$$\dot{M}_{wind} \sim 4 \times 10^{-10} \, \Phi_{ion_{41}}^{1/2} \, M_{*_{\odot}}^{1/2} \, M_{\odot} \, yr^{-1}$$

40 Myr to evaporate even min. mass solar nebula

- low! Shu et al 1993 suggested consequences for envelope masses of giant planets

i.e effects at $\gtrsim r_G$

- picture changes when combine this wind prediction with secular ("viscous") evolution of disc: (Clarke, Gendrin + Sotomayer 2001)

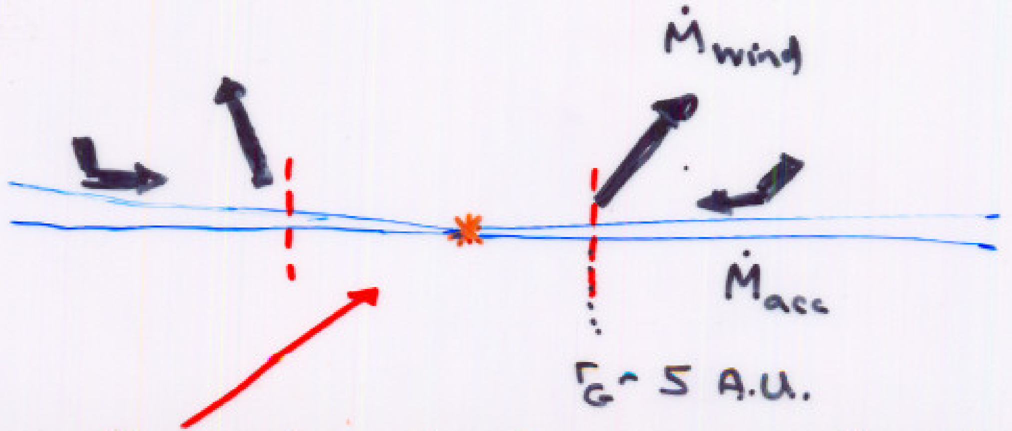
$$\dot{M}_{acc} \gg \dot{M}_{wind}$$

wind negligible

time

$$\dot{M}_{acc} \sim \dot{M}_{wind}$$

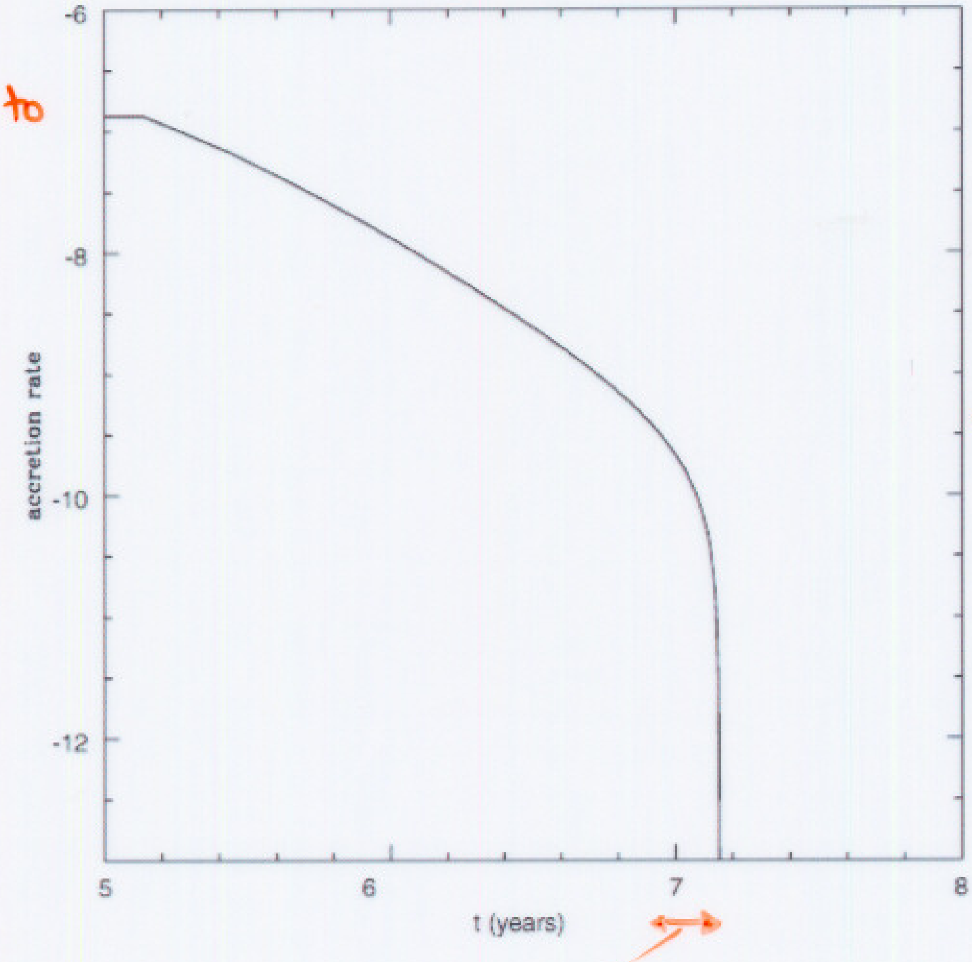
rapid draining of $\boxed{\text{inner}}$ disc



inner disc starved of re-supply: drains on $t_\nu(R_G)$.

← set by $t_\nu(R_{\frac{1}{2}})$ →
in phenomenological viscosity model

$\dot{M}$ on to star



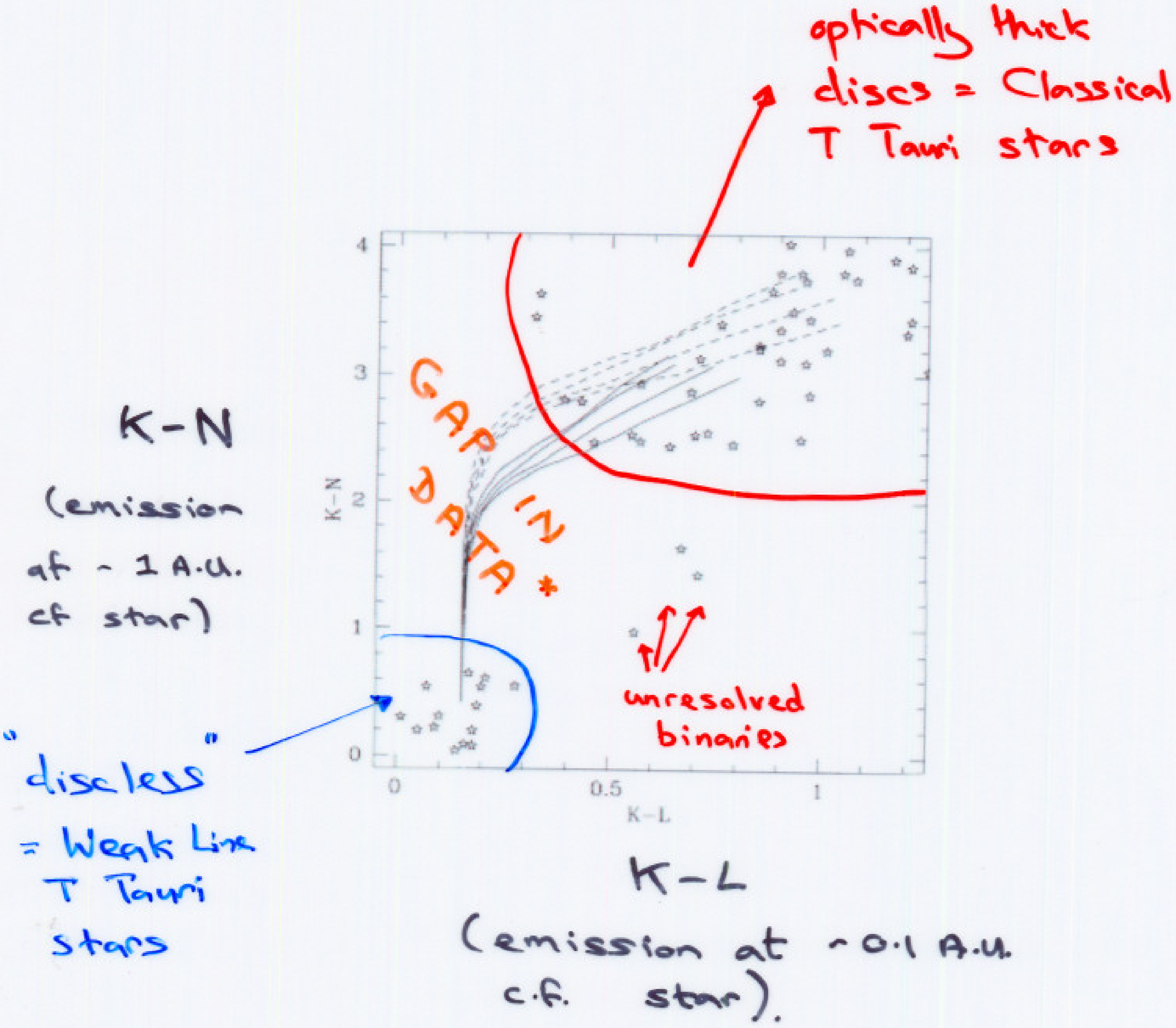
← $\dot{M}_{wind}$

set by $t_\nu(R_g)$ in phenomenological viscosity model.

Clarke et al 2001.

