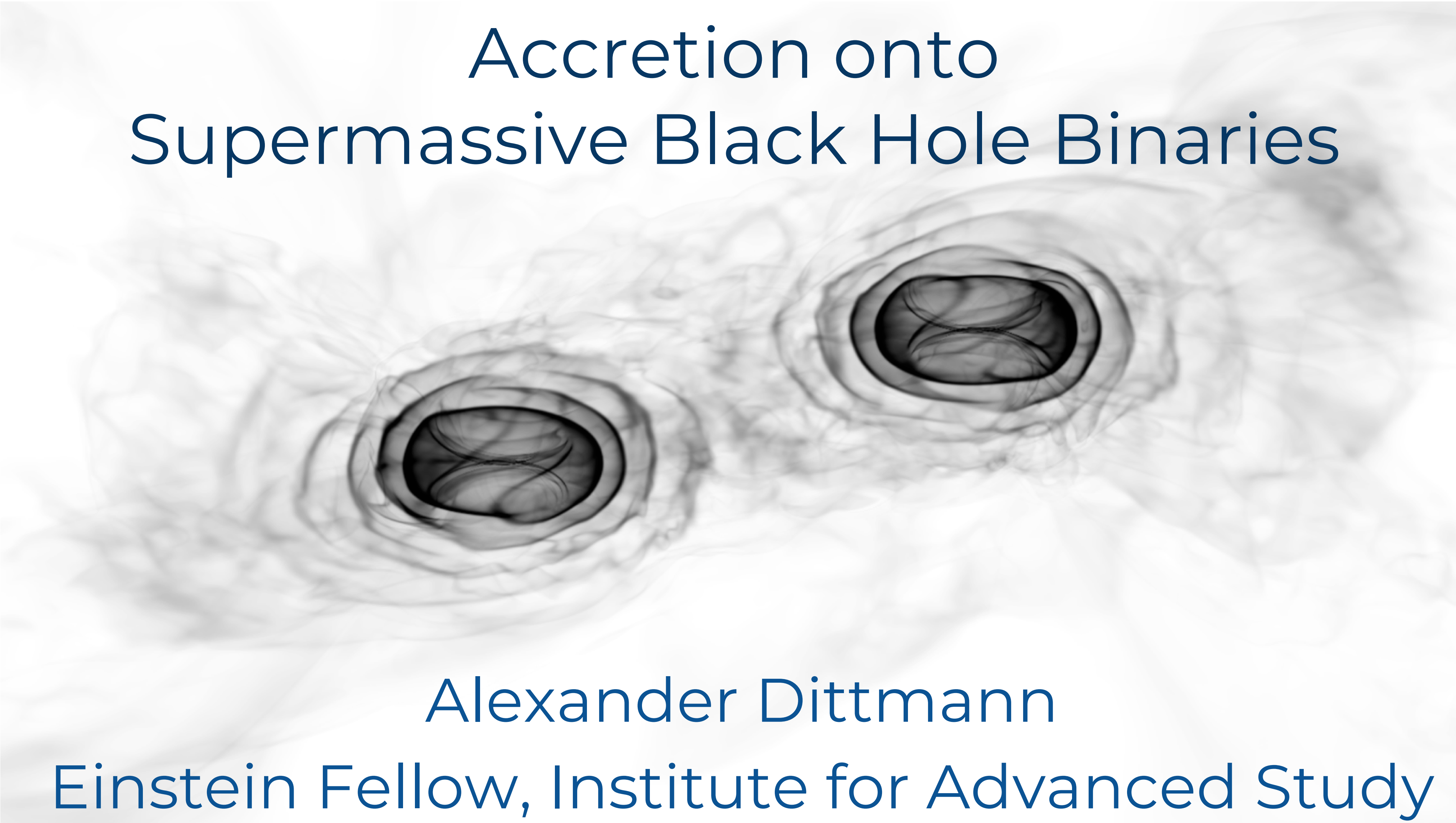
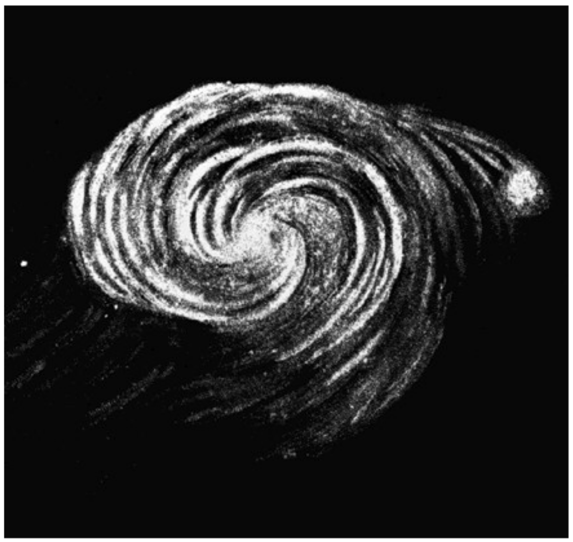
Accretion onto Supermassive Black Hole Binaries



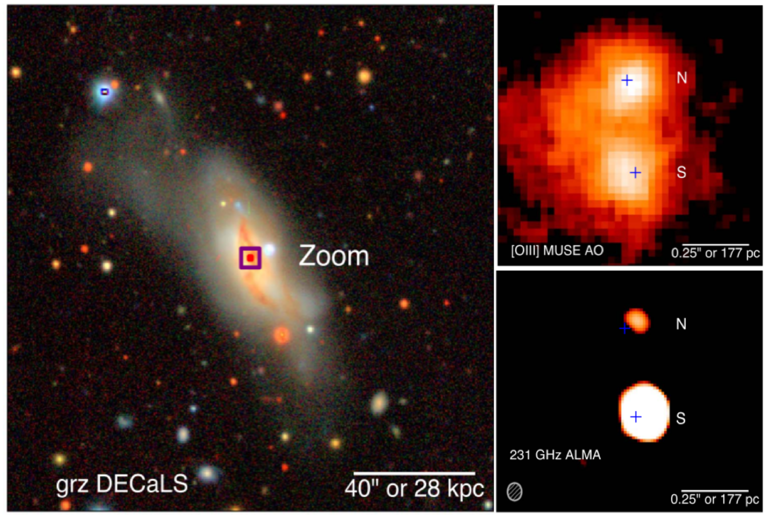
Alexander Dittmann

Einstein Fellow, Institute for Advanced Study

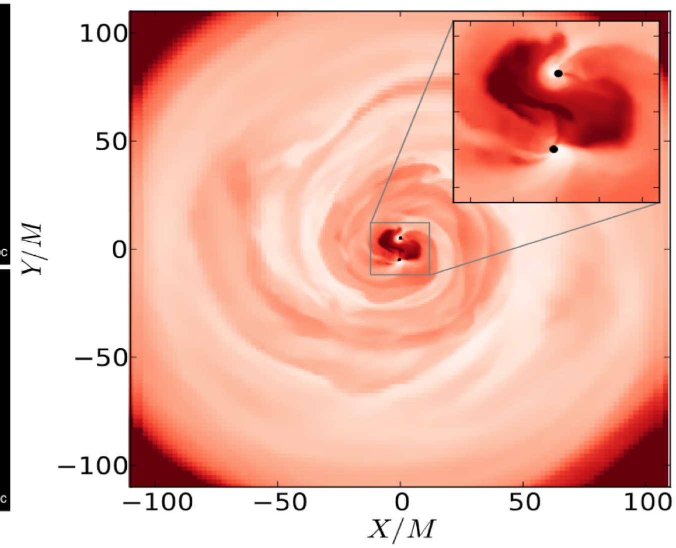
Binaries merge..... eventually



M51 (Rosse 1845)



UGC 4211 - 230 pc separation (Koss+ 2023)

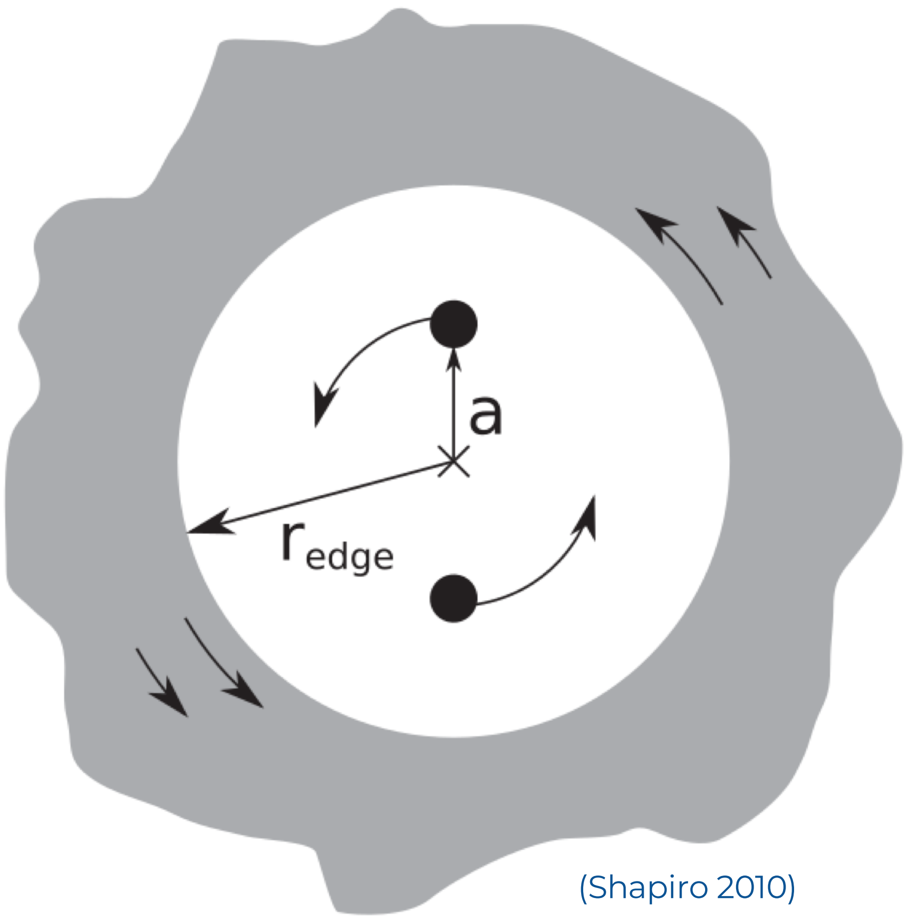


Numerical relativity - 10 r_g separation (Farris+ 2012)

Dynamical friction
+ stellar scattering

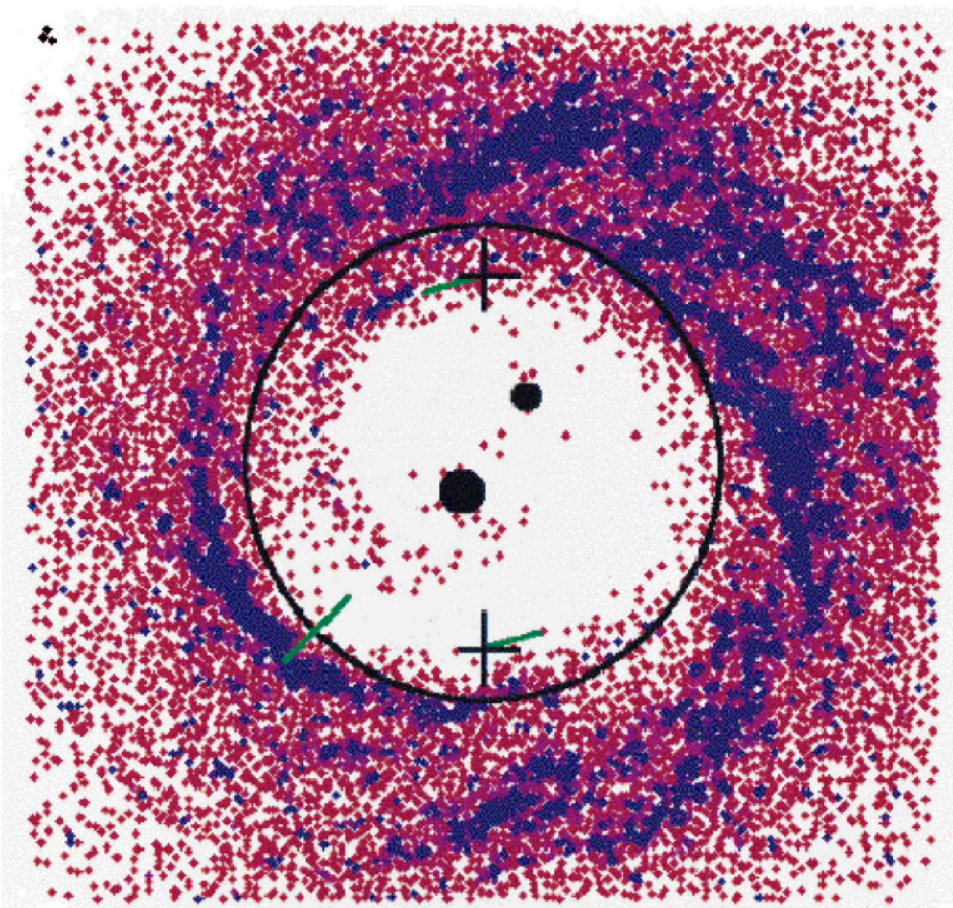
Gas torques
+ gravitational waves

Can binaries accrete?

