IoA Conference 2006:
The Planet-Disc Connection

Dust Evolution in Photoevaporating Protoplanetary Disks

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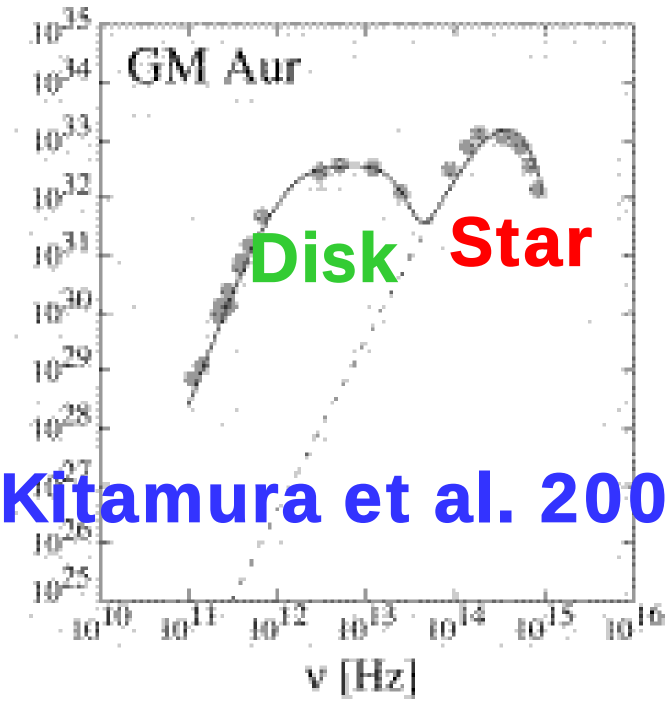
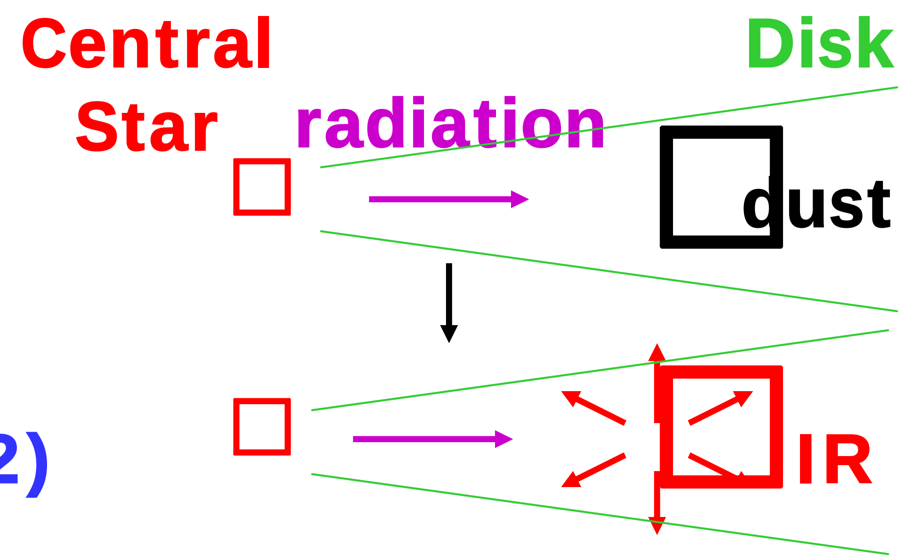
§1 Introduction

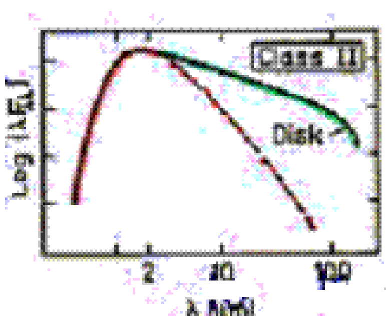
SED of Protoplanetary Disks

SED of TTS + disk



(Kitamura et al. 2002)

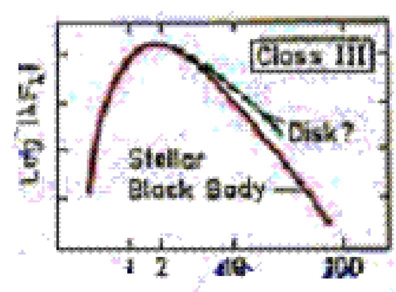




CTTS

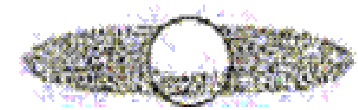
(Class II)

10^6yr



WTTS

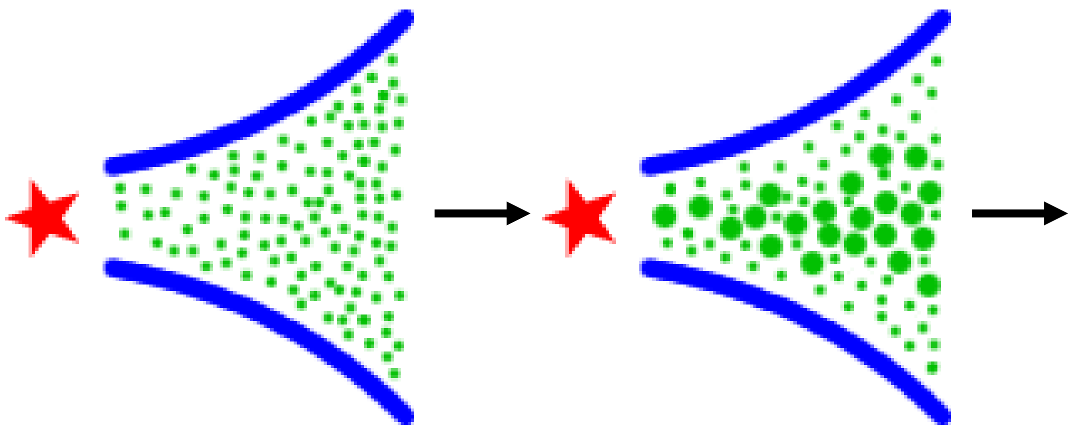
(Class III)



