Workshop on Magneto-Rotational Instability in Protoplanetary Disks

Dust evolution in protoplanetary disks: Effect on observations of dust emission

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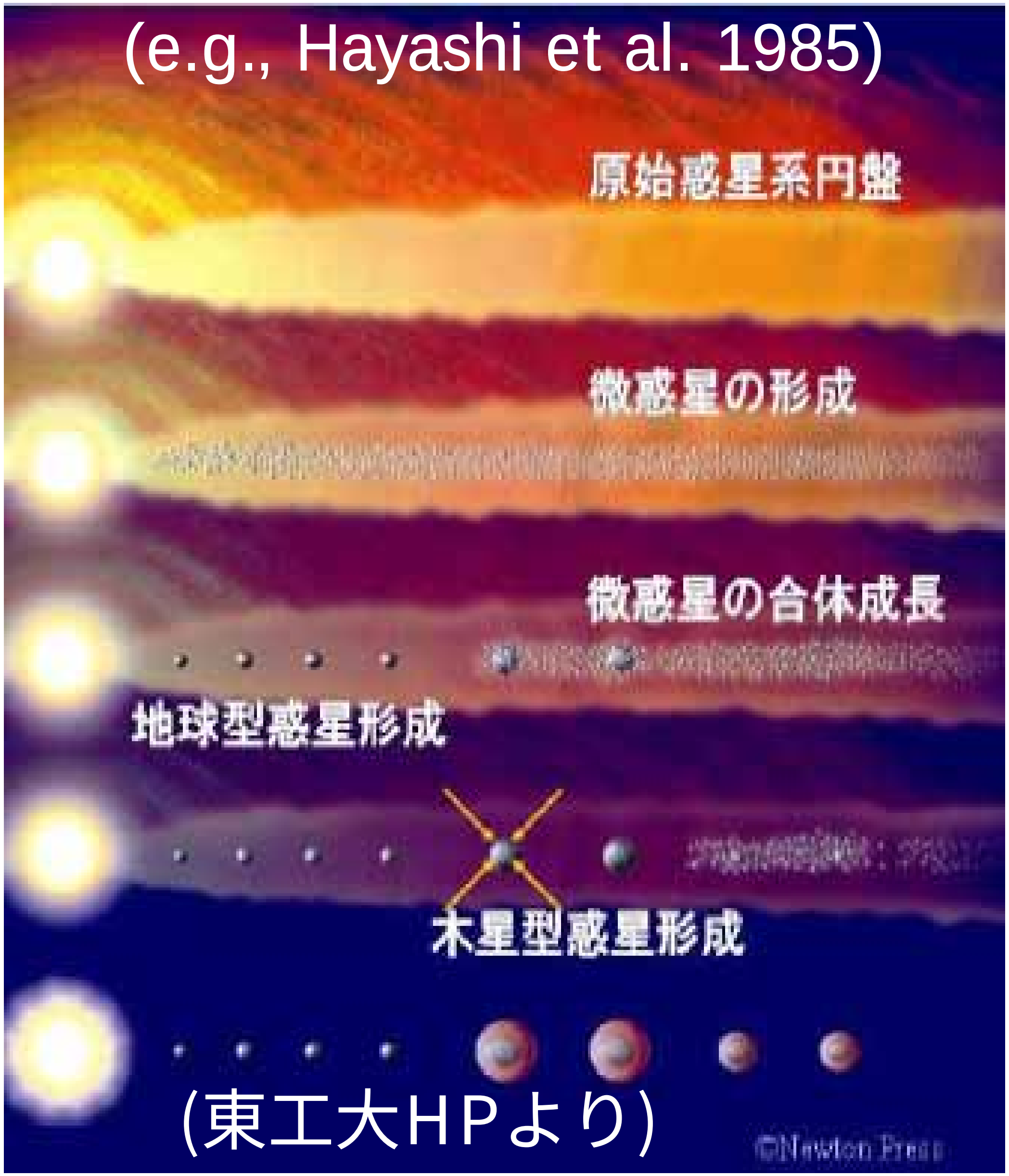
§ 1 Introduction

From protoplanetary disk to planets


(e.g., Hayashi et al. 1985)

(東工大HPより)

Dust size growth & settling

↓

Planetesimal formation

↓

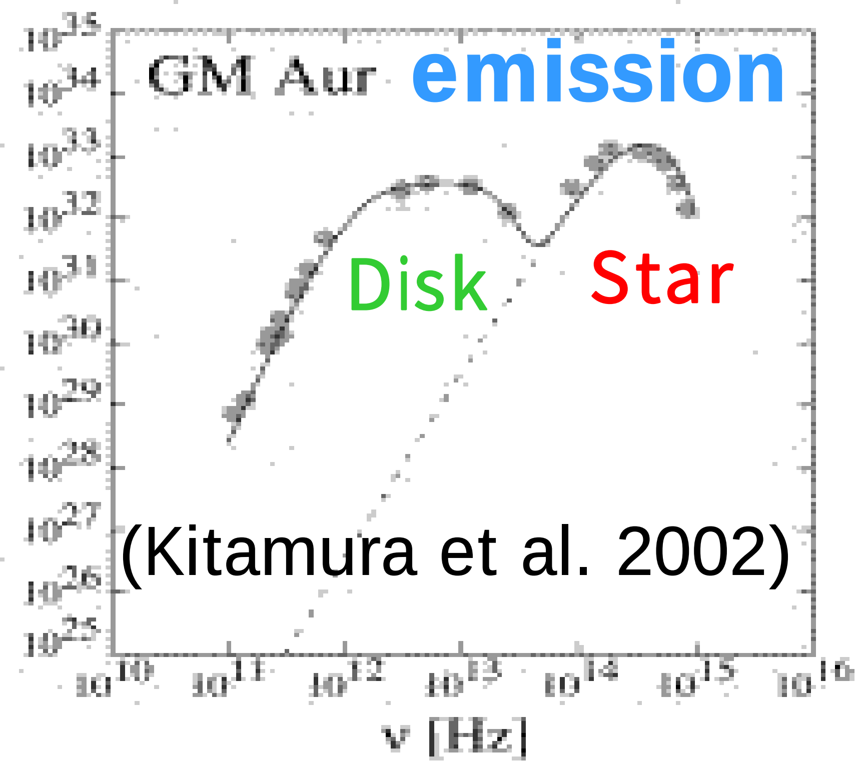
Collisional growth, Planet formation

↓

Gas dispersal → Planetary system formation

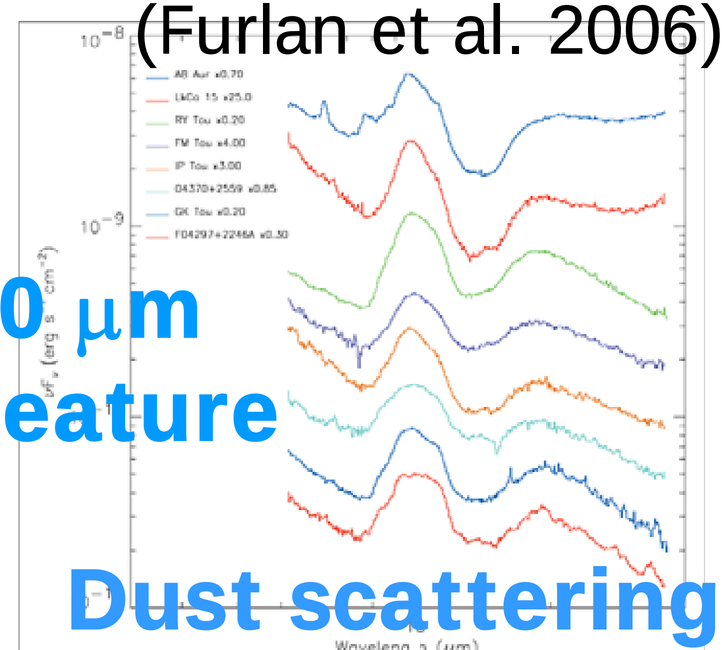
Obs. of Dust Emission from PPDs

Thermal dust emission



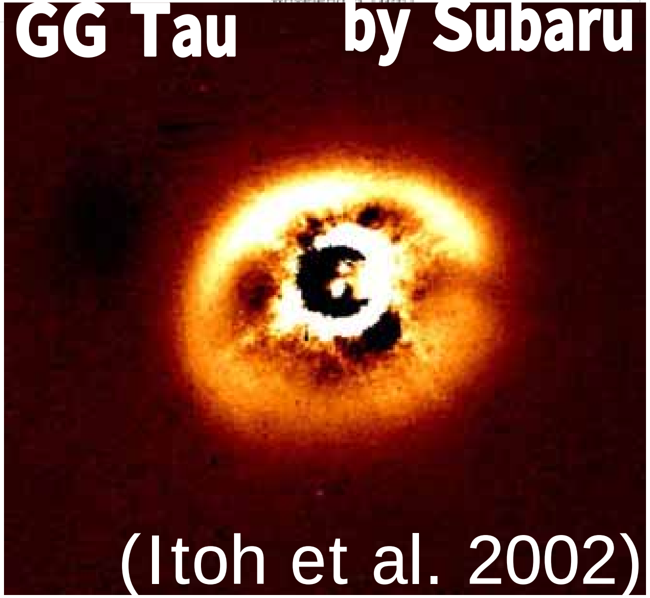
(Kitamura et al. 2002)

