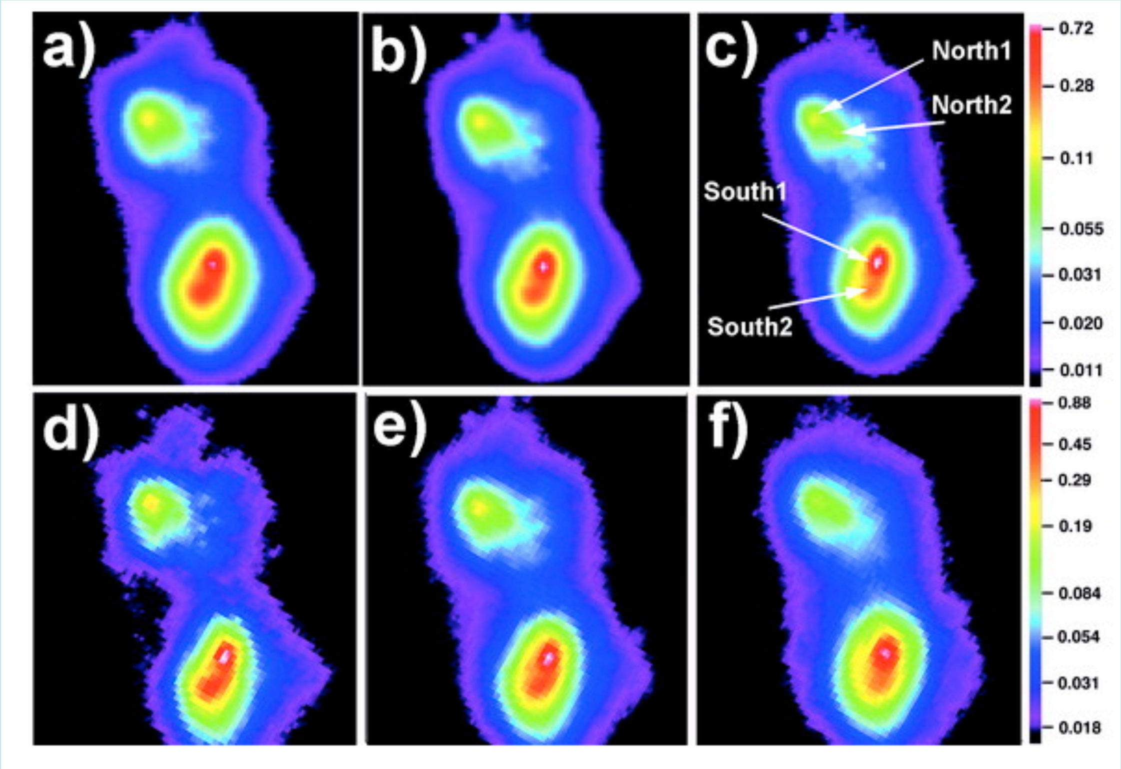
Eccentricity of Supermassive Black Hole Binaries Coalescing from Gas-rich mergers



Priya Natarajan

Radcliffe & Yale

In Collaboration with Philip Armitage (Boulder & JILA)

The dying gasps of merging supermassive black hole binaries

ROLE OF GAS DISKS IN EFFECTING BBH MERGERS:

1. Does the gas in a circumbinary disk remove the angular momentum? Observationally, AGN appear to host disks of a few X 0.1 pc
2. Are there electromagnetic counterparts: precursors / afterglow?
3. Does the gravitational wave signature preserve information about cause of merger?

Observationally BBHs clearly exist some with sub-parsec separation Boroson & Lauer (2009) objects, Rodriguez+ (2006); NGC 6240; Komossa+ 2003,07,08

Armitage & PN 2002, 2005; PN & Armitage 2006; PN 2007
Milosavljevic & Phinney 2005
Macfadyen & Milosavljevic 2006
Escala et al. 2004, 2005; Kocsis+ 2007; Dotti+2007; Sesana+ 2006

The merging of DM halos in LCDM

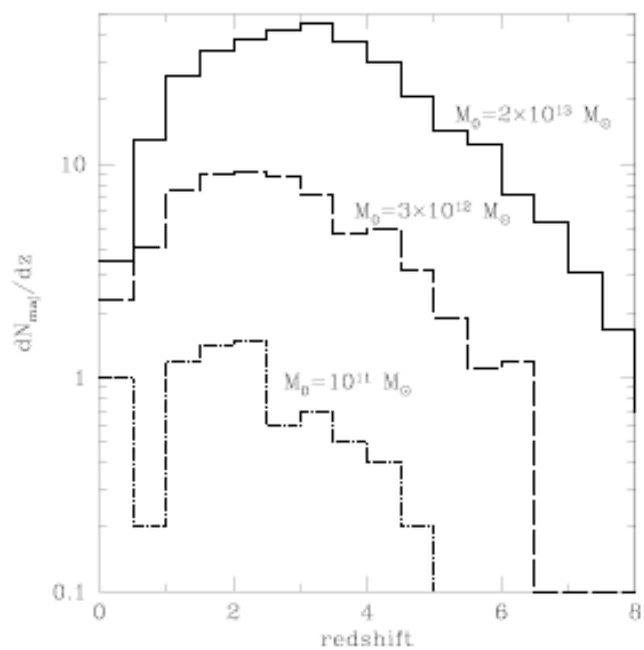


FIG. 3.— Mean number of major mergers experienced per unit redshift by halos with masses $> 10^{10}$ $M_\odot$. *Solid line:* progenitors of a $M_0 = 2 \times 10^{13}$ $M_\odot$ halo at $z = 0$. *Dashed line:* same for $M_0 = 3 \times 10^{12}$ $M_\odot$. *Dotted line:* same for $M_0 = 10^{11}$ $M_\odot$.

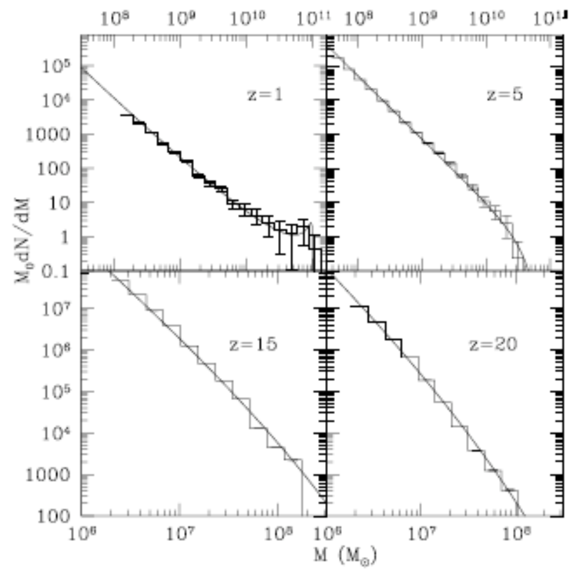


FIG. 1.— Mean number of progenitors with mass M for a $z_0 = 0$, $M_0 = 10^{11}$ $M_\odot$ parent halo, at redshifts $z = 1, 5, 15, 20$. *Solid lines:* predictions of the EPS theory. *Histograms:* results for the merger tree (mean of 50 realizations), $M > 2 \times M_{res}$. Error bars represent the Poissonian error in the counts.

