

# Gas Dynamics of Black Hole Binary Mergers

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- Merger physics on sub-pc scales
- Limits to the disk mass on “large” ( $\sim 10^{-2}$  pc) scales?
  - relevant to “last parsec” problem, EM counterparts due to black hole kick
- Importance of disk *vertical* structure on small scales ( $\sim 10^{2-3} R_s$ ) for EM counterparts due to mass loss

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## Disk conditions at $r \ll 1$ pc

Scales: radius where gravitational wave angular momentum loss dominates, irrespective of disk properties

$$r \sim 10^2 \frac{GM_p}{c^2} \sim 5 \times 10^{-6} \left( \frac{M_p}{10^6 M_{sun}} \right) \text{ pc}$$

Scales: radius where gravitational waves become inefficient

$$a \approx 5 \times 10^{-4} \left( \frac{M_p}{10^6 M_{sun}} \right)^{3/4} \left( \frac{t_{gw}}{10^8 \text{ yr}} \right)^{1/4} f(q) \text{ pc}$$

Scales: radius where disk rotational velocity equals *post-merger* kick velocity

$$r \approx 0.02 \left( \frac{M_p}{10^6 M_{sun}} \right) \left( \frac{v_{kick}}{500 \text{ km/s}} \right)^{-2} \text{ pc}$$

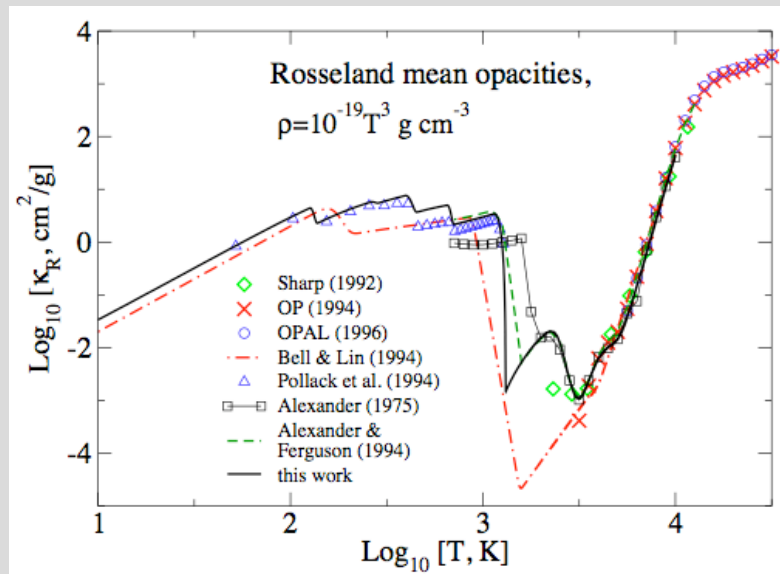
# Relevant disk physics

“Last parsec” problem and predictions for EM counterparts are conceptually distinct: involve different disk physics

		Typical disk mass?	Self-gravity	Viscosity: small $r$	Inviscid hydro response	Radiative properties
<b>EM counterparts</b>	<b>Last parsec problem</b>					
	<b>Precursors</b>					
	<b>Viscous refilling</b>					
	<b>Mass loss</b>					
	<b>Radiation recoil</b>					

# Disk conditions at $r \ll 1$ pc

Surface density of 0.01 pc disk with  $10^3 M_{\text{sun}}$  of gas  $\sim 10^3 \text{ g cm}^{-2}$



→ dynamically important disk will be optically thick, able to cool efficiently

*Semenov et al. (2003)*

Limit luminosity to Eddington limit, for  $10^6 M_{\text{sun}}$  black hole characteristic  $T \sim 4000 \text{ K}$

Sound speed  $\sim 7 \text{ km s}^{-1}$ , vs orbital (“virial”) velocity  $\sim 700 \text{ km s}^{-1}$

