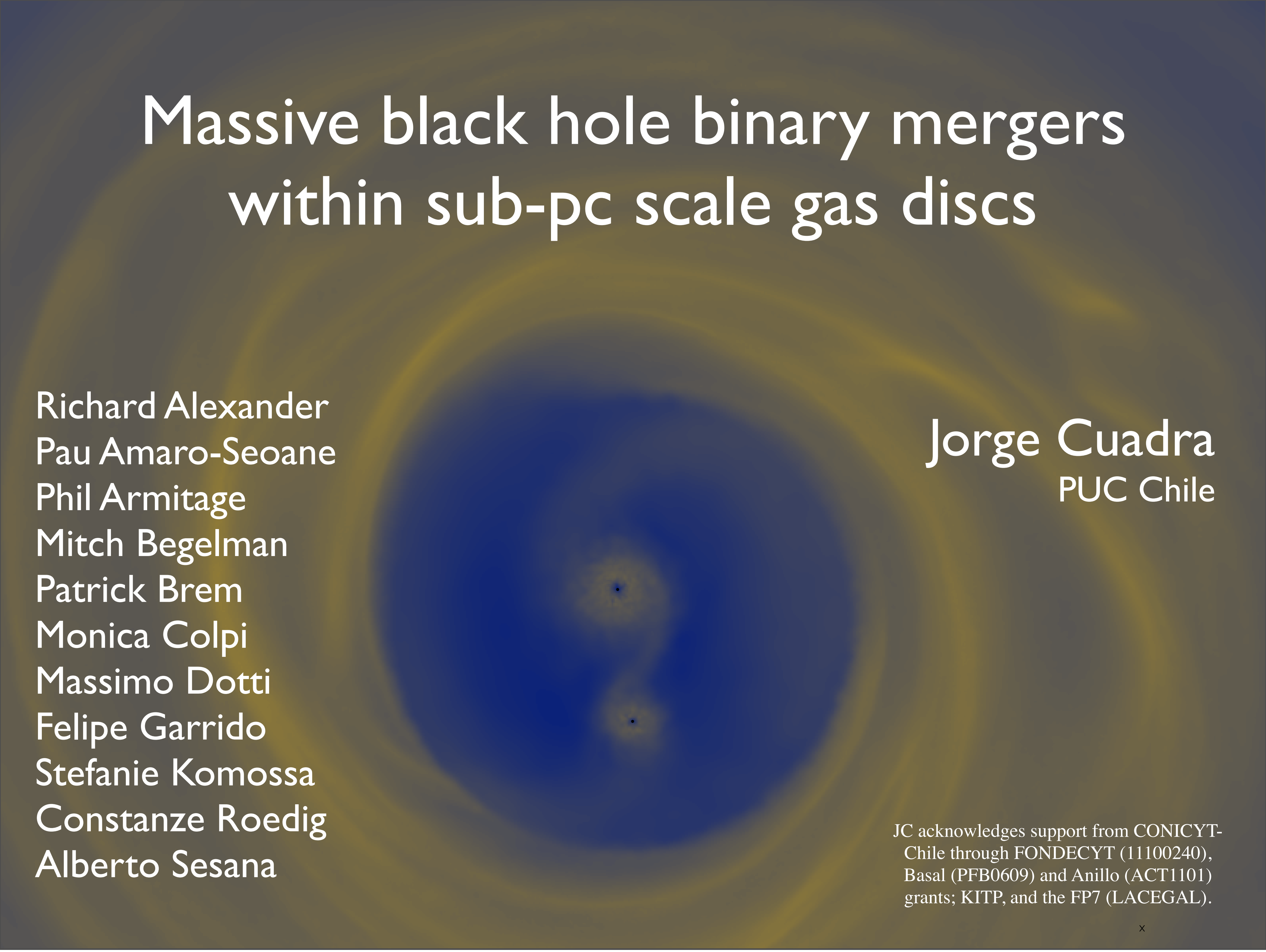


Massive black hole binary mergers within sub-pc scale gas discs

Richard Alexander
Pau Amaro-Seoane
Phil Armitage
Mitch Begelman
Patrick Brem
Monica Colpi
Massimo Dotti
Felipe Garrido
Stefanie Komossa
Constanze Roedig
Alberto Sesana

Jorge Cuadra
PUC Chile

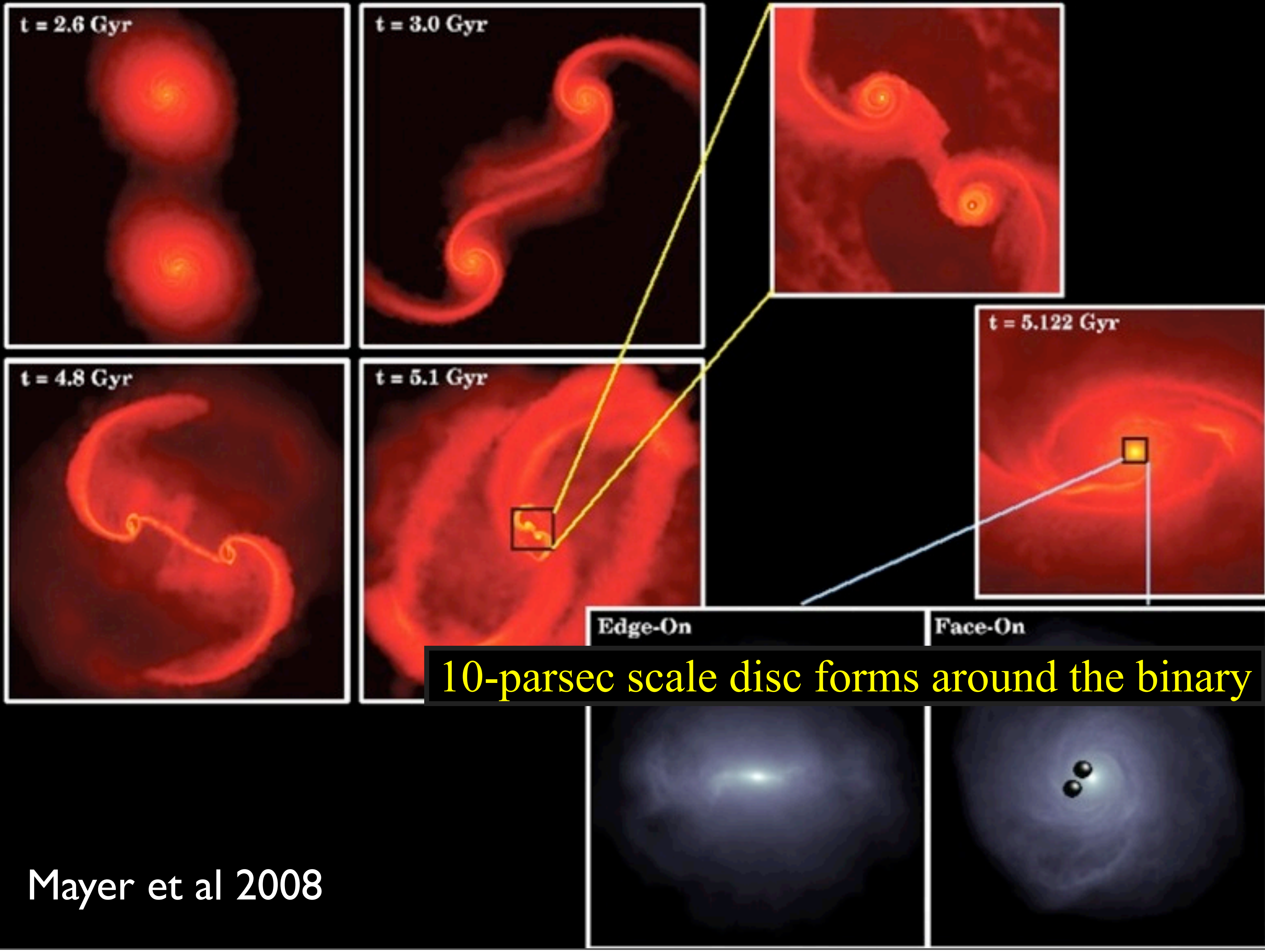
JC acknowledges support from CONICYT-Chile through FONDECYT (11100240), Basal (PFB0609) and Anillo (ACT1101) grants; KITP, and the FP7 (LACEGAL).

x

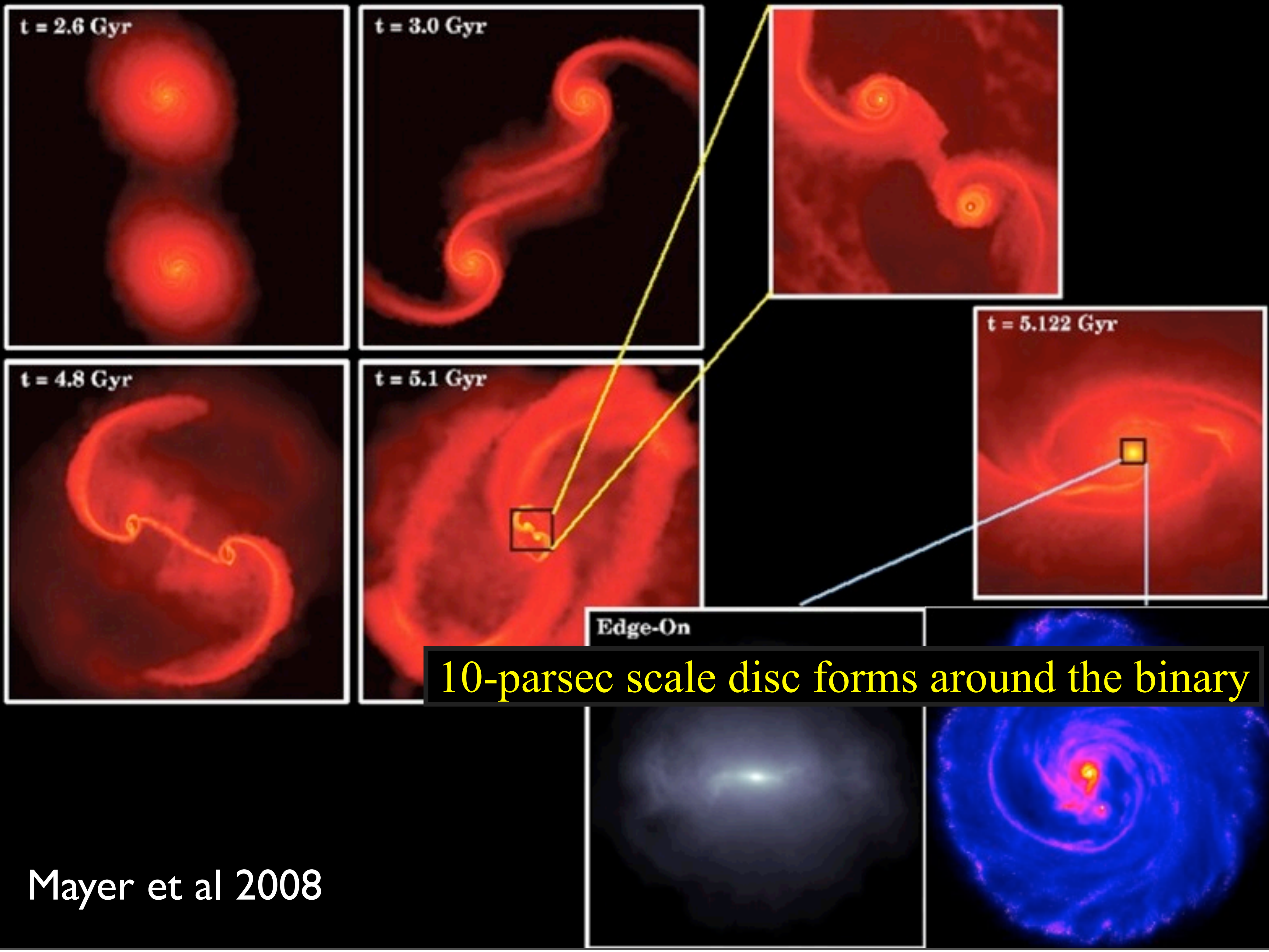
Gas-driven mergers at large scales

e.g., Escala et al 2004, 2005; Mayer et al 2008; Dotti et al 2009
see M. Colpi's, P. Capelo's and D. Fiacconi's 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 2008



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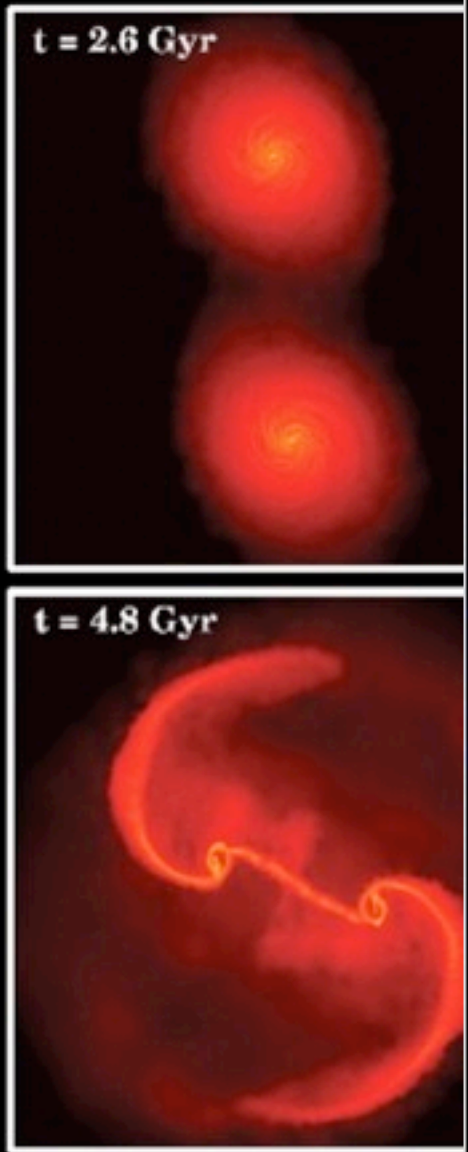
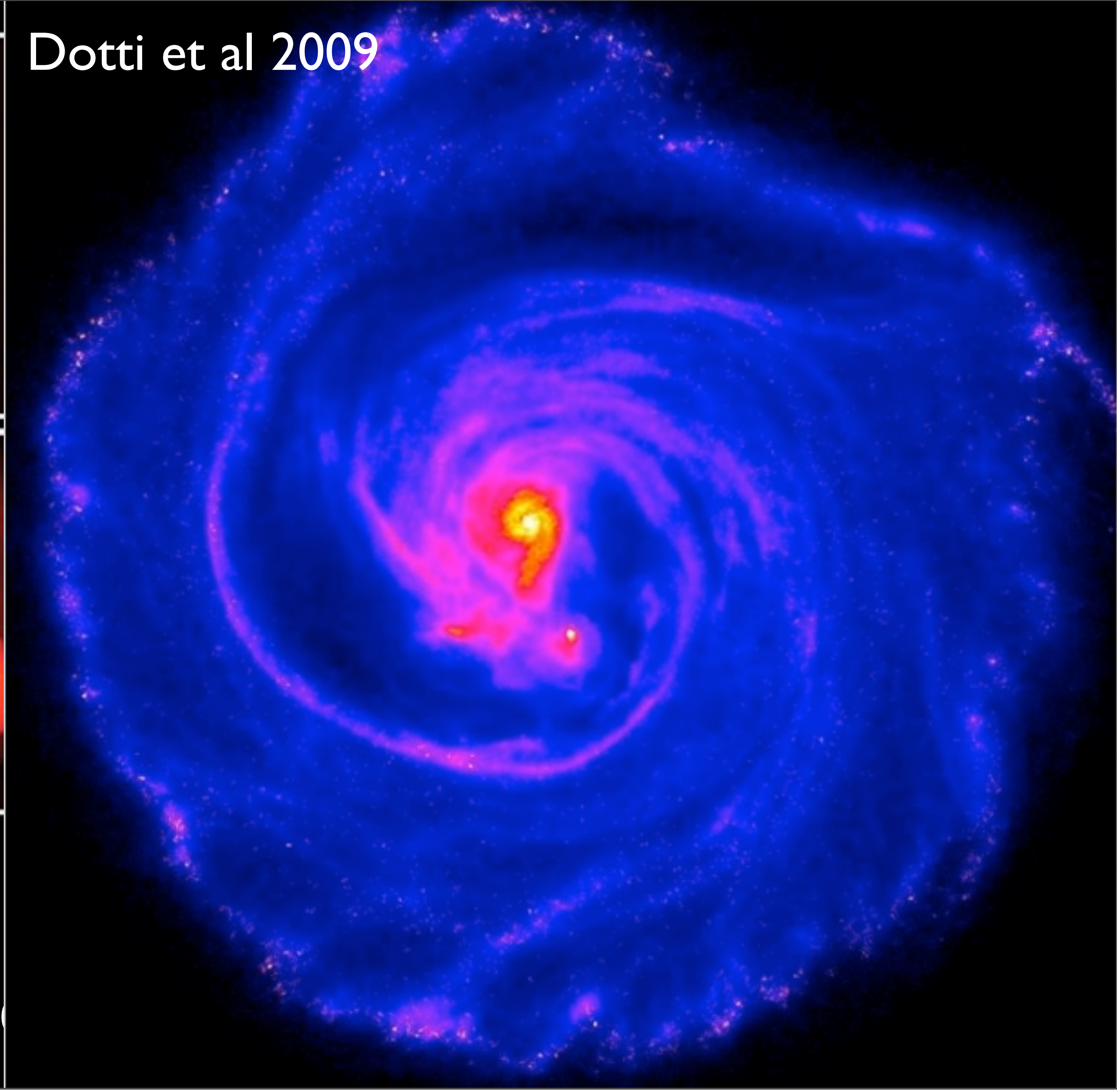