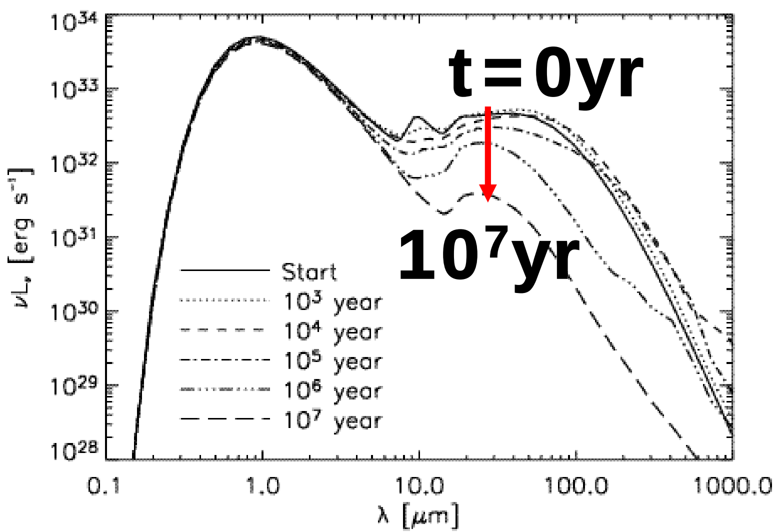
10^7yr

(Andre et al. 1994)

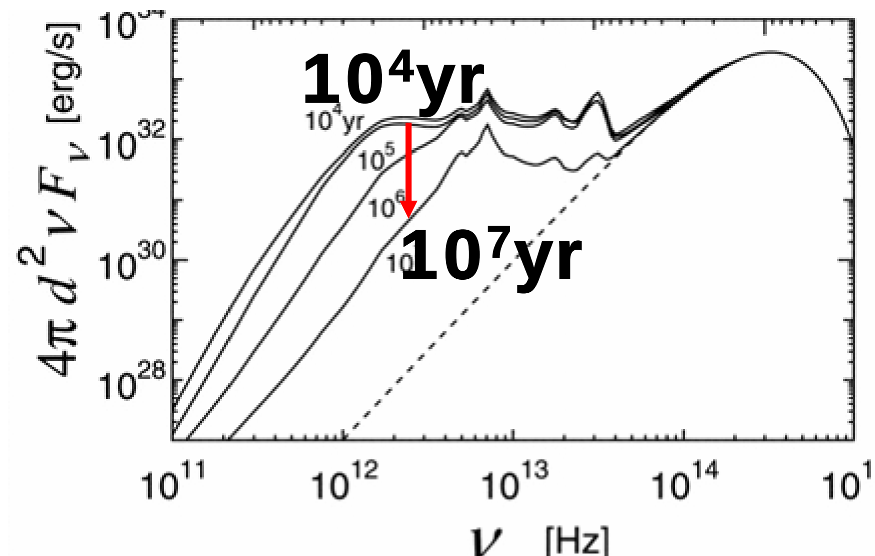
Dust Evolution & SED



Planet Formation



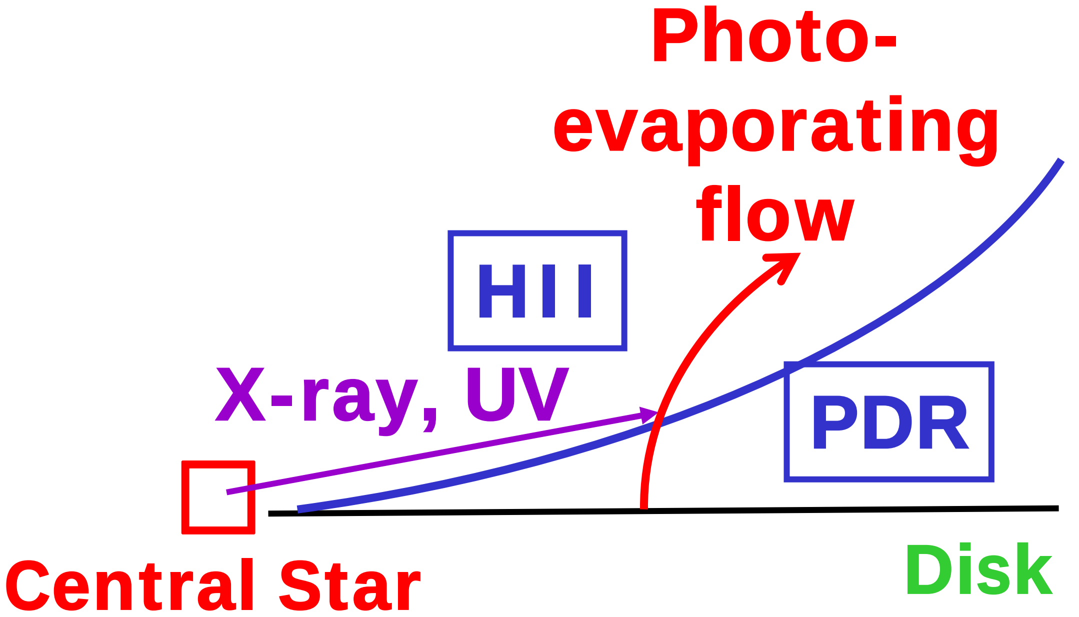
(Dullemond & Dominik 2005)



