times C_{df} \qquad C_{df} \approx 0.6$$

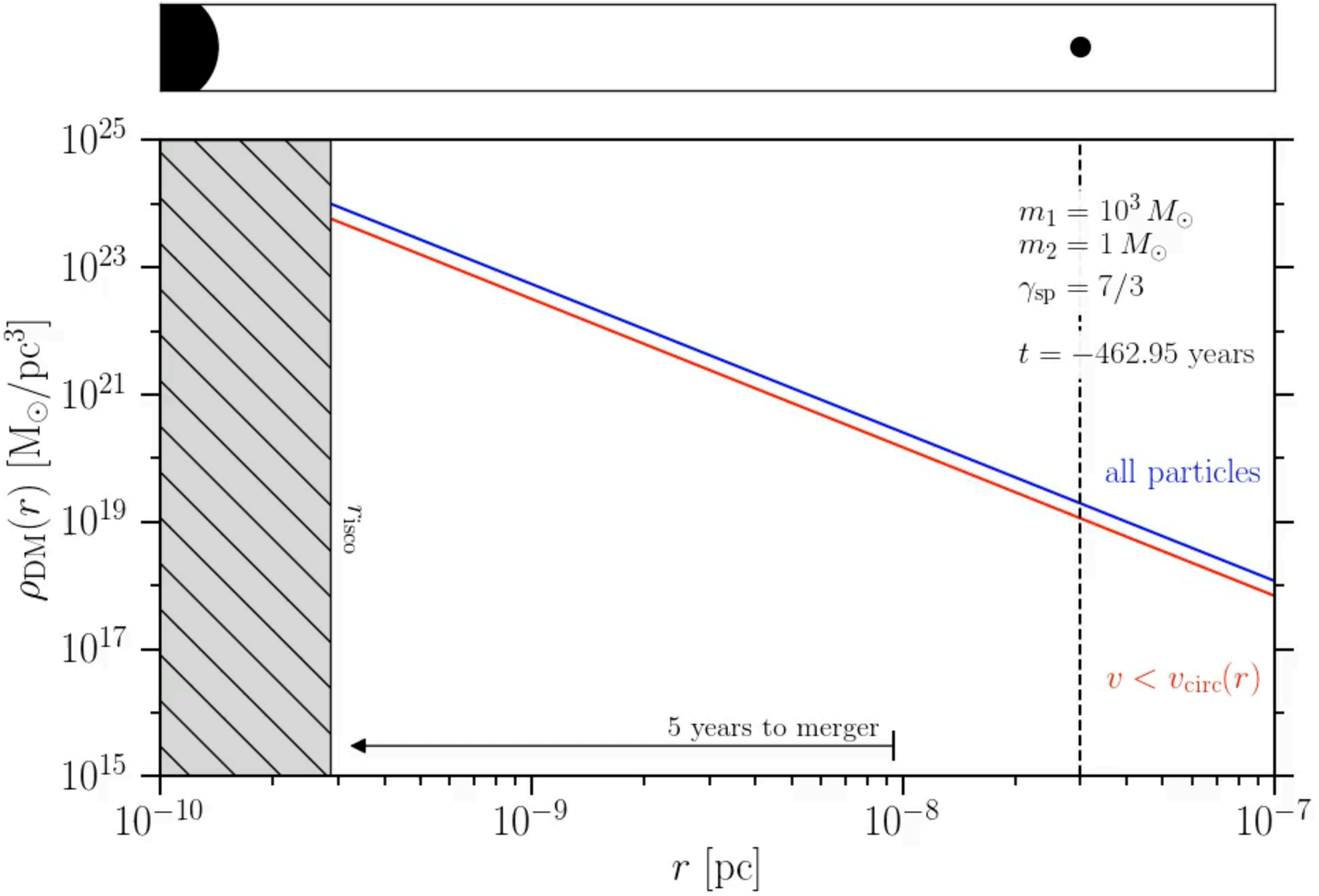
Why should you care for order 1 corrections?

