Shadows in planet forming disks

Ralf Siebenmorgen & Frank Heymann

- **Gaps and ring-like structures:**

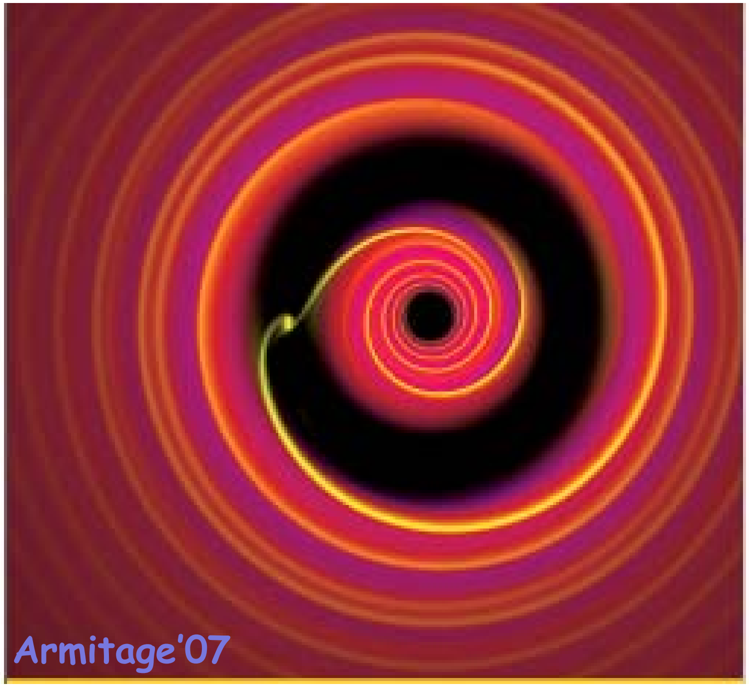
  ... are caused by hydrostatic + radiation balance without the need to postulate a companion/planet (SH, 2012).

- **PAH emission from disks:**

  Low / high detection statistics of PAH in T Tauri / Herbig Ae stars is consistent with X-ray destruction of PAH (Siebenmorgen & Krűgel 2010).

General picture

gaps and ring-like structures in hydro-dynamical simulations

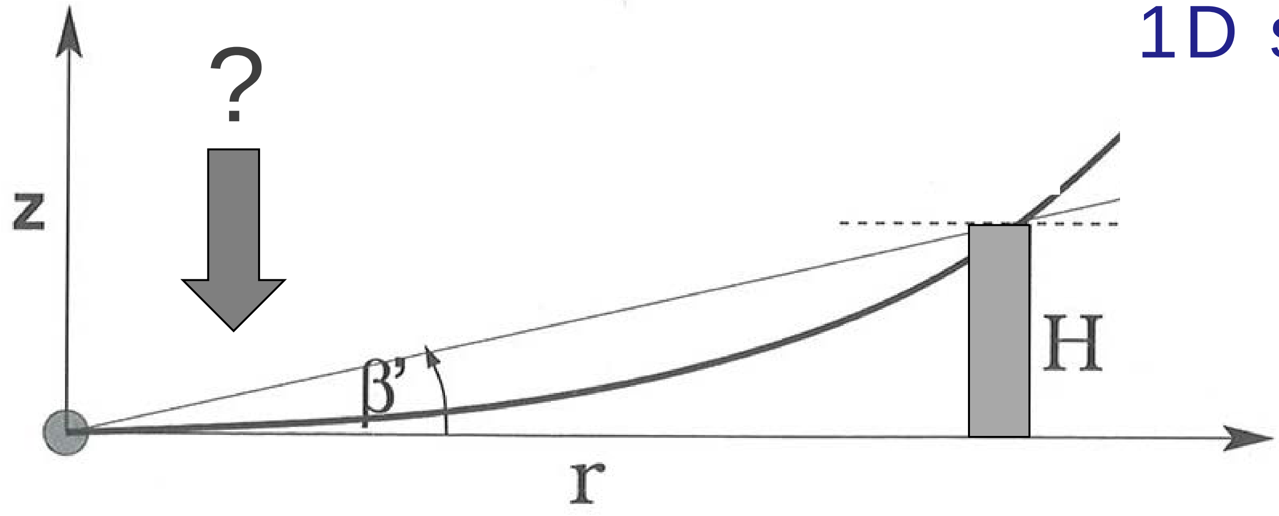


"…validates the use of **disk structures** as **fingerprints** of embedded **planets.**"