(Tanaka et al. 2005)

Dust evolution → SED model calculation

Photoevaporation of PPDs



(e.g., Shu et al. 1993)

Physical structure of photoevaporating disks

+ Dust dynamics & coagulation in the disks

→ Effect of photoevaporation flow on dust evolution & SEDs of PPDs

§2 Effect of Photoevaporating Flow on Dust Dynamics

Basic Equations of Gas Flow

1D steady flow in vertical direction

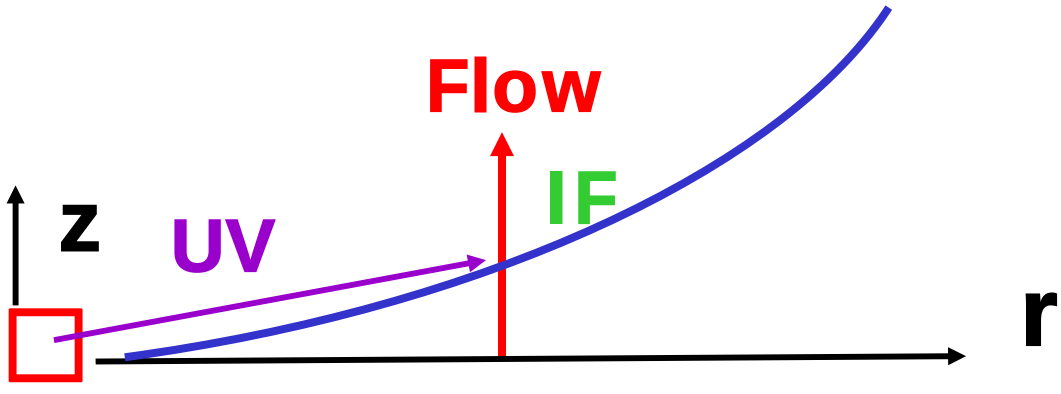
Mass Cons. Eq. : $\rho v_z = \text{const.}$

Momentum Cons. Eq. : $v_z \frac{dv_z}{dz} = -\frac{1}{\rho}\frac{dP}{dz} - \frac{GM_*}{r^2}\frac{z}{r}$ $\quad P = \frac{\rho k T}{m_\mu}$

Boundary Condition :

Jump condition at ionization front

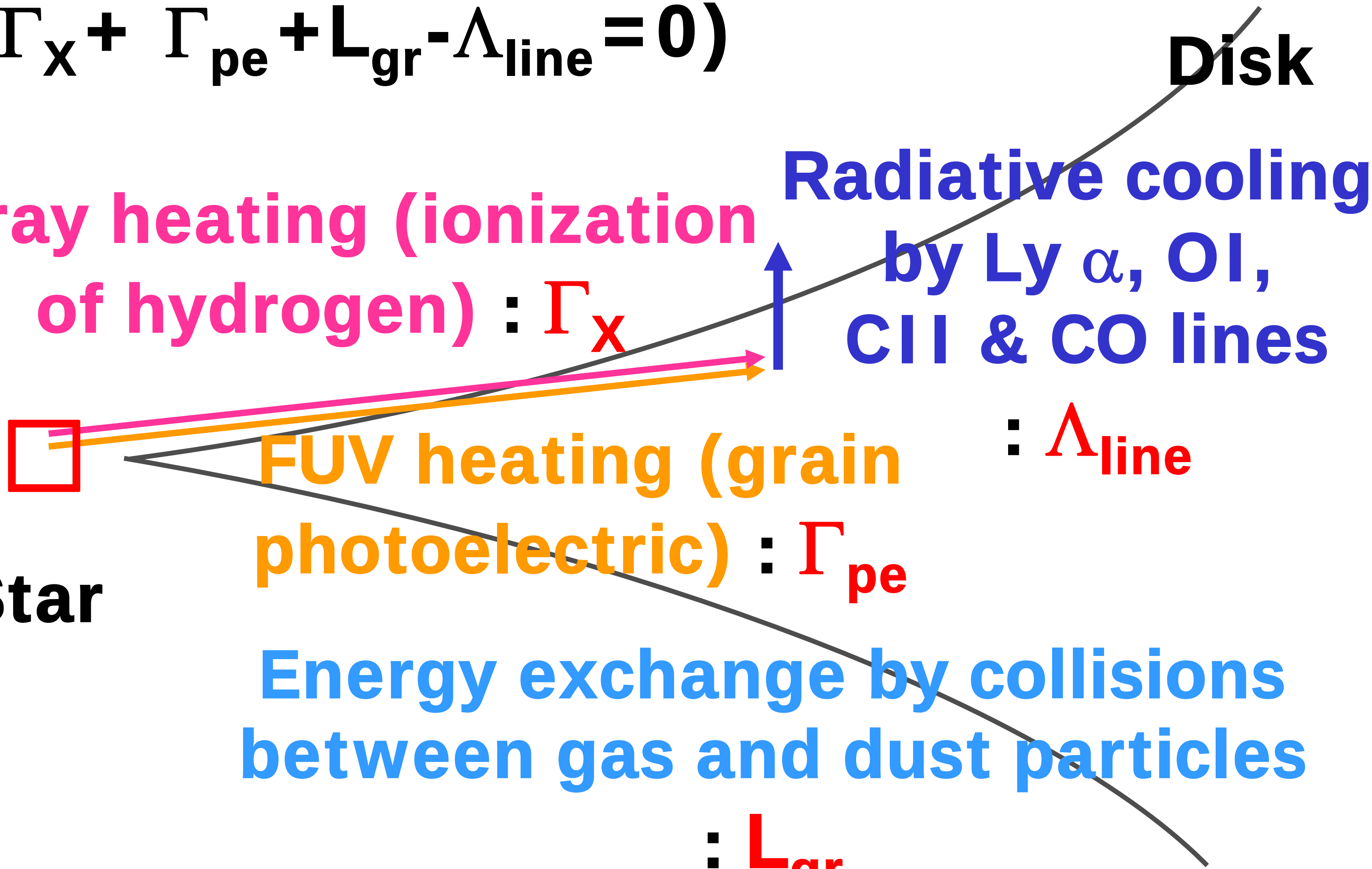
$$v_{IF} = c_I^2 / 2c_{II},\ \rho_{IF} = (2c_{II}^2 / c_I^2)\rho_{II}$$



