Accretion disks around supermassive black-hole binaries can break

Davide Gerosa

University of Milano-Bicocca

Jun 17, 2022

EuCAPT workshop: Gravitational wave probes of black hole environments

Rome, Italy

with: G. Rosotti, R. Barbieri, R. Nealon, E. Ragusa, N. Steinle, G. Lodato, B. Veronesi

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Supermassive BHs: the road to merger

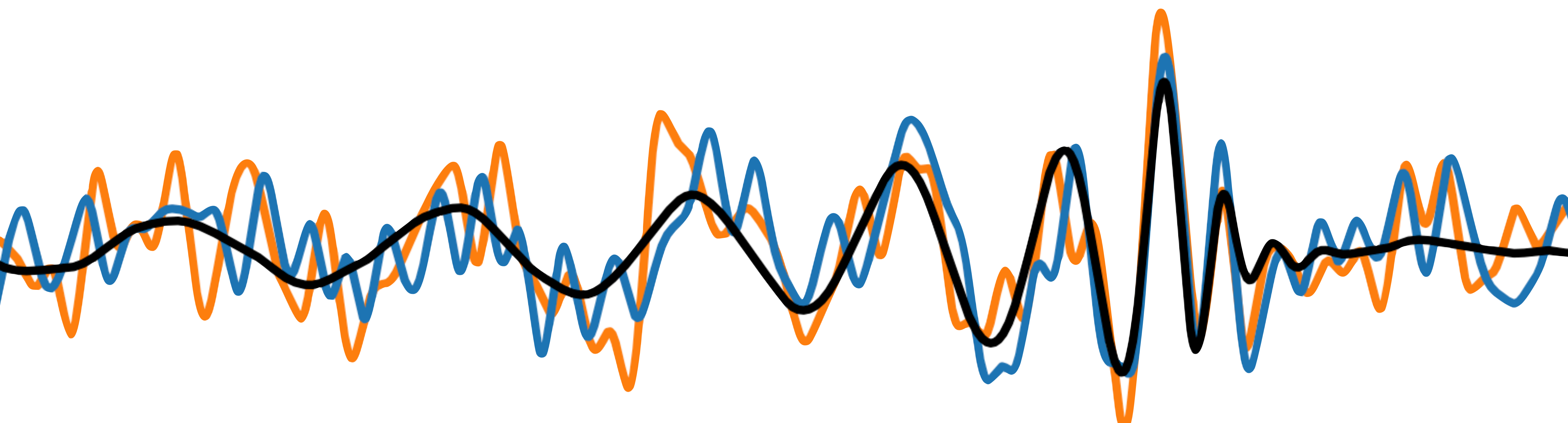
Begelman, Blandford, Rees 1980 (seminal) Colpi 2014 (review)

1. Galaxy mergers → SMBHs left at **~kpc** scale.
2. Dynamical friction → Down to **~10 pc.** Binary formation
3. Star scattering → Loss-cone refilling, triaxiality. Down to **~1pc**
   Merritt Poon 2004
4. Gas-driven phase → Possibly **~0.01pc**.
5. Gravitational-waves → $t_{\rm GW} \sim r^4 \ldots$ prompt merger **if** r~0.01pc
   Peters & Mathews 1963
6. Merger → **LISA detection!**
7. Recoil: ejections? → up to 5000 Km/s **> escape speed** of galaxies
   Gonzales et al. 2007; Campanelli et al. 2007

Do gravitational waves remember the disk?

Can't really say with the masses, but **spins are the secret**

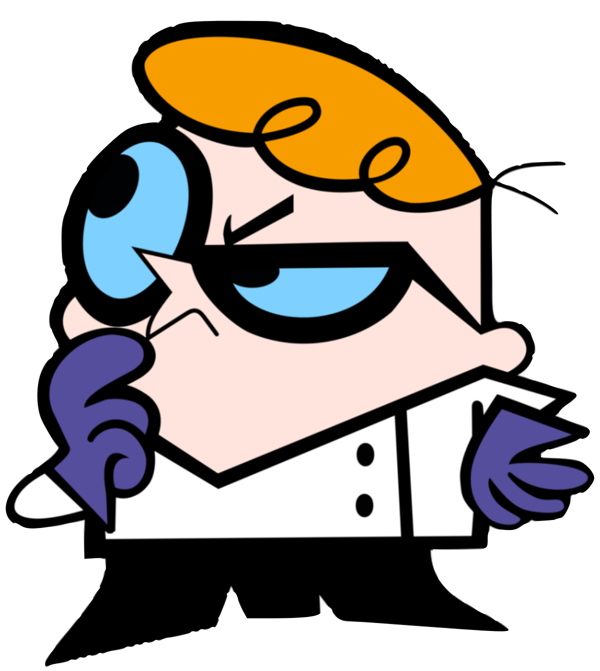
- If misaligned: relativistic spin precession in the LISA band
- Unique signal morphology
- Measurable with LISA's signal-to-noise ratios
- Superkicks strongly correlated with spin dynamics



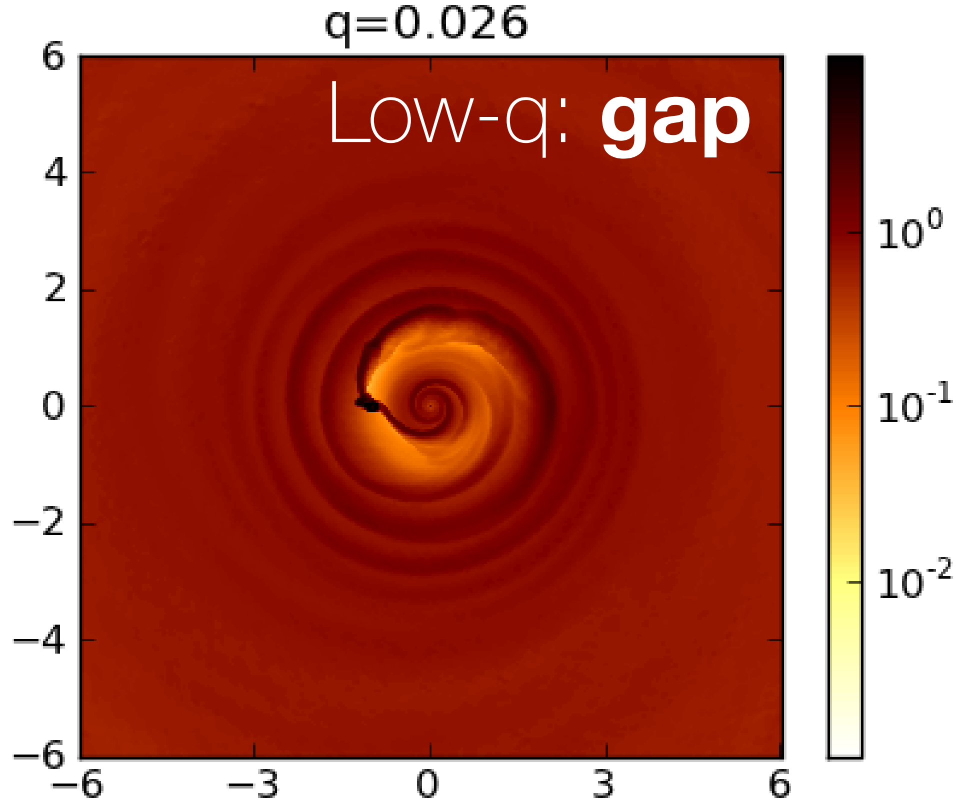
Step 1 arXiv:1503.06807

What are the timescales involved?

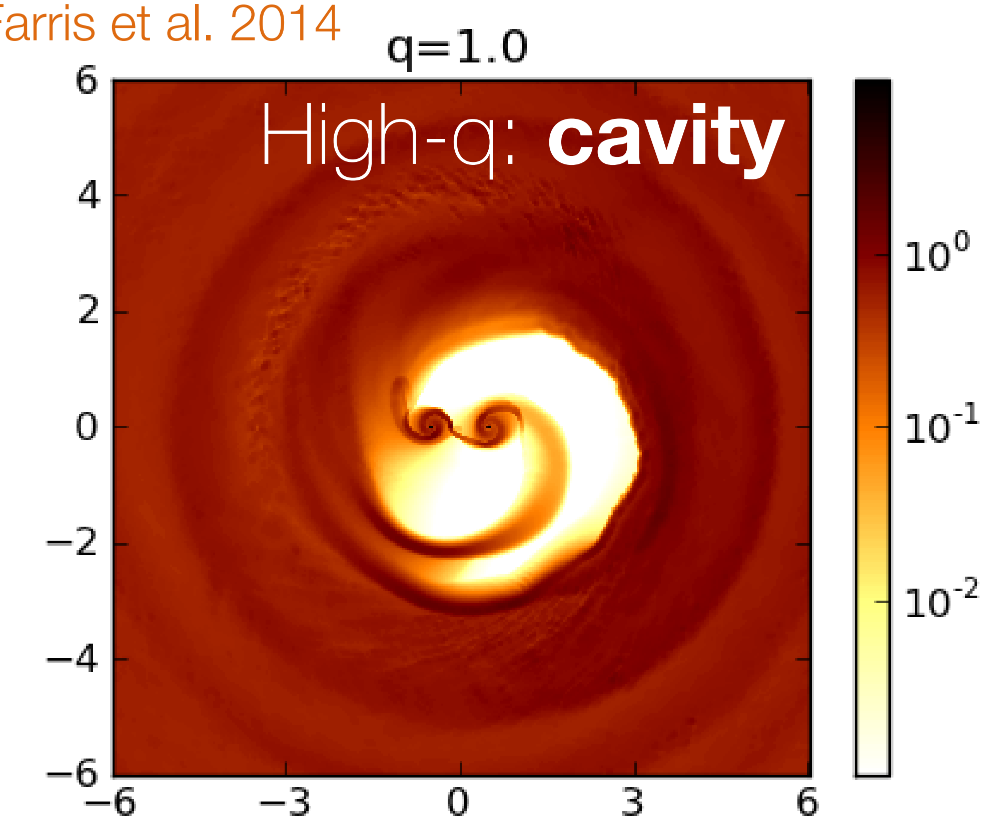
Inspiral and spin alignment take place simultaneously in the race towards merger



Gas-driven migration



Farris et al. 2014



Inspiral: circumbinary disk

Alignment: individual disks

Definitions

Primary BH: M_1

Secondary BH: M_2

Mass ratio: $q = M_2/M_1 \leq 1$

Disk mass: $M(R)$
within the binary separation

$$t_{\rm in}(R) = \frac{M_1}{M_1 + M_2} \frac{M_2 + M(R)}{M(R)} t_\nu(R)$$

High-q: speed up
Rafikov 2013

Low-q: viscous time
Armitage & Natarajan 2002

Massive secondary: slow down
Syer & Clarke 1995; Ivanov et al. 1999; Lodato et al. 2009