(Lagrange et al, Science 2010)

Radiative transfer

1D slab geometry



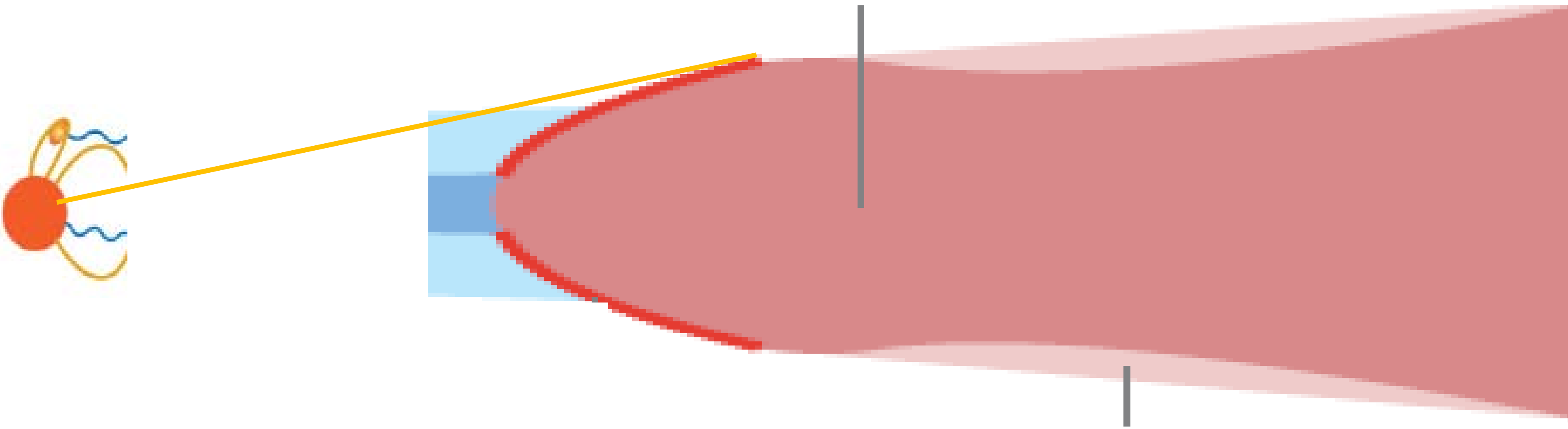
Initially we assume that the disk is isothermal in z, and the density is given by

$$\rho(r,z) = \sqrt{\frac{2}{\pi}}\,\frac{\Sigma(r)}{H(r)}\,\mathrm{e}^{-z^2/2H^2}$$

with scale height $H^2 = kT_{\mathrm{mid}} r^3/GM_* m$, surface density $\Sigma(r)$,

