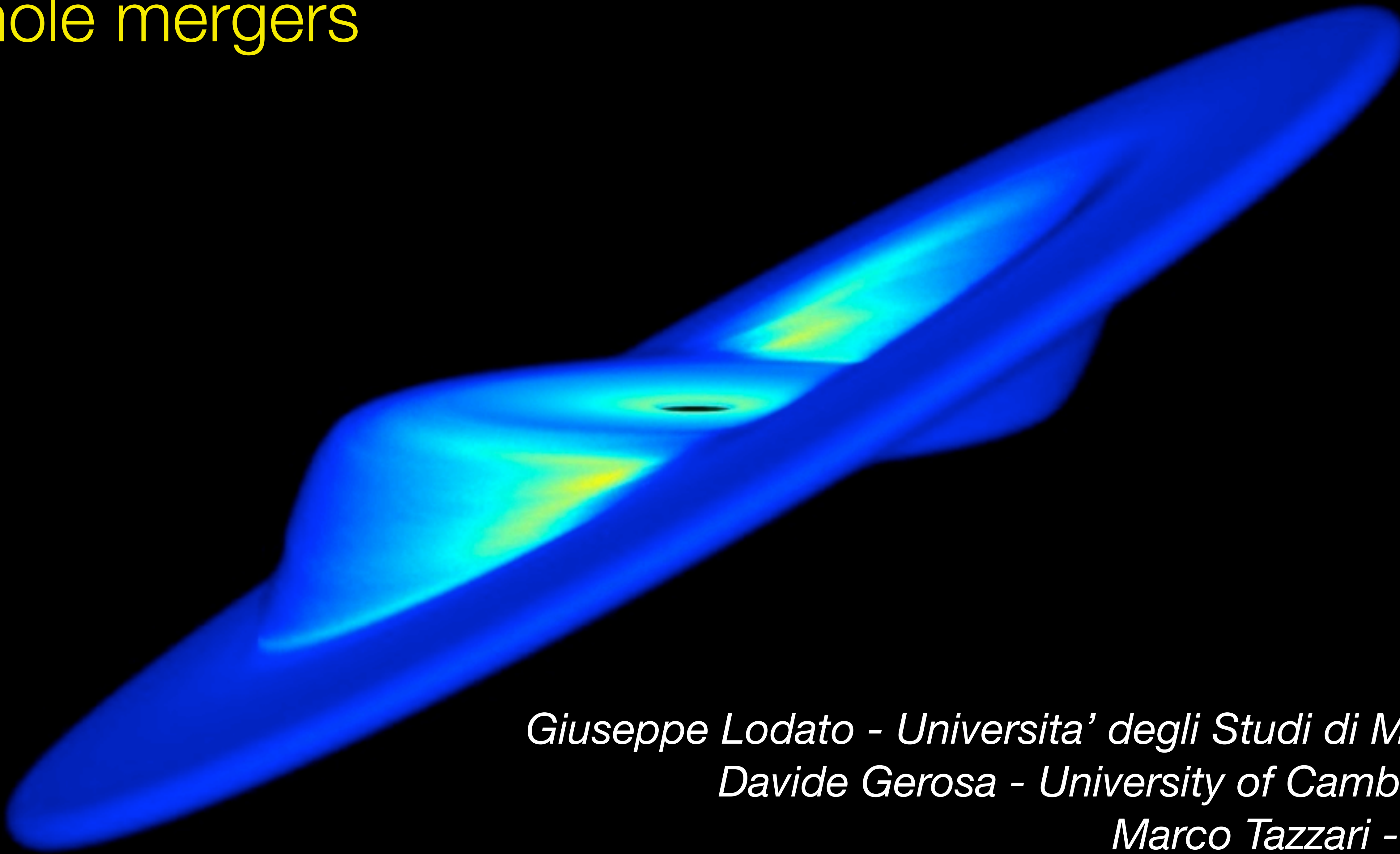
Prompt electromagnetic emission of binary black hole mergers