→ Rotationally supported disk will be geometrically **thin**

$$\frac{h}{r} = \frac{c_s}{v_{\text{Kep}}} \sim 0.01$$

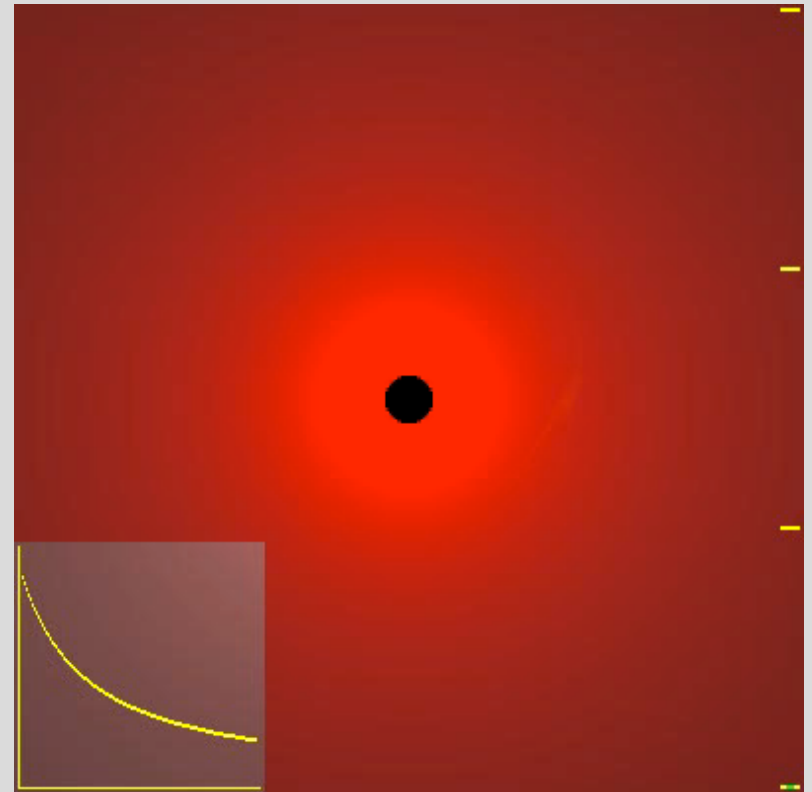
# Dynamics of binary-disk interaction

Binary will resonantly truncate circumbinary disk if torque from binary exceeds “viscous” torque in disk

e.g. for 2:1 OLR of circular binary, need mass ratio:

$$q \geq \frac{2^{9/2}}{3\pi^{1/2}} \alpha^{1/2} \left( \frac{h}{r} \right)$$
$$\geq 5 \times 10^{-3} \left( \frac{\alpha}{0.01} \right)^{1/2} \left( \frac{h/r}{0.01} \right)$$

*Lubow & Artymowicz (1994)*



**Massive binaries will open a gap or inner cavity in the disk, intermediate mass black holes remain fully embedded**

# Dynamics of binary-disk interaction

Low mass (IMBH) interaction is not well understood

Dissipative IMBH / disk interactions will damp isotropic population of IMBHs into disk plane (**BUT** competition with inclination resonances that excite  $i$ ) c.f. *Lubow & Ogilvie (2001)*