Dullemond et al.2001
Kama et al. 2010

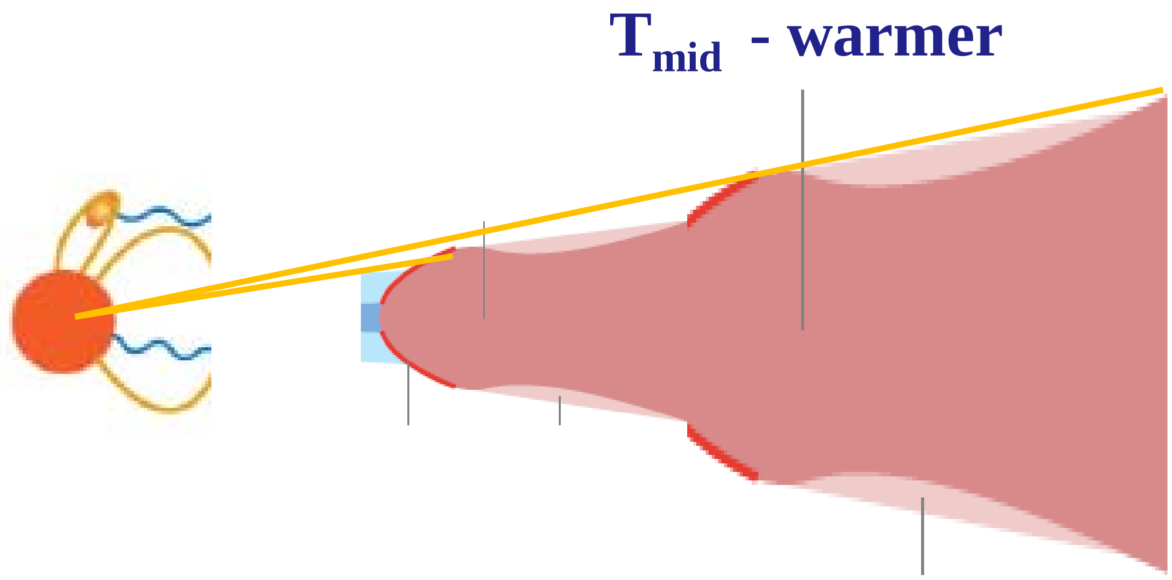
Puffed up inner rim



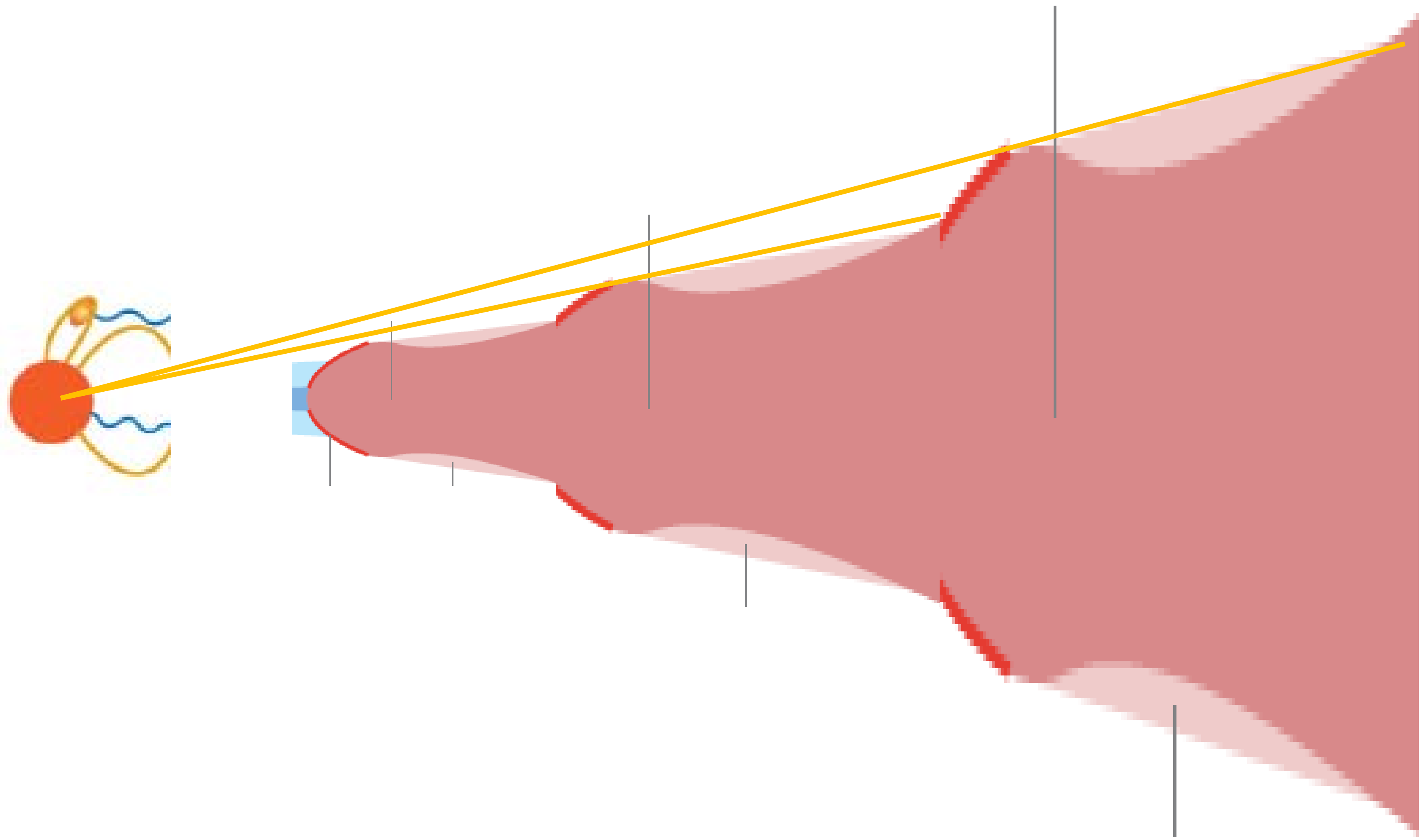