Minor mergers outrank major mergers, in particular minor mergers with mass ratios M_2/M_1 < 0.1 are more frequent at higher redshifts

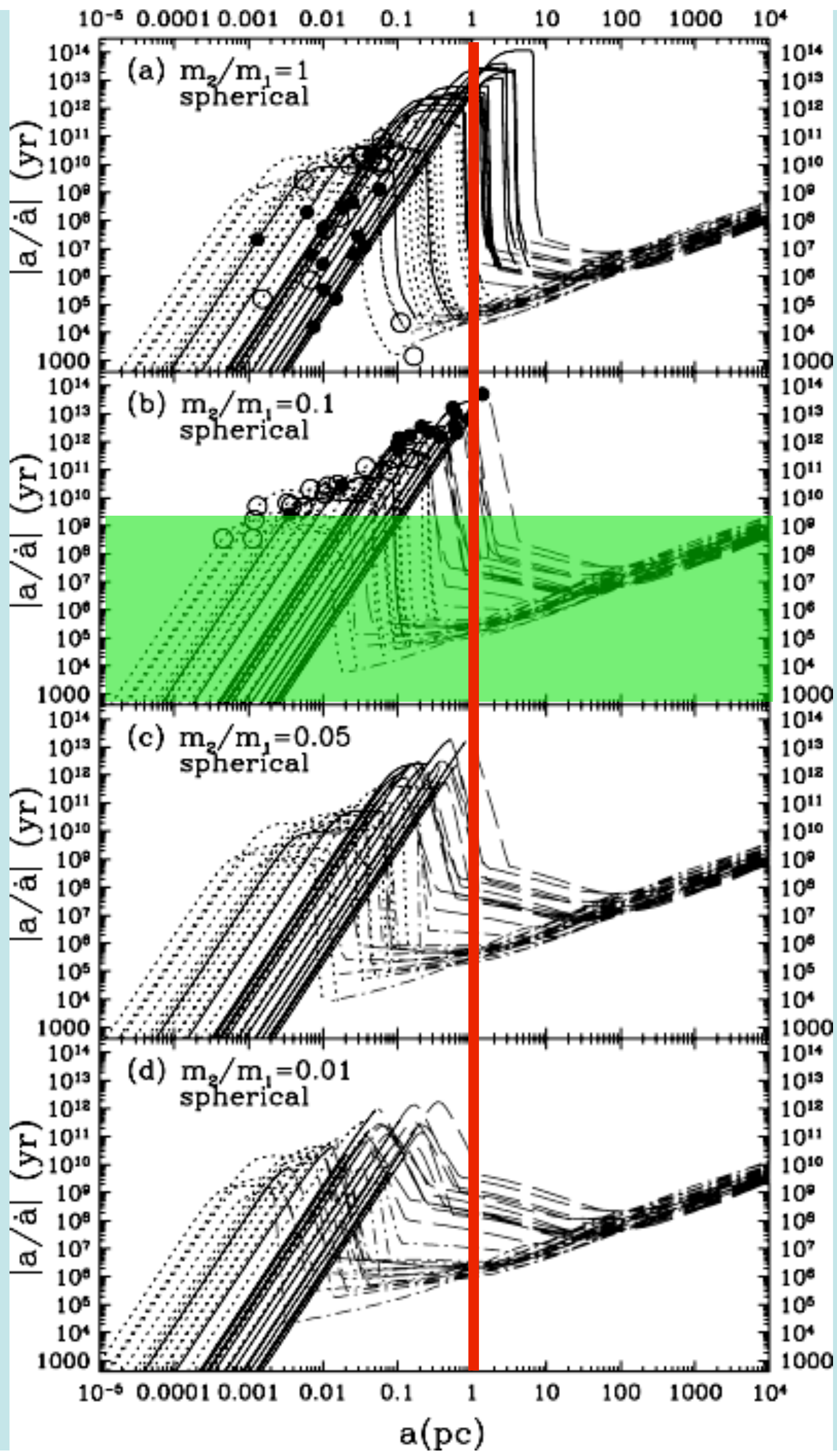
The last parsec problem

Merger timescale from stellar dynamics is long

Binary ejects stars and decay stalls

$$\frac{a_{stall}}{r_h} \approx 0.2 \frac{q}{(1+q)^2}$$

Begelman, Blandford & Rees (1980)



$t < t_H$

Yu (2002)

Electromagnetic & other counter-parts to BBH mergers?

Motivation: identification of LISA sources; astrophysics

Merger driven by stellar dynamics:

perhaps (resonant capture of low mass stars + tidal disruption possible channel)

Merger driven by gas dynamics:

- delayed X-ray rebrightening
- impulsive disk response to change in potential (probably unobservable)
- bright, variable precursors
- Pre-merger variability
- Finite final eccentricity

Expectations for gas driven mergers

Transition between: gas driven merger at large radius (0.1 pc) followed by gravitational radiation inspiral at small radius

$$\dot{a}_{\rm visc} \simeq -\frac{3}{2}\left(\frac{h}{r}\right)^2 \alpha v_{\rm K},$$

$$\dot{a}_{\rm GW} = -\frac{64 G^3 M_1 M_2 (M_1 + M_2)}{5 c^5 a^3},$$

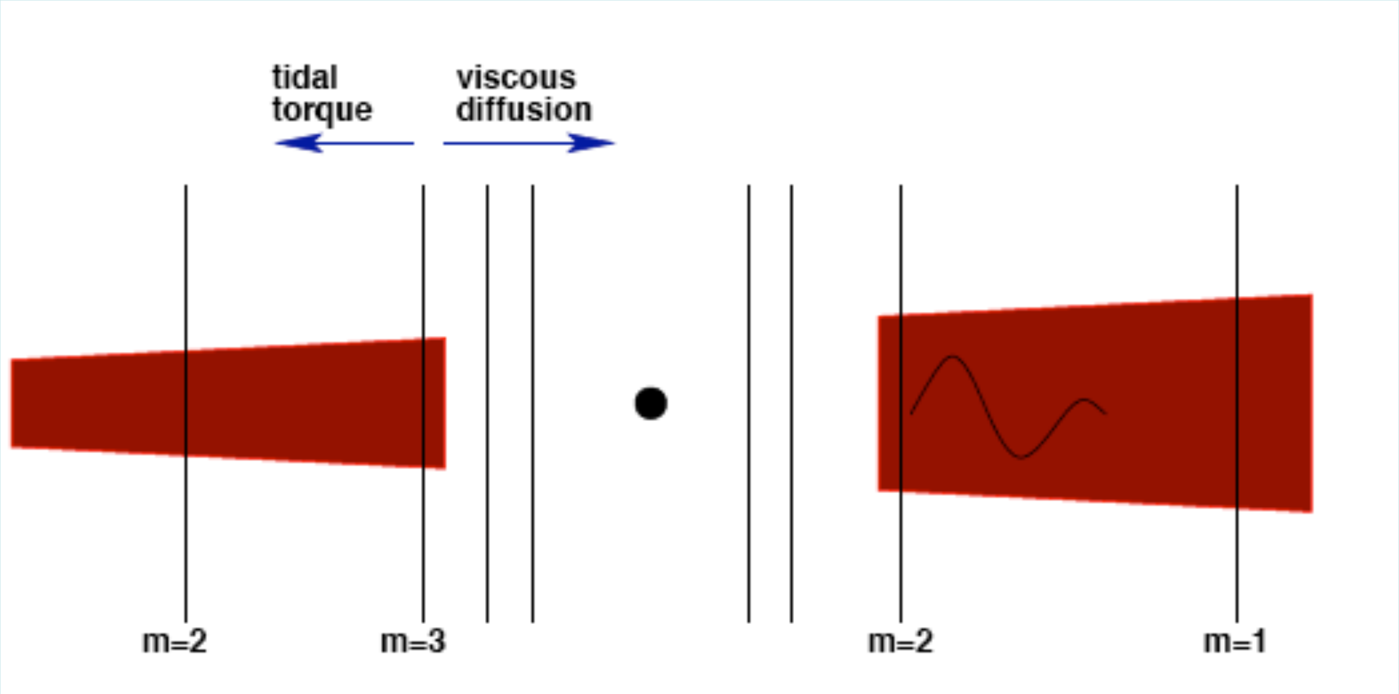
$$a_{\rm crit} = \left(\frac{128}{5}\right)^{2/5} \left(\frac{h}{r}\right)^{-4/5} \alpha^{-2/5} q^{2/5} \left(\frac{GM_1}{c^2}\right)$$

Transition radius depends on disk parameters and the mass ratio q

Probable consequences: disk interaction imparts significant eccentricity to binary probably for $q > 0.05$ (Papaloizou, Nelson & Masset 2001); possibly for lower q (Goldreich & Sari 2002)