Phase Dependence changes eccentricity evolution



N Becker et al, PRD (2022)

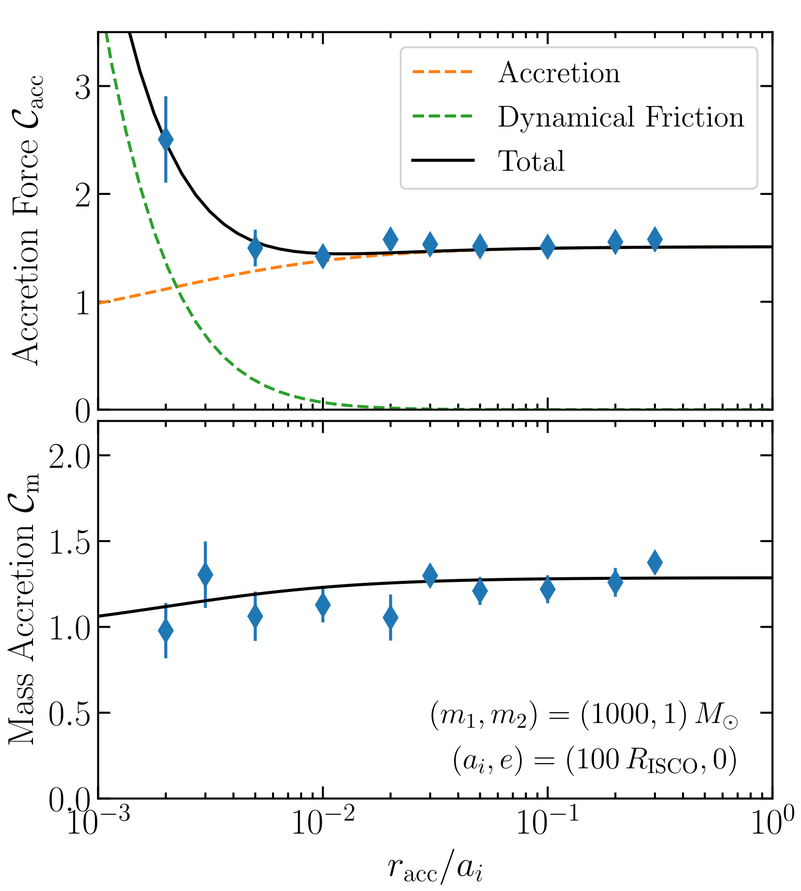
Phase Dependence and energy feedback for $q \lesssim 10^{-5}$

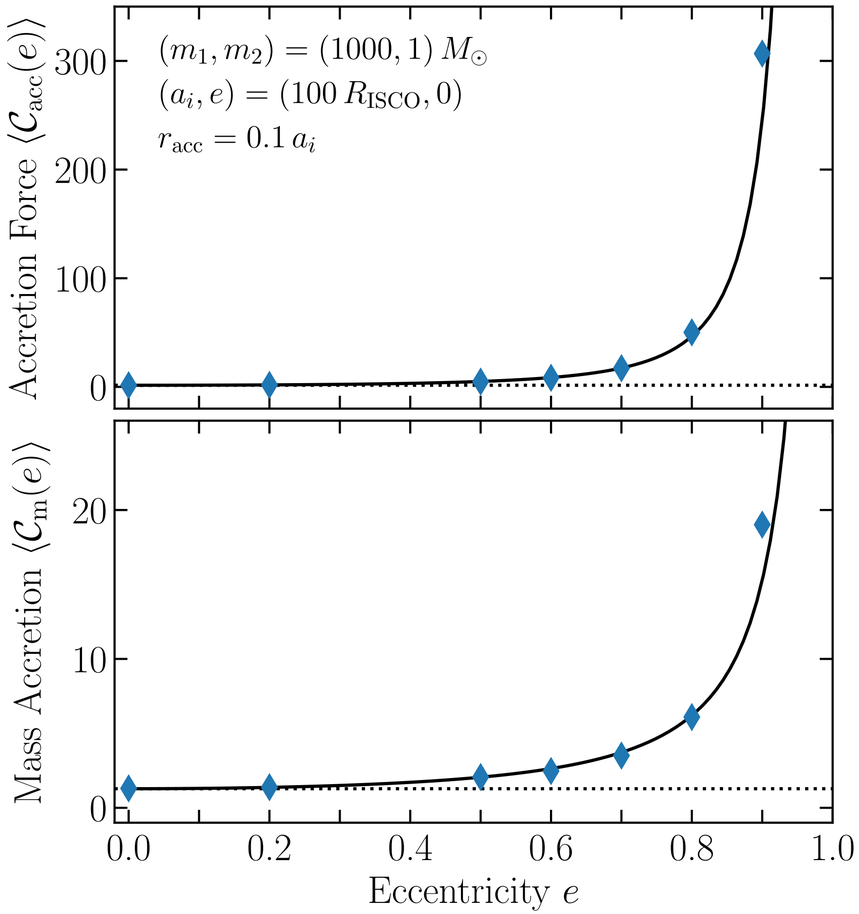


BJK, et al. PRD 102, 083006 (2020)