(Furlan et al. 2006)

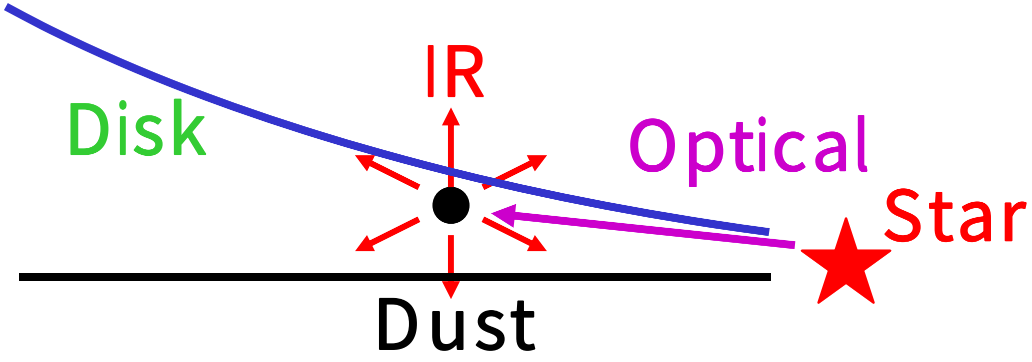


10 μm Si feature

Dust scattering

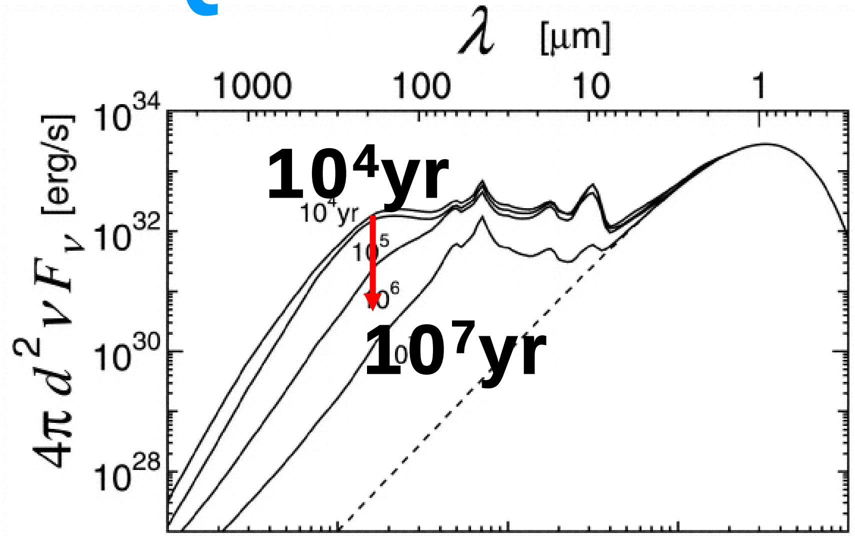


(Itoh et al. 2002)



Dust Evolution & SED

Quiescent disk

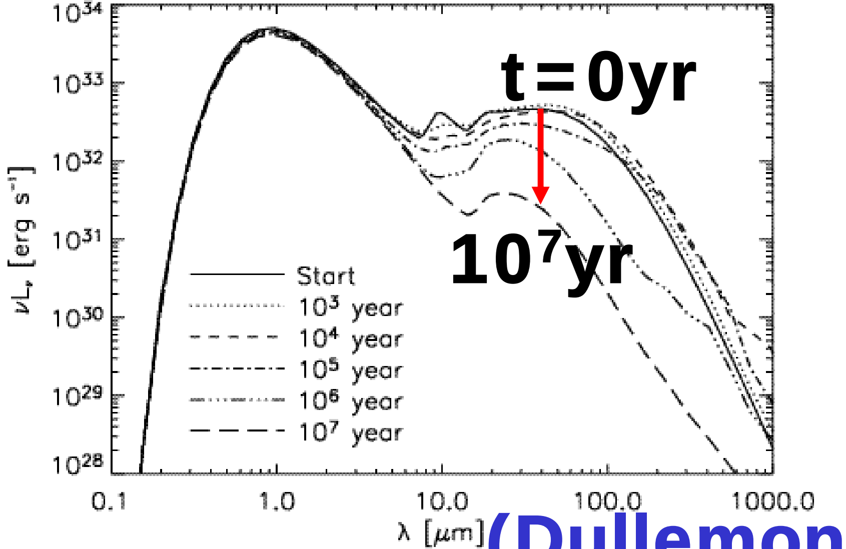


(Tanaka et al. 2005)