Shadow

T_{mid} - lower

Puffed up second rim

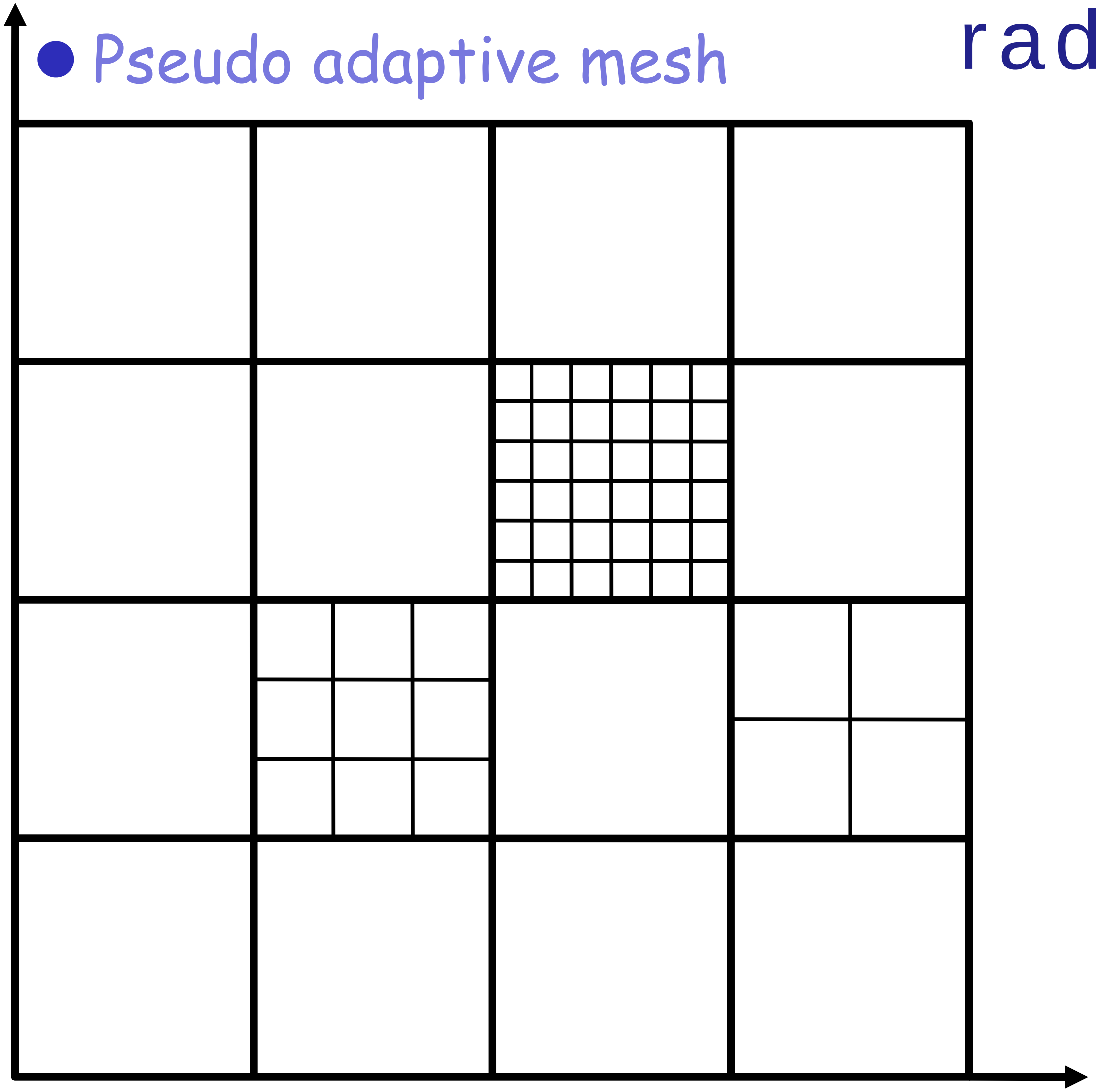


Puffed up third rim