Gas disks can align the spins

Bardeen-Petterson effect

Bardeen & Petterson 1975; Rees 1978

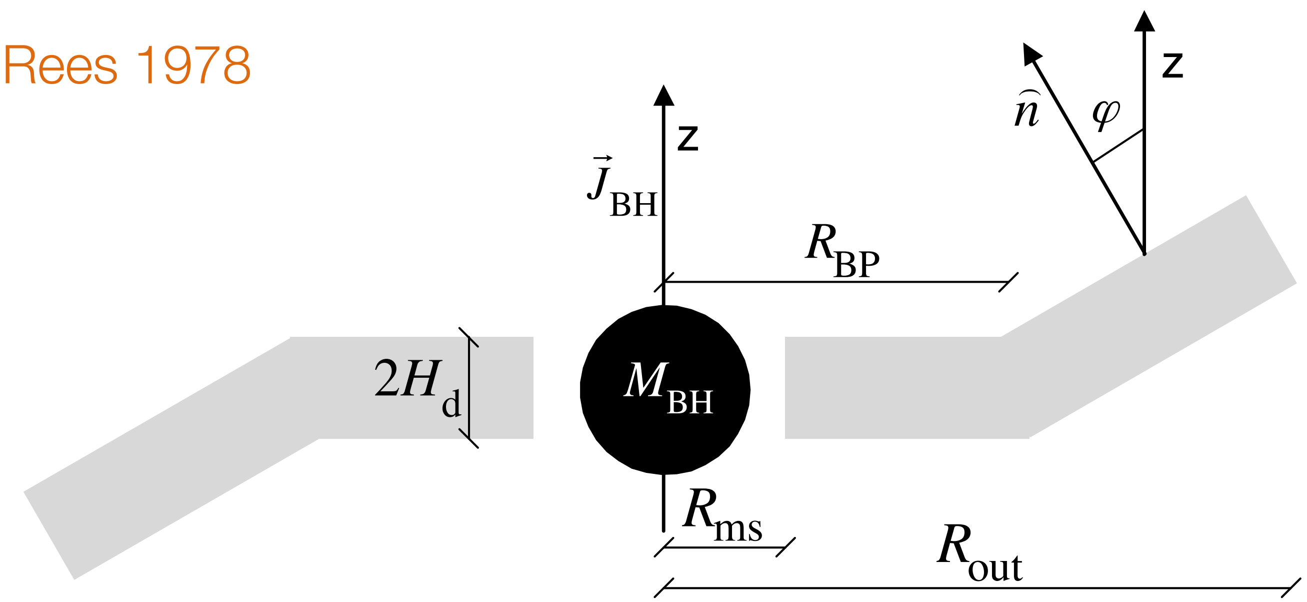
1. Lense-Thirring (GR) precession: **inner disk** quickly aligns

$$R_{\rm BP} \simeq \left(\frac{\chi}{\alpha_2}\right)^{2/3} \left(\frac{H}{R}\right)^{4/3} \left(\frac{GM}{c^2}\right) \sim 10^{-3}{\rm pc}$$

2. Reaction: the **outer disk** pulls the BH spin on a timescale

$$t_{\rm align} \simeq \frac{M}{\dot M} \alpha \left(\frac{\chi}{\alpha_2} \frac{H}{R}\right)^{2/3} \simeq 5\,{\rm Myr}$$

Scheuer Feiler 1996
Natarajan Pringle 1998
Martin+ 2007, 2009
Lodato **DG** 2012

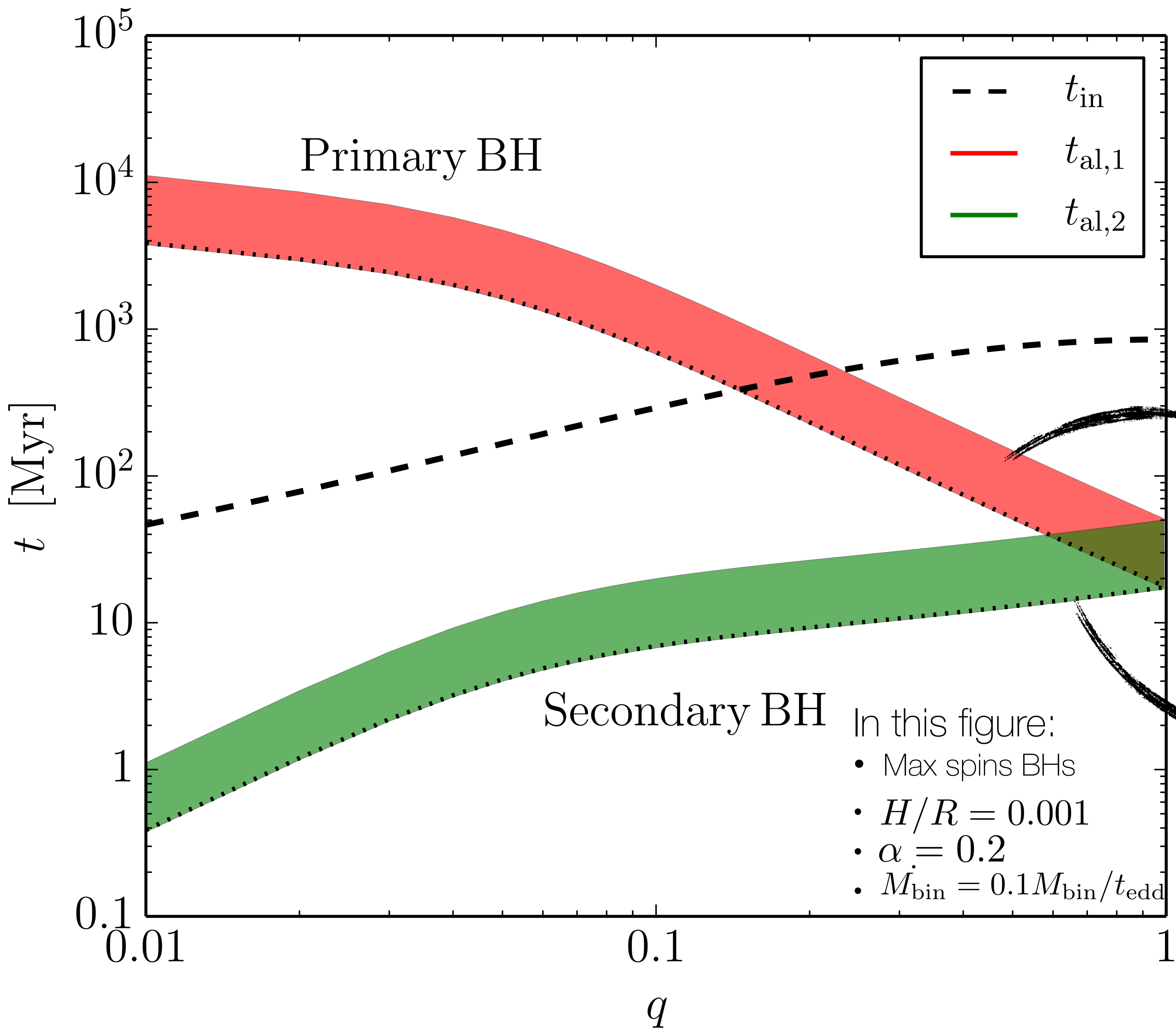


Adapted from Caproni et al. 2006

In a binary: is there enough time to align the spins?

A tale of three timescales

DG+ 2015



Larger inspiral time for q~1

Misaligned primaries! at q~0.2

(maybe even q~0.4!) Young, Clarke 2015

Aligned secondaries: differential accretion

Using cosmologically-motivated distributions: **~10% of misaligned primaries!**

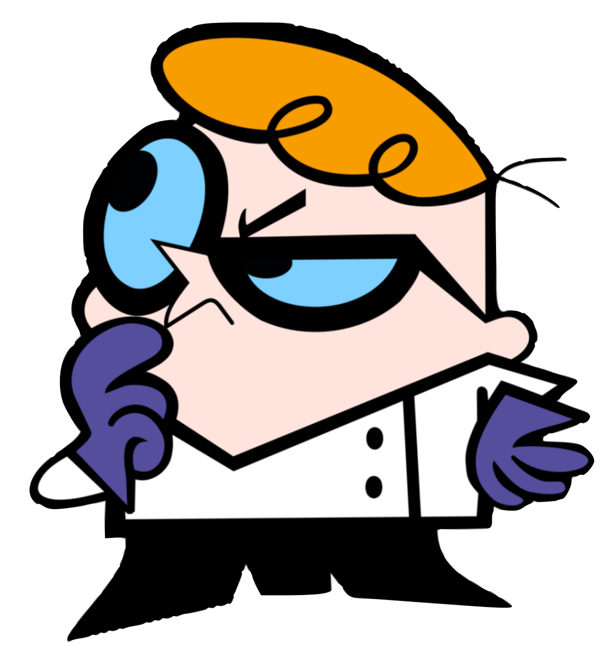
Arun et al. (LISA team) 2008; Sesana+ 2011

Small secondaries prevent primaries from aligning!

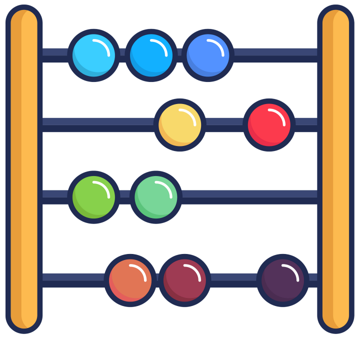
Step 2 arXiv:2004.02894

How to go beyond timescales and predict the residual misalignments?

A systematic approach to solve for structure of the disks and the backreaction onto the BH



Warped accretion disks



Pringle 1992

Mass conservation

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu_1 \Sigma R^{1/2}\right)\right] + \frac{1}{R}\frac{\partial}{\partial R}\left[\nu_2 \Sigma R^2 \left|\frac{\partial \hat{\mathbf{L}}}{\partial R}\right|^2\right]$$

Momentum conservation

$$\frac{\partial \hat{\mathbf{L}}}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[\frac{R^{1/2}}{\Sigma}\frac{\partial}{\partial R}\left(\nu_1 \Sigma R^{1/2}\right)\hat{\mathbf{L}}\right] + \frac{1}{R}\frac{\partial}{\partial R}\left[\left(\nu_2 R^2 \left|\frac{\partial \hat{\mathbf{L}}}{\partial R}\right|^2 - \frac{3}{2}\nu_1\right)\hat{\mathbf{L}}\right] + \frac{1}{R}\frac{\partial}{\partial R}\left(\frac{1}{2}\nu_2 R L \frac{\partial \hat{\mathbf{L}}}{\partial R}\right) + \frac{\partial}{\partial R}\left(\nu_3 R \mathbf{L} \times \frac{\partial \hat{\mathbf{L}}}{\partial R}\right) + \frac{2G}{c^2}\frac{\mathbf{J}\times\mathbf{L}}{R^3} + \frac{3GM_\star \Sigma R^2}{4R_\star^3}\left(\hat{\mathbf{L}}\cdot\hat{\mathbf{L}}_\star\right)\left(\hat{\mathbf{L}}\times\hat{\mathbf{L}}_\star\right)$$

ν_1	Shear viscosity	$\mathbf{J}$	Lense-Thirring torque
ν_2	Vertical viscosity (warps)	$\mathbf{L}_\star$	Binary companion torque

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Pringle 1992,
Lodato Price 2010