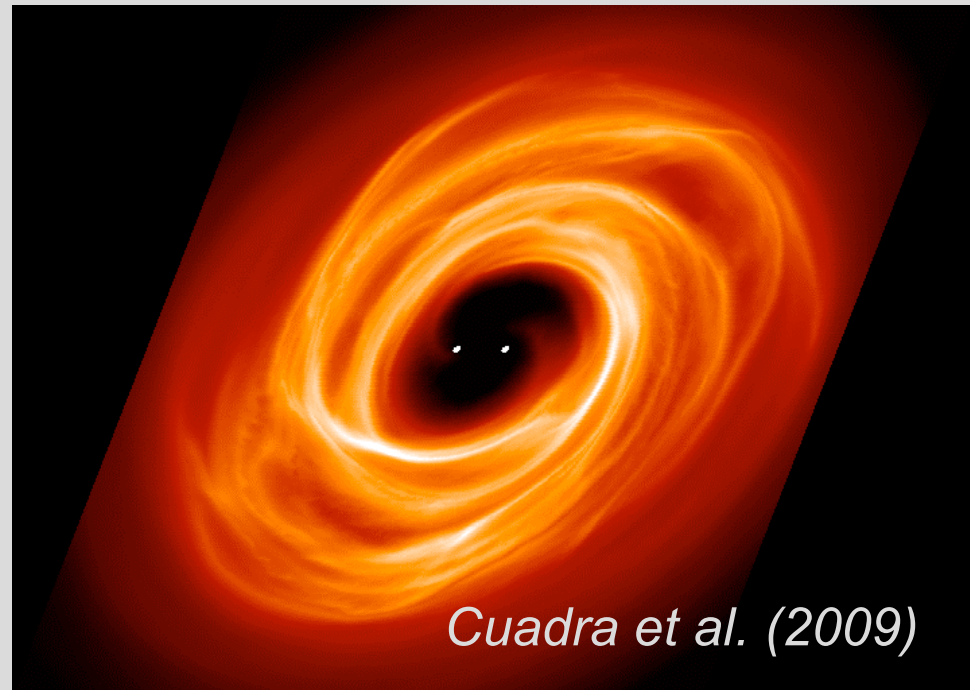
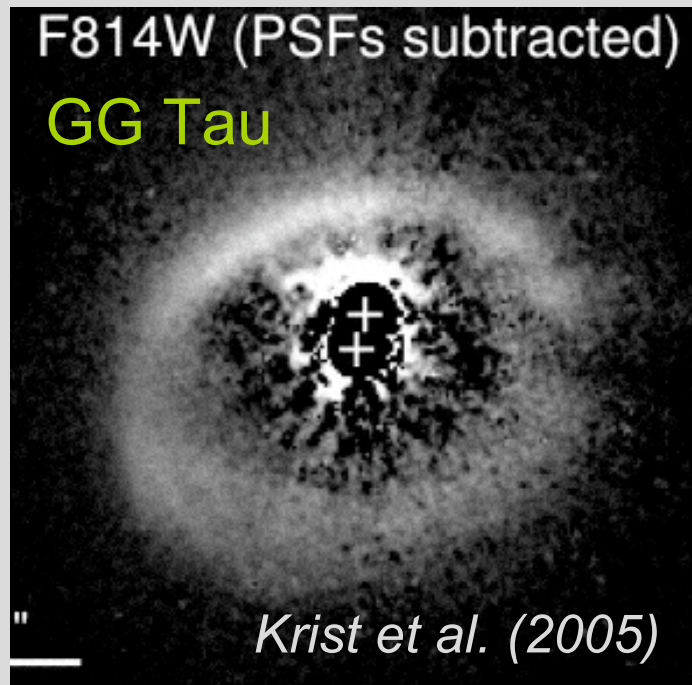
Once in the disk plane, in regime of “Type I” migration

Long thought to be **inward** and **rapid**, recent work suggests may be **outward** and **rapid** in optically thick disks (*Paardekooper et al. 2010*)

**Implications for gas-driven EMR inspiral rate???**

# Dynamics of binary-disk interaction

Evolution of massive binaries within gas disks...



- binary opens a cavity within gas disk
- some accretion normally continues onto disks around individual black holes
- binary orbit shrinks as angular momentum is lost to gas

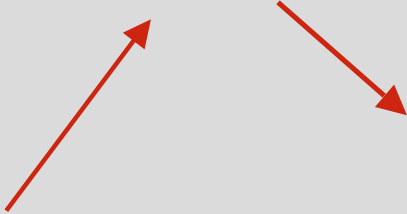
# Merger dynamics within gas

Timescales:

