

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

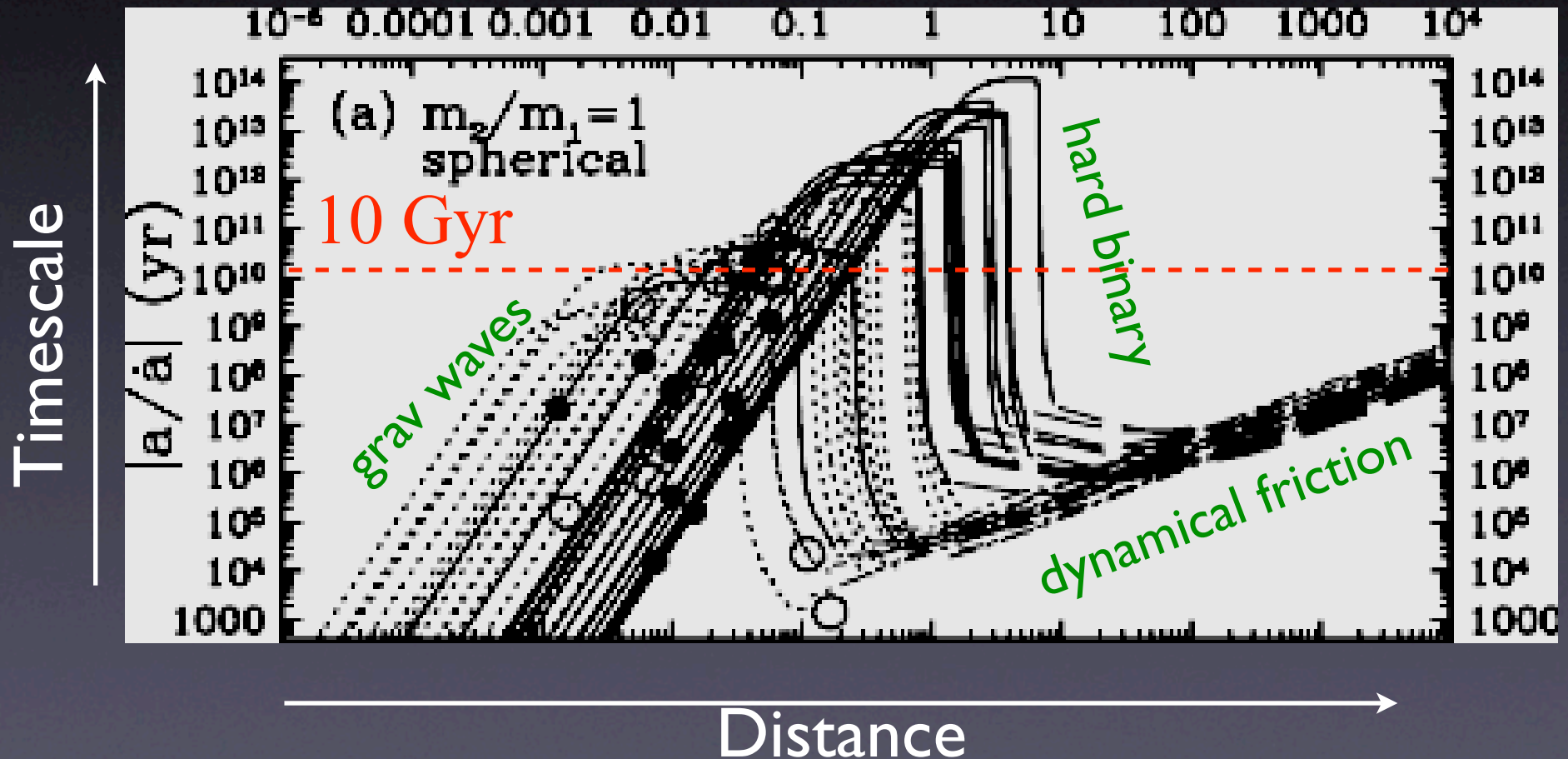
MNRAS 393, 1423 (2009)