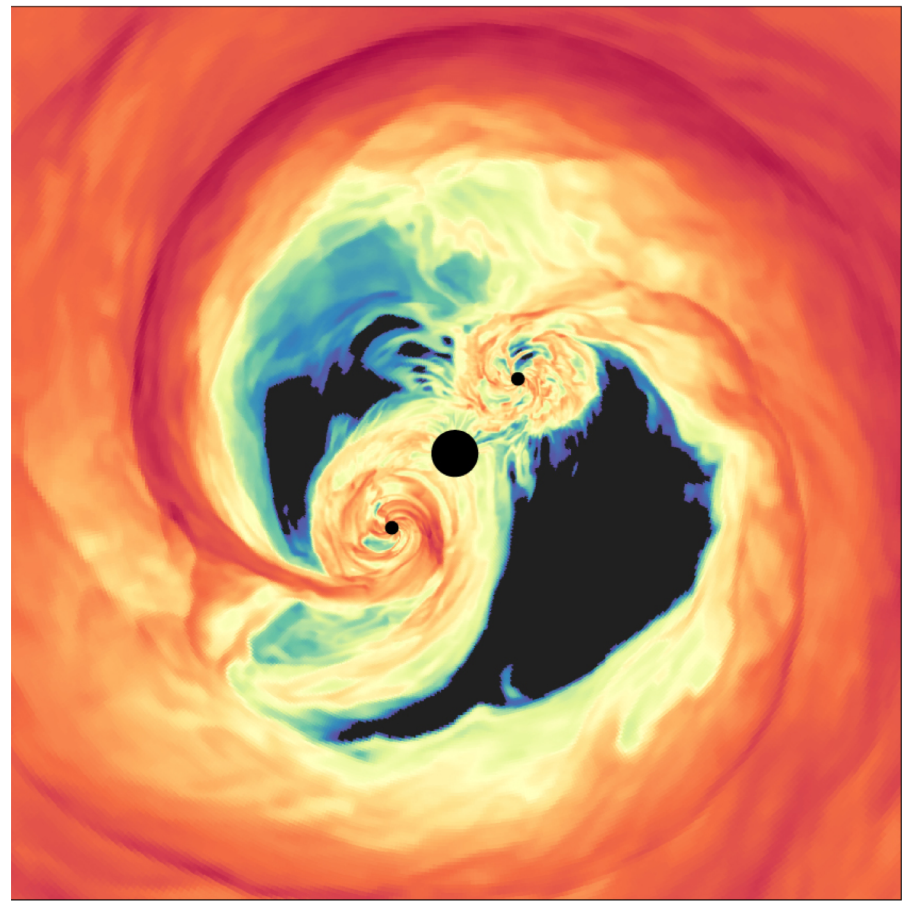


(Shapiro 2010)

Yes!



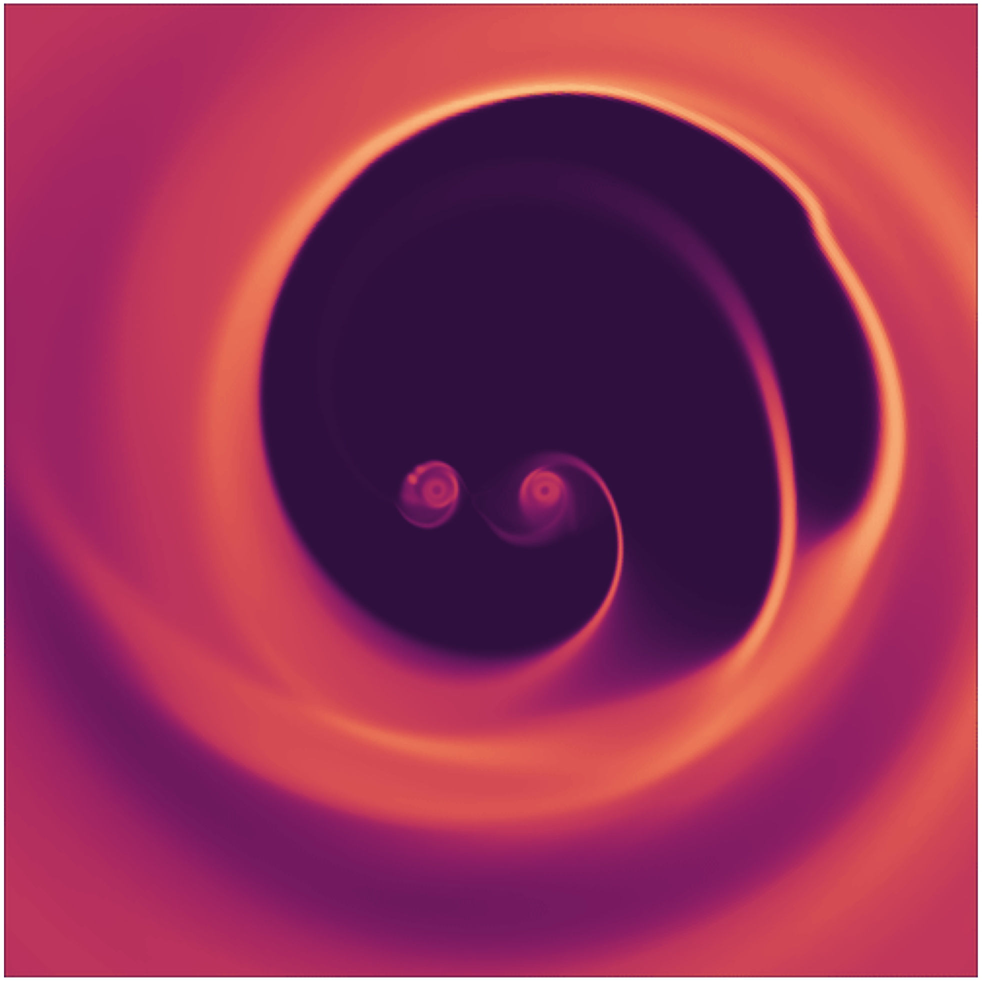
(Artymowicz & Lubow 1996)



(Bowen+ 2019)

Equal-mass binaries

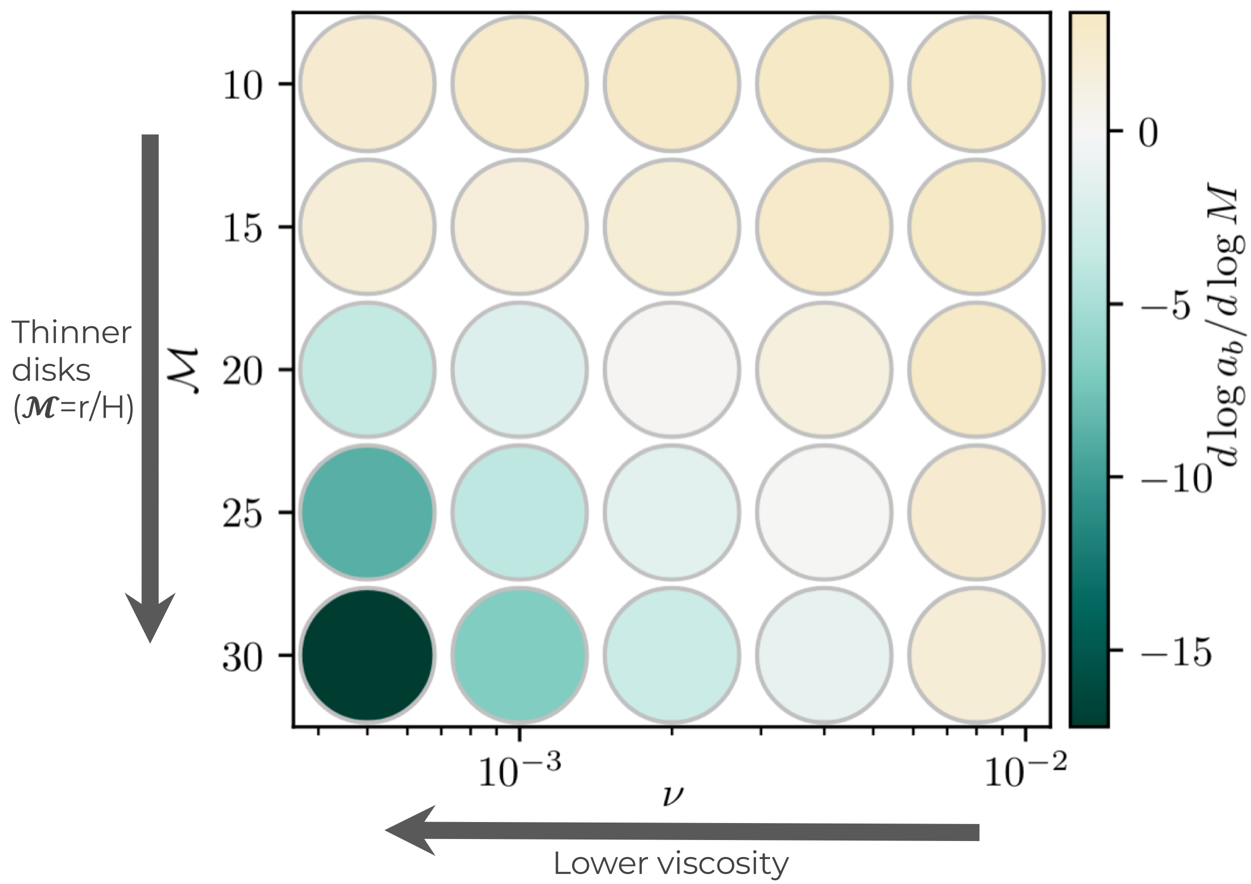
- Eccentric cavity forms
- Each SMBH forms own ‘minidisk’
- Torque contributions:
  - accretion
  - wave excitation
  - streams
- Matter passes between disks



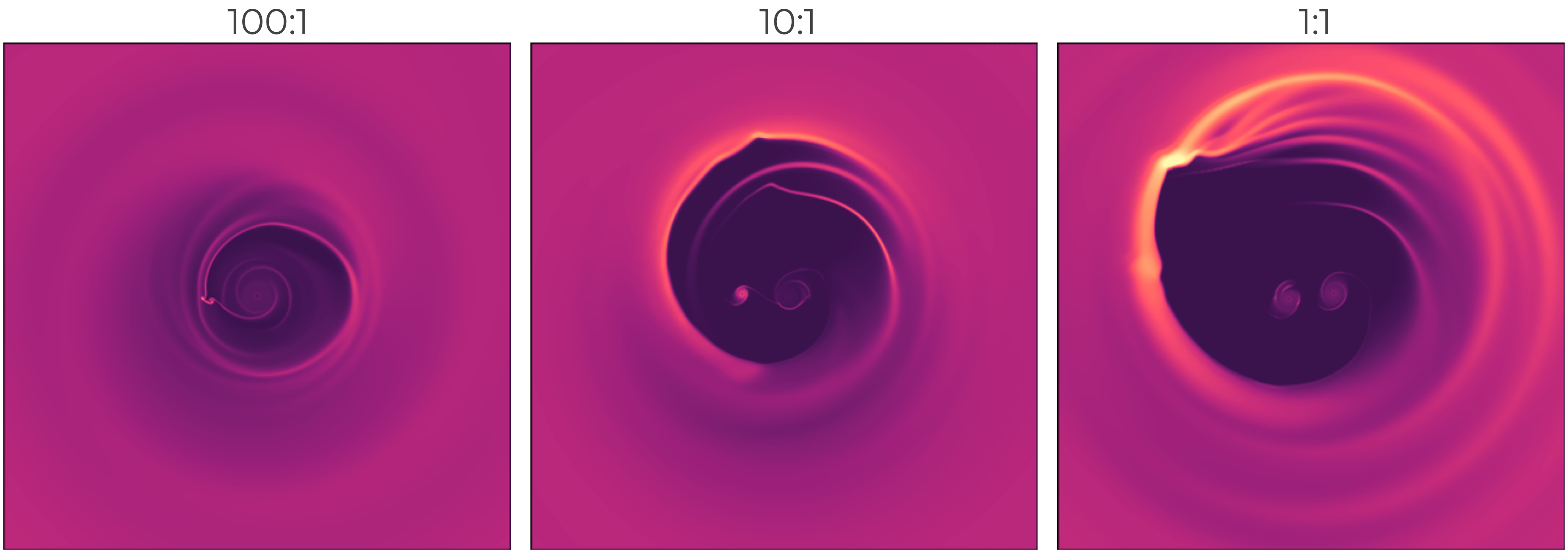
Equal-mass evolution

- Disk thickness strongly affects torques
- Less gas from streams captured in thin disks
- Binaries may shrink very rapidly
  ...or expand

(Dittmann & Ryan 2022)