**Gravitational wave merger time**  $t_{gw} = t_{gw}(M_p, q, e)$

**Disk viscous timescale**  $t_v = \frac{1}{\alpha\Omega} \left(\frac{h}{r}\right)^{-2}$

**Binary decay timescale**  $t_{decay} \sim \frac{M_s + M_{disk}}{M_{disk}} t_v$


$$M_{disk} = 4\pi a^2 \Sigma(a)$$

Scaling depends on porosity of tidal barrier, disk physics, history of system (*Syer & Clarke 1995; Ivanov et al. 1999; Lodato et al. 2009*)

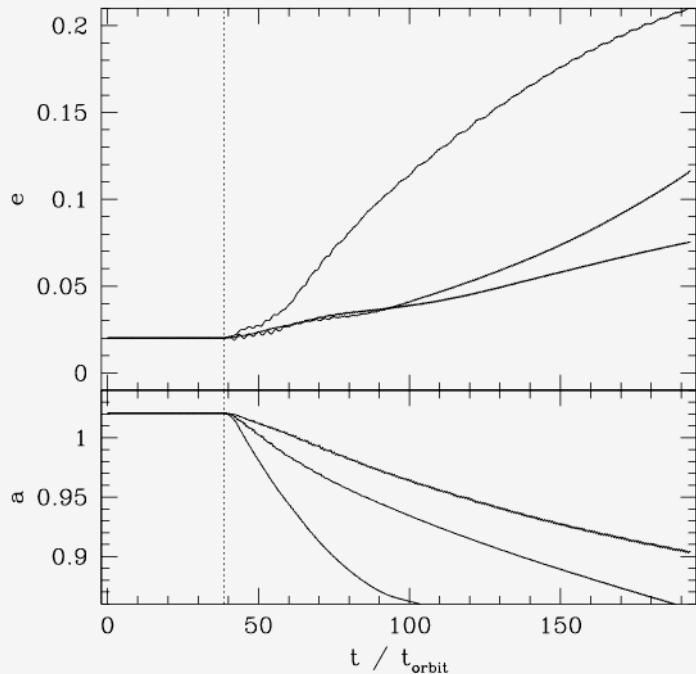
# Merger dynamics within gas

$t_{\text{decay}} < t_{\text{gw}}$ : disk drives merger

$M_p = 10^6 M_{\text{sun}}$ , binary separation 0.01 pc

$$t_{\text{decay}} \approx 1.5 \times 10^8 \left( \frac{M_s / M_{\text{disk}}}{100} \right) \left( \frac{\alpha}{0.1} \right)^{-1} \left( \frac{h/r}{0.01} \right)^{-2} \text{ yr}$$

...merger possible if disk is not very low mass / very thin



**Expect binary eccentricity to rise during disk driven merger phase, though not to  $e \sim 1$  (Artymowicz et al. 1991)**

