

Massive black hole binary mergers within sub-pc scale gas discs

MNRAS, in press (arXiv:0809.0311)

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Galaxies and Super-Massive Black Holes

- Super-massive black holes at the centre of most galaxies.
- Galaxies merge to create larger galaxies.
- Do the black holes also merge?
- Indirect evidence (e.g., $M-\sigma$ relation) suggests they do!



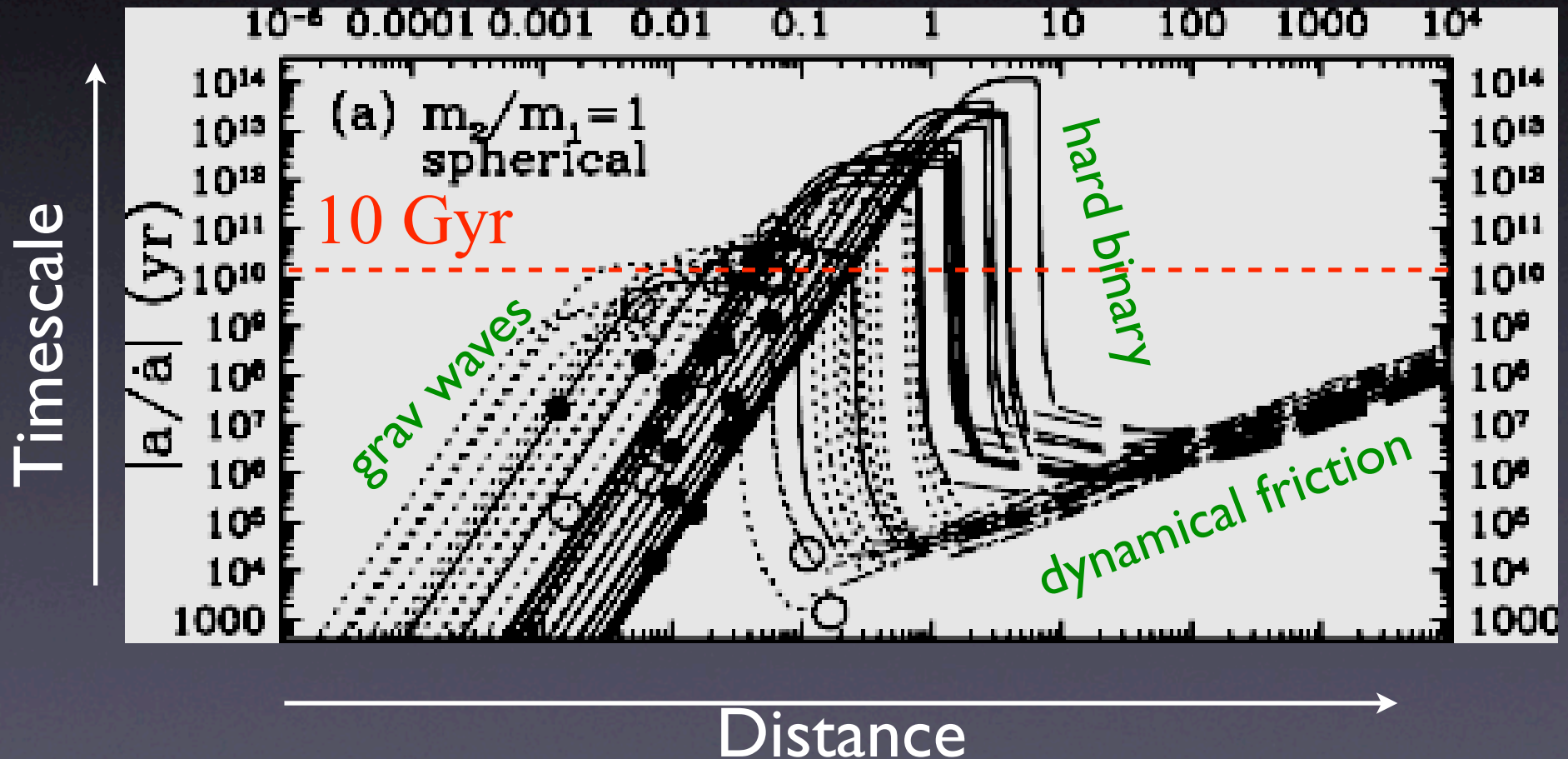
Formation And Evolution of SMBH Binaries

Begelman et al 1980

1. Black holes sink due to dynamical friction
2. Binary forms and hardens kicking stars out
3. Gravitational waves release remaining energy and produce the coalescence

“Last Parsec Problem”

Milosavljevic & Merritt 2001; Yu 2002



Effect of gas?

