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

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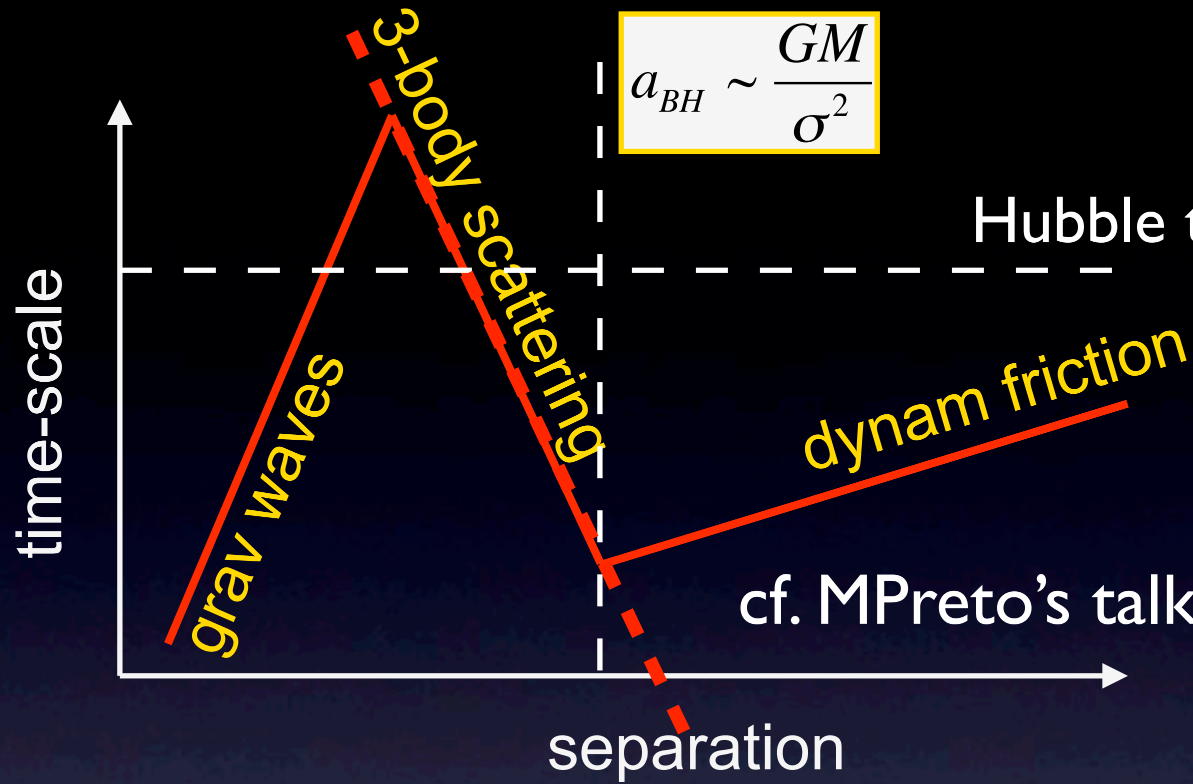


Dynamical friction is fast for large separations...

but it becomes inefficient when stellar mass ~ BH mass

Then slowly kick out individual stars...

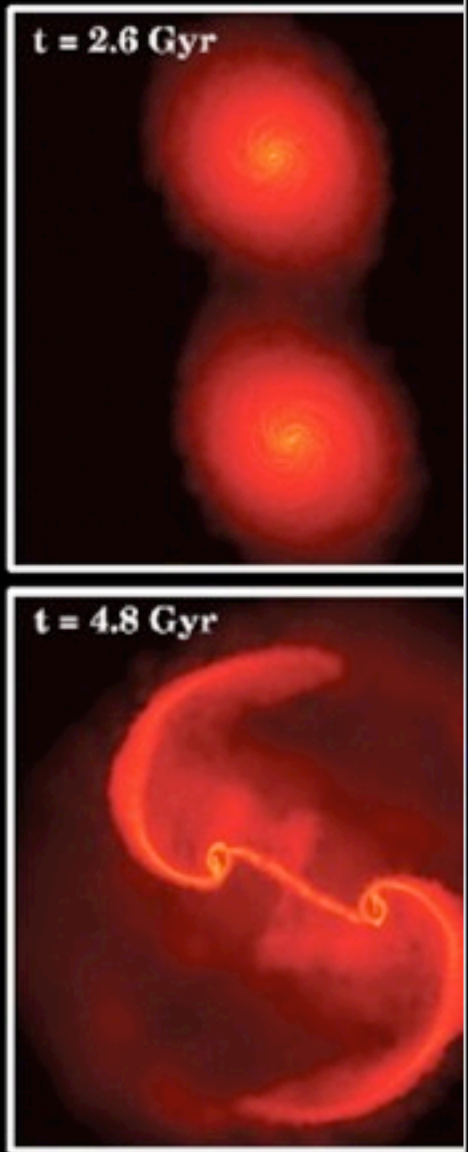
until it reaches the relativistic regime, where $t \sim a^4$

However, there's no time to get there.
"Last-parsec problem"

