Transitional Disks

Theories and Observations

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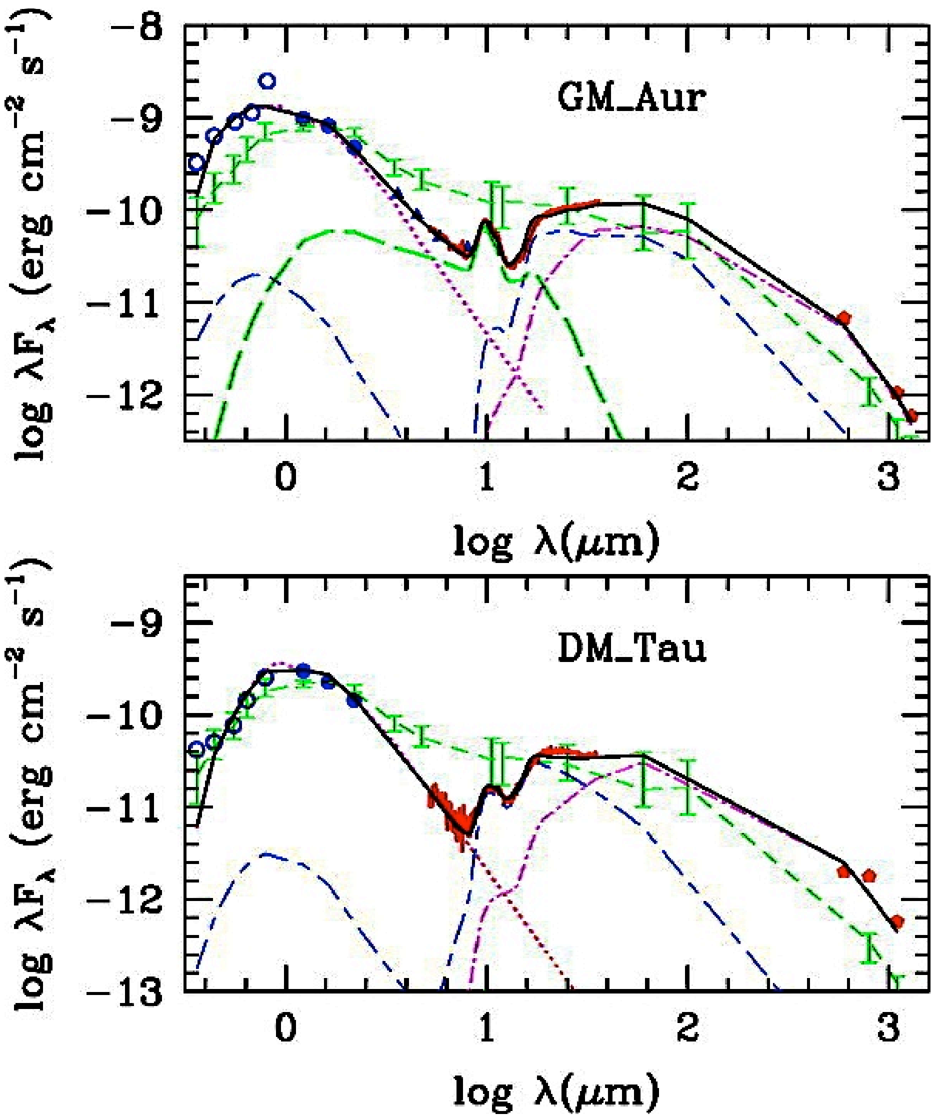
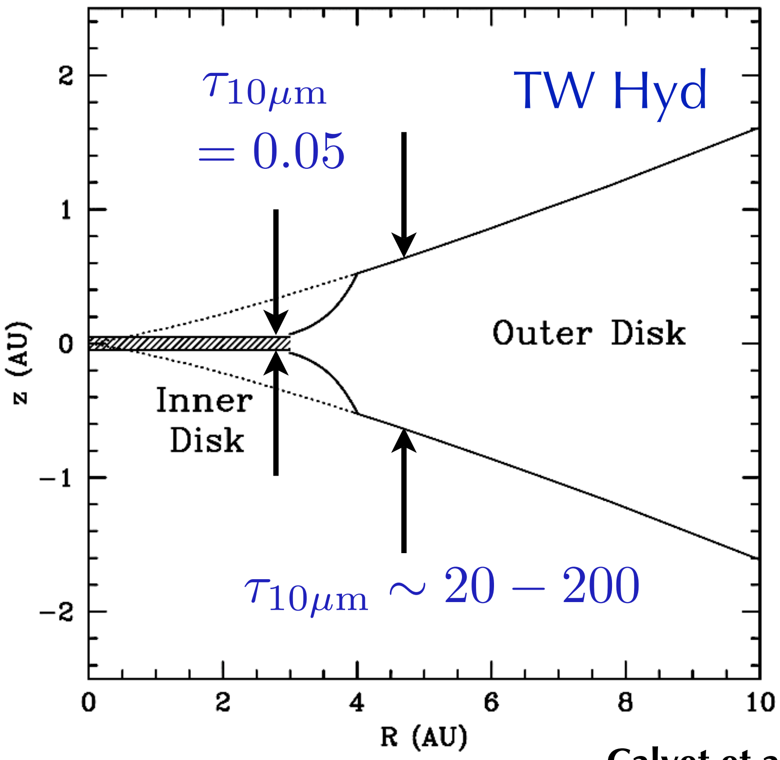
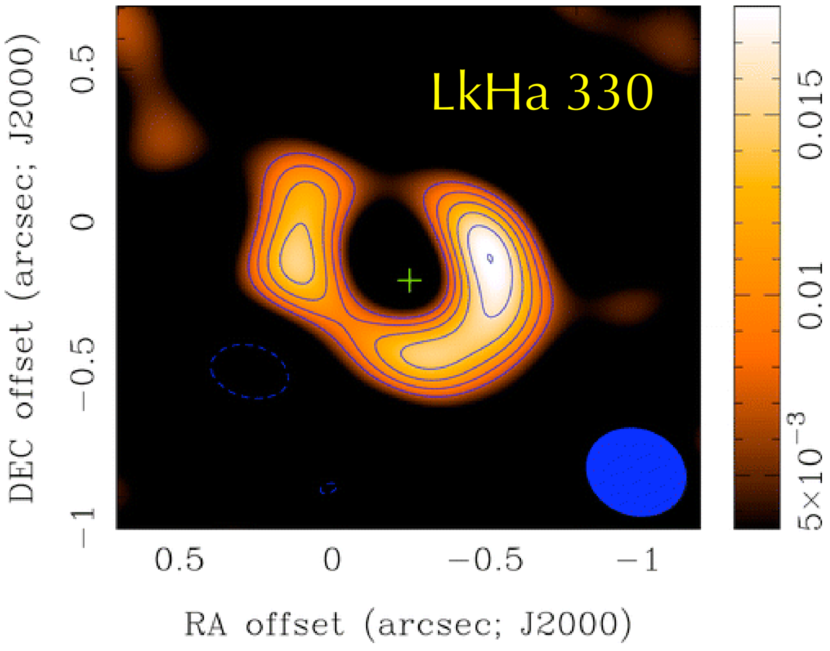