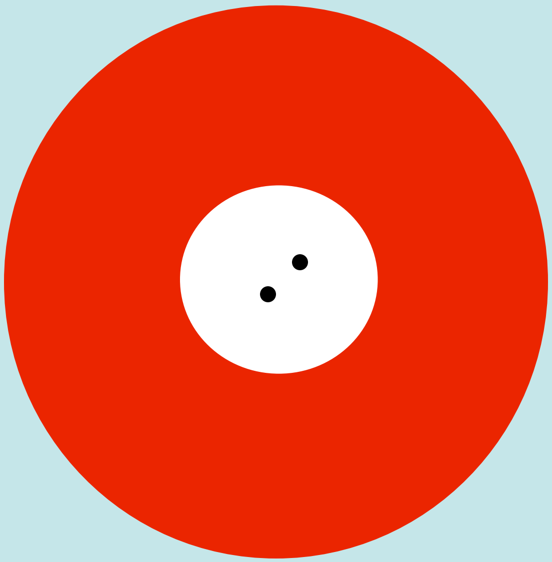
Spin of the primary could warp disk interior to the binary orbit, timescale for realignment uncertain (PN & Pringle 1998; Martin & Pringle 2007)

Opening up of a gap in the accretion disk and migration



A gap can open when the time scale for opening a gap of width Δr due to tidal torques becomes shorter than the time scale on which viscous diffusion can refill the gap.

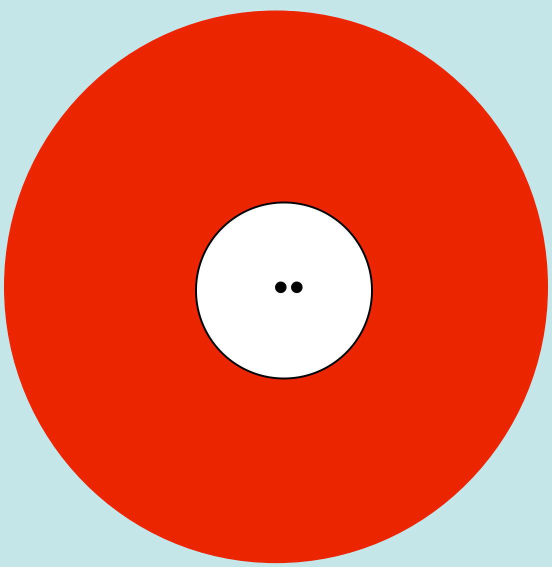
Stages of gas-driven mergers



Eventually: $t_{GW} < t_{decay}$

Gas ceases to be dynamically significant, but disk inner edge still moves in fast enough to keep up with binary

Typical scale: a_{crit}



And finally: $t_{GW} < t_{viscous}$

$t_{GW} \sim a^4$ $\quad$ $t_{viscous} \sim a^2$

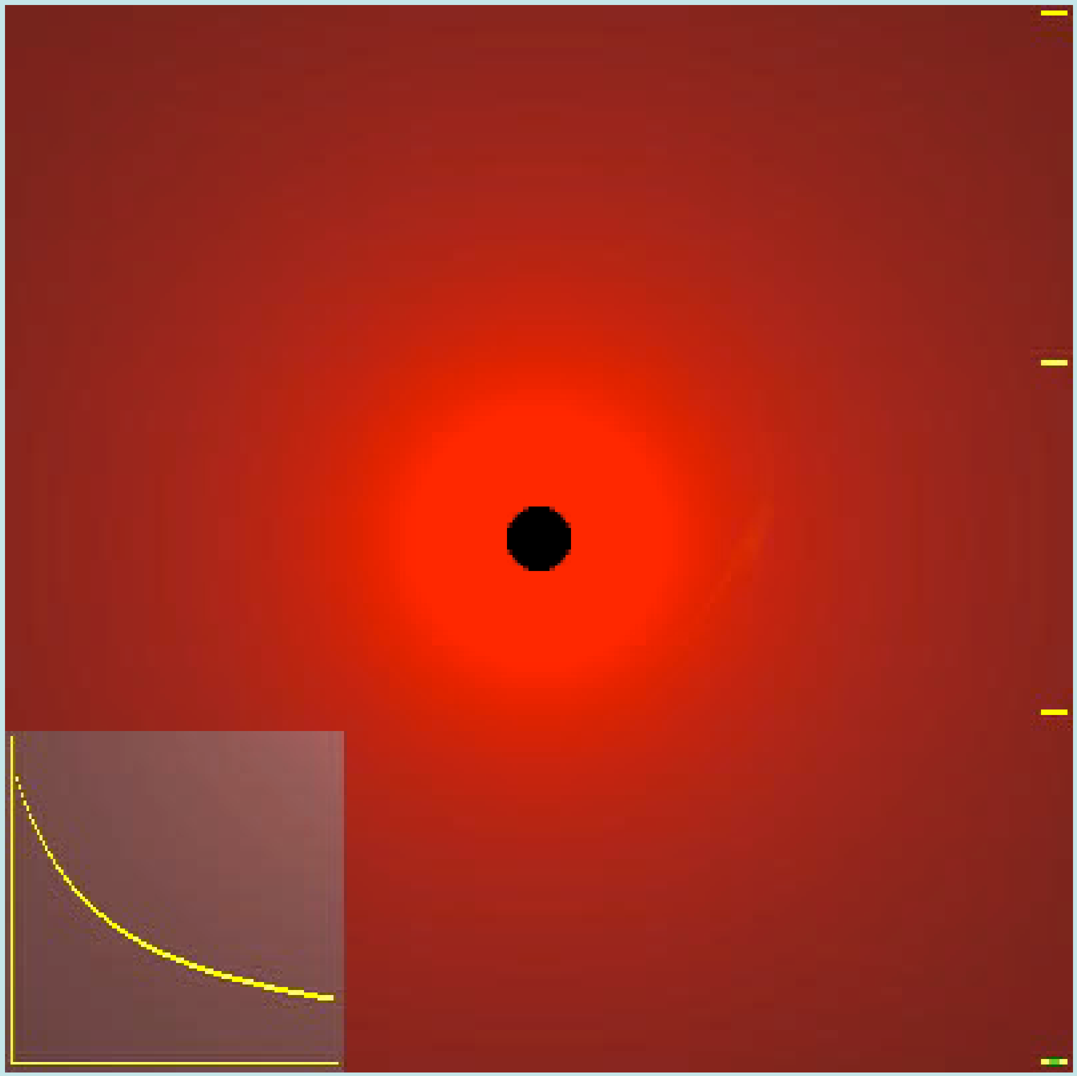
Gas can't keep up, binary merges while gas disk remains Frozen