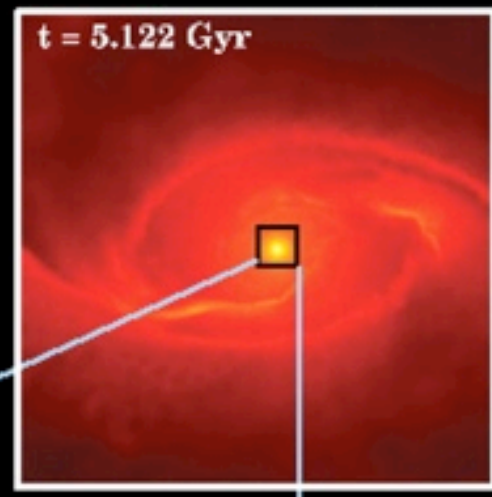
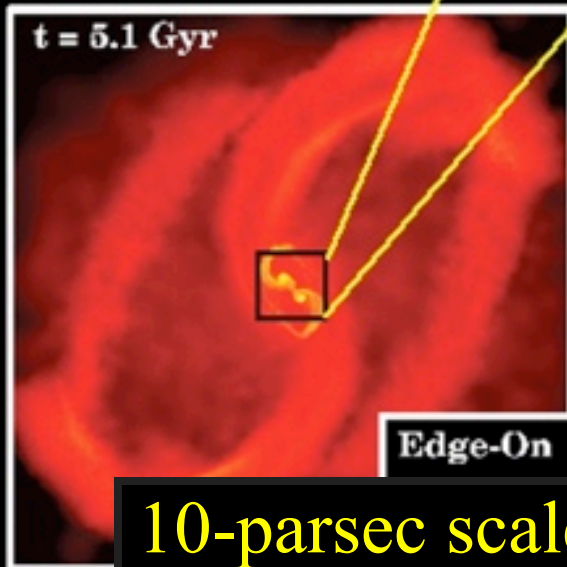
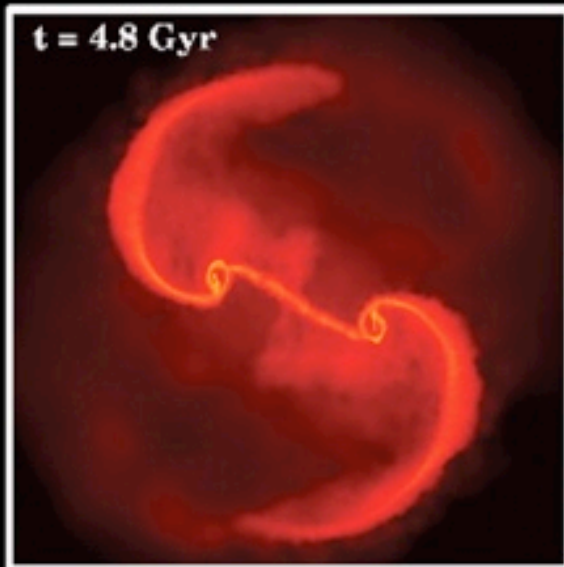
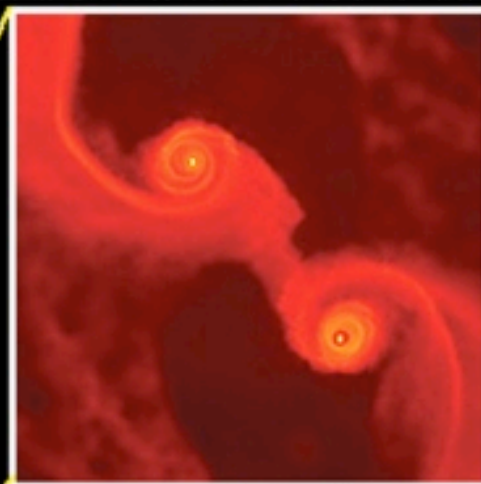
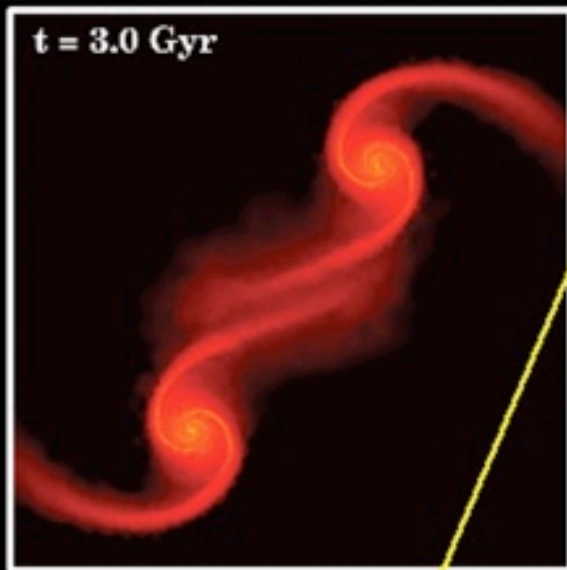
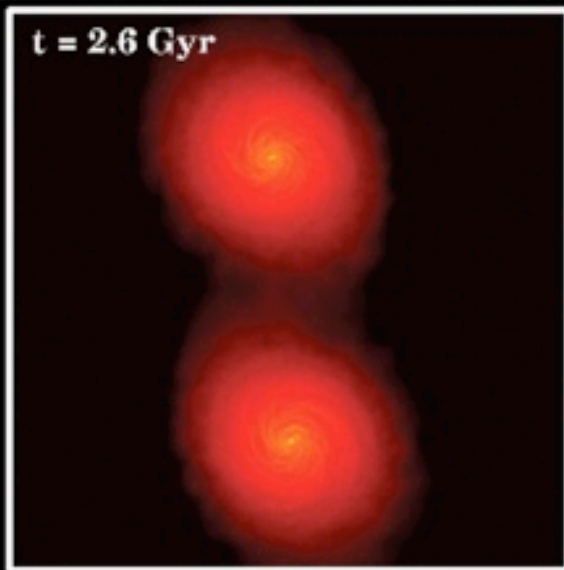
- Stars apparently fail to produce a merger, maybe gas can help.

- Presence of gas can also create luminous counterpart to grav wave signal, helping to identify them.

(e.g., Armitage & Natarajan 02; Milosavljević & Phinney 05; Lippai et al. 08)

- Galaxy merger studies show gas brings black holes to the inner few parsecs fast!

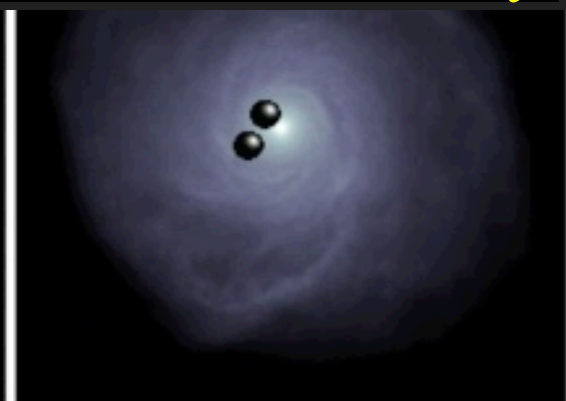
(e.g., Escala et al. 04, 05; Mayer et al 08)



Edge-On

Face-On

10-parsec scale disc forms around the binary



Mayer et al 2008

Massive Nuclear Discs

Gammie 2001; Rice, Lodato, Armitage, et al 2005, etc

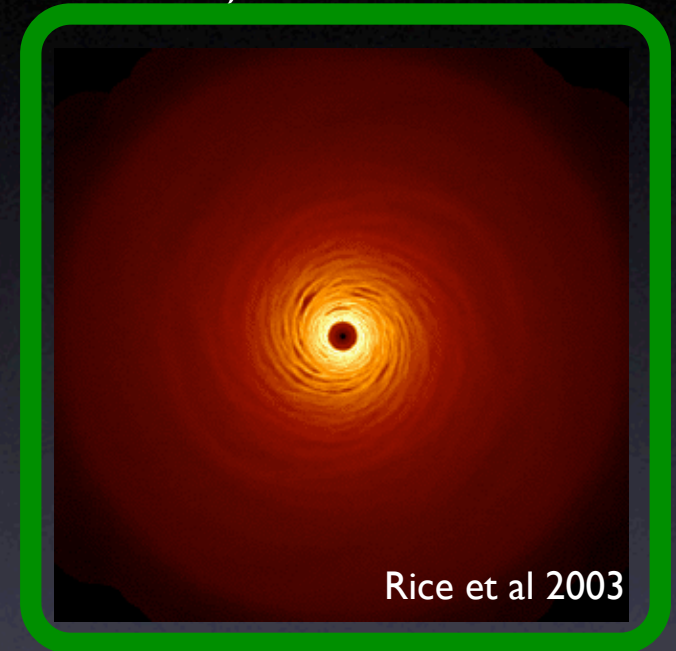
- Discs will be unstable to self-gravity