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Summary

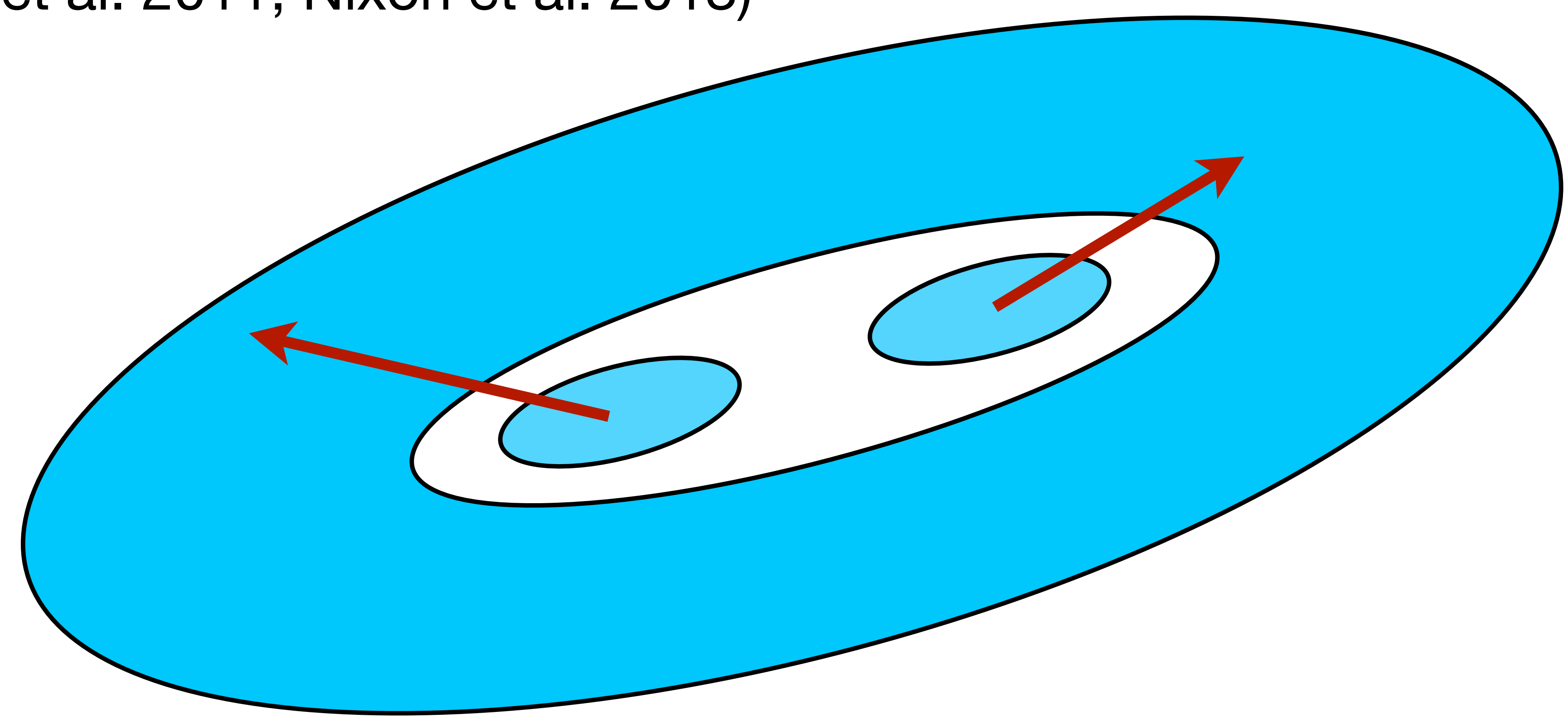
- **Part 1: Likelihood of fast recoils after a BH binary mergers**
  - Importance of including non-linear warp dynamics to estimate alignment timescale
  - Lodato and Gerosa, MNRAS, 429, L30 (2013)
- **Part 2: Estimating the fossil circumprimary disc mass at decoupling**
  - Importance of correctly implementing the tidal torque in 1D models
  - Tazzari and Lodato, in preparation

Part 1: Spin evolution in gaseous environments

Lodato & Gerosa (2013)

- **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}~10^7 yrs; Dotti et al 2009, Escala et al 2005) due to the Bardeen-Petterson effect.

- 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)



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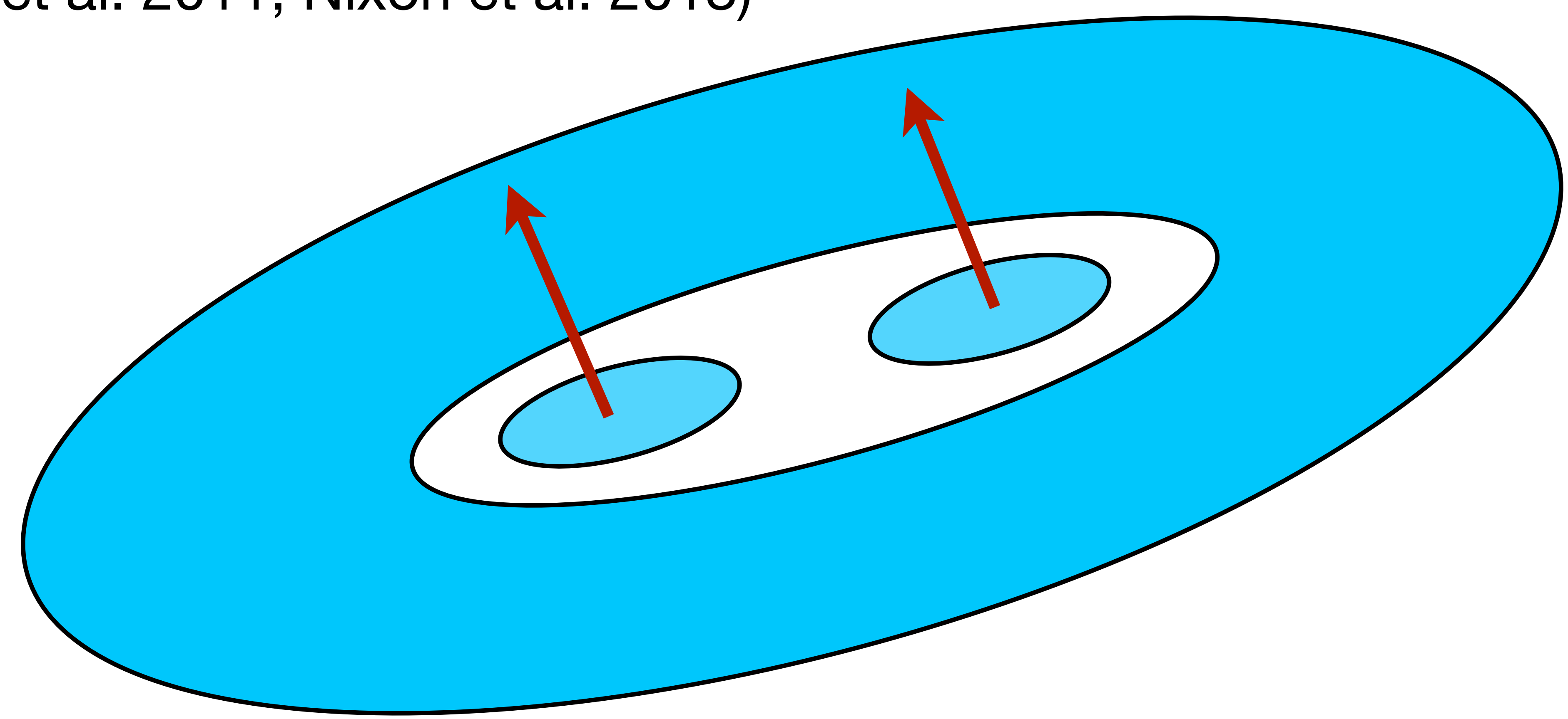

