The Bardeen-Petterson Effect in accreting supermassive black-hole binaries

Disc breaking and critical obliquity

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PHANTOM

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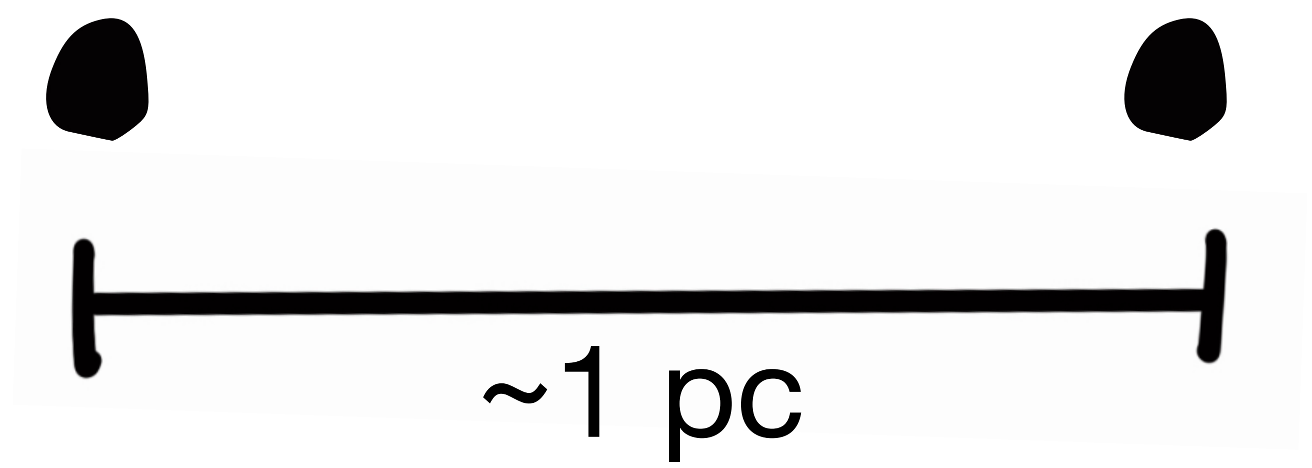
How do supermassive black holes merge?

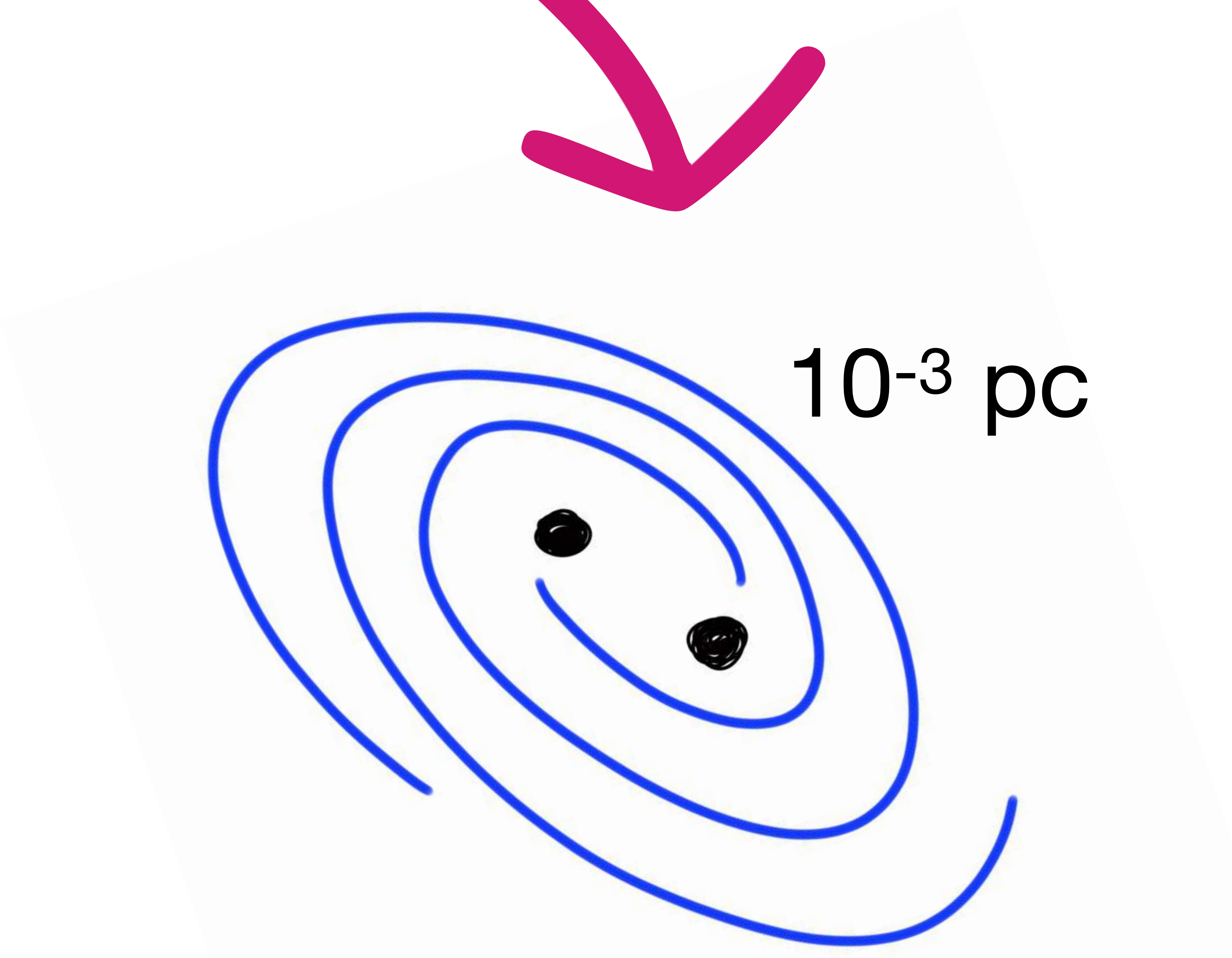
(ESA/NASA)

How do supermassive black holes merge?



<u>The Final Parsec Problem</u>

- Triaxial galactic potentials (Poon and Merritt 2004)
- Dynamical interactions in supermassive black hole triples (Bonetti et al. 2019)
- Gas accretion (e.g. Armitage and Natarajan 2002 and many others)

