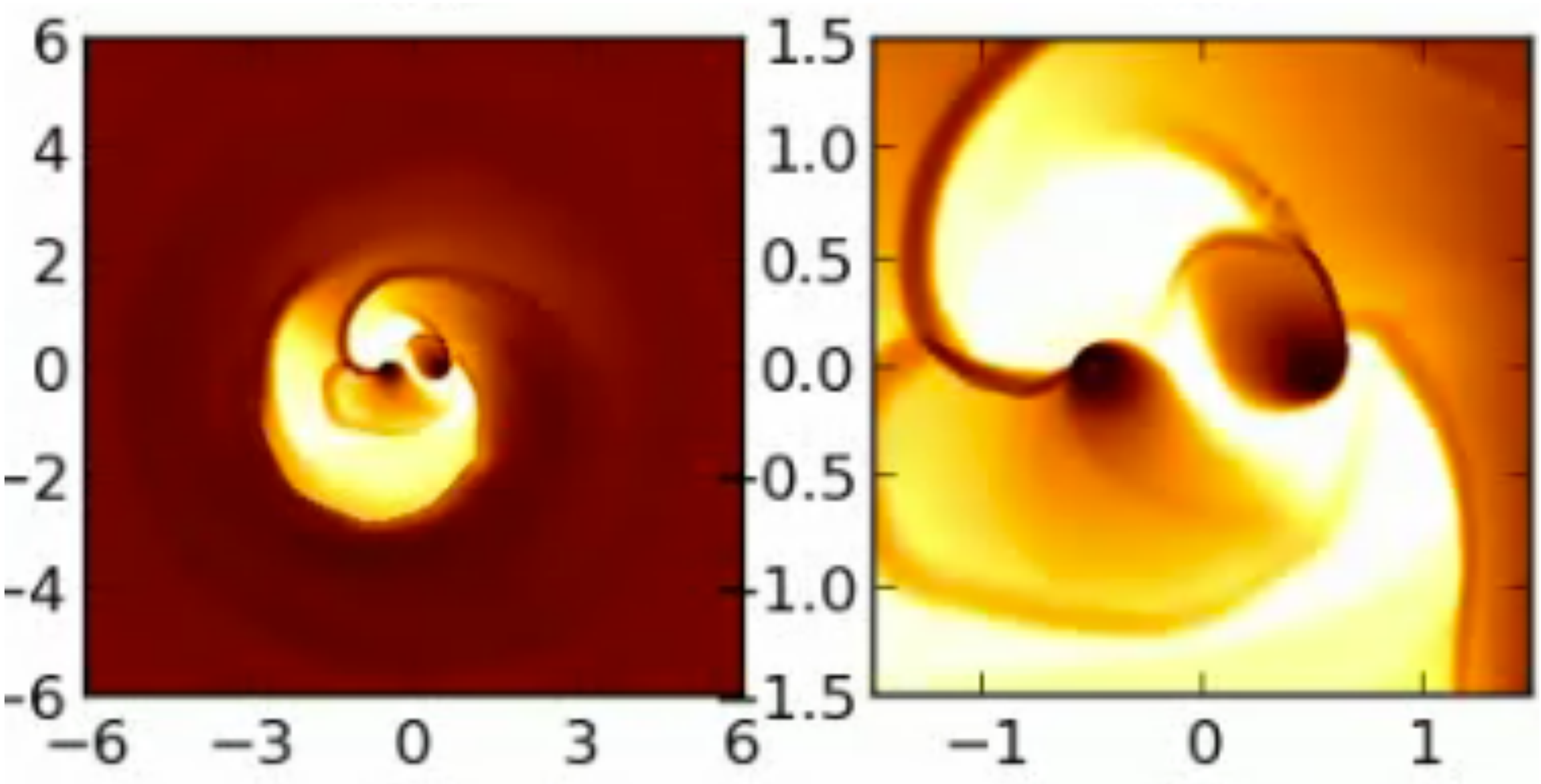
Binary Black Hole Accretion



Andrew MacFadyen (NYU)

Brian Farris (NYU/Columbia), Paul Duffell (Berkeley),
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Farris+ (2013, 2015ab)

Physical Picture

- All bulge galaxies have SMBH at center with $M \sim 10^5 - 10^9 M_\odot$
- Galaxy mergers → formation of massive BH binary in merged remnant.
- Separation decreases by:
  1. dynamical friction
  2. gravitational slingshot interactions
  3. gravitational radiation
- The Final Parsec Problem is Not a Problem? (see e.g. Preto et al, 2011)
- Circumbinary disk forms

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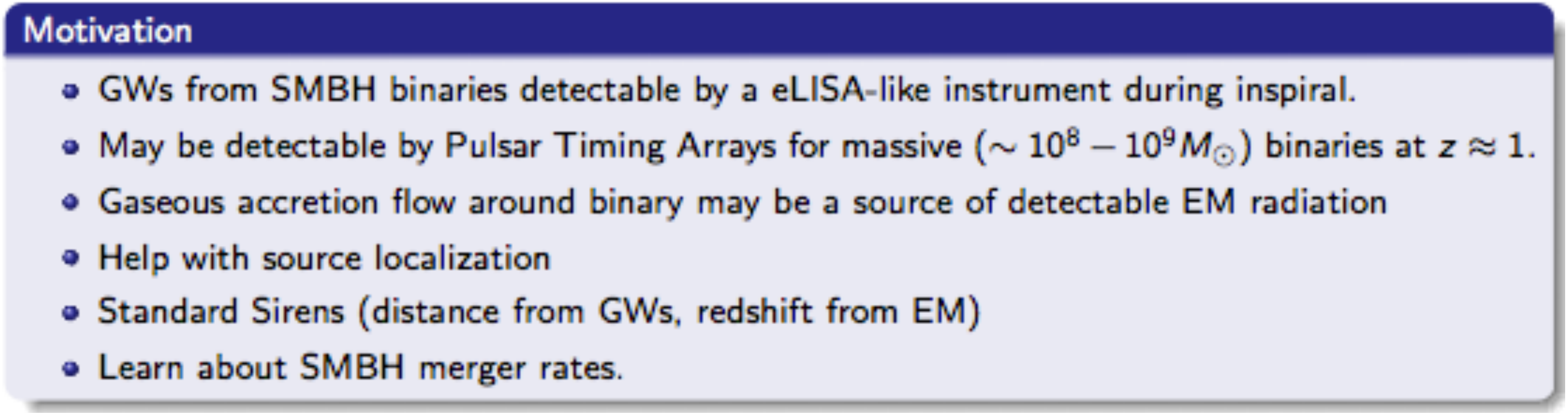
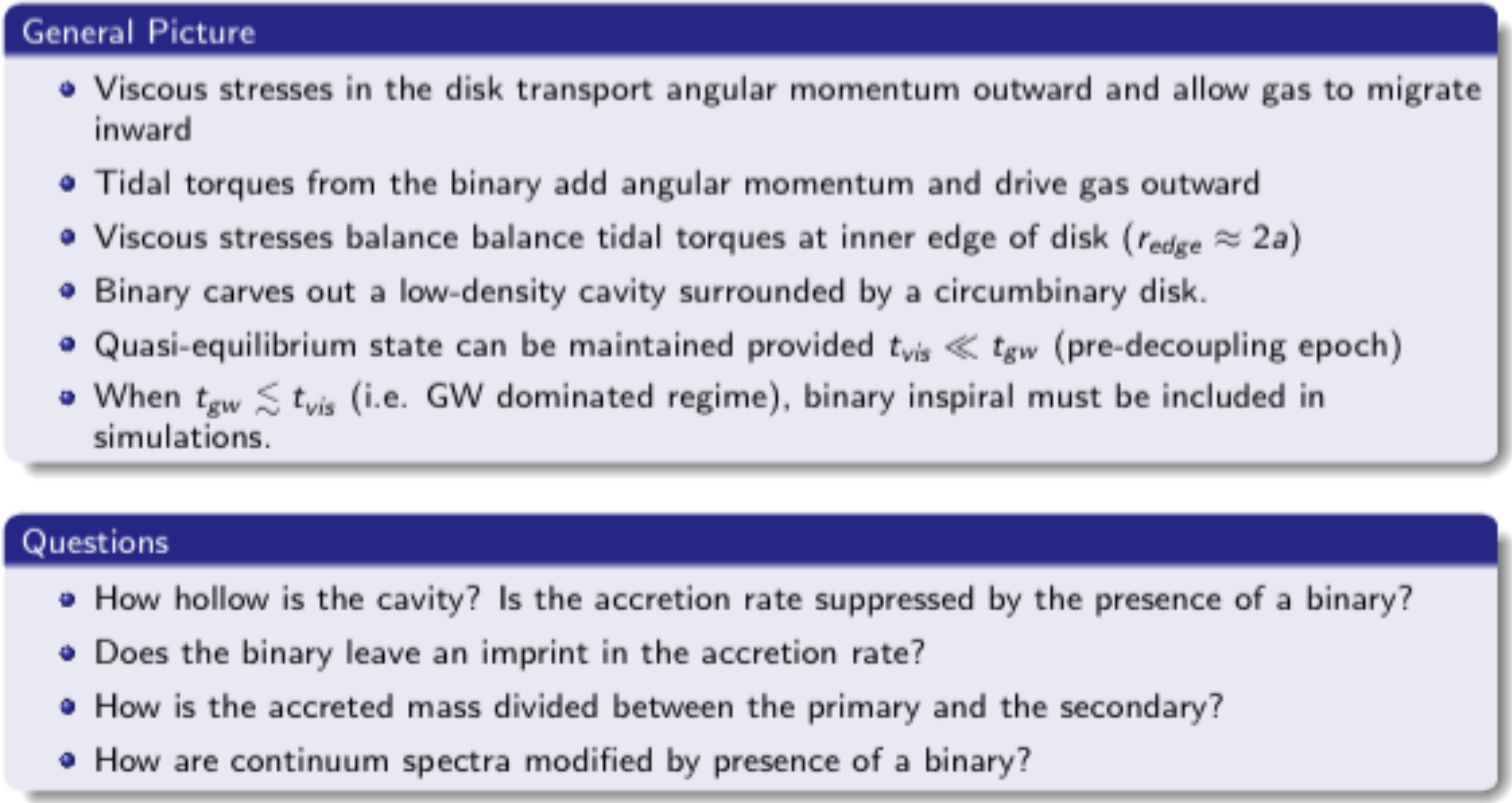


Motivation

- GWs from SMBH binaries detectable by a eLISA-like instrument during inspiral.
- May be detectable by Pulsar Timing Arrays for massive ($\sim 10^8 - 10^9 M_\odot$) binaries at $z \approx 1$.
- Gaseous accretion flow around binary may be a source of detectable EM radiation
- Help with source localization
- Standard Sirens (distance from GWs, redshift from EM)
- Learn about SMBH merger rates.



General Picture

- Viscous stresses in the disk transport angular momentum outward and allow gas to migrate inward
- Tidal torques from the binary add angular momentum and drive gas outward
- Viscous stresses balance balance tidal torques at inner edge of disk ($r_{edge} \approx 2a$)
- Binary carves out a low-density cavity surrounded by a circumbinary disk.
- Quasi-equilibrium state can be maintained provided $t_{vis} \ll t_{gw}$ (pre-decoupling epoch)
- When $t_{gw} \lesssim t_{vis}$ (i.e. GW dominated regime), binary inspiral must be included in simulations.

Questions

- How hollow is the cavity? Is the accretion rate suppressed by the presence of a binary?
- Does the binary leave an imprint in the accretion rate?
- How is the accreted mass divided between the primary and the secondary?
- How are continuum spectra modified by presence of a binary?

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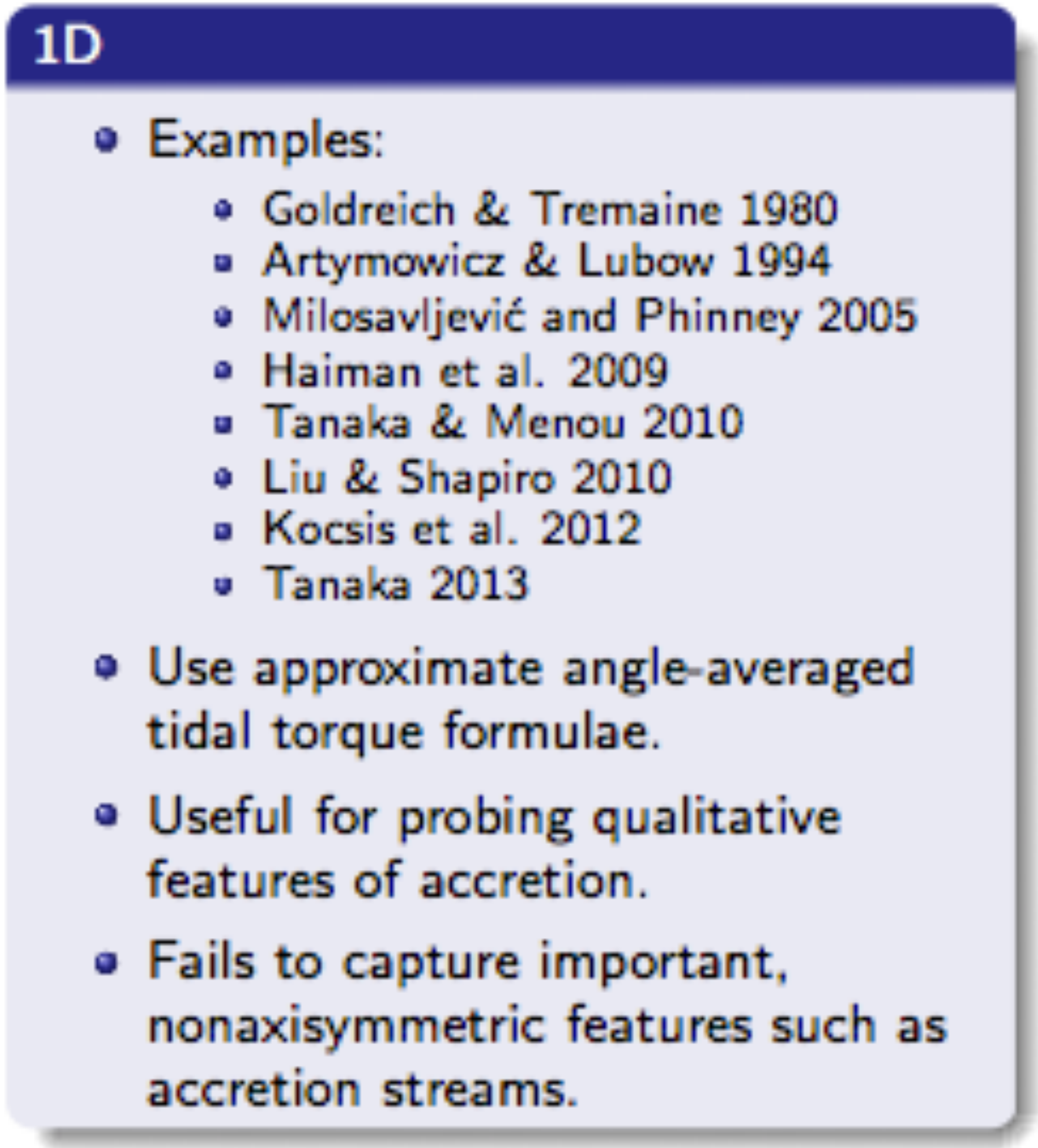
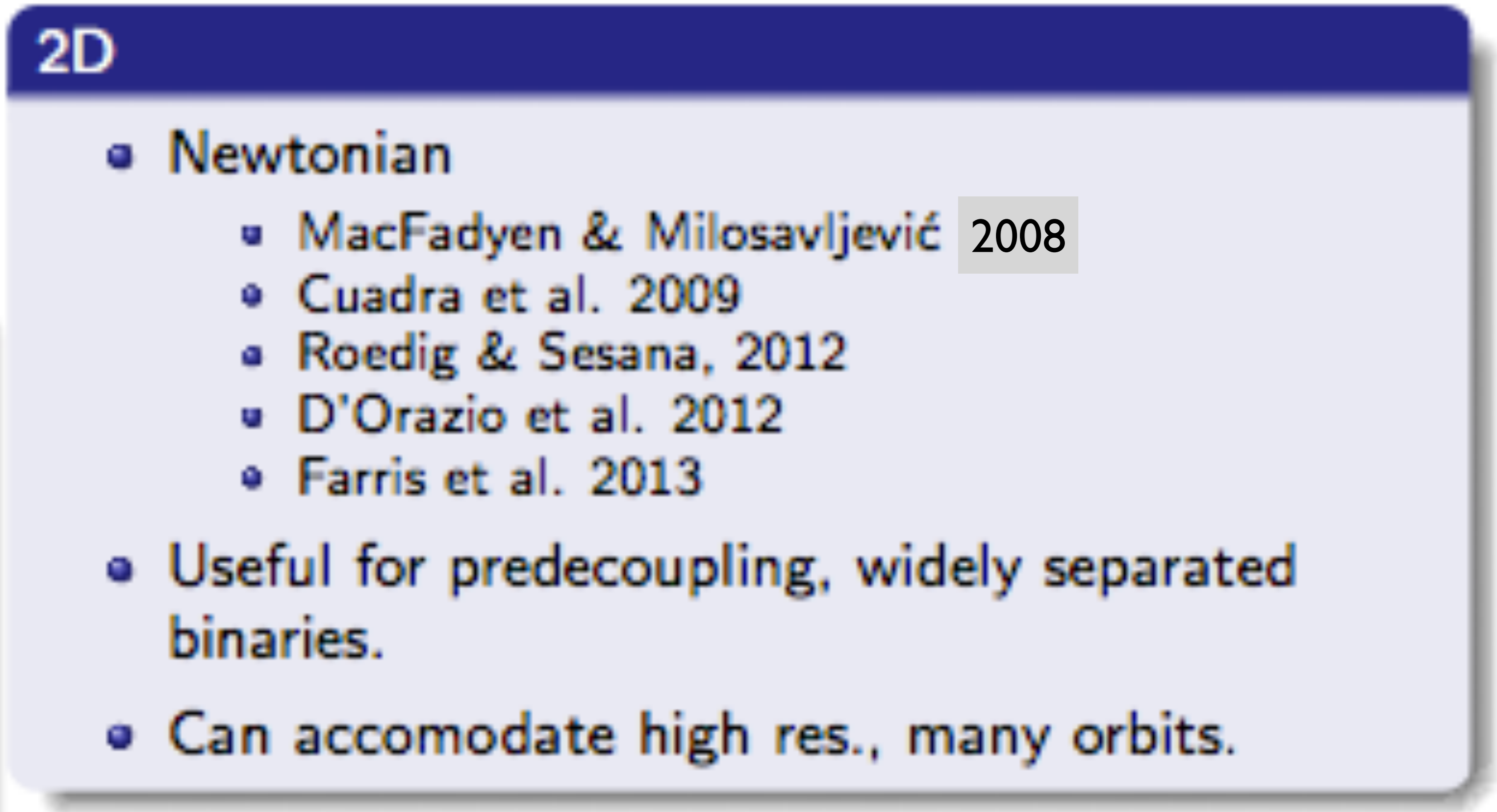