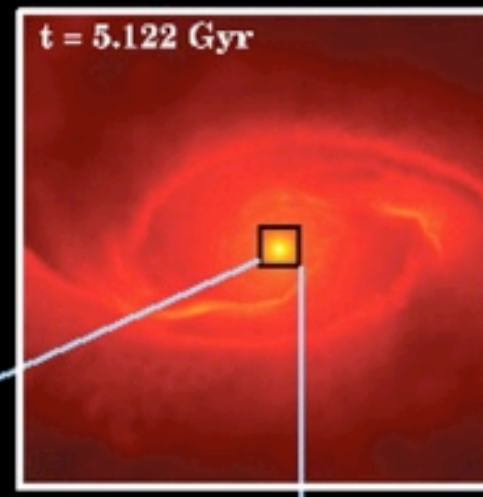
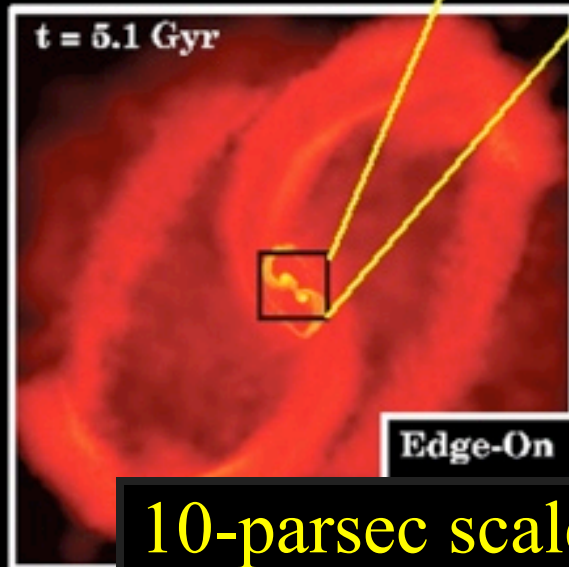
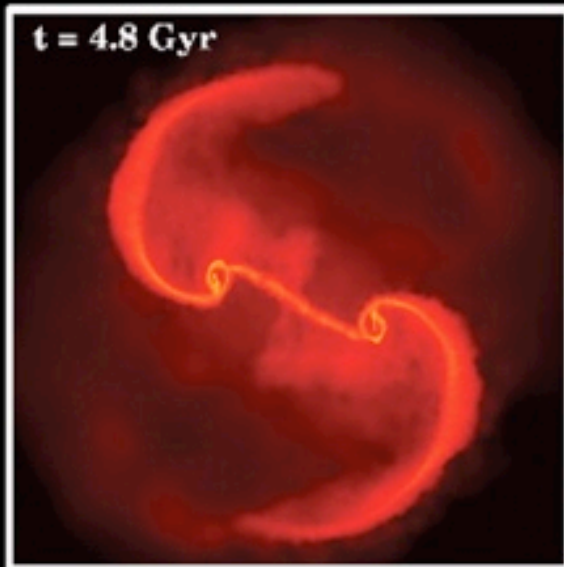
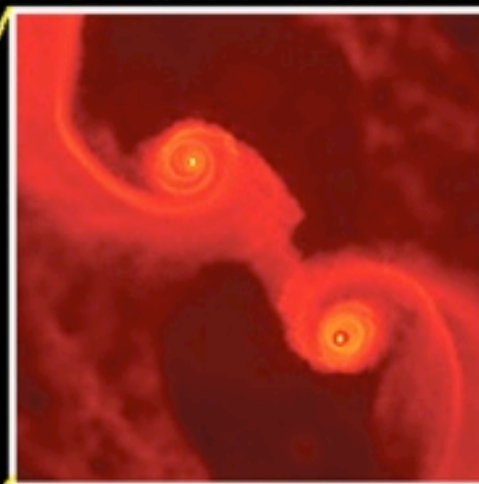
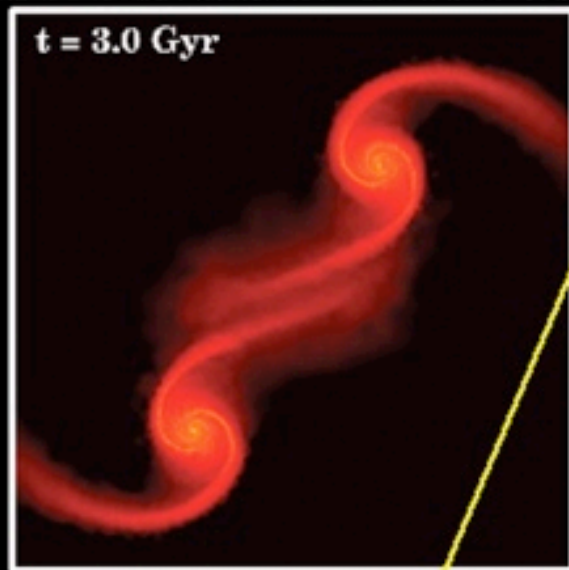
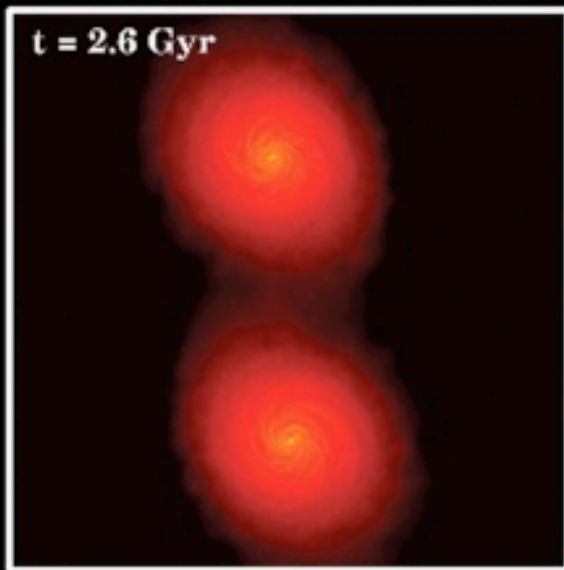
Jorge Cuadra
MPA-Garching

Phil Armitage, Richard Alexander, Mitch Begelman
University of Colorado

“Last Parsec Problem”