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \sim \frac{H}{R} \frac{M_{BH}}{M_{disc}} < 1$$

- Two possibilities:

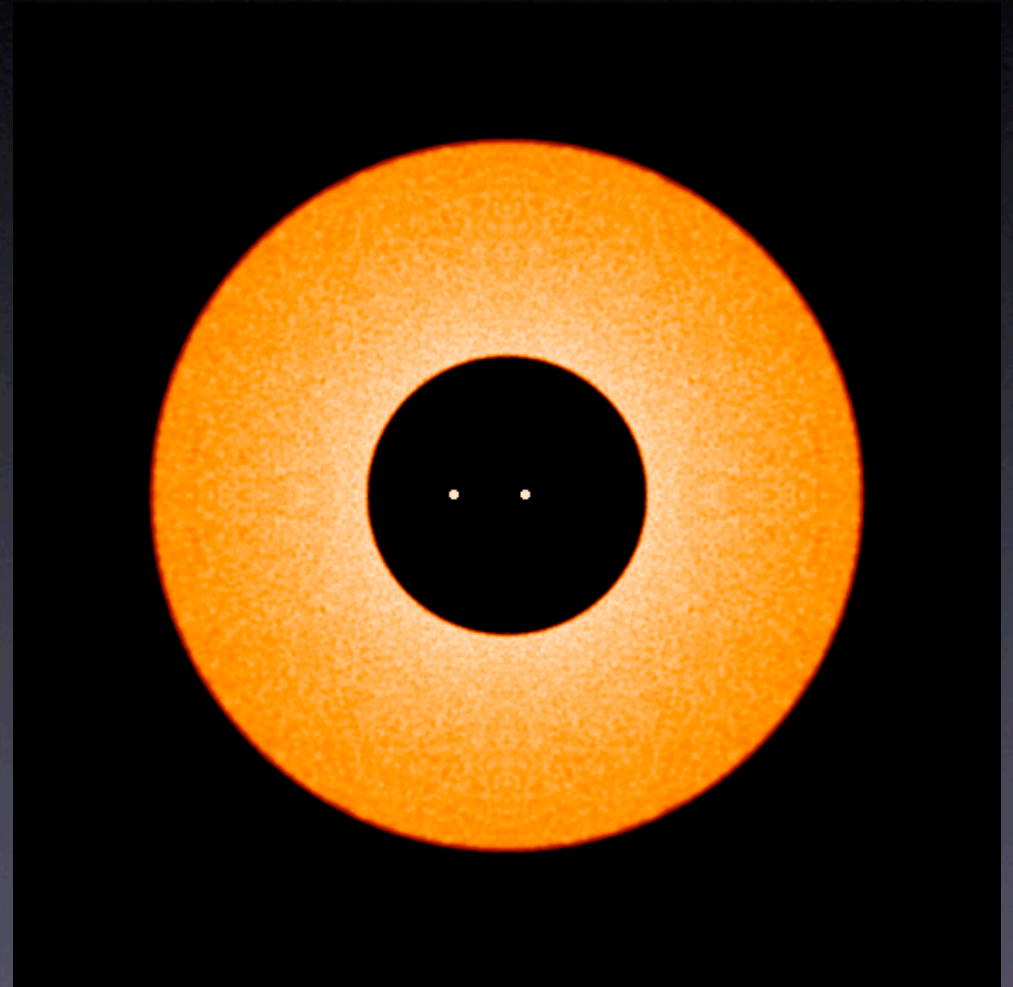
- slow cooling:
transport angular momentum

- fast cooling:
fragmentation and star formation



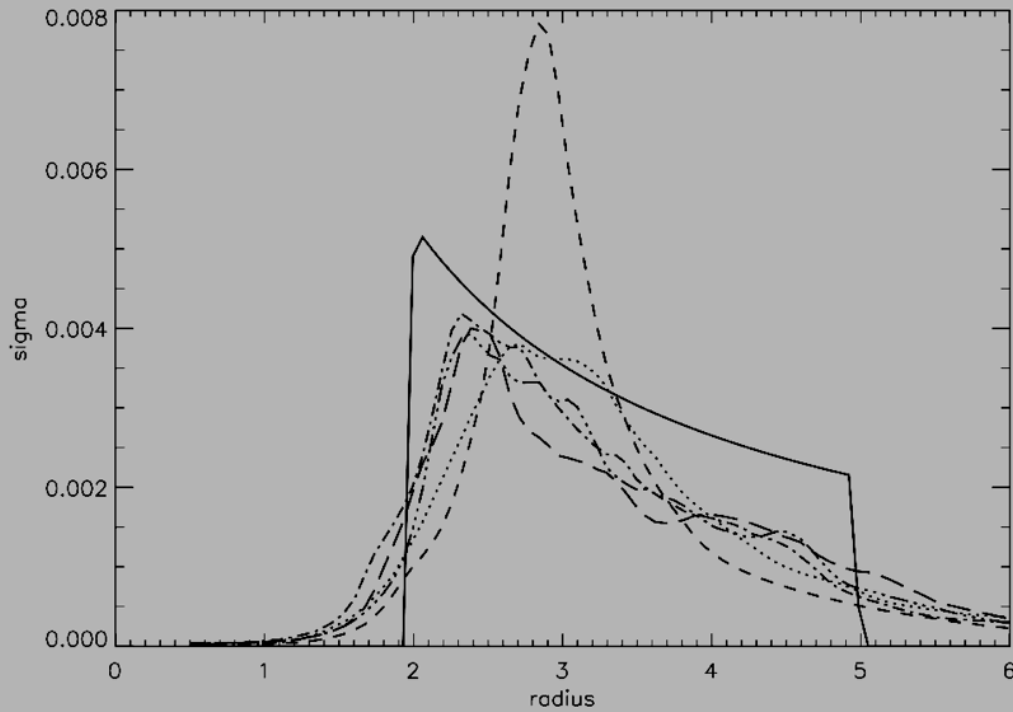
Numerical Models

- 3:1 mass ratio binary
- $M_{\text{disc}} = 0.2 M_{\text{BH}}$
- Prescribe slow cooling
- **Physical** angular momentum transport due to self-gravity
- Modified Gadget-2 (SPH code by Springel 2005)