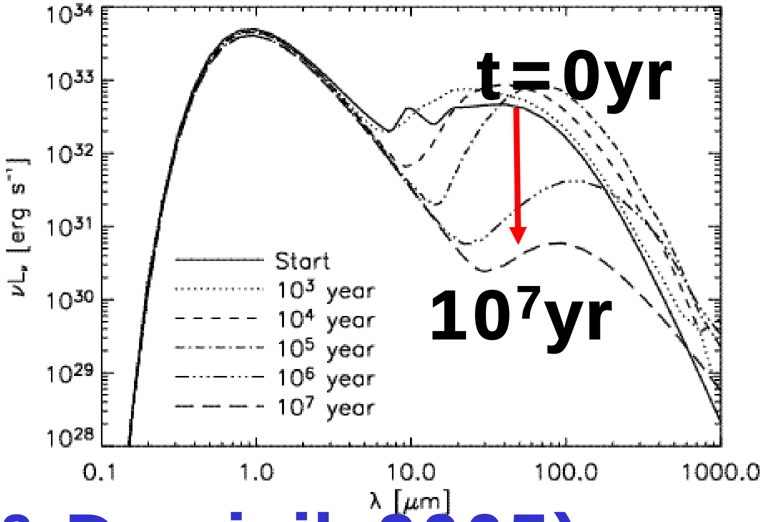
Dust evolution in disks

→ SED model calculation

Unable to reproduce observations especially in turbulent disks



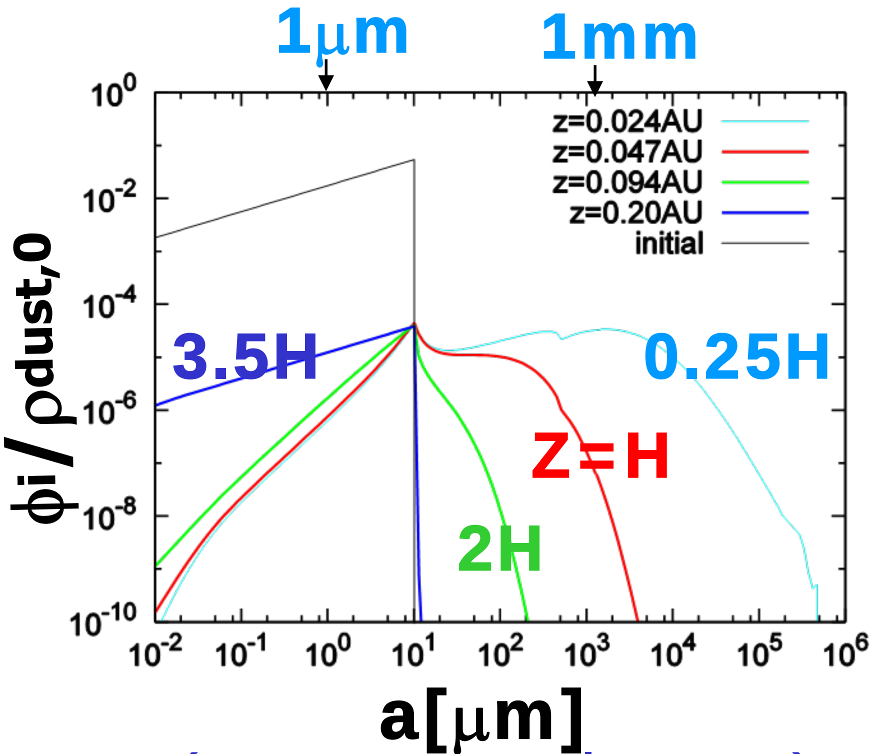
Turbulent disk



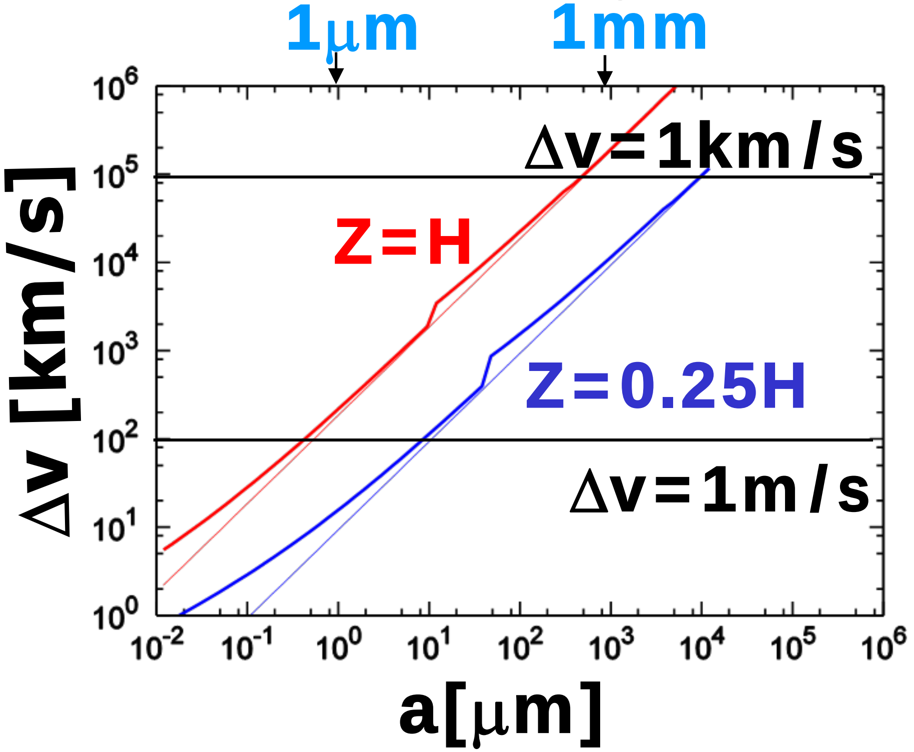
(Dullemond & Dominik 2005)

How to Supply Small Dust Grains?

Turbulent disk, R=1AU, t=10^6yr



(Nomura et al. 2007)



→ **Fragmentation ?**

Supply of small dust grains to inner disk

- **Vertical: cloud → disk midplane**
- **Radial: migrate with gas accretion flow**

§ 2

Size growth, settling, & migration of dust particles and Disk model

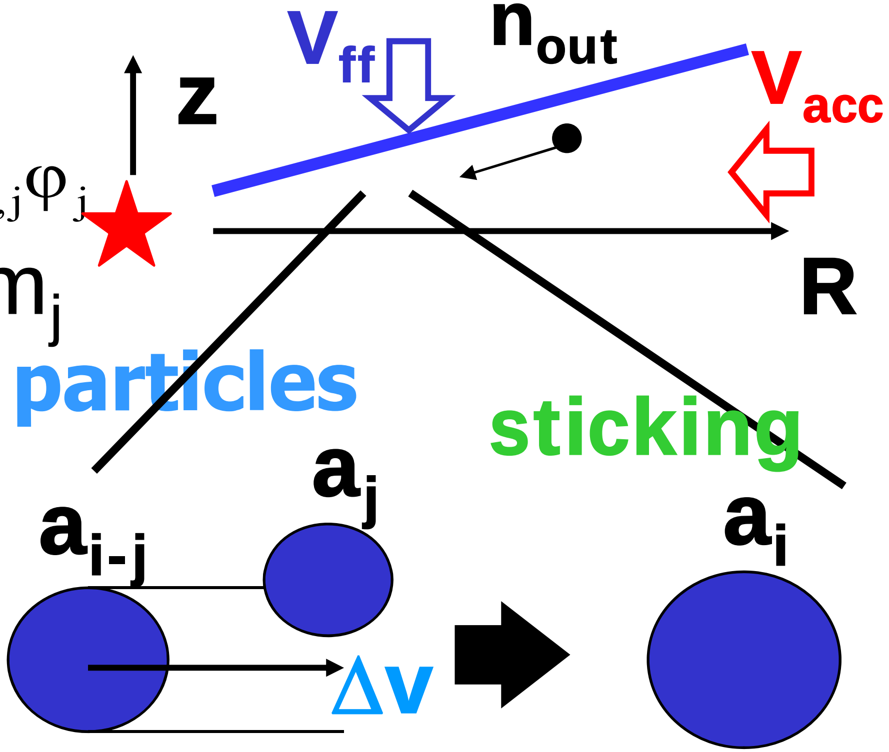
Dust size growth, settling, migration

Coagulation eq. for dust particles

$$\frac{\partial\varphi_i}{\partial t} + \frac{1}{R}\frac{\partial(R\varphi_i v_R)}{\partial R} + \frac{\partial(\varphi_i v_z)}{\partial z}$$

$$= \frac{1}{2} m_i \sum_{j=1}^{i-1} \beta_{i-j,j}\varphi_{i-j}\varphi_j - m_i\varphi_i \sum_{j=1}^{N} \beta_{i,j}\varphi_j$$

$$\beta_{i-j,j} = \pi(a_{i-j}+a_j)^2 \Delta v\, p_s/m_{i-j}m_j$$



Δv: relative velocity bw. particles

-Brownian motion
-settling & radial velocity differences
-turbulent induced velocity differences

Turbulent mixing

$$V_z\varphi_i = -\left(\Omega_z^2 z/D\right)\varphi_i - D_0\left(\partial\varphi_i/\partial z\right)$$

$$D_0 = \alpha c_s H/\left(1+\Omega_K/D\right) \qquad D = \rho_{gas} c_s/a$$

Velocity of Dust particles (V_R&V_Z)

Eq. of motion for dust

a : dust radius

$$\frac{d\mathbf{U}}{dt} = -D(\mathbf{U}-\mathbf{u}) - \frac{GM_*}{R^3}\mathbf{R} \approx 0$$

$$D = \rho_{gas} c_s / a$$

Eq. of motion for gas

$$\frac{d\mathbf{u}}{dt} = -\frac{\rho_{dust}}{\rho_{gas}} D(\mathbf{u}-\mathbf{U}) - \frac{GM_*}{R^3}\mathbf{R} - \frac{\nabla P_{gas}}{\rho_{gas}} + \frac{\nabla \cdot \boldsymbol{\sigma}}{\rho_{gas}} \approx 0$$

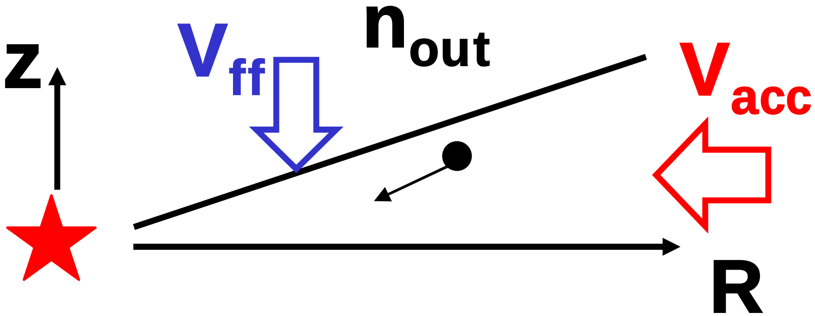
$$V_z = -\left(\Omega_K^2 / D\right) Z$$

$V = U - v_K$、 $v = u - v_K$

$$V_R = -\frac{\rho_{gas}}{\rho_{gas}+\rho_{dust}}\left(\frac{2D\Omega_K}{D^2+\Omega_K^2}\eta + \frac{2D^2}{D^2+\Omega_K^2}\zeta\right)v_K$$

$$\zeta = -\frac{1}{2}\frac{1}{\rho_{gas}}\frac{\partial}{R\partial R}\left(R\rho_{gas}\alpha c_s h \Omega_K\right)\frac{1}{R\Omega_K^2}$$

$$\eta = -\frac{1}{2}\frac{1}{\rho_{gas}}\frac{\partial p_{gas}}{\partial R}\frac{1}{R\Omega_K^2}$$