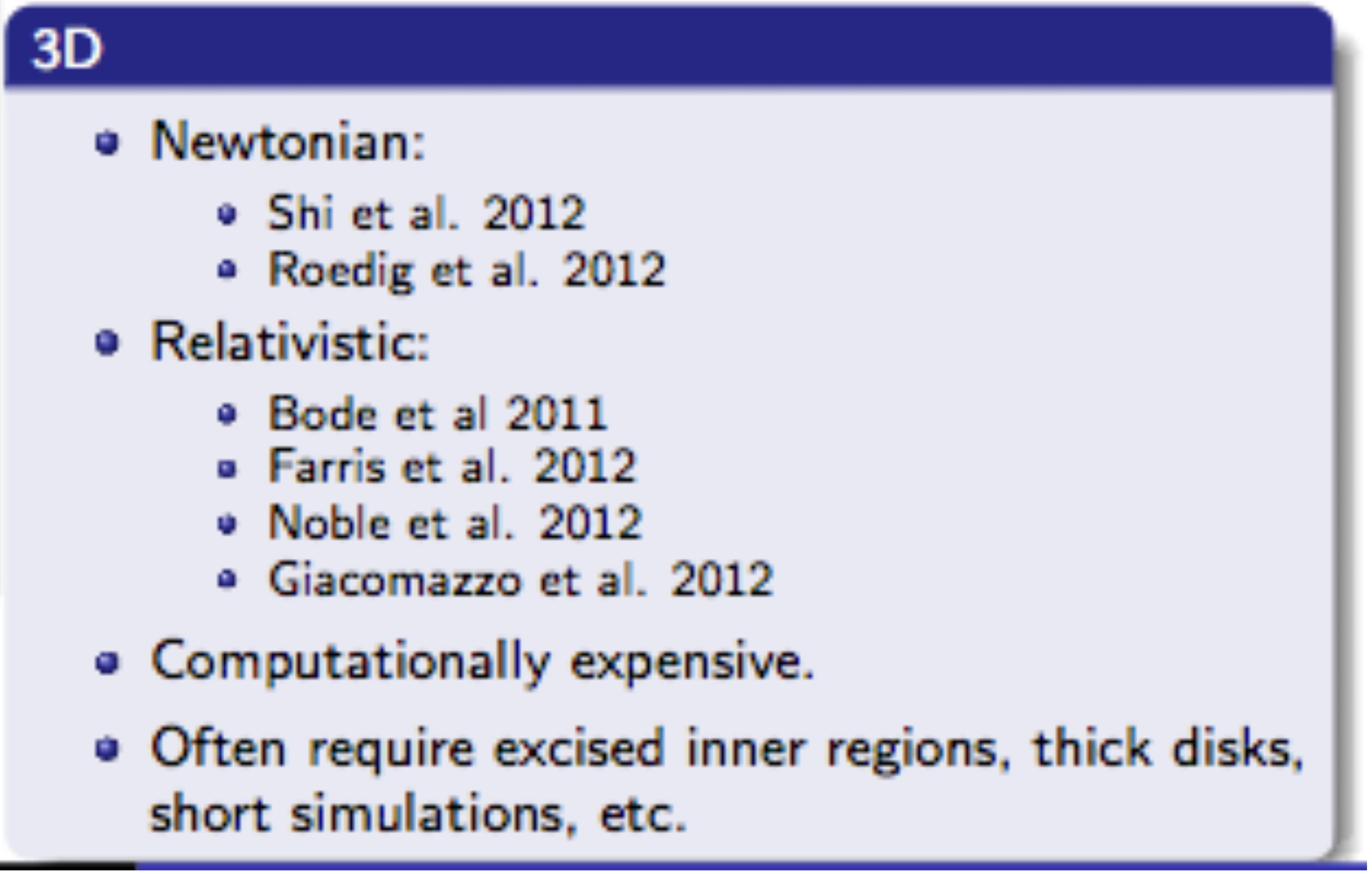
1D

- Examples:
  - Goldreich & Tremaine 1980
  - Artymowicz & Lubow 1994
  - Milosavljević and Phinney 2005
  - Haiman et al. 2009
  - Tanaka & Menou 2010
  - Liu & Shapiro 2010
  - Kocsis et al. 2012
  - Tanaka 2013
- Use approximate angle-averaged tidal torque formulae.
- Useful for probing qualitative features of accretion.
- Fails to capture important, nonaxisymmetric features such as accretion streams.



2D

- Newtonian
  - MacFadyen & Milosavljević 2008
  - Cuadra et al. 2009
  - Roedig & Sesana, 2012
  - D'Orazio et al. 2012
  - Farris et al. 2013
- Useful for predecoupling, widely separated binaries.
- Can accomodate high res., many orbits.



3D

- Newtonian:
  - Shi et al. 2012
  - Roedig et al. 2012
- Relativistic:
  - Bode et al 2011
  - Farris et al. 2012
  - Noble et al. 2012
  - Giacomazzo et al. 2012
- Computationally expensive.
- Often require excised inner regions, thick disks, short simulations, etc.

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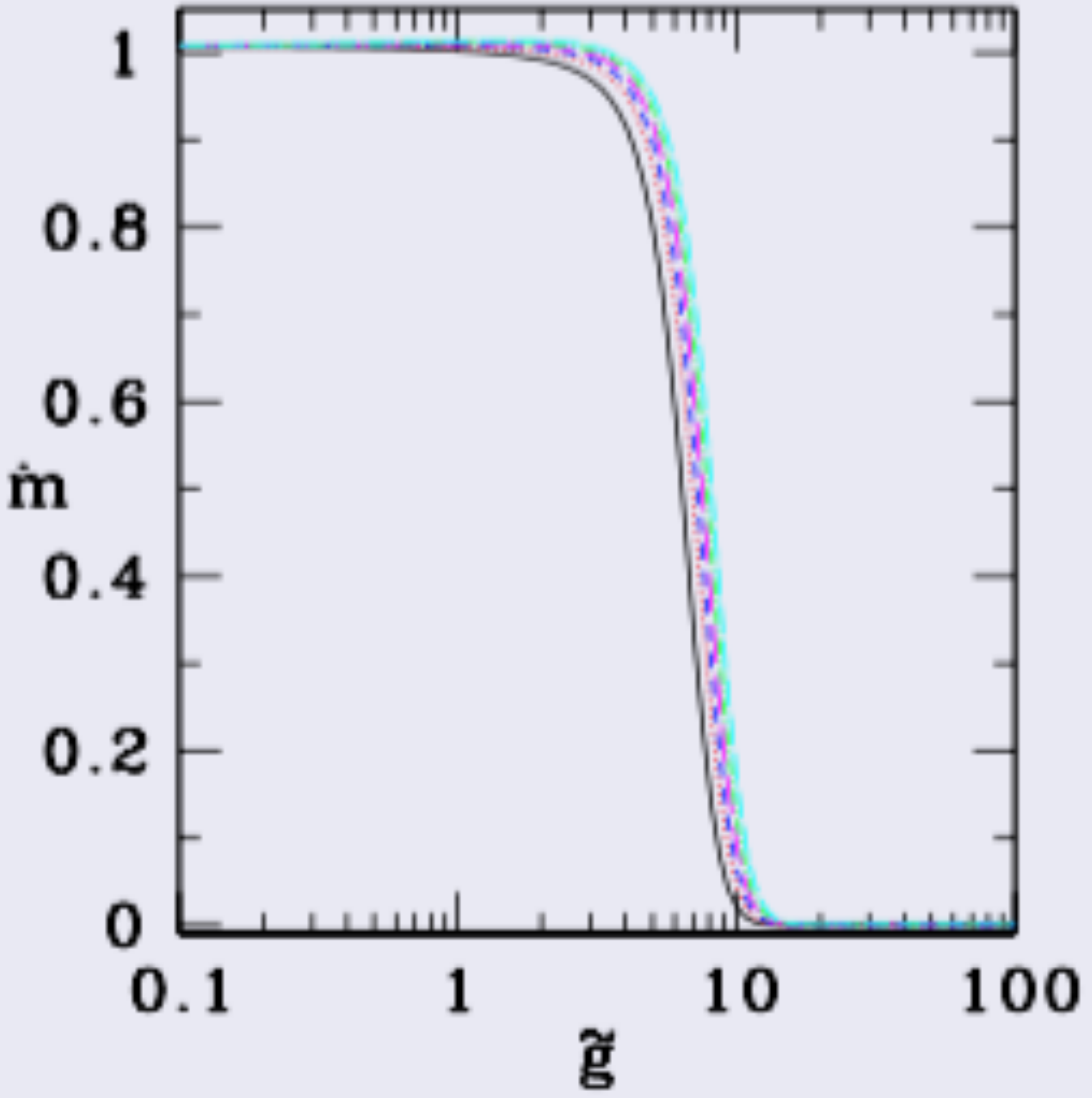
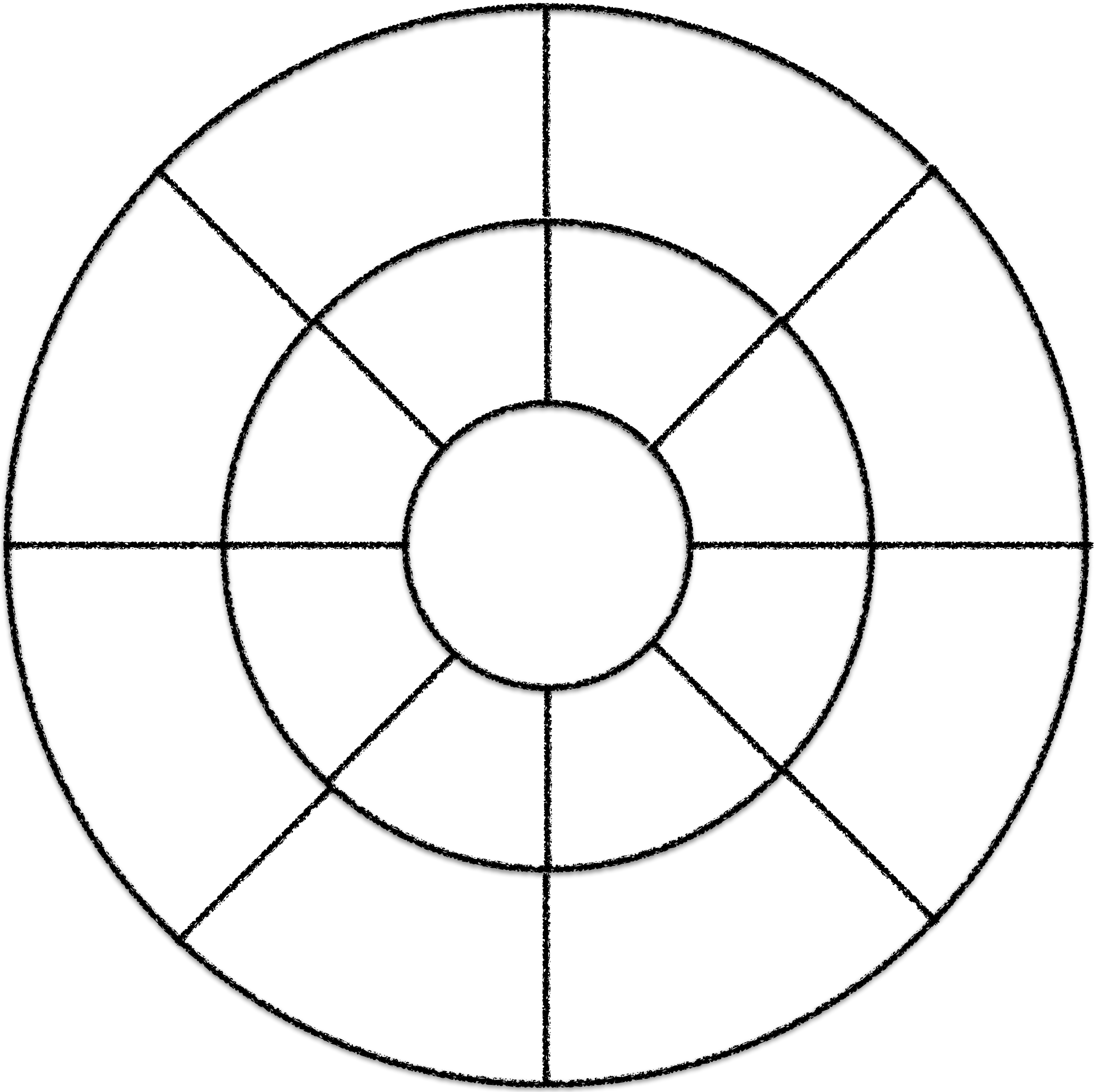
1D model

- Analytic approx. to sum over Lindblad resonances $\Lambda = \Lambda(q, M, r, a, h)$ (Armitage and Natarajan, 2002)
- $\dot{M} \equiv \dot{M}/3\pi\nu_{out}\Sigma_{out}$
- $\tilde{g} \equiv T_{tid}(a)/T_{vis}(a)$
- Transition corresponds to $q \sim 4 \times 10^{-3}$
- Seems to show accretion choked off for modest mass ratios.
- Does this picture hold when we move to 2D and drop assumption of axisymmetry?

Liu and Shapiro, 2010





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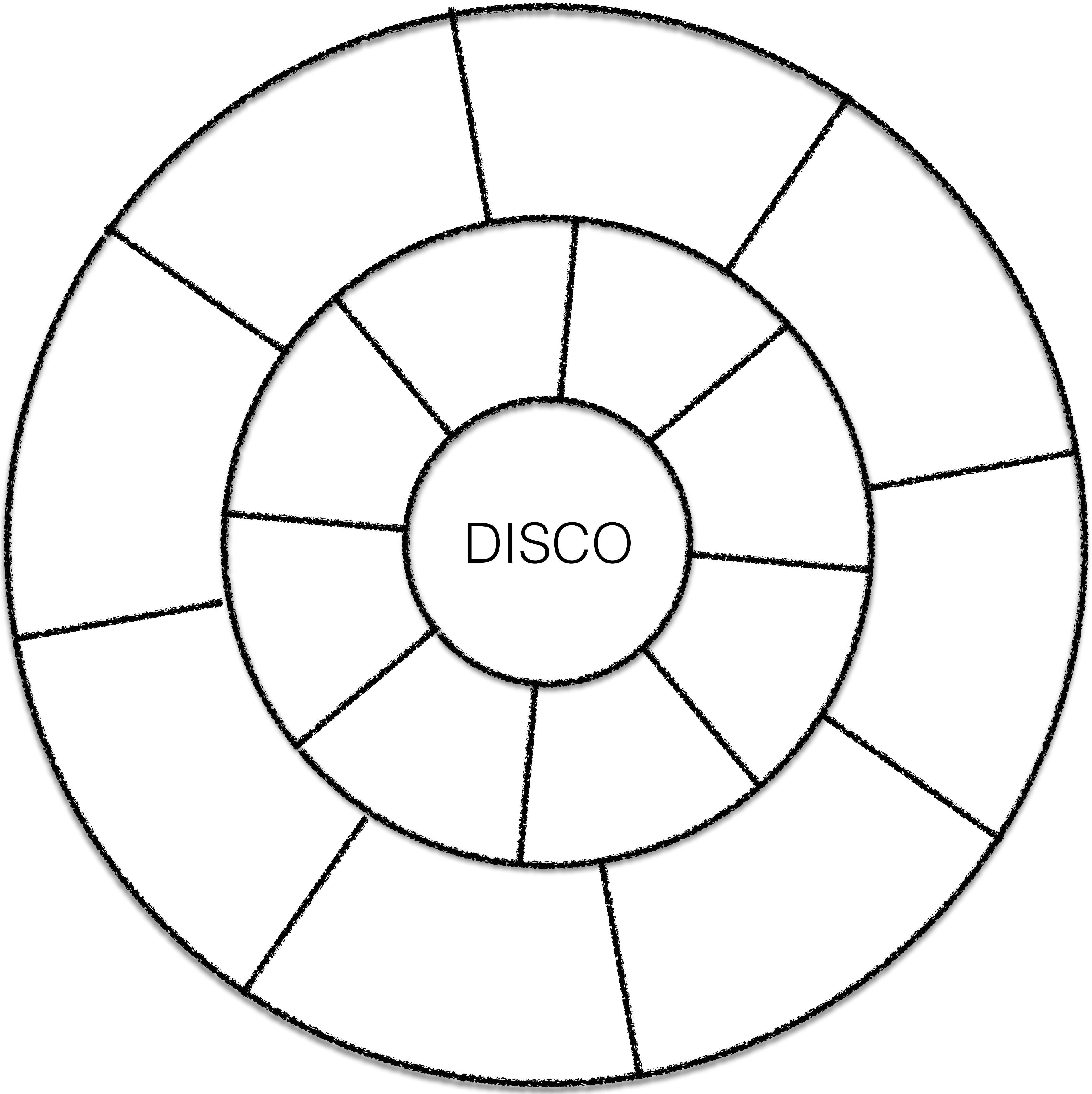