Gas Temperature

Local Thermal Equilibrium

$$(\Gamma_X + \Gamma_{pe} + L_{gr} - \Lambda_{line} = 0)$$

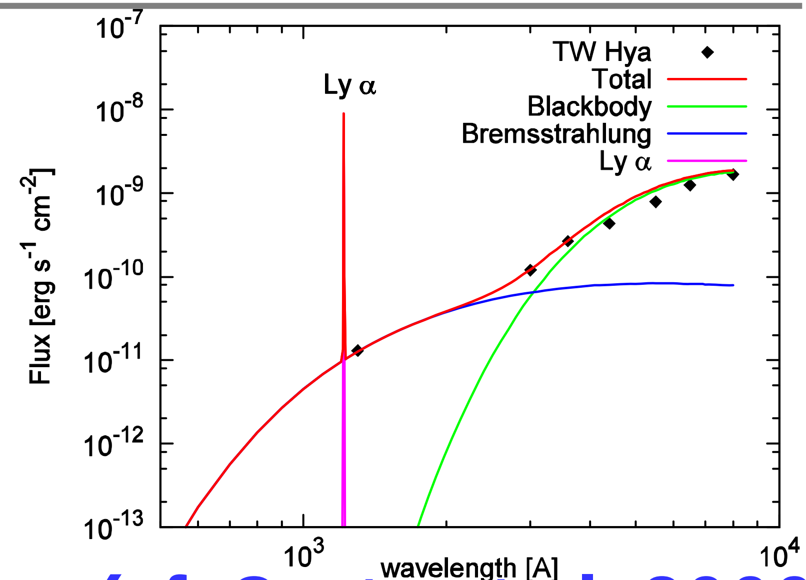


UV & X-ray Rad. from Central Star

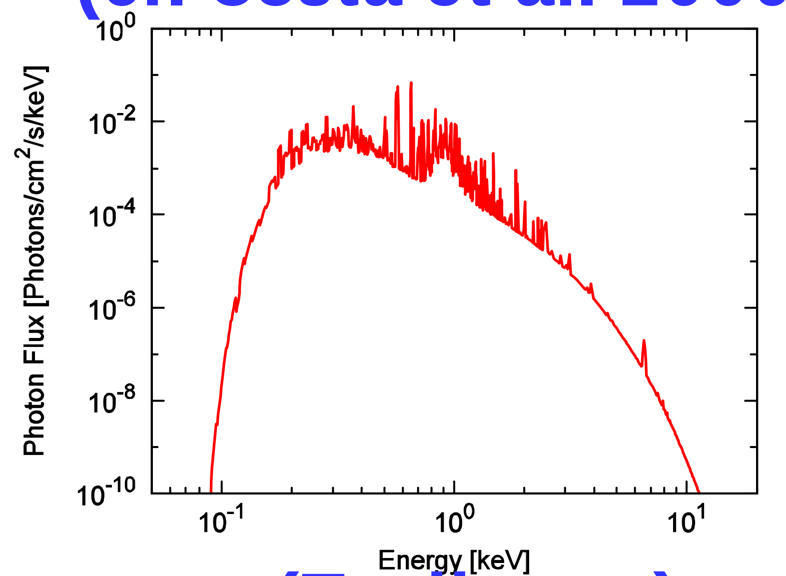
TW Hydra Model

UV Stellar blackbody
+ Thermal bremsstrahlung
(T_{br} = 2.5 x 10^4K)
+ Lyα emission

X-ray
Two temperature Raymond-Smith model
(kT_1 = 0.2keV, kT_2 = 0.8keV)