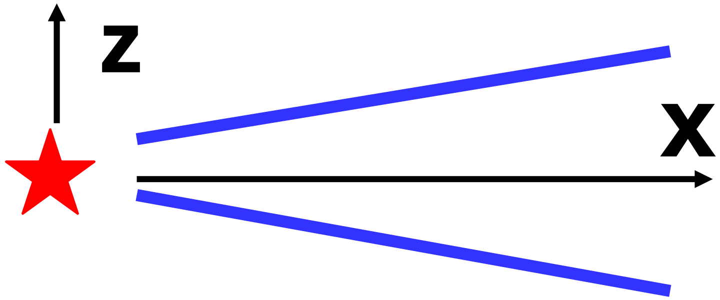


Gas Density Profile

Hydrostatic equilibrium in z-direction

$$\frac{dP}{dz} = -\rho g_z = -\frac{\rho G M_* z}{(x^2+z^2)^{3/2}}$$

$P=\rho kT/\mu m_p$, $M_*=0.5\ M_s$



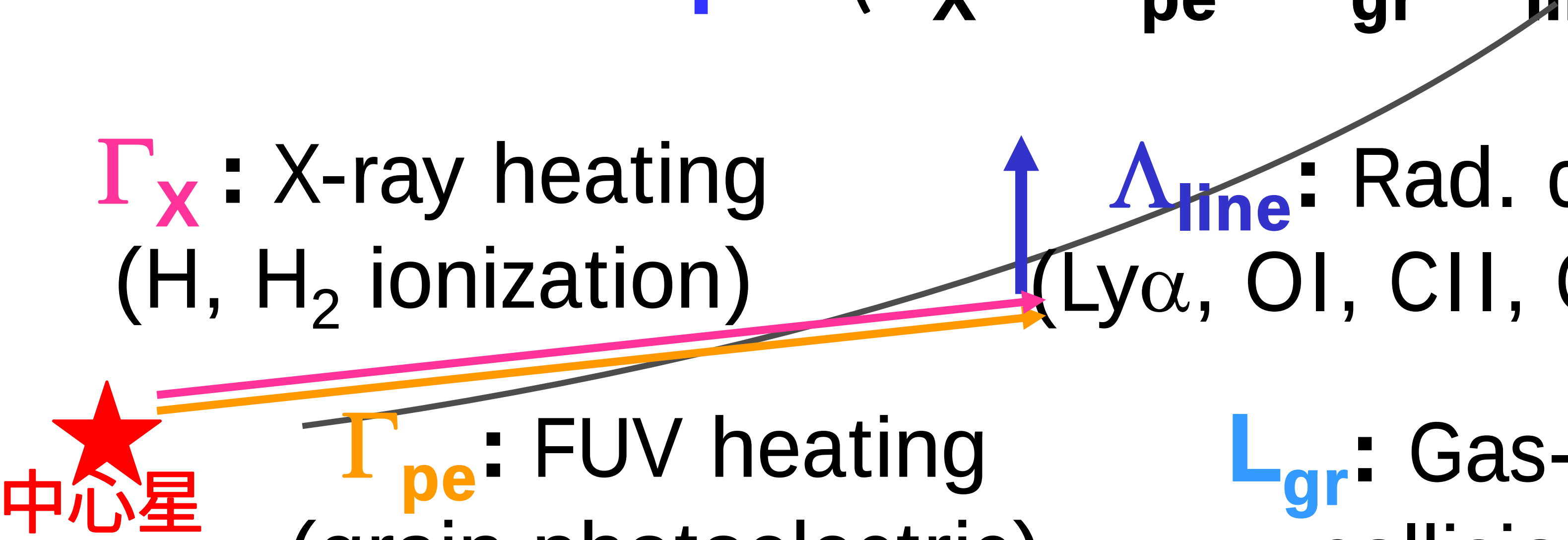
Surface density: Σ (←energy balance)

$$\frac{9}{4}\Sigma\alpha c_{s0}^2\Omega = \frac{3GM_*\dot{M}}{8\pi x^3}\left[1-\left(\frac{R_*}{x}\right)^{1/2}\right]$$

$\dot{M}_{acc}=1\times10^{-8}M_s/yr$ (=const.), $\alpha=0.01$

Gas & Dust Temperature Profile

Gas: **Thermal equi.** $(\Gamma_X + \Gamma_{pe} + L_{gr} - \Lambda_{line} = 0)$



Γ_X : X-ray heading
(H, H_2 ionization)

Λ_{line}: Rad. cooling
(Lyα, OI, CII, CO lines)

Γ_{pe}: FUV heating
(grain photoelectric)

L_{gr}: Gas-dust
collisions

Dust: **Local radiative equilibrium**

$$\int_0^\infty d\nu\, \kappa_\nu \oint I_\nu d\Omega = 4\pi \int_0^\infty d\nu\, \kappa_\nu B_\nu(T_{gr})$$

Heating: Irradiation from central star
Cooling: Dust thermal radiation

§ 3

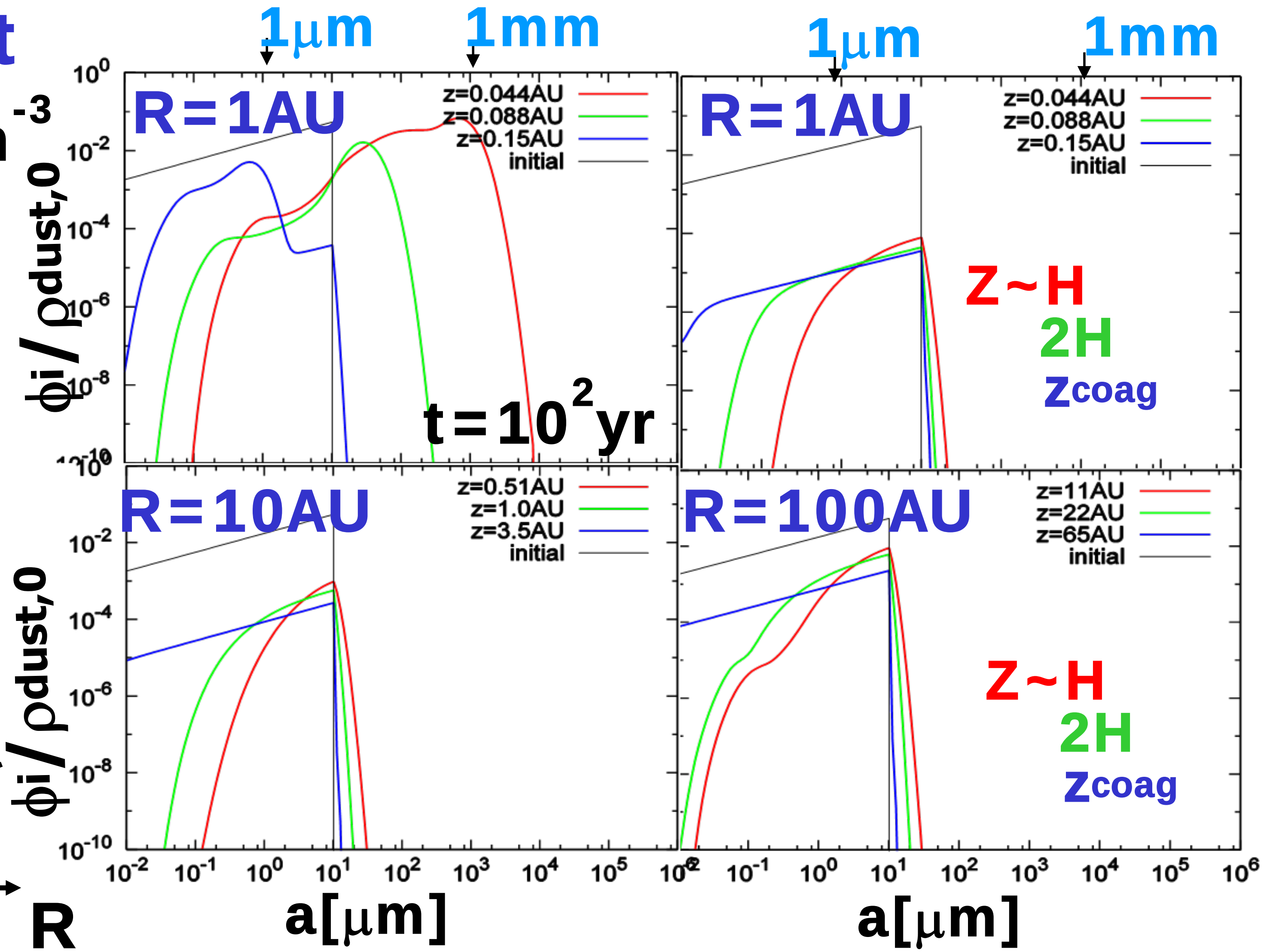
Resulting Dust Size & Spatial Distributions