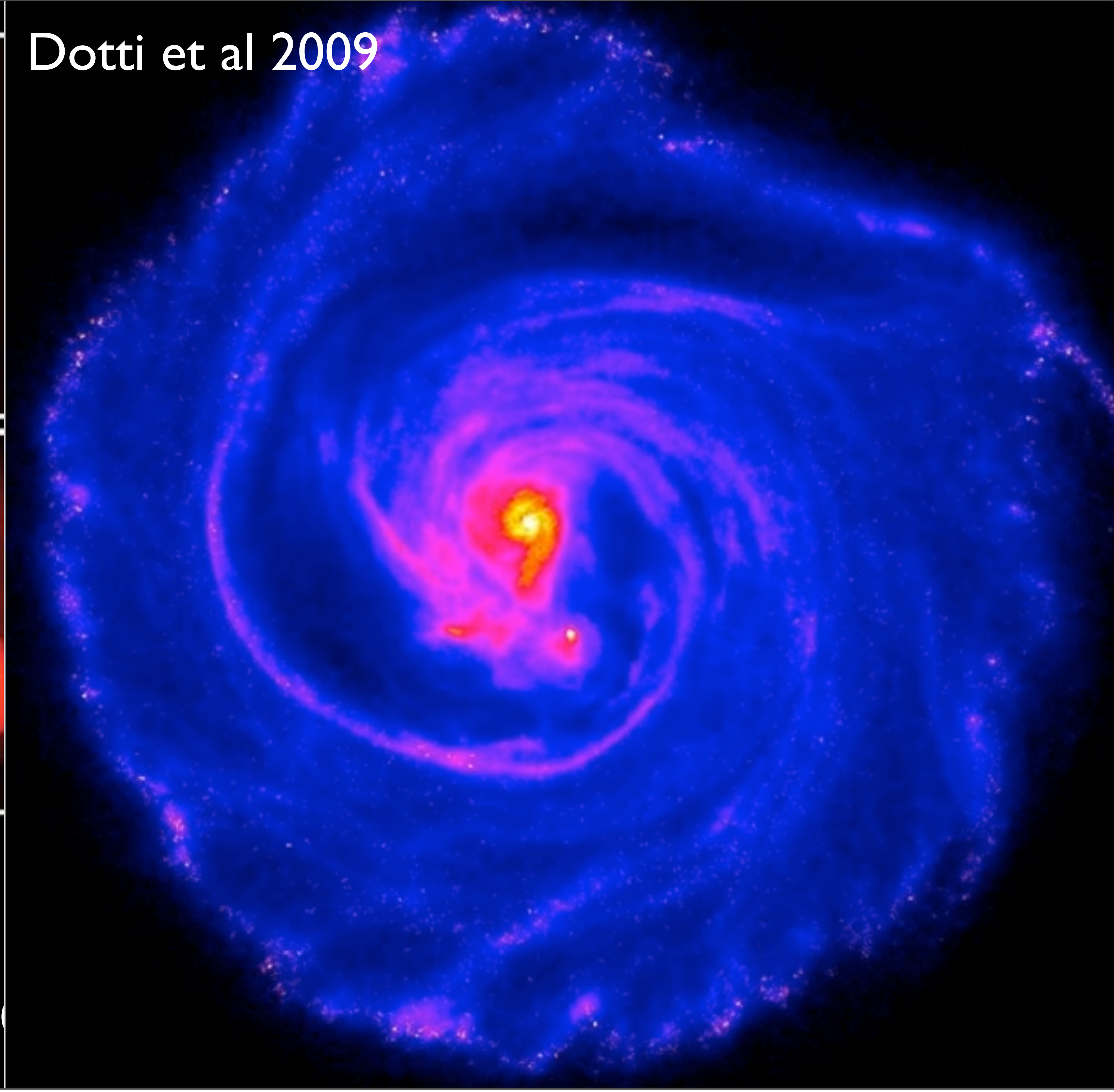
Gas-driven mergers at large scales

e.g., Escala et al 2004, 2005; Mayer et al 2008; Dotti et al 2009
MDotti, SvWassenhove & JGuedes' talks

- When galaxies merge, large amounts of gas are funnelled to the centre
- This gas can absorb the binary angular momentum faster than stars
- Efficiently bring the black holes to parsec distances
- Binary gets circular and coplanar with gas



Mayer et al 20(



Dotti et al 2009

Binary + Disc Numerical Models

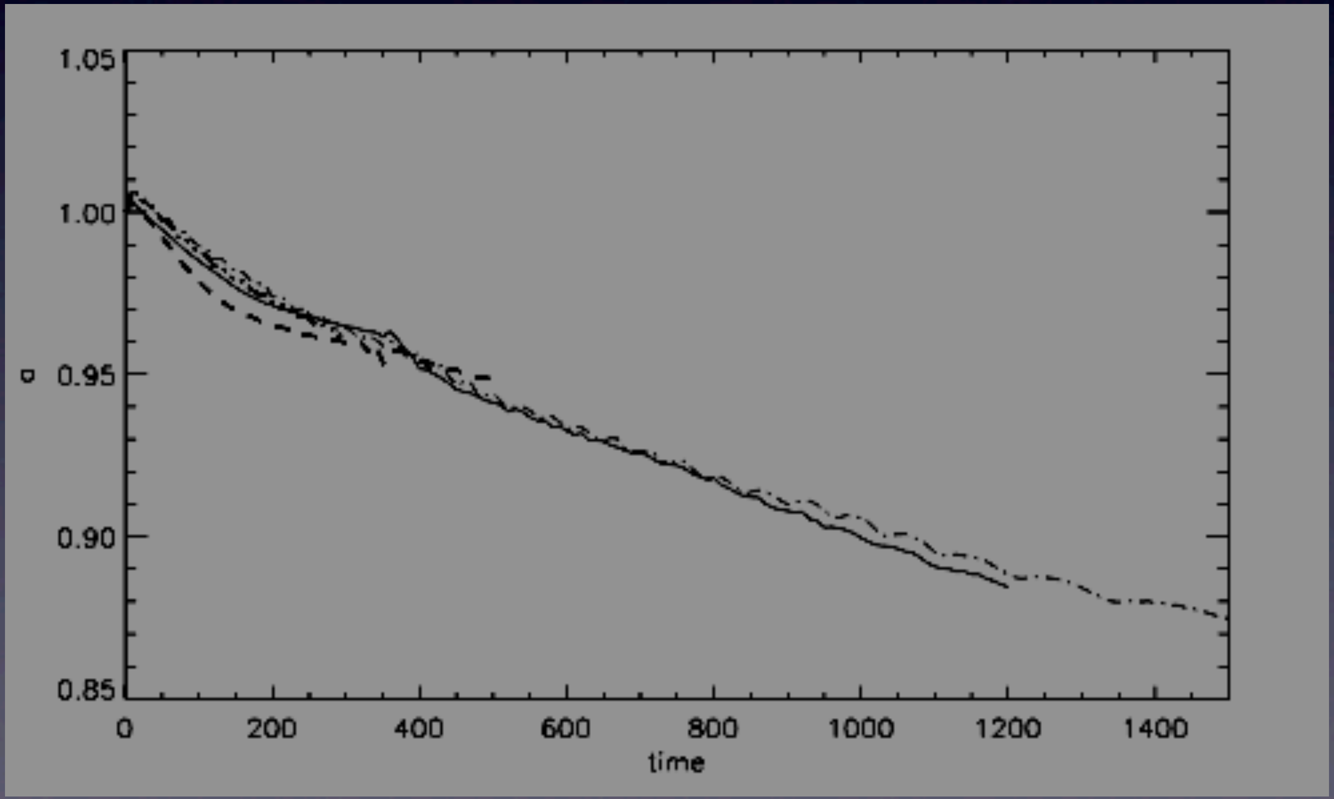
Cuadra, Armitage, Alexader, Begelman 2009