* ⇒ inner disc must drain QUICKLY cf lifetime in either CTT or WTT state

(early refs: Skrutskie et al 1990
Hartigan et al 1990).



optically thick discs = Classical T Tauri stars

GAP IN DATA *

unresolved binaries

"discless" = Weak Line T Tauri stars

K−N (emission at ~ 1 A.U. cf star)

K−L (emission at ~0.1 A.U. c.f. star).

data from Kenyon and Hartmann 1995

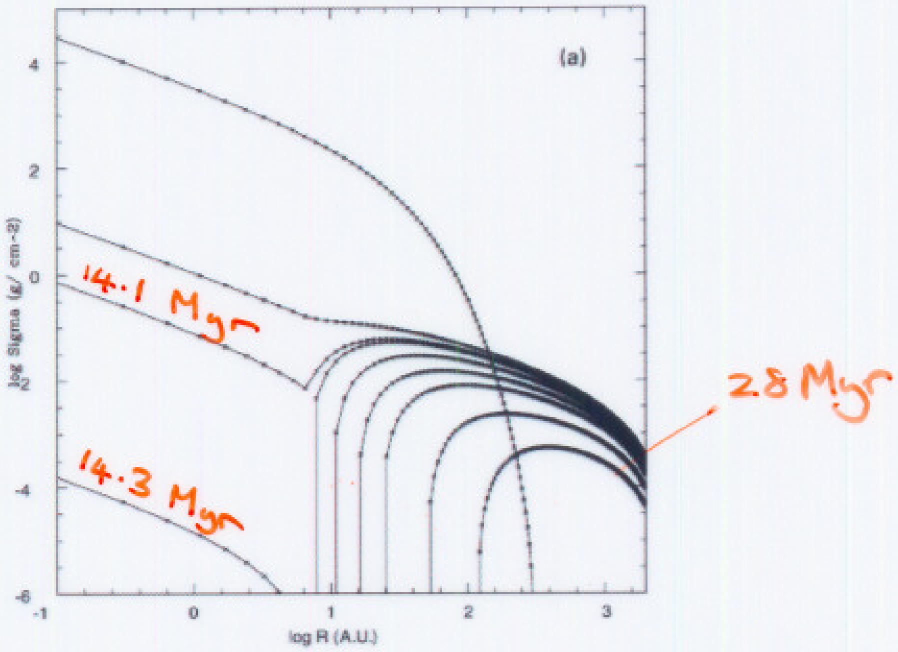
tracks for magnetospheric clearing models
Armitage, Clarke + Tout 1999.

Clarke et al 2001:

snapshots of $\Sigma(R)$: viscous evolution

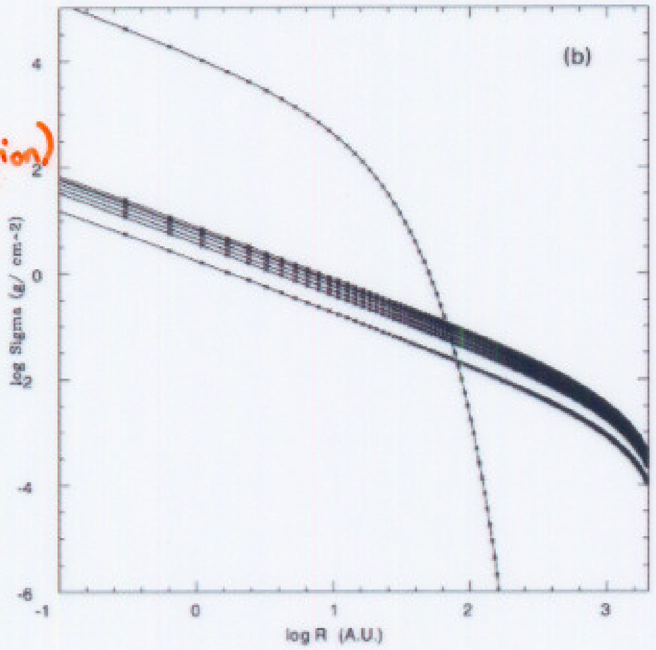
($\nu \propto R$) + constant photoevaporation:

inner disc
drains on
~ 10^5 years



<u>control</u>

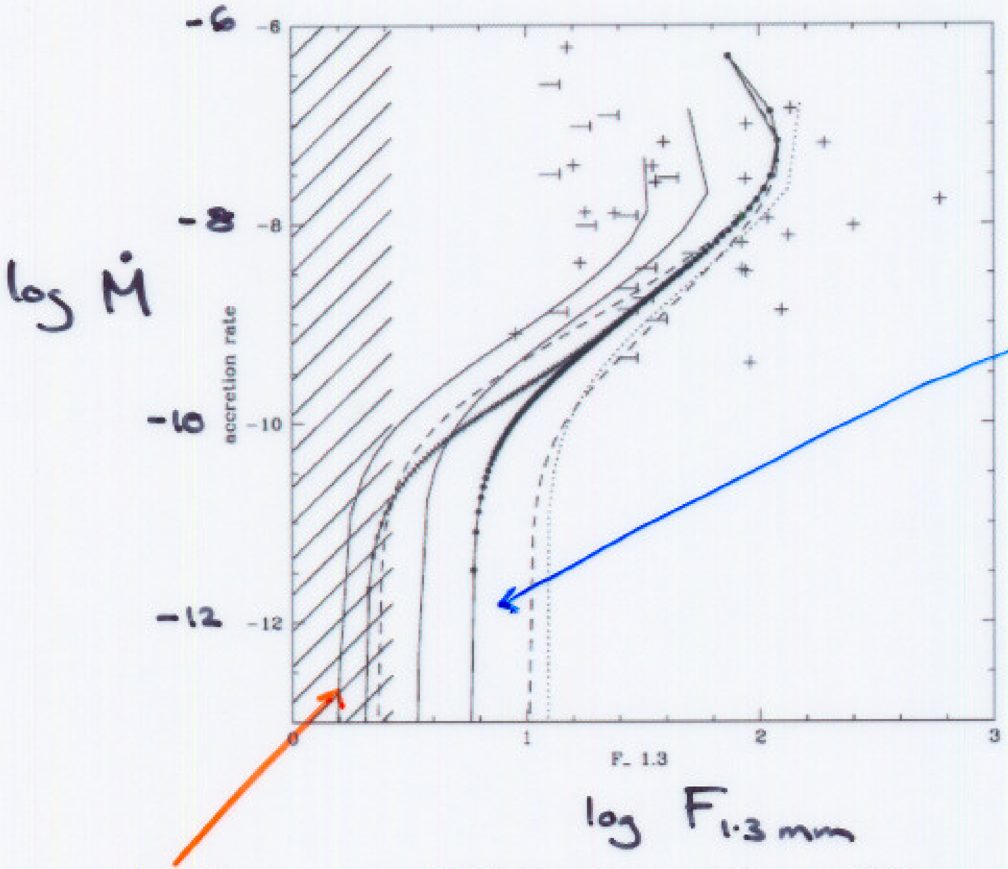
(no photoevaporation)



Problem with the model:

predicts outer disc ($> r_G$) drains too slowly.

Clarke et al 2001.

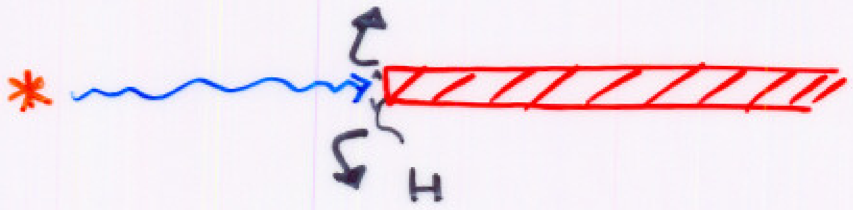


measures outer disc mass

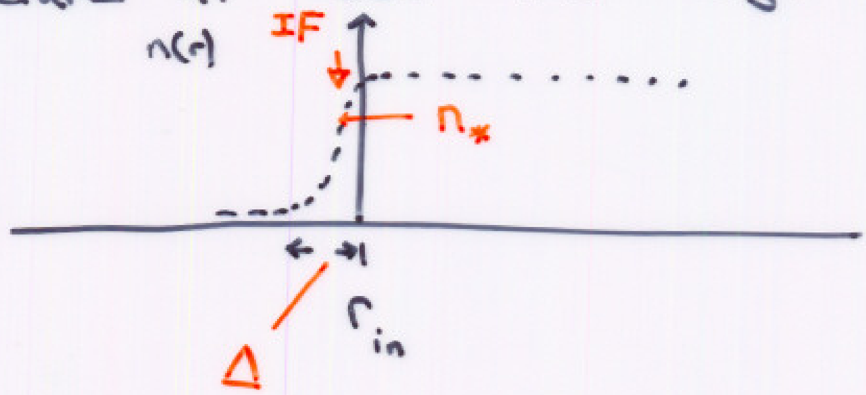
theoretical tracks move slowly through region of diagram where there are no sources.

upper limit for mm detections of non-accreting T Tauri stars [Duvert et al 2000; see also Andrews and Williams 2005).

But Hollenbach et al (diffuse field) model shouldn't apply once inner disc is gone!