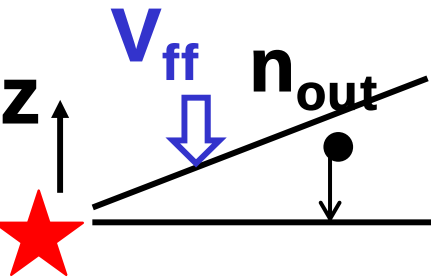
Dust size distribution (only V_z)

Quiescent

$n_{out} = 10^4 cm^{-3}$

$t = 10^6 yr$





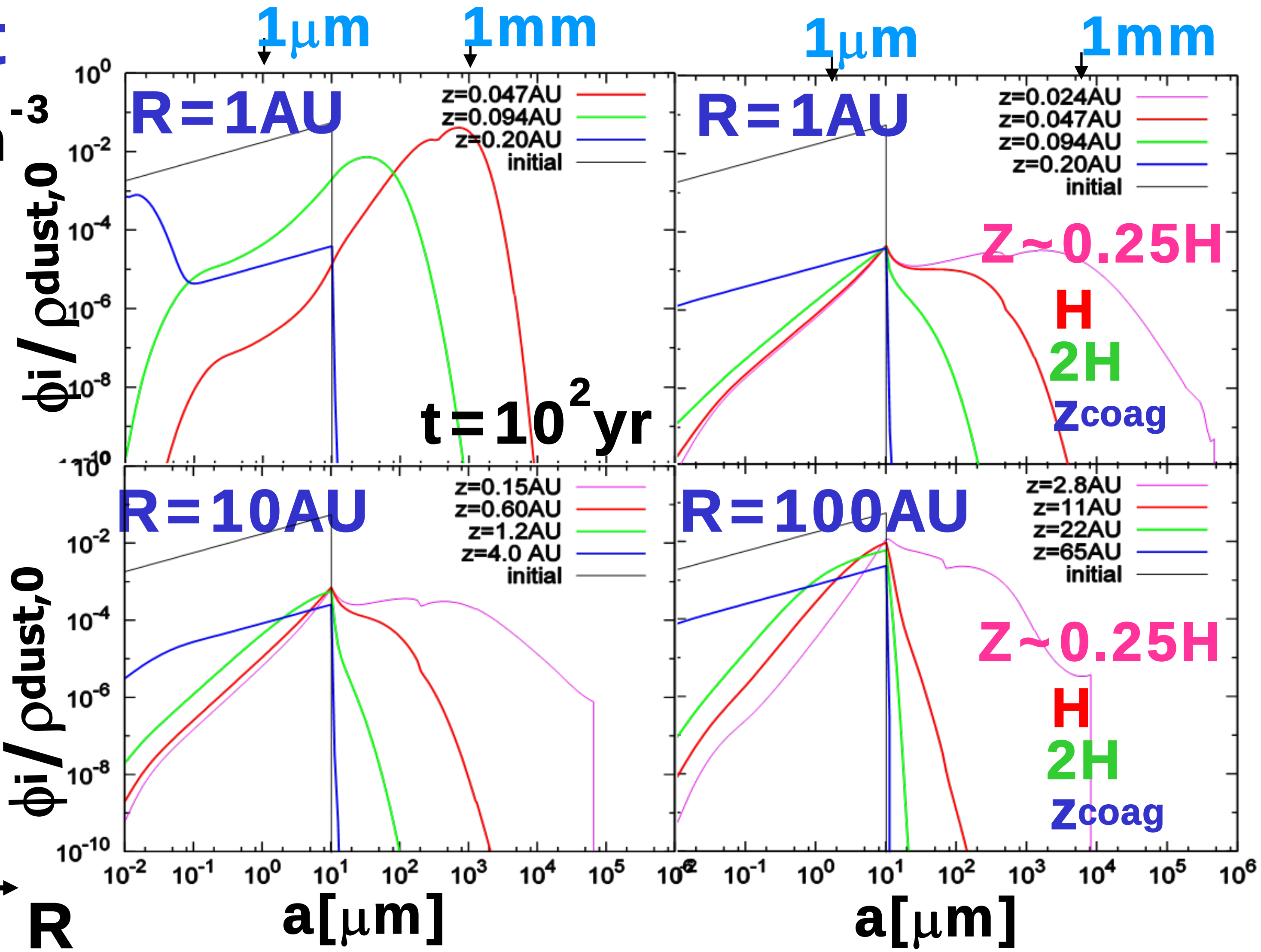
$t = 10^6 yr$: large dust → settle, R ↘ → $\phi_i / \rho_{dust,0}$ ↘

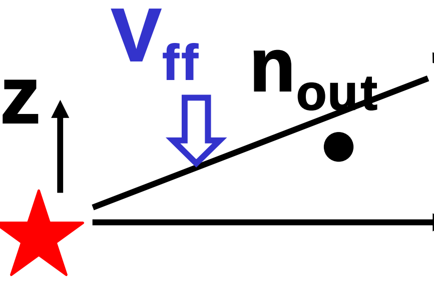
Dust size distribution (only V_z)

Turbulent

$n_{out} = 10^4 \mathrm{cm}^{-3}$

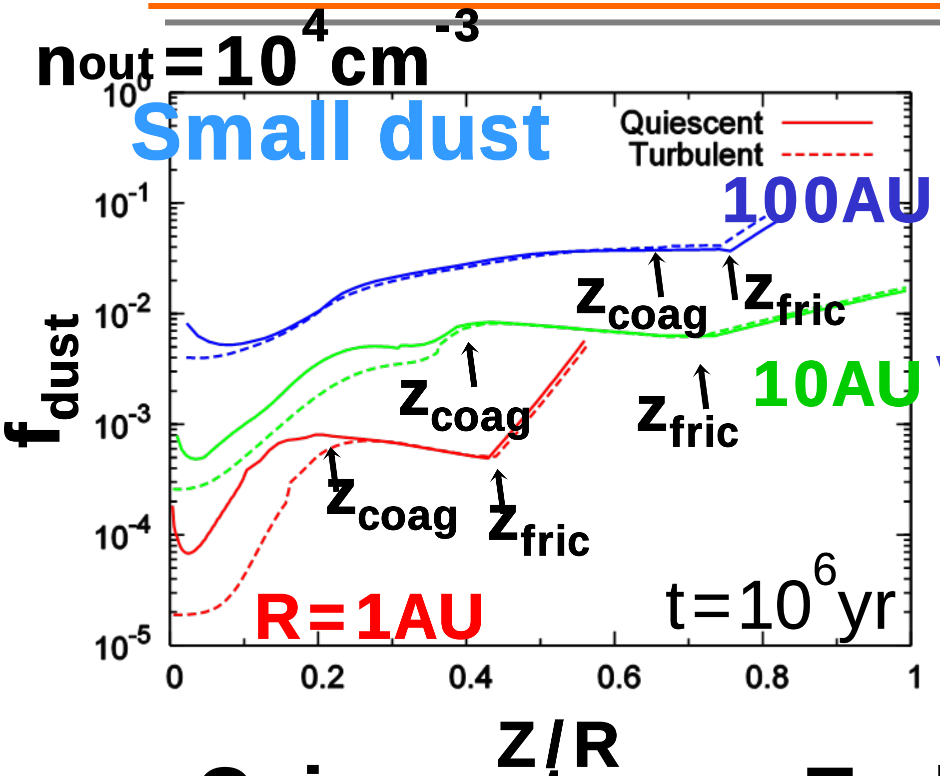
$t = 10^6 \mathrm{yr}$





Large grains exist due to turbulent mixing

Small-dust/Gas Ratio (only V_z)



