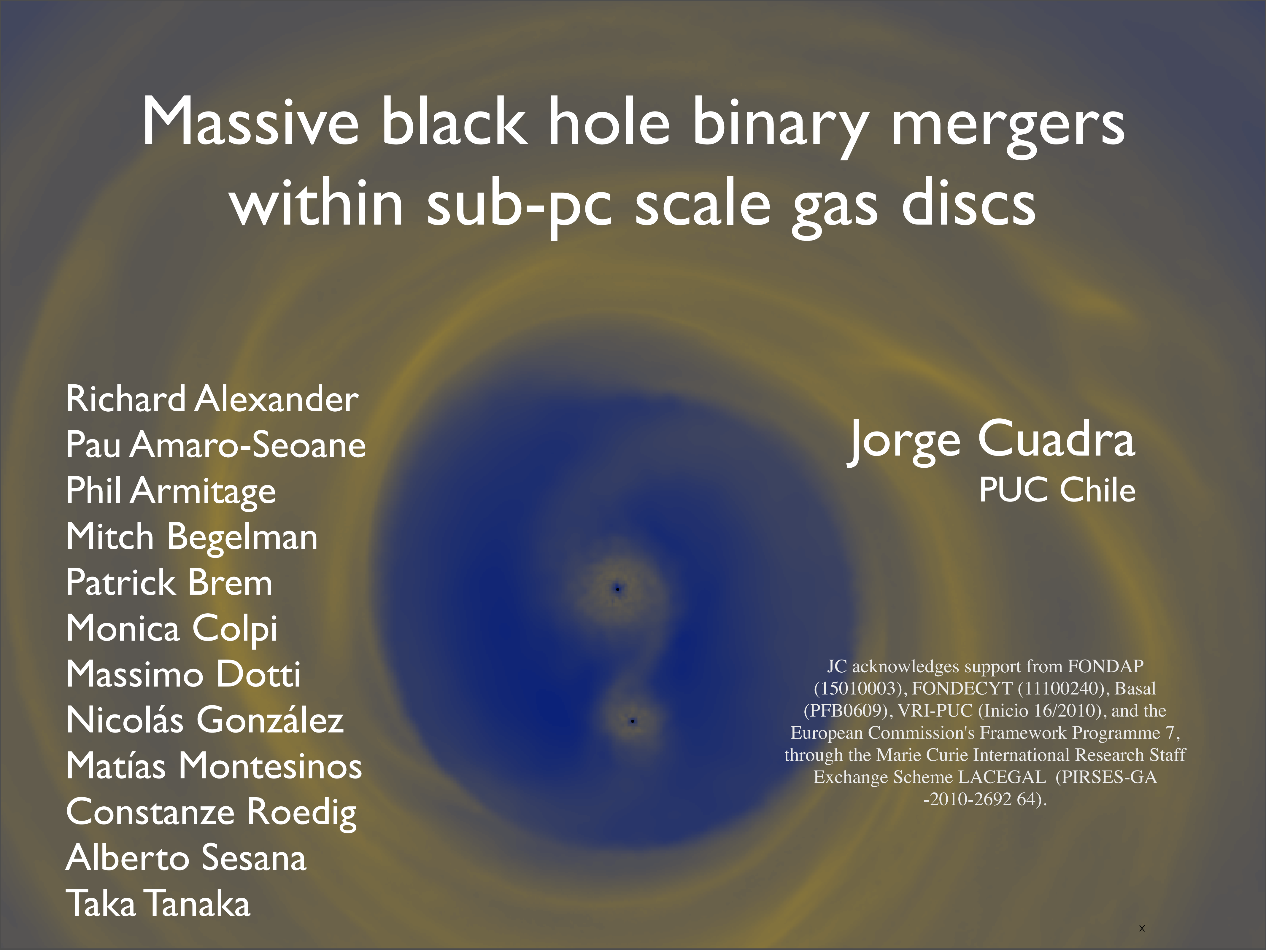

Massive black hole binary mergers within sub-pc scale gas discs

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Jorge Cuadra
PUC Chile

JC acknowledges support from FONDAP (15010003), FONDECYT (11100240), Basal (PFB0609), VRI-PUC (Inicio 16/2010), and the European Commission's Framework Programme 7, through the Marie Curie International Research Staff Exchange Scheme LACEGAL (PIRSES-GA -2010-2692 64).

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Latin American Chinese European Galaxy Formation Network (LACEGAL)

- Follow-up of the ALFA LENAC programme (2004–7)
- Funds exchange between network nodes.

- Network coordinator: Carlton Baugh (Durham)
- MPA coordinator: Simon White
- PUC coordinator: Nelson Padilla

- **Felipe Barrientos** – Galaxy evolution and morphology. Elliptical galaxies. Clusters of galaxies. Observational cosmology.
- **Franz E. Bauer** – AGN Demographics, Feeding, and Evolution. Coeval Growth of Galaxies and Super-Massive Black Holes.
- **Márcio Catelan** – Stellar structure and evolution. Globular clusters. Variable stars. Stellar Populations. Galaxy formation and evolution.
- **Alejandro Clocchiatti** – Supernovae, near and far. Radiative Transfer. Galaxy Clusters. Cosmology.
- **Jorge Cuadra** – Numerical astrophysics. Galactic nuclei. Super-massive black holes.
- **Rolando Dünner** – Large scale structure and cosmology. Astronomical instrumentation.
- **Gaspar Galaz** – Stellar population in galaxies. Galaxy evolution. Statistical properties of the galaxy distribution.
- **Leopoldo Infante** – Galaxy and structure evolution. Pairs, groups and clusters of galaxies. LSB, dwarf and star forming galaxies.
- **Andrés Jordán** – Search and characterization of transiting exoplanets. Galaxies in nearby clusters. Star clusters.
- **Dante Minniti** – Globular clusters. Stellar populations and evolution. Extrasolar planets. Galaxy formation. Galactic structure.
- **Nelson Padilla** – Numerical astrophysics. Galaxy and Structure Formation. Cosmology.
- **Thomas H. Puzia** – Star clusters and star cluster systems. Chemical evolution and enrichment histories of galaxies. Galaxy formation.
- **Hernán Quintana** – Observational astrophysics. Clusters of galaxies. Interacting galaxies. Large scale structure.
- **Andreas Reisenegger** – Theoretical Astrophysics and Cosmology. Neutron Stars. Stellar Magnetic Fields. Structure Formation.
- **Manuela Zoccali** – Stellar Populations in the Milky Way. The Galactic Bulge. Star Clusters. Chemical Abundances.

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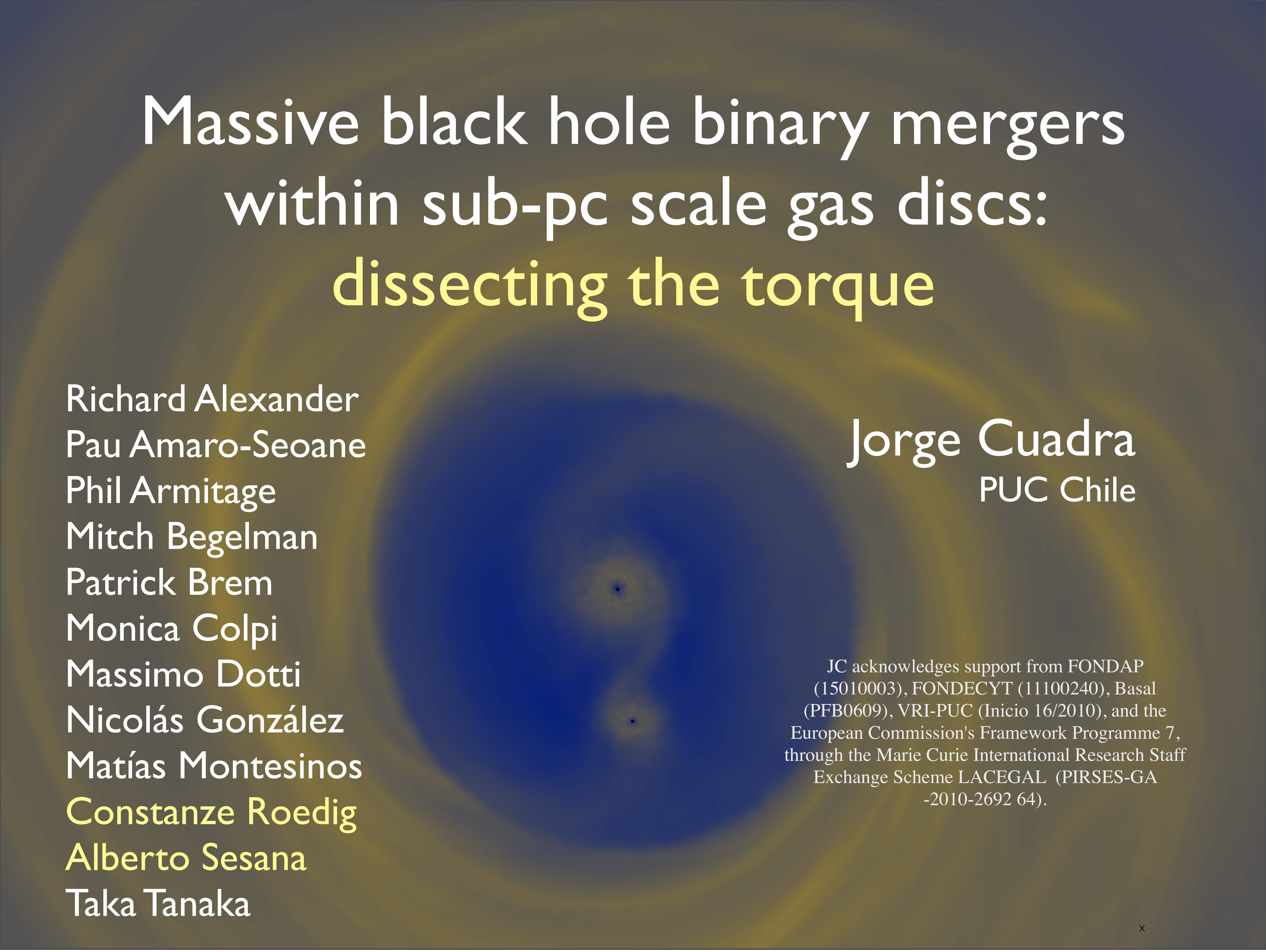
http://www.flickr.com/photos/frguerre/2745284406/



Massive black hole binary mergers within sub-pc scale gas discs: dissecting the torque

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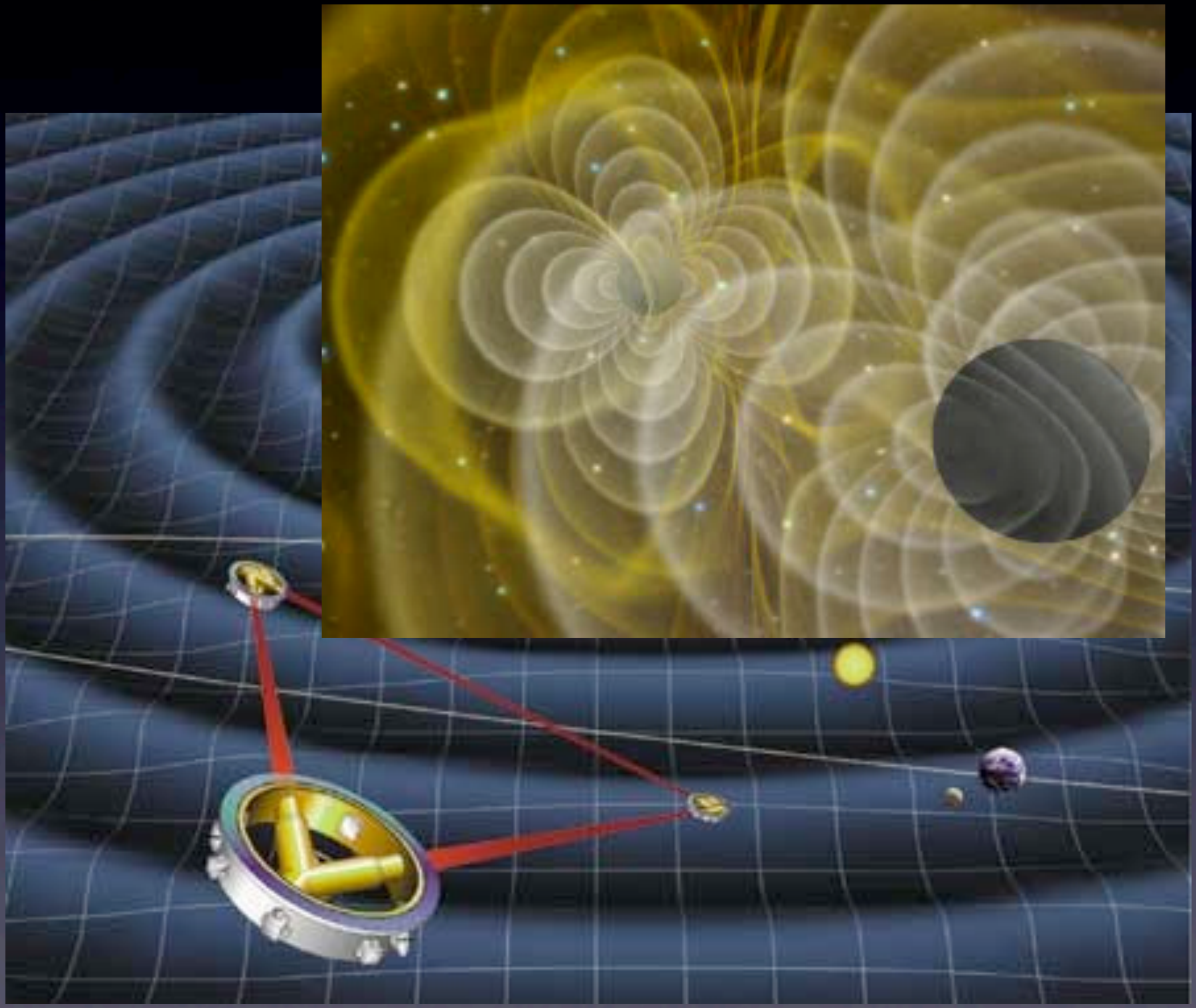
Galaxies and Super-Massive Black Holes

- Super-massive black holes at the centre of most galaxies.
- Galaxies merge to create larger galaxies.
- Do the black holes also merge?