- now inner rim (height H) is directly illuminated
- ionised gas expands out of sight line
- recombination integral* depends on density structure at disc inner edge

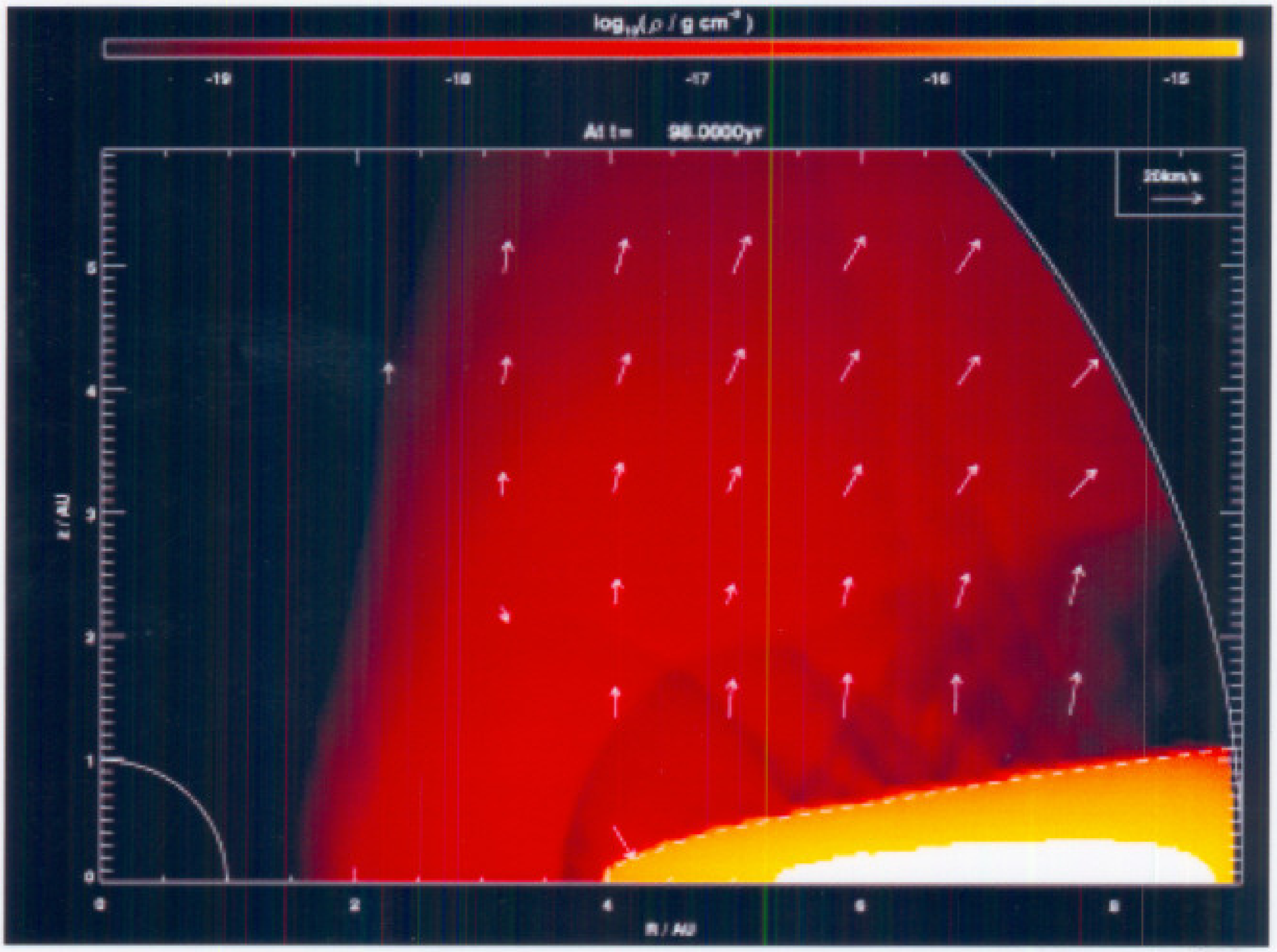


* $n_*^2 \Delta$ = ionising flux $\propto \frac{\Phi_{in}}{r_{in}^2}$.

now $\Delta \sim H_{neutral}$ (if $\Delta < H_{neutral}$: strong ∇P : resulting $\Omega(r)$ violates Rayleigh criterion).

so $n_* \propto r_{in}^{-1.5} \left(\frac{H}{R}\right)^{-0.5}$ ← increases as r_{in} ↑

$\Rightarrow \dot{M} \propto n_* H c_s r_{in} \propto r_{in}^{0.5} \left(\frac{H}{R}\right)^{0.5}$

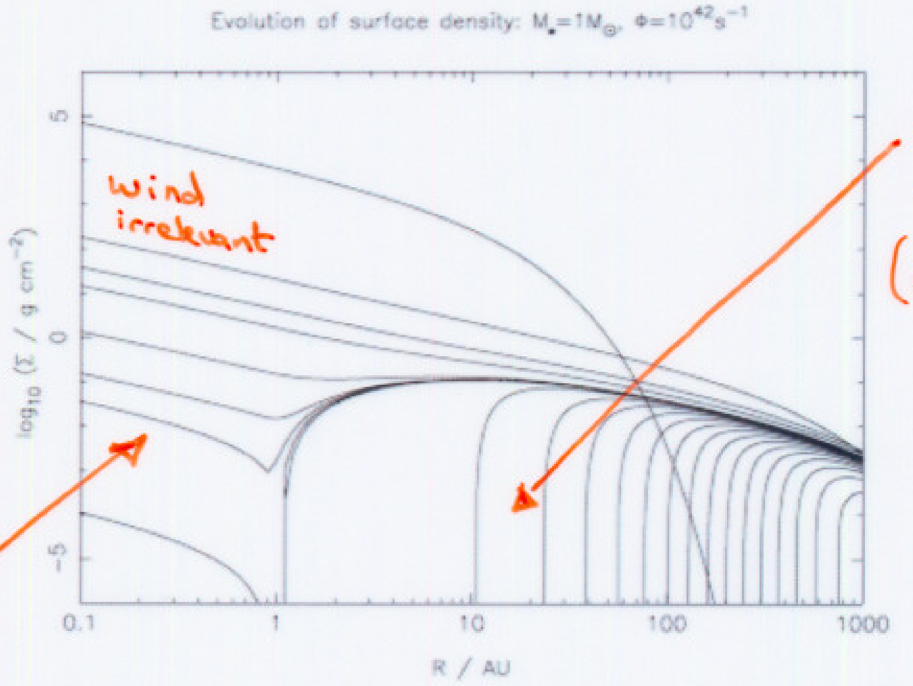


from Alexander, Clarke + Pringle 2006 a)

ZEUS 2D + ionising radiation

$\Sigma(r)$ snapshots for directly illuminated inner hole case

Alexander et al 2006.



wind irrelevant

inner hole grows (direct wind).

diffuse wind clears inner hole

~ 10^5 years.

Once inner hole forms, hole size grows QUICKLY. (timescale = few × hole clearing timescale).

diffuse

$\dot{M}_w \propto r_{in}^{-0.5}$

direct

$\dot{M}_w \propto r_{in}^{0.5}$

gap opens when
$\dot{M}_w = \dot{M}_{acc}$

accretion
dominates
wind as $r_{in} \uparrow$

$\Downarrow$

material only last
in wind when
brought in by accretion

$\Rightarrow$ need to wait
$t_\nu(R_{out})$ "long"

wind increasingly
dominates accretion
at large r_{in}

$\Downarrow$

as $r \to \infty$, wind
front over-runs
"frozen" disc

"short"

Statistics of "inner hole sources" based on photoevaporation model

if $\Sigma \propto r^{-a}$

$$t_{wind} \propto r_{in}^{1.5-a}$$

$r_{in} \to 2 r_{in}$

$$\Rightarrow \frac{dN}{d\log r_{in}} \propto r_{in}^{\boxed{1.5-a}}$$

$\Rightarrow$ for $1.5 \gtrsim a \gtrsim 1$ $\downarrow$ weak function of r_{in} i.e. neither large or small holes strongly favoured.

$$\text{e.g. } t_{wind}(100\,\text{A.U.}) \sim \underset{\downarrow}{t_{wind}(r_g)} \left(\frac{100\,\text{A.U.}}{r_g}\right)^{0.5}.$$

$\equiv t_\nu(r_g)$

$\simeq$ inner disc clearing time.

$\Rightarrow$ # growing holes $\simeq$ few × # clearing holes.

Some properties of photoevaporative clearing:

- there is a phase of HOLE CLEARING* when $\dot{M}_*$ goes from $\dot{M}_{wind}$ ($\sim 10^{-10}\, \Phi_{41}^{1/2}\, M_\odot\, yr^{-1}$) to zero

[* hole size ~ few × 0.1 $\frac{GM_*}{c_{II}^2} \doteq R_{h_{init}}$]

- this is followed by HOLE GROWTH* (lasts few times above) when $\dot{M}_*$ is zero (centrifugal barrier).

hole size : $R_{h_{init}} \to \infty$

- $\dot{M}_{wind} \propto \Phi_{ion}^{1/2}\, M_*^{1/2}$

$\dot{M}_{acc} \propto M_*^2$ (?)

who knows in T Tauri regime?

depending on $\boxed{\Phi_{ion}(M_*)}$ wind may be more/less important at low M_*....

Observational situation regarding disc clearing

- few WTTs have significant disc emission
  - .... 5/83 detected 3.6 – 70 μm | Padgett et al 2006
  - ..... 12% WTTs in IC 348 have optically thick discs | Lada et al 2006
- inner holes observed with range of sizes:
  - e.g. bd 316 in IC 348 $r_{in} \sim 0.5-0.9$ A.U. | Muzerolle et al 2006
  - Sz 84 : $r_{in} \sim 3$ A.U. | Padgett et al 2006
  - GM Aur : $r_{in} \sim 24$ AU | Calvet et al 2005
- some inner hole sources are accreting
  - e.g. GM Aur ($\sim 10^{-8} M_\odot yr^{-1}$; Gullbring et al 1998).
  - TW Hya ($\sim 10^{-10} M_\odot yr^{-1}$, Calvet et al 2002).
  - Sz 84 (? ; Padgett et al 2006).

