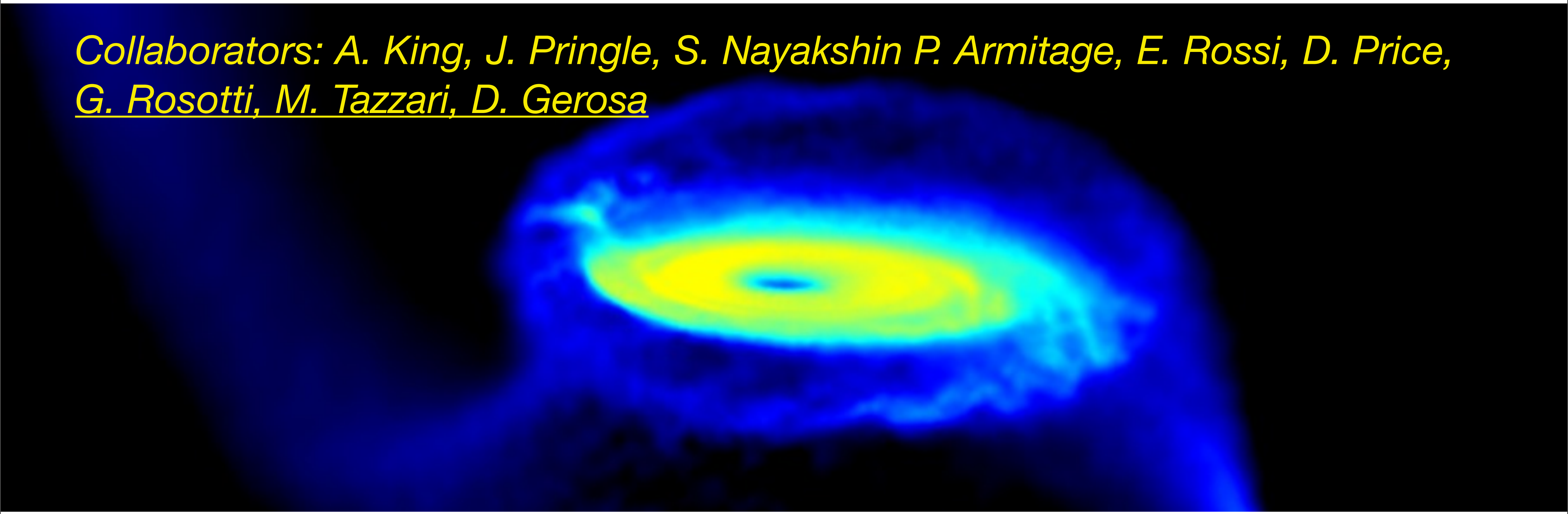
Dynamics of binary supermassive black holes in gaseous environments

Giuseppe Lodato - Università degli Studi di Milano



Collaborators: A. King, J. Pringle, S. Nayakshin P. Armitage, E. Rossi, D. Price, <u>G. Rosotti, M. Tazzari, D. Gerosa</u>

Summary

- Introduction
- The "last parsec problem": role of gaseous discs (GL, Nayakshin, King & Pringle 2009)
- Electromagnetic counterparts to GW emission:
  - Precursor: disc emission prior to merger (GL, Nayakshin, King & Pringle 2009)
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Introduction: observational evidences for SMBH binaries

- Standard cosmologies predict that galaxies undergo frequent mergers.
- If each galaxy contains a SMBH, expect to produce BH pairs/binaries (Mayer and co.)
- Observationally, BH pair at kpc scales have been found (e.g. Komossa et al 2003, NGC 6240, but see also Piconcelli et al 2010, Bianchi et al 2008,...)
- Rodriguez et al 2006: bound binary at 7pc separation
- The situation at sub-pc scales is more difficult: impossible to resolve the binary, rely on spectroscopic signatures, such as a velocity shift of the BLR
- Several candidates found but no unambiguous interpretation (Dotti et al. 2009, Boronson & Lauer 2009, De Carli et al 2010, Civano et al 2012)

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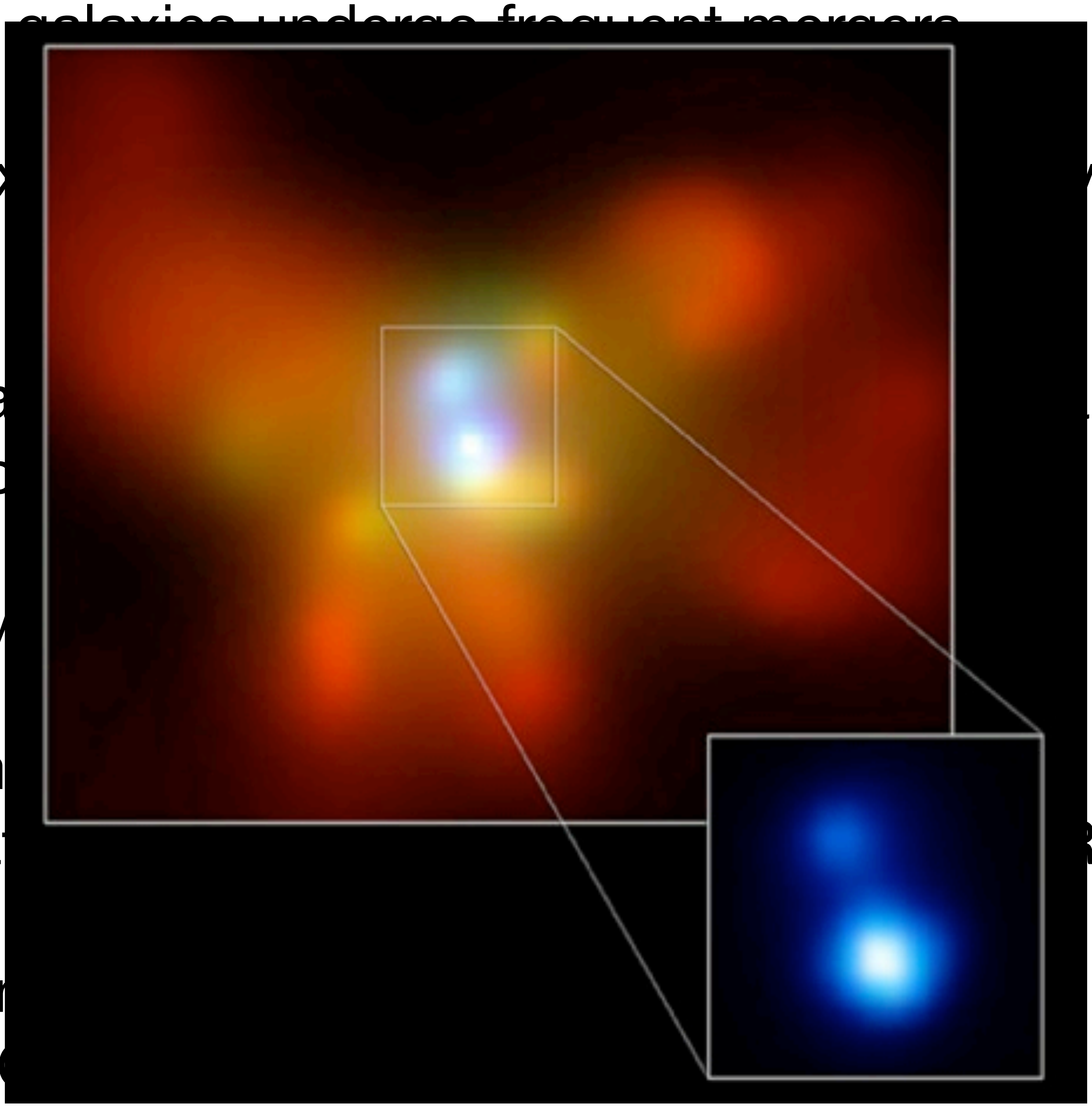

Komossa et al 2003

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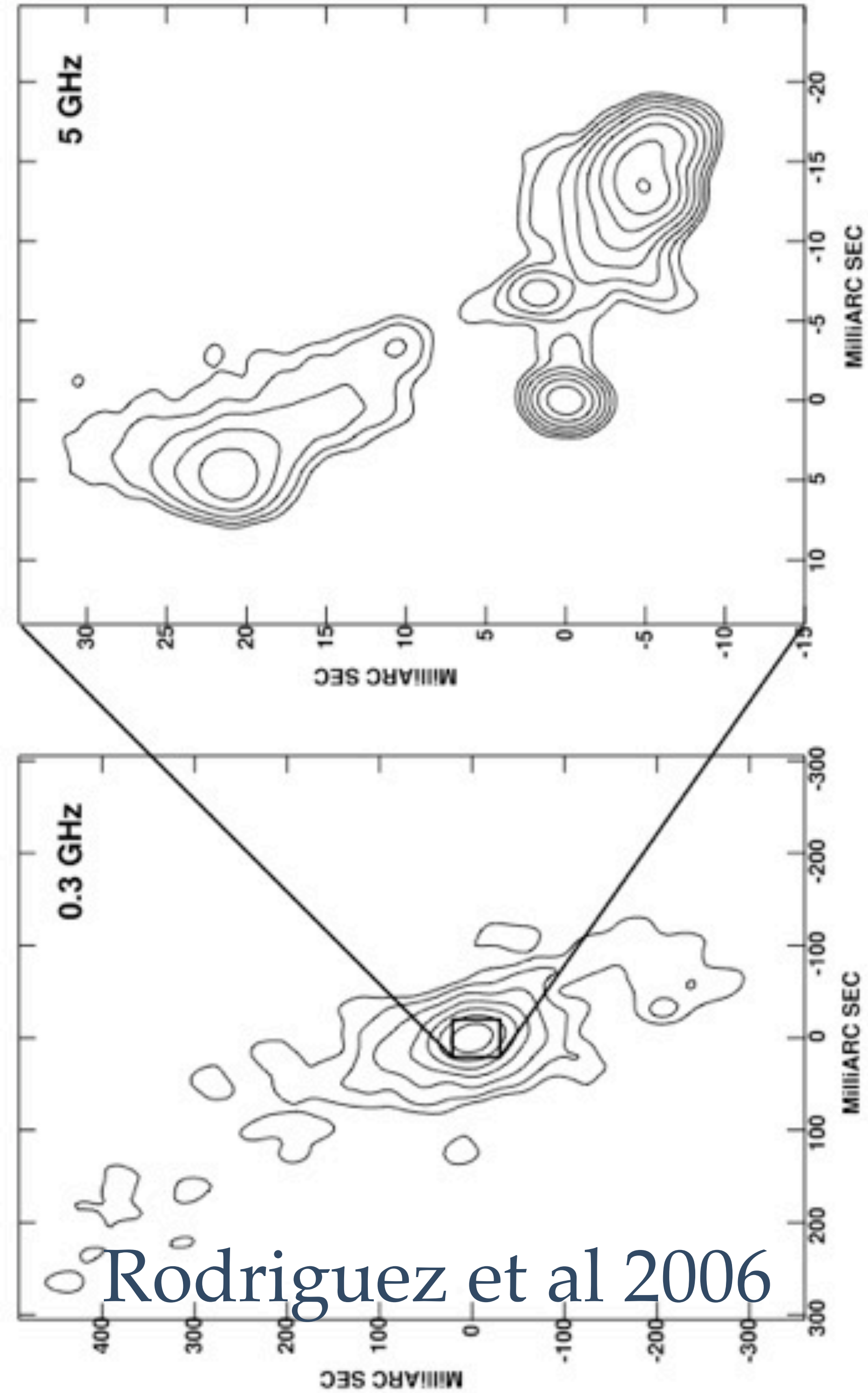

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Introduction: SMBH mergers in the context of BH growth and GW emission

- The growth of SMBH is dominated by accretion (possibly driven by galaxy mergers, Volonteri) rather than actual mergers
- Still BH binaries affect significantly the BH spin, with consequences on accretion efficiency
- Additionally, SMBH mergers are a powerful source of GW (possibly detectable by eLISA?)
- GW emission is likely to produce strong recoil velocities (up to > 1000 km/sec, Campanelli et al 2007): ejection from gas rich galaxy core?
- BH merger is likely to produce a variety of EM counterparts that can be used to characterize the GW source (if found)

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The ‘last parsec problem’

- How to shrink a massive BH binary:
  - Stellar dynamical processes have a bottleneck at ~ 1 pc (Milosavljevic and Merritt)
  - Gas dynamical processes often invoked to overcome this (Mayer et al 2007, Dotti et al 2007), but....
  - they too might have a bottleneck further down, at ~ 0.1 pc!
  - The (poorly understood) disc dynamics at this scale is thus crucial to assess the viability of disc assisted binary shrinkage

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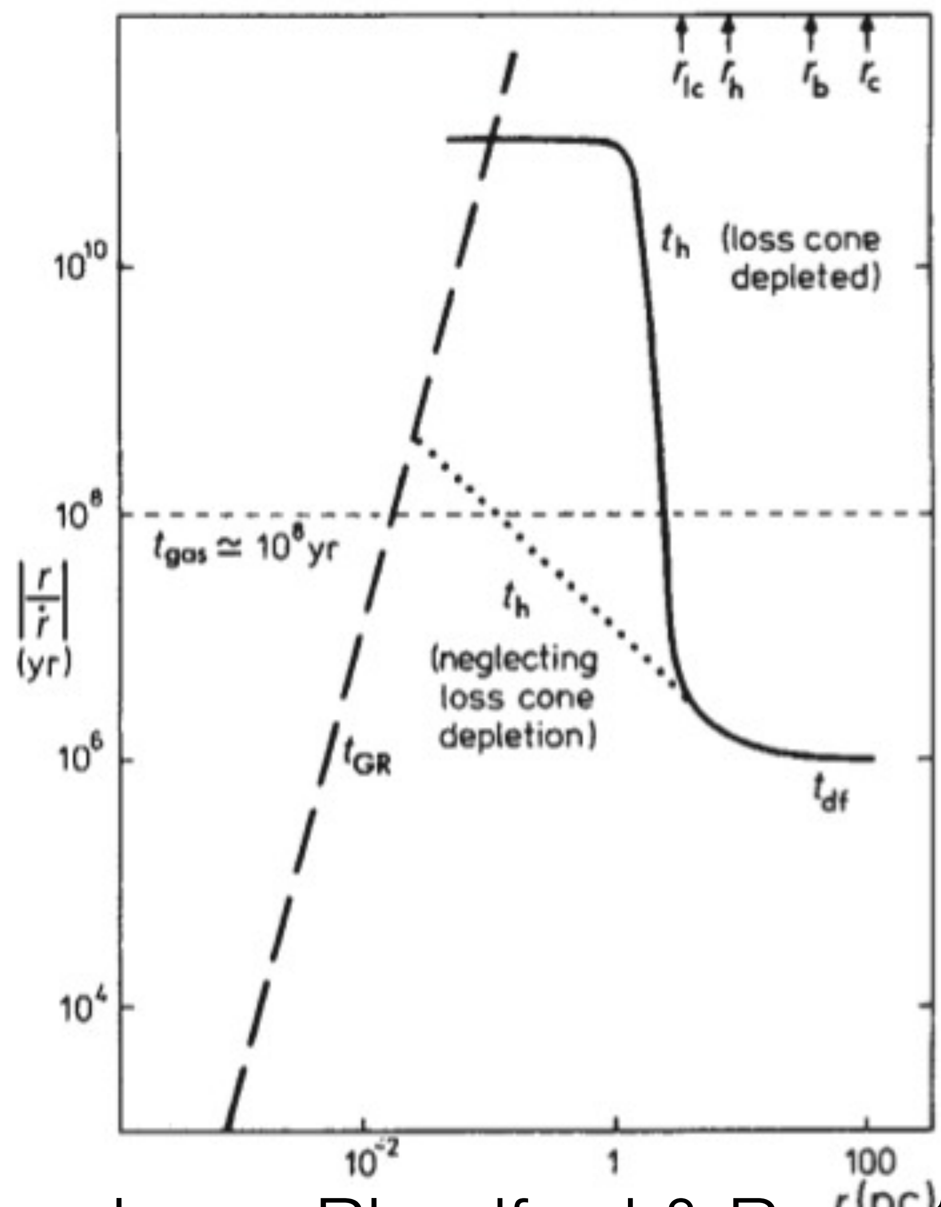

Begelman, Blandford & Rees 1980

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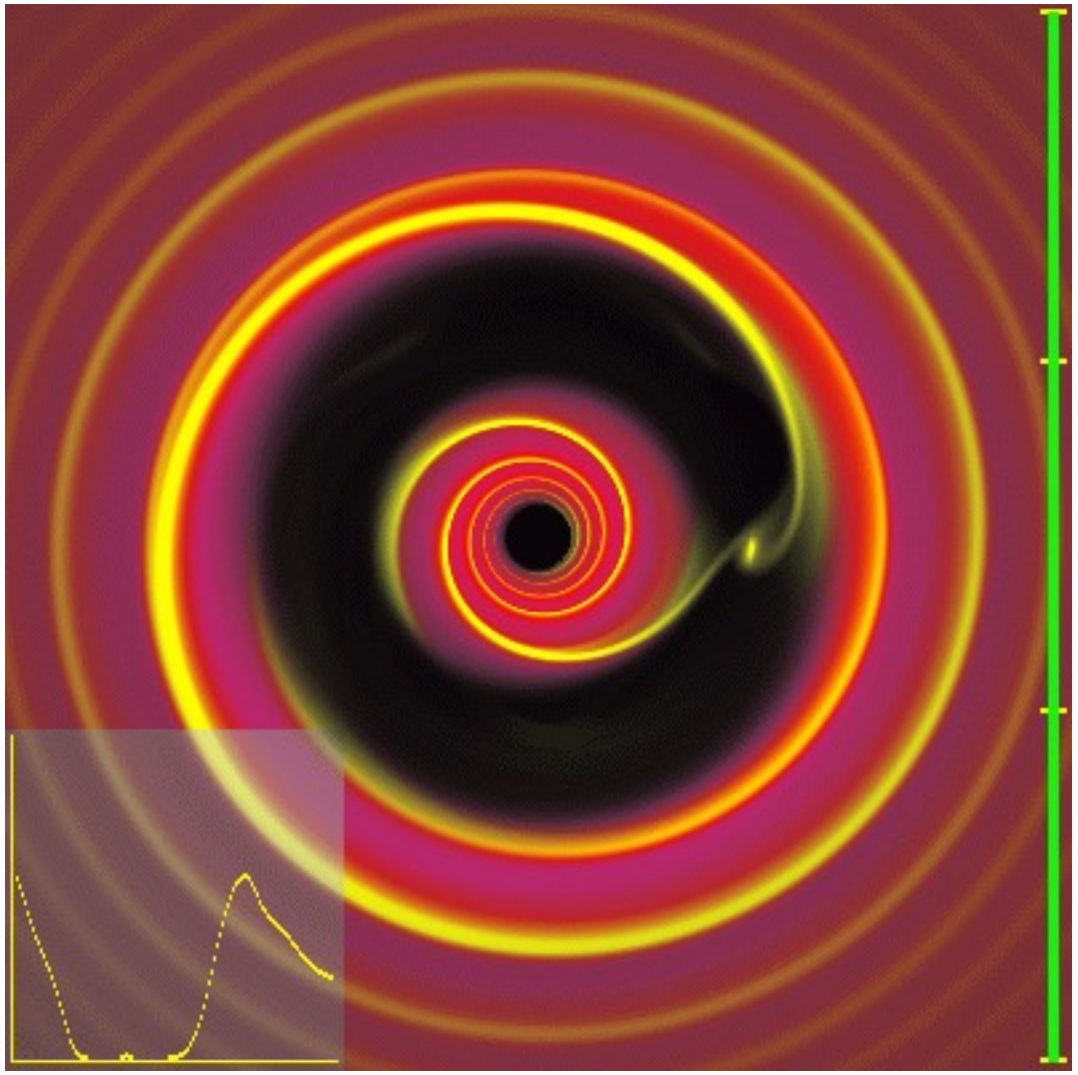
What's the problem?