3D Monte Carlo radiative transfer

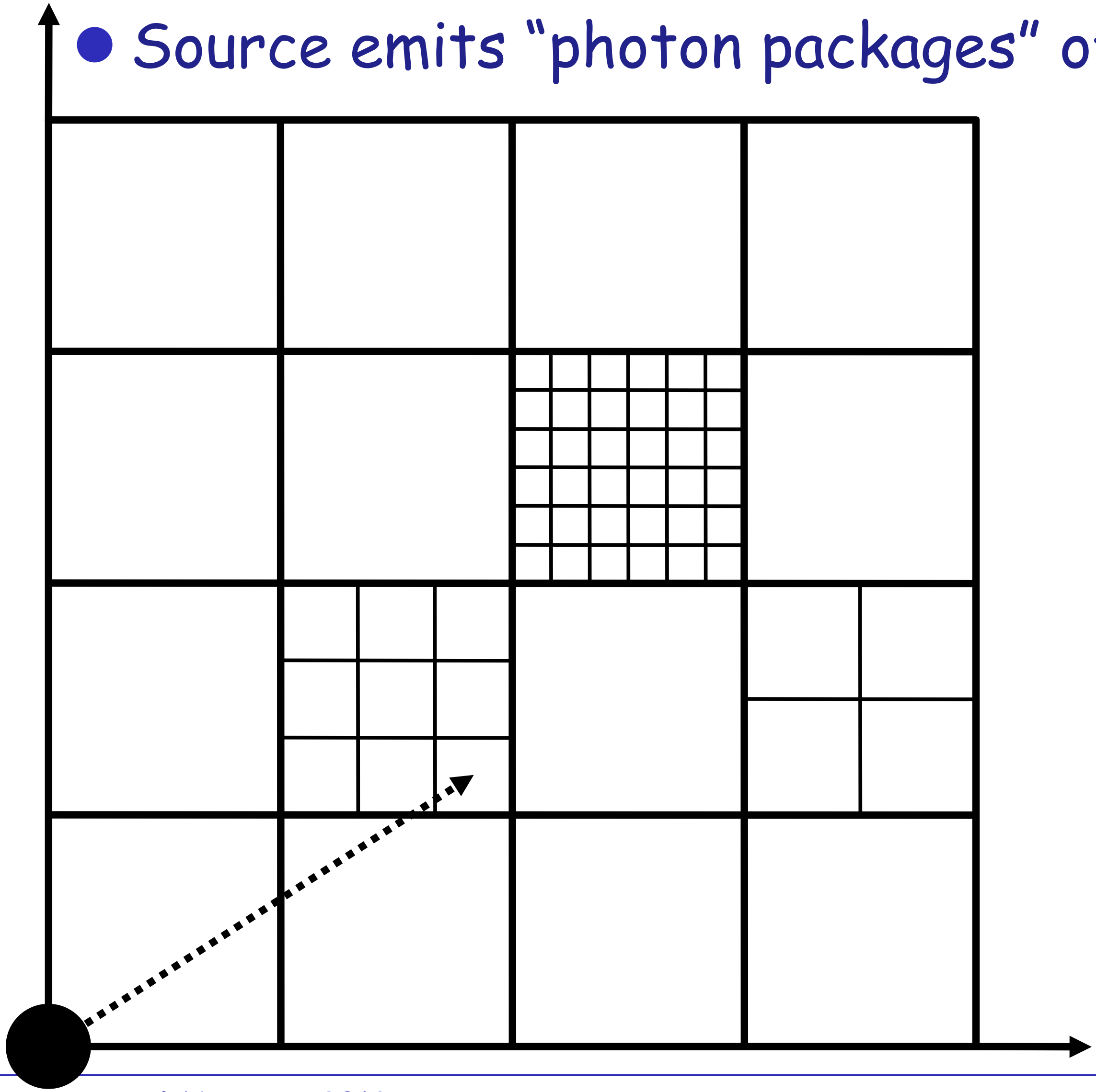
- **Arbitrary dust distribution**
- Pseudo adaptive mesh