*Armitage & Natarajan (2005); Cuadra et al. (2009)*

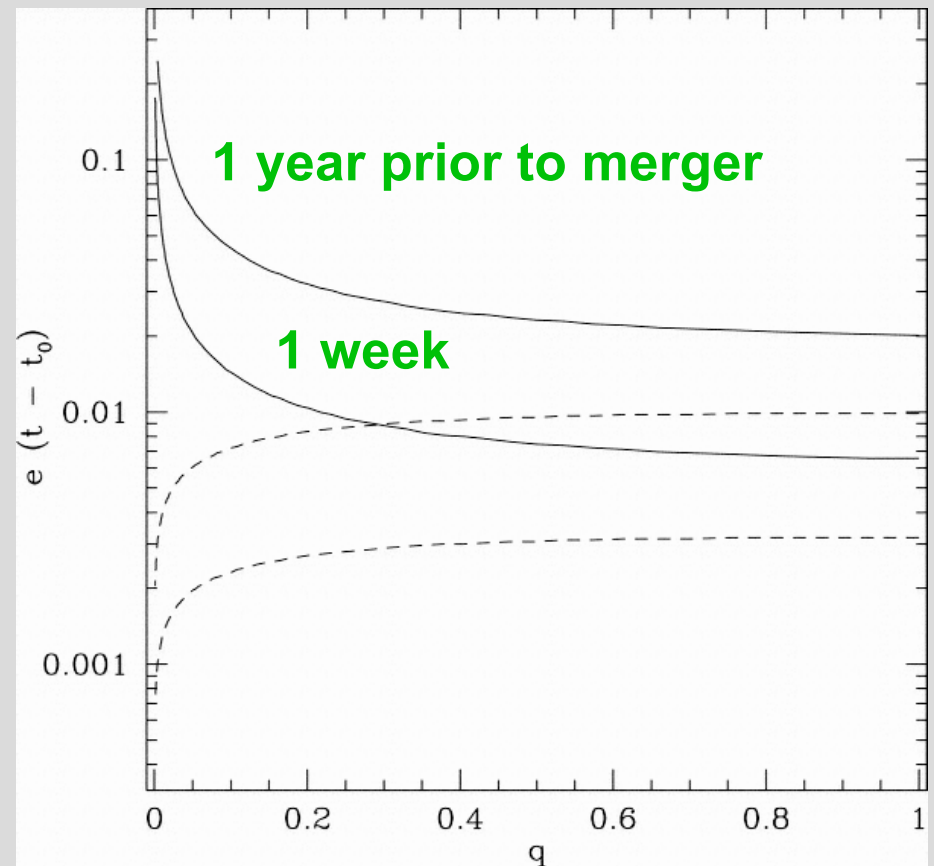
# Merger dynamics within gas

$t_v < t_{\text{gw}} < t_{\text{decay}}$ : gas disk follows merger

angular momentum loss predominantly via GW, but gas flows inward fast enough to maintain tidal contact with binary. Eccentricity damps.

Eccentricity damps to  $e \sim 10^{-2}$  (at most) for  $q \sim 1$  systems, but would be larger for unequal mass ratios

*Armitage & Natarajan (2005)*



# Merger dynamics within gas

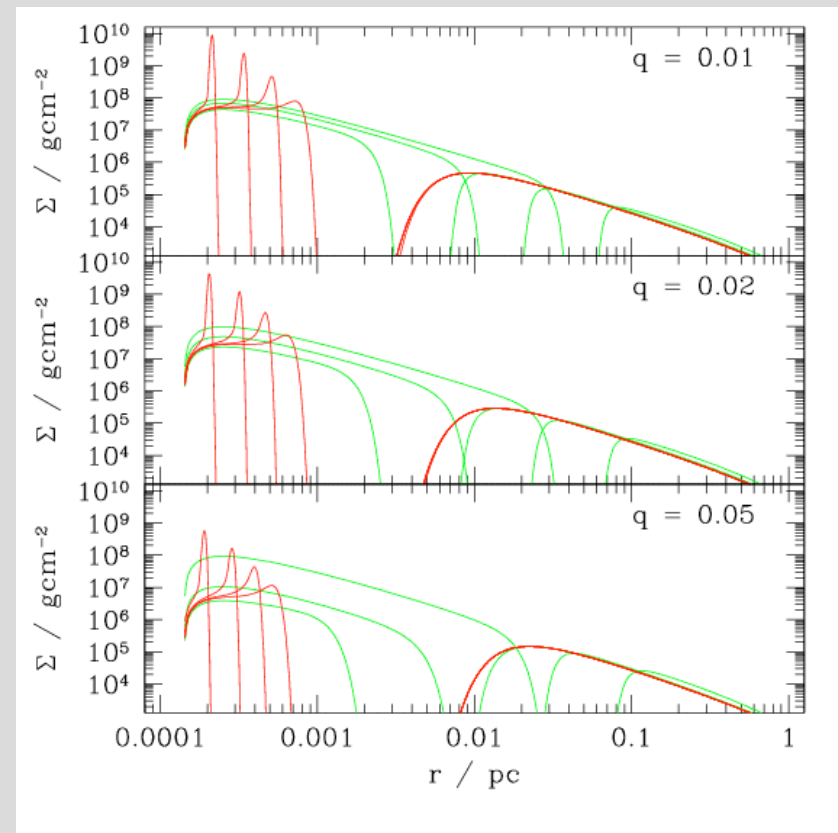
$t_{\text{gw}} < t_{\text{v}}$ : decoupling

gas disk remains “frozen” as final merger proceeds within low density cavity of scale

$$r \approx 120 \frac{GM_p}{c^2}$$

Any gas surviving in either circumprimary / circumsecondary disks will be tidally squeezed and heated: possible **EM precursor**