Calvet et al. 05



Calvet et al. 02



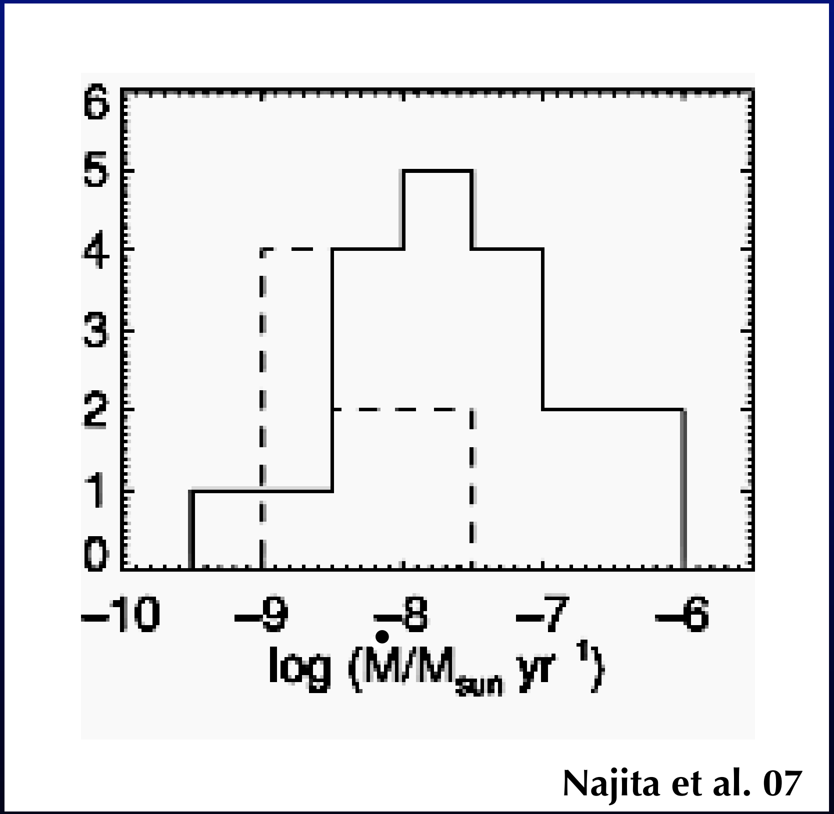
Brown et al. 08

Holes are not empty

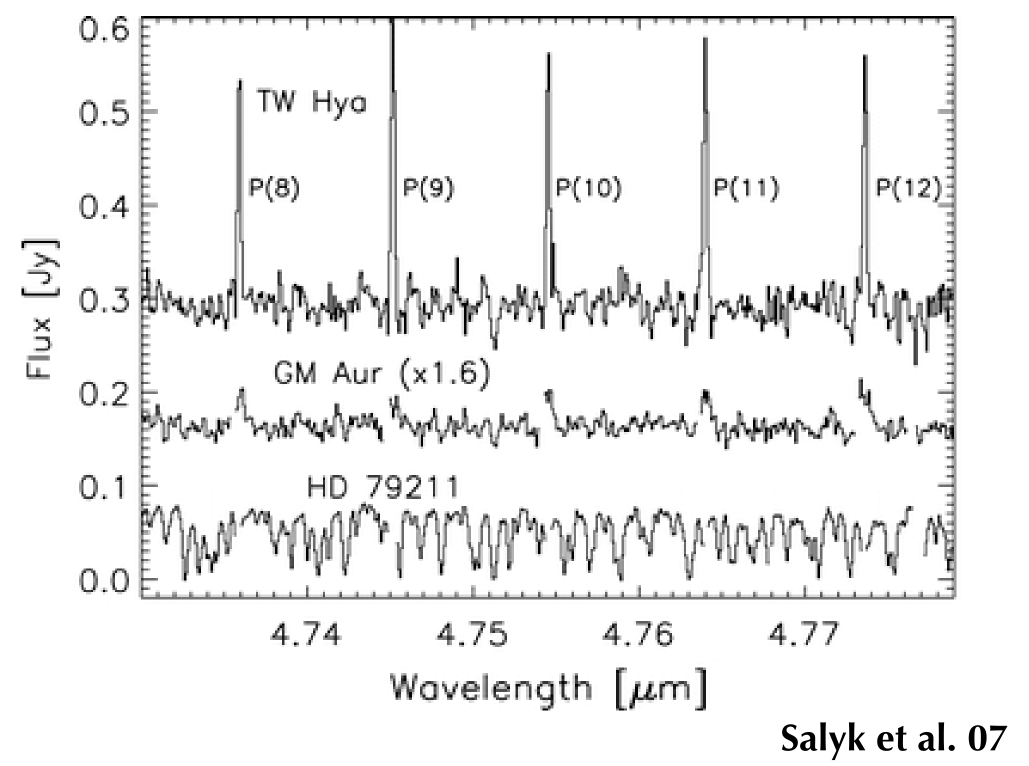
- Mild near-IR excesses in some sources
  $\tau_{10\mu m} \sim 0.002 - 0.05$

- Some accrete
  $\dot{M} \sim 0.1 \times \mathrm{median\,T\,Tauri}$

- Inner molecular gas disks
  $\Sigma(\mathrm{H_2}) > 0.1\,\mathrm{g\,cm^{-2}}$ at $\sim 0.2\mathrm{AU}$

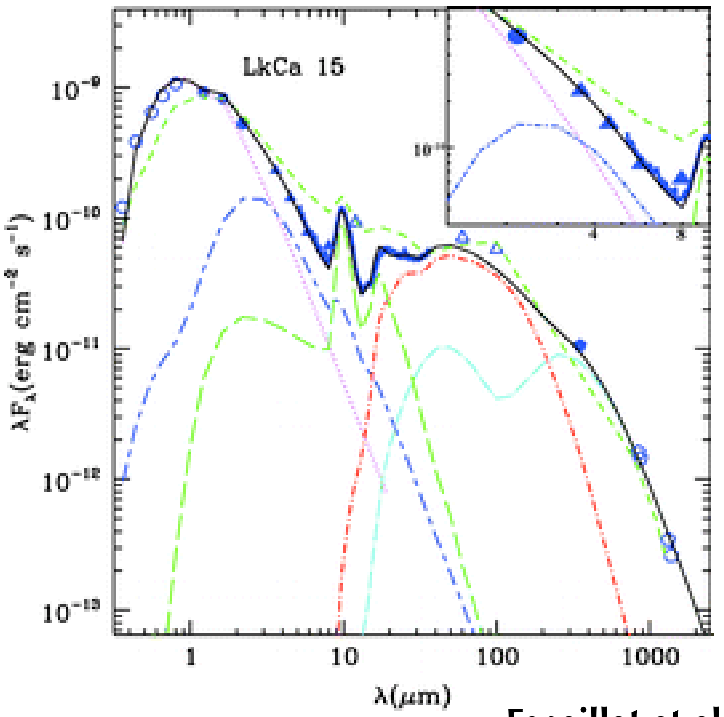


Najita et al. 07

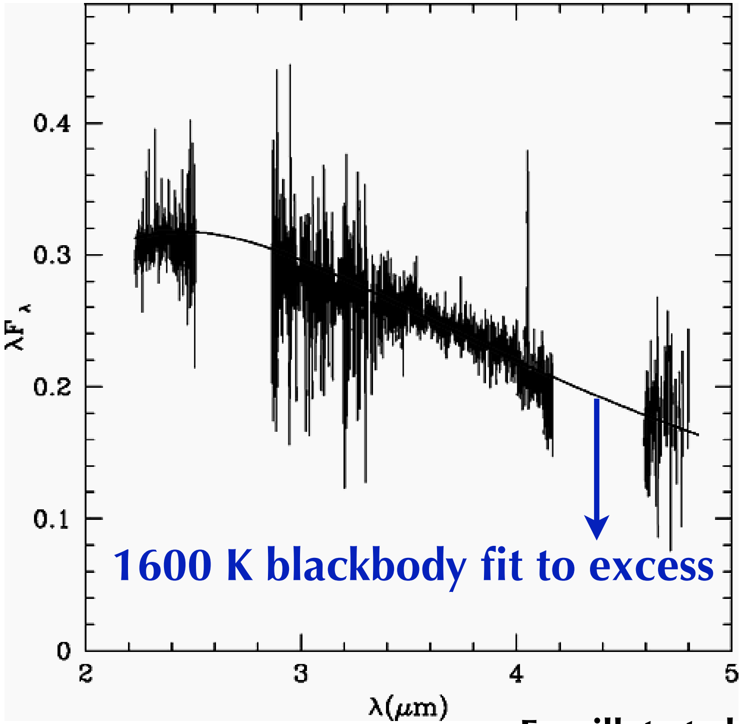


Salyk et al. 07

“Pre-transitional” Gapped Disks

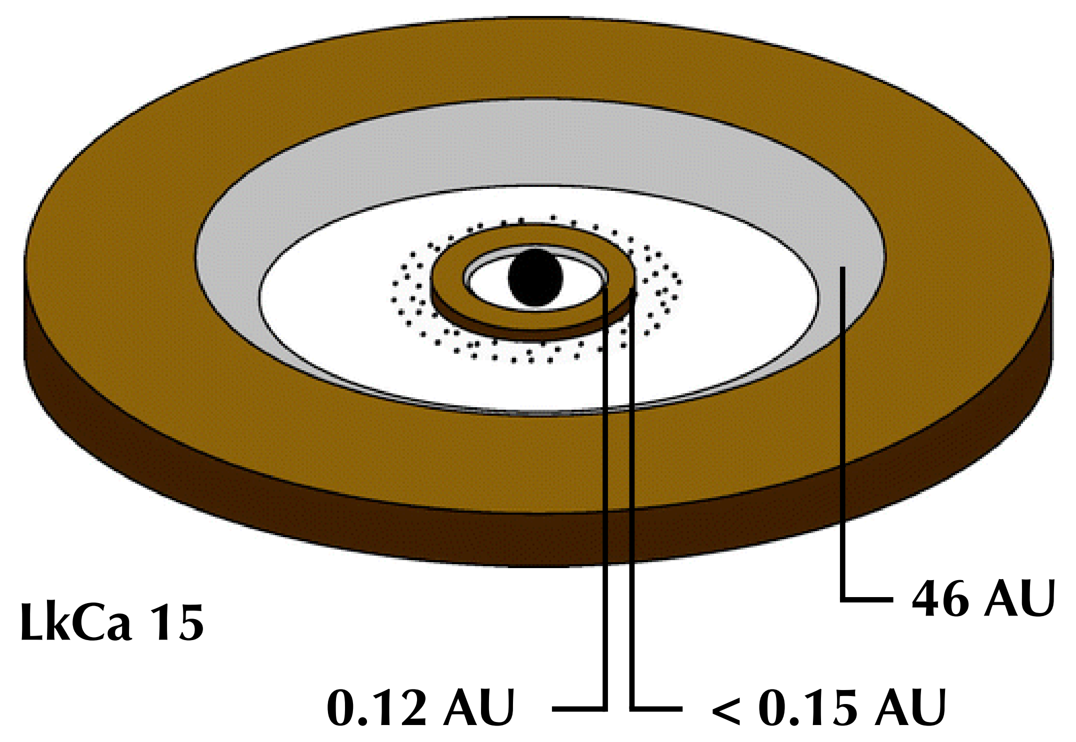


Espaillat et al. 07



1600 K blackbody fit to excess

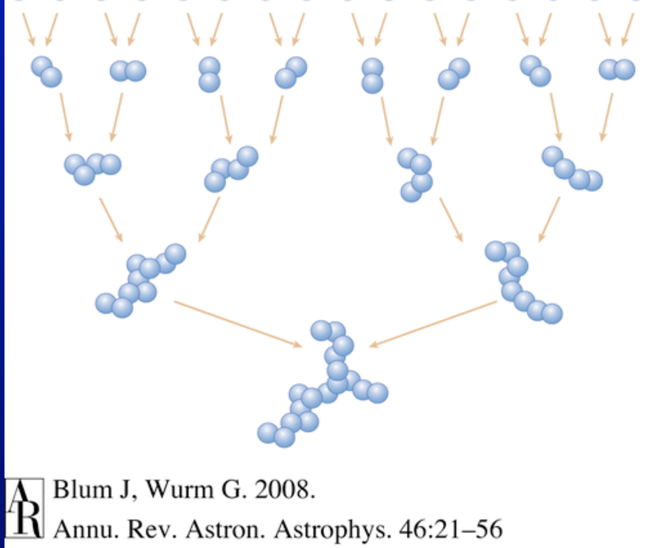
Espaillat et al. 08



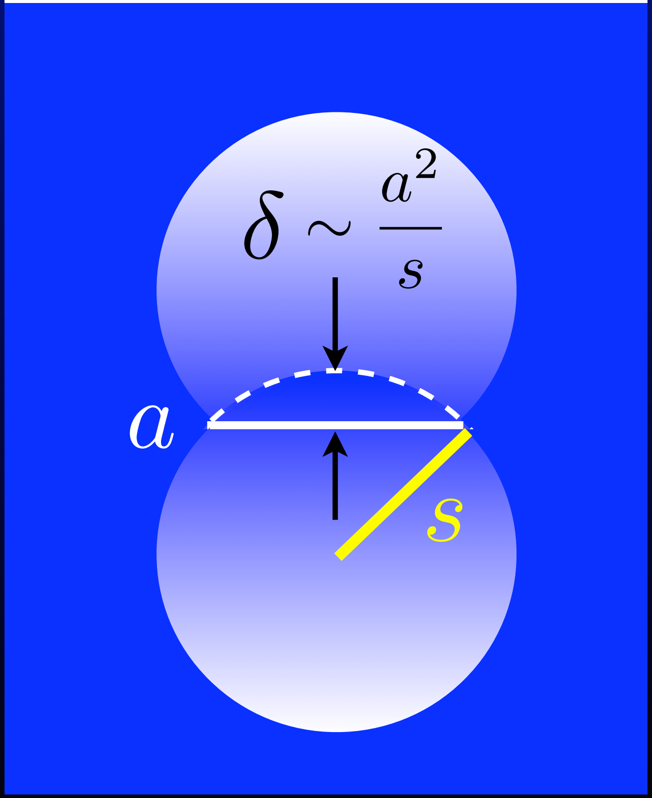
Theories

- Grain growth
- Planet clearing
- Inside MRI / outside radiation pressure
- Viscous accretion / photoevaporation