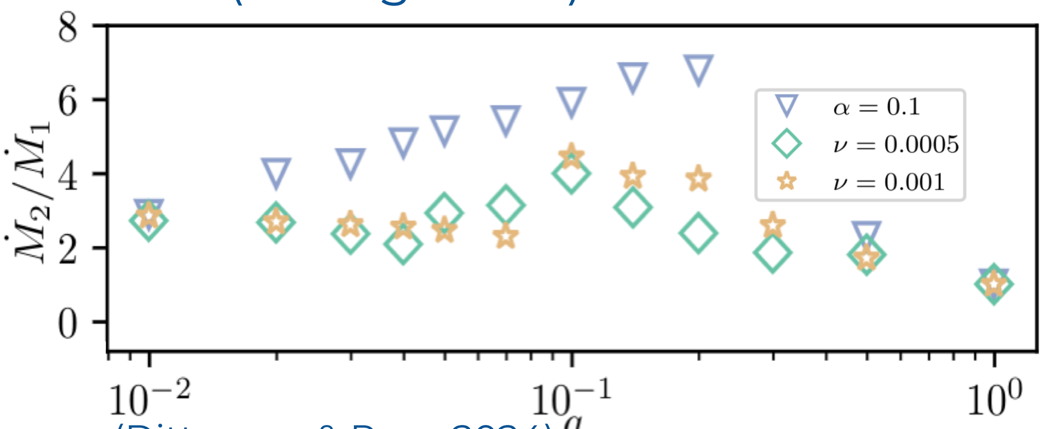
Unequal-mass binaries



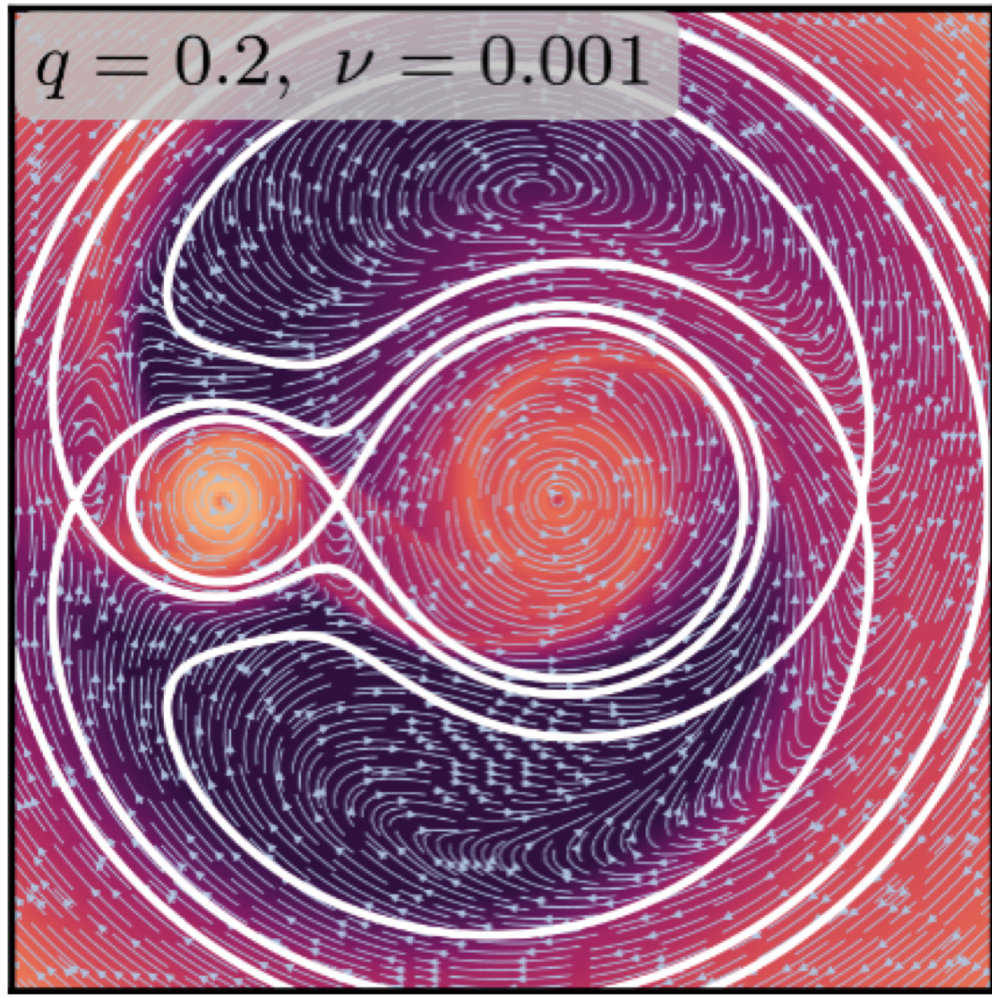
- Smaller cavities, less pronounced lumps for lower mass ratios
  - Still far from well-behaved

Accreting unequal-mass binaries

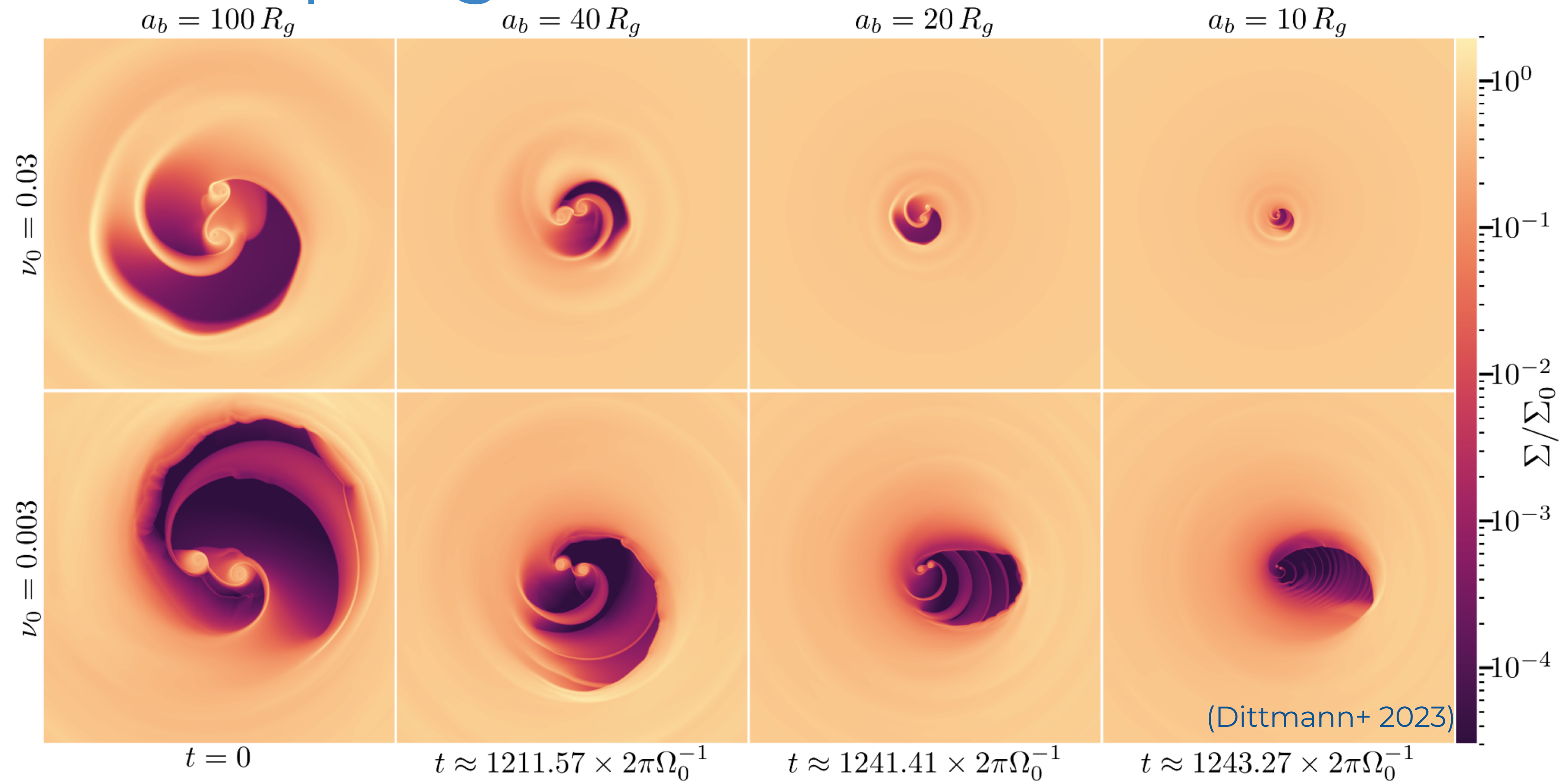
- Secondary often accretes more
- Degree depends on viscosity, (flow through L1)
  - Also thermodynamics (Young+ 2015)



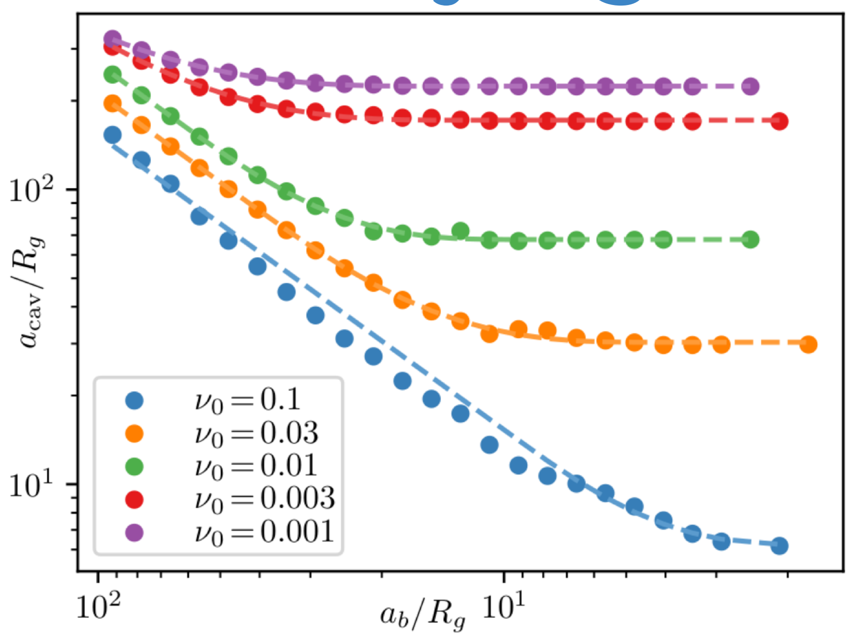
(Dittmann & Ryan 2024)



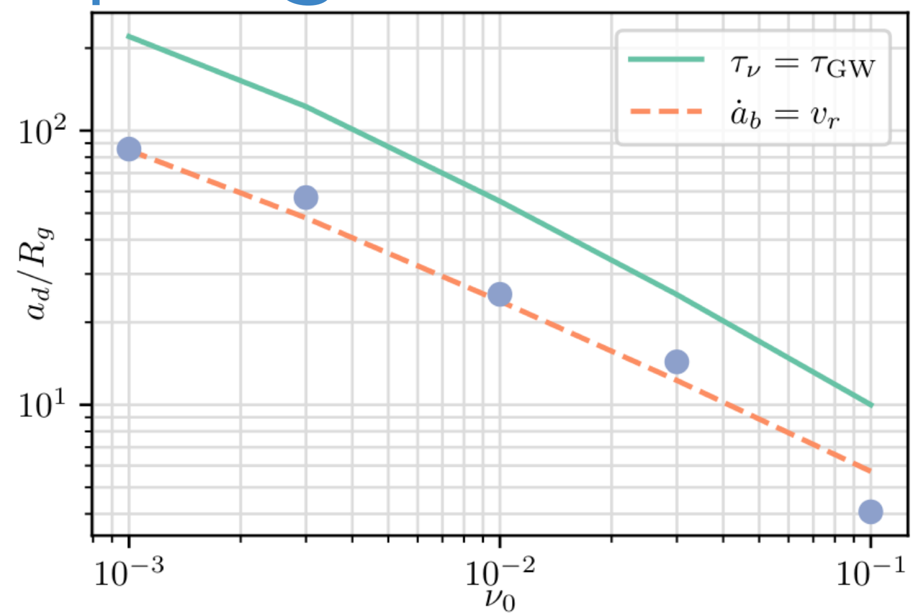
Decoupling


$a_b = 100\,R_g$
$a_b = 40\,R_g$
$a_b = 20\,R_g$
$a_b = 10\,R_g$
$\nu_0 = 0.03$
$\nu_0 = 0.003$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Σ/Σ_0
(Dittmann+ 2023)
$t = 0$
$t \approx 1211.57 \times 2\pi\Omega_0^{-1}$
$t \approx 1241.41 \times 2\pi\Omega_0^{-1}$
$t \approx 1243.27 \times 2\pi\Omega_0^{-1}$

Quantifying Decoupling



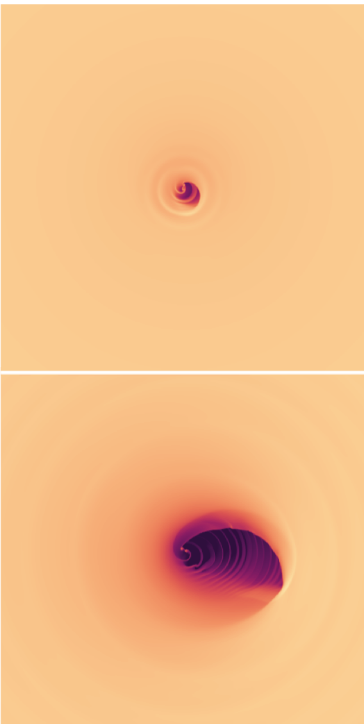
Measured cavity size vs binary semi-major axis