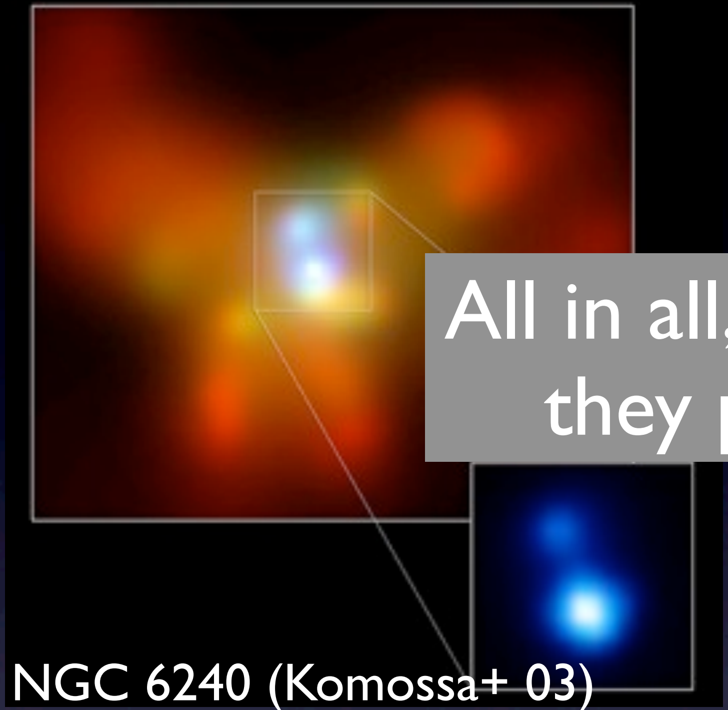
Black hole mergers

Centrella et al

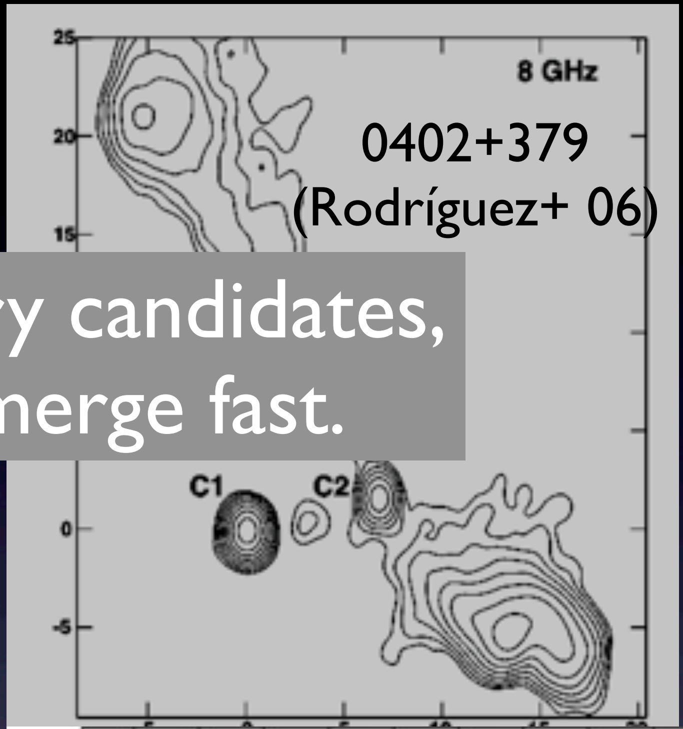


- Sources of grav waves
- Test general relativity
- Should be detectable with *eLISA* in ~2020
- Will give much info about BHs

Observational Evidence for Binaries

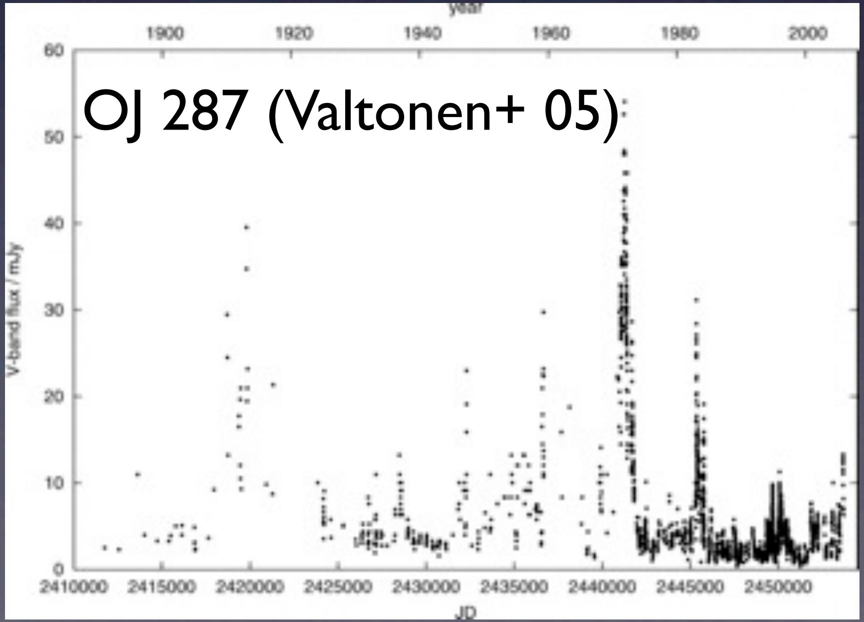


NGC 6240 (Komossa+ 03)

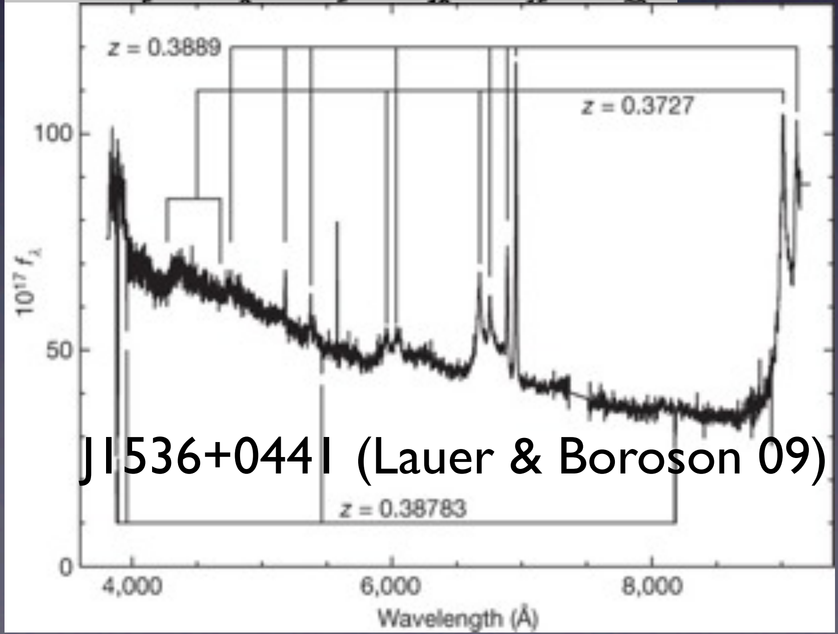


0402+379 (Rodríguez+ 06)

All in all, few binary candidates, they probably merge fast.



OJ 287 (Valtonen+ 05)

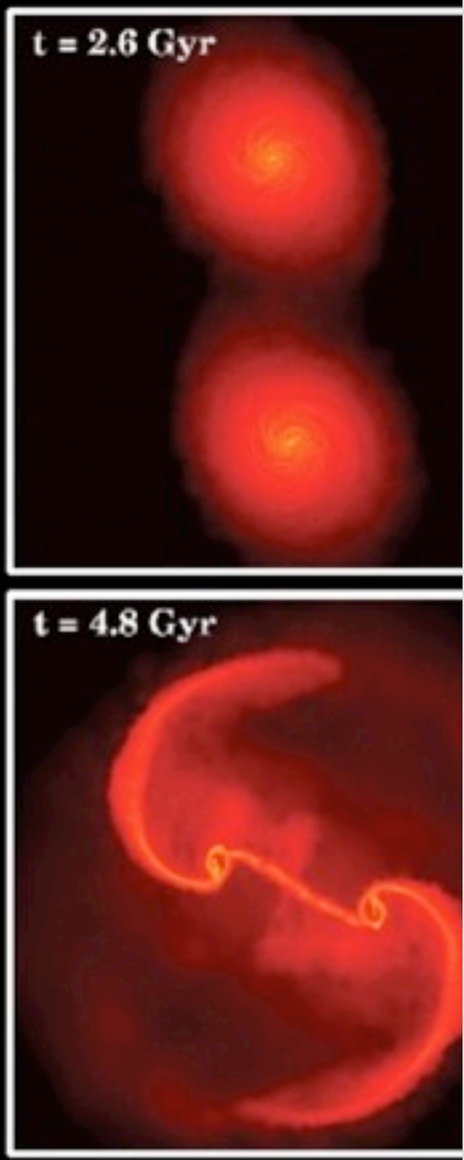


J1536+0441 (Lauer & Boroson 09)