- There are actually two problems:
  - **Angular momentum removal:** we need to remove the angular momentum of the secondary (with a mass ~ 10% of the primary) orbiting at 0.1 pc to bring it to 0.001 pc, where GW emission takes over (for a 10^6 M_{sun} primary)
    - Analogous to BH feeding for a single BH in AGNs (cf King & Pringle 2006)
  - **Disc self-gravity:** this might severely limit the ability of the disc to take up the required angular momentum (Lodato, Nayakshin, King and Pringle 2009)

Angular momentum removal

- Secondary BH and disc can exchange angular momentum through tidal forces
- Gap formation --> Type II migration (well studied for planets)
- However, for migration to be efficient, angular momentum must be removed from gap edges via “viscous torques”
- Migration timescale related to disc viscous timescale

$$t_{\rm shrink} = \frac{M_{\rm d}(a) + M_{\rm s}}{M_{\rm d}(a)} t_\nu$$



Armitage

Required disc properties at 0.1pc

- How massive should the disc be to allow the BHs to merge?

$$t_{\rm shrink} = \frac{M_{\rm d}(a) + M_{\rm s}}{M_{\rm d}(a)} t_\nu$$

- Typical parameters:

$M_p = 10^6 M_{sun}$
$M_s = 0.1 M_p$
$\alpha = 0.1$
$H/R = 0.005$

$$t_\nu \sim 2 \times 10^8 \text{yrs}$$

- To be grav. stable, $M_{disc} < (H/R) M_p = 0.005\ M_p = 0.05\ M_s$

$$t_{\rm shrink} \gtrsim 4 \times 10^9 \text{yrs}$$

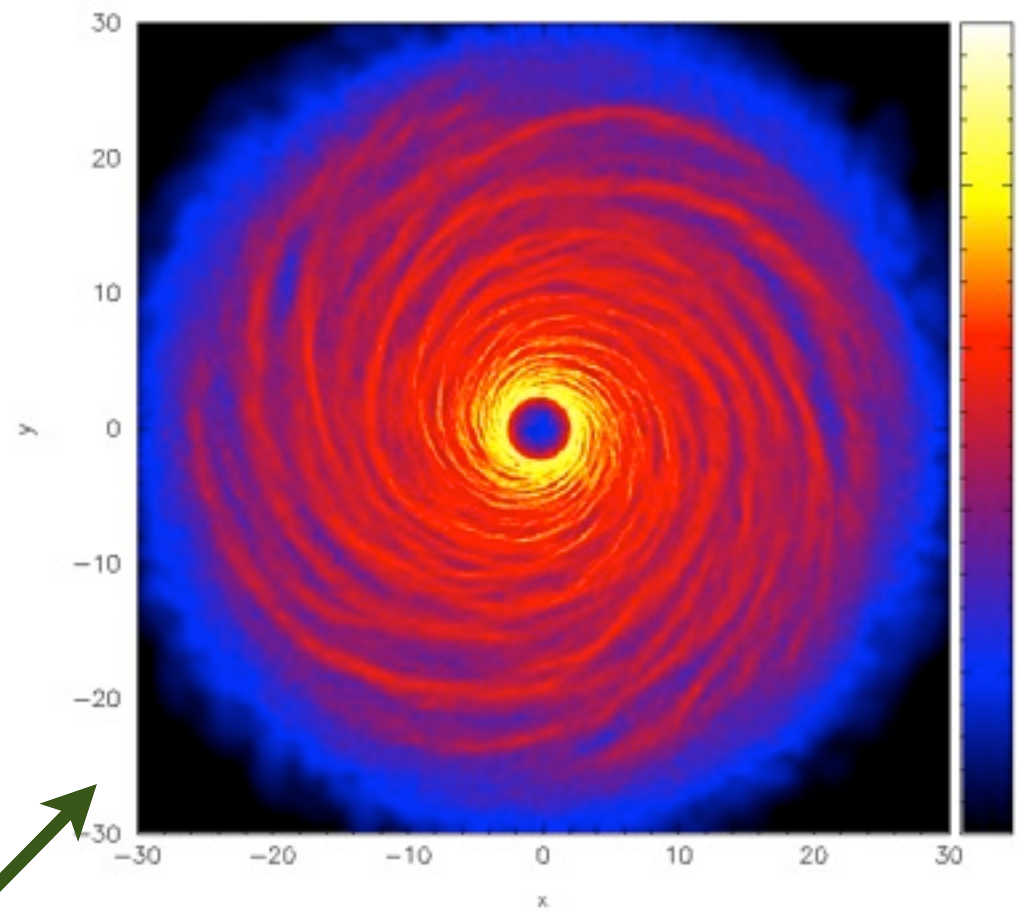
- Discs that allow BH mergers from 0.1 pc <u>have to be self-gravitating</u> (i.e. subject to gravitational instabilities)

Self-gravitating accretion discs: what we do know

- Very well studied in recent years (Gammie 2001, Lodato & Rice, 2004, 2005, Rice, Lodato & Armitage 2005, Cossins, Lodato & Clarke 2009)
- Linear stability: determined by $Q = \dfrac{c_{\rm s}\kappa}{\pi G \Sigma}$
- Non linear saturation determined by $\beta = \Omega t_{\rm cool}$
- If $\beta \gtrsim \beta_{\rm crit}$ the instability saturates at a finite amplitude
- If $\beta \lesssim \beta_{\rm crit}$ runaway growth ---> fragmentation, star formation

Simulations by Cossins, Lodato & Clarke (2009)

Self-gravitating accretion discs: v



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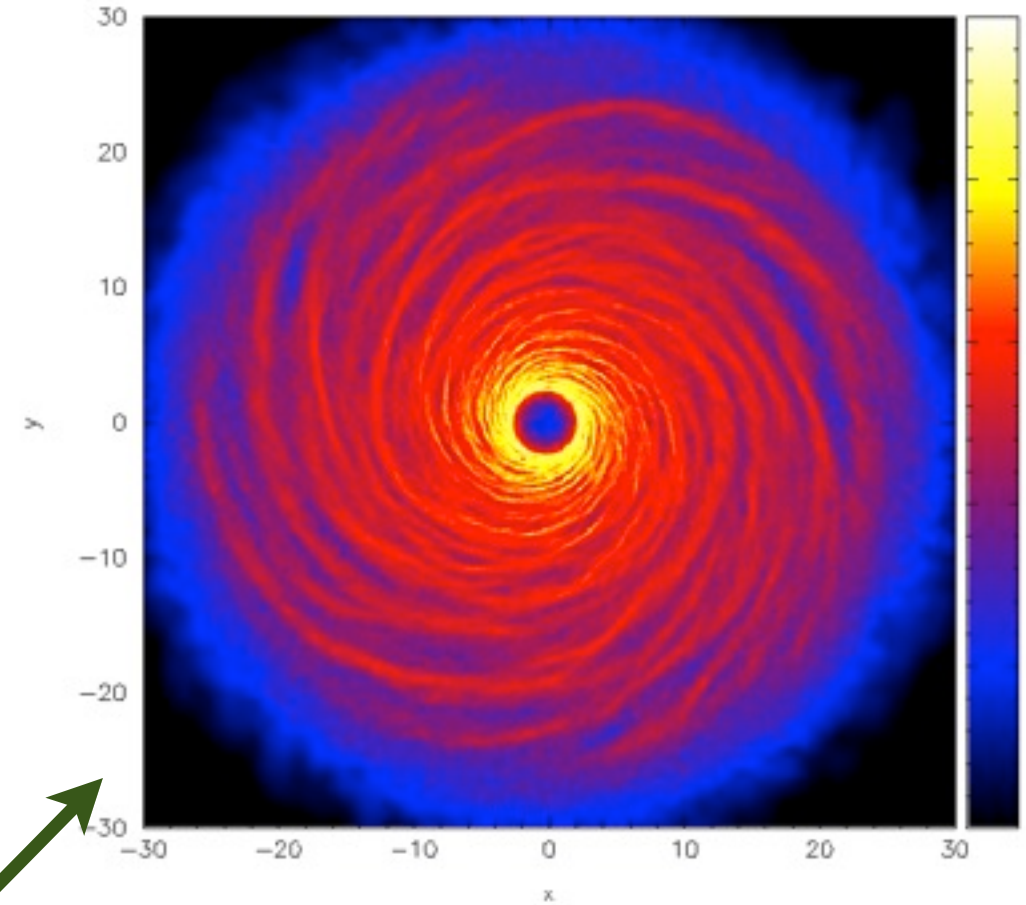

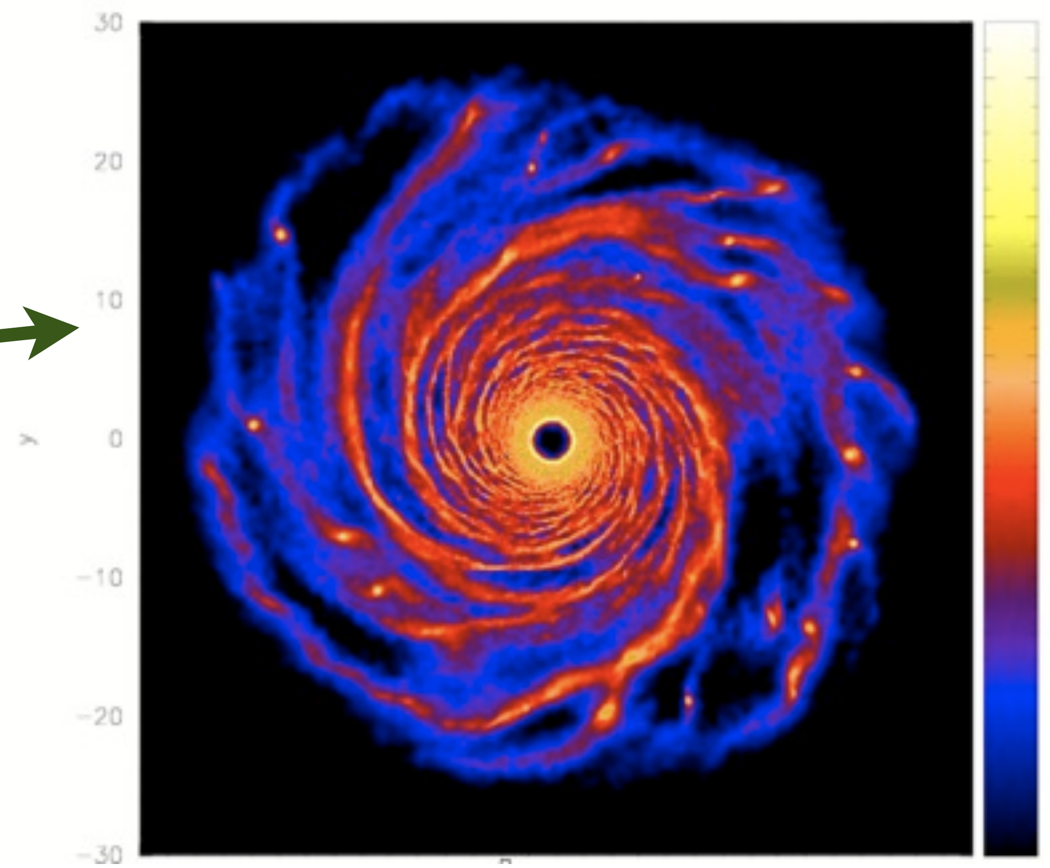

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  - Does fragmentation lead to SF, or to clumps which are supported by turbulent motion (cf local star forming clouds)?
  - If turbulence dominates, “cooling time” is actually the turbulence decay time, which corresponds to $\beta \sim 1$ (Begelman & Shlosman 2009)

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  - Just enough for SF to provide required heating in a marginally stable disc (Lodato et al 09, see also Nayakshin, Cuadra & Springel 07)?

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$$\epsilon \dot{\Sigma}_{\rm sf} c^2 = \sigma_B T_{\rm eff}^4$$

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- Angular momentum transport in a gaseous/stellar disc?
  - Purely gaseous discs provide $\alpha \sim 0.05$ (Rice, Armitage & Lodato 05)
  - Gas + stars might lead to stronger torques (Hopkins & Quataert 10)
  - Bars? Bars within bars?

Effects of SF on binary shrinkage

Lodato, Nayakshin, King & Pringle 09

- Run time-dependent models of a binary BH embedded in a disc with finite initial mass
- Standard "migration" problem (cf. planets)

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left(R^{1/2}\frac{\partial}{\partial R}(R^{1/2}\nu\Sigma)\right) - \frac{1}{R}\frac{\partial}{\partial R}\left(2\Omega R^2\lambda\Sigma\right)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(M_{\mathrm{s}}\Omega_{\mathrm{s}}a^2) = -\int_{R_{\mathrm{in}}}^{R_{\mathrm{out}}} 2\pi\Omega^2 R^3\lambda\Sigma\mathrm{d}R$$

Effects of SF on binary shrinkage

Lodato, Nayakshin, King & Pringle 09

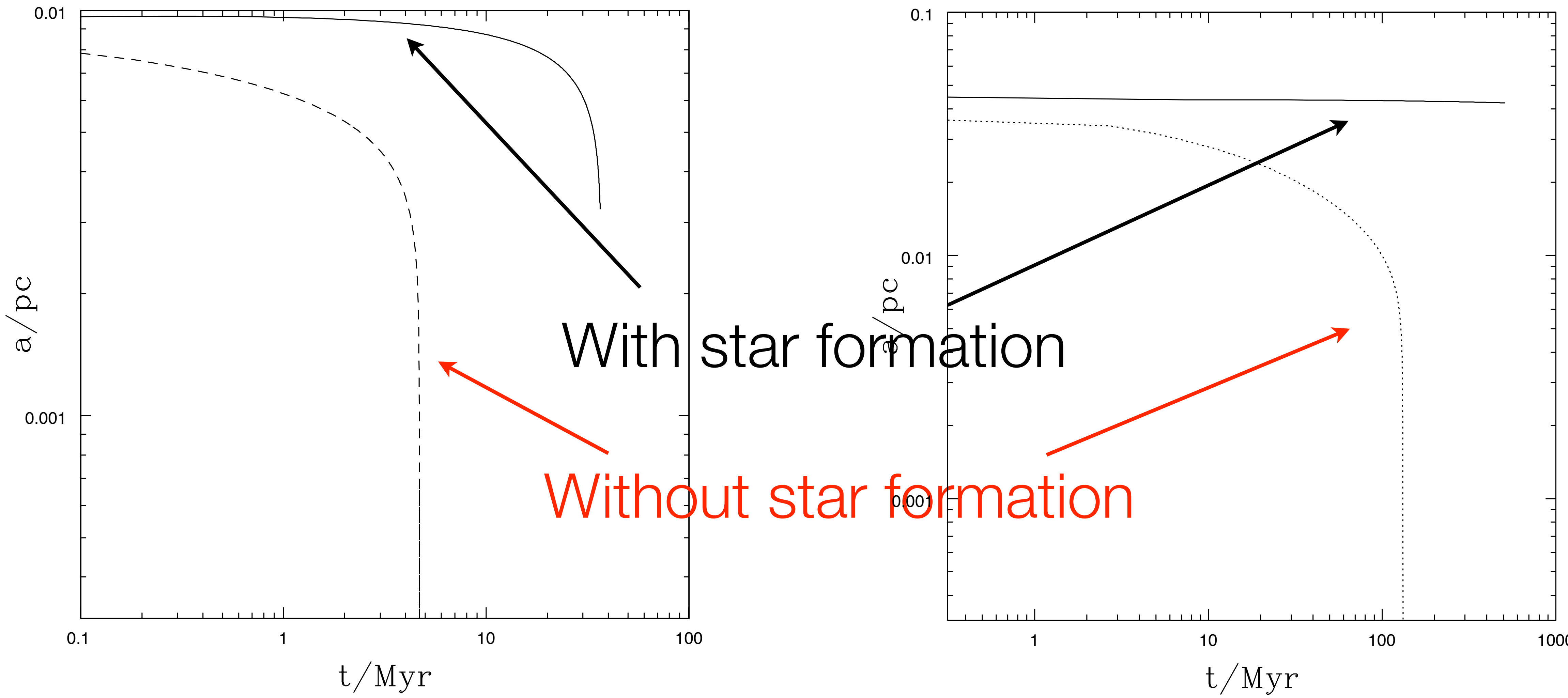
- Run time-dependent models of a binary BH embedded in a disc with finite initial mass
- Standard "migration" problem (cf. planets)

- Consider two cases:
  - No fragmentation
  - Fragmentation, according to $\epsilon\dot{\Sigma}_{\rm sf}c^2 = \sigma_B T_{\rm eff}^4$
- System parameters: $M_p = 10^8 M_{sun}$
  $M_s = 0.1 M_p$
  $M_d = 0.1 M_p \quad \alpha = 0.1$

Effects of star formation

- General effect is to slow down migration significantly (by at least a factor 10)

$t_{gw} = 2\ 10^{8}$ yr $\quad t_{visc} = 3\ 10^{6}$ yr $\qquad\qquad t_{gw} = 10^{11}$ yr $\quad t_{visc} = 5\ 10^{7}$ yr