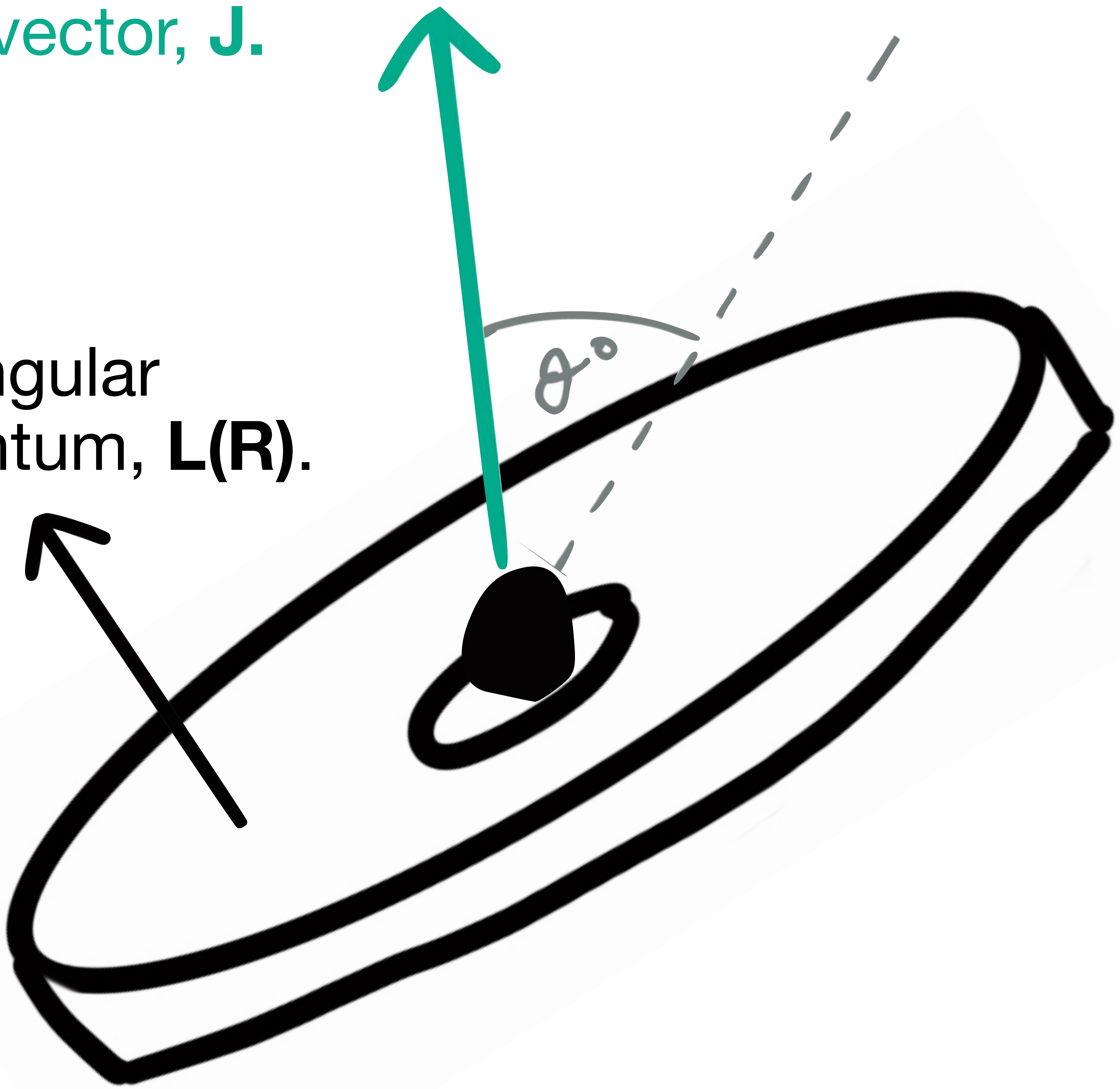


The emission of gravitational waves are responsible for the final merge

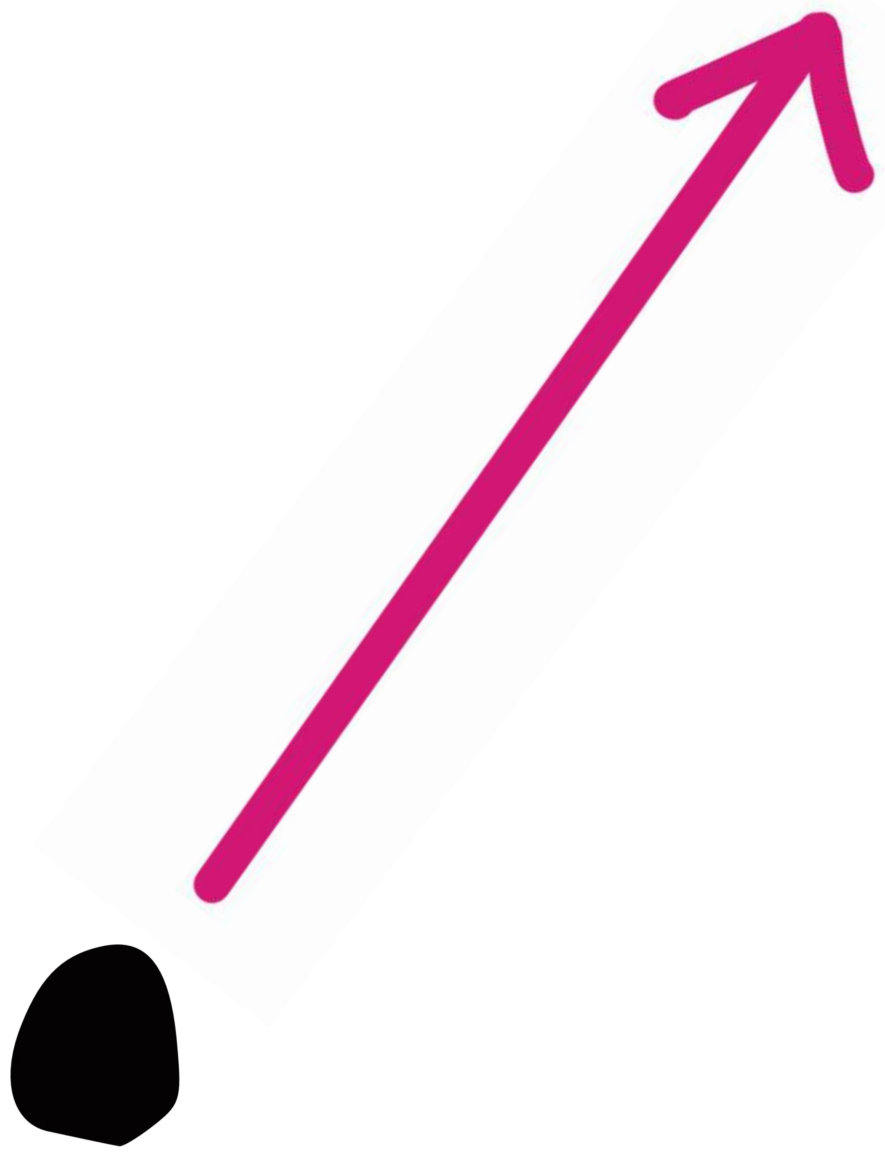
Disc driven migration

Primary black hole
spin vector, **J**.

Disc angular
momentum, **L(R)**.



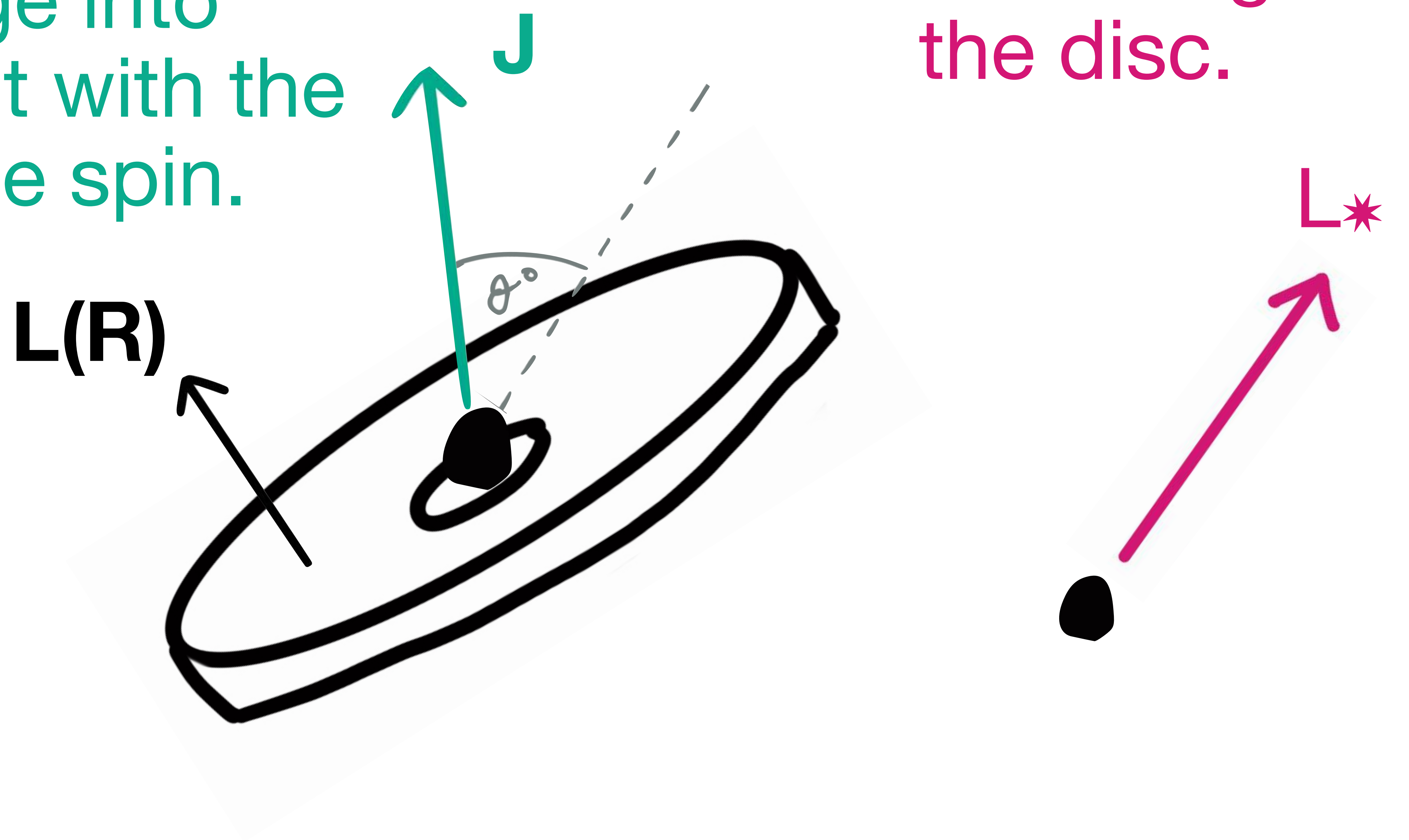
Orbital angular momentum of
secondary, L_*.



Disc driven migration

$$\frac{\mathrm{d}\cos\theta}{\mathrm{dt}} = \frac{\mathrm{d}\hat{\boldsymbol{J}}}{\mathrm{dt}} \cdot \hat{\boldsymbol{L}}_*$$

$$\frac{\mathrm{d}\boldsymbol{J}}{dt} = -\int_{R_{\min}}^{R_{\max}} \frac{2G}{c^2} \frac{\boldsymbol{J} \times \boldsymbol{L}}{R^3} 2\pi R \mathrm{dR}$$



1. What shape does the disc take?
2. How does this affect the alignment of the black holes?

(Gerosa et al. 2020)

A semi-analytic model

$$\frac{\partial \sigma}{\partial r} = -\left(\beta + \frac{1}{2}\right)\frac{\sigma}{r} - \frac{\zeta \sigma \psi^2}{3r}\frac{\tilde{\alpha}_2(\alpha,\psi)}{\tilde{\alpha}_1(\alpha,\psi)} + \frac{r^{-\beta-1}}{3\tilde{\alpha}_1(\alpha,\psi)} - \frac{\sigma}{\tilde{\alpha}_1(\alpha,\psi)}\frac{\partial \tilde{\alpha}_1(\alpha,\psi)}{\partial r},$$

$$\frac{\partial^2 \hat{\boldsymbol{L}}}{\partial r^2} = \frac{\partial \hat{\boldsymbol{L}}}{\partial r}\left[-\frac{2r^{-\beta-1}}{\zeta\,\tilde{\alpha}_2(\alpha,\psi)\sigma} + \frac{3}{\zeta r}\frac{\tilde{\alpha}_1(\alpha,\psi)}{\tilde{\alpha}_2(\alpha,\psi)} - \left(\beta + \frac{3}{2}\right)\frac{1}{r} - \frac{1}{\sigma}\frac{\partial \sigma}{\partial r} - \frac{1}{\tilde{\alpha}_2(\alpha,\psi)}\frac{\partial \tilde{\alpha}_2(\alpha,\psi)}{\partial r}\right] - \frac{\psi^2}{r^2}\hat{\boldsymbol{L}} - \left(\frac{R_{\rm LT}}{R_0}\right)\frac{r^{-\beta-3}}{\tilde{\alpha}_2(\alpha,\psi)}(\hat{\boldsymbol{J}} \times \hat{\boldsymbol{L}}) - \left(\frac{R_{\rm tid}}{R_0}\right)^{-7/2}\frac{r^{-\beta+3/2}}{\tilde{\alpha}_2(\alpha,\psi)}(\hat{\boldsymbol{L}} \cdot \hat{\boldsymbol{L}}_\star)(\hat{\boldsymbol{L}} \times \hat{\boldsymbol{L}}_\star).$$

Change of variables …

$$r = \frac{R}{R_0}, \qquad \sigma = \frac{2\pi}{\dot{M}}\alpha \nu_0 \Sigma\,;$$

and using

$$R_{\rm LT} = \frac{4G^2M^2\chi}{c^3\alpha\nu_0\zeta},$$

$$R_{\rm tid} = \left(\frac{2}{3}\frac{\sqrt{GM}}{GM_\star}R_\star^3\alpha\nu_0\zeta\right)^{2/7}$$

Aligns the inner disc with the black hole spin

Aligns the outer disc with the binary orbit

(Gerosa et al. 2020)

A semi-analytic model

Where the Lense-Thirring torque most strongly affects the warp profile

$$R_{\rm LT} = \frac{4G^2M^2\chi}{c^3\alpha\nu_0\zeta},$$

Where the tidal external torque most strongly affects the warp profile

$$R_{\rm tid} = \left(\frac{2}{3}\frac{\sqrt{GM}}{GM_\star}R_\star^3\alpha\nu_0\zeta\right)^{2/7}$$

Also introduce the convenient parameter:

$$\kappa = \left(\frac{R_{\rm tid}}{R_{\rm LT}}\right)^{-7/2}$$

The non-dimensional parameter κ

$$\kappa \simeq 0.66 \left(\frac{M}{10^7 M_\odot}\right)^2 \left(\frac{\chi}{0.5}\right)^2 \left(\frac{M_\star}{10^7 M_\odot}\right) \left(\frac{R_\star}{0.1\mathrm{pc}}\right)^{-3} \times \left(\frac{H_0/R_0}{0.002}\right)^{-6} \left(\frac{\alpha}{0.2}\right)^{-3} \left[\frac{\zeta}{1/(2\times 0.2^2)}\right]^{-3},$$

Measures the relative importance of the binary.