Mayer et al 20(



Massive Nuclear Discs

Gammie 2001; Rice, Lodato, Armitage, et al 2005, etc
cf B. McKernan's talk

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

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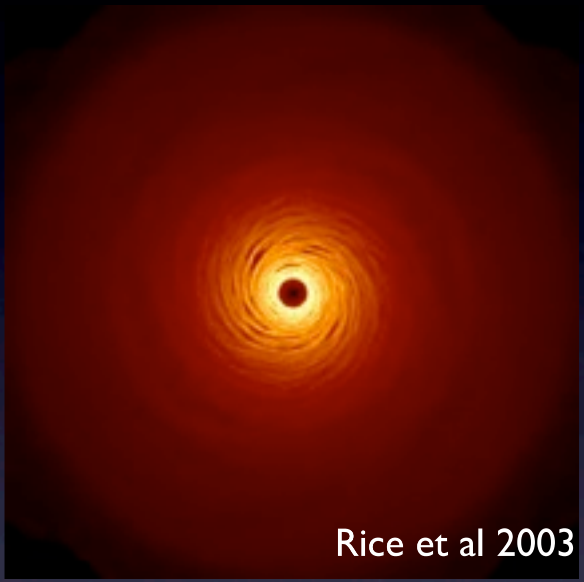
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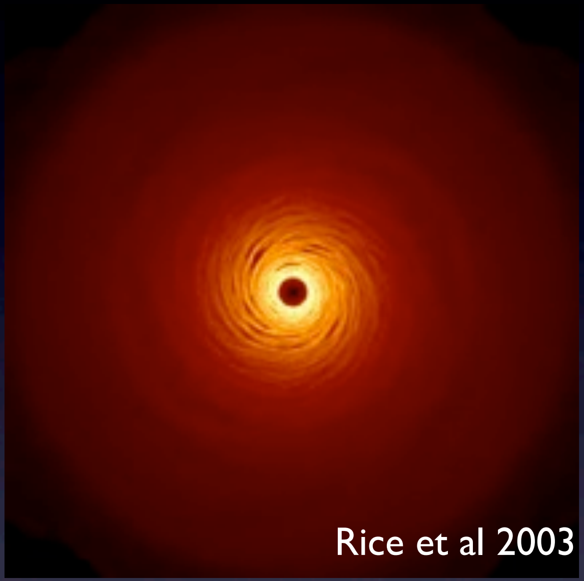
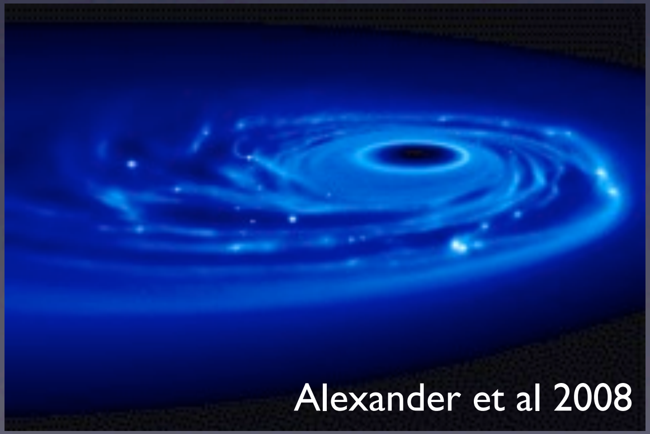


Rice et al 2003



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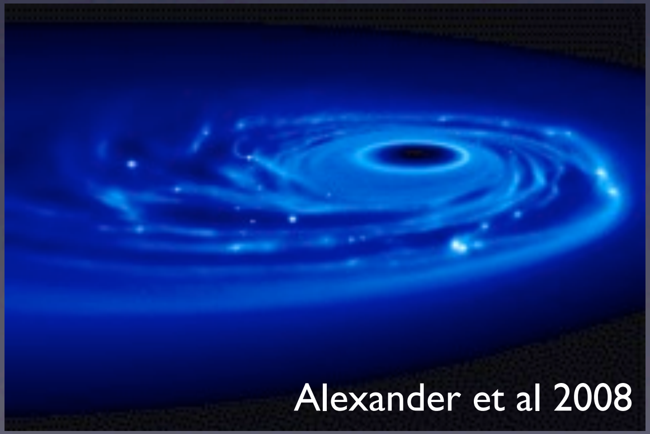
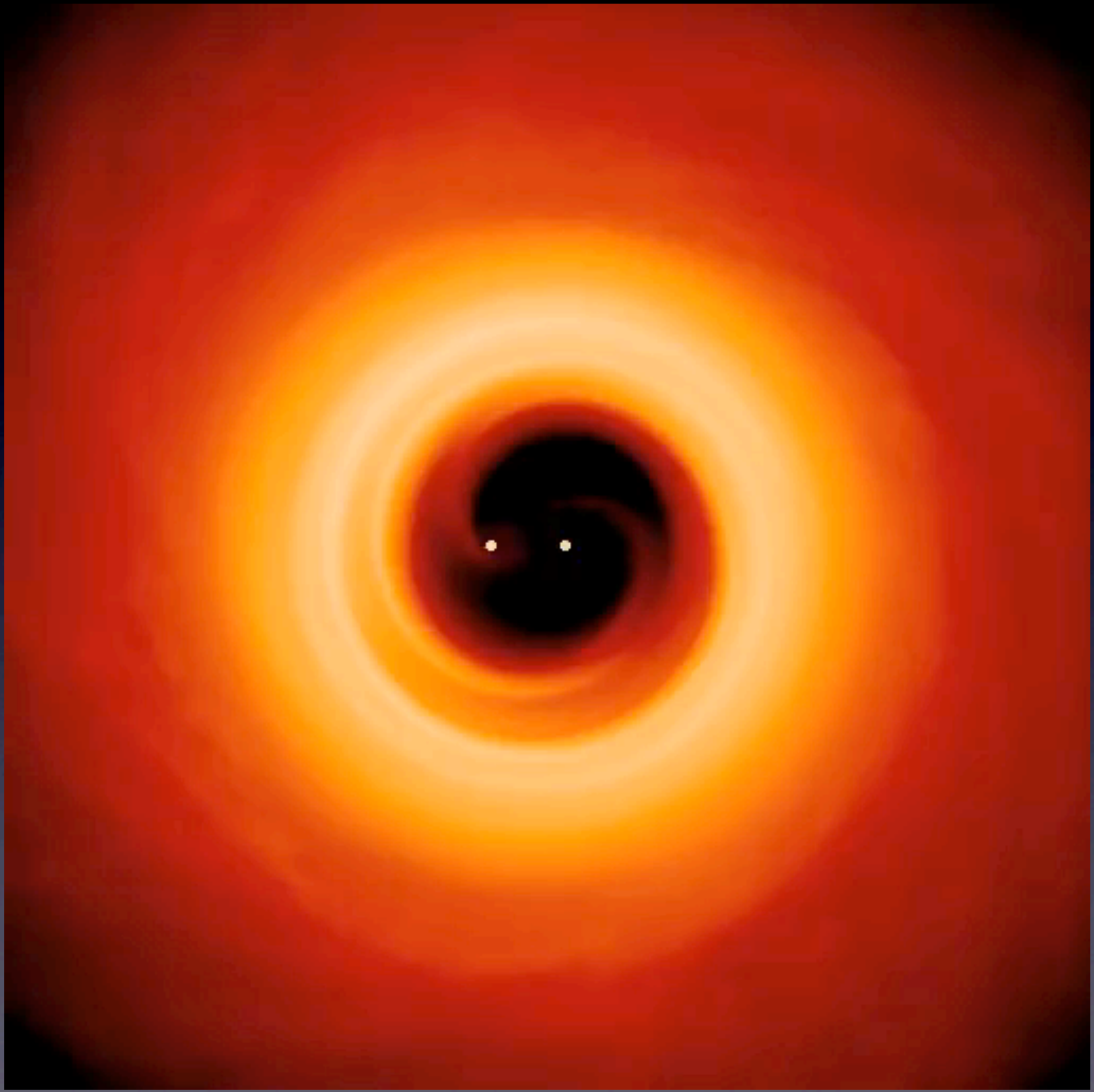


Alexander et al 2008

Numerical Models

Cuadra, Armitage, Alexander, Begelman 2009

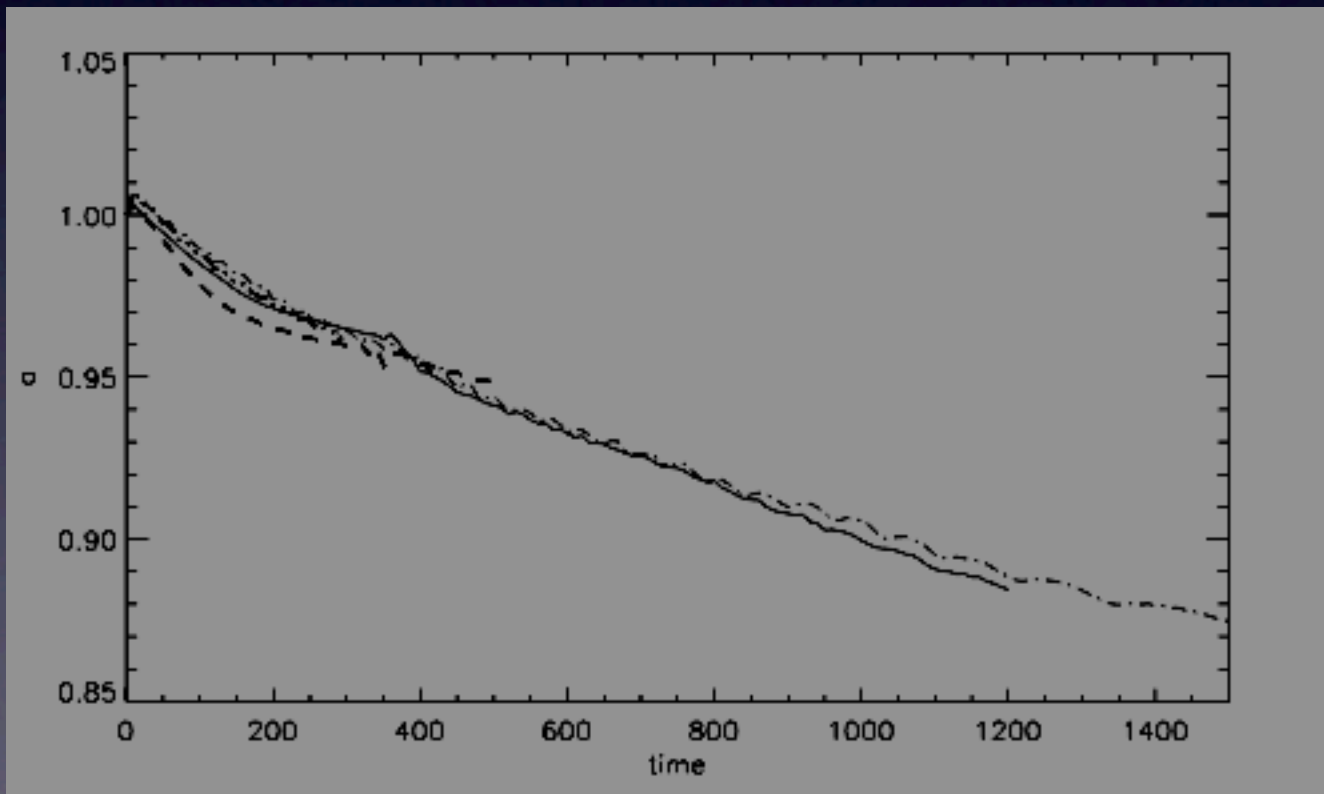
- 3:1 mass ratio binary
- $M_{disc} = 0.2\ M_{BH}$
- Physical angular momentum transport due to self-gravity
- Modified Gadget-2 (SPH code by Springel 2005)
- Goal: find evolution of binary
  - time-scale for merger
  - eccentricity evolution



Binary Orbit Evolution

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

Semi-major axis



Time

Scaling to real systems

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- Our simulations agree well...
- We can then scale results to different disc properties using analytical models.

Maximum disc mass

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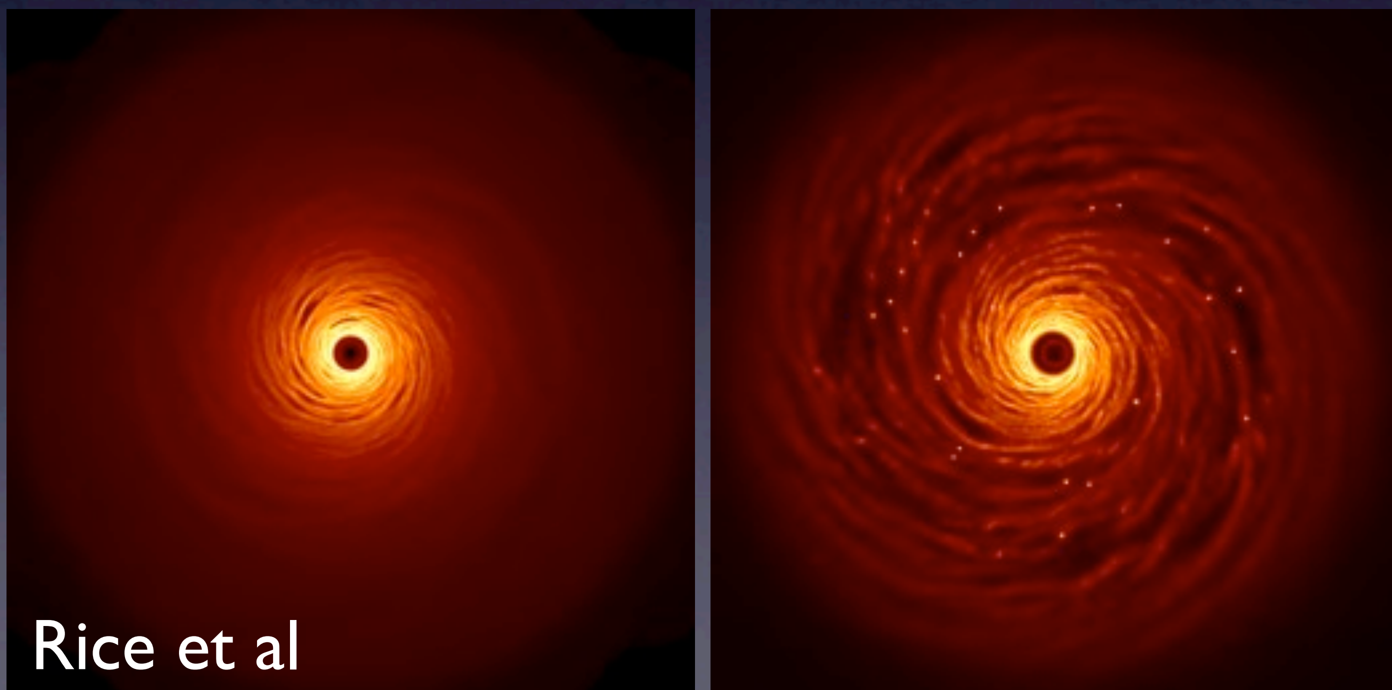
- Can't we just have a very large disc to make sure there's a merger?

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.



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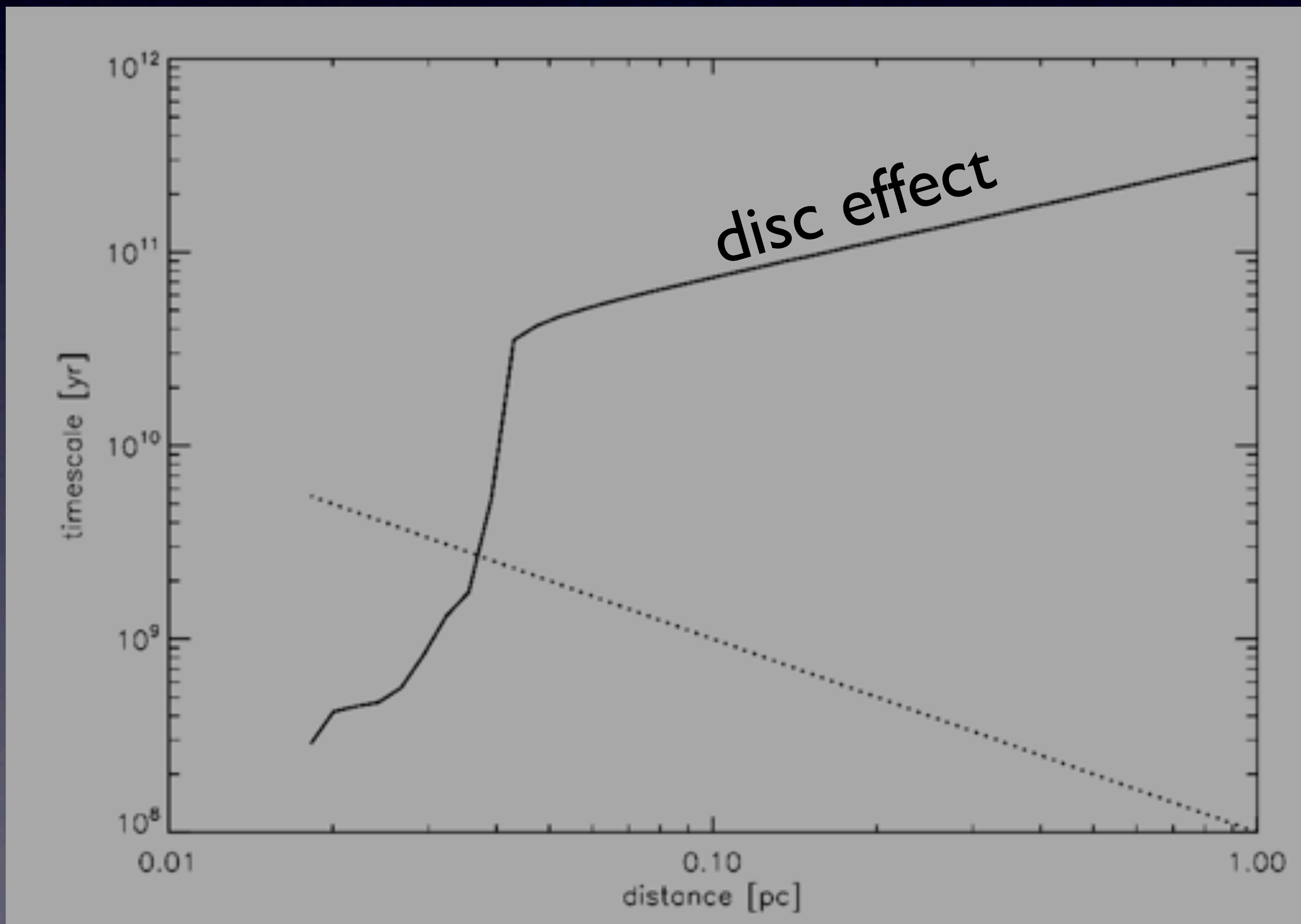