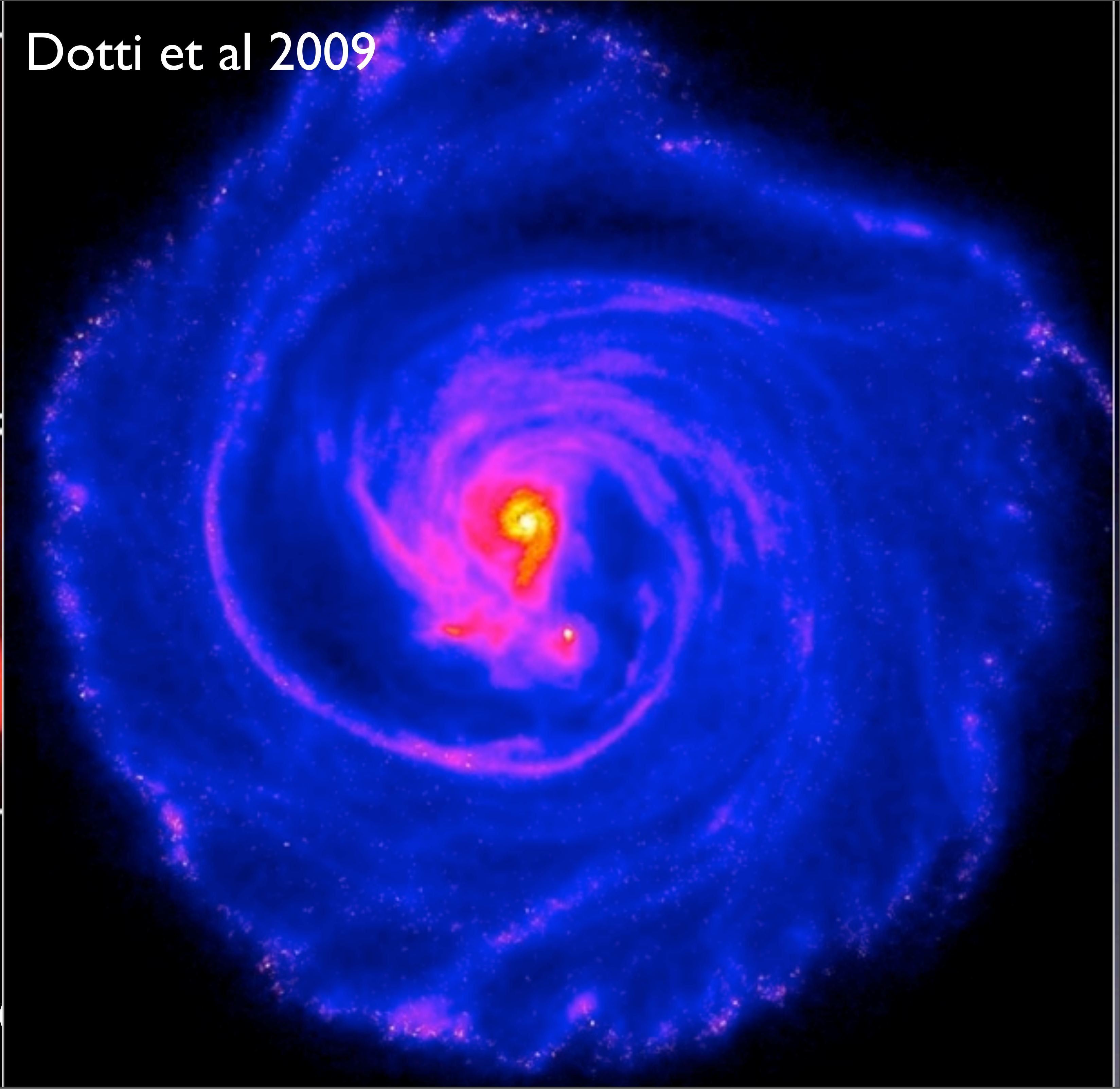
Gas-driven mergers at large scales

e.g., Escala et al 2004, 2005;   Mayer et al 2008;   Dotti et al 2009

- 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

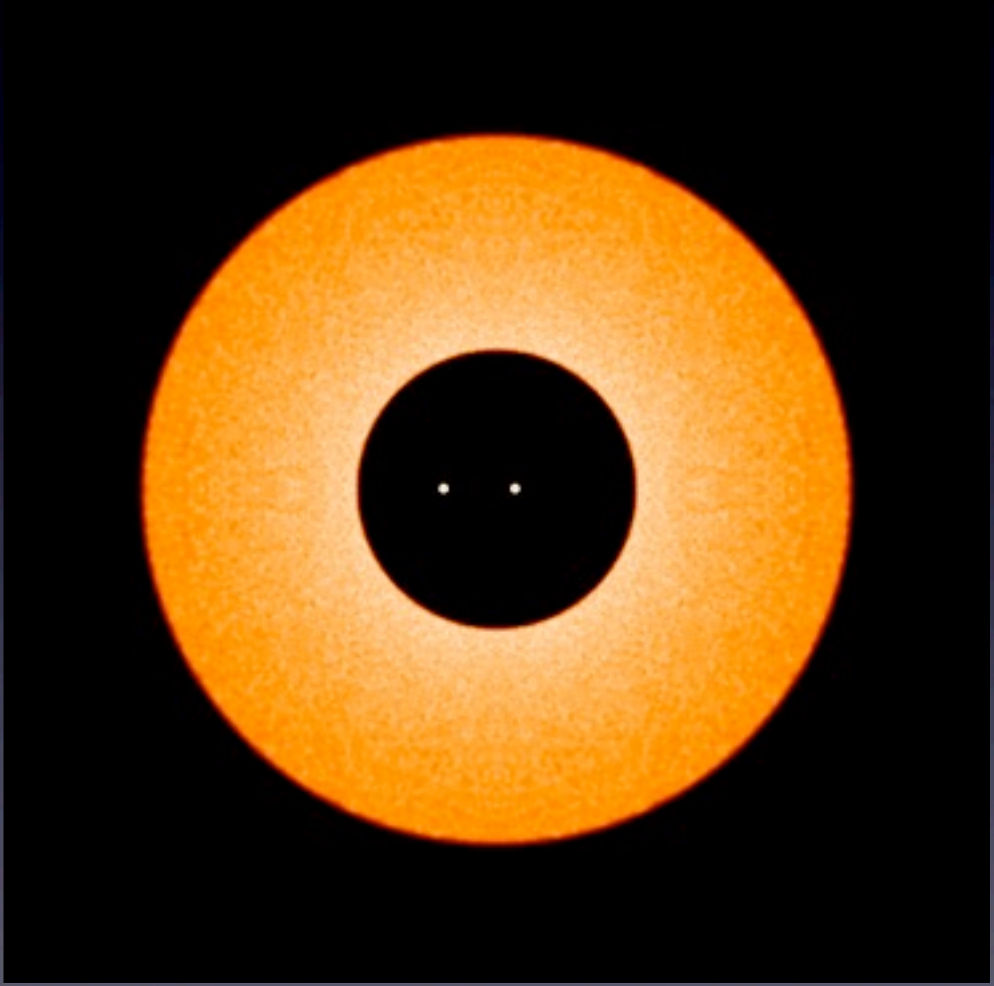


Dotti et al 2009

Binary + Disc Numerical Models

Cuadra et al 2009

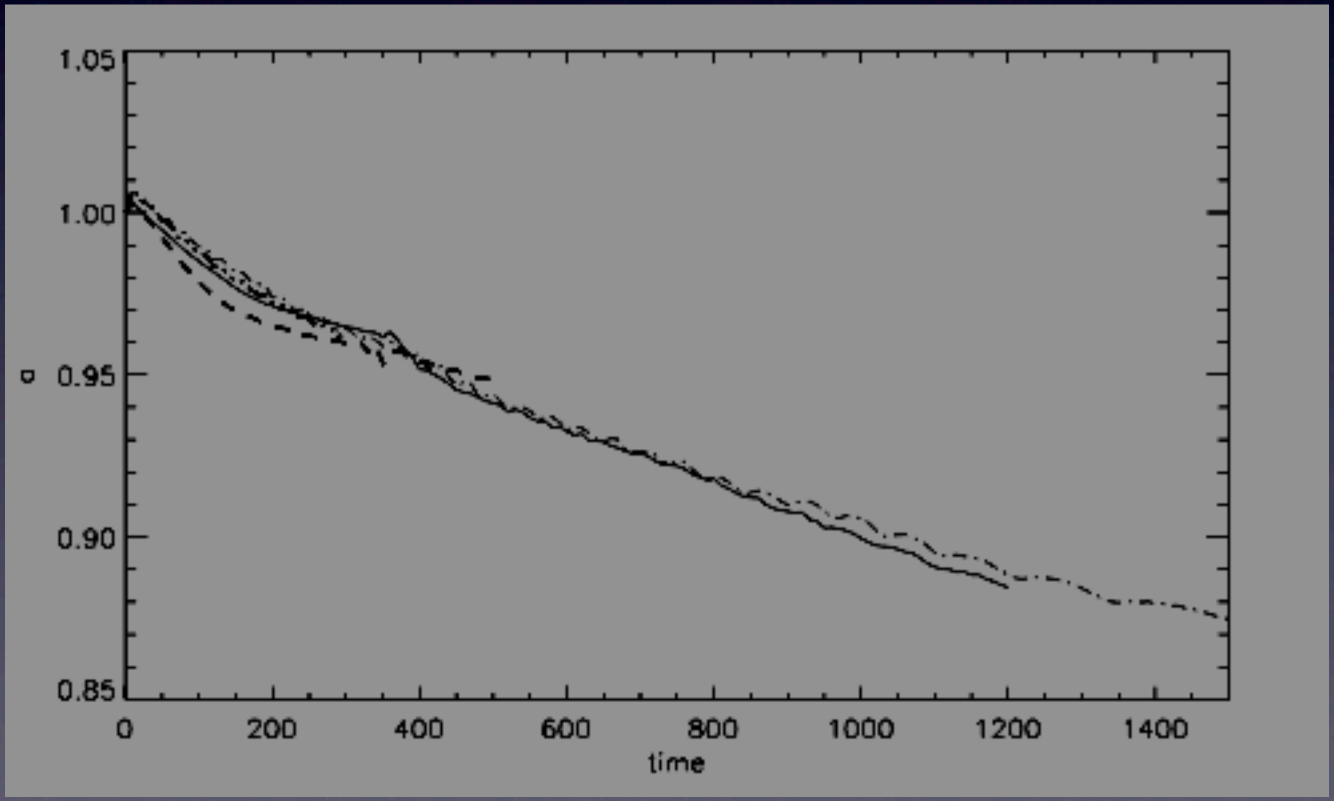
- 3:1 mass ratio binary
- $M_{disc} = 0.2\ M_{BH}$
- Physical angular momentum transport due to self-gravity
- Modified Gadget-2 (SPH code by Springel 2005)
- Goal: find evolution of binary
  - time-scale for merger
  - eccentricity evolution



Binary Orbit Evolution

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

Semi-major axis



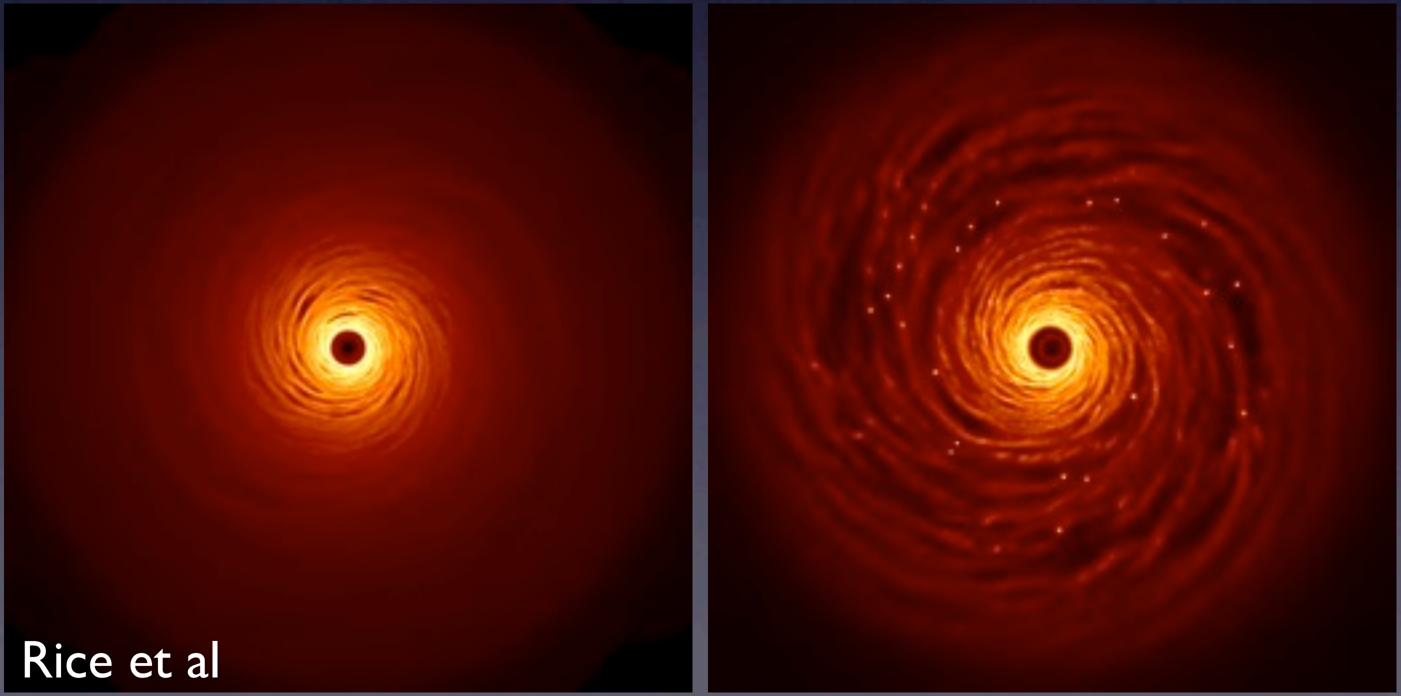
Time

Scaling to real systems

- 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

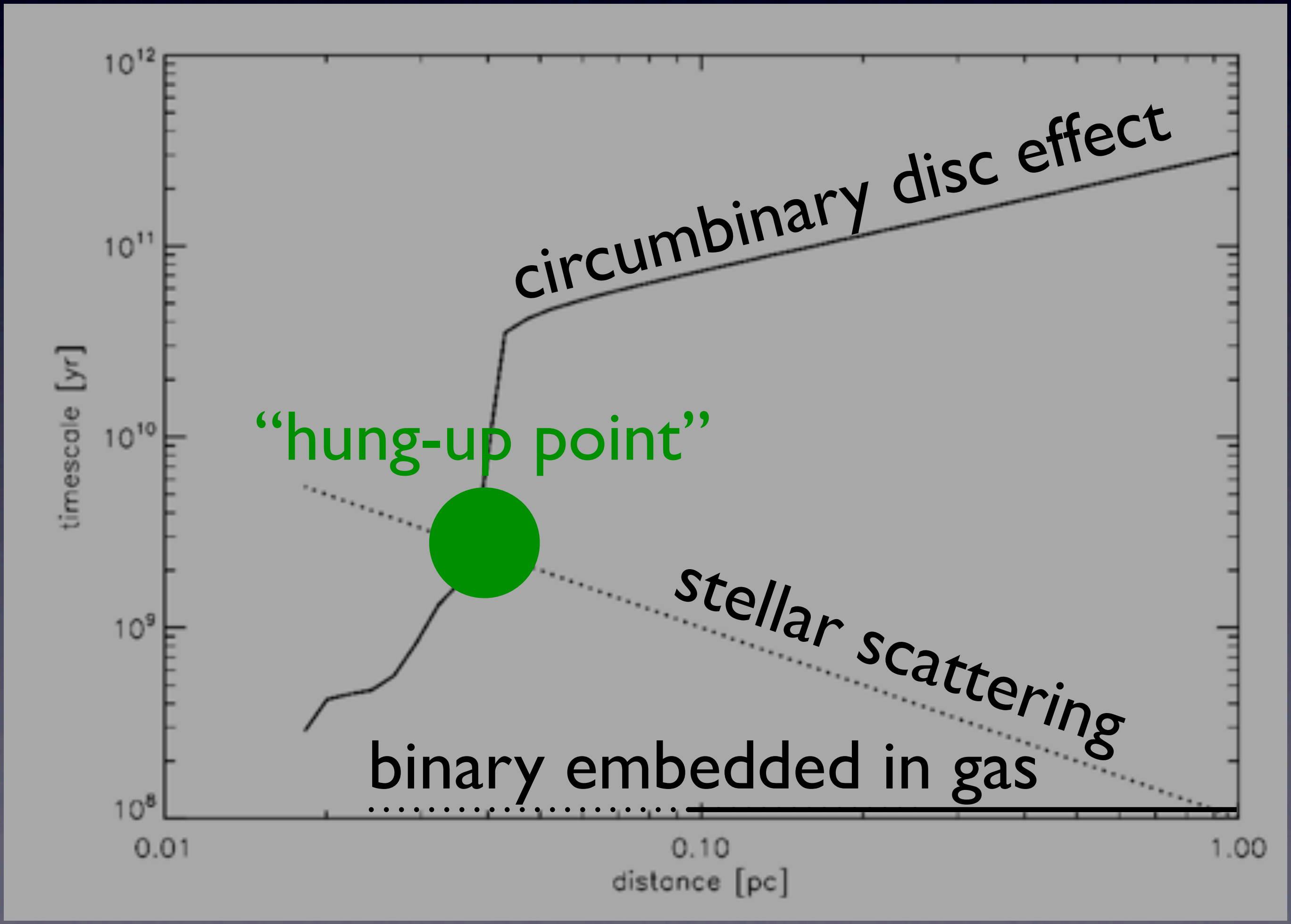
- Can’t we just have a very large disc to make sure there’s a merger?
- No! There’s a maximum mass beyond which cooling will be too fast and produce fragmentation instead of transport angular momentum.