Large κ means the binary is very important.

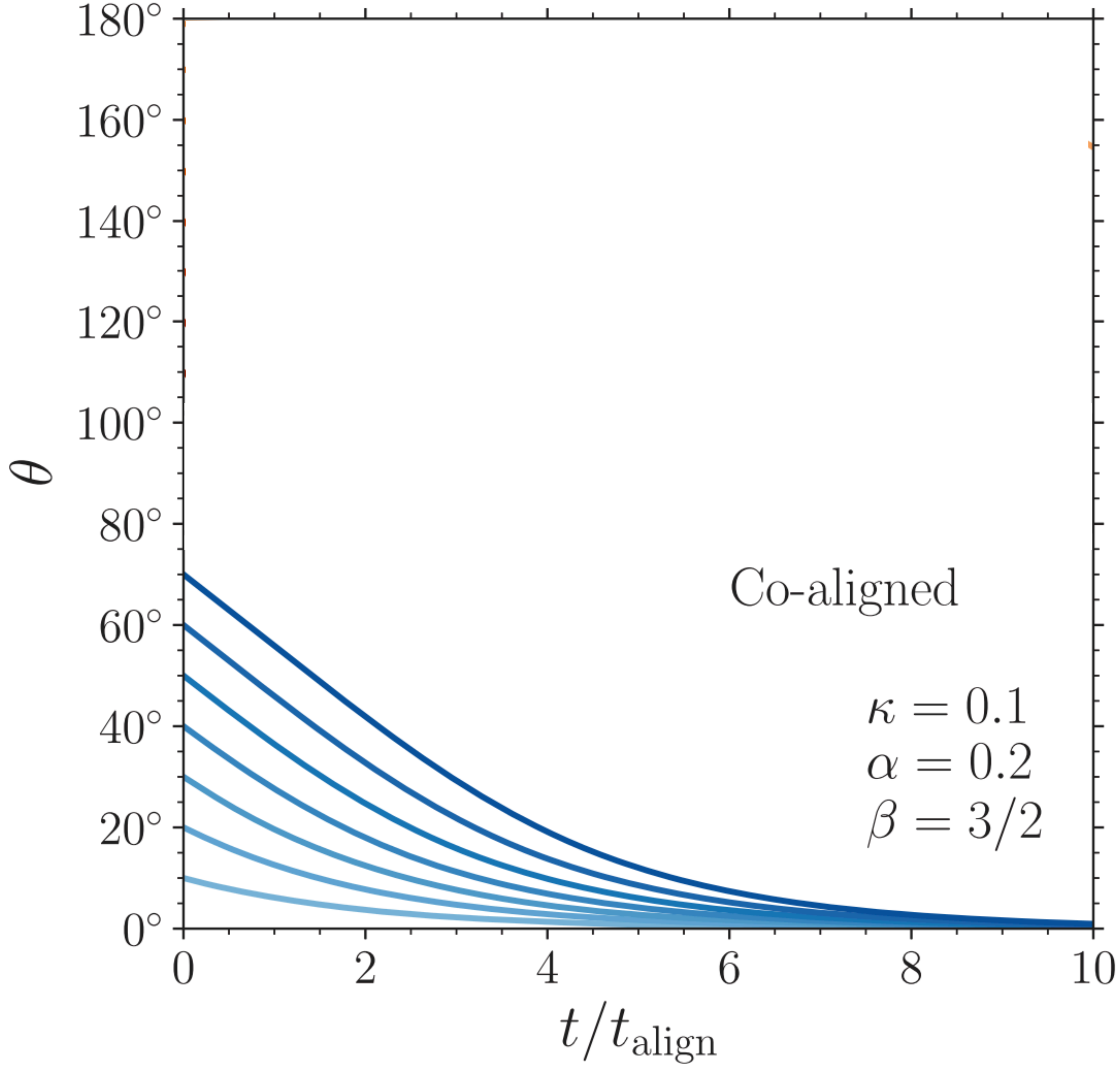
Small κ means the binary is not important at all.

(κ=0 reduces to a single black hole around the primary)

(Gerosa et al. 2020)

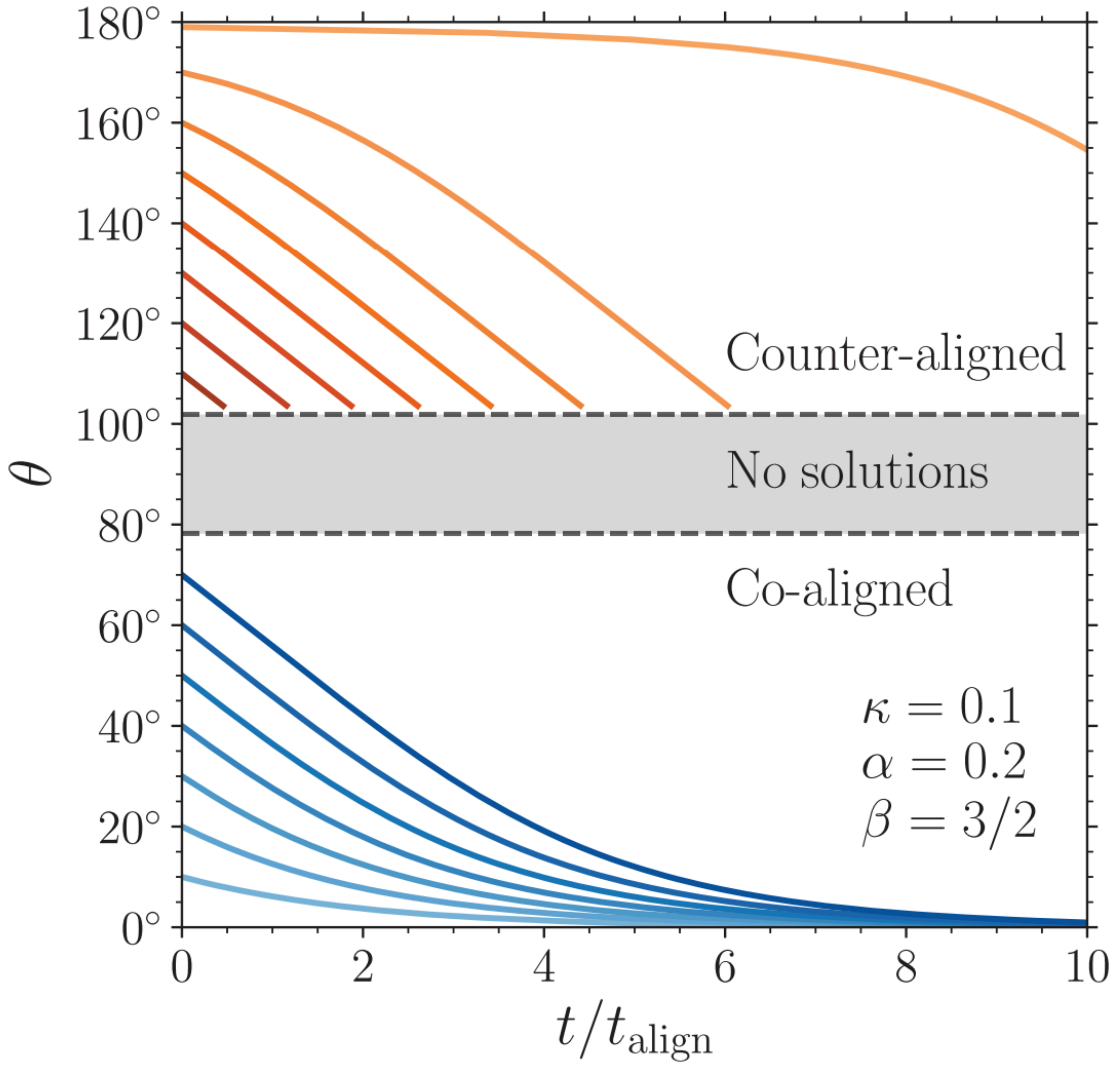
Solving the semi-analytic model

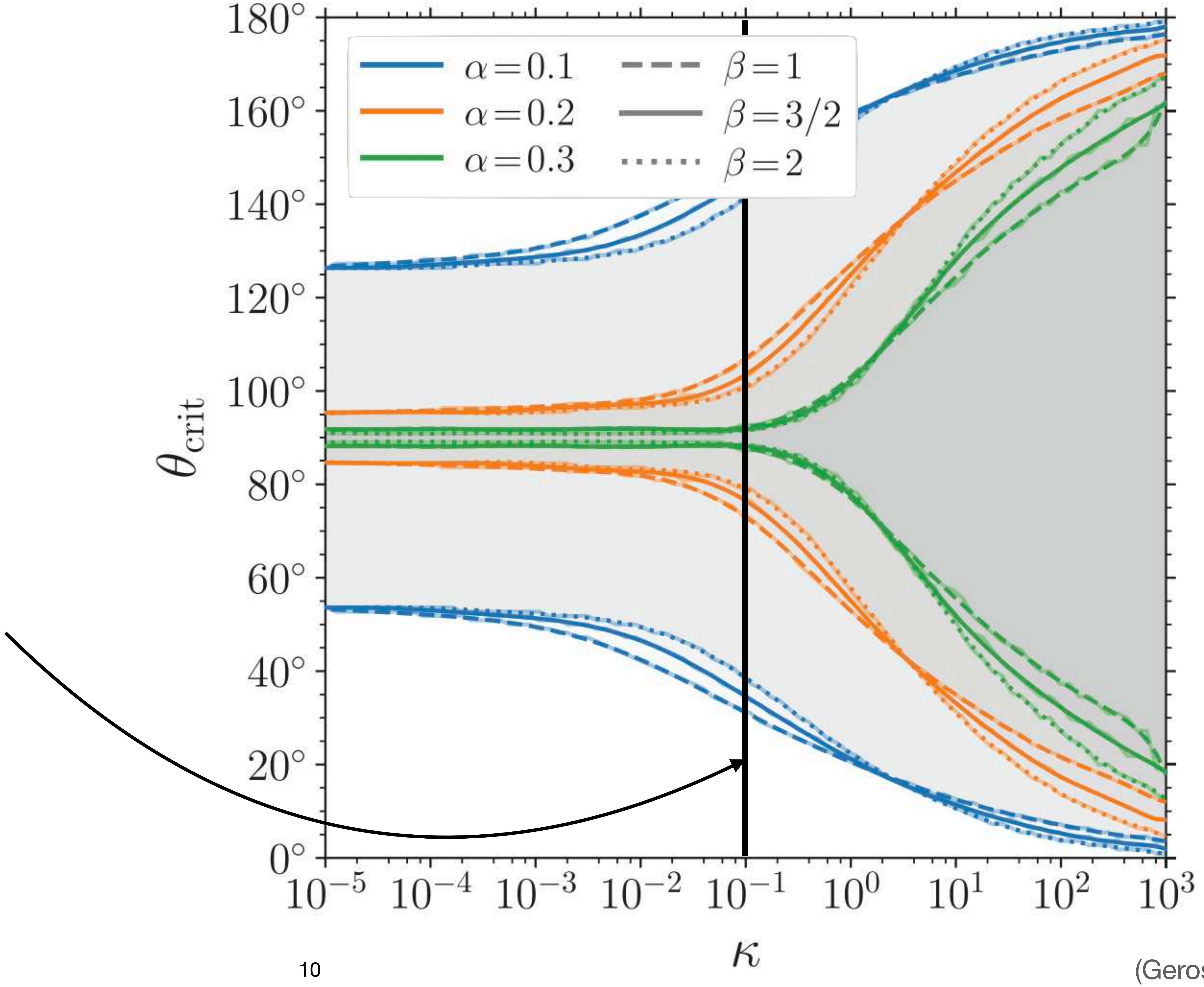
1. Choose disc parameters and parametrise the result with κ.
2. For a given angle, solve for the evolution of the surface density and angular momentum of the disc.
3. Repeat this for a range of inclinations.