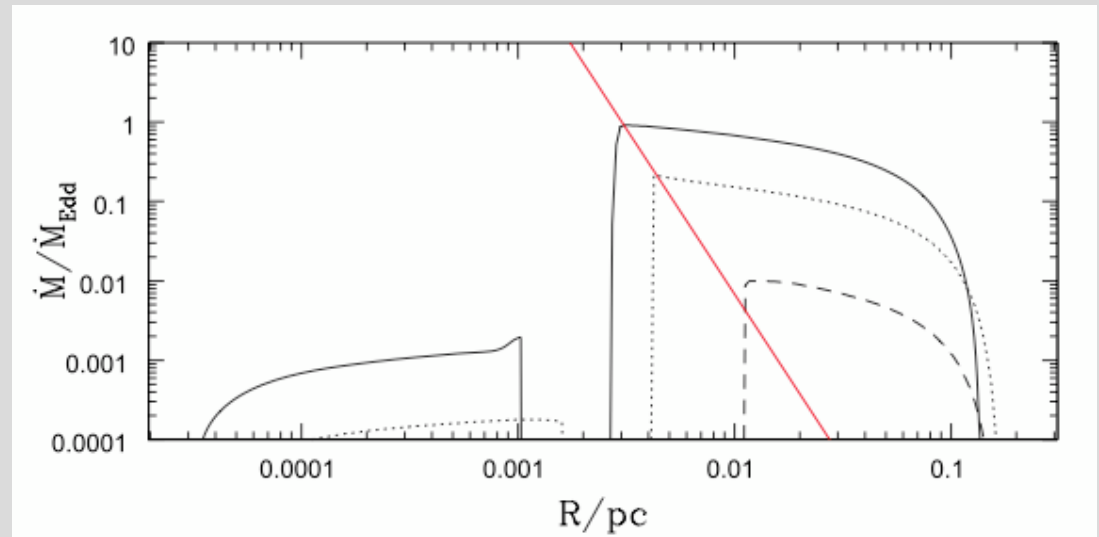
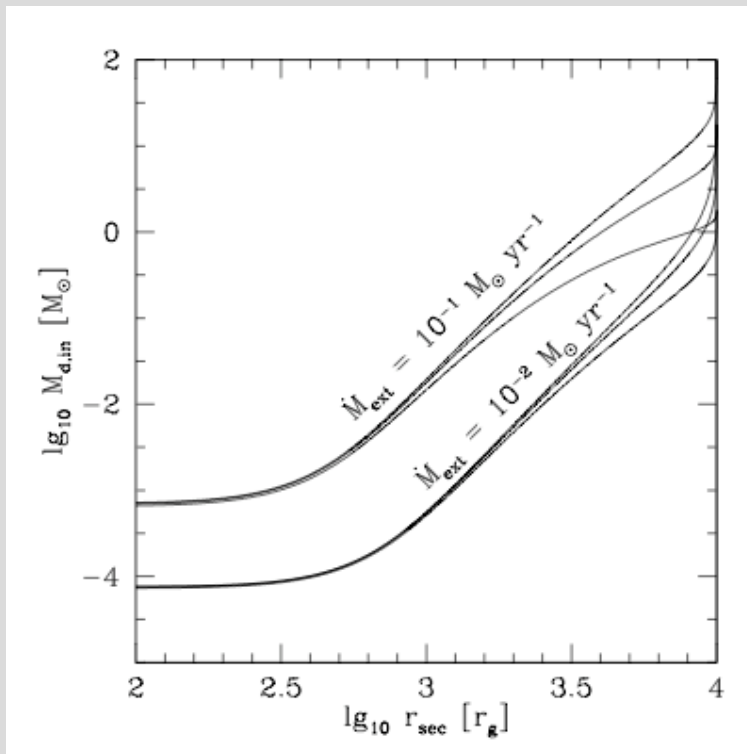
*Armitage & Natarajan (2002)*