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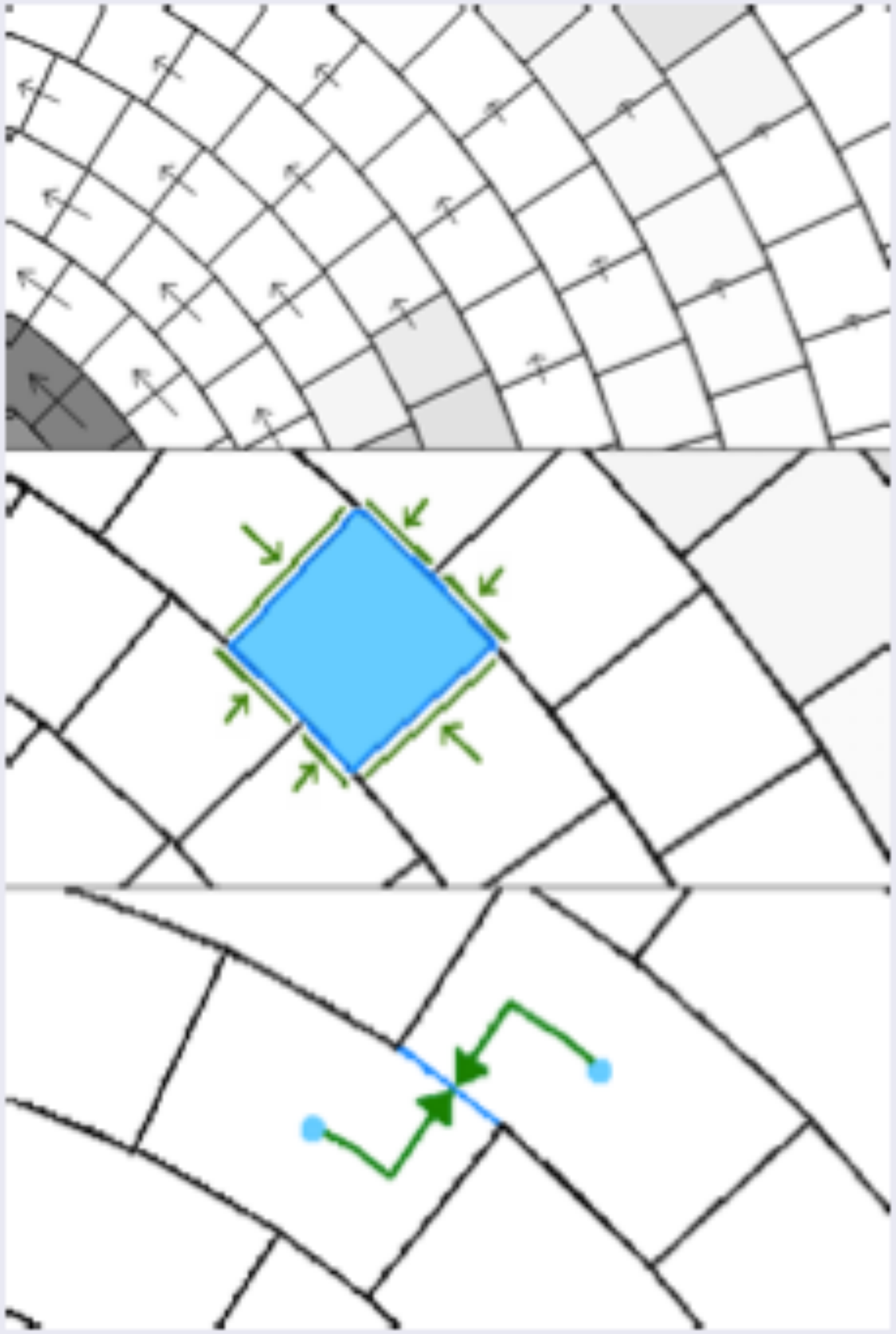

DISCO - Duffell & MacFadyen 2012, 2013

- Solves (Magneto)Hydrodynamics equations
- Uses conservative, shock-capturing finite-volume methods
- Effectively "Lagrangian", as cells are able to move with fluid
- Minimizes advection errors, allows for longer timesteps

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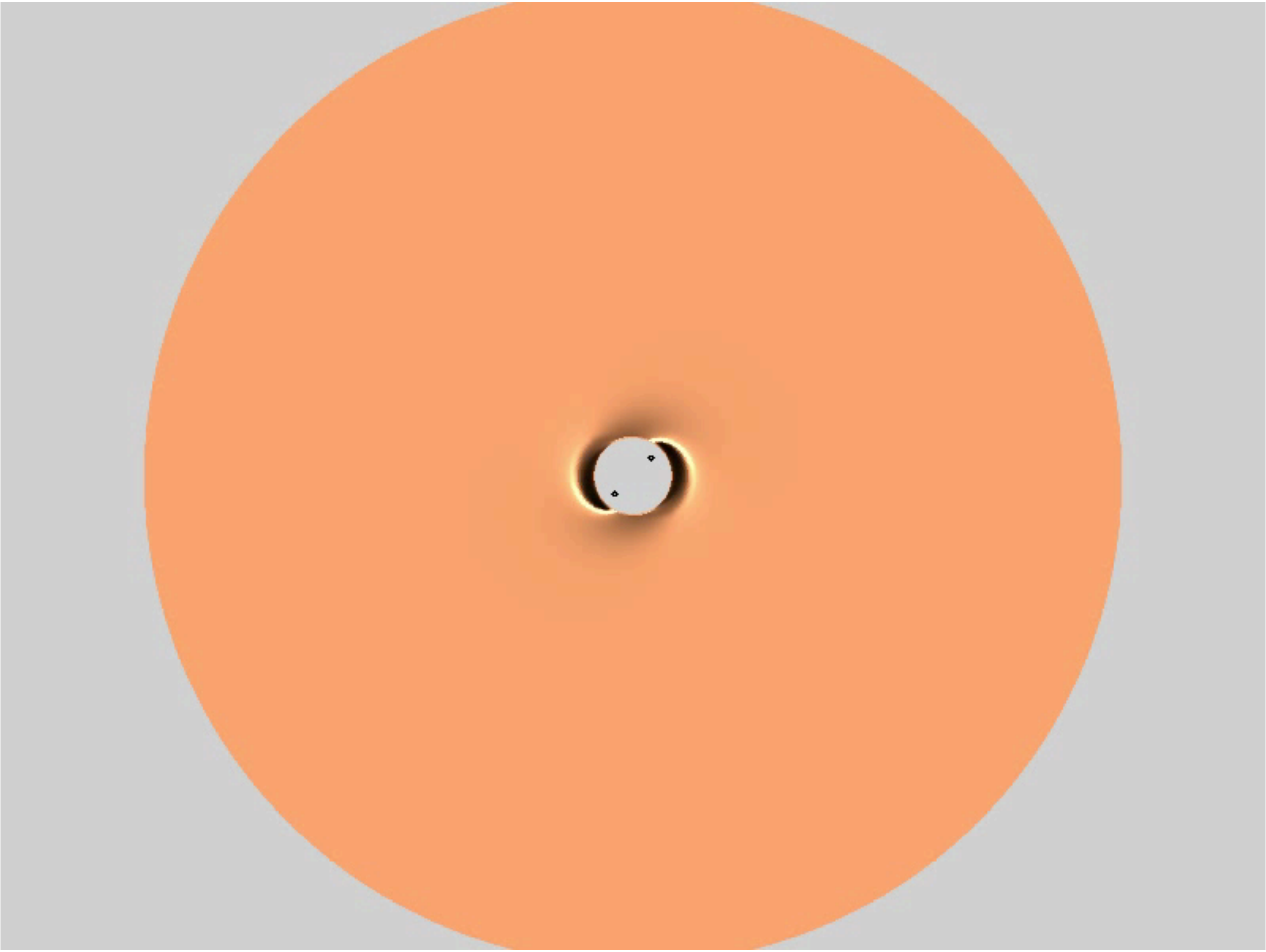

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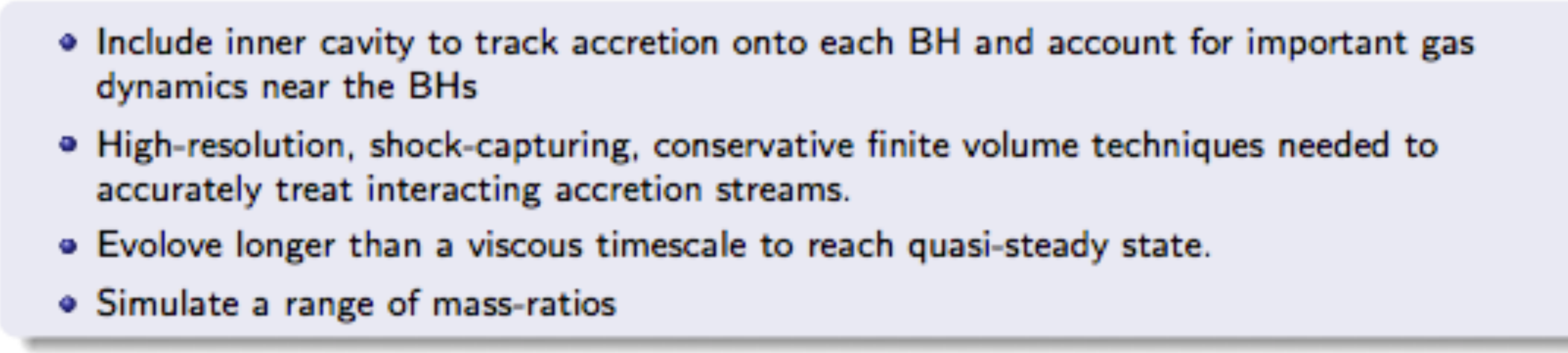
MacFadyen & Milosavljevic (2008) w/ DISCO



- Include inner cavity to track accretion onto each BH and account for important gas dynamics near the BHs
- High-resolution, shock-capturing, conservative finite volume techniques needed to accurately treat interacting accretion streams.
- Evolove longer than a viscous timescale to reach quasi-steady state.
- Simulate a range of mass-ratios

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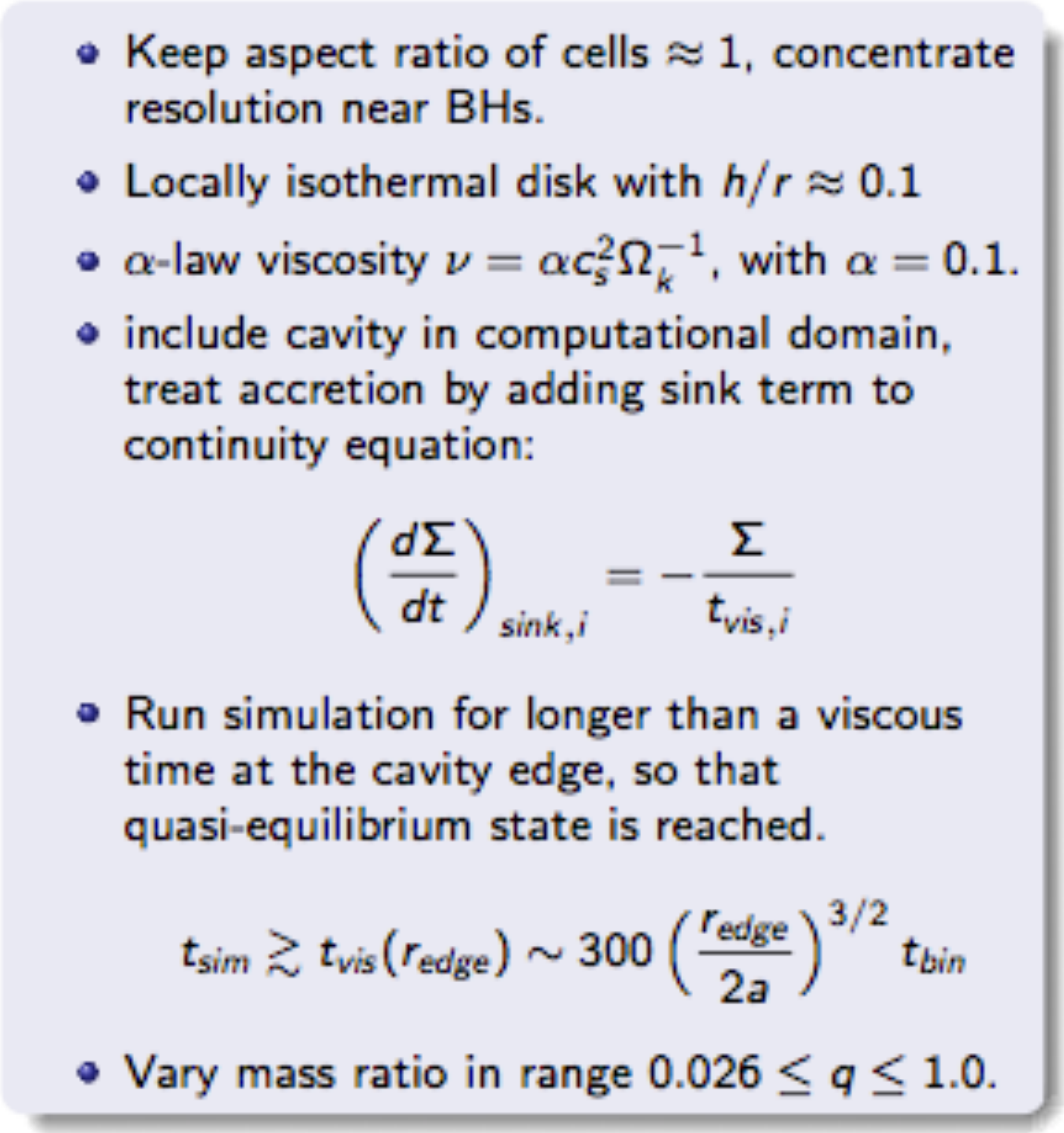


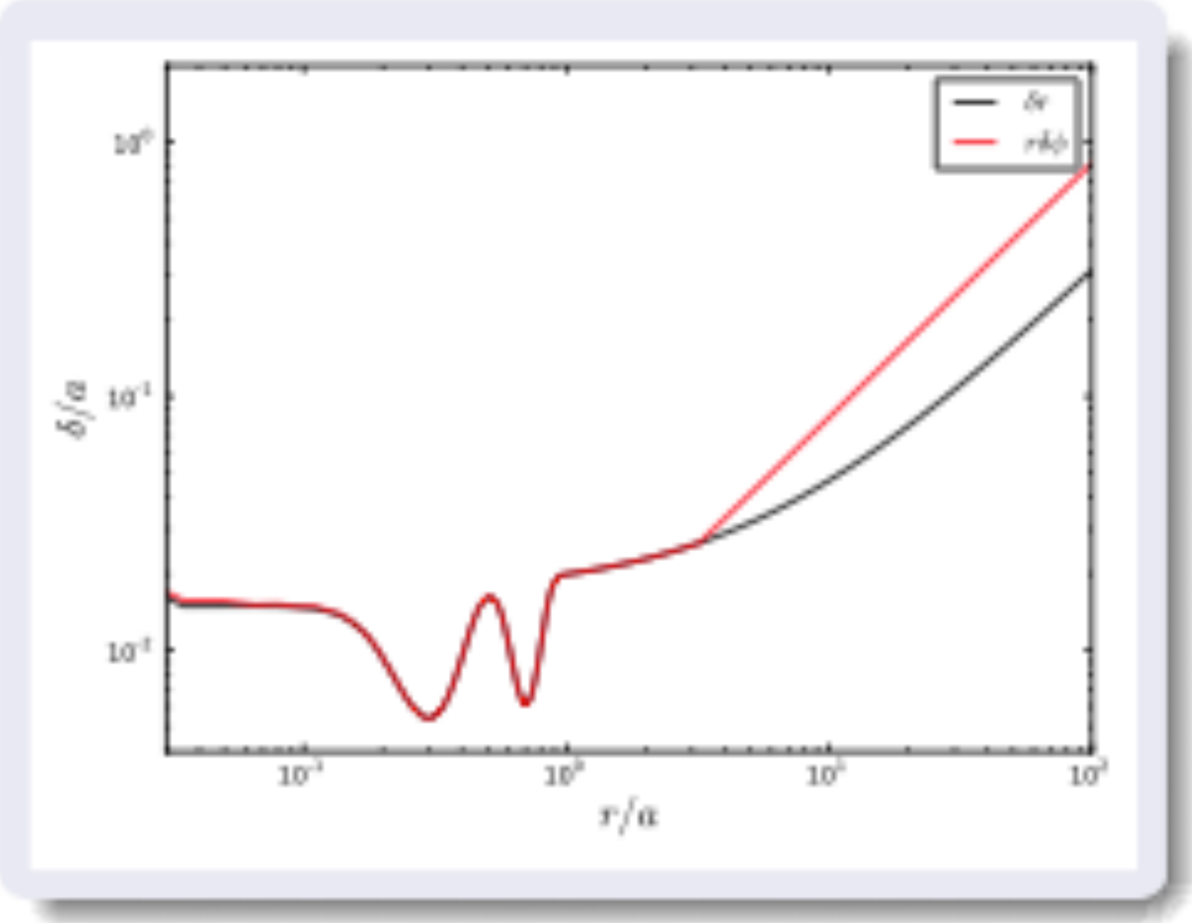
- Keep aspect ratio of cells ≈ 1, concentrate resolution near BHs.
- Locally isothermal disk with $h/r \approx 0.1$
- α-law viscosity $\nu = \alpha c_s^2 \Omega_k^{-1}$, with $\alpha = 0.1$.
- include cavity in computational domain, treat accretion by adding sink term to continuity equation:

$$\left(\frac{d\Sigma}{dt}\right)_{sink,i} = -\frac{\Sigma}{t_{vis,i}}$$

- Run simulation for longer than a viscous time at the cavity edge, so that quasi-equilibrium state is reached.

$$t_{sim} \gtrsim t_{vis}(r_{edge}) \sim 300 \left(\frac{r_{edge}}{2a}\right)^{3/2} t_{bin}$$

- Vary mass ratio in range $0.026 \leq q \leq 1.0$.