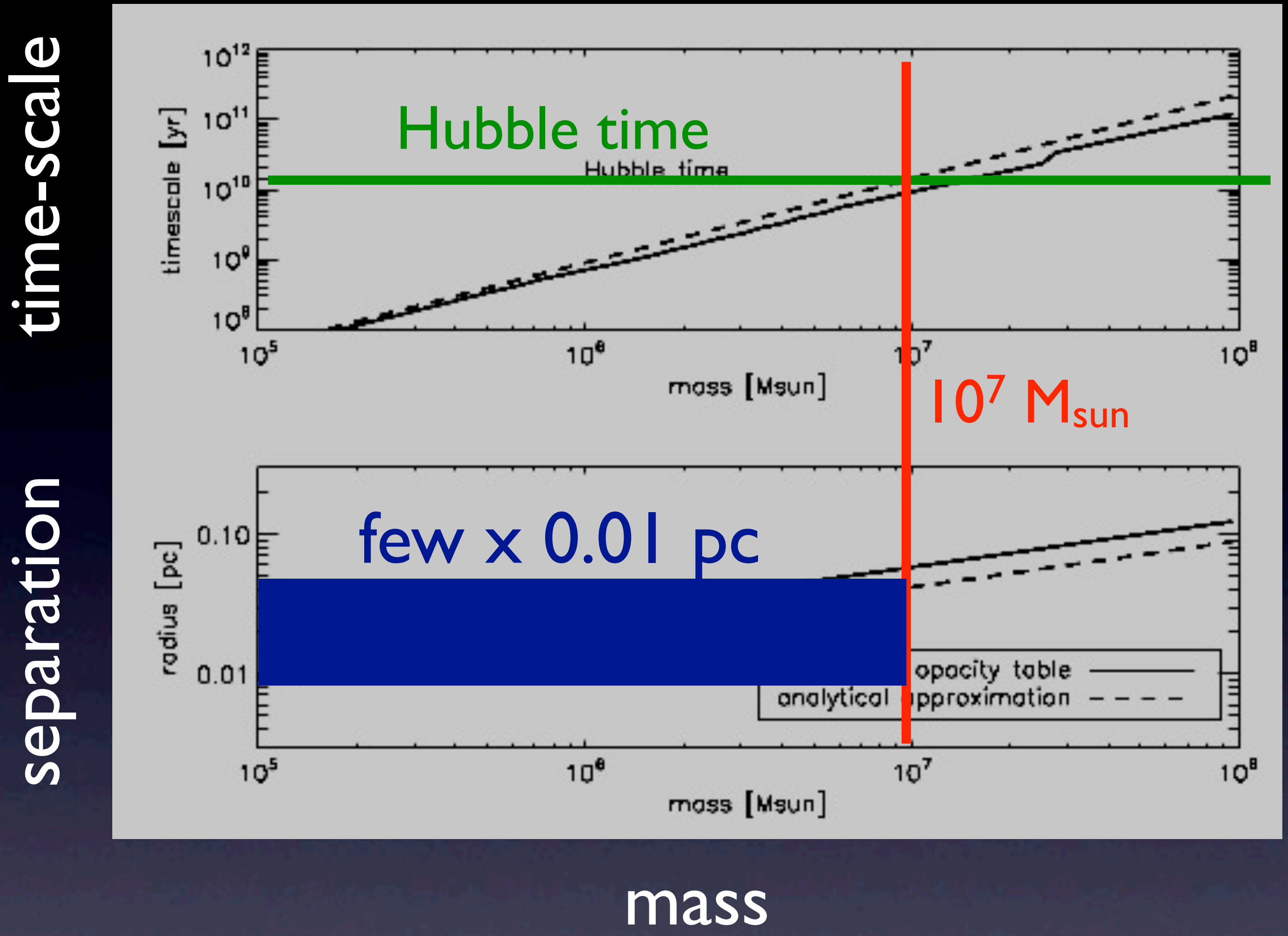


Rice et al

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.





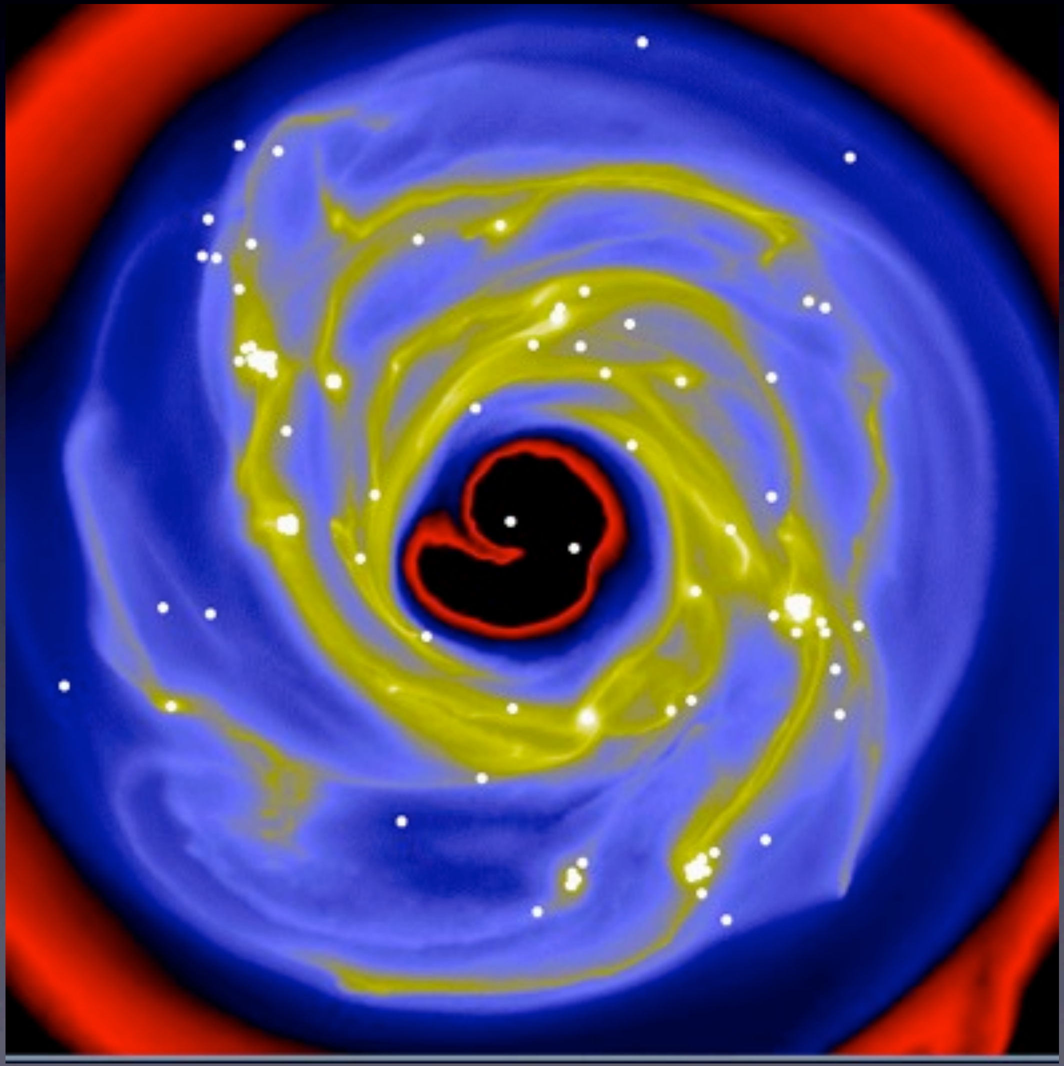
Binaries smaller than 10^7 M_{sun} could merge.

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

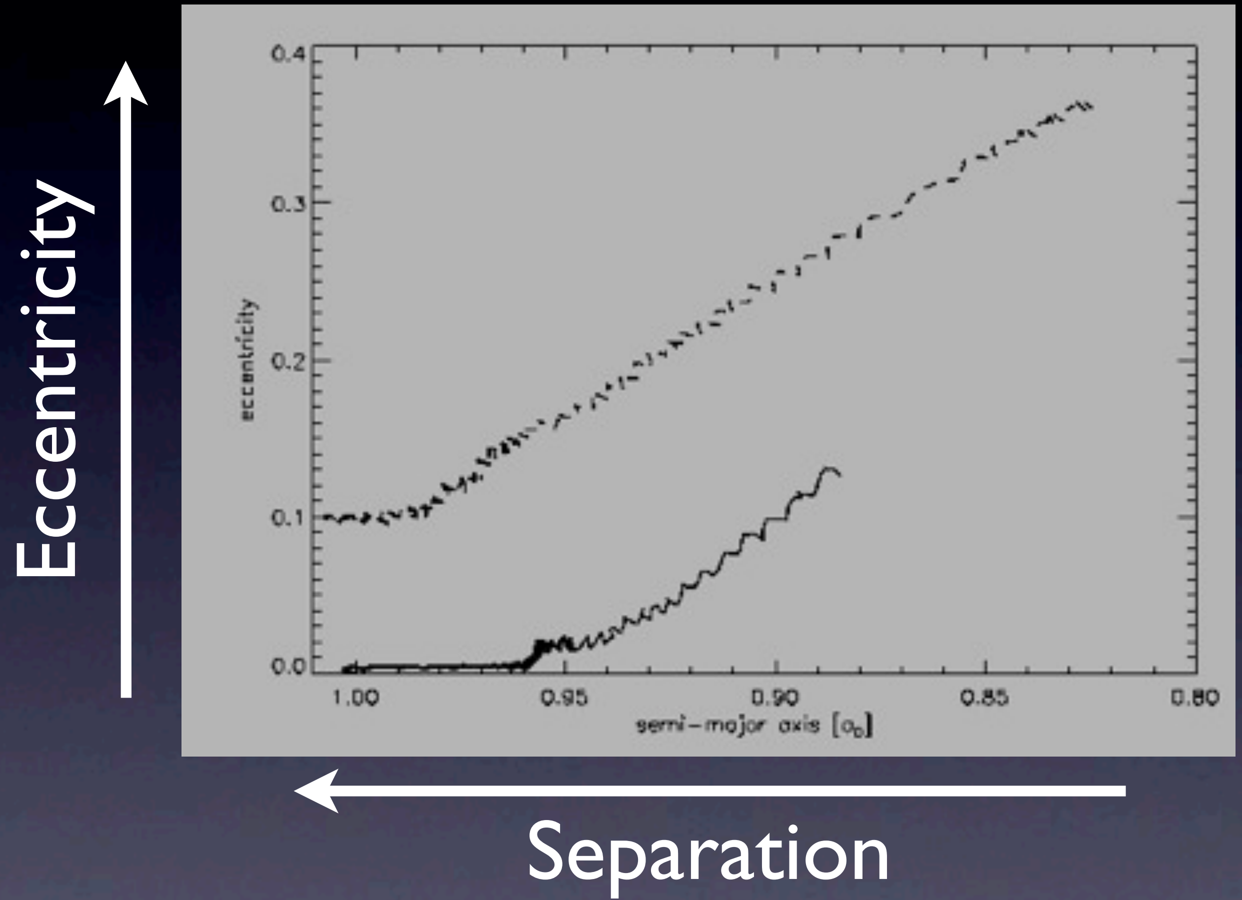
Star-forming discs

Work in progress with Pau Amaro-Seoane & Patrick Brem

- 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.

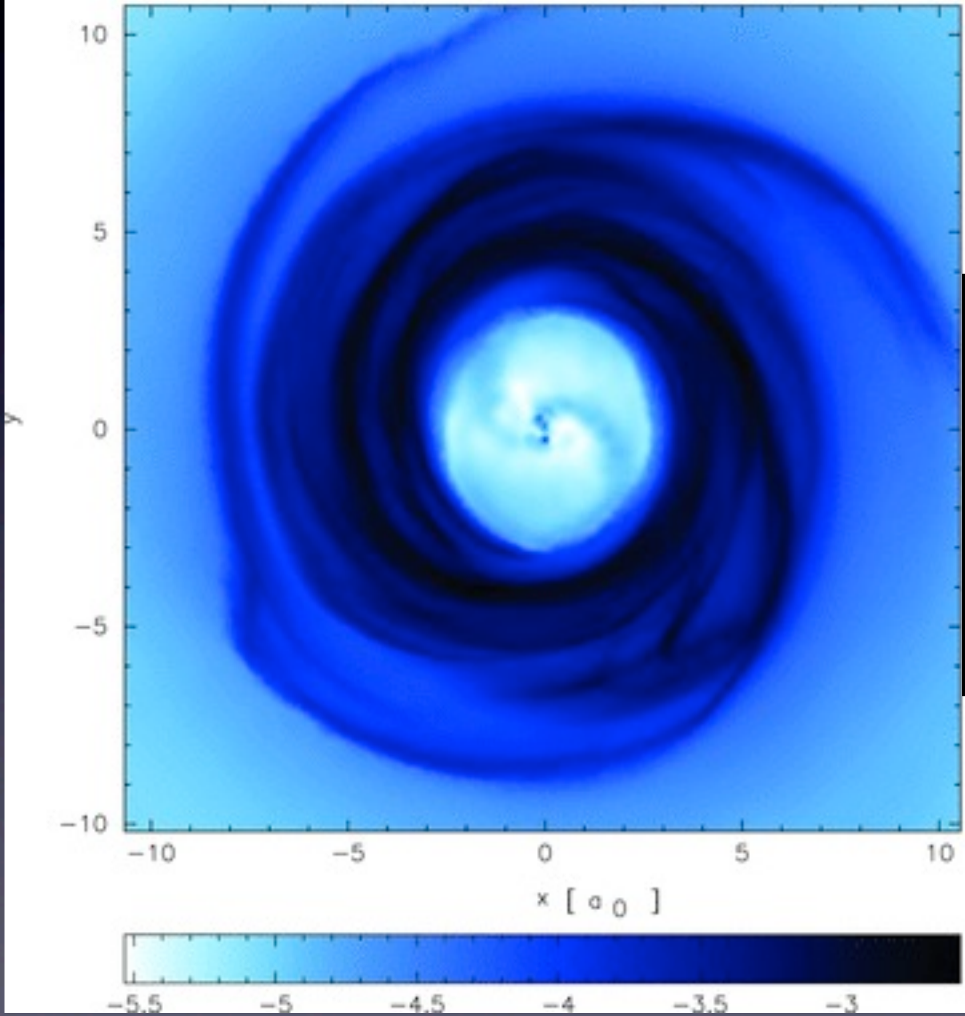
No sign of saturation.