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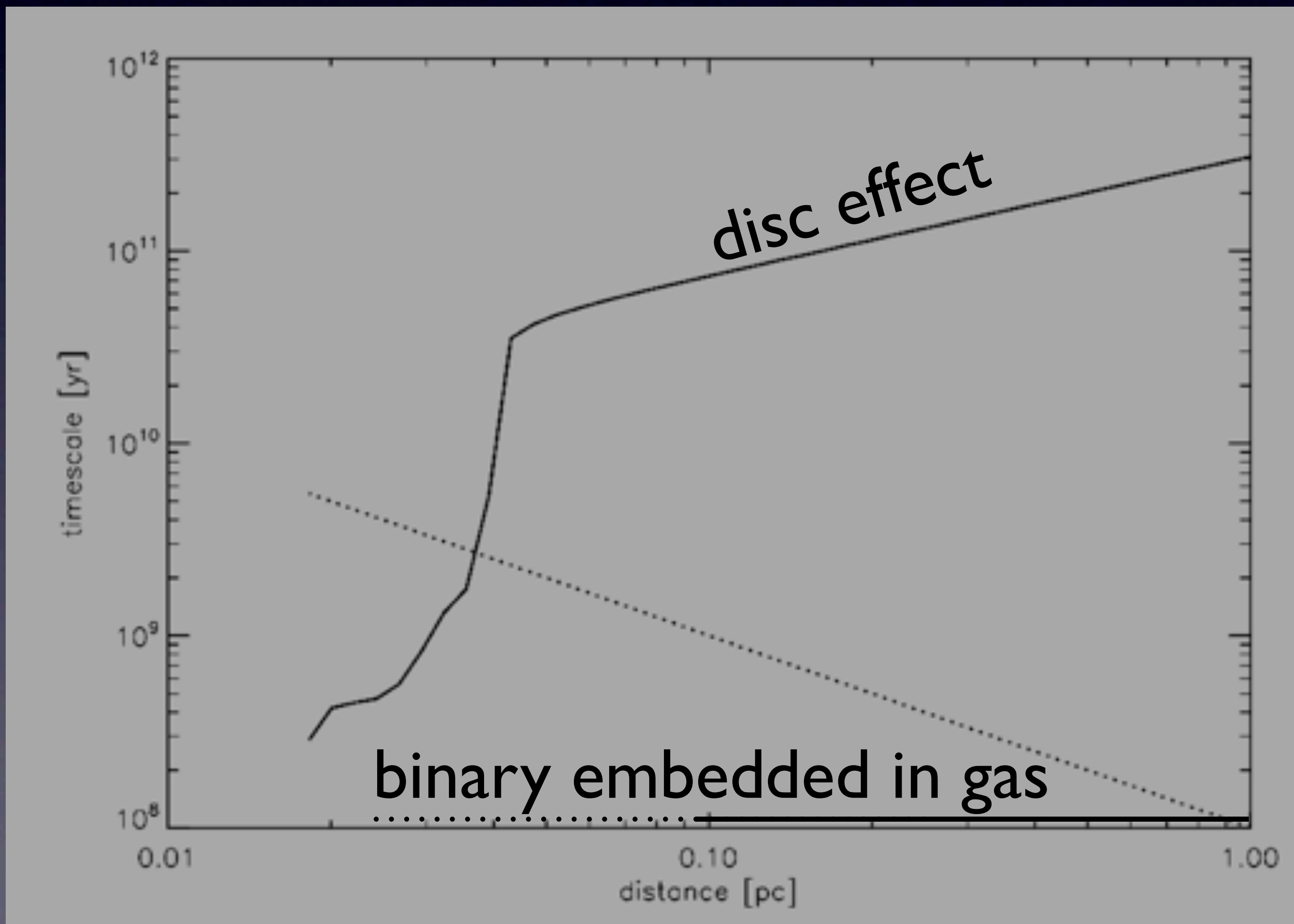

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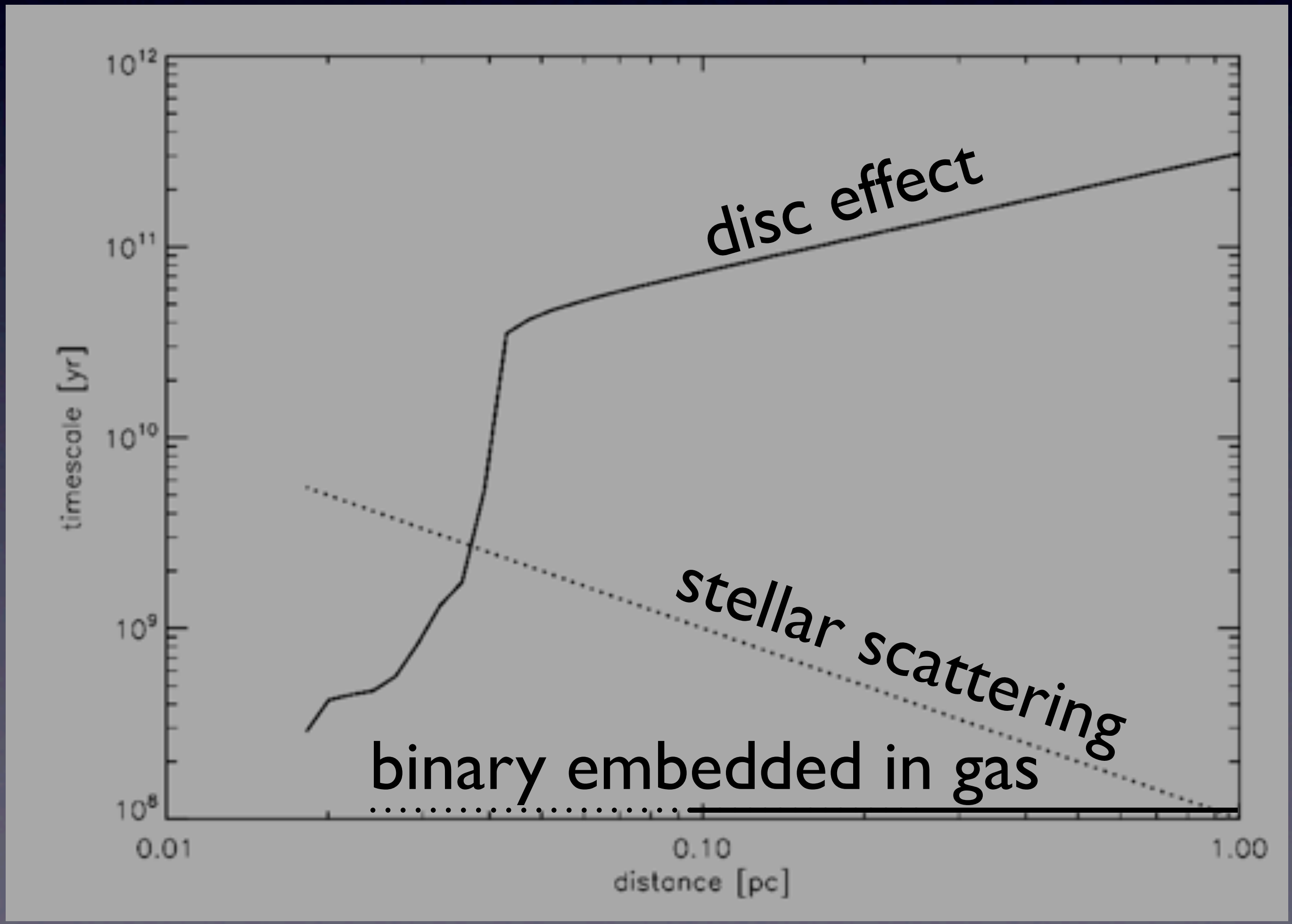

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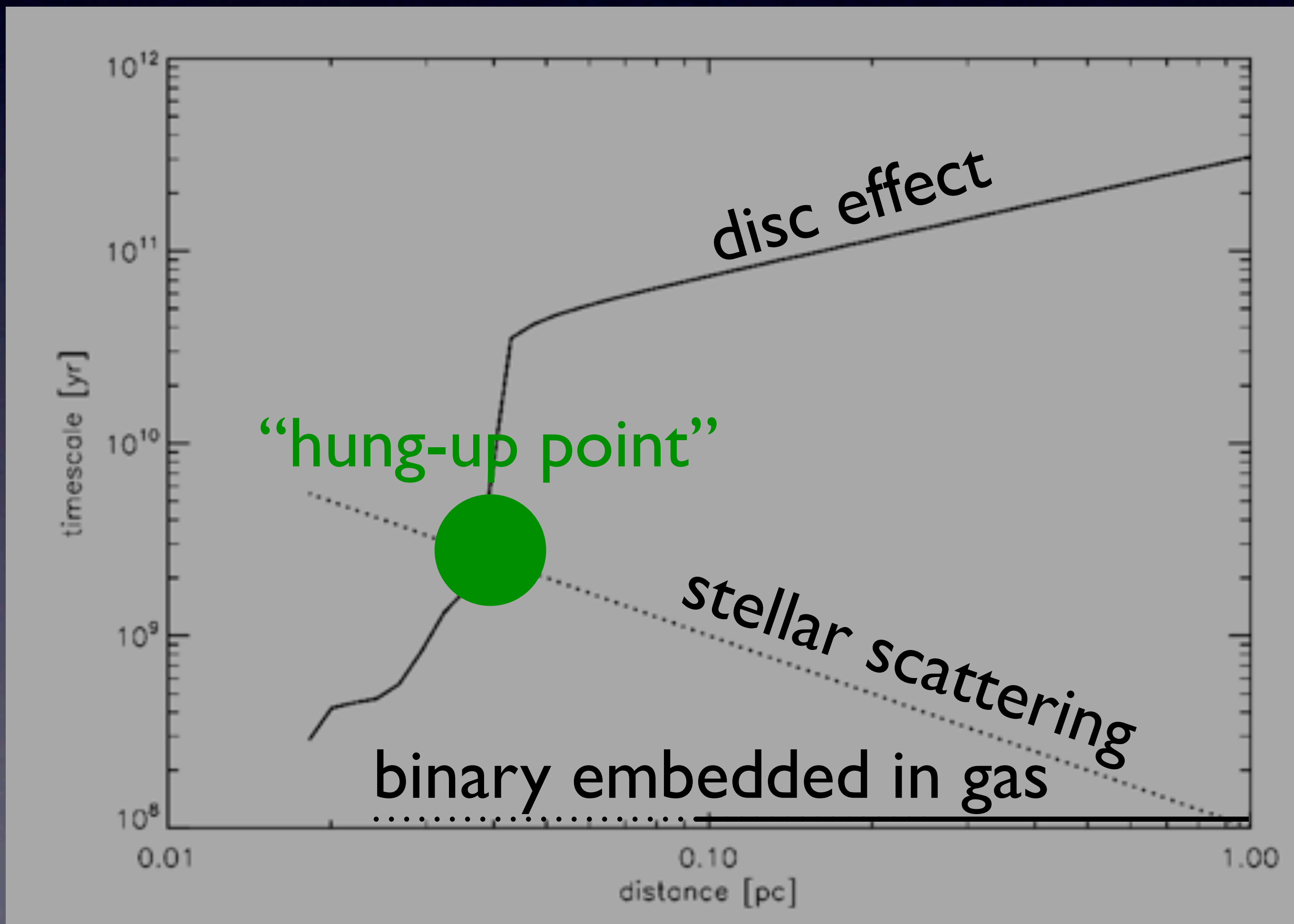
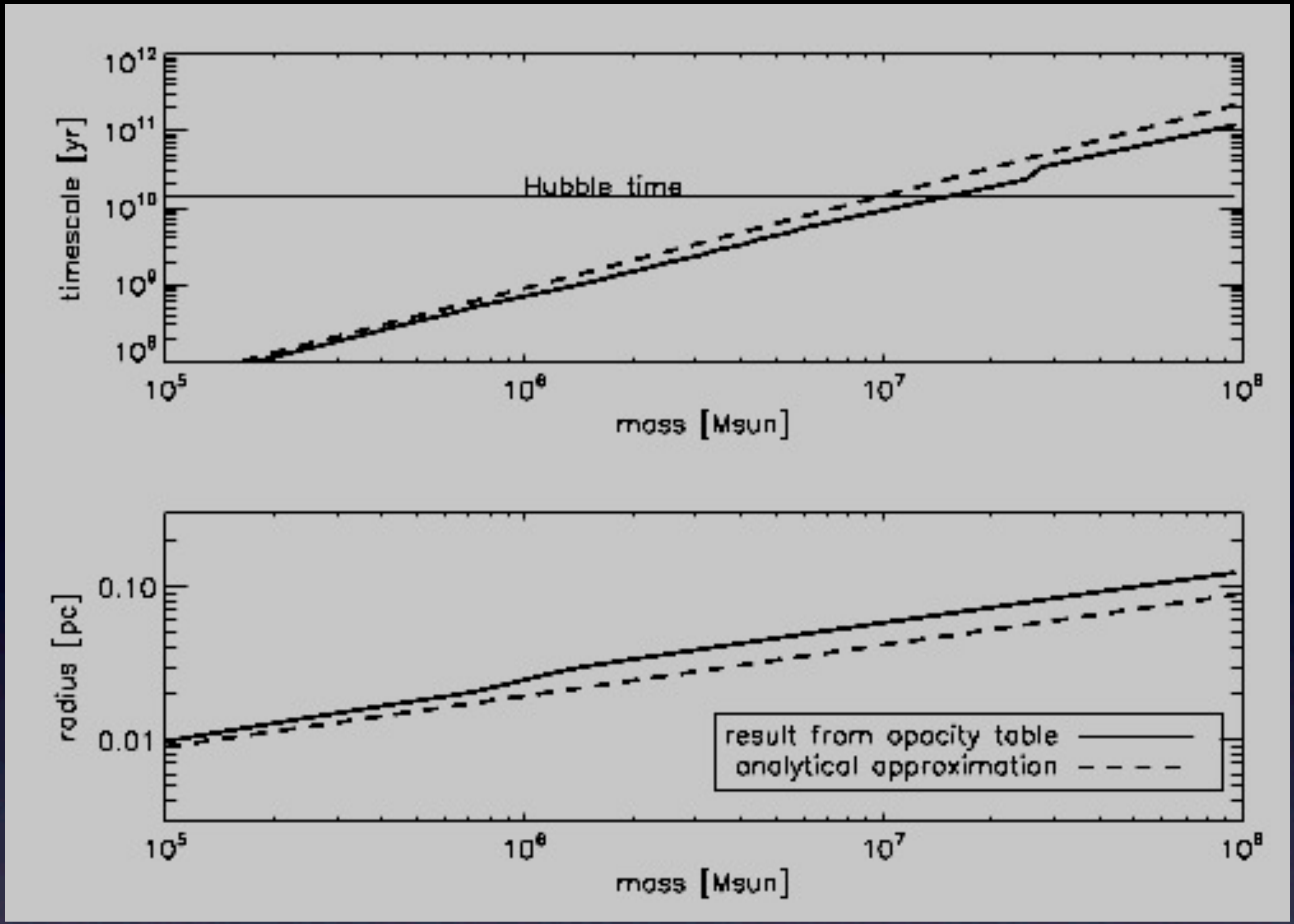
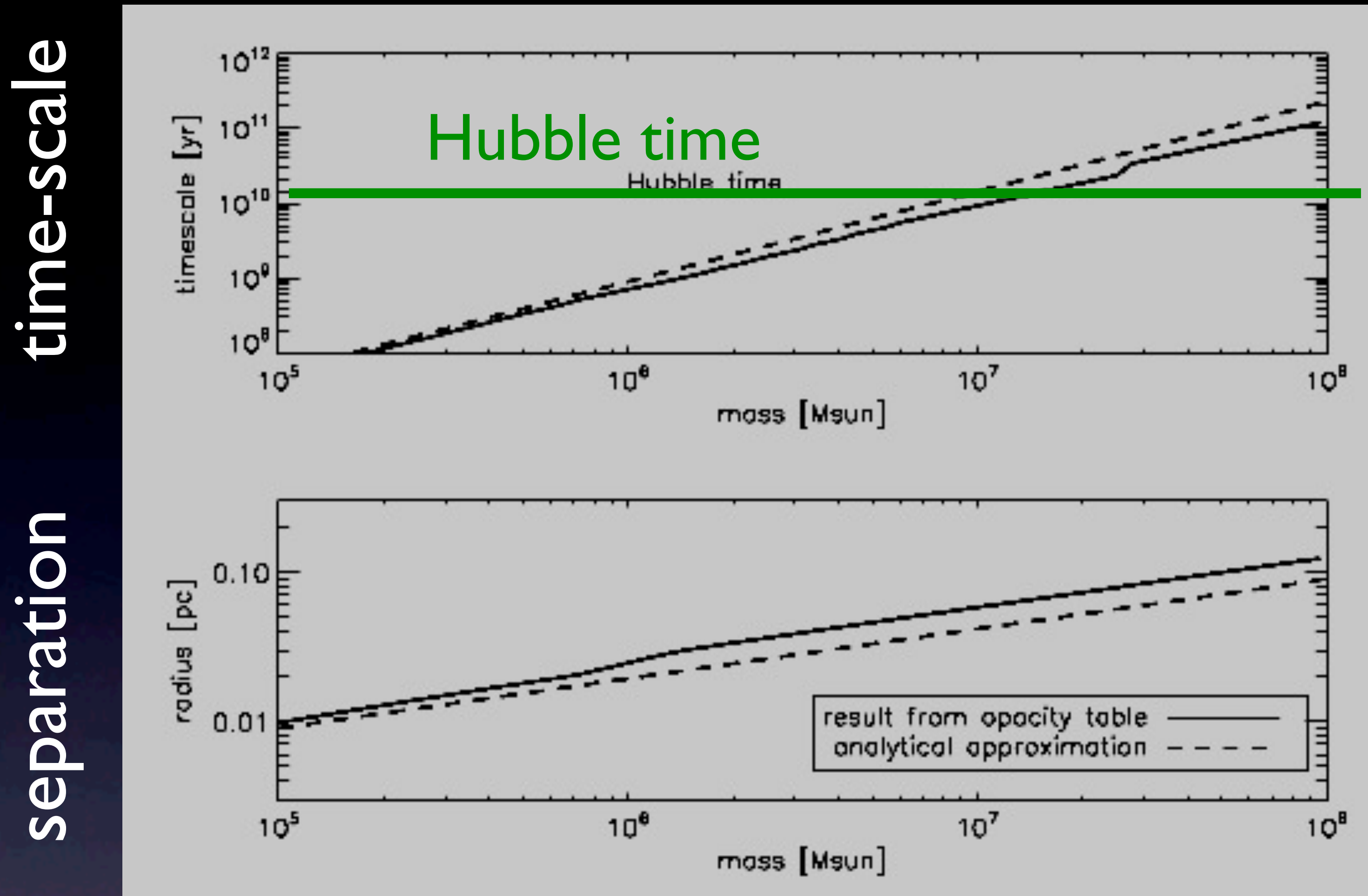