(Gerosa et al. 2020)

The break-down of the semi-analytic model



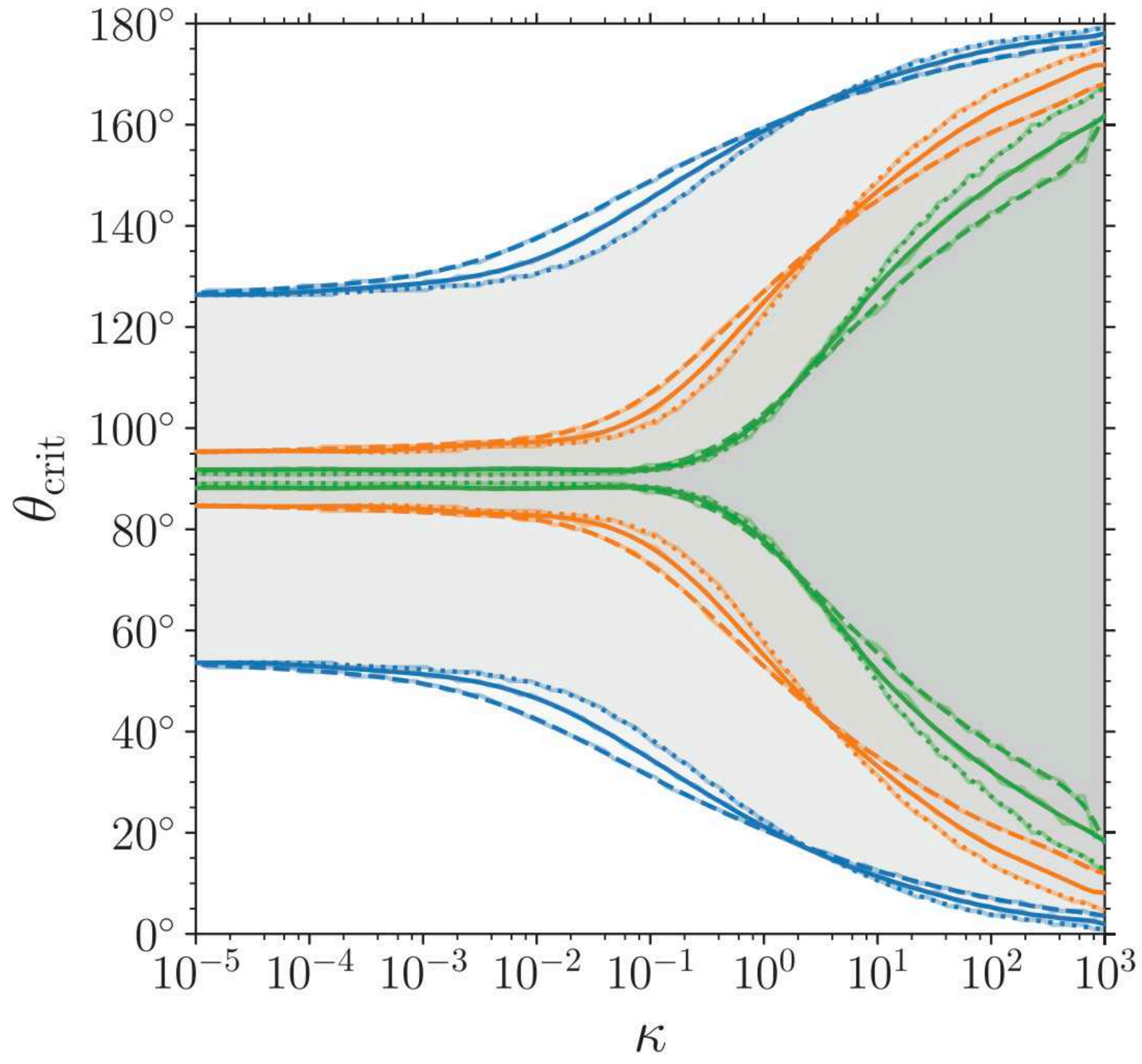


(Gerosa et al. 2020)

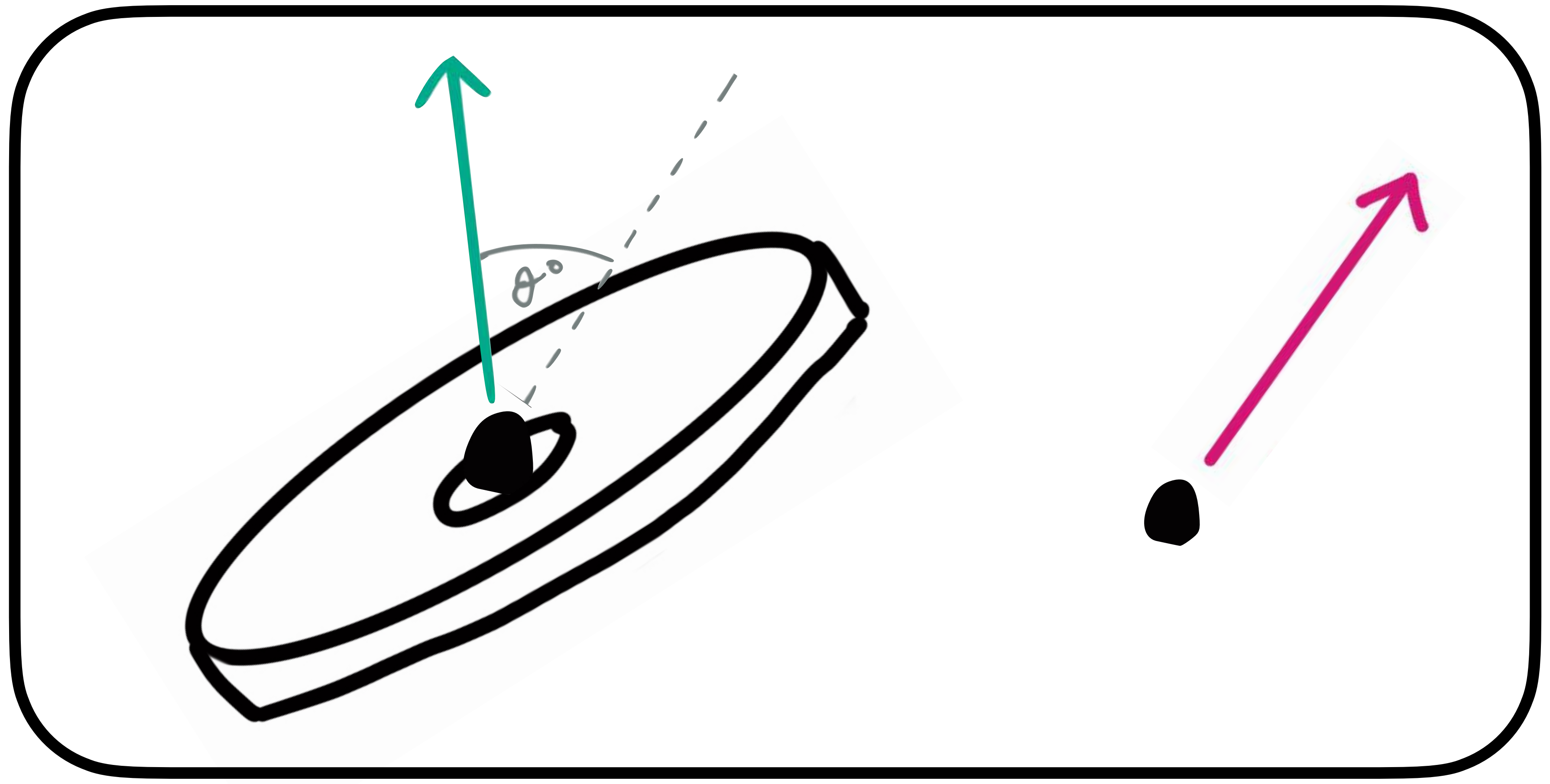
Our simulation suite

<u>143 simulations in total:</u>

- 2 binary separations
- Four viscosities
- Four aspect ratios
- Inclinations between 20 and 160 degrees
- 12 κ values