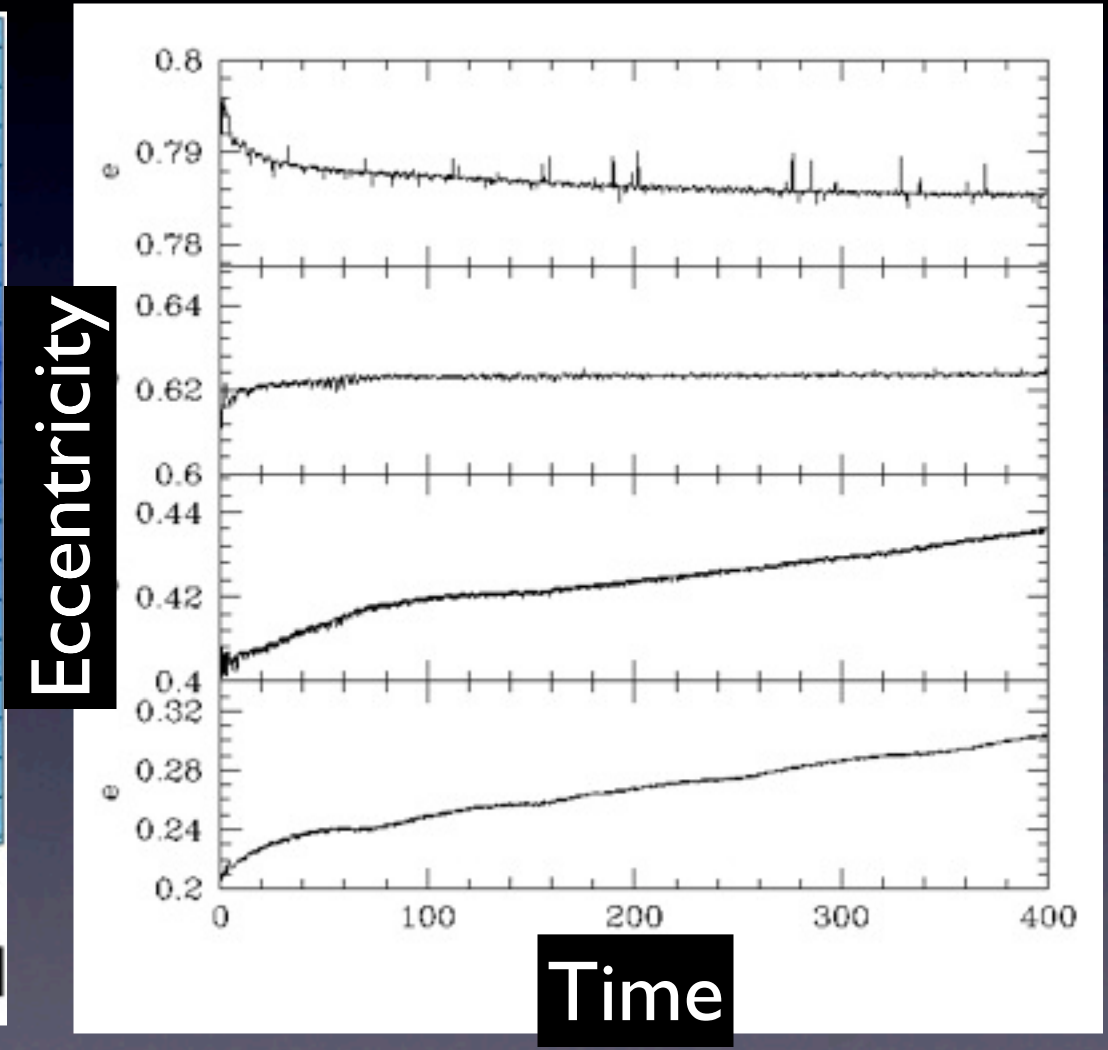
Will it grow to e ~ 1 ?

Trying different initial eccentricities...

Rödig, Dotti, Sesana, Cuadra, Colpi 2011

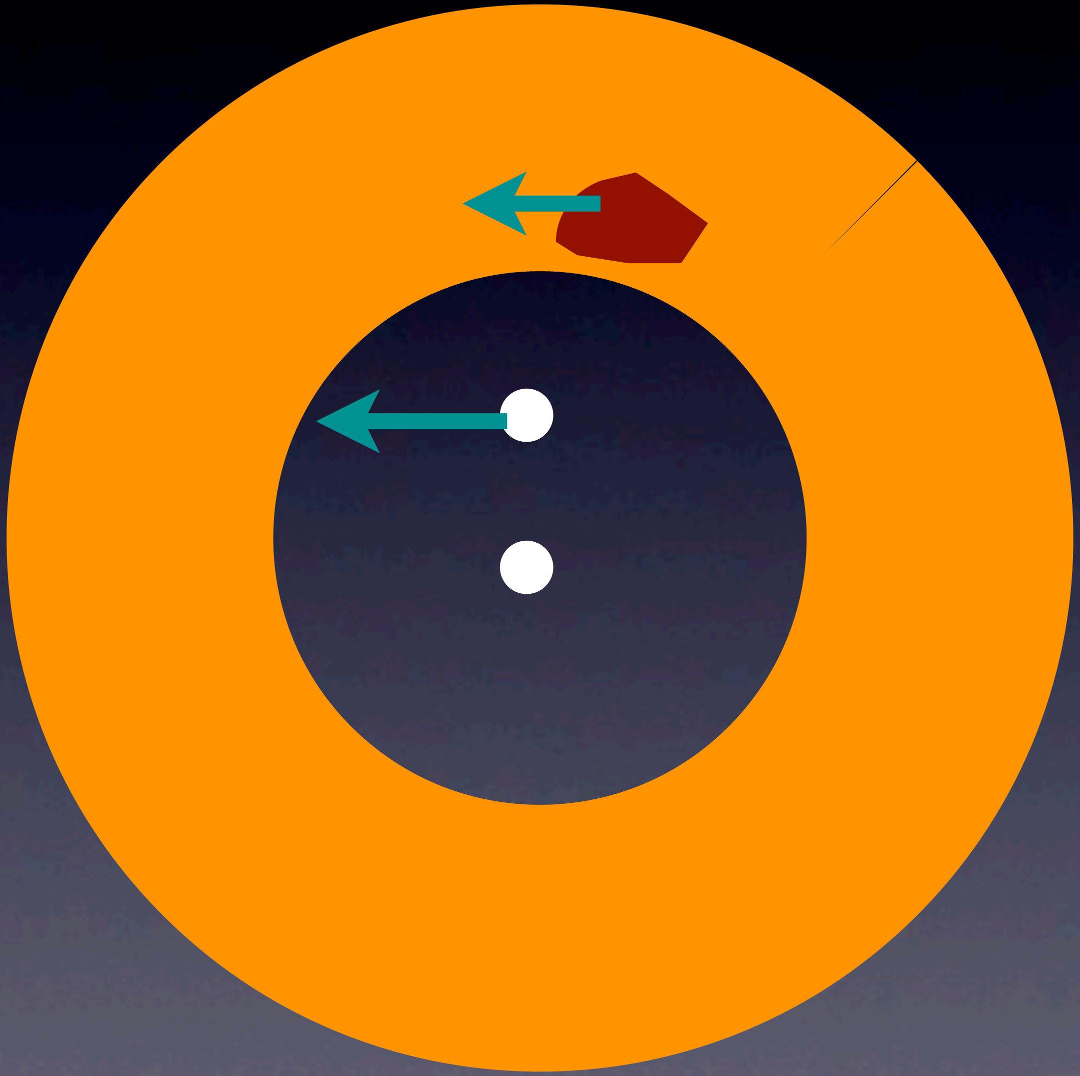
Eccentricity seems to converge to e ~ 0.6 !





Eccentricity evolution

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

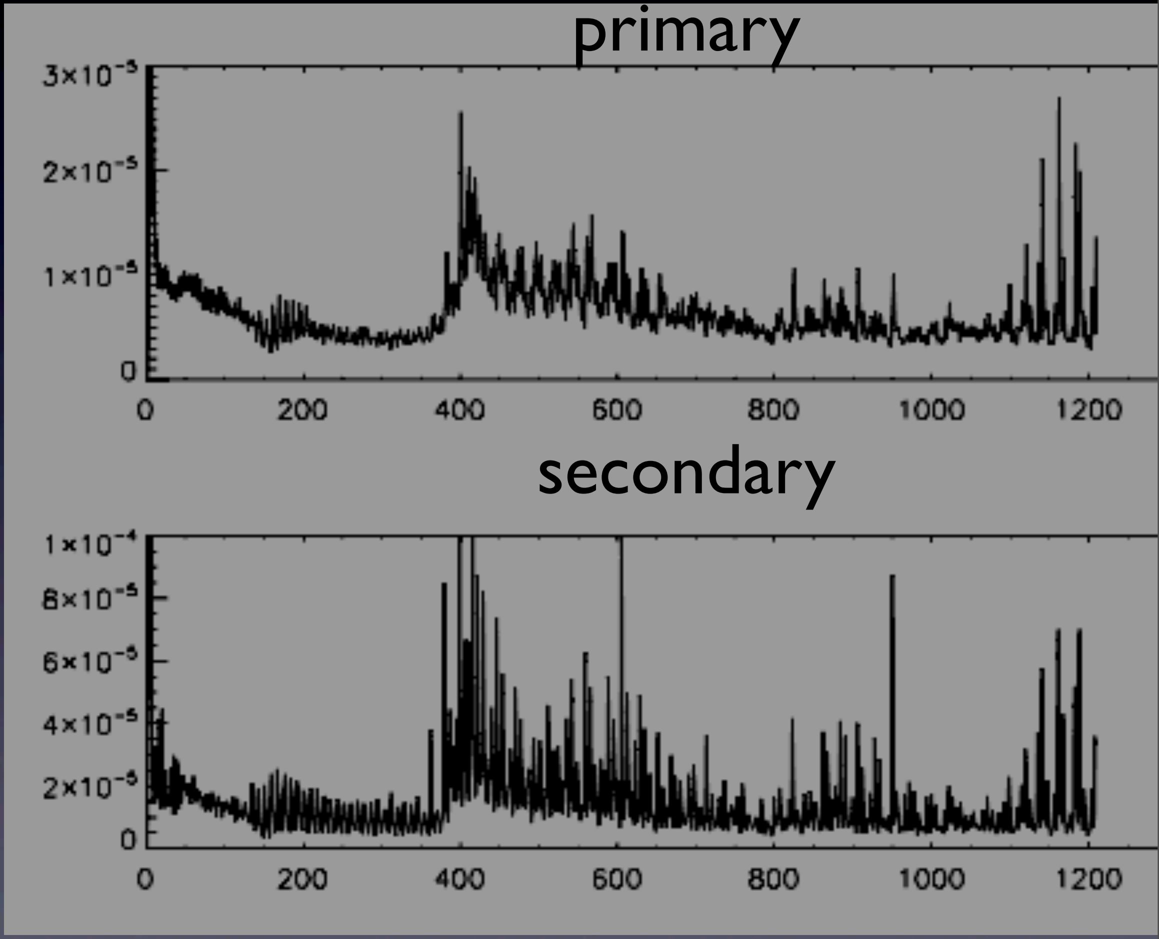


Eccentricity evolution

- 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.