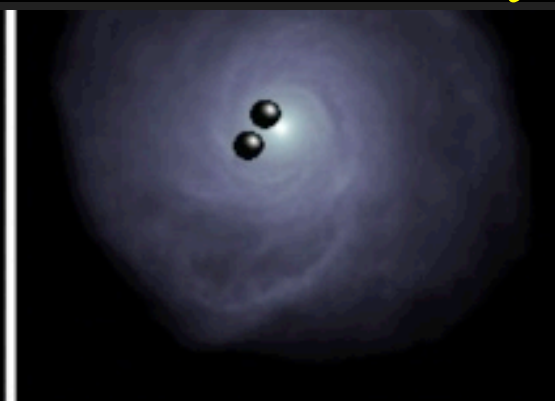
Milosavljevic & Merritt 2001; Yu 2002





Edge-On Face-On

10-parsec scale disc forms around the binary



Massive Nuclear Discs

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

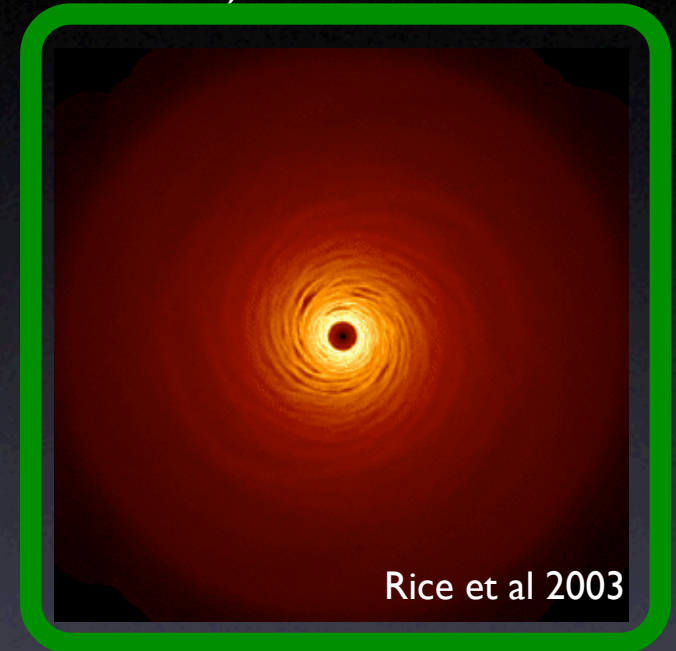
- Discs will be unstable to self-gravity

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

- Two possibilities:

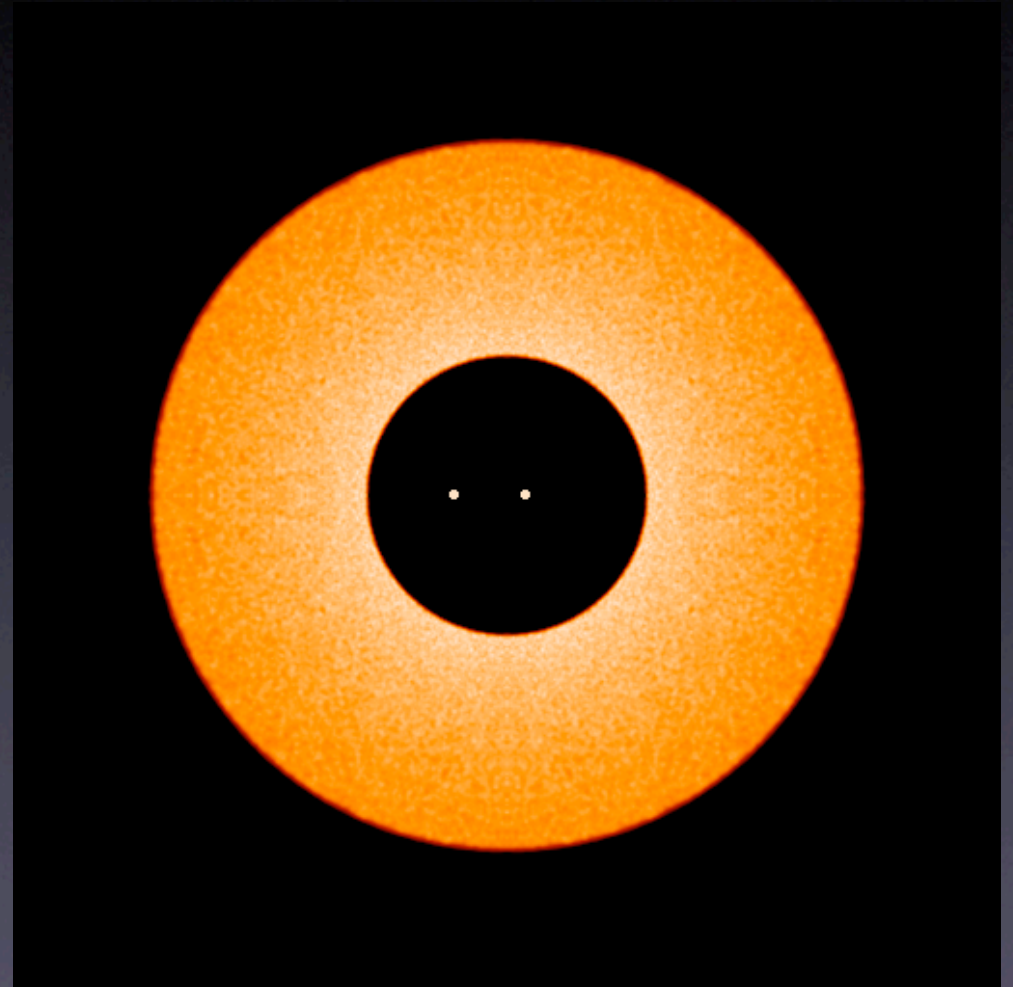
- slow cooling:
transport angular momentum