Farris, Duffell, MacFadyen & Haiman (2013)

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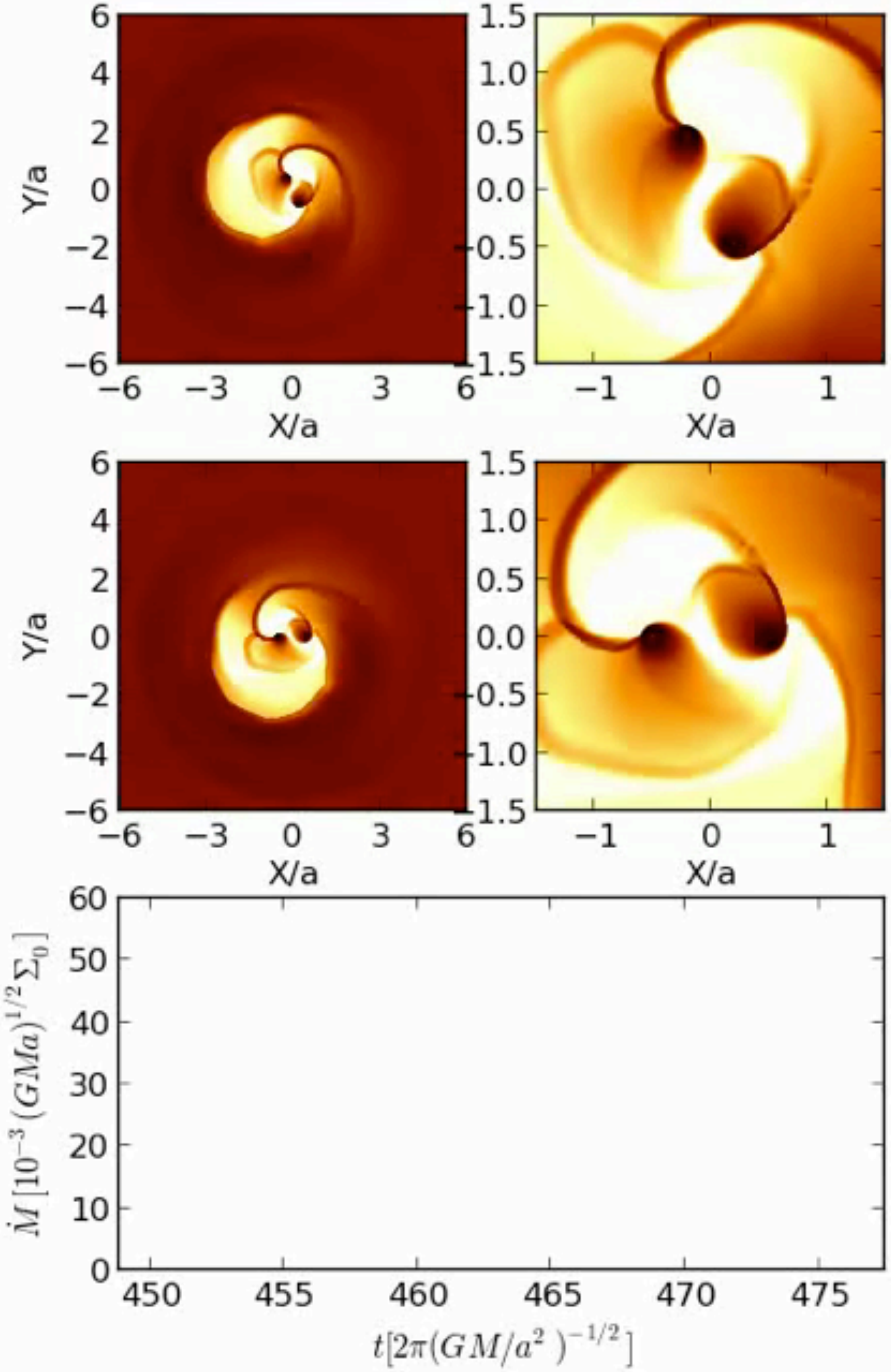
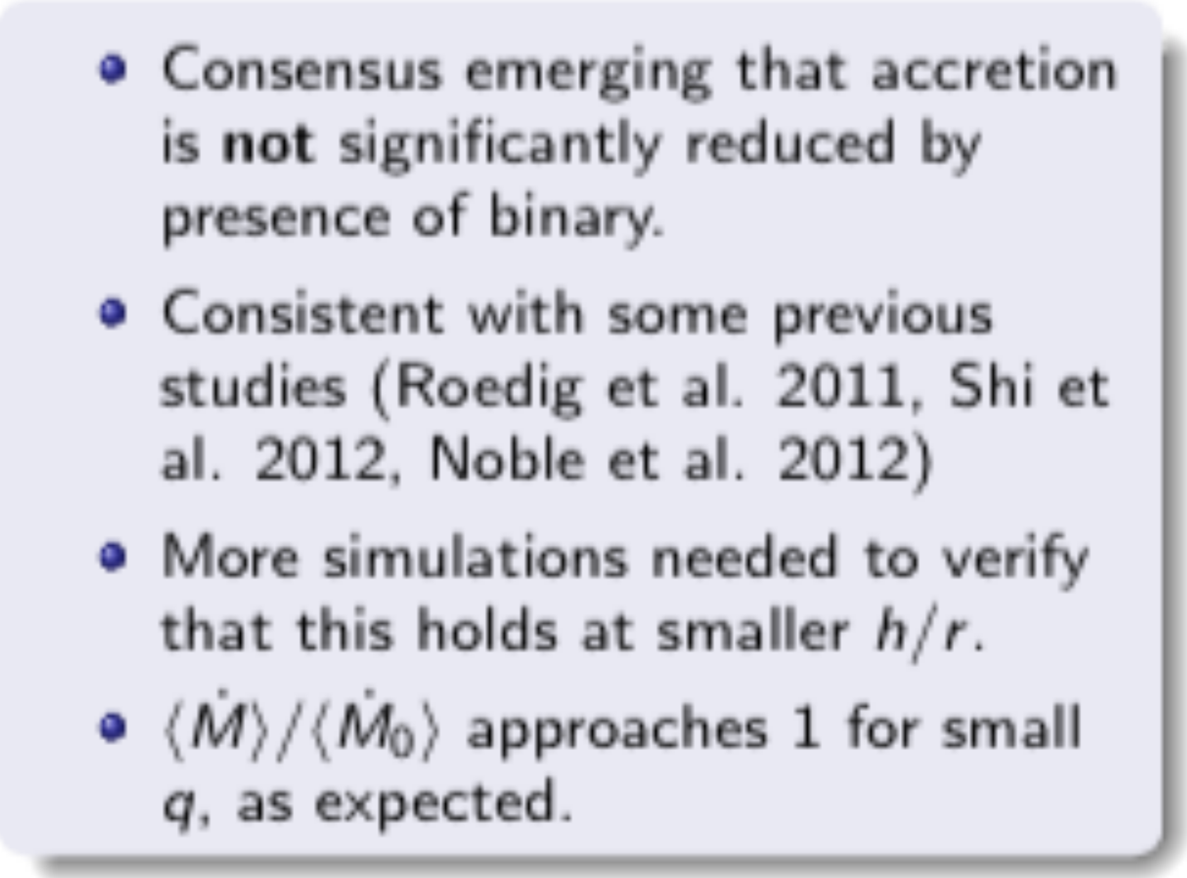
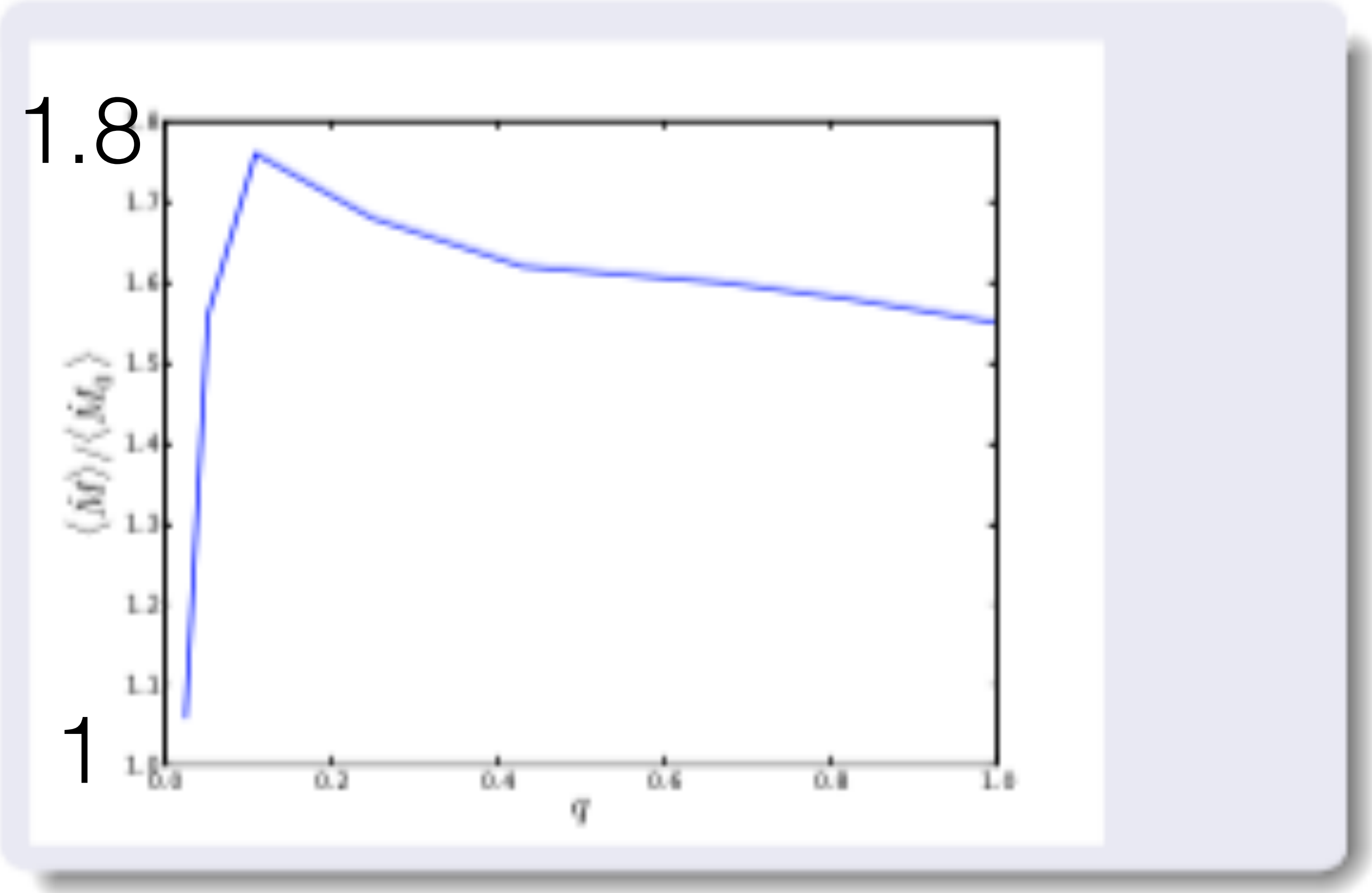

Y/a
6
4
2
0
−2
−4
−6
−6
−3
0
3
6
X/a
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1
0
1
X/a
Y/a
X/a
X/a
$\dot{M}\,[10^{-3}(GMa)^{1/2}\Sigma_0]$
60
50
40
30
20
10
0
450
455
460
465
470
475
$t[2\pi(GM/a^2)^{-1/2}]$

Farris+ (2013)



- Consensus emerging that accretion is **not** significantly reduced by presence of binary.
- Consistent with some previous studies (Roedig et al. 2011, Shi et al. 2012, Noble et al. 2012)
- More simulations needed to verify that this holds at smaller h/r.
- $\langle \dot{M} \rangle / \langle \dot{M}_0 \rangle$ approaches 1 for small q, as expected.



Farris+ (2013)

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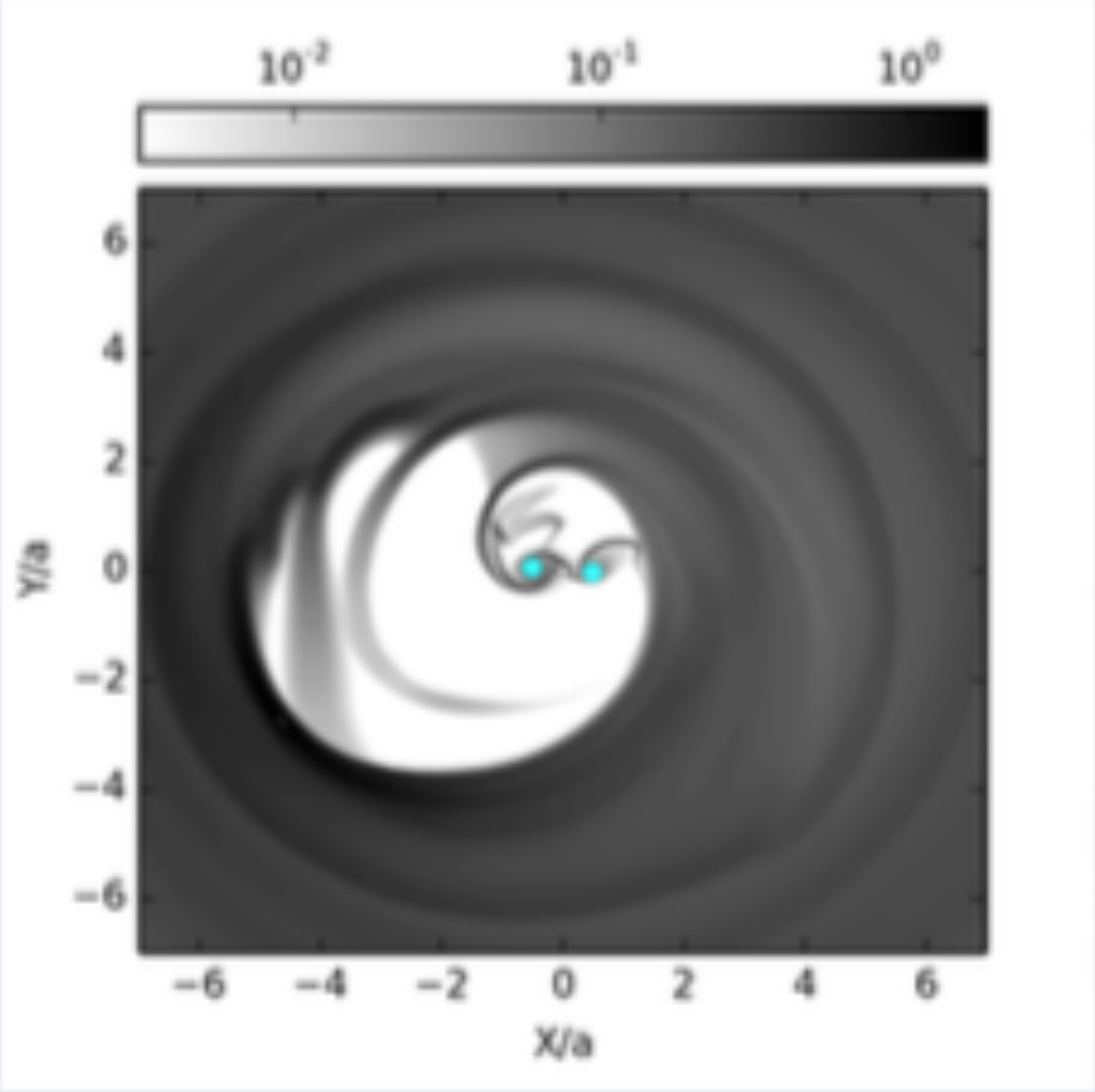
- Eccentric inner cavity for large mass ratio binaries seen in many calculations, e.g.
  - MacFadyen and Milosavljević 2008
  - D'Orazio et al. 2012
  - Shi et al. 2012
  - Noble et al. 2012
  - Farris et al. 2012
- A fraction of gas in each stream does not accrete onto BH, but rather is flung outward.
- This fraction impacts cavity wall on the opposite side from which it entered.
- If one stream is slightly larger it will push the opposity wall more, weakening the opposite stream.
- $\Rightarrow$ the imbalance grows.