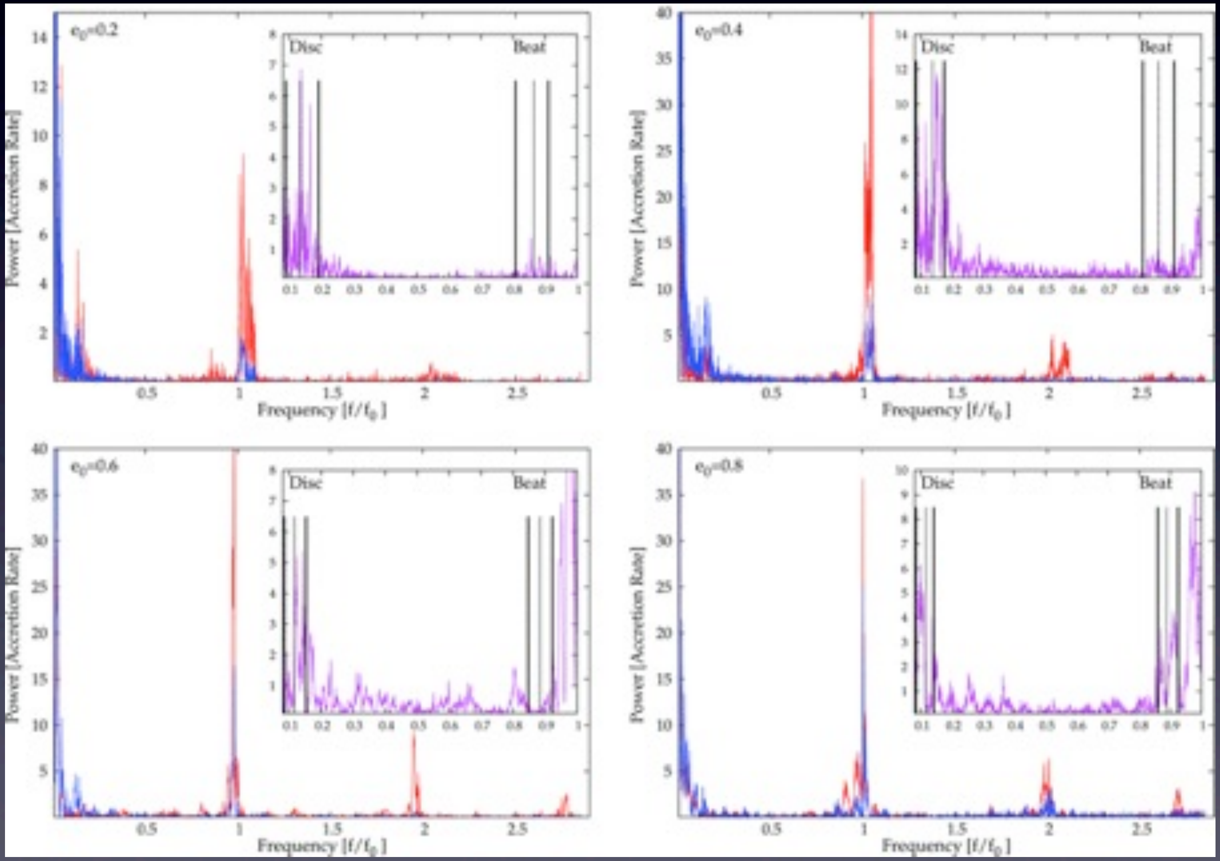


primary

secondary

“Observable” consequences

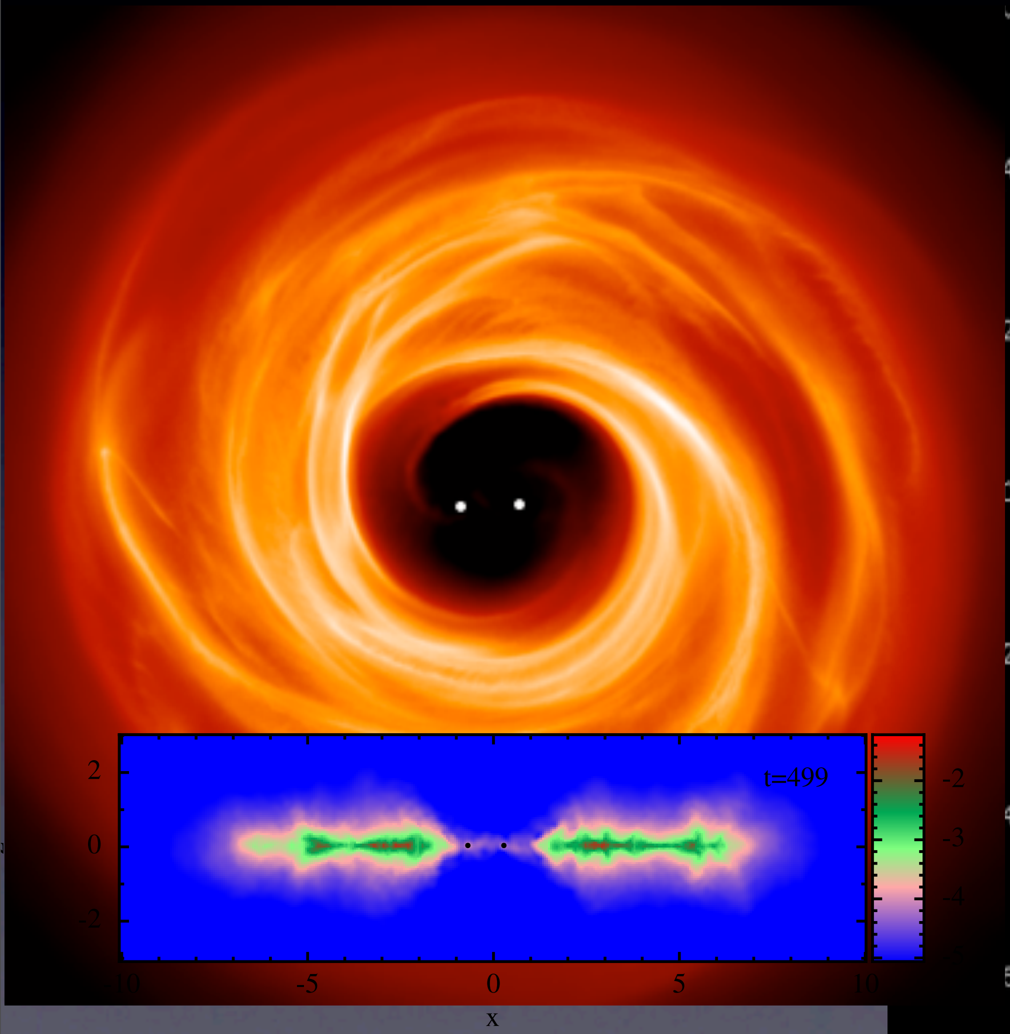
- Higher eccentricity enhances accretion rate variability.
- Gravitational wave observations would detect remnant $e \sim 10^{-2} – 10^{-3}$.

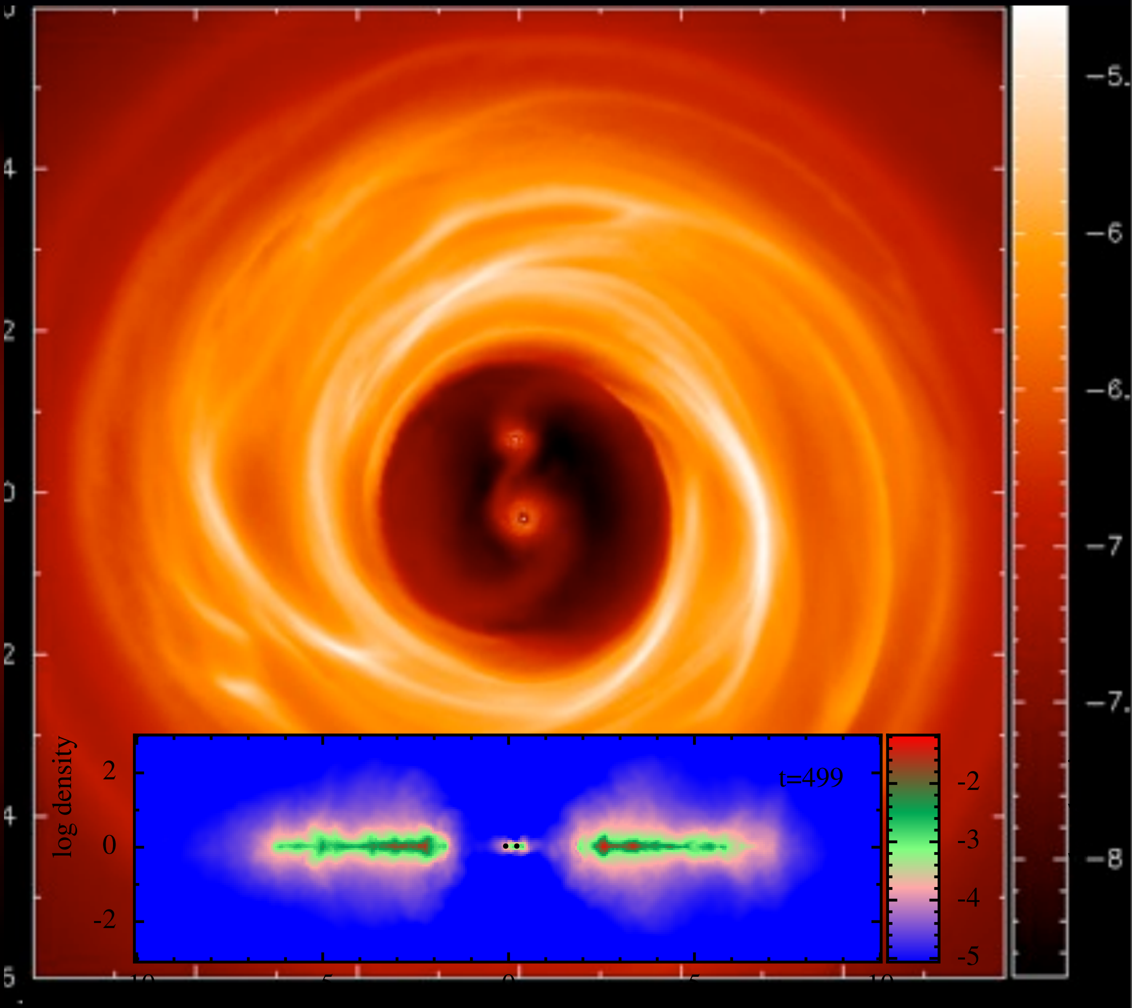


How robust are the results?

Trying different thermodynamics at the cavity...

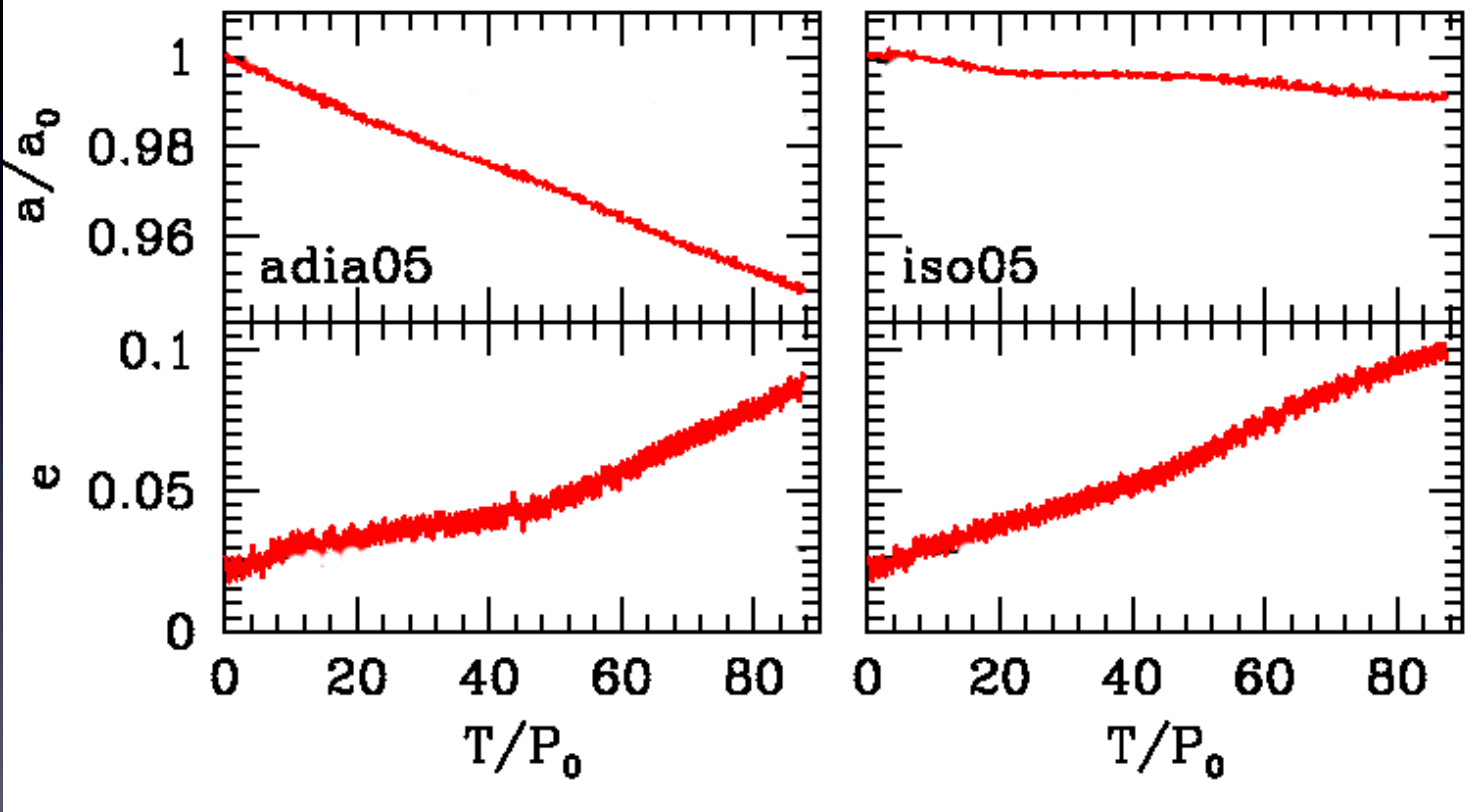
Adiabatic EoS plus cooling time proportional to orbital time