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- Key role is played by the diffusion coefficient of the warp α_2

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

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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)
- *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>

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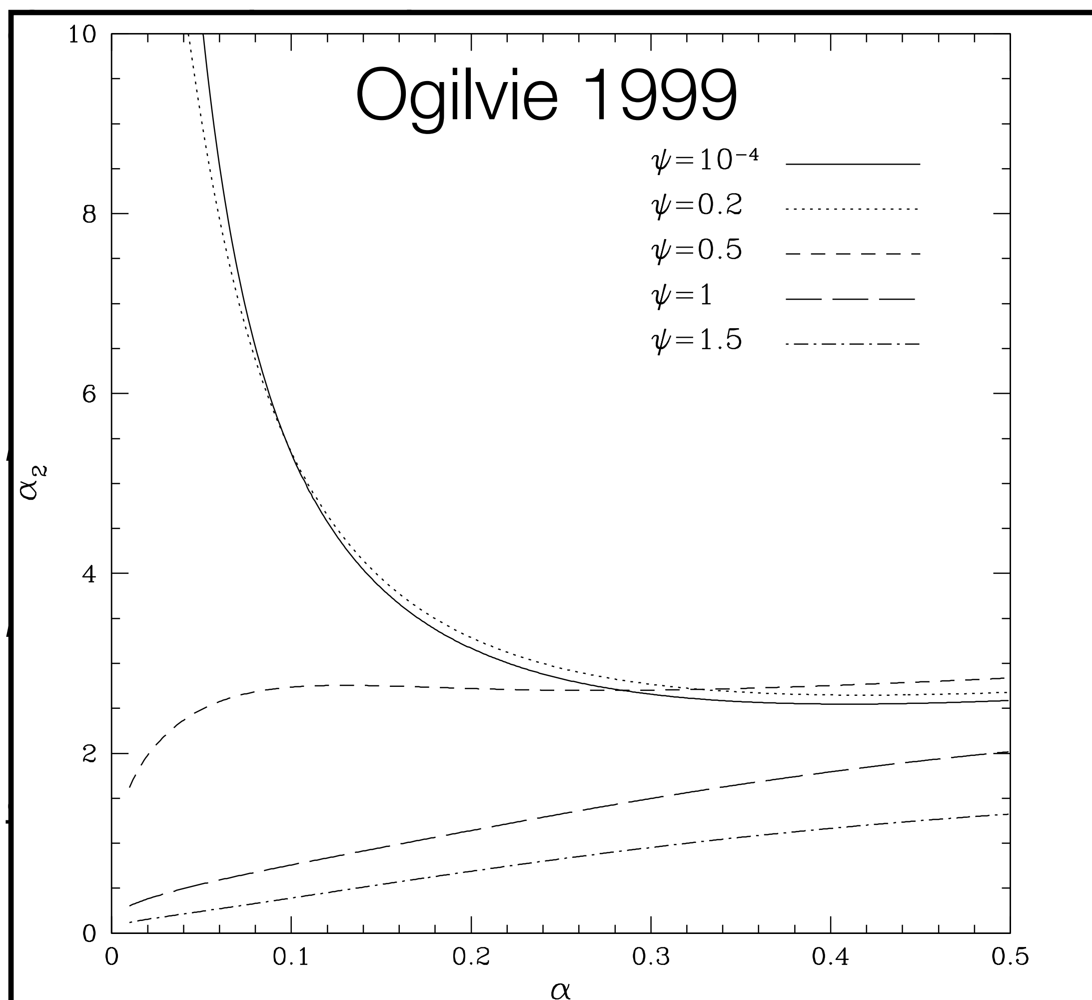

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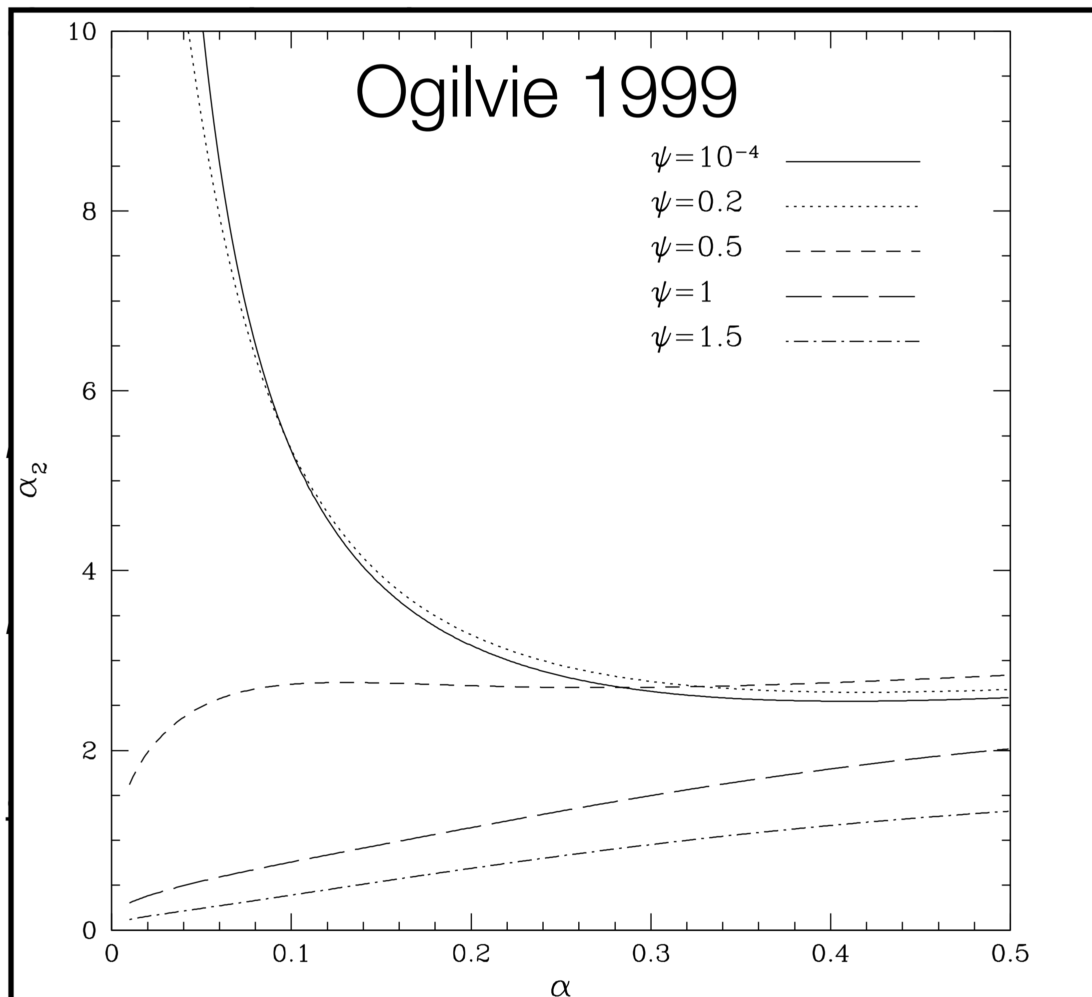