Theory I: Grain growth



Blum J, Wurm G. 2008.
Annu. Rev. Astron. Astrophys. 46:21–56



$$\boxed{v_{\rm crit} \sim 1\,{\rm m/s} \text{ for } s \sim 1\,\mu{\rm m}}$$

Repulsion (elastic modulus E)

$$\text{Stress}\, \sigma \sim E \nabla \xi \sim E \frac{\delta}{a}$$

$$\sigma \sim \frac{mv}{(\delta/v) \times a^2}$$

$$\text{Repulsive force}\, F_R \sim \sigma a^2 \sim \mu^{3/5} E^{2/5} s^2 v^{6/5}$$

Adhesion (surface tension γ)

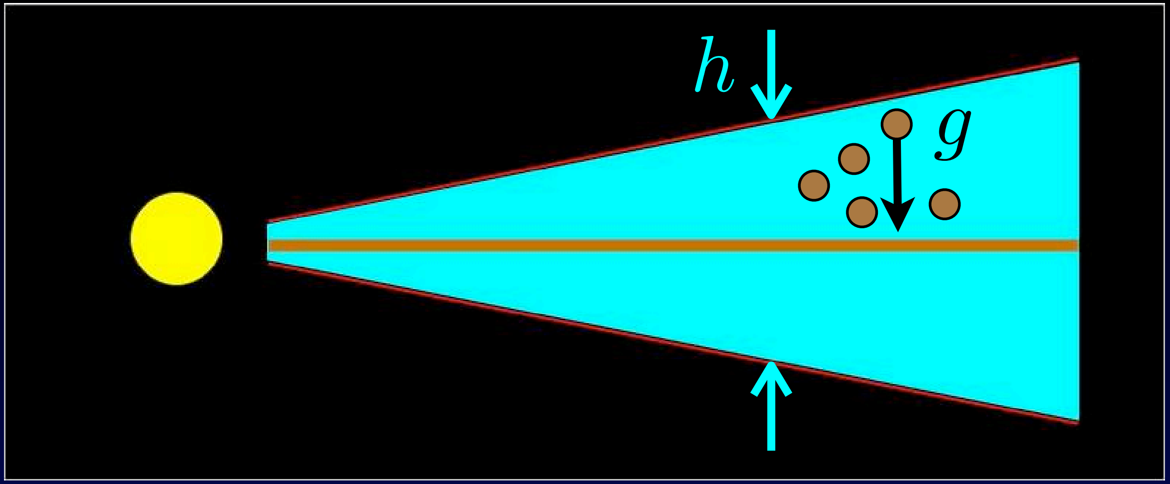
$$\text{Binding energy}\, U \sim \gamma a^2$$

$$\text{Binding force}\, F_B \sim \frac{U}{\delta} \sim \gamma s$$

$$F_R = F_B \longrightarrow v_{\rm crit} \sim 4 \frac{\gamma^{5/6}}{E^{1/3} \mu^{1/2} s^{5/6}}$$

Hertz 1882, Chokshi et al. 93

Theory I: Grain growth



$$mg \sim F_{\rm drag}(v)$$

$$\mu s^3 \Omega^2 h \sim \rho_g s^2 c_s v$$

$$\longrightarrow \text{Terminal } v \sim \frac{\mu}{\rho_g} \Omega s$$ (bigger is faster)

$$\text{Accretion } \frac{d}{dt}(\mu s^3) \sim \rho_d v s^2 \longrightarrow \dot{s} \sim \frac{\rho_d}{\mu} v$$ (faster is bigger)

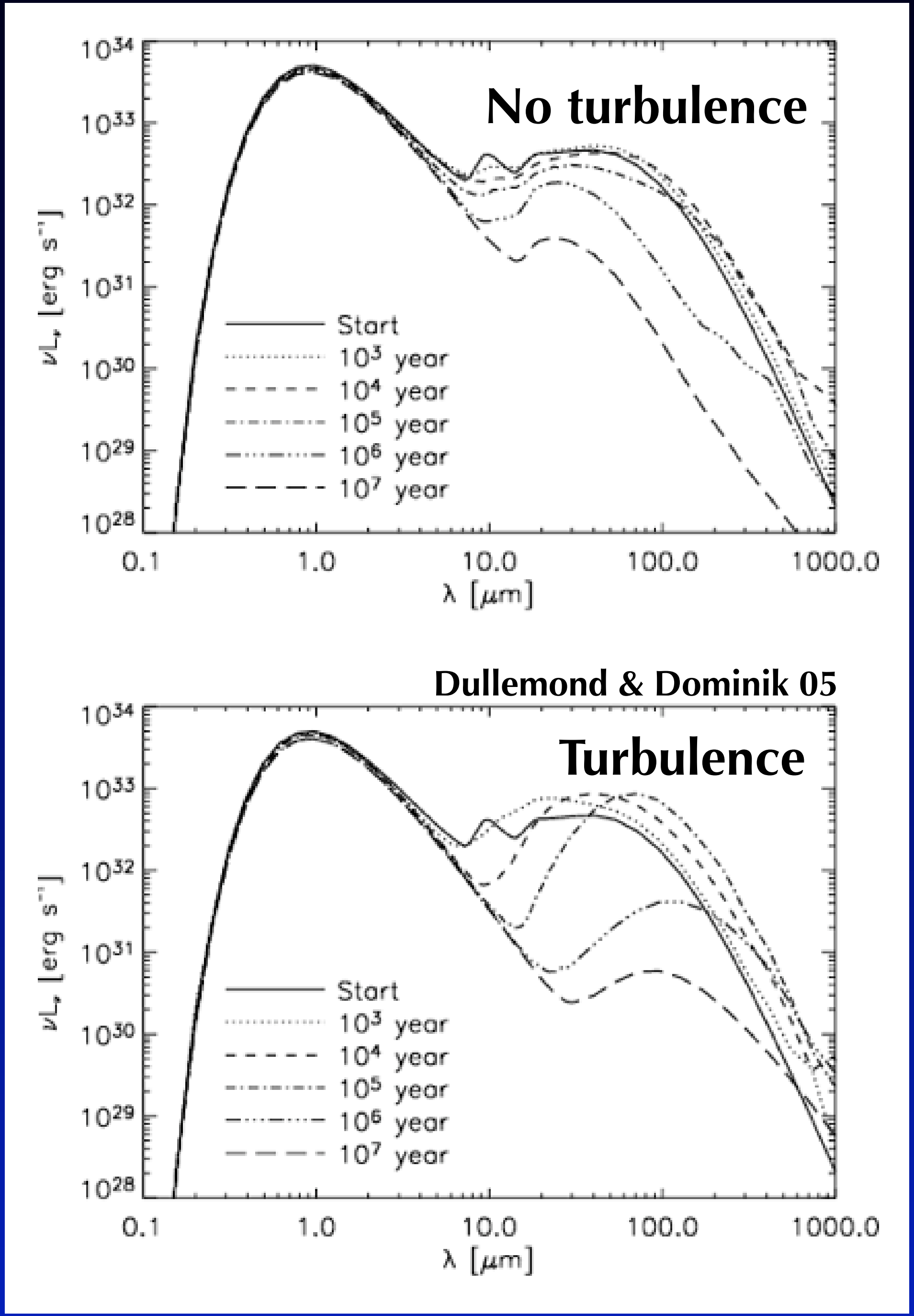
$$\longrightarrow \text{Exponential growth } s \sim s_0 \exp(\rho_d \Omega t / \rho_g)$$ (fastest growth in inner disk)

$$\text{Since } t \sim h/v \longrightarrow s \sim s_0 \exp(\Sigma_d / \mu s)$$

$$\left.\begin{aligned} s_0 &\sim 1\,\mu\mathrm{m} \\ \mu &\sim 1\,\mathrm{g\,cm^{-3}} \\ \Sigma_d &\sim 10\,\mathrm{g\,cm^{-2}} \end{aligned}\right\} \quad \begin{aligned} s &\sim 1\,\mathrm{cm} \\ t &\sim 100\,\mathrm{yr} \\ v &\sim 1\,\mathrm{m/s} \end{aligned}$$