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

Binary Orbit Evolution

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

Semi-major axis



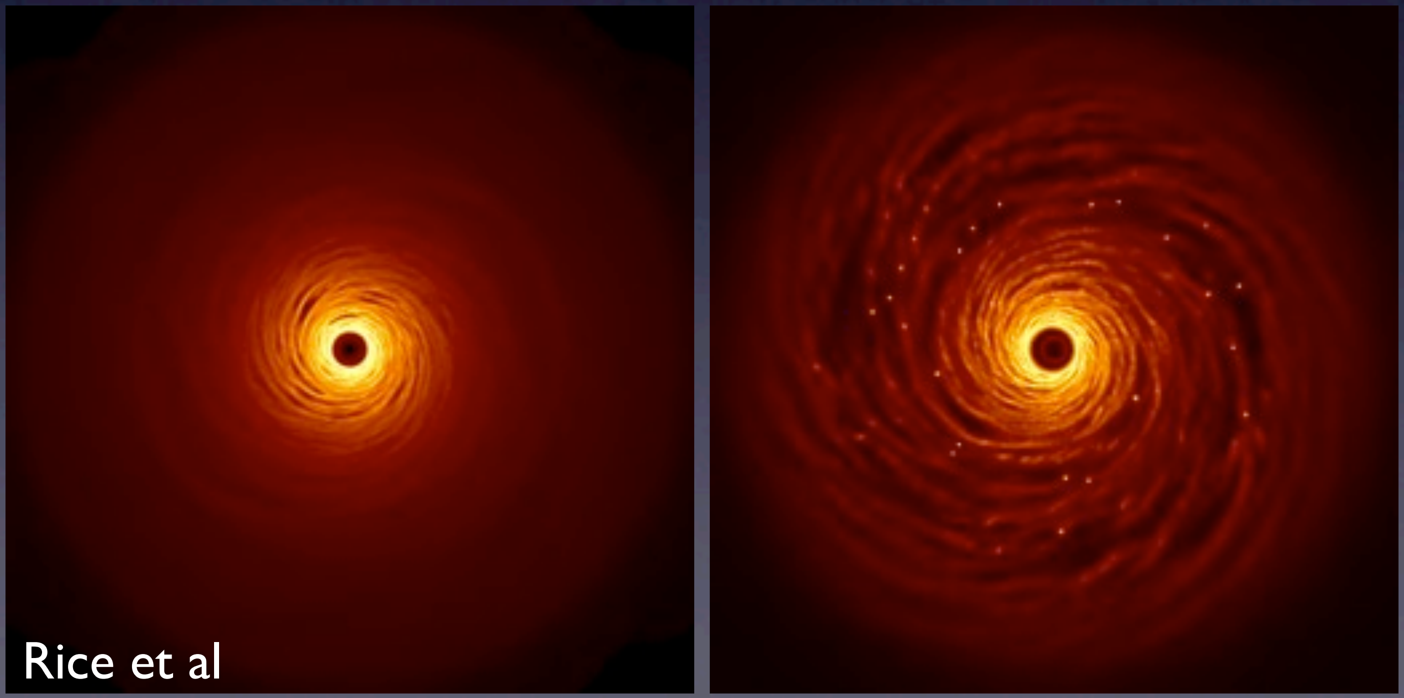
Time

Scaling to real systems

- Simulations done for given mass ratios and chosen cooling time... need to generalise
- Analytical predictions show d*a*/d*t* 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.