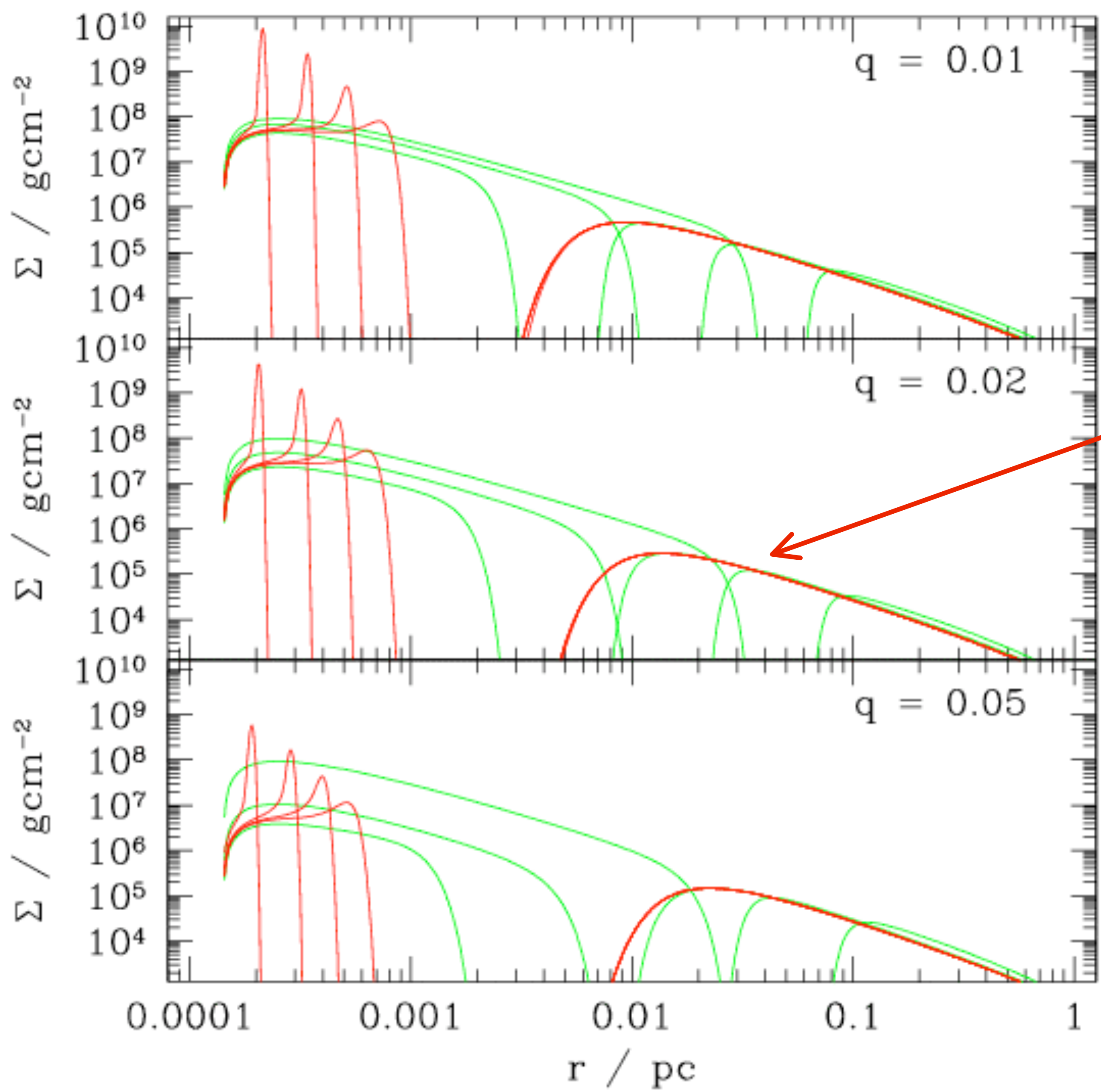
Typical scale: a_{detach}

Disk response to a perturber

- grows slowly, so that the disk is in almost a steady state
- from $q=10^{-5}$ to 10^{-2}
- 2D, hydro only using ZEUS (Eulerian-mesh code Stone & Norman)
- viscosity included such that alpha ~ 0.01 in the vicinity of the secondary.
- In movie: inset shows azimuthally averaged surface density profile.

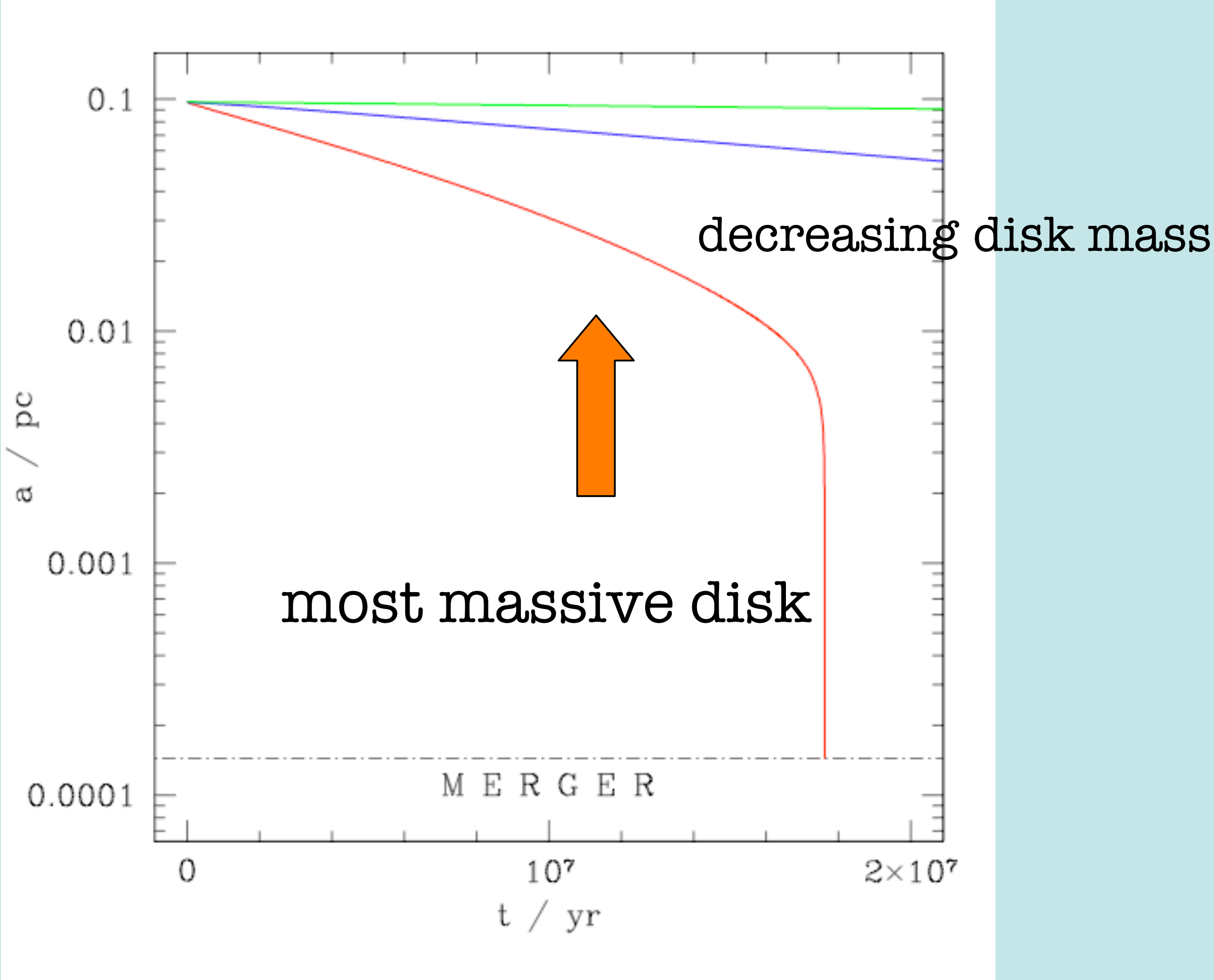
We are ignoring the evolution of the spins, precession effects, recoils





frozen circumbinary gas disk as binary merges

Armitage & PN 2002



$$t_{\rm merge} = \frac{1}{2c}\left(\frac{128}{5}\right)^{3/5}\left(\frac{h}{r}\right)^{-16/5}\alpha^{-8/5}q^{3/5}\left(\frac{GM_1}{c^2}\right)$$

Some typical numbers....