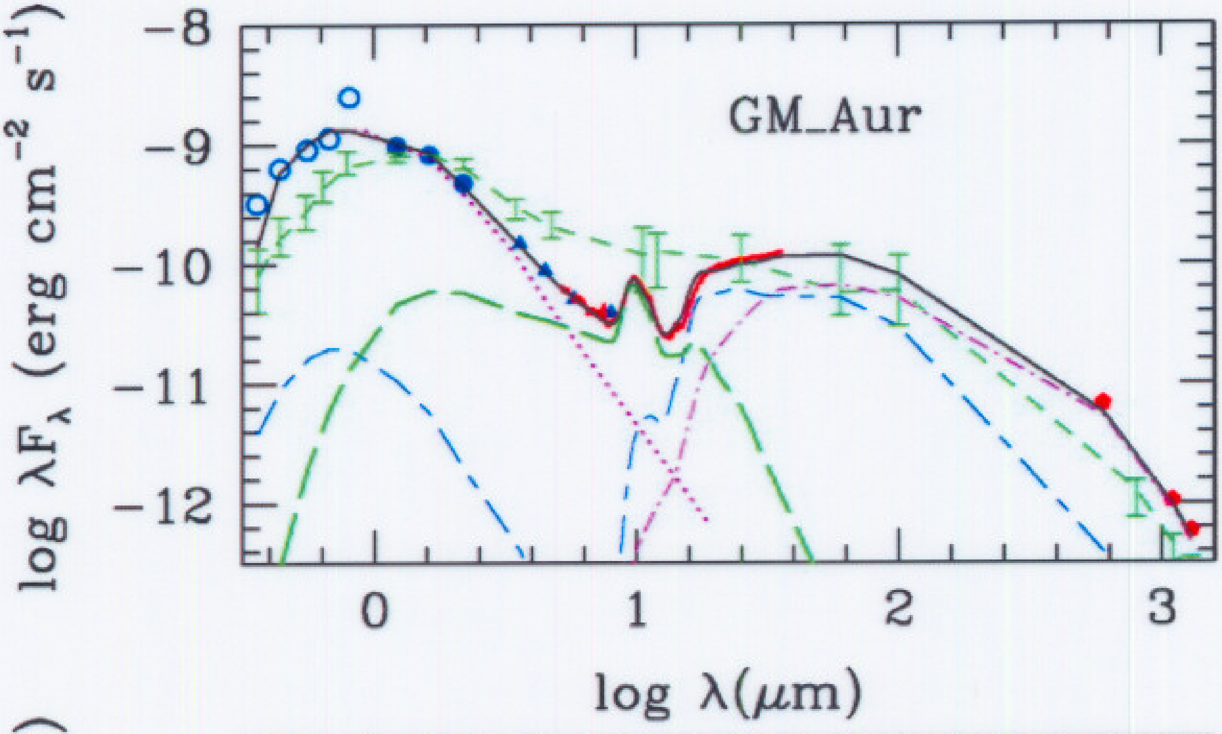
... but

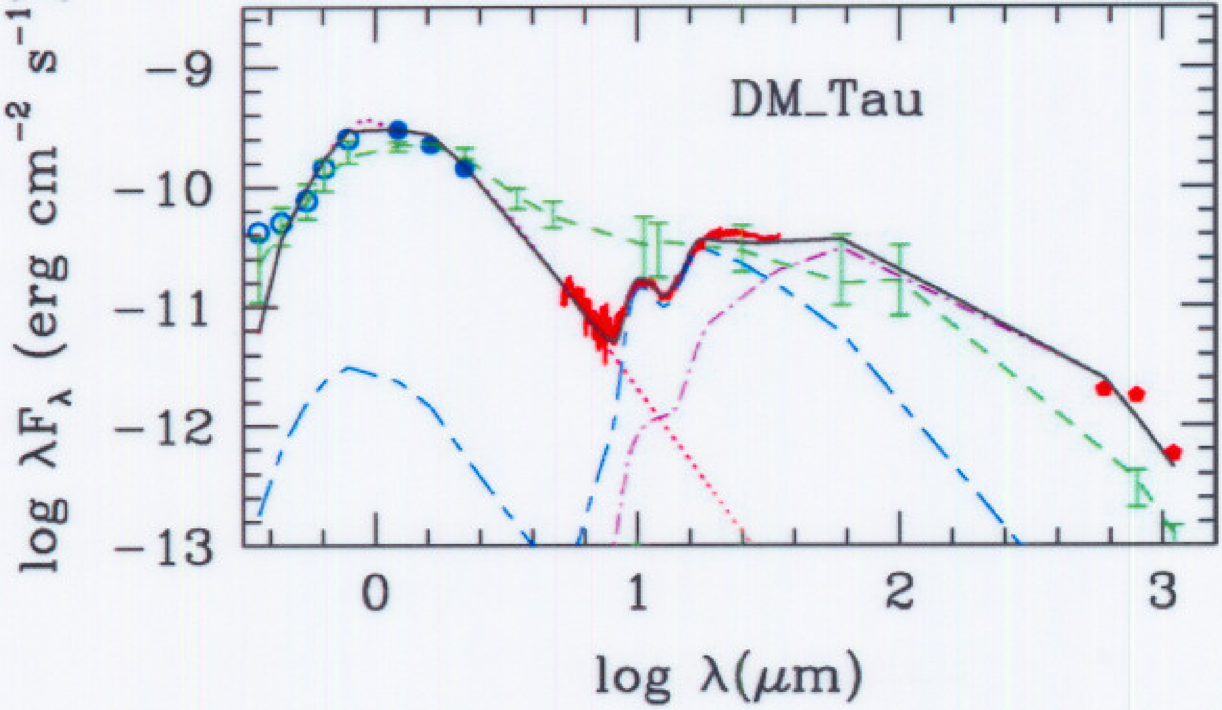
others aren't

e.g. Co Ku Tau 4 (d'Alessio et al 2005)
L316 (Muzerolle et al 2006).

- some evidence that late type stars are more likely to exhibit disc emission only at > 10 μm ..
  Lada et al 2006,
  McCabe et al 2006.

3.

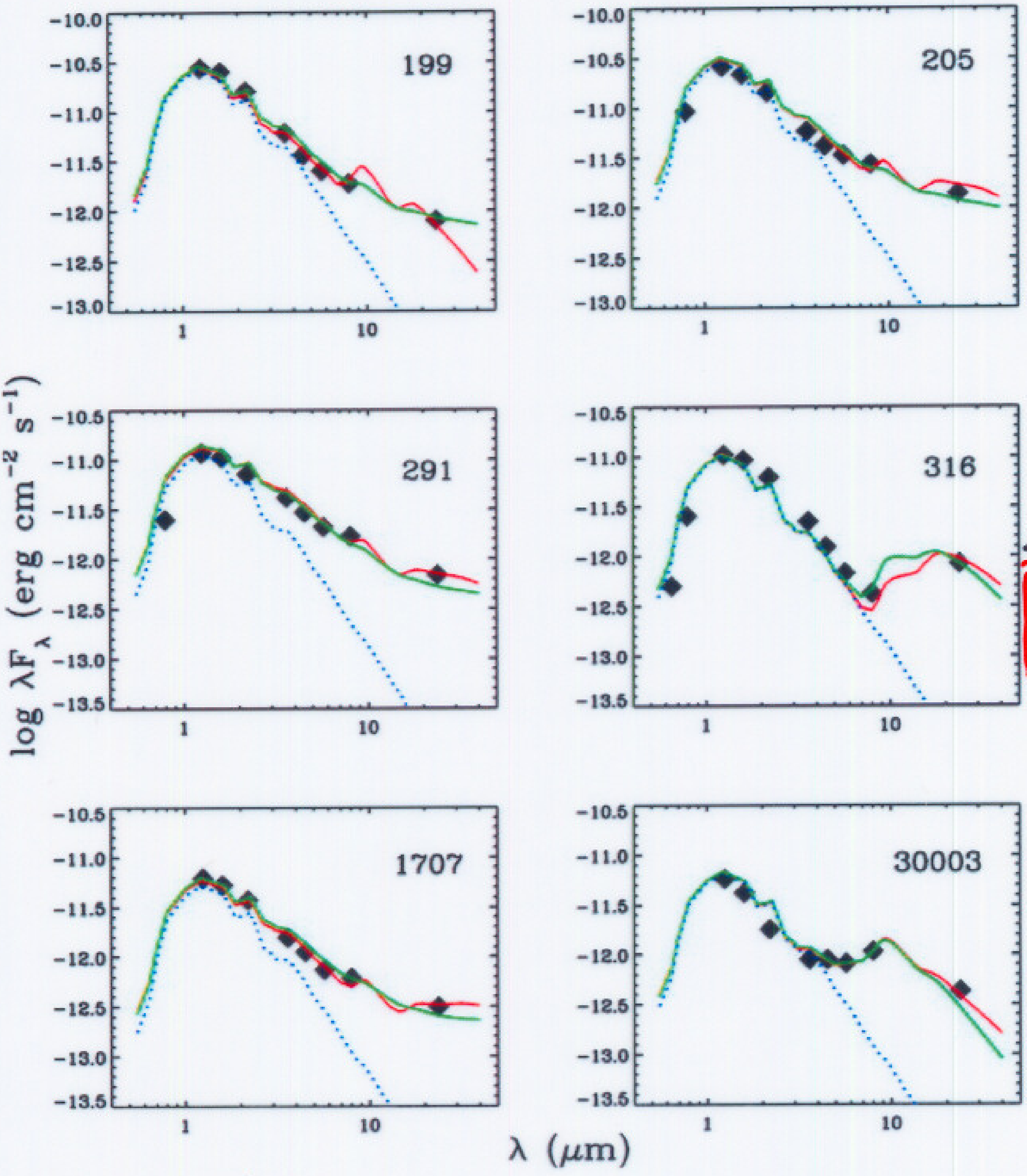




Calvet et al 2005

SEDs for sources in IC 348 with spectral type M6 or later and 24 μm detections.

see Muzerolle et al 2006
Lada et al 2006.