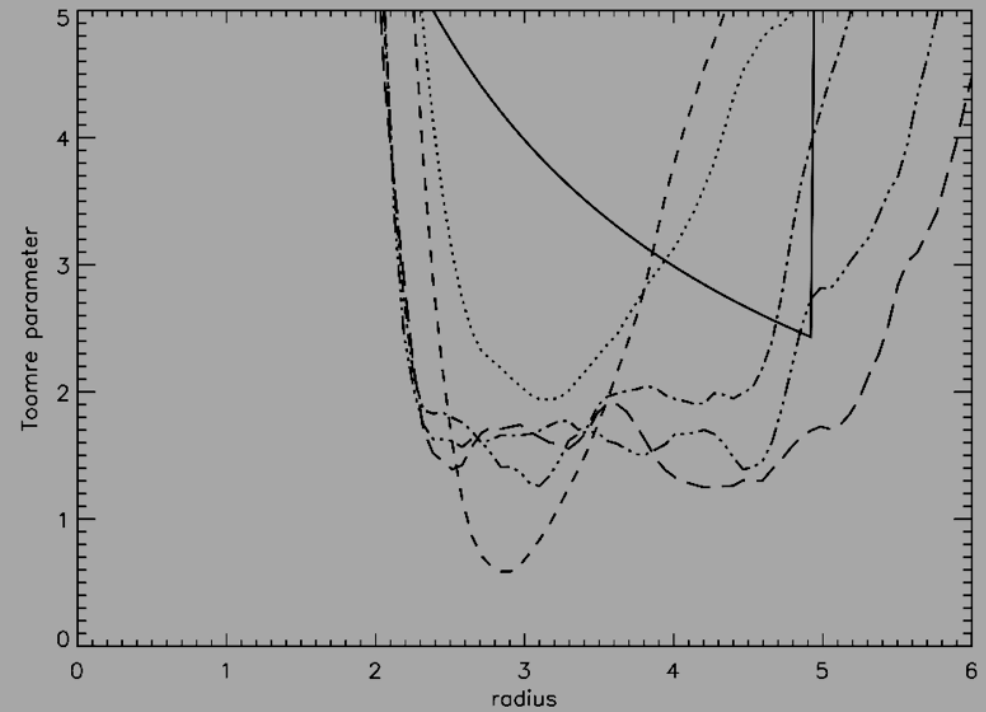


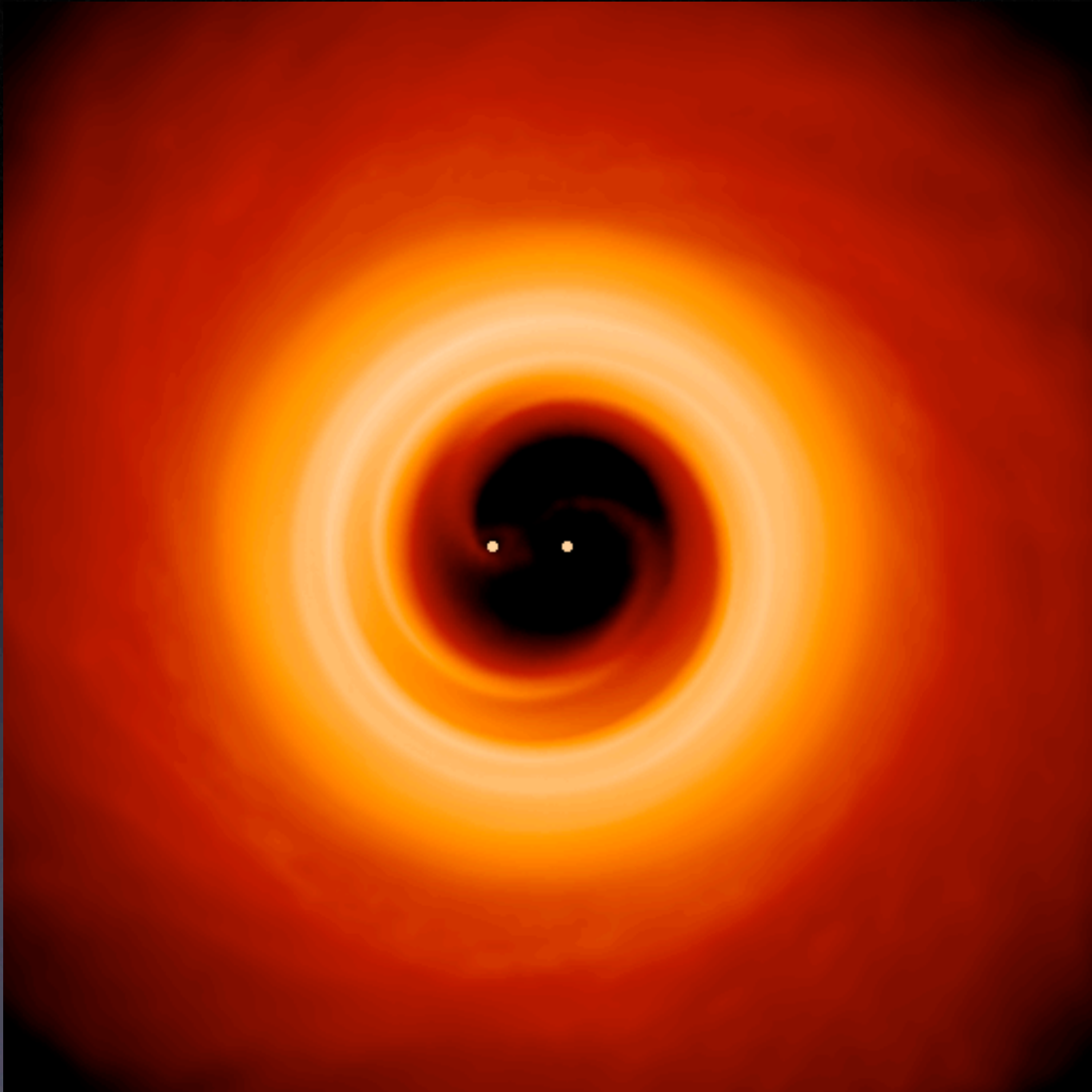
Disc Evolution

Density profile



Toomre parameter