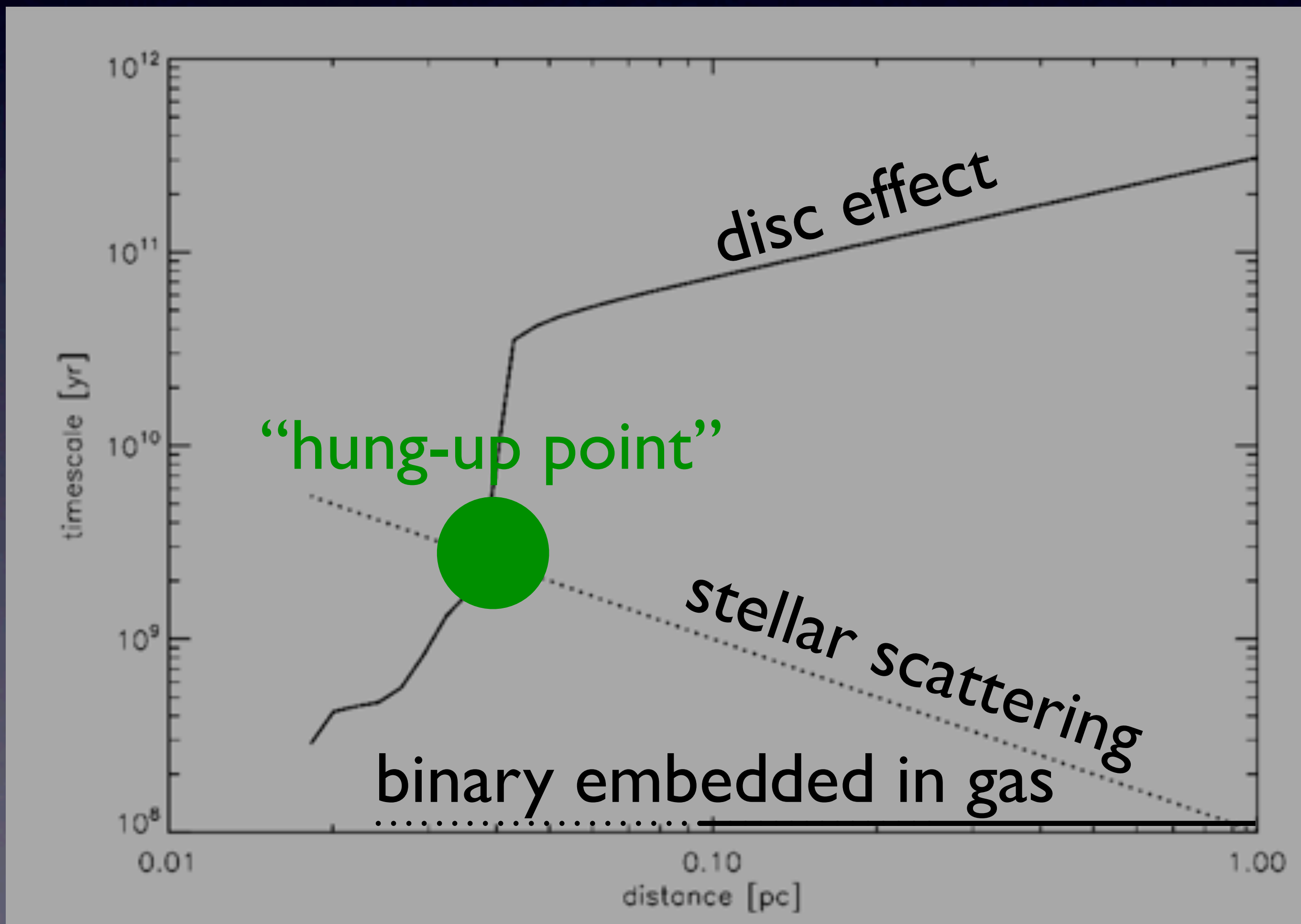
Maximum disc mass

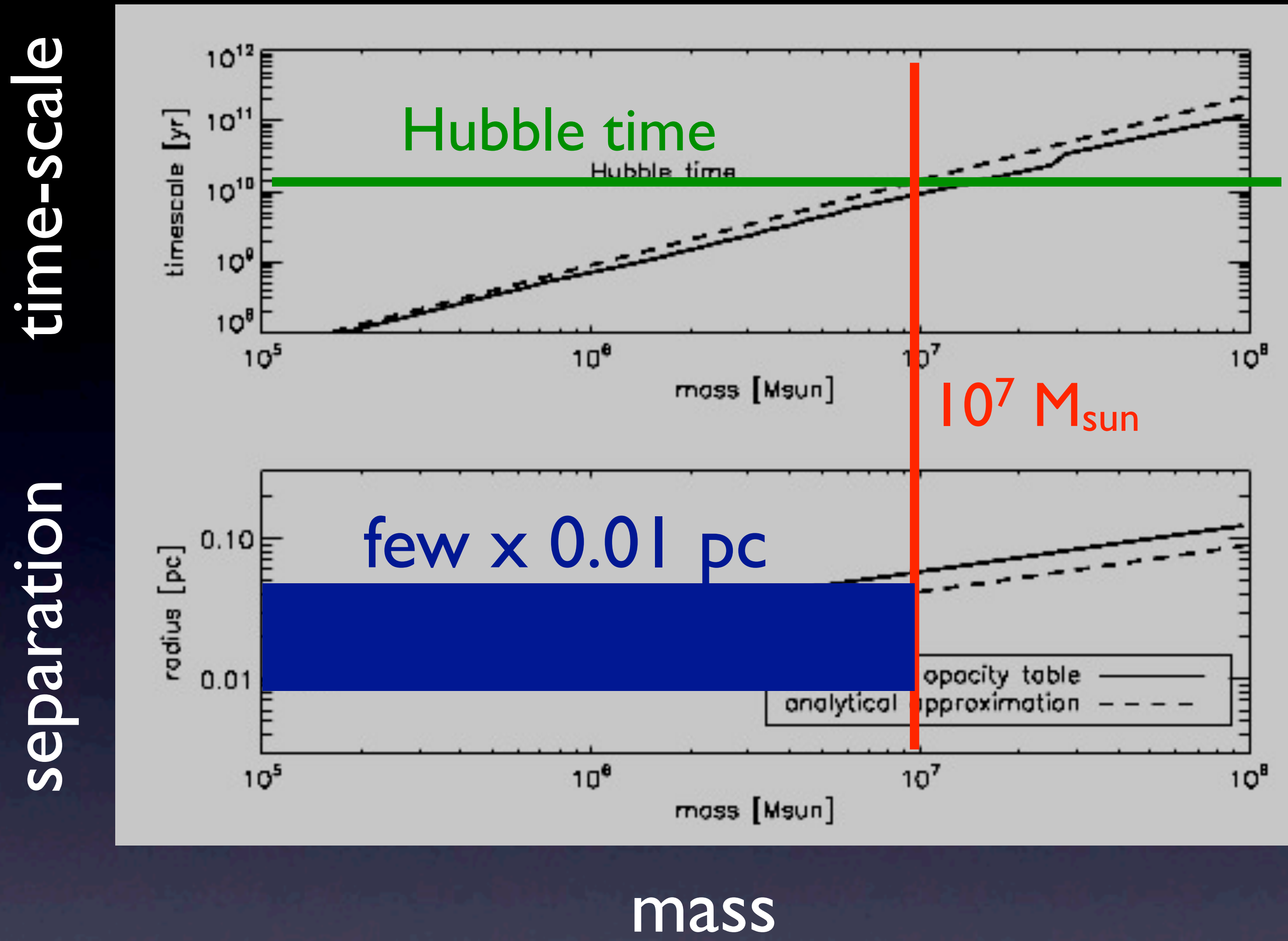
- Can't we just have a very large disc to make sure there's a merger?
- No! There's a maximum mass beyond which cooling will be too fast and produce fragmentation instead of transport angular momentum.



Maximum decay rate

- We combine analytical estimates of max Σ (Levin '07) and d*a*/d*t* to calculate the *maximum* decay rate a disc can produce.





Binaries smaller than 10^7 M_{sun} could merge.

Binaries will spend most time at few 0.01 pc separations (hard to observe)

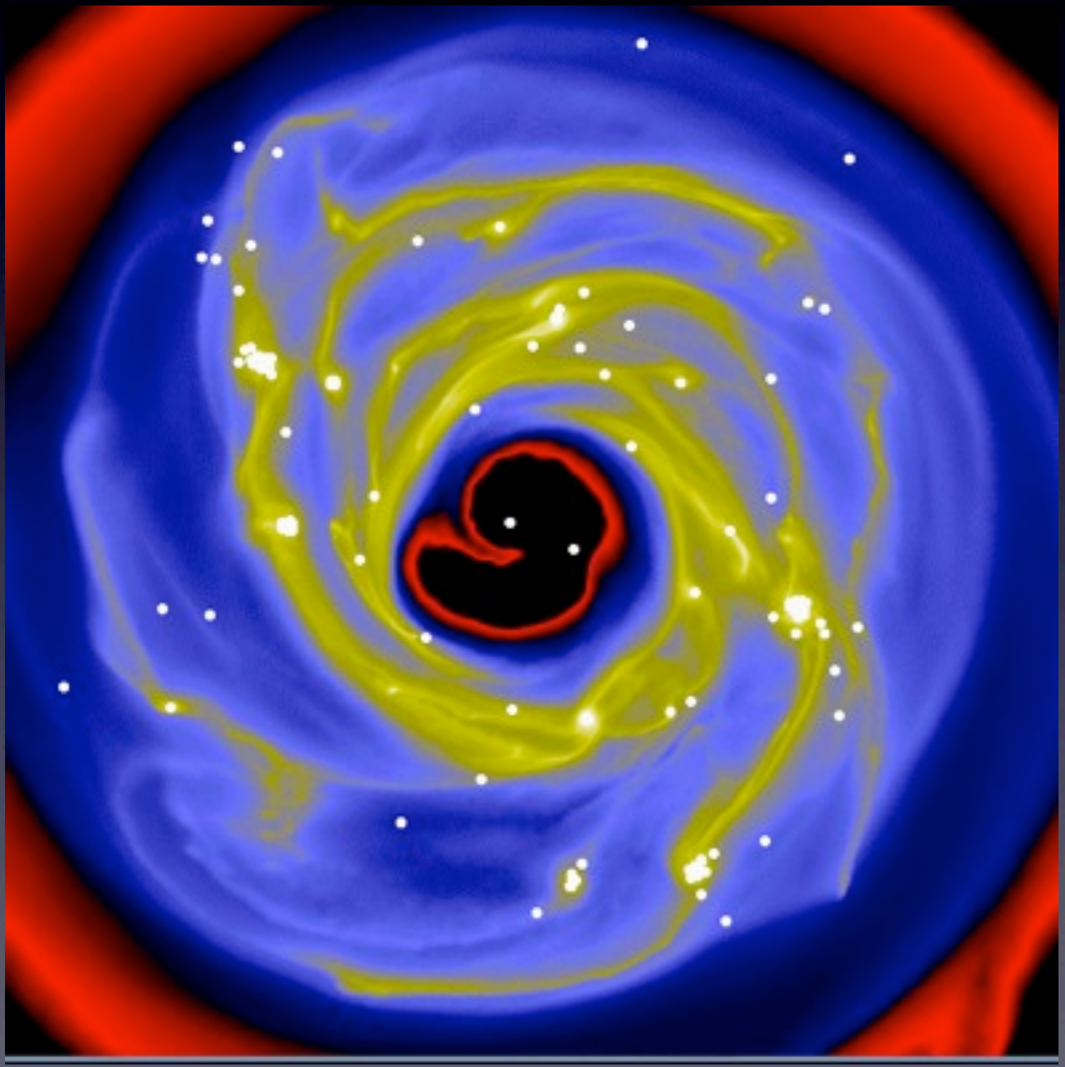
What about larger binaries?