Cavity modelled isothermally

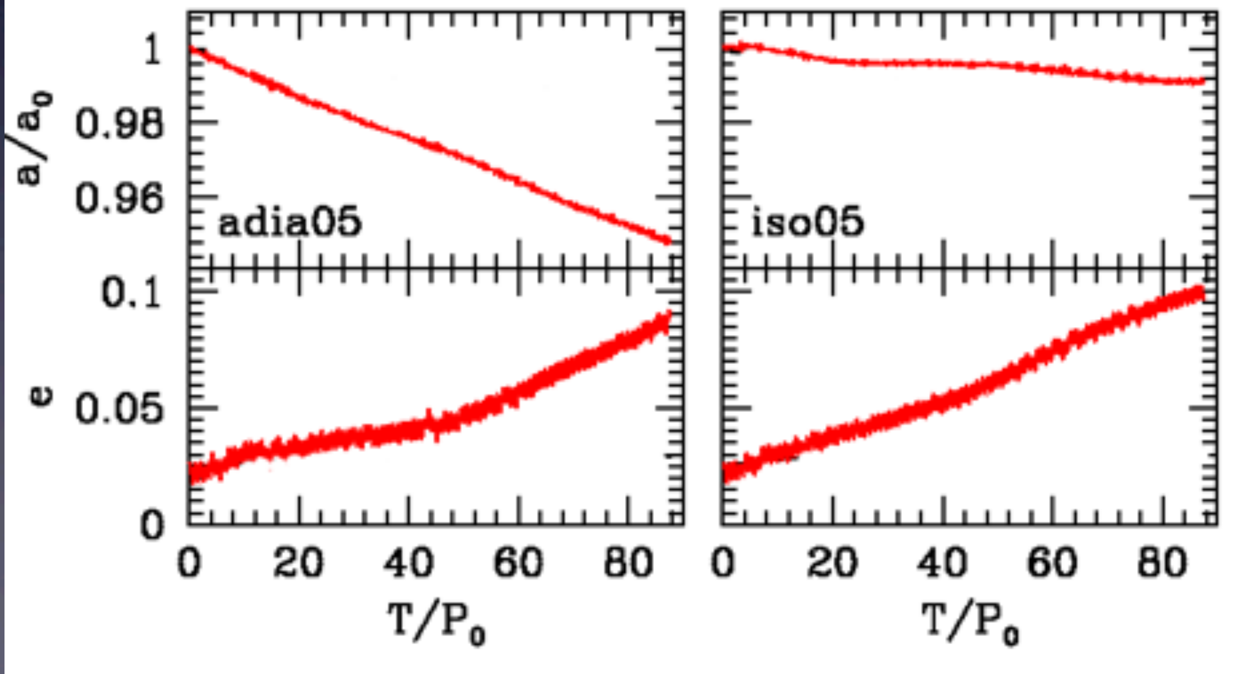
Orbital Evolution



Roedig, Sesana, Dotti, Cuadra, Amaro-Seoane 2012

Orbital Evolution

- Eccentricity evolution is the same.
- Rate of decay, different.
- If the decay is driven by the disc, why the conditions in the *cavity* change it?

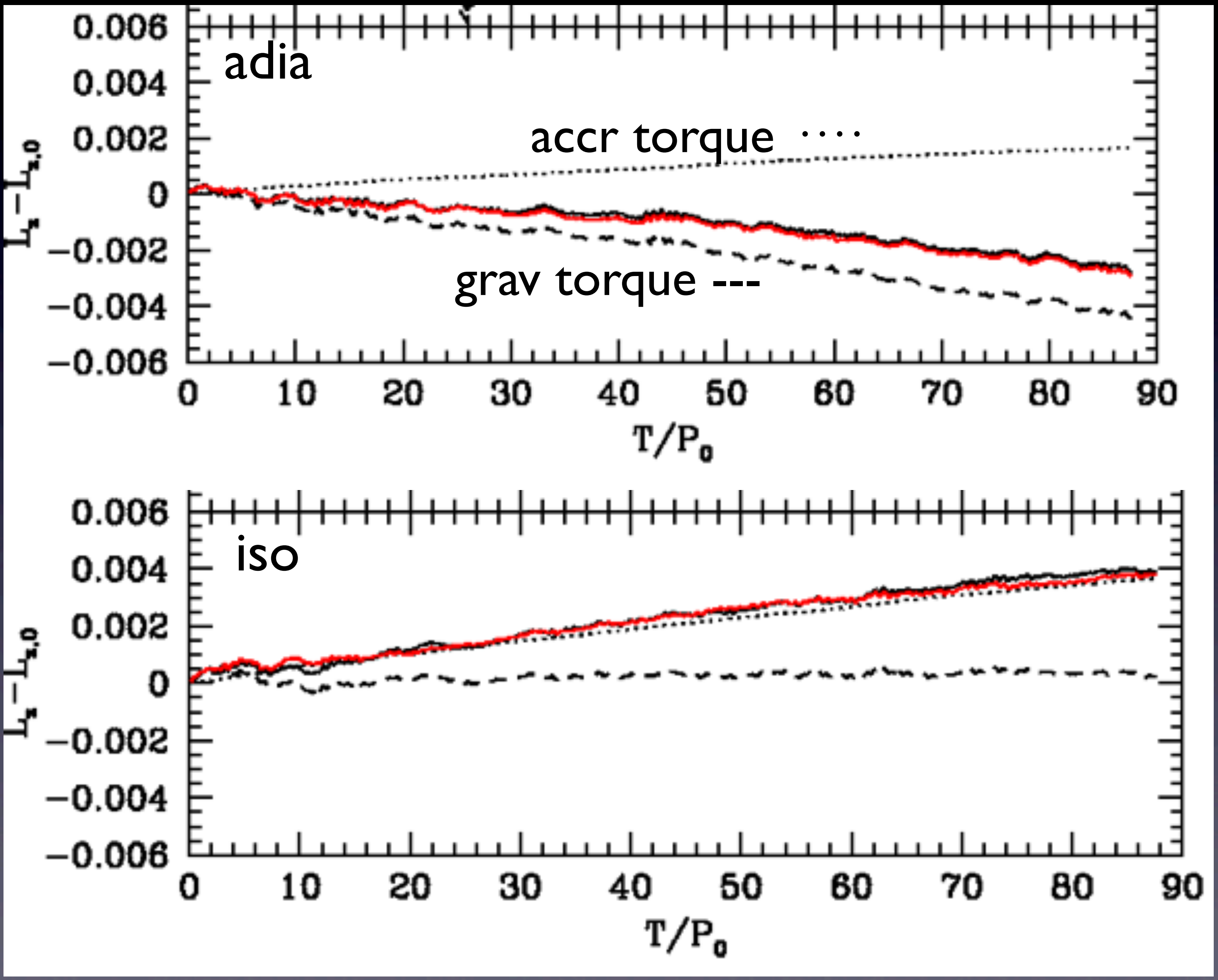


Torque analysis: gravity and accretion

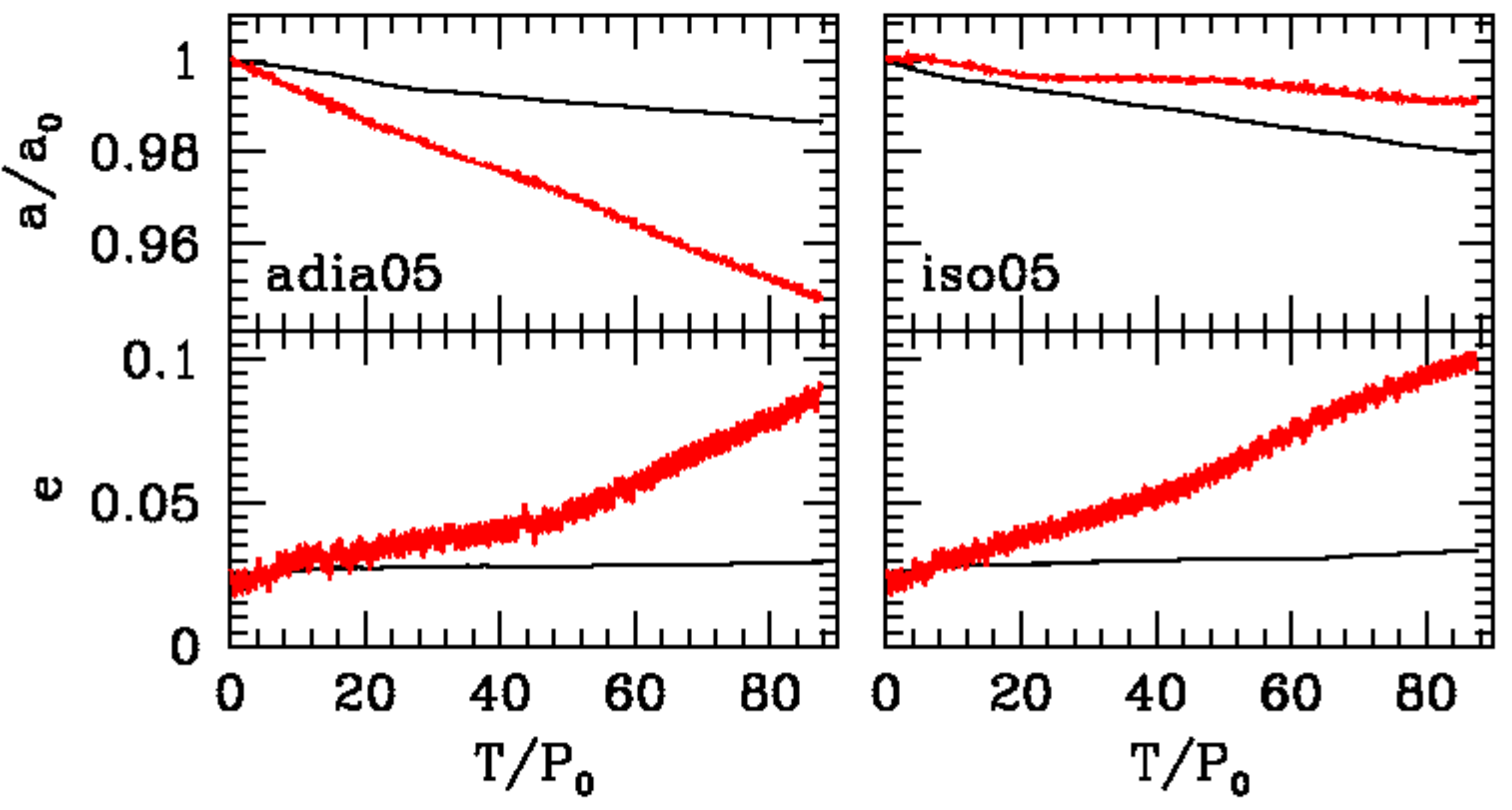
$$\frac{d\mathbf{L}}{dt} = \mathbf{T}_{\mathrm{G}} + \frac{d\mathbf{L}}{dt}_{\mathrm{acc}}$$

$$\mathbf{T}_{\mathrm{G}} = \sum_{j=1}^{N}\sum_{k=1}^{2} \mathbf{r}_k \times \frac{GM_k m_j(\mathbf{r}_j - \mathbf{r}_k)}{|\mathbf{r}_j - \mathbf{r}_k|^3}$$

Ang.mom. conservation and torque origin



Evolution due to accretion



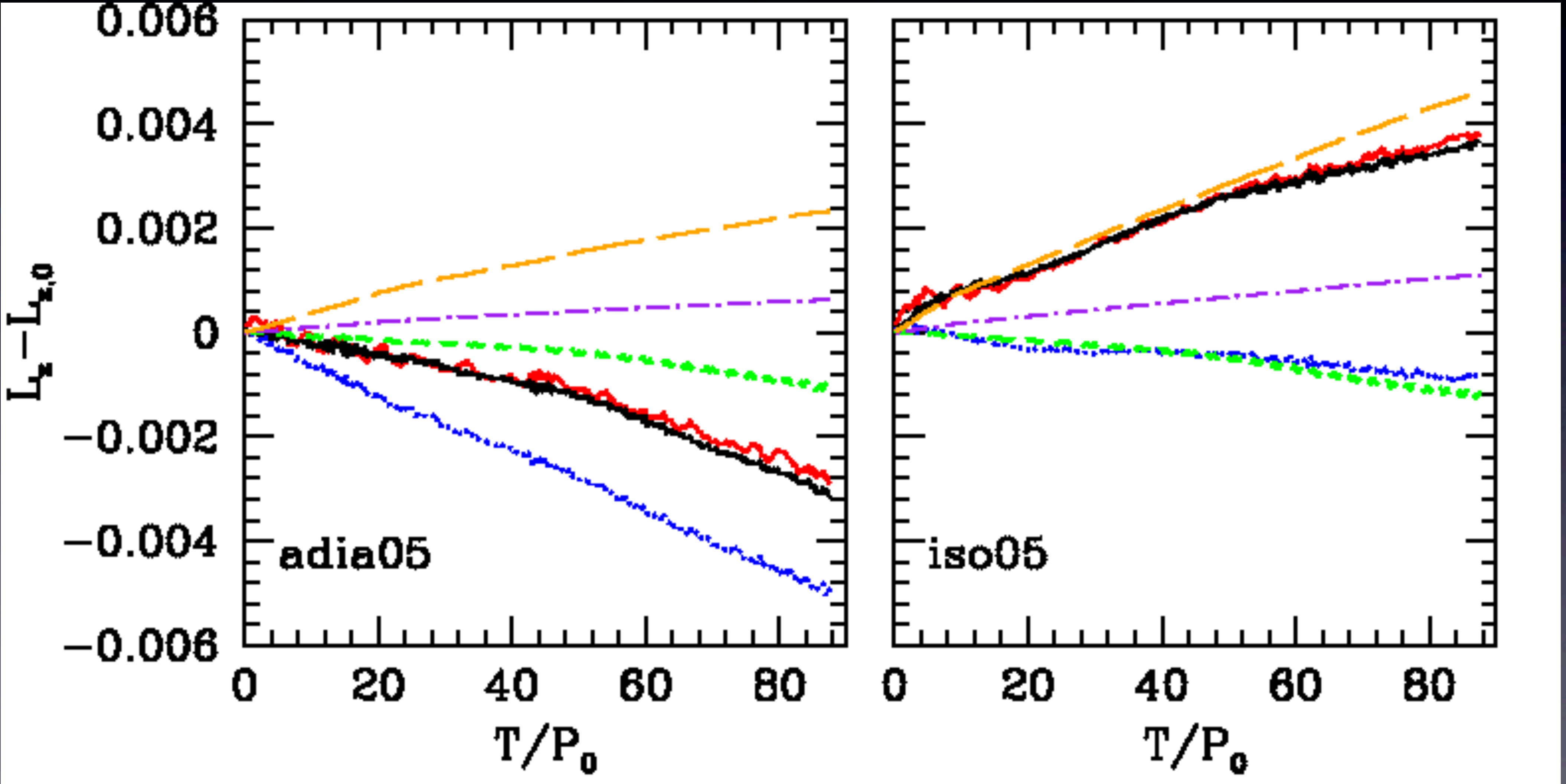
Binary ang.mom. analysis: orbital elements