$q = 0.01$, $M_1 = 5 \times 10^8 M_{sun}$

Separation **a**

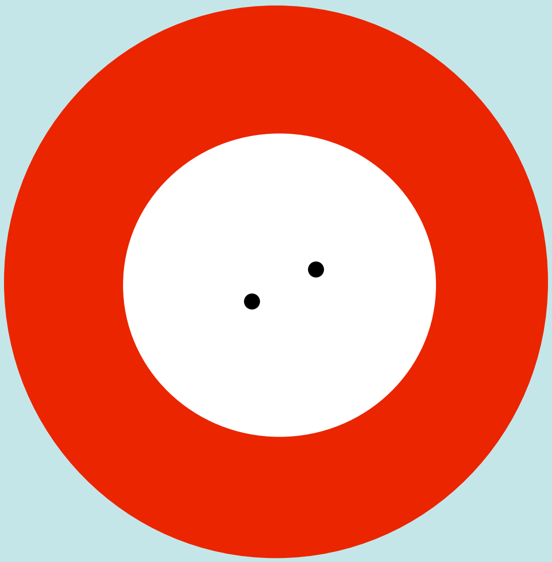
R_S a_{detach} a_{crit} $a_{hang\text{-}up}$

- Cold disk, alpha = 0.01
- $a_{hang\text{-}up} \sim 1 - 0.1$ pc
- $a_{crit} = 100\ GM_1/c^2 = 3.5 \times 10^{-3}$ pc
- $R_S \sim 2 \times 10^{-5}$ pc
- $t_{merge} \sim 10^7$ yr
- separation shrinks slower, disk driven migration still seen but not as efficient as for the hotter disk

- Hot disk, alpha = 0.2
- $a_{hang\text{-}up} \sim 1 - 0.1$ pc
- $a_{crit} = 5 \times 10^{-4}$ pc
- $R_S \sim 2 \times 10^{-5}$ pc
- $t_{merge} \sim 10^6$ yr
- separation shrinks faster, disk driven migration more efficient

NOTE: migration is less efficient for lower mass disks

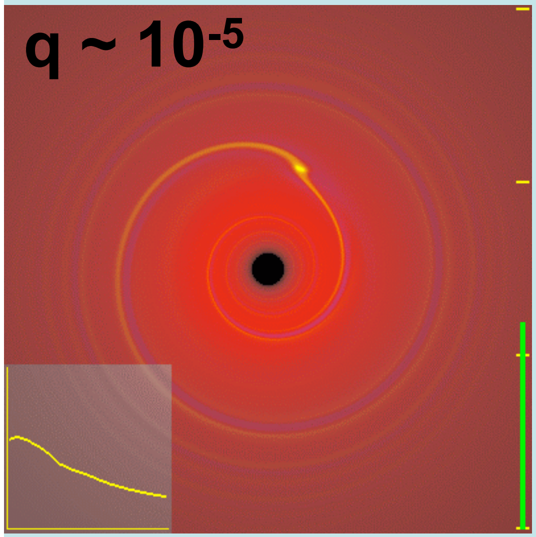
Stages of gas-driven mergers

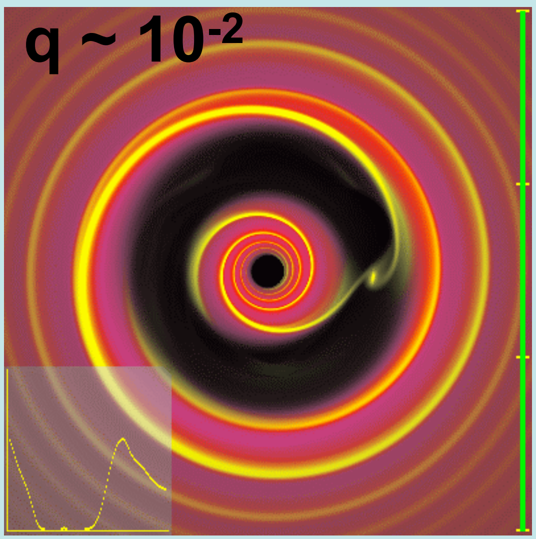


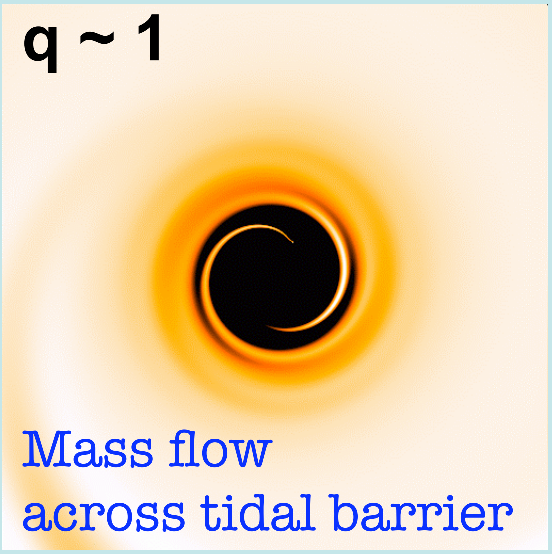
Binary orbits within hole in gas disk - loses angular momentum to gas through gravitational torques

$$\frac{t_{decay}}{t_{viscous}} \sim \left(\frac{M_{disk}(local)}{M_{secondary}}\right)^{\beta}$$

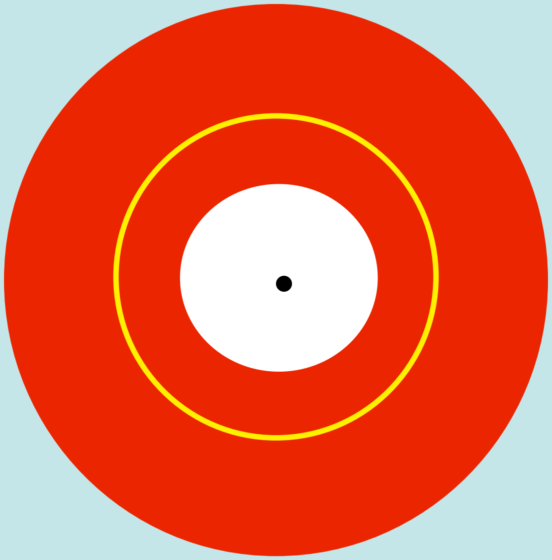
β ~ 0.5







Prompt EM emission?

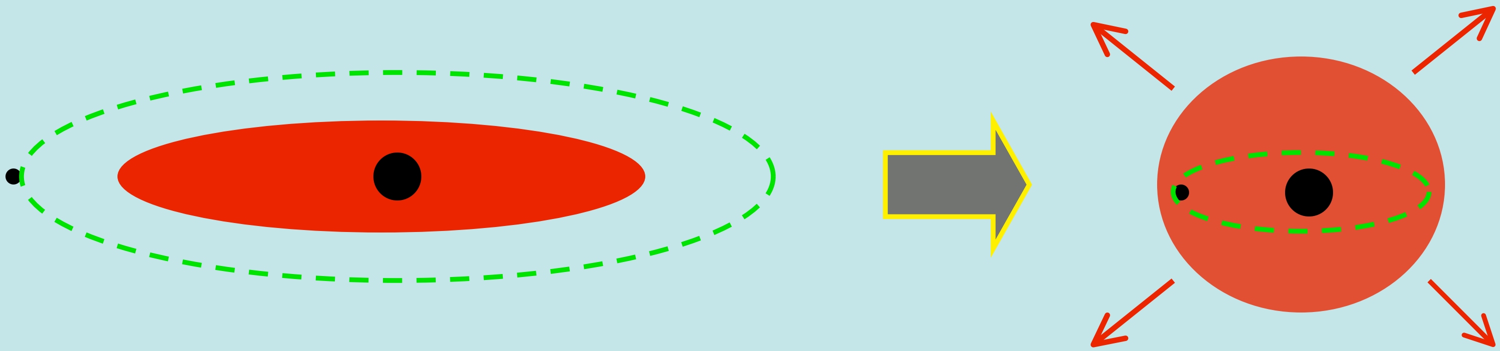


At merger, energy radiated in gravitational waves makes small change in potential (+ possible recoil)

→ Waves in surrounding gas which will dissipate on fraction of sound crossing time scale

Prompt (but small?) change in the thermal disk emission in the IR...

Precursors?