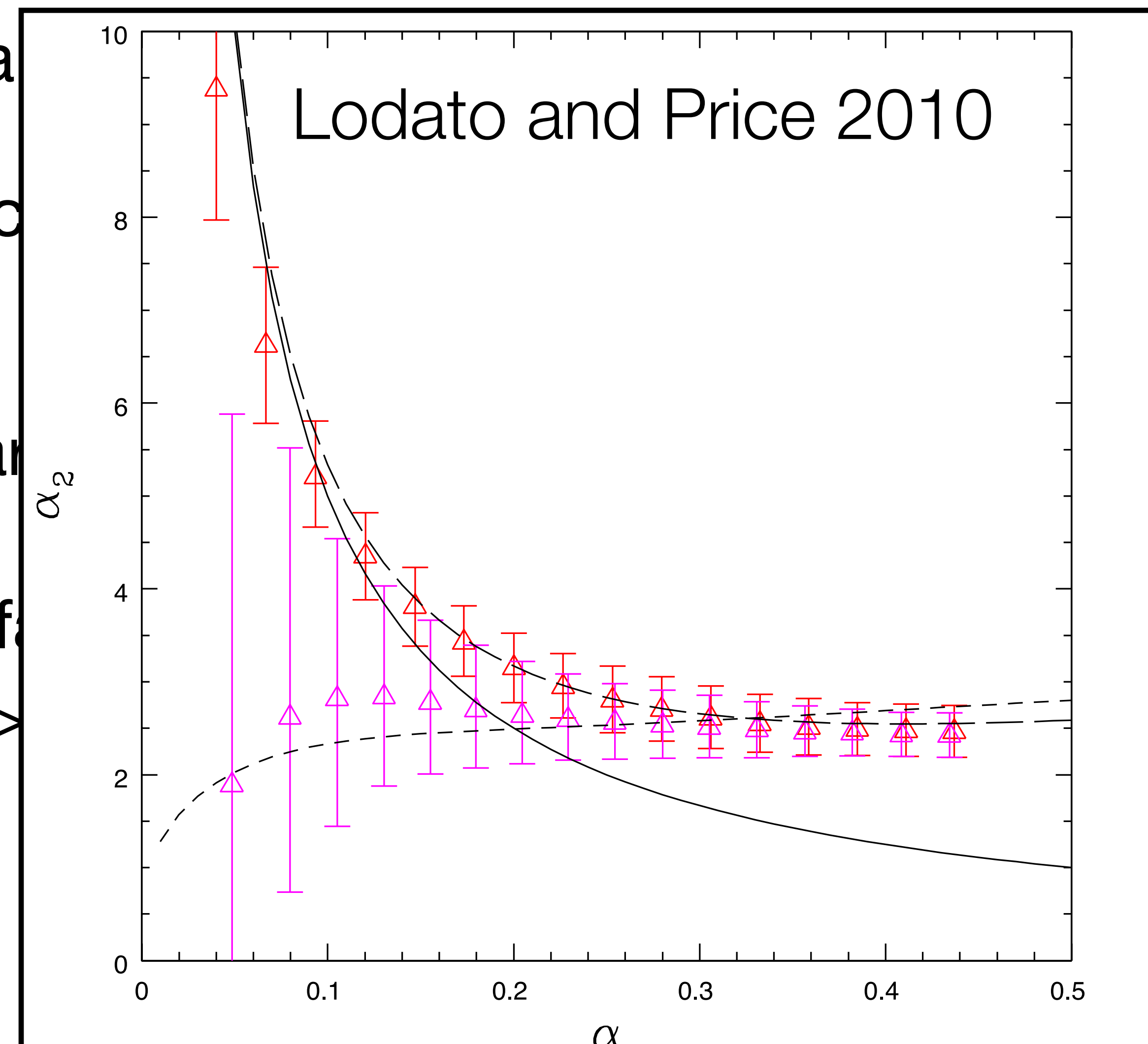

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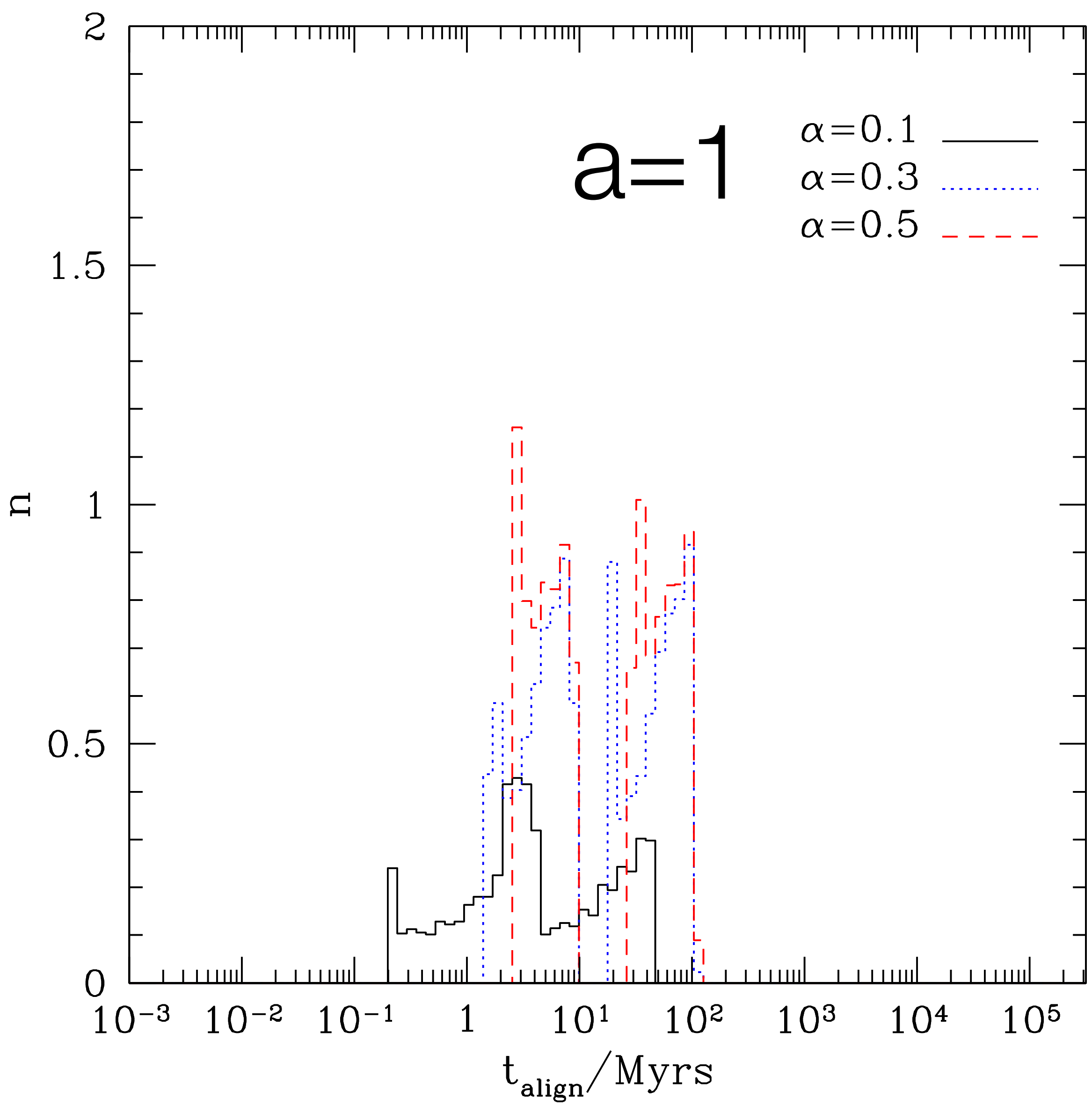
Our approach