Safronov 1969

Theory I: Grain growth: Right sign, wrong magnitude



No turbulence

Dullemond & Dominik 05

Turbulence

Sticks too well

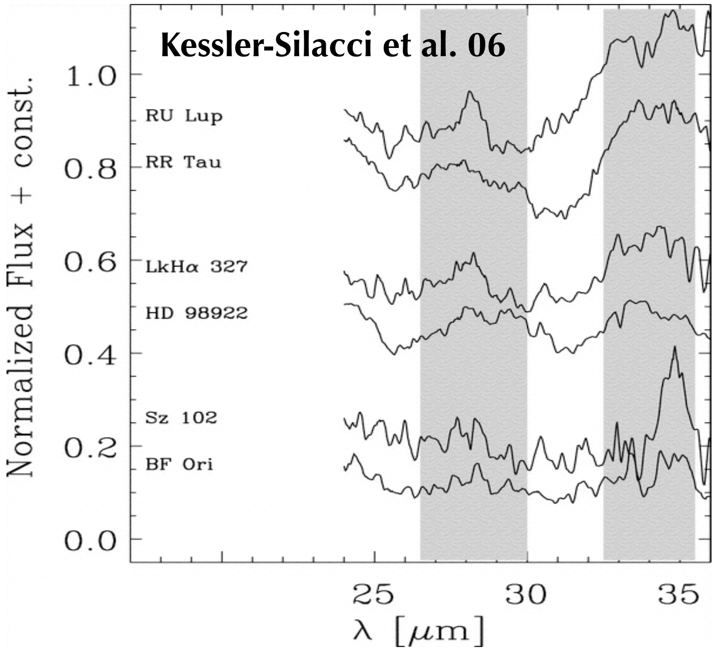
Problem persists even if

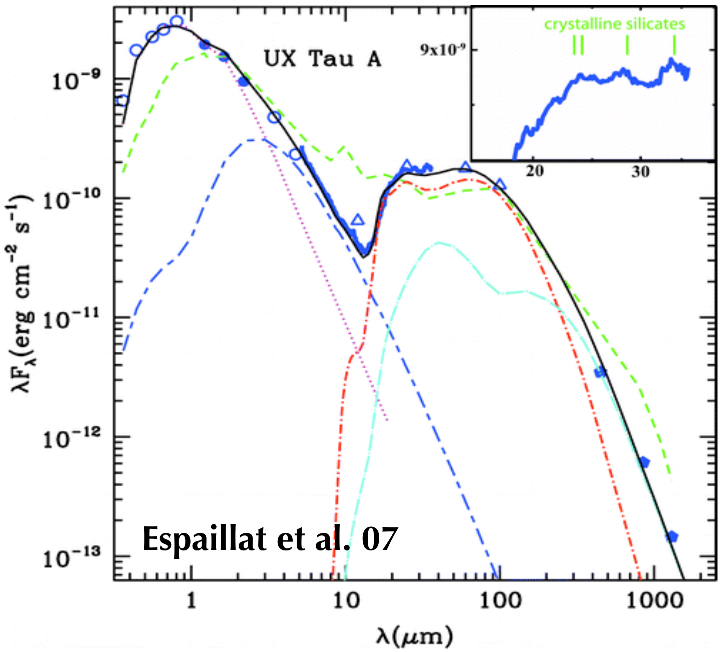
- grains are fractal
- monomers are nonspherical

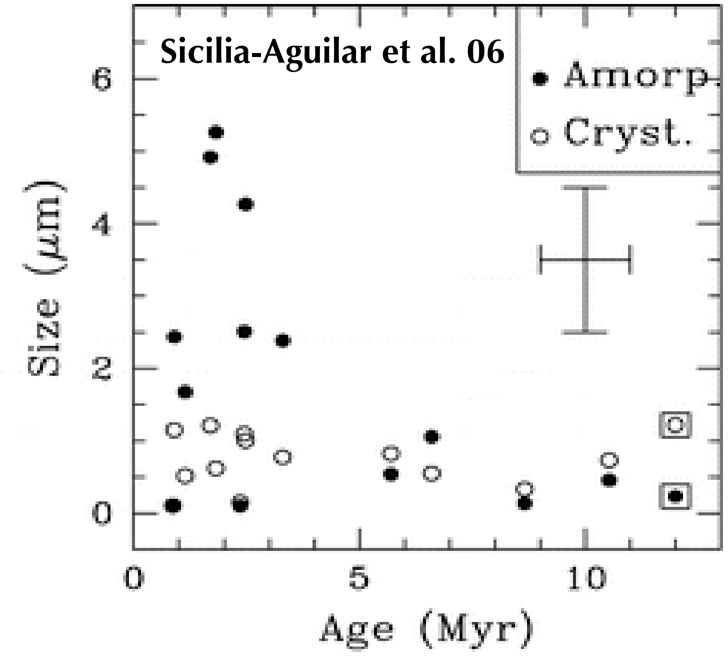
Proposed solution:

Replenishment of micron-sized grains (near-IR opacity) by fragmentation

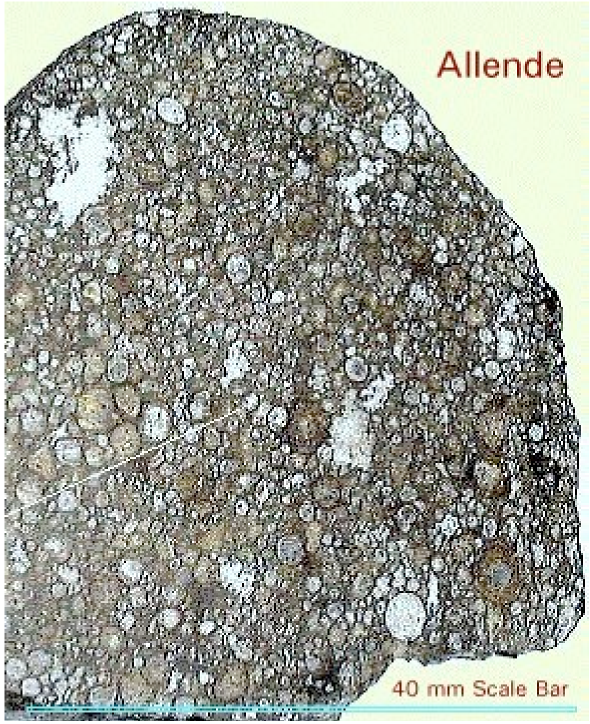
Theory I: Grain growth: Heating largely ignored ...





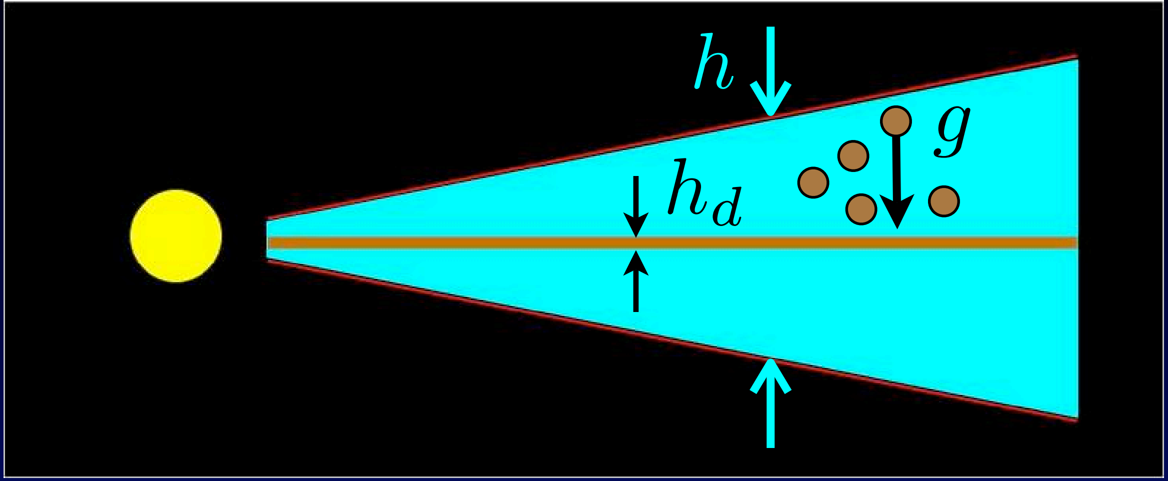


... but see Ciesla (2007)

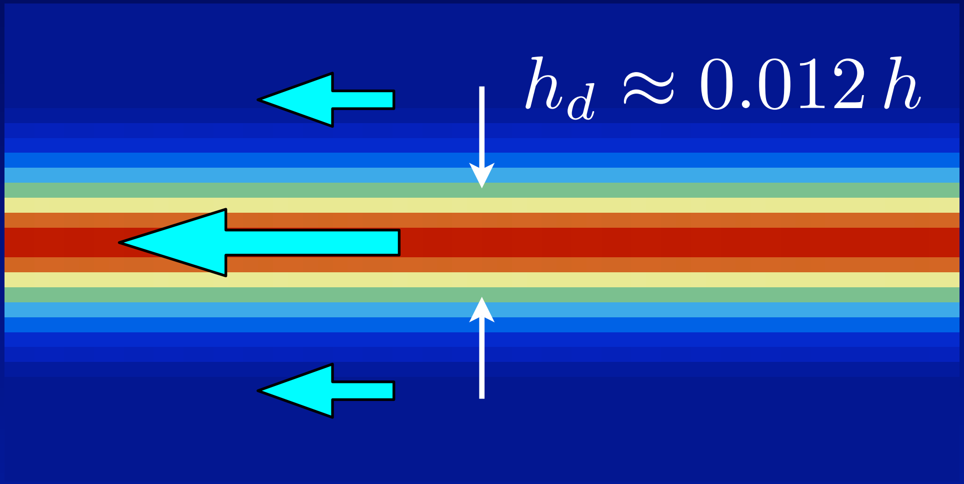


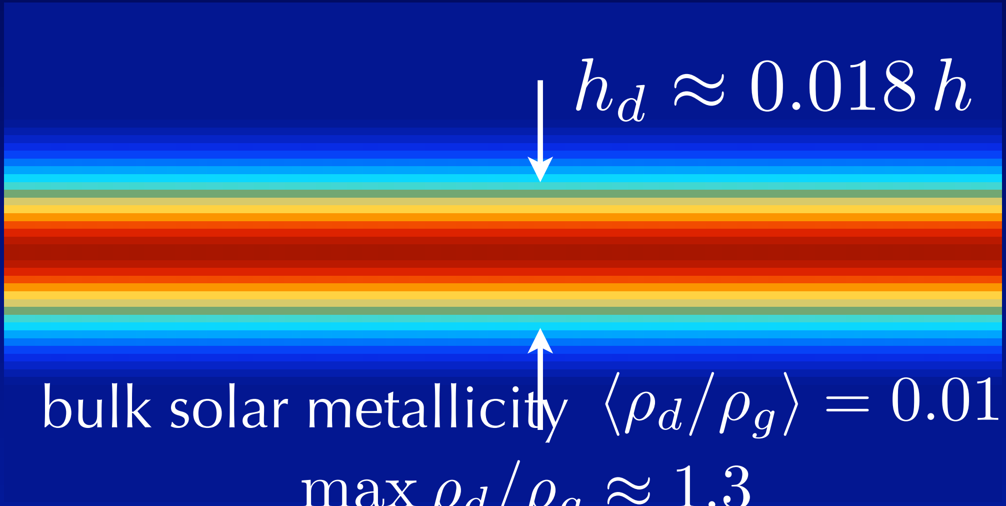
Theory I: Grain growth: Beyond cm sizes

Gravitational instability of
dust sub-layer
But Kelvin-Helmholtz
shearing instability interferes