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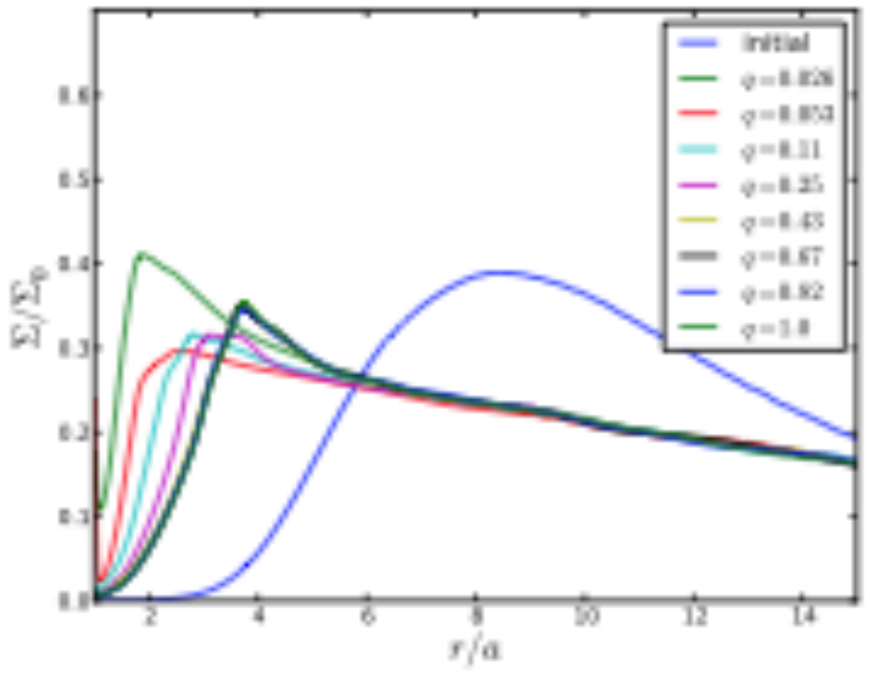
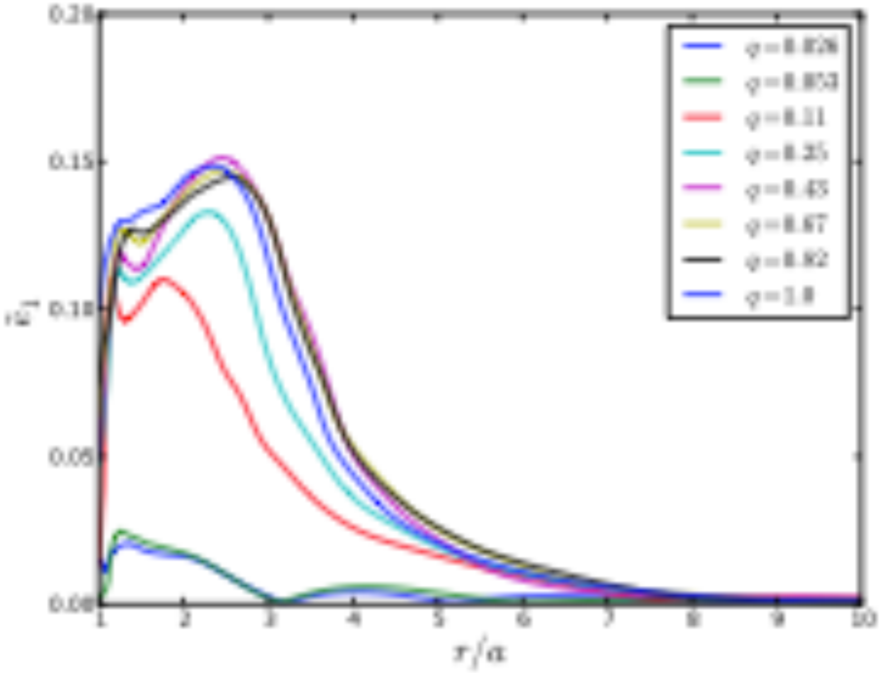
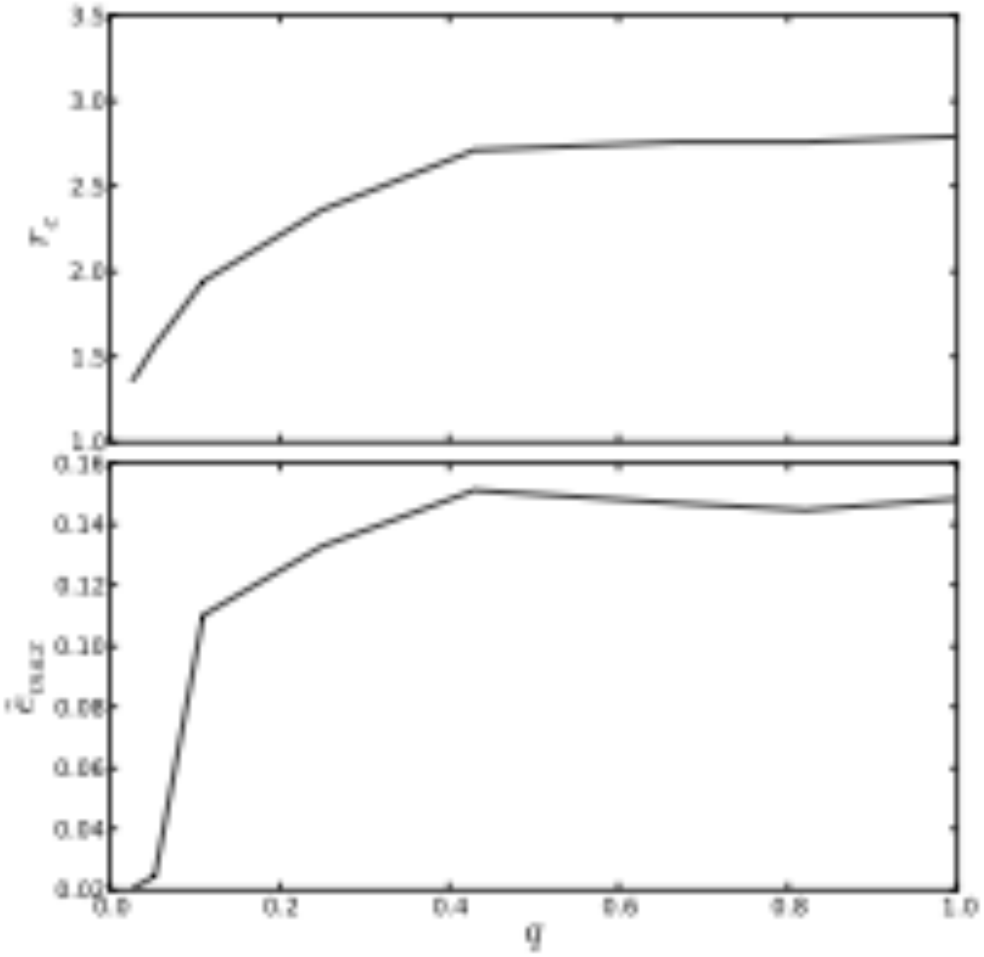
Surface Density



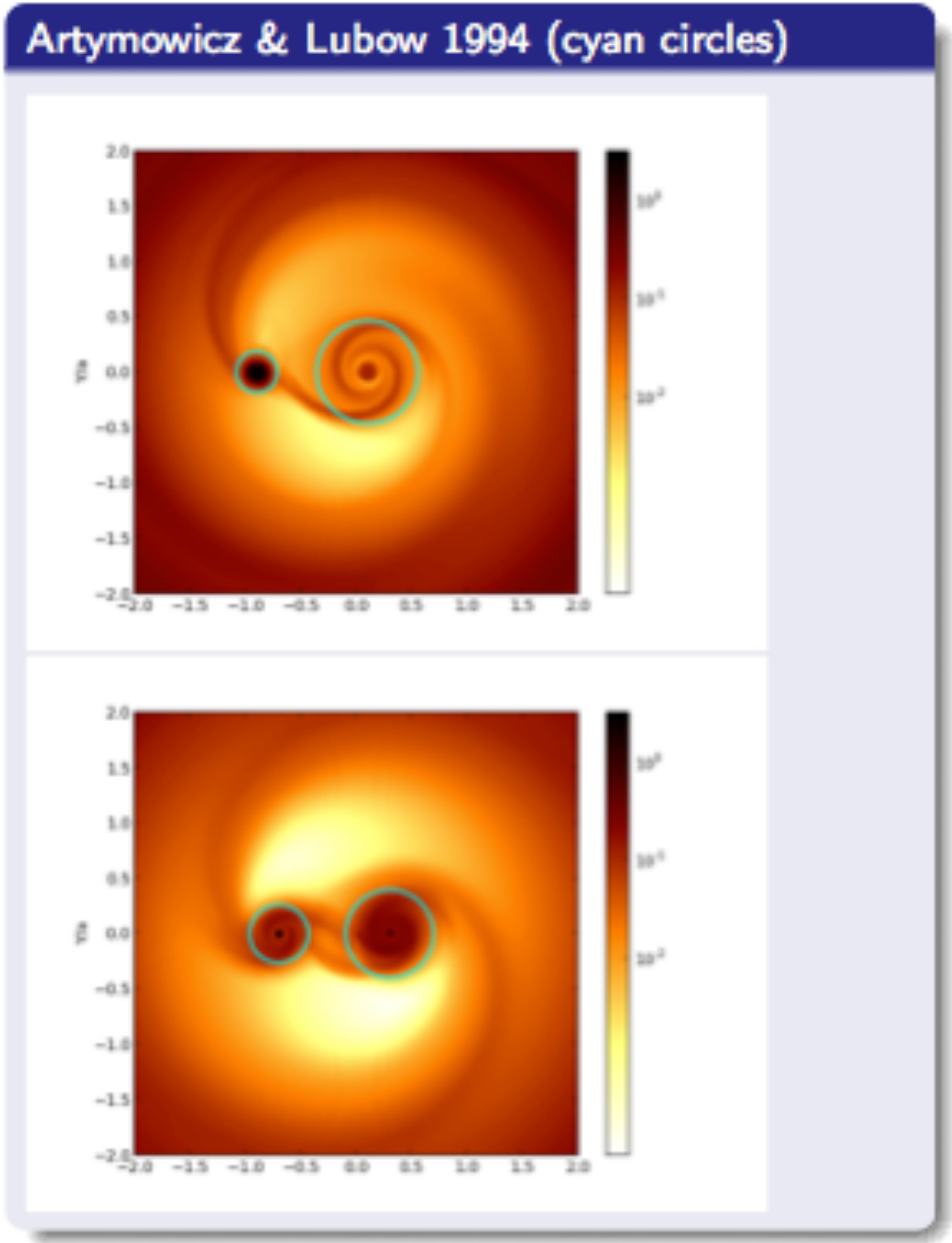
Eccentricity



cavity size and max eccentricity vs q



Farris+ (2013)



Artymowicz & Lubow 1994 (cyan circles)

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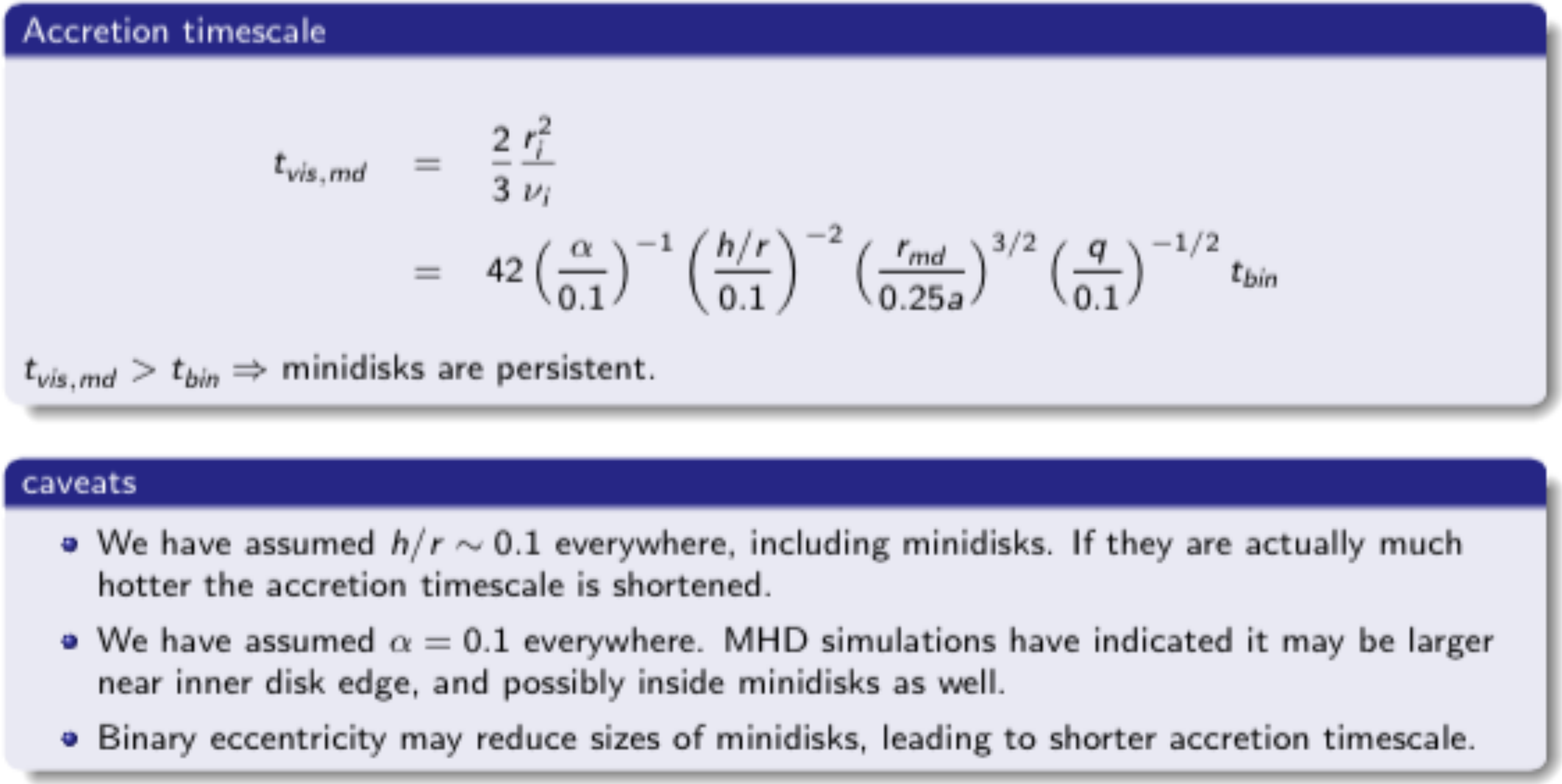

Accretion timescale

$$\begin{aligned} t_{vis,md} &= \frac{2}{3}\frac{r_i^2}{\nu_i} \\ &= 42\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{h/r}{0.1}\right)^{-2}\left(\frac{r_{md}}{0.25a}\right)^{3/2}\left(\frac{q}{0.1}\right)^{-1/2} t_{bin} \end{aligned}$$

$t_{vis,md} > t_{bin} \Rightarrow$ minidisks are persistent.

caveats

- We have assumed $h/r \sim 0.1$ everywhere, including minidisks. If they are actually much hotter the accretion timescale is shortened.
- We have assumed $\alpha = 0.1$ everywhere. MHD simulations have indicated it may be larger near inner disk edge, and possibly inside minidisks as well.
- Binary eccentricity may reduce sizes of minidisks, leading to shorter accretion timescale.

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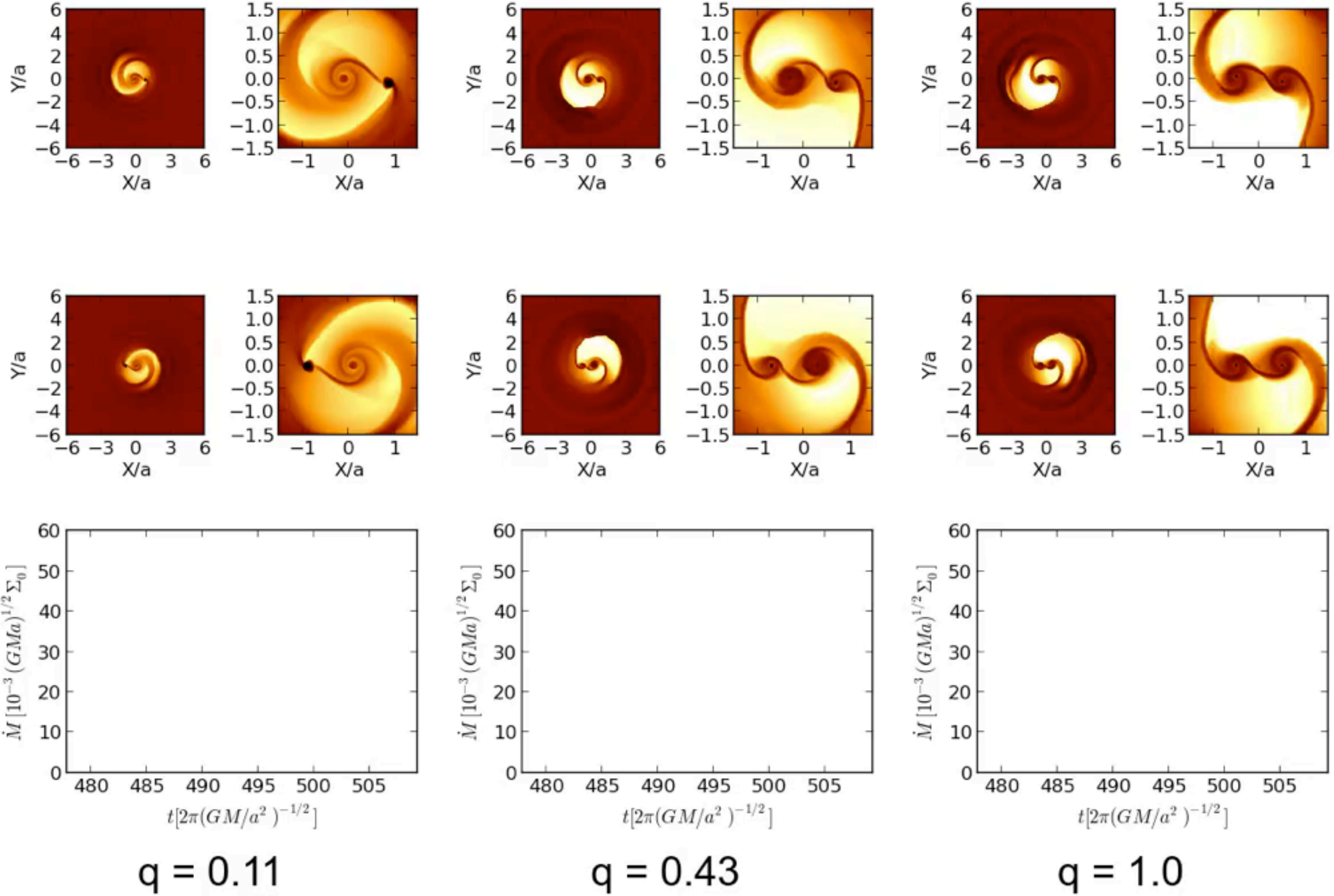