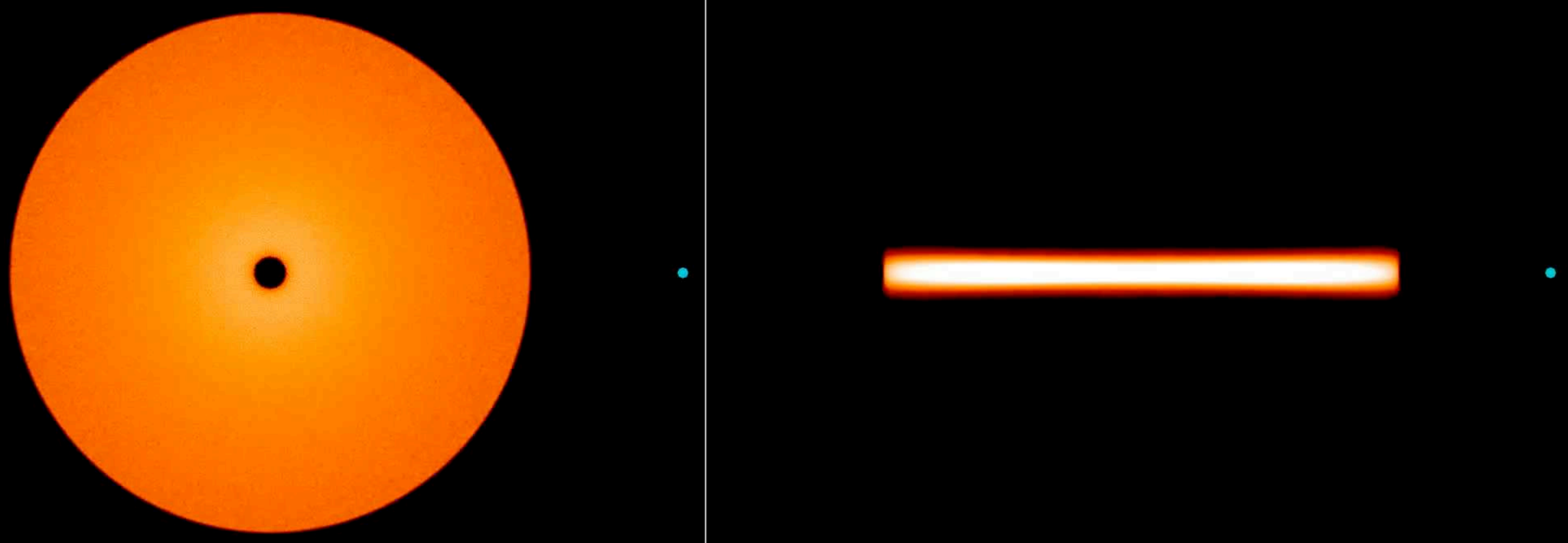


Cover this with these



- Use a fixed post-Newtonian potential
- Secondary is much lower mass than primary
- Black hole spin of a=0.9
- Disc mass is 10^{-6} of the primary black hole
- Minimum time of 150 orbits at $R_{\rm ref}$ (or 3 orbits of the outer binary)

Warping



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Breaking/tearing

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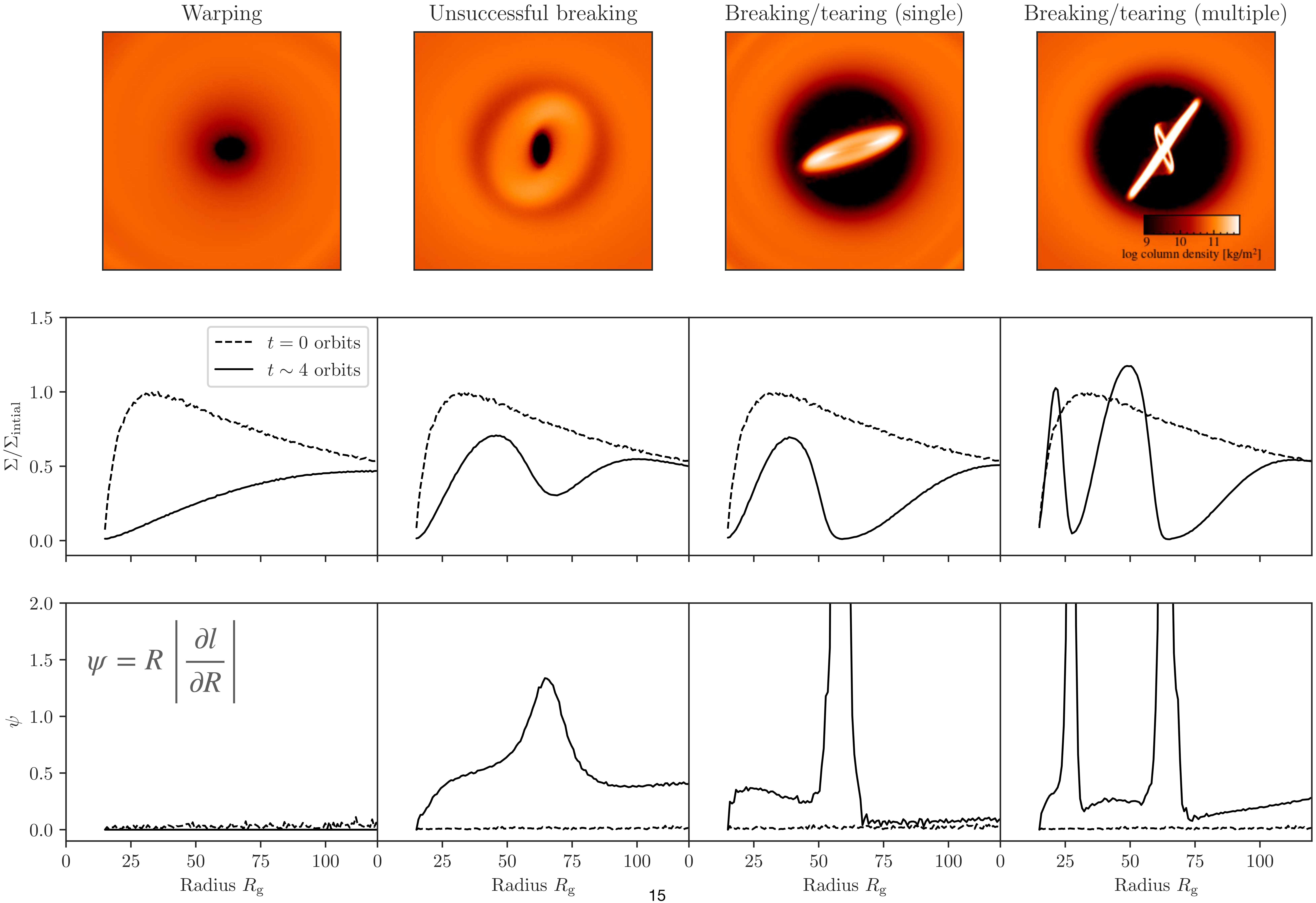
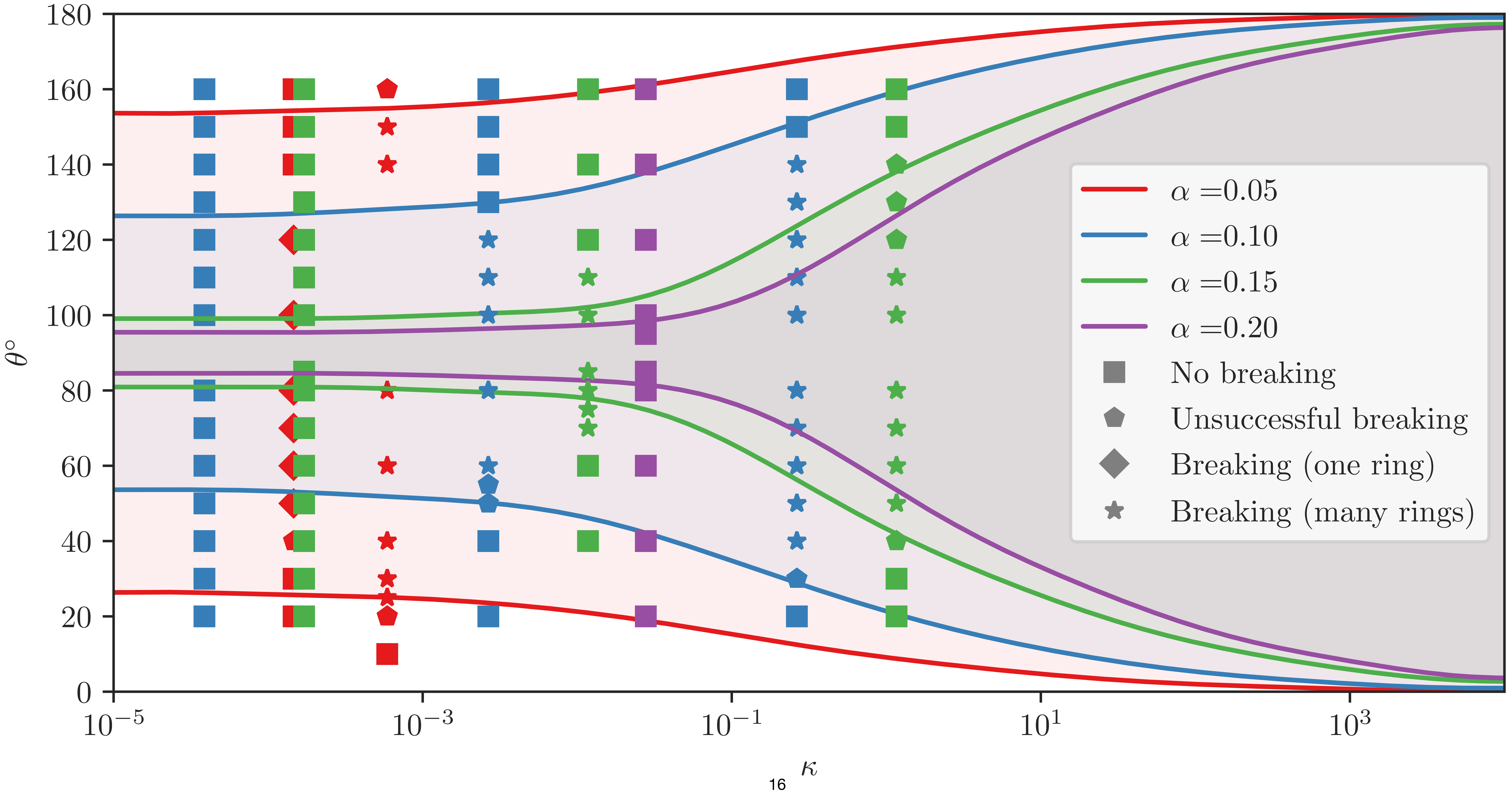
Unsuccessful breaking