- Efficient stellar dynamics (tri-axiality or rotation, cf Miguel's talk).
- 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

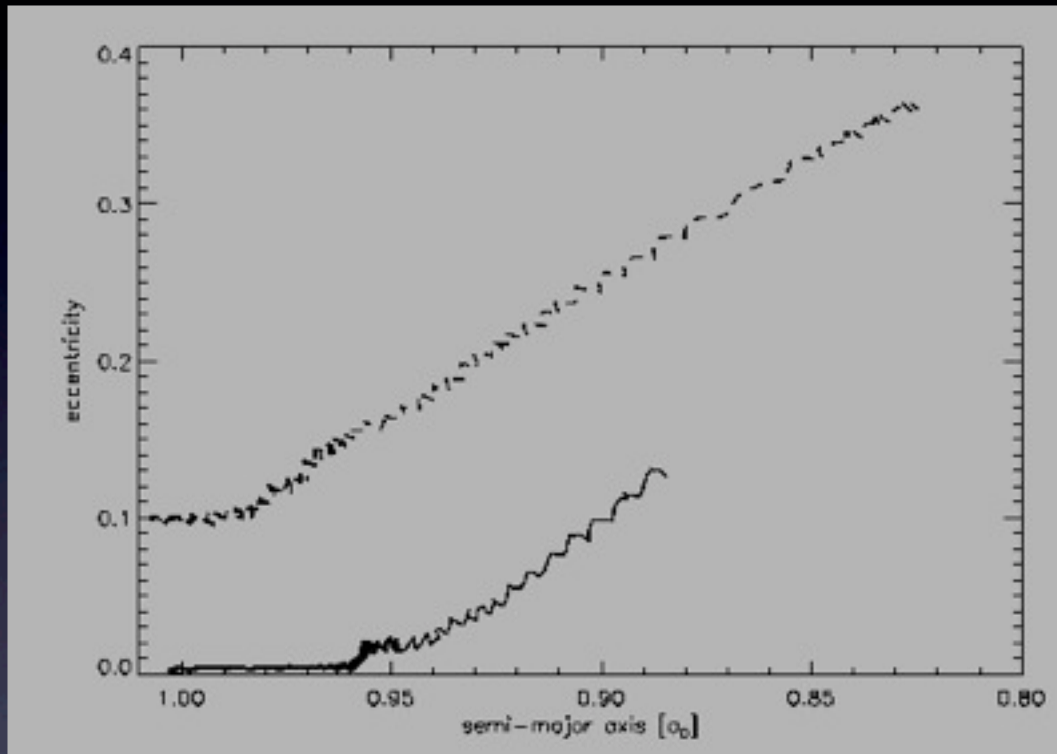
Work in progress with Pau Amaro-Seoane

- 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.