Initial separation 0.01pc $\qquad\qquad$ Initial separation 0.05pc

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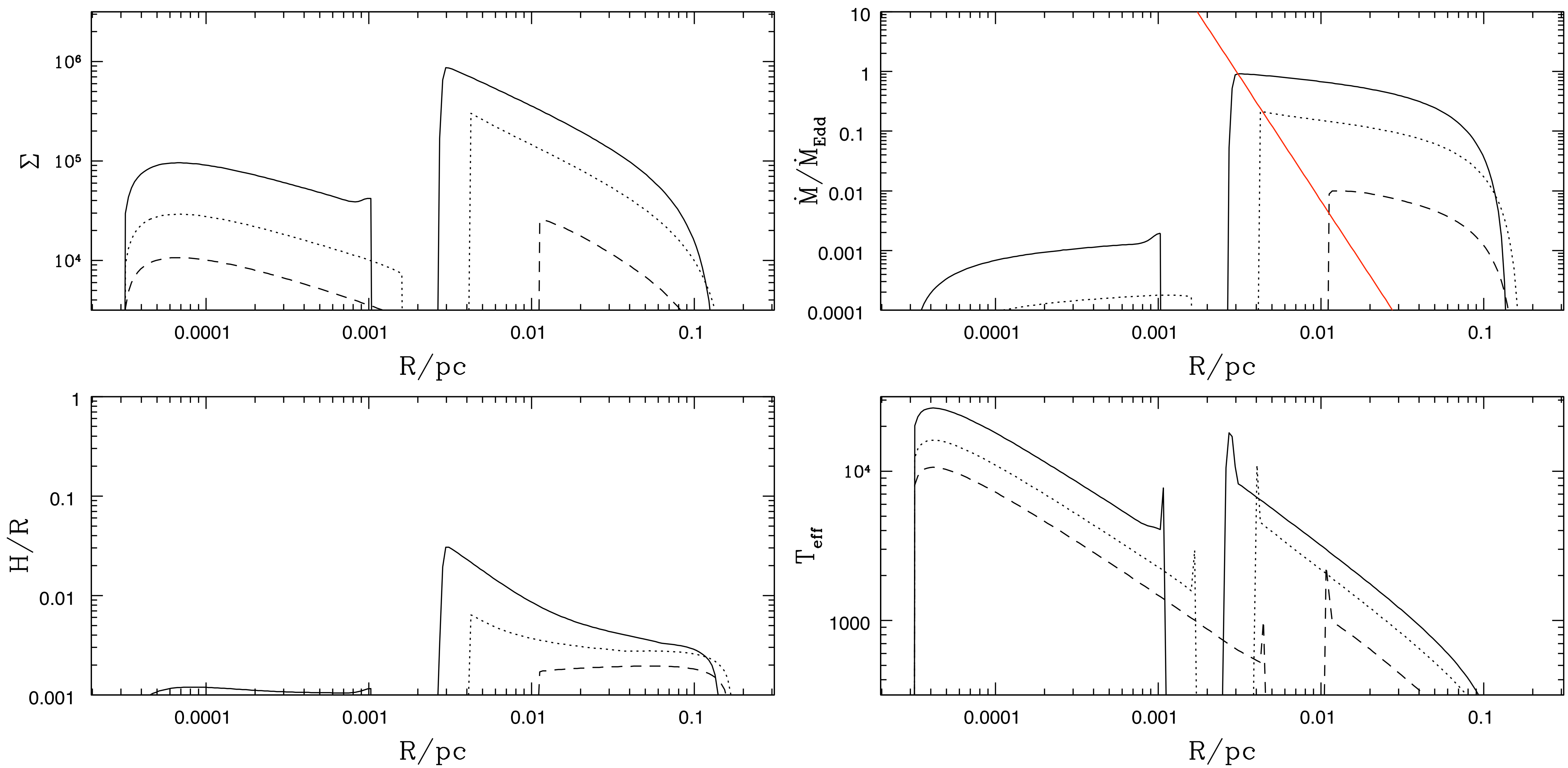
Merging discs at decoupling

Here M_p=$10^8 M_{Sun}$, q= 0.1, a_0 = 0.01 pc, M_{disc} = 1, 0.5, 0.1 M_s

- Disc structure at decoupling



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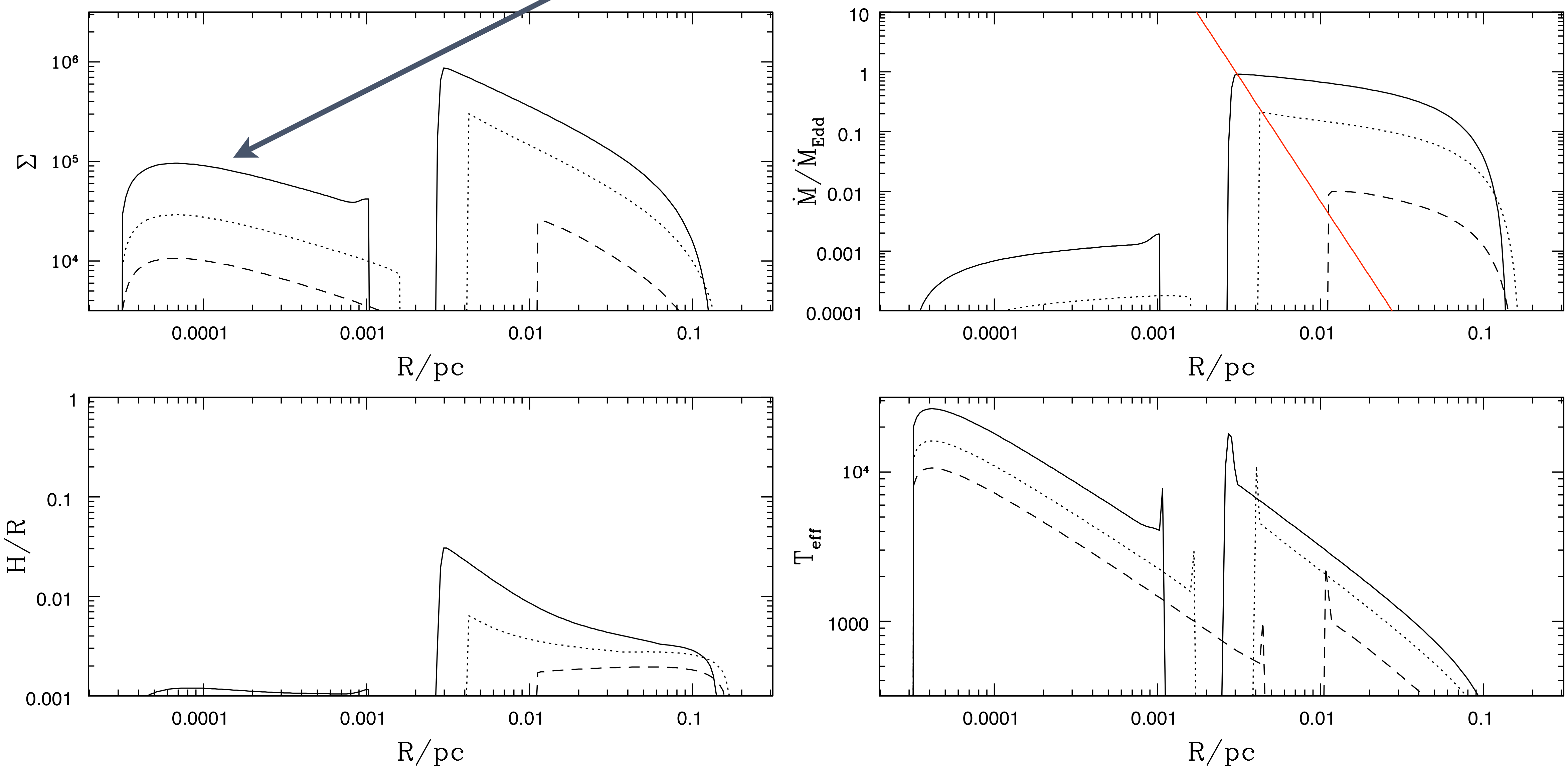
Low density inner disc present (cf. Chang et al 2009)



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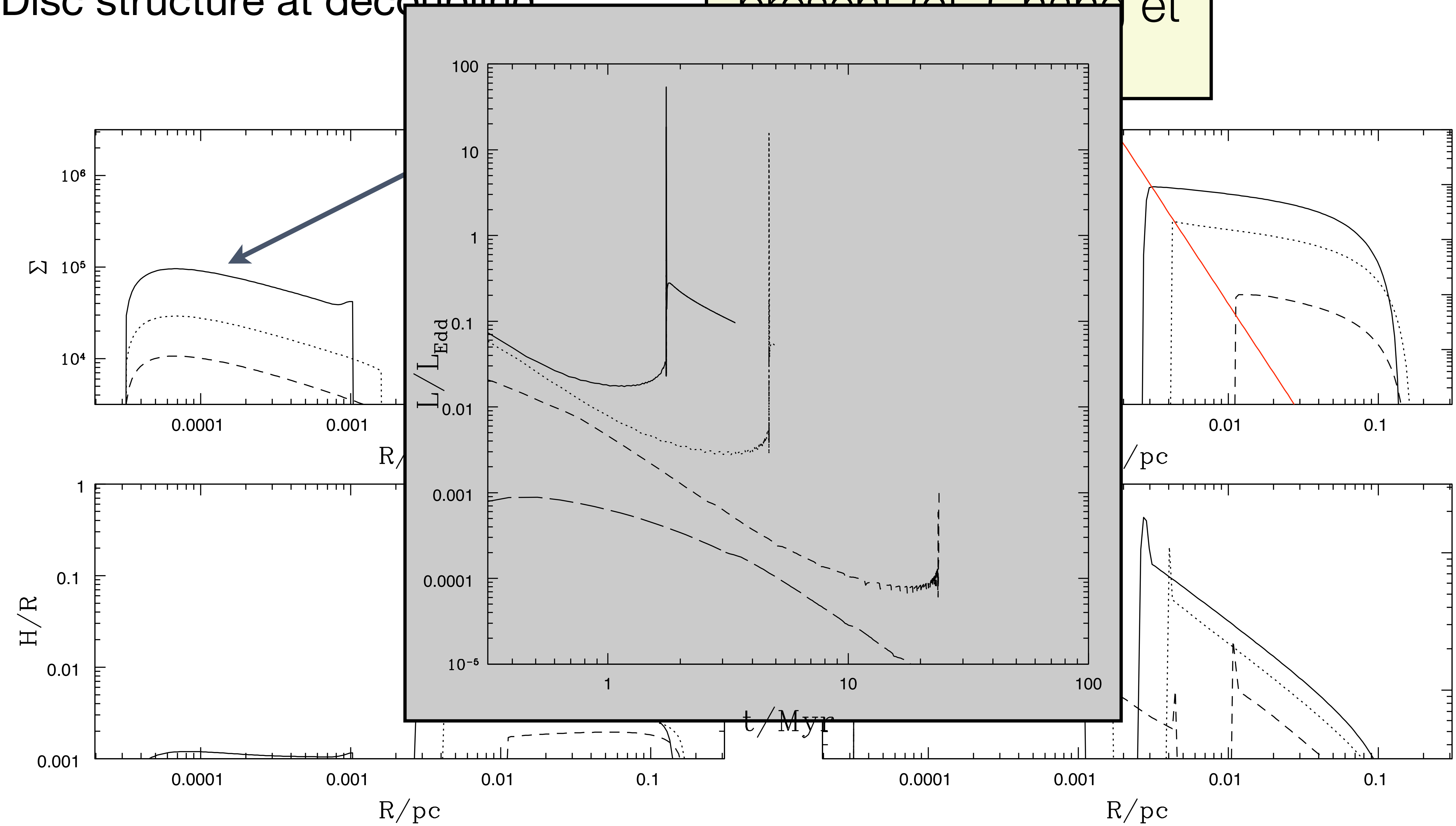

Merging discs at decoupling

Mass flux profile consistent with decretion disc

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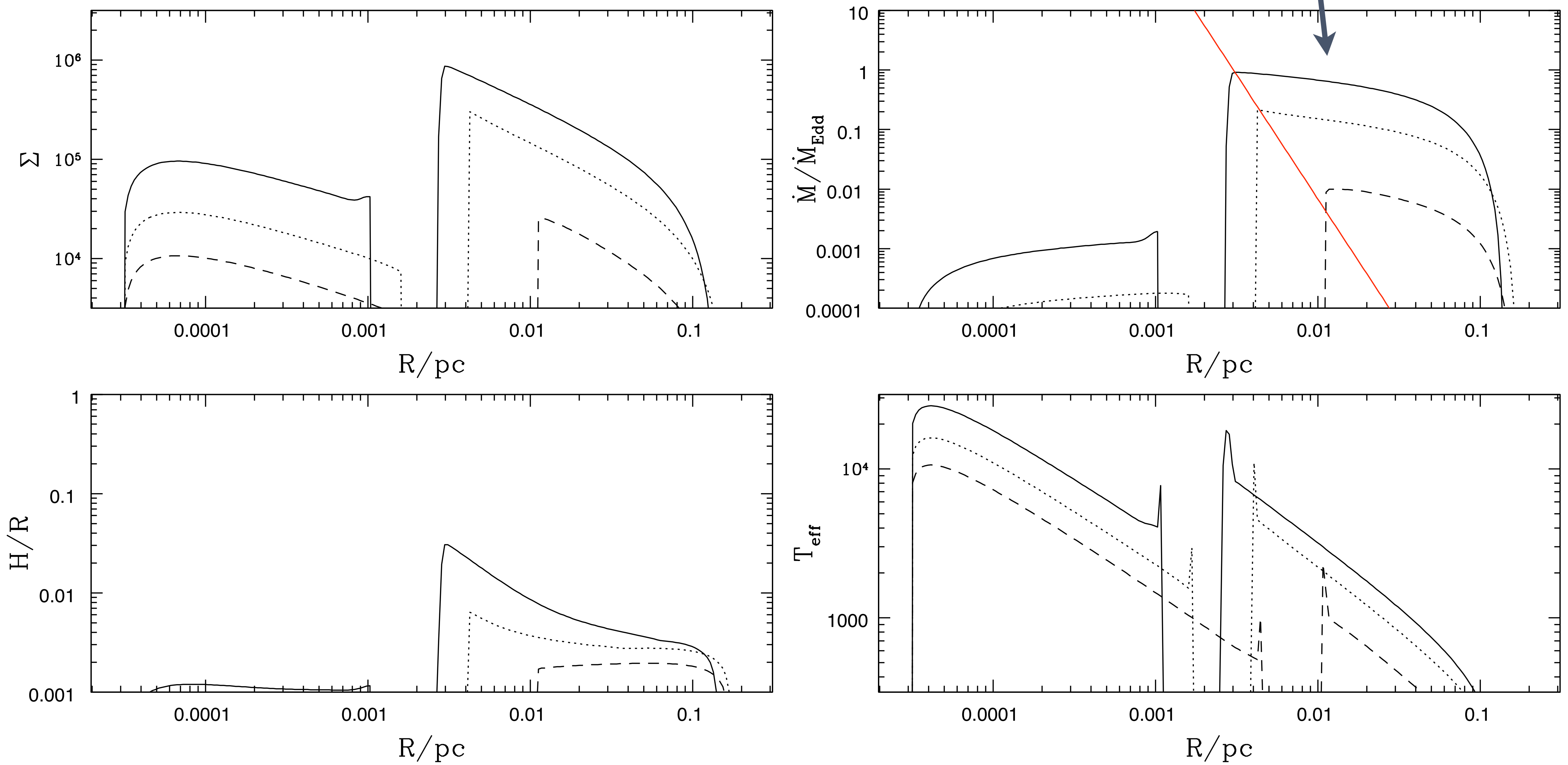

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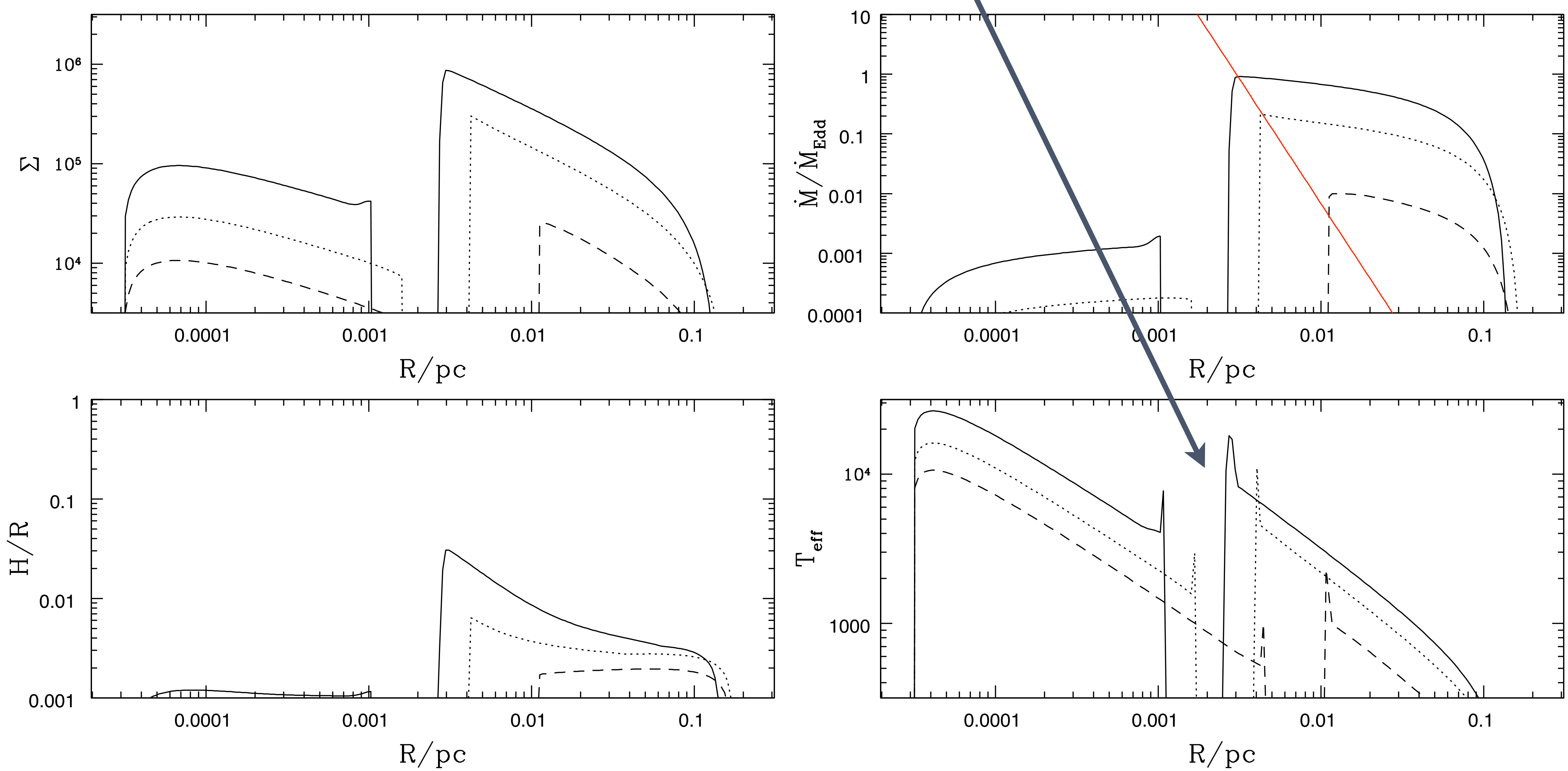
Hot inner edges due to tidal heating

