Massive Black Hole Binaries in Viscous Disks: Dynamics and Signatures

Andrew MacFadyen (NYU)

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Merging Visions: Exploring Compact-Object Binaries with Gravity and Light 6/27/19 KITP

- Supermassive Black Hole Binaries:

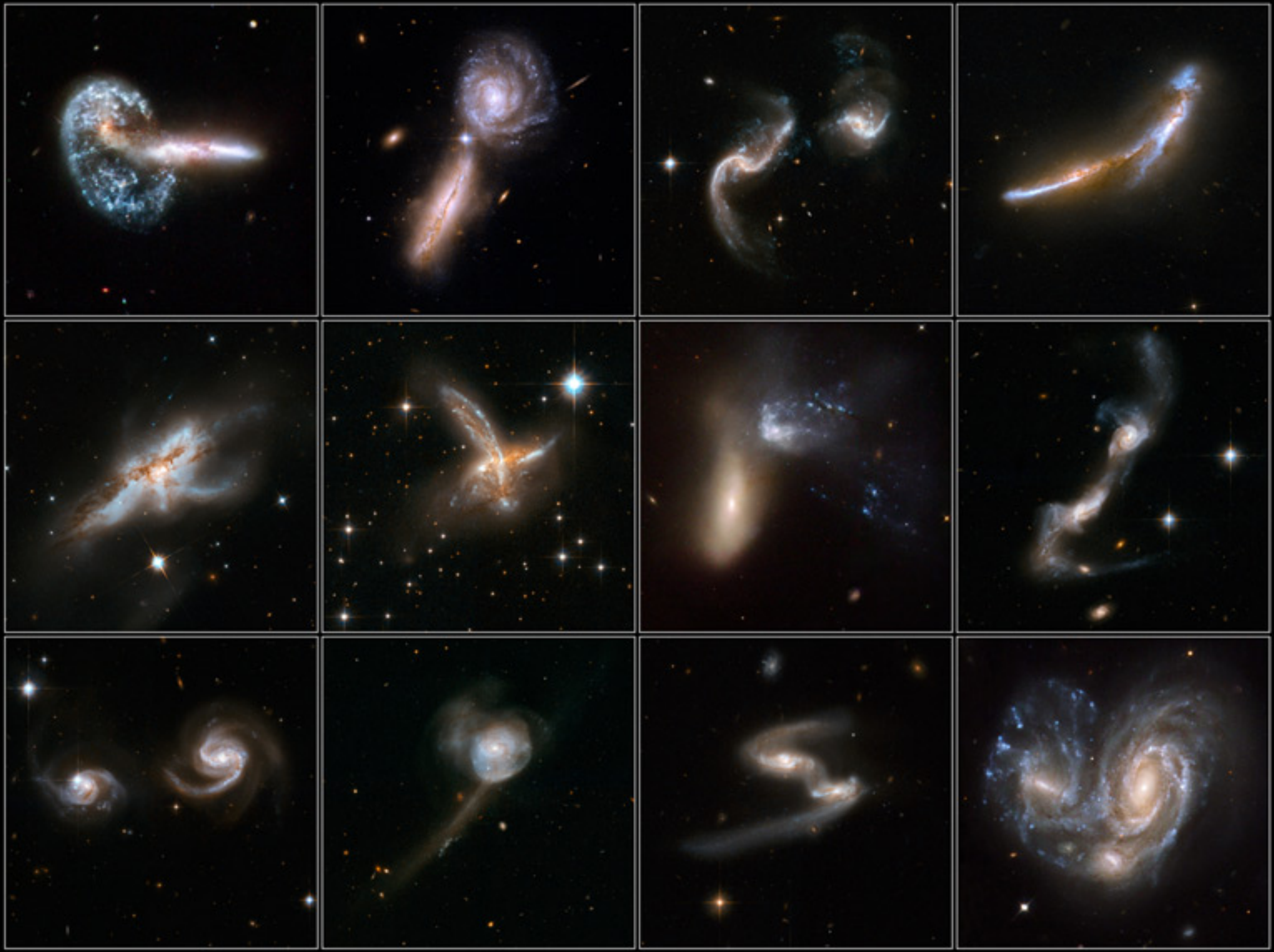
  LISA/PTA sources

- Stellar Mass Binaries in Gas
  e.g. AGN disk, triples:

  LIGO/Virgo sources

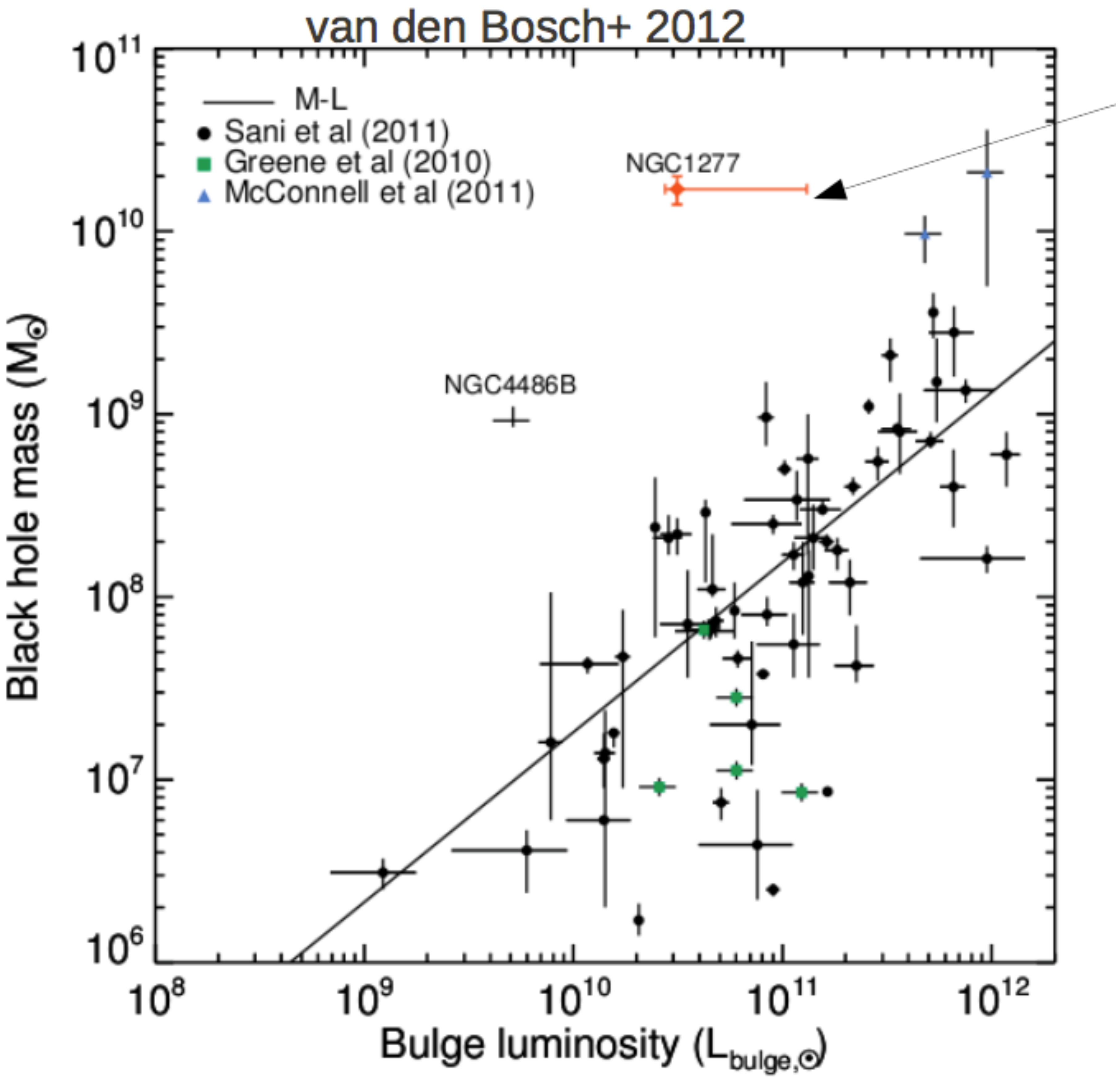
Interacting Galaxies

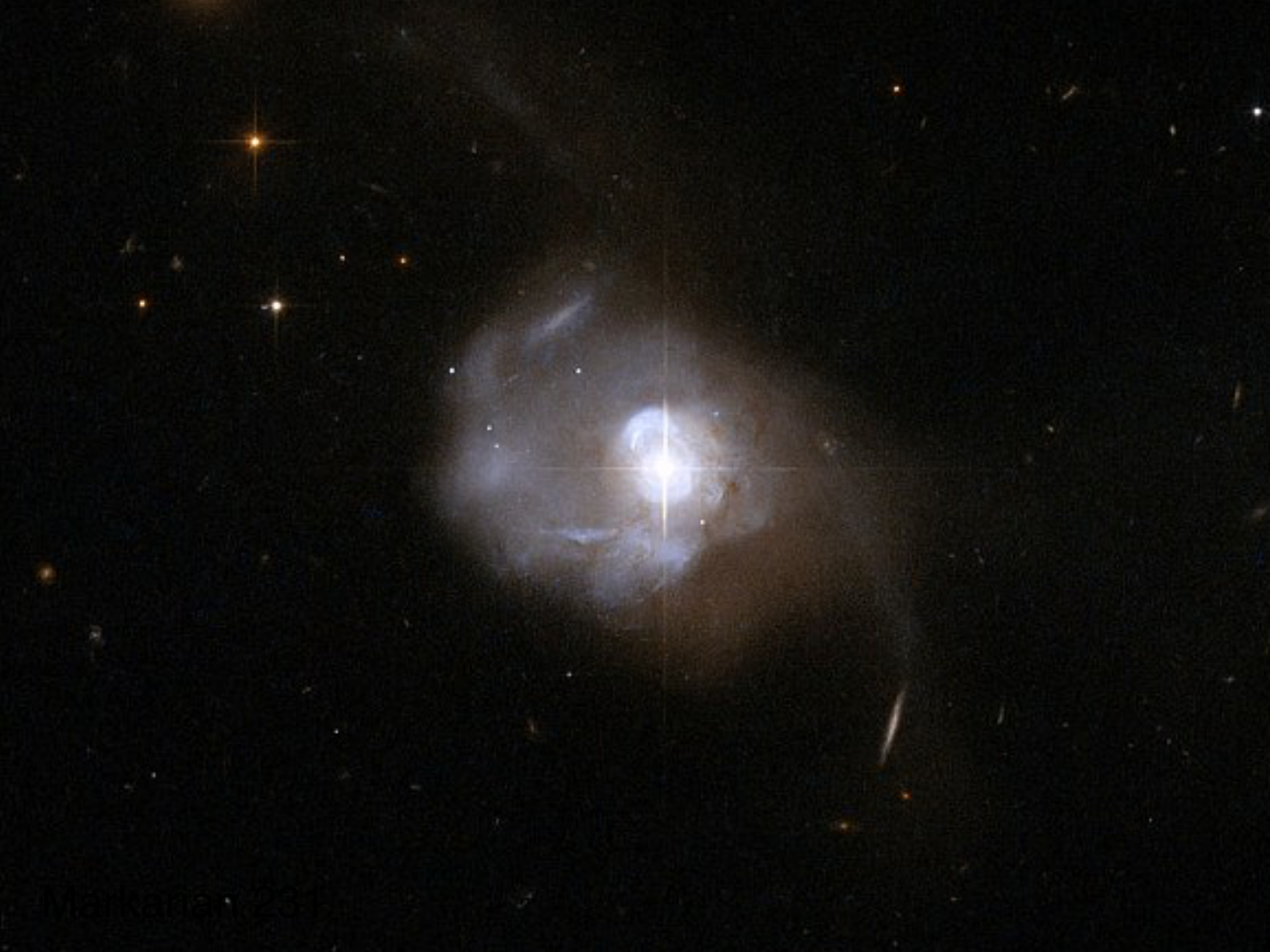
Hubble Space Telescope • ACS/WFC • WFPC2



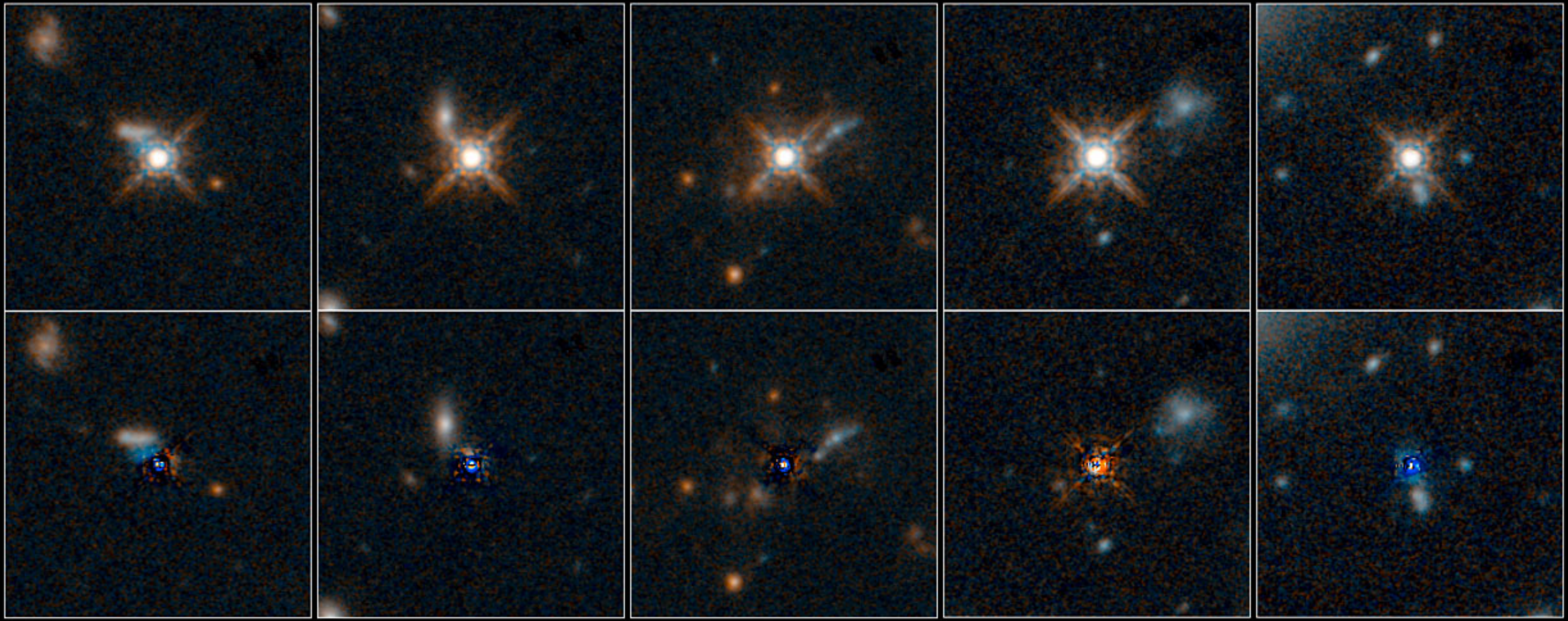
NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a


van den Bosch+ 2012
M-L
● Sani et al (2011)
🟩 Greene et al (2010)
▲ McConnell et al (2011)
NGC1277
NGC4486B
Black hole mass ($M_\odot$)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
Bulge luminosity ($L_{bulge,\odot}$)



Markarian 231



Quasars in Interacting Galaxies

Hubble Space Telescope ▪ WFC3/IR

NASA and ESA

STScI-PRC15-20a

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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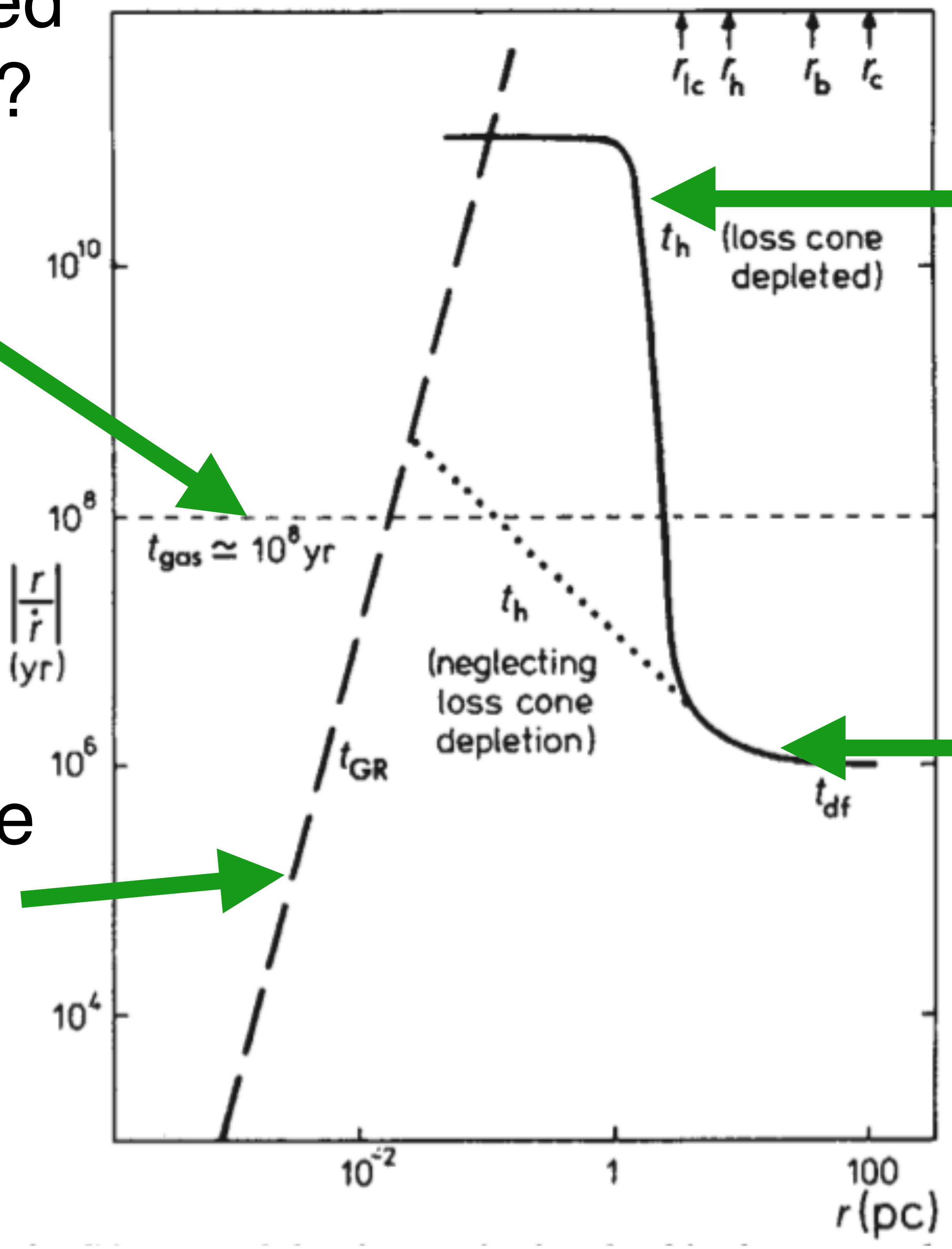
Final parsec problem

No mergers? Need migration in gas?

t_gas = 1e8 yr

Gravitational wave emission



Loss cone depletion

Dynamical friction

Begelman, Blandford & Rees (1980)

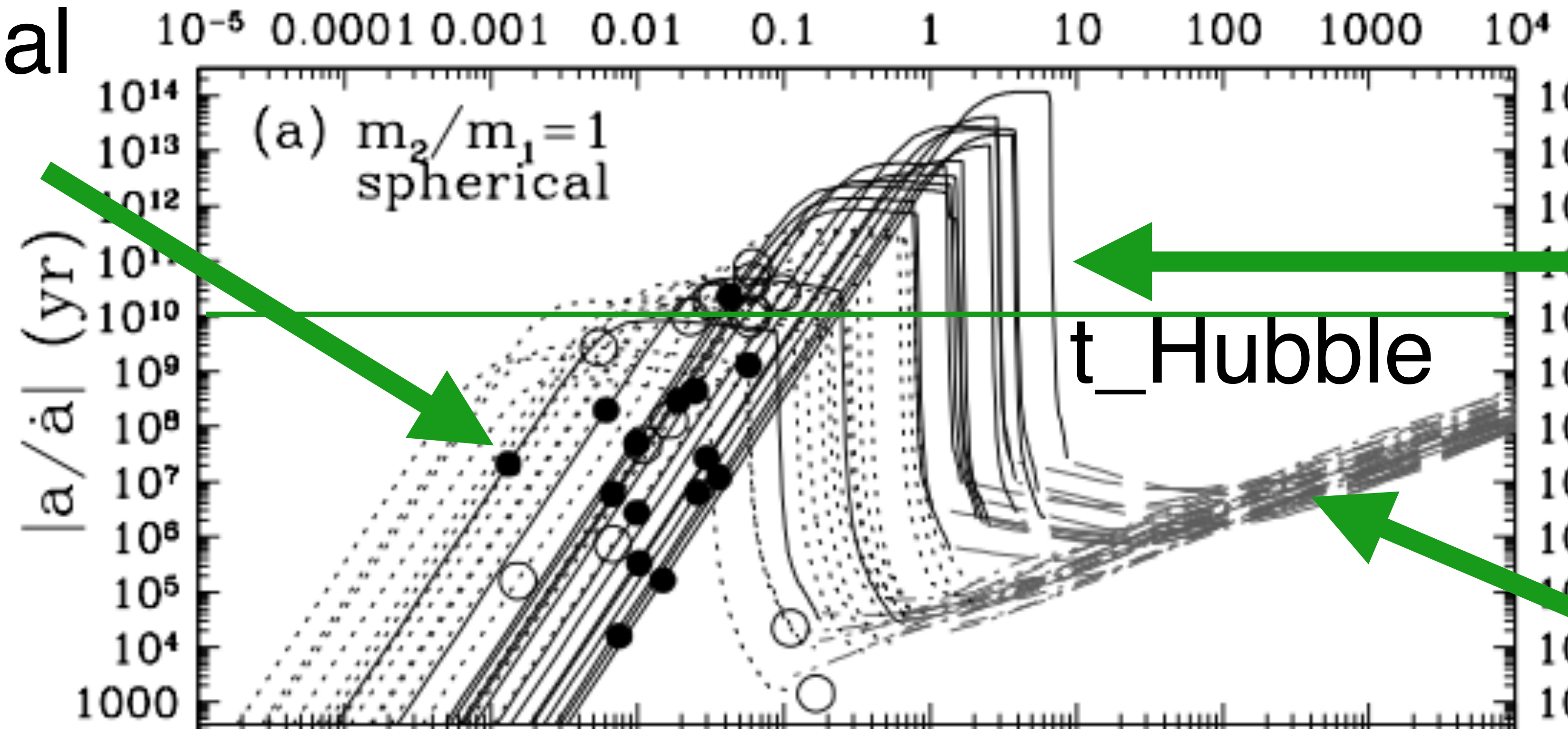
Final parsec problem

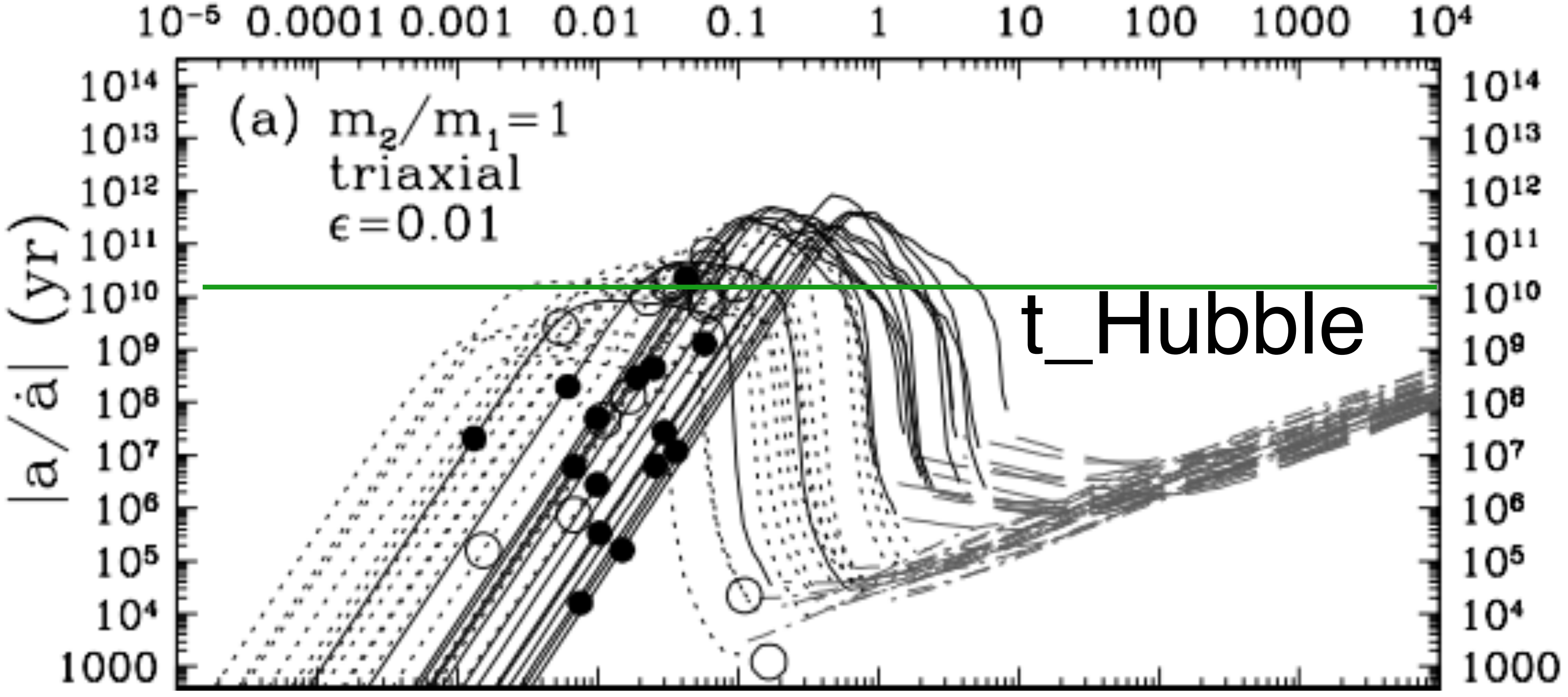
No mergers or need gas!

Gravitational wave emission

Loss cone depletion

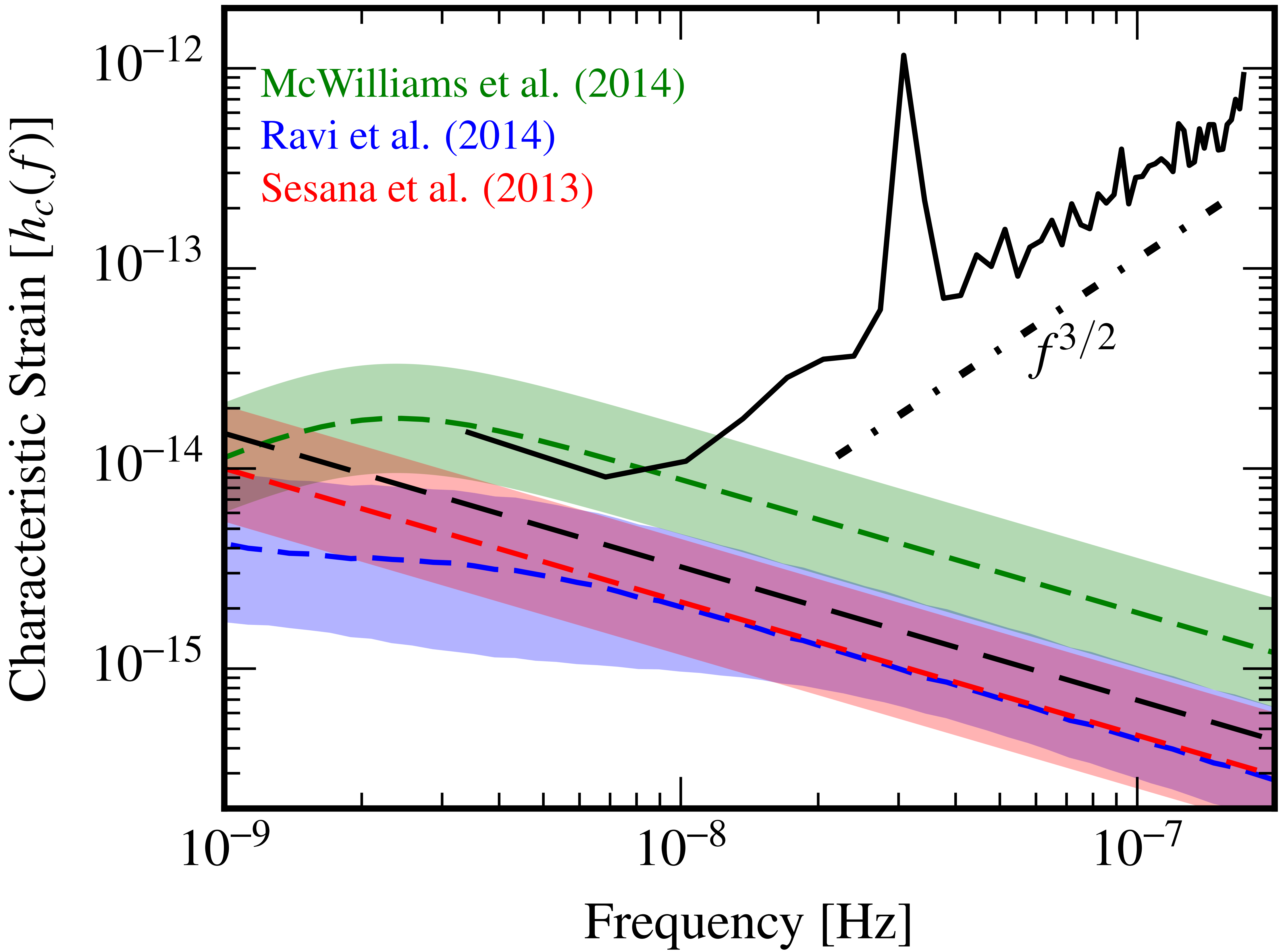
Dynamical friction



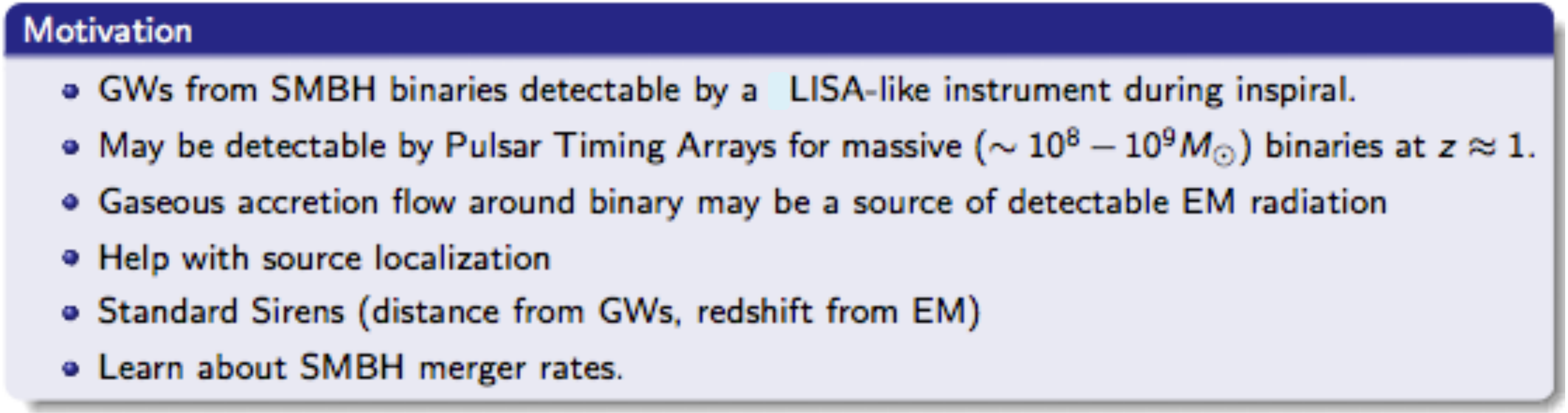


Triaxiality of stellar distribution can help Yu (2002)

No GW detection by nanograv PTAs in 9 years of data



nanograv collaboration - Arzoumanian++ (2015)



Motivation

- GWs from SMBH binaries detectable by a LISA-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.