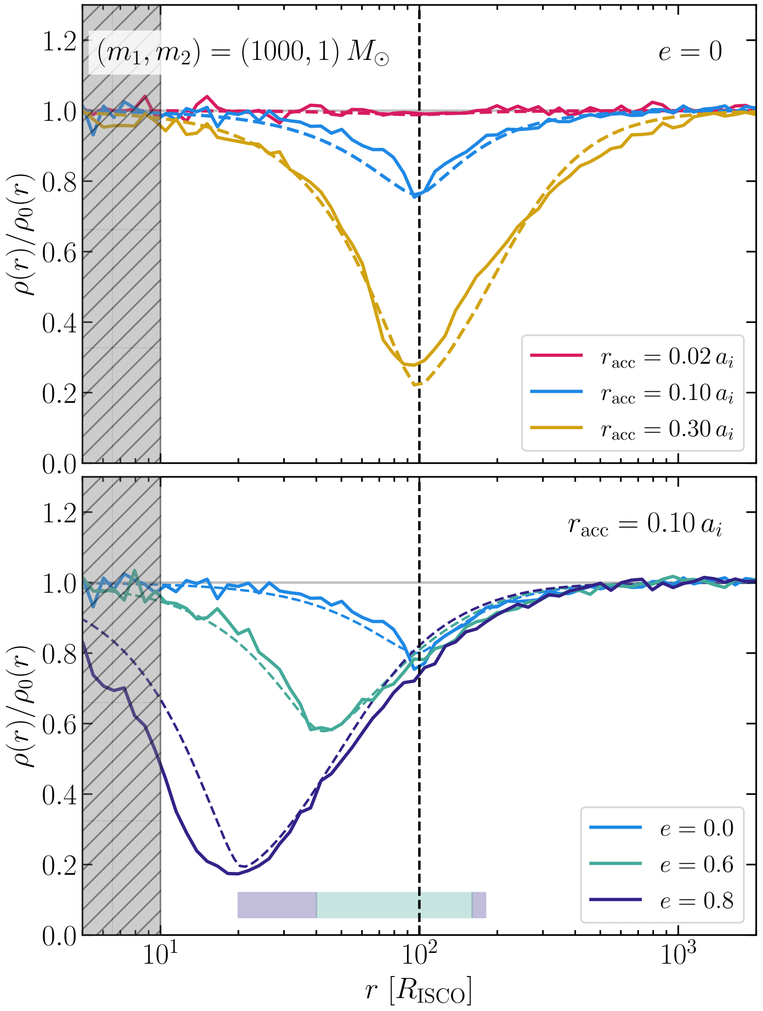
Validating with N-body simulations - Accretion