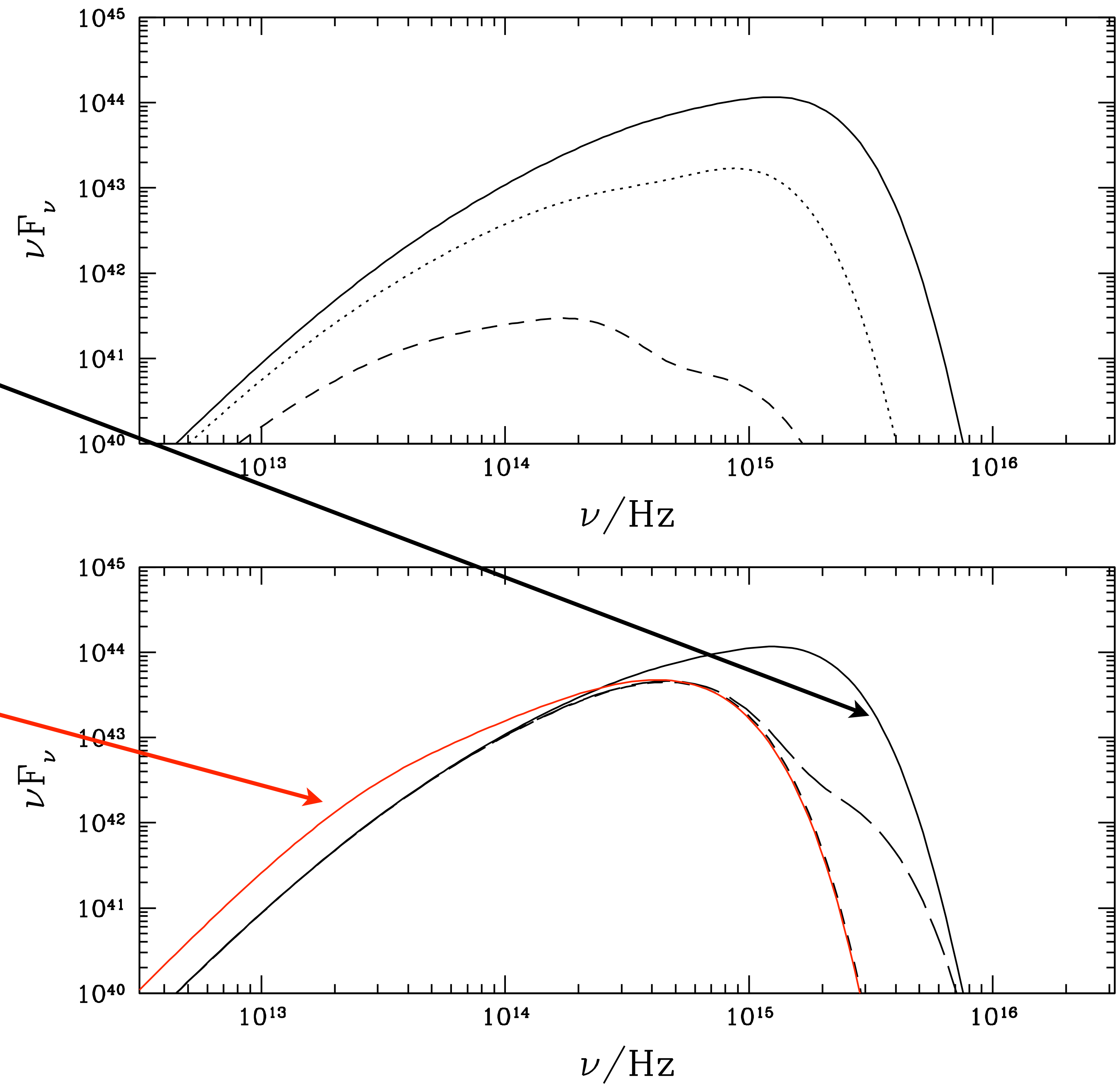


Merging discs at decoupling

- How does the SED look like?

Emission from gap edges

Milosavljevic & Phinney (1995) truncated disc models



Summary: discs at decoupling

- The appearence of the disc at decoupling is significantly different than previously thought:
  - SED steeper because of “decretion disc” like structure
  - Hot gap edges provide a high energy emission, not accounted for by truncated disc models
  - If this feature is variable (as it might be due to non-axisymmetric structures, eccentricity... see Haiman et al 2009), it would provide a high-energy spectral component (typical of inner disc) variable on a long timescale (typical of outer disc)
  - Inner low density disc present: provides super-Eddington flare during the final coalescence (Armitage & Natarajan 02, Chang et al 10, Tanaka & Menou 10)

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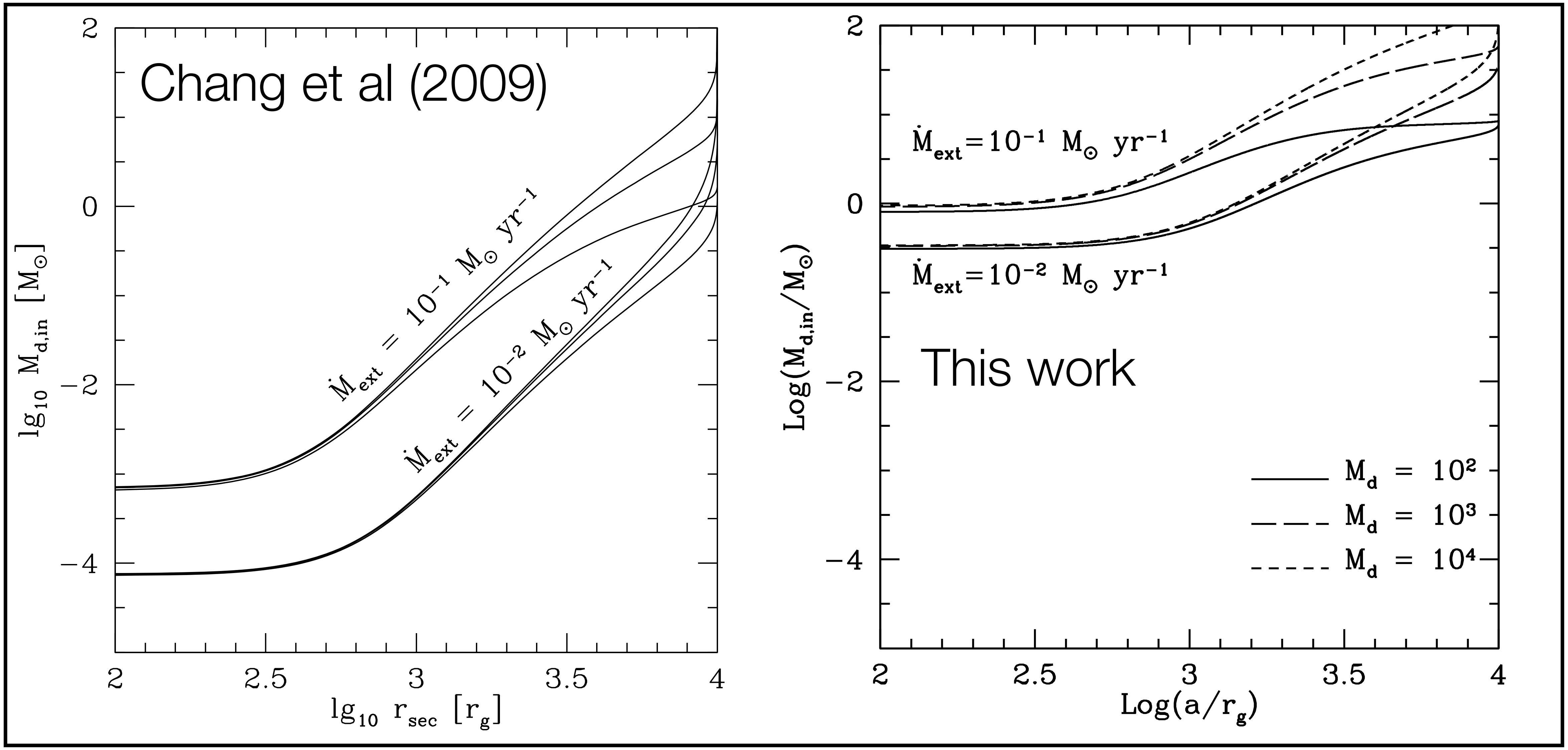
Estimating the fossil disc mass

Tazzari & Lodato (2014)

- Armitage and Natarajan (2002): Large flare when circumprimary disc is accreted much faster than its own viscous time during GW driven merger
- Chang et al (2010): Fossil disc mass is very small (< $1M_{Jupiter}$), so very small flare expected
- Both Armitage and Natarajan (2002) and Lodato et al (2009) estimate much larger masses at decoupling
- Origin of the discrepancy?
- Re-do step by step and using exactly identical conditions of Chang et al
    - 1D evolution, using a simple diffusion equation for the disc density + tidal torques

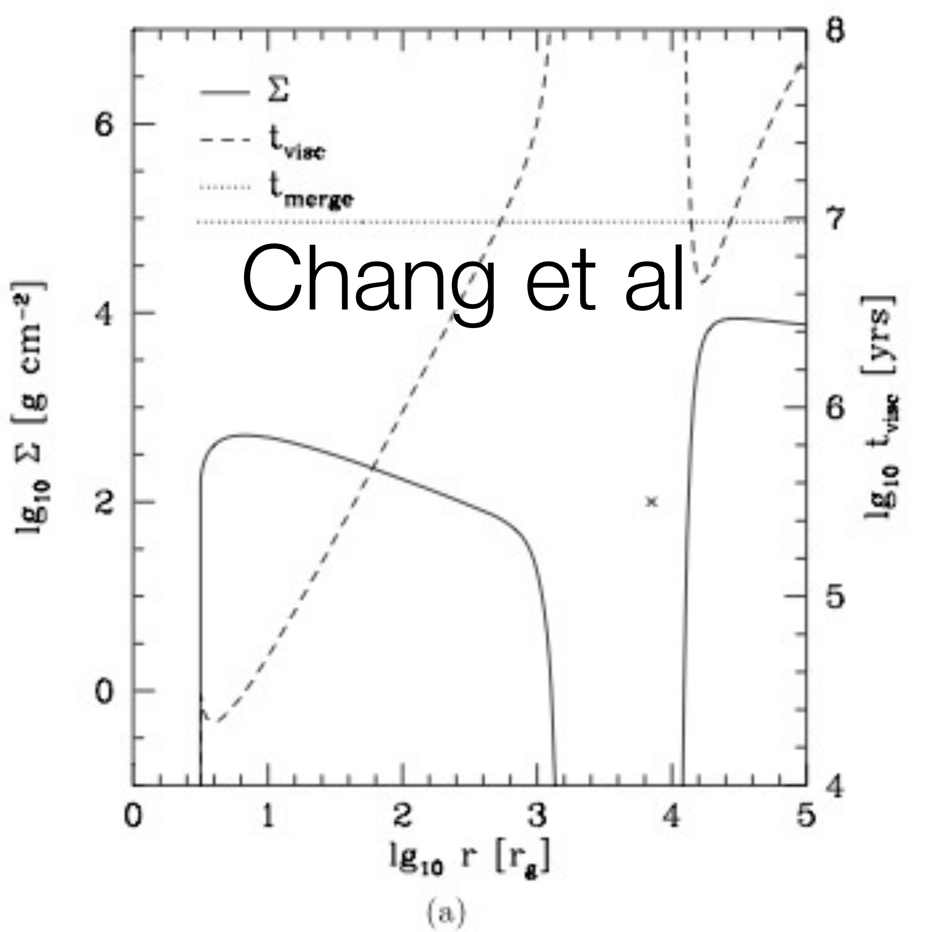
Results

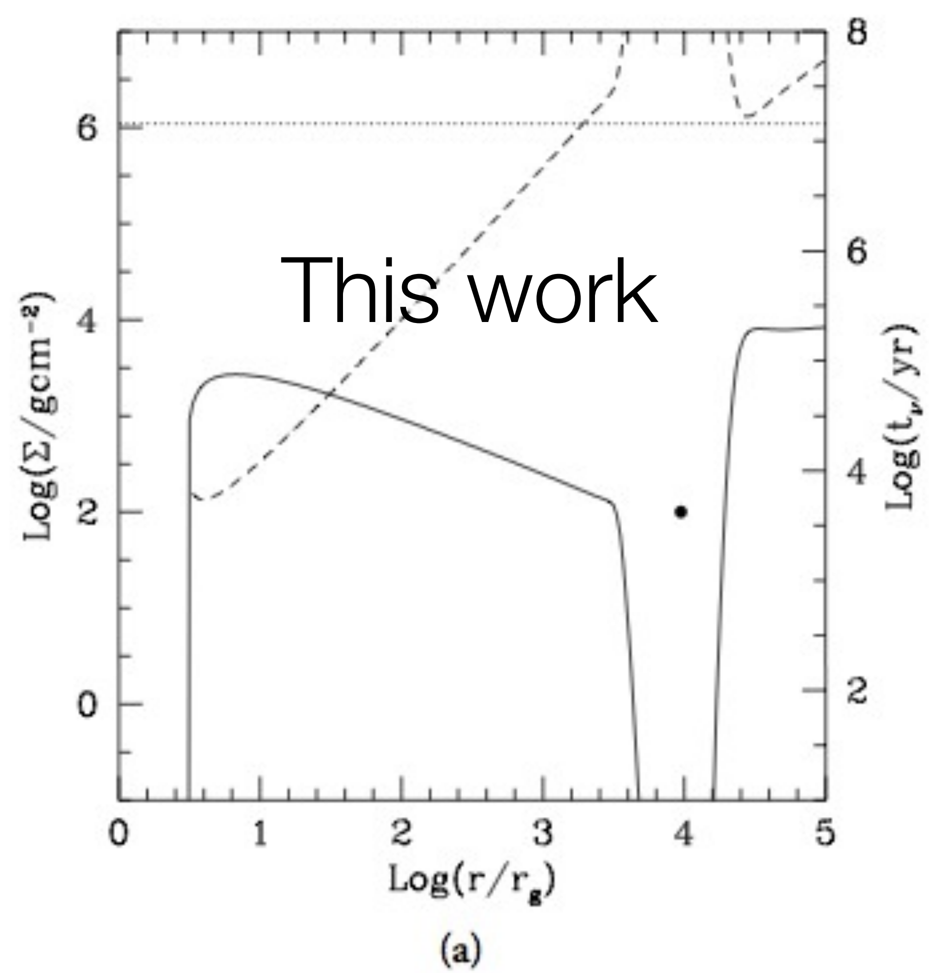
- Example evolution for $M_p = 10^7 M_{Sun}$, $q = 0.1$
- Inner disc mass discrepant by a factor ~ 1000 !
- Large exploration of parameter space: while Chang et al always predict sub-Eddington flares, we estimate flare luminosities $1 < L/L_{Edd} < 30$



Origin of the discrepancy

- Chang et al use an incorrect torque approximation in their 1D code
- Allow the torque to be significant also at distances from the secondary much larger than the outermost Lindblad resonance ---> too large gap sizes
- In our approach, we truncate the torque in such a way to recover the correct gap size as estimated numerically by Artymowicz and Lubow (1994).





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- It can be shown analytically that the fossil disc mass scales with the outer edge of the inner disc as $R_{edge}^{7/2}$, fully explaining the discrepancy
- **Big caveat**: these simulations neglect completely any mass flow through the gap!
  - Artymowicz and Lubow (1994): reduction in mass flux by a factor 10
  - D'Orazio et al (2013) strong dependence on mass ratio.
  - Need to explore mass flow though gaps as a function of H/R

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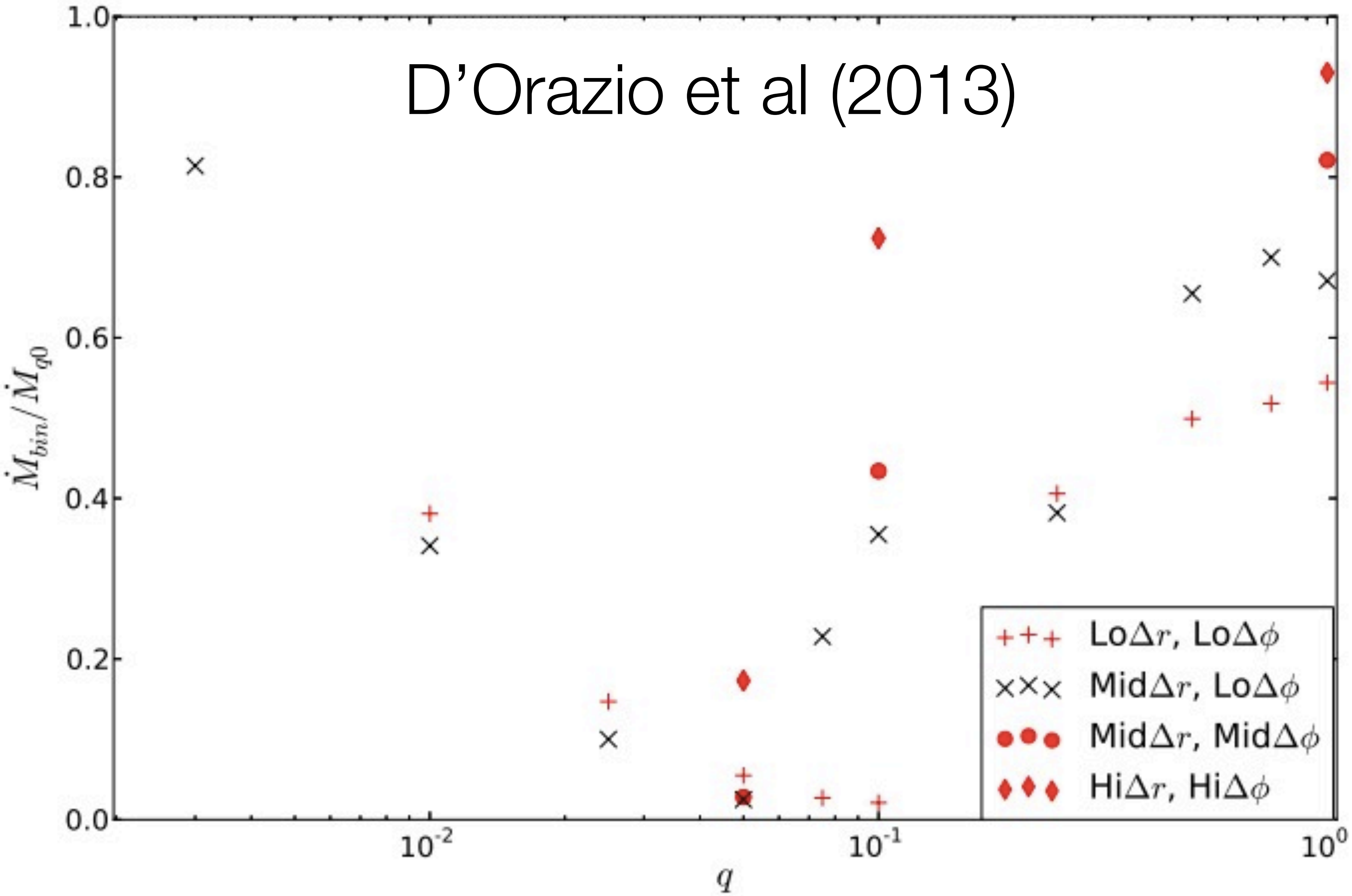

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Mass leakage during super-Eddington flare

- One-dimensional models (Armitage and Natarajan, Chang et al, Lodato et al) do not allow matter to flow past the secondary orbit: no mass leaks out of the circumprimary disc, even when the merger speeds up
- Baruteau, Ramirez-Ruiz, Masset: 2D simulations show that leakage is very strong
- Need 3D models to assess

Price & Lodato, in prep.