* ← a brown dwarf.

*.

* = inner hole

Padgett et al 2006

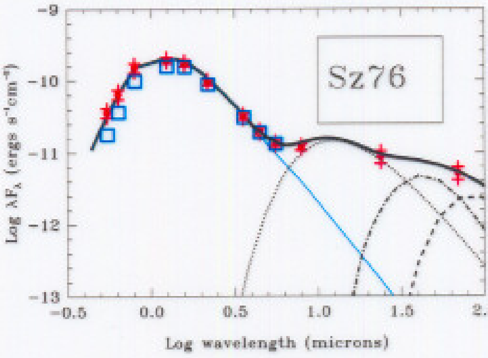


Fig. 6.— Sz 76 SED and disk model. The bold solid line indicates the integrated model flux. The fainter solid line shows the stellar photosphere. The dotted curve represents the contribution from the disk inner rim, the dash-dot curve represents the disk photosphere, and the dashed curve represents the disk interior flux.

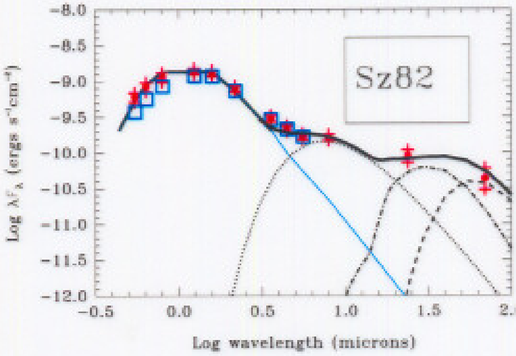


Fig. 7.— Sz 82 SED and model as in Figure 6

CTT with hole
with Rin ~ 3 A.U.

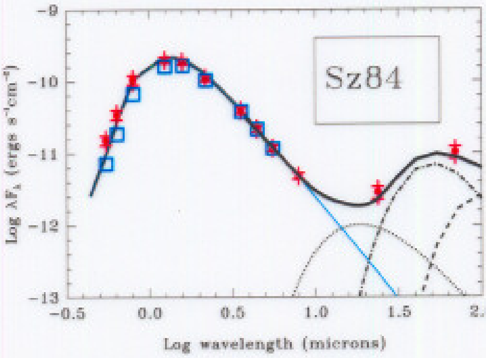


Fig. 8.— Sz 84 SED and model as in Figure 6

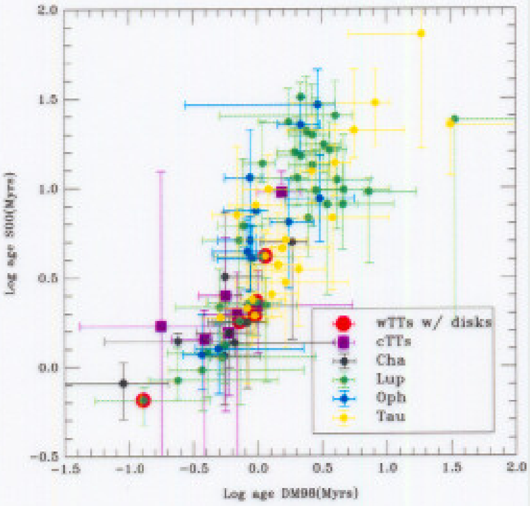


Fig. 9.— Ages of WTTS with and without disks as derived from the model tracks of Siess et al (2001; S01) and D'Antona & Mazzatelli (1997; DM97). Note that the distance uncertainties to the stars dominate this plot.

What about planets?

influence gas only when open a gap*

→ Type II migration.

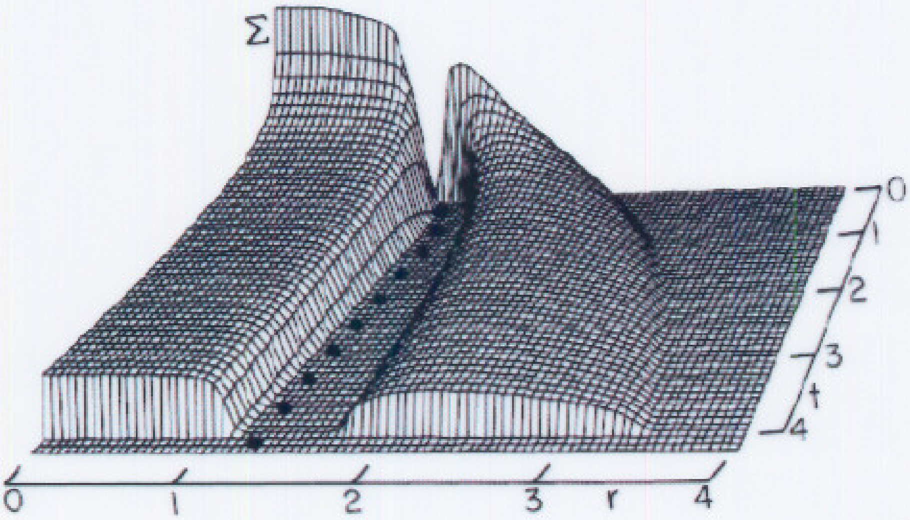


FIG. 4a

* viscous criterion for gap opening

$$\frac{M_p}{M_*} > \frac{40}{\boxed{R_e}}$$

Reynolds number

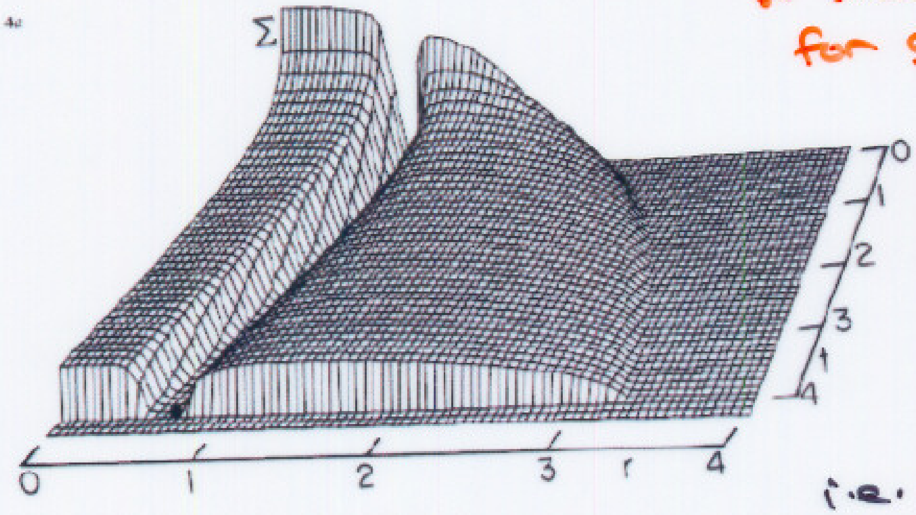


FIG. 4b

i.e. $$\frac{M_p}{M_*} > \frac{40}{\left(\frac{R}{H}\right)^2 \alpha^{-1}}$$

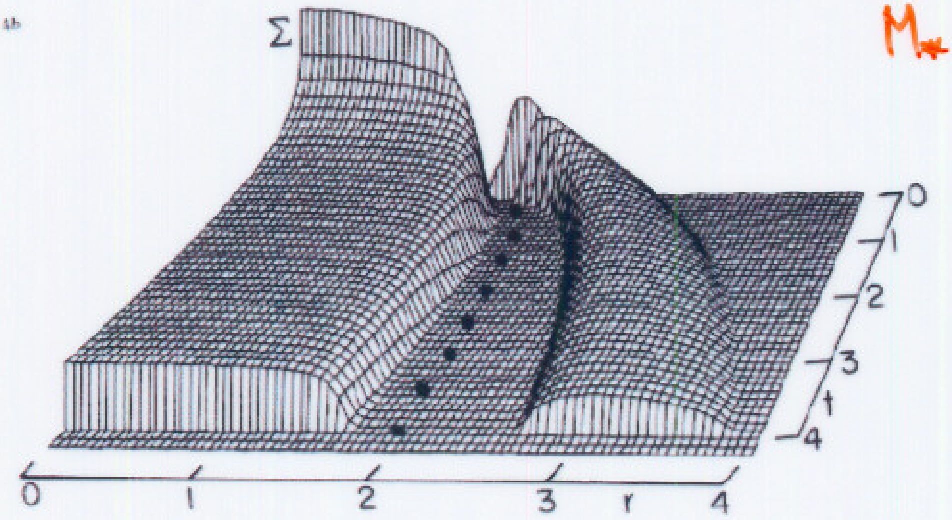
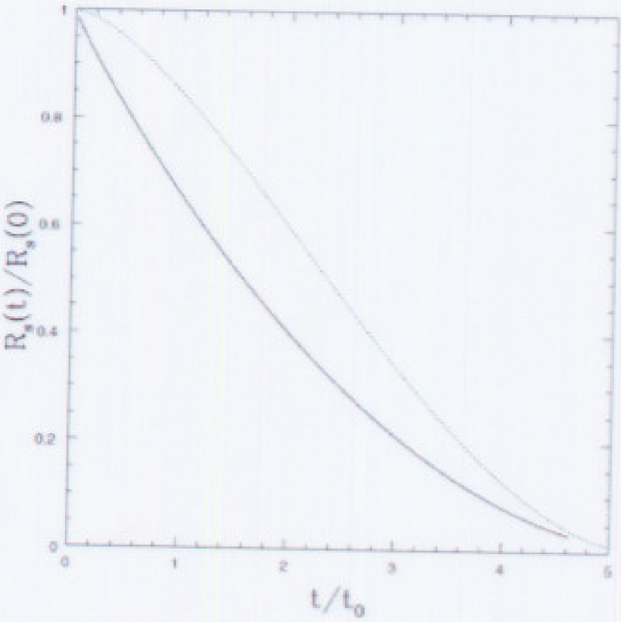