$$A(R, z) = \int \pi a^2 \frac{dn(R, z)}{da} da$$

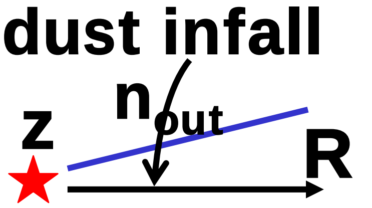
$$f_{dust}(R, z) = A(R, z)/A_0(R, z)$$

Vertical velocity of dust

$$\frac{dV_z}{dz} = \underbrace{-DV_z}_{\text{gas drag}} \underbrace{- \frac{GM_*}{r} z}_{\text{gravity}}$$

$$D = \rho_{gas} c_s / a$$

—— Quiescent ········ Turbulent



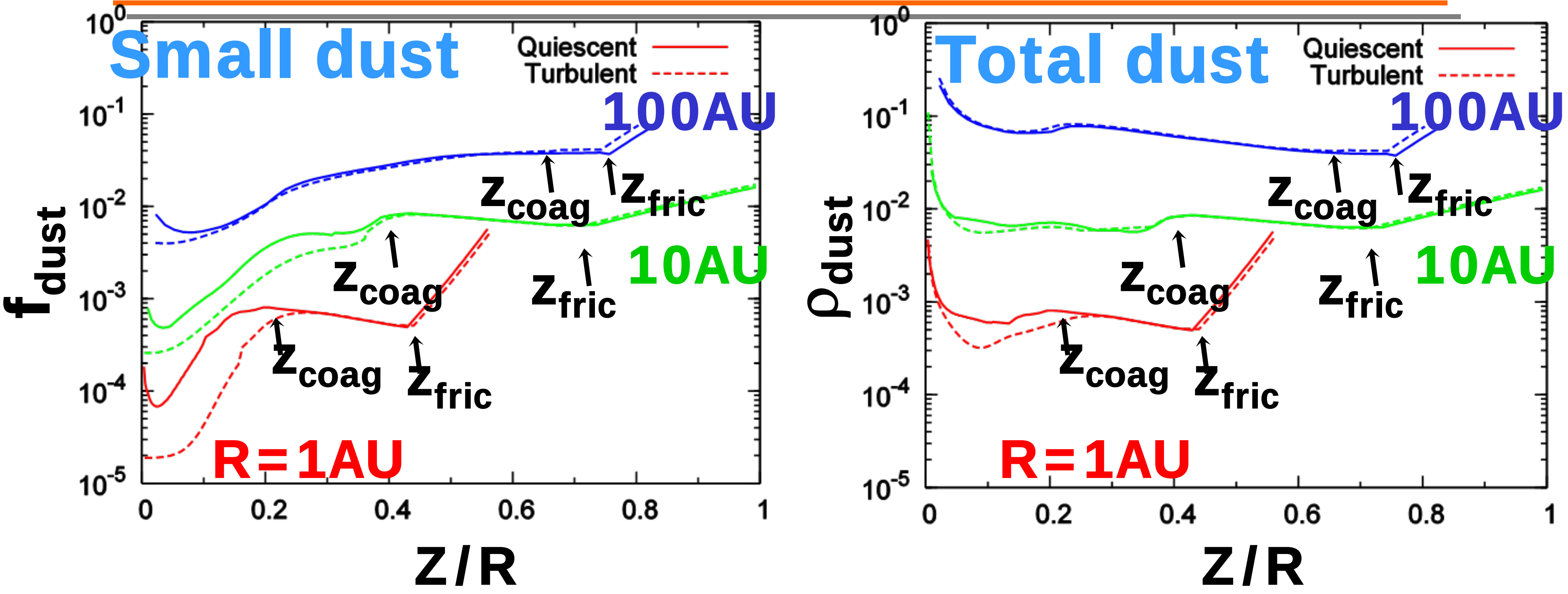
Surface layer ($z_{fric} < z$, ρ_{gas}: small)

V_z : free-fall (only graviry) → $f_{dust} \propto 1/\rho_{gas}$

Middle layer ($z_{coag} < z < z_{fric}$)

gravity~gas drag $\longrightarrow V_z = \frac{GM_*}{Dr} z$ → $f_{dust} \propto 1/z$

Small-dust/Gas Ratio (only V_z)



——**Quiescent** ············ **Turbulent** (Nomura et al. 2007)

Midplane **($z<z_{coag}$, ρ_{dust}: large)**

$$\tau_{coag} < \tau_{sed}, \quad \tau_{coag} \sim 1/\left(n_{dust}\pi a^2 \Delta V_z\right), \quad \tau_{sed} \sim z/V_z$$

→ f_{dust} : small (smaller in turbulent disk)

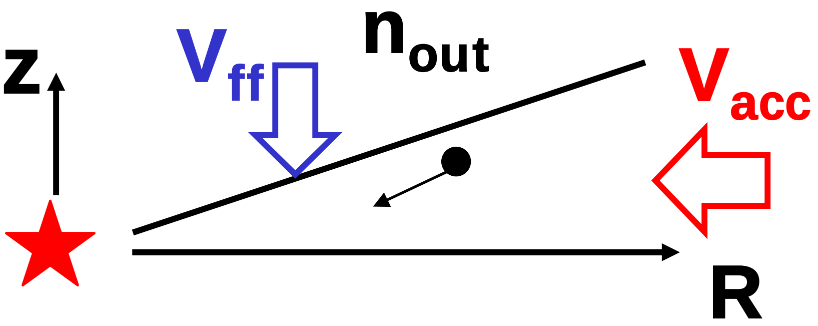
Effect of radial migration: V_R vs. V_Z

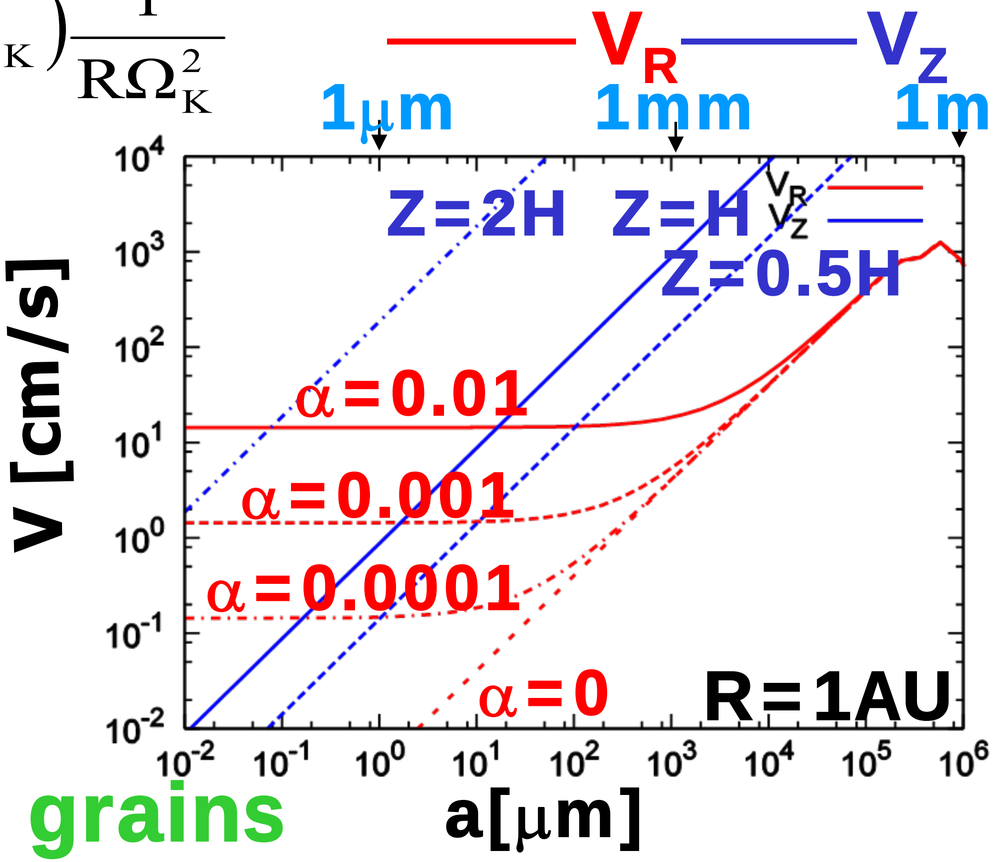
$$V_R = -\frac{\rho_{gas}}{\rho_{gas}+\rho_{dust}}\left(\frac{2D\Omega_K}{D^2+\Omega_K^2}\eta+\frac{2D^2}{D^2+\Omega_K^2}\zeta\right)v_K \qquad D=\rho_{gas}c_s/a$$

$$\zeta = -\frac{1}{2}\frac{1}{\rho_{gas}}\frac{\partial}{R\partial R}\left(R\rho_{gas}\alpha c_s h\Omega_K\right)\frac{1}{R\Omega_K^2}$$

$$\eta = -\frac{1}{2}\frac{1}{\rho_{gas}}\frac{\partial p_{gas}}{\partial R}\frac{1}{R\Omega_K^2}$$

$$V_z = -\left(\Omega_K^2/D\right)Z$$





Amount of small dust grains

⇔ dust inflow in vertical & radial directions

⇔ n_{out} & α

Dust size distribution (V_z & V_z)