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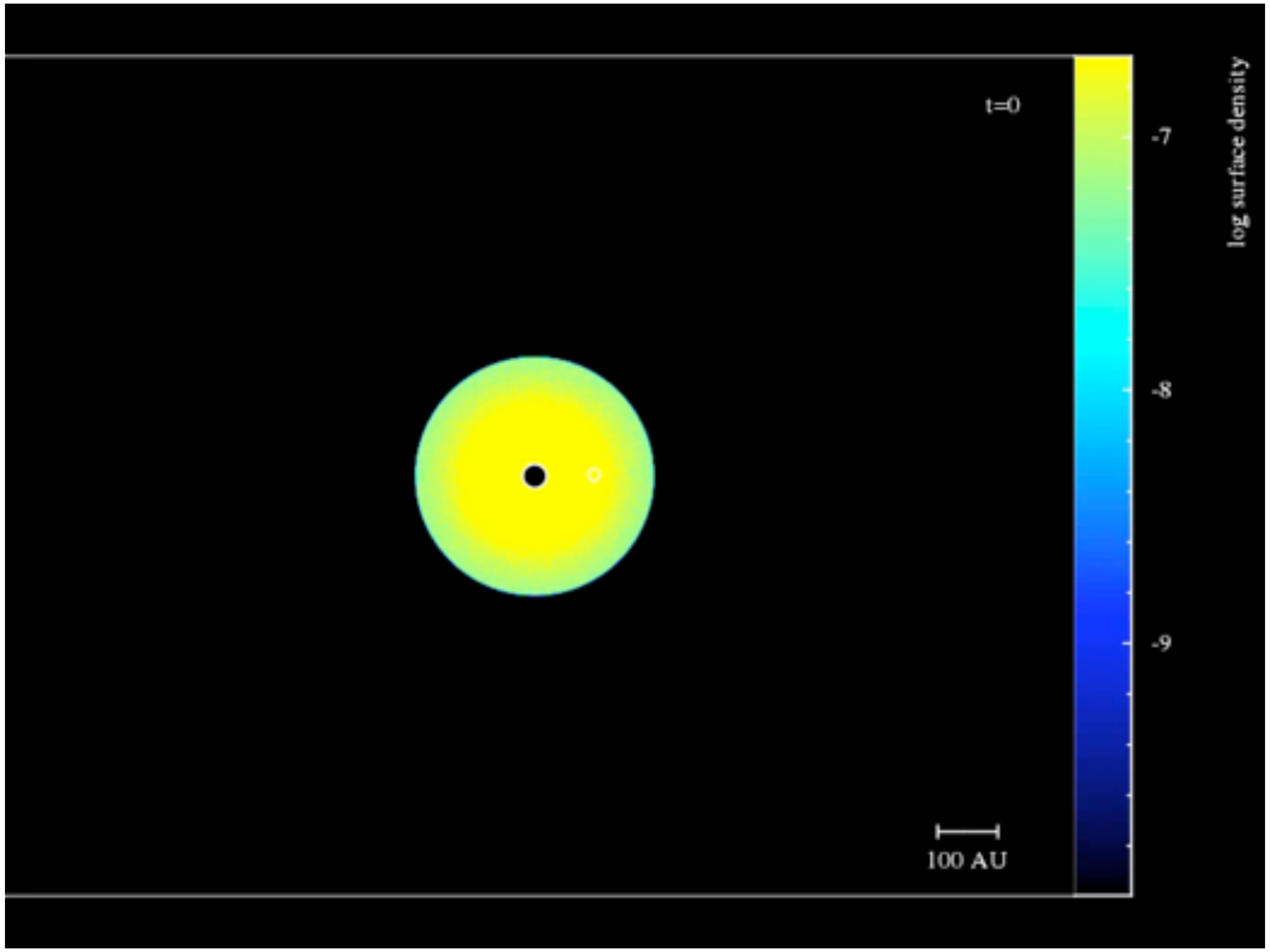
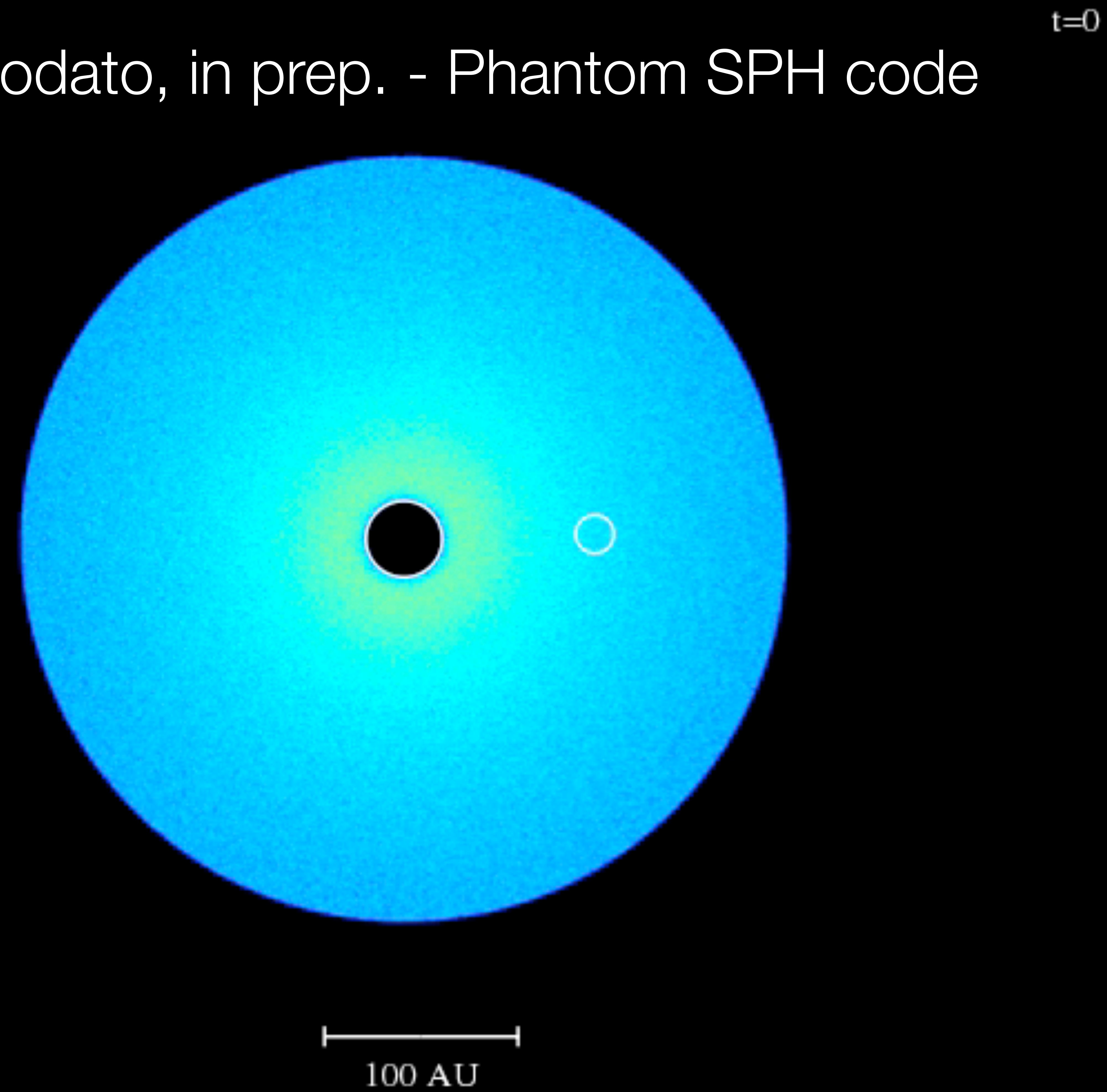


Price & Lodato, in prep.

Price & Lodato, in prep. - Phantom SPH code



Mass leakage during super-Eddington flare

- One-dimensional models (Armitage and Natarajan, Chang et al, Lodato et al) do not allow matter to flow past the secondary orbit: <u>no mass leaks out of the circumprimary disc</u>, even when the merger speeds up
- Need 3D models to assess (Lodato & Price, in prep)
- Preliminary results in that a significant amount of mass leaks out, reducing strongly the strength of the burst
- Proper estimate of fossil mass in circumprimary disc is essential (cf. Tazzari & Lodato 2014)!

Summary

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Prompt emission: BH recoil/mass loss

- Anisotropic emission of GW leads to a significant recoil of the remnant black hole.
- Energy emitted by GW imply remnant BH has lower mass
- Part of the circumbinary discs stays bound to the remnant and readjusts to new equilibrium ---> energy release
- Extensively studied in the last years: Schnittman & Krolik - Rossi, Lodato et al - Corrales et al - Megevand et al - O’Neill et al - Zanotti et al. ....

Prompt emission: typical scales

- Typical scales of the problem
  - R_V: radius within which disc remains bound after recoil (for 90° kicks)

$$R_{\rm V} = \frac{GM}{V^2} = \left(\frac{c}{V}\right)^2 R_g \approx 0.5{\rm pc}\left(\frac{M}{10^6 M_\odot}\right)\left(\frac{V}{100{\rm km/sec}}\right)^{-2}$$

  - R_{sh}: radius outside which velocity perturbation is supersonic

$$R_{\rm sh} \approx \left(\frac{H}{R}\right)^2 R_{\rm V} \approx 10^{-4} R_{\rm V}$$

  - R_m: radius within which mass loss dominates over recoil

$$R_{\rm m} = \left(\frac{c}{V}\right)^2 \left(\frac{\delta M}{M}\right)^2 R_{\rm g} = \left(\frac{\delta M}{M}\right)^2 R_{\rm V}$$

Prompt emission: typical scales

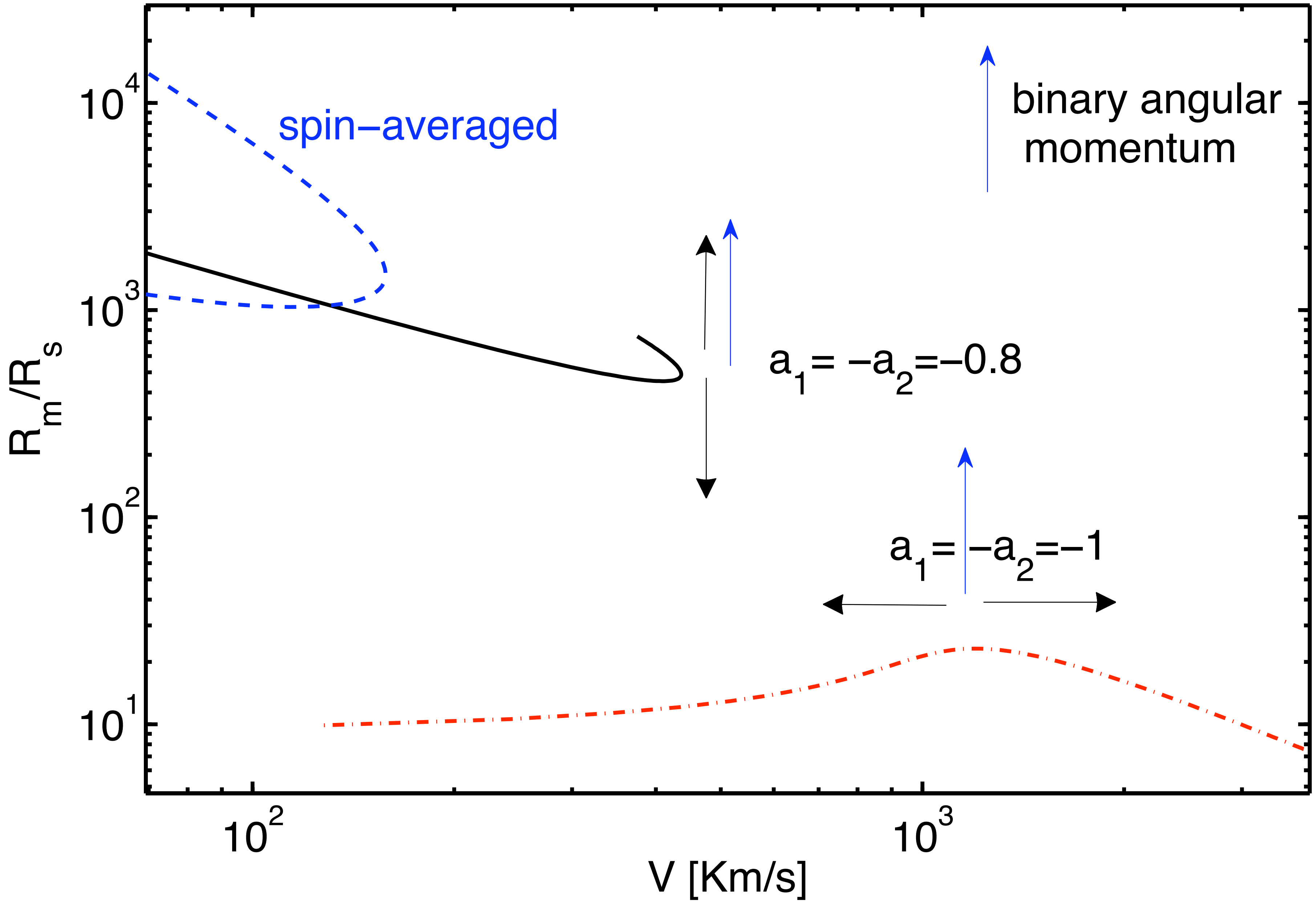
- Typi

  - R

$R_{\rm V}$ =

  - R

  - R



$)^{-2}$

sec

Prompt emission: luminosity scales

- Naive expectation for luminosity, based on release of **kinetic energy** (Schnittmann & Krolik 2008)

$$L \approx \Sigma R^2 \Omega V^2$$

- Most of the energy released from large radii (~R_V), but luminosity is dominated by contribution at small radii (R_{sh})

- Limits on disc mass (need to study precursor!):

  1. Corrales et al (study inner disc): Eddington-limited Shakura-Sunyaev at small radii (actually incorrect)

  2. Rossi et al (study outer disc): Marginally gravitationally stable disc (much steeper profile, although chosen for numerical convenience)

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Only valid for 90 degrees kicks!

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$$\text{Case 1: } \frac{L}{L_{\rm Edd}} \approx \frac{1}{\alpha\epsilon}\left(\frac{V}{c}\right)^2\left(\frac{H}{R}\right)^{-2} \approx 1$$

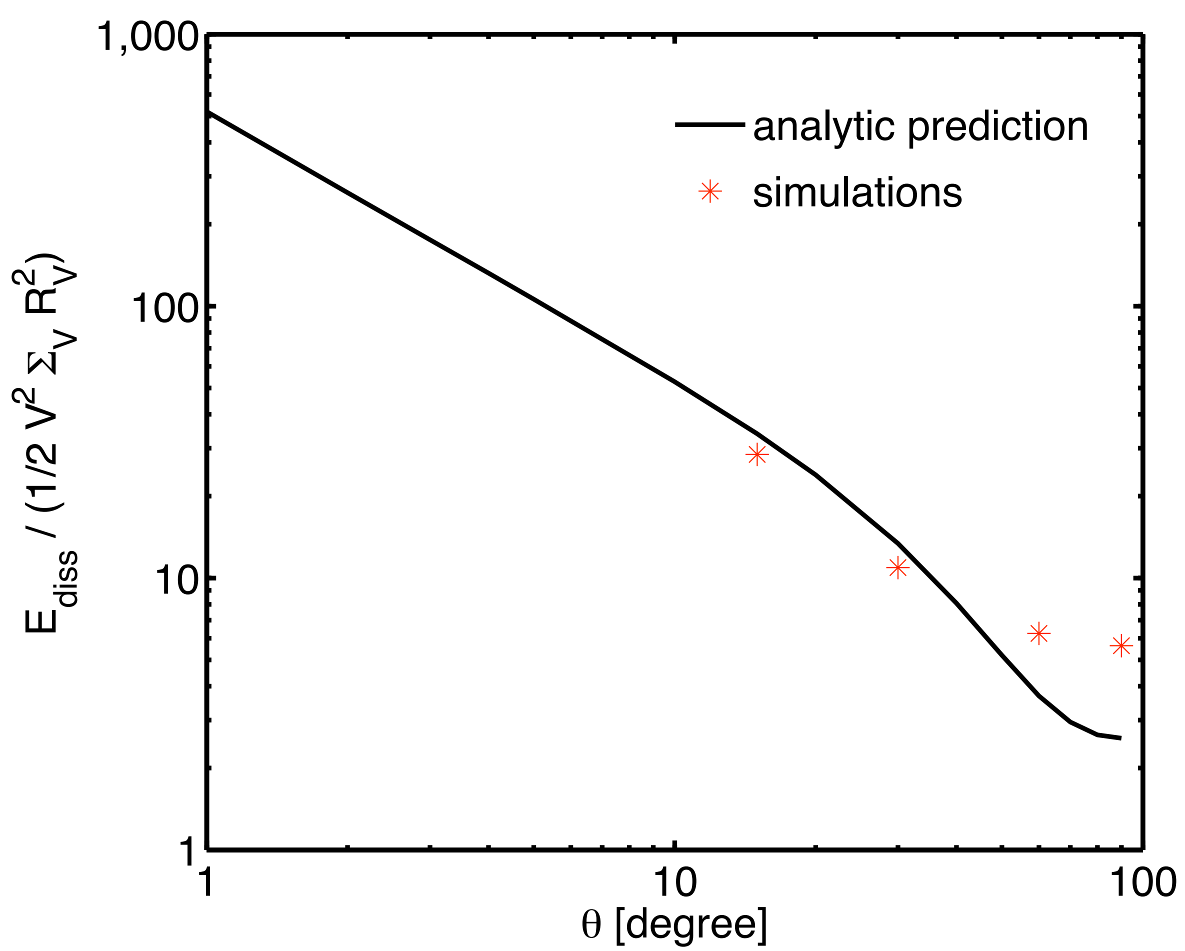
$$\text{Case 2: } \frac{L}{L_{\rm Edd}} \approx \left(\frac{V}{c}\right)^2\left(\frac{H}{R}\right)\Omega t_{\rm Edd} \approx 1$$

$$t_{\rm Edd} = \frac{\kappa_{\rm T} c}{4\pi G} \approx 0.45 \rm Gyrs$$

Additional luminosity from recoil

Rossi, Lodato, Armitage, King, Pringle, MNRAS 2010

- If recoil has a significant component in the disc plane, gas suddenly changes its angular momentum ---> flows in the inner disc ---> additional release of **potential energy**



Kick simulations

- Rossi et al: we have run both 2D ZEUS simulations (cf. Corrales) and 3D SPH ones