Nealon, Ragusa, Gerosa, Rosotti & Barbieri 2022

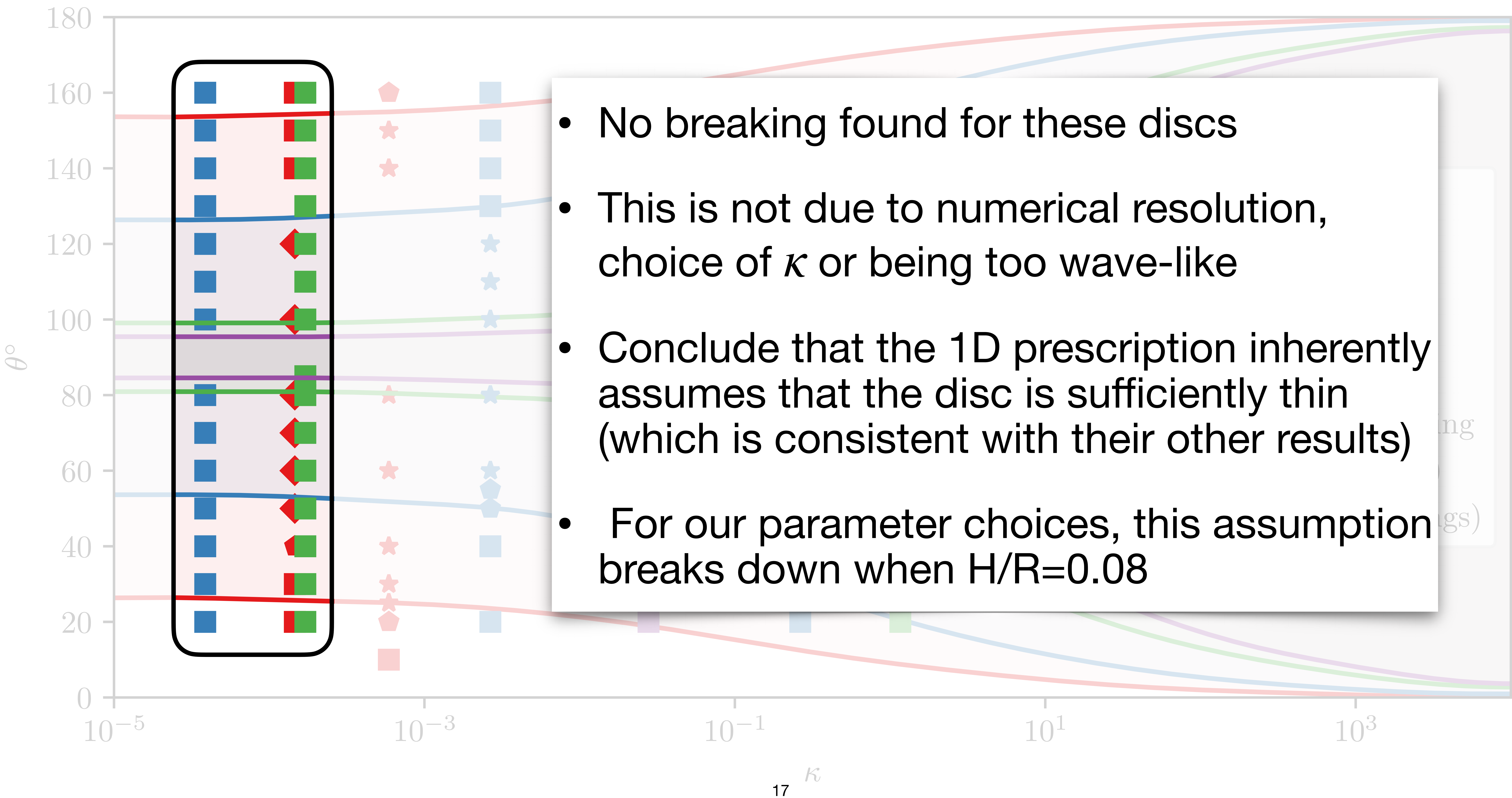
Defining a break



Comparing simulations and semi-analytic theory



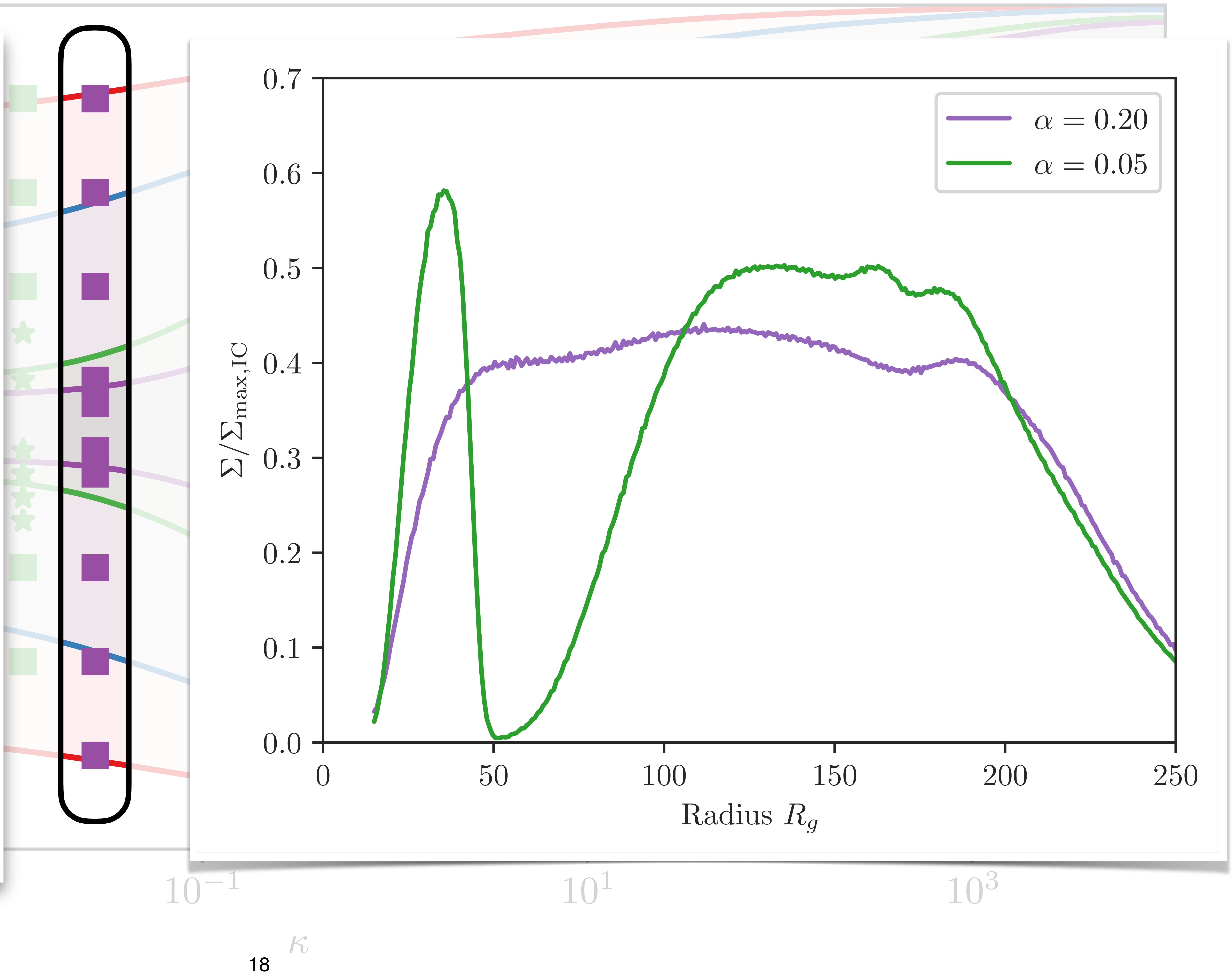
Thick discs don’t break



- No breaking found for these discs
- This is not due to numerical resolution, choice of κ or being too wave-like
- Conclude that the 1D prescription inherently assumes that the disc is sufficiently thin (which is consistent with their other results)
- For our parameter choices, this assumption breaks down when H/R=0.08

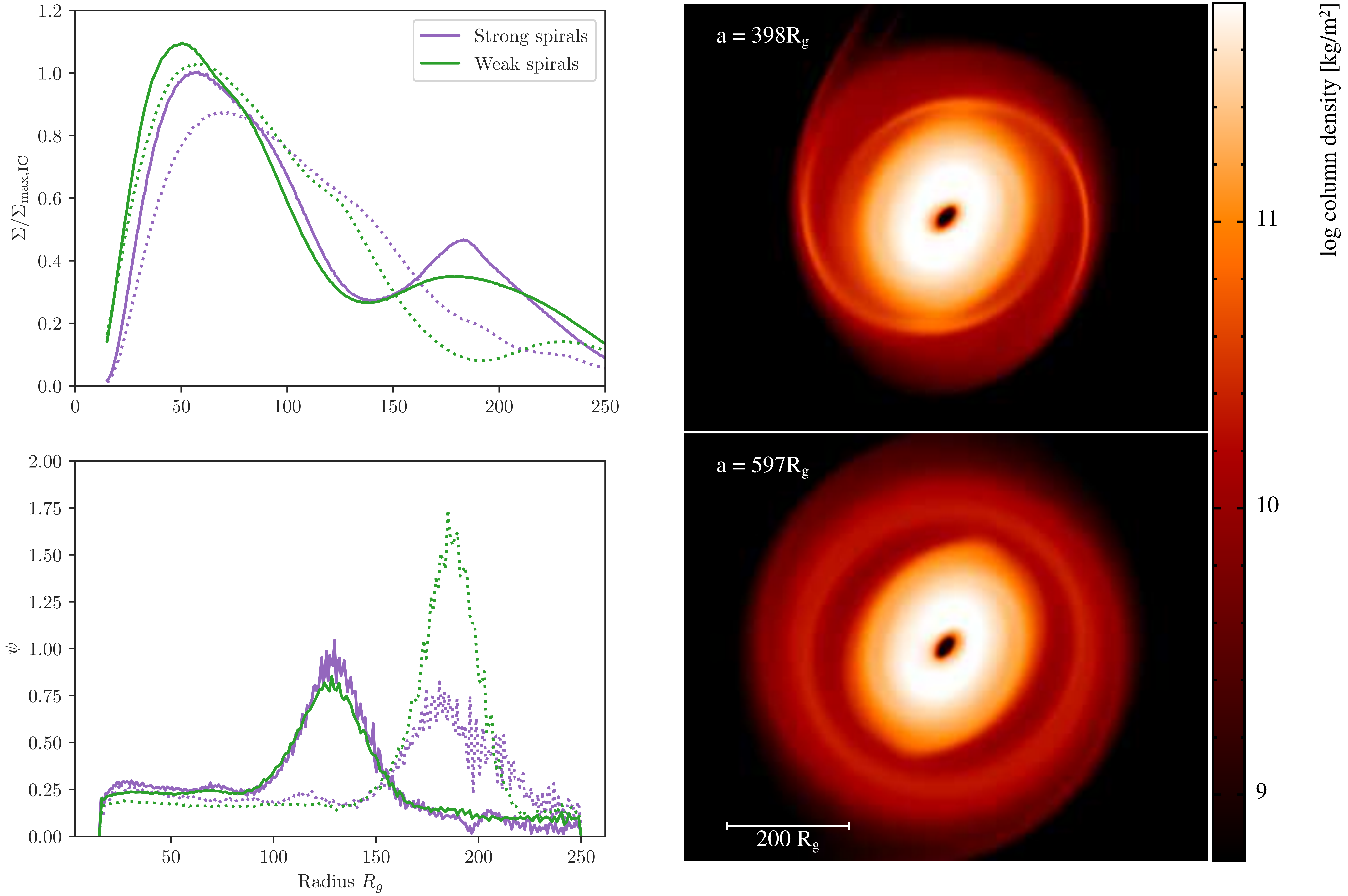
High viscosity discs don’t break

- Again, not likely due to limitations of the simulations
- But looking at the surface density profile, we find that the inner disc accretes rapidly
- If breaking were to occur, this is where the inner ring would form
- Not enough material to make that inner ring -> no breaking