FIG. 4c

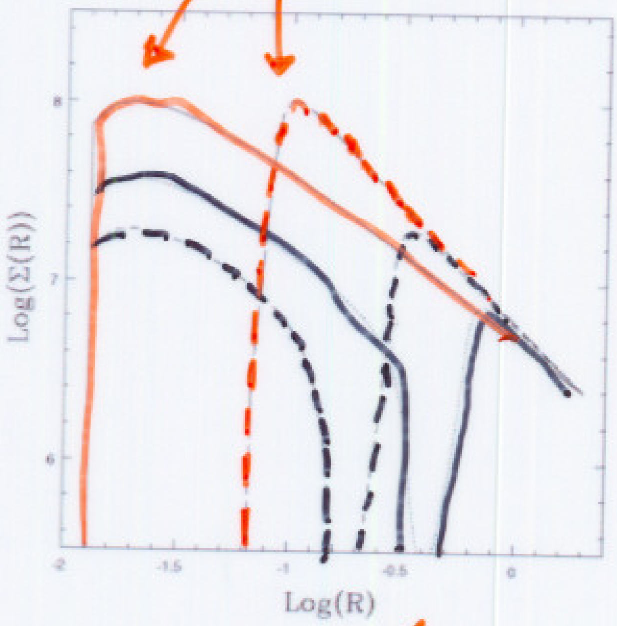
FIG. 4.—Evolution of the disk's Σ distribution and the protoplanet's orbit. For every case $A = 10^{-3}$, $B = 20$, and $h_0 = 0.05$. Initial r_p = (a) 0.6, (b) 0.7 and (c) 0.8. At $t = 0$, $\Sigma = 1$ for $r \leq$ and 0 elsewhere. The location of th protoplanet is indicated by a fille circle.

Lin & Papaloizou 1985.

- planet behaves as "representative fluid element" in disc if $M_p \ll 4\pi \Sigma R^2$
- planet & gap co-move and global disc profile little changed
- when $M_p > 4\pi \Sigma R^2$ ⇒ heavy planet regime: inner disc accretes and outer disc has to bank up to move planet ⇒ hole



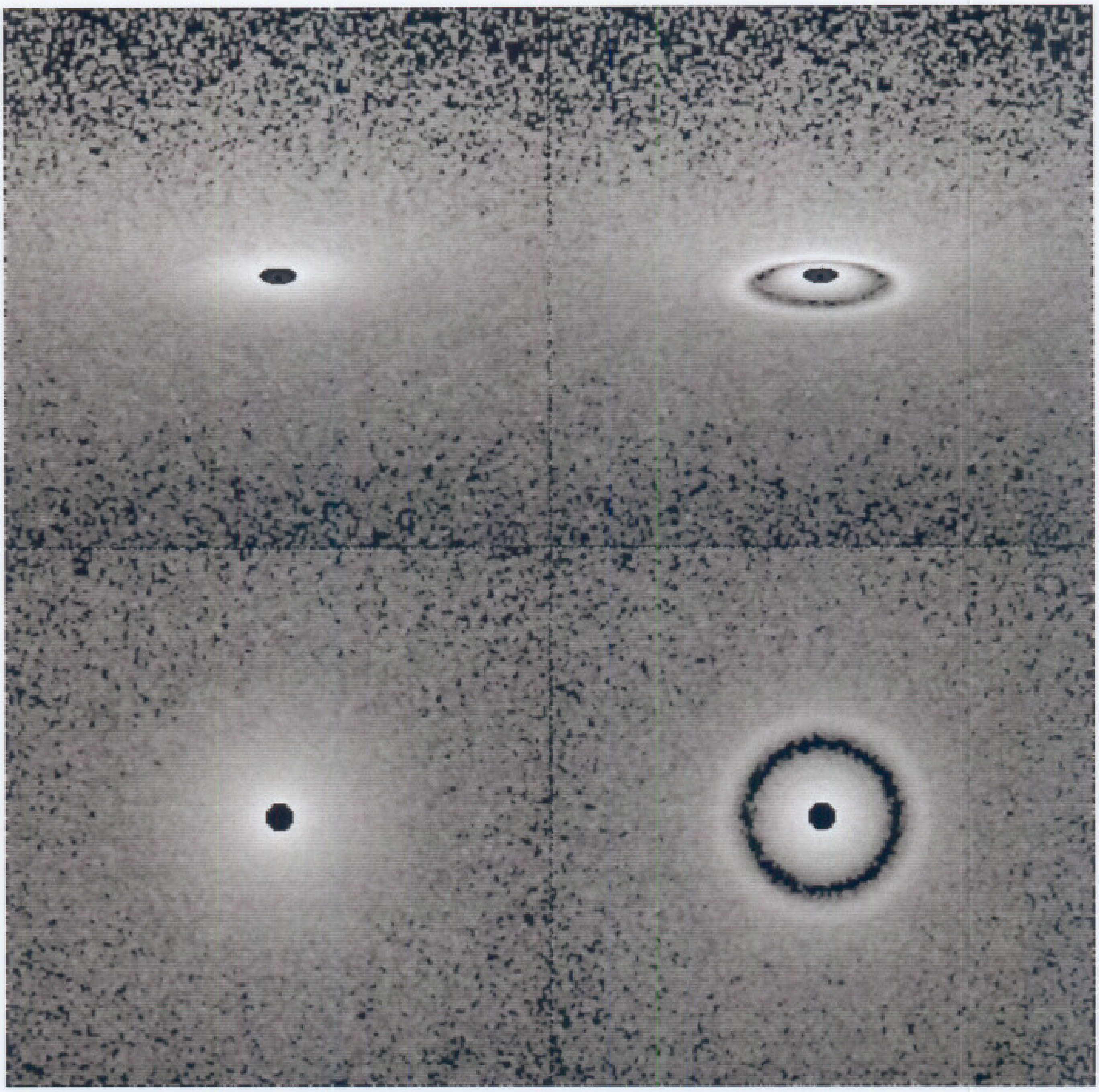
heavy planet regime: banked up outer disc and HOLE.



light planet regime i.e. GAP.

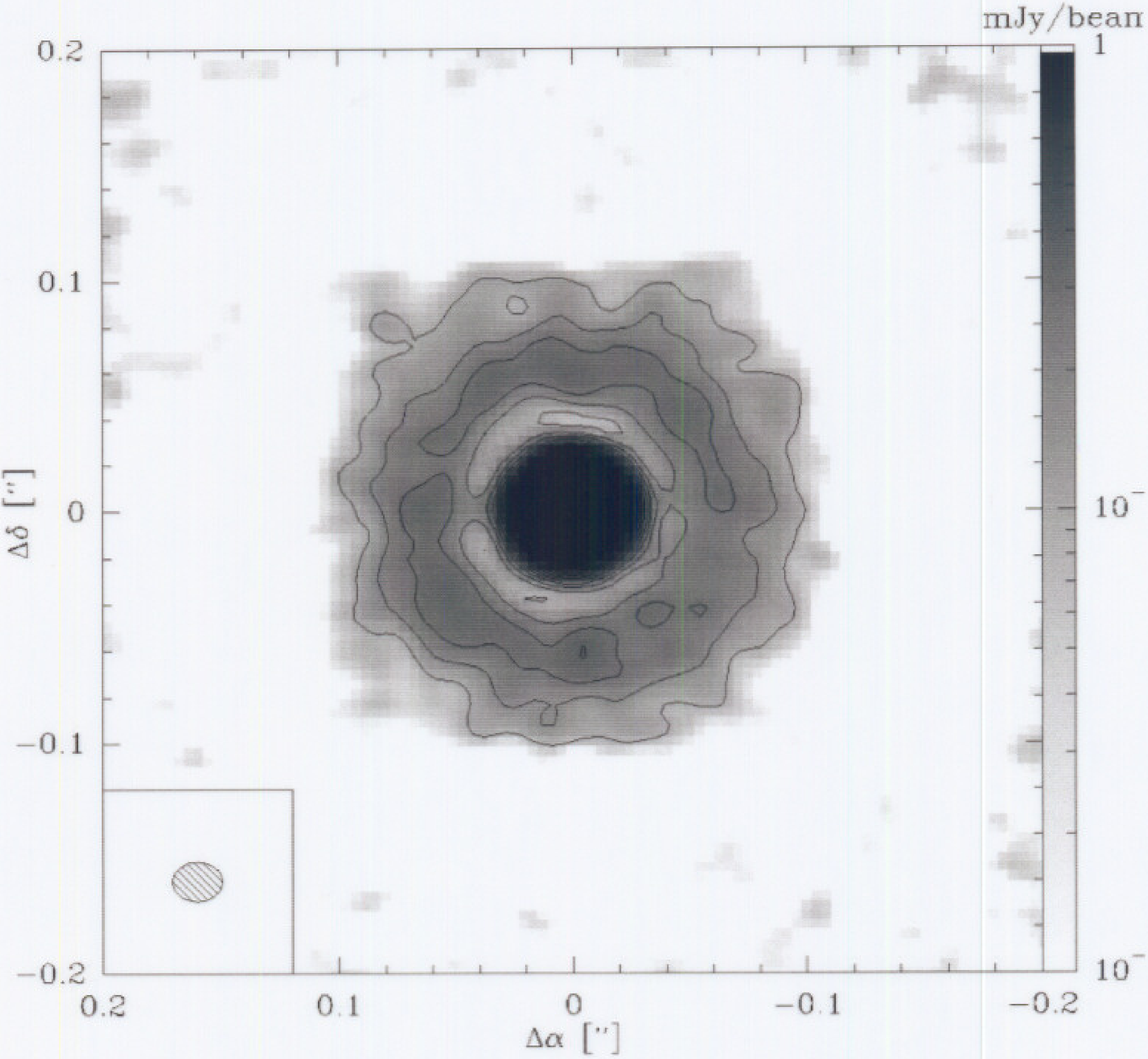
Lodato & Clarke 2004
Ivanov et al 1999
Clarke & Syer 1995.