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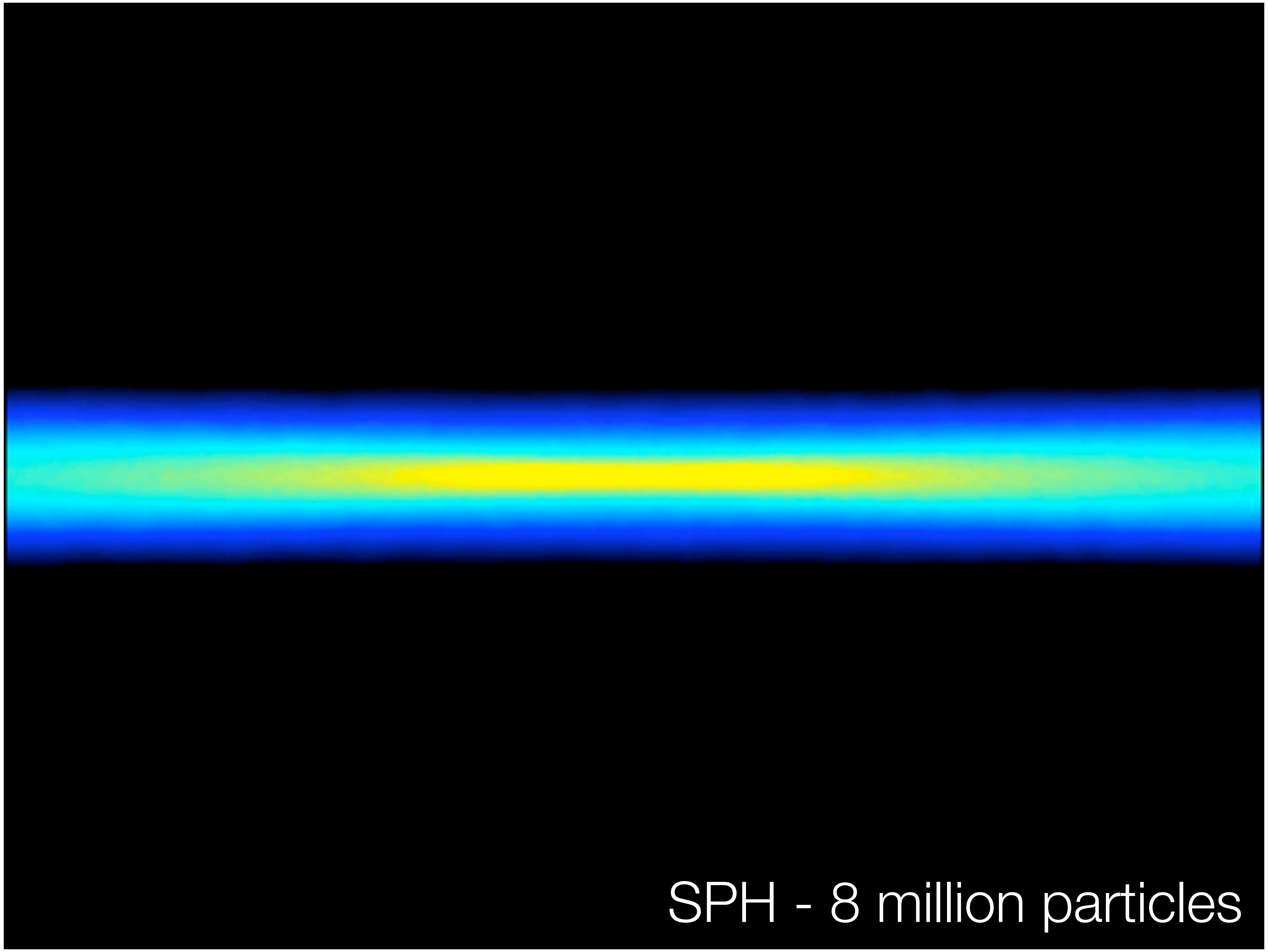

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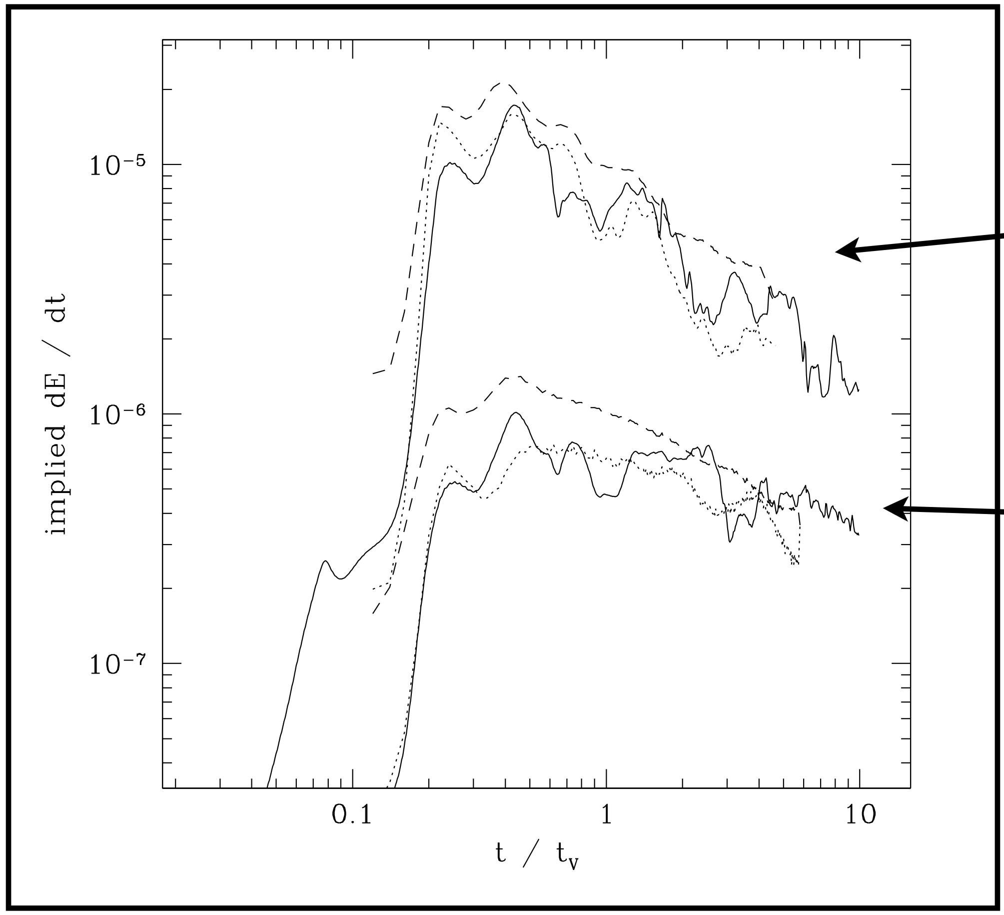
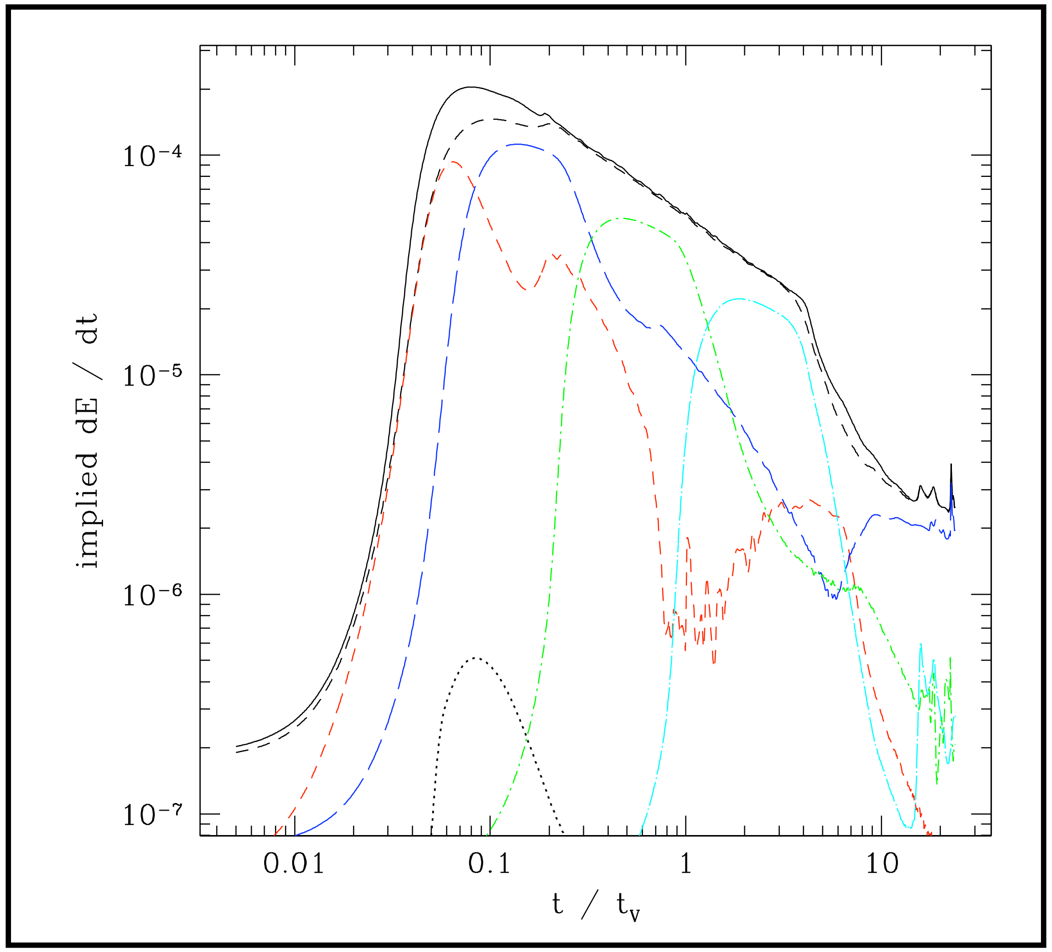


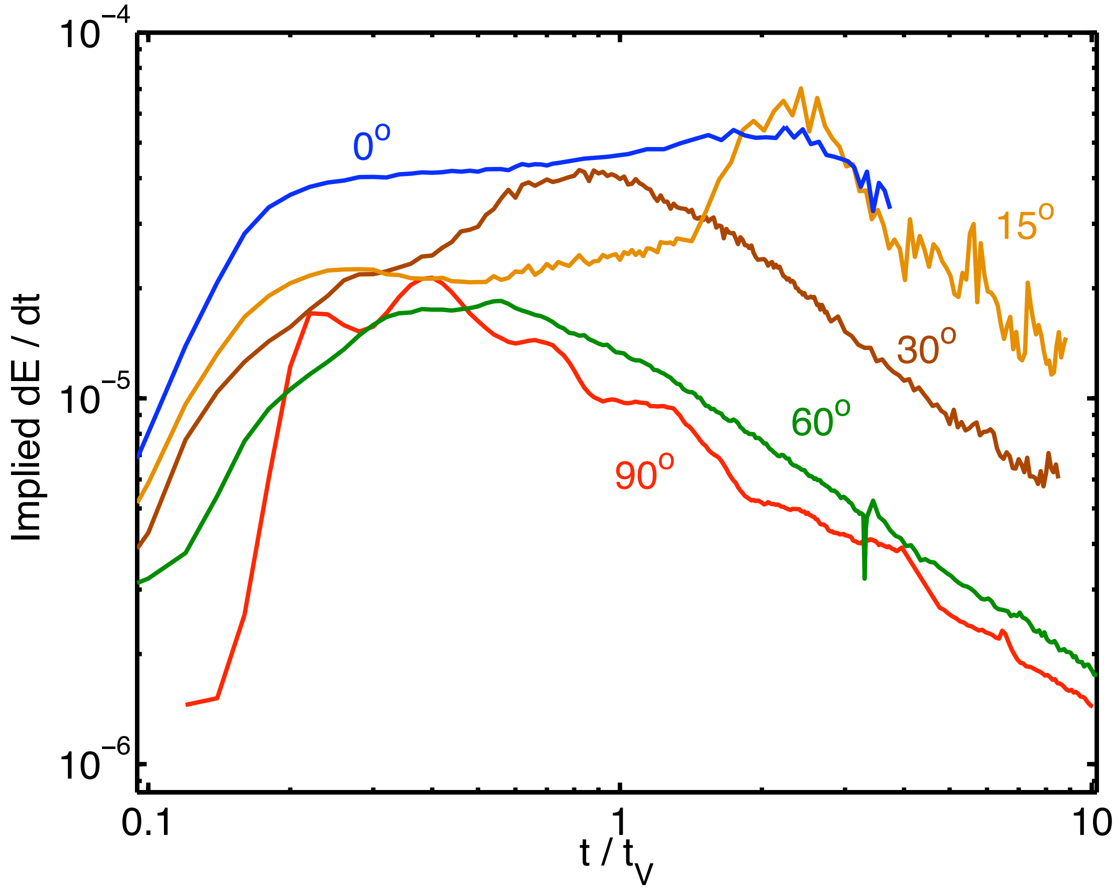
Steeper profile: $R^{-3/2}$

Shallower profile: $R^{-0.6}$

Kick simulations

- Rossi et al: we have run both 2D ZEUS simulations (cf. Corrales) and 3D SPH ones
- For in-plane kicks significant differences





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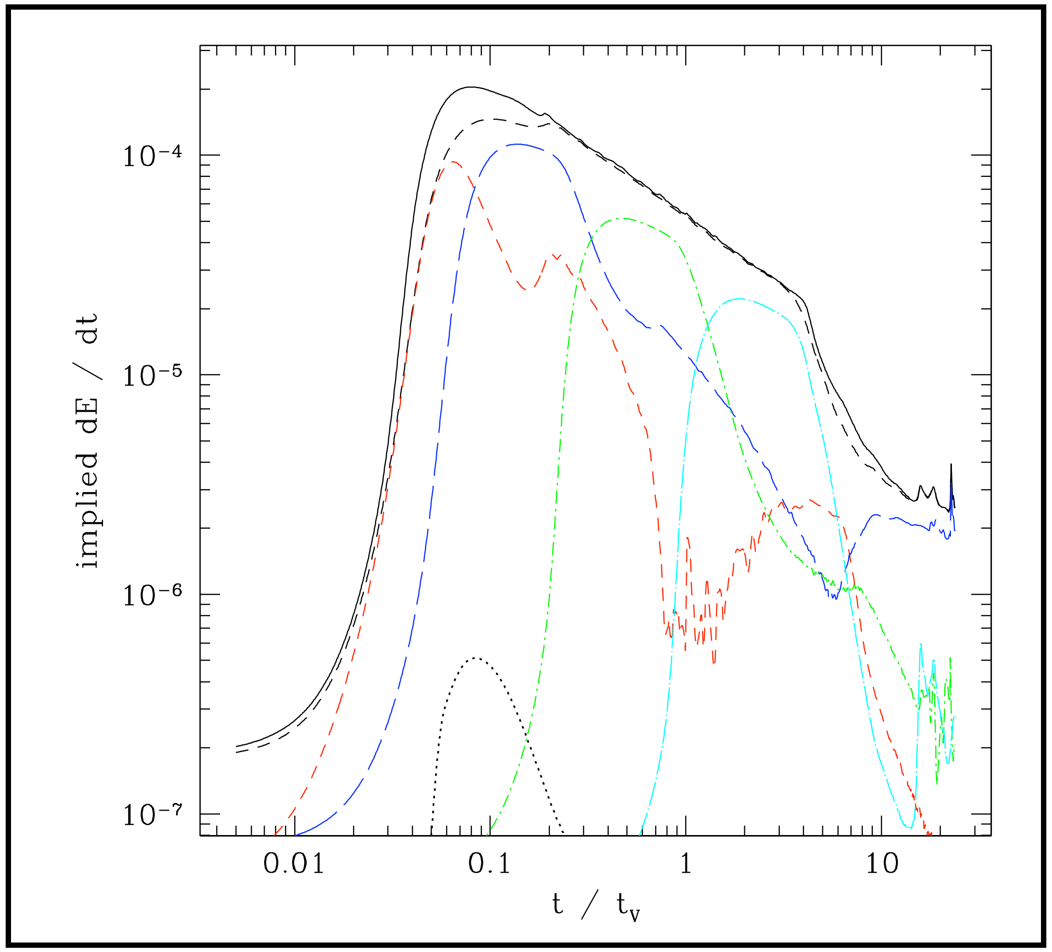
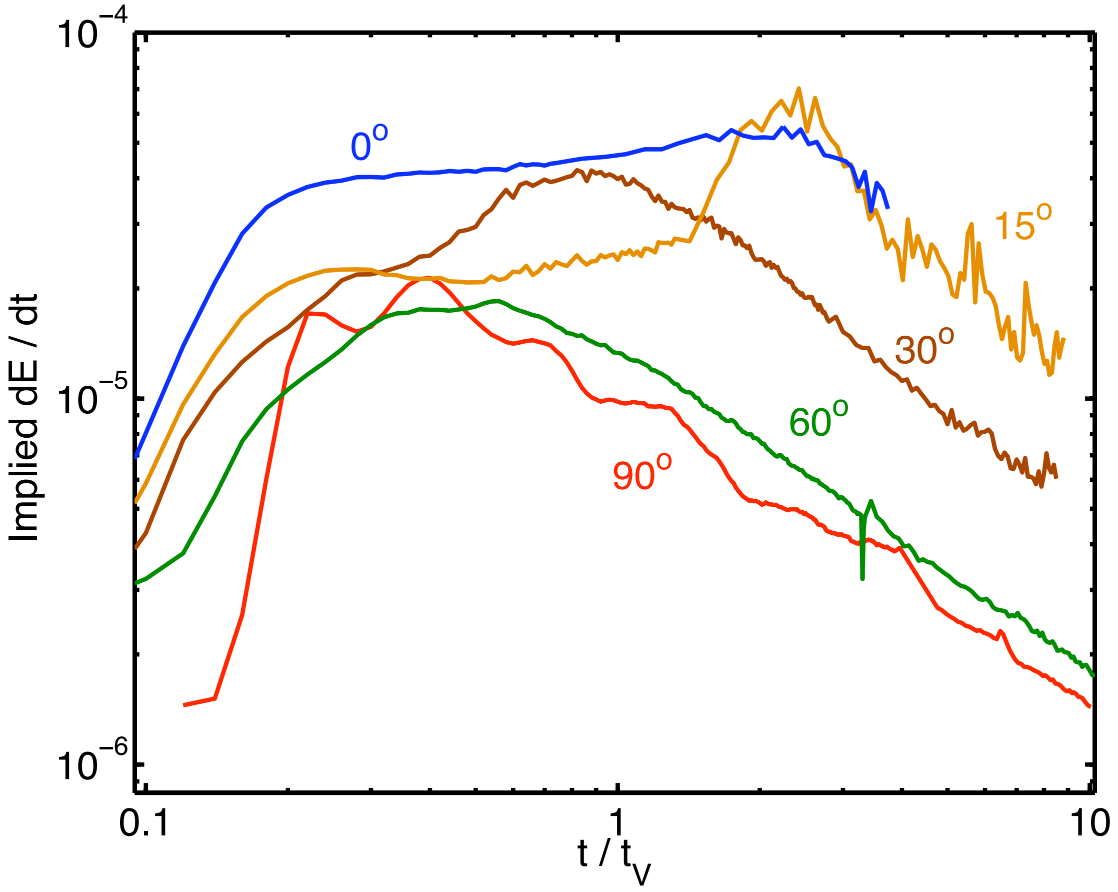
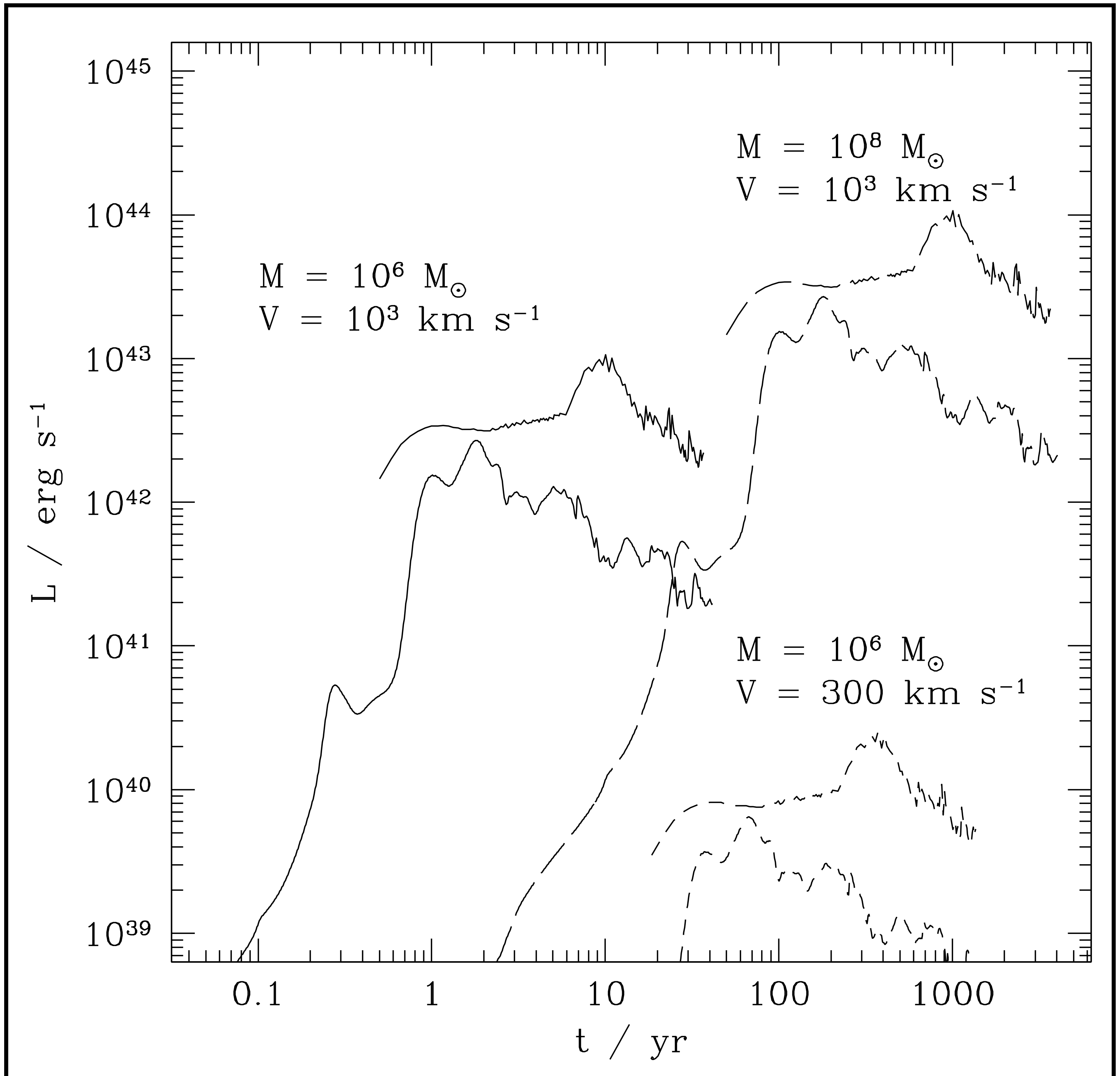
- For in-plane k