Spiral arms can prevent disc breaking

- We identify this one as unsuccessful breaking
- As the warp propagates out, it increases in amplitude until it hits the spiral arms
- Spiral arms increase the local disc viscosity, which in turn makes it harder to break the disc



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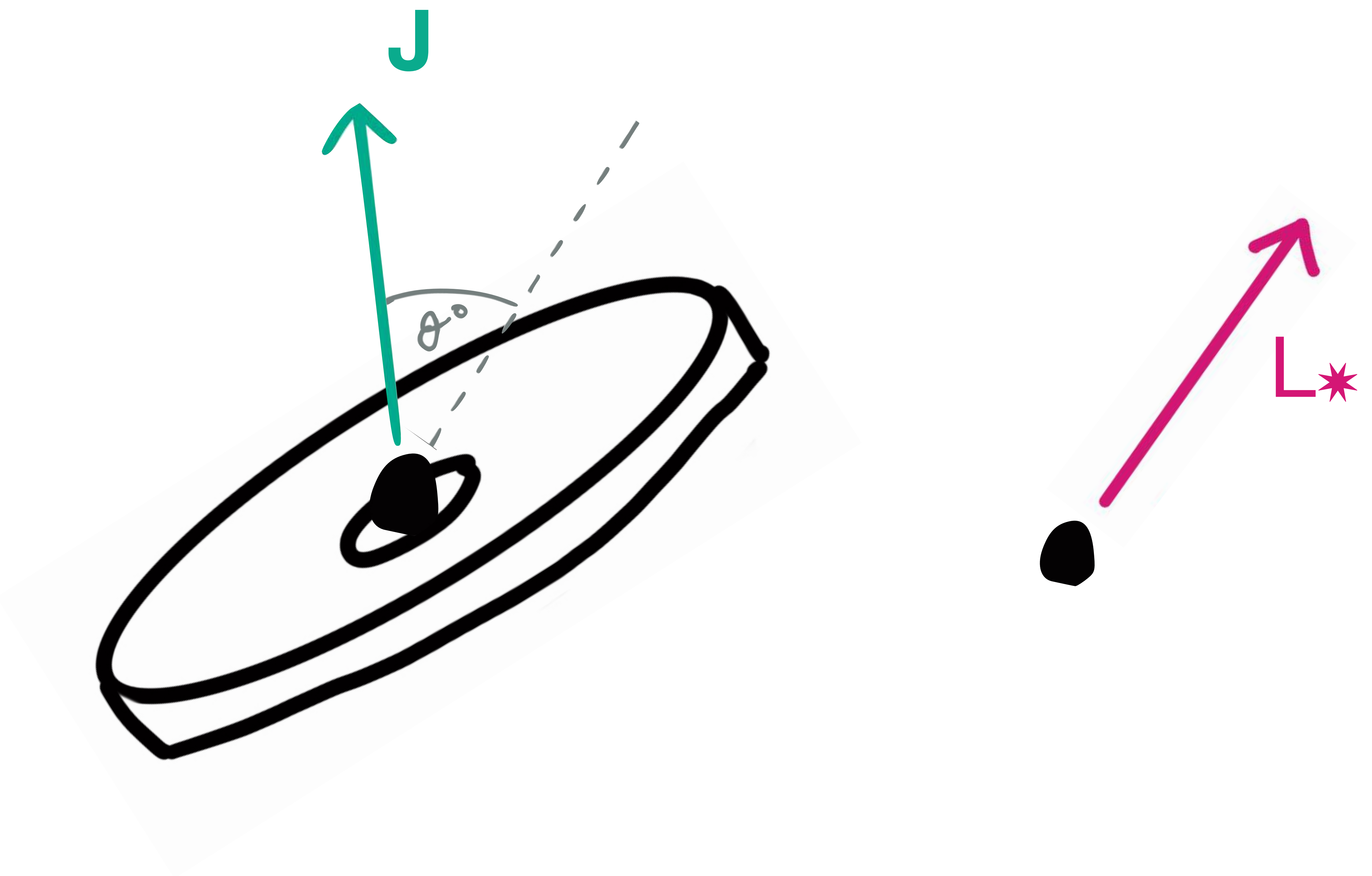

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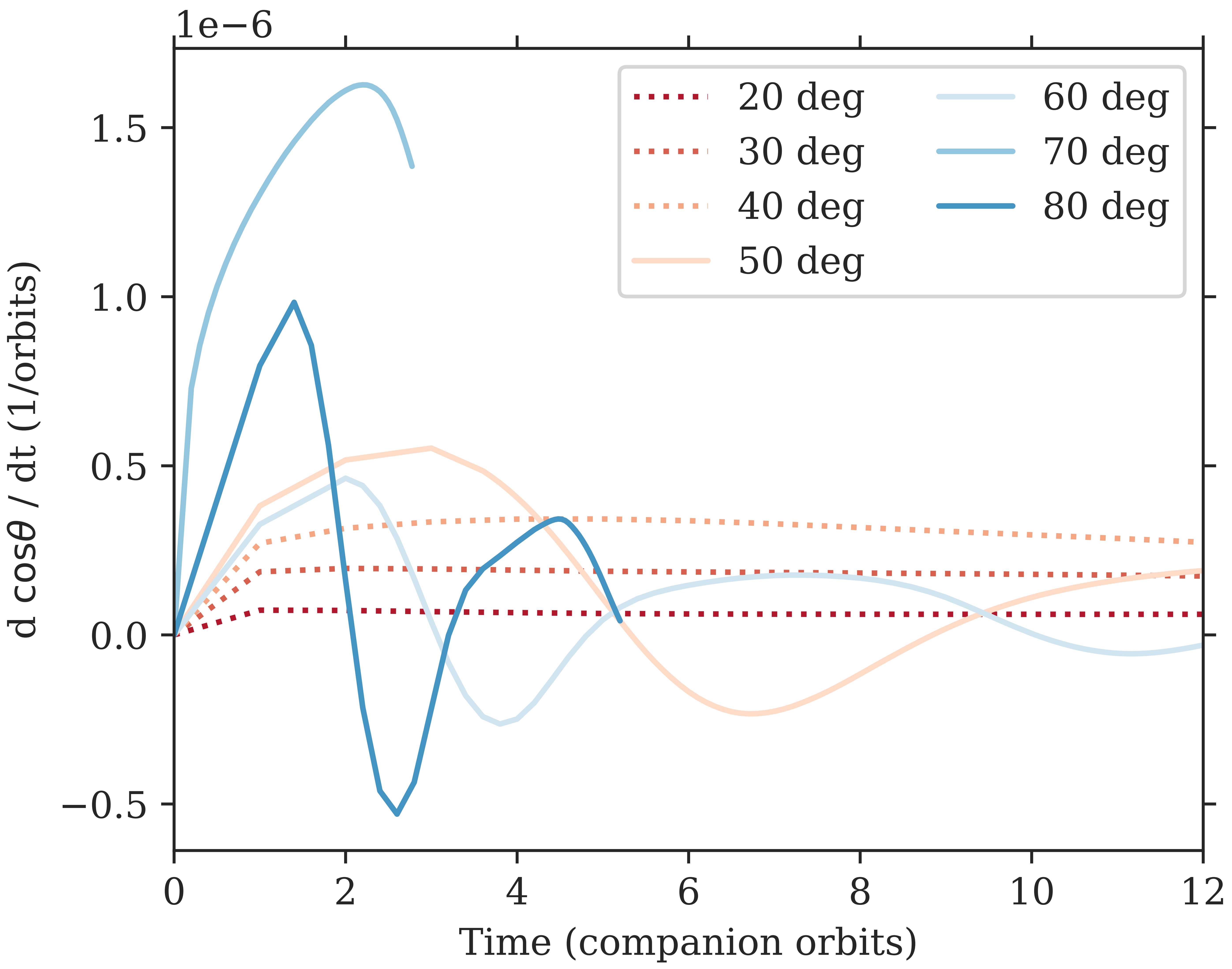
(Gerosa et al. 2020)