time-scale

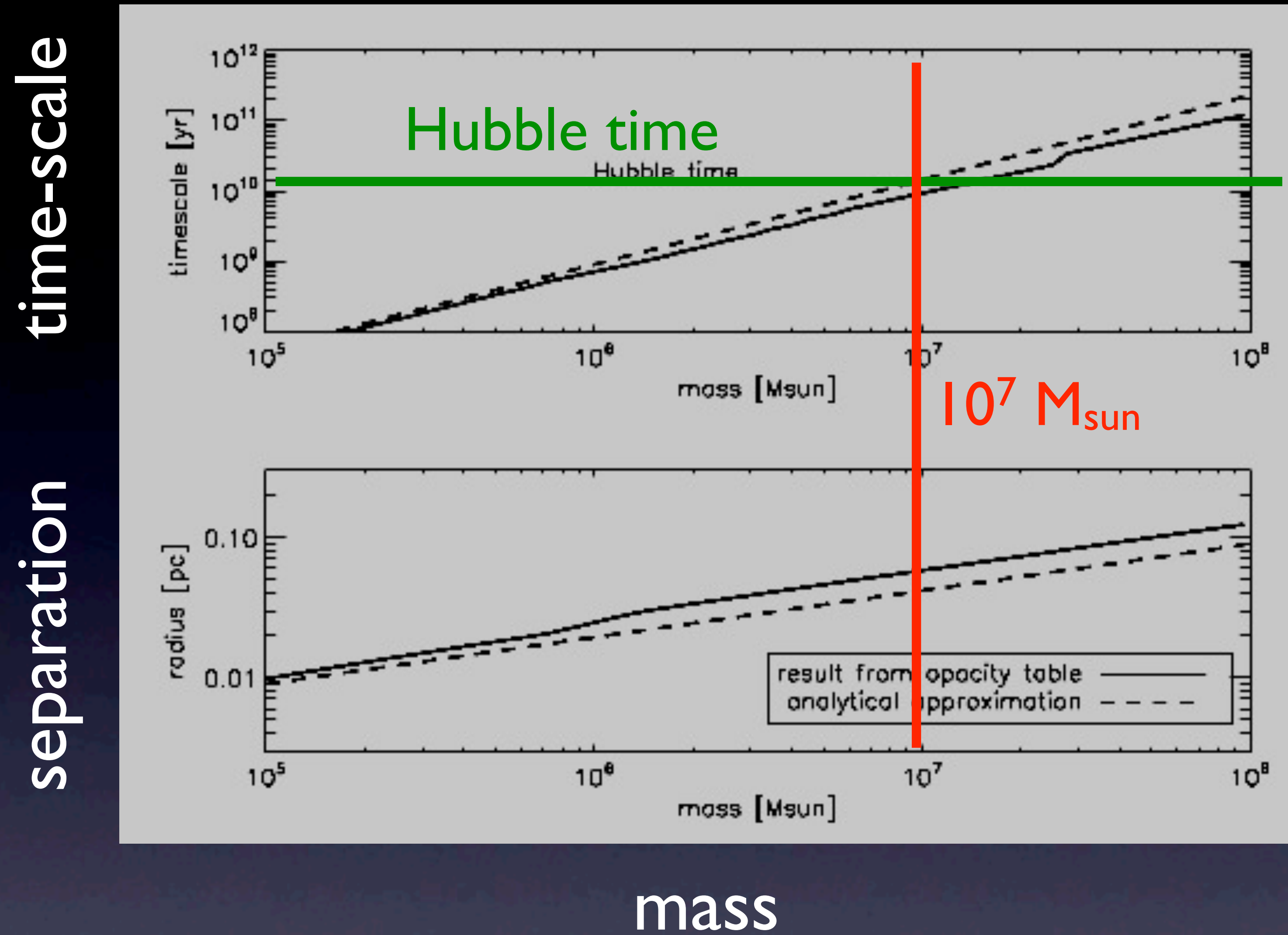
separation



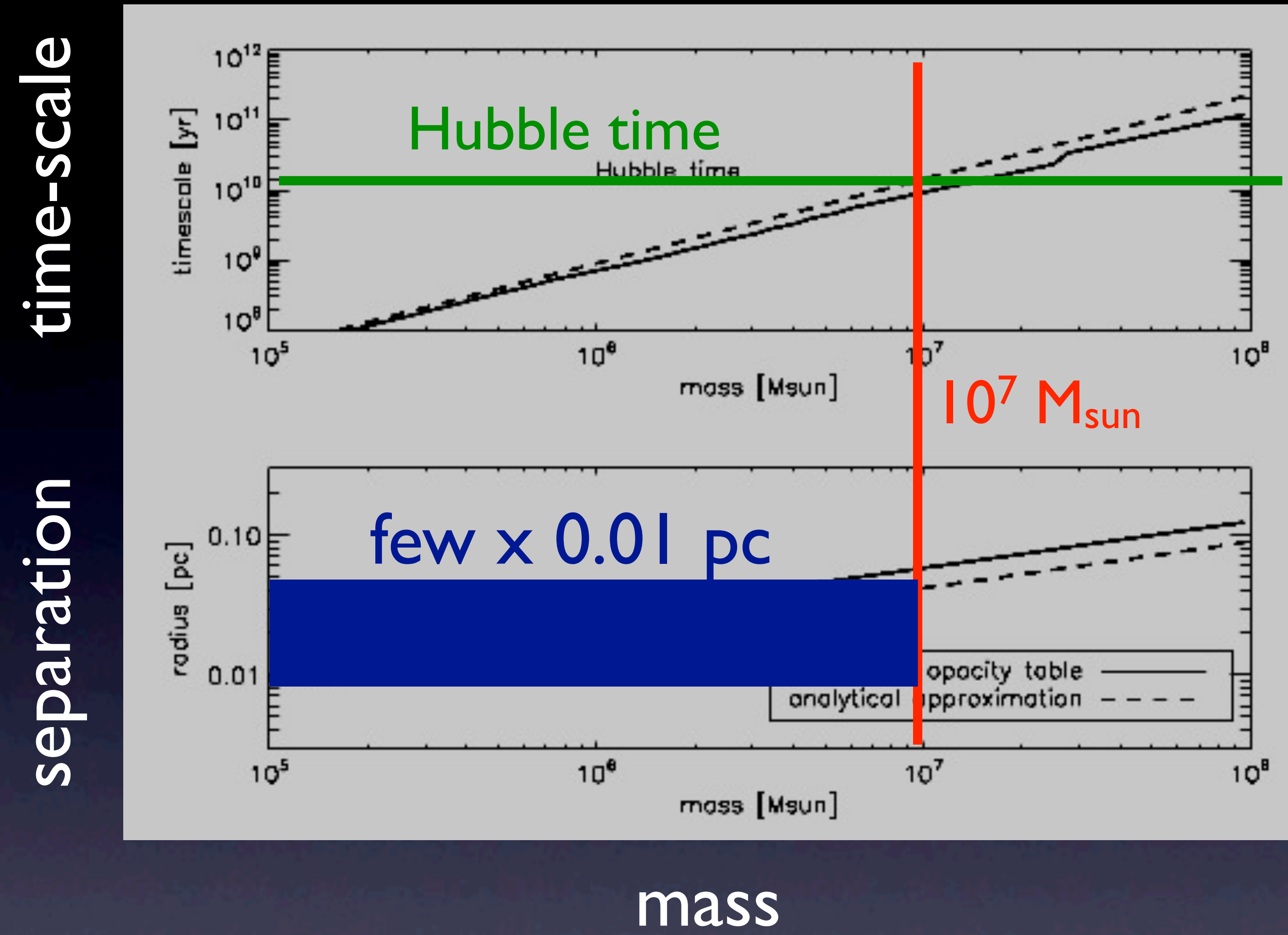
mass


time-scale
separation
Hubble time
Hubble time
timescale [yr]
mass [Msun]
radius [pc]
result from opacity table
analytical approximation

mass



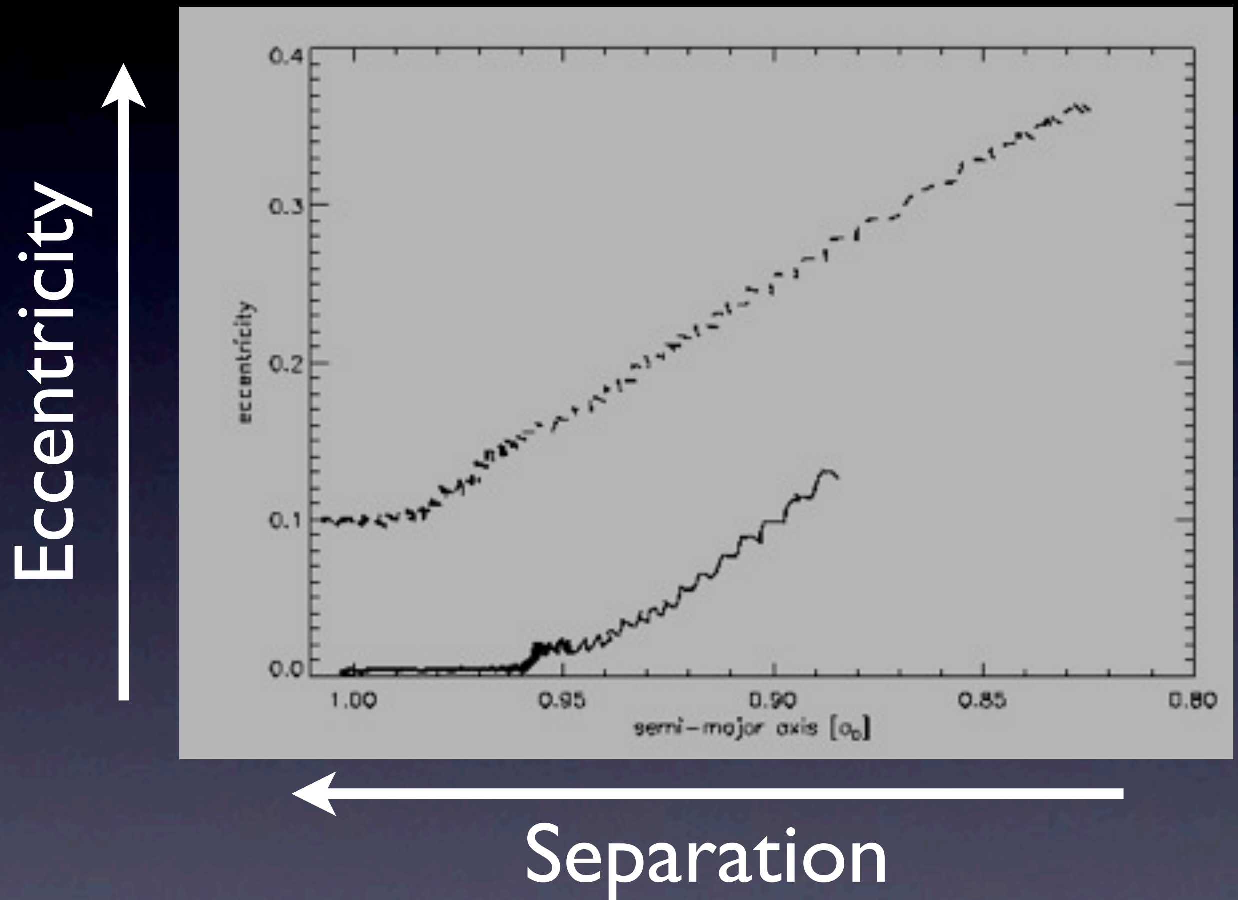
Binaries smaller than 10^7 M_{sun} could merge.



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

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

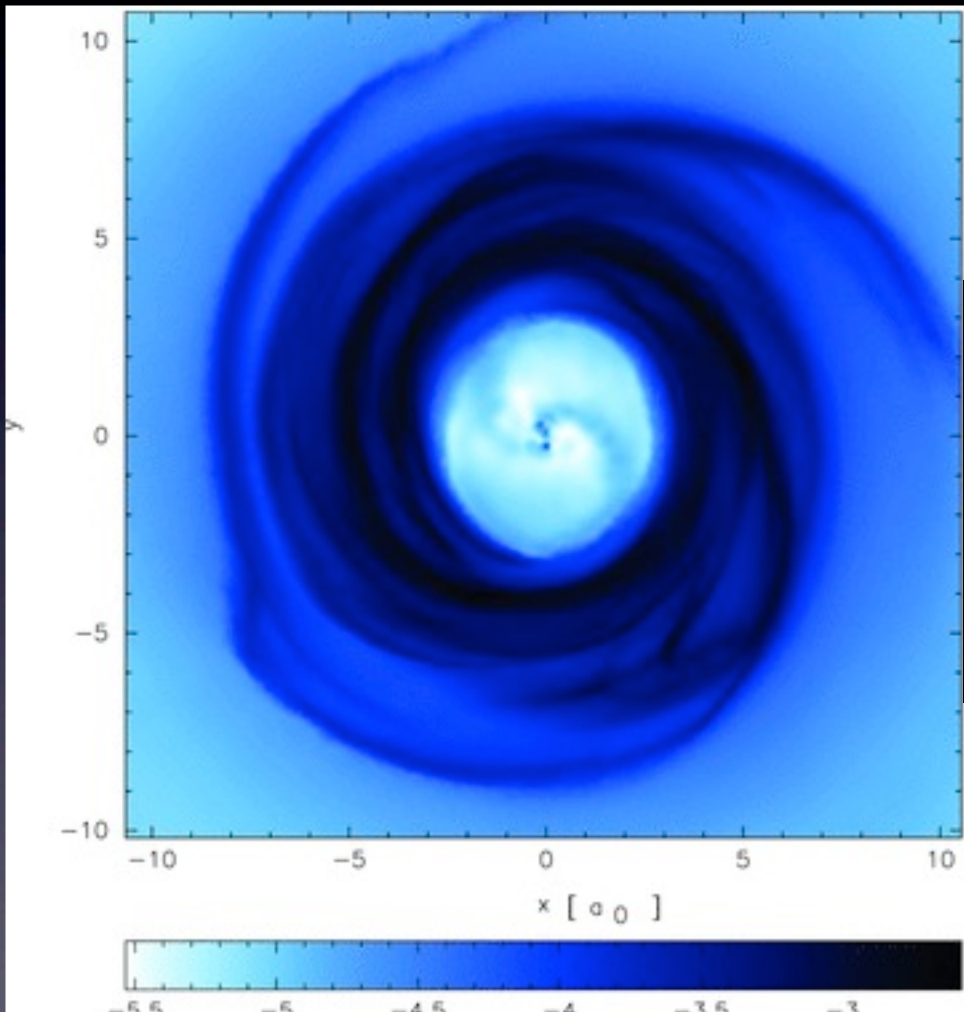
Eccentricity Evolution

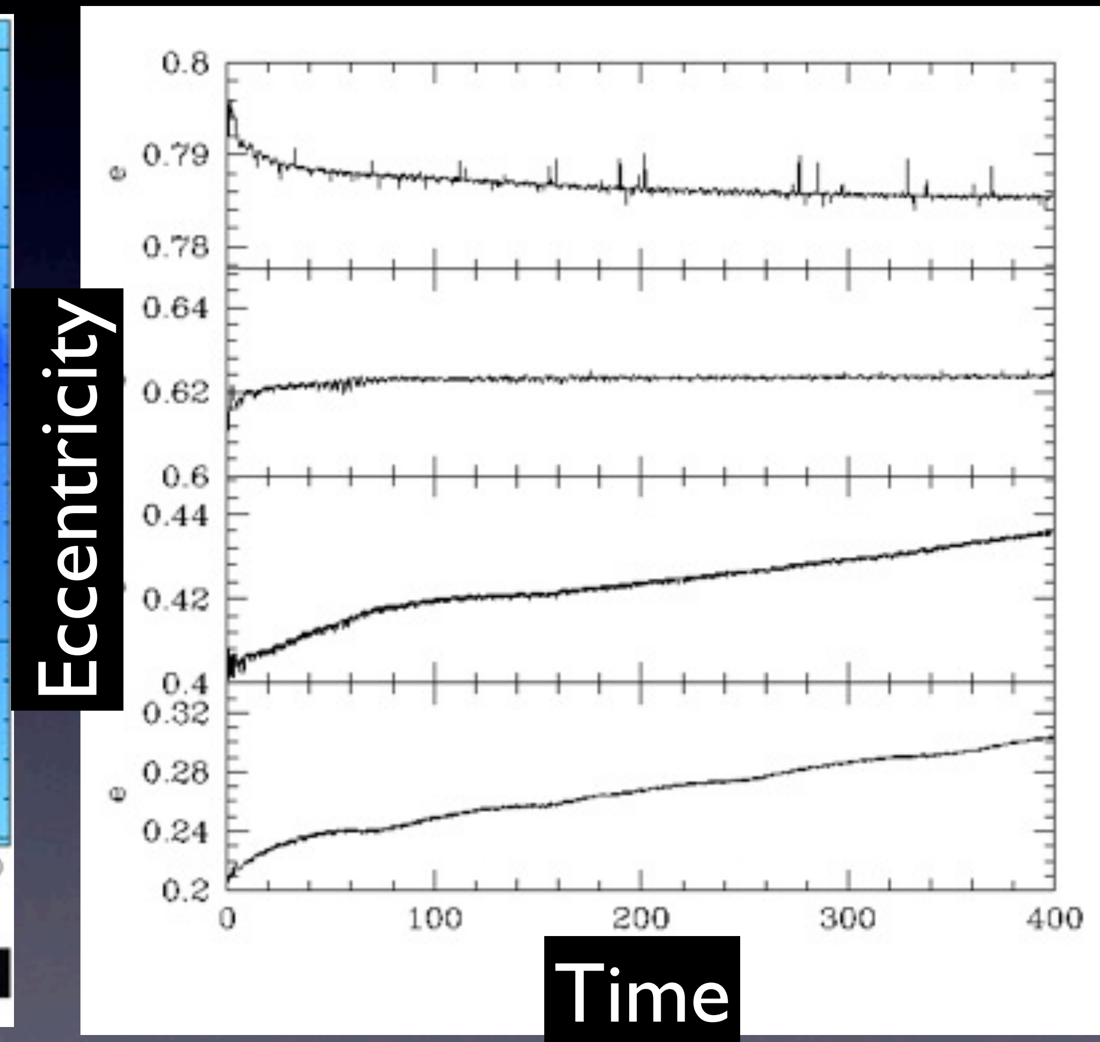


Eccentricity reaches ~0.35 by the end of the simulation.
No sign of saturation.
Will it grow to e ~ 1 ?

Trying different initial eccentricities...