3D shearing box simulations
of dust+gas mixture





bulk solar metallicity $\langle \rho_d/\rho_g \rangle = 0.01$

$\max \rho_d/\rho_g \approx 1.3$

$\max(\rho_d + \rho_g) \sim 10\%$ Roche density
if minimum mass nebula

Chiang 2008

Theory I: Grain growth

Gravitational instability of dust sub-layer

$\max(\rho_d + \rho_g) \sim$ Roche density

requires some combination of:

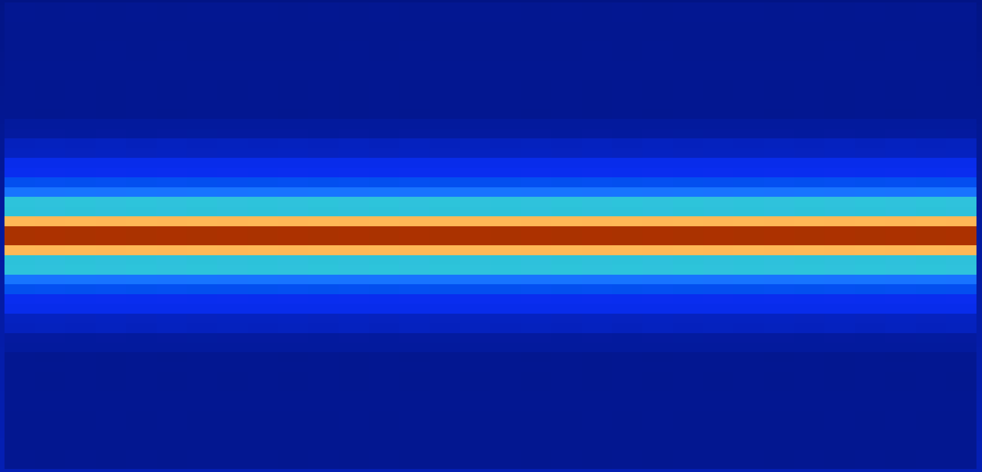
A. Disk masses > minimum-mass nebula

$\rho_g \uparrow \rho_d \uparrow$ at fixed ρ_d/ρ_g

B. Super-solar bulk metallicities

$\langle \rho_d/\rho_g \rangle \uparrow$ at fixed ρ_g

$\Big\}$ Enough to increase by factors of ~5

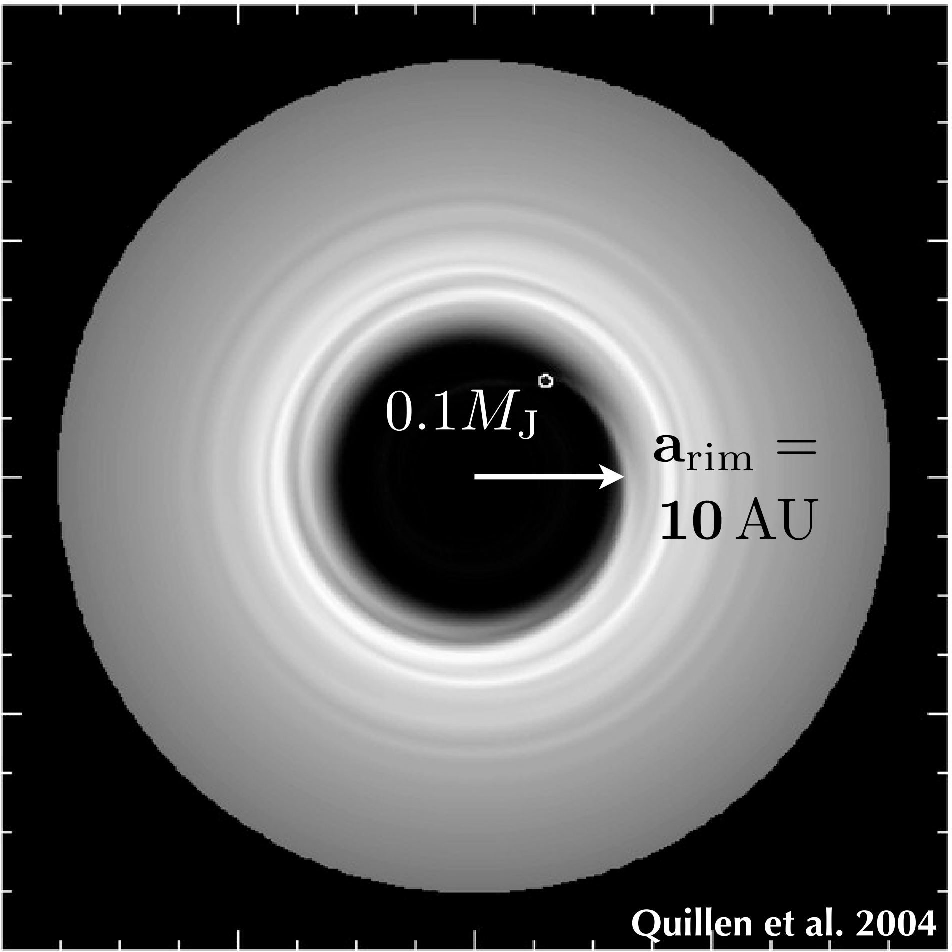


$\langle \rho_d/\rho_g \rangle = 0.03$

$\max \rho_d/\rho_g \approx 6$

Chiang 2008

Theory II: Planet Clearing



Quillen et al. 2004

Initial $\Sigma_\mathrm{inner} / \Sigma_\mathrm{outer} = 0.01$

Run duration = 100 orbits

≪ Viscous time t_diff ~ 10000 orbits

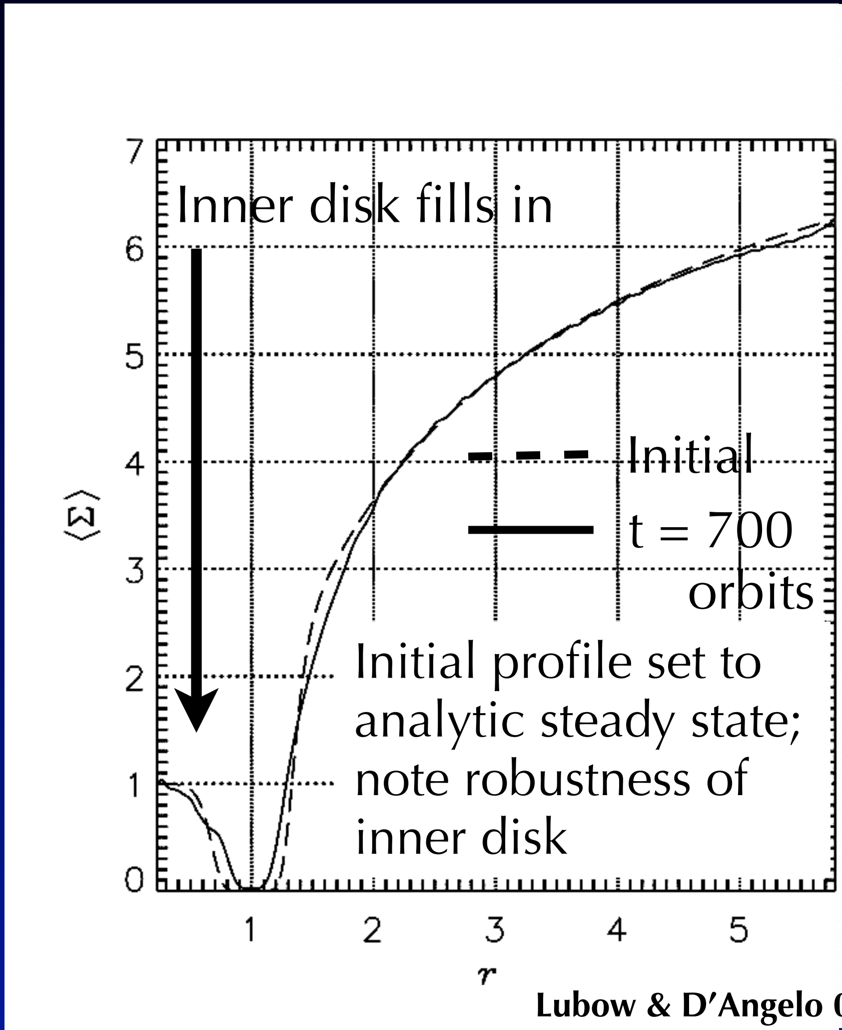
$$t_\mathrm{diff} \sim a_\mathrm{rim}^2 \;/\; \boxed{\nu}$$

$$\nu = \boxed{\alpha}\, c_s h$$

0.004 (assumed)

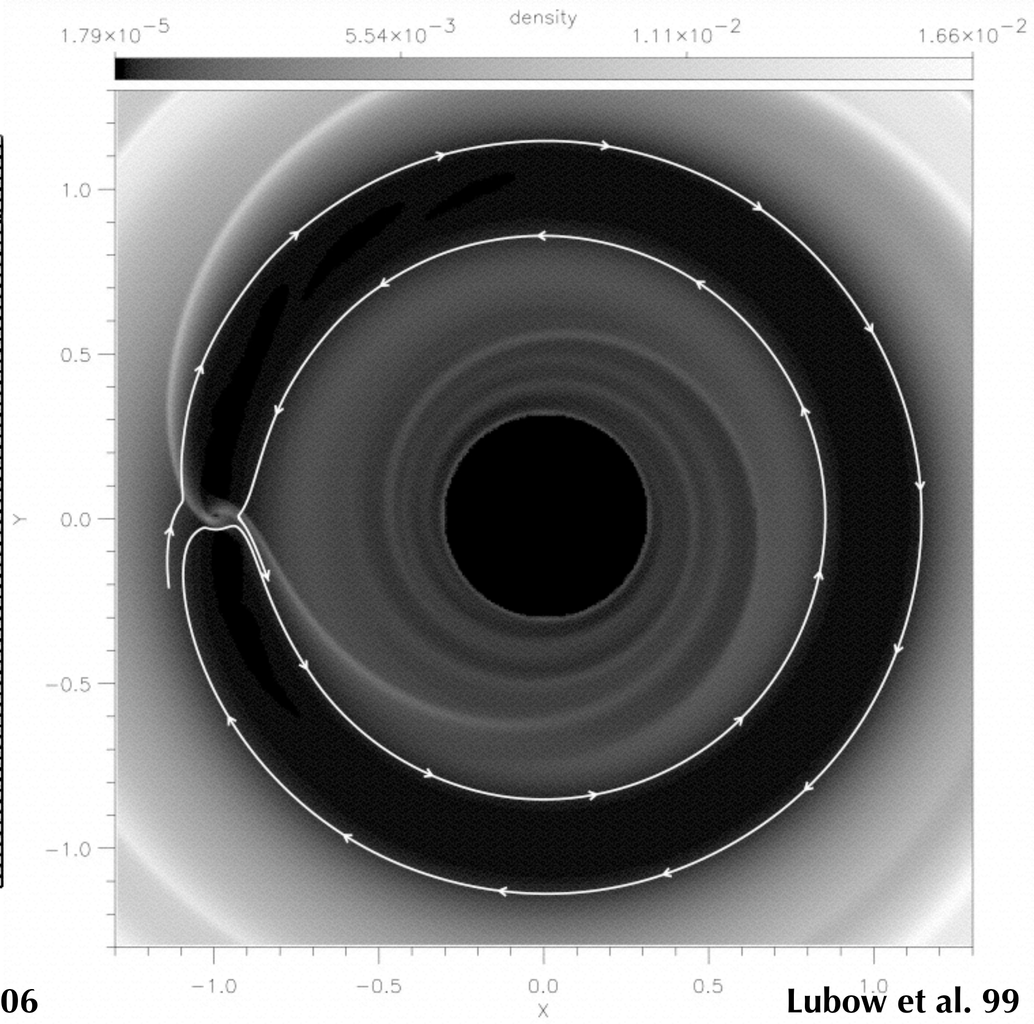
∴ Hole in simulation reflects assumed initial conditions