- 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

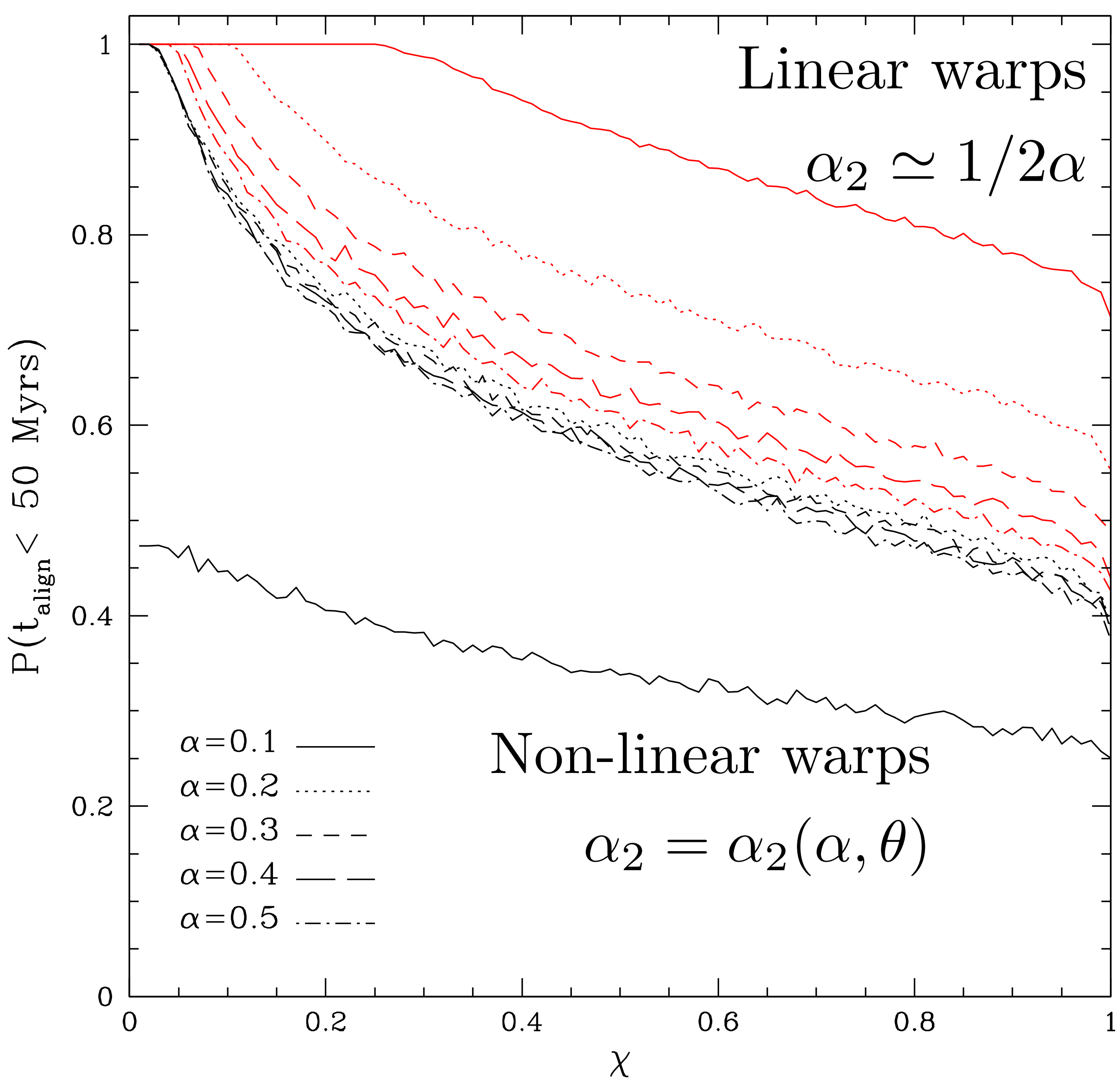
- Perform Monte Carlo simulation varying the initial misalignment
- Given α (viscosity parameter), *a* (spin parameter) and $f_{\rm Edd} = \dot{M}/\dot{M}_{\rm Edd}$ we compute the alignment time



- 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

Conclusions: Part 1

- **Spin alignment of binary black holes**
  - Earlier claims that gaseous discs are extremely effective in aligning the spins are not confirmed
  - Taking into account non-linearity in warp propagation leads to alignment times comparable to merger times, especially for rapidly spinning black holes
  - In order to avoid strong recoils, the BH must have a spin parameter $a < 0.4$
  - **Note**: aligning effect of binary torques (Miller & Krolik 2013) only efficient at small binary separations ($\ll$ *0.01* pc)
- **To do list**
  - Simple approximation for disc shape, needs to be computed consistently
  - Dependence of merger time on system parameters