Roedig, Dotti, Sesana, Cuadra, Colpi 2011

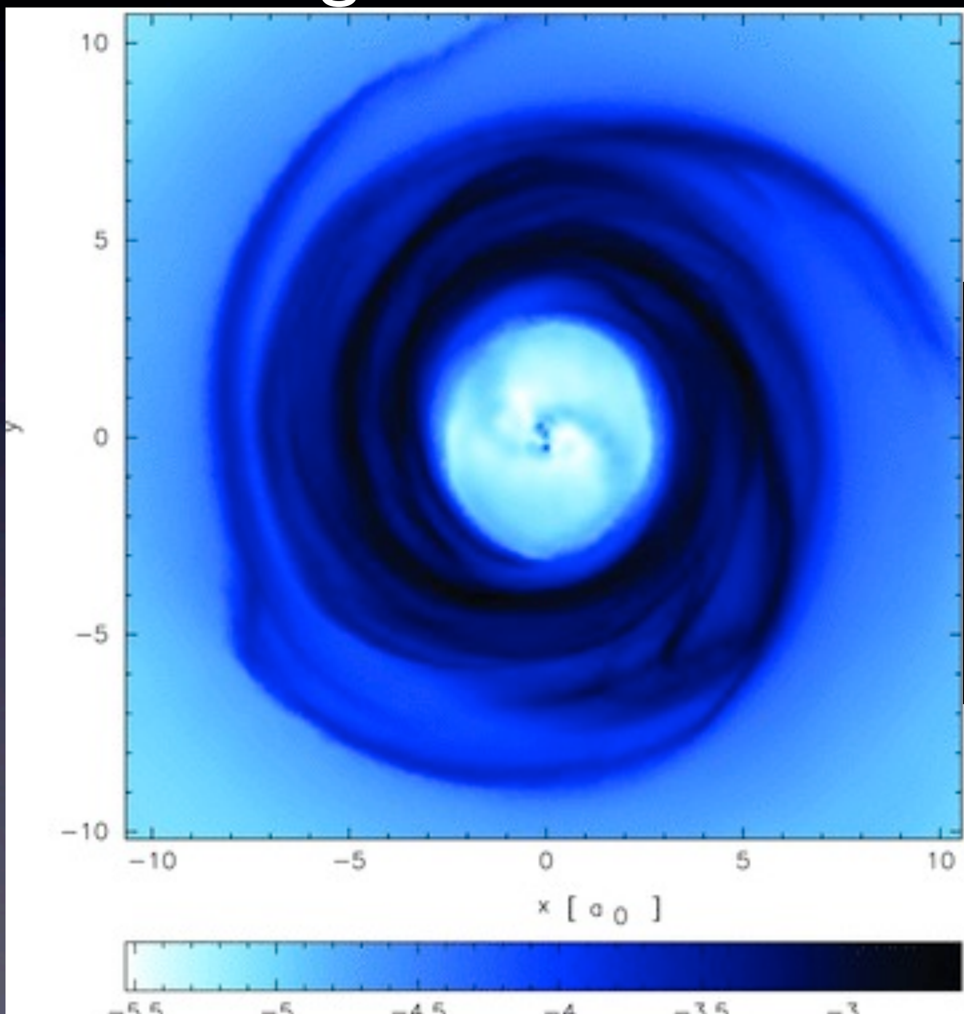


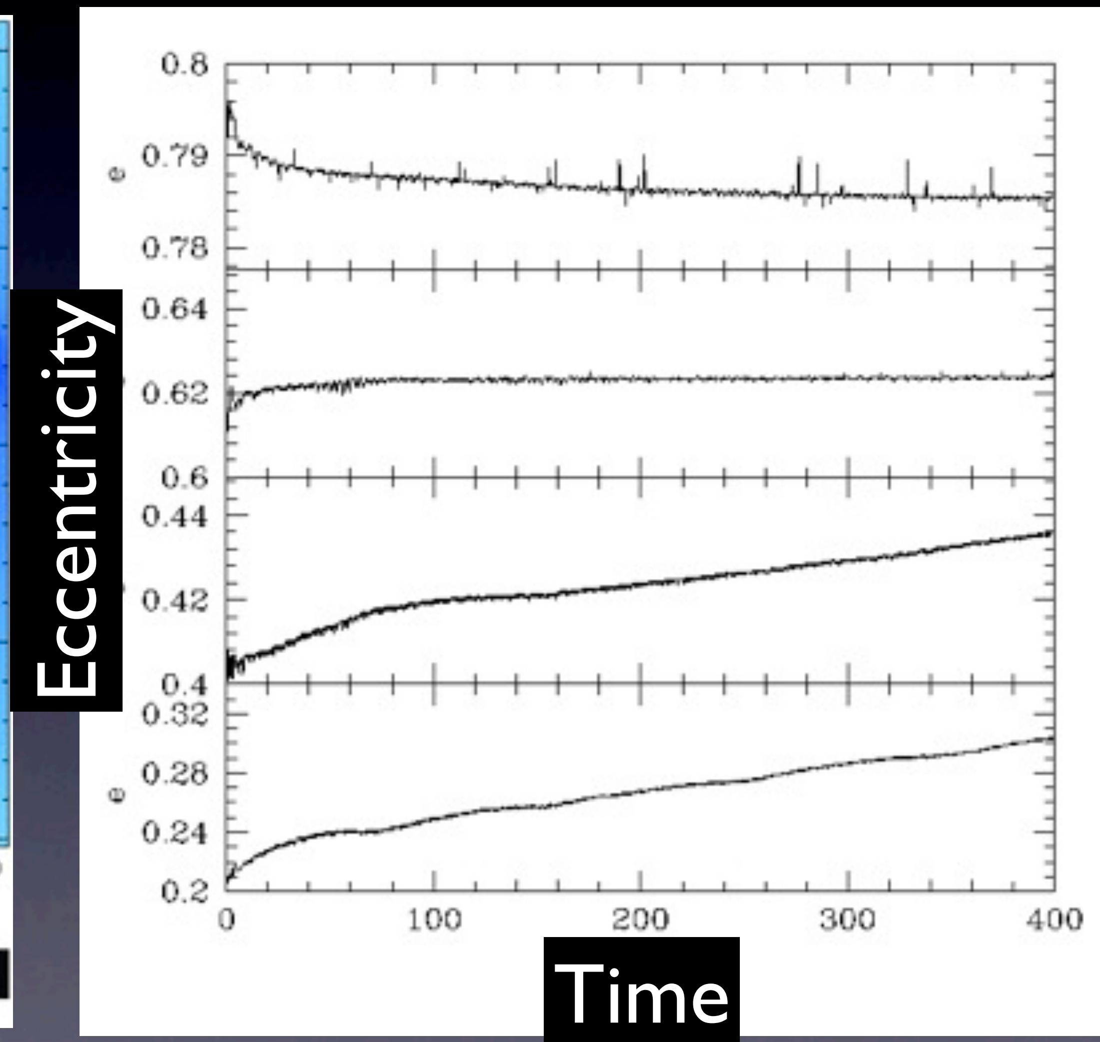


Trying different initial eccentricities...

Roedig, Dotti, Sesana, Cuadra, Colpi 2011

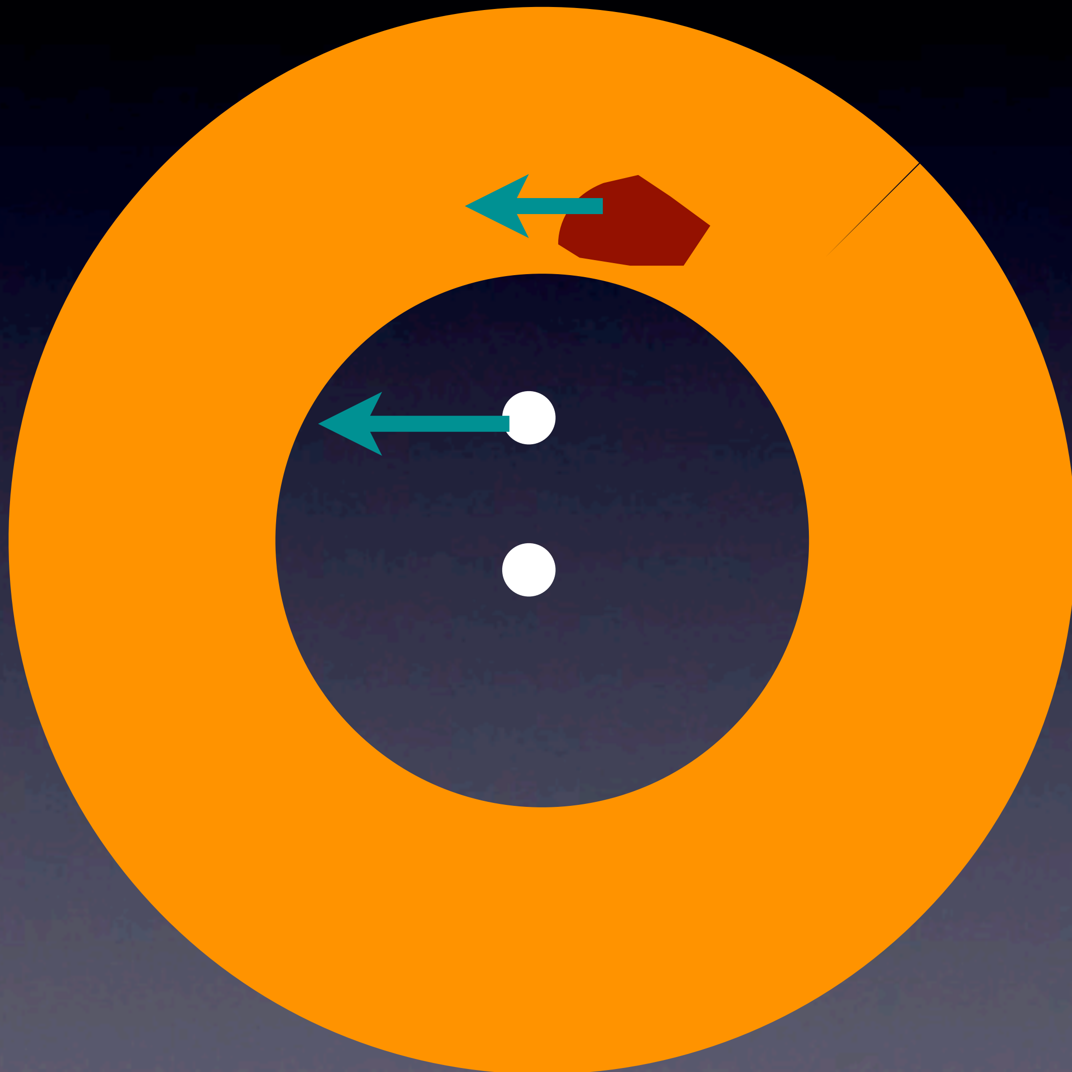
Eccentricity seems to converge to e ~ 0.6 !