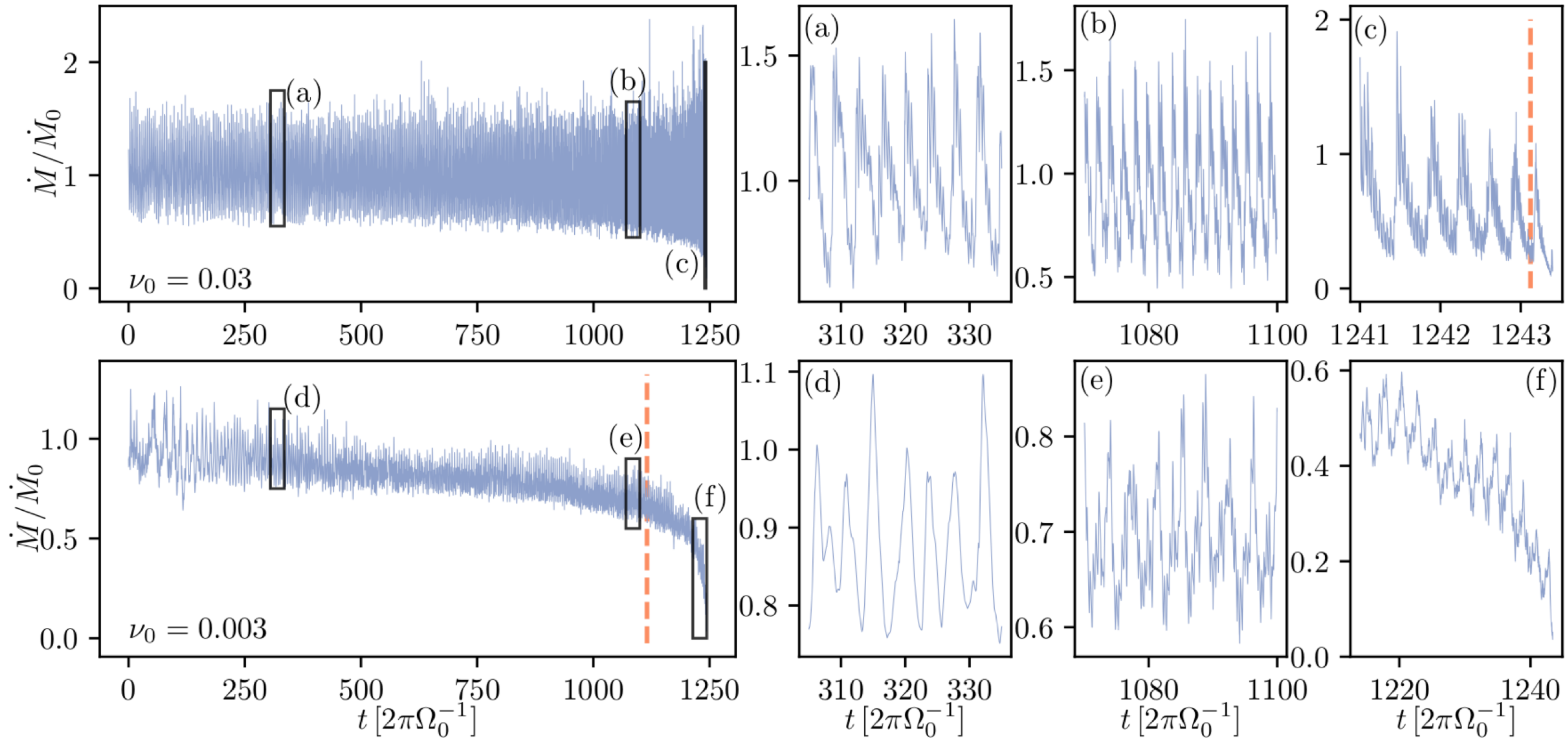


☹ prediction based on timescales (green) (e.g. Milosavljević & Phinney 2005)

☺ prediction based on velocities (orange) (e.g. Armitage & Natarajan 2002)

Variability

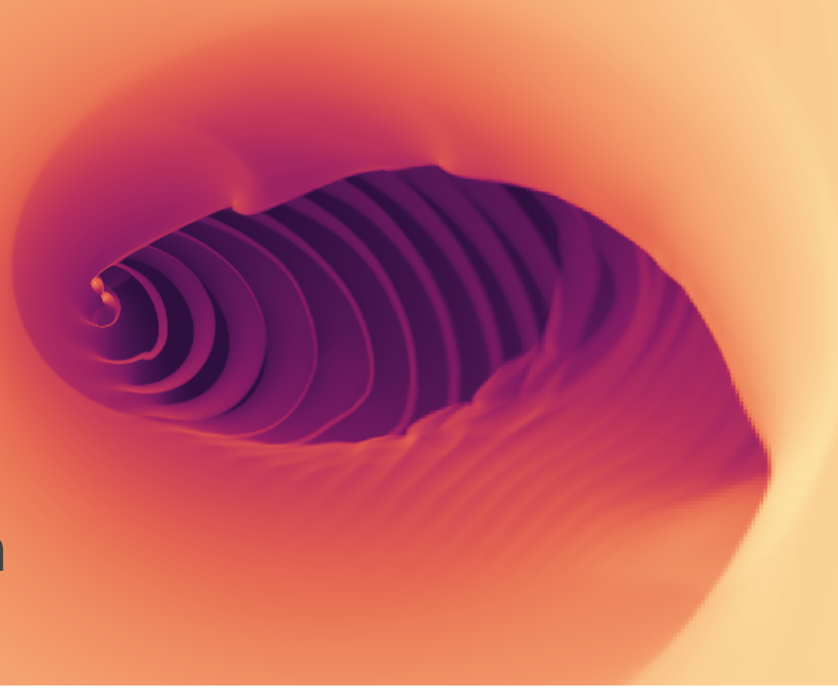




$$2\pi\Omega_0^{-1} \approx 8.6(M/10^6\, M_\odot)\ \text{hours}$$

In Conclusion

- Binary evolution depends sensitively on disk conditions
- Thinner (thicker) disks drive inspiral (outspiral)
- Binaries should continue to accrete through the LISA band
  - Variability will evolve with binary, but accretion rate may sharply decline

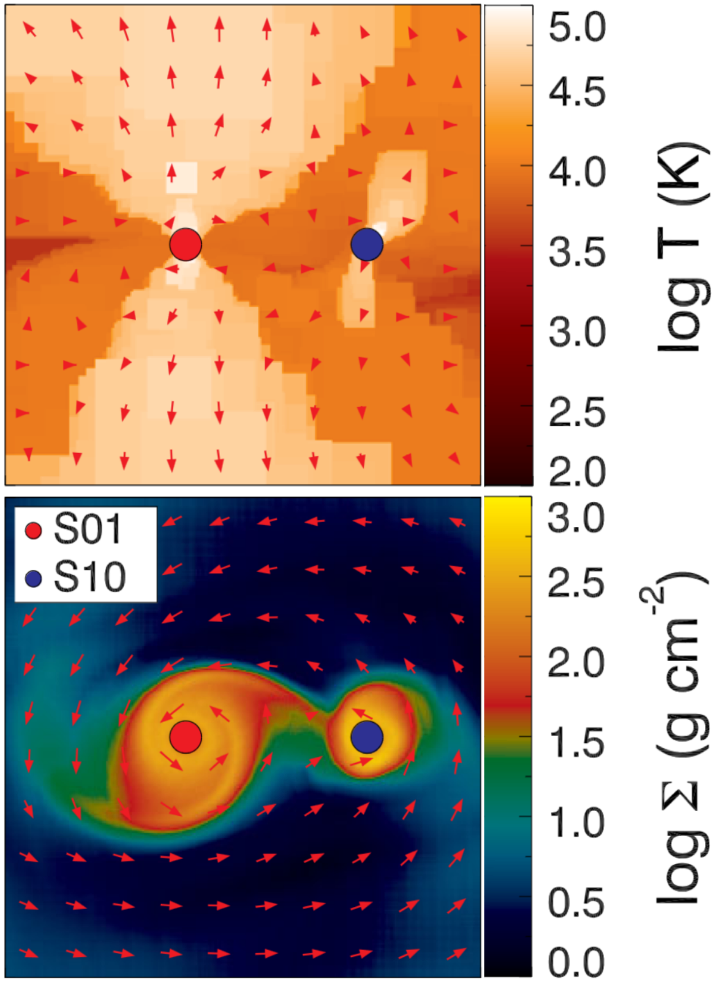


High-q evolution: 3D + physics

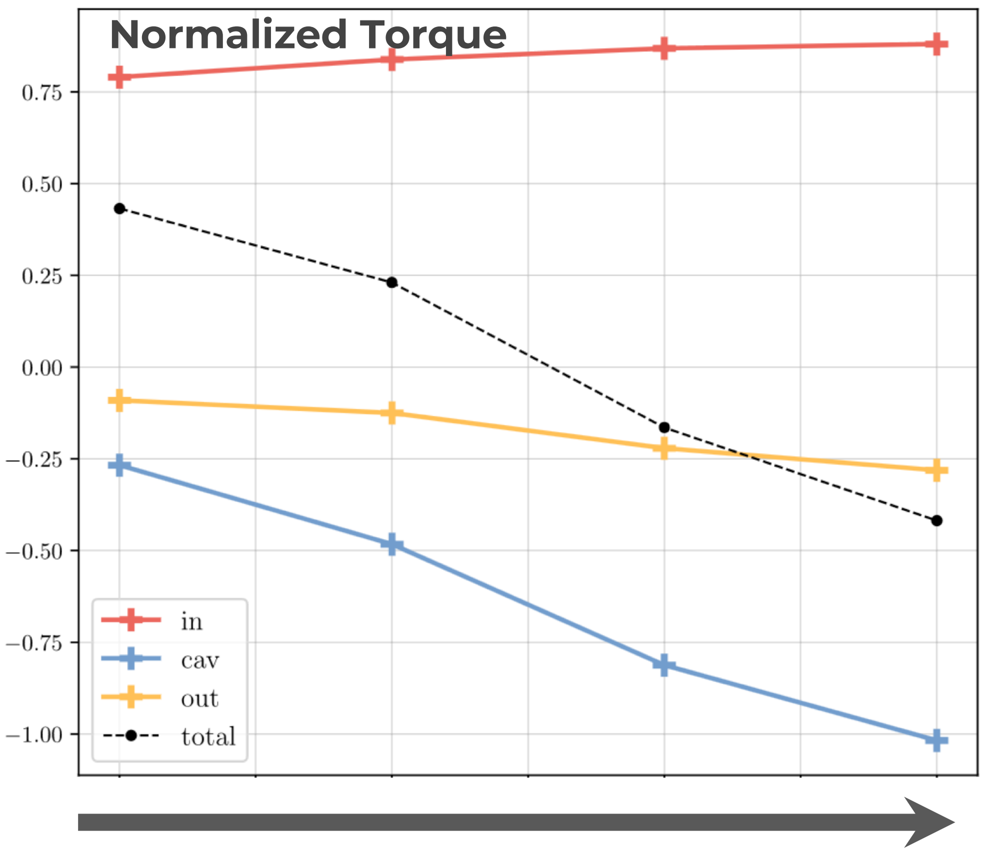
- Hydrodynamics
  + radiation
  + star formation
  finds similar results

- Low metallicity, less cooling
  - population III outspirals
    (Park+ 2024)

- Solar metallicity, cools more easily, leads to inspirals
  (He & Ricotti 2023)



High-q evolution - Simplified 2D



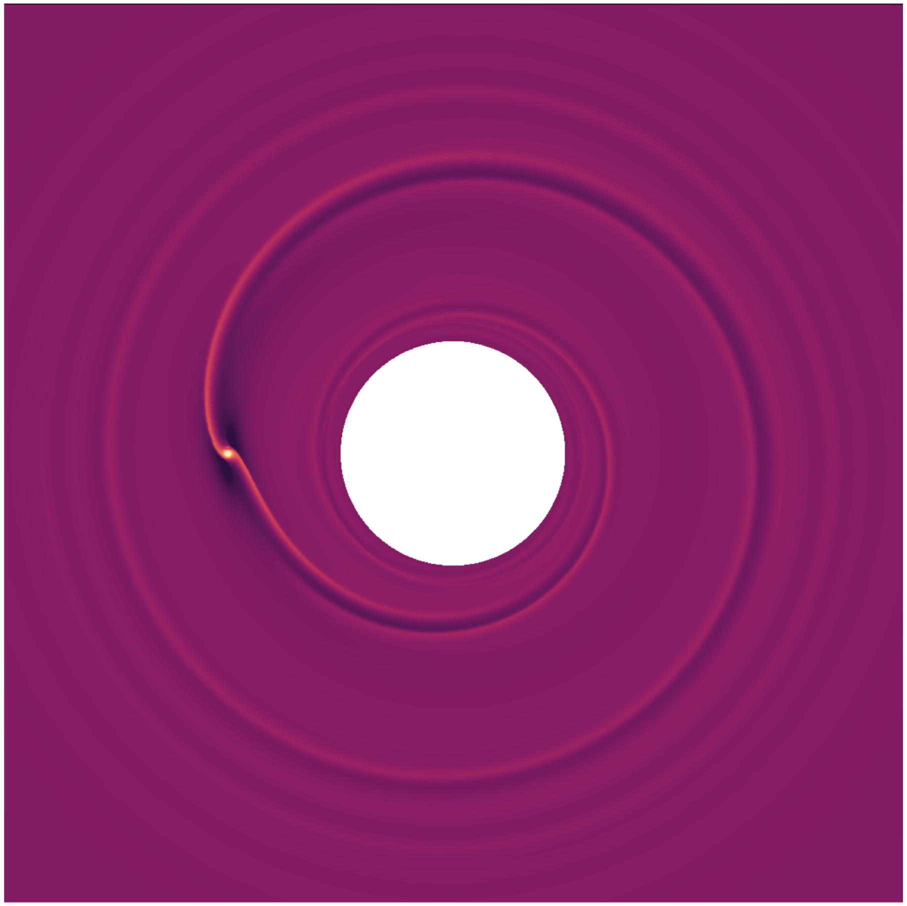
Thinner disks ($\mathcal{M}$=r/H)
(Tiede+ 2020)