Eccentricity Evolution

Eccentricity



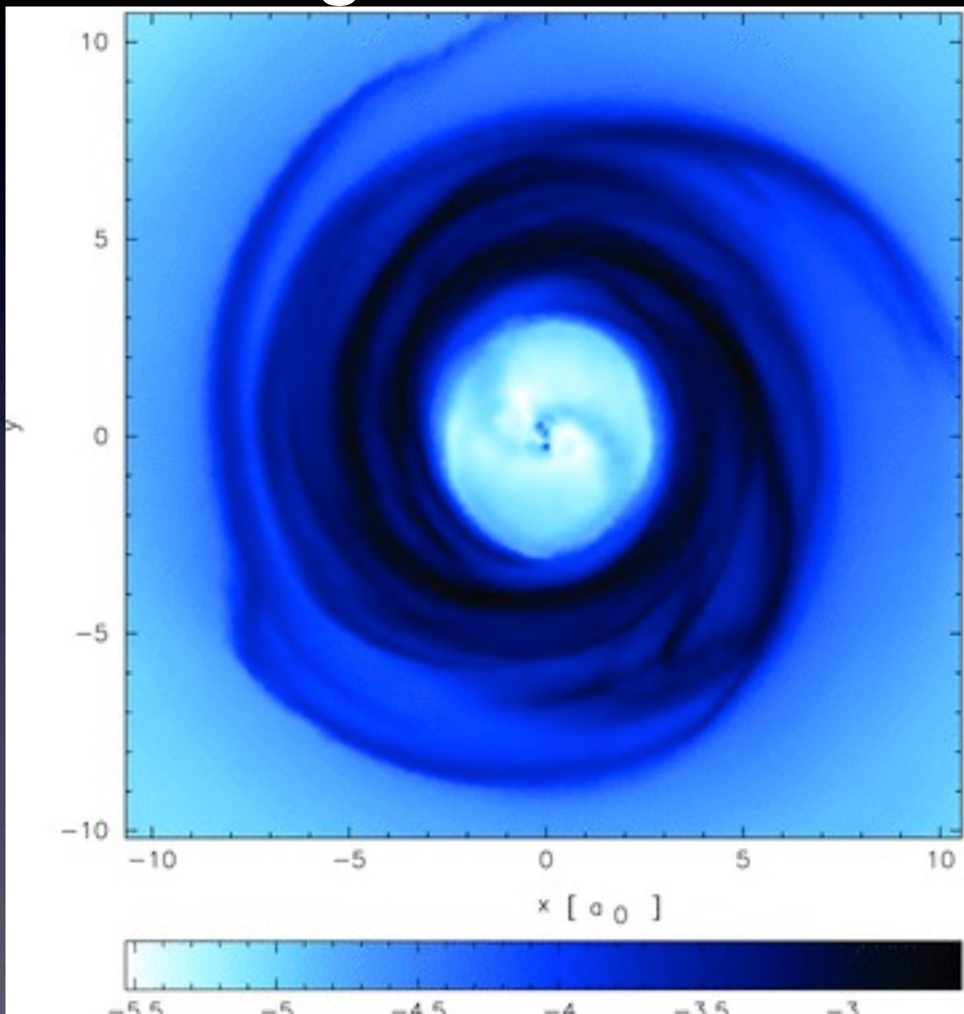
Separation

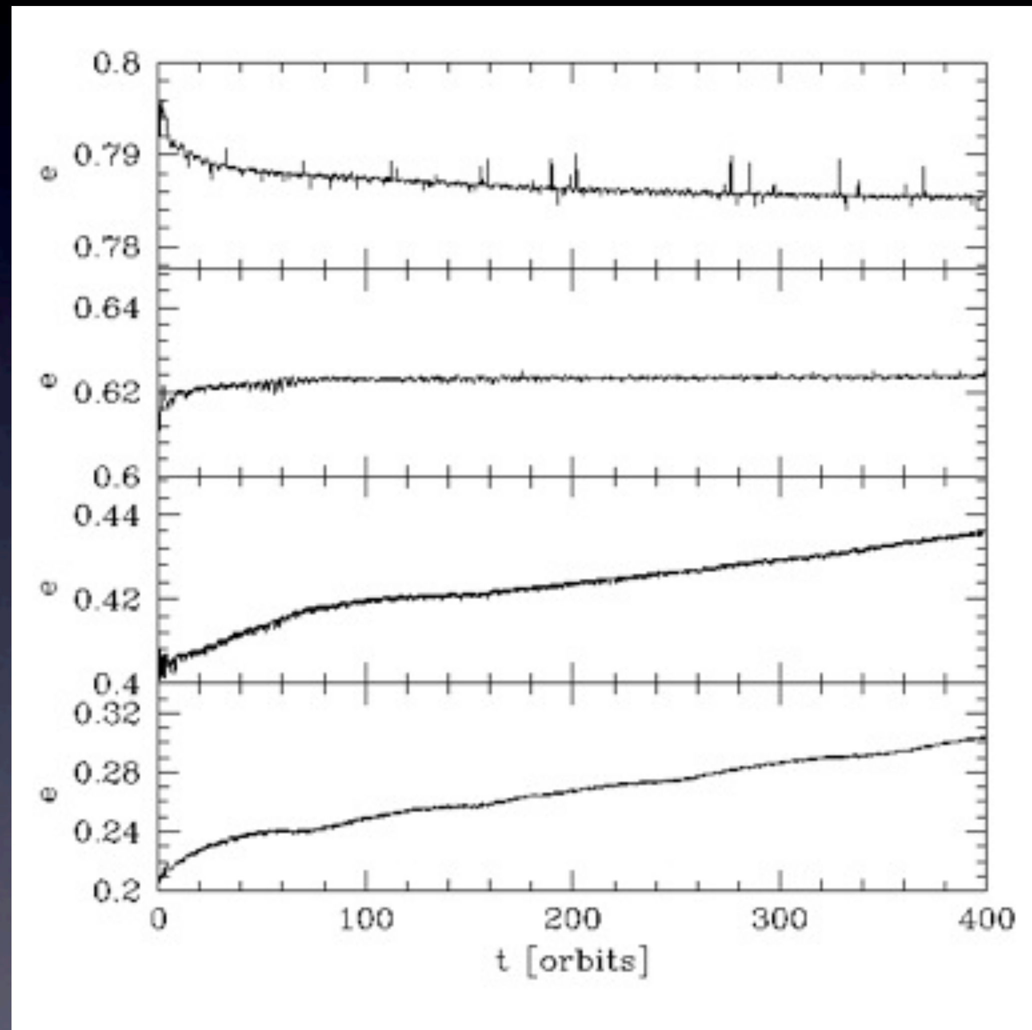
Eccentricity reaches ~0.35 by the end of the simulation.
No sign of saturation.
Will it grow to e ~ 1 ?

Trying different initial eccentricities...

Rödig, Dotti, Sesana, Cuadra, Colpi 2011

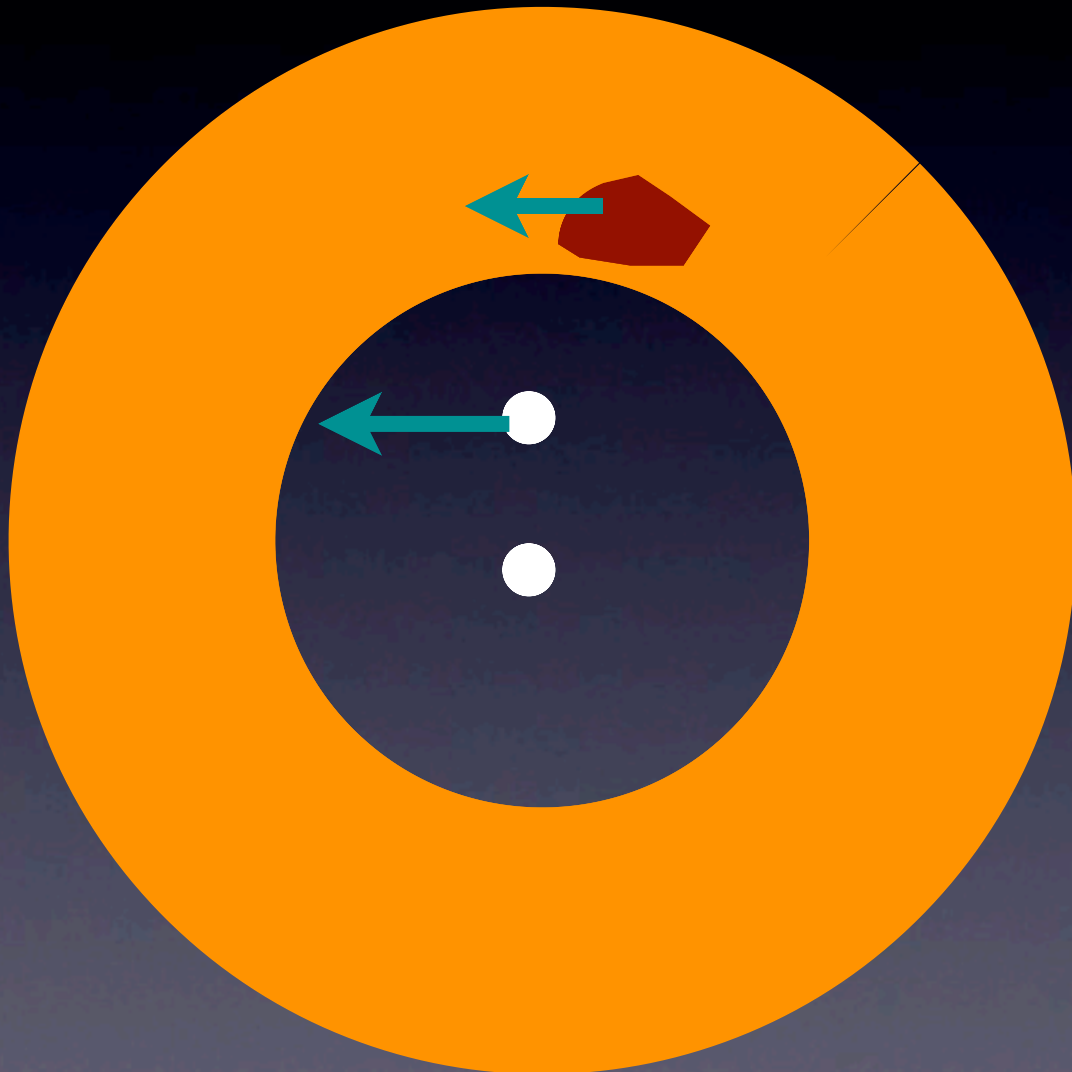
Eccentricity seems to converge to e ~ 0.6 !