If one or both black holes have *individual* disks after time when gravitational waves dominate inspiral:

- gas is driven inward until Eddington limit exceeded
- binary merges within thick “common envelope”
- obscured, variable X-ray precursor

Or

perhaps X-ray afterglows, if gas is present, disk cavity (few x 10^2 GM/c^2) will be refilled viscously post-merger (Milosavljevic & Phinney 2005)

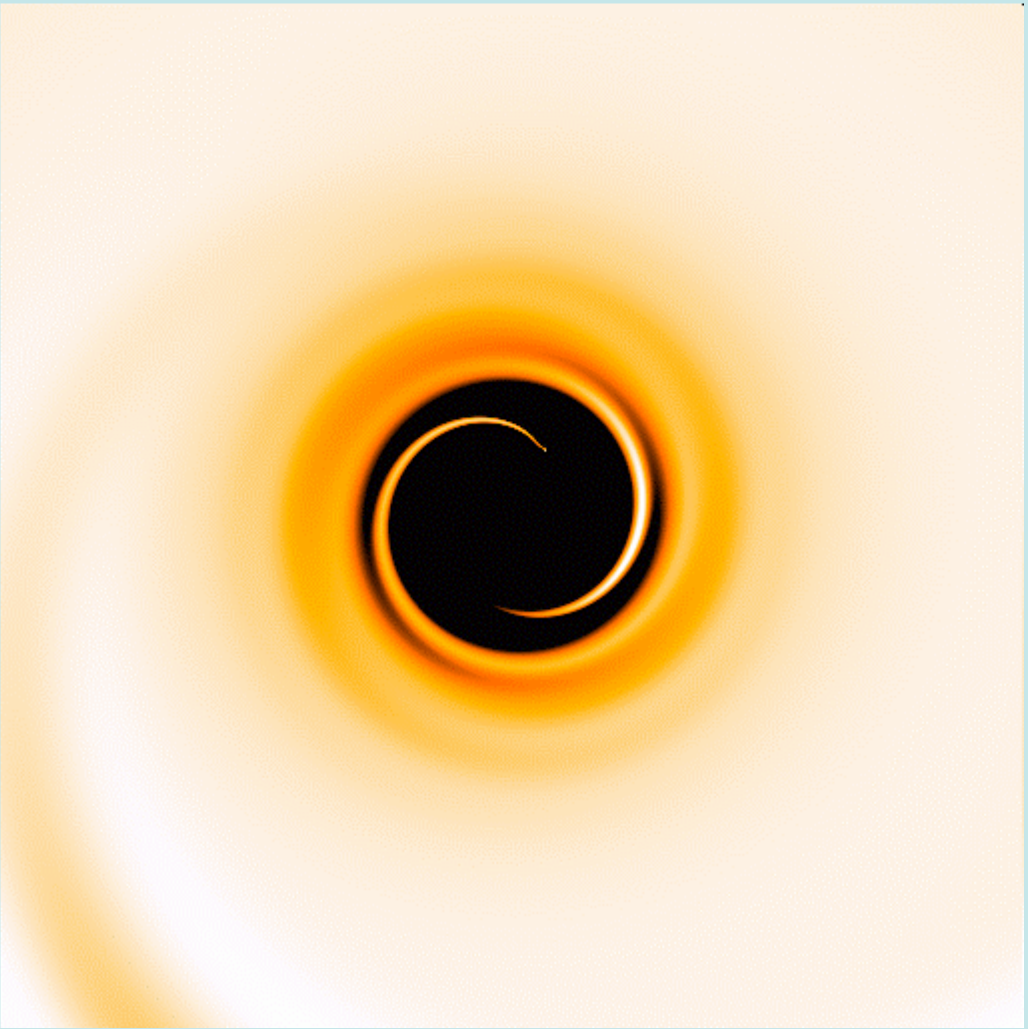
Whether this happens depends on disk structure in radiation pressure dominated regime…

Armitage & PN 2002

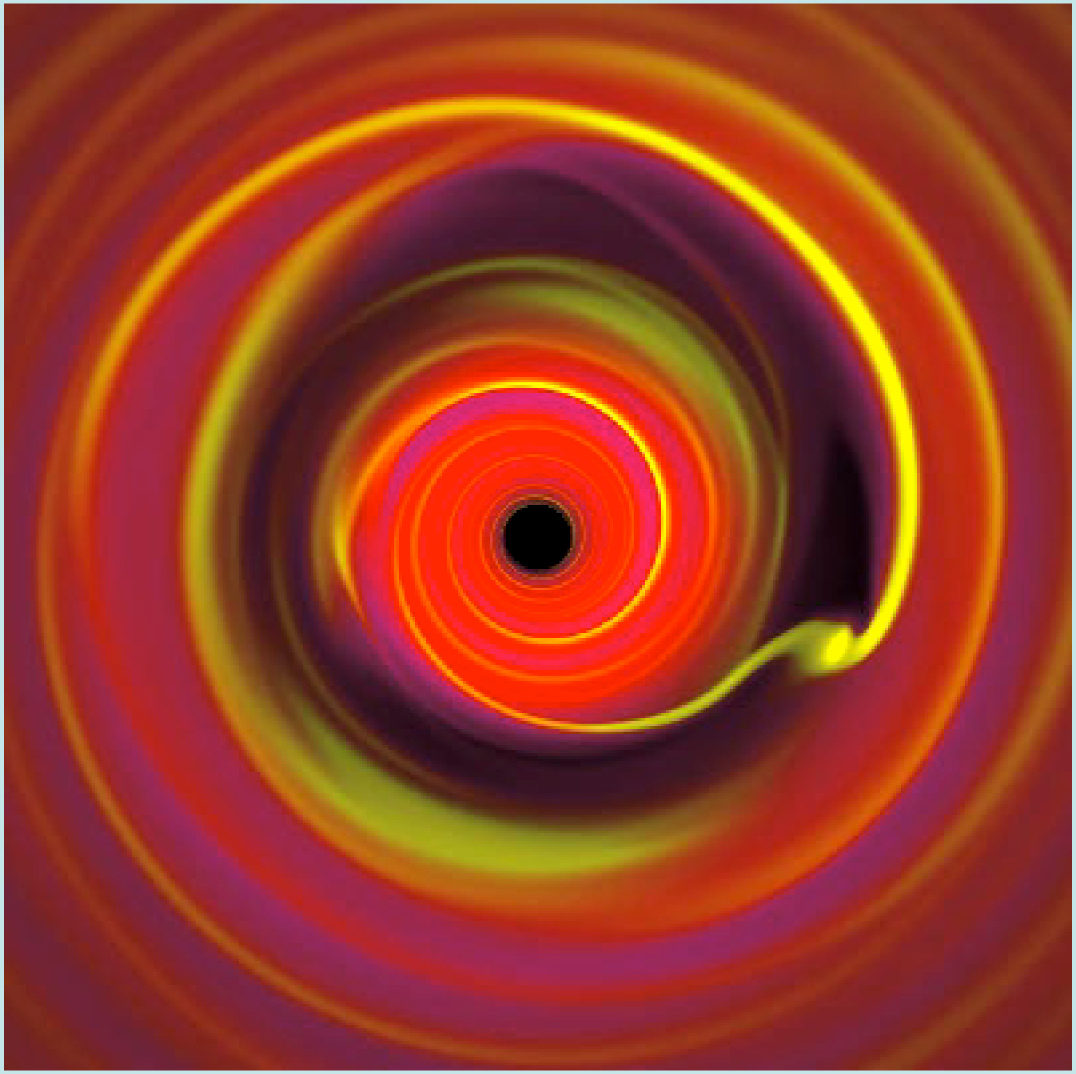
Evidence of merger cause in gravitational waves?