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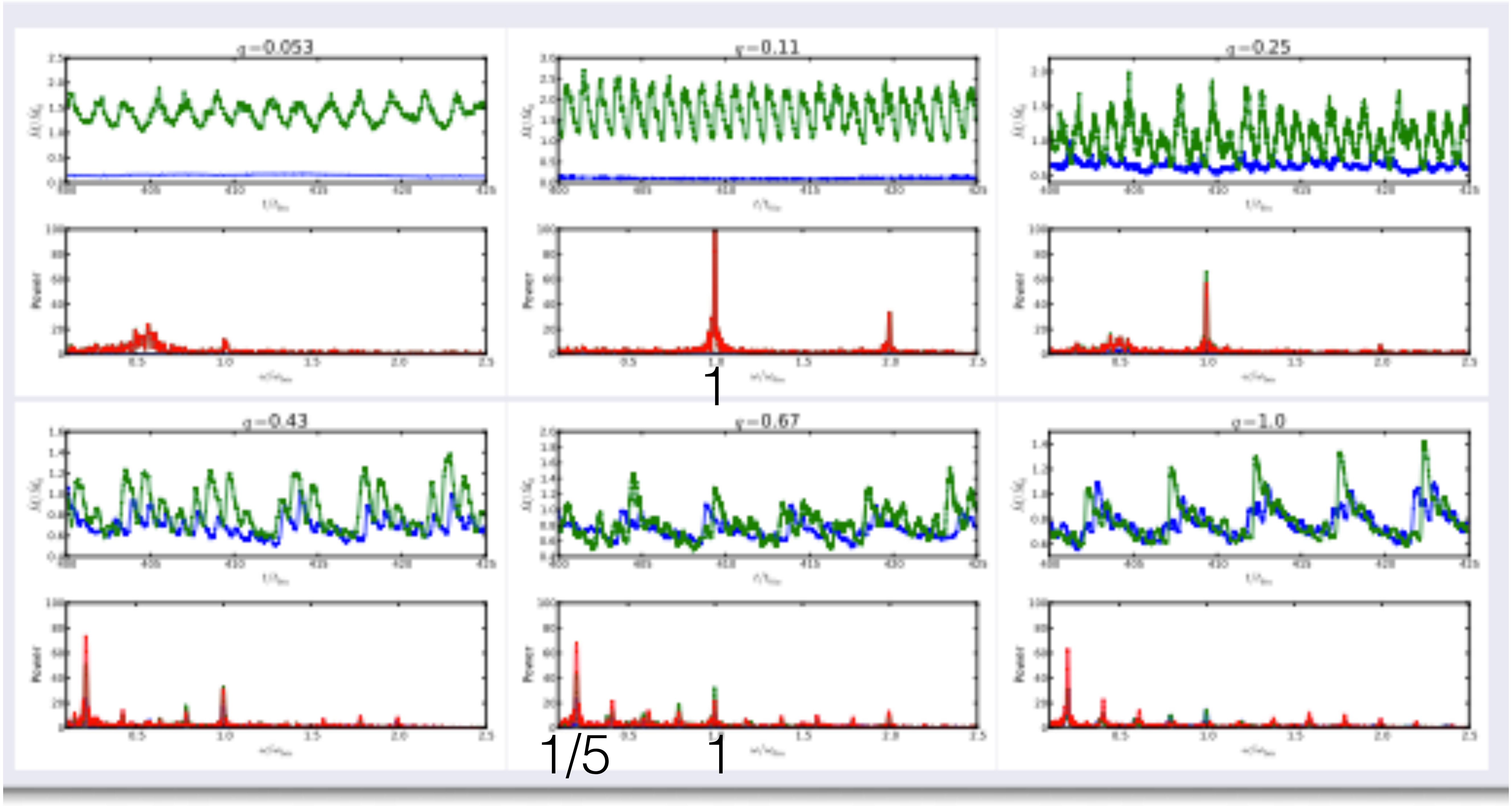
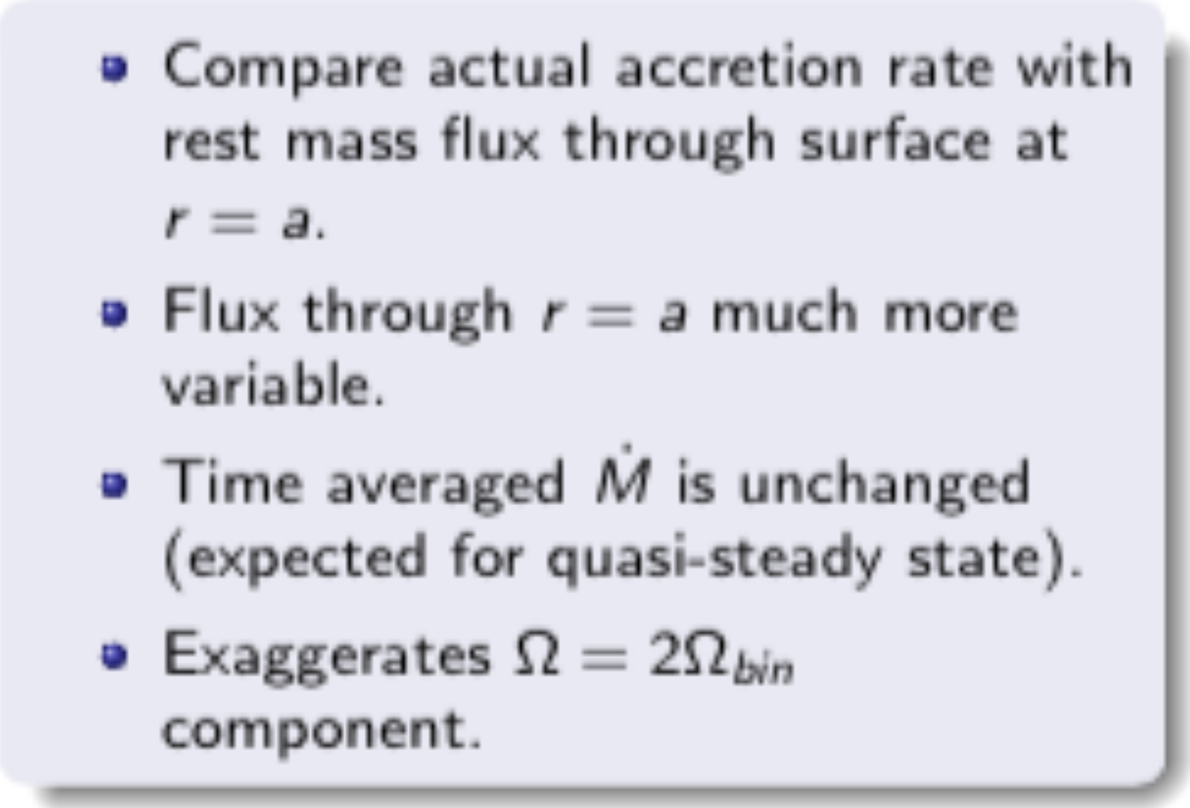


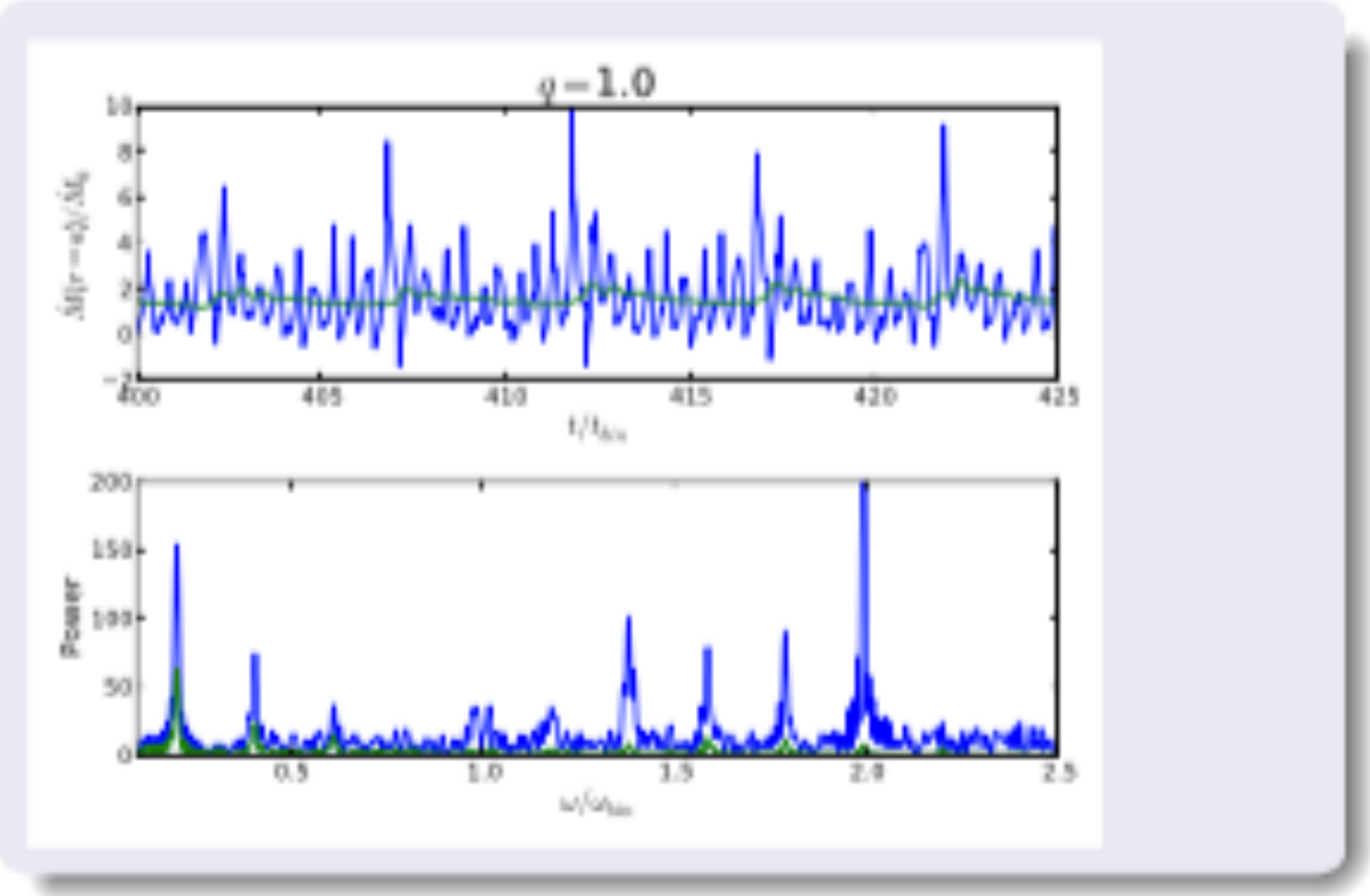
Farris+ (2013)

Observed Period may be LOWER than binary period

Mini-disks damp accretion variability



- Compare actual accretion rate with rest mass flux through surface at $r = a$.
- Flux through $r = a$ much more variable.
- Time averaged $\dot{M}$ is unchanged (expected for quasi-steady state).
- Exaggerates $\Omega = 2\Omega_{bin}$ component.



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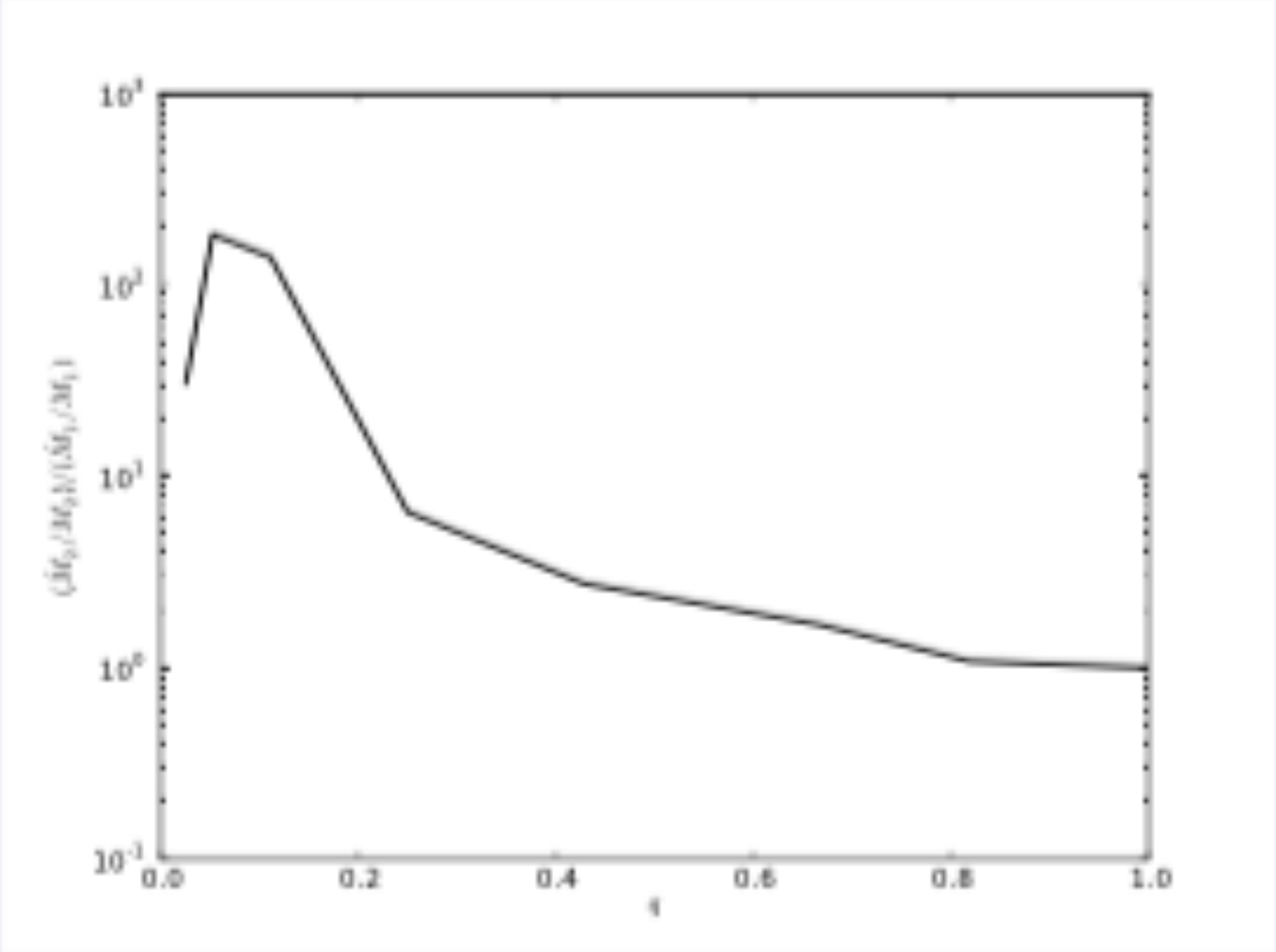
Binaries Driven toward Equal Mass

$$\frac{dq}{dt} = \frac{d}{dt}\left(\frac{M_2}{M_1}\right) = \frac{M_2}{M_1}\left(\frac{\dot{M}_2}{M_2} - \frac{\dot{M}_1}{M_1}\right)$$

$$\dot{M}_2/M_2 > \dot{M}_1/M_1 \Rightarrow q \text{ increasing}$$

- Ratio > 1 for all cases. Binary driven toward equal mass.
- Consistent with previous studies (Hayasaki et al. 2007, Cuadra et al. 2009, Roedig et al. 2011,2012, Hayasaki et al. 2012)
- Possible that ratio < 1 for q less than some q_0, leading to bimodal mass-ratio distribution.