Disc-black hole misalignment

- Warping results in alignment

- Breaking with one ring results in oscillations, with occasional anti-alignment

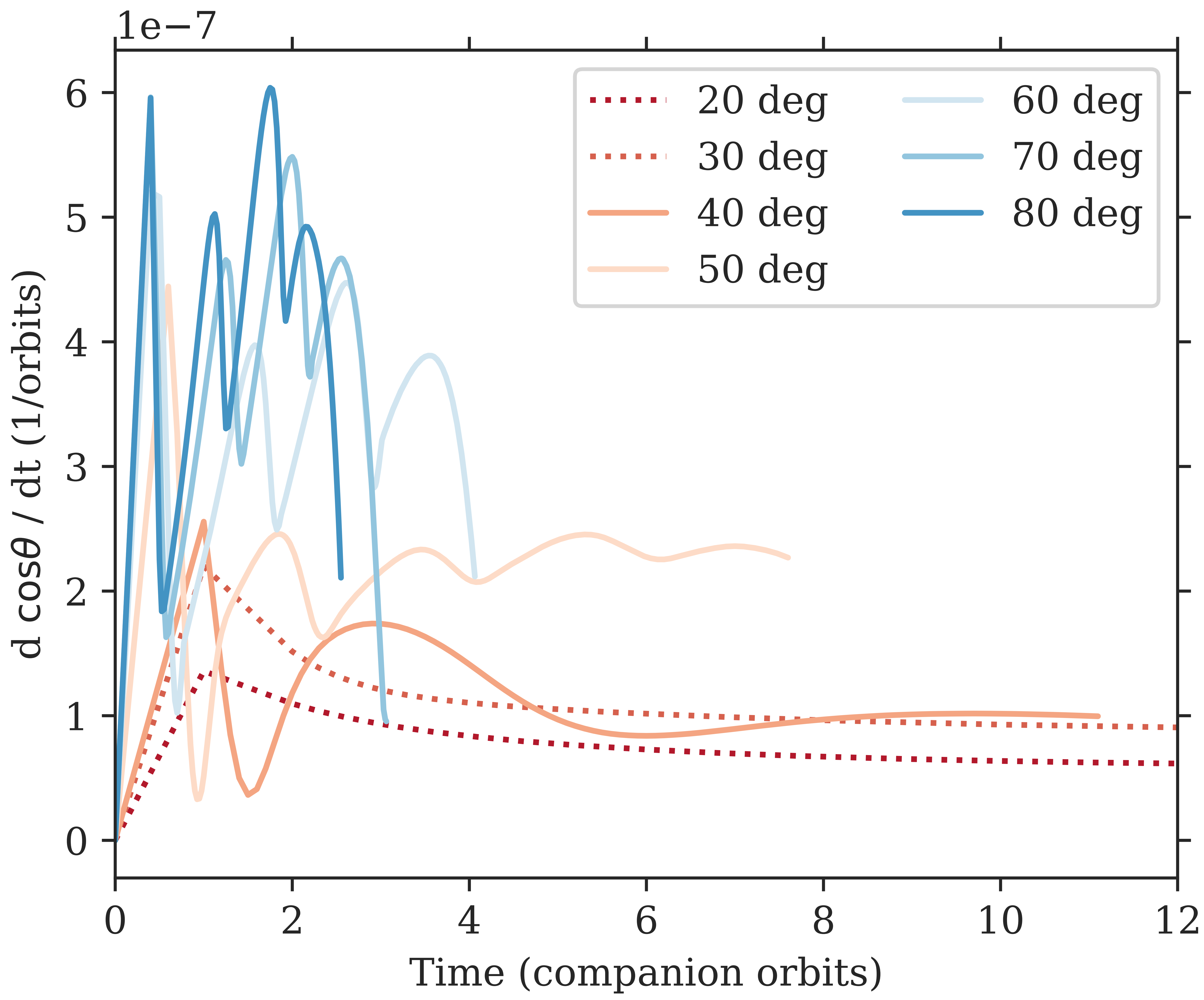


Disc-black hole misalignment

- Warping results in alignment

- Breaking with one ring results in oscillations, with occasional anti-alignment

- Breaking with multiple rings results in unpredictable oscillations



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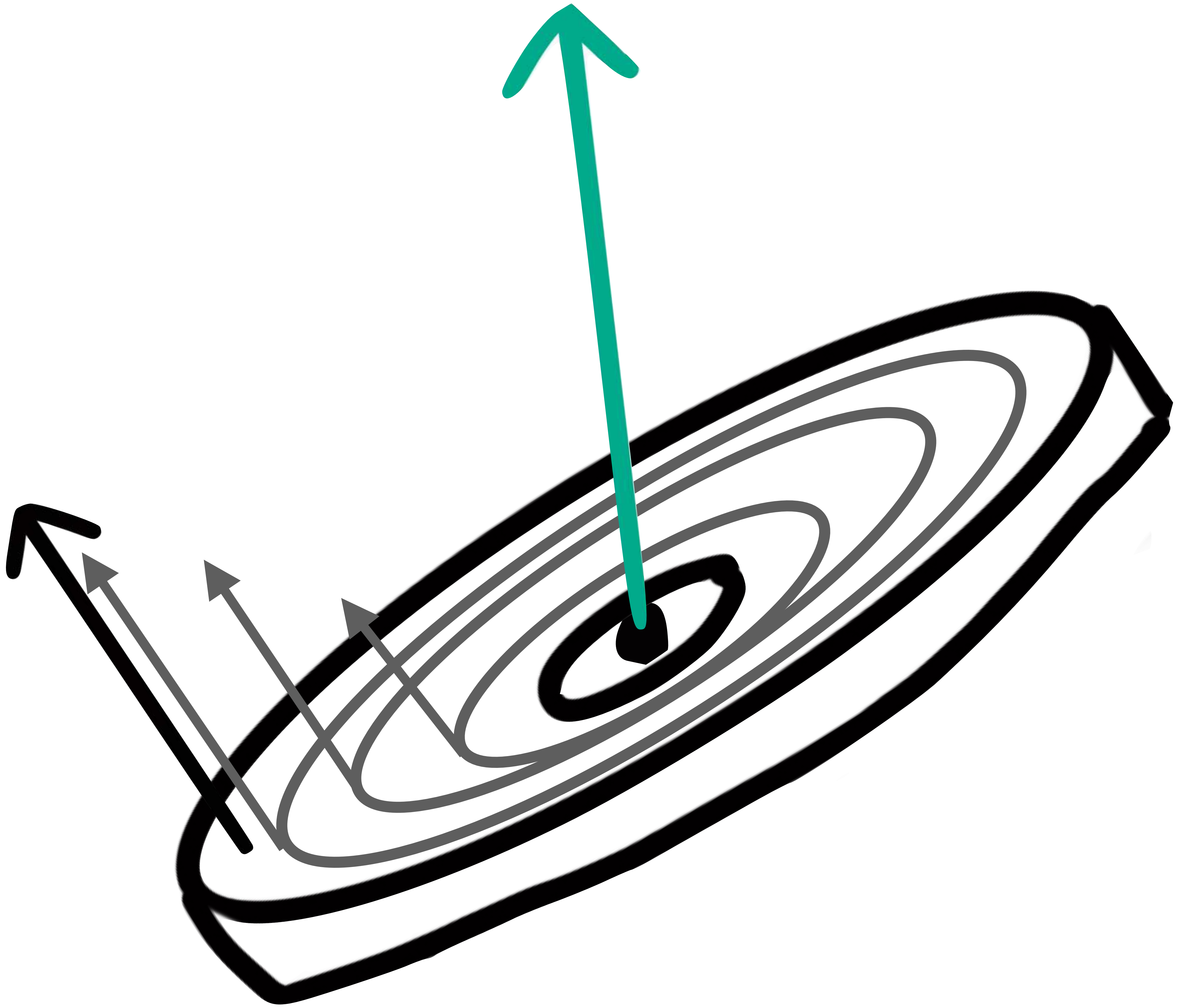

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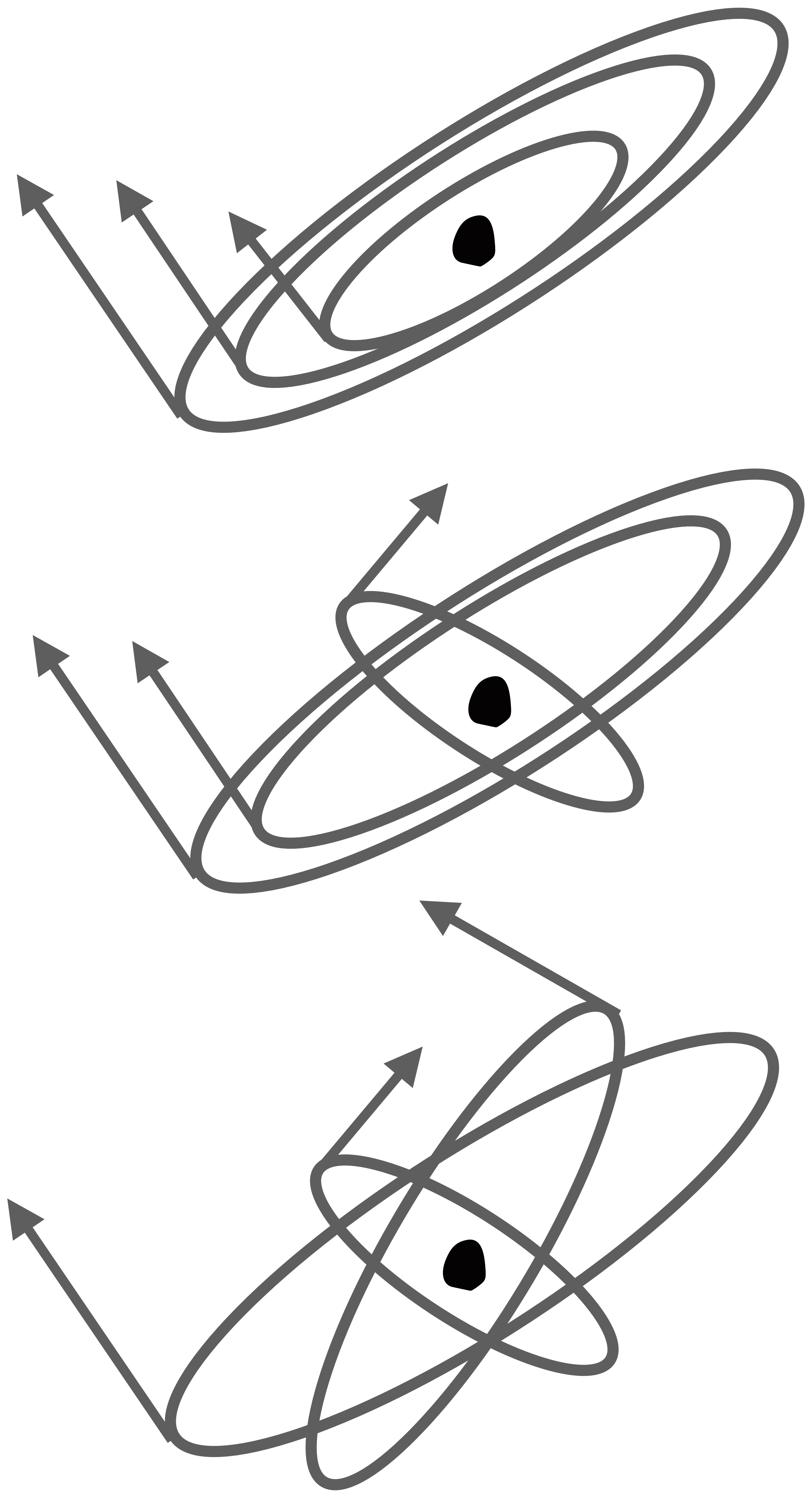

- Only warping results in alignment

- Breaking with one ring results in oscillations, with occasional anti-alignment

- Breaking with multiple rings results in unpredictable oscillations

Our results

- We find excellent agreement with the semi-analytic model of Gerosa et al. 2020
    - In the region where the semi-analytic model breaks down, we demonstrate that the discs are breaking
    - We have explained exceptions for very thick discs, large alpha and very large κ
- Spiral arms can stabilise the disc against disc breaking
- Disc breaking hinders (and in some cases prevents) alignment between the disc and the black hole

- Followed up by Steinle & Gerosa et al. 2023, showing that there are likely to be distinct populations that should be observable