Differences likely due to different relative contribution of potential energy release





Expected lightcurves from recoil



Peak luminosity at ~ 0.1 L_{Edd}

Expect emission for extended period of time, from a few days (inner disc, Corrales et al.), to a few years (outer disc, modeled here)

Emitted spectrum depends on where is energy deposited:

-) in the midplane (Schnittmann & Krolik 2008) ---> infrared

-) on the surface ---> X-rays

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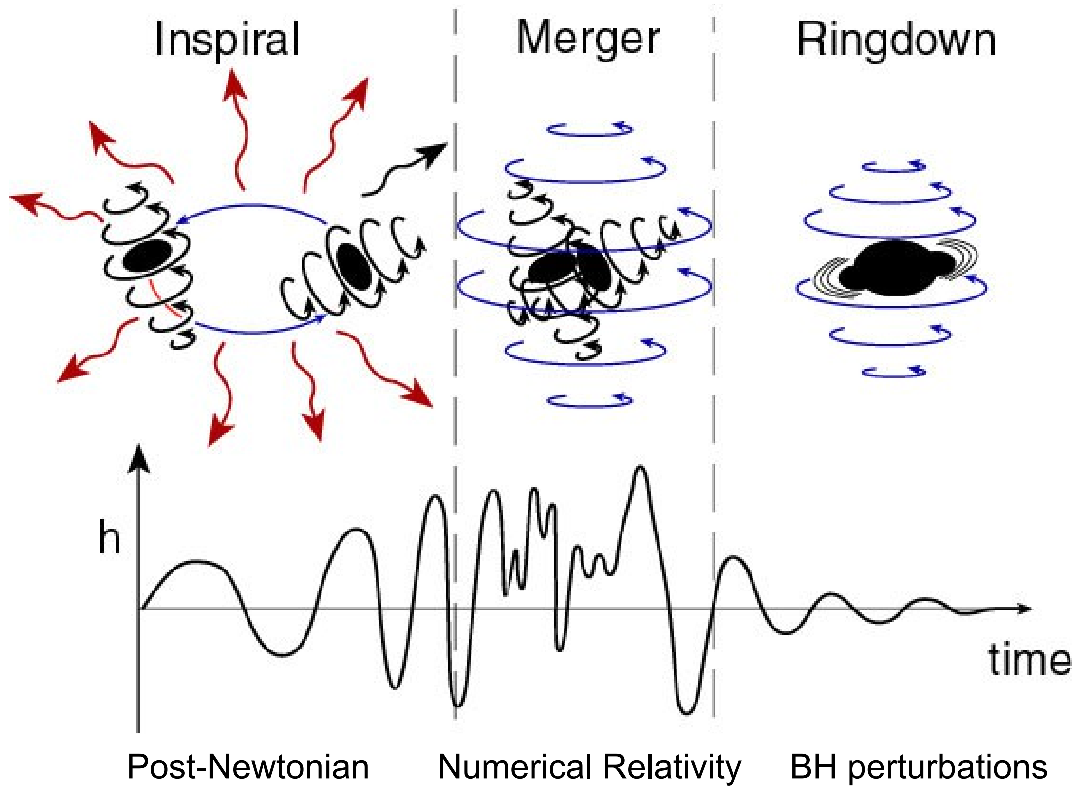
SMBH mergers and role of BH spin

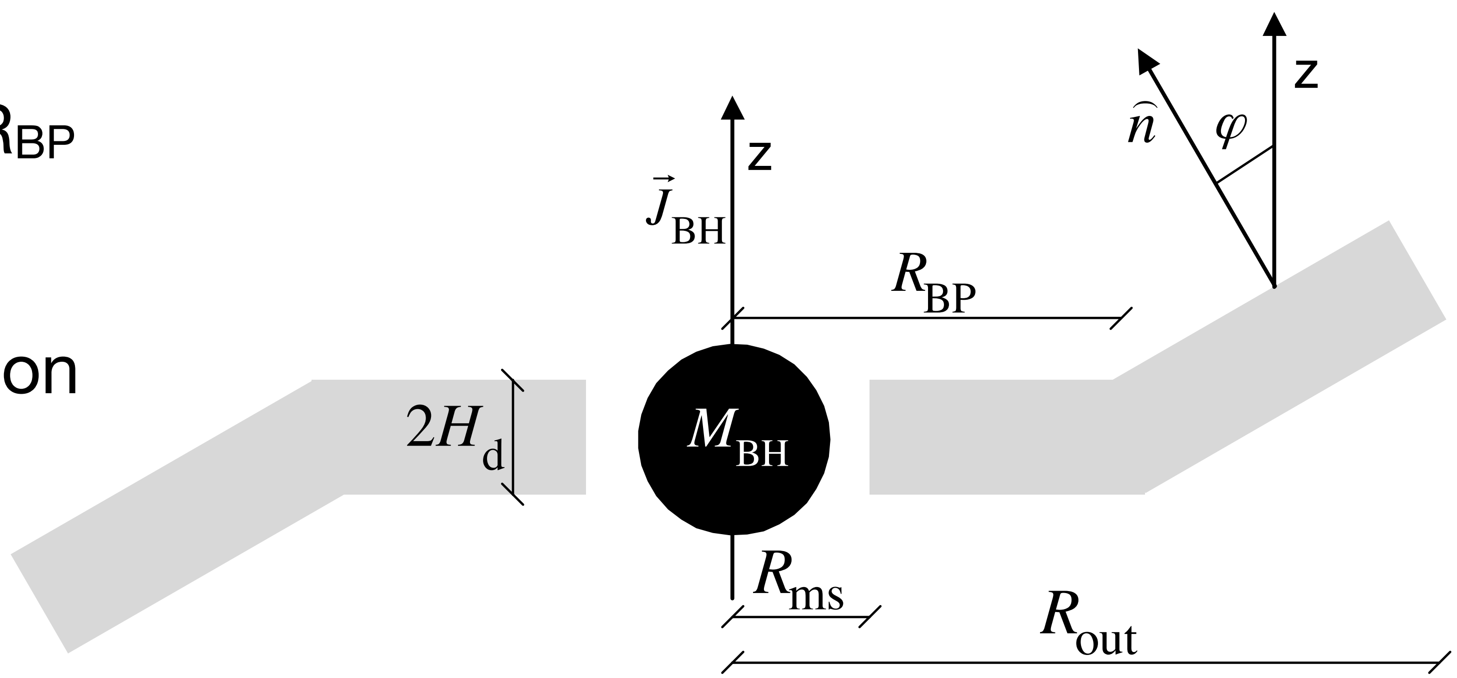
- The spin orientation and magnitude at coalescence is essential in determining several properties
  - Shape of the GW waveform (if and when GW detectors will fly)
  - If: (a) **spin magnitude a is large** and (b) **spins are significantly misaligned** ---> asymmetric GW emission ---> <u>superkick</u> configuration (with recoil velocities up to 4000 km/sec, Campanelli et al 2007)
  - Recoiling black holes rarely observed (Civano et al 2012)
  - A recoiled BH is removed from gas-rich nuclear region ---> Effects on BH growth



Spin evolution in gaseous environments

- Consider a single BH and its accretion disc
- Lense-Thirring precession in the disc induces a warp (the Bardeen-Petterson effect) (Bardeen and Petterson 1975, Scheuer and Feiler 1996, Lodato and Pringle 2006)
- Inner disc align with BH, out to R_{BP}
- Location of R_{BP}: precession timescale equals warp propagation timescale

$$\Omega_{\rm LT}^{-1} = t_{\nu_2}$$



- On longer timescale, BH spin aligns (or counter-aligns, see King et al 2005) with disc (Natarajan and Pringle 1998)

$$t_{\rm align} \simeq 7 \times 10^6 \left(\frac{a}{\alpha_2}\right)^{2/3} \left(\frac{\alpha}{0.1}\right) \left(\frac{H/R}{0.01}\right)^{2/3} \left(\frac{\dot{M}}{0.1\dot{M}_{\rm Edd}}\right)^{-1} \left(\frac{\epsilon}{0.1}\right) {\rm yr}$$

Spin evolution in gaseous environments

- **Bogdanovic, Reynolds and Miller (2007)**: in gas rich mergers, the two BH spin likely end up aligned (alignment time much shorter than merger time $t_{merge} \sim 10^7$ yrs; Dotti et al 2009, Escala et al 2005)

- Fundamental assumption: only need each black hole to align with its own disc! (Might be very optimistic if the circumbinary disc plane is not stable, see Nixon et al. 2011, Nixon et al. 2013)

- **Perego et al. (2009)**: more detailed investigation. $t_{\rm align} \sim 10^6 \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{-1}$ yrs

- Key role is played by the diffusion coefficient of the warp α_2

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How fast do warps propagate in accretion discs?

- Several theories have been developed for warp propagation in discs
- Papaloizou and Pringle (1983) estimate $\alpha_2 \sim 1/2\alpha$, for small warps and small viscosity
- Ogilvie (1999) provides a fully non-linear theory of warp propagation
  - For large warps, the warp diffusion coefficient is severely reduced (longer diffusion time-scale)

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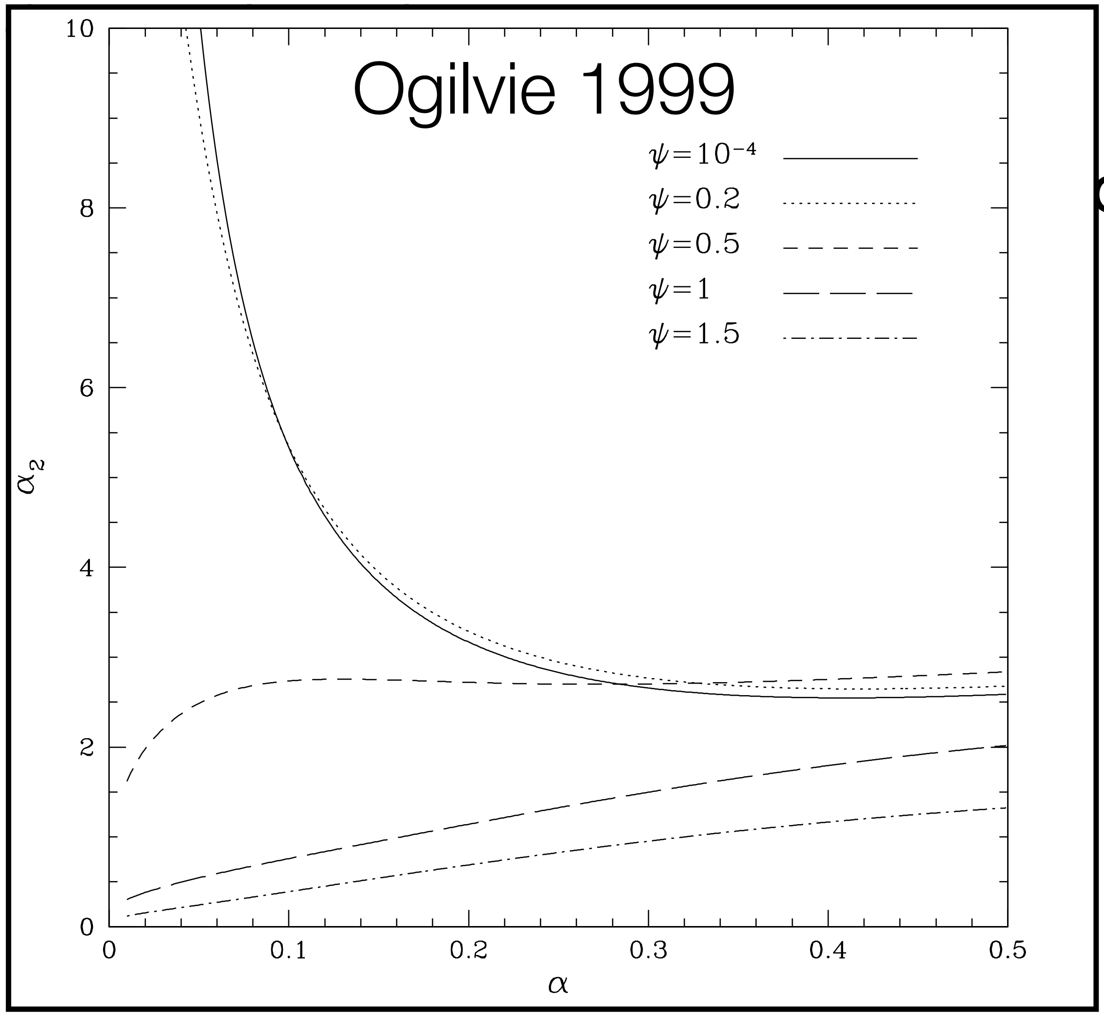

$$\psi = \frac{\mathrm{d}\beta}{\mathrm{d}\ln R}$$

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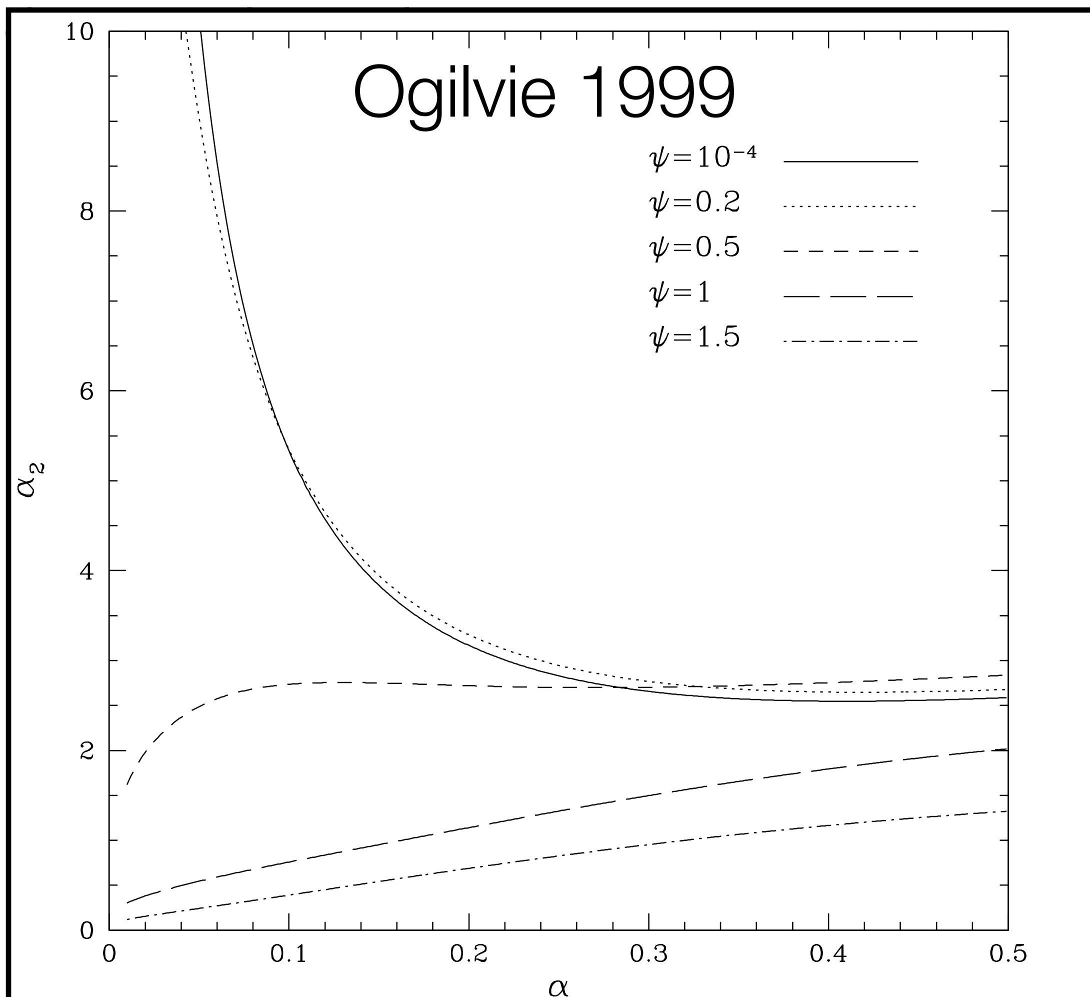