$$L_z = \mu\sqrt{GMa(1-e^2)}$$

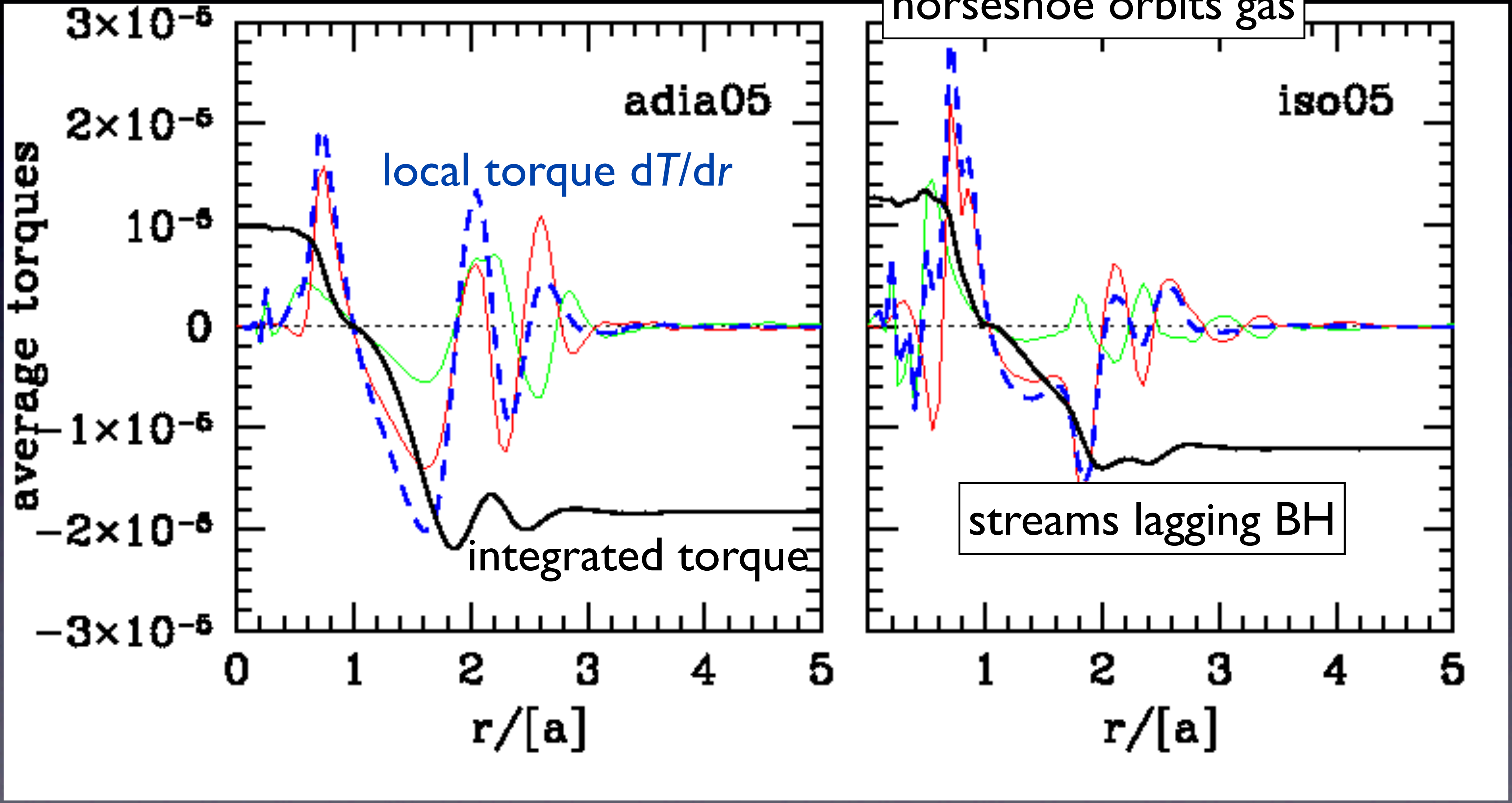
$$\frac{\dot{L}_z}{L_z} = \frac{\dot{a}}{2a} + \frac{\dot{M}}{2M} + \frac{\dot{\mu}}{\mu} - \frac{e}{1-e^2}\dot{e}$$

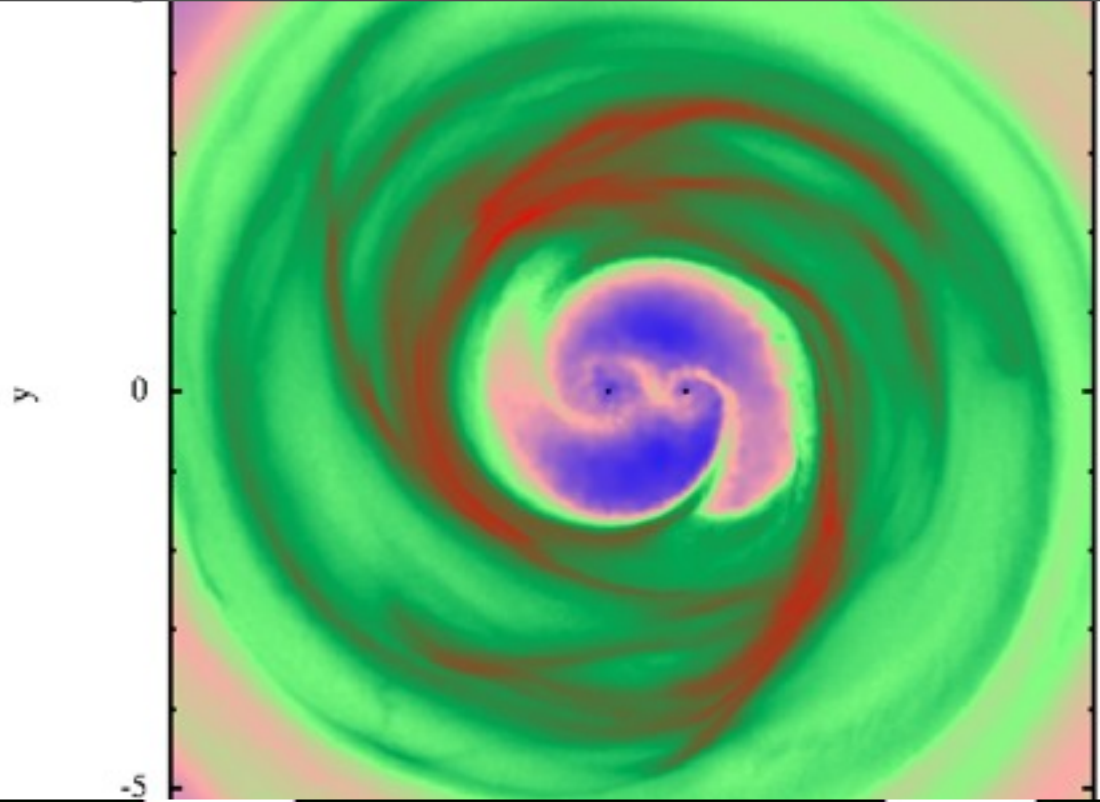
Binary can shrink and become eccentric while its ang.mom. increases, provided accretion is important.

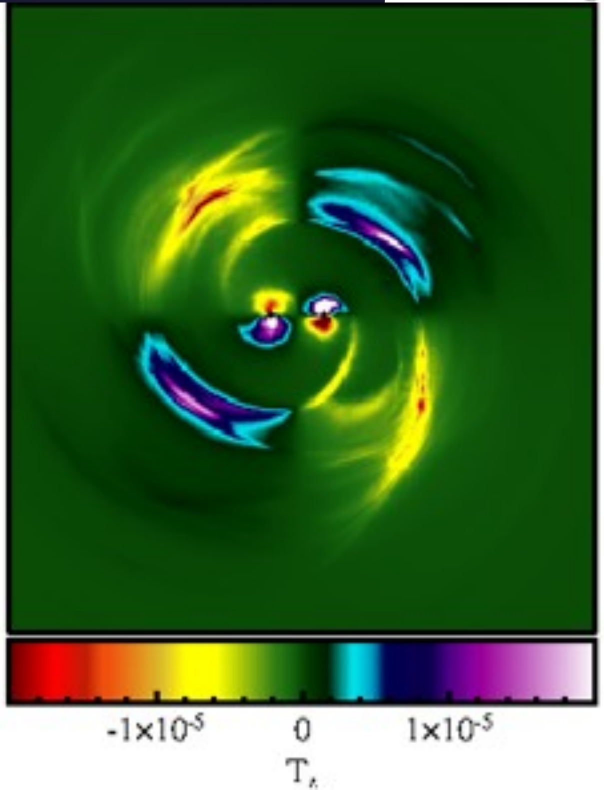
$$\frac{\dot{L}_z}{L_z} = \frac{\dot{a}}{2a} + \frac{\dot{M}}{2M} + \frac{\dot{\mu}}{\mu} - \frac{e}{1-e^2}\dot{e}$$

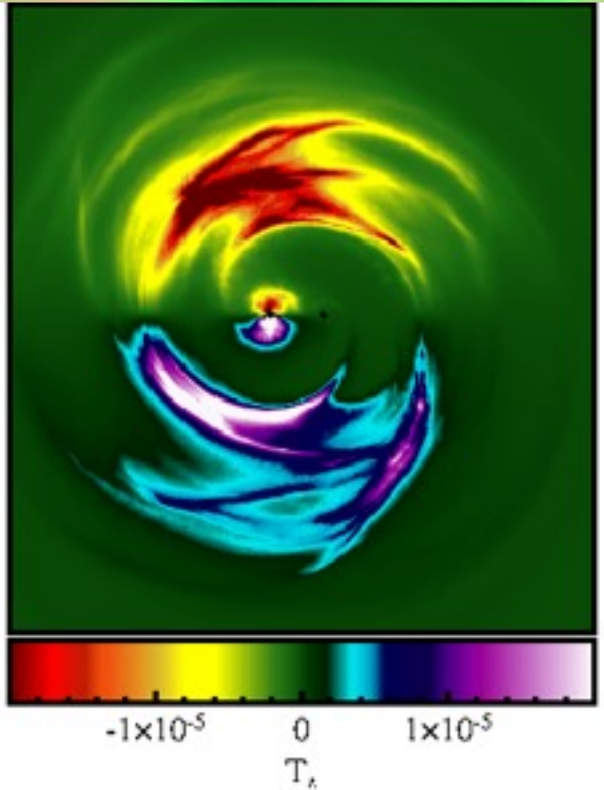


Origin of the gravitational torque




y
0
-5


-1×10^{-5}
0
1×10^{-5}
T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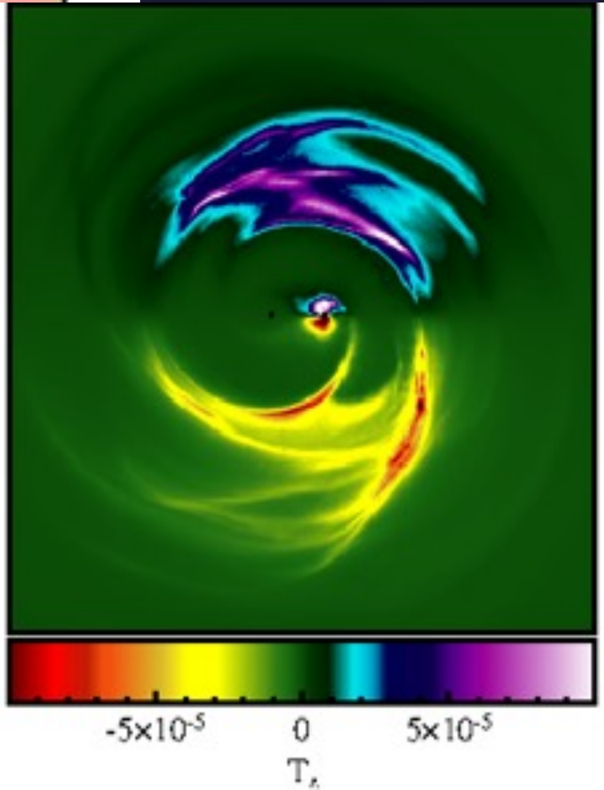
-5×10^{-5}
0
5×10^{-5}
T

Conclusions

- In simple models, 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.
- More thorough investigation shows a very complex situation.
  - Evolution depends on the balance of opposite sign torques.
  - Different thermodynamics and accretion recipes influence results.
  - More realistic models are required.