- Thinner / cooler disks lead to less gas being captured by the binary "cav"
- minor changes in wave torque contributions
- Isothermal EOS, 2D, equal-mass

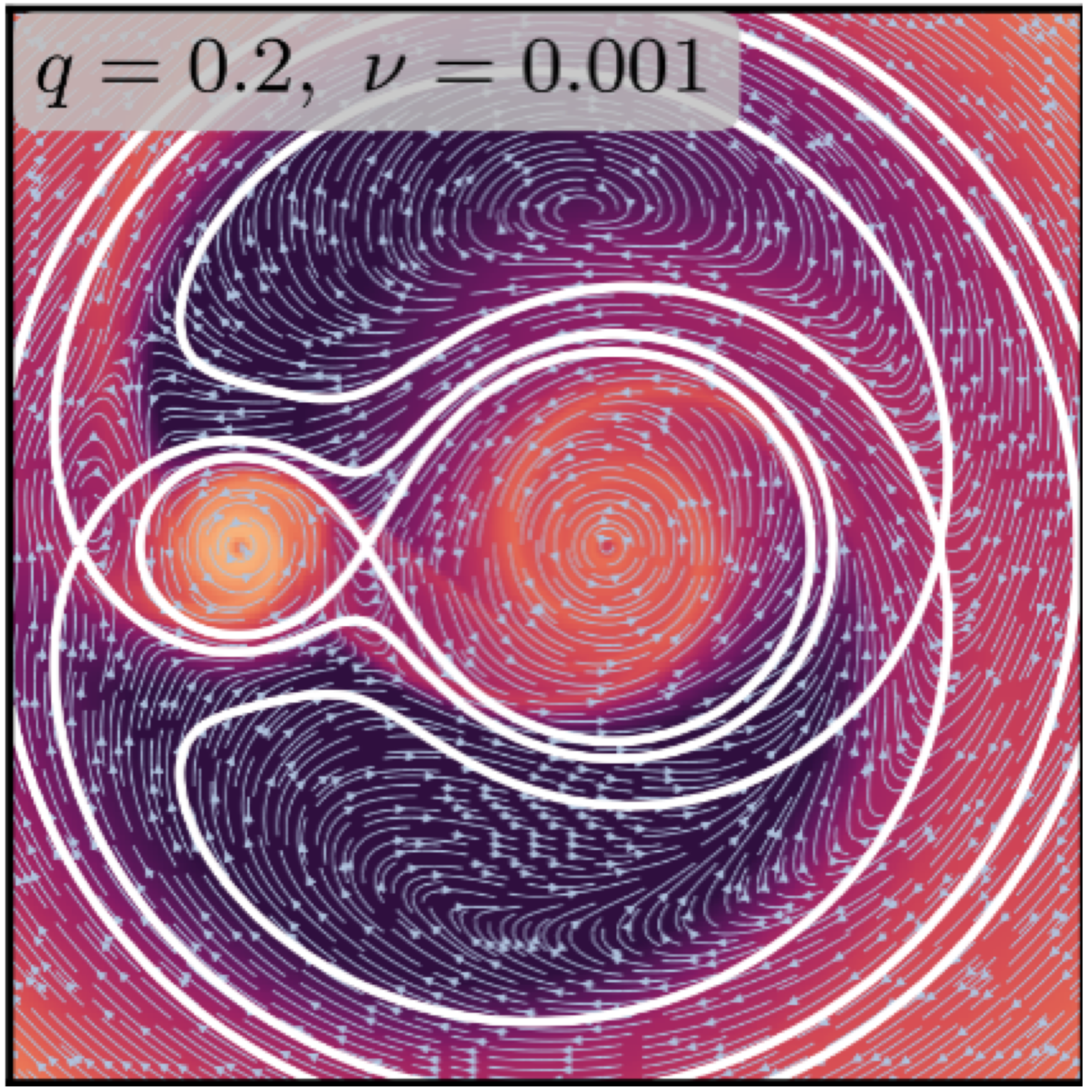
Low-mass objects

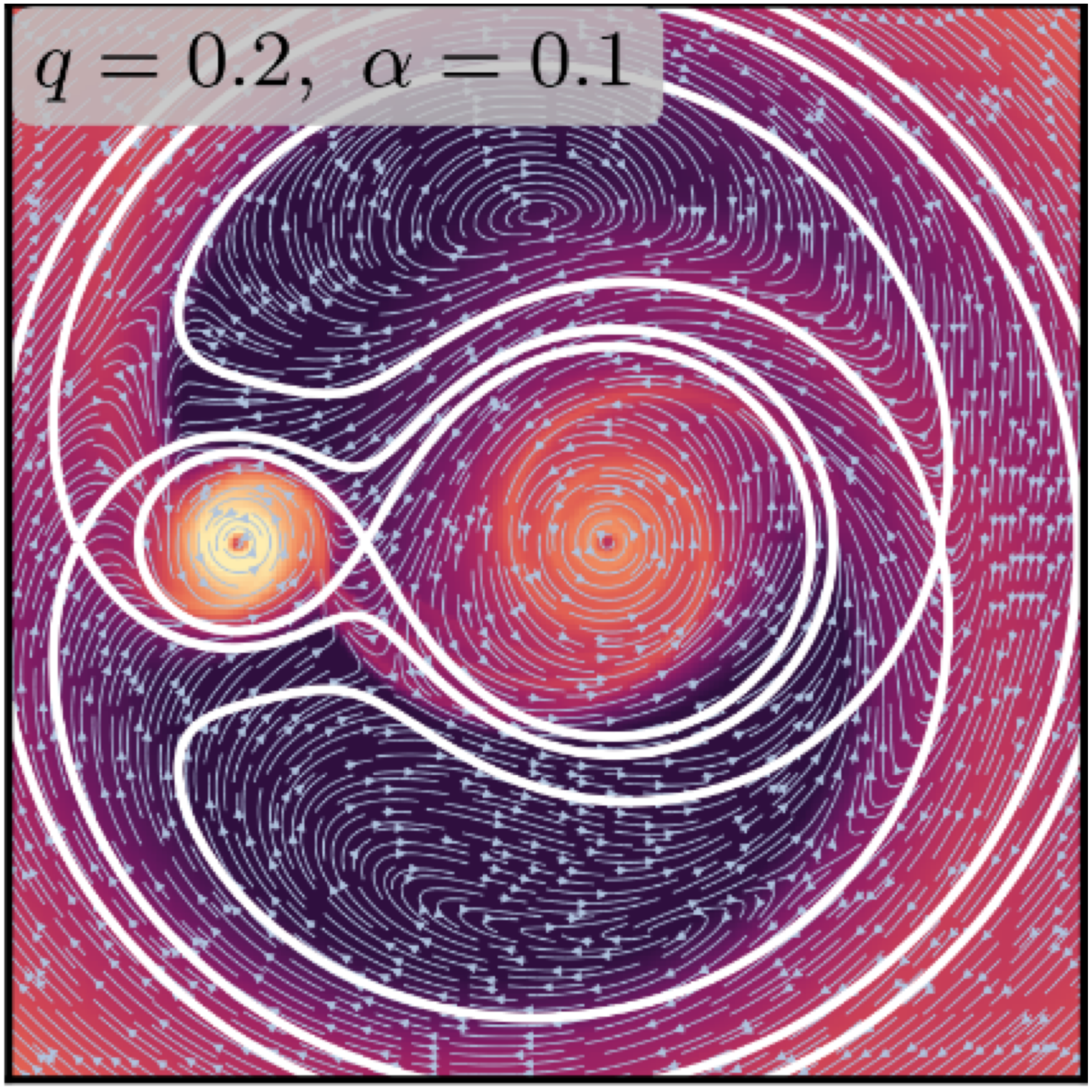
- Low-mass objects excite waves linearly, (usually) leading to inward migration (e.g. Goldreich and Tremaine 1980, Tanaka+ 2002, Tanaka & Ward 2004)

- Linear when $(M_2/M_1)^2 << (H/r)^3$
  - but disks can be quite thin

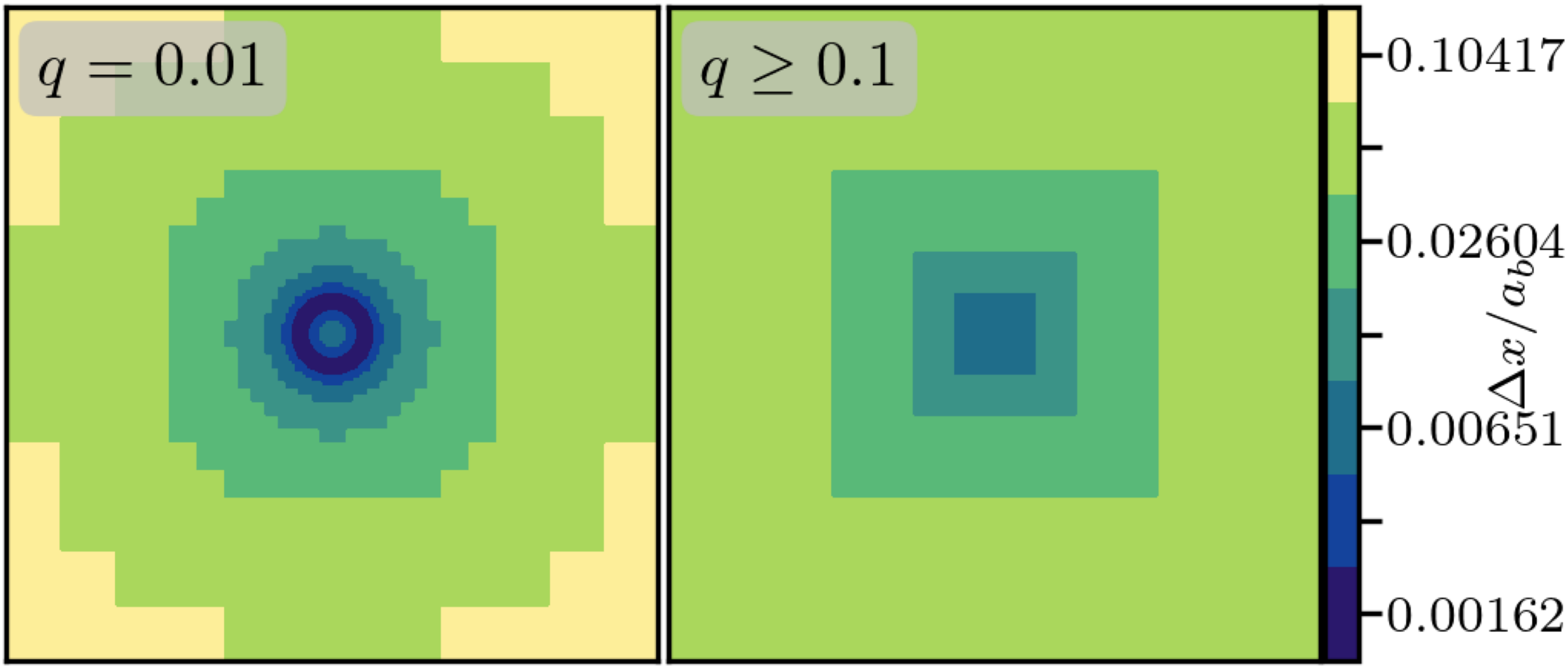


Waves excited by a $q=10^{-4}$ planet.