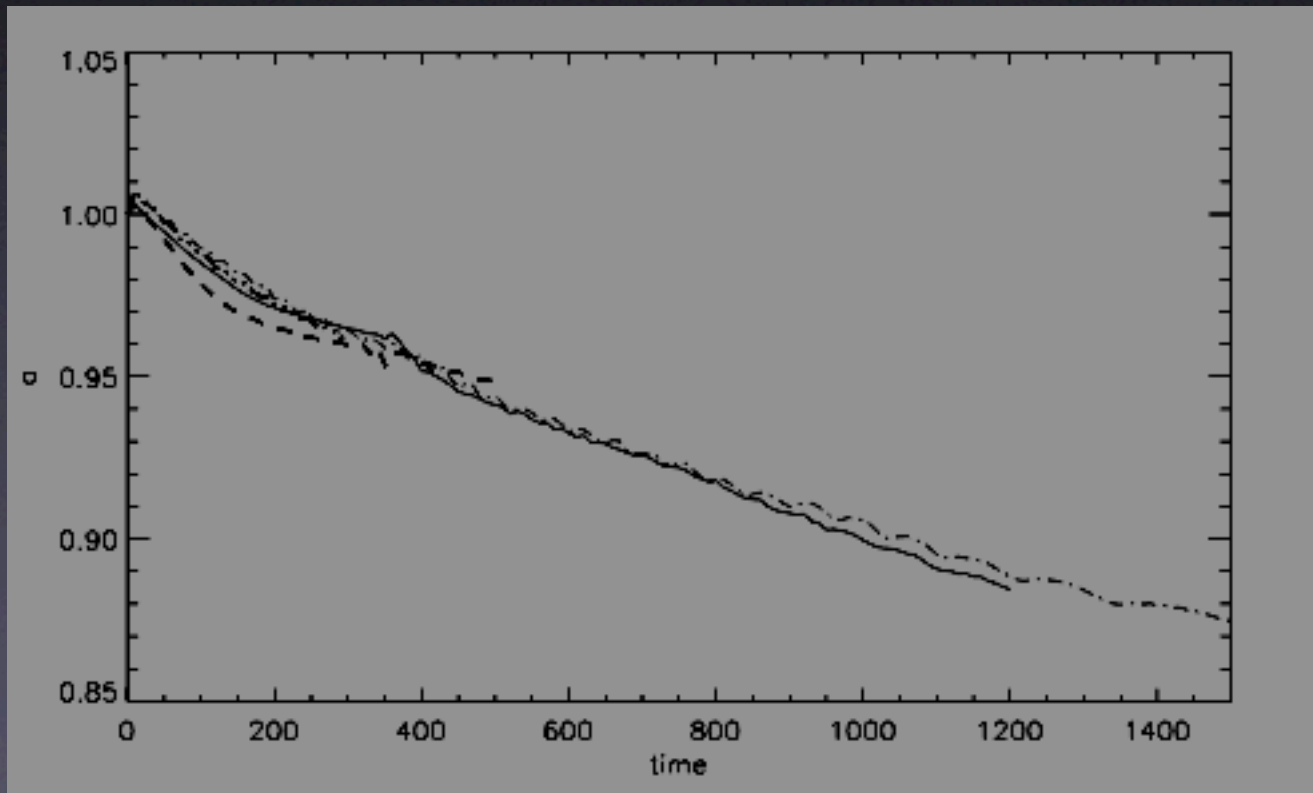




Binary Orbit Evolution

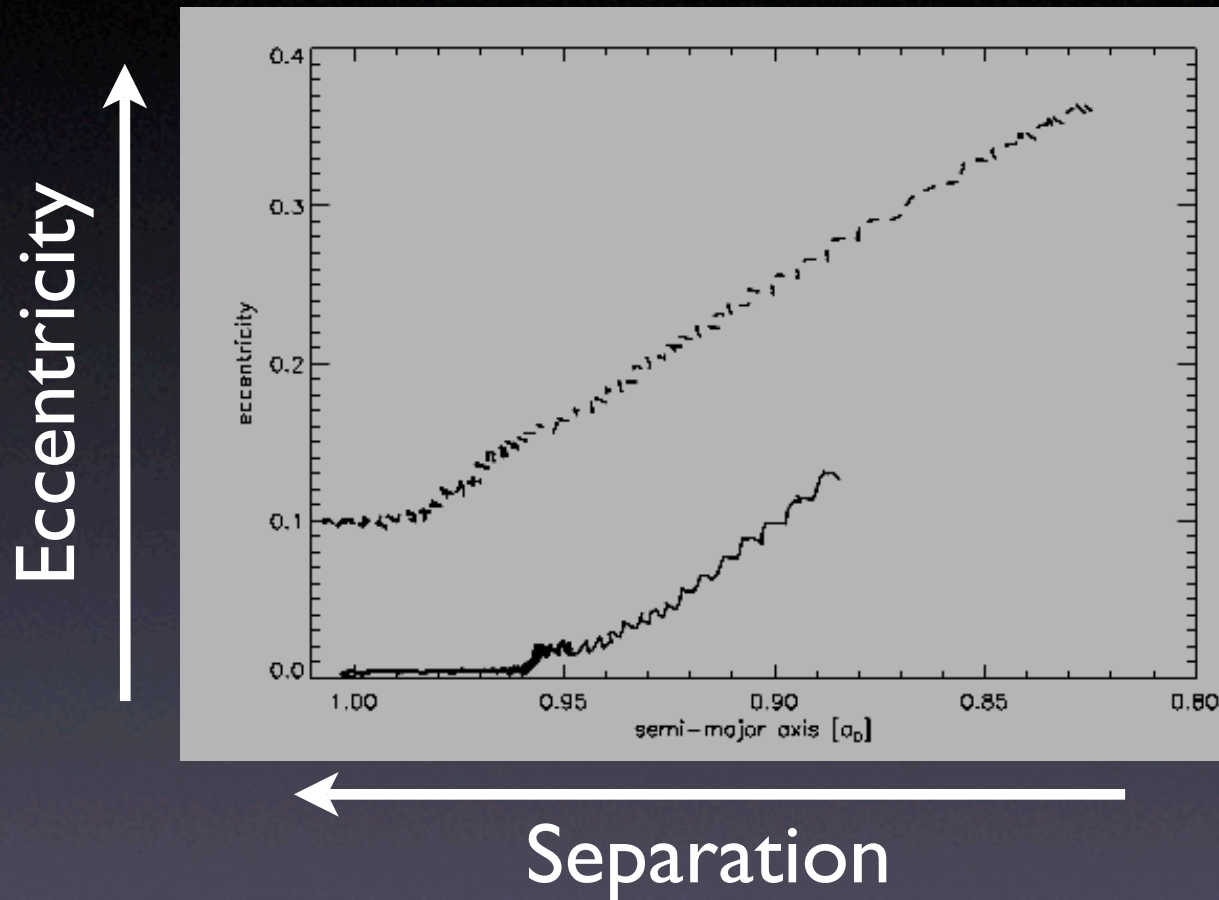
$$\frac{da}{dt} \approx 10^{-4} a_0 \Omega_0$$