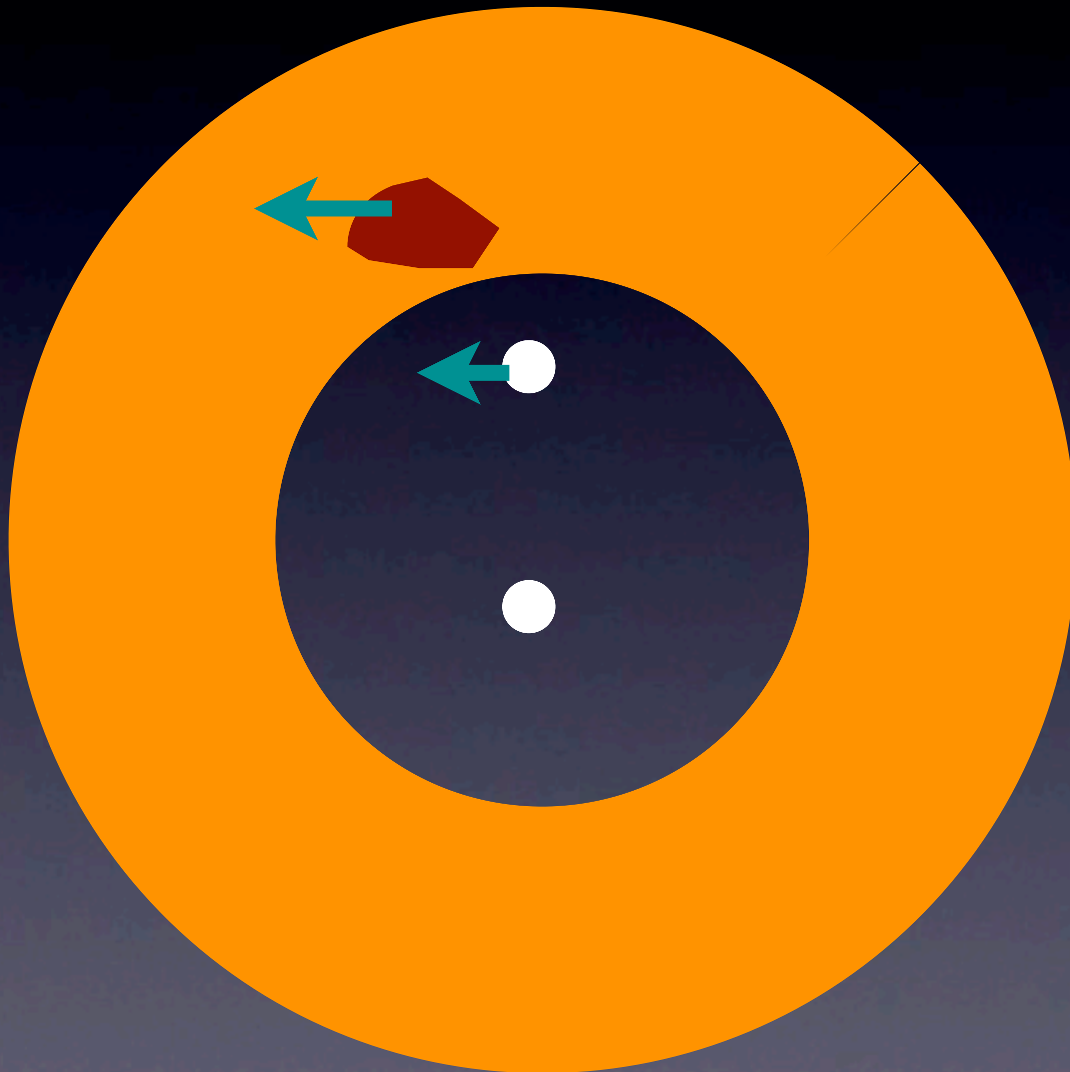
Eccentricity evolution

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



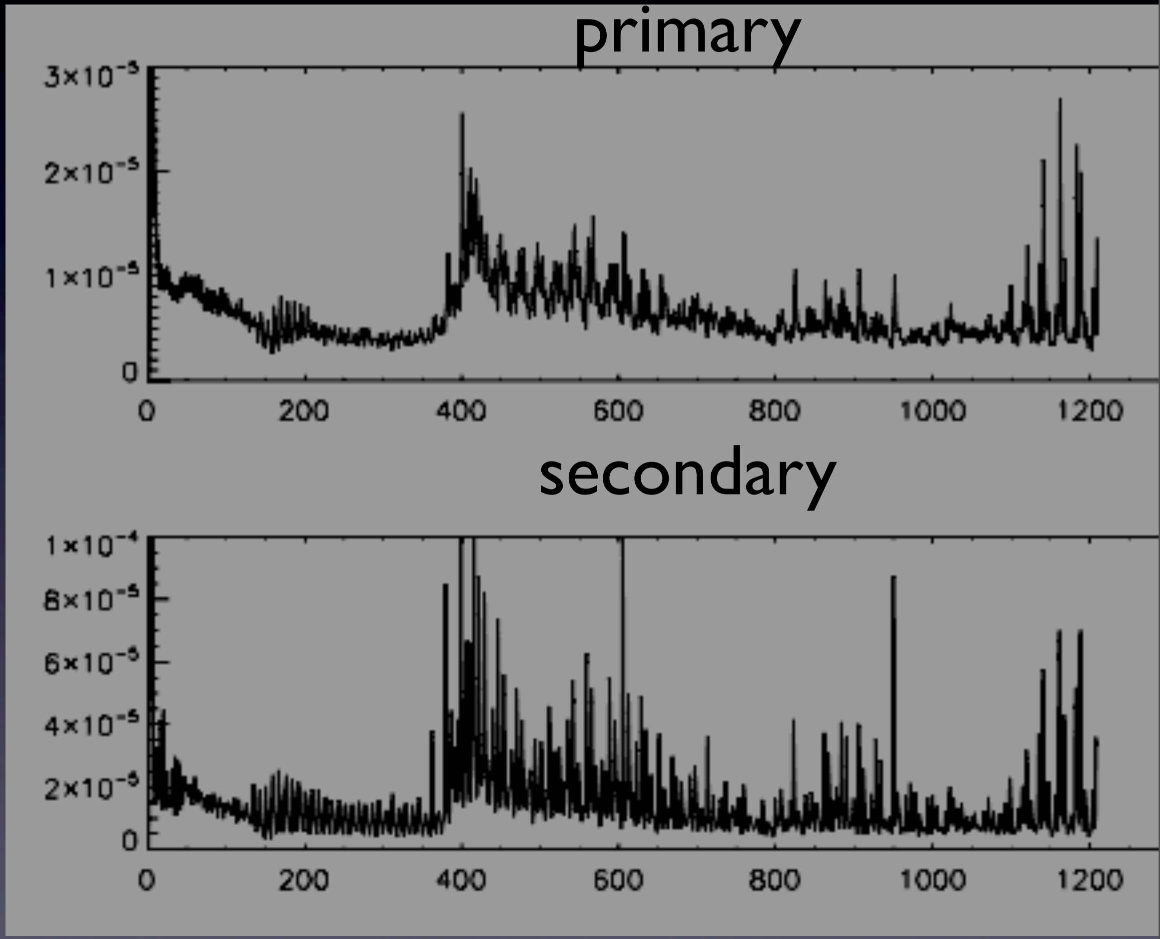
Eccentricity evolution

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



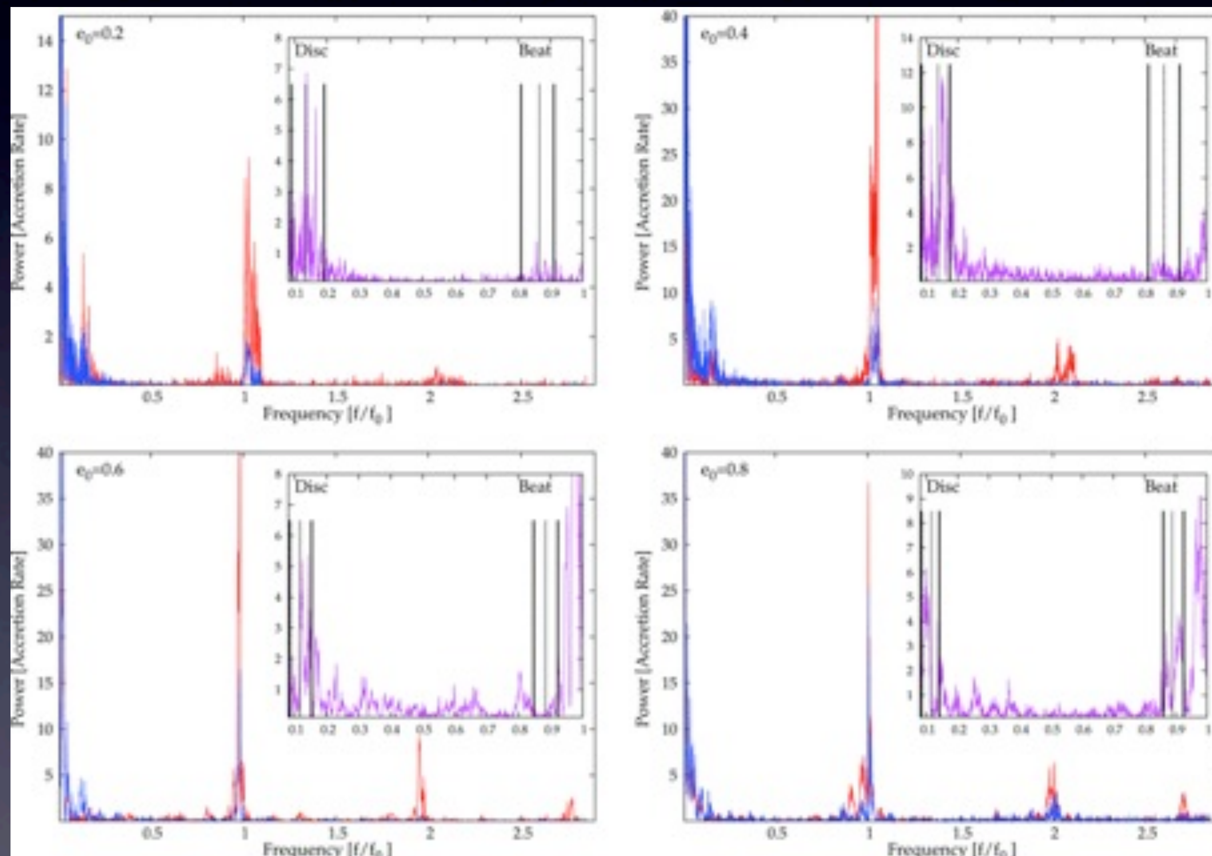
Accretion

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



cf S. Noble's talk

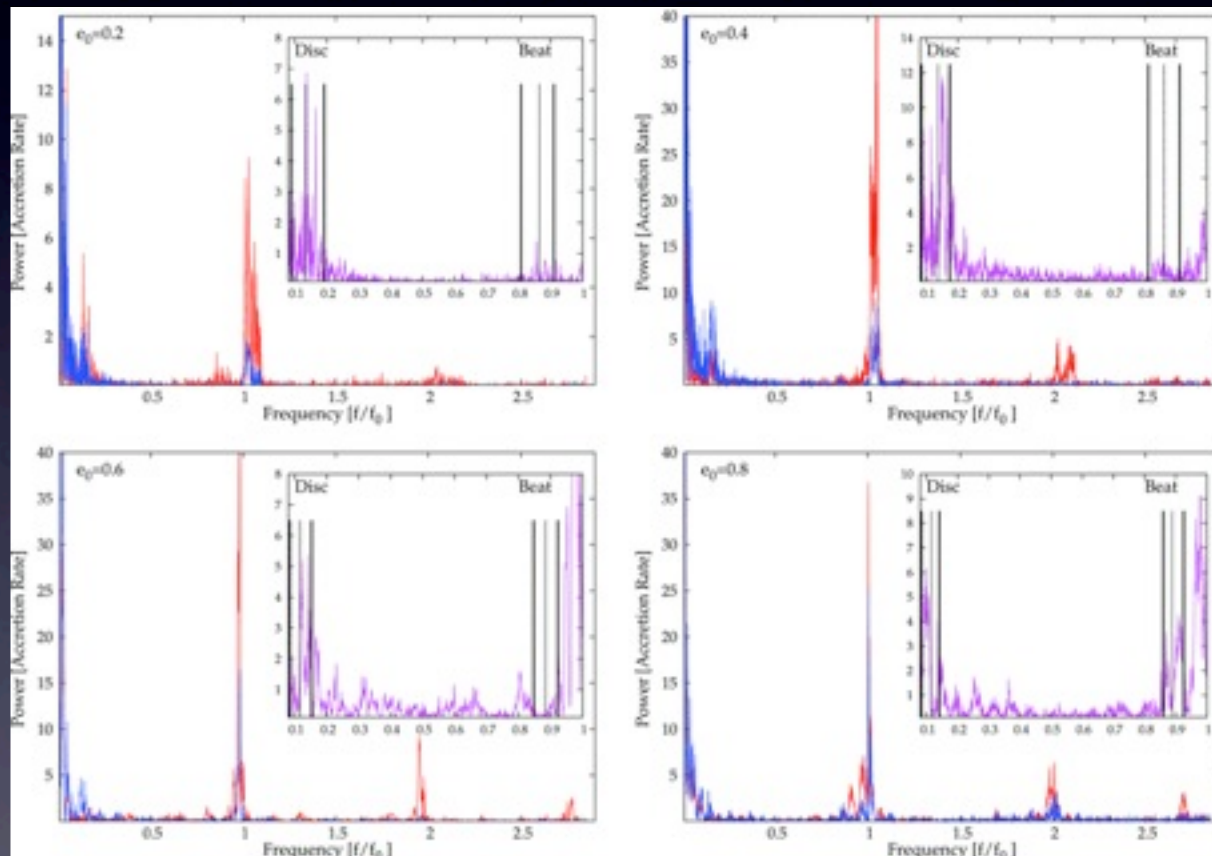
“Observable” consequences



see C. Roedig’s talk

“Observable” consequences

- Higher eccentricity enhances accretion rate variability.

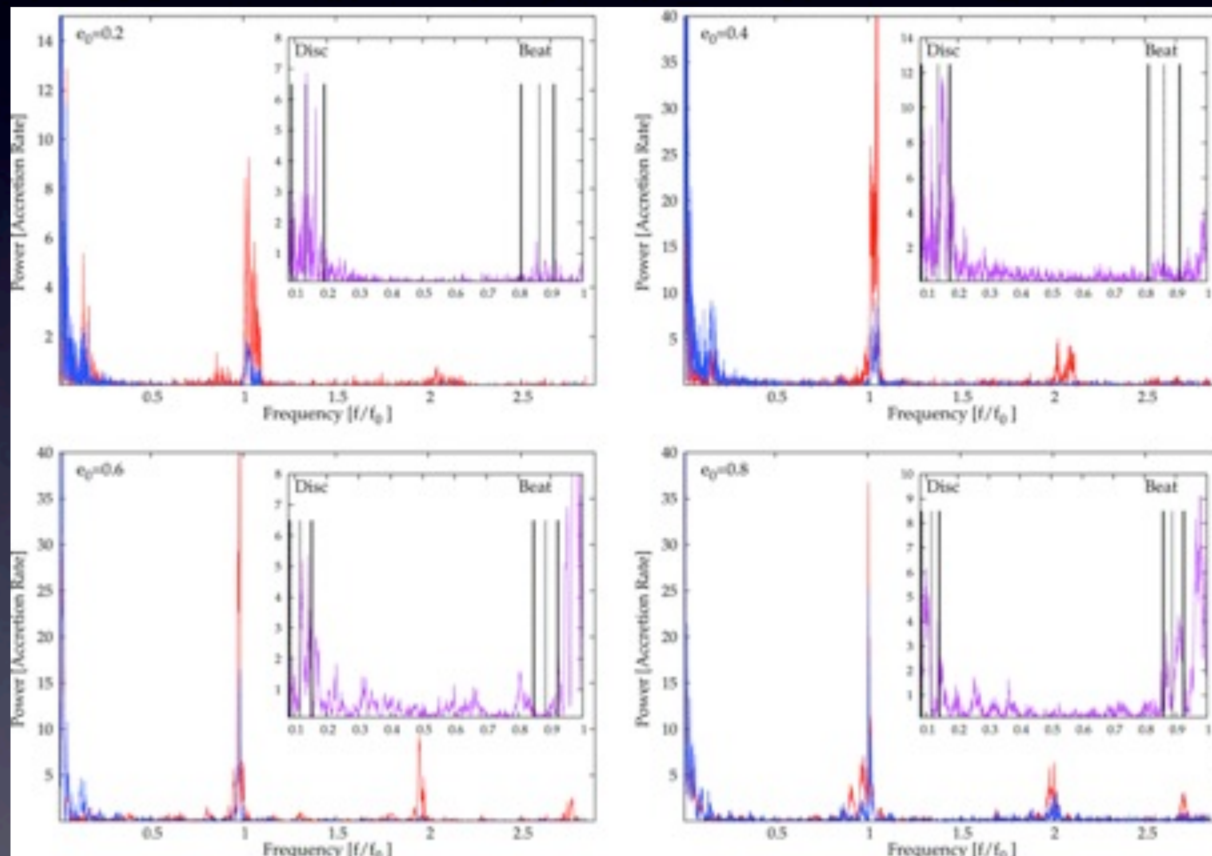


see C. Roedig’s talk

“Observable” consequences

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

see A. Sesana’s talk.



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- More efficient stellar dynamics.
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- 3-body interactions with new black holes.
- More massive discs... star formation could supply new stars to scatter with 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:
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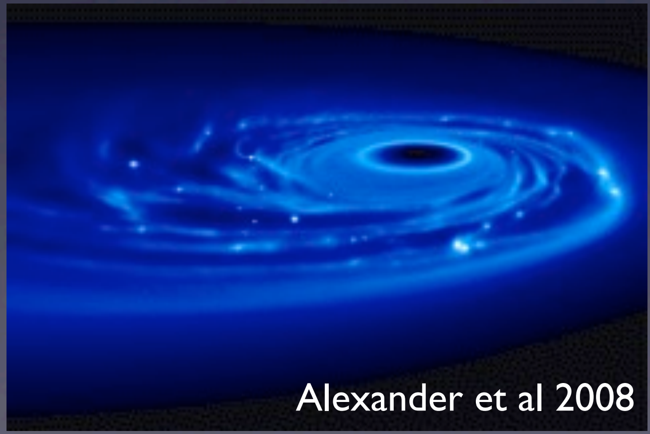
Rice et al 2003



Alexander et al 2008

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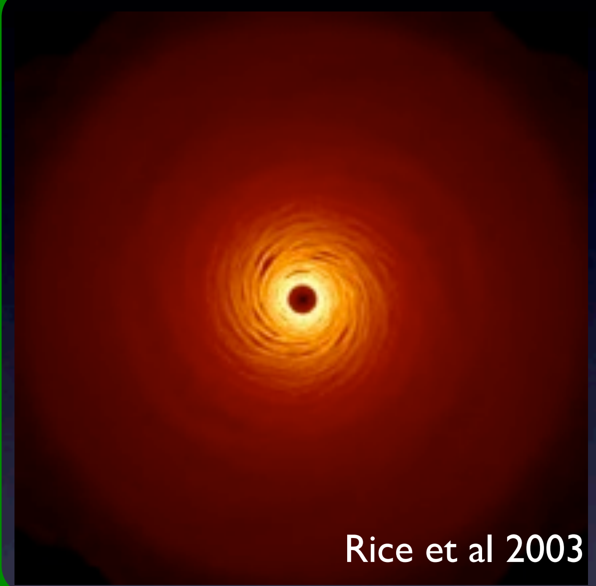
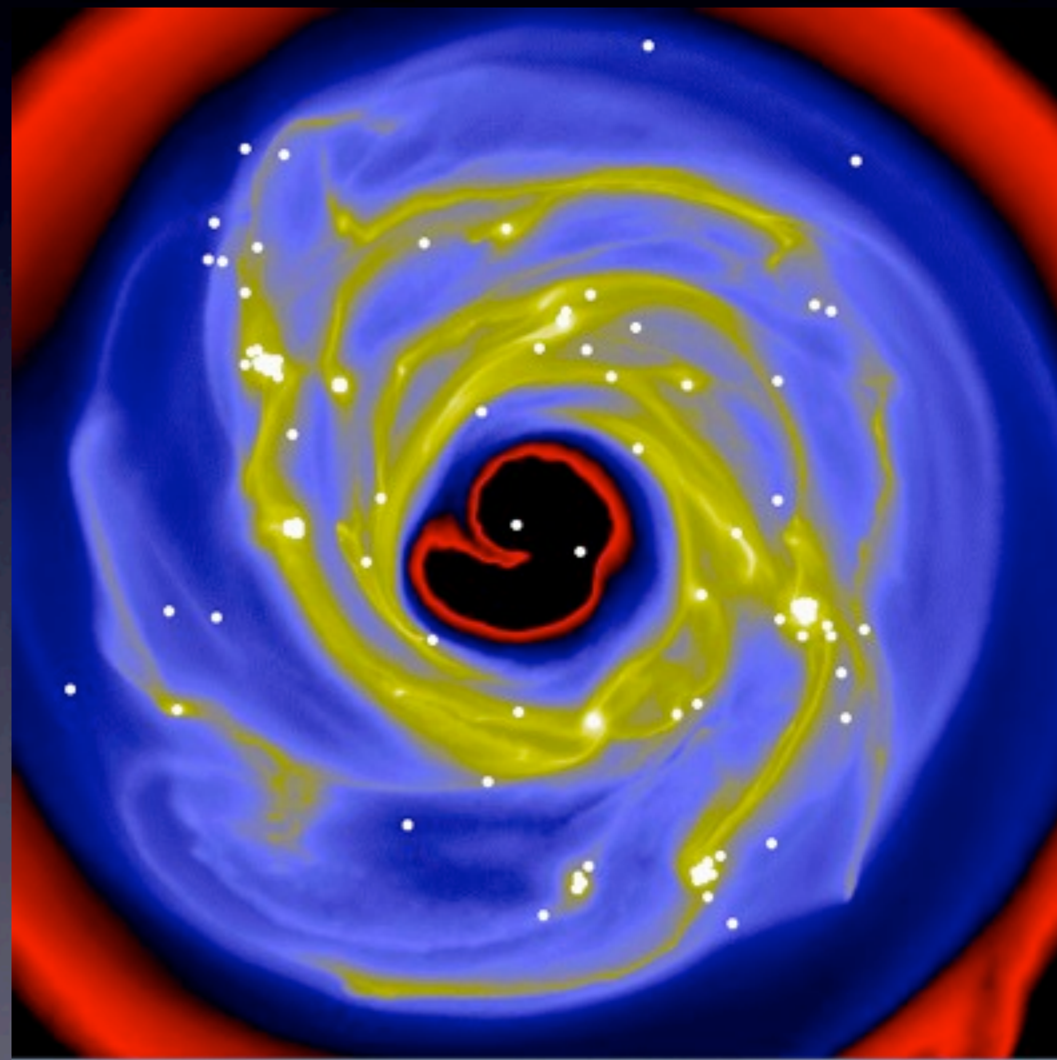


Fragmenting Discs

Amaro-Seoane, Brem & Cuadra, 2013.



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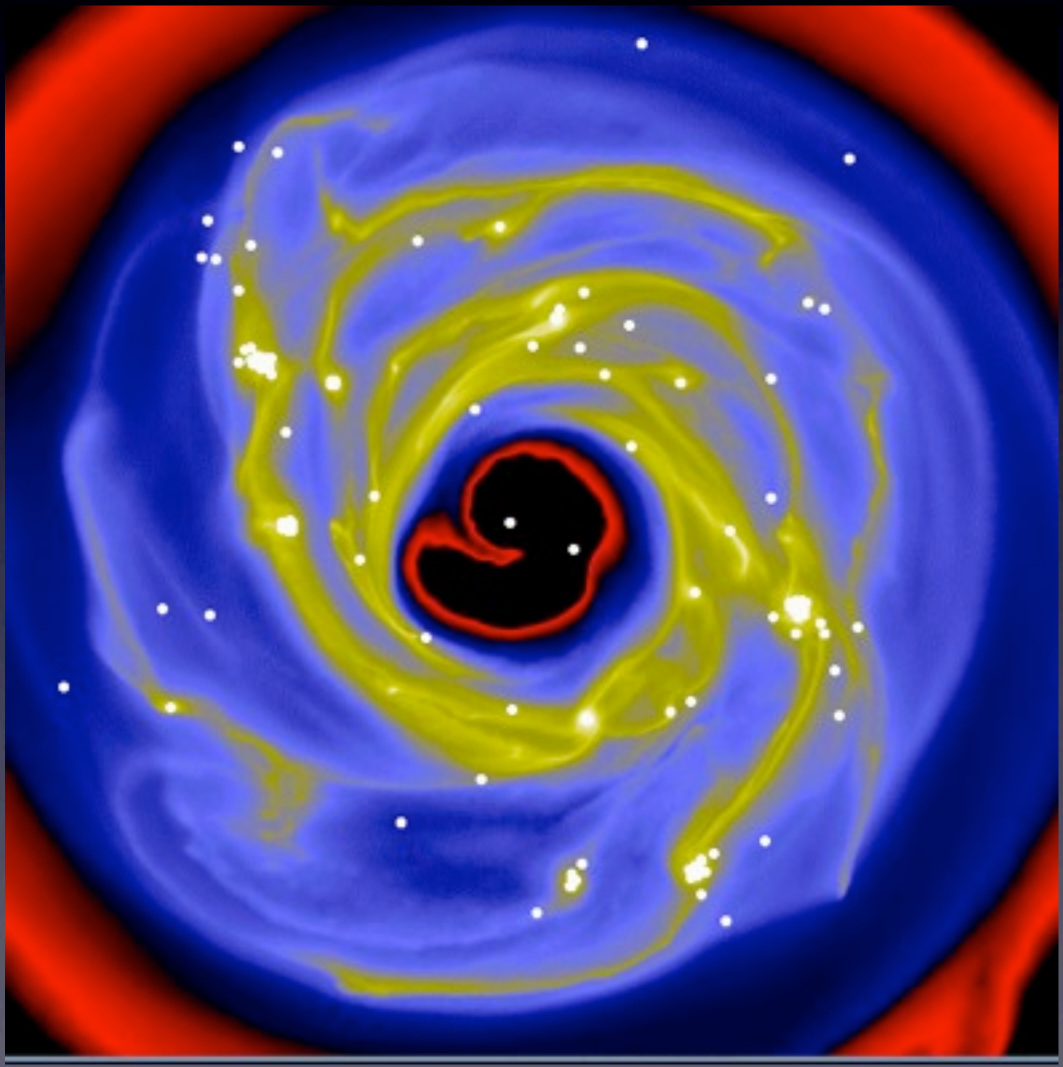

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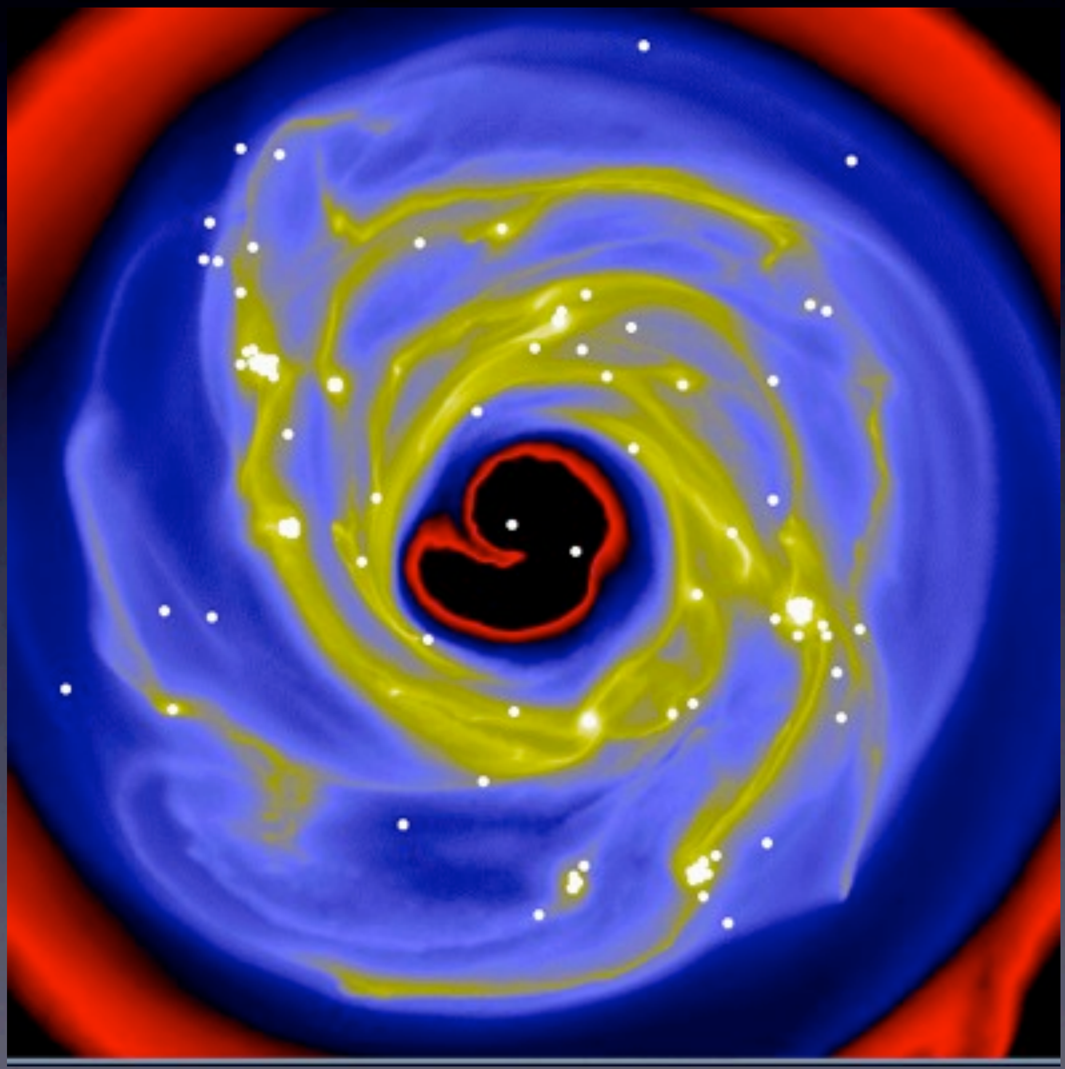
  - Also get stellar disruptions?