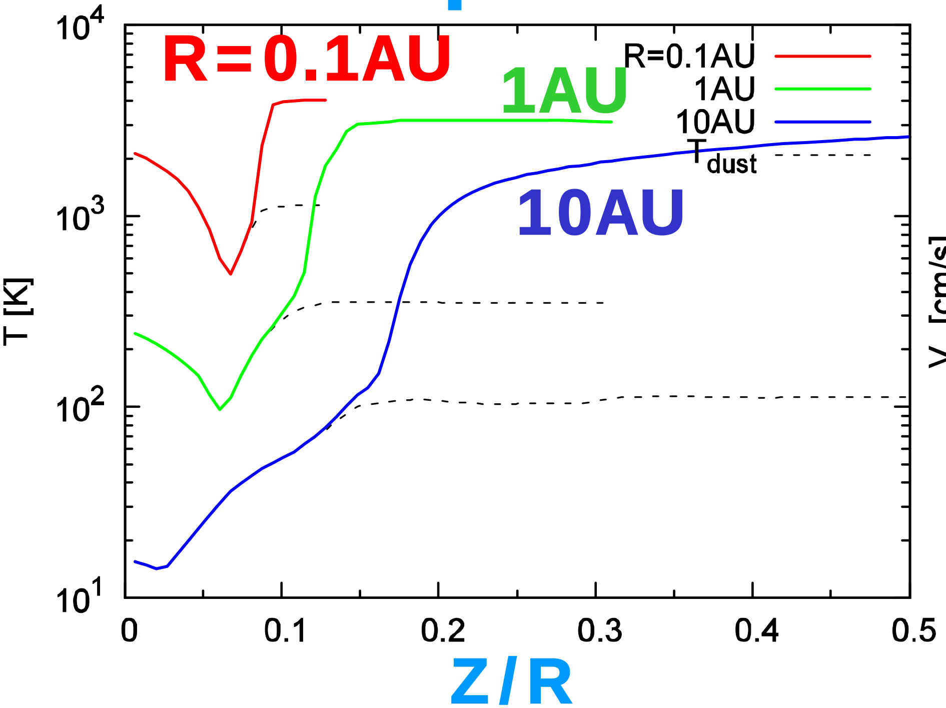
(cf. Costa et al. 2000)



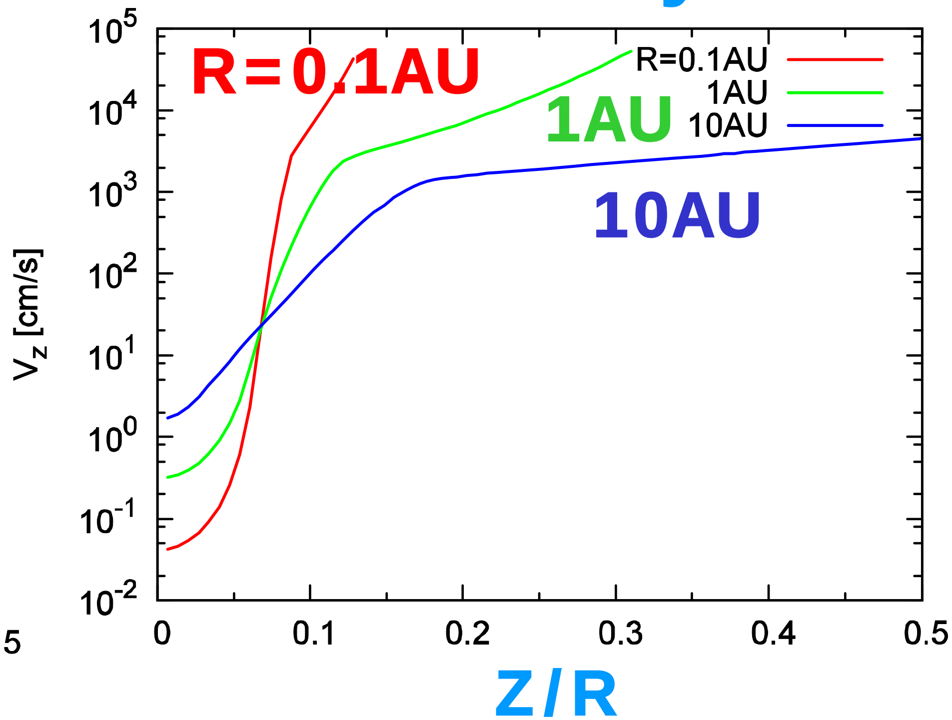
(Tsujimoto)