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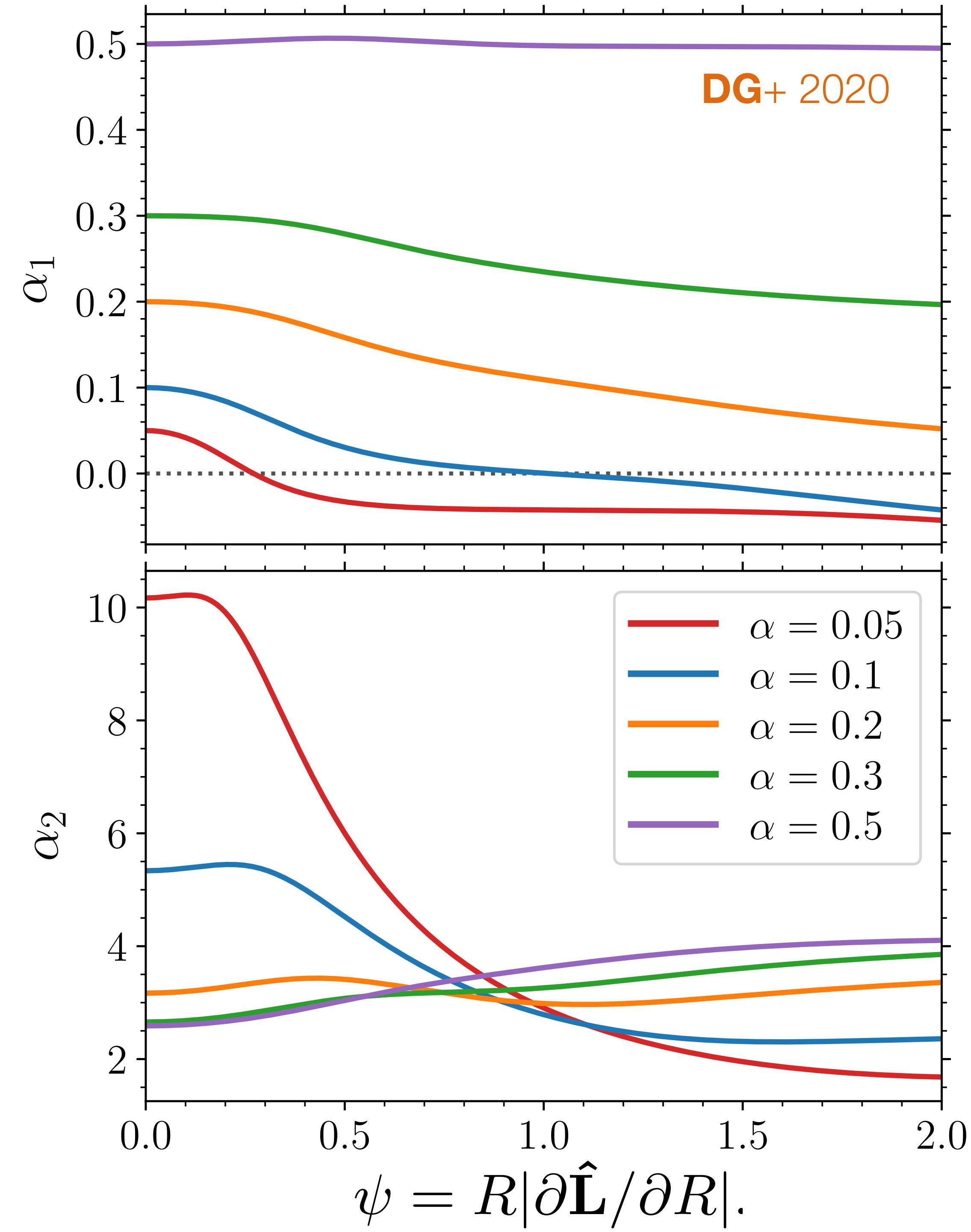
An iterative boundary value problem

- Look for stationary solutions
- Inner disk is aligned with the BH, outer disk aligned with the binary
- But viscosities are non linear! $\nu = \nu(\alpha, \partial \hat{\mathbf{L}} / \partial R)$

  Ogilvie 1999, Ogilvie Latter 2013
- A **new iterative scheme**, which simultaneously solves for the viscosity and the disk dynamics