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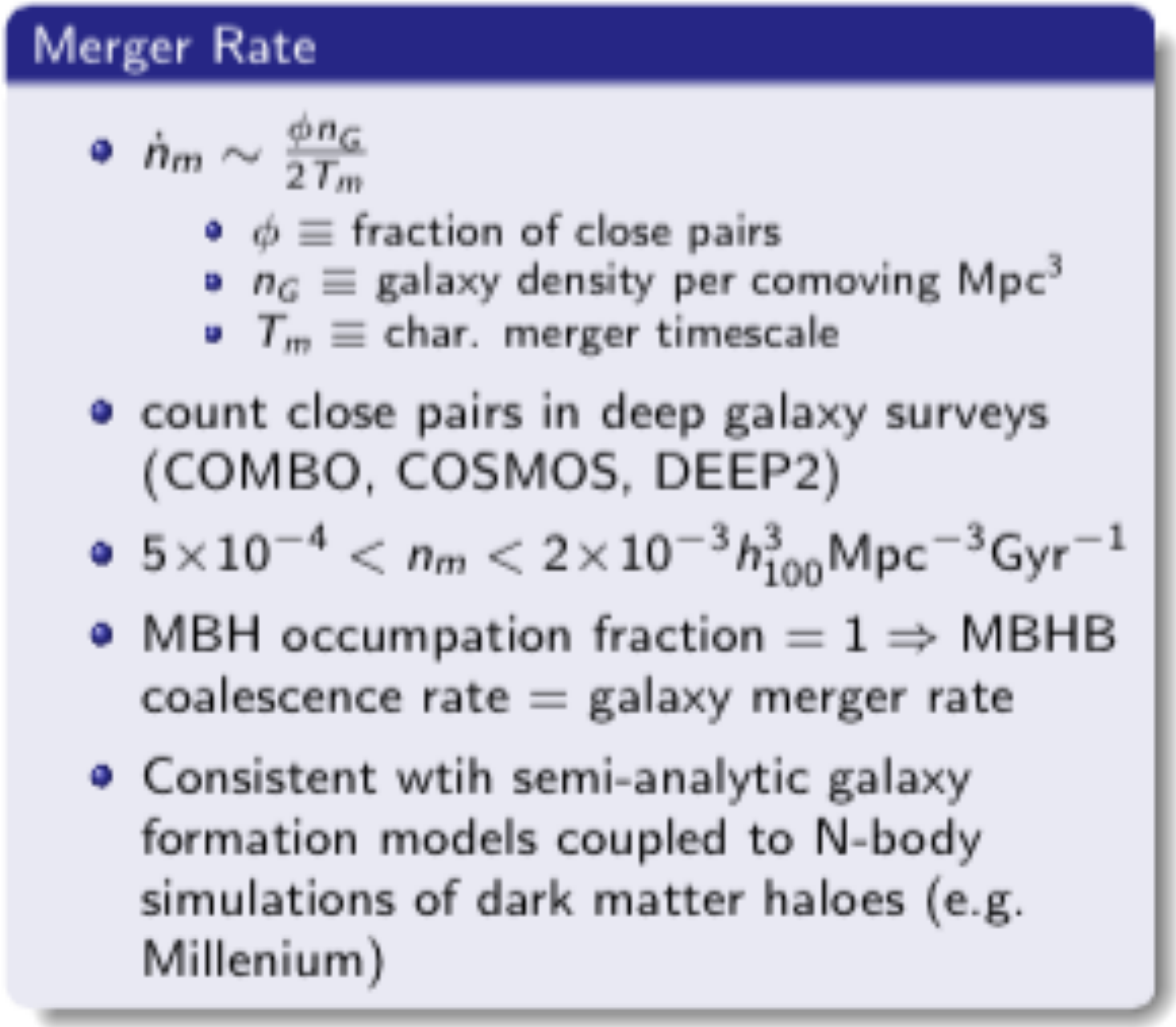
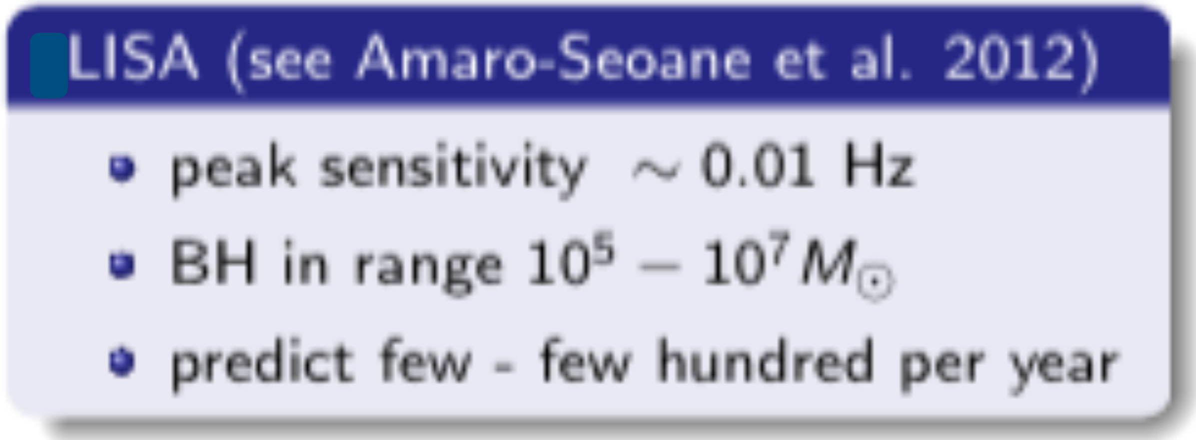


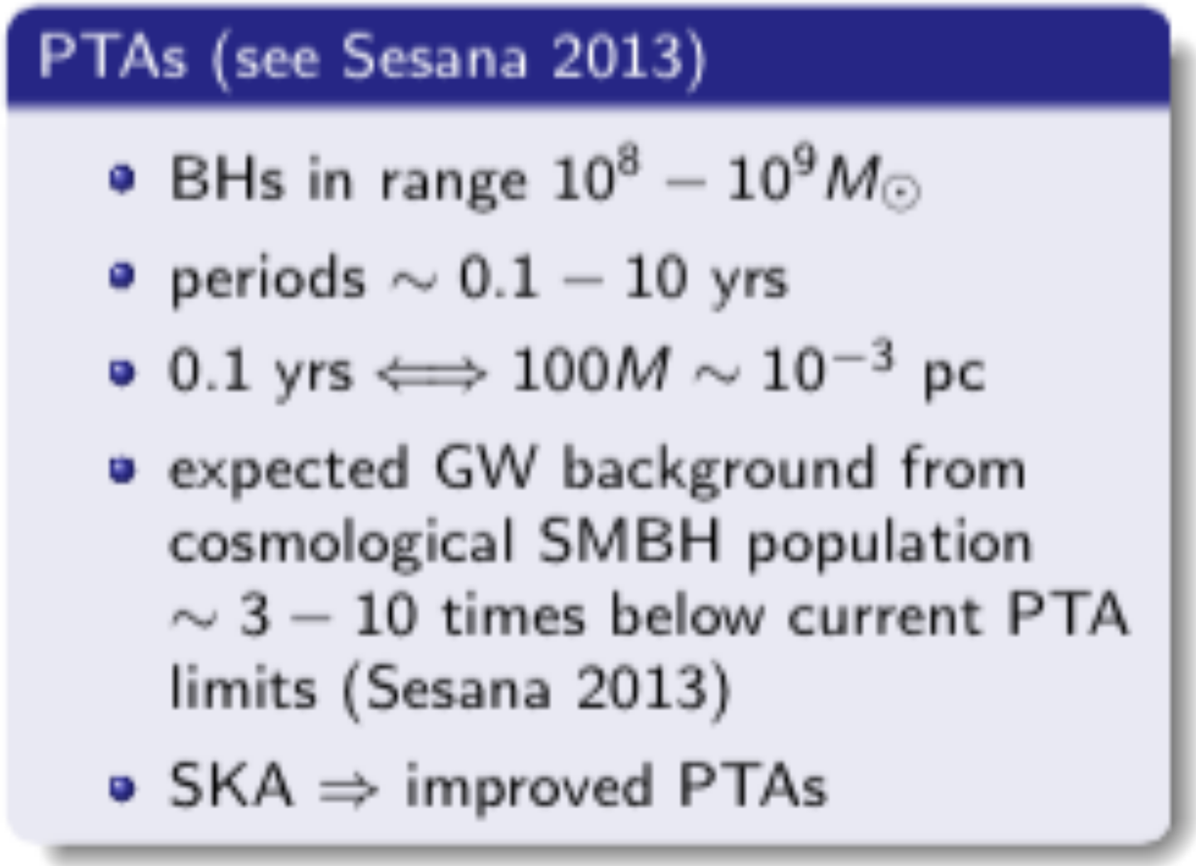
Merger Rate

- $\dot{n}_m \sim \frac{\phi n_G}{2T_m}$
  - $\phi \equiv$ fraction of close pairs
  - $n_G \equiv$ galaxy density per comoving Mpc^3
  - $T_m \equiv$ char. merger timescale
- count close pairs in deep galaxy surveys (COMBO, COSMOS, DEEP2)
- $5 \times 10^{-4} < n_m < 2 \times 10^{-3} h_{100}^3 \mathrm{Mpc}^{-3} \mathrm{Gyr}^{-1}$
- MBH occupation fraction $= 1 \Rightarrow$ MBHB coalescence rate $=$ galaxy merger rate
- Consistent wtih semi-analytic galaxy formation models coupled to N-body simulations of dark matter haloes (e.g. Millenium)



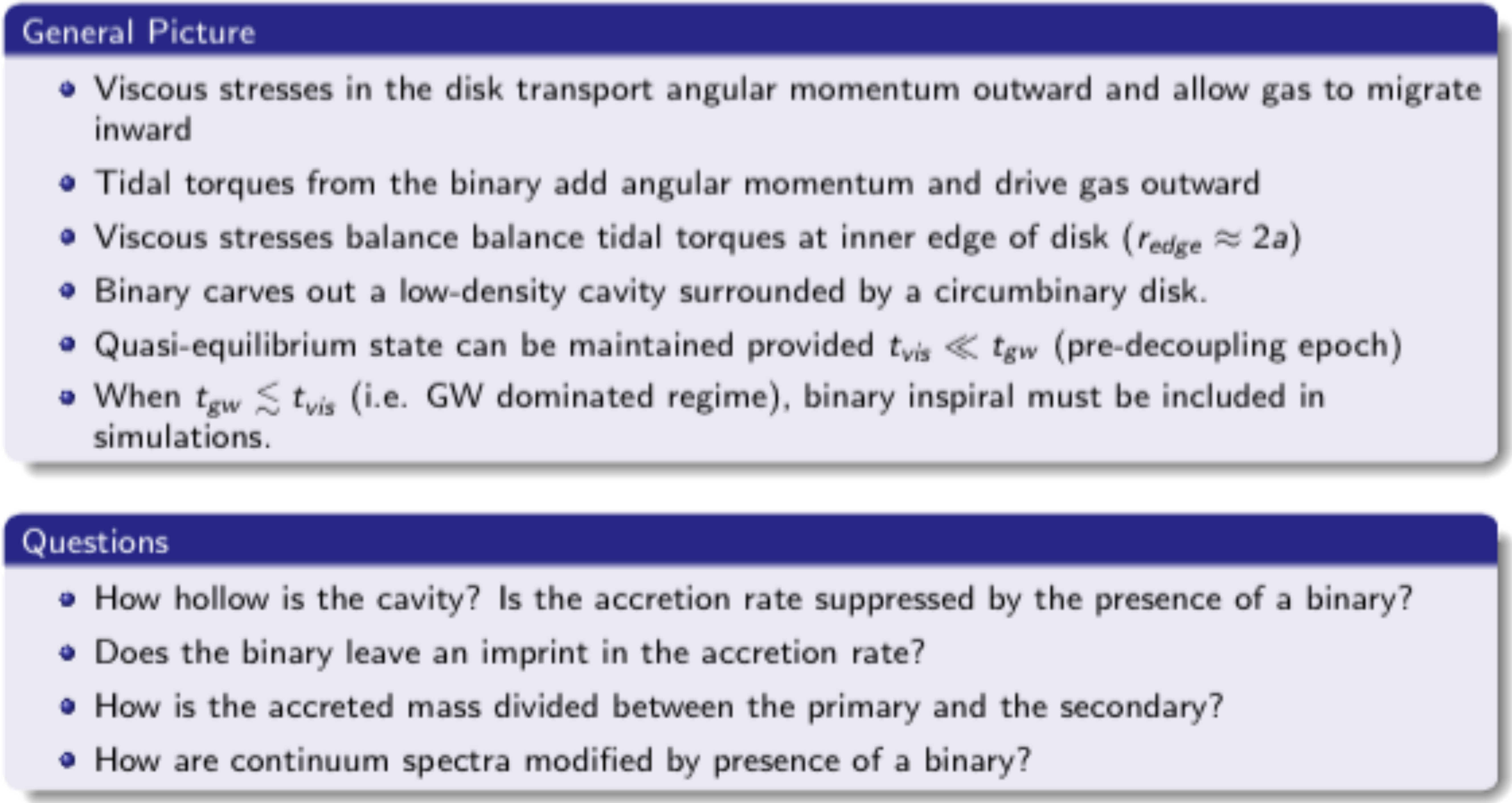
LISA (see Amaro-Seoane et al. 2012)

- peak sensitivity ~ 0.01 Hz
- BH in range $10^5 - 10^7 M_\odot$
- predict few - few hundred per year



PTAs (see Sesana 2013)

- BHs in range $10^8 - 10^9 M_\odot$
- periods $\sim 0.1 - 10$ yrs
- 0.1 yrs $\Longleftrightarrow 100M \sim 10^{-3}$ pc
- expected GW background from cosmological SMBH population $\sim 3 - 10$ times below current PTA limits (Sesana 2013)
- SKA $\Rightarrow$ improved PTAs



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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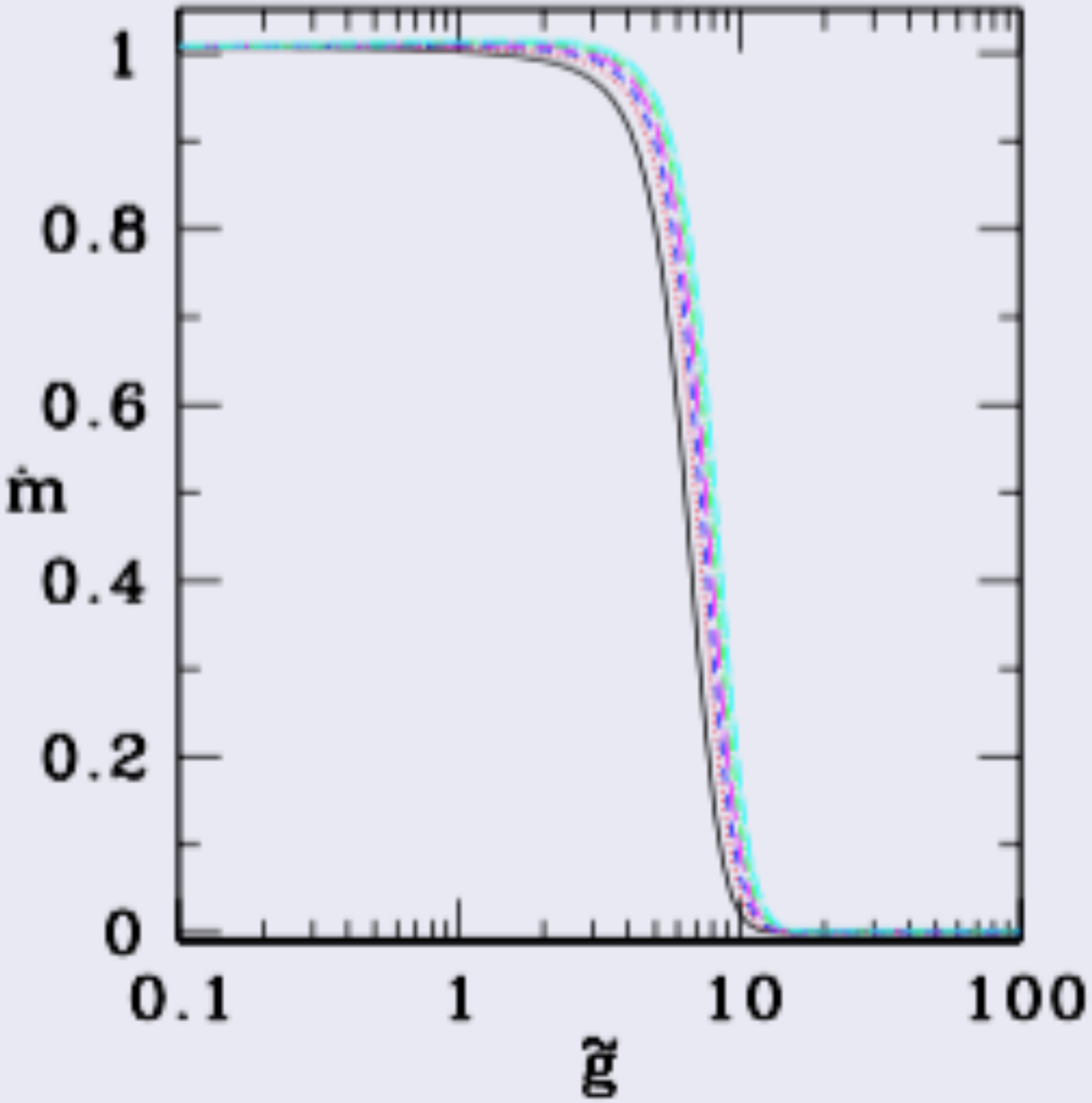
Accretion Choked?

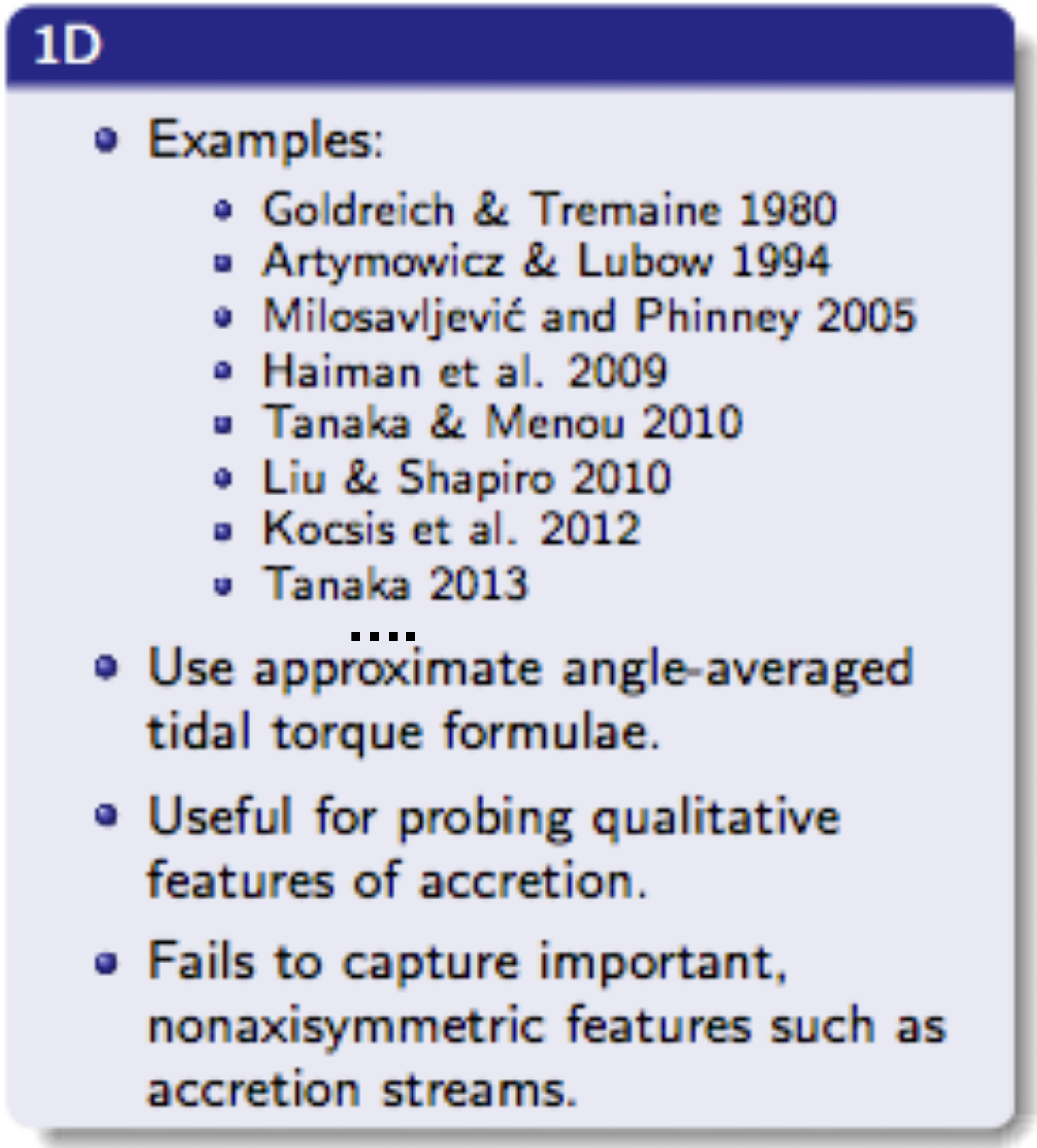
1D model

- 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



Previous Work



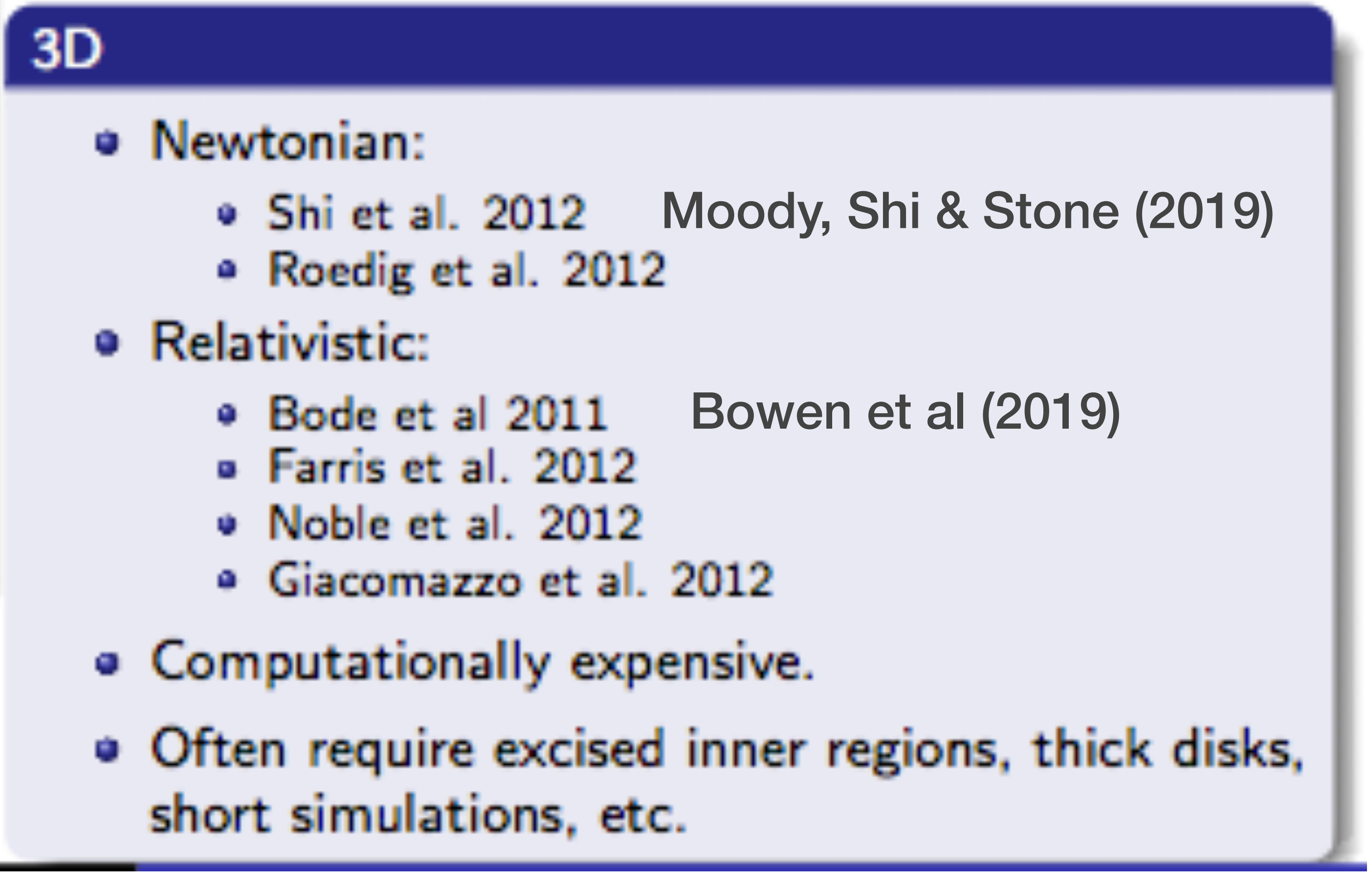
1D

- 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

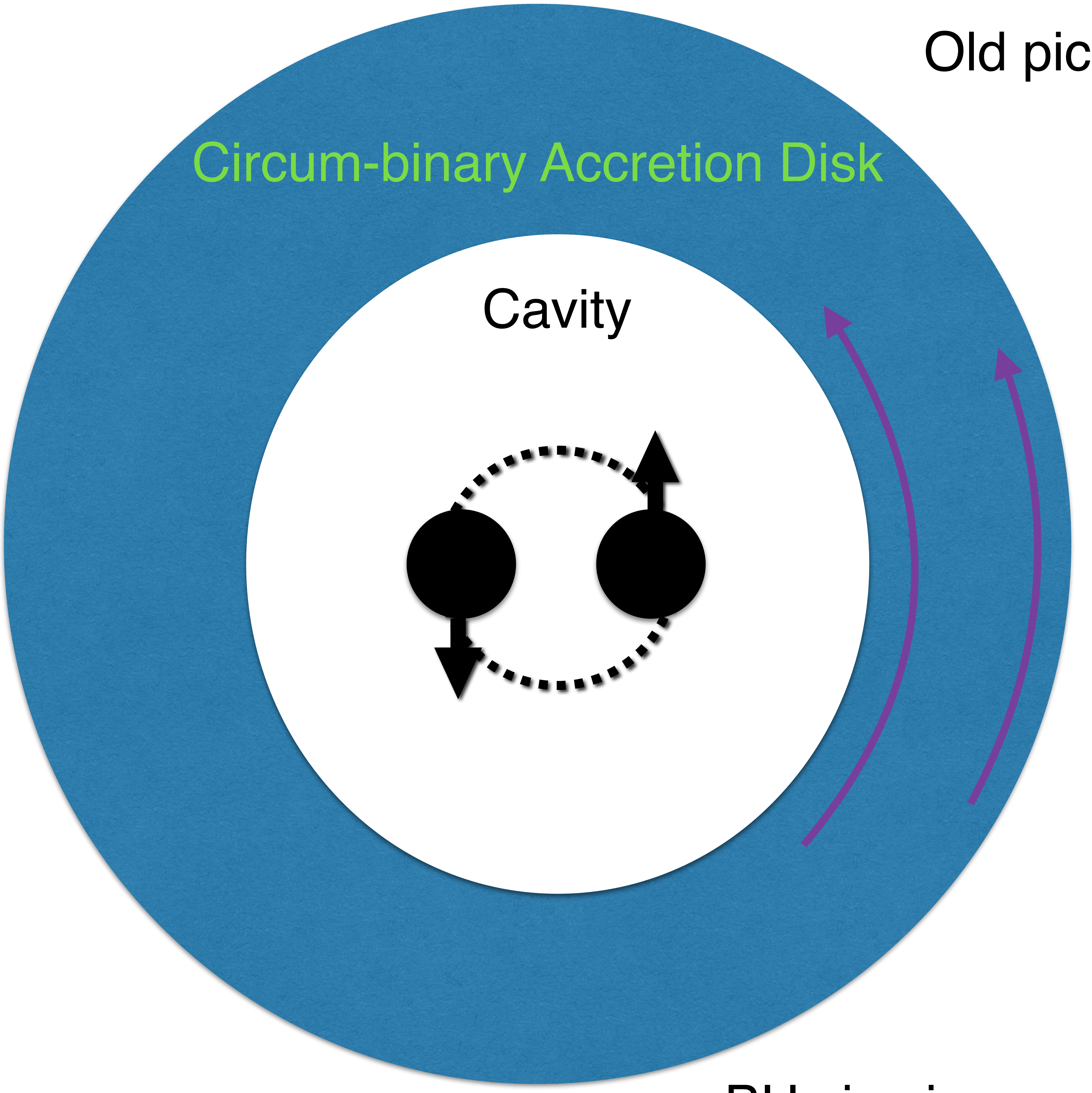
- Newtonian
    - **Armitage & Natarajan 2002**
    - MacFadyen & Milosavljević 2008
    - Cuadra et al. 2009
    - Roedig & Sesana, 2012
    - D'Orazio et al. 2012,Tang, AM & Haiman (2017)
    - Farris et al. 2013,Munoz, Miranda & Lai (2018)
- Useful for predecoupling, widely separated binaries.
- Can accomodate high res., many orbits.



3D

- Newtonian:
    - Shi et al. 2012 Moody, Shi & Stone (2019)
    - Roedig et al. 2012
- Relativistic:
    - Bode et al 2011 Bowen et al (2019)
    - Farris et al. 2012
    - Noble et al. 2012
    - Giacomazzo et al. 2012
- Computationally expensive.
- Often require excised inner regions, thick disks, short simulations, etc.