- fast cooling:
fragmentation and star formation



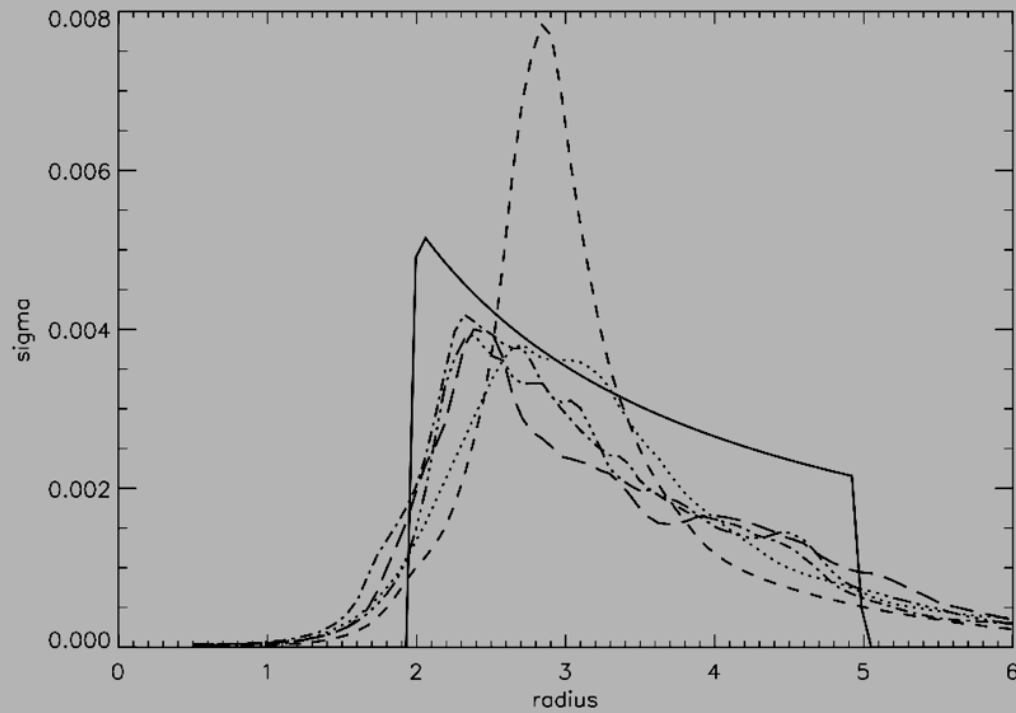
Numerical Models

- 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)