Accretion-related factors





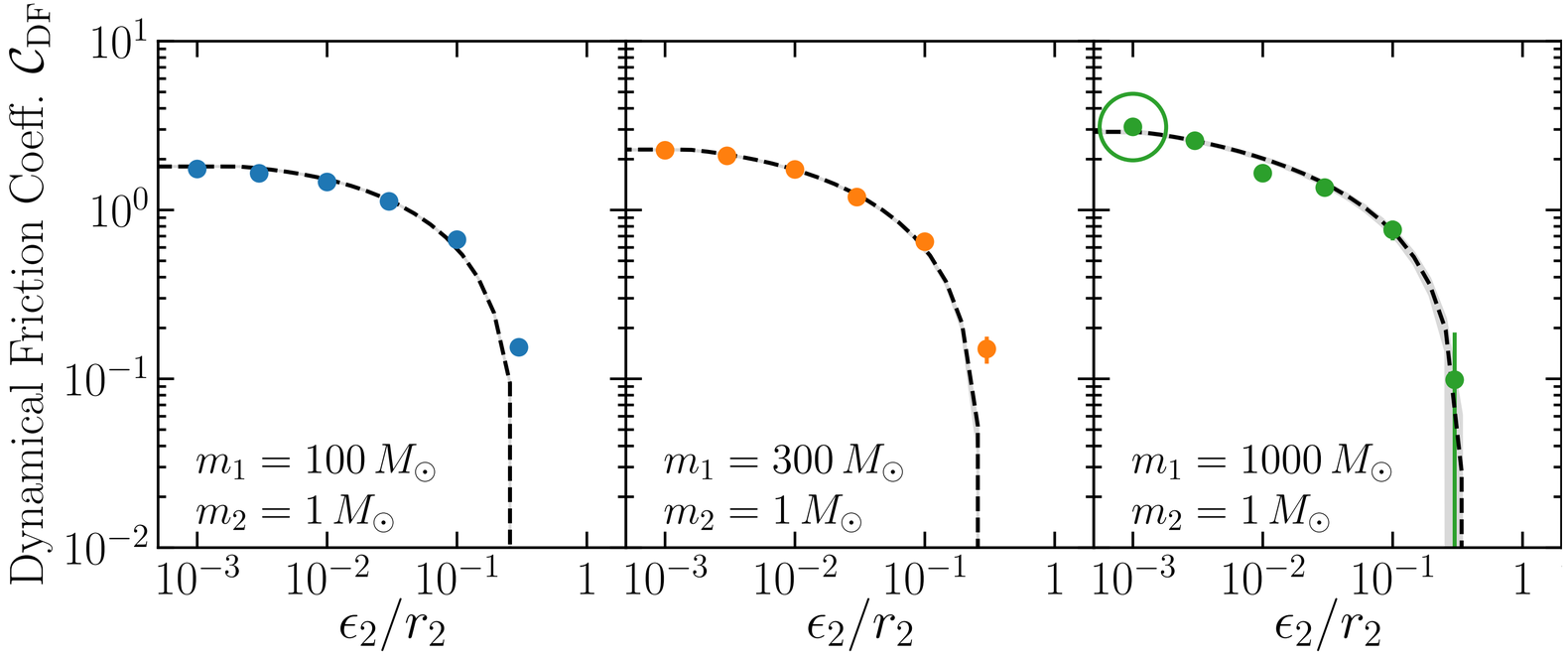
Accretion feedback



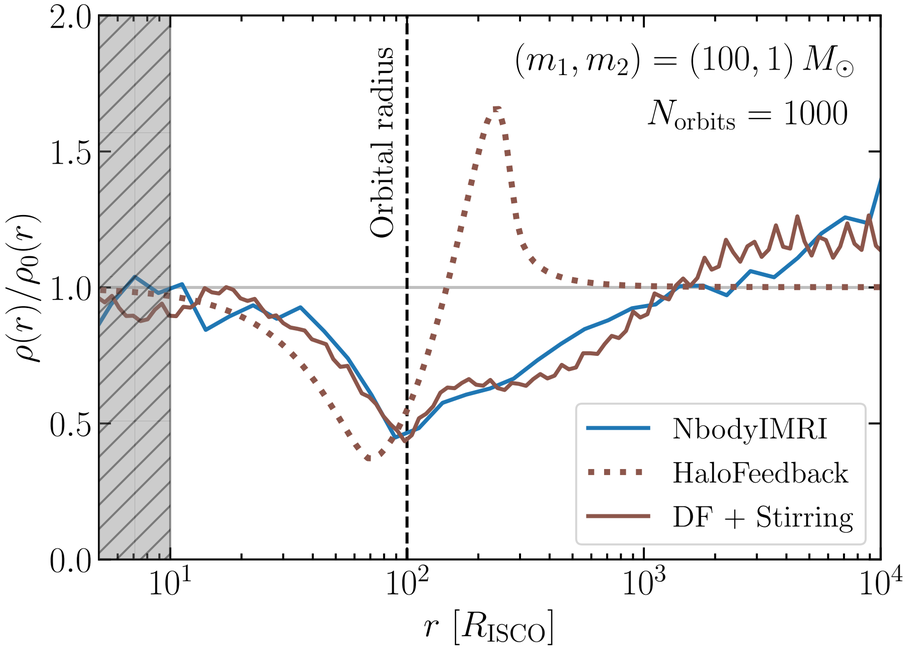
TK, PRD 111, 063070 (2025)

Validating with N-body simulations - Dynamical Friction

Dynamical friction



Energy Feedback



BJ Kavanagh, **TK**, GB, PdC, MP, PRD 111, 063070 (2025)