Theory II: Planet Clearing



Initial profile set to analytic steady state; note robustness of inner disk

Lubow & D'Angelo 06



Lubow et al. 99

$$\dot{M}_{\rm inner} \approx 0.1 \dot{M}_{\rm outer}$$

neglecting migration

- Reduces stellar accretion rate by 10 x
- Does not explain observed 1000 x reduction in dust
- Discrepancy should worsen if migration is included

Theory II: ~~Planet~~ Star Clearing: ~~Transitional~~ Circumbinary Disk

Binary separation

$a_{\text{binary}} \approx 8$ AU

$\approx$ Hole radius

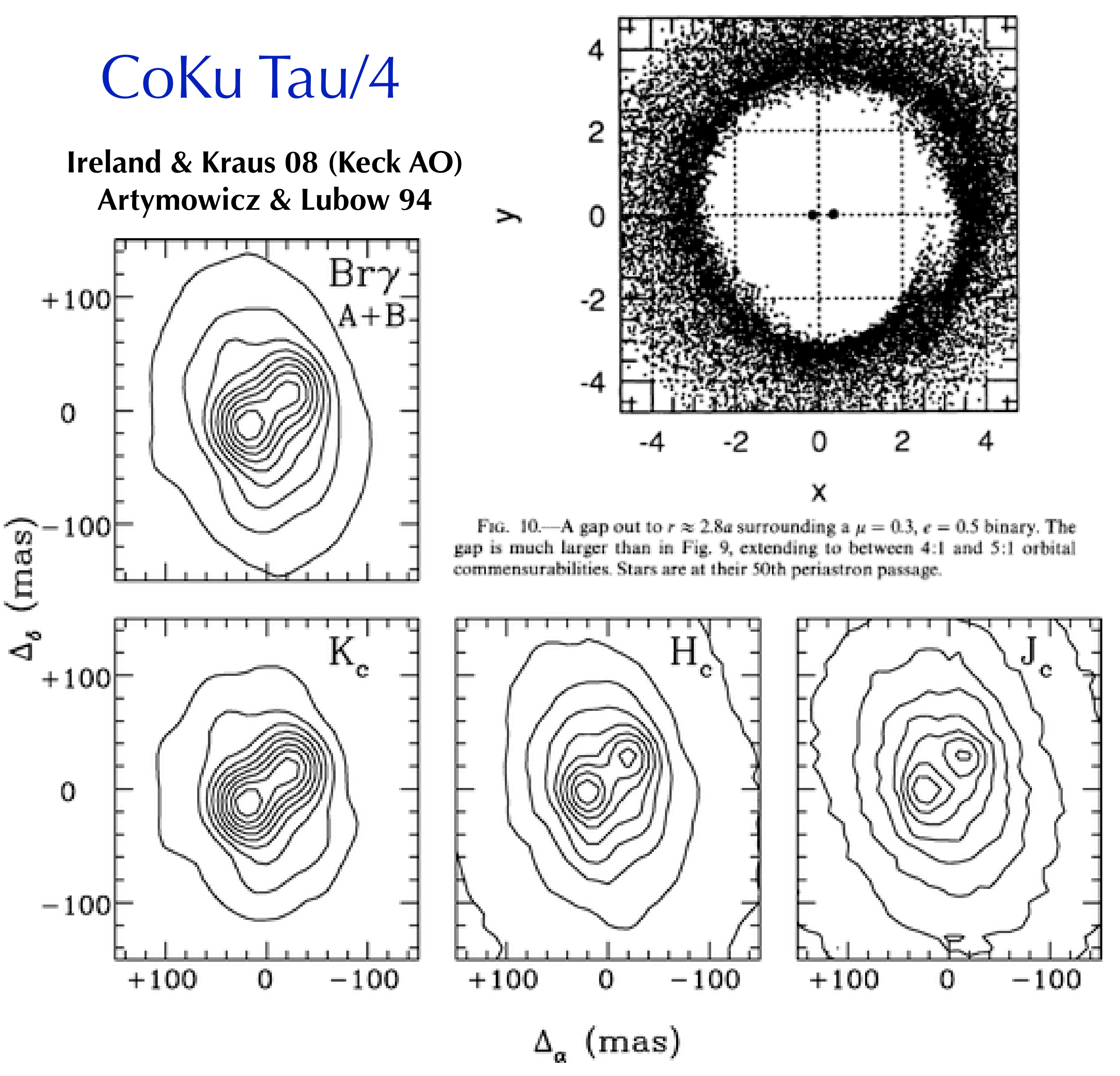
$a_{\text{rim}} \approx 10$ AU

$\tau_{10\mu\text{m}} < 0.002$

$\dot{M}_* < 10^{-10} M_\odot/\text{yr}$

No CO gas out to 2 AU

D'Alessio et al. 05
Najita et al. 07
Blake, Salyk, personal comm.



CoKu Tau/4

Ireland & Kraus 08 (Keck AO)
Artymowicz & Lubow 94

FIG. 10.—A gap out to $r \approx 2.8a$ surrounding a $\mu = 0.3$, $e = 0.5$ binary. The gap is much larger than in Fig. 9, extending to between 4:1 and 5:1 orbital commensurabilities. Stars are at their 50th periastron passage.

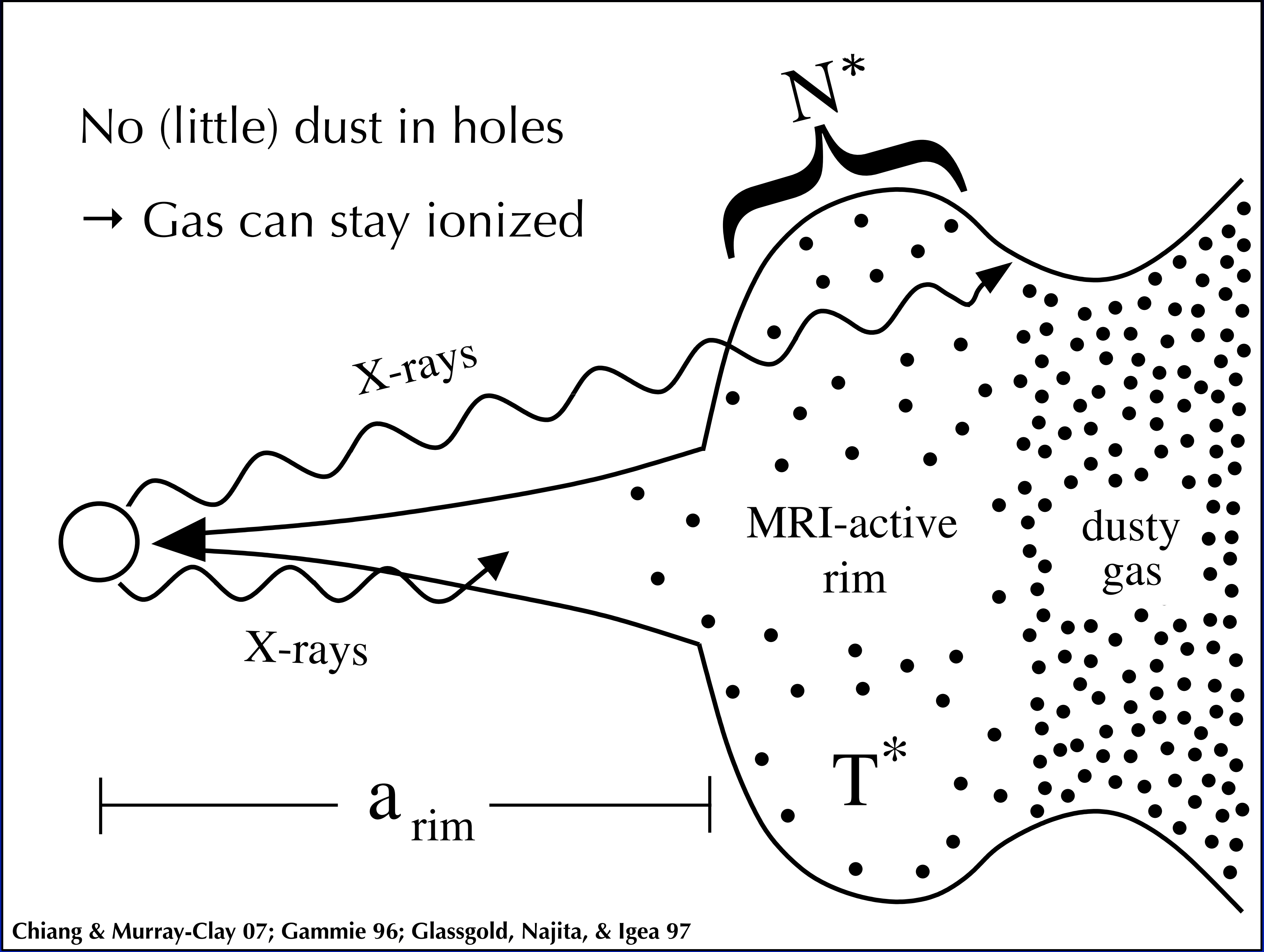
Summary so far

1. Grains grow.
   But growth alone cannot explain transitional disks.
   - Does not address $\dot{M}_*$ ~ 0.1 conventional T Tauri rate
   - Hard to reconcile with gapped / "pre-transitional" disks