Gas Temp. & Velocity Profiles

Temperature



Velocity



T_{gas}~ a few x 10^3K >> T_{dust} @ disk surface

: heated by X-ray & UV rad. from star

V_z~10^{-2}-10^5 cm/s @ 0.1~10AU

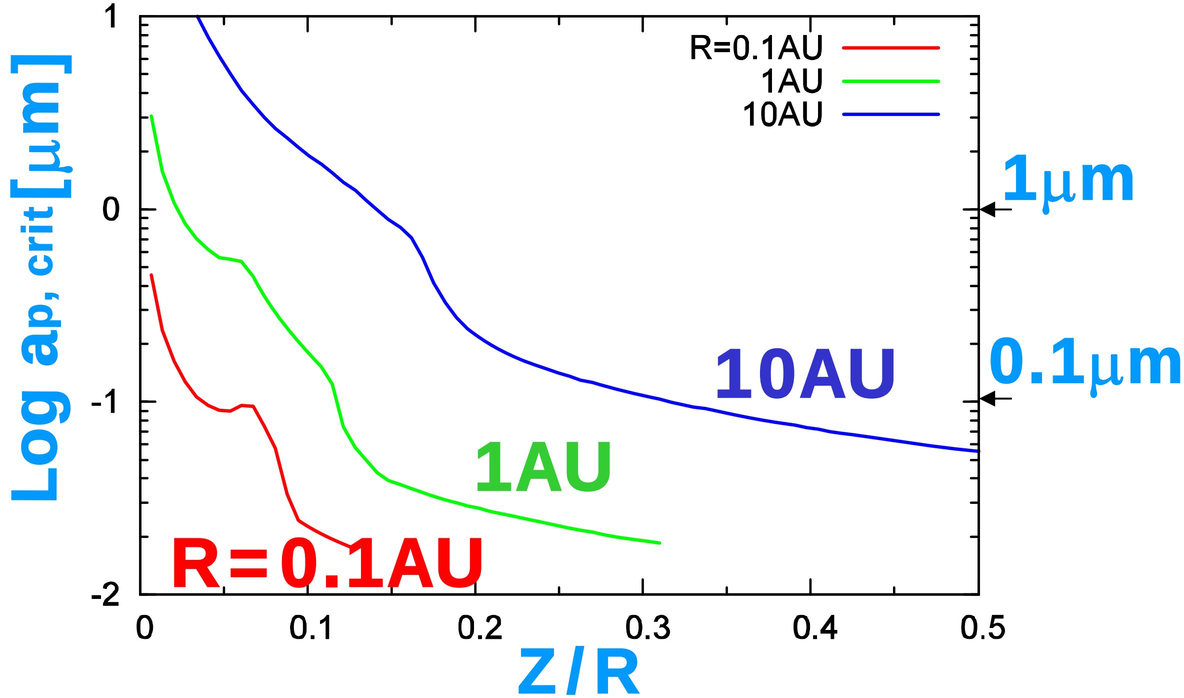
Effect on Dust Dynamics

$$\Omega^2 z = (\rho_{gas} c_s / \rho_s a_p)(V_{dust} - v_{gas}) \rightarrow a_{p,\,crit}$$

Critical dust radius

$a_p < a_{p,\,crit}$ → **upward**

$a_p > a_{p,\,crit}$ → **downward**



Sub μm - μm sized grains move toward disk surface with gas flow @ 0.1-10AU

→ **Effect on observational properties ?**

(cf. Nomura & Inutsuka 2004)

§3
Dust Evolution in Photoevaporating Protoplanetary Disks

Equation of Dust Evolution

Coagulation equation for dust particles