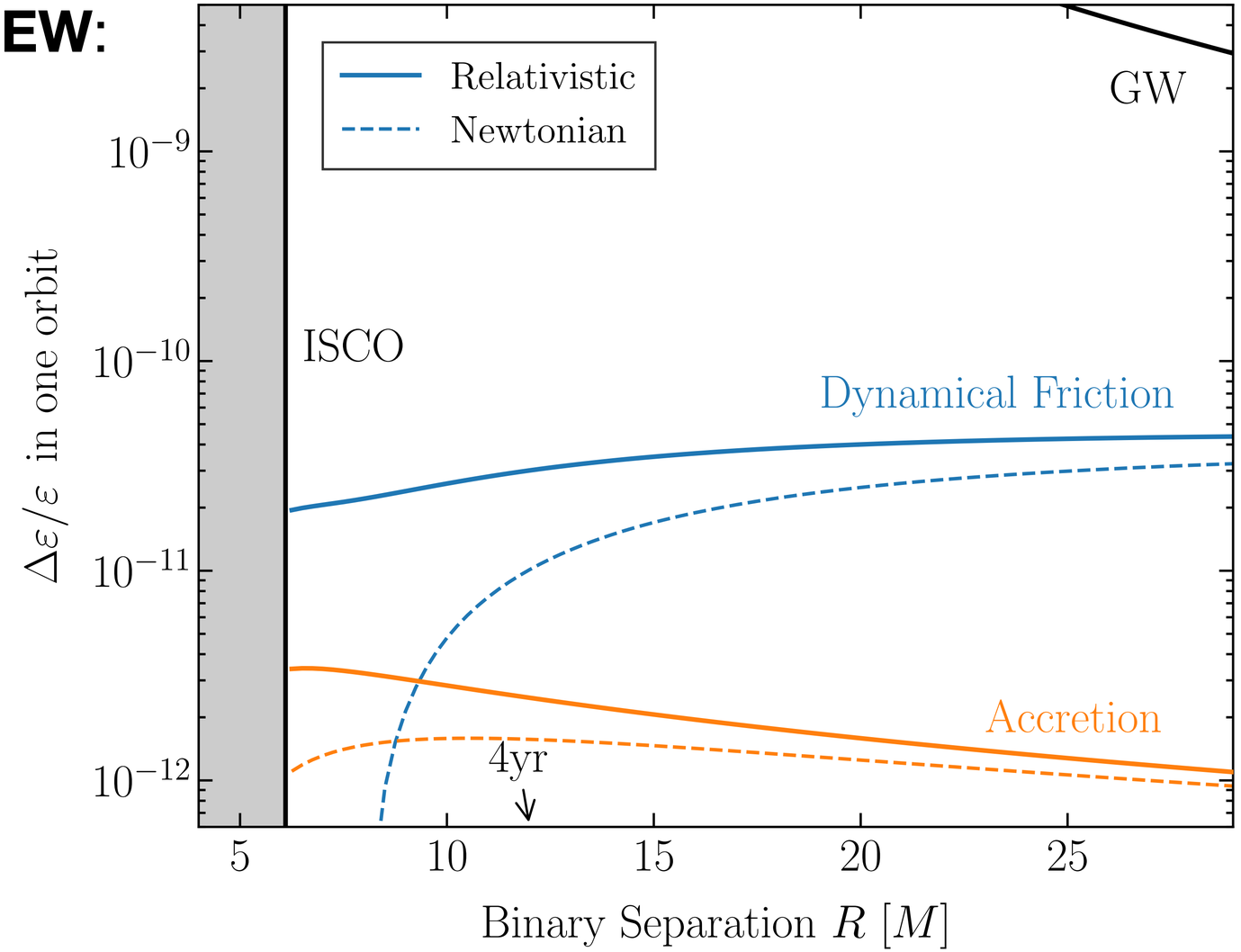
Relativistic Framework - Large difference in energy loss

Adiabatic modeling of EMRIs within **FEW**:

- Inspiral = Sequence of geodesics/constants of motion.
- GWs at leading order in 1st GSF

Find what the new “forces” should be:

$$a = \frac{1}{m}\int \frac{dN}{dVd^3v^i} v\left[\sigma_{\rm acc}(v) + \sigma_{\rm scat}(v)\right] p_\perp d^3v^i$$