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Amaro-Seoane, Brem & Cuadra, 2013.

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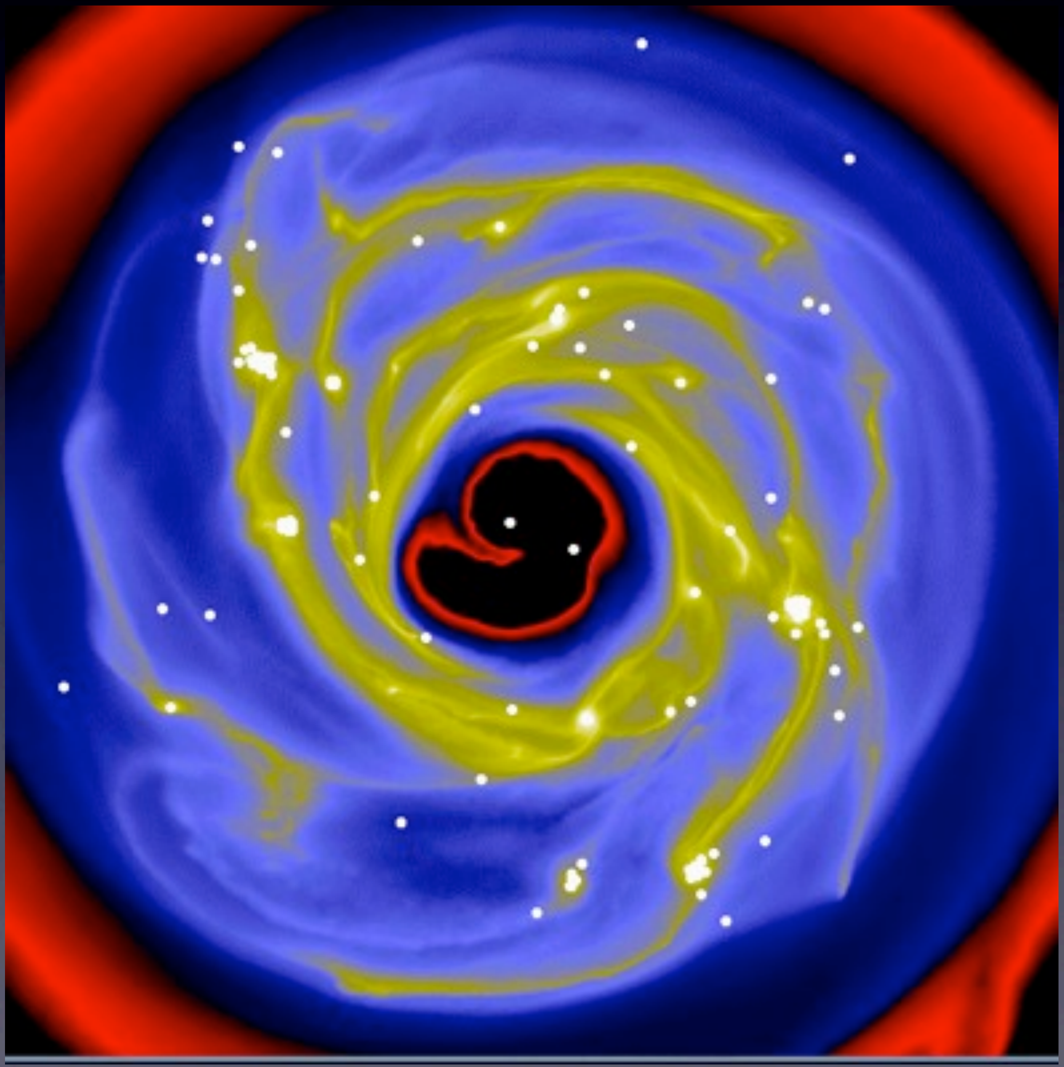
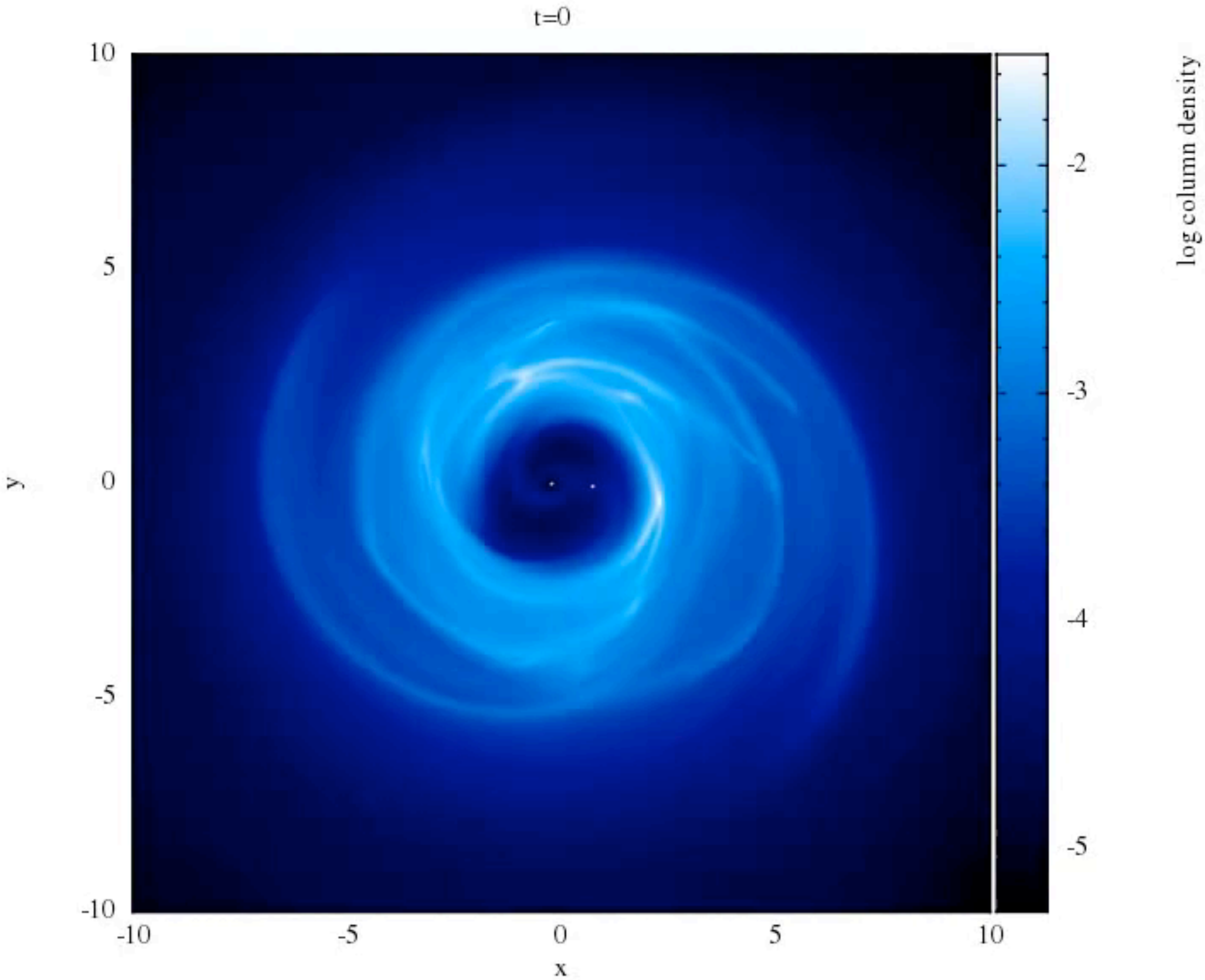
- Complex process: star formation and dynamics will influence evolution.




t=0
10
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y
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10
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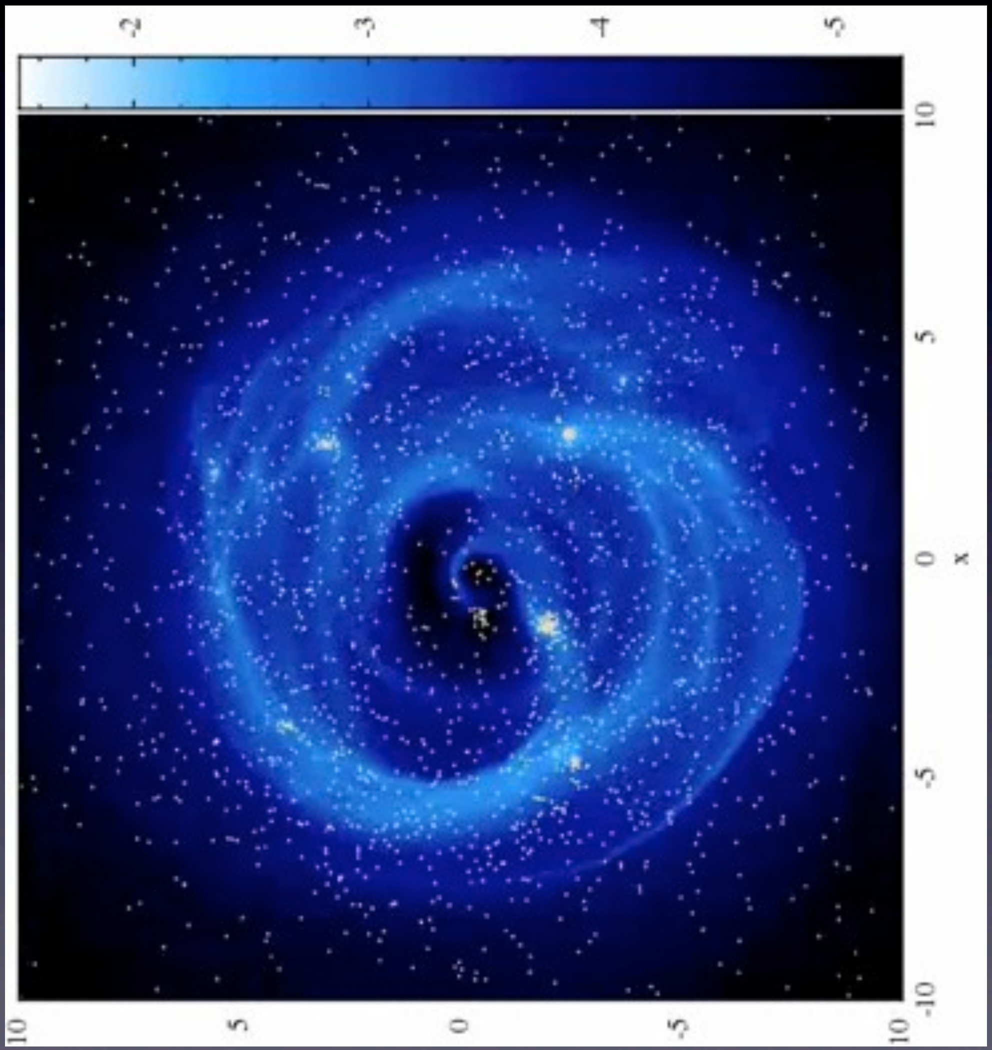
-2
-3
-4
-5
log column density

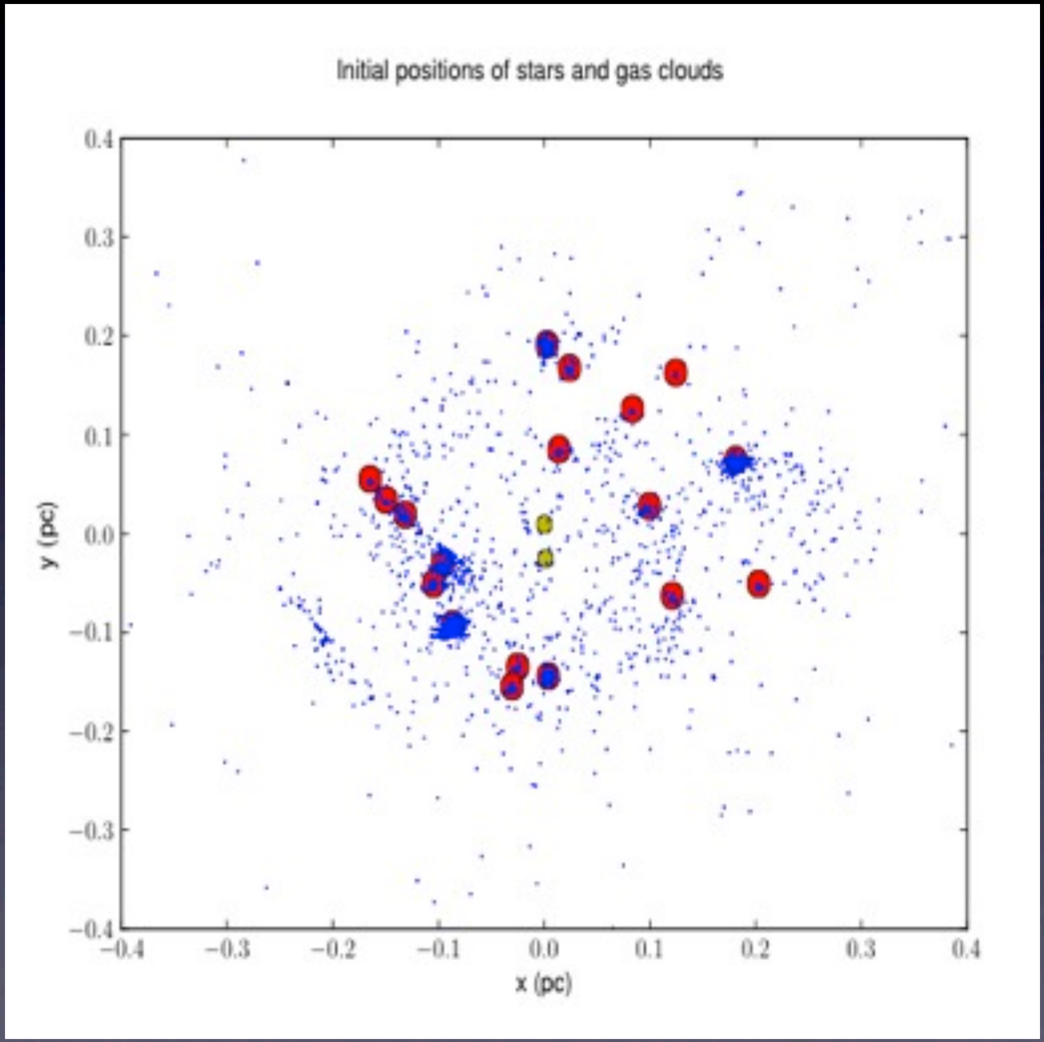
Long-term evolution



- After most gas is turned into stars, stop SPH simulation and follow binary + stars system with N-body approach.