$q = 0.2,\ \nu = 0.001$

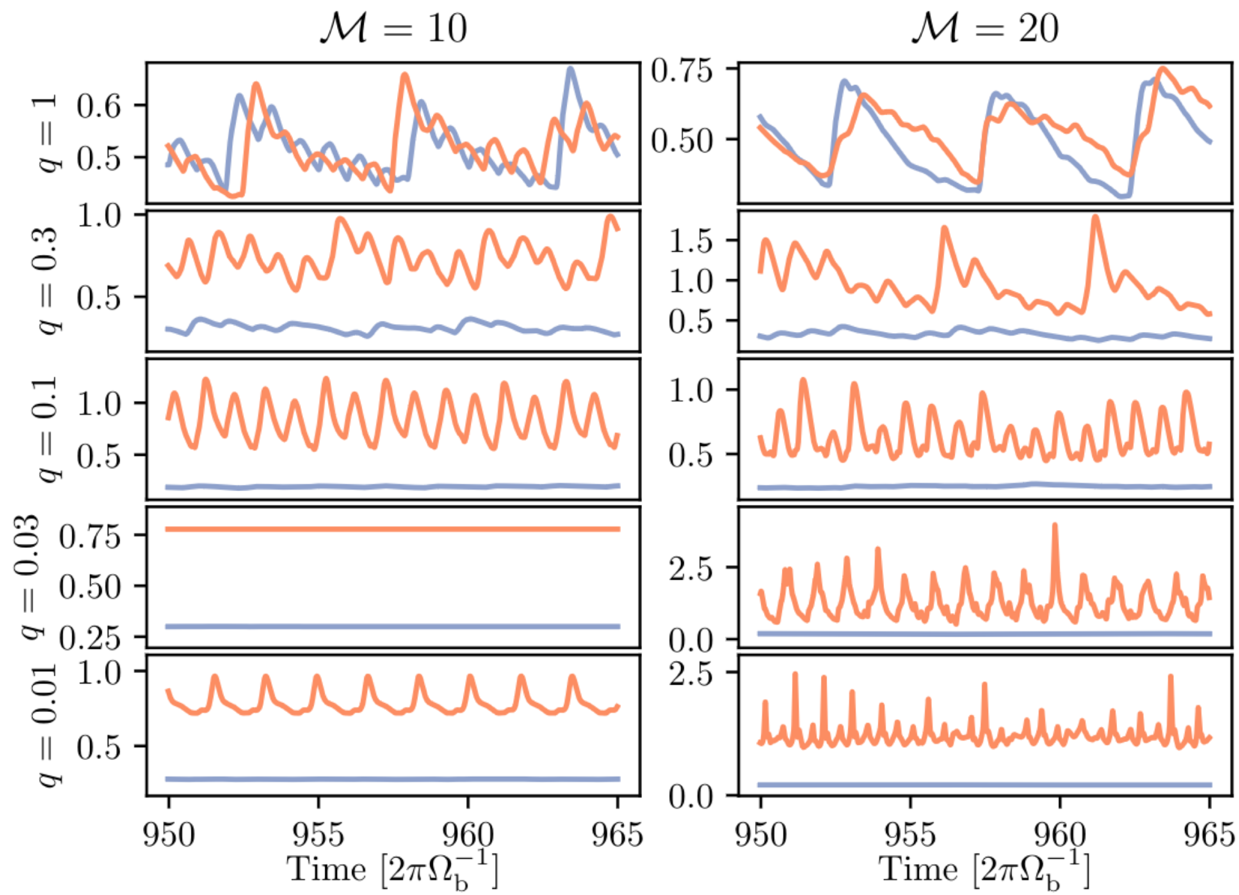

$q = 0.2,\ \alpha = 0.1$

Resolution



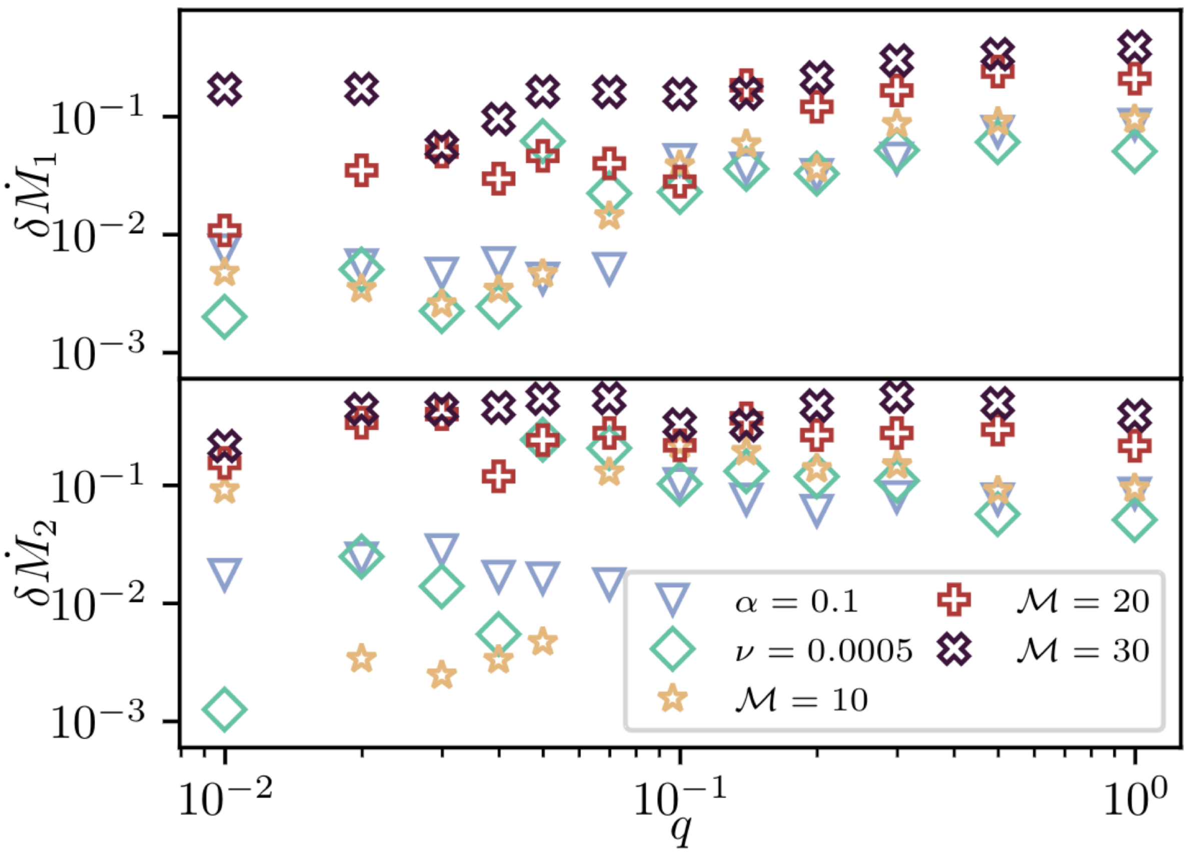
Accretion Variability

- Plenty of variability to go around
  - even at low mass ratios
- Accretion rates become ~constant for circular disks



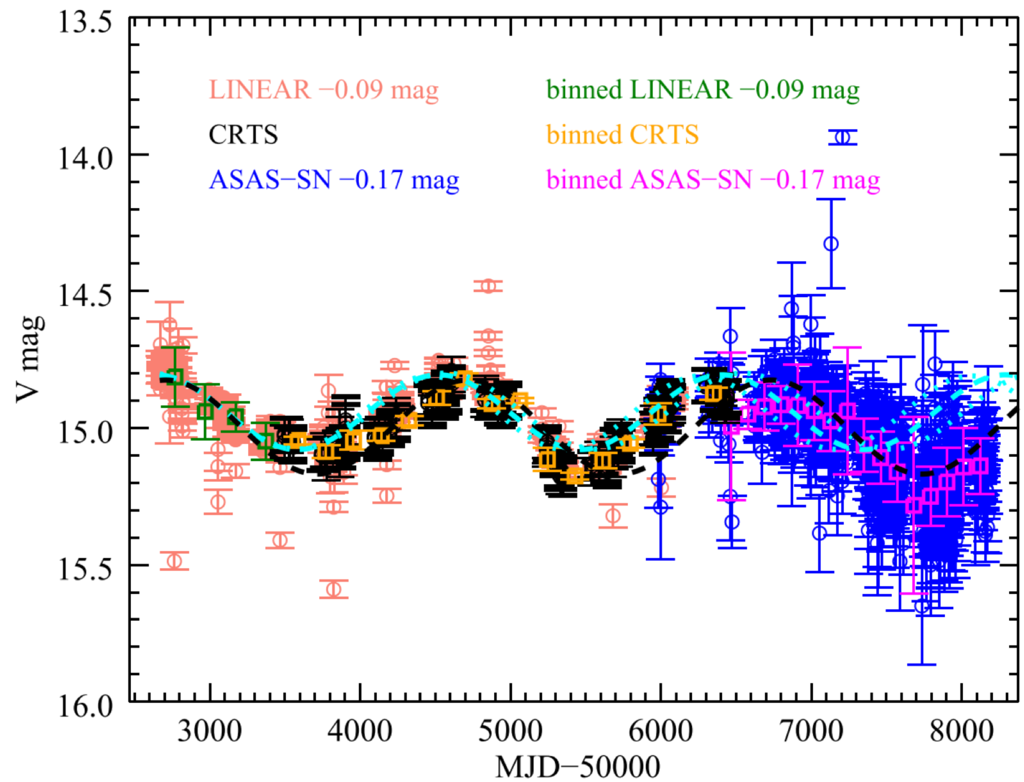
More Variability

- Plenty of variability, even at very small mass ratios
  - More so for the secondary
  - And for thinner disks



Intrinsic AGN variability

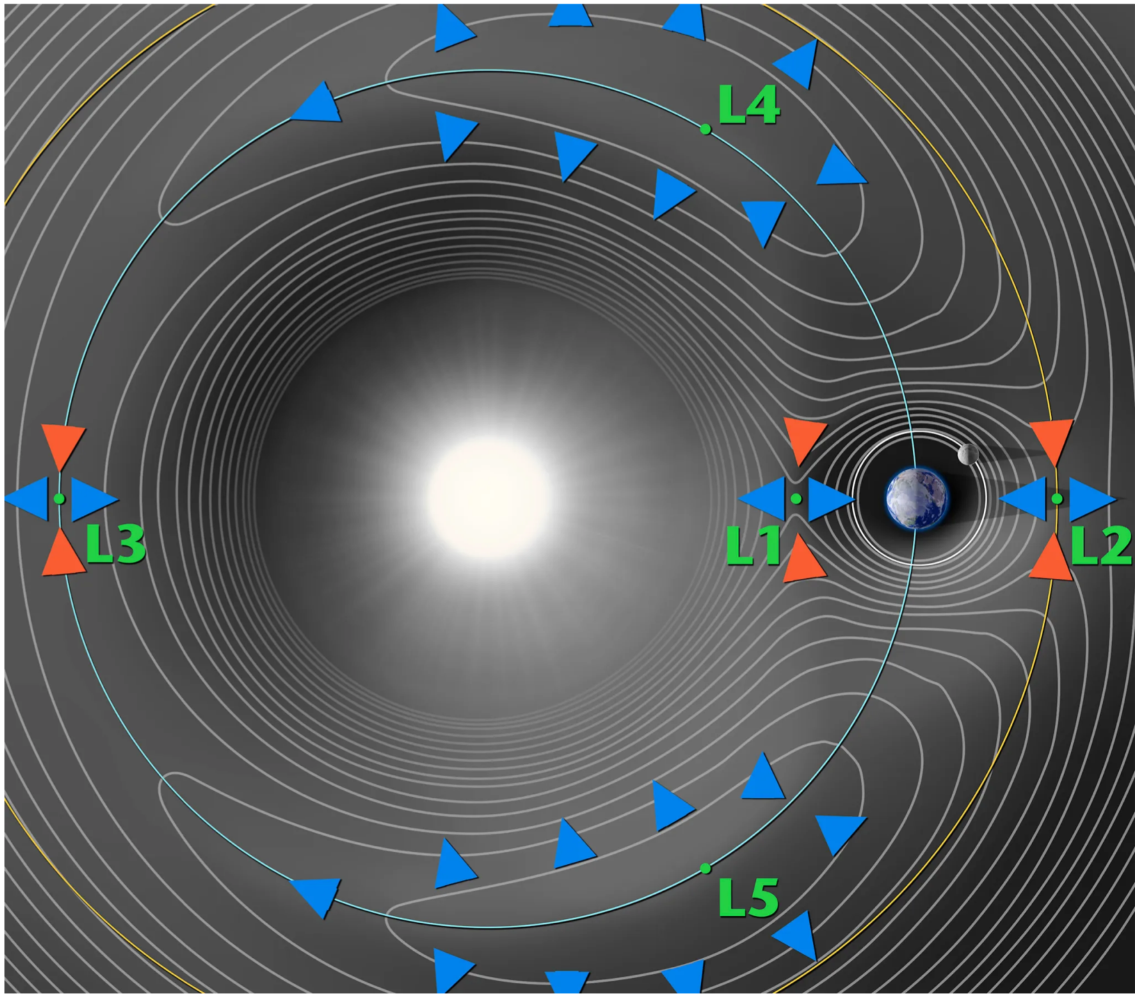
- AGN vary on timescales of ~hours to ~years
- Long-term variability can mimic periodicity
- High cadence and long baseline observations (e.g. Rubin) might help?