For a **single** BH, the solution is self similar

Scheuer Feiler 1996, Martin+ 2007

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

For a **binary**, there's an additional parameter

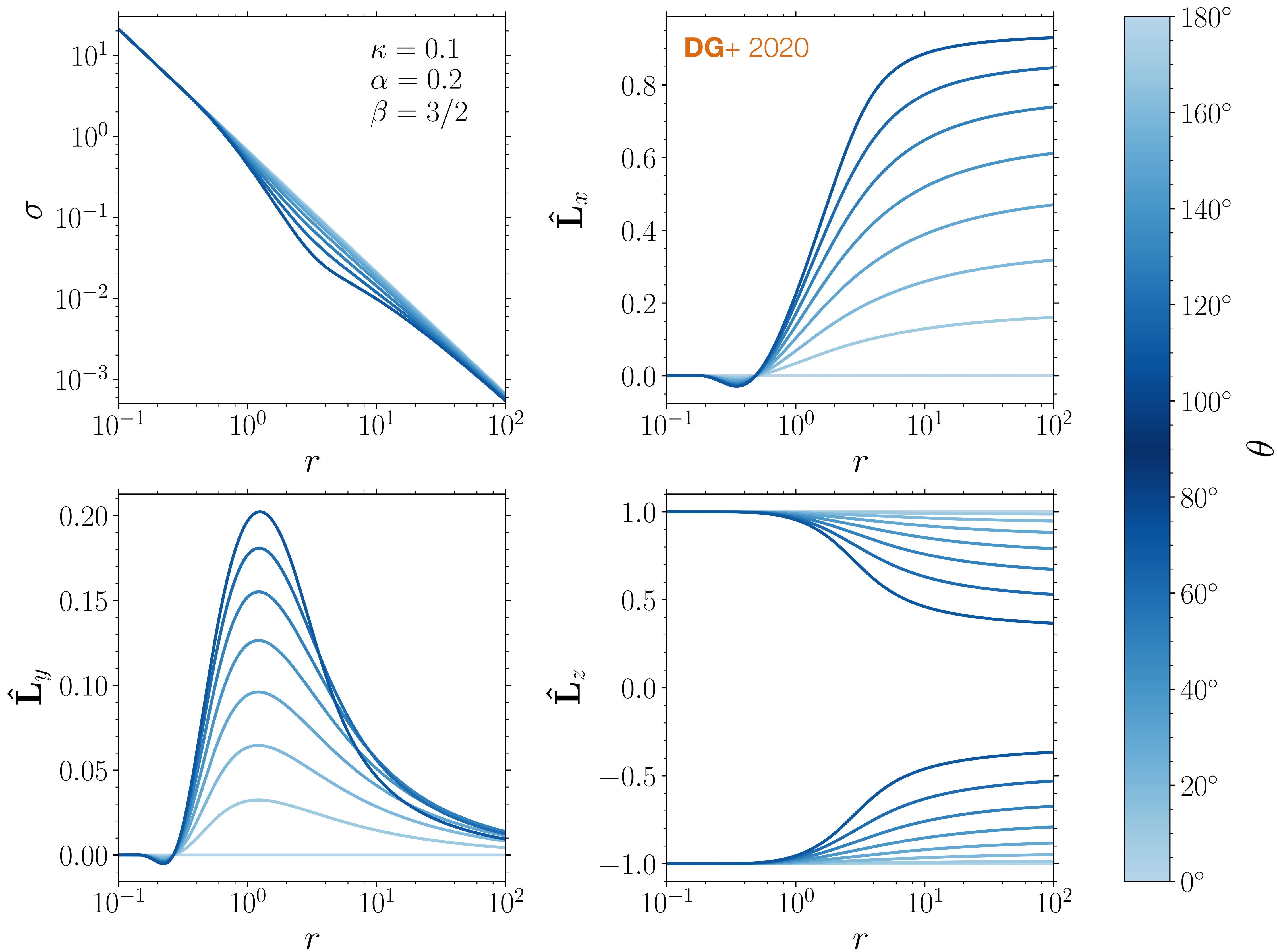
Tremaine Davis 2014, **DG**+ 2020

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

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

binary separation

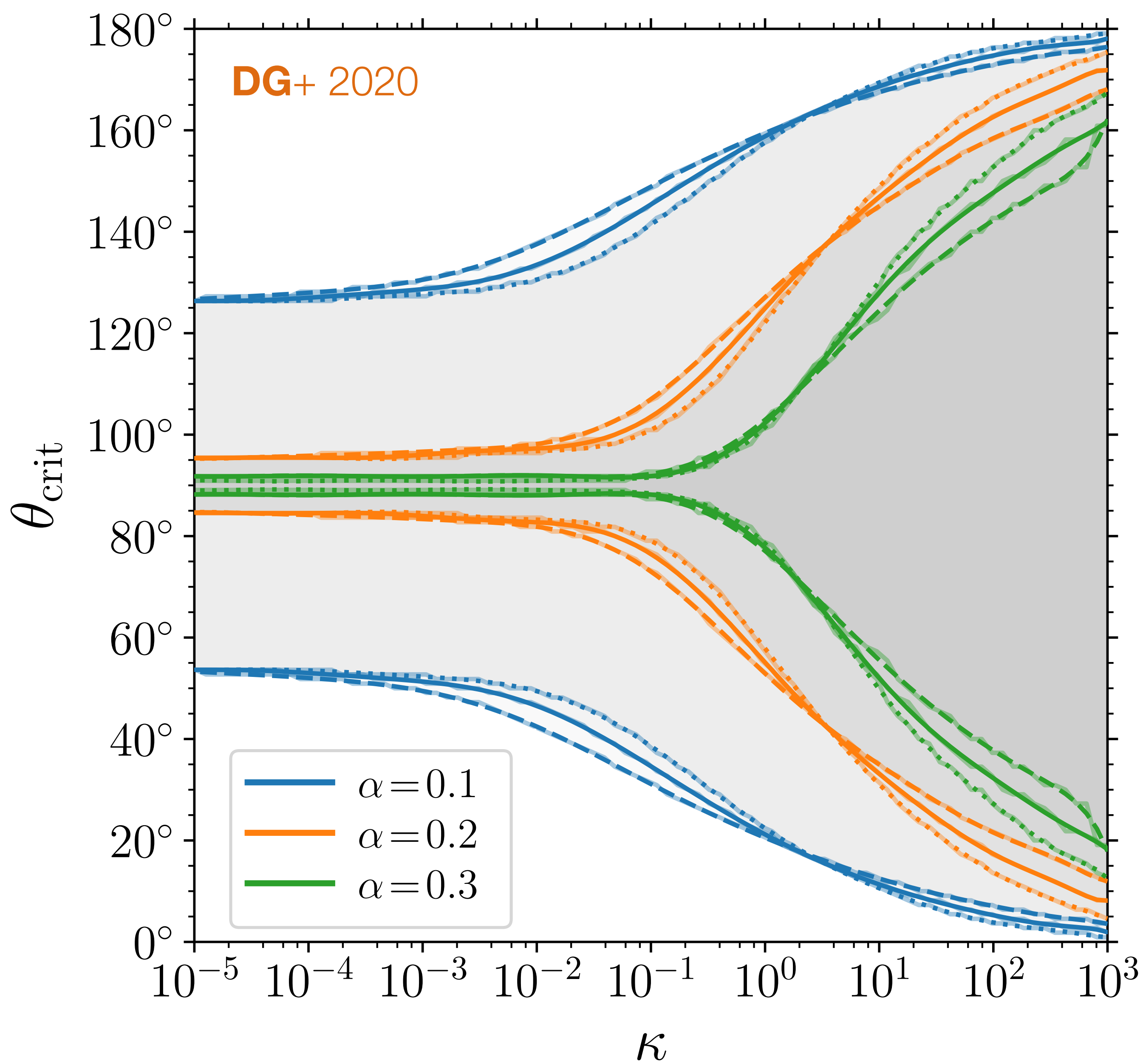
The shape of the disk

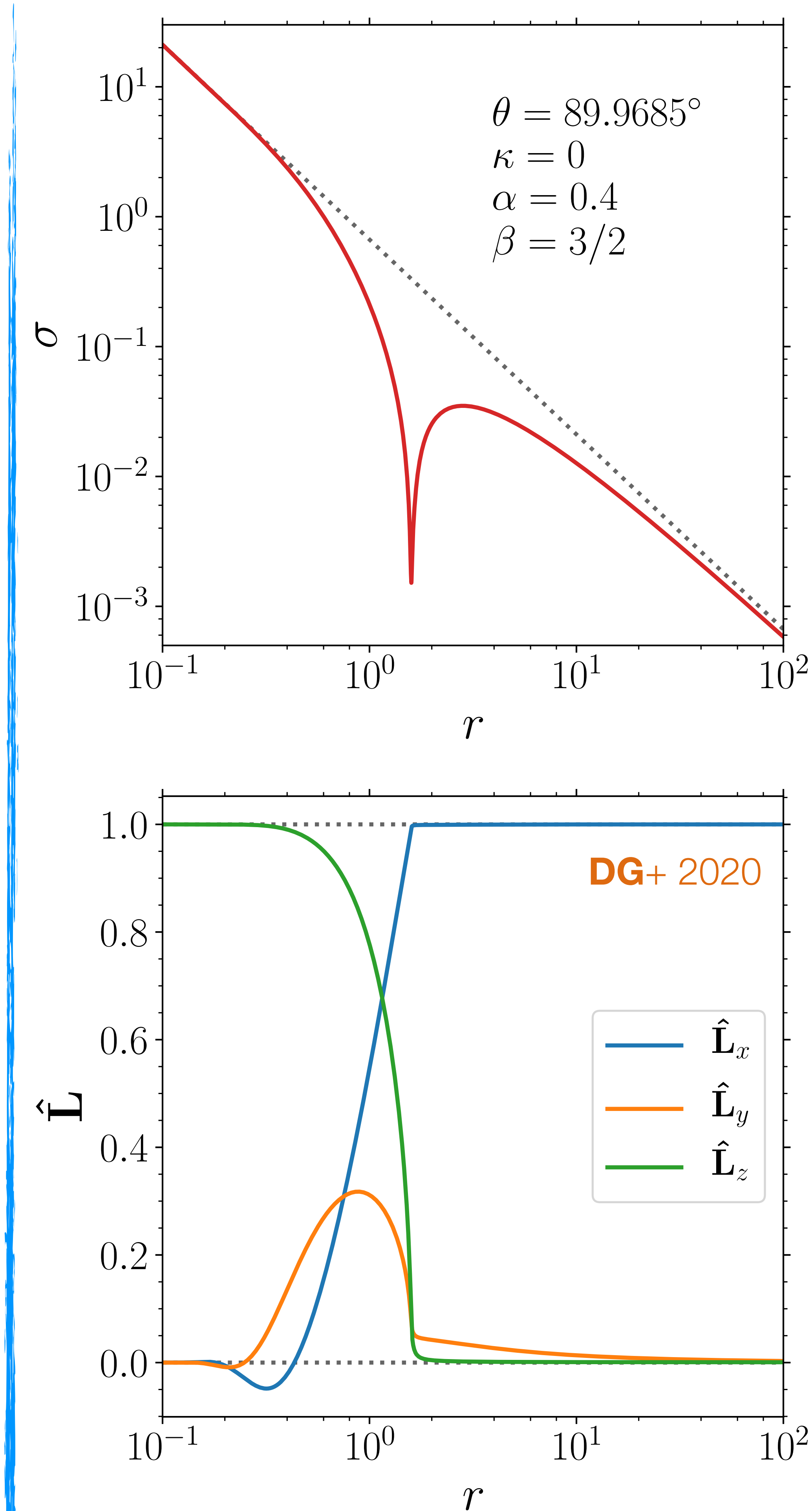


Critical obliquity

(these are the individual disks, not circumbinary)

- Solutions ceases to exists!
- Strong indication this is a physical effects
- Hints previously reported Tremaine and Davis 2014





Coupled alignment and inspiral

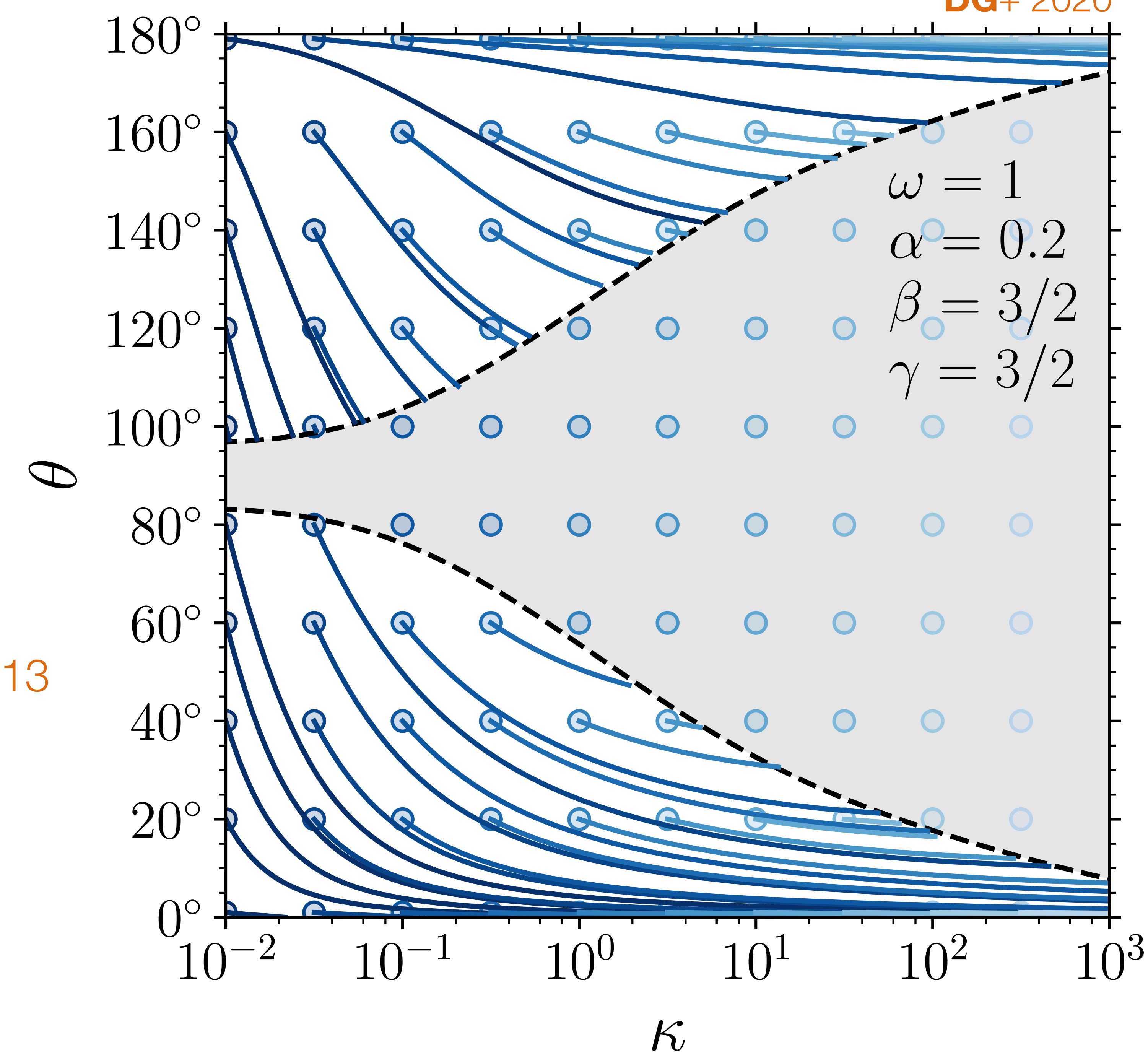
Back reaction from the disk onto the BH

$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}\ln\kappa} = -\omega\,\kappa^{-\gamma/3}\int_{r_{\min}}^{r_{\max}} (\hat{\mathbf{J}}\times\hat{\mathbf{L}})\cdot\hat{\mathbf{L}}_\star\,\frac{\sigma}{r^{3/2}}\,\mathrm{d}r$$

A history of solutions, just one more dimensionless parameter: **migration** ω

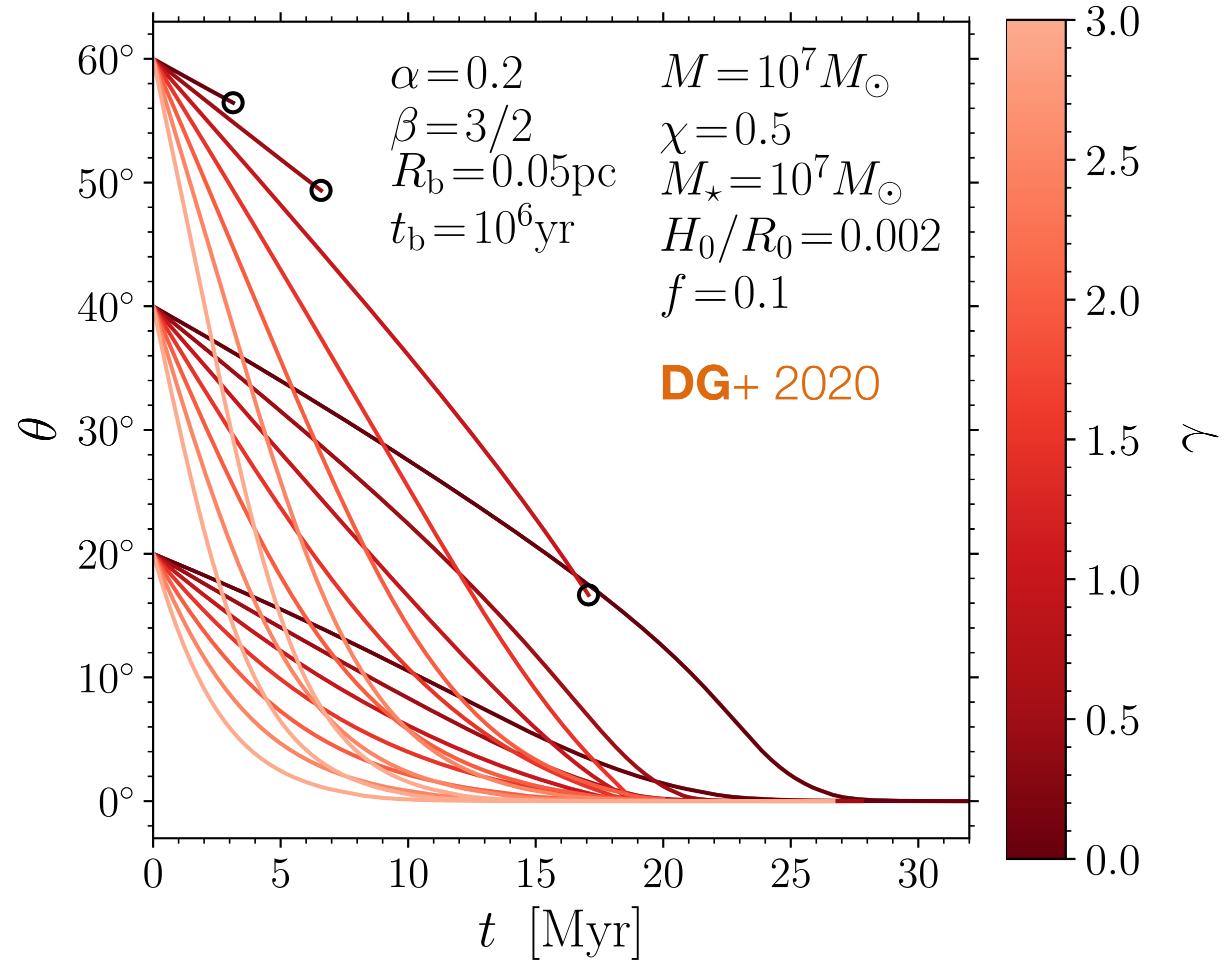
- Companion speeds up the alignment: warp radius moves inwards, material is misaligned closer to the BH Miller and Krolik 2013
- Warp non linearities are important! Surface density depletion right at the warp radius **DG**+ 2020