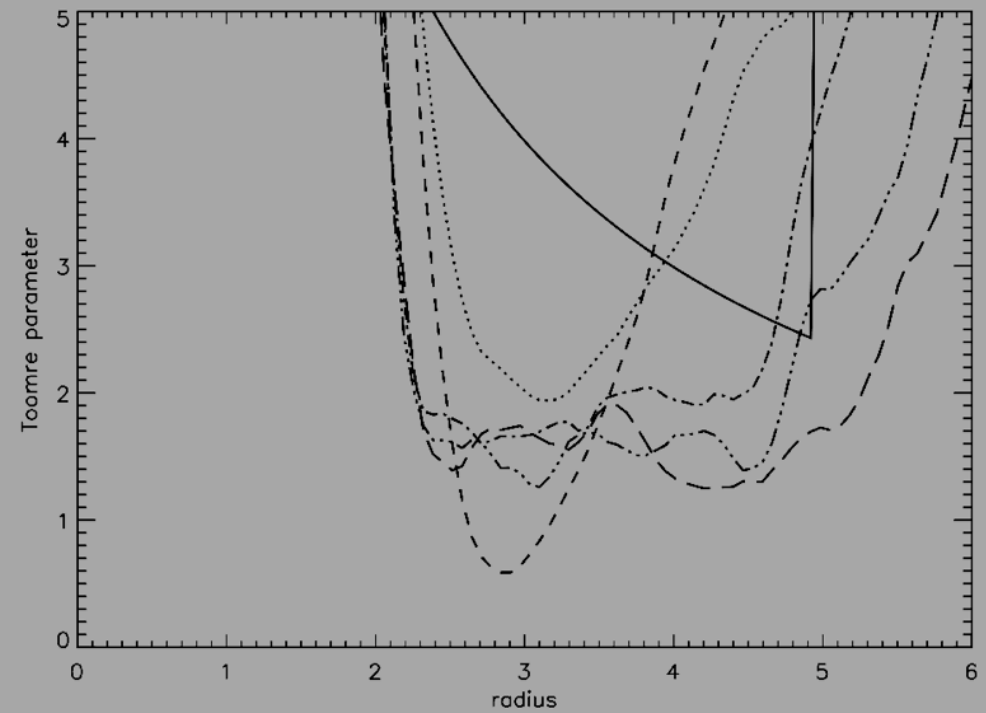


Disc Evolution

Sigma profile



Toomre parameter



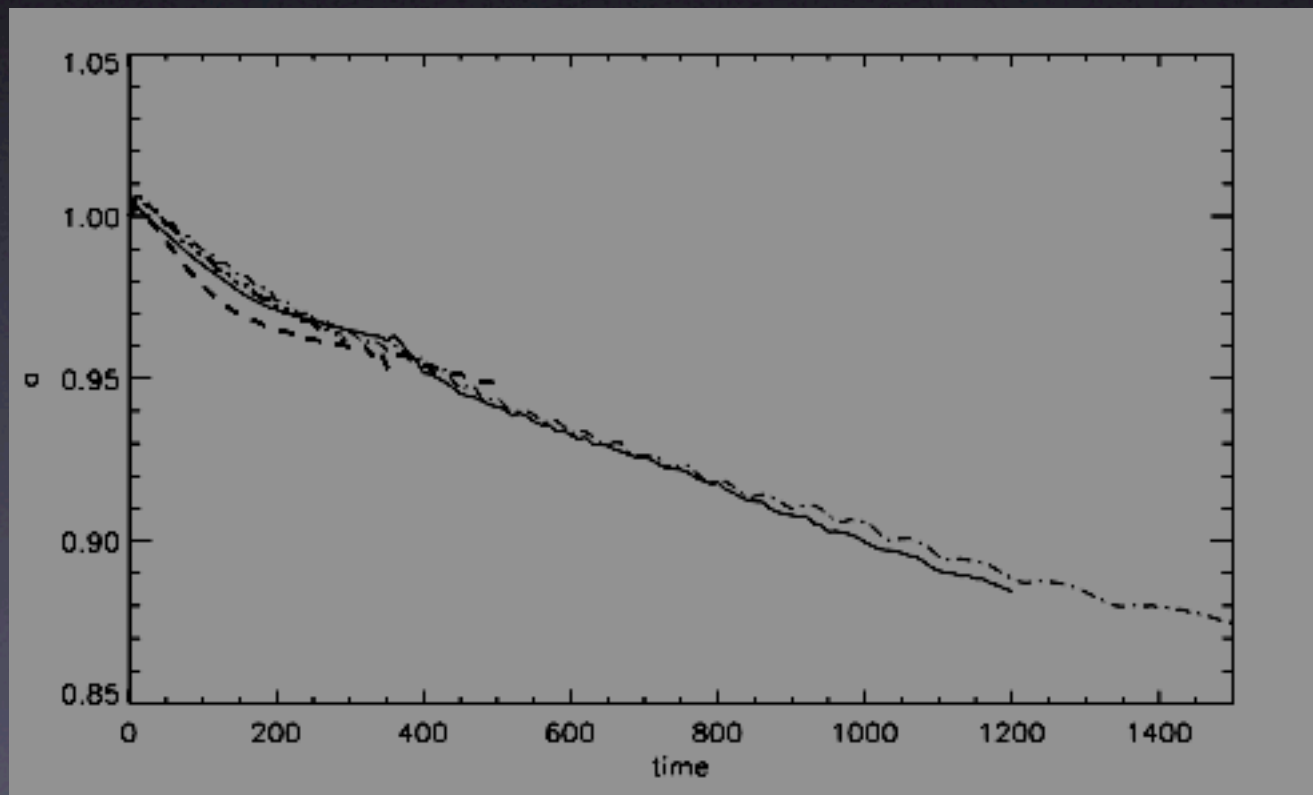


Jorge Cuadra - Binary Black Hole Mergers within Gas Discs - Zürich Feb '10

Binary Orbit Evolution

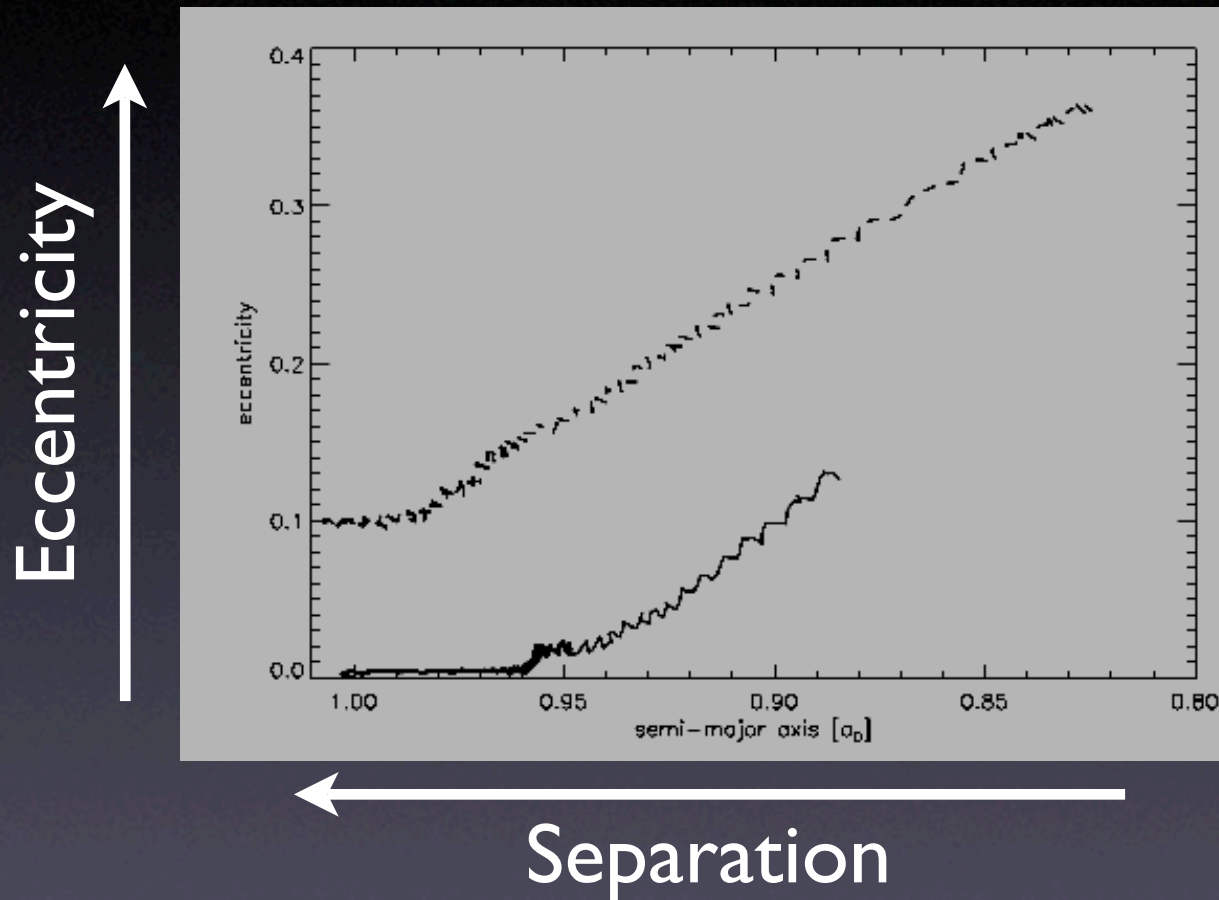
$$\frac{da}{dt} \approx 10^{-4} a_0 \Omega_0$$