Old picture



Circum-binary Accretion Disk

Cavity

BH size is exaggerated

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BH size is exaggerated

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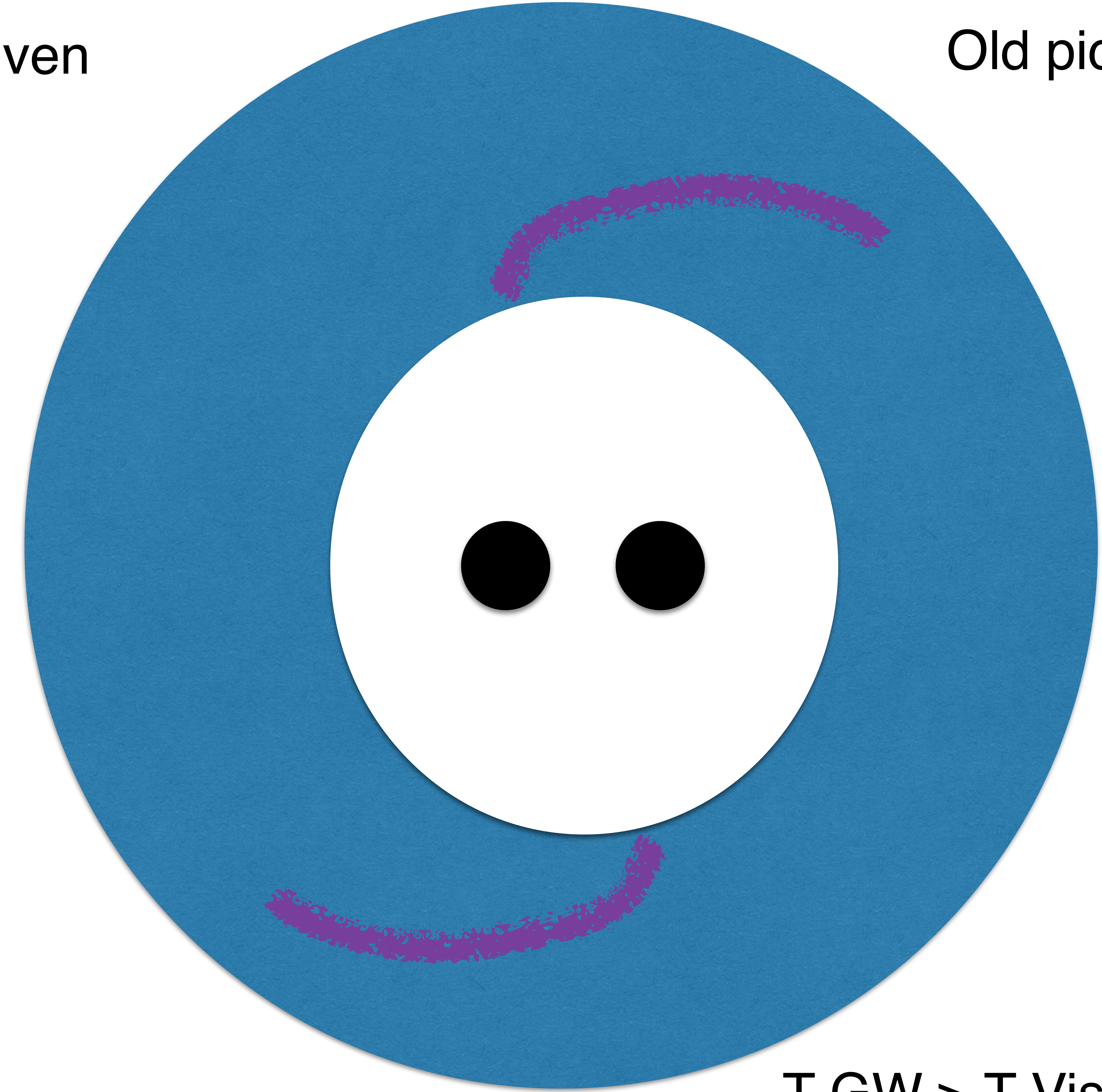
Gas Driven

Old picture



T GW > T Viscous

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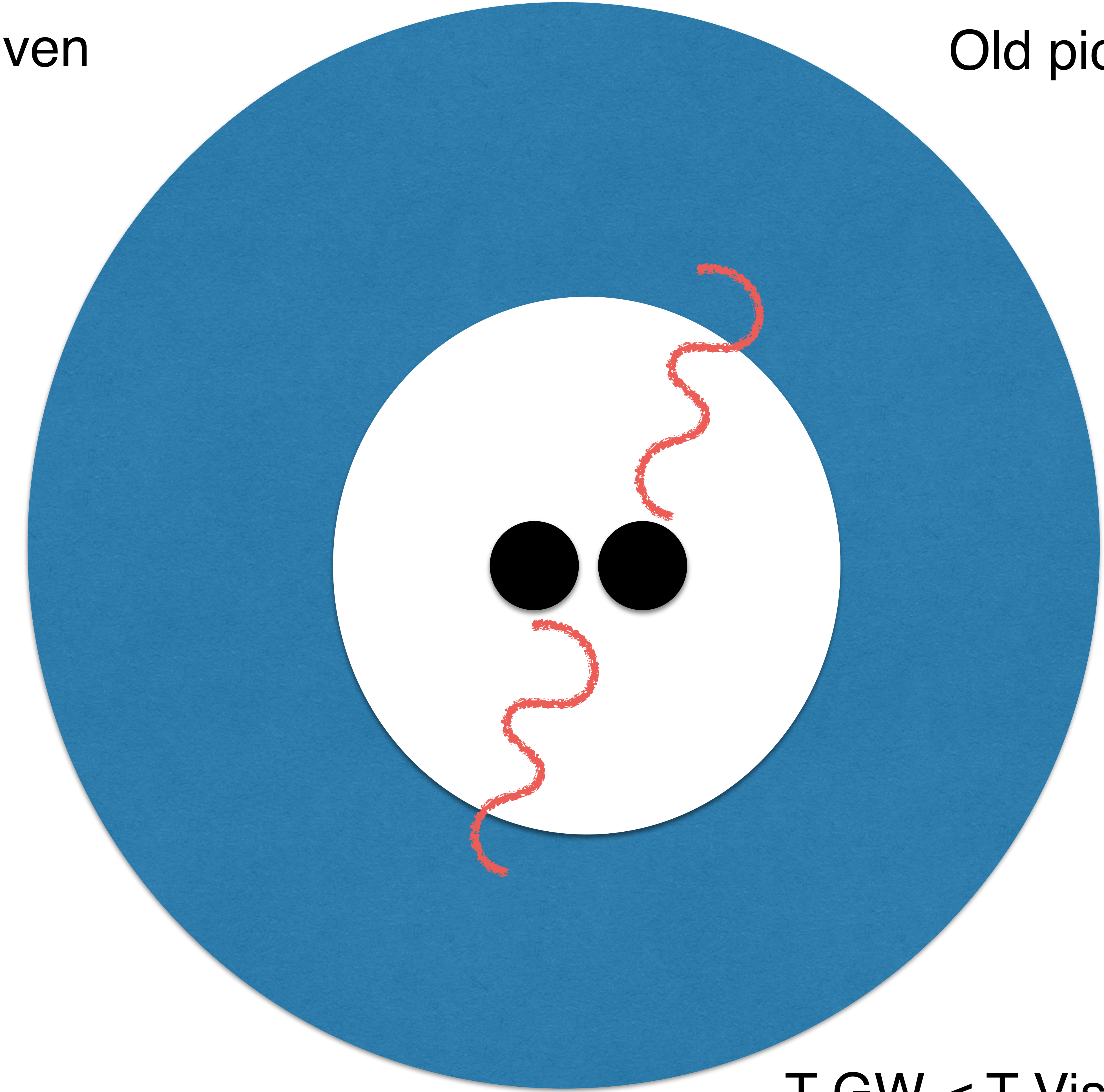
GW Driven

Old picture



T GW < T Viscous

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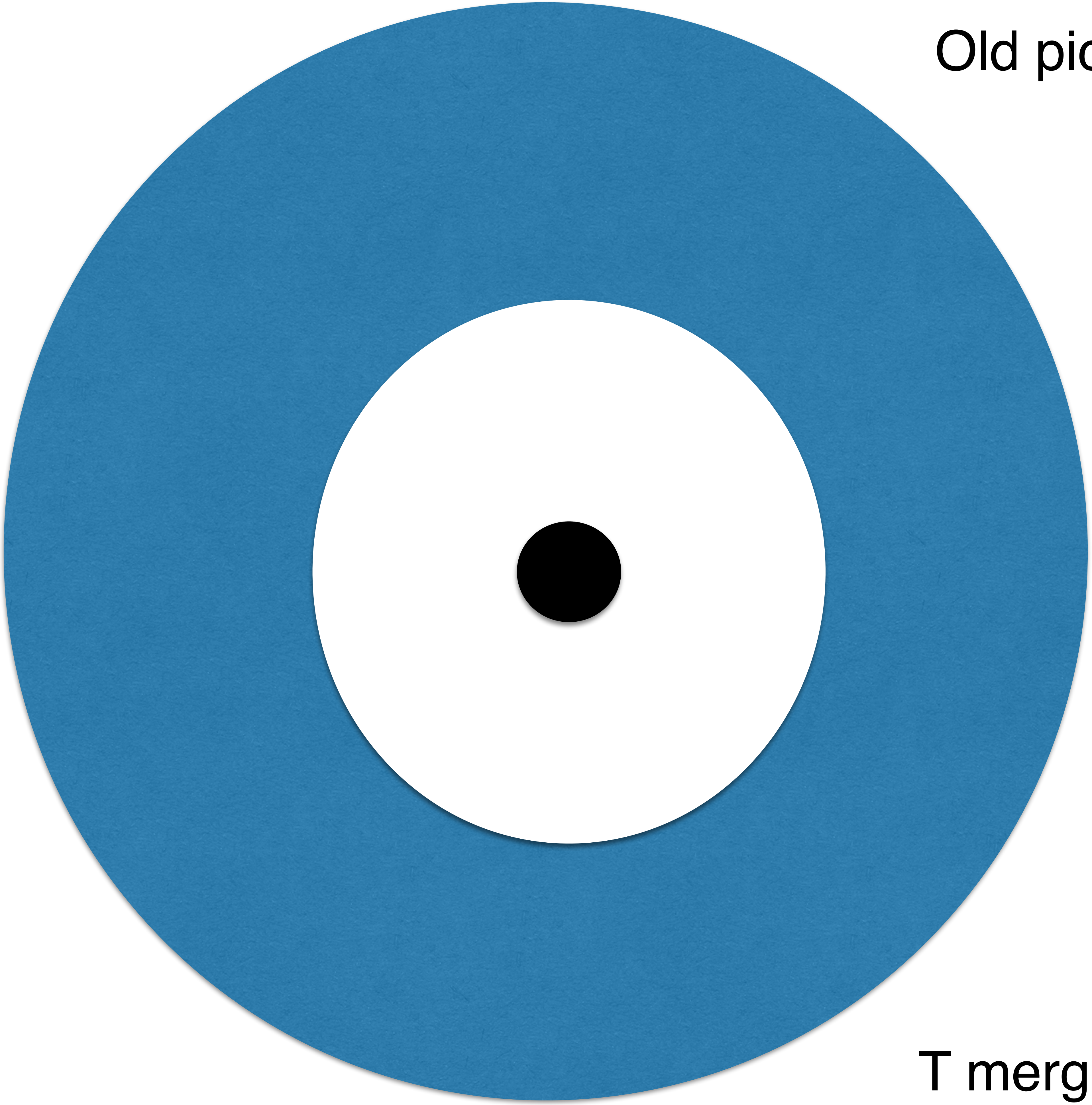
Old picture



T merger

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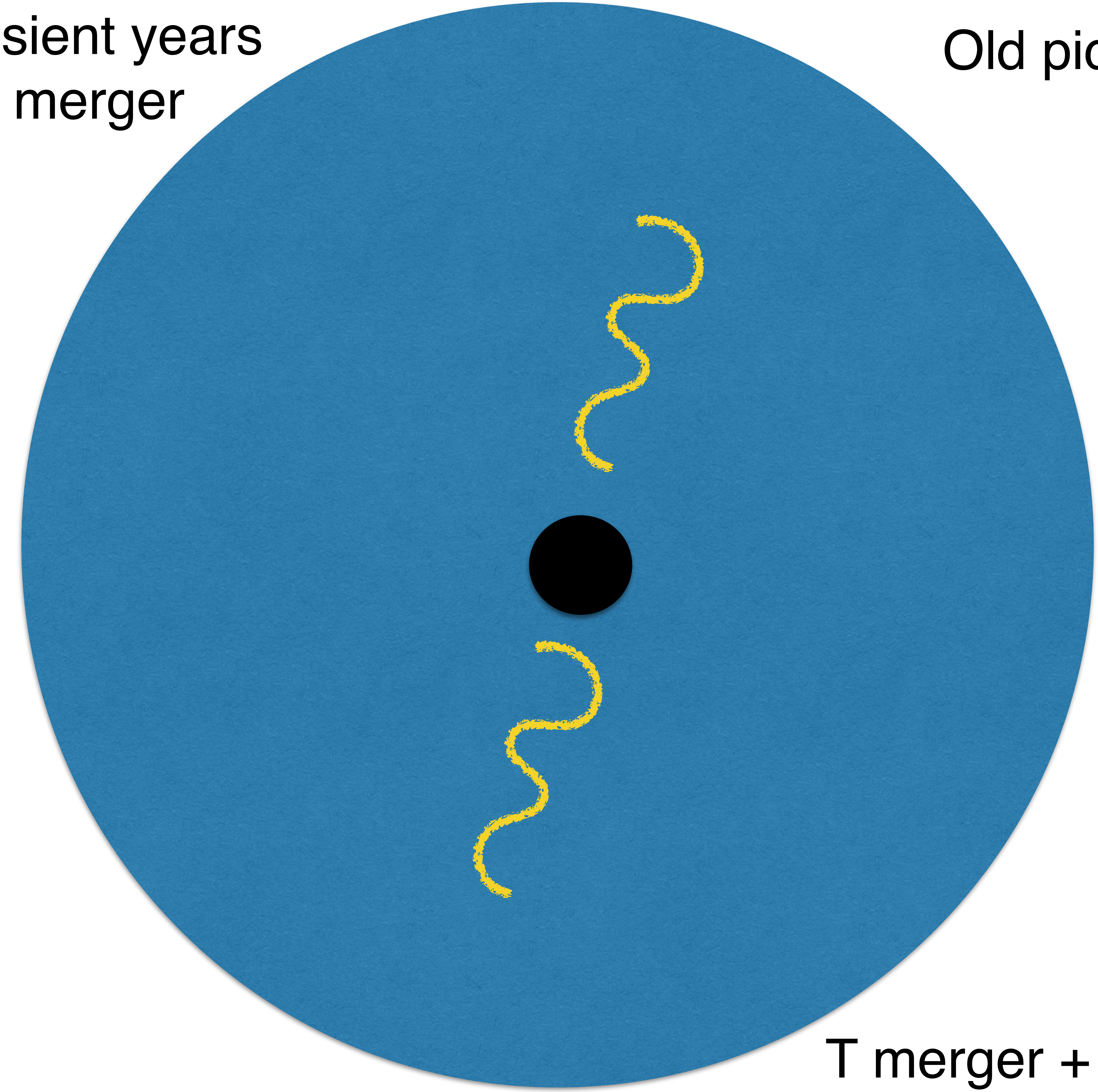
EM transient years
after merger

Old picture



T merger + T visc

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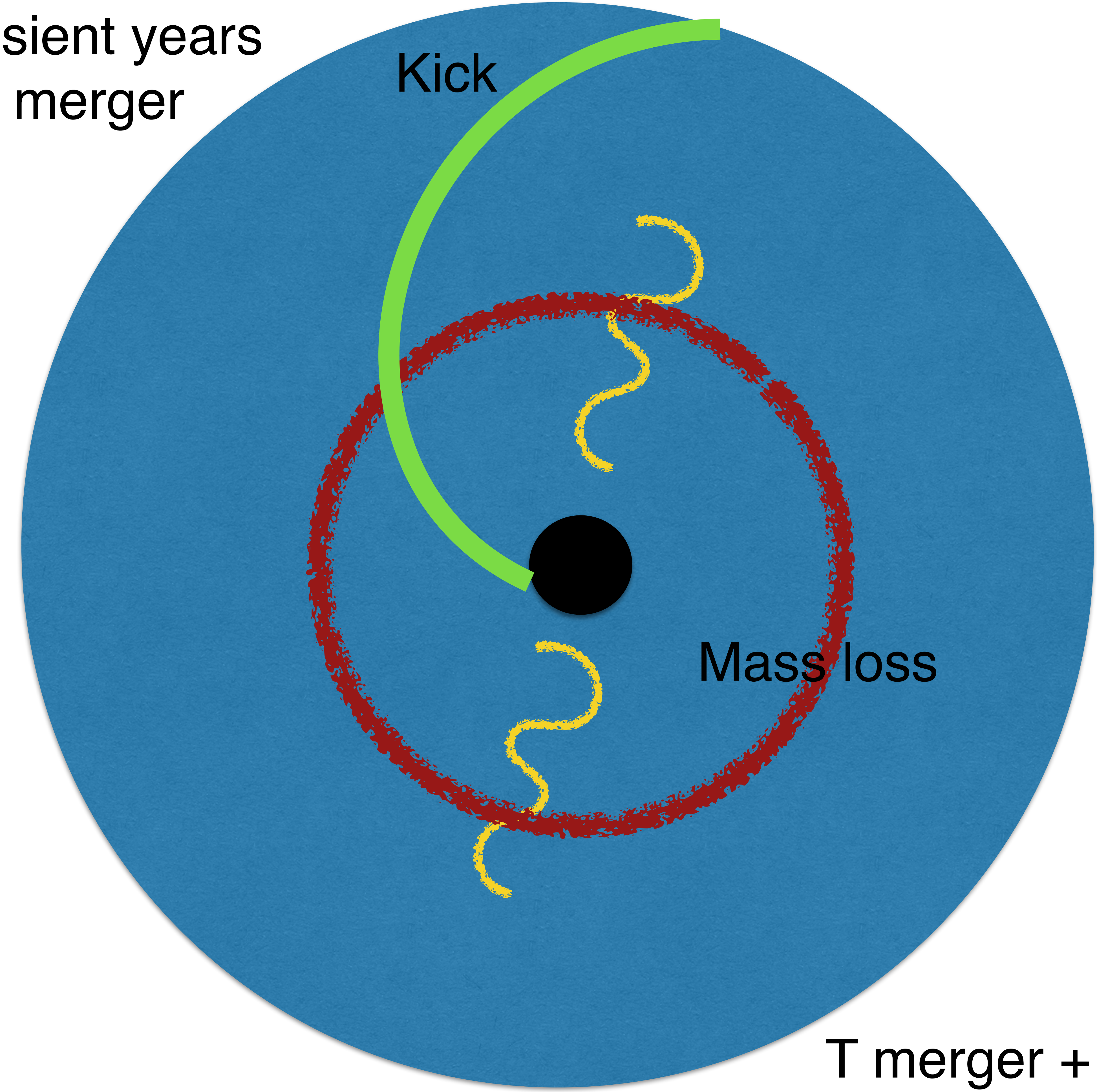
EM transient years after merger



T merger + T visc

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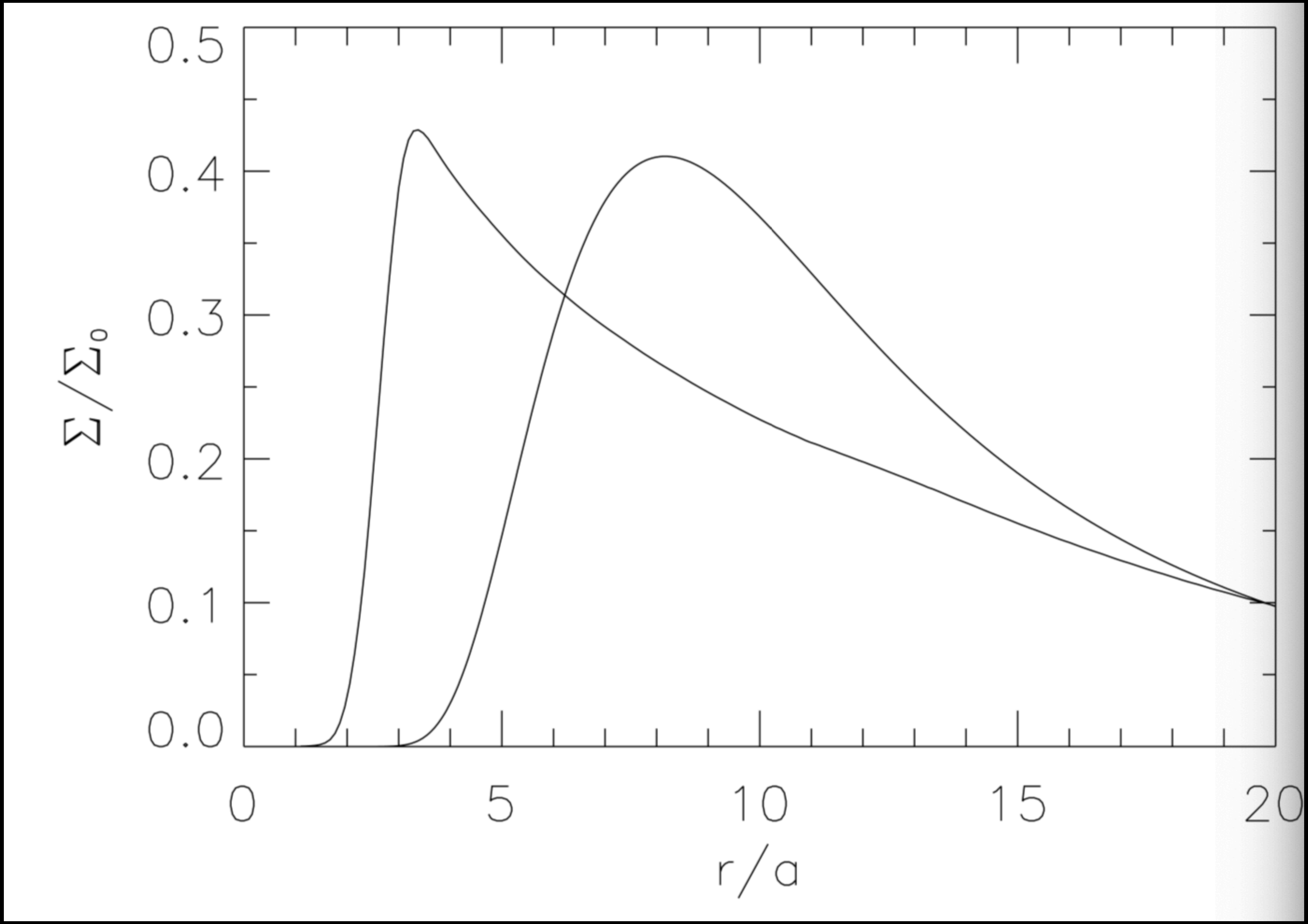
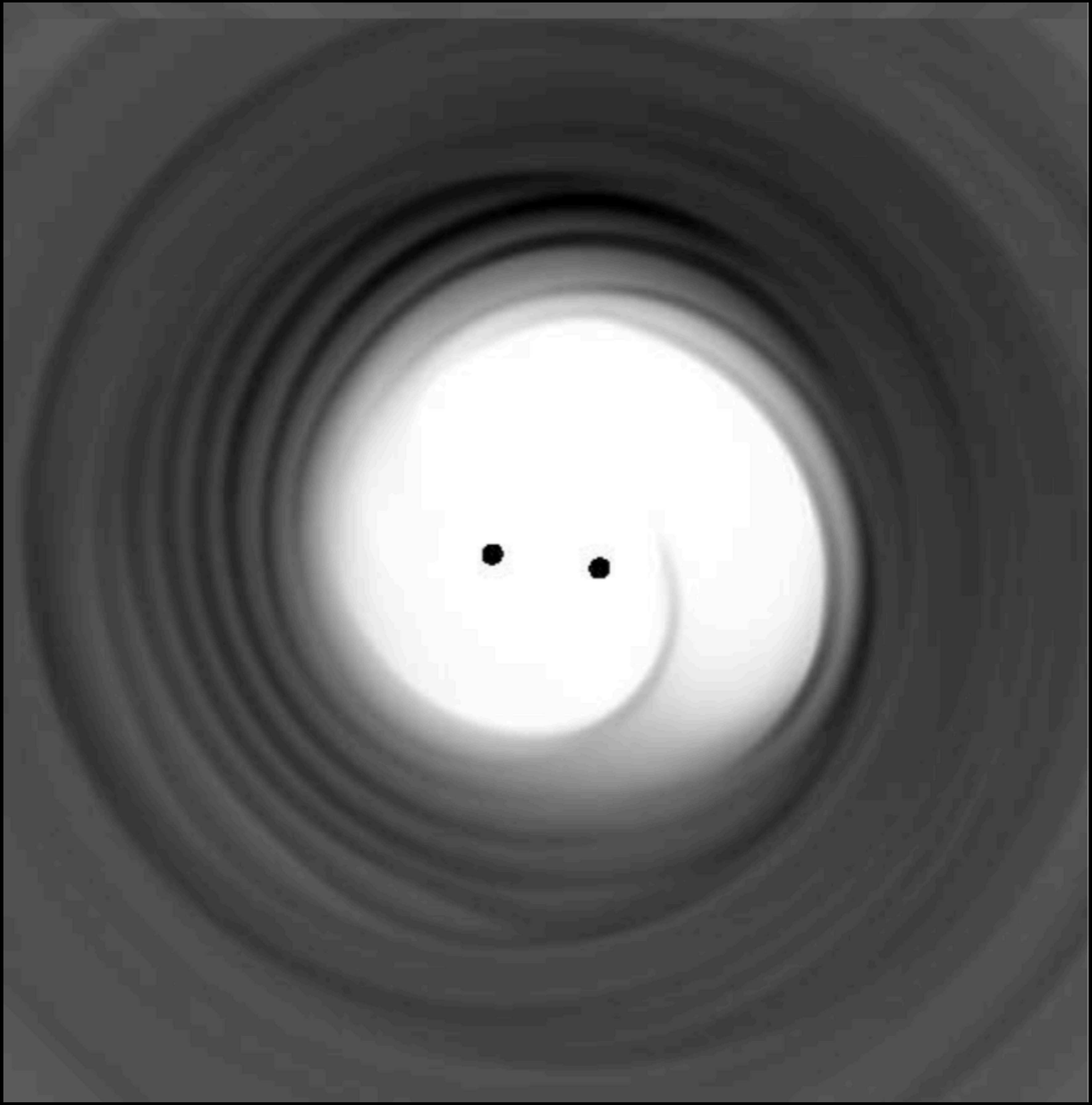
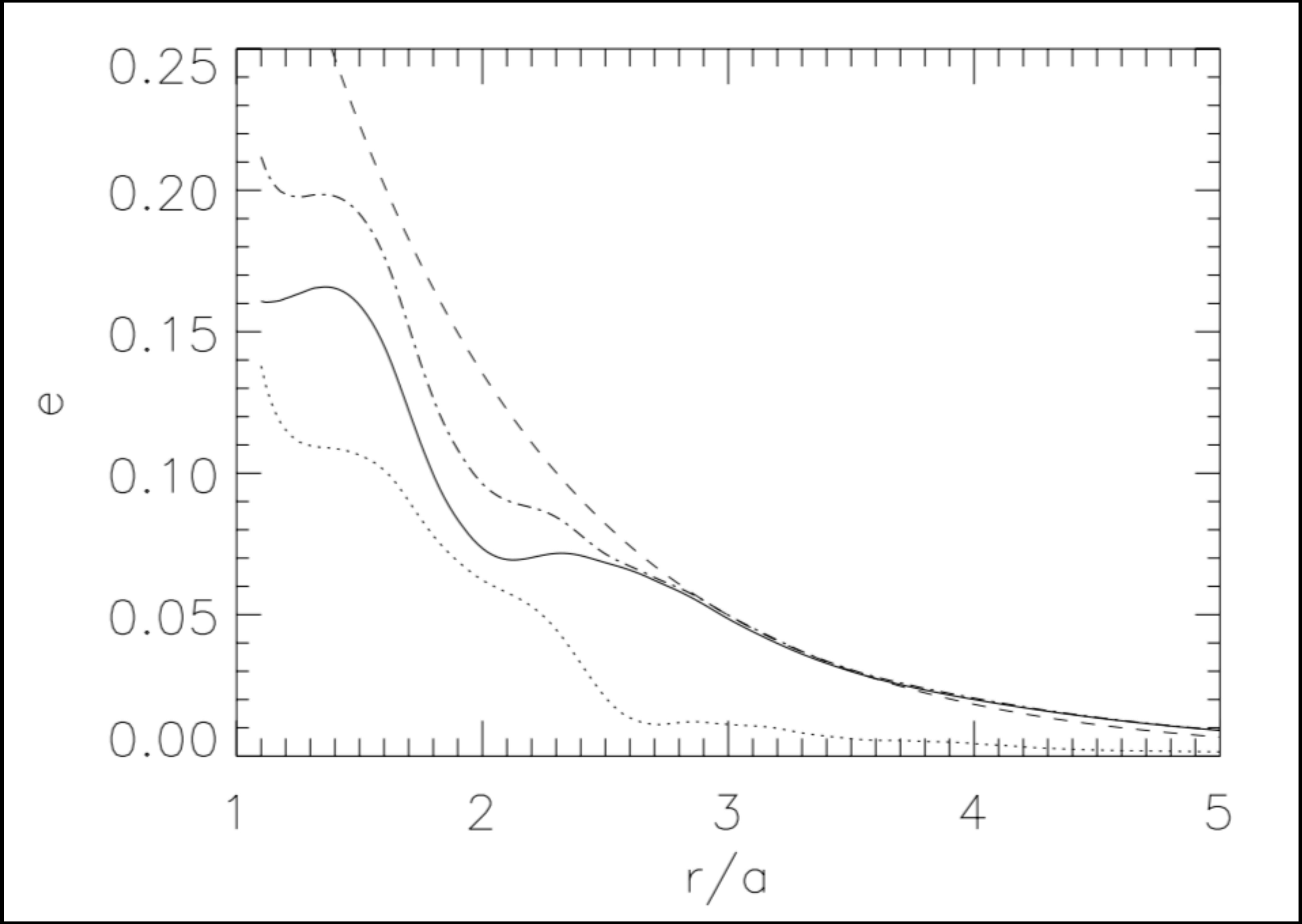
Is this picture correct?