DG+ 2020

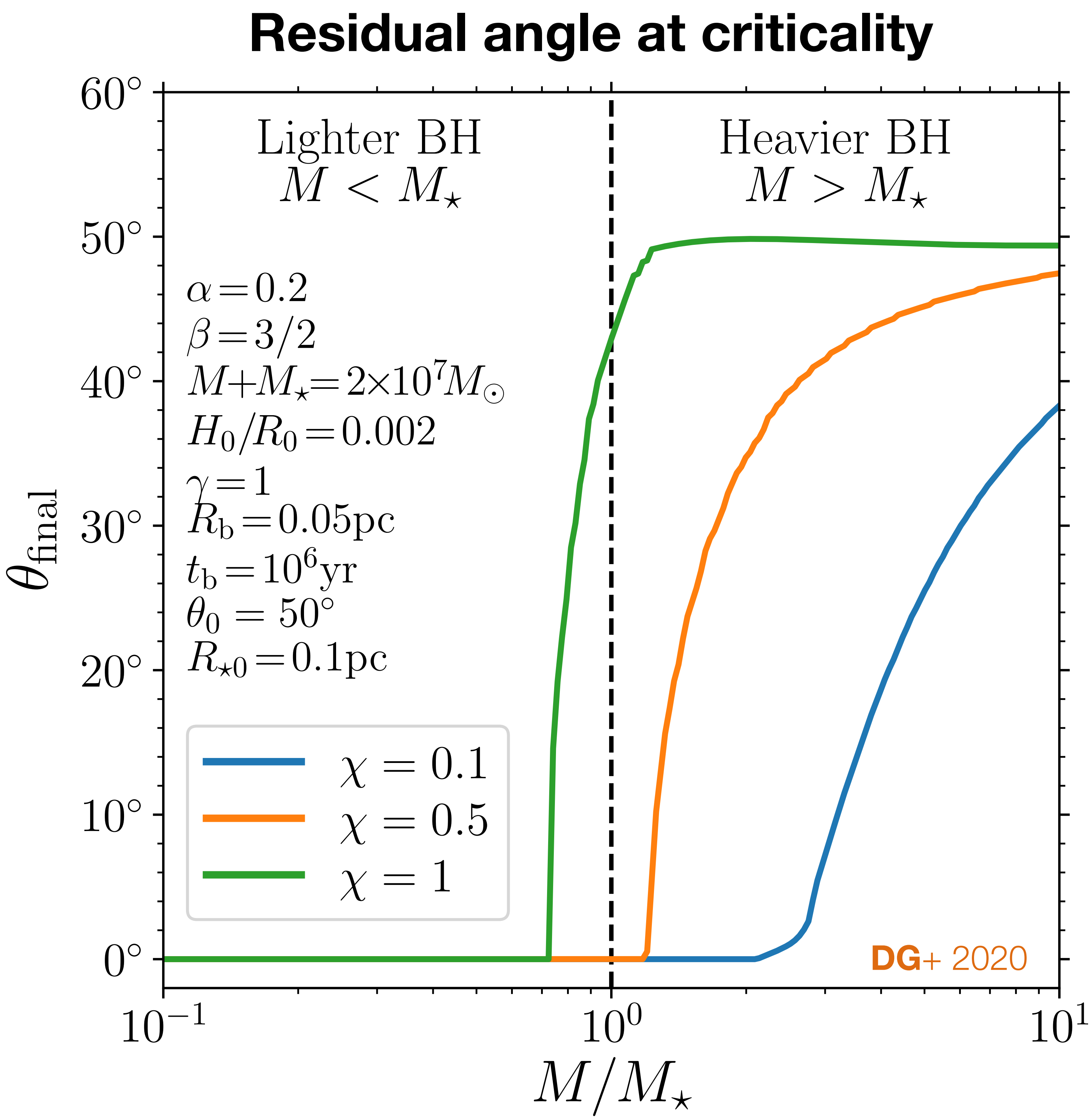


A secular path to disk breaking?

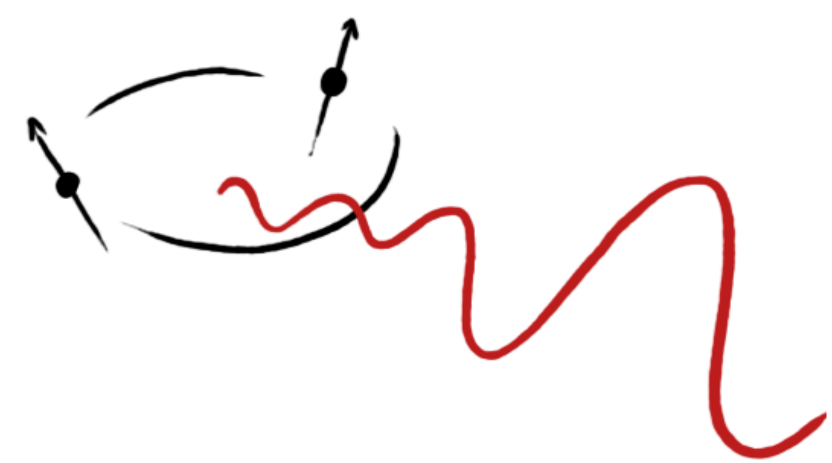
- Do physical disks surrounding BH in binaries actually break?
- Something as simple as the inspiral might do it!
- What happens to the disk at the breaking point?
- And **what happens to the black holes**?



Disk physics with gravitational waves?



- Secondary BH align quickly
- Primary BH does not accrete much, hence become critical.
- Do they stay misaligned till merger?



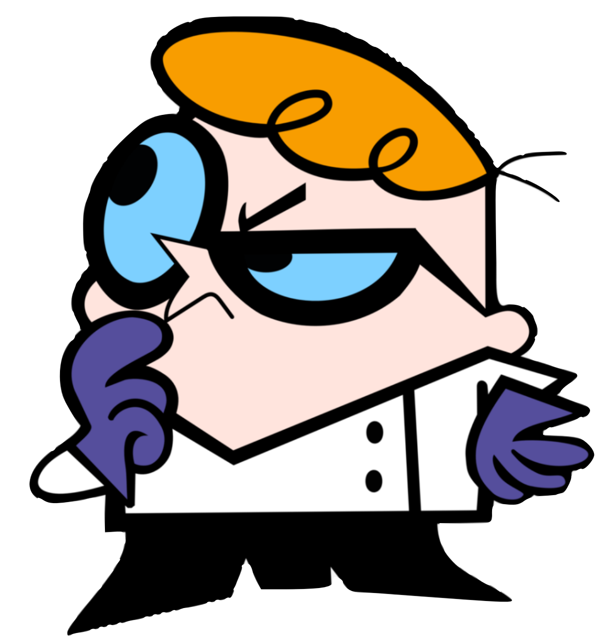
Steinle's talk

Putting this together with relativistic evolutions and LISA predictions!

Step 3 arXiv:2111.08065

Is the critical obliquity really there?

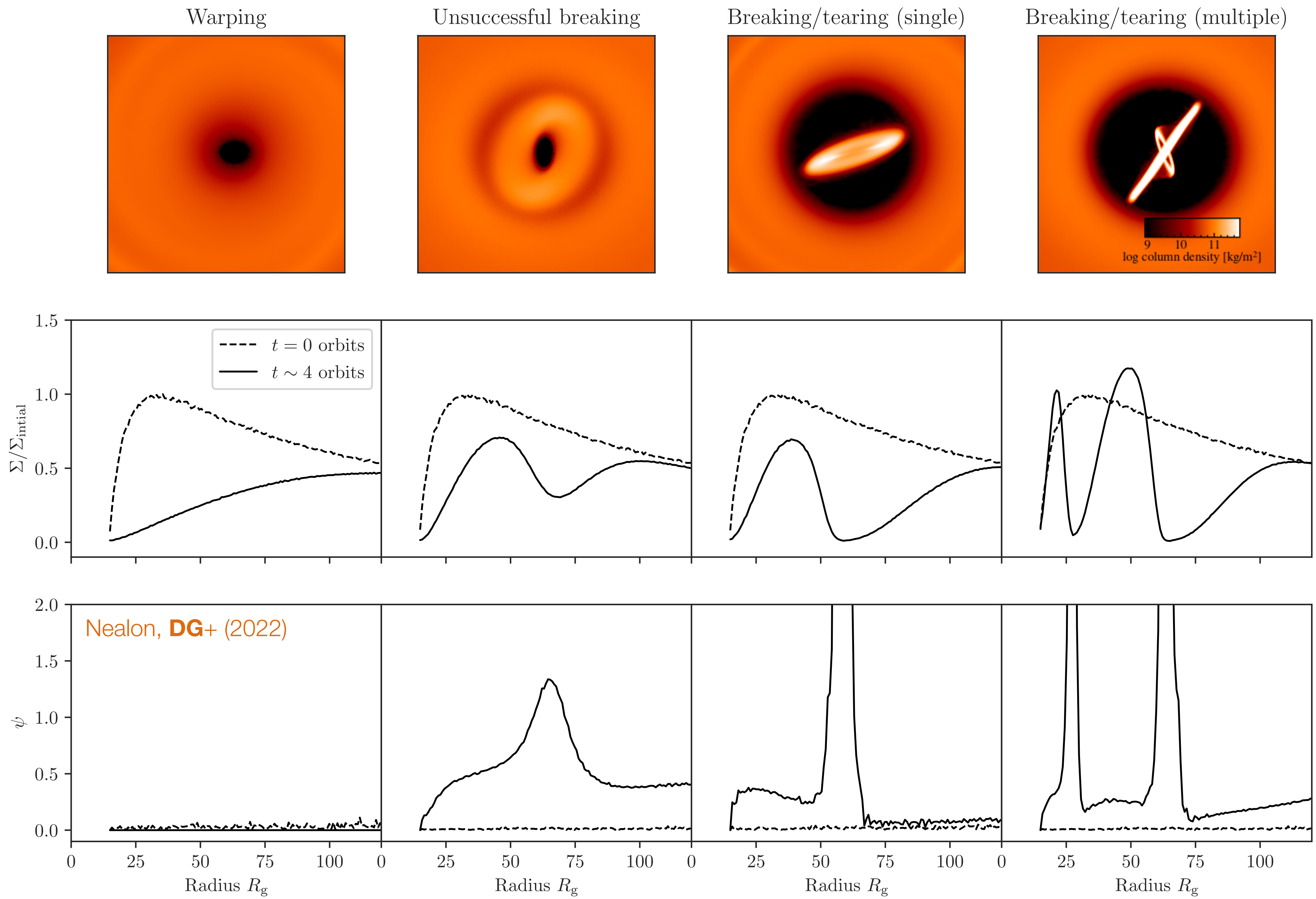
Check my 1D stationary solutions against 3D SPH