Semi-major axis



Time

Binary Orbit Evolution



Eccentricity reaches ~ 0.35 by the end of the simulation.

No sign of saturation.

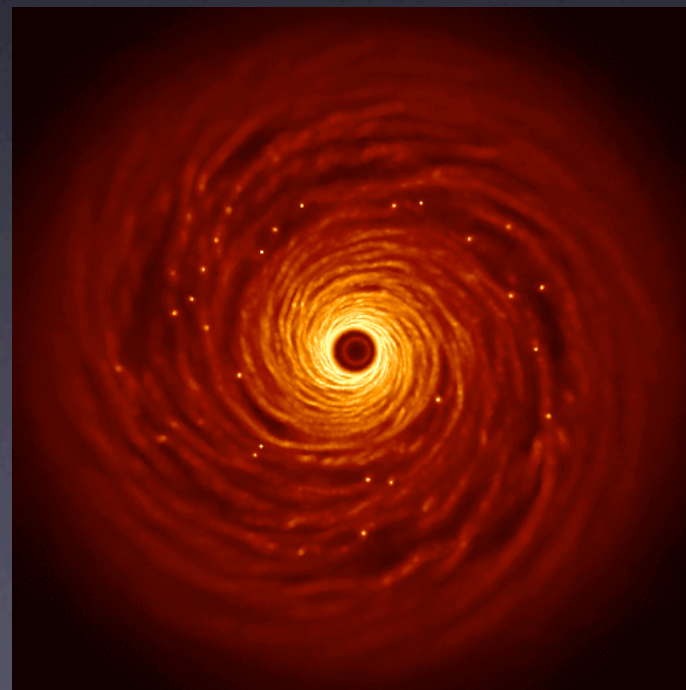
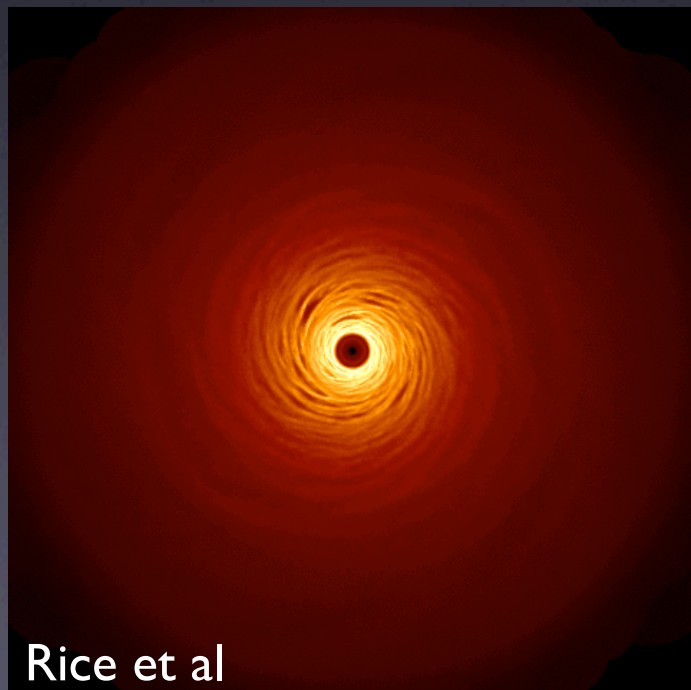
Some eccentricity may remain in the final coalescence.

Scaling to real systems

- Simulations done for given mass ratios and chosen cooling time... need to generalise
- Analytical predictions show da/dt dependence on disc mass and viscosity law (Syer & Clarke '95; Ivanov et al '99)
- Our simulations agree well...
- We can then scale results to different disc properties using analytical models.