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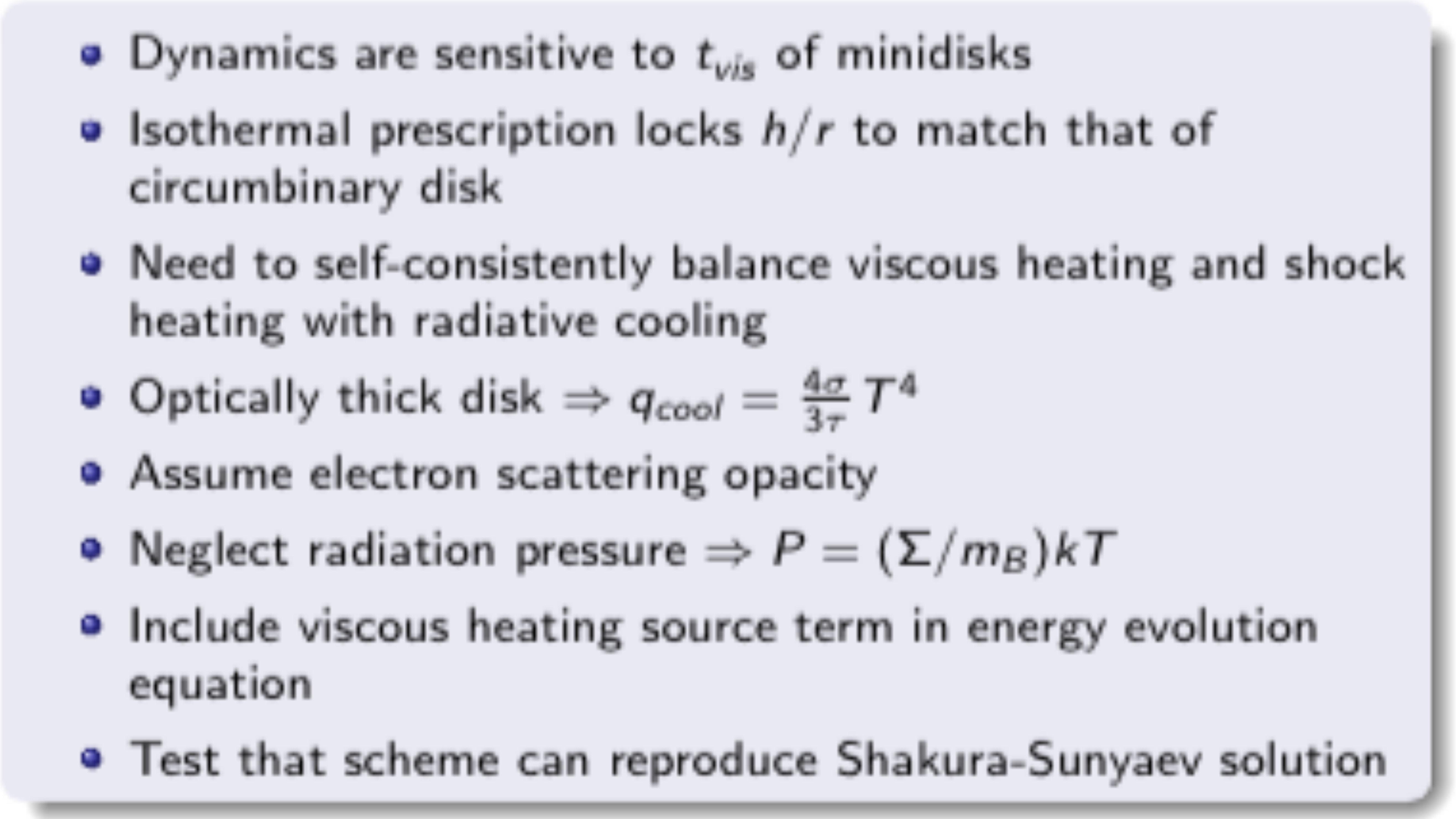
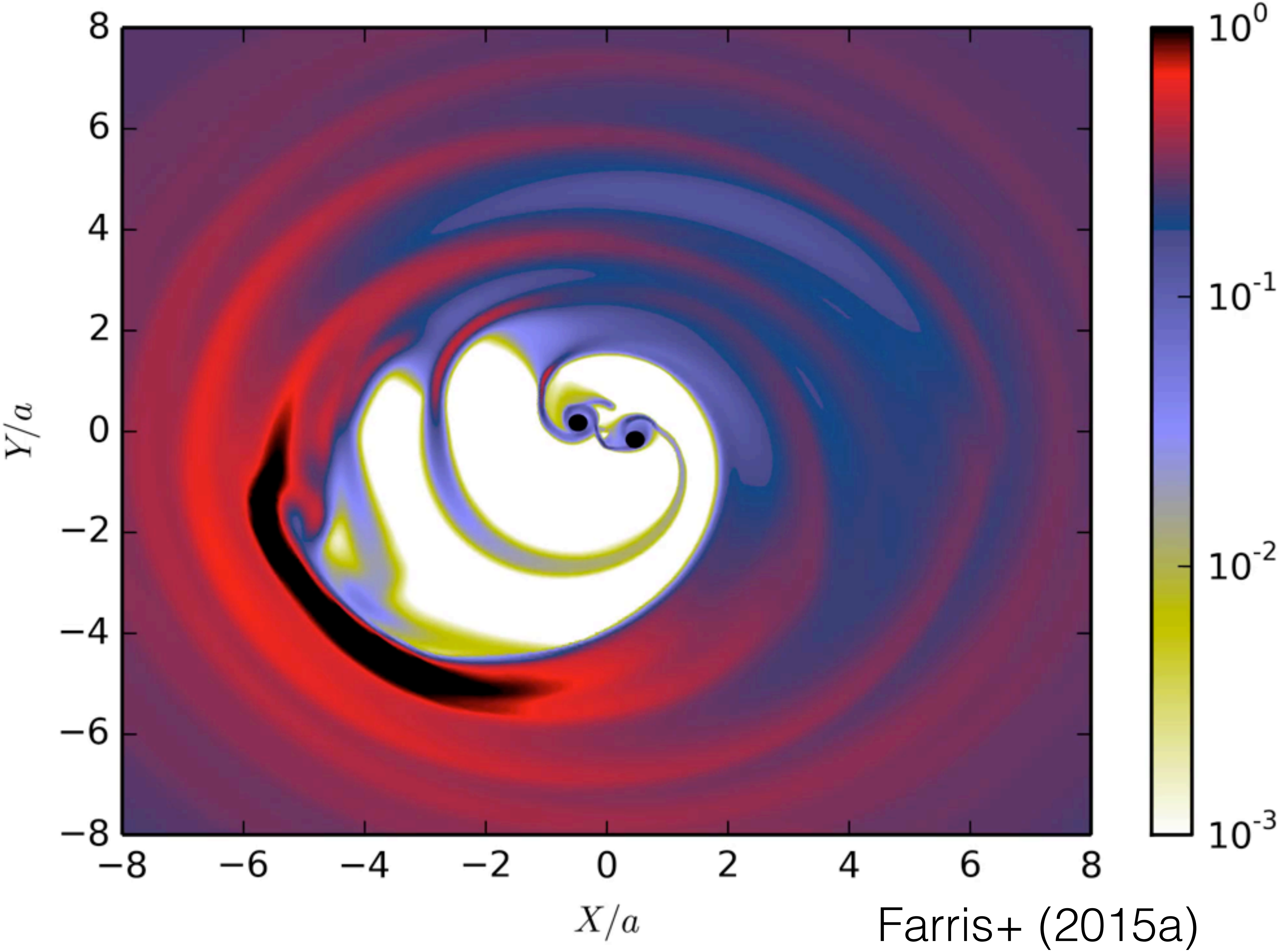
Radiative Cooling



- Dynamics are sensitive to t_{vis} of minidisks
- Isothermal prescription locks h/r to match that of circumbinary disk
- Need to self-consistently balance viscous heating and shock heating with radiative cooling
- Optically thick disk $\Rightarrow q_{cool} = \frac{4\sigma}{3\tau} T^4$
- Assume electron scattering opacity
- Neglect radiation pressure $\Rightarrow P = (\Sigma/m_B)kT$
- Include viscous heating source term in energy evolution equation
- Test that scheme can reproduce Shakura-Sunyaev solution

Farris+ (2015a)



Farris+ (2015a)

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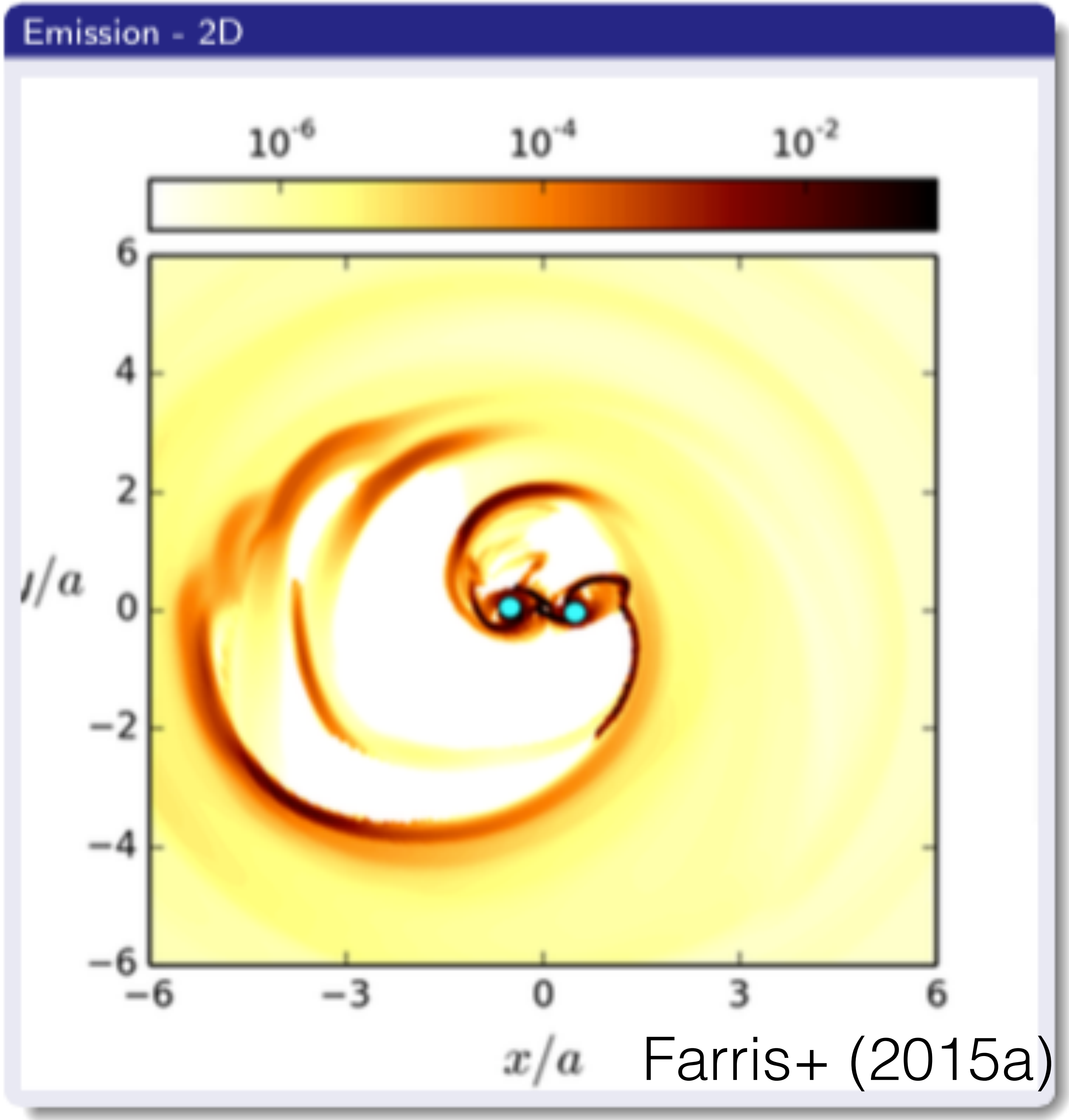
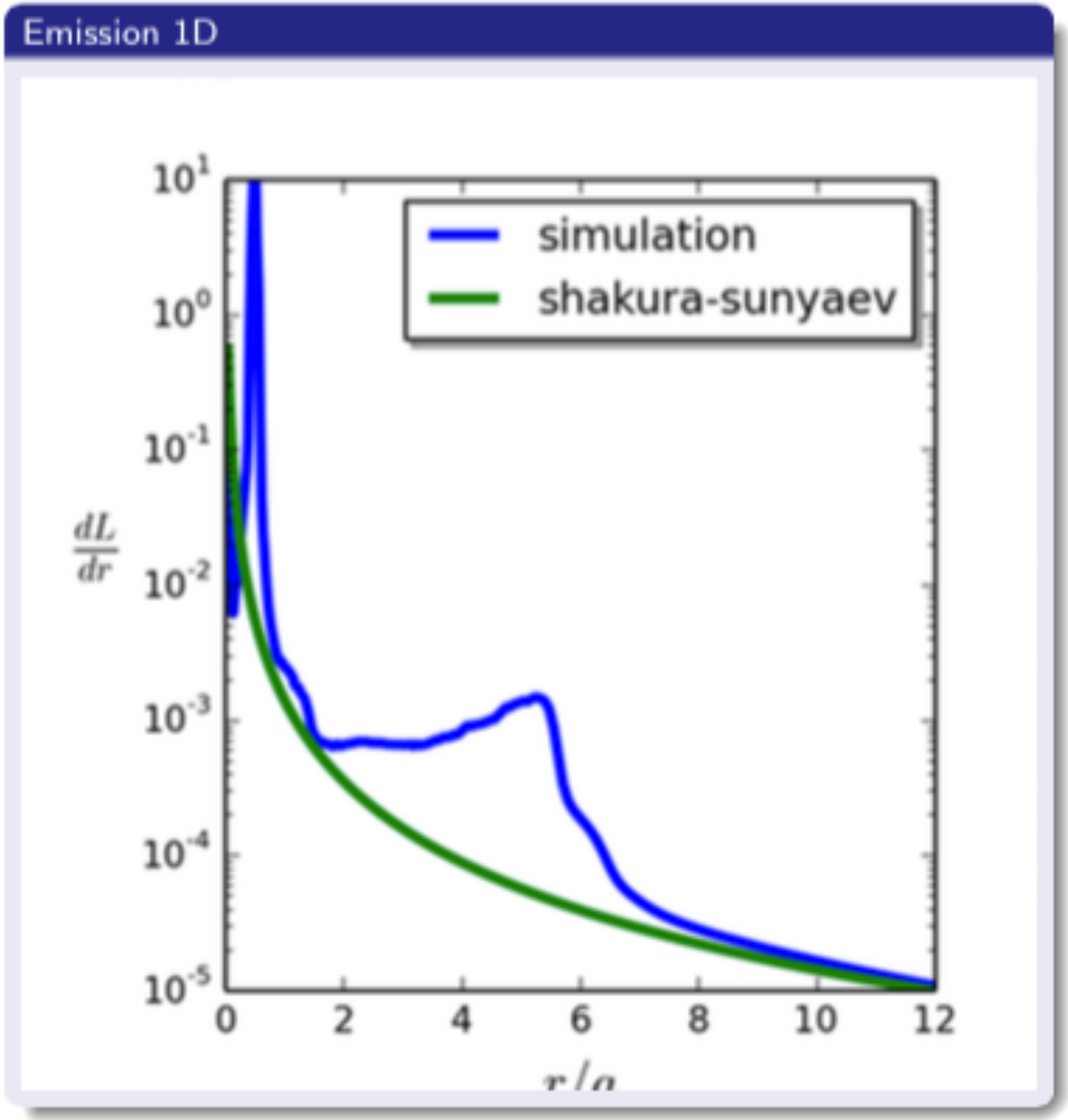


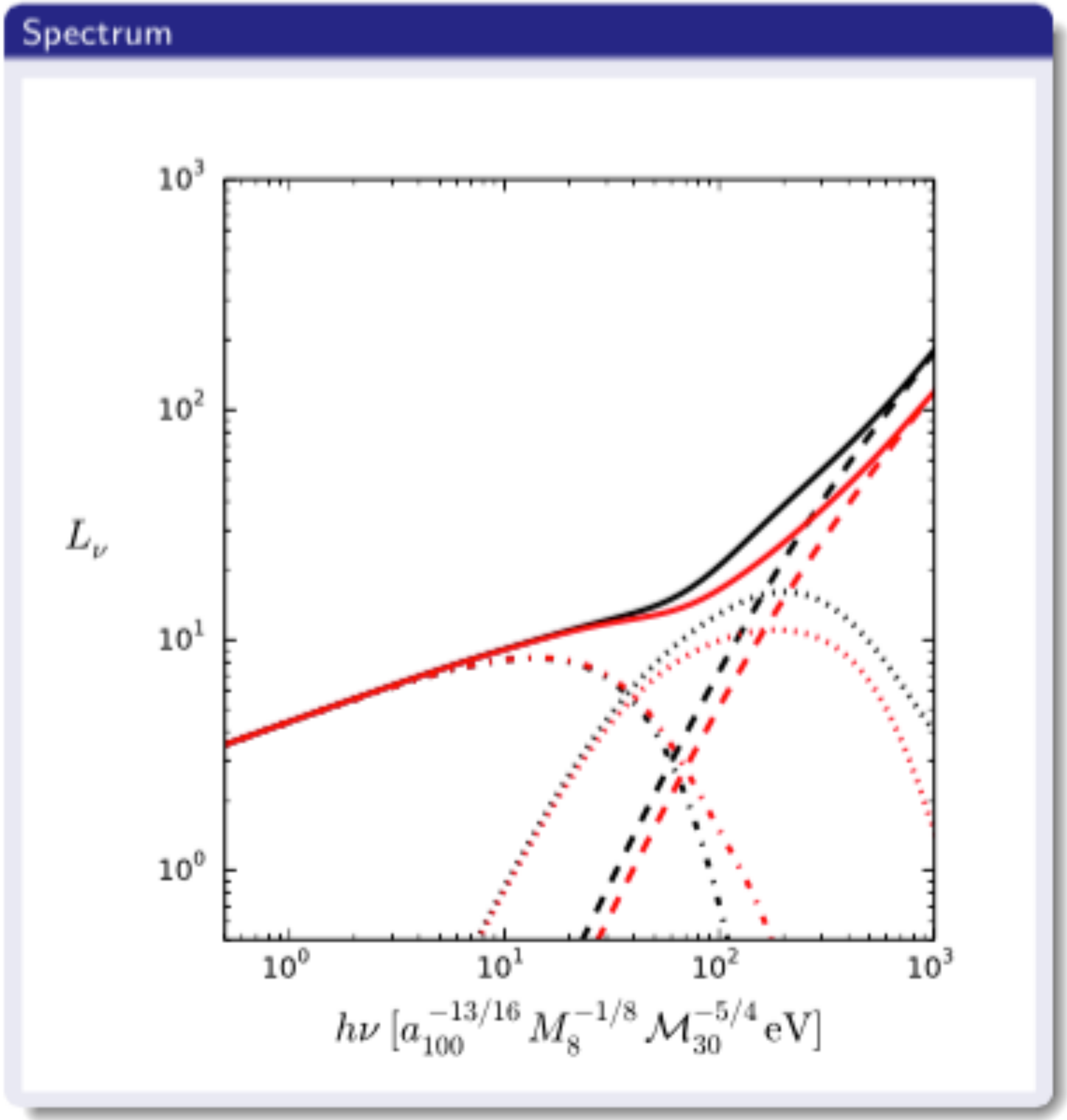
Emission - 2D

Farris+ (2015a)



Emission 1D

Farris+ (2015)



Spectrum

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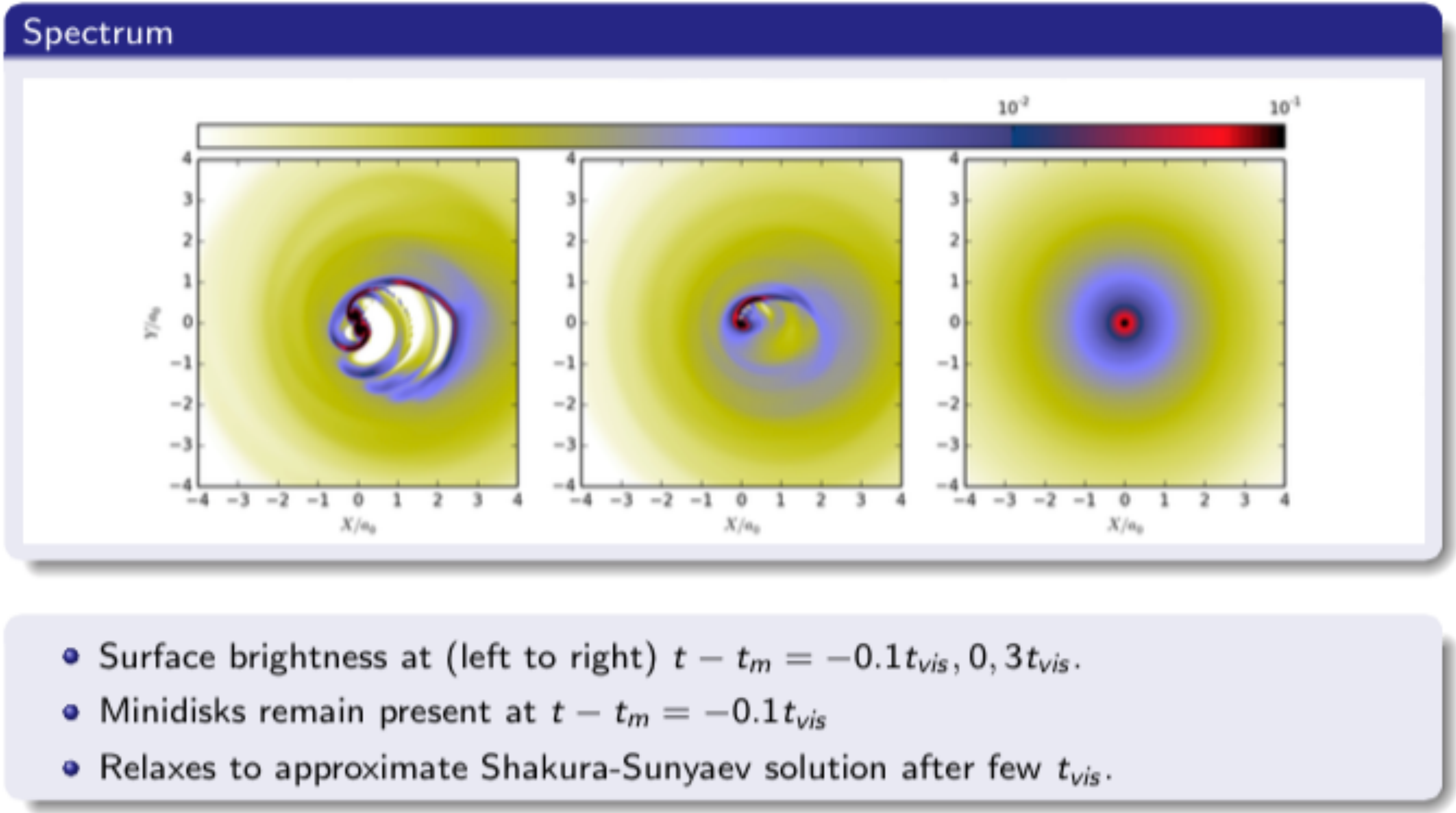
Decoupling



Spectrum

- Surface brightness at (left to right) $t - t_m = -0.1t_{vis}, 0, 3t_{vis}$.
- Minidisks remain present at $t - t_m = -0.1t_{vis}$
- Relaxes to approximate Shakura-Sunyaev solution after few t_{vis}.