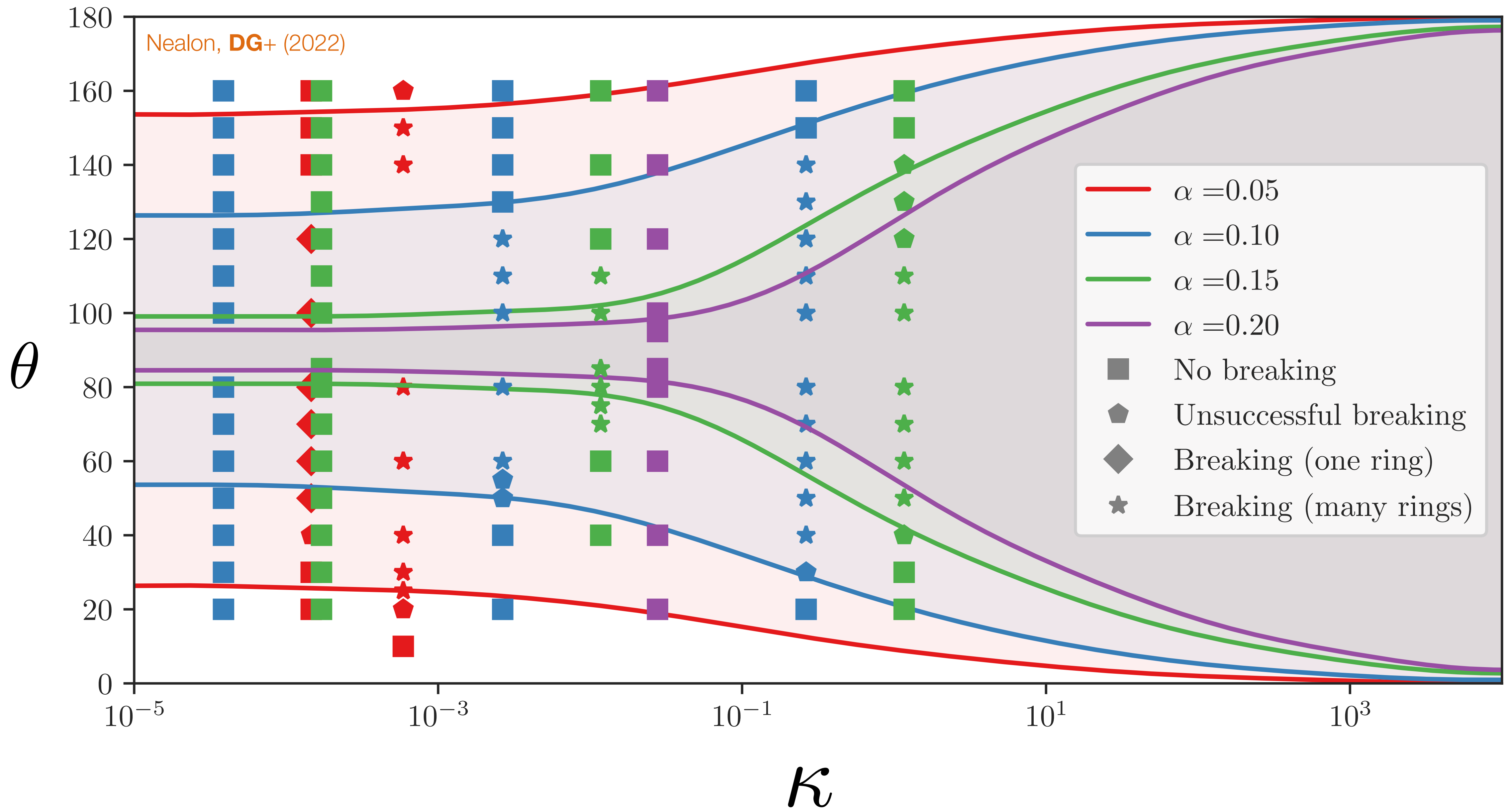
Tackling the problem head on

Nealon, **DG**+ (2022)

Large suite of >70 SPH runs



A surprising agreement…



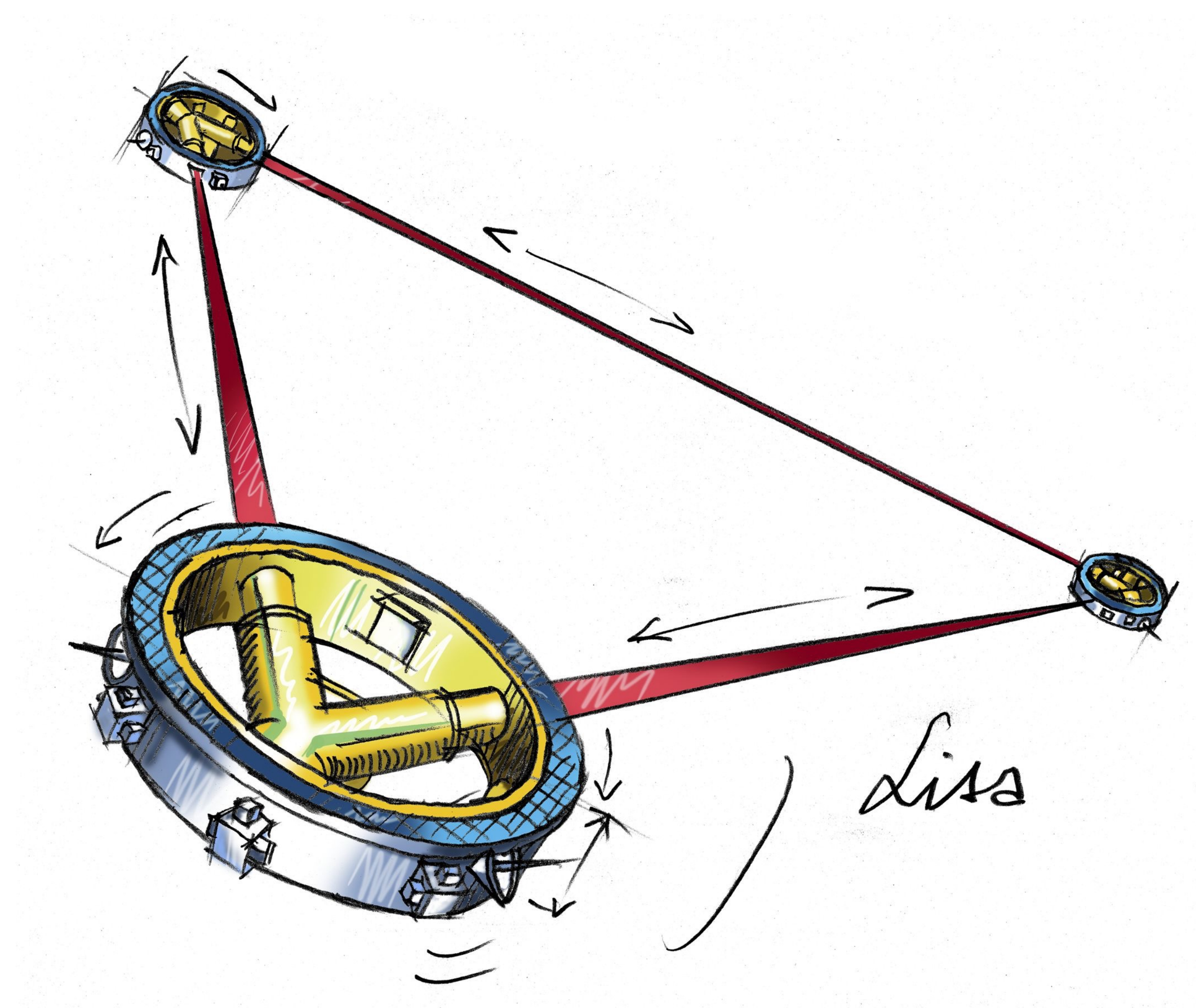
…with some interesting 3D effects on top

(e.g. spirals can prevent breaking)

Can LISA teach us something about disk warps?

Haven't really tackled the LISA problem yet…

but **now we have all the ingredients we need…**



DG+, arXiv:1503.06807

DG+ arXiv:2004.02894

Nealon, **DG**+ arXiv:2111.08065

Steinle, **DG** arXiv:22xx.soon

Next episode in this story…

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Rome, Italy

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Backup: scalings

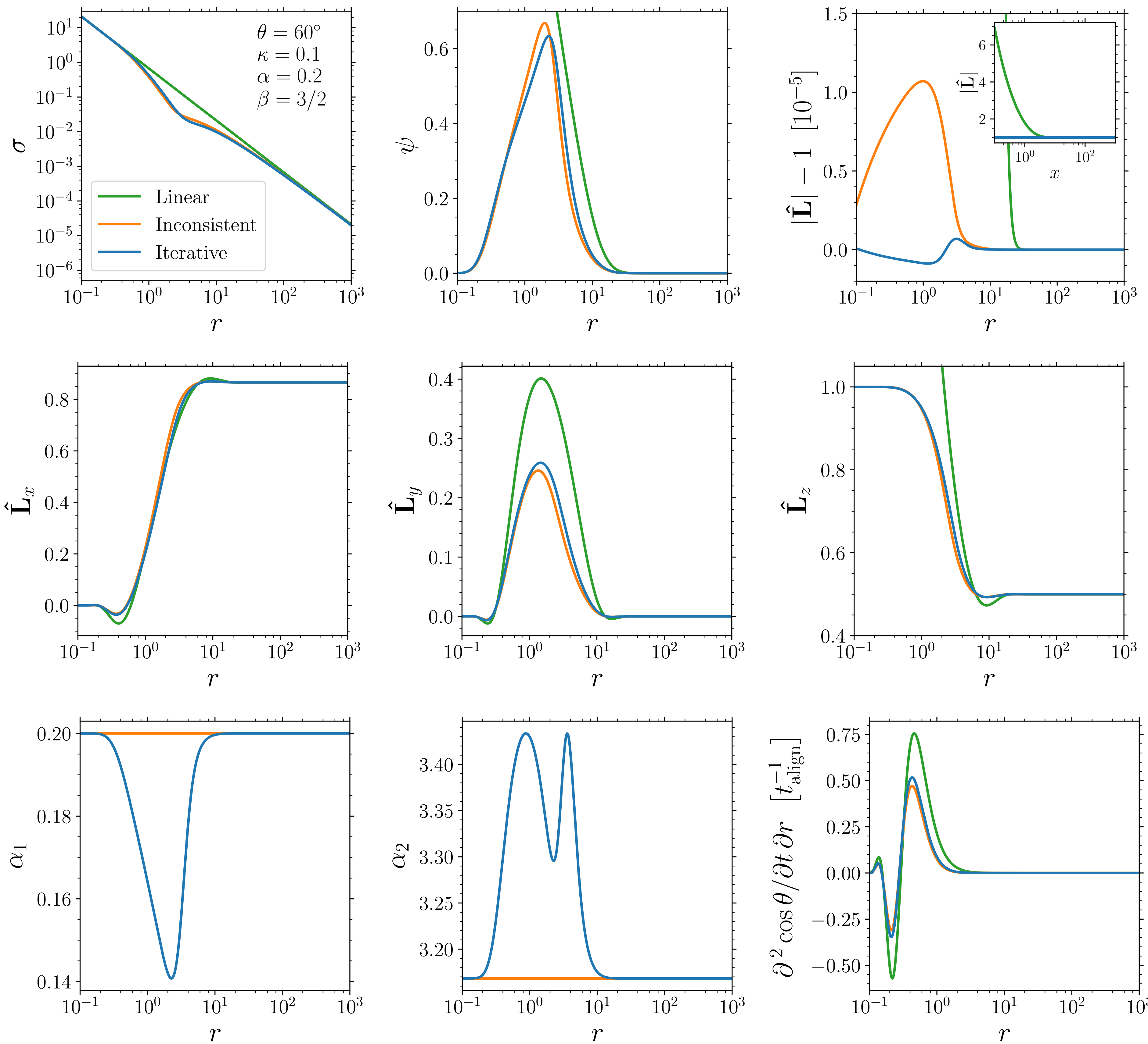
$$R_{\rm LT} \simeq 1.6 \times 10^{-3} \left(\frac{M}{10^7 M_\odot}\right) \left(\frac{\chi}{0.5}\right)^{2/3} \left(\frac{H_0/R_0}{0.002}\right)^{-4/3} \times \left(\frac{\alpha}{0.2}\right)^{-2} \left[\frac{\zeta}{1/(2\times 0.2^2)}\right]^{-2} {\rm pc}\,,$$