$$\frac{\partial \varphi_i}{\partial t} + \mathrm{Advect.} = \frac{1}{2} m_i \sum_{j=1}^{i-1} \beta_{i-j,j} \varphi_{i-j} \varphi_j - m_i \varphi_i \sum_{j=1}^{N} \beta_{i,j} \varphi_j$$

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

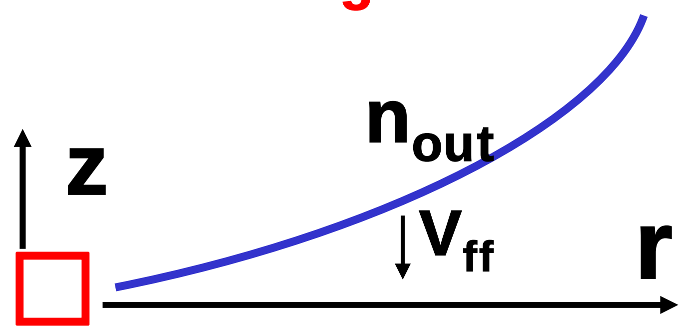
$$\mathrm{Advect.} = \begin{cases} d(V_z \phi_i)/dz & \text{(quiescent)} \\ d(V_z \phi_i - D_0 \rho [d(\phi_i/\rho)/dz])/dz & \text{(turbulent)} \end{cases}$$

$$V_z\,(\mathrm{dust}) - v_z\,(\mathrm{gas}) = -(\rho_s a / c_s \rho_g)\, \Omega_K^2\, Z$$

Boundary condition

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

$V_{z,\,BC} = V_{ff}$



Radial motion

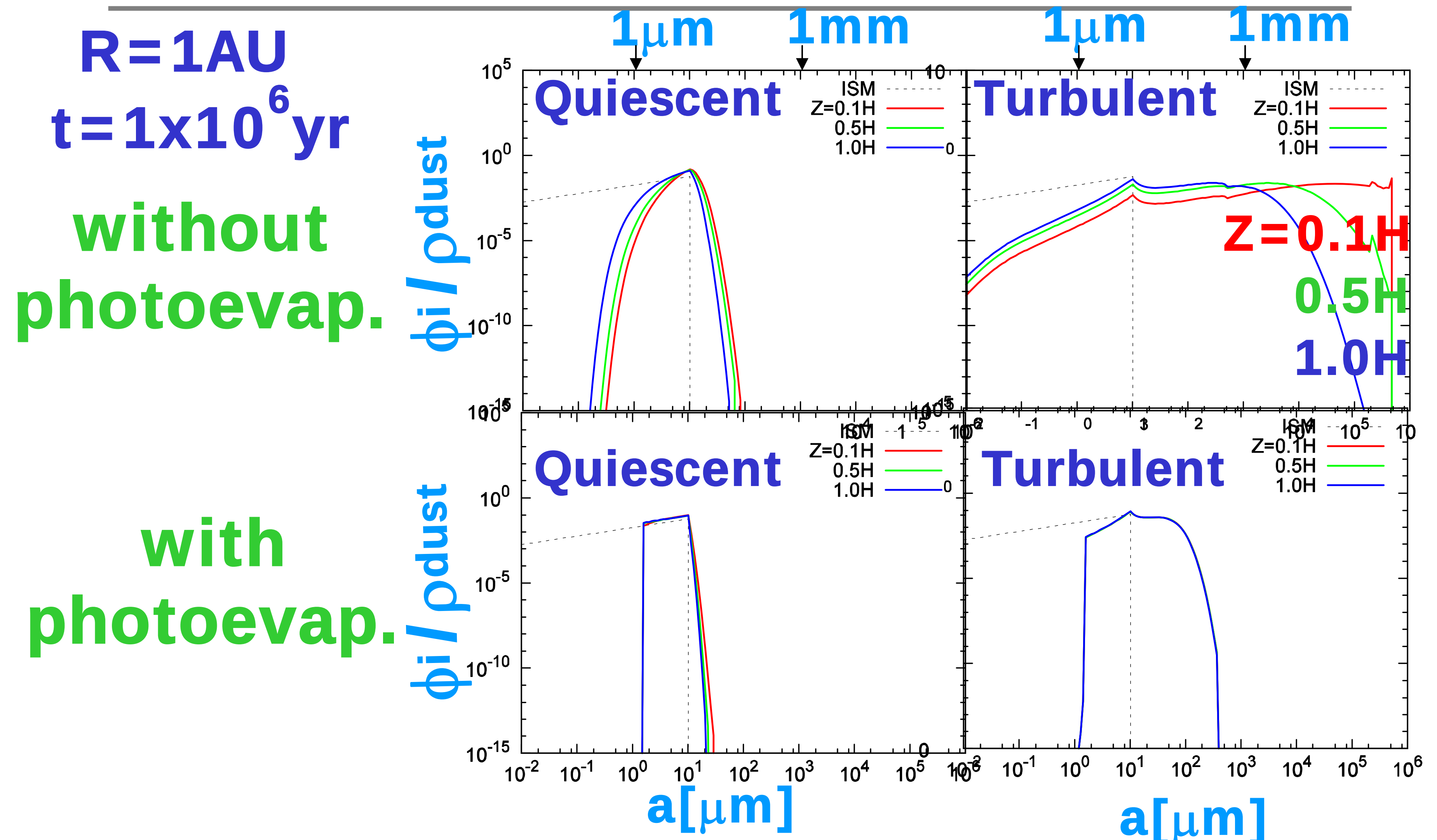
$a > a_{trap}$ ($t_{fric} > t_{eddy}$) ⟶ **move inward rapidly**