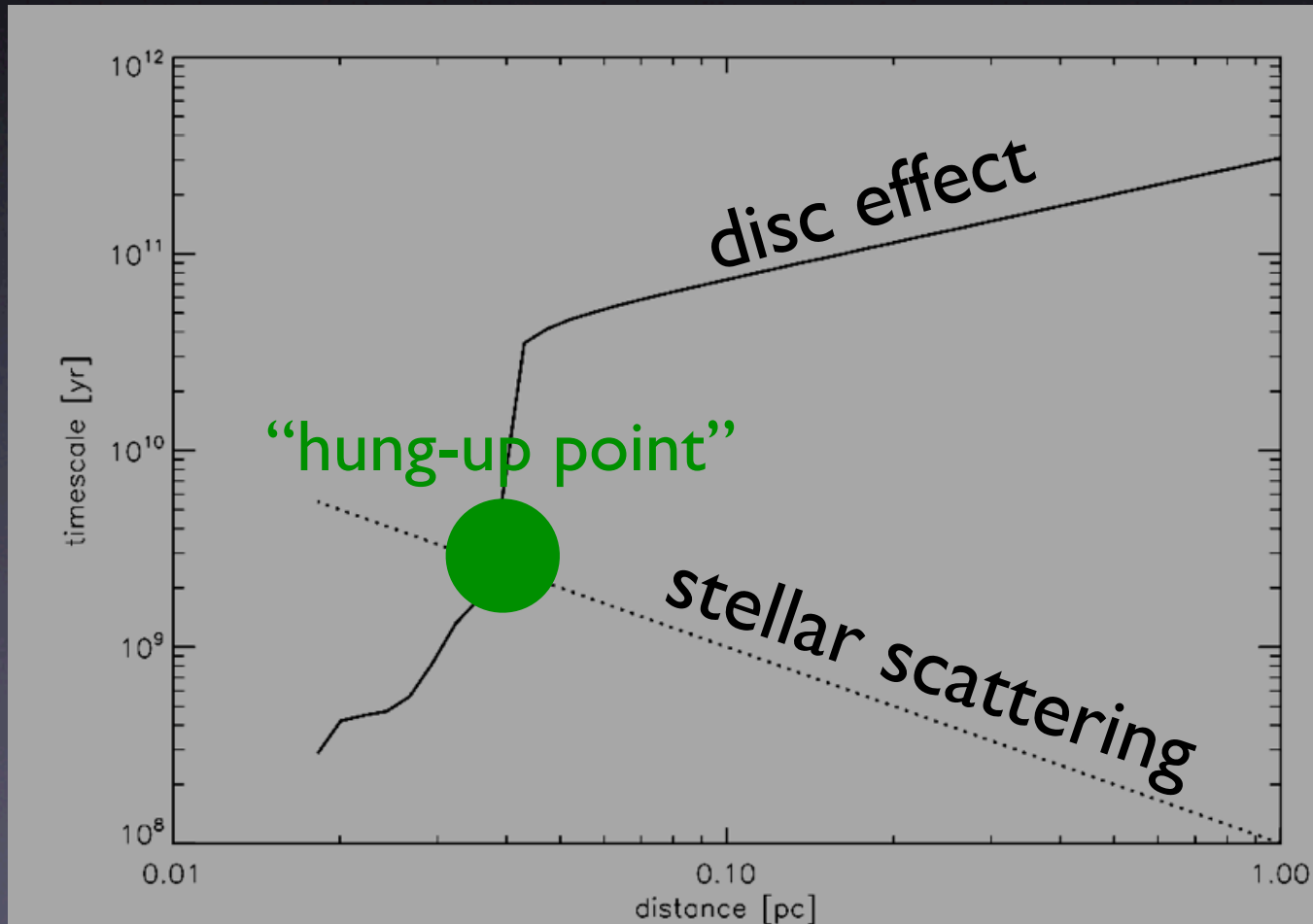
Maximum disc mass

- Can't we just have a very large disc to make sure there's a merger?
- No! There's a maximum mass beyond which cooling will be too fast and produce fragmentation instead of transport angular momentum.