If gas disk drives merger, expect that interaction excites eccentricity of both binary and gas disk

Understood as a consequence of tides clearing gas from nearby resonances
e grows easily for
$q > q_{crit}(h/r)$

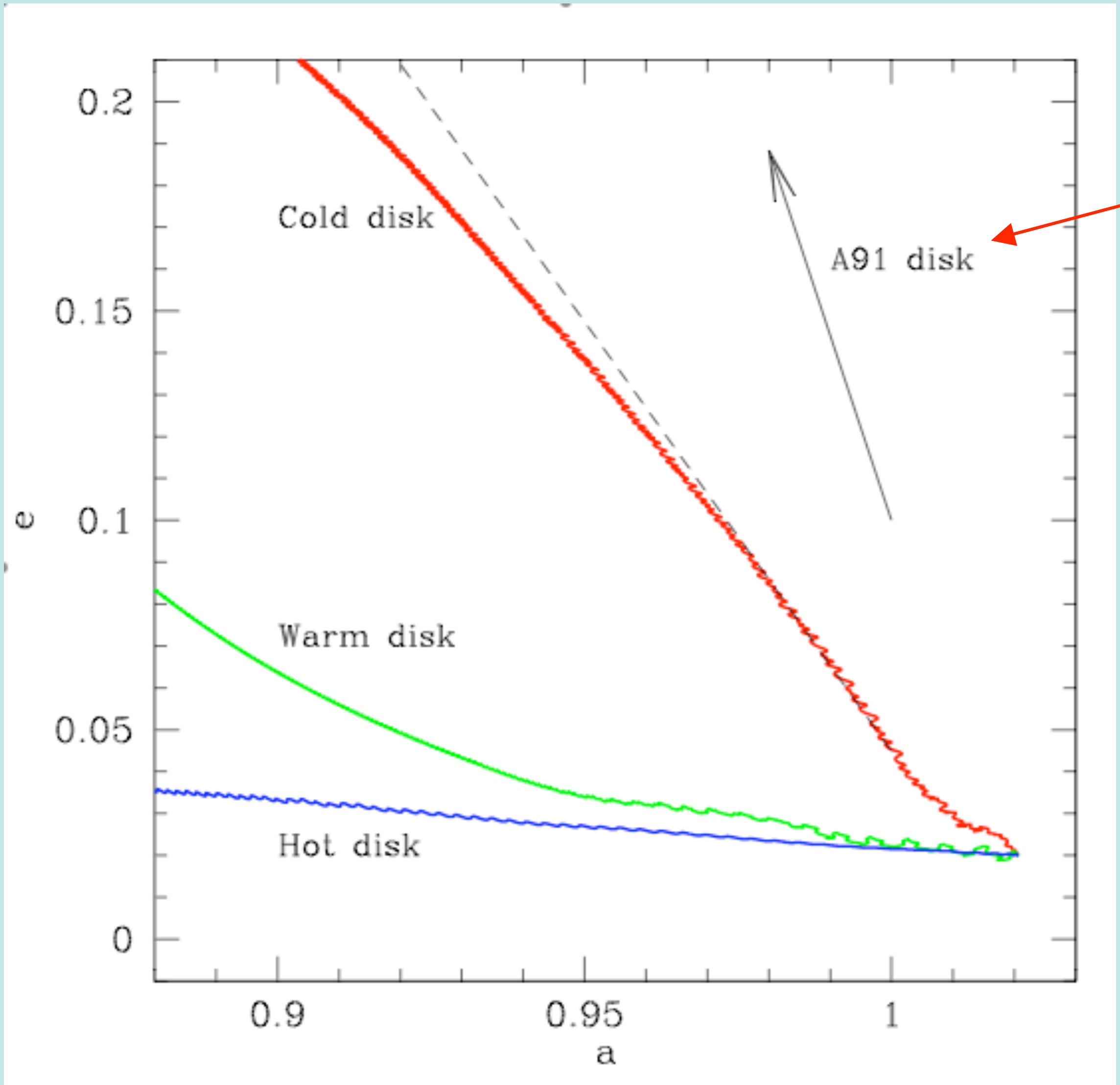


Strting with a modestly eccentric orbit



same general behavior as before..

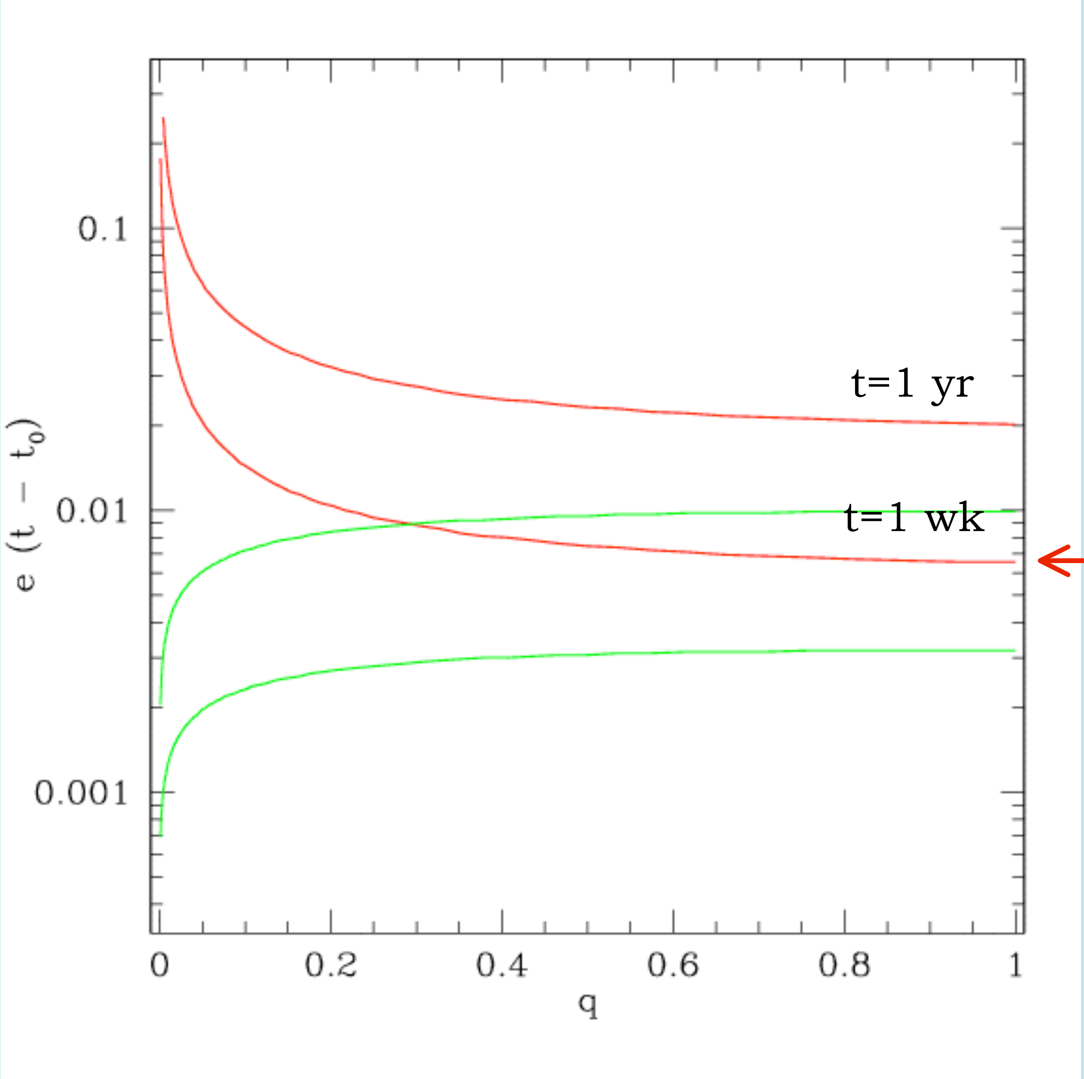
Evolution of the eccentricity



effect seen in SPH simulations of circumbinary disks by Artymowicz et al. (1991)

Highest initial e growth for coolest, thinnest disk

Eccentricity will damp once disk dynamically unimportant, small eccentricity may survive until immediate pre-merger