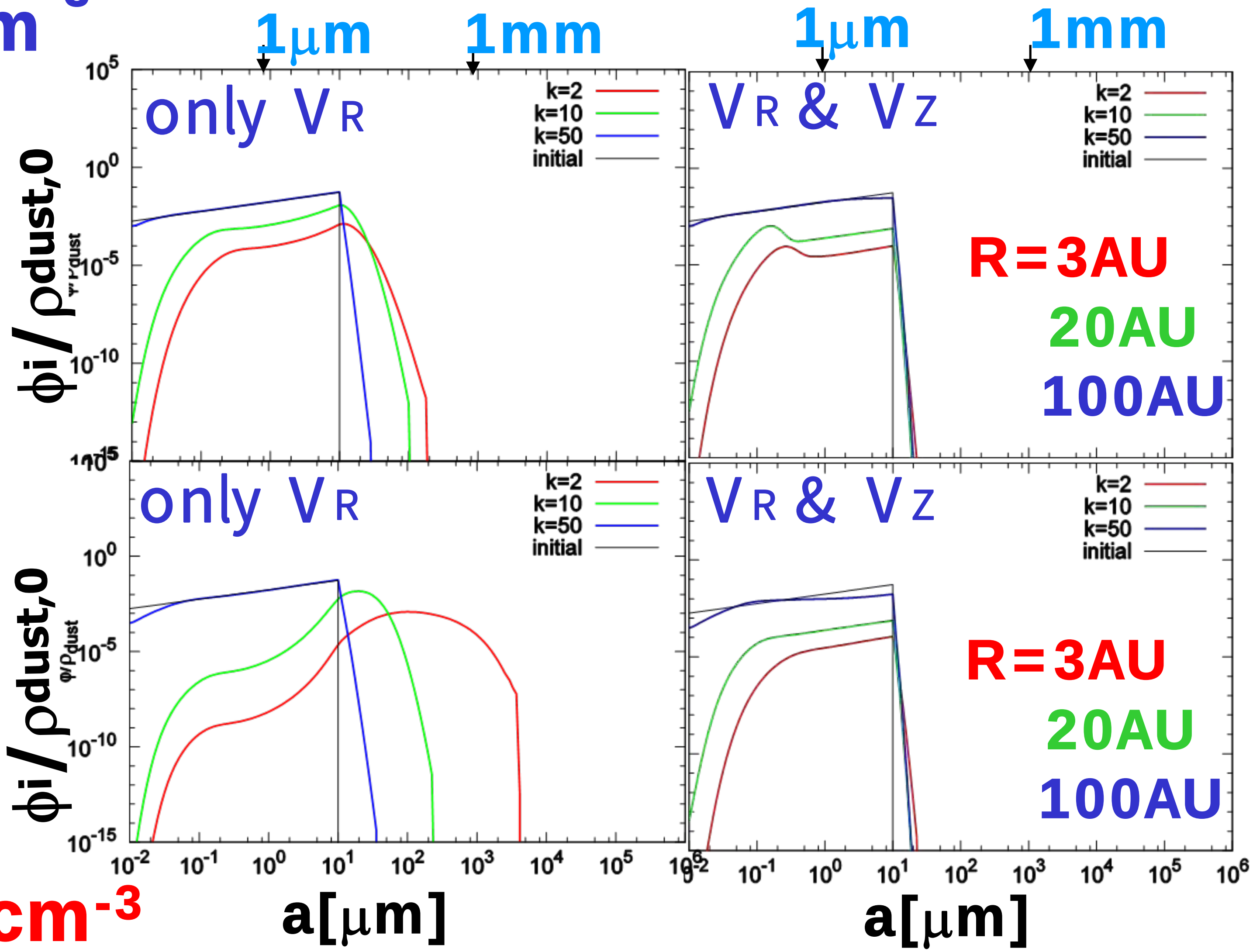
$n_{out} = 10^4 cm^{-3}$

$t = 10^6 yr$

$z = H$

$\alpha = 0.01$

$\alpha = 0.001$



$n_{out} = 10^4 cm^{-3}$

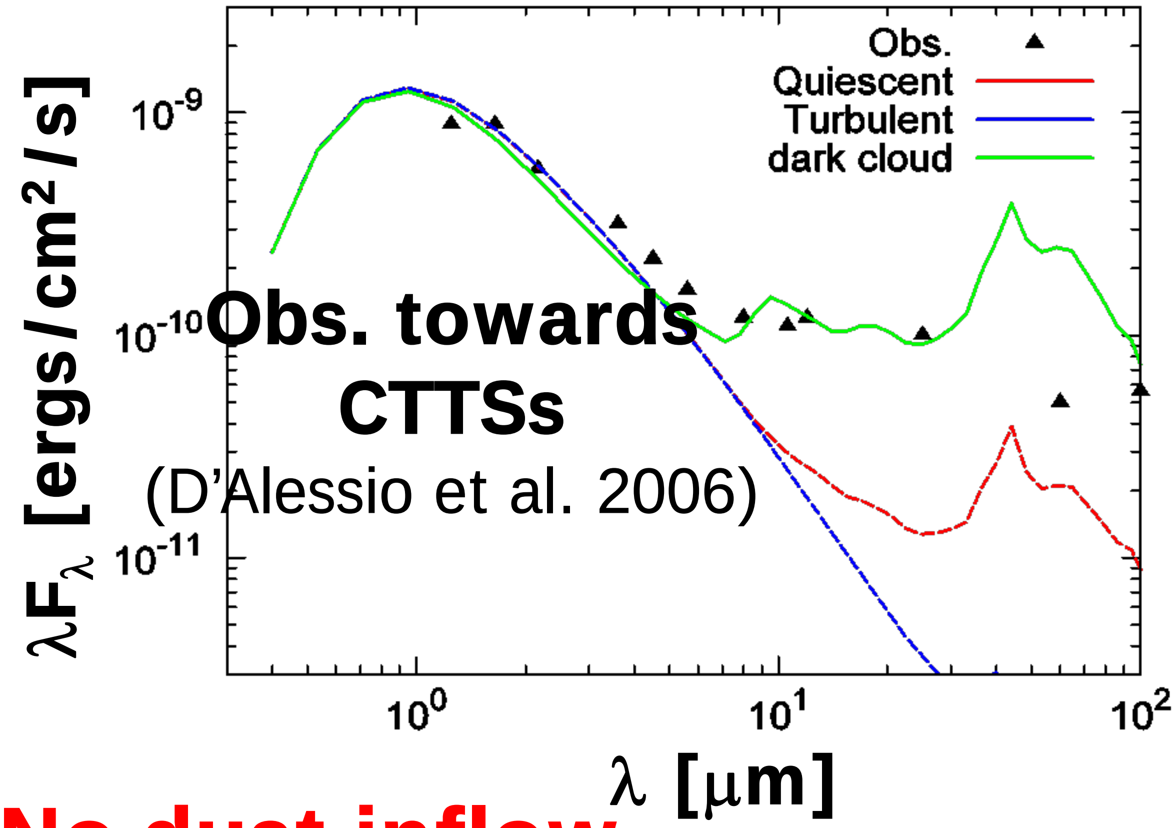
→ accretion flow dominant if $\alpha > 10^{-2\sim-3}$

§ 4

Effects on Dust Continuum Emission

Effect of dust inflow on SED

Disk temp. & density + Dust evolution + Dust opacity + Rad. transfer → SED



Obs. towards CTTSs

(D’Alessio et al. 2006)