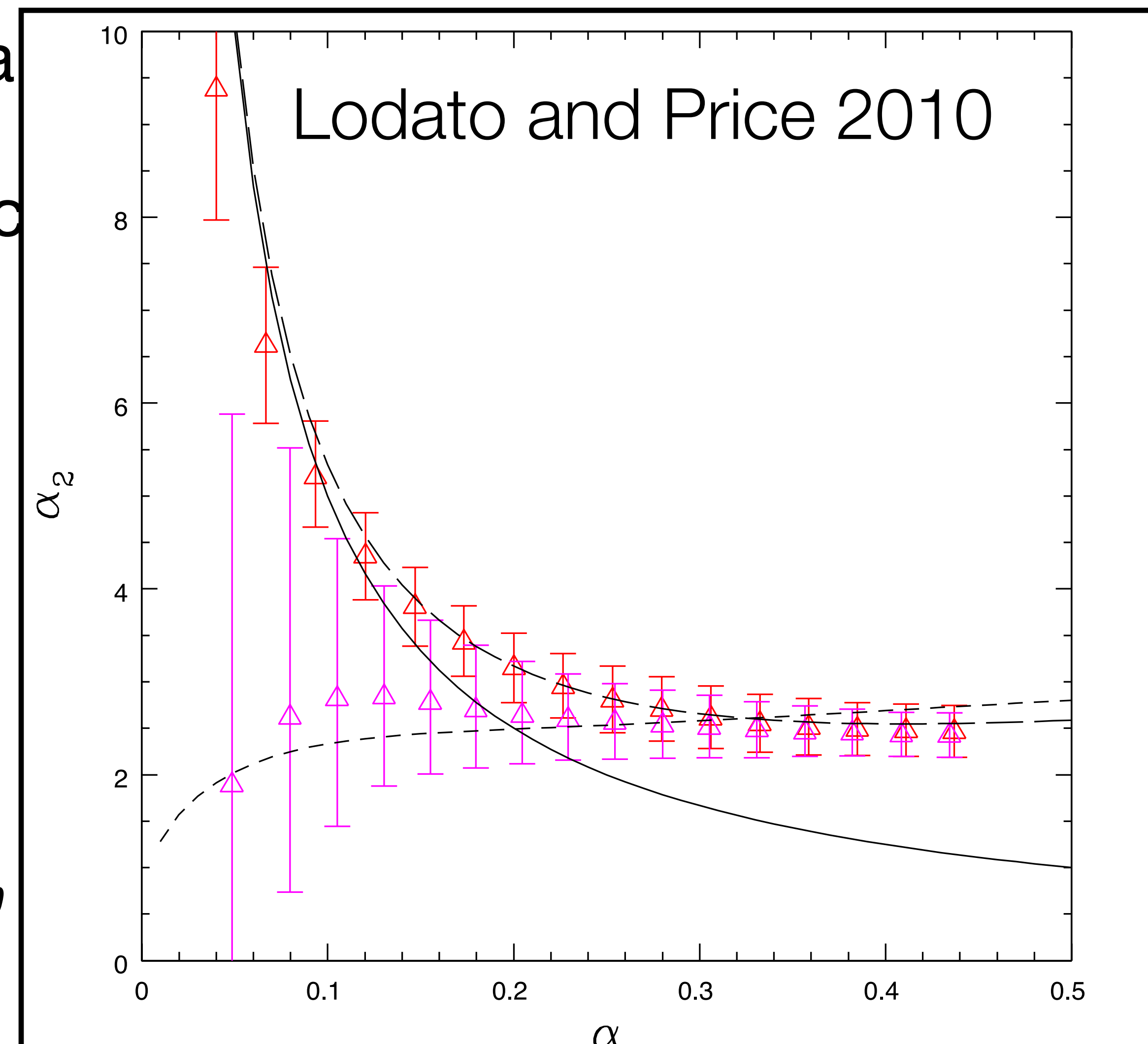

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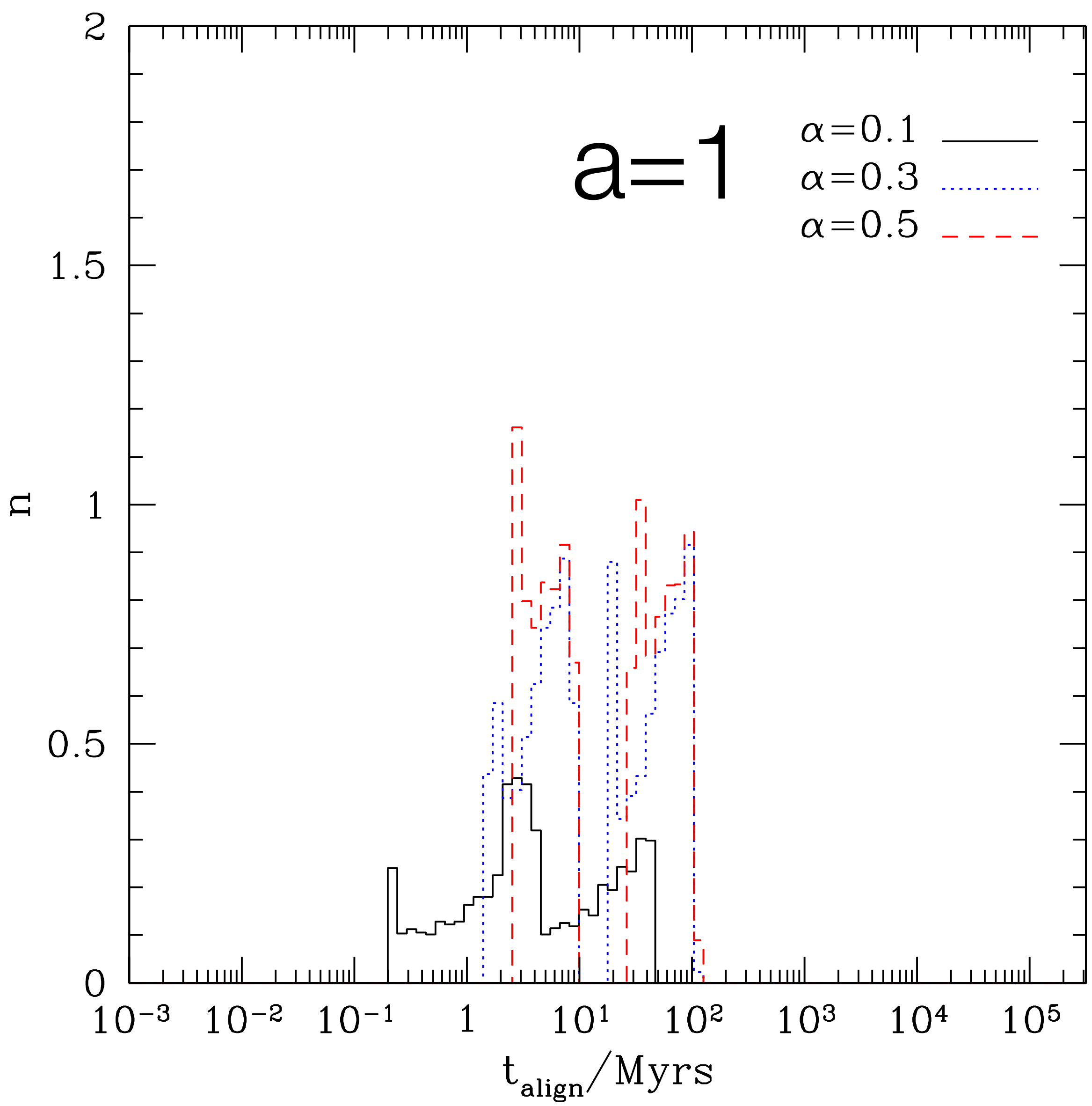
  - For large warps, the warp diffusion coefficient is severely reduced (longer diffusion time-scale)
- Bogdanovic et al: assume the small warp value
- Perego et al: artificially reduce α_2 by a factor up to 3 (following the numerical results of Lodato and Pringle 2007) ---> <u>Still no dependence on the warp amplitude</u>

Our approach

- As in previous works, only study the alignment of a single BH with its own disc
- Assume that the disc inclination varies on the scale R (no sharp warp): $\psi \approx \theta$
  - A more complete analysis would require a self-consistent calculation of the disc shape
- For low viscosities, the disc may break (Nixon et al, Lodato and Price, Larwood and Papaloizou): assume no alignment in this case
- All above assumptions tend to **favour alignment** (very optimistic)
- Now, alignment time does depend on the initial misalignment θ

Results for constant Eddington ratio

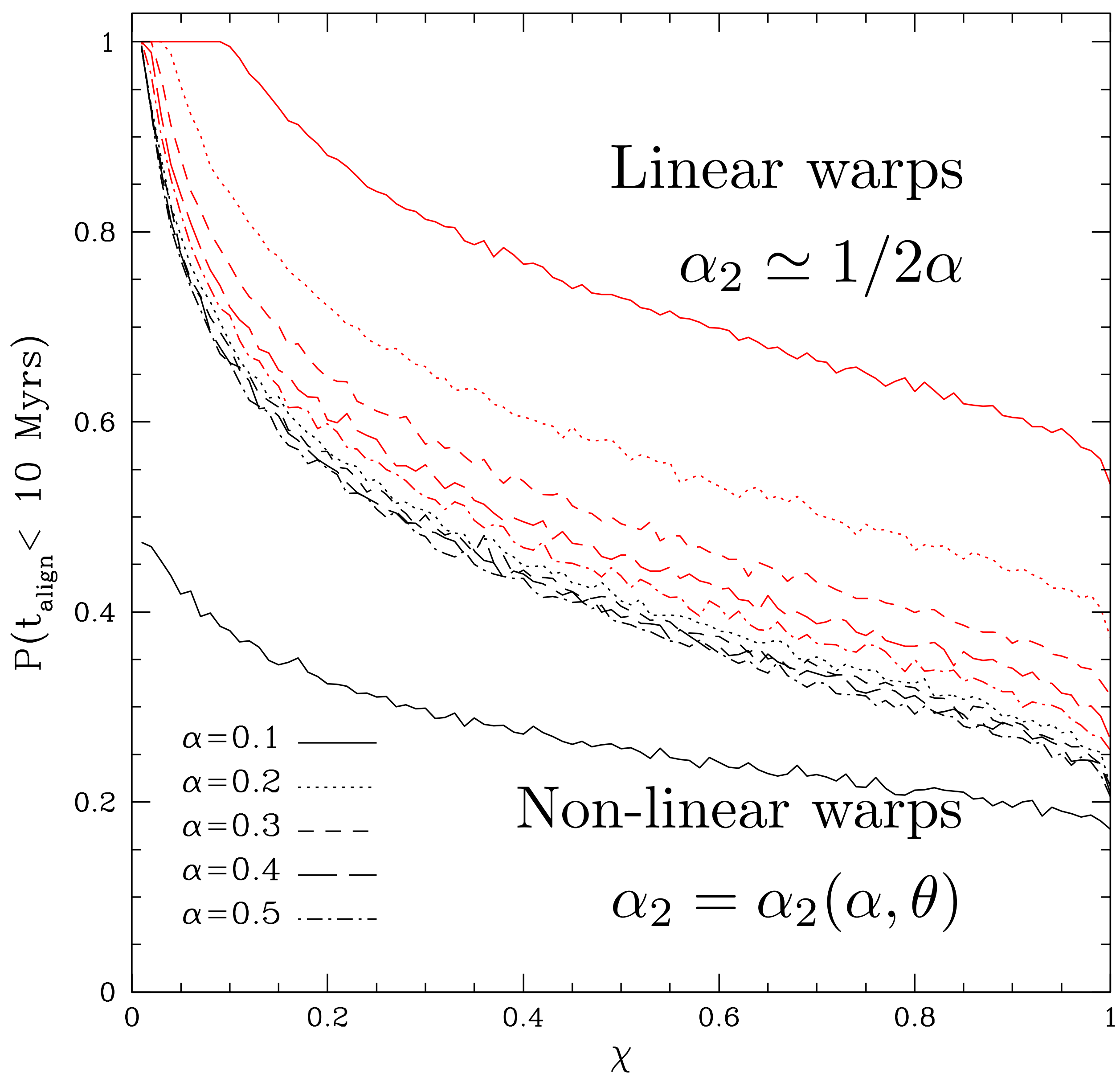
- Perform Monte Carlo simulation varying the initial misalignment
- Given α (viscosity parameter), *a* (spin parameter) and $f_{\rm Edd} = \dot{M}/\dot{M}_{\rm Edd}$ we compute the alignment time



- Here assume f_{Edd}=0.1, *a*=1
- Perego et al: t_{align}~10 Myr
- When dependence on misalignment in included, the timescale becomes longer by up to an order of magnitude
- Alignment would seem unlikely in this case for a large fraction (~50%) of the cases

Varying the Eddington ratio

- Here we also Monte Carlo over the Eddington ratio f_{Edd} in $[10^{-4},1]$



- In the fully non-linear case, much weaker dependence on α
- Highly spinning black holes highly unlikely to align within a merger time
- If a > 0.4, BH keep misalignment in more than 40% of the times

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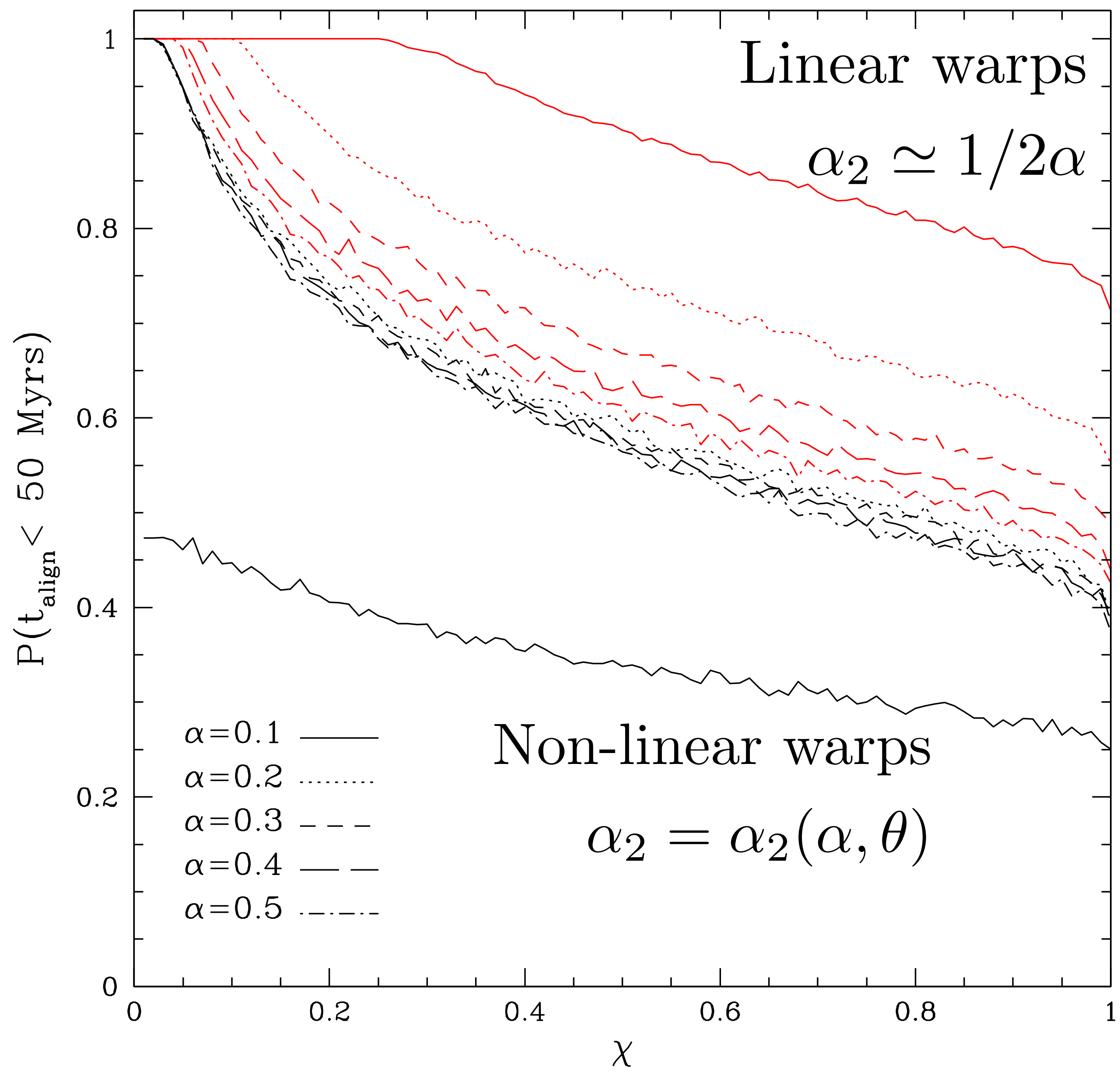

- Even if we assume a longer merger timescale, e.g. 50 Myr, most of highly spinning black holes still do not have time to align their spins

Conclusion

- The hydrodynamics of disc during SMBH merger is complex
- Scales of ~ 0.1 pc are critical and difficult to study: too small to be resolved effectively in galaxy-scale simulations (e.g. Mayer et al, Dotti et al), but small slace - often 1D - models might miss the large scale dynamics.
- The last ‘0.1 pc” problem is probably still unsolved
- A variety of electromagnetic signals from the merger depend heavily on the disc dynamics:
  - Super-Eddington flares? Assessing thhe available mass and role of ‘leaky dams’ essential (Tazzari & Lodato 2014)
  - Disc readjustment after BH recoil might produce near-Eddington flares (Rossi, GL et al 2010)
  - The very occurence of super-kicks and the GW signal depends on spin orientation, which is highly uncertain: most likely highly spinning systems might be strongly misaligned (Lodato & Gerosa 2013)