planet induced gaps potentially detectable
in scattered light images
.... but hard from SED



Varniere et al 2006

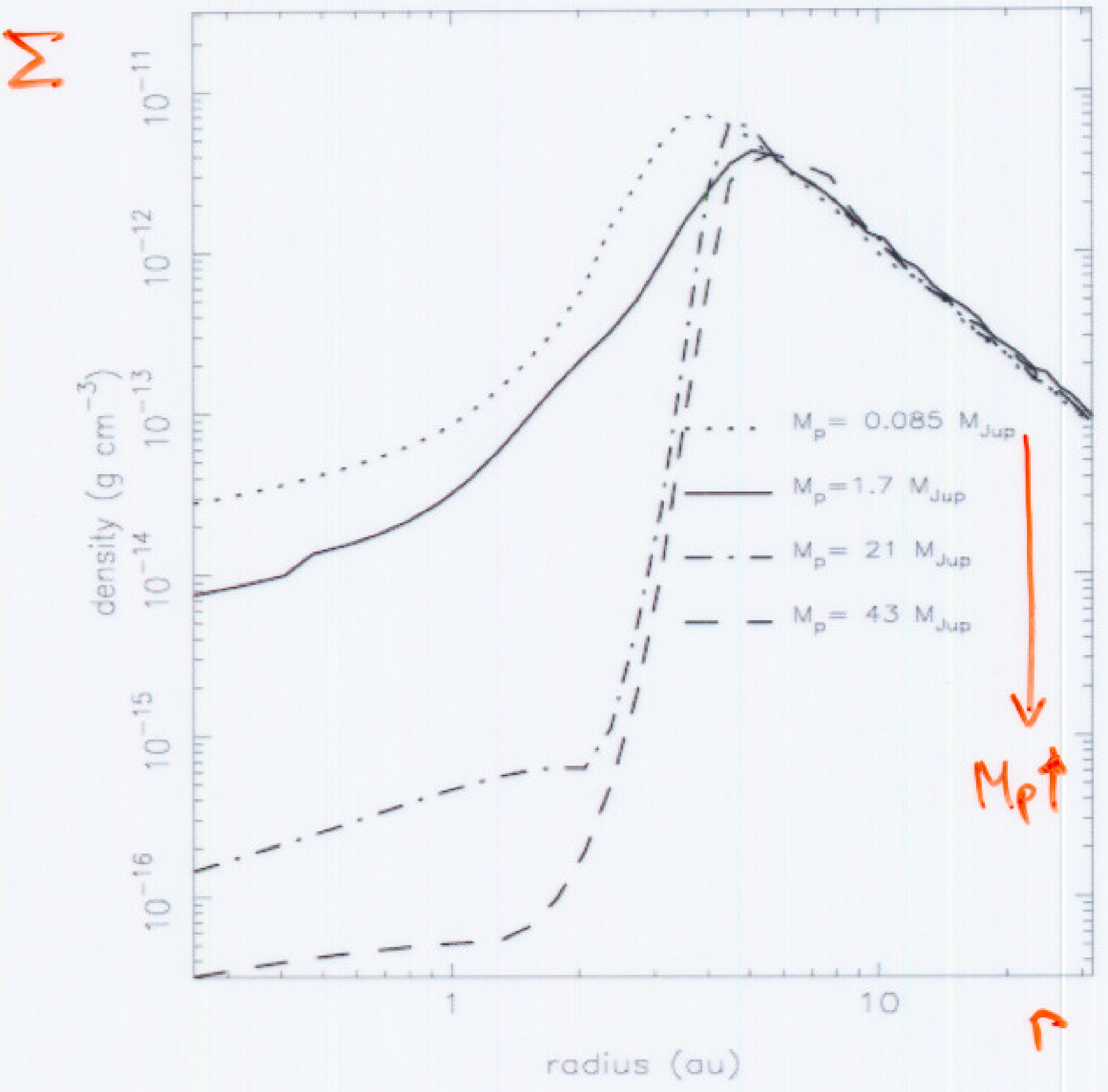
The ALMA view of a planet induced gap



Wolf et al 2002.

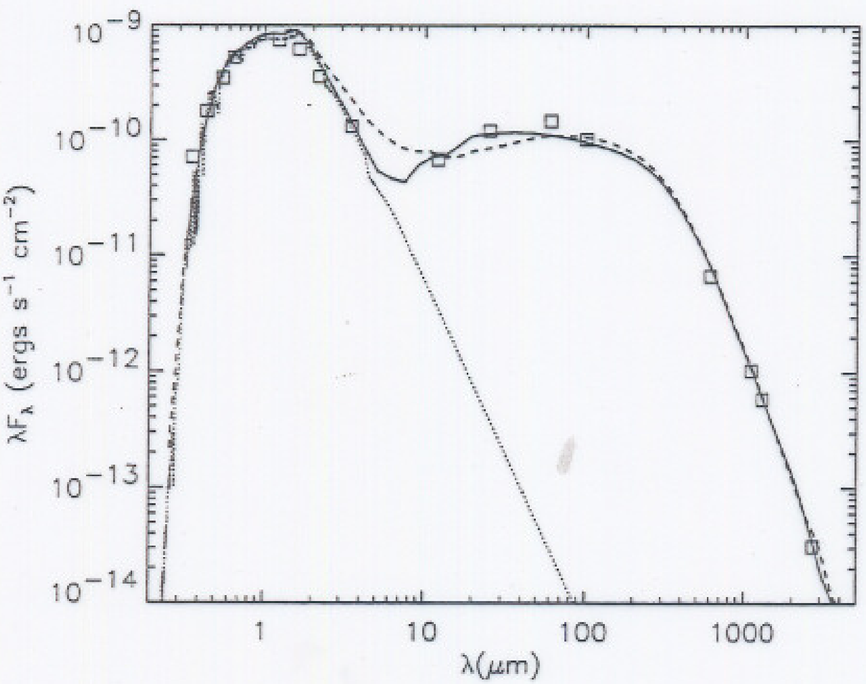
Accretion through gap or hole depends sensitively on planet mass

[.... and disc viscosity]



Rice et al 2003

82 *W. K. M. Rice et al.* 2003



(old!)

← SED for GM Aurigae

can tune planet mass and position s.t.

... allow observed high $\dot{M}$ onto star

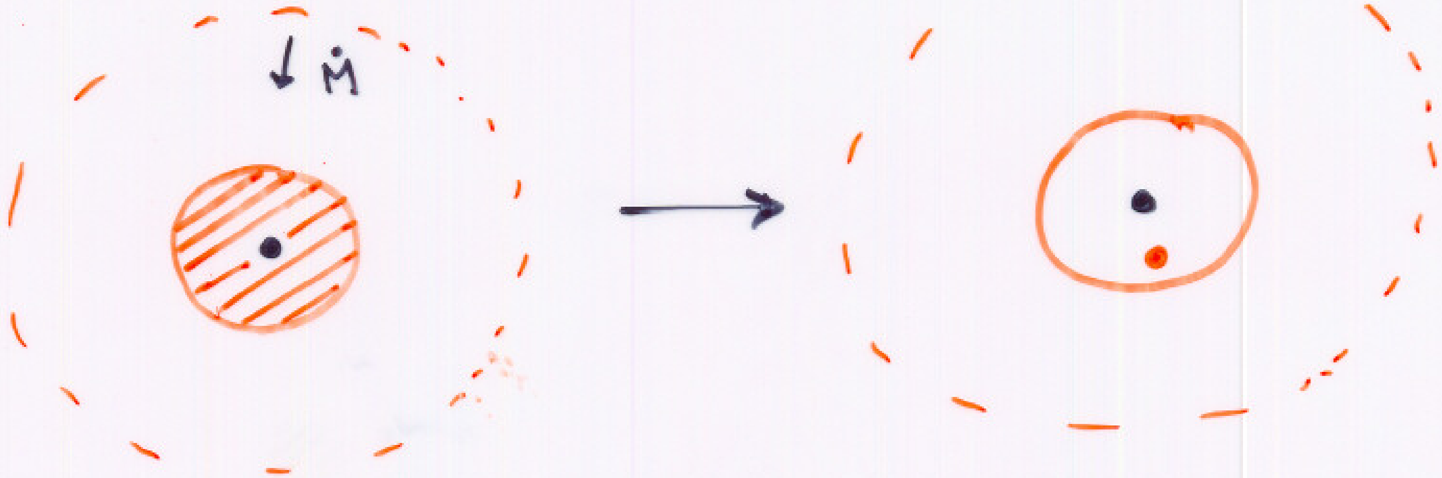
$\sim 10^{-8}$ $M_\odot$ yr^{-1}!

.... can reproduce SED

Monte Carlo rad. transfer code

assumes dust tracks gas.