$t=1\text{x}10^{6}$yr

Dark clouds dust

Quiescent

Turbulent

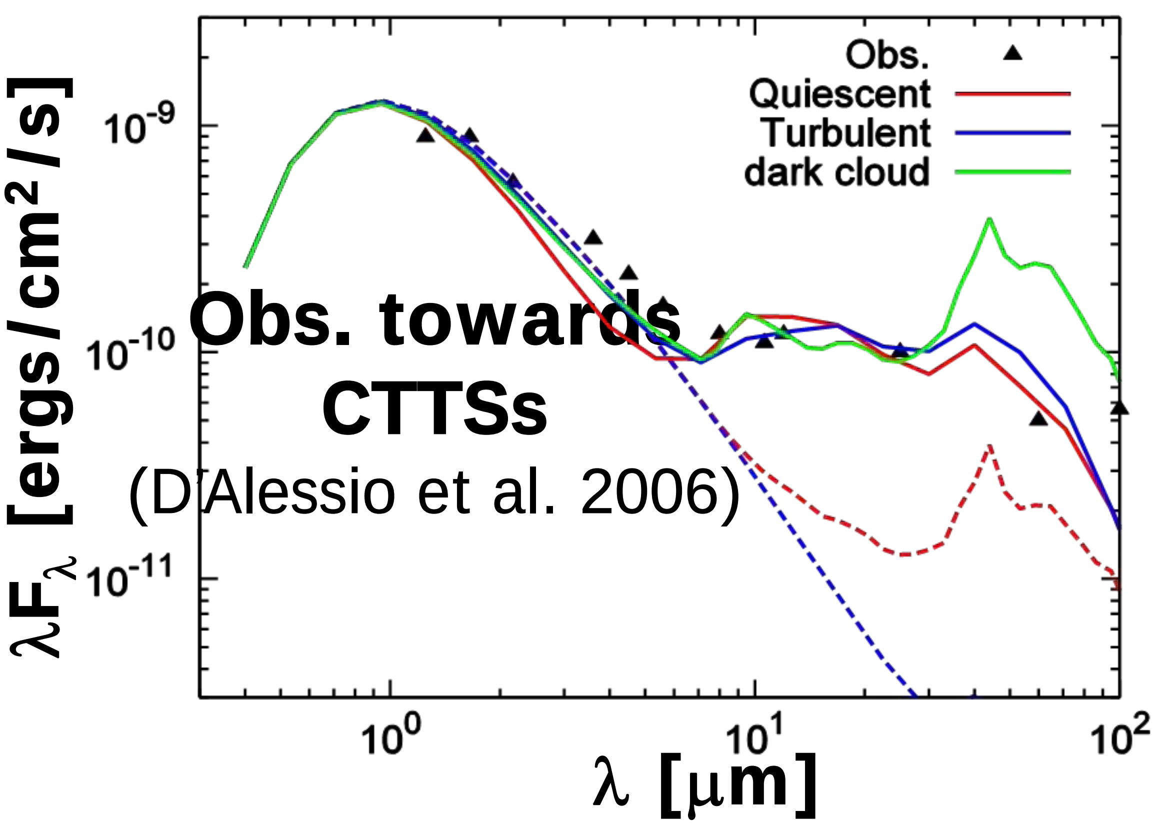
No dust inflow ($n_{out}=0$, $\alpha=0$)

No dust inflow

→ Model cannot reproduce observations

Effect of dust inflow on SED

Disk temp. & density + Dust evolution
+ Dust opacity + Rad. transfer → SED



Obs. towards CTTSs

(D'Alessio et al. 2006)

$t=1\times10^{6}$ yr

Dark clouds dust

Quiescent

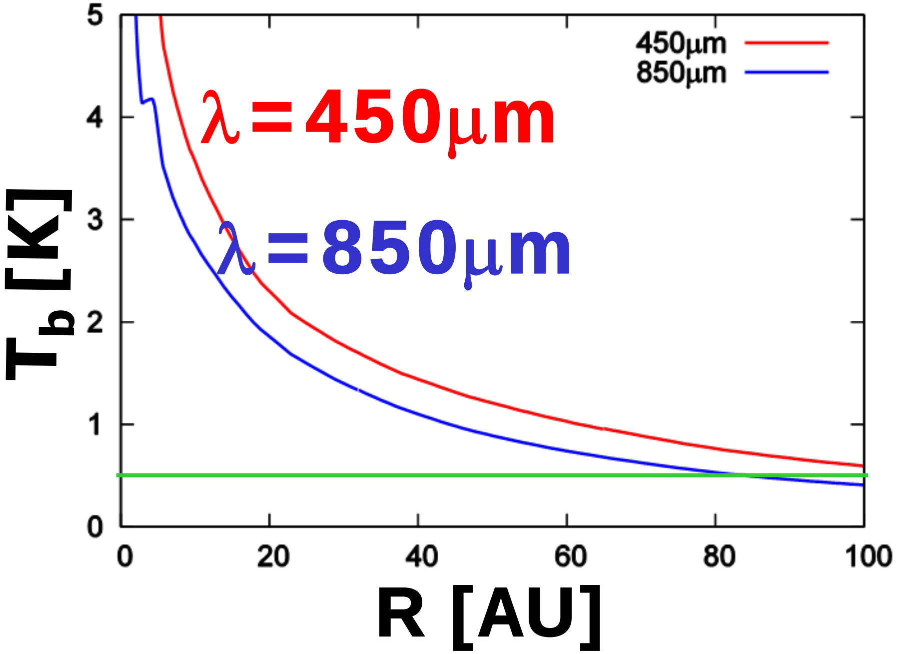
Turbulent

dust inflow
($n_{out}=10^{4}$cm^{-3})

No dust inflow
($n_{out}=0$, $\alpha=0$)

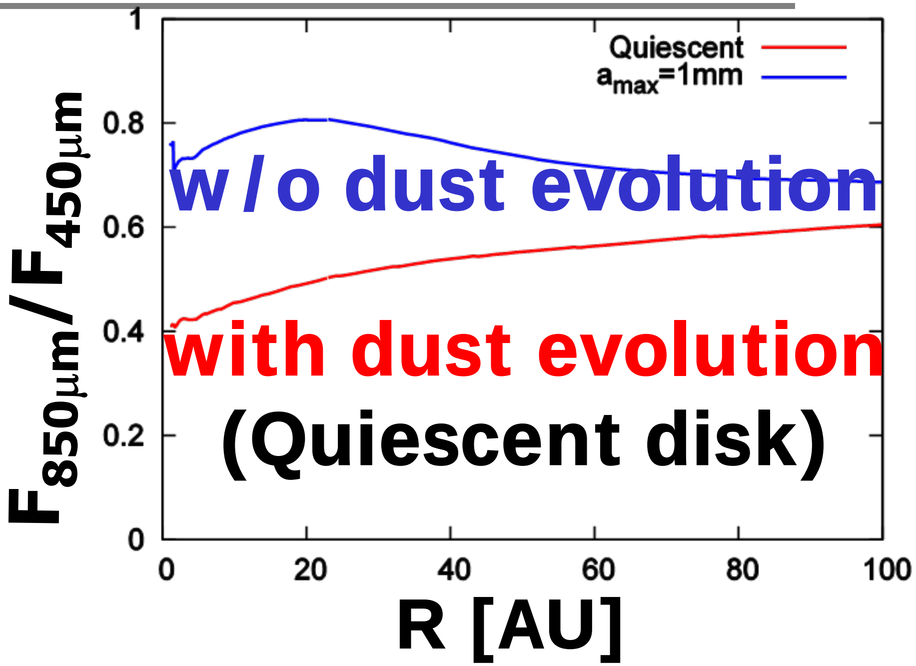
$n_{out}>10^{4}$cm^{-3} or $\alpha>10^{-2\sim-3}$
→ consistent with observations

Spatial distri. of dust emission



$\lambda = 450\mu m$

$\lambda = 850\mu m$



w/o dust evolution

with dust evolution

(Quiescent disk)

ALMA 5σ detection limit

50 antennas, 0”.1, 600s

Dust evolution →

$F_{850\mu m}/F_{450\mu m}$ ↘

@ inner disk

Dependence of spatial distribution of dust flux ratio on dust evolution

→ Observable by ALMA

§ 5 Summary

Dust size growth, settling, and radial migration in protoplanetary disks

Supply of small dust grains to inner disk

$$\begin{cases}\text{Vertical: cloud} \rightarrow \text{disk midplane} \Leftrightarrow n_{out} \\ \text{Radial: migrate with gas accretion} \Leftrightarrow \alpha\end{cases}$$

SED model calculations

$n_{out} > 10^4 cm^{-3}$ or $\alpha > 10^{-2\sim-3}$

→ consistent with observations

Effects on spatial distri. of dust emission

: $F_{850\mu m}/F_{450\mu m}$ ↘ @ inner disk

→ Observational diagnostics by ALMA