Periodic + damped random walk fits to binary AGN candidate lightcurve (PG1302-102) (Liu+ 2018)
Light curve can be modeled by Doppler-boosted disks (D'Orazio + 2015)

Lagrange points

- L1, L2, L3 unstable equilibria
- L4, L5 stabilized by coriolis acceleration for low mass ratios
- Viscosity destabilizes L4, L5
  - more so L5 at low mass ratios
    (e.g. Murray 1994, D'Orazio+2016)

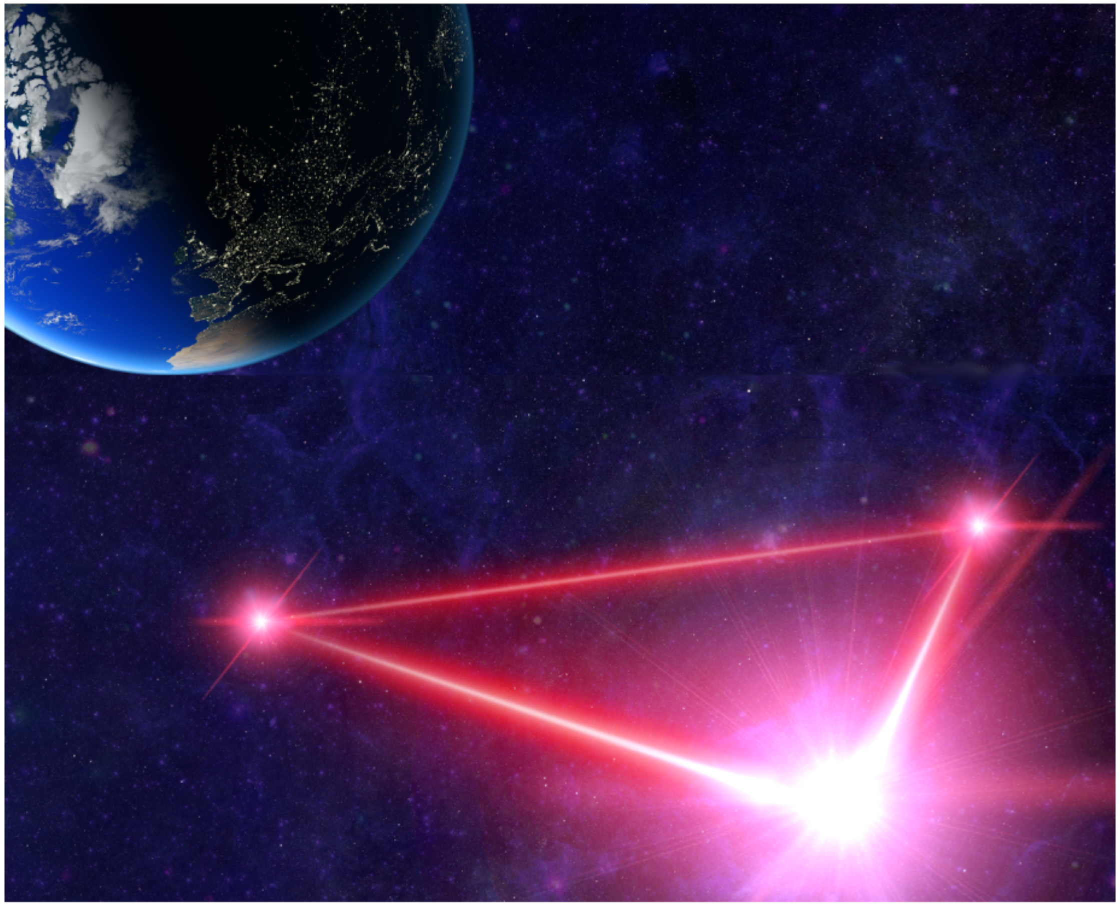


Gravitational Waves and LISA

$$h \propto \frac{(G\mathcal{M}_z)^{5/3} f^{2/3}}{D_L}$$

$$\dot{f} \propto (G\mathcal{M}_z)^{5/3} f^{11/3}$$

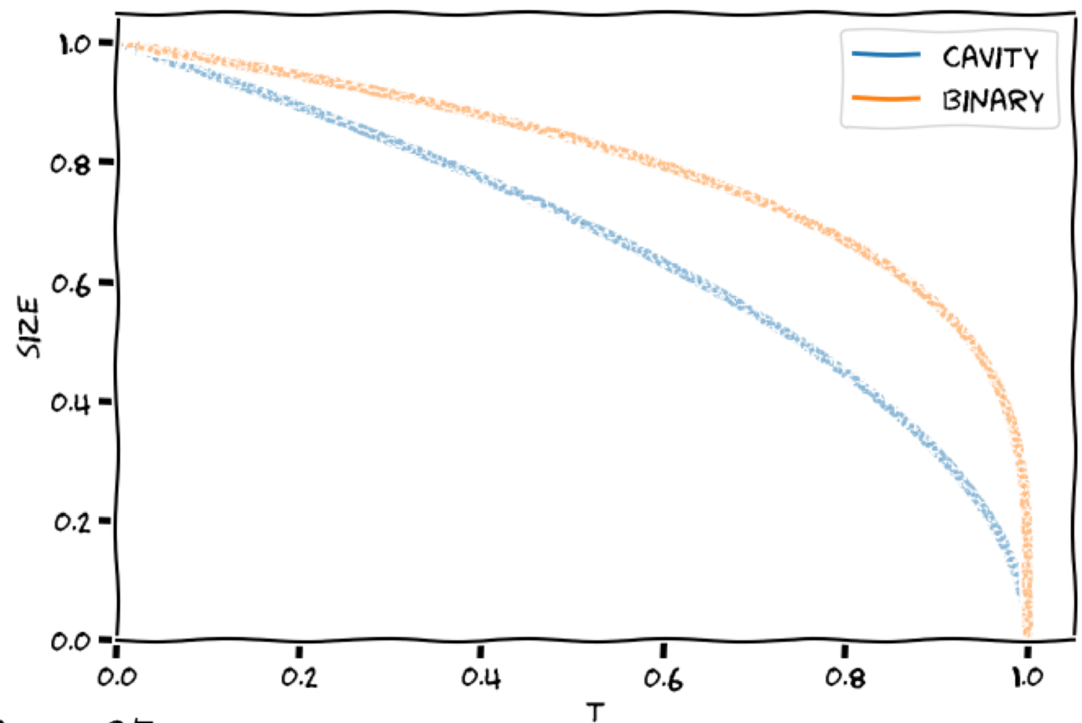
$$\mathcal{M}_z \equiv (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$



(Simon Barke) - LISA mission proposal

When does the system decouple?

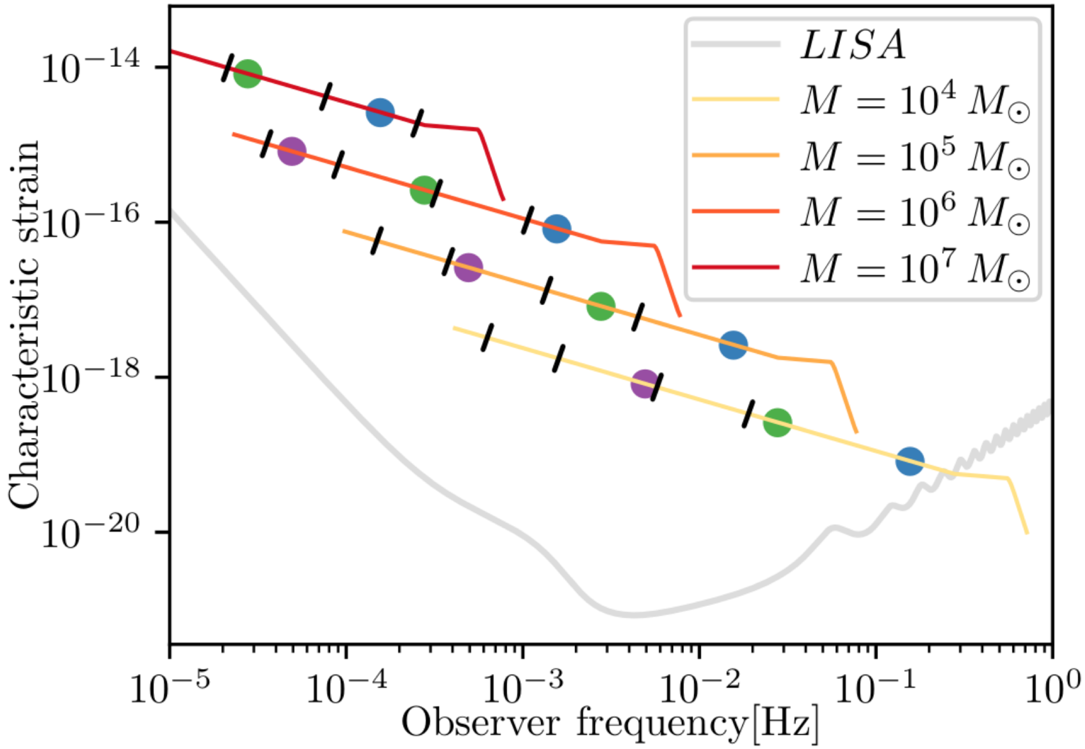
- Common argument is that the system decouples when $t_{GW} \sim t_{\nu}$
  - Good enough for ord of-magnitude estimates



$$v_r = -\frac{3}{2}\frac{\nu}{r}$$

$$\left\langle \frac{da}{dt} \right\rangle = -\frac{64}{5} \frac{G^3 m_1 m_2 (m_1 + m_2)}{c^5 a^3 (1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right)$$

Gravitational Waves

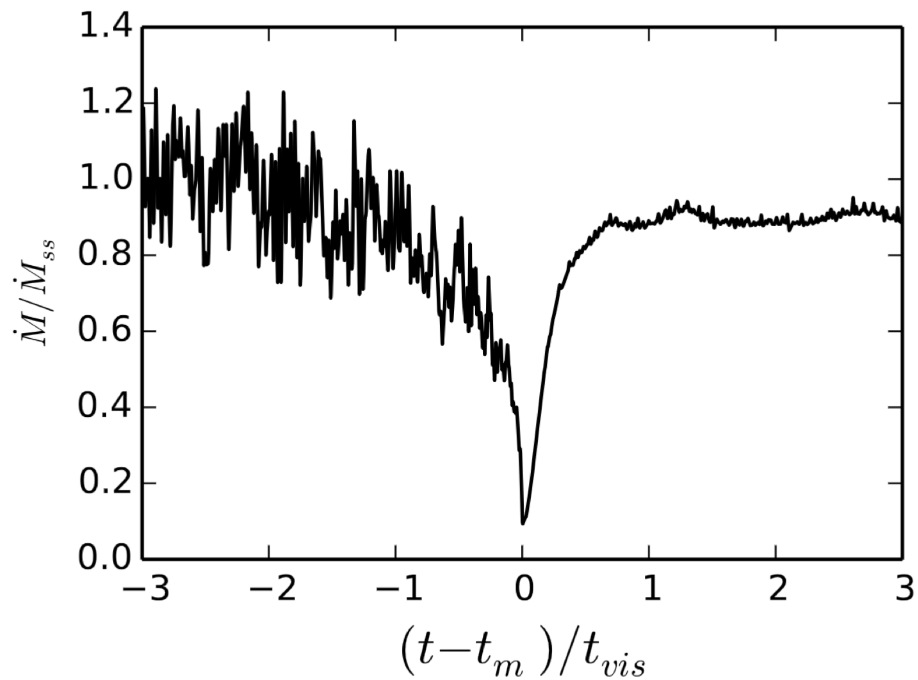


Blue →ν_0=0.1, Green →ν_0=0.01, Purple →ν_0=0.001
Gray: projected LISA sensitivity curve (Robson+ 2019)
Red/Orange/Yellow: PhenomA inspiral models (Ajith+ 2007)
Black dashes: year/month/day/hour before merger.

- Binaries may decouple in LISA band
- Could localize host galaxies pre-merger
  - Better prospects for higher-mass binaries

The Aftermath

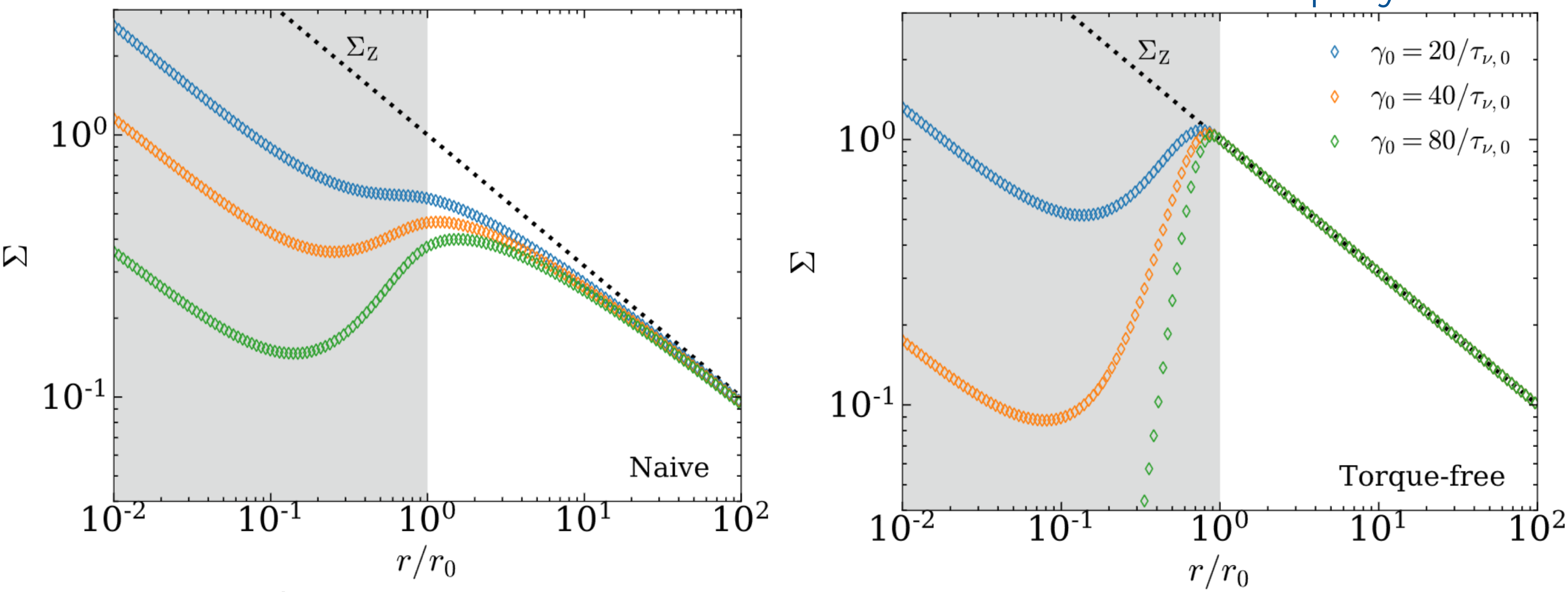
- If the GW kick is not too large, eventually rebrightens as a single AGN (e.g. Milosavljević & Phinney 2005, Shapiro 2010, Farris+ 2015)