Semi-major axis



Time

Binary Orbit Evolution



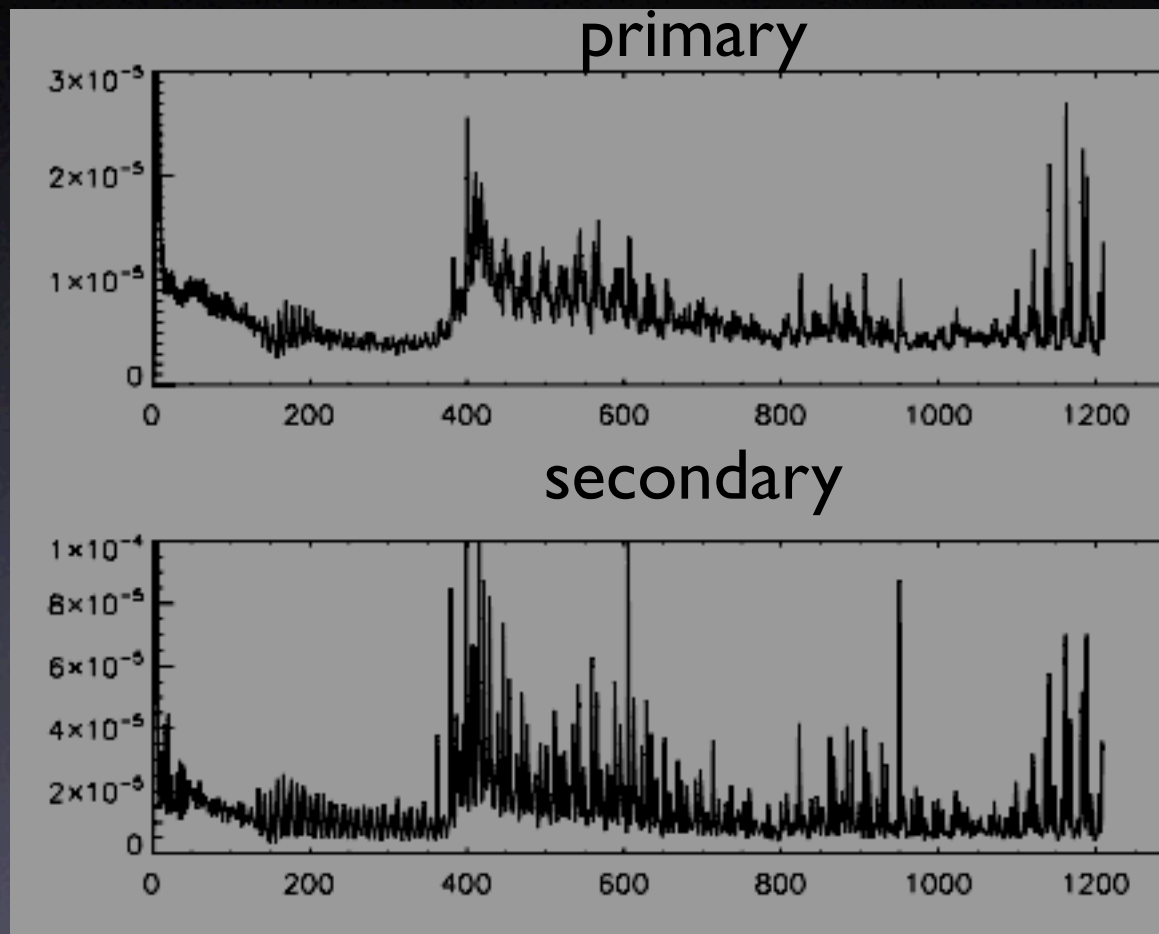
Eccentricity reaches ~ 0.35 by the end of the simulation.

No sign of saturation.

Some eccentricity may remain in the final coalescence.

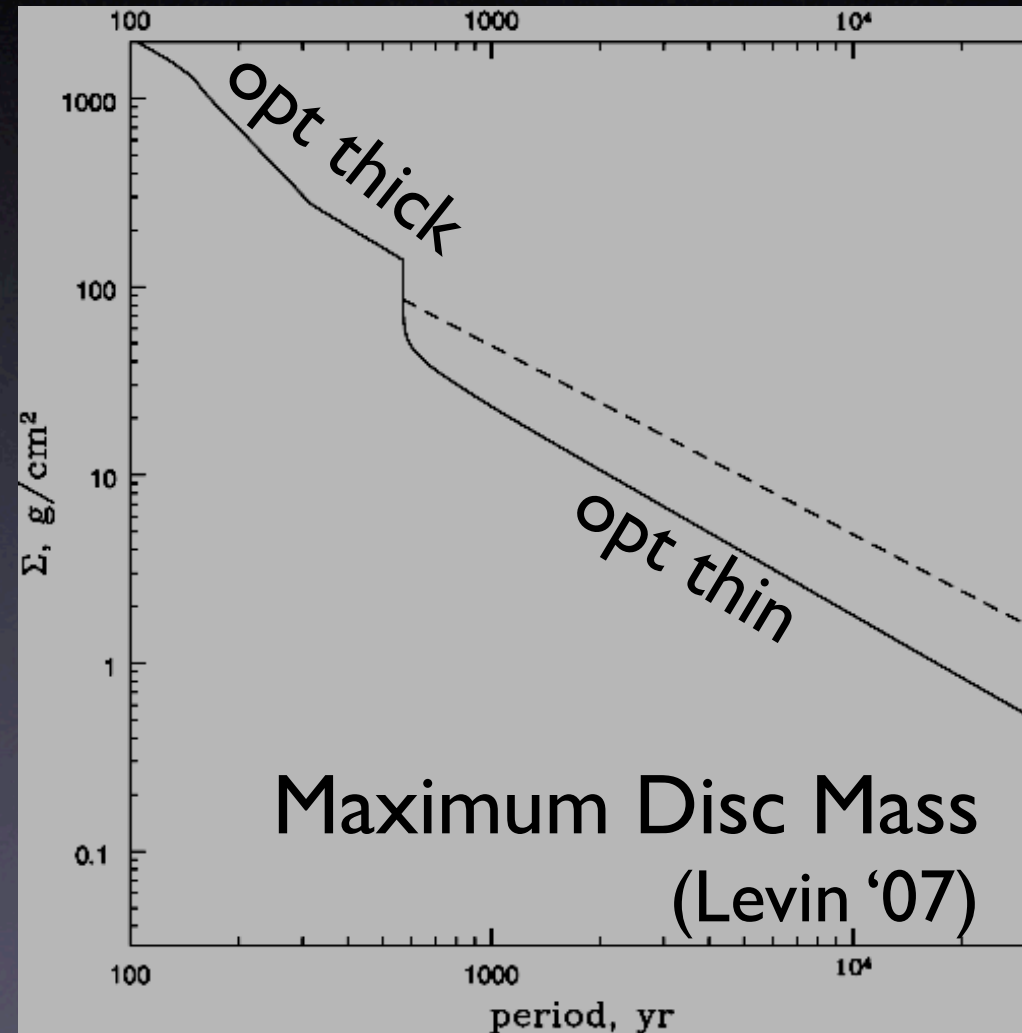
Accretion

- Keep track of gas “accreted” by each BH ($R < 0.1a$)
- More accretion on to the secondary
- Variability roughly on orbital time-scale.