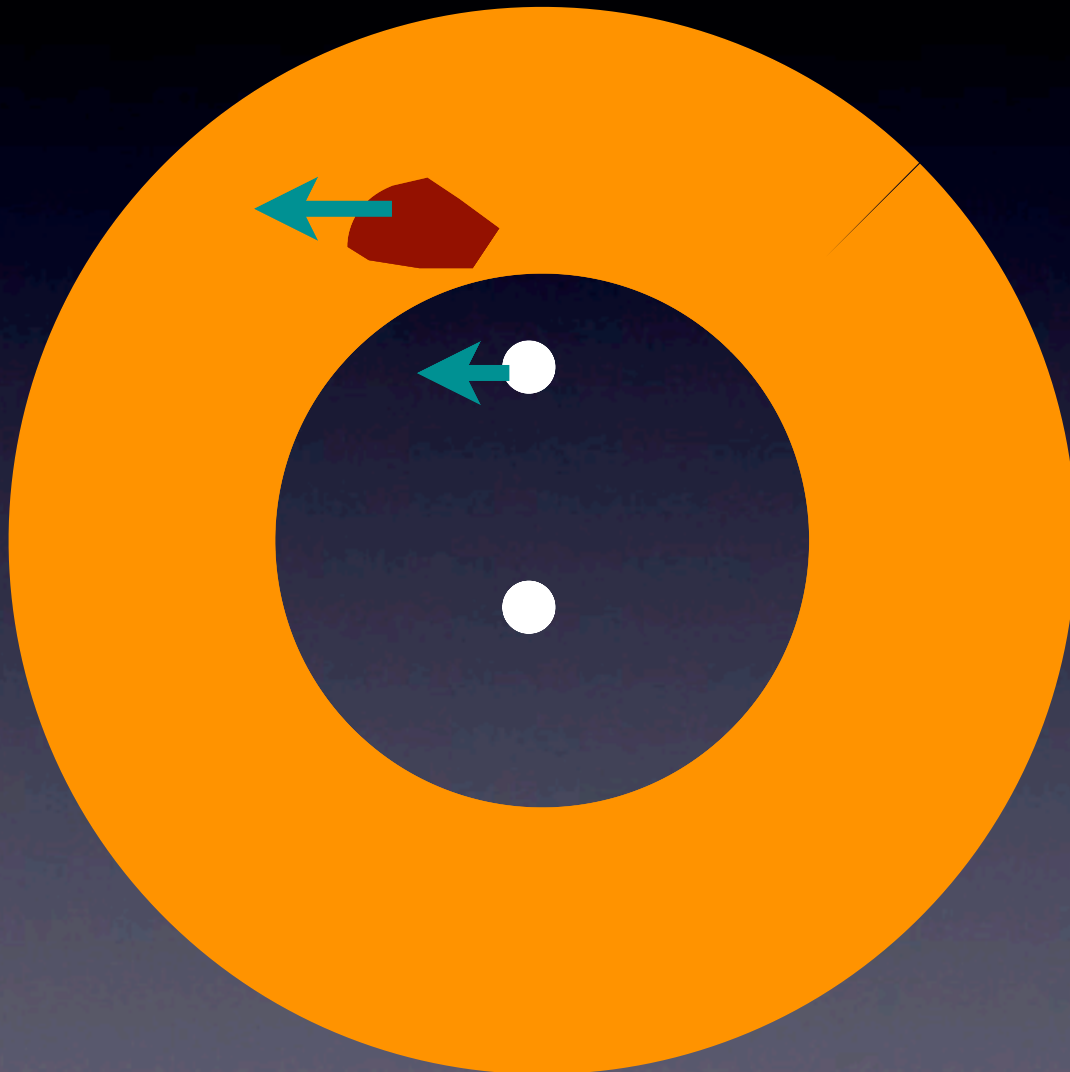
Eccentricity evolution

- Secondary produces *instantaneous* overdensity in inner part of disc.
- If eccentricity is *low*, overdensity *decelerates* secondary at apocentre, increasing eccentricity.