Planet scenario may be problematical for holes with low $\dot{M}$ and low disc mass:



- $\underline{\text{if}}$ form planet from former hole material

$$M_p < M_{in} \sim \dot{M}\,\Omega^{-1}\,\mathcal{R}_e \leftarrow \mathcal{R}_e \equiv \frac{t_\nu}{\Omega^{-1}}$$

$\uparrow$ planet small, viscosity small

- but gap opening requires

$$M_p > \frac{40\,M_*}{\mathcal{R}_e}$$

$\uparrow$ planet large, viscosity small.

Compatible only for low viscosity

e.g. $\mathcal{R}_e > \sqrt{\frac{40\,M_*\Omega}{\dot{M}}} > 10^6$ CoKu Tau 4

$\Rightarrow \alpha < 10^{-4}$

Muzerolle et al 2006

Alexander + Armitage 06

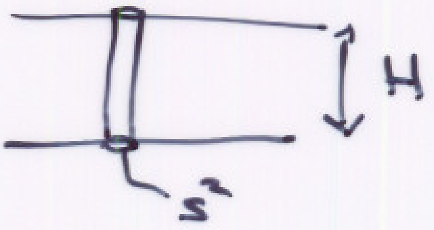
What about dust?

Focus on changes in grain location and size distribution in response to changes in gas distn..

due to planet or photoevaporation or viscosity.

- Dust response depends on dimensionless "stopping time" (due to grain-gas drag):

$$T_s = \frac{\pi \rho_{grain} s}{2 \Sigma_{gas}}$$



(~ ratio grain mass : mass of gas swept out by grain over epicyclic excursion).

- 3 régimes:

$T_s \ll 1$	$T_s \sim 1$	$T_s \gg 1$
tightly coupled to gas, so follows its evolution	intermediate régime: grains can migrate radially wrt gas	v. weakly coupled: little orbital evolution

↑

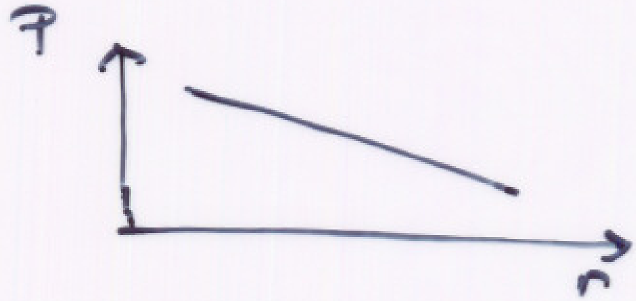
typically @ 1 mm.

Behaviour of grains in régime $T_s \lesssim 1$.

- grains torqued $\left\langle \begin{array}{l} \text{up} \\ \text{down} \end{array} \right.$ by $\begin{array}{l} \text{super-} \\ \text{sub-} \end{array}$ Keplerian gas

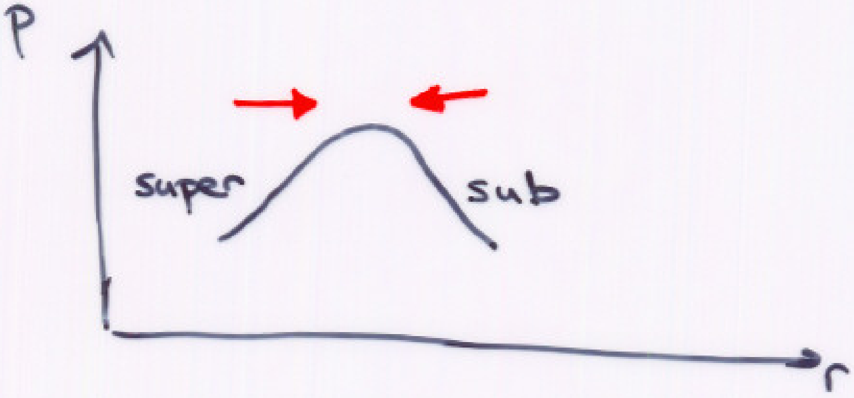
/ Keplerian.

e.g.



gas sub-Keplerian
⇒ grains ←

e.g.

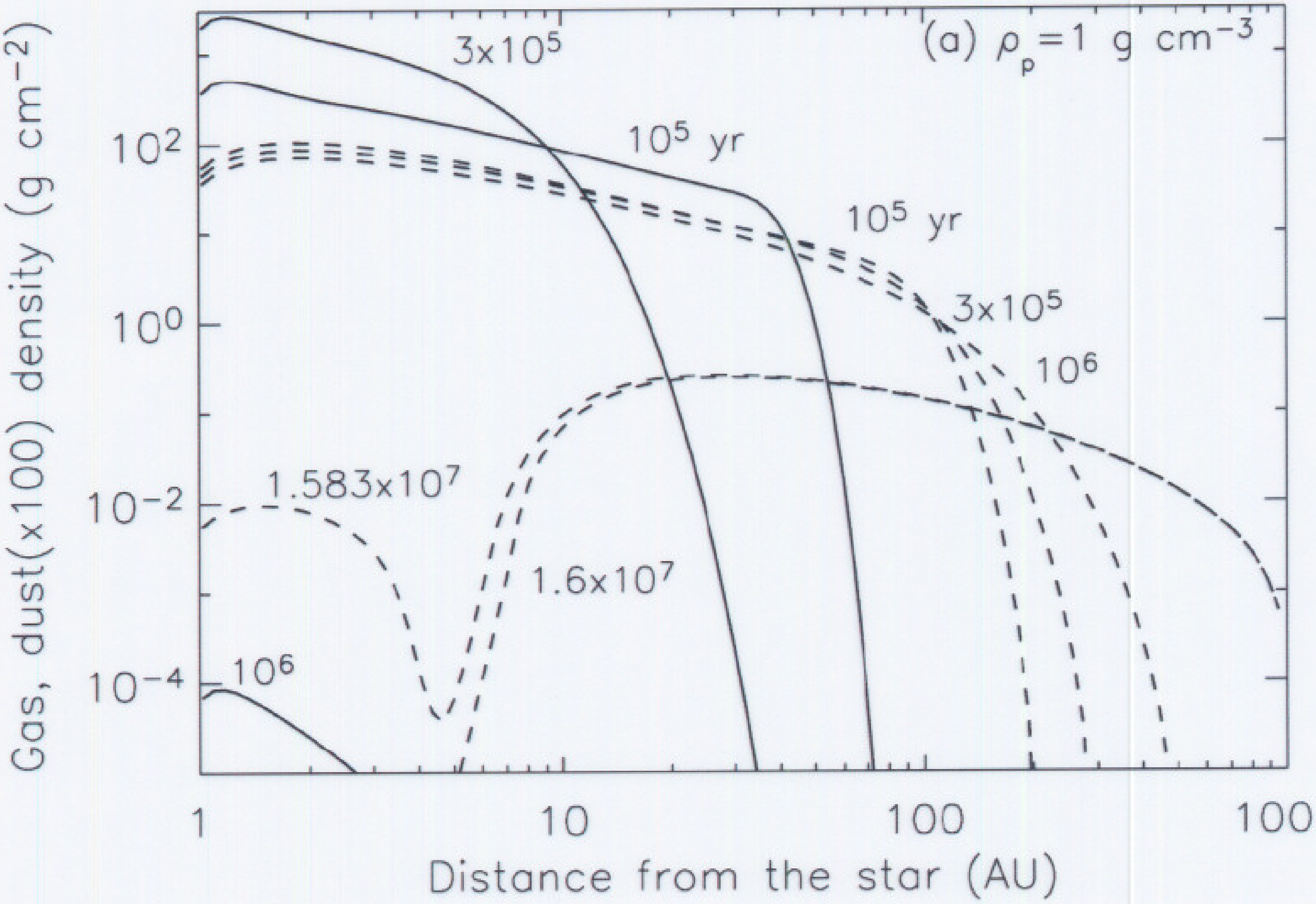


dust concentrates at P (or ρ) maxima.
(Klahr + Lin 2005)

see Takeuchi + Lin 2002, 2003, 2005
Takeuchi, Clarke + Lin 2005.

if not replenished, mm grains → star well before gas

✗ lack of CTTs without mm emission
Andrews + Williams 2005.


(a) ρp=1 g cm−3
3x10^5
10^5 yr
10^5 yr
3x10^5
10^6
1.583x10^7
1.6x10^7
10^6
10^2
10^0
10^−2
10^−4
1
10
100
100
Gas, dust(x100) density (g cm−2)
Distance from the star (AU)

Response of dust to inner hole creation.

Photoevaporation

- only grains with $s \lesssim f_{e10} \times 0.1\,\mu m\, \Phi_{41}^{1/2}$ leave with wind (sublime)

$\Rightarrow$ most grains left in disc in T Tauri case [but for O star case, grains with s up to ~ 0.5 mm go with wind (depletion of remaining disc)]

- ~ mm size grains swept up in receding disc edge (= pressure max.). smaller (μm size) grains follow gas

(Alexander + Armitage 2006)

Planet

- small grains follow gas, so if there is an accretion flow should contain small (μm size) dust
- large grains concentrated at disc inner edge.

$\Rightarrow$ lack of large grains in inner hole sources. ✓

↑

"grain size sorter"

(Rice et al 2006.).

Summary

Planets:

- can readily explain accreting sources
- inner holes containing small grains
- non-accreting inner holes require uncomfortably large planet mass or low α

Photoevaporation

- can readily explain non-accreting sources
- predict inner holes should contain no gas and no dust
- can't explain high $\dot{M}$ sources.

After word:

Any process that clears the inner disc (out to ~ r_G) exposes inner rim to direct uv field – remaining disc evaporated rapidly thereafter.

Planet formation models need to consider this.