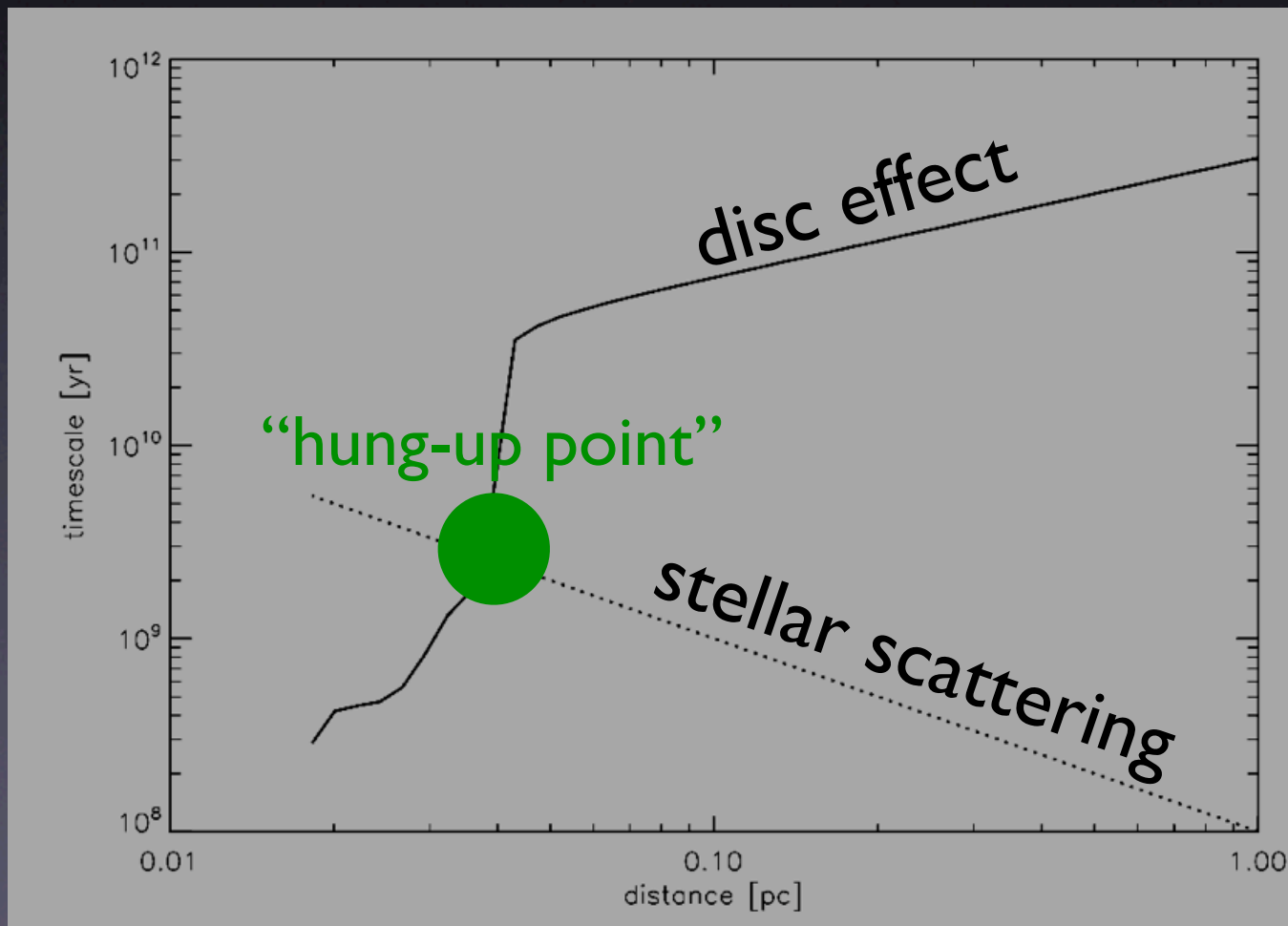
Scaling to real systems

- Simulations assumed slow radiative cooling.
- More massive discs will cool faster and fragment.
- Scale results with analytical models (Syer & Clarke; Ivanov et al).
- Use maximum disc mass below fragmentation.