Accretion rate during and following binary inspiral (Farris+ 2015)

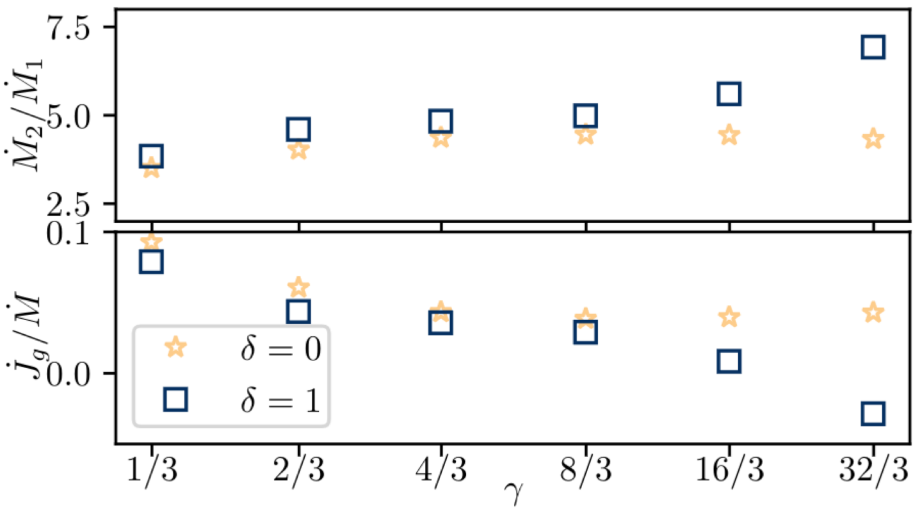
(Aside on sink particles)

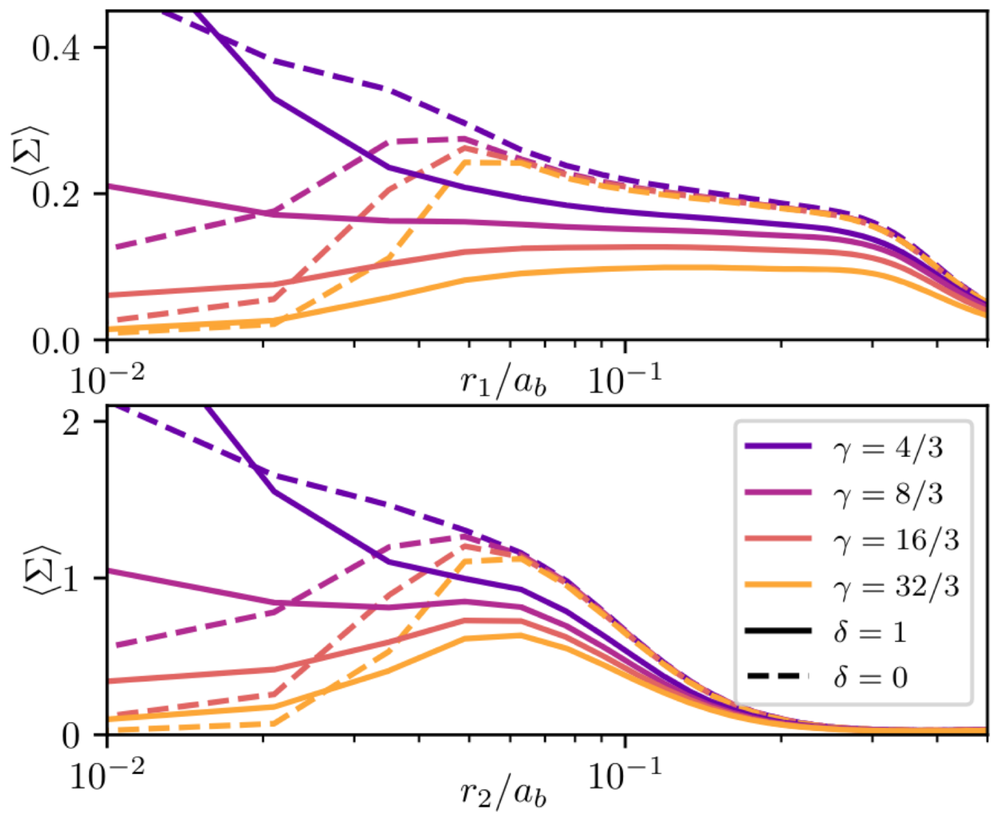
Dempsey+ 2020



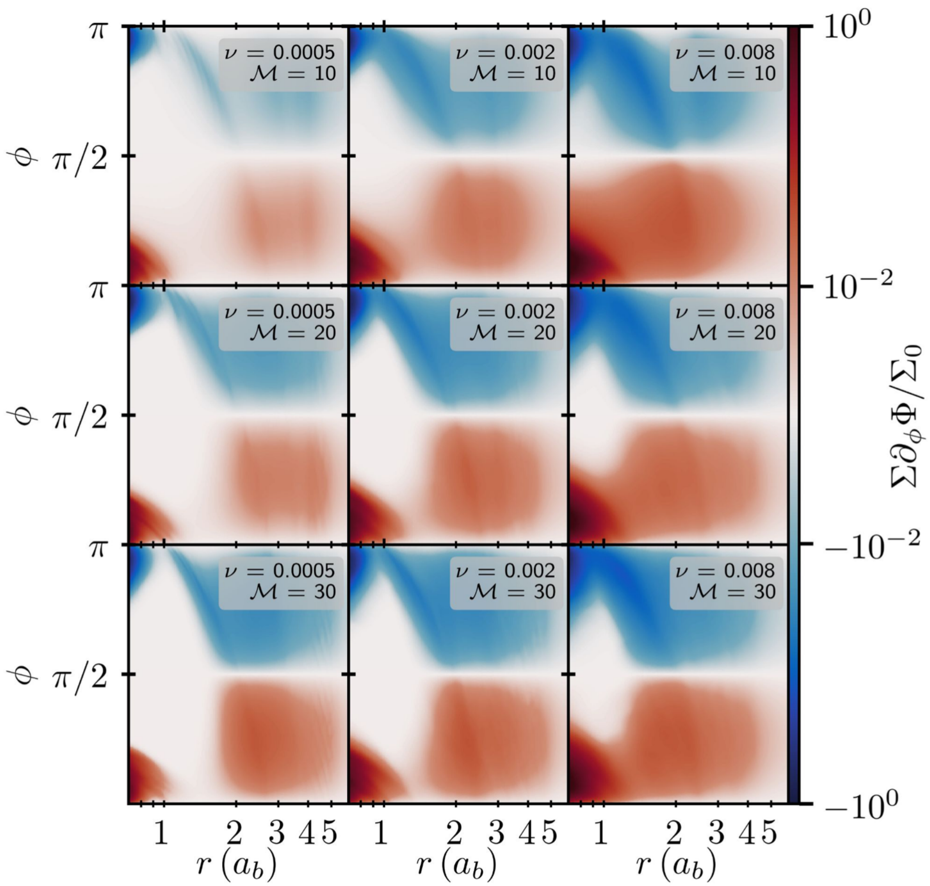
"naive"/"standard" sink particles source an angular momentum current through the disk
(usually many orders of magnitude too large)

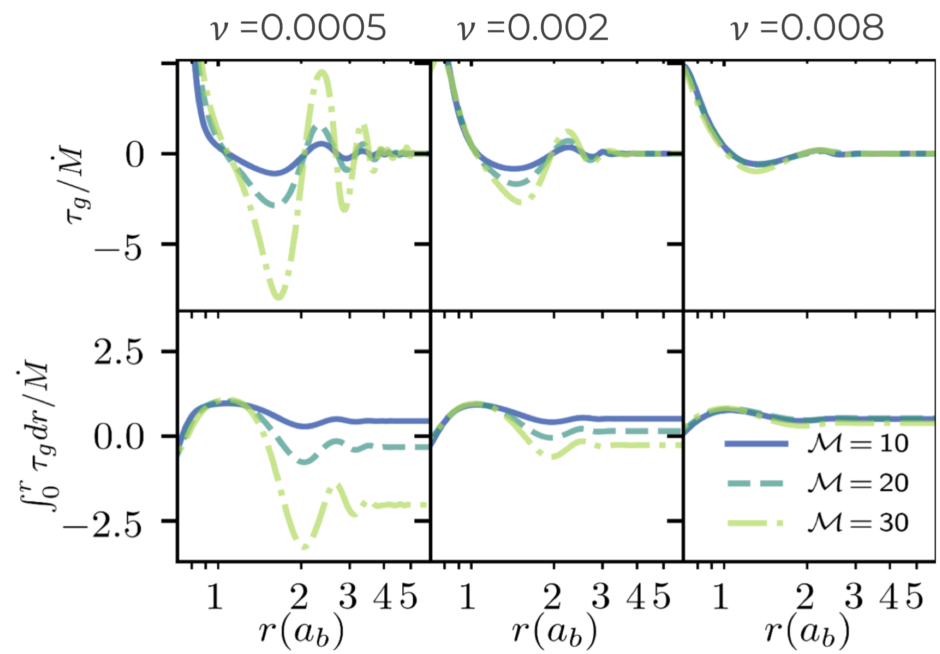
Sink prescriptions, q=0.1



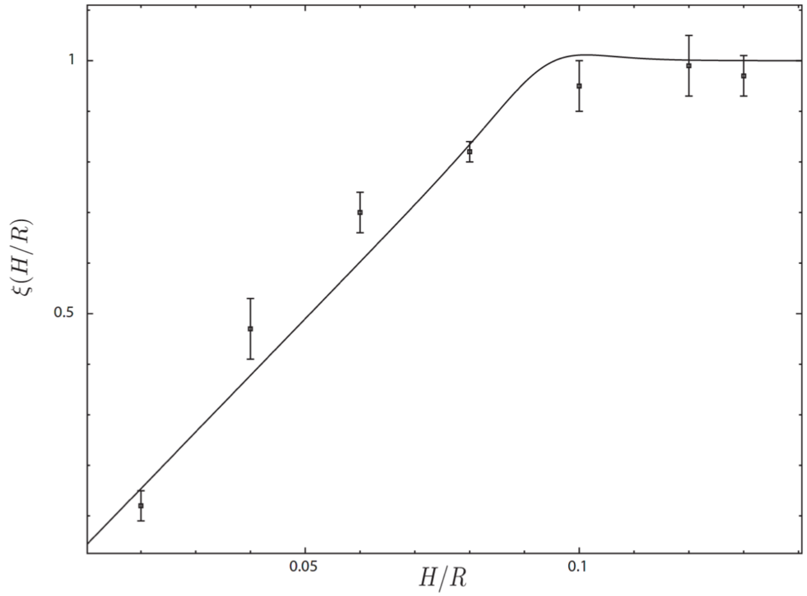


More Orbital Evolution



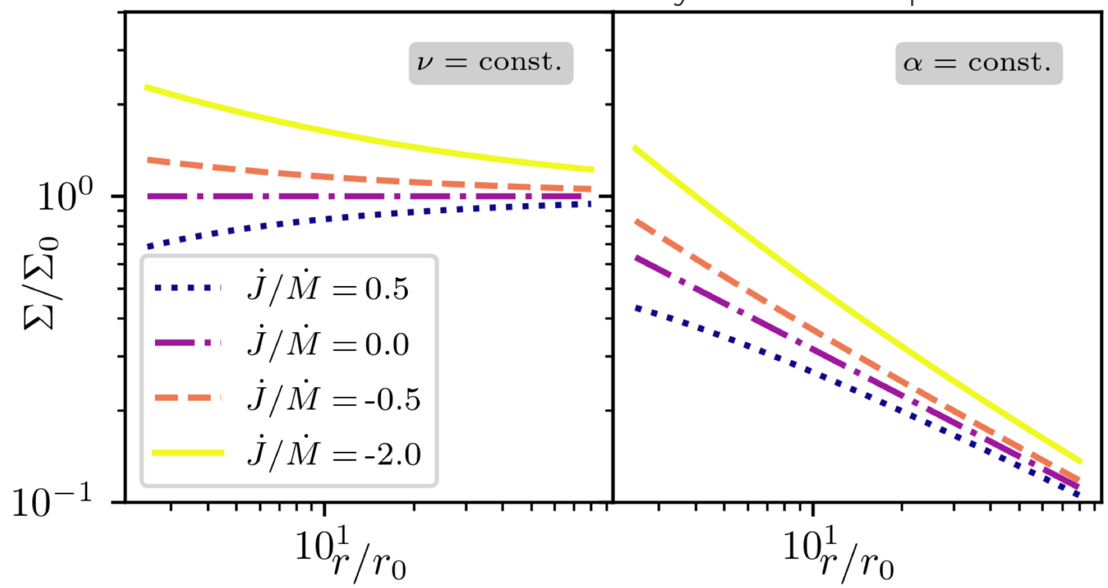


Accretion rate and torque



Accretion rate suppression (Ragusa+ 2016)

Steady-state 1D disk profiles



- Some claims that accretion is suppressed in thin disks (e.g. Ragusa+ 2016, Heath & Nixon 2021)
- A consequence of initial conditions (Dittmann & Ryan 2022)
  - Accretion rate enhancement if the torque on the binary is positive (Rafikov 2013, 2016, Miranda+ 2017)