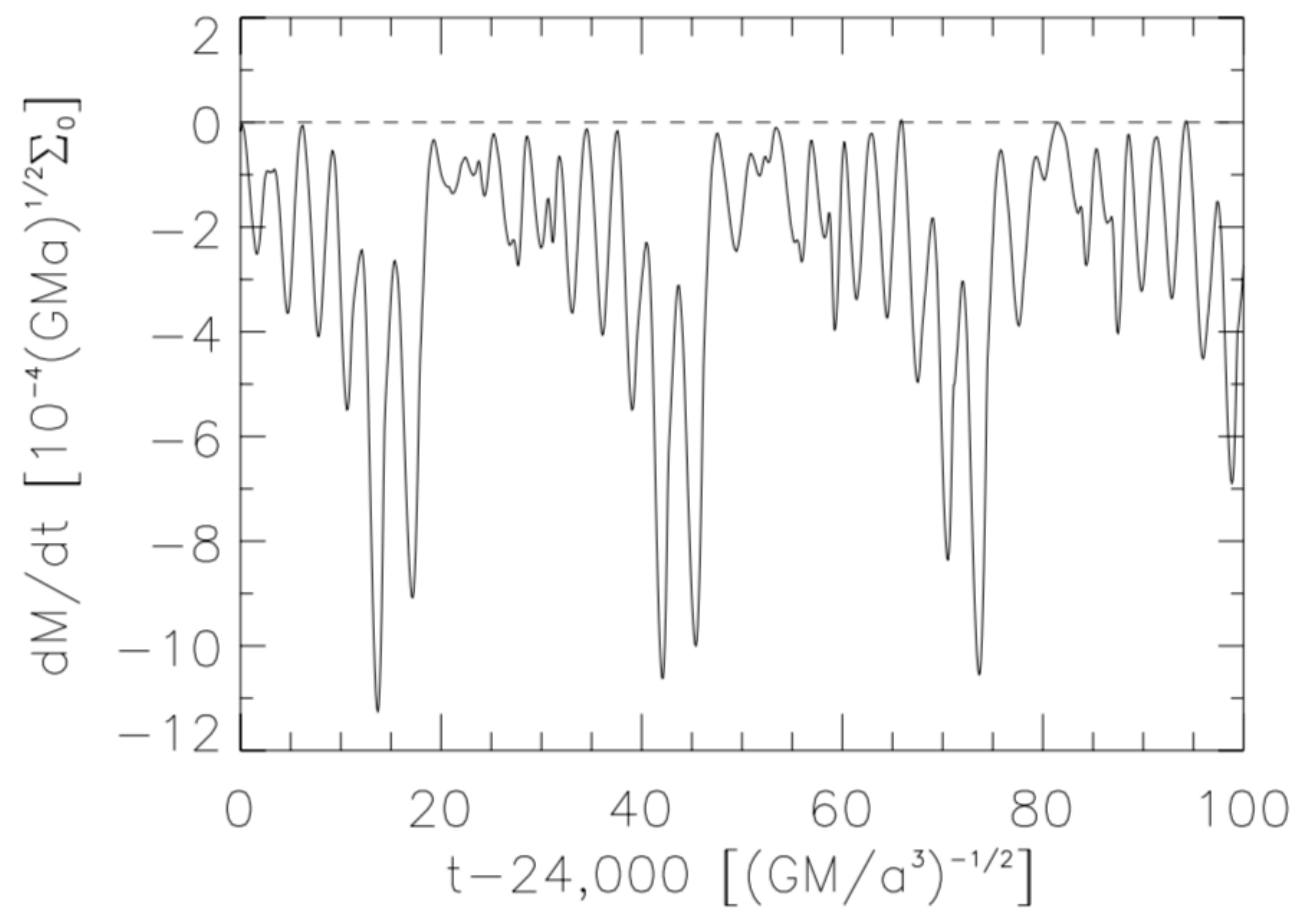
AM & Milosavljevic (2008)



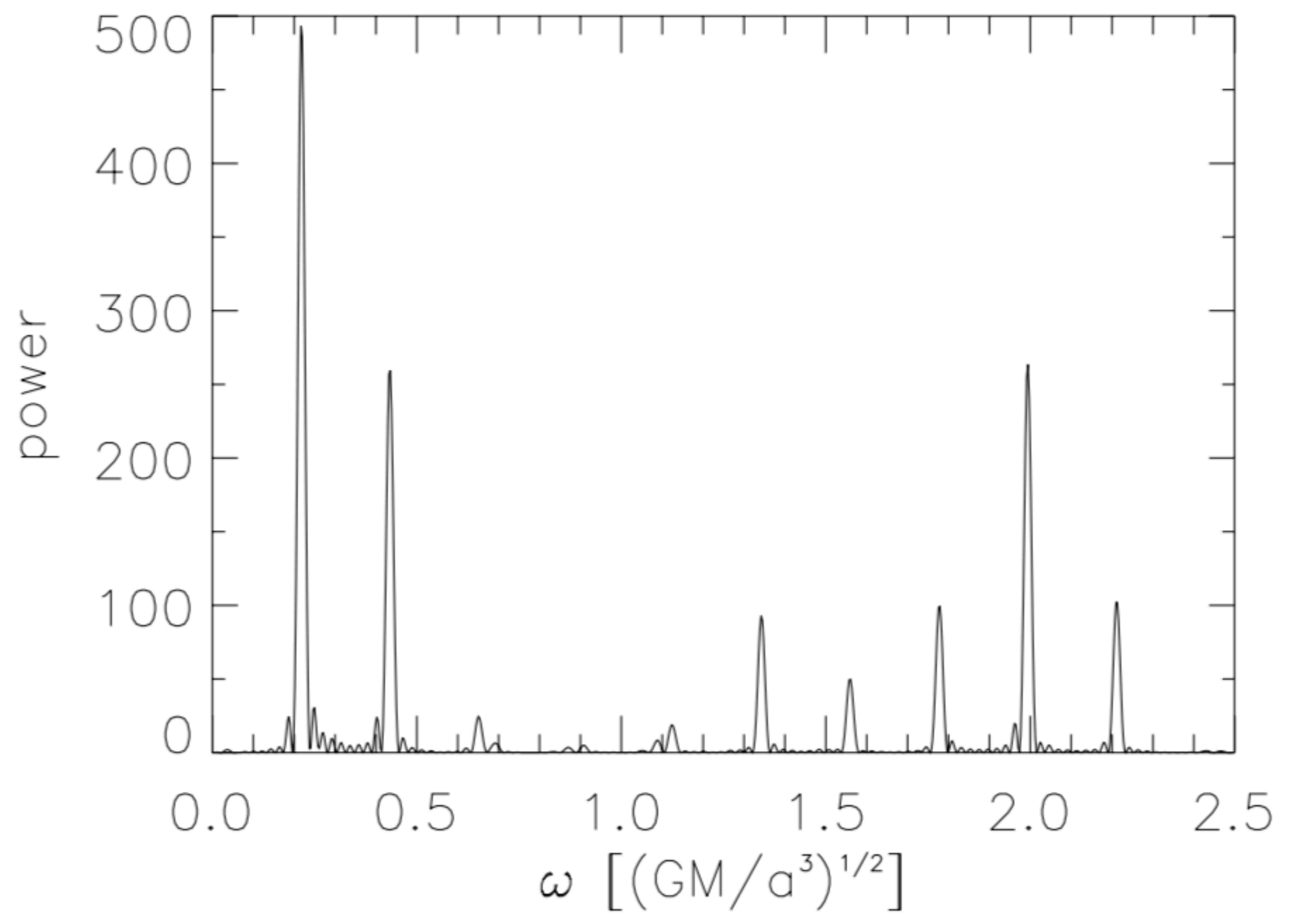
AM & Milosavljevic (2008)



AM & Milosavljevic (2008)



AM & Milosavljevic (2008)

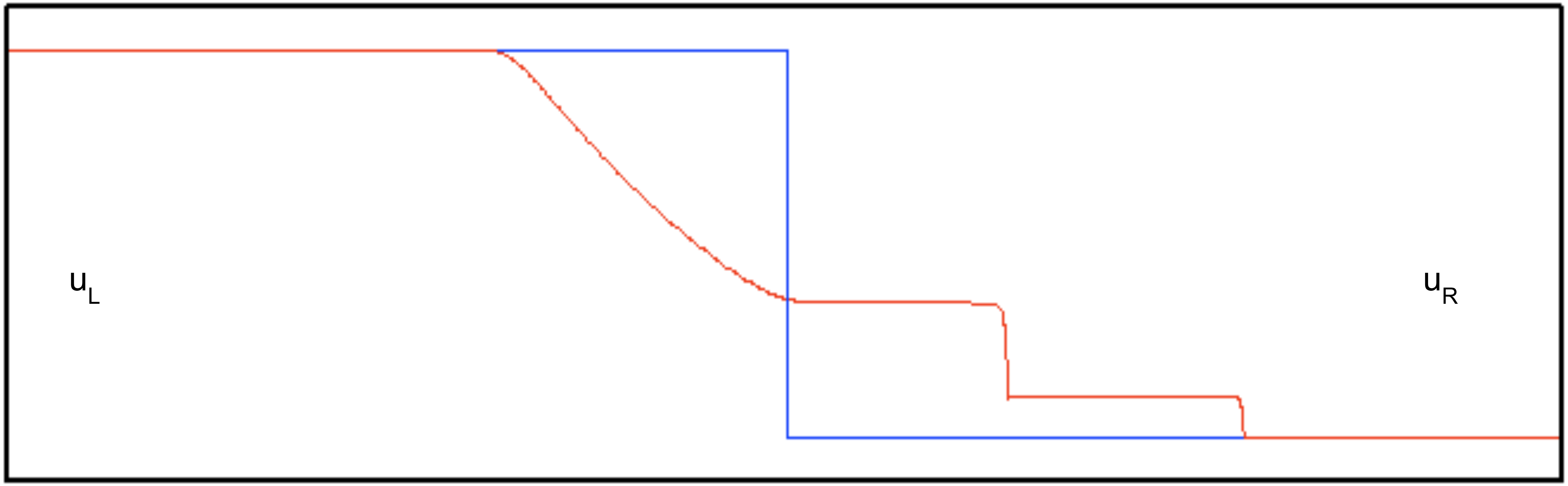


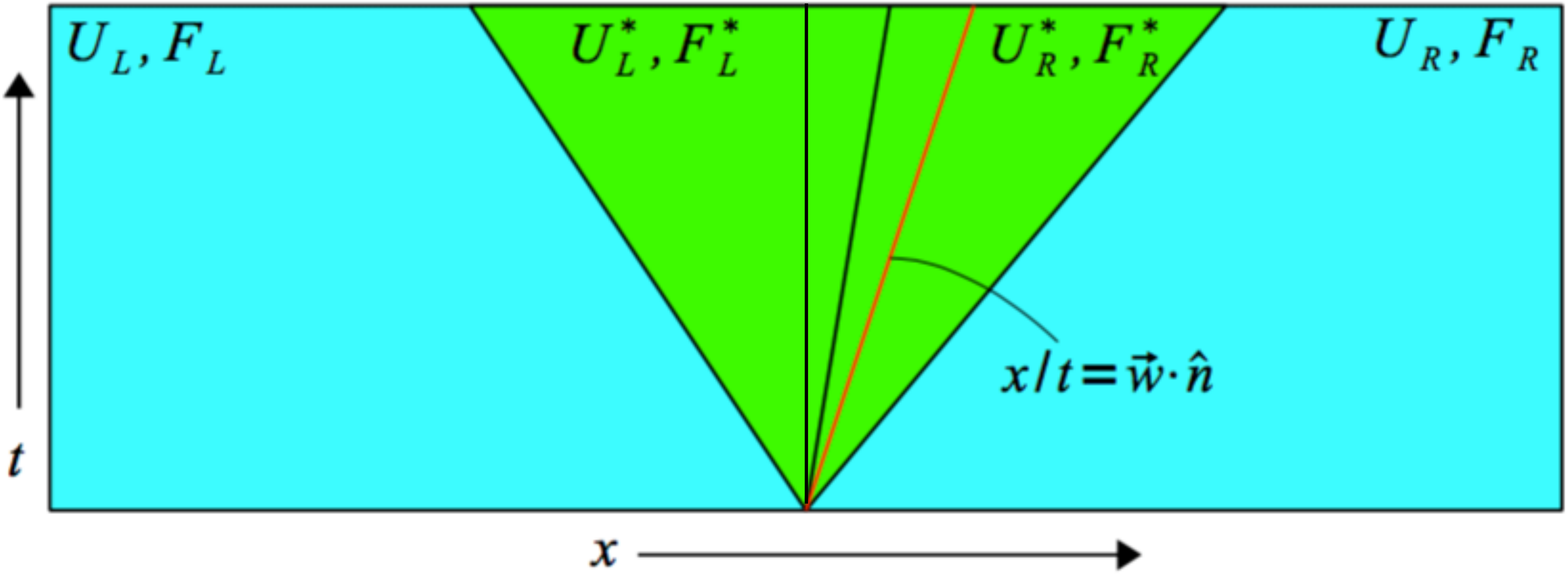
AM & Milosavljevic (2008)

TESS

“Moving Mesh”

Duffell & AM (2011)





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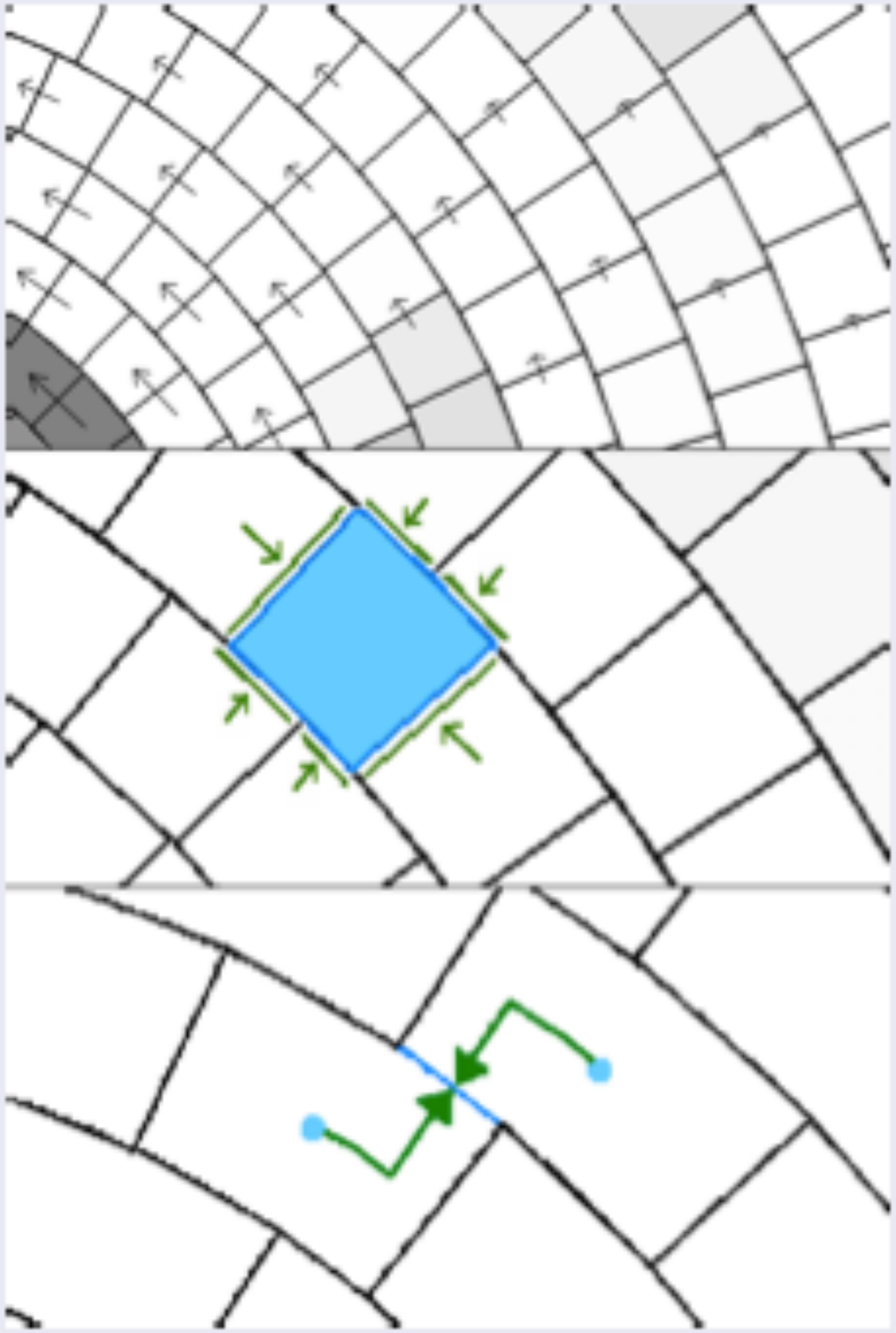
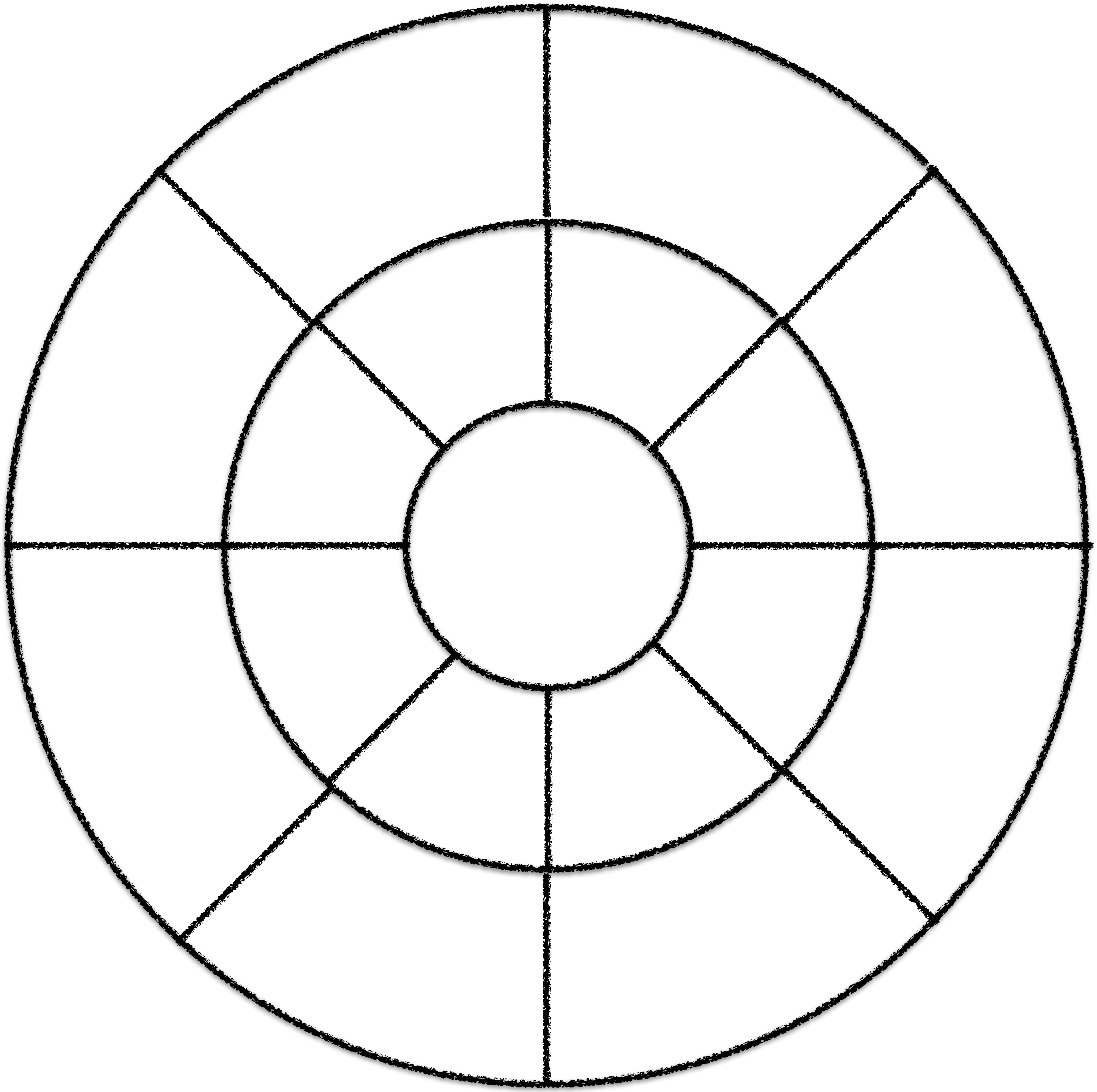
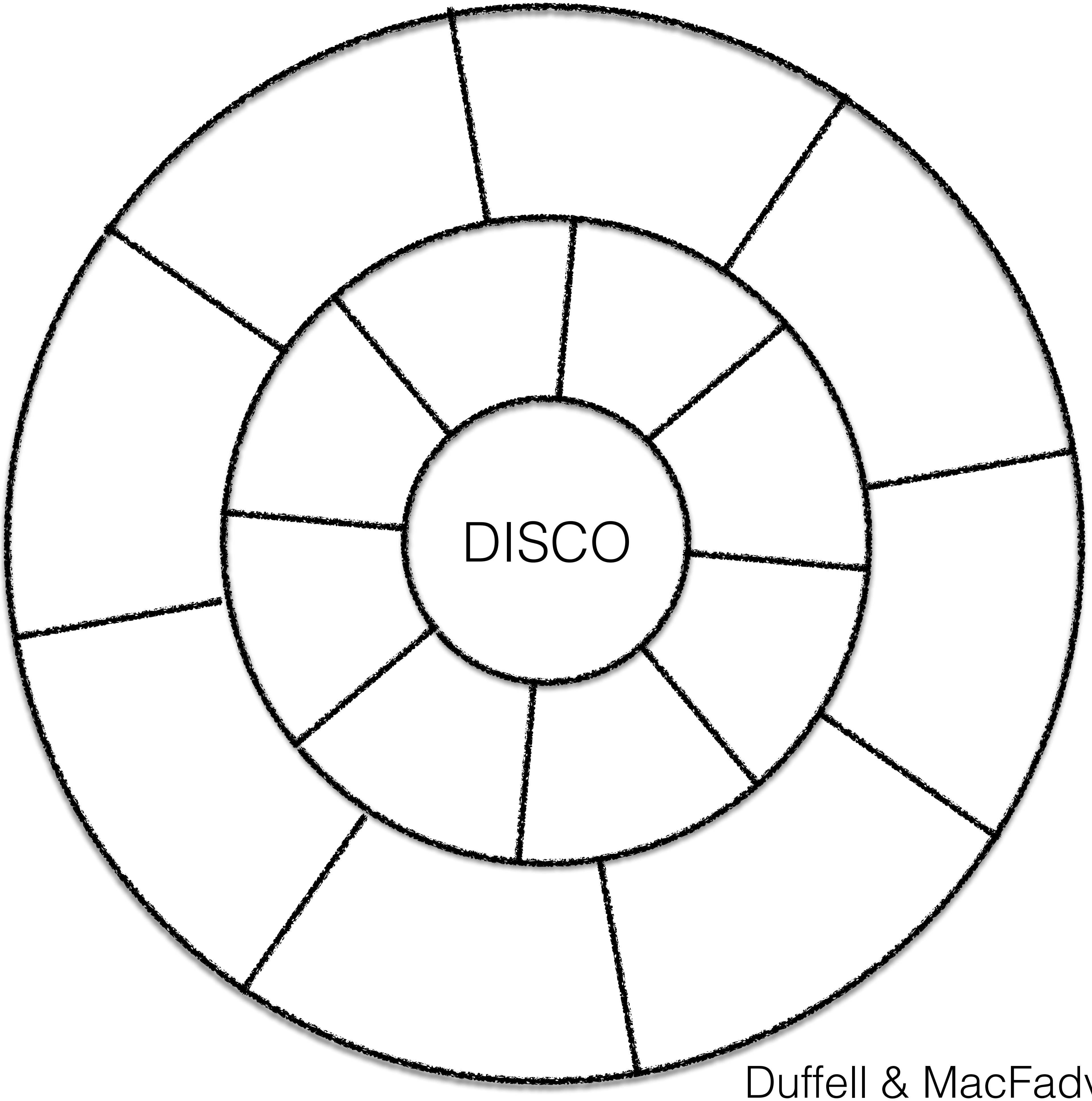


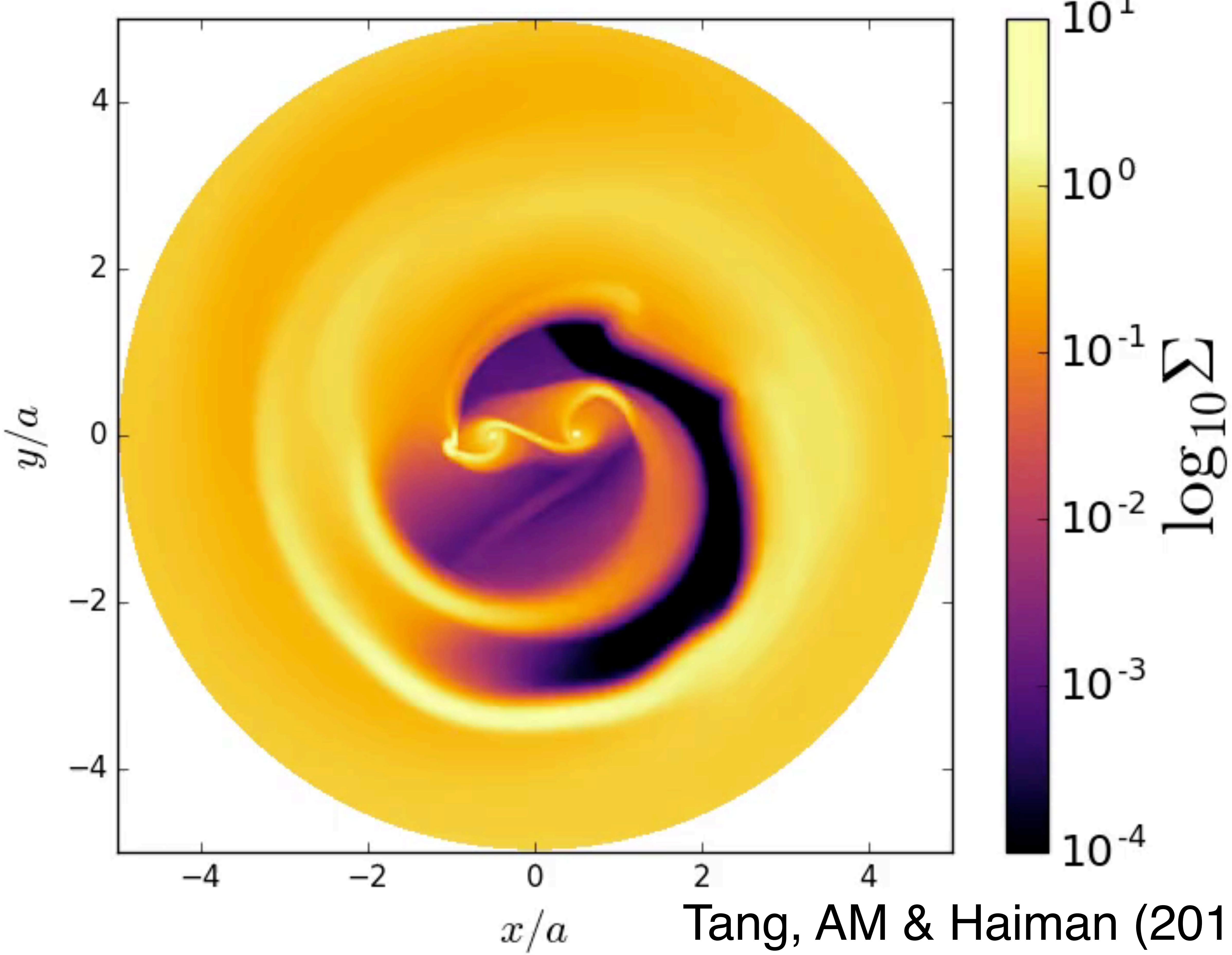
DISCO - Duffell & MacFadyen 2012, 2013

- 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



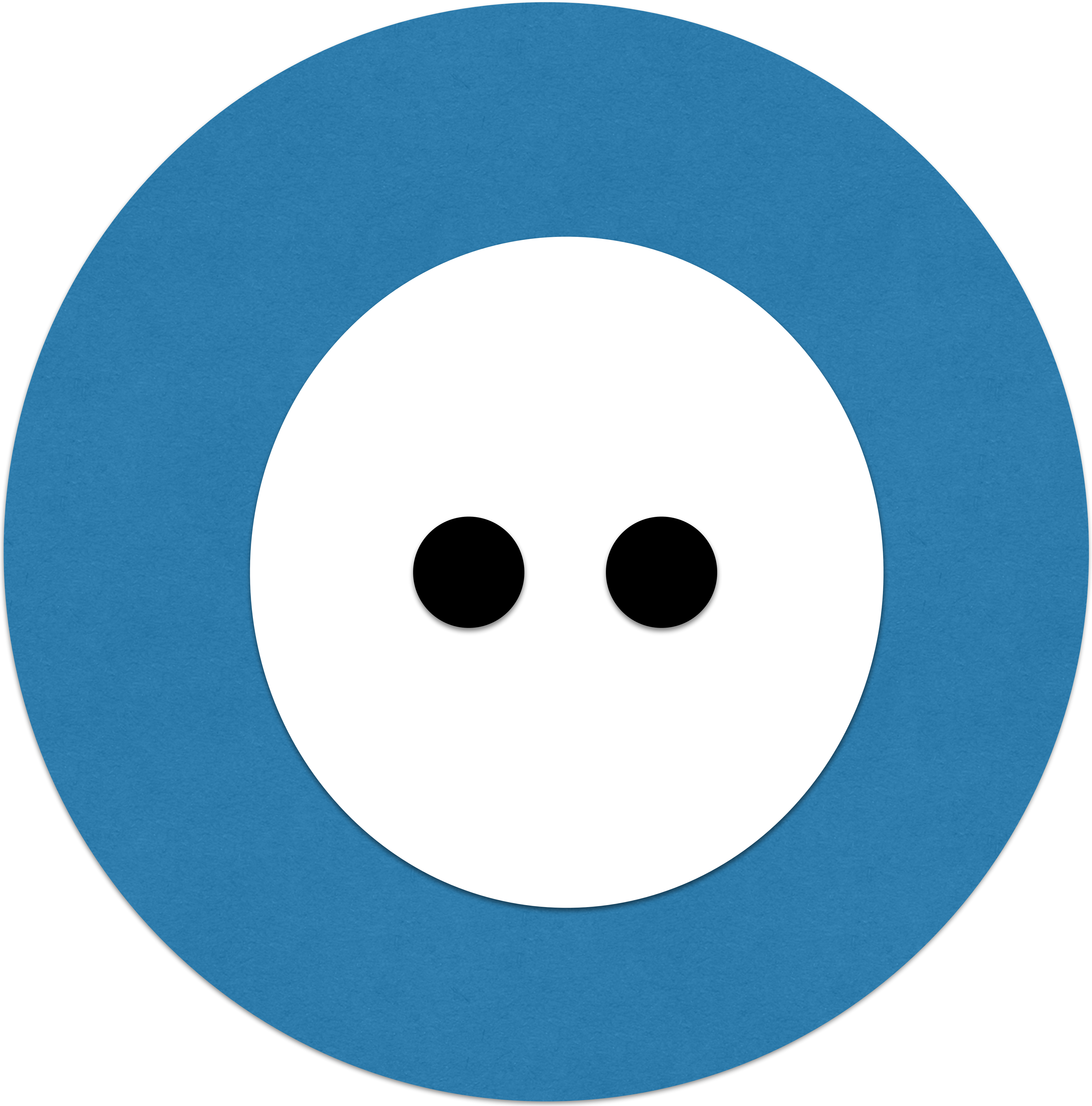


Duffell & MacFadyen (2012)