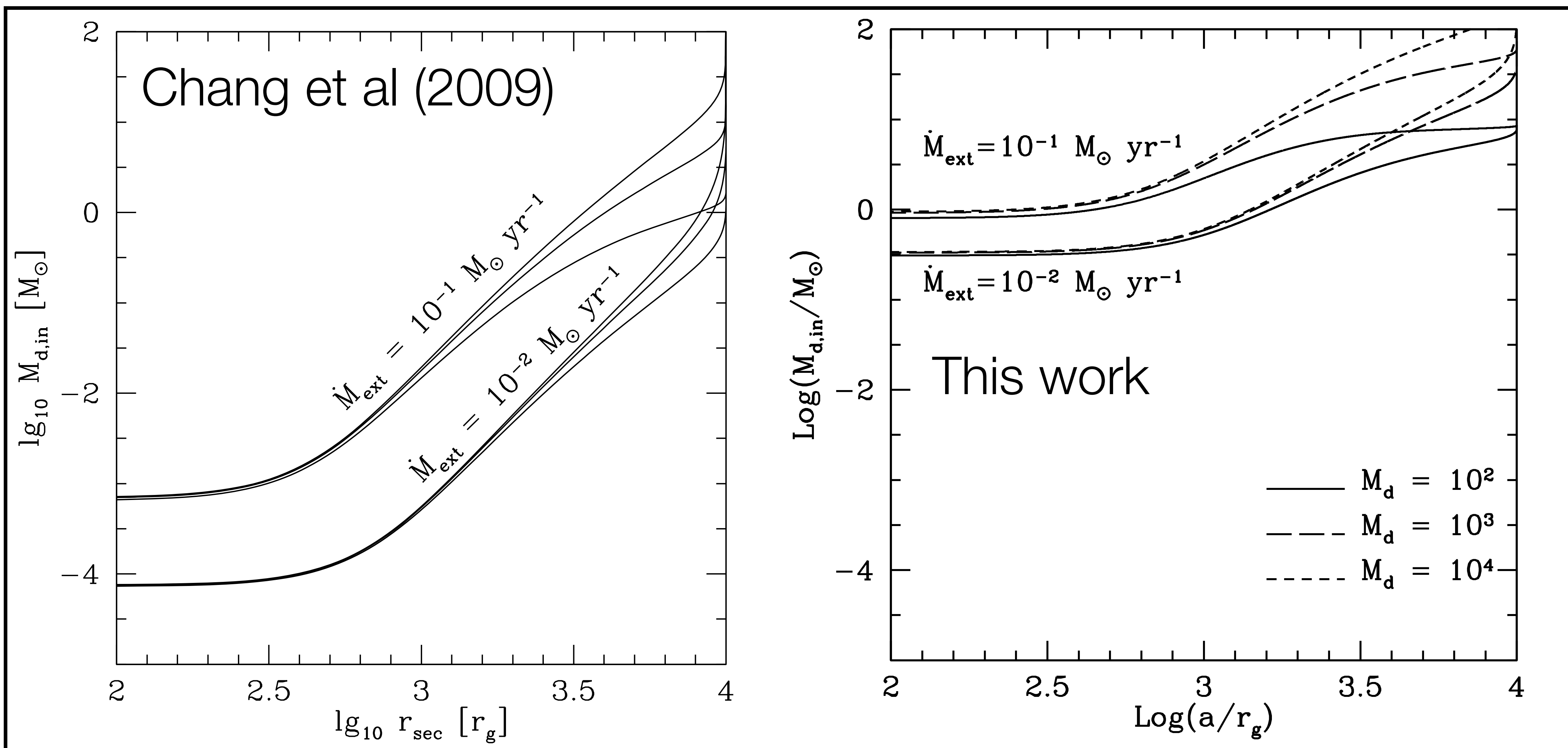
Part 2: Estimating the fossil disc mass

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

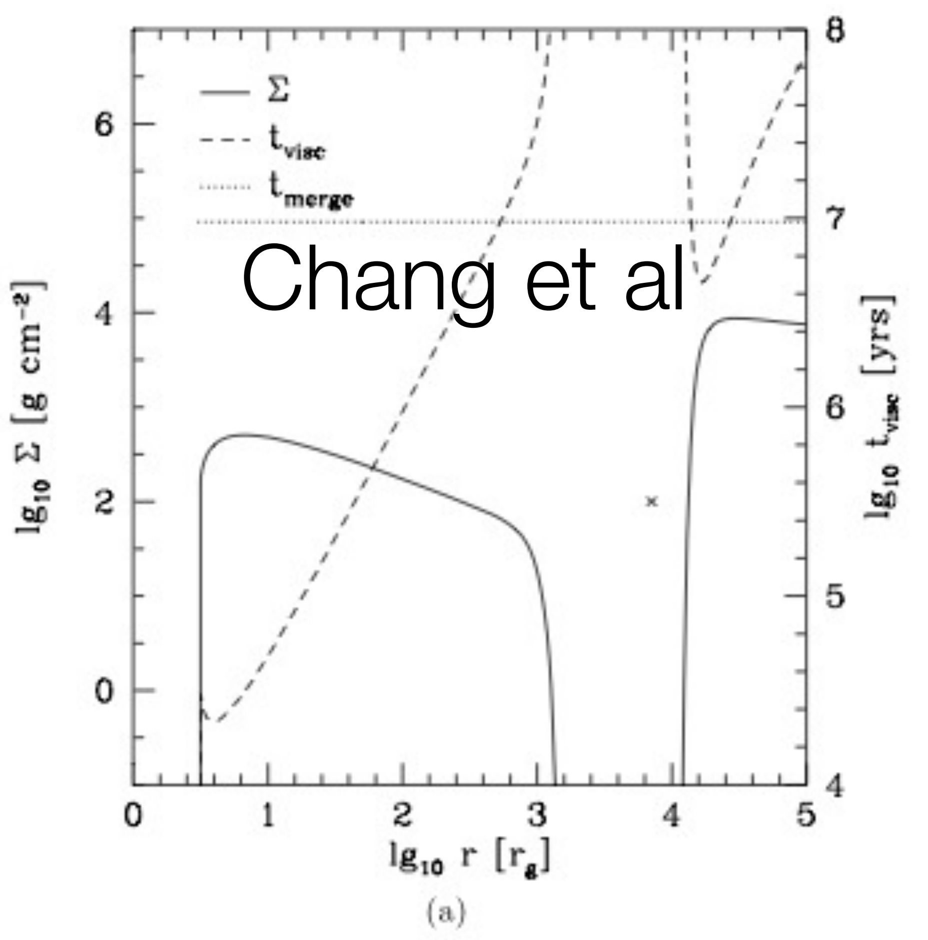
Results

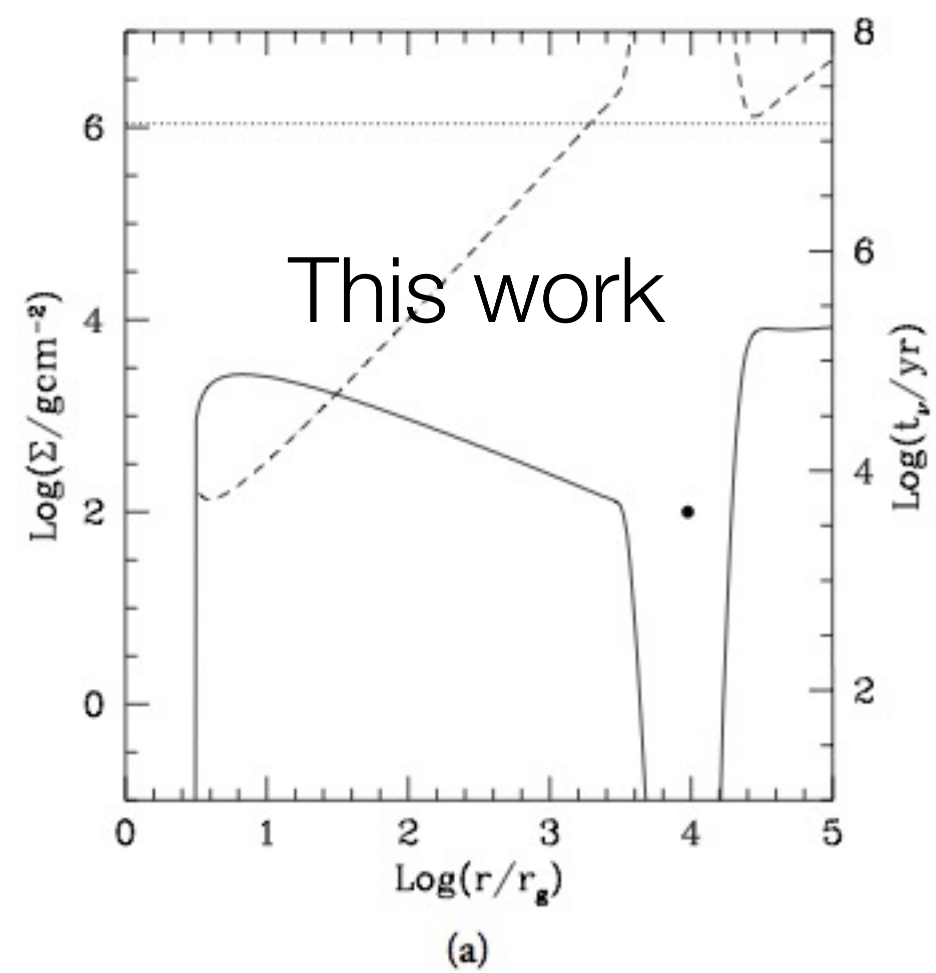
- Example evolution for $M_p=10^7 M_{Sun}$, $q=0.1$
- Inner disc mass discrepant by a factor ~ 1000 !
- Large exploration of parameter space: while Chang et al always predict sub-Eddington flares, we estimate flare luminosities $1 < L/L_{Edd} < 30$