*Milosavljević & Phinney (2005); Lodato et al. (2009);  
Chang et al. (2009); Tanaka & Menou (2010)*

# Merger dynamics within gas

Small amounts of gas may survive around black holes



*Lodato et al. (2009)*

*Chang et al. (2009)*

+ merger-driven accretion of  $\sim 10^{-3} M_{\text{sun}}$  during last 25 GM /  $c^2$  of inspiral is enough to exceed Eddington limit

- existence of even this trace of gas depends on details of disk viscosity on small scales / low surface densities

## Limits to the large-scale disk mass

Instability of disk to **fragmentation** (into stars) appears to limit viability of gas-driven mergers / luminosity of afterglows powered by kick-driven accretion

Gas disk becomes *gravitationally unstable* when:

$$Q = \frac{c_s \Omega}{\pi G \Sigma} < 1$$

Equivalent to condition:  $\frac{M_{disk}}{M_{BH}} > \frac{h}{r}$

**OK: self-gravitating disk *can* stably transport angular momentum, with sizeable  $\alpha \sim 0.1$**

**BUT gas disk on 0.01 pc scales cannot have large  $h / r$  without violating Eddington limit, hence can't have arbitrarily large mass**

# Limits to the large-scale disk mass

Gravitationally unstable disk *fragments* if its cooling time is shorter than the dynamical time

$$t_{cool} = \frac{U}{2\sigma T_{eff}^4} < \beta\Omega^{-1} \quad \text{with } \beta \sim 5 \text{ (Gammie 2001; Rice et al. 2003; Rice, Lodato \& Armitage 2005)}$$

Expect fragmentation (independent of opacity) when:

$$\Sigma > \Sigma_{crit} = (\pi G)^{-6/5} \left[ \left( \frac{k_B}{\mu m_p} \right)^4 \frac{1}{2\sigma\beta(\gamma-1)} \right]^{1/5} \Omega^{7/5} \quad \text{(Rafikov 2005; Levin 2007)}$$