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

$$\omega \simeq \left(0.54 \times 10^{0.55\gamma}\right) \left(\frac{M}{10^7 M_\odot}\right)^{-1+2\gamma/3} \left(\frac{\chi}{0.5}\right)^{2(\gamma-1)/3} \times \left(\frac{M_\star}{10^7 M_\odot}\right)^{1+\gamma/3} \left(\frac{R_{\rm b}}{0.05{\rm pc}}\right)^{-\gamma} \left(\frac{t_{\rm b}}{10^6{\rm yr}}\right) \times \left(\frac{H_0/R_0}{0.002}\right)^{-2(\gamma+1/3)} \left(\frac{\alpha}{0.2}\right)^{-\gamma-1/3} \left[\frac{\zeta}{1/(2\times 0.2^2)}\right]^{2/3-\gamma}$$

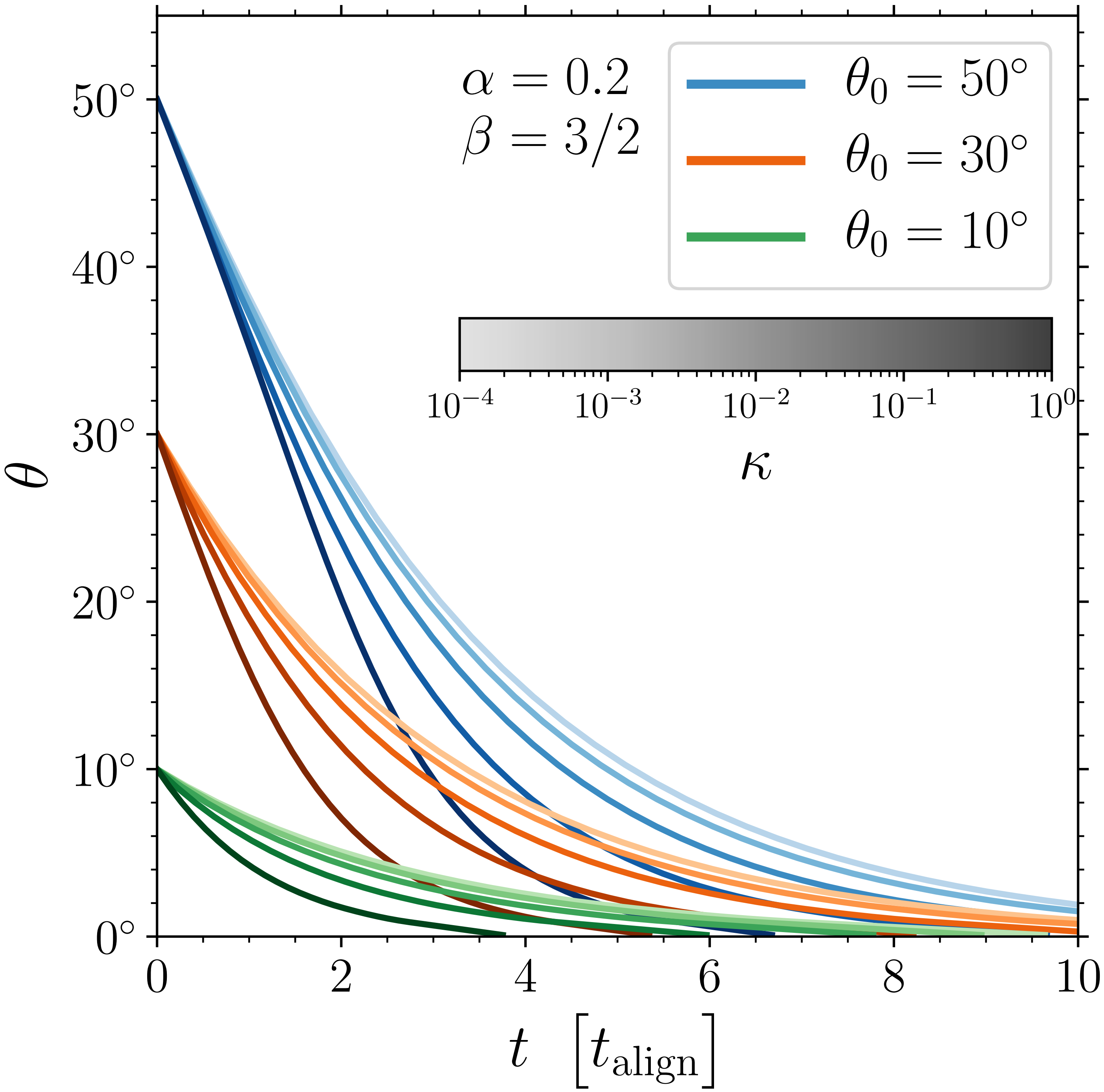
(5

Backup: linear vs nonlinear

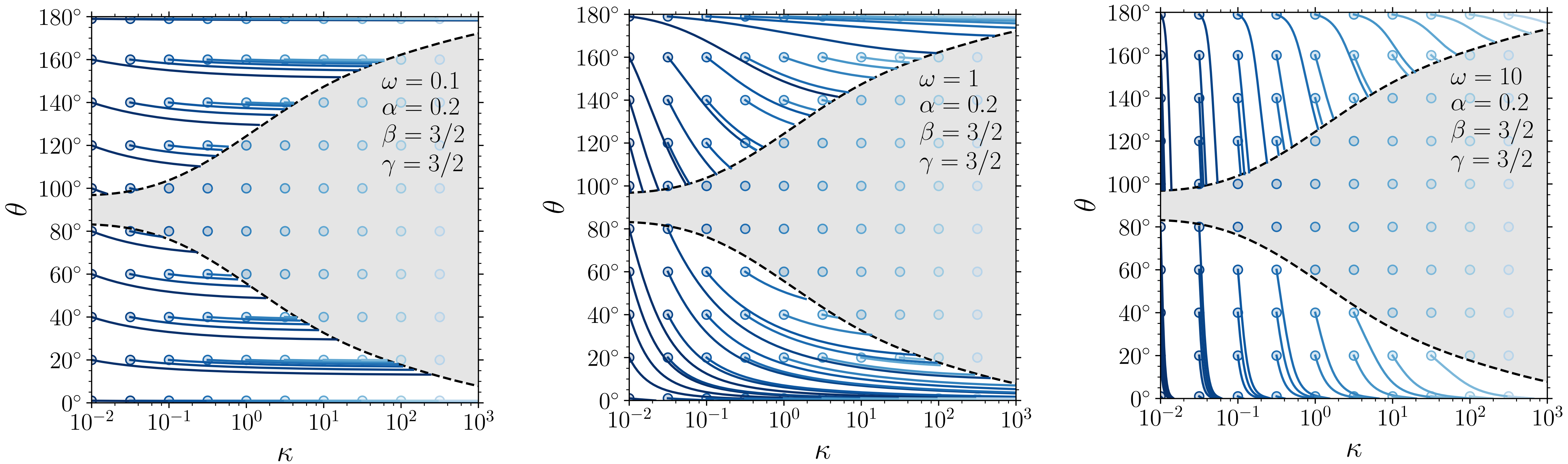


Backup: backreaction

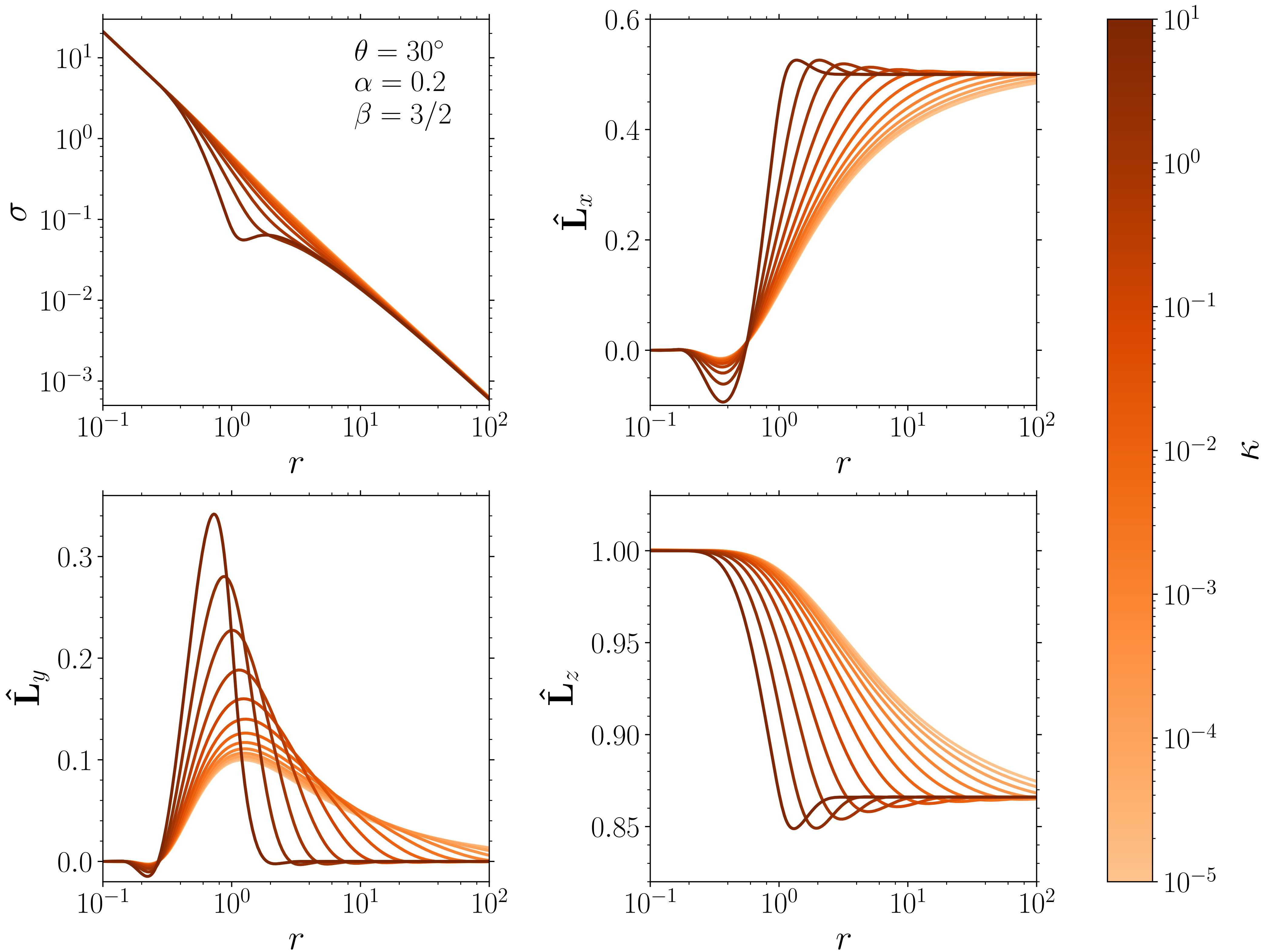
$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}t} = \frac{\mathrm{d}\hat{\mathbf{J}}}{\mathrm{d}t}\cdot\hat{\mathbf{L}}_\star = -\frac{1}{t_{\mathrm{align}}}\int_{r_{\mathrm{min}}}^{r_{\mathrm{max}}}(\hat{\mathbf{J}}\times\hat{\mathbf{L}})\cdot\hat{\mathbf{L}}_\star\frac{\sigma}{r^{3/2}}\,\mathrm{d}r$$