Initial condition

Dark cloud model

Effect of Photoevap. on Size Distri.

R=1AU
t=1x10^{6}yr



Sub-μm sized particles disappear due to coagulation & photoevaporating flow

§4 Effect on Spectral Energy Distribution

Calculate SEDs of Disks

Dust Size & Spatial Distributions

↓

Dust Opacity

↓

Disk Structure (Temp. & Density)
+ Radiative Transfer

↓

Thermal Dust Emission from Disks

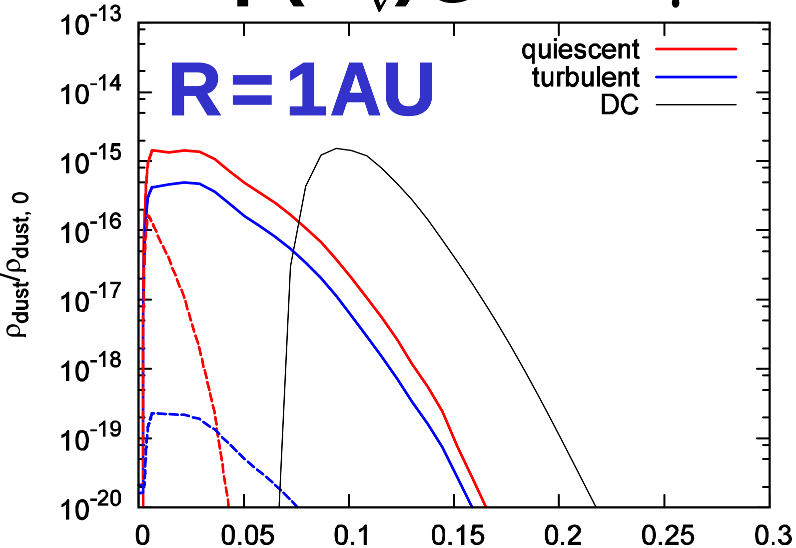
Resulting SEDs

without photoevap. $t = 1\times10^6$ yr

Quiescent — Turbulent — Dark cloud ········ $n_{out} = 0$

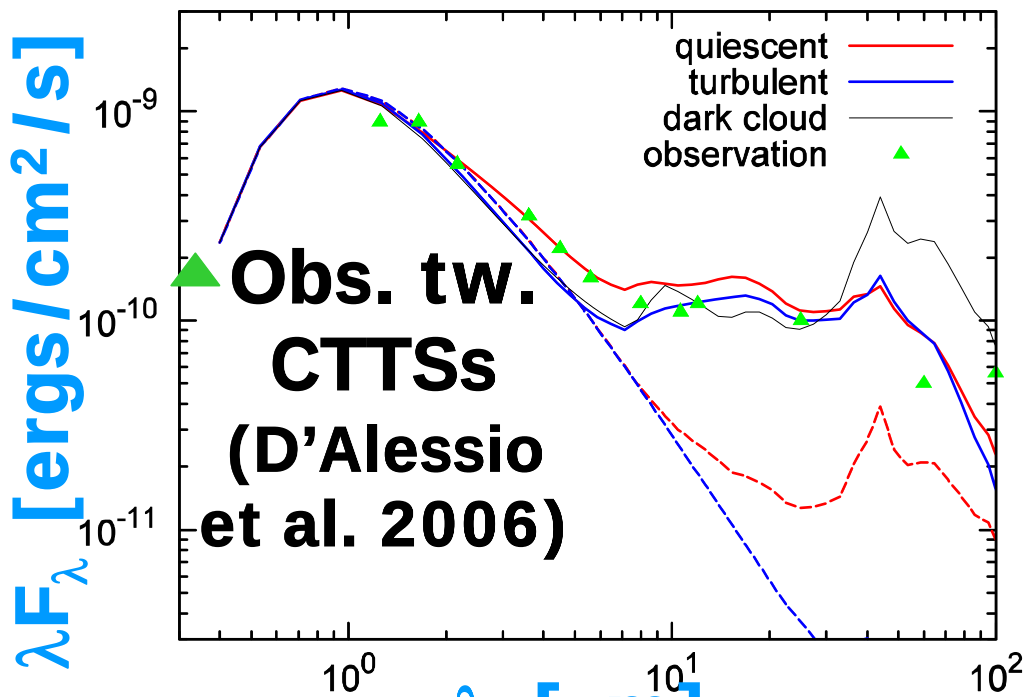
Dust Emissivity

$\rho_{dust}\kappa_\nu B_\nu(T_{dust})$
$*\exp(-\tau_\nu)@\lambda = 10\mu m$



z [AU]

SED



λ [μm]

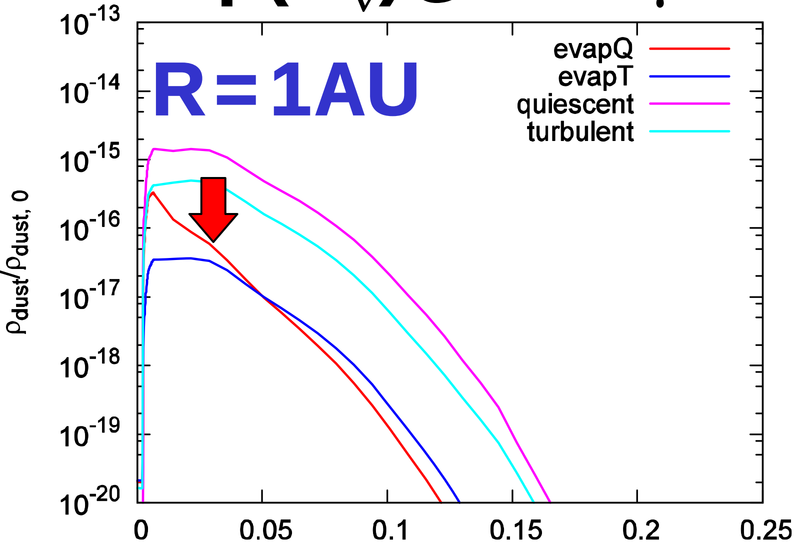
Model calculations without photoevap. reproduce observations of CTTS disks

Effect of Photoevaporation on SED

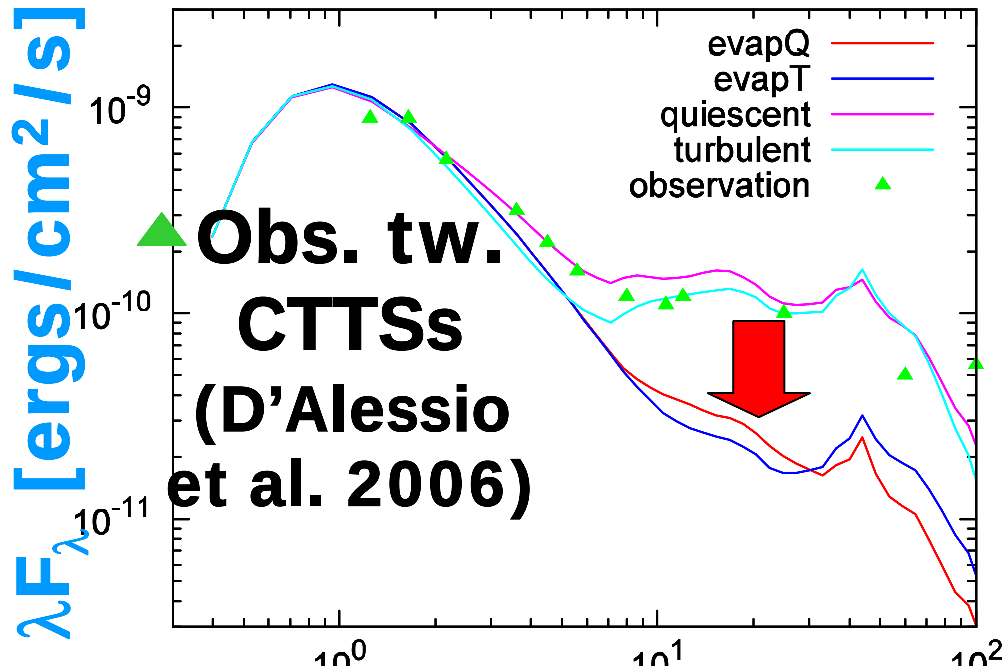
with photoevap. — Quiescent — Turbulent
w/o photoevap. — Quiescent — Turbulent

Dust Emissivity

$\rho_{dust}\kappa_\nu B_\nu(T_{dust})$
$*\exp(-\tau_\nu)@\lambda=10\mu m$



SED $t=1x10^6$yr



Photoevaporating flow → Emissivity ↘ →
Rad. flux @ MIR-FIR ↘ (Class III-like ?)

§5 Summary

Physical Structure of Photoevaporating Protoplanetary Disks

↓

Sub μm - μm sized grains move toward disk surface with gas flow @ 0.1-10AU

Dust Evolution in Photoevaporating Disks

→ **Sub μm - μm sized particles disappear**

↓

Spectral Energy Distribution Models

w/o photoevap. : reproduce obs. of CTTSs

with photoevap. : Rad. flux @ MIR-FIR ↘ (Class III-like ?)