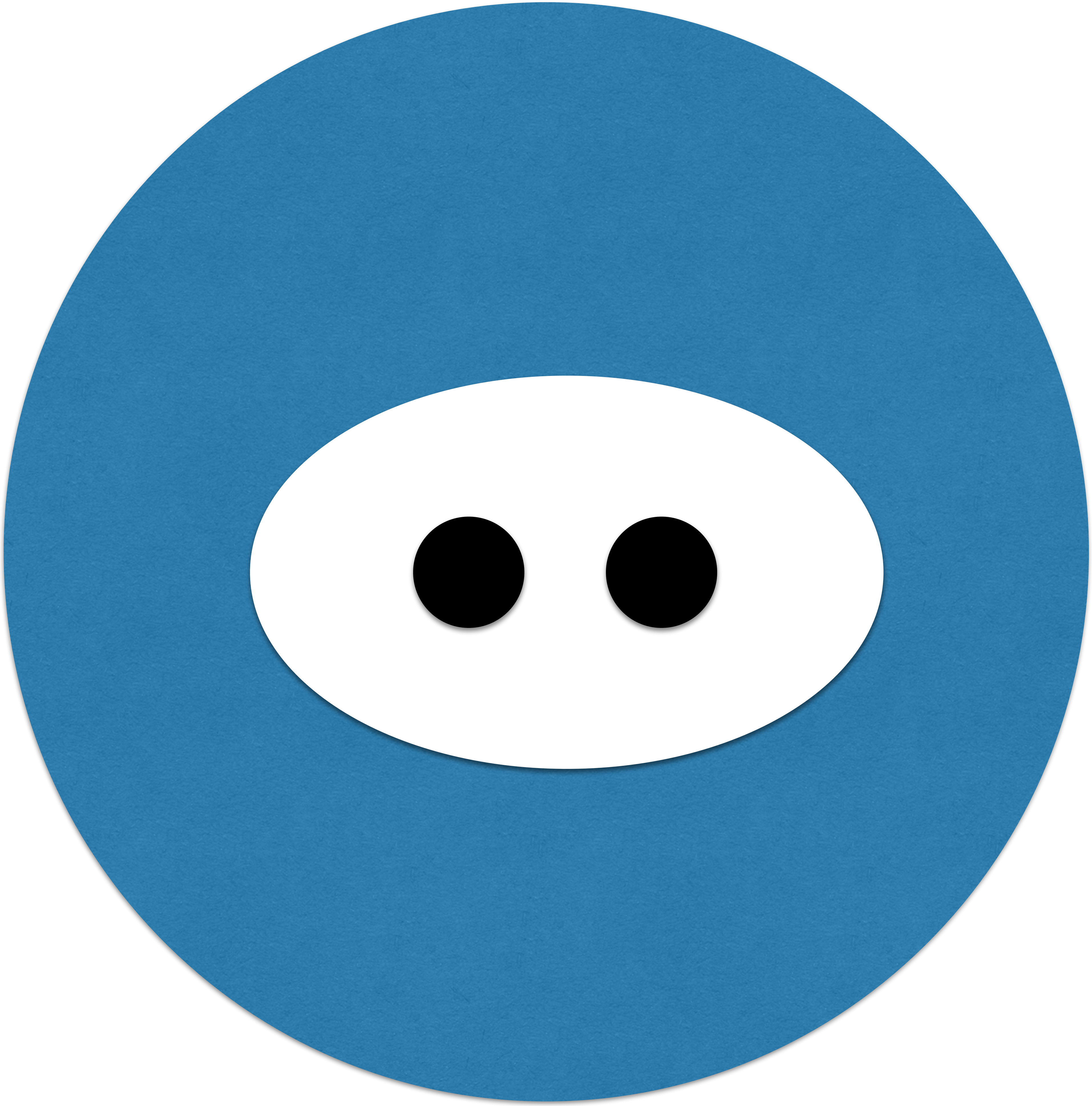


Tang, AM & Haiman (2017)

This Talk



This Talk



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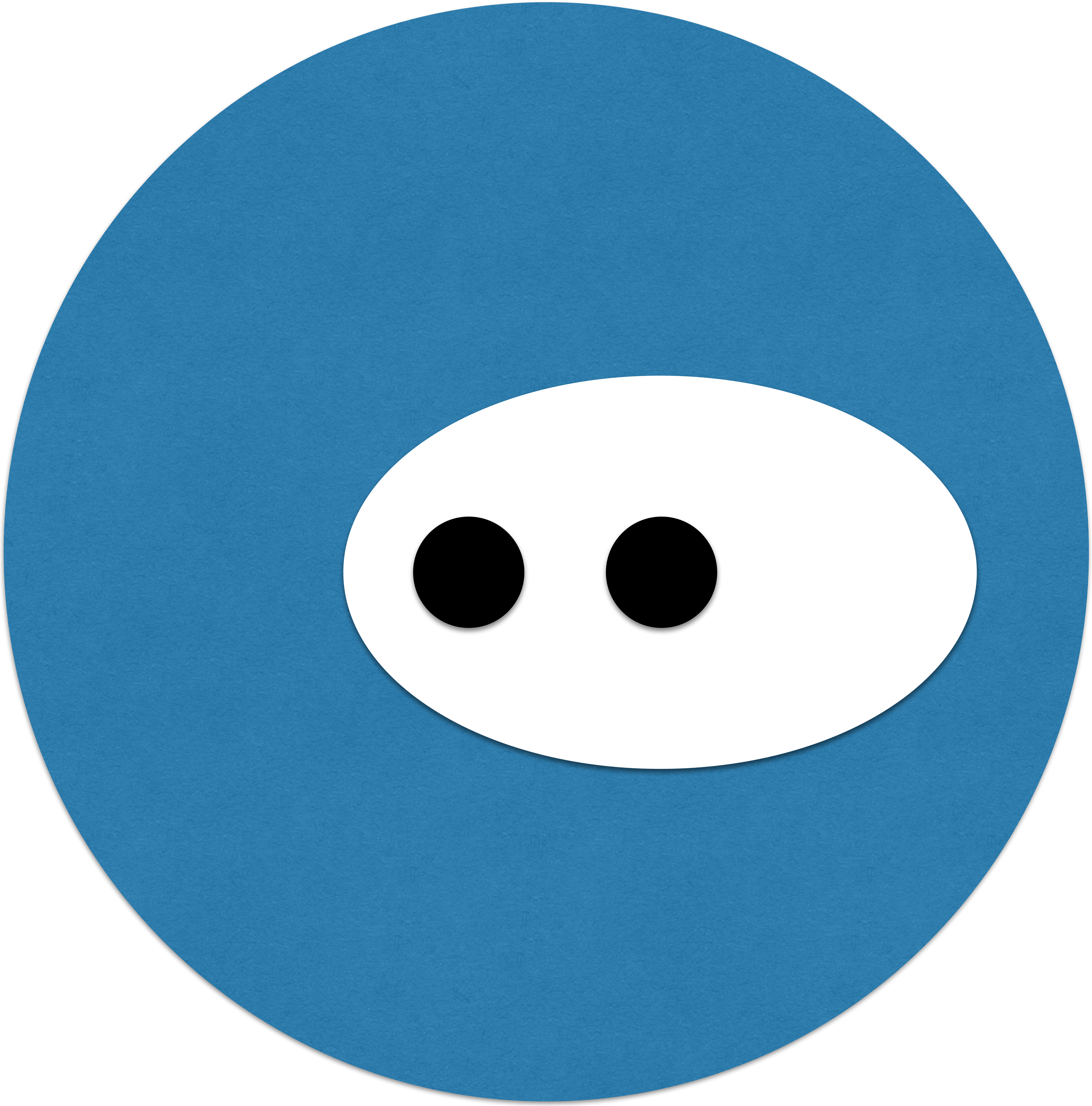

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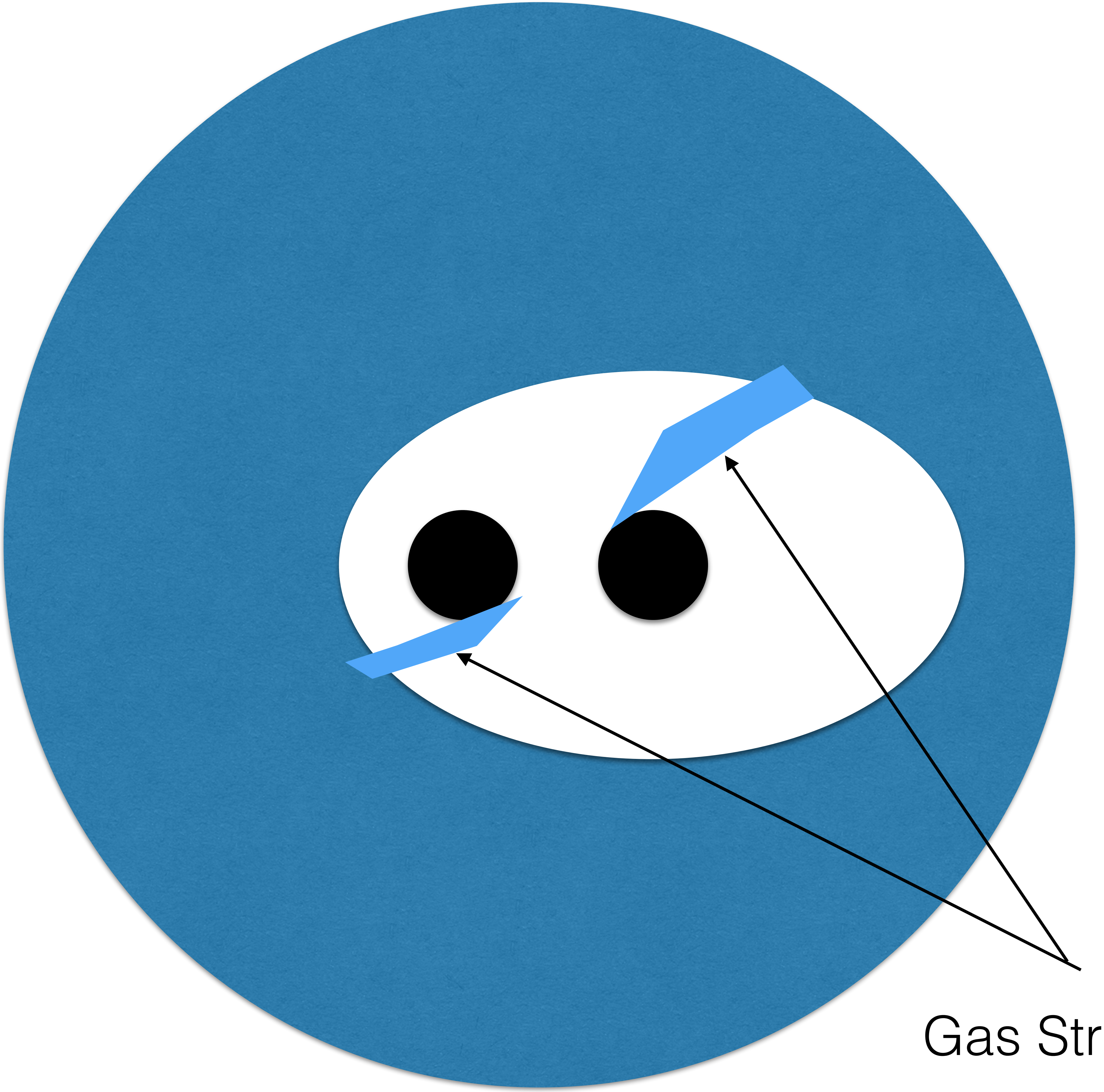
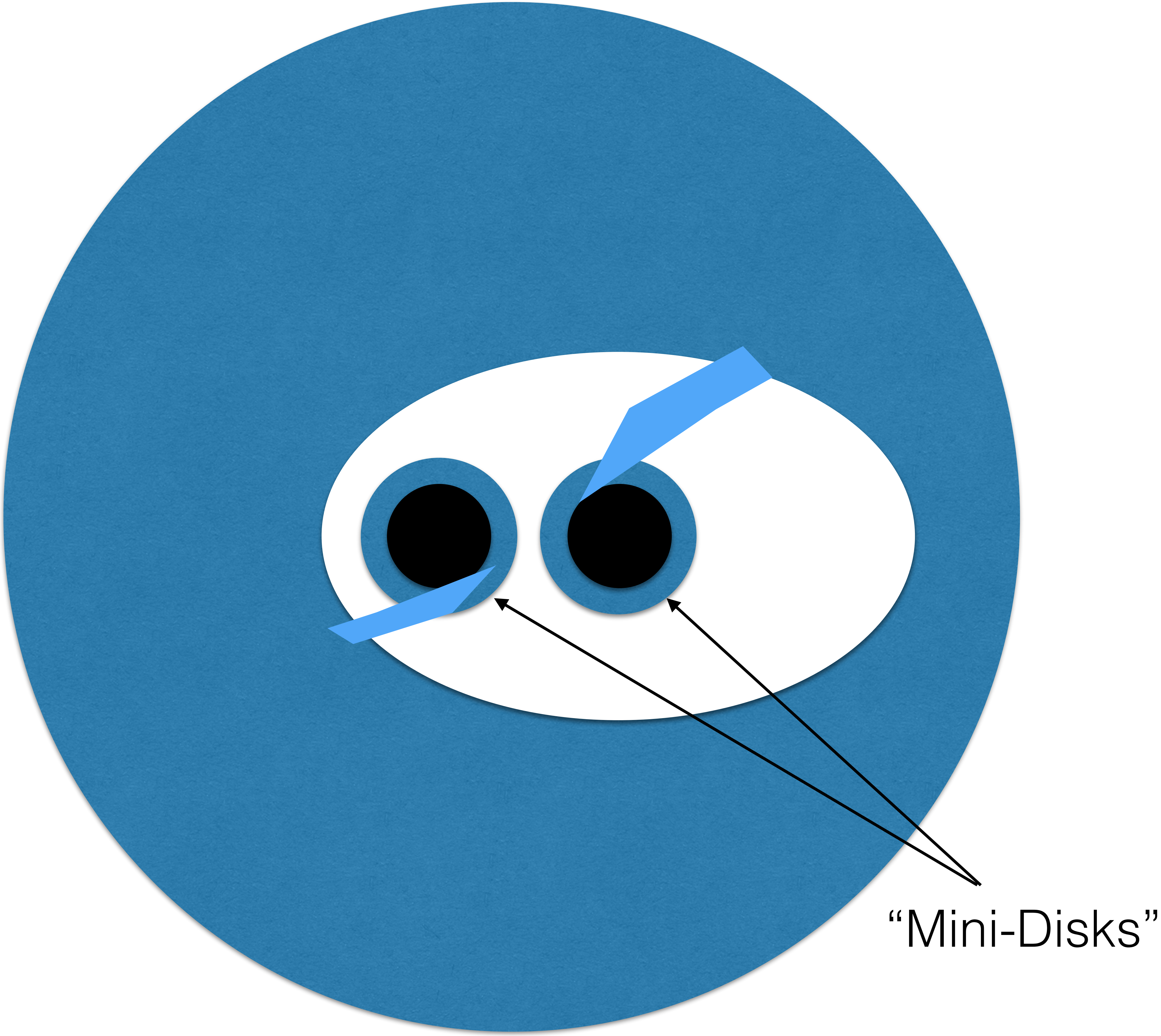

Gas Streams


“Mini-Disks”

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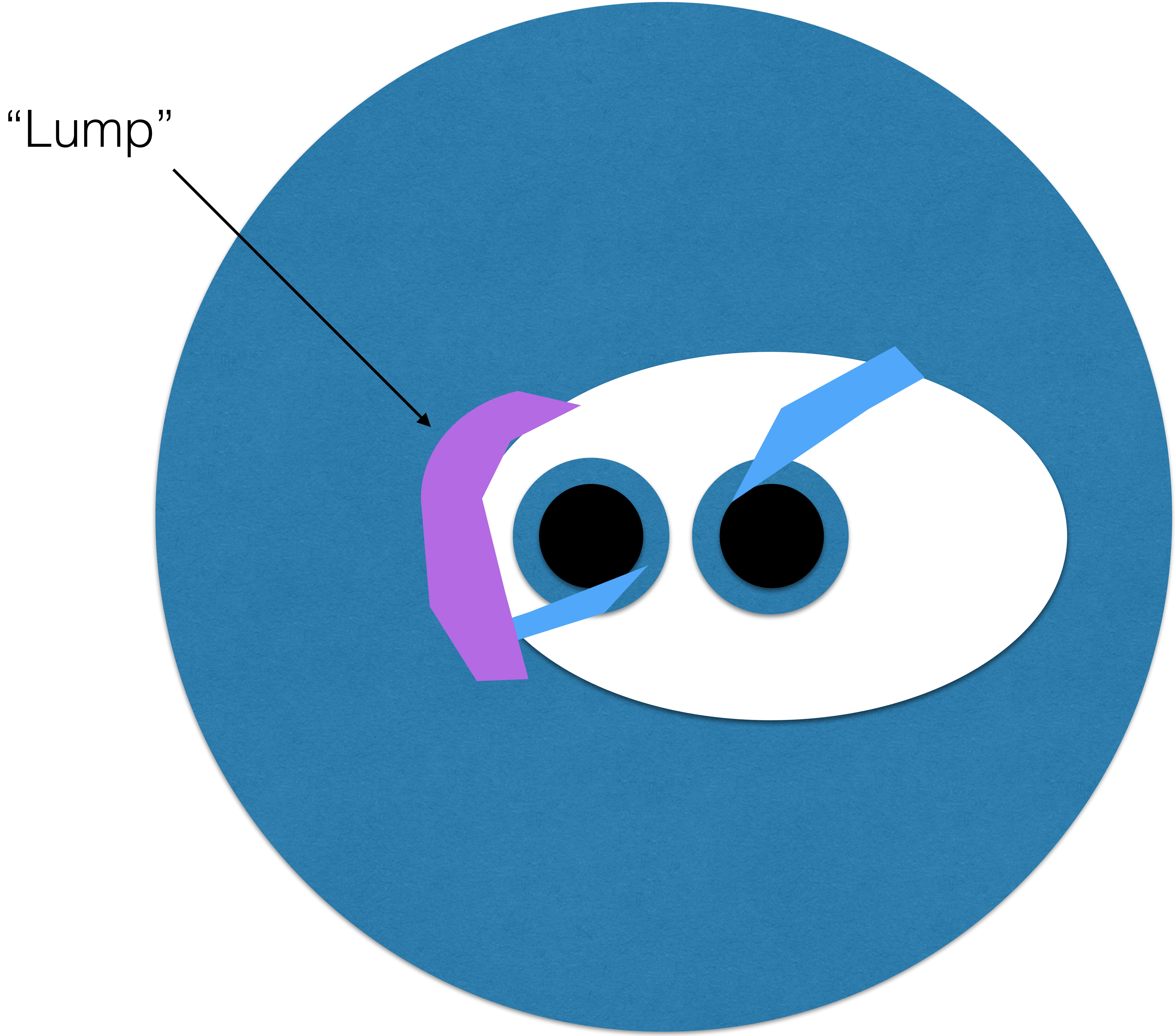

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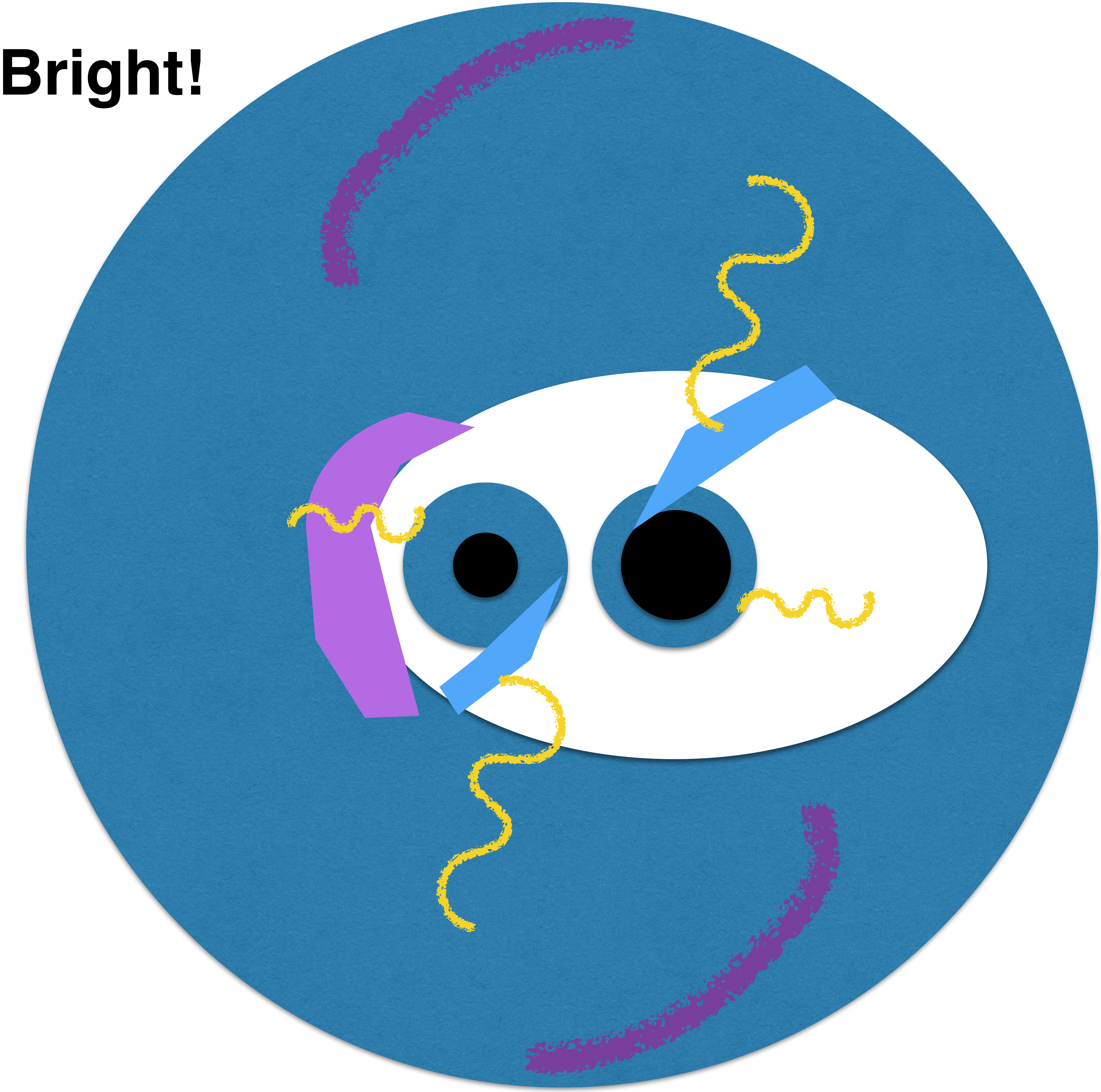
X-Ray Bright!



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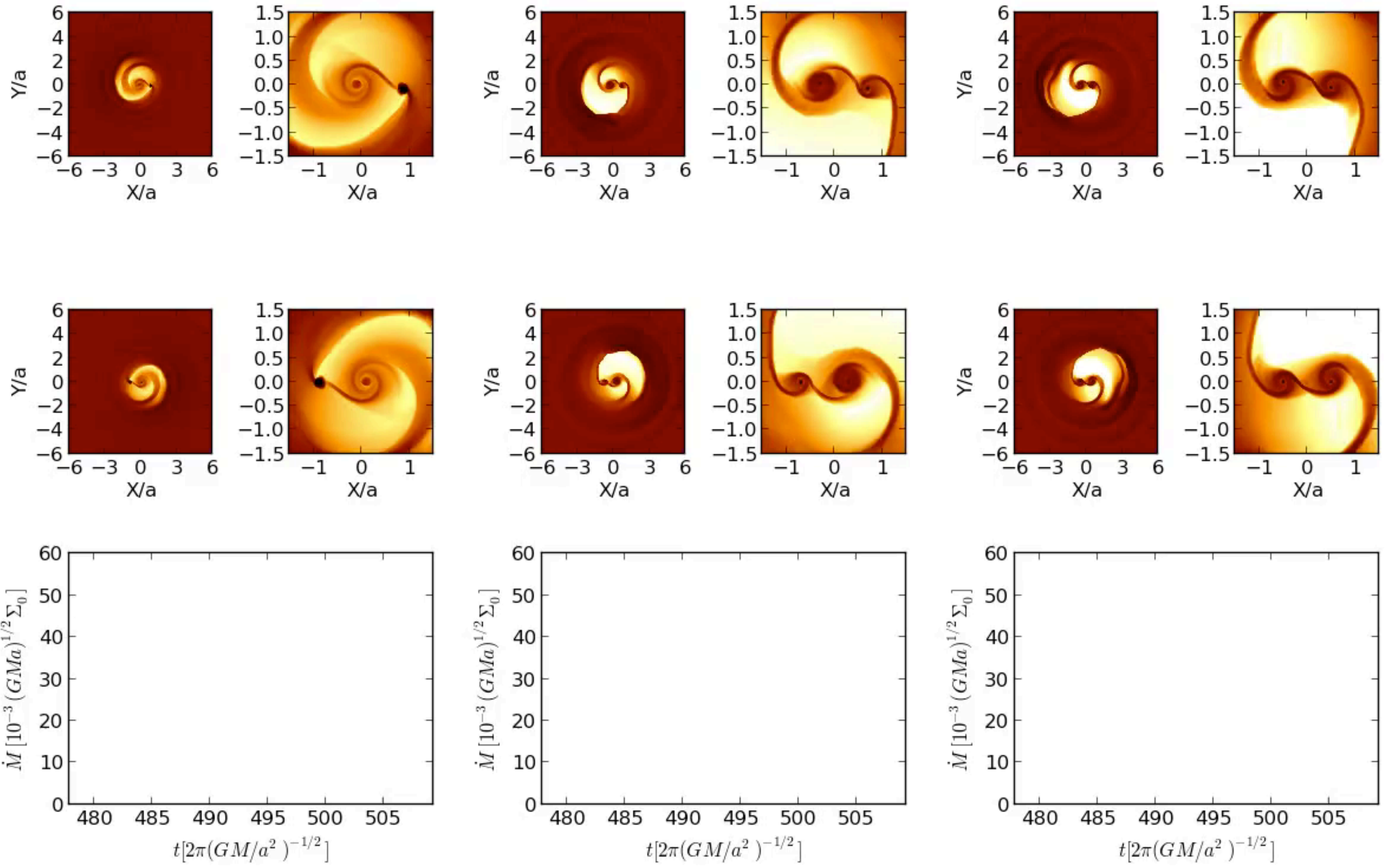

q = 0.11

q = 0.43

q = 1.0

Farris+ (2013)

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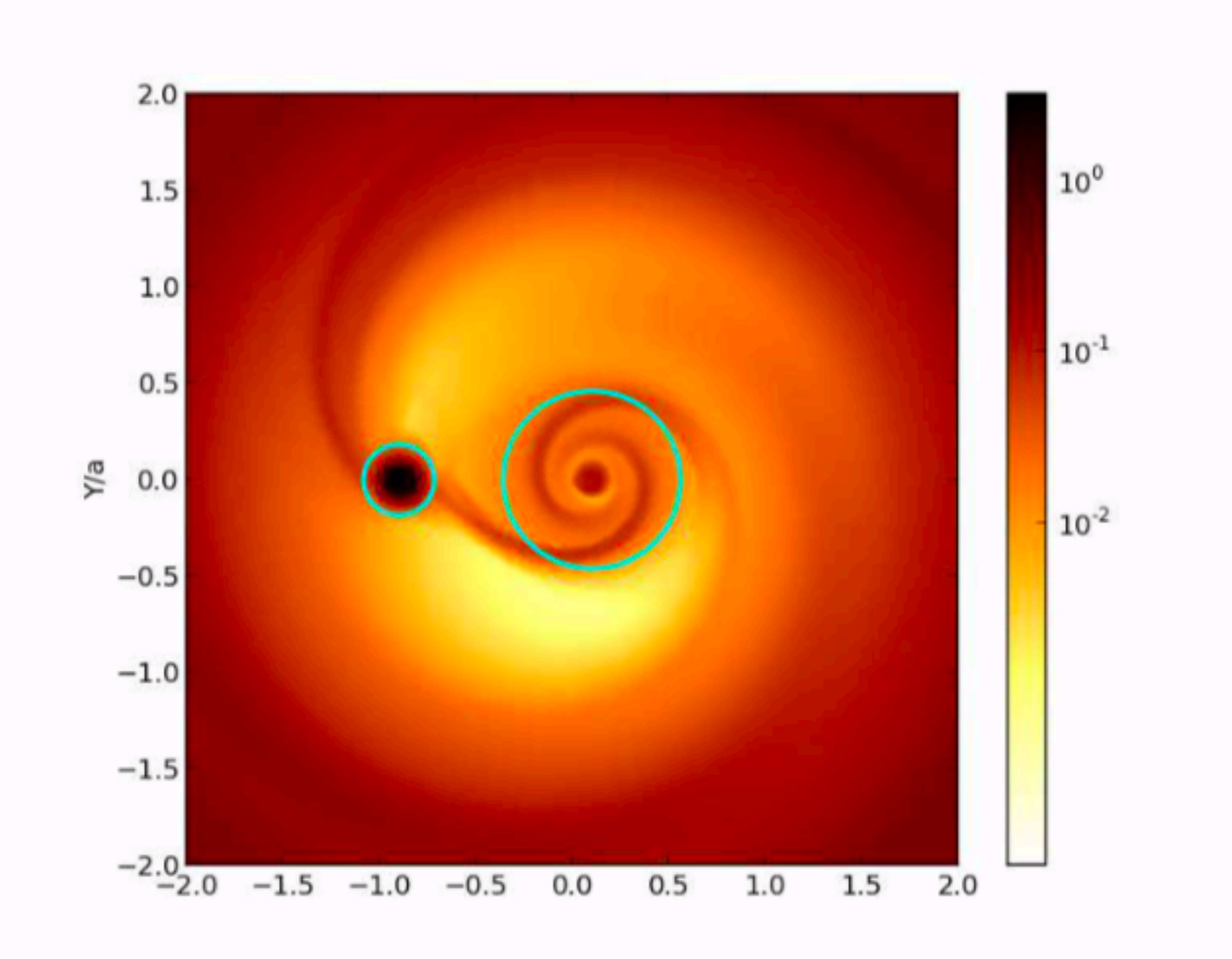
2.0
1.5
1.0
0.5
Y/a
0.0
−0.5
−1.0
−1.5
−2.0
−2.0
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−0.5
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1.0
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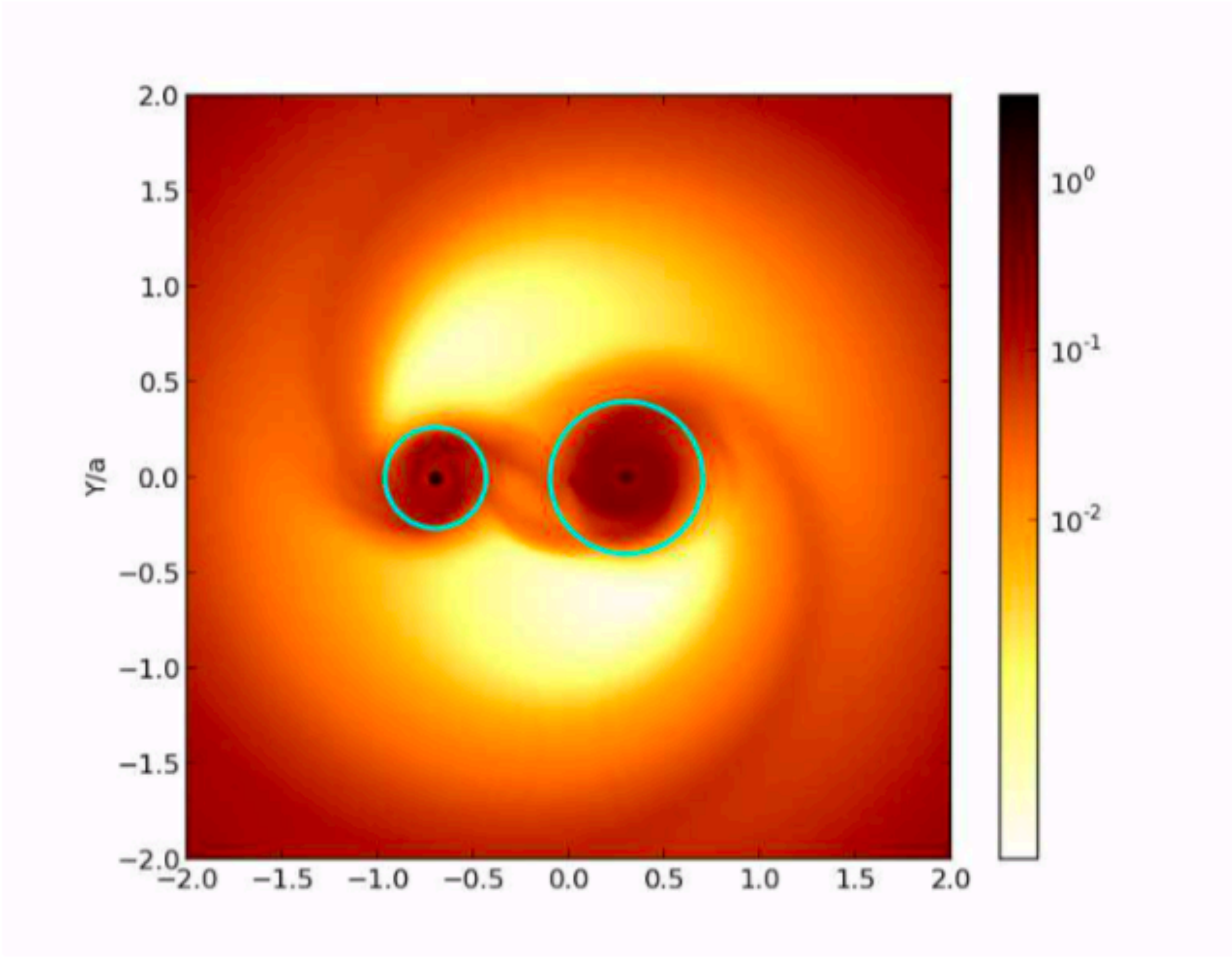
2.0
10^0
10^{-1}
10^{-2}