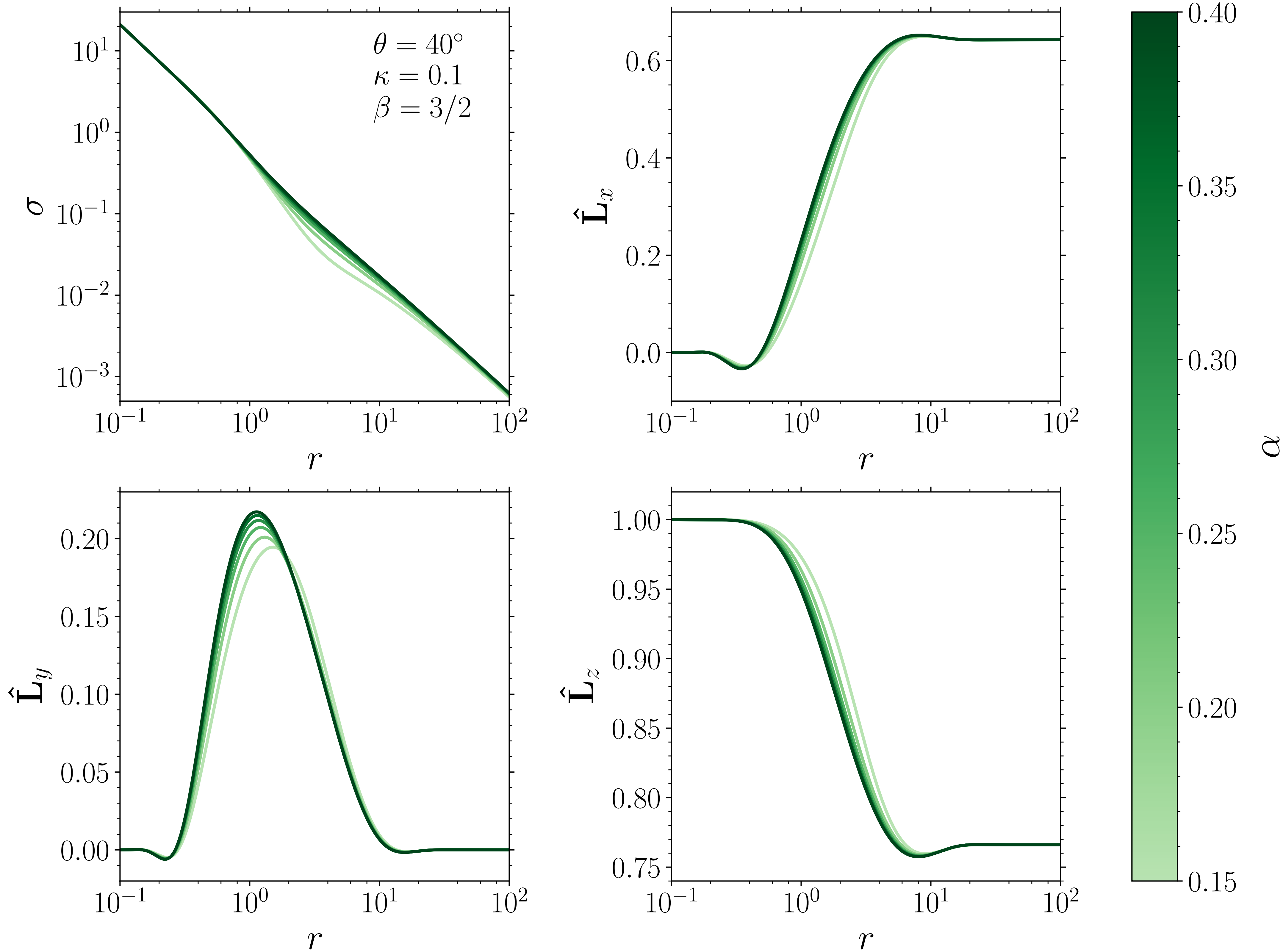
Backup: impact of the migration parameter



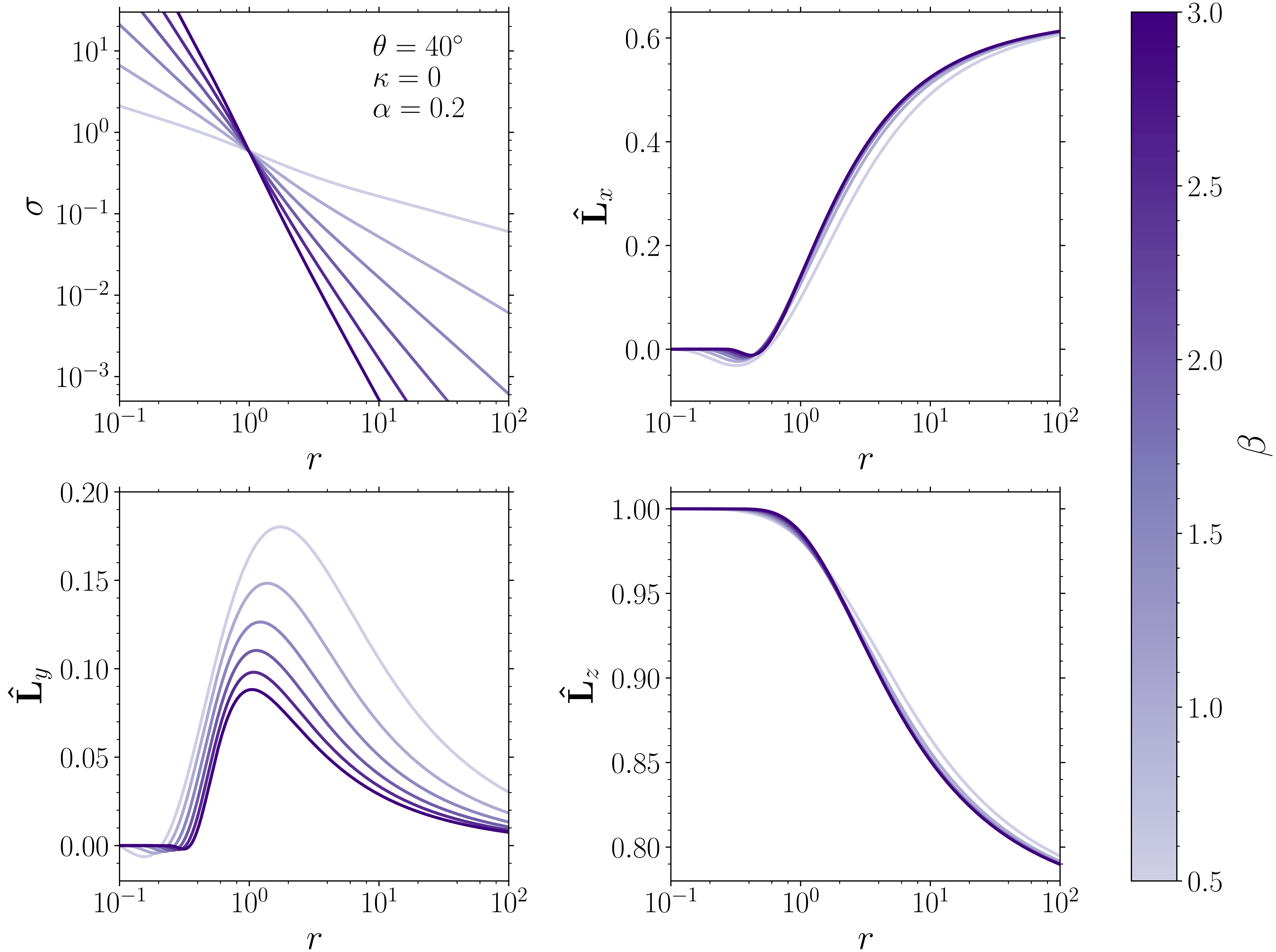
Backup: disk structure



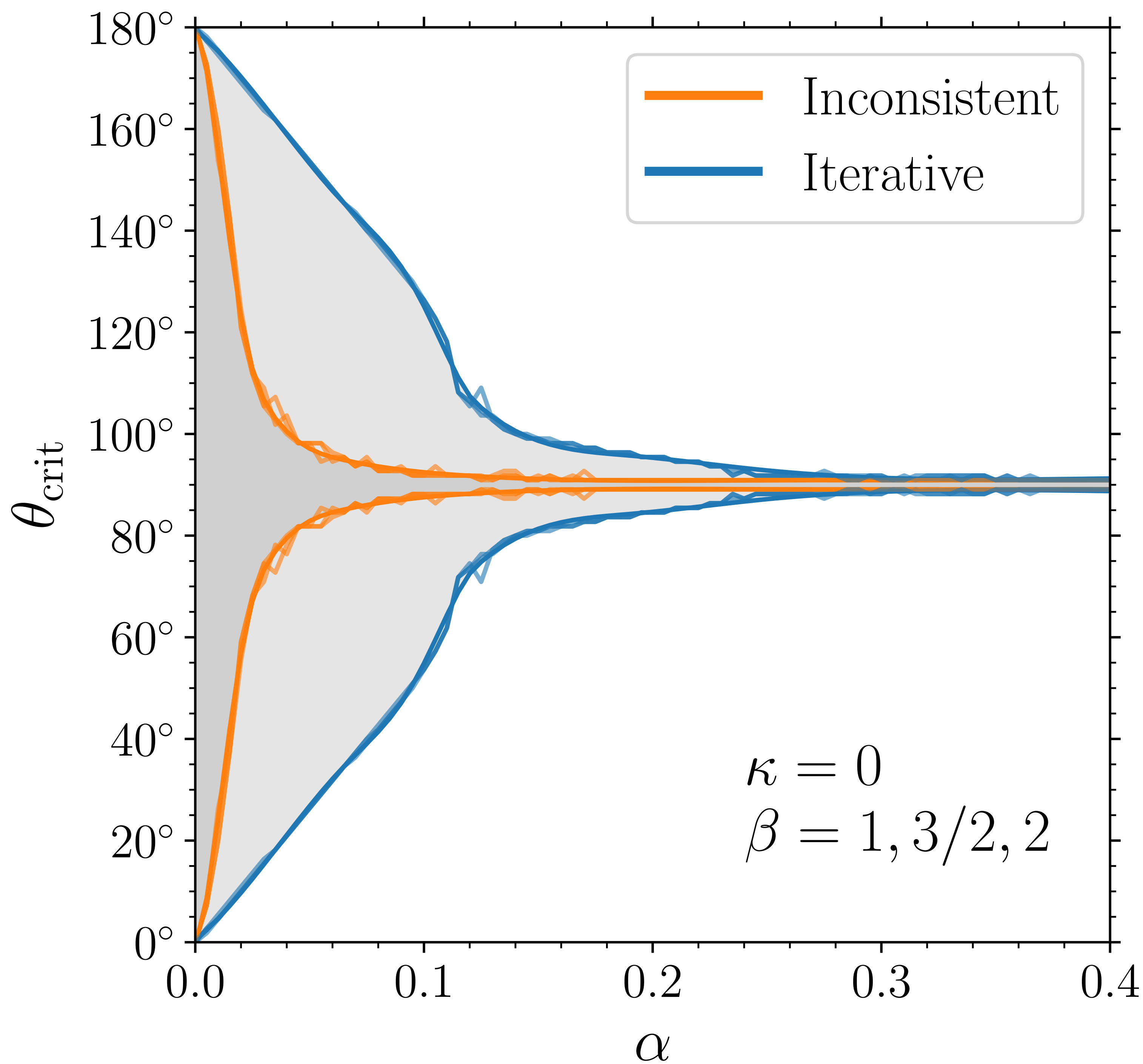
Backup: disk structure



Backup: disk structure



Backup: importance of iterative procedure



Backup: no solution region