Transition occurs close to gas / radiation pressure boundary in disk

10^6 Solar masses, merger - 1 week

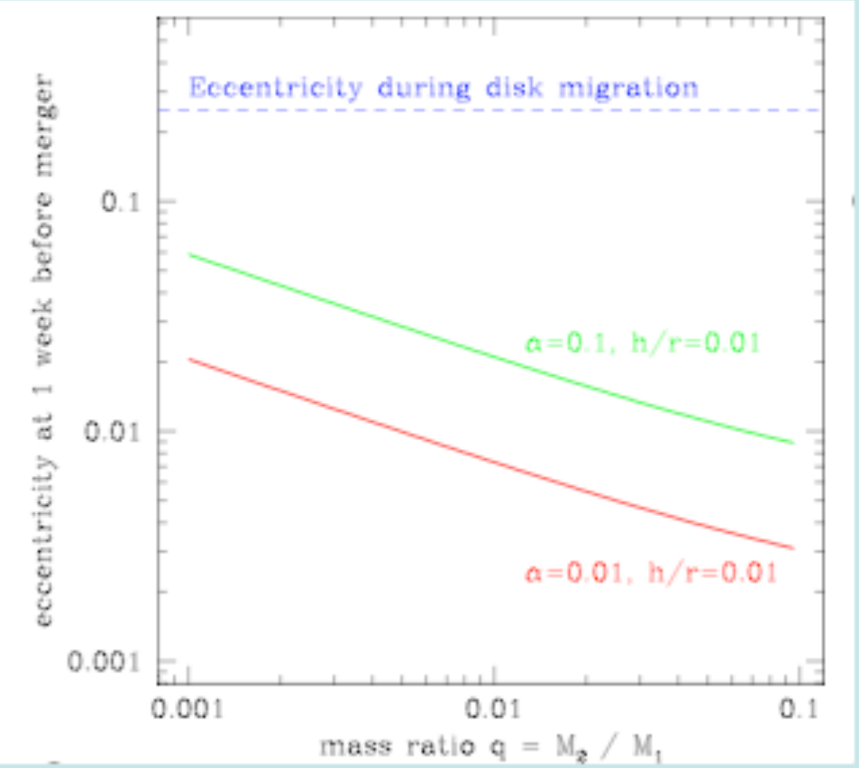
Stronger effect for extreme mass ratios

alpha = 0.01, e_init = 0.25 (gas driven stage), M_1+M_2= 10^6

Armitage & PN (2005)

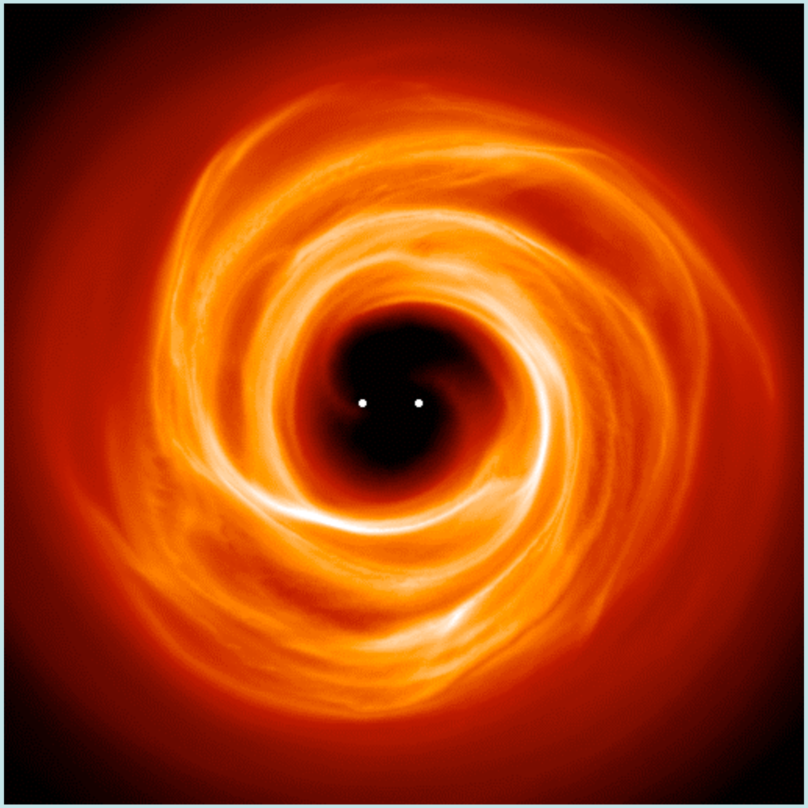
Consequences for gravitational radiation

- Disk torques are negligible during final spiral for all mass ratios
- e if excited during disk interactions for low q, may not have time to damp to negigible final values
- Assume e = 0.25 for $a > a_{crit}$
- For $a < a_{crit}$ e is damped by gravitational radiation
- Small but non-zero e ~0.01 rising to more extreme mass ratios appears plausible



Higher resolution 3D simulation of self-gravitating disk with initial e

- More physical scenario; with self-gravitating disk ~100 pc; confirms earlier result of PJA & PN
- Eccentricity grows in the binary
- e(a) independent of M_{disk}
- Confirmed for a range of mass ratios



Cuadra+ 2007

Eccentricity growth is robust

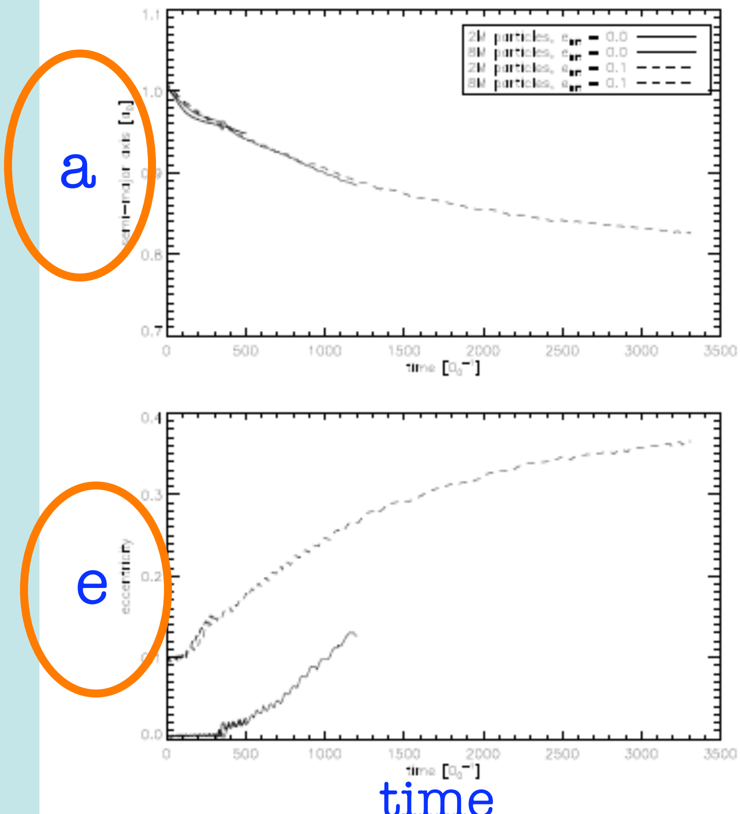


Figure 8. Evolution of the binary orbit elements a (top panel) and e (bottom) for the different simulations. Solid lines show simulations with the binary in an initially circular orbit, while dashed lines show binaries with $e = 0.1$ initially. In both cases the eccentricity grows, and the orbital decay proceeds at the same rate. Thicker lines show shorter simulations with higher resolution that agree remarkably with the standard runs.

- For a given mass ratio, in a cold disk (alpha is lower); e grows more rapidly while the decay rate for a is slower
- For cold disks there does not appear to be a saturation value for e
- In contrast a decays most rapidly for the hottest disks
- Caveat -- migration rate in the radiation pressure dominated disk is uncertain

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- $R_S \sim 2 \times 10^{-5}$ pc
- $t_{merge} \sim 10^6$ yr
- e grows slower, separation shrinks faster

Counter-parts signaling BBH mergers

- Gas in galactic nuclei remains a plausible sink of binary angular momentum

- Final eccentricity before merger (Armitage & PN) if disks catalyze low mass ratio binary mergers, binary-gas interaction excites eccentricity, which is damped to $e \sim 0.01$ shortly prior to coalescence, LISA sensitive to $e \sim 10^{-4}$ (Barack & Cutler 2004)

- Electromagnetic counterparts: precursors and afterglows (Armitage & PN; Milos & Phinney; Dotti+); X-ray afterglows challenging to detect

- On longer timescales impulsive changes to the final BH spin following merger (Hughes & Blandford)

- Changes in directions of jets launched (Merritt & Ekers)