2.0
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−1.0
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0.0
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1.0
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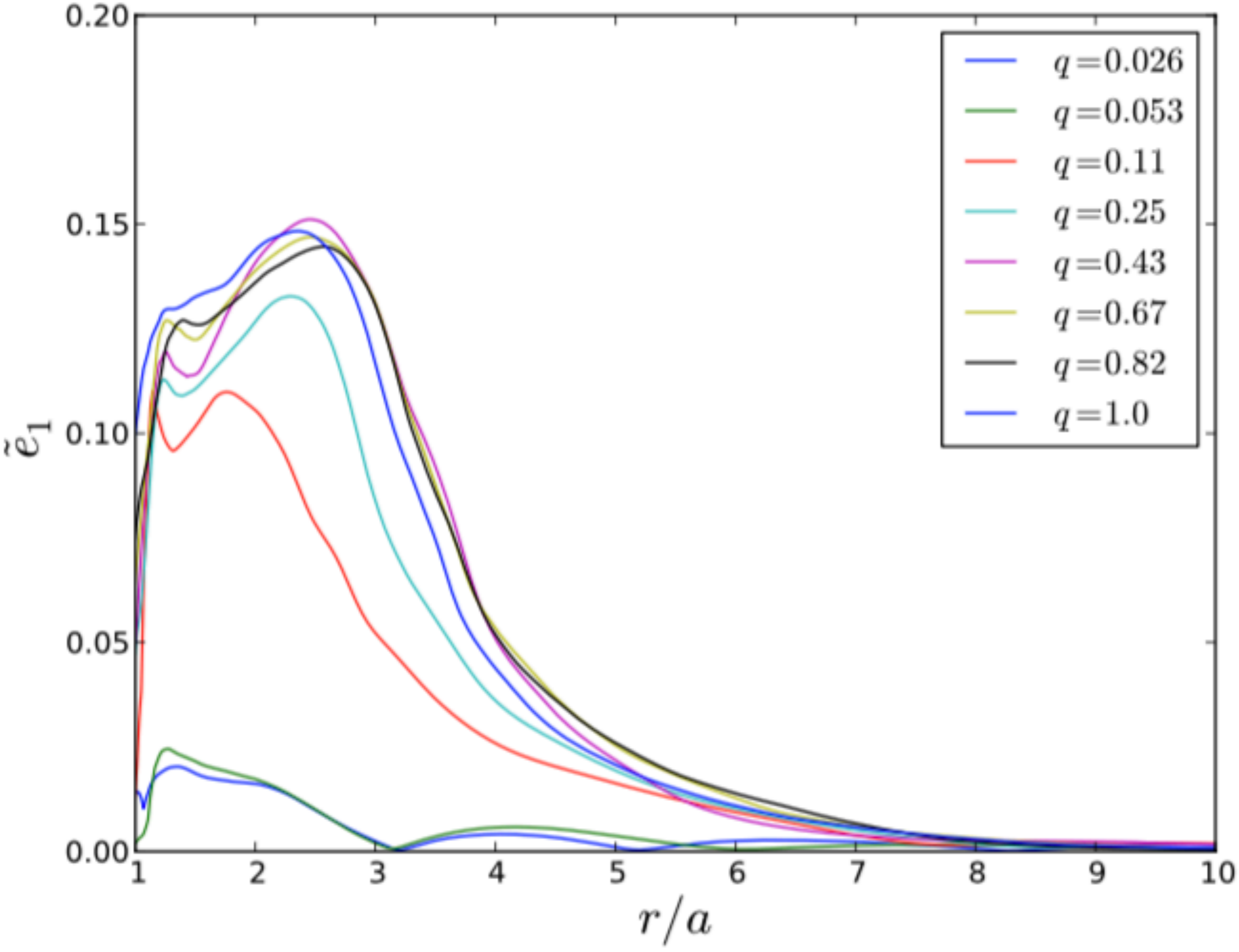
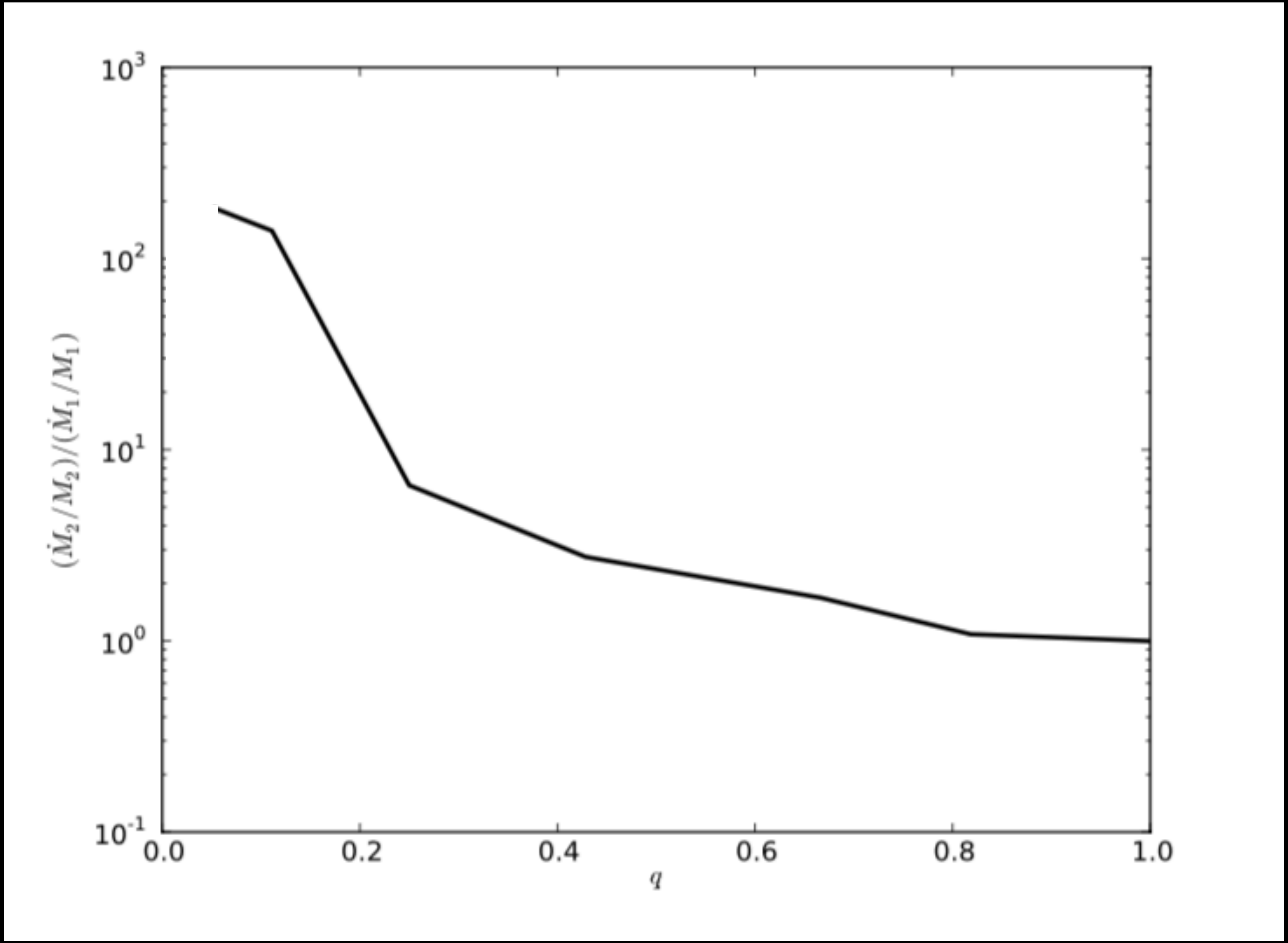
2.0
10^0
10^{-1}
10^{-2}

Farris+ (2013)


0.20
0.15
0.10
0.05
0.00
$\tilde{e}_1$
1
2
3
4
5
6
7
8
9
10
r/a
$q = 0.026$
$q = 0.053$
$q = 0.11$
$q = 0.25$
$q = 0.43$
$q = 0.67$
$q = 0.82$
$q = 1.0$

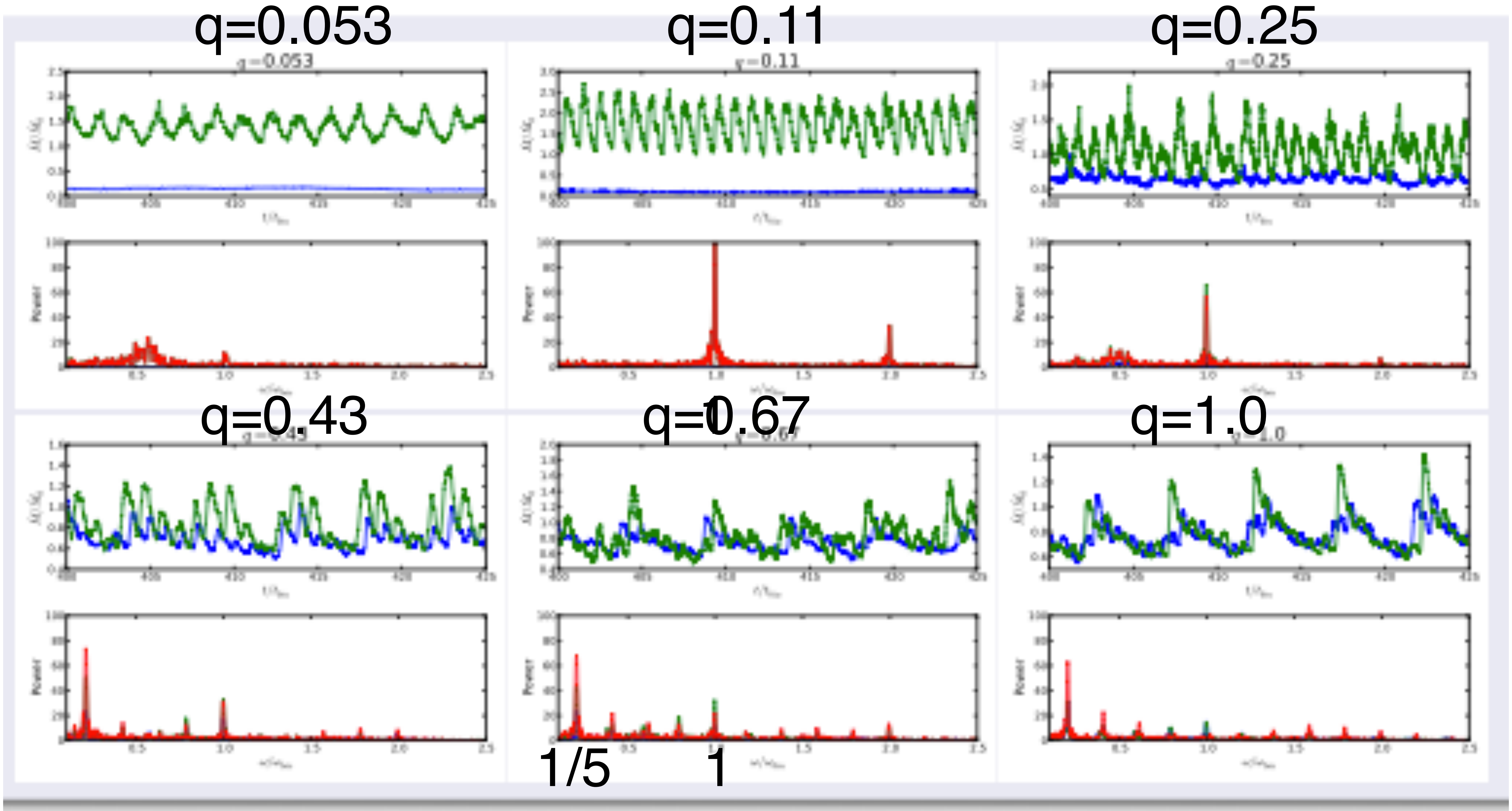
Farris+ (2013)

Binaries are Driven to Equal Mass



Farris+ (2013)

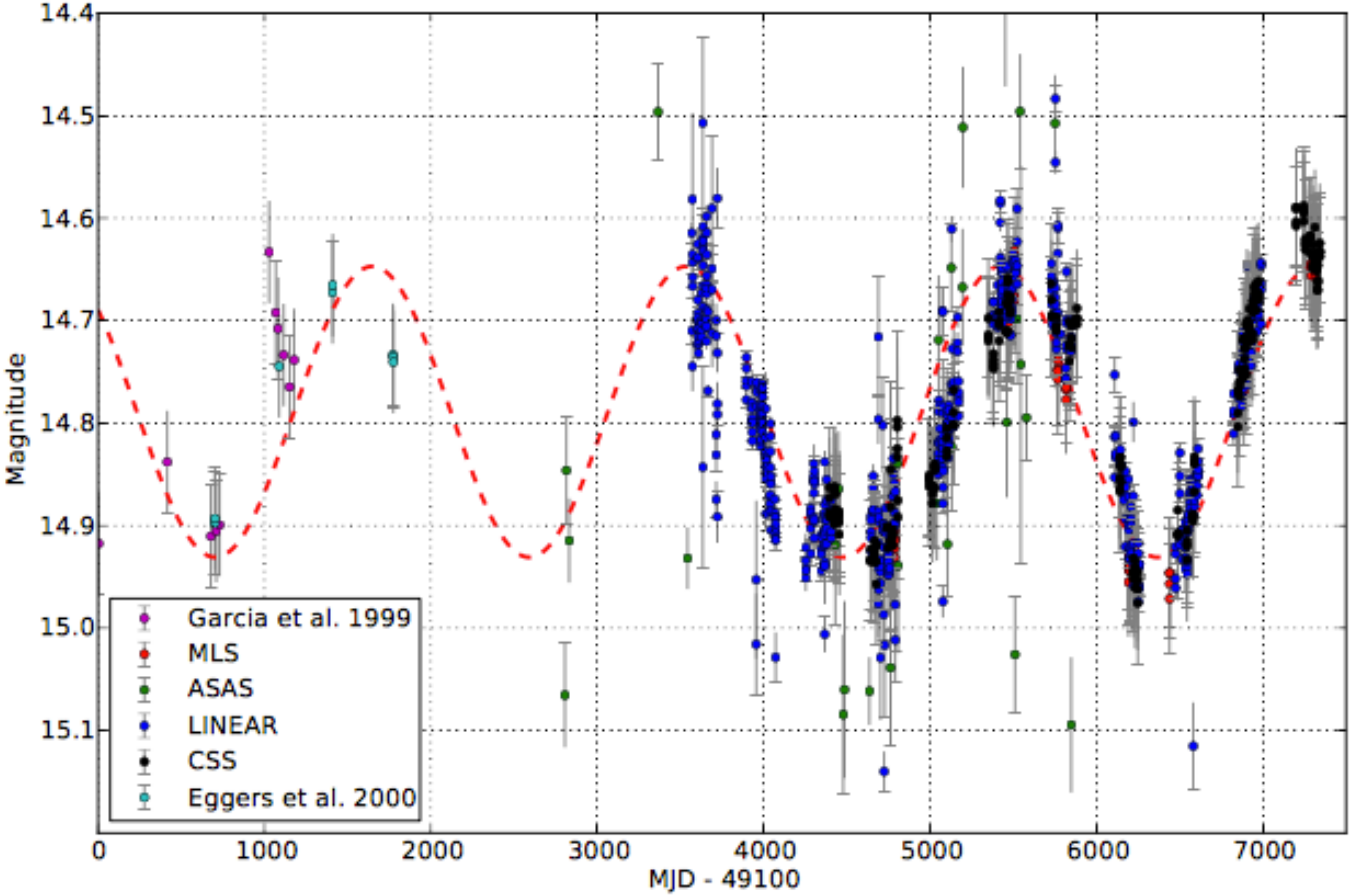
Accretion rate vs. time
Green=secondary Blue=primary Red=Periodogram



Observed Frequency may be LOWER than binary frequency!

Farris+ (2013)

PG 1302-102



Graham+ (Nature, 2015)

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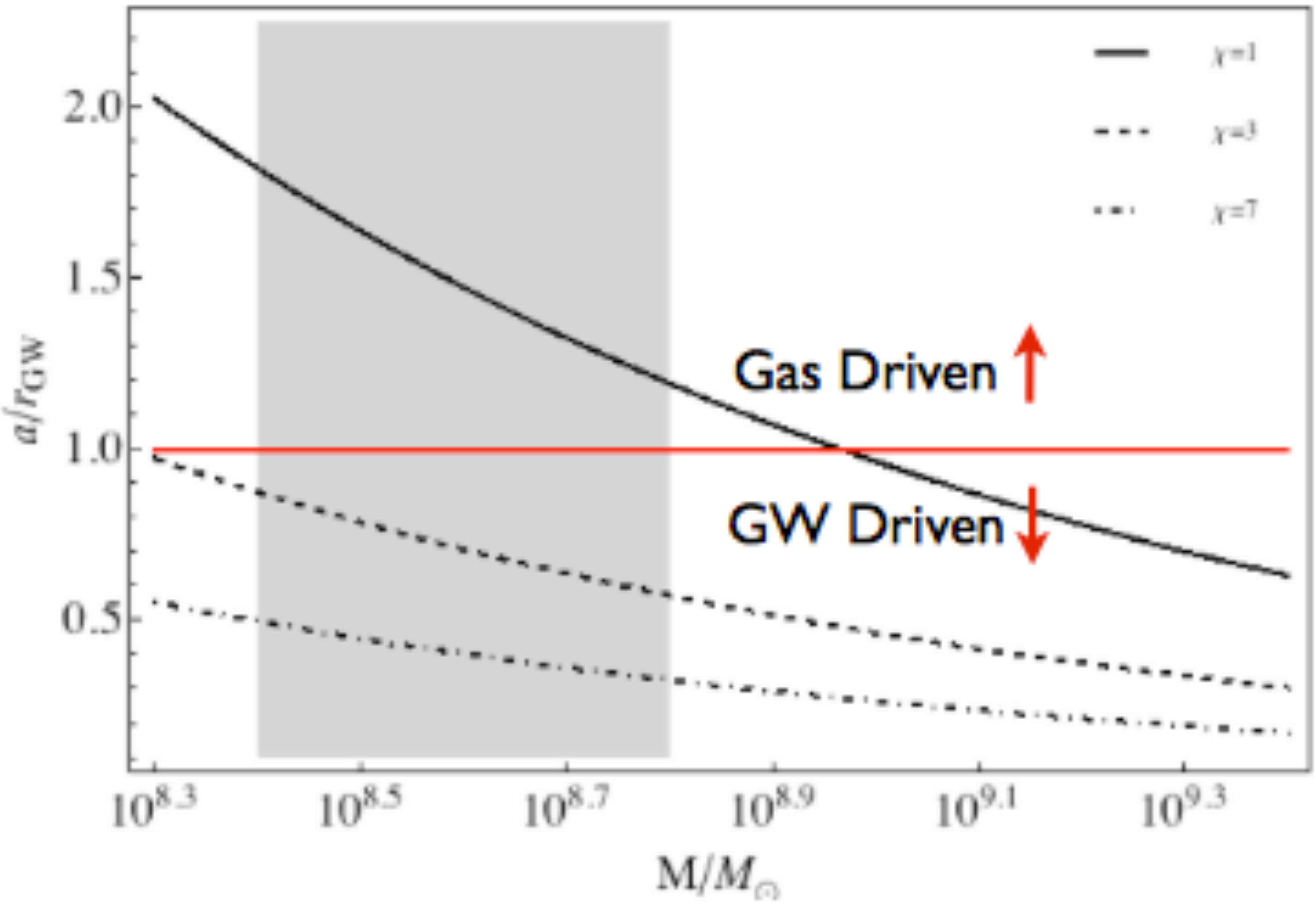
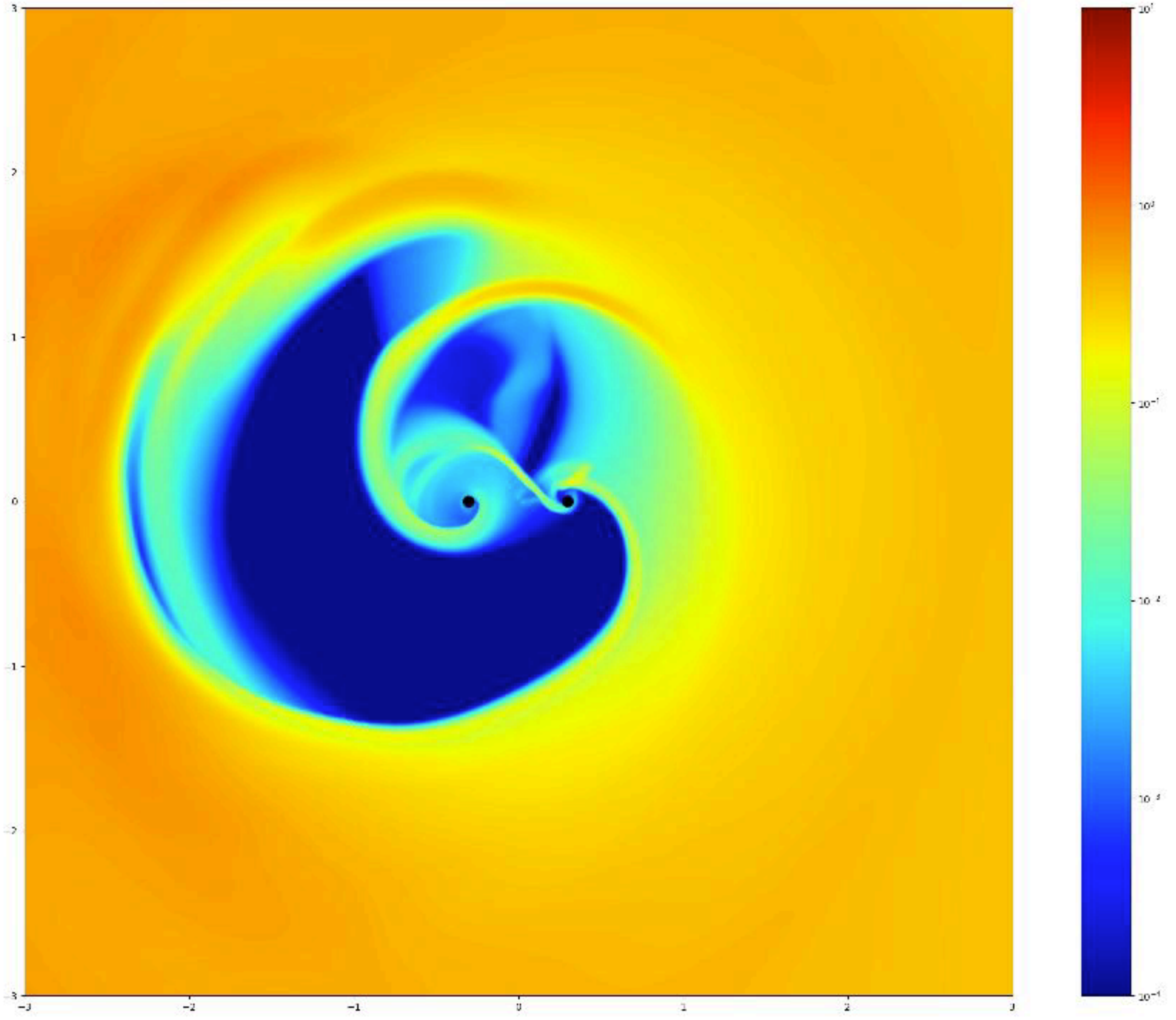
Migration by gas and GW for PG 1302-102



D’Orazio+ (2015)

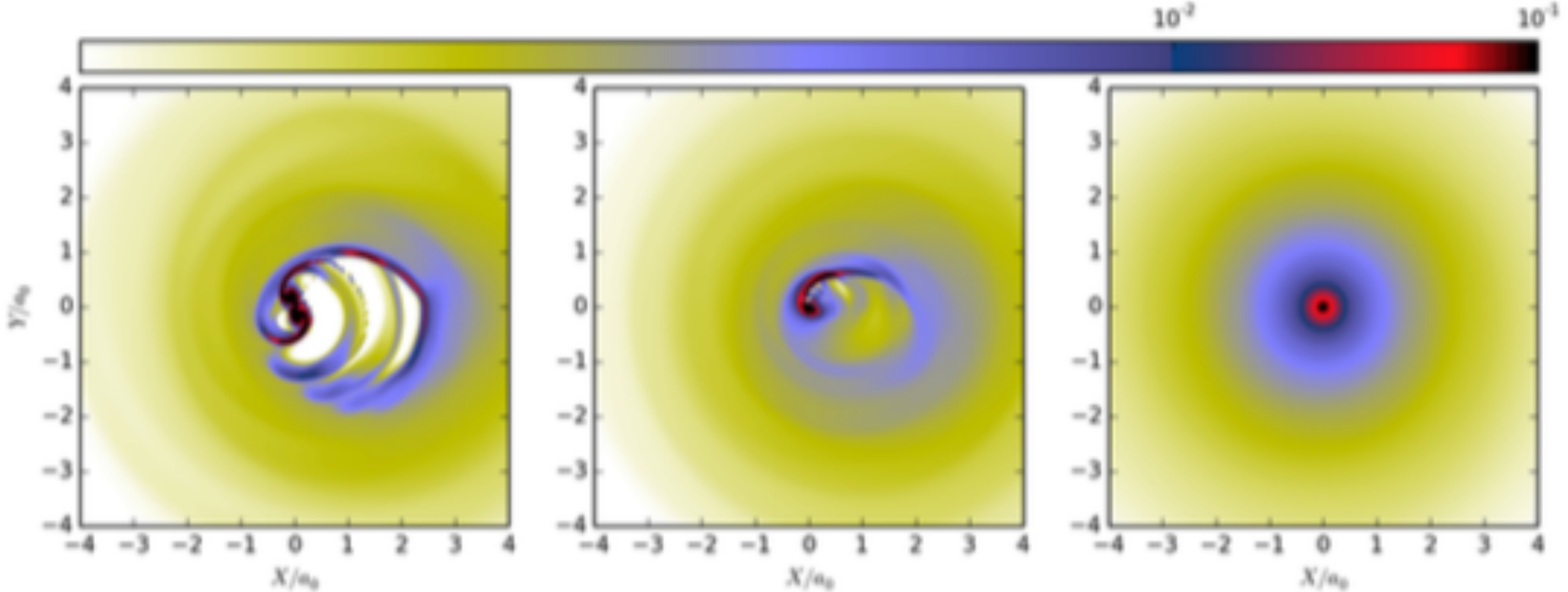
Inspiral due to GW emission: **No Decoupling!**



Tang, Haiman, AM (2018), Noble+ (2012)