**At 0.01 pc around  $10^6 M_{sun}$  BH,  $\Sigma_{crit} \sim 400 \text{ g cm}^{-2}$**

**Implies  $M_{disk} / M_{BH} < 10^{-3}$ , and that  $h / r < 10^{-3}$**

**Gas driven mergers need to *start* with the black holes already at small separation, or decay time scale is too long**

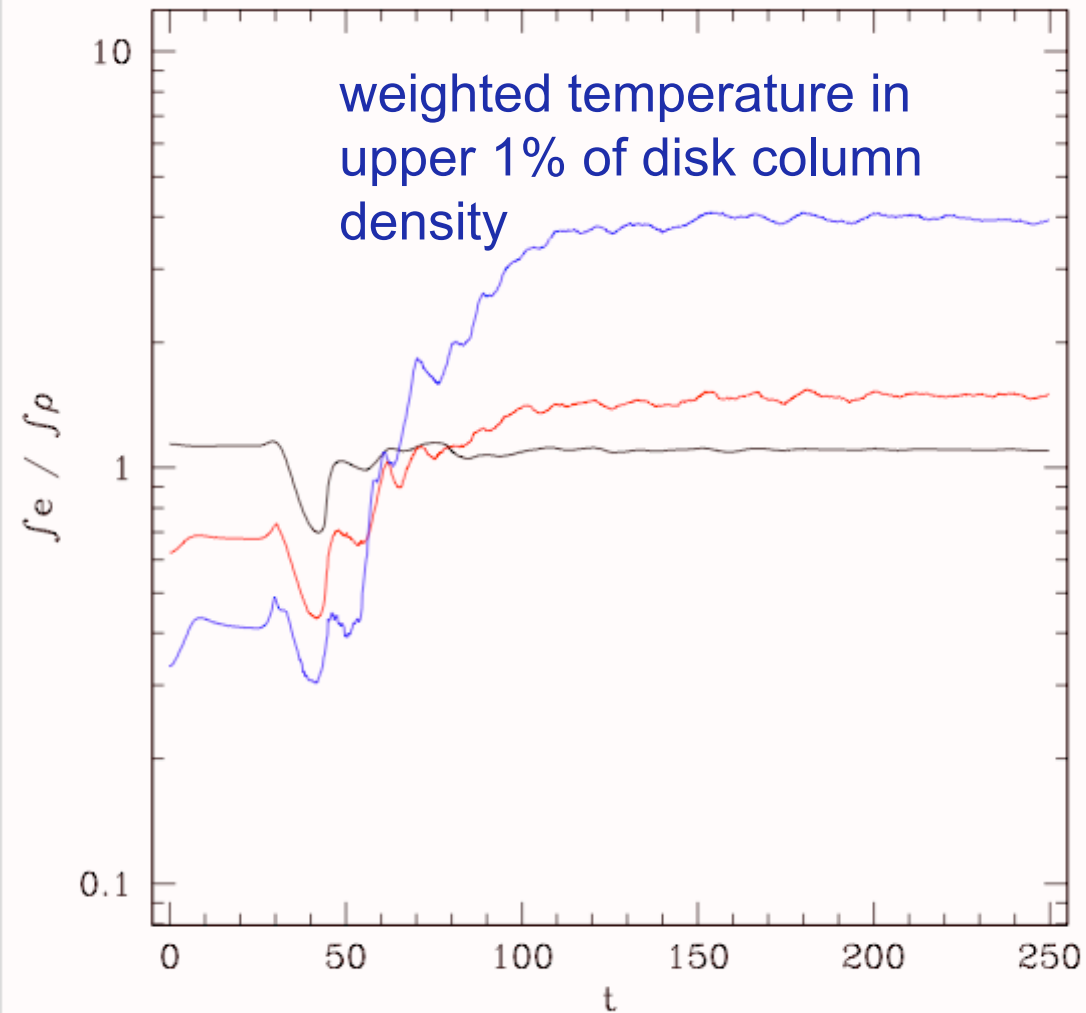
# Importance of disk vertical structure

Mass loss / recoil kick upon merger can generate afterglows if merger occurs within gas:

- set up waves within disk
  - $m = 0$  (mass loss, kick perpendicular to disk)
  - $m = 1$  (kick directed into disk plane)
- dissipation of these waves heats disk and generates afterglow (though **accretion** induced by kick can be more important e.g. *Rossi et al. 2010*)

**Although *perturbations* are (at most) 2D (axisymmetric or in-plane), disk *response* is always 3D unless the disk is vertically isothermal - which it is not...**

**In non-isothermal disks, wave energy is channelled toward disk atmosphere and dissipation predominantly occurs at  $\tau \sim 1$  (c.f. *Bate et al. 2002*)**



Wave energy dissipation is *not* proportional to gas density

Dissipation is greatly enhanced in disk surface layers

*Rossi, Armitage & Lodato, in prep*

**Preliminary: afterglows from kicks and mass loss on small scales may involve harder emission components**

## Open questions...

**Can fragmentation limit on disk mass be evaded?**

**Does gas at  $r < 10^{-2}$  pc attend mergers if gas does *not* play a dynamical role?**

**Are there “vacuum” EM counterparts from hot ( $\sim$ virial T) accretion flows / magnetic fields anchored to the holes?**

**How do low mass BHs (stellar / intermediate mass) grow and / or migrate within gas disks?**

**Is there an EM precursor from tidally squeezed disks?**

**Do we understand disk physics enough to predict the spectra of afterglows from kicks, mass loss, or viscous evolution?**