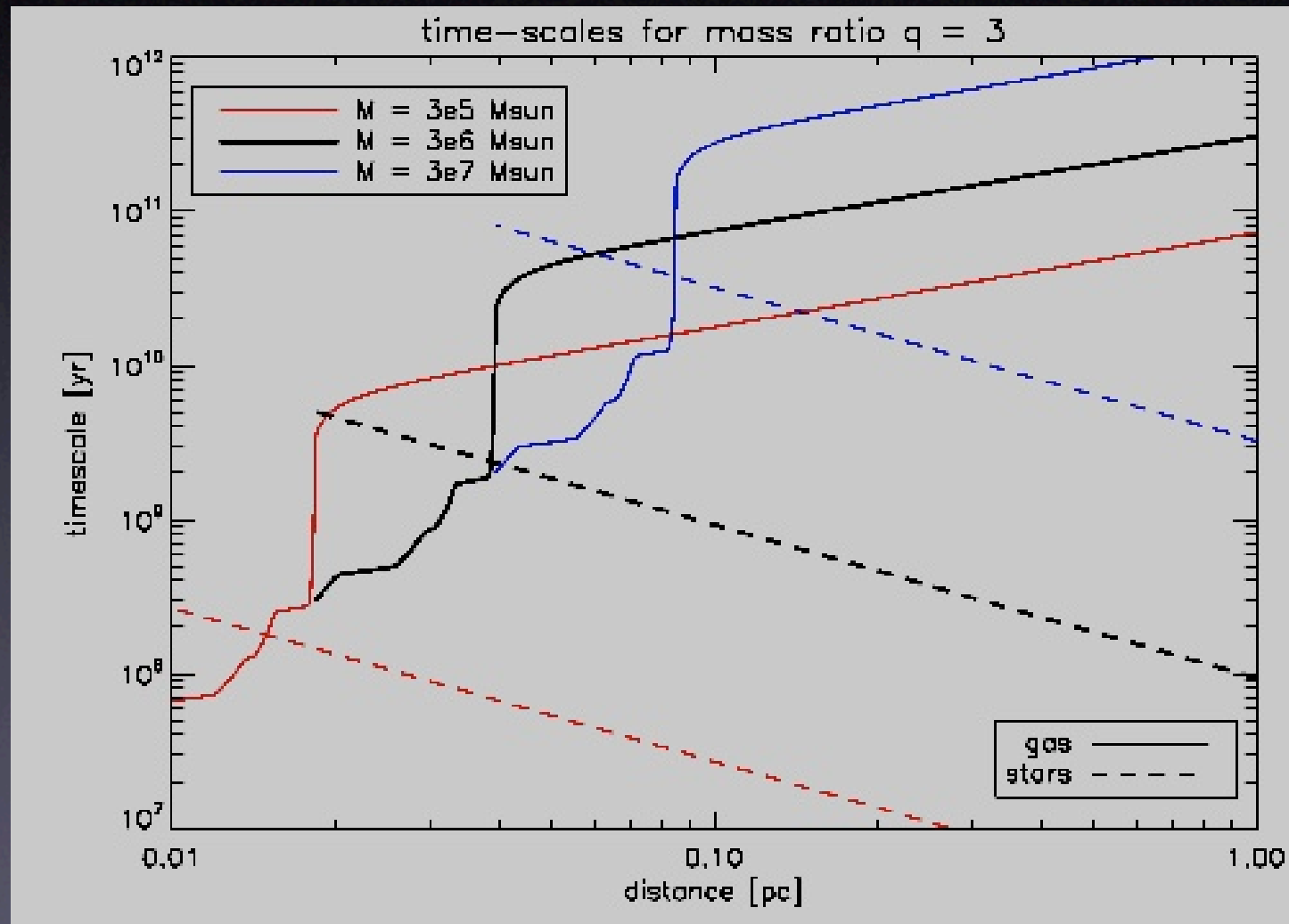


Maximum decay rate

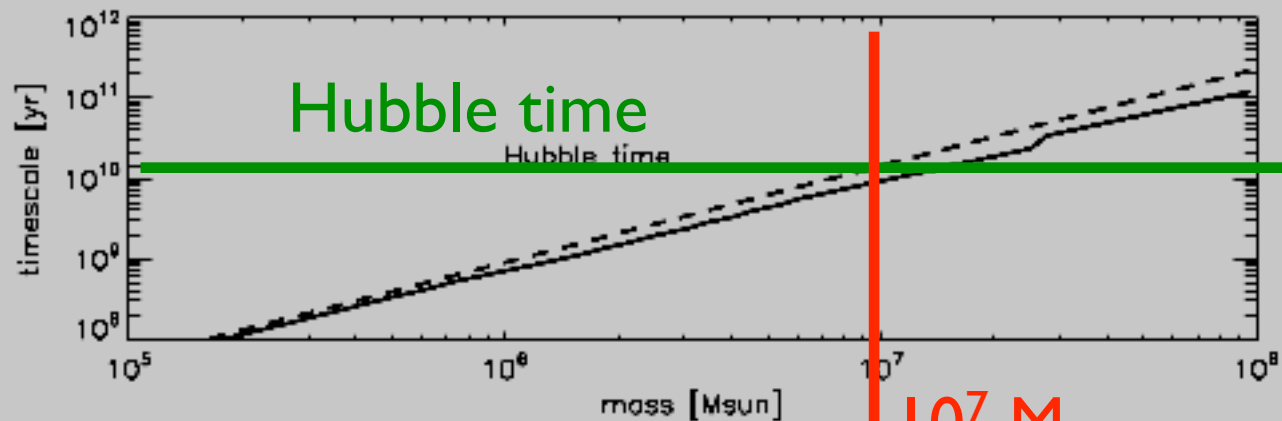
- We combine analytical estimates of $\max \Sigma$ and da/dt to calculate the maximum decay rate a disc can produce.



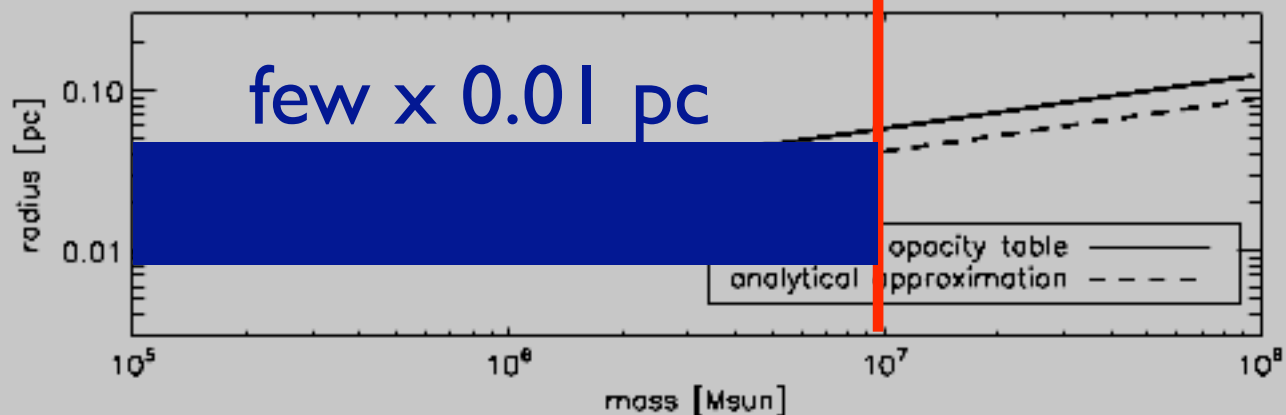
Easily repeat for different binary masses



time-scale



separation



mass

Binaries smaller than $10^7 M_{\text{sun}}$ could merge.
Binaries will spend most time at few 0.01 pc separations
(hard to observe)

What about larger binaries?

- More efficient stellar dynamics (tri-axiality).
- 3-body interactions with new black holes.
- They just don't merge.
- More massive discs... star formation could refill the “loss cone”.

Conclusions

- Gas disc can achieve coalescence of $M < 10^7 M_{\text{sun}}$ binaries. Luminous counterpart to *LISA* detections.
- Last-parsec problem still unsolved for larger binaries. Star-forming discs?
- Expect many binaries at few 0.01 pc separations.
- Binaries become eccentric -- influence the gravitational wave signal at final coalescence.
- Accretion variability may help to identify close binaries.