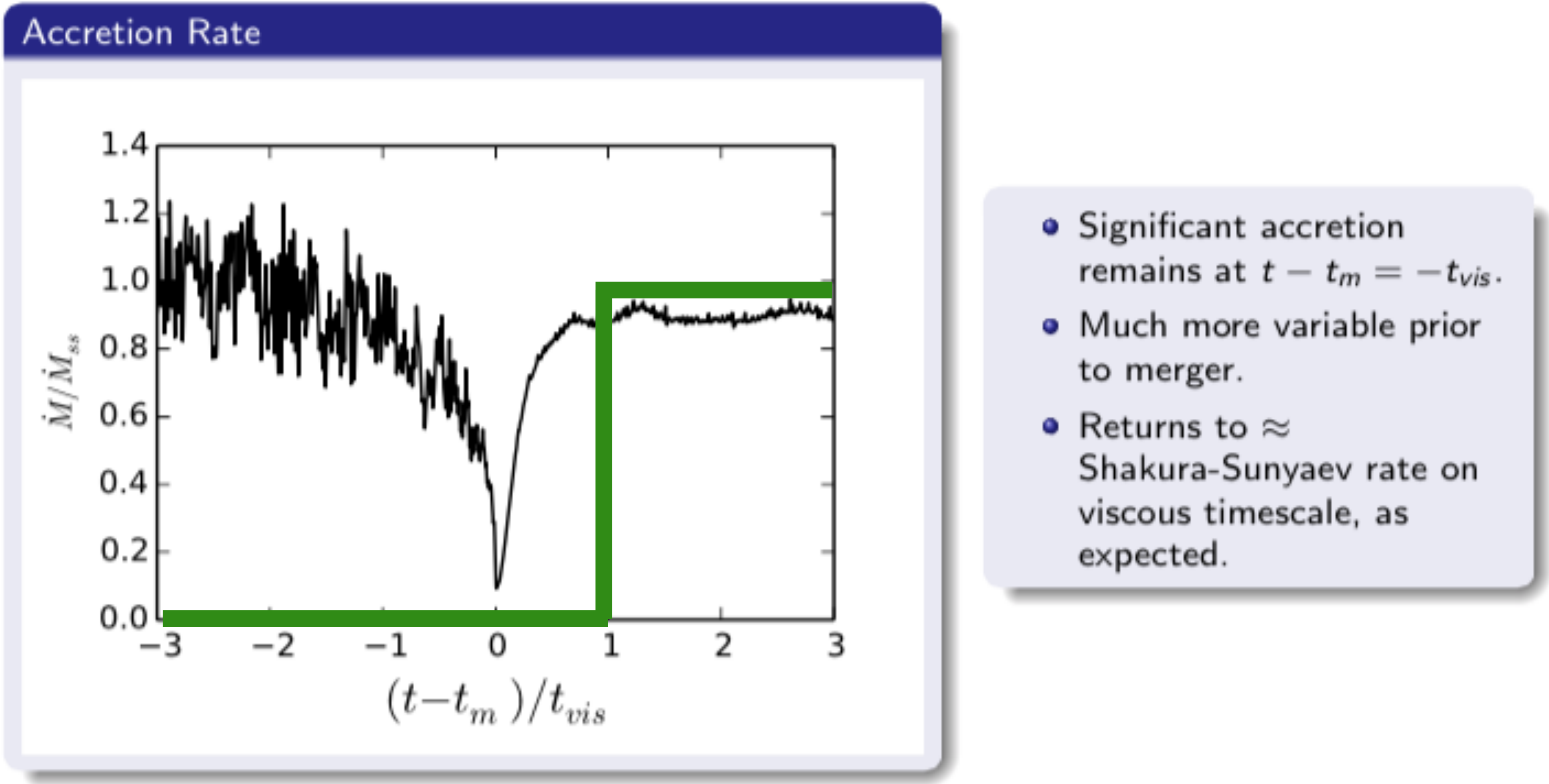
No Decoupling

Spectrum



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

A. MacFadyen (NYU)

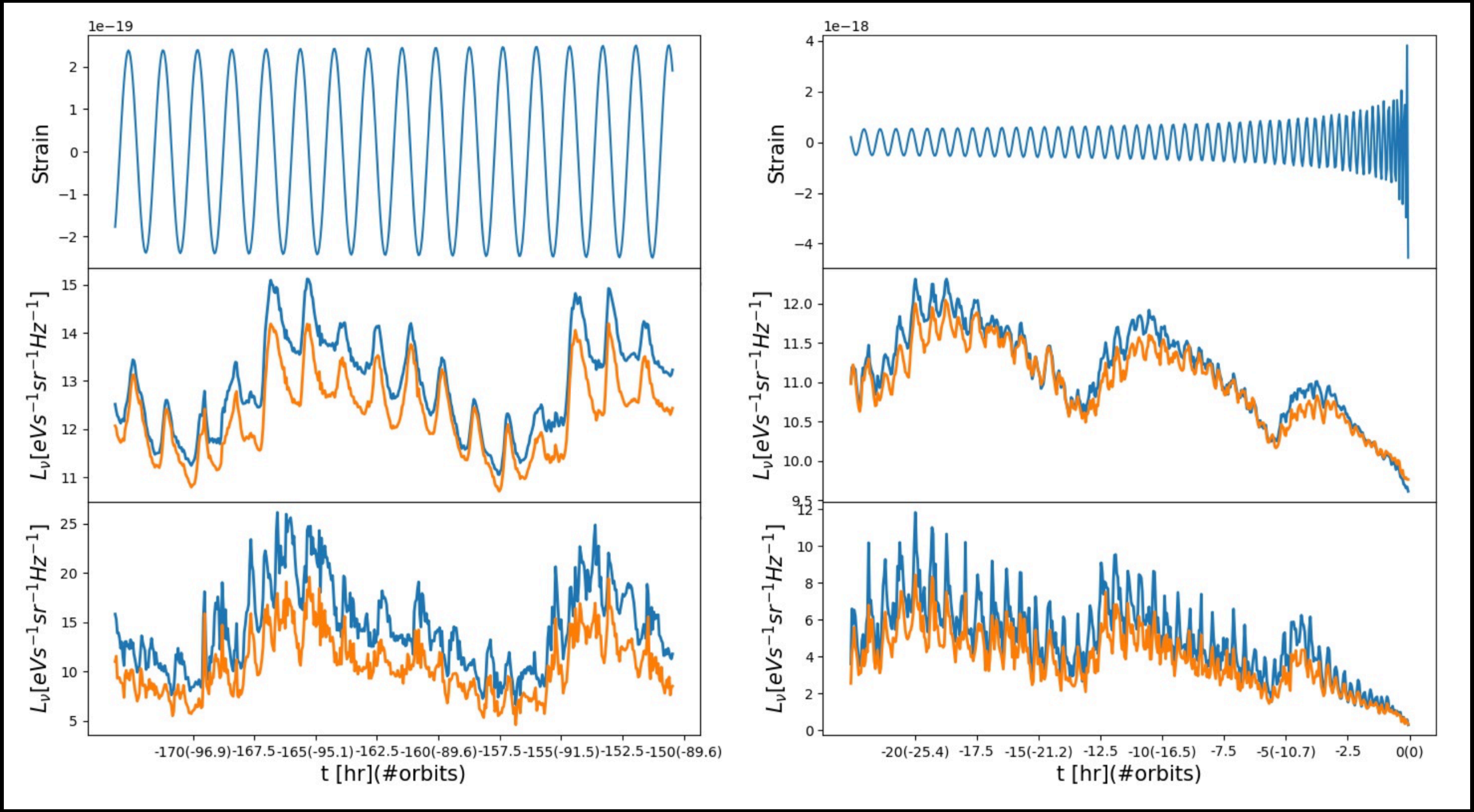


Accretion Rate

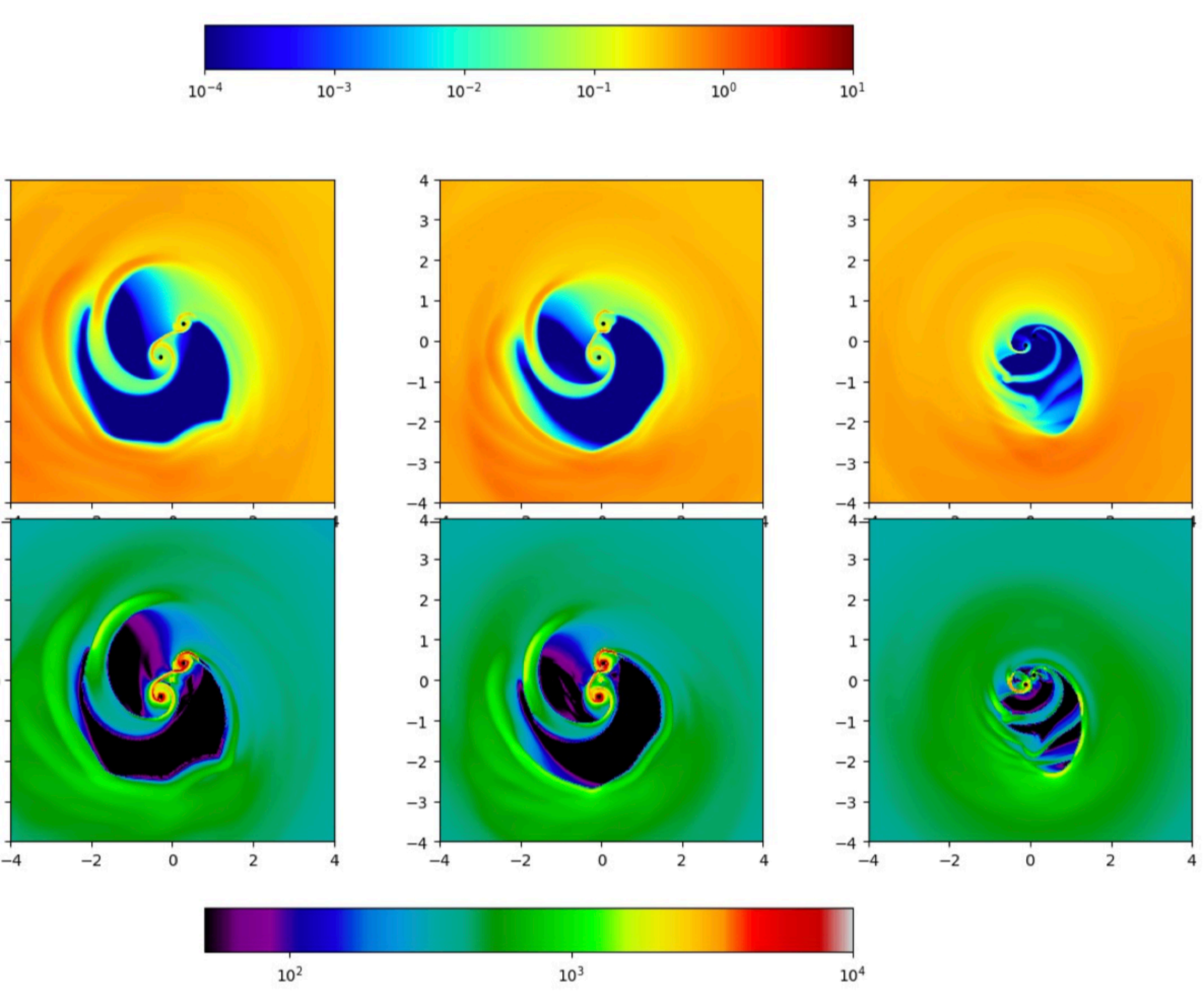
- Significant accretion remains at $t - t_m = -t_{vis}$.
- Much more variable prior to merger.
- Returns to ≈ Shakura-Sunyaev rate on viscous timescale, as expected.

Farris+ (2015)

Photons until Merger!

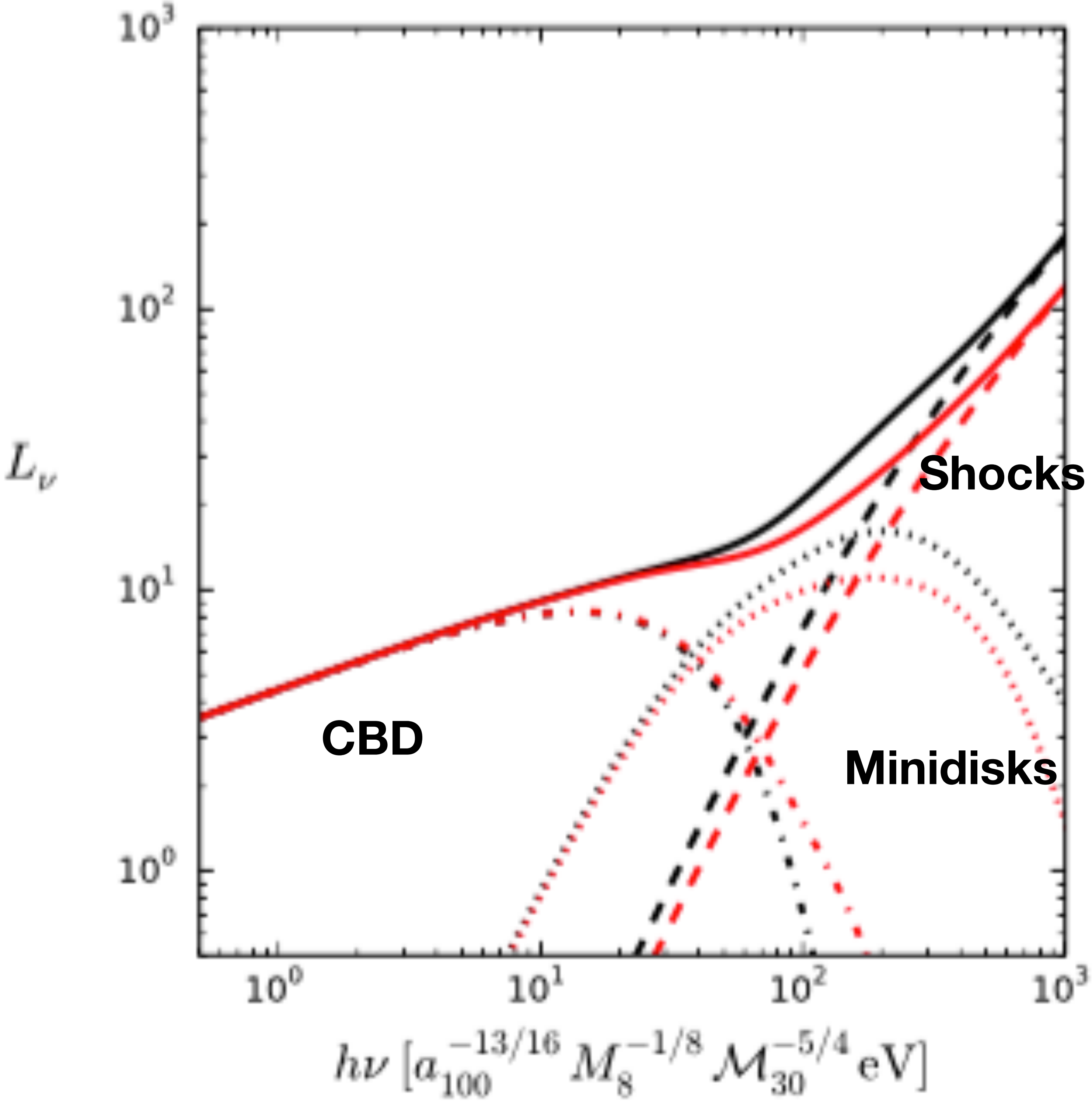


Tang, Haiman & AM (2018)

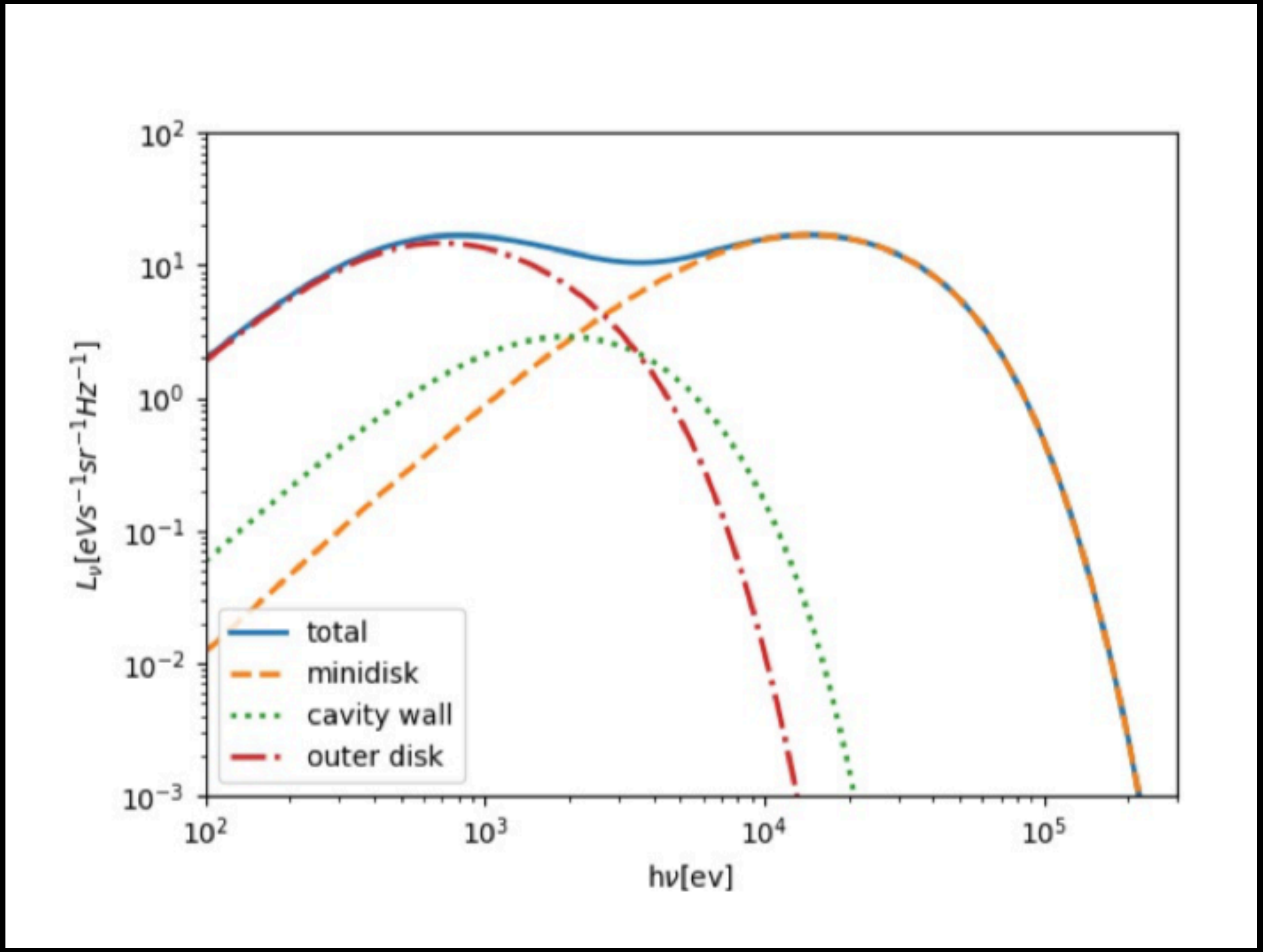


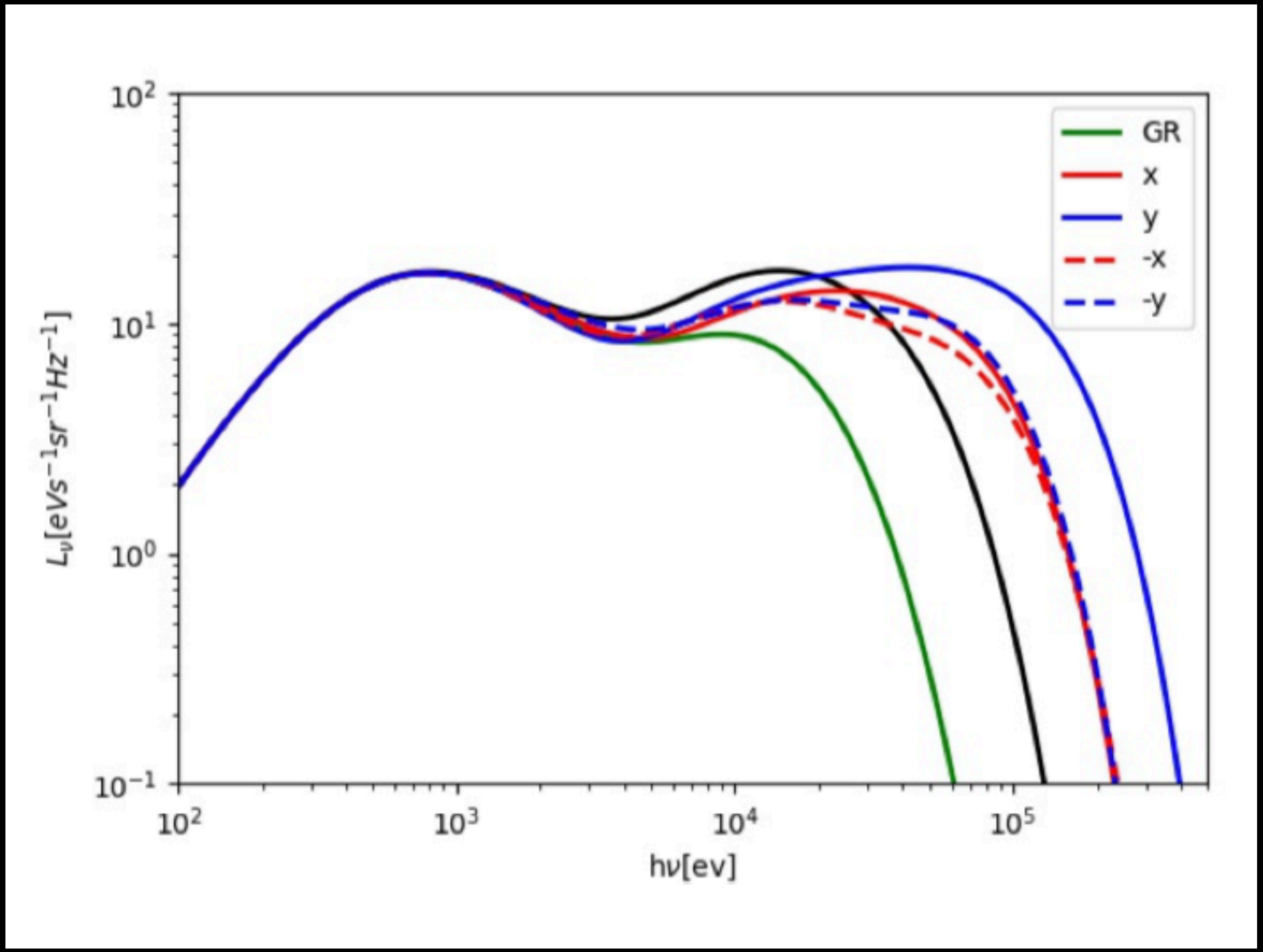
Tang, Haiman & AM (2018)

Spectrum

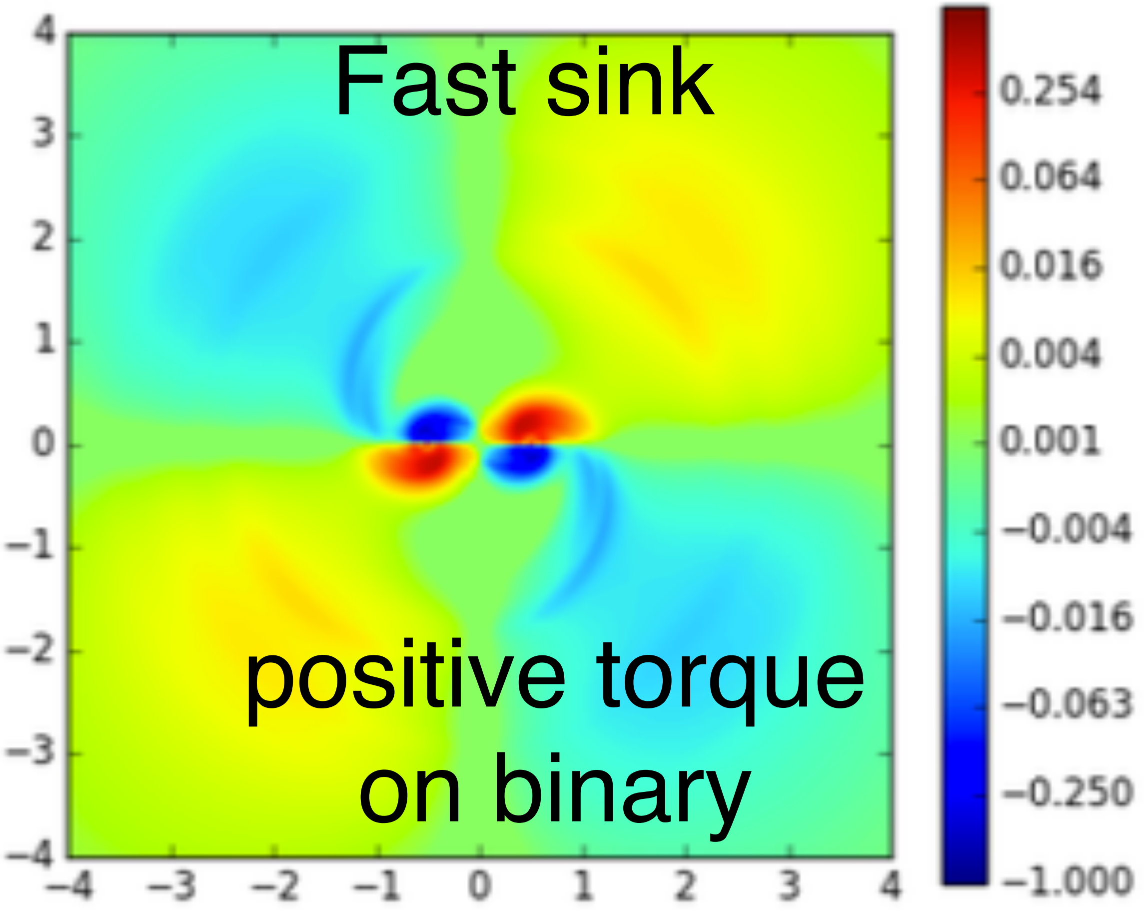


A. MacFadyen (NYU)



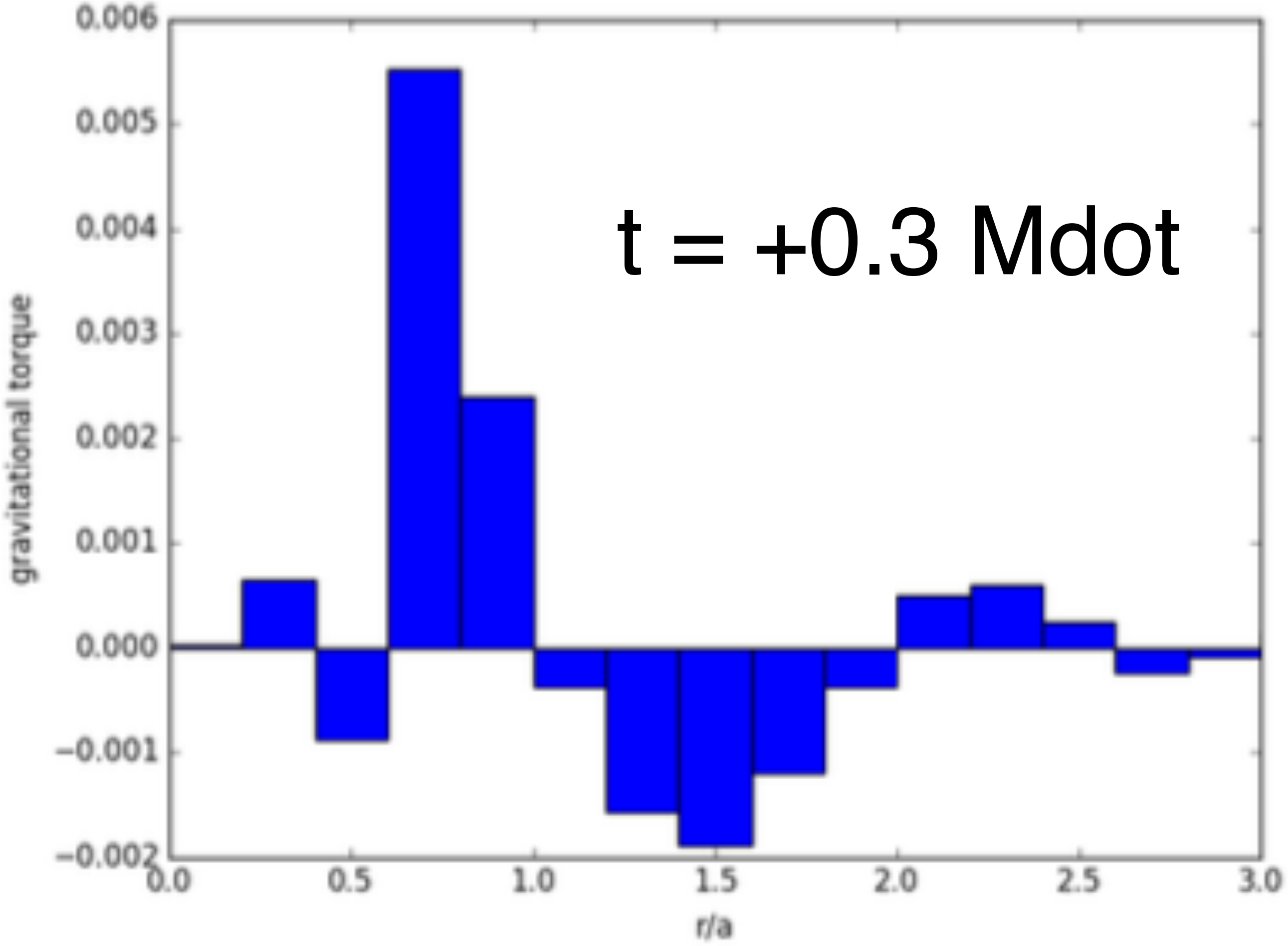


Tang, Haiman & AM (2018)