2. Non-accreting transitional disks are circumbinary disks.

3. Single Jupiter-mass or smaller planets have too narrow gaps to explain either transitional or gapped disks.
   - Does not reconcile $1000 \times$ smaller $\tau_{10\mu\mathrm{m}}$ with $10 \times$ smaller $\dot{M}_*$

Theory III: Inside MRI / Outside Radiation Pressure

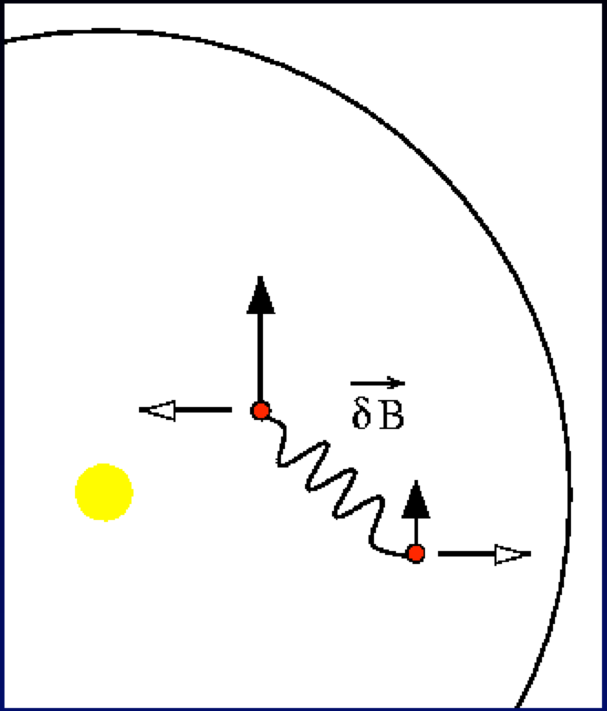


No (little) dust in holes

→ Gas can stay ionized

Chiang & Murray-Clay 07; Gammie 96; Glassgold, Najita, & Igea 97

Theory III: Inside MRI / Outside Radiation Pressure



- Linear instability afflicting weakly magnetized, outwardly shearing flows
- Instability drives turbulence that transports angular momentum outward and mass inward

Requirements

1. Magnetic flux freezing

   (Fleming, Stone, & Hawley 00)

$$\mathrm{Re_M} \equiv \frac{c_s h}{\eta} \propto \frac{n_e}{n}$$

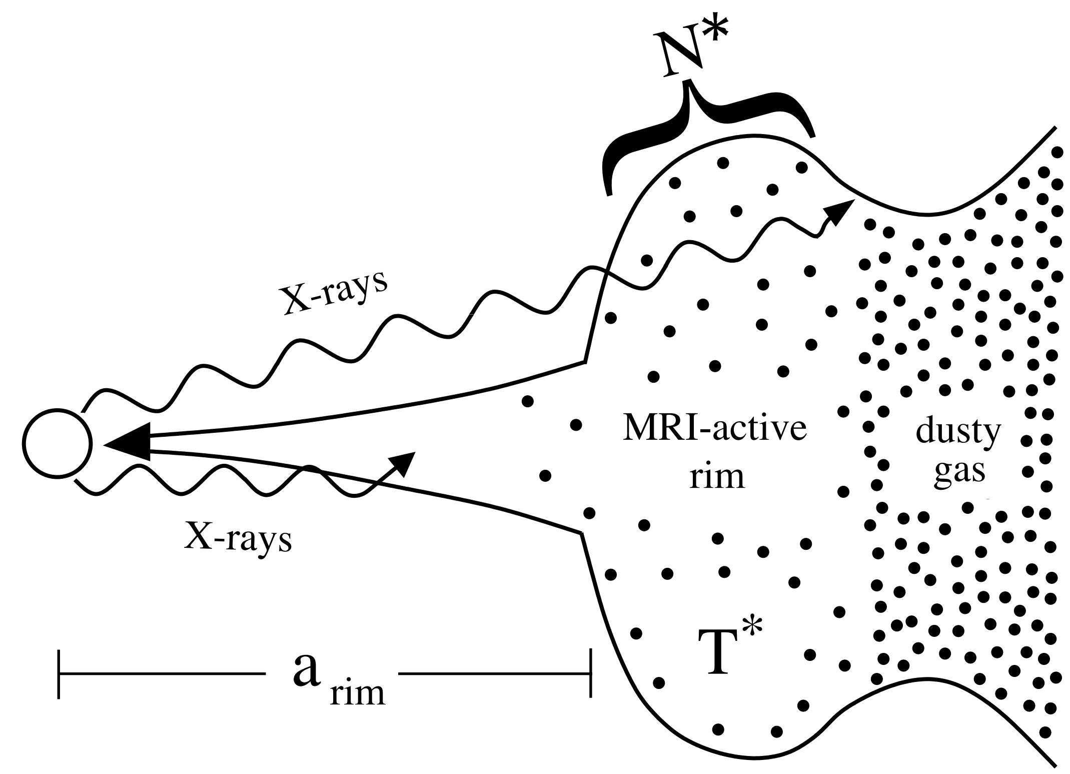
$$> \mathrm{Re_M^*} \approx 10^2 - 10^4$$

2. Good neutral-ion coupling

   (Blaes & Balbus 94
   Hawley & Stone 98)

$$\mathrm{Am} \equiv \frac{n_i \langle \sigma v \rangle_{in}}{\Omega} > \mathrm{Am}^* \approx 100$$

Theory III: Inside MRI / Outside Radiation Pressure



$$M_{\rm rim} = 2\pi a_{\rm rim} \times 2h \times \overset{10^{24}\ \mathrm{cm}^{-2}}{\boxed{N^*}}\ \mu$$

$$t_{\rm diff} \sim a_{\rm rim}^2 \ / \boxed{\nu}$$

$$\nu = \underset{0.01\ \text{(MRI gives } 10^{-4}\text{-}10^{-1}\text{)}}{\boxed{\alpha}} c_s h$$

$$\dot{M} \sim \frac{M_{\rm rim}}{t_{\rm diff}} \sim \frac{12\pi\alpha N^* a_{\rm rim}^2 \left(k\ \underset{230\ \mathrm{K}}{\boxed{T^*}}\ \right)^{3/2}}{GM_*\mu^{1/2}}$$

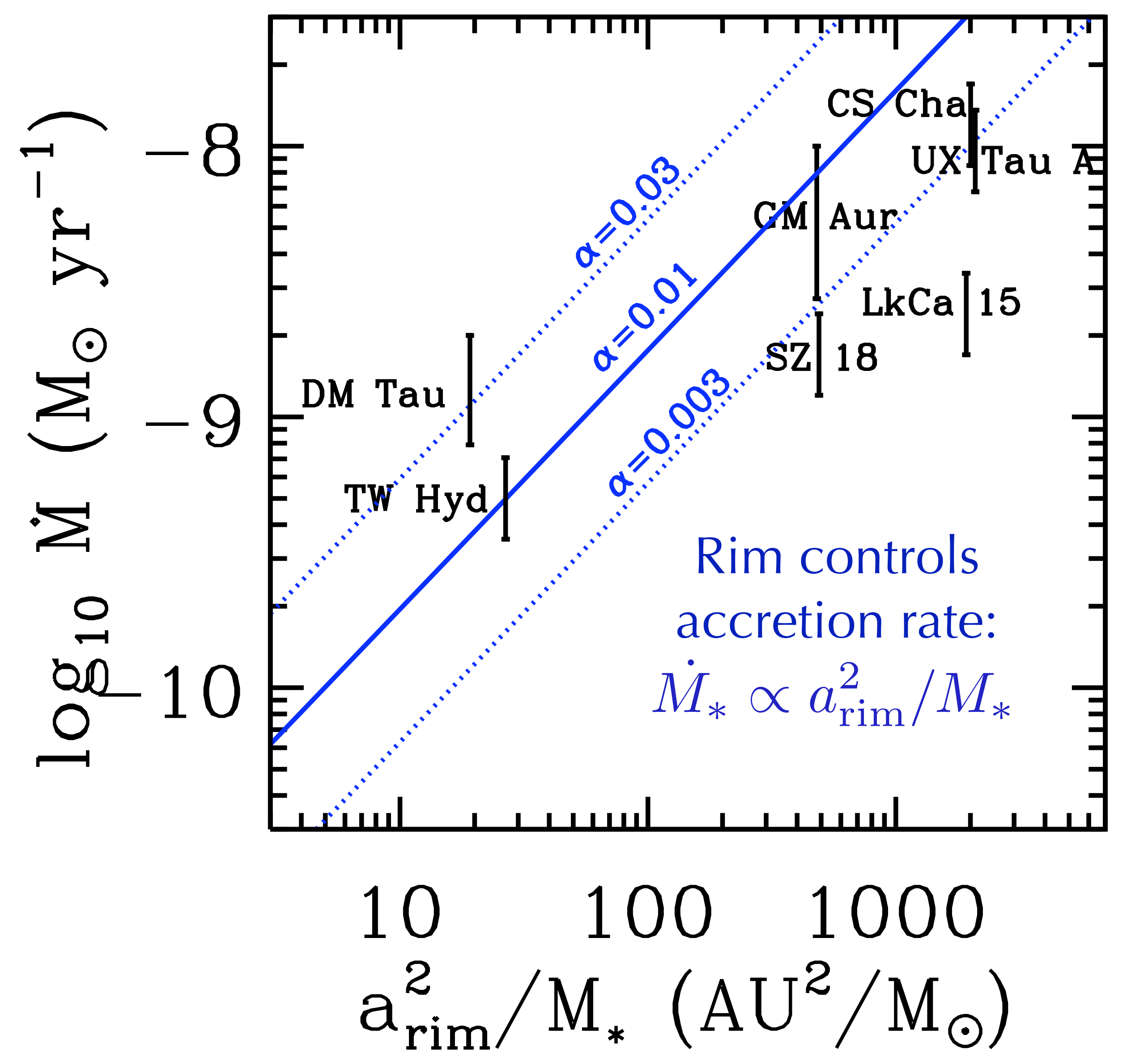
$$\frac{L_X \sigma_X e^{-N^*\sigma_X} f_{\rm heat}\, n}{4\pi a_{\rm rim}^2} \sim \Lambda_{\rm CO}(T^*)$$