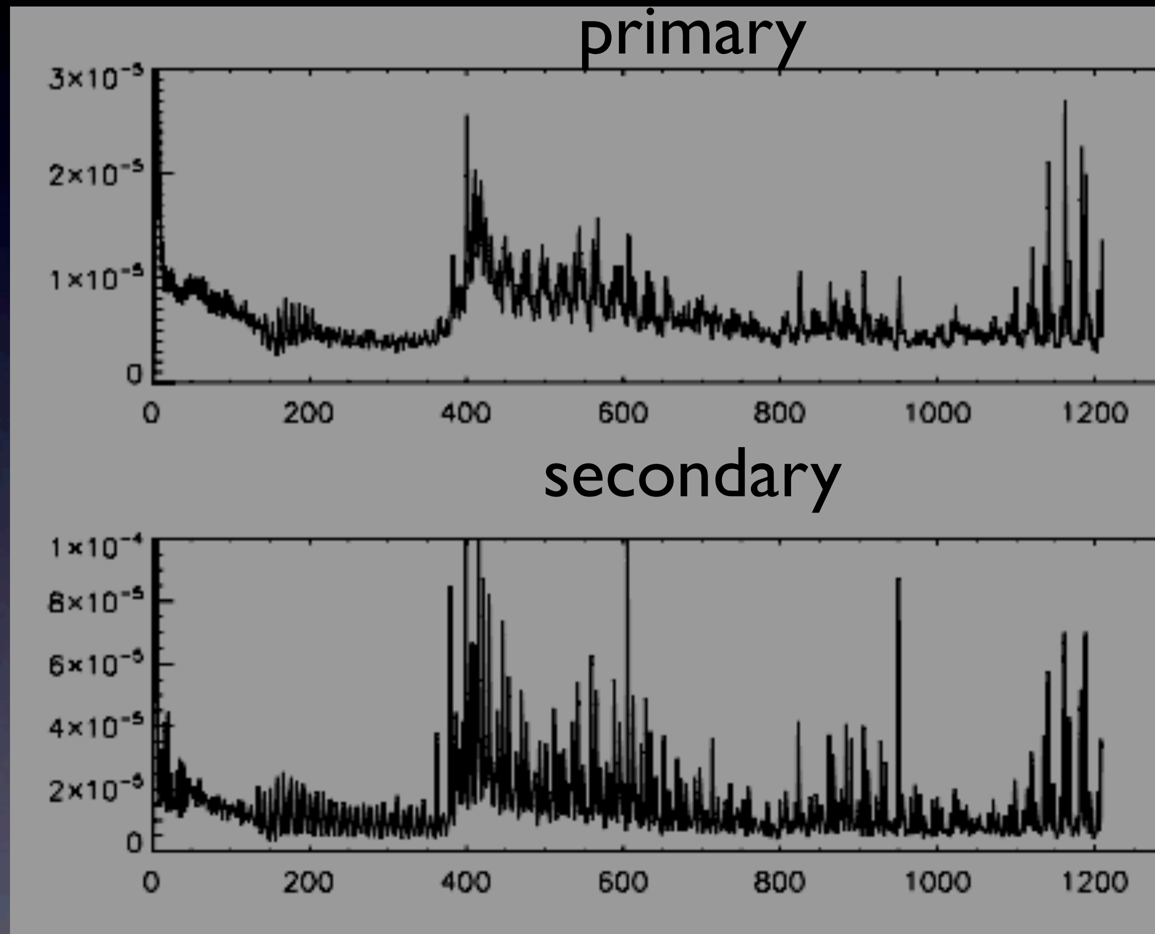
Eccentricity evolution

- If eccentricity is *high*, overdensity *accelerates* secondary at apocentre, decreasing eccentricity.
- Equilibrium where angular velocities are equal, at e ~ 0.6.



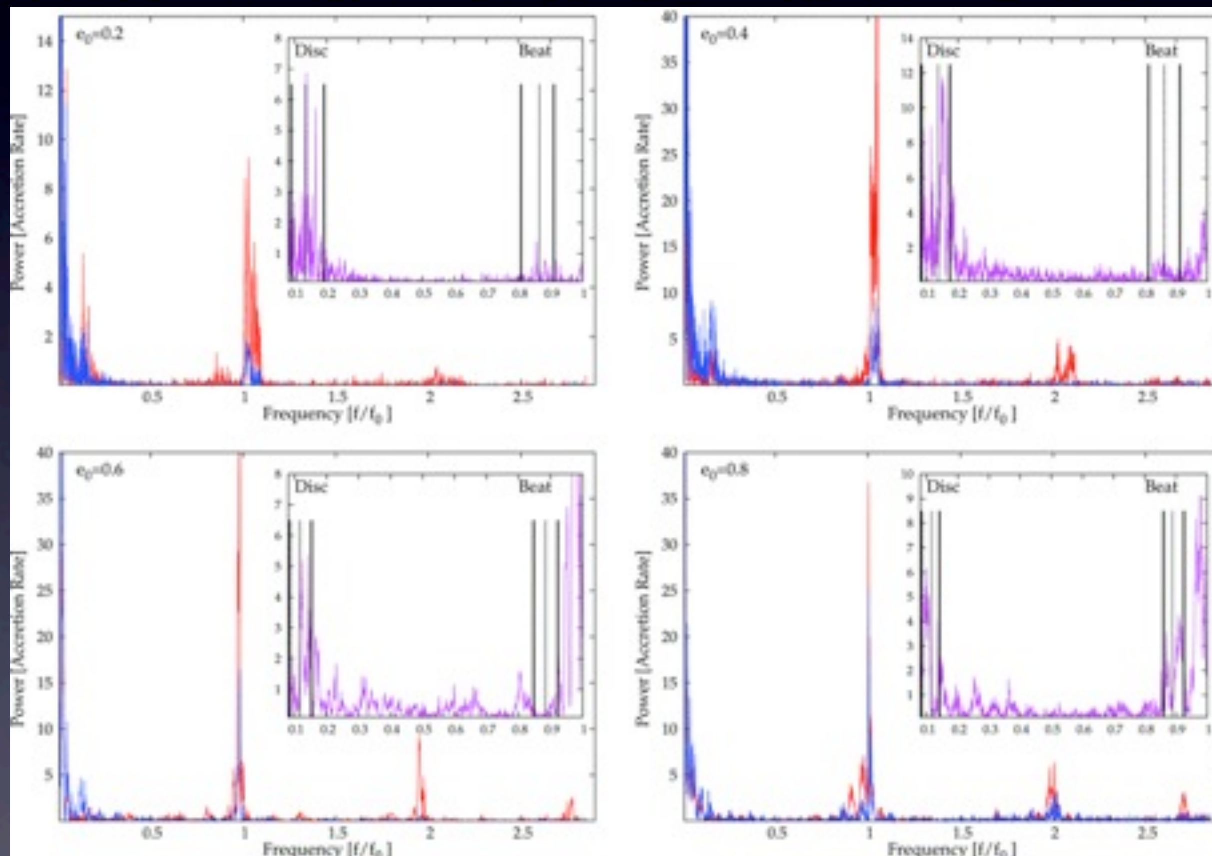
Accretion

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



“Observable” consequences

- Higher eccentricity enhances accretion rate variability.
- GW observations would detect remnant $e \sim 10^{-2} – 10^{-3}$.



Conclusions

- Gas discs are able to produce coalescence of $M < 10^7$ M_{sun} binaries.
- Expect many binaries at few 0.01 pc separations.
- Binaries become eccentric -- influence the accretion rate and the gravitational wave signal at coalescence.
- For more massive binaries star-forming discs may help.

Open Questions

- Is the "last-parsec problem" really solved?
- When is the binary + circumbinary disc model appropriate? (cf L del Valle poster)
- Can we use circumbinary simulations to identify signatures of sub-pc binaries?
- How important is treating properly the disc thermodynamics?
- How much gas follows the disc to produce an electromagnetic counterpart?