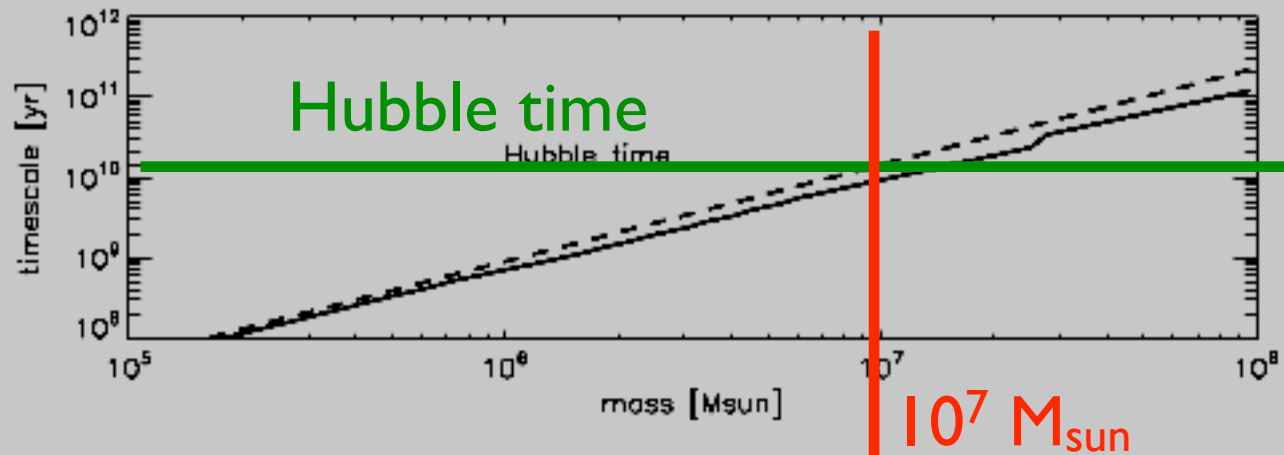


Maximum decay rate

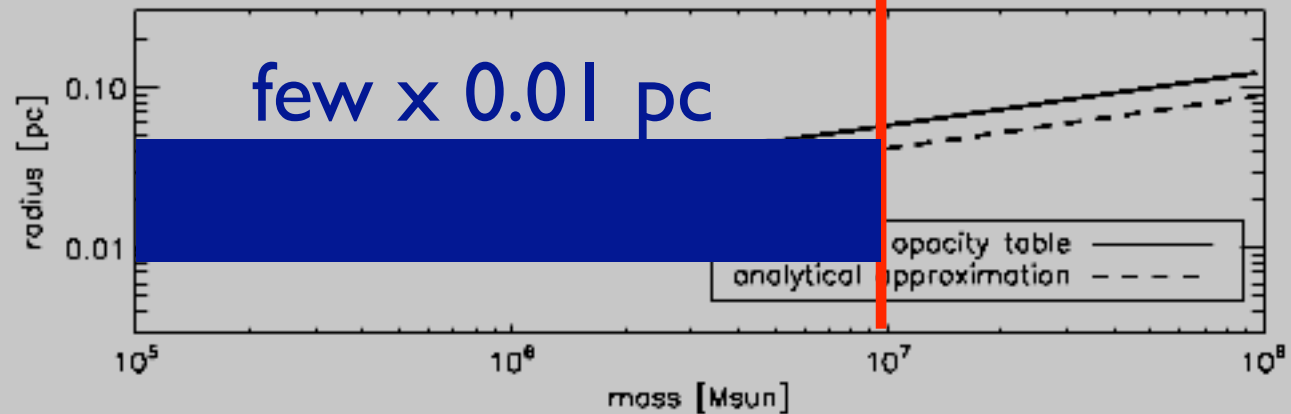
- We combine analytical estimates of $\max \Sigma$ (Levin '07; Armitage's talk) and da/dt to calculate the maximum decay rate a disc can produce.



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)

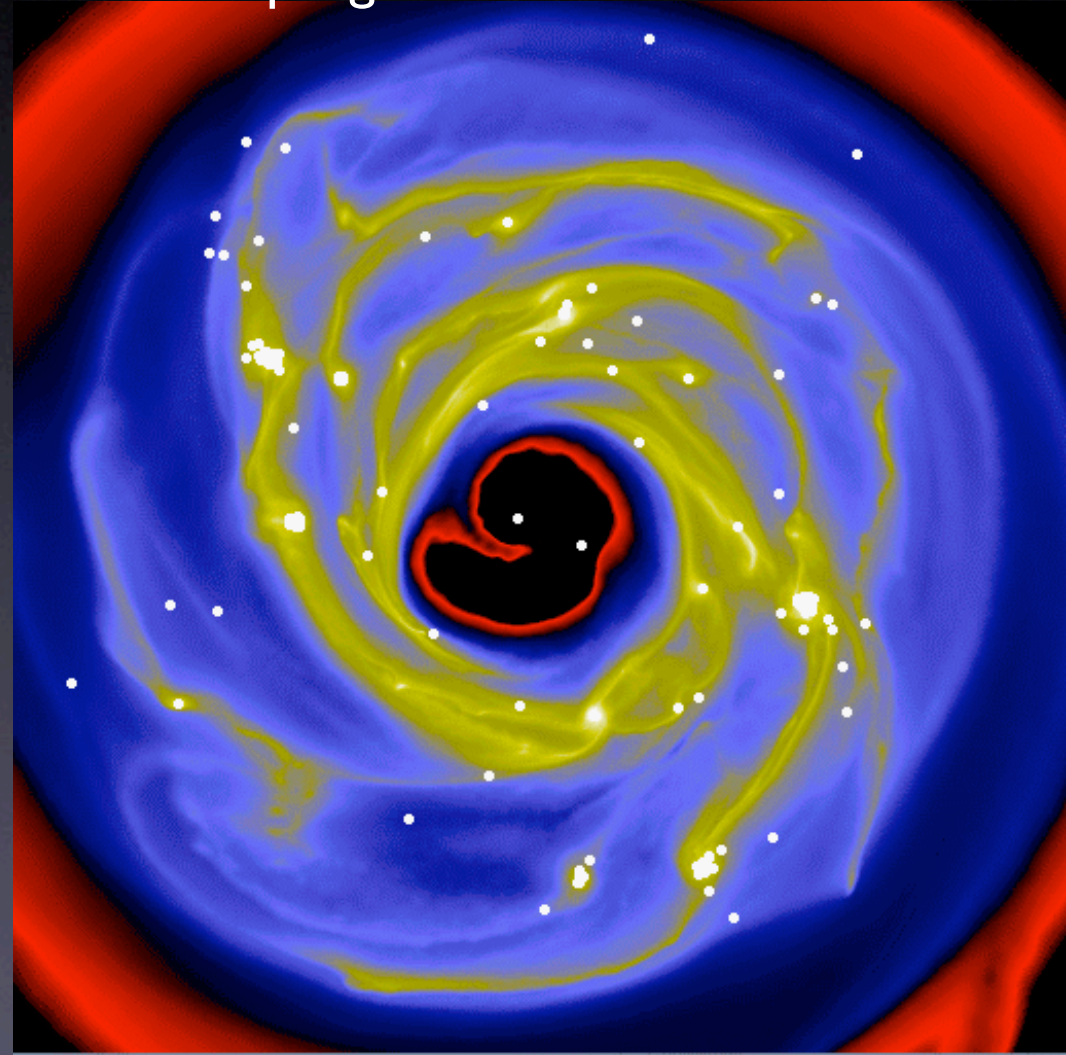
What about larger binaries?

- 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”.

Star-forming discs

- More massive discs will cool faster, then fragment and form stars.
- Stellar scattering continues driving the merger process.
 - Also get stellar disruptions.
- Complex process: star formation and dynamics will influence evolution.

Work in progress with Amaro-Seoane



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.