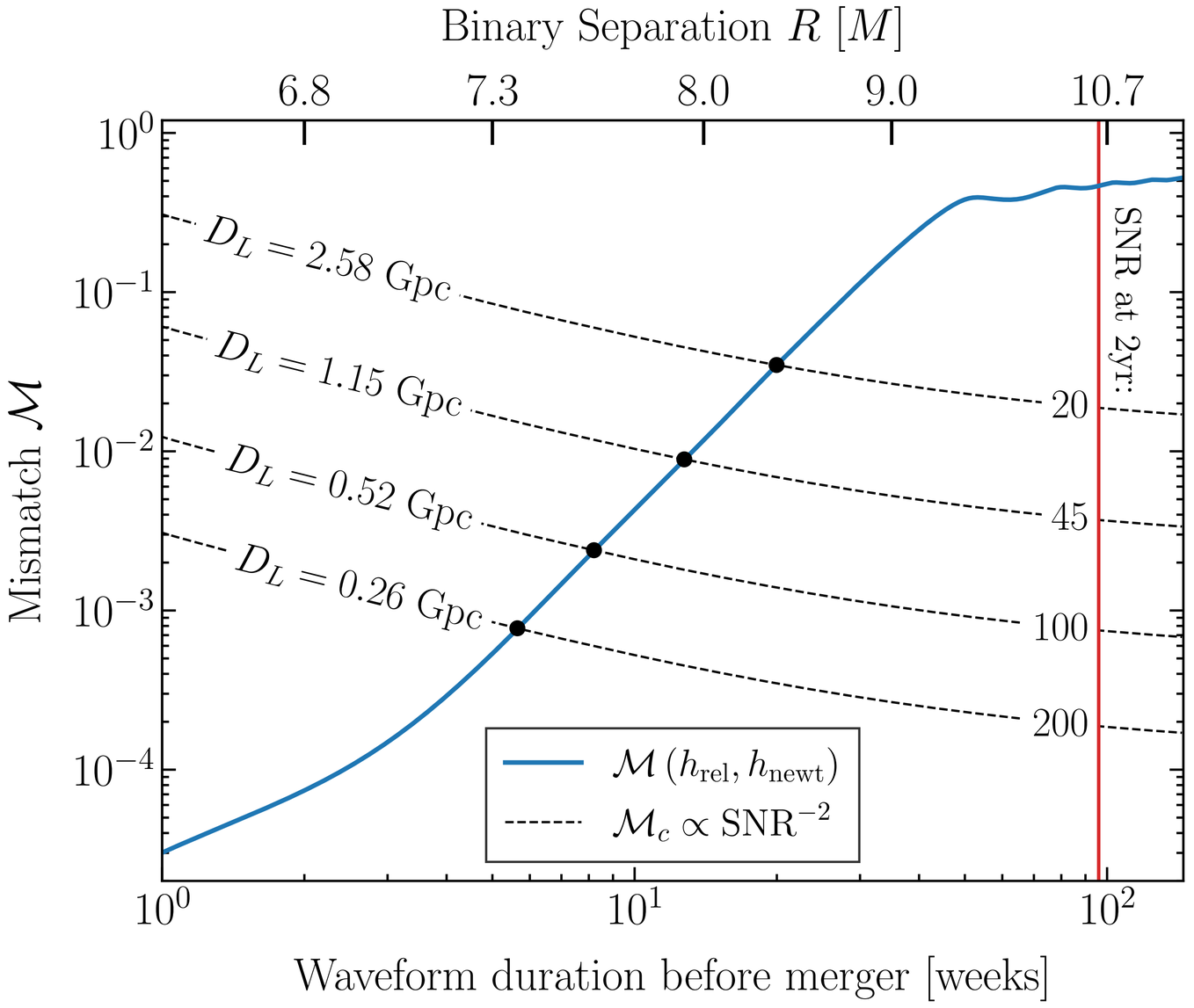


RV, **TK**, GB, arXiv:2505.09715 (2025)

Mismatch plots

Waveform difference is significant whenever the mismatch is larger than a critical value.

Typically within weeks.



RV, **TK**, GB, arXiv:2505.09715 (2025)

Summary & Outlook

What have we learned thus far?

1. Dark matter spikes offer unique to measure DM properties through GWs.
2. Must be careful when modelling environmental effects (phase space dependence).
3. We have a very good handle on the non-relativistic limit of the physics.
4. First steps in the fully relativistic domain completed.