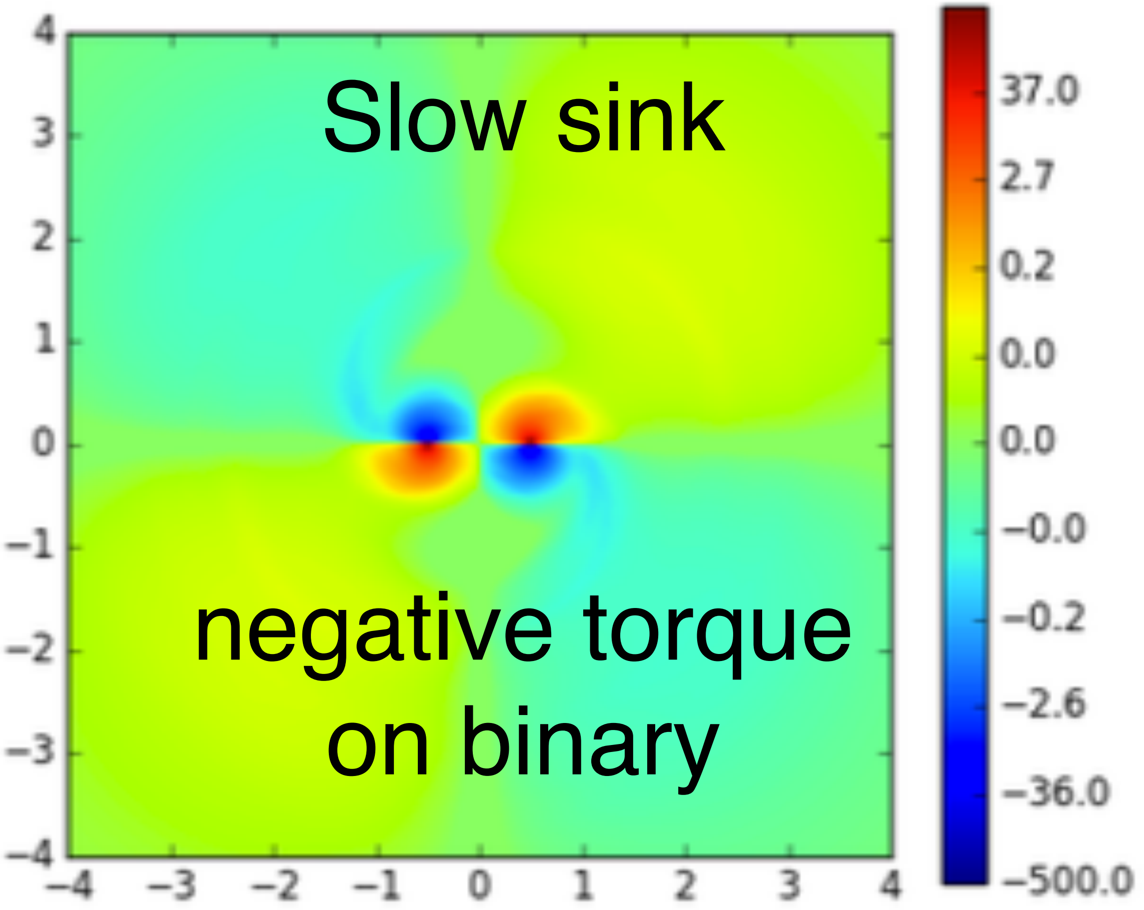


Fast sink

positive torque on binary

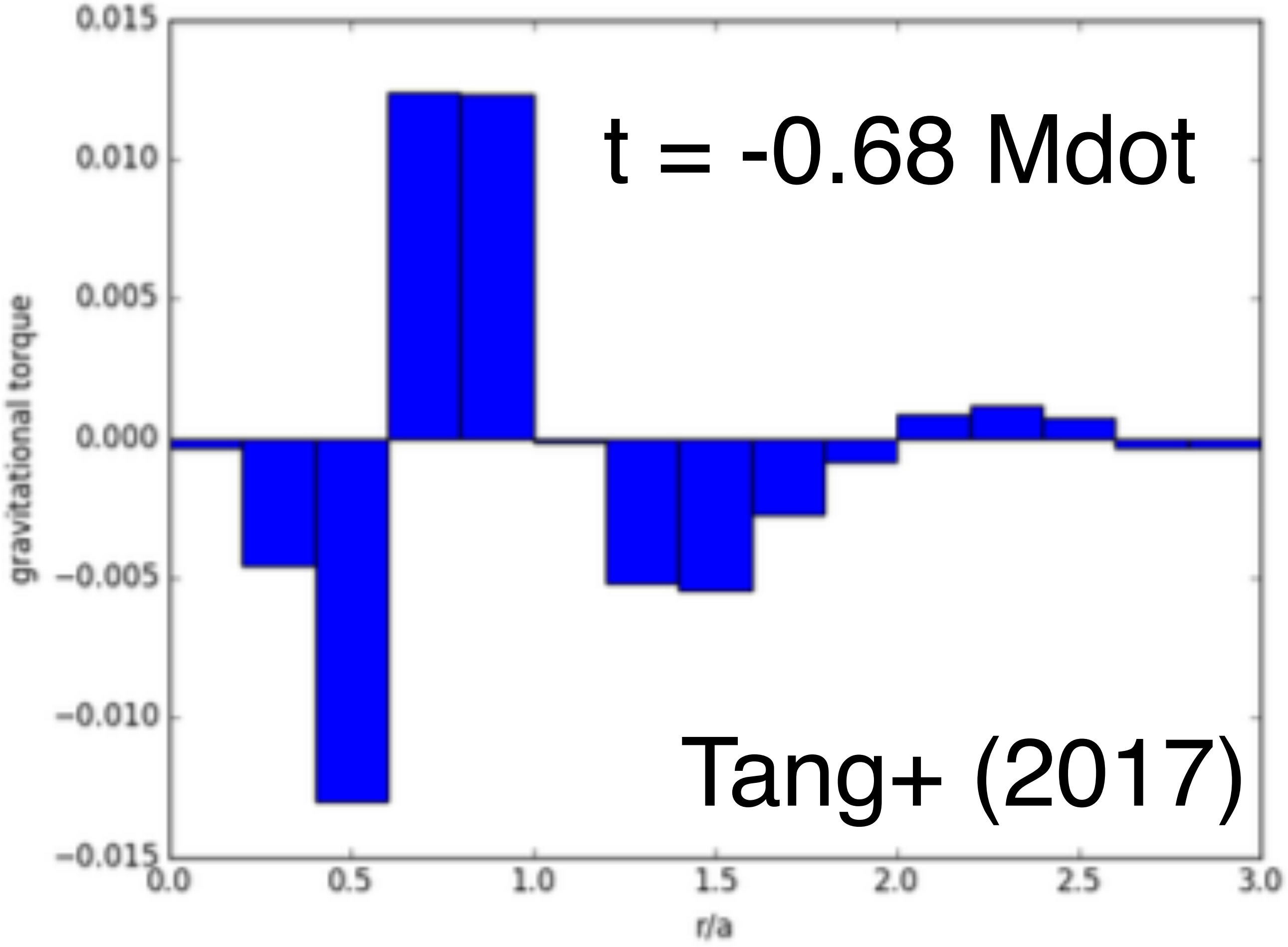


t = +0.3 Mdot



Slow sink

negative torque on binary

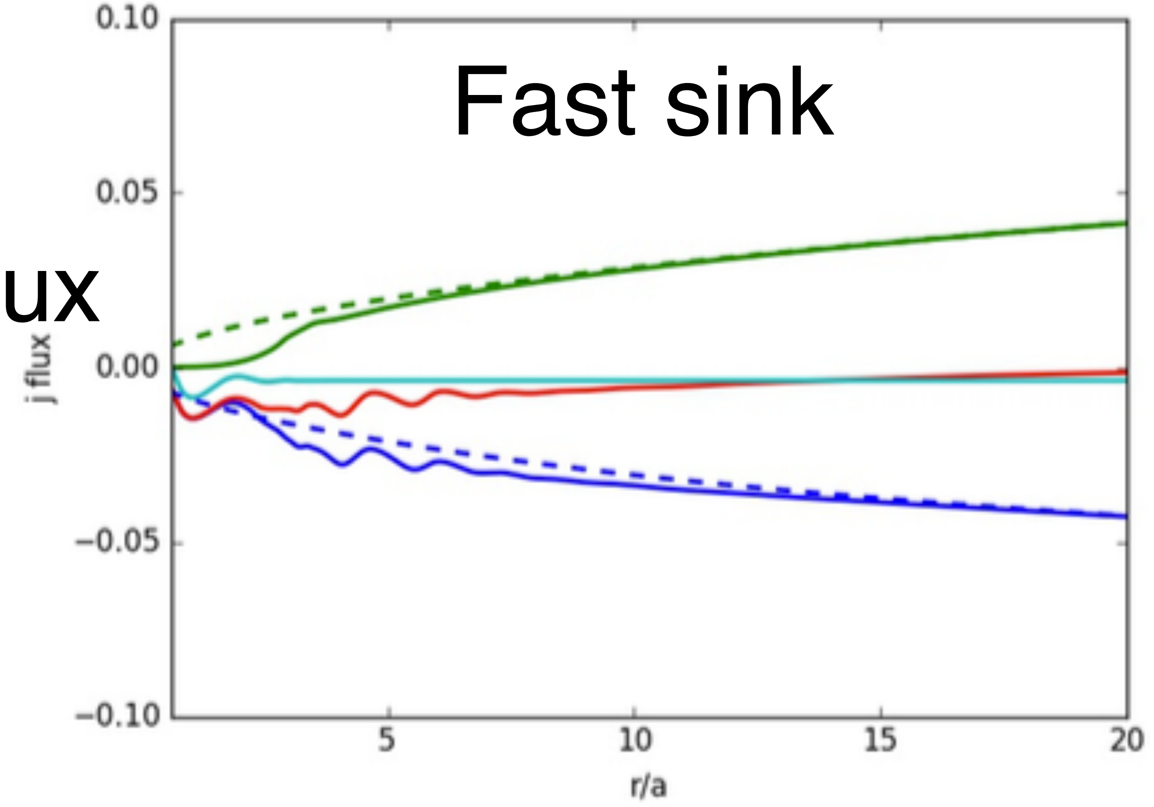


t = -0.68 Mdot

Tang+ (2017)

Angular Momentum Fluxes

j flux



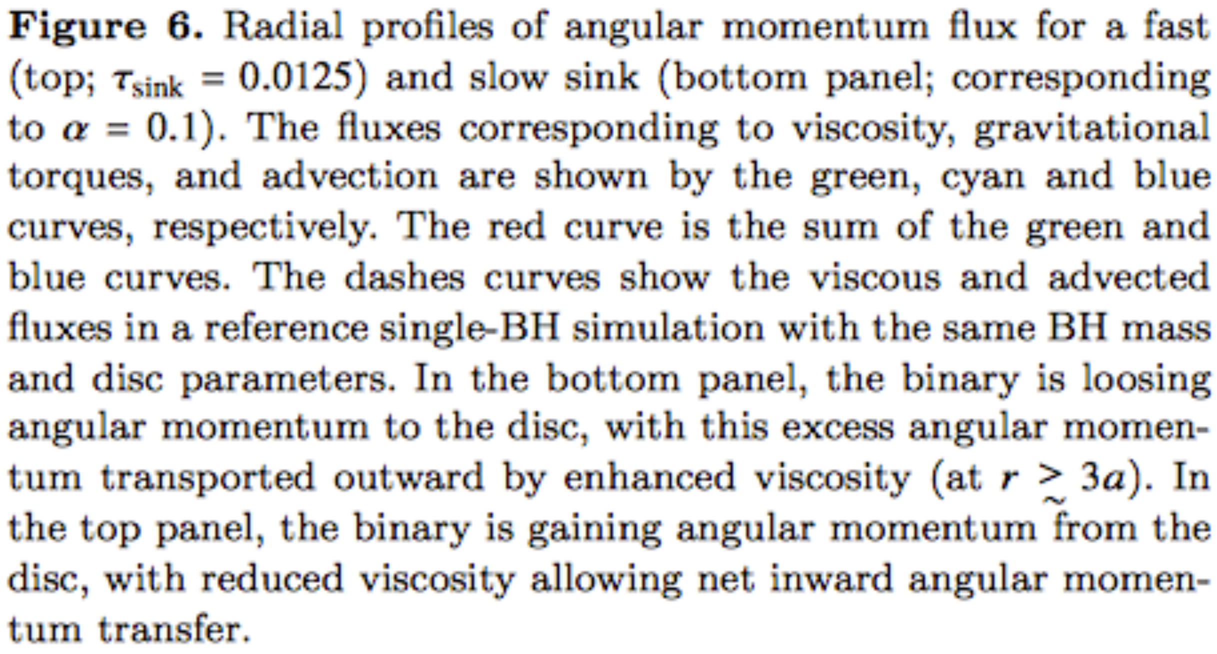
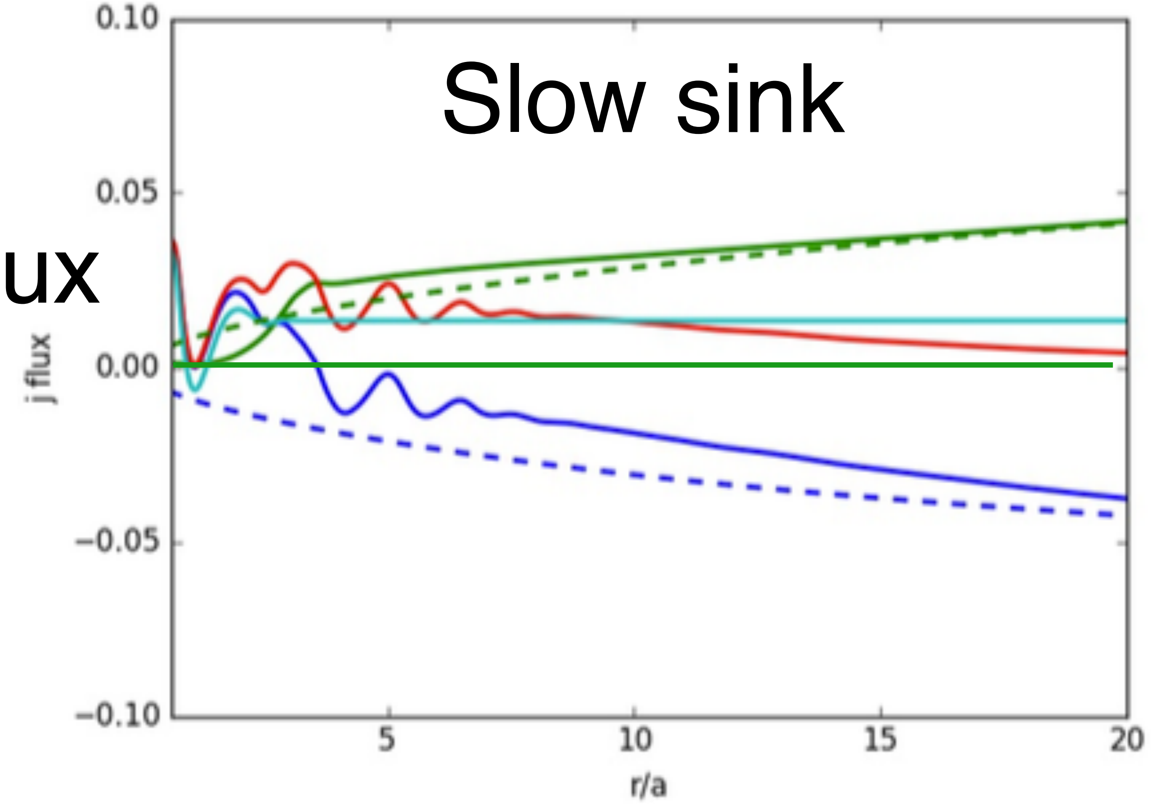


Figure 6. Radial profiles of angular momentum flux for a fast (top; $\tau_{\rm sink} = 0.0125$) and slow sink (bottom panel; corresponding to $\alpha = 0.1$). The fluxes corresponding to viscosity, gravitational torques, and advection are shown by the green, cyan and blue curves, respectively. The red curve is the sum of the green and blue curves. The dashes curves show the viscous and advected fluxes in a reference single-BH simulation with the same BH mass and disc parameters. In the bottom panel, the binary is loosing angular momentum to the disc, with this excess angular momentum transported outward by enhanced viscosity (at $r \gtrsim 3a$). In the top panel, the binary is gaining angular momentum from the disc, with reduced viscosity allowing net inward angular momentum transfer.

j flux



r/a

viscosity

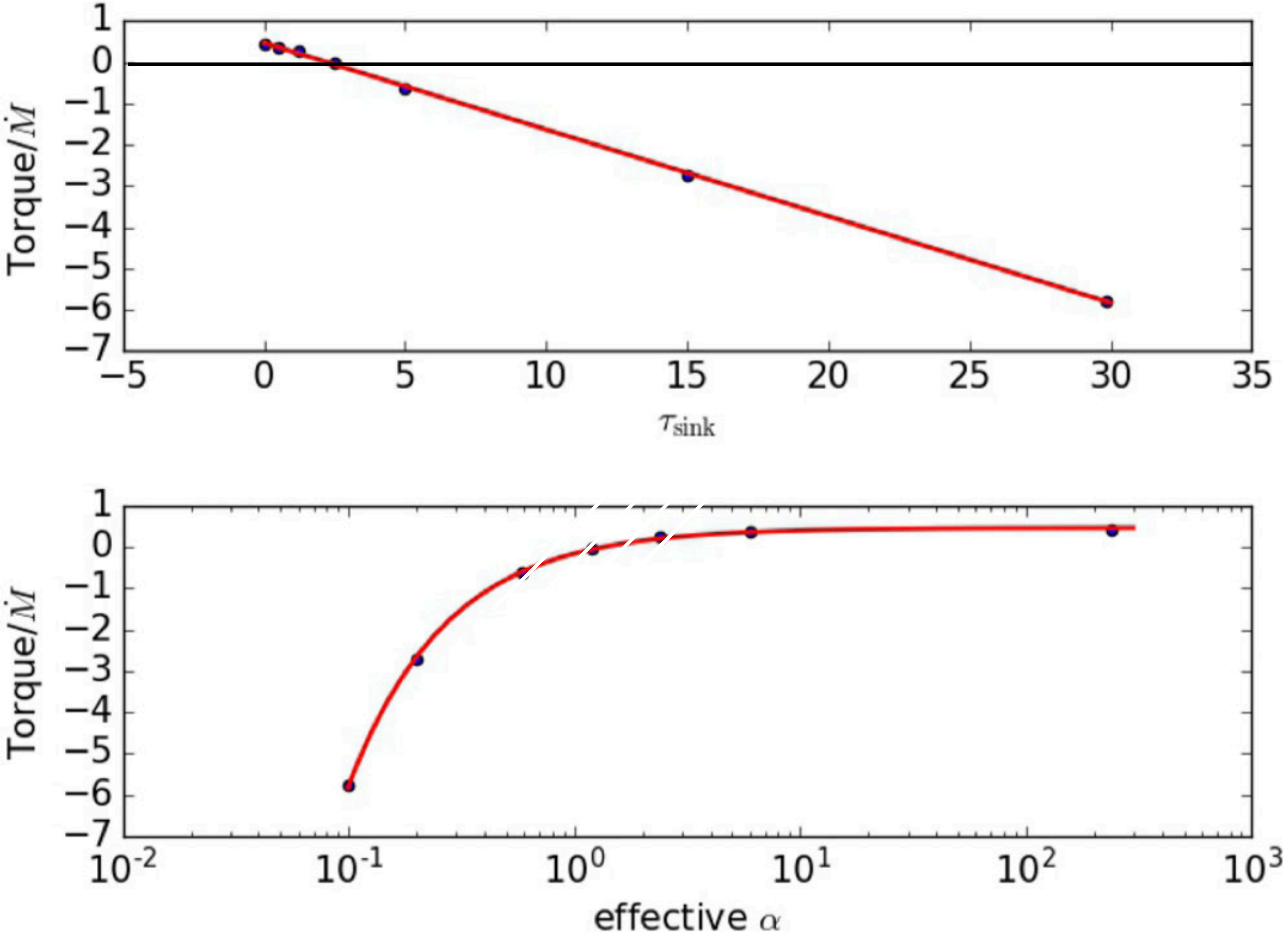
gravity

viscosity+advection

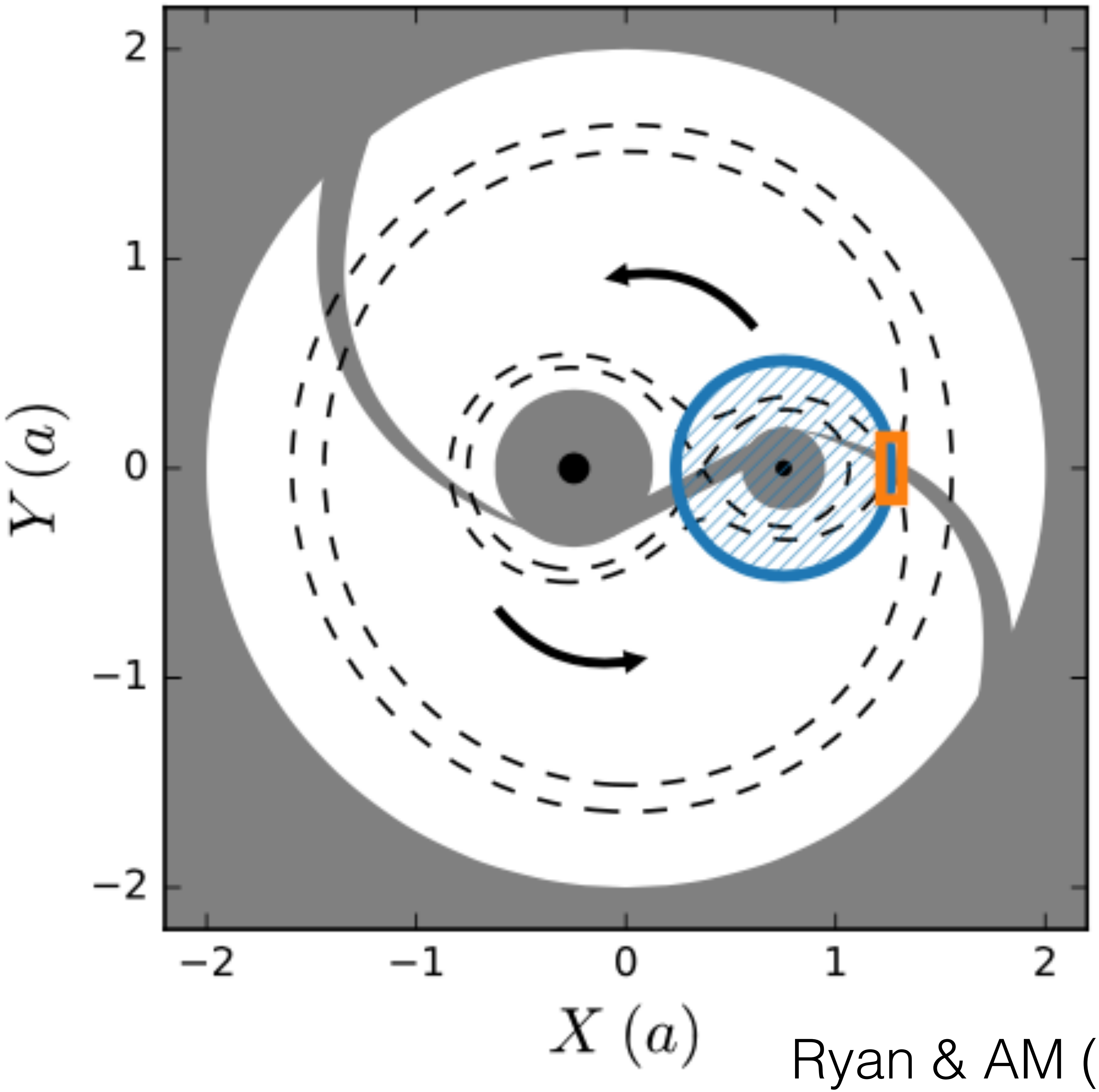
advection

Tang, AM & Haiman (2017)

Positive Torque for Fast Sink

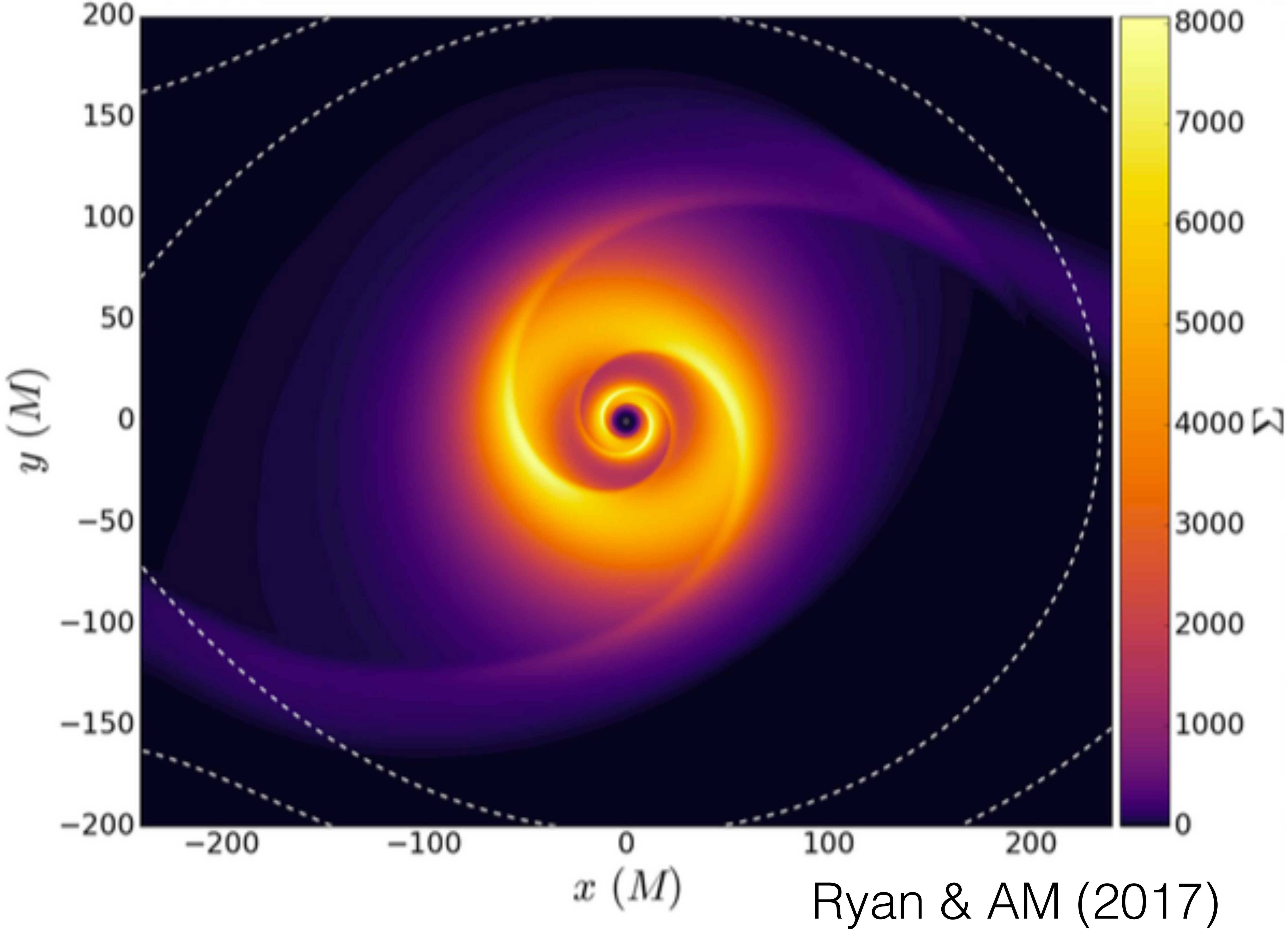


Tang, AM & Haiman (2017)



Ryan & AM (2017)

Accretion due entirely to Spiral Shock (no MRI)



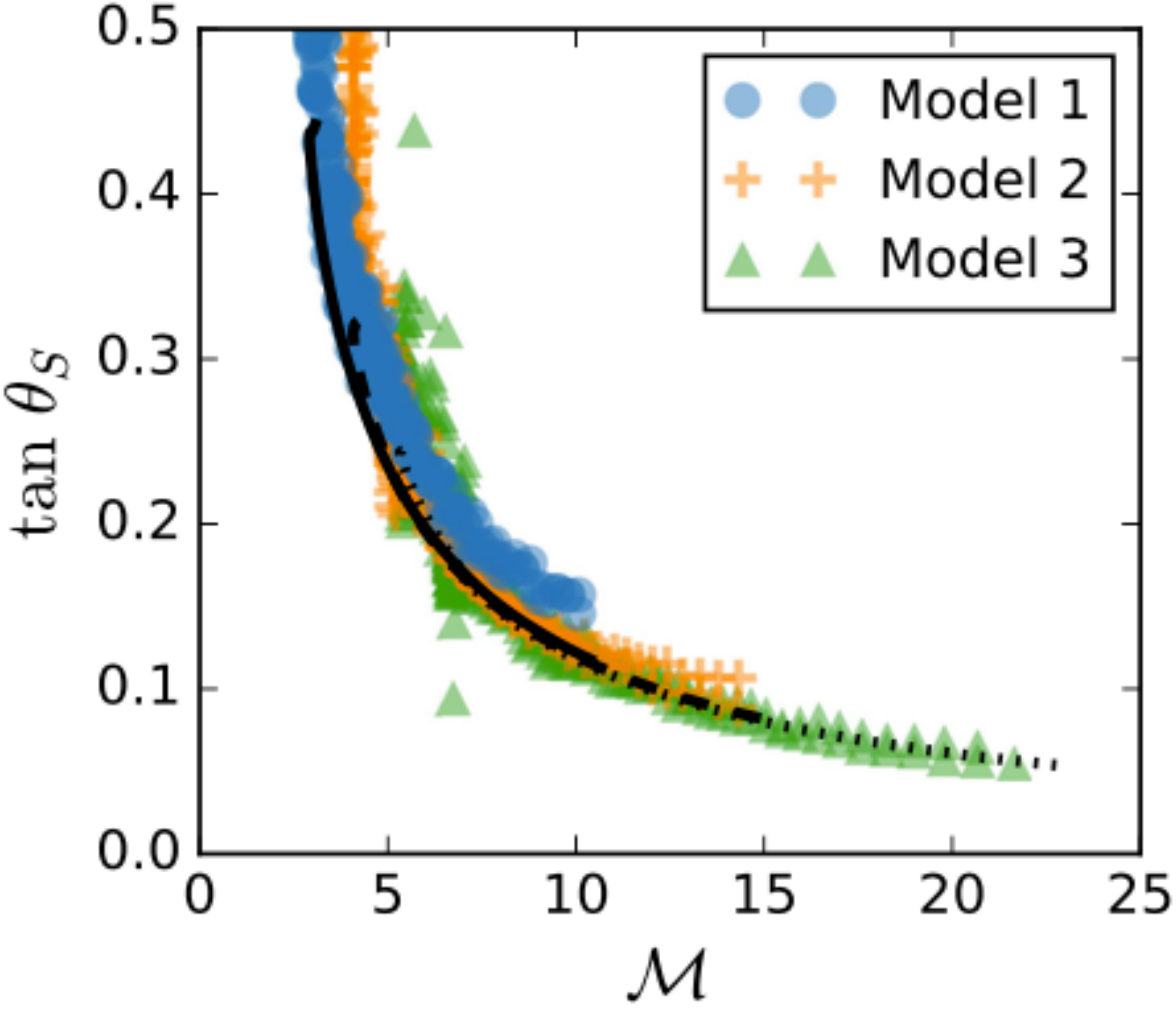
Ryan & AM (2017)

DISPERSION RELATION

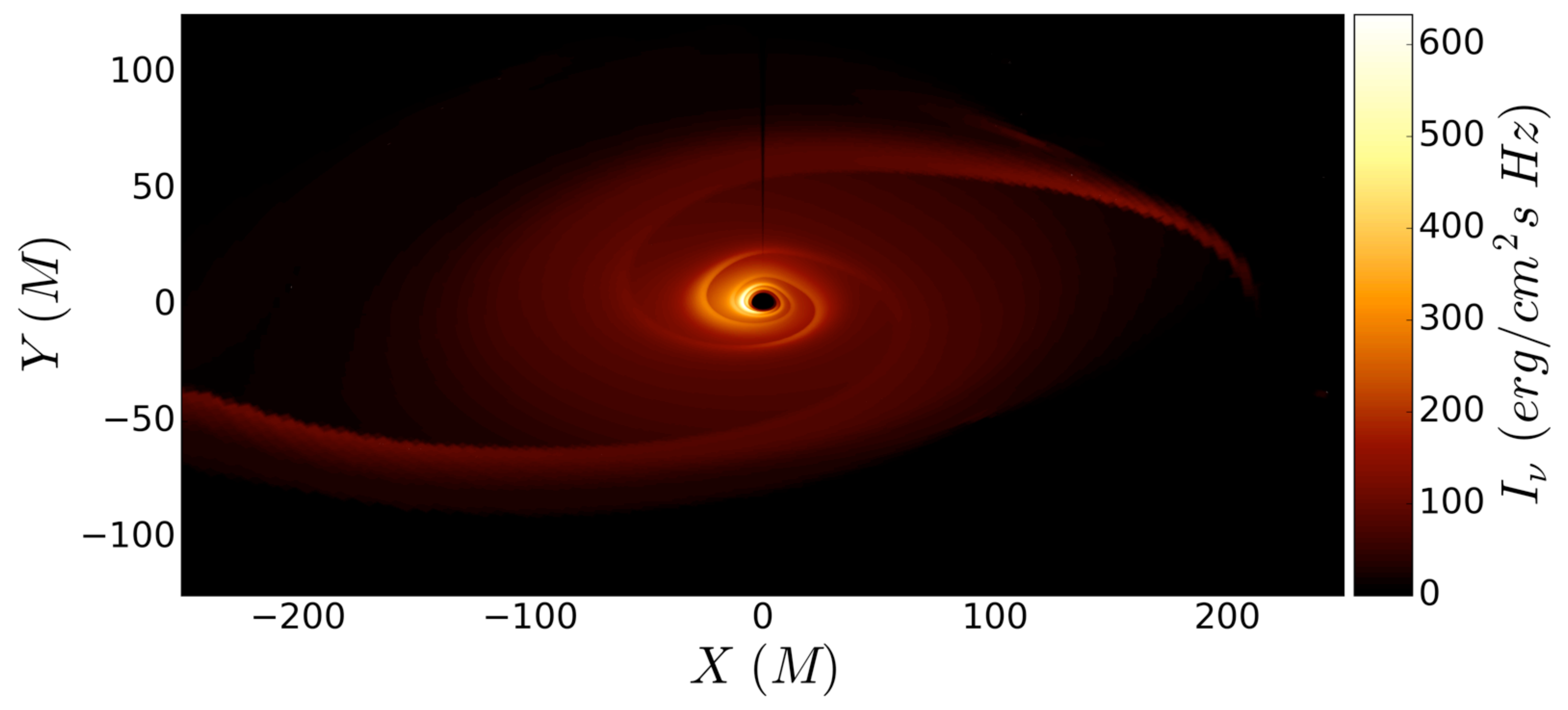
Binney & Tremaine:
Tightly wound spiral
density waves

$$\tan\theta_S \propto \frac{c_s}{r\Omega} = \mathcal{M}^{-1}$$

Pitch Angle in GR



EMISSION



$Y\ (M)$
100
50
0
−50
−100
−200
−100
0
100
200
$X\ (M)$
600
500
400
300
200
100
0
$I_\nu\ (erg/cm^2 s\ Hz)$

Conclusions

- Binary black holes can accrete & until merger ->EM+GW
- Multi-period light curves ~5:1
- Gas torques can be positive
- Mini-disks accrete by spiral shocks (no MRI required)