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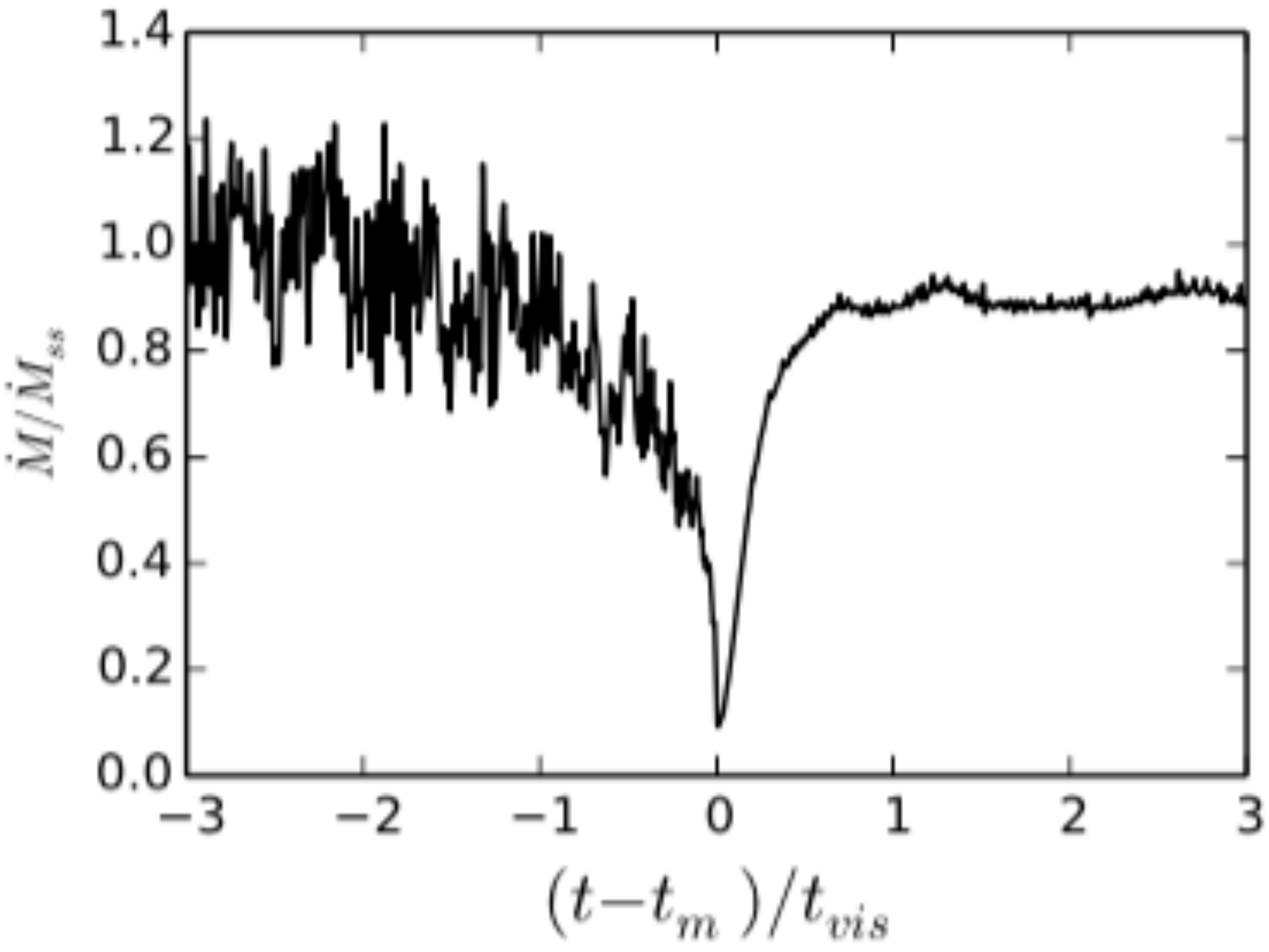
Accretion Rate



- Significant accretion remains at $t - t_m = -t_{vis}$.
- Much more variable prior to merger.
- Returns to $\approx$ Shakura-Sunyaev rate on viscous timescale, as expected.

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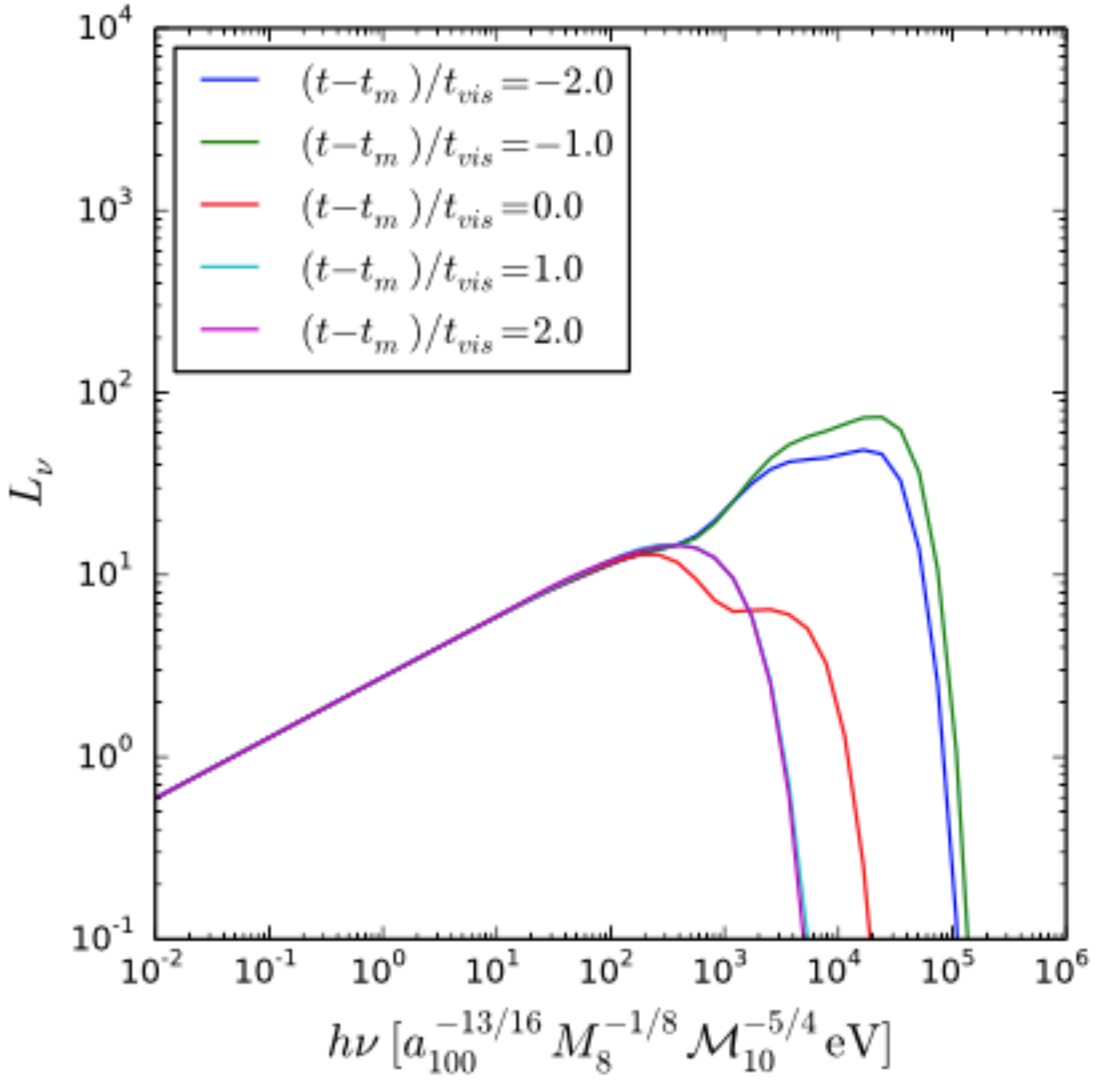
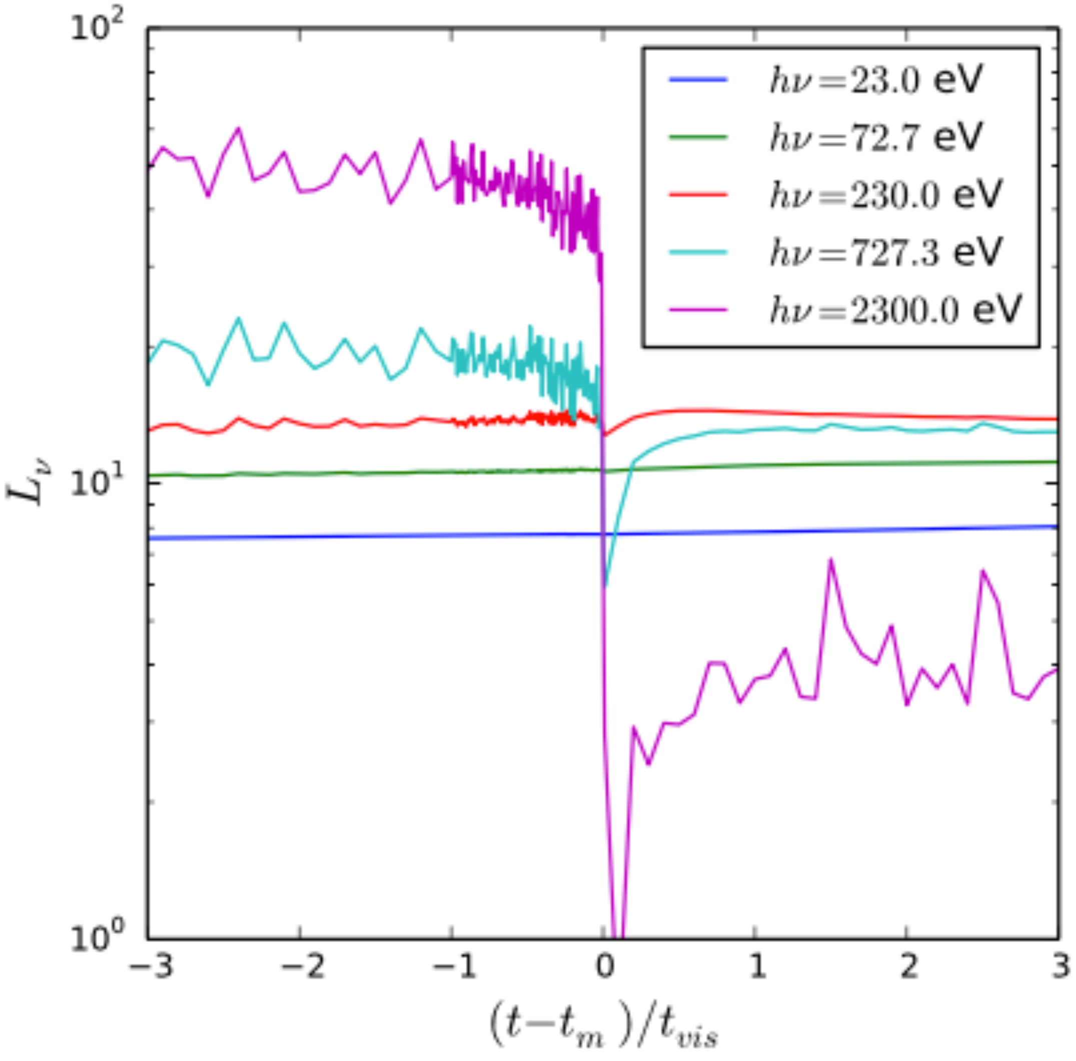
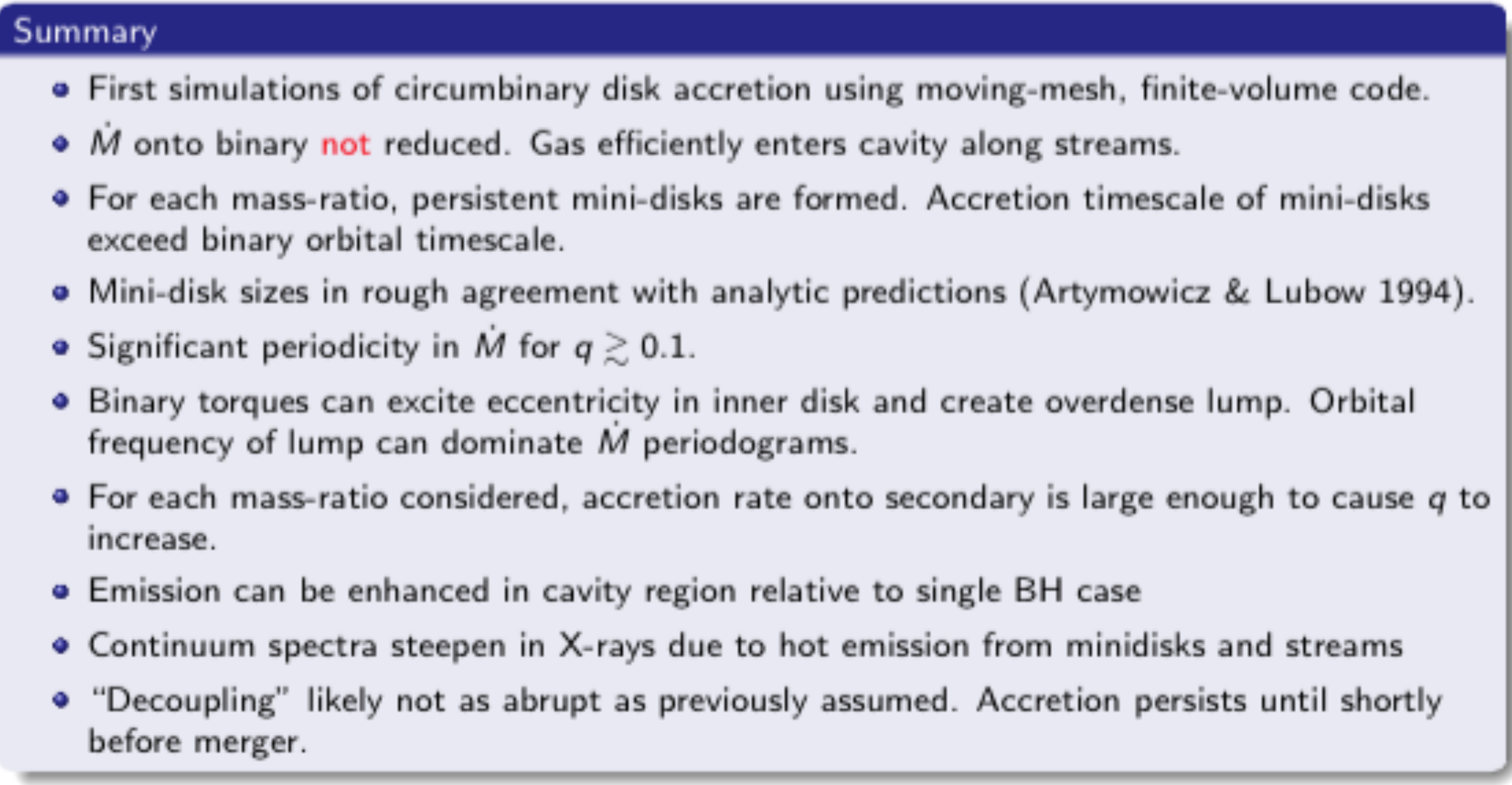




Farris+ ArXiv:1409.5124



Summary

- First simulations of circumbinary disk accretion using moving-mesh, finite-volume code.
- $\dot{M}$ onto binary not reduced. Gas efficiently enters cavity along streams.
- For each mass-ratio, persistent mini-disks are formed. Accretion timescale of mini-disks exceed binary orbital timescale.
- Mini-disk sizes in rough agreement with analytic predictions (Artymowicz & Lubow 1994).
- Significant periodicity in $\dot{M}$ for $q \gtrsim 0.1$.
- Binary torques can excite eccentricity in inner disk and create overdense lump. Orbital frequency of lump can dominate $\dot{M}$ periodograms.
- For each mass-ratio considered, accretion rate onto secondary is large enough to cause q to increase.
- Emission can be enhanced in cavity region relative to single BH case
- Continuum spectra steepen in X-rays due to hot emission from minidisks and streams
- "Decoupling" likely not as abrupt as previously assumed. Accretion persists until shortly before merger.

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