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
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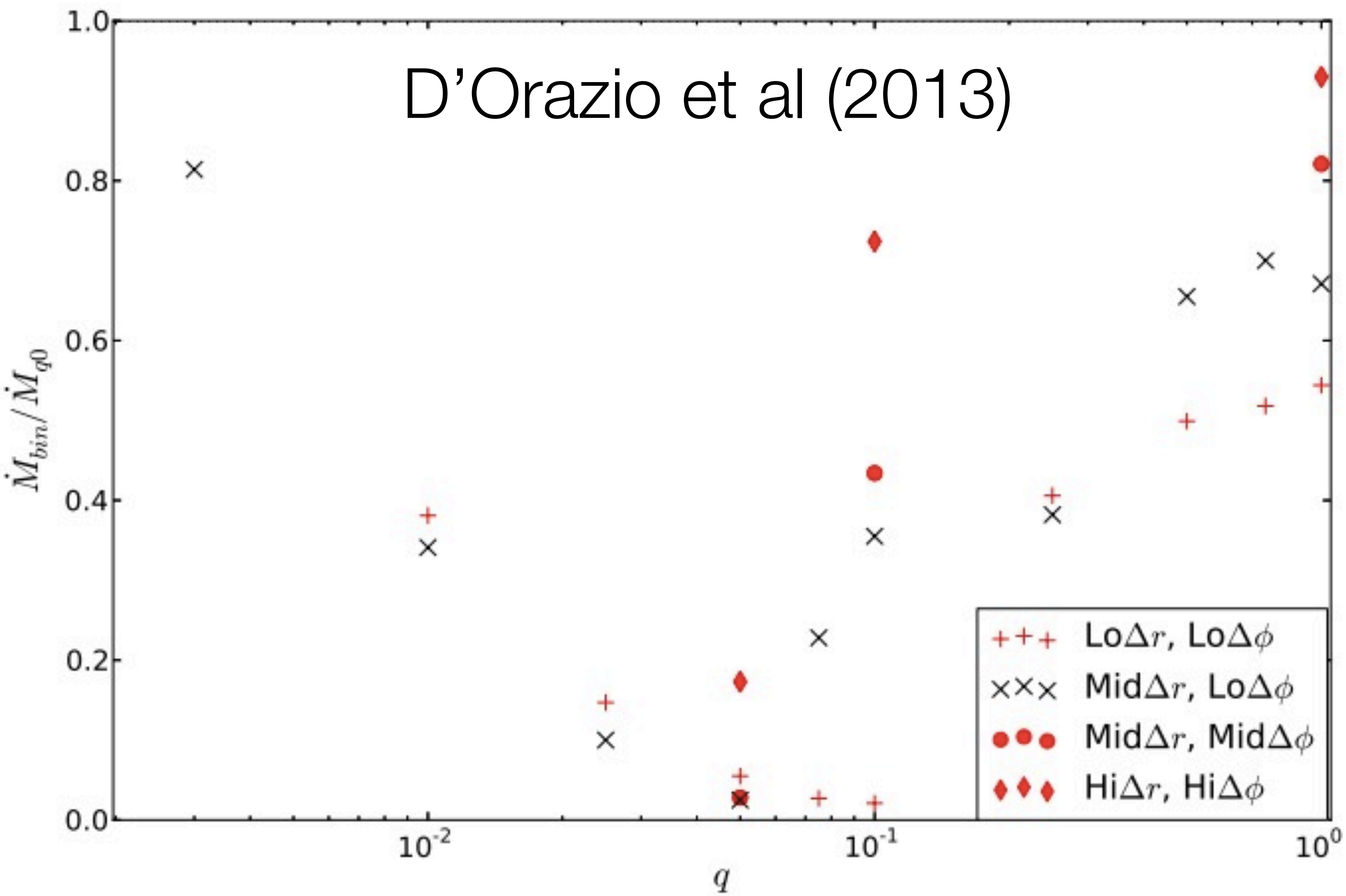

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Conclusions: Part 2

- **Fossil disc mass**
  - Earlier claims that fossil discs have very small masses (below $1\ M_{Jupiter}$) are not confirmed
  - Care should be taken in computing the tidal torque for non extreme mass ratios, in order to compute gap sizes accurately
  - Accretion of fossil disc leads to strongly super-Eddington flares during GW driven evolution
- **To do list**
  - Consider mass flow through the gap (possibly already in 1D codes)
  - Evaluate mass flow as a function of *H/R*
  - Is the whole fossil disc accreted during GW phase (Baruteaou et al. 2012)?