N-body simulations

- N-body simulations are better suited to study stellar dynamics.
- Take SPH snapshot and move to NBODY6, including "gas clouds".
- Calculate rate of stellar disruptions: up to 10^{-4}–10^{-3} per yr



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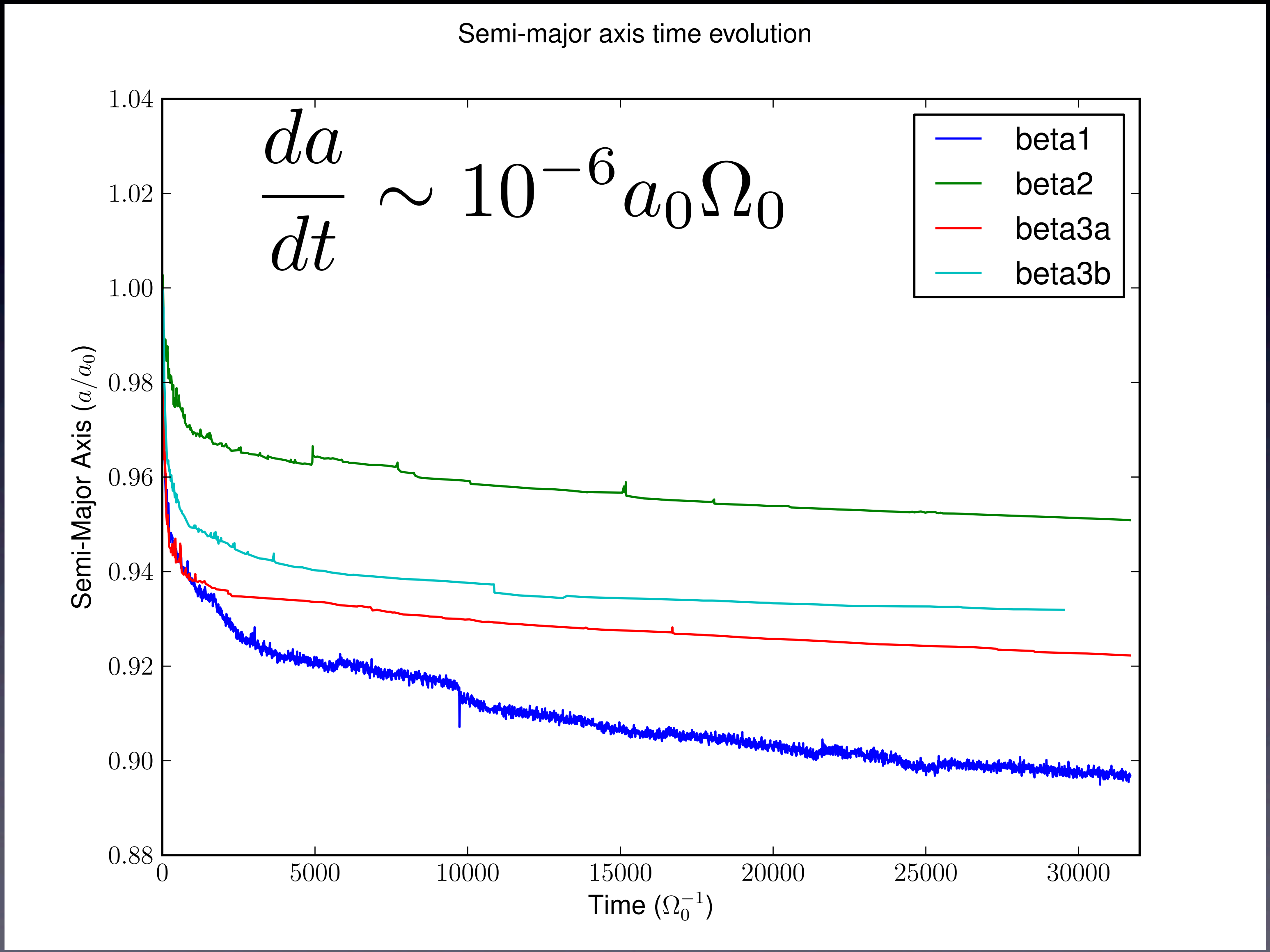
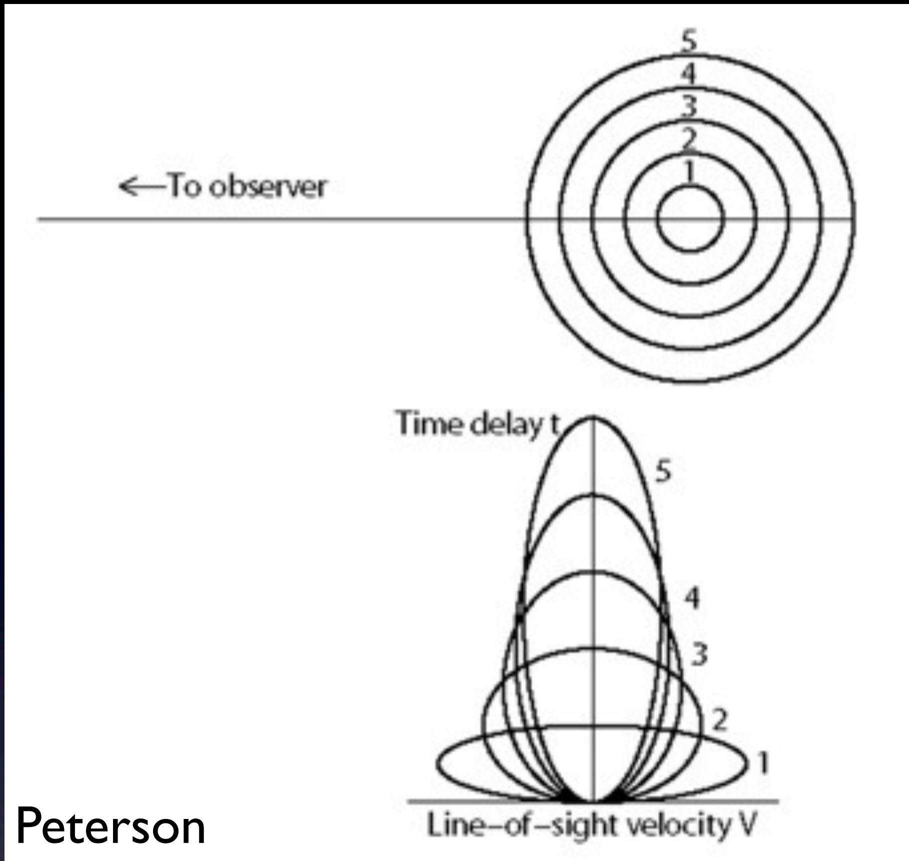
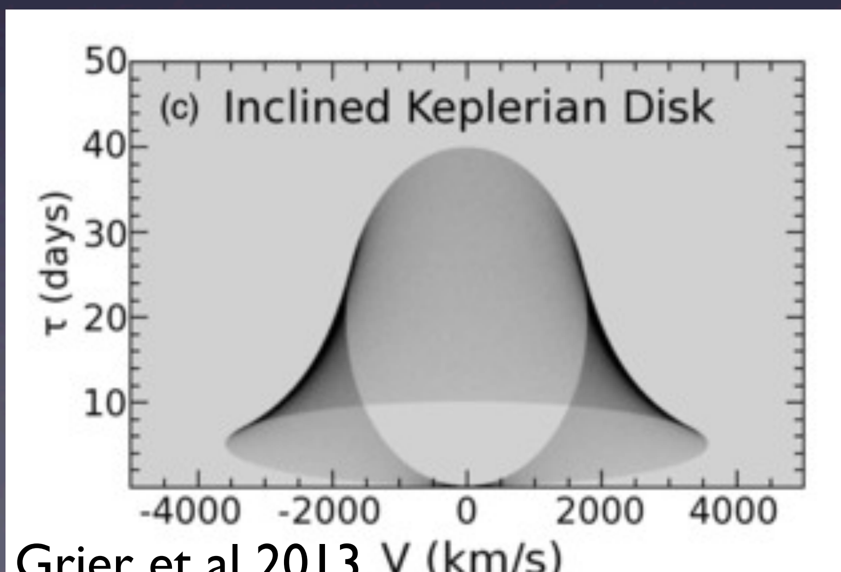


Reverberation Mapping



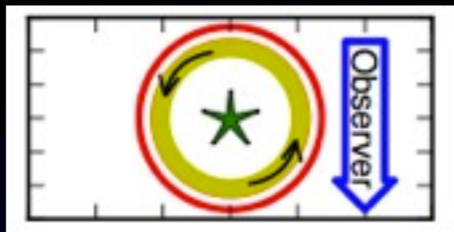
Peterson

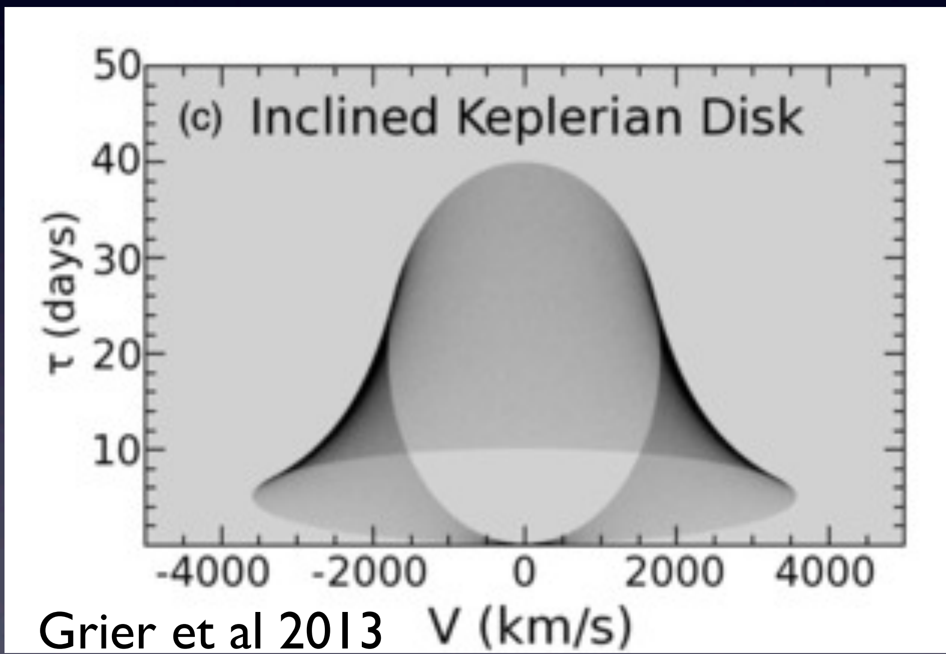


Grier et al 2013

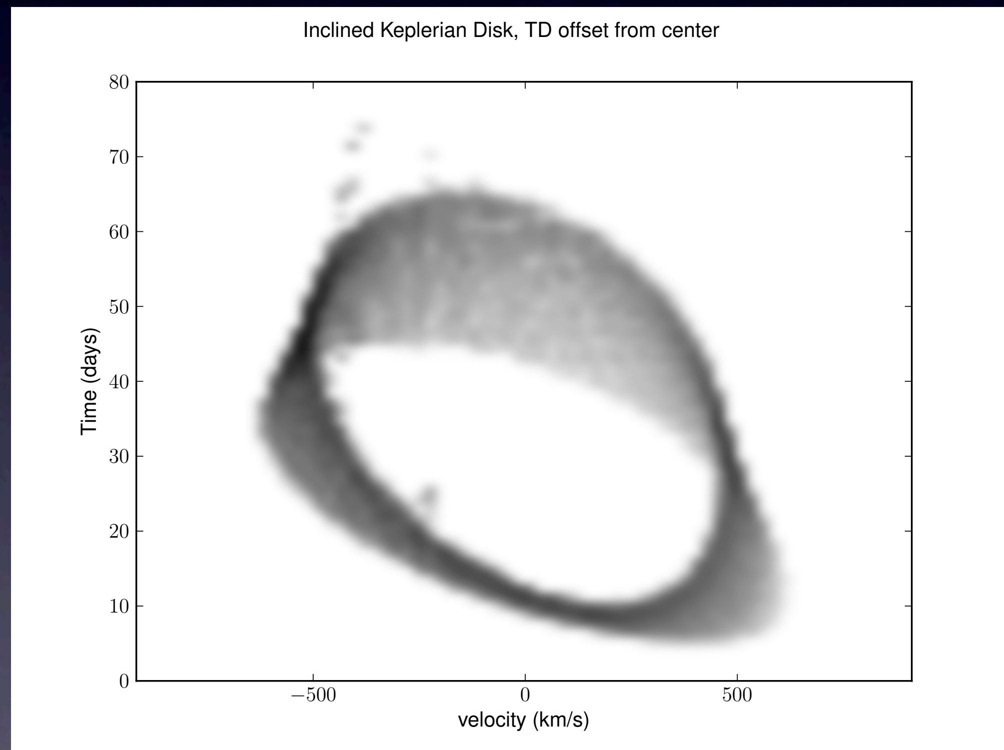
- Reconstruct morphology of central region around AGN.
- TDE provide very clean opportunity (e.g., Komossa+'08)
- Otherwise, "normal" accretion on to secondary BH.

Reverberation mapping of tidal disruption events in binaries





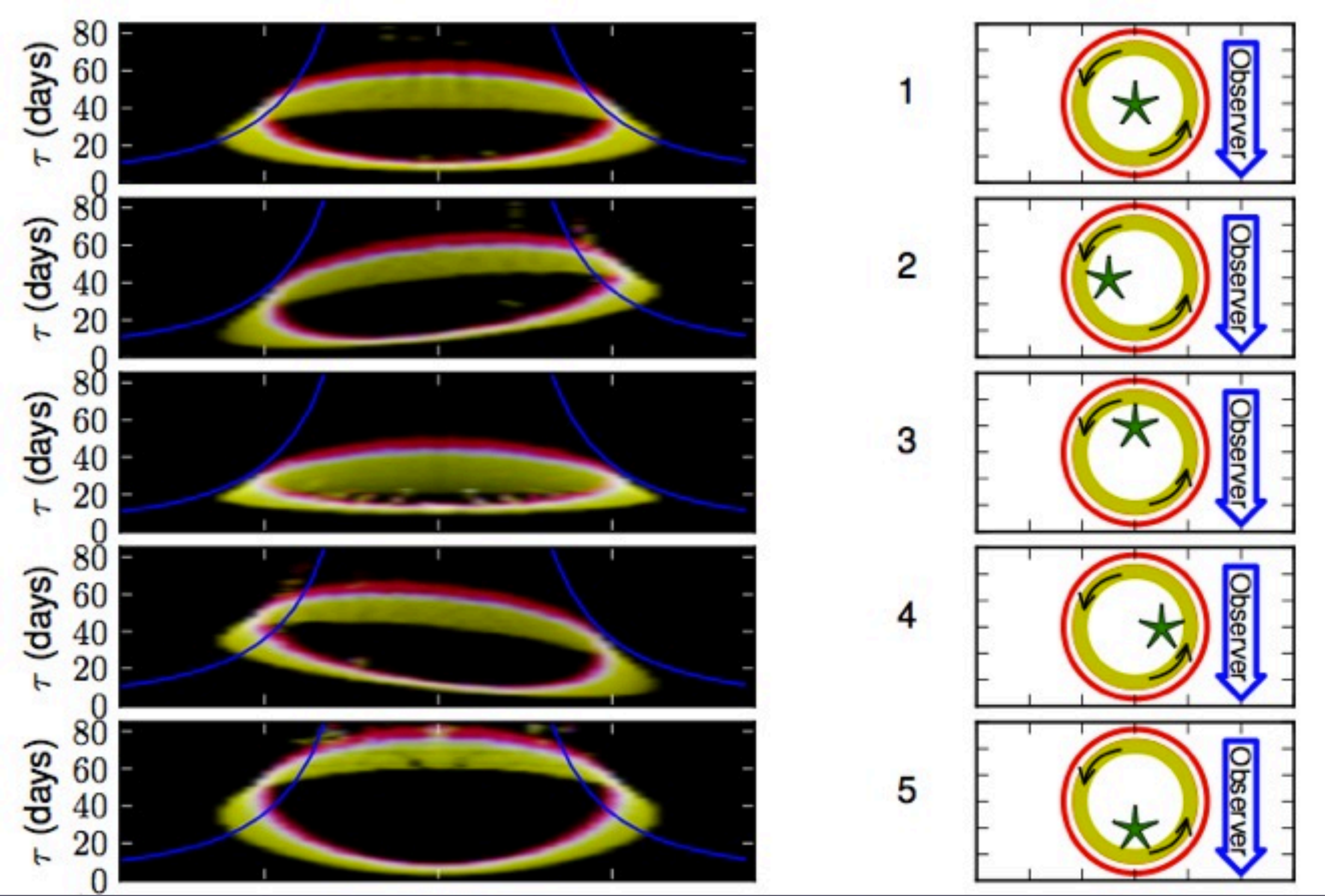
Grier et al 2013



off-centre source produces asymmetric map

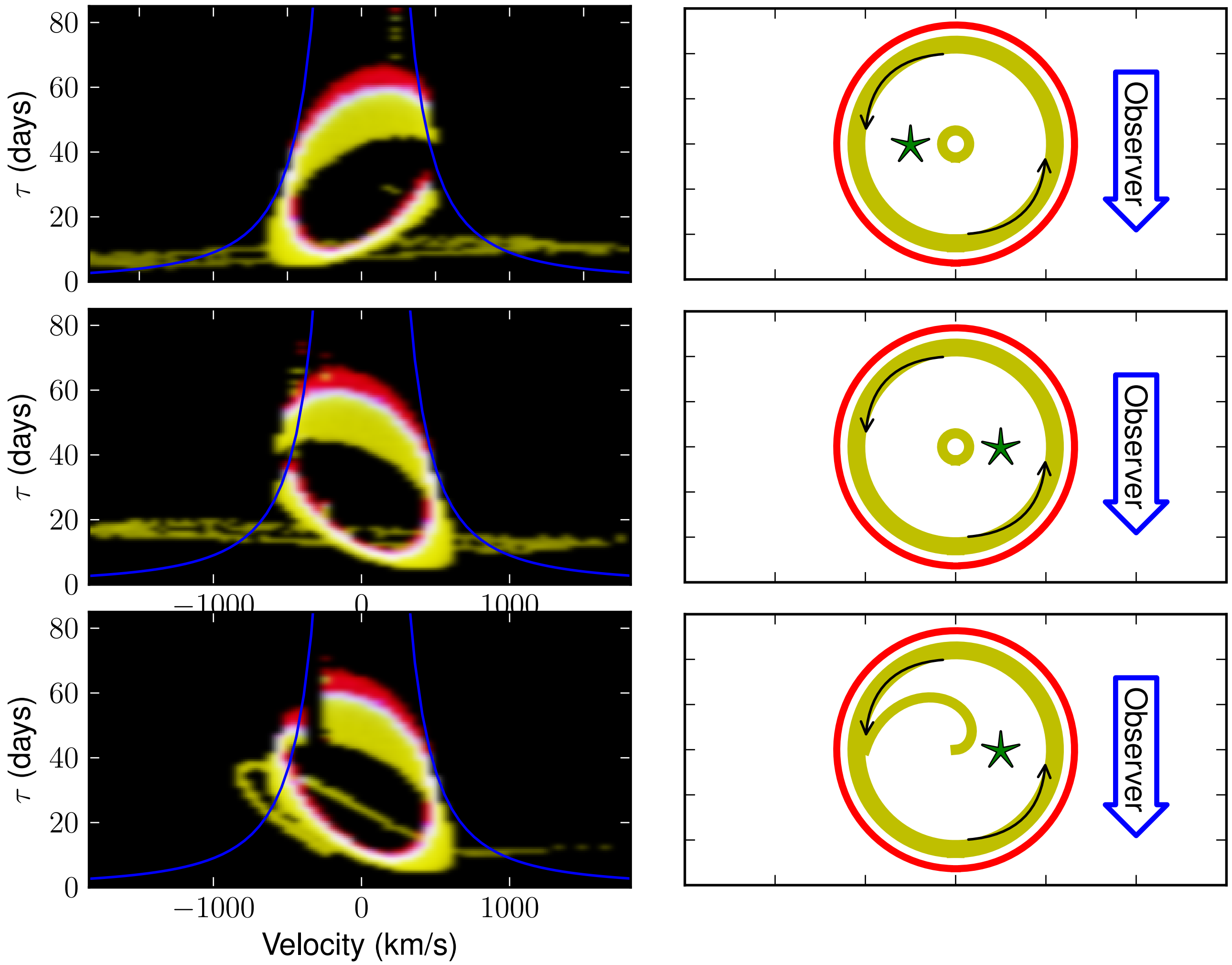
Brem, Cuadra, Amaro-Seoane, et al, in prep

Orbital phase could be inferred



Brem, Cuadra, Amaro-Seoane, et al, in prep

Circum-primary discs and streams could be detected



Conclusions

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- Gas disc can achieve coalescence of $M < 10^7$ M_{sun} binaries. Luminous counterpart to *LISA* detections.
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- N-body scattering of those stars keep driving binary shrinking, although at a slower pace.