photo-ionization heating — CO ro-vibrational cooling

Glassgold, Najita, & Igea 04

Chiang & Murray-Clay 07

Theory III: Inside MRI / Outside Radiation Pressure: Testing Predictions



Rim controls accretion rate: $\dot{M}_* \propto a^2_{rim}/M_*$

$$\dot{M} \sim \frac{12\pi\alpha N^* a^2_{rim}(kT^*)^{3/2}}{GM_*\mu^{1/2}}$$

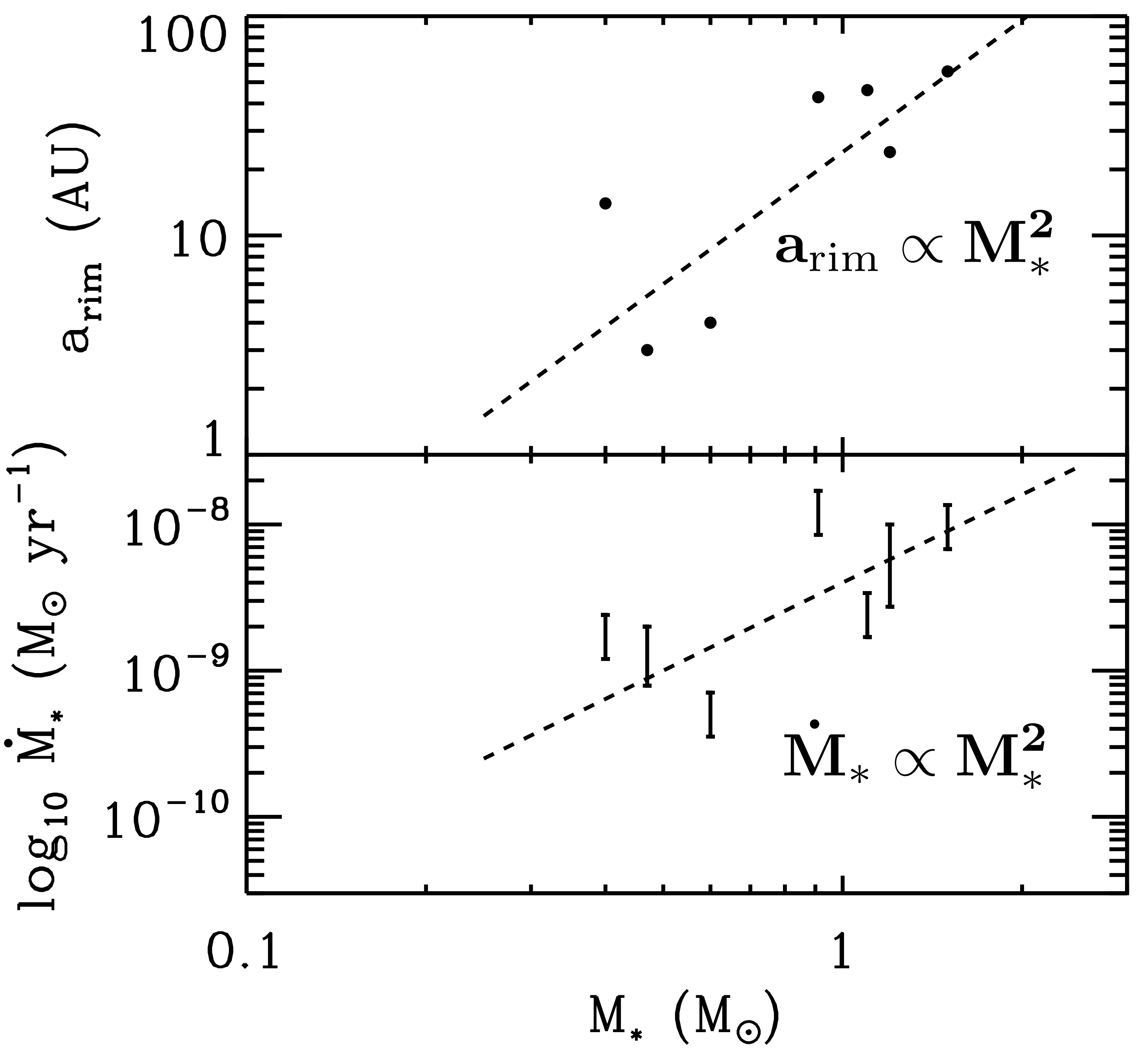
Further predicts
$\Sigma_{gas} \sim 1 - 10\,\mathrm{g\,cm^{-2}}$
@ 1 AU

- 100-1000 x lower density than MMSN
- Satisfies CO lower limits

But cannot explain origin of hole

Chiang & Murray-Clay 07

But deeper correlations may exist …



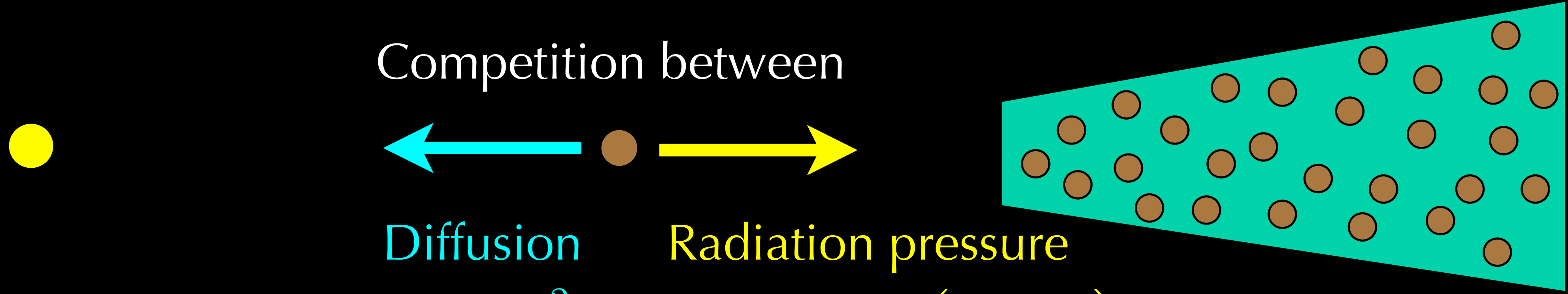
Why?

And does similar relation hold for debris disks?

Same $\dot{M}_* \propto M_*^2$ holds for non-transitional disks

Theory III: Inside MRI / Outside Radiation Pressure

Goal: Keep just enough dust in



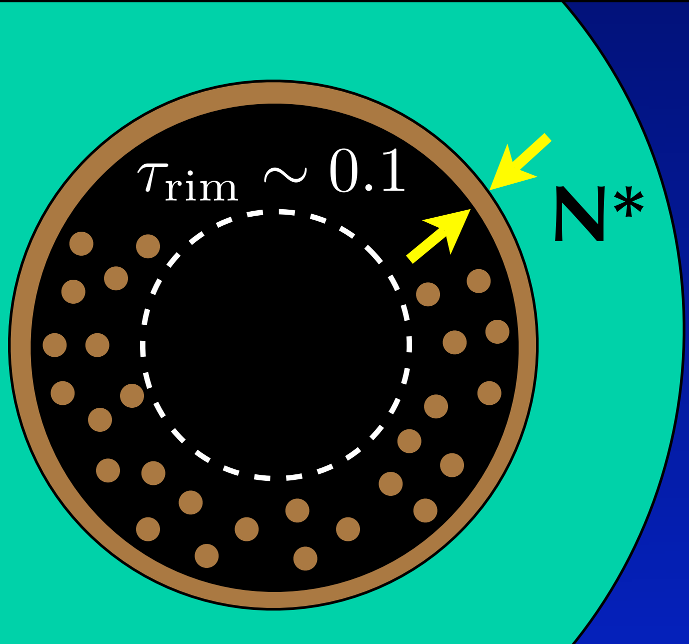
Competition between

Diffusion

Radiation pressure

$$t_{\rm diff} \sim \frac{a^2}{\nu} \qquad t_{\rm blow} \sim \frac{1}{\Omega}\left(\frac{1}{\Omega t_{\rm stop}}\right)$$

$$\text{At } a_{\rm rim},\ t_{\rm blow} \sim t_{\rm diff} \Longrightarrow \sim 1/2 \text{ rim dust leaks to a}_{\rm rim}/2$$



- Does leaked dust keep leaking in?

  $$\frac{t_{\rm blow}}{t_{\rm diff}} \propto \Sigma_{\rm gas} T a \uparrow\downarrow \text{ with } a?$$

- Leaked dust might concentrate at $a \ll a_{\rm rim}$, restoring $\tau_{10\mu{\rm m}} > 1$: gapped disk possible
- Situation unclear without further modeling

Chiang & Murray-Clay 07

Summary

1. Grains grow.
   But growth alone cannot explain transitional disks.
   - Does not address $\dot{M}_*$ ~ 0.1 conventional T Tauri rate
   - Hard to reconcile with gapped / “pre-transitional” disks

2. Non-accreting transitional disks are circumbinary disks.

3. Single Jupiter-mass or smaller planets have too narrow gaps to explain either transitional or gapped disks.
   - Does not reconcile $1000\times$ smaller $\tau_{10\mu\mathrm{m}}$ with $10\times$ smaller $\dot{M}_*$

4. Inside-out MRI can account for $\dot{M}_*$, given $\alpha \sim 0.01$
   - Predicts $\Sigma_{\mathrm{gas}} \sim 1-10\,\mathrm{g\,cm}^{-2}$ @ 1 AU
   - Predicts $\dot{M}_* \propto a_{\mathrm{rim}}^2/M_*$ (if all other factors equal)
   - Cannot explain origin of AU-sized hole

Future directions

Key puzzle: $1000 \times$ smaller $\tau_{10\mu\mathrm{m}}$ with $10 \times$ smaller $\dot{M}_*$

1. Theories are not mutually exclusive.

Planets +	Grain growth +	MRI +	Radiation pressure
smaller $\dot{M}_*$	smaller $\tau_{10\mu\mathrm{m}}$	origin of viscosity	smaller $\tau_{10\mu\mathrm{m}}$
Multiple planets may be required to explain factor of 10 and prolong Type II migration	Implied by planets!		Imperfect clearing can lead to gapped disks (e.g. LkCa 15)

2. What is the origin of viscosity prior to transitional phase?

Gravitational torques? See papers by Vorobyov and Basu