1. geometry

Monte Carlo

- Source emits "photon packages" of equal energy

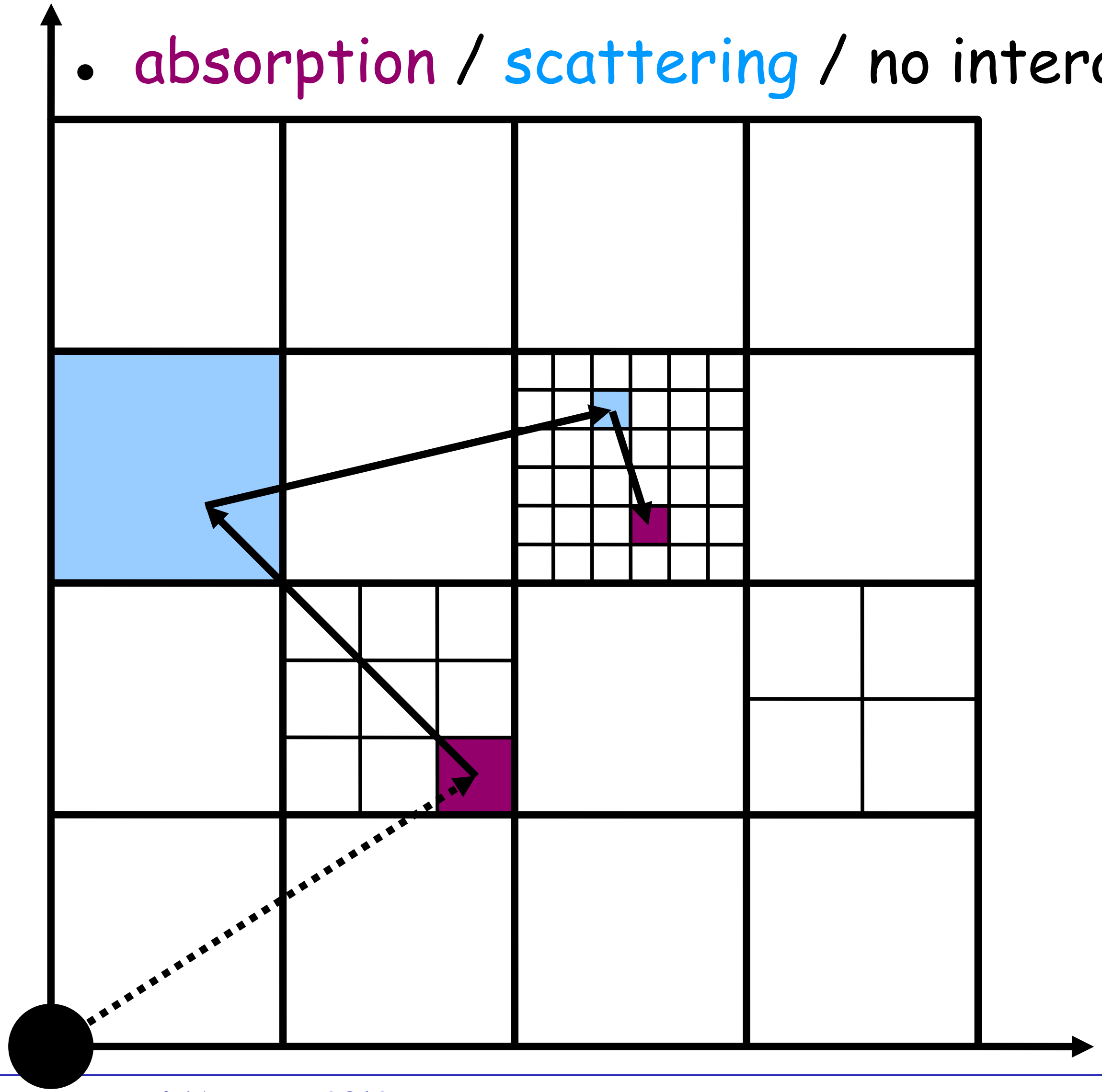


1. geometry
2. source

Monte Carlo

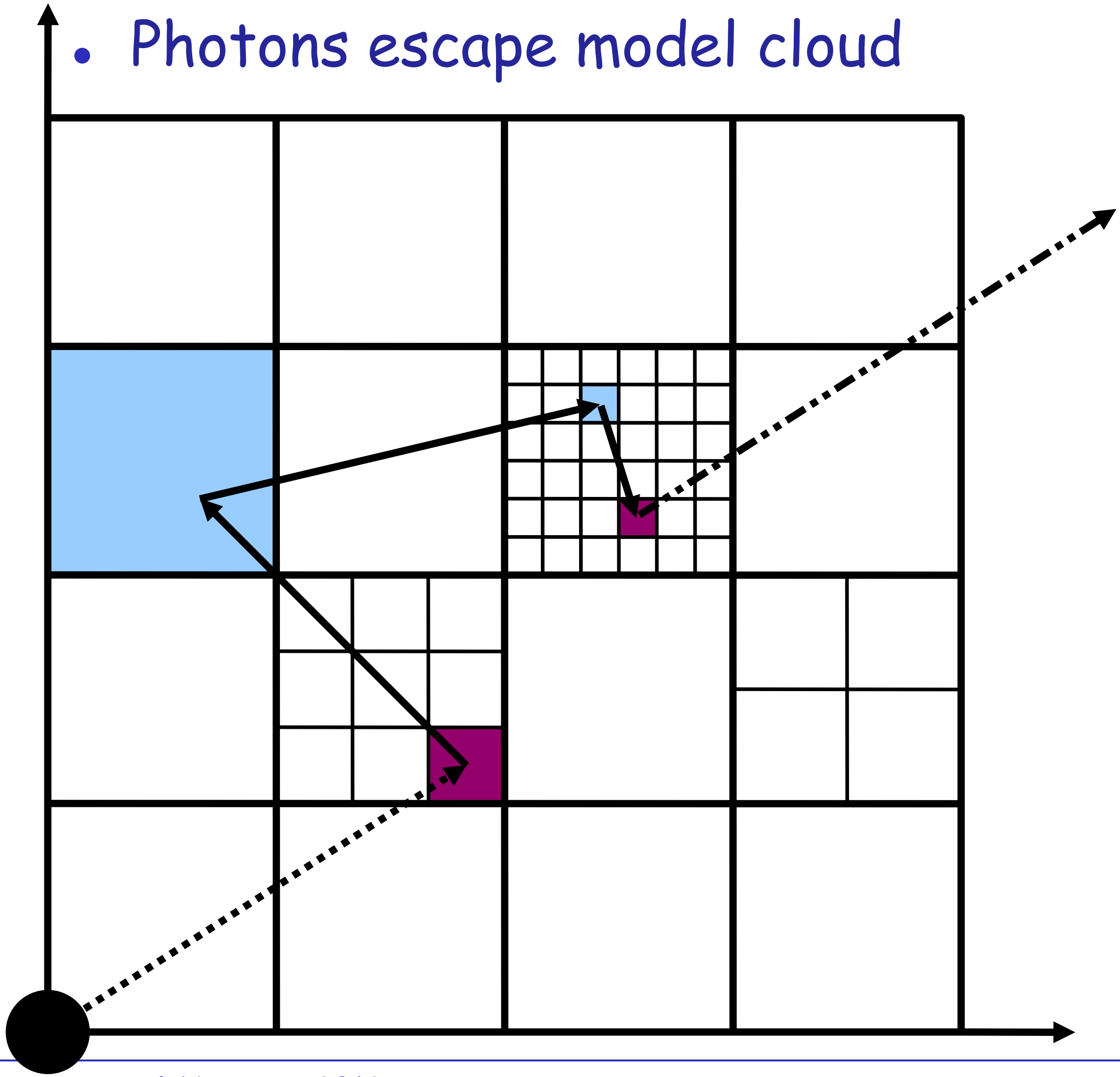
$\tau = -\ln(\zeta)$

- absorption / scattering / no interaction



1. geometry
2. source
3. inter-action
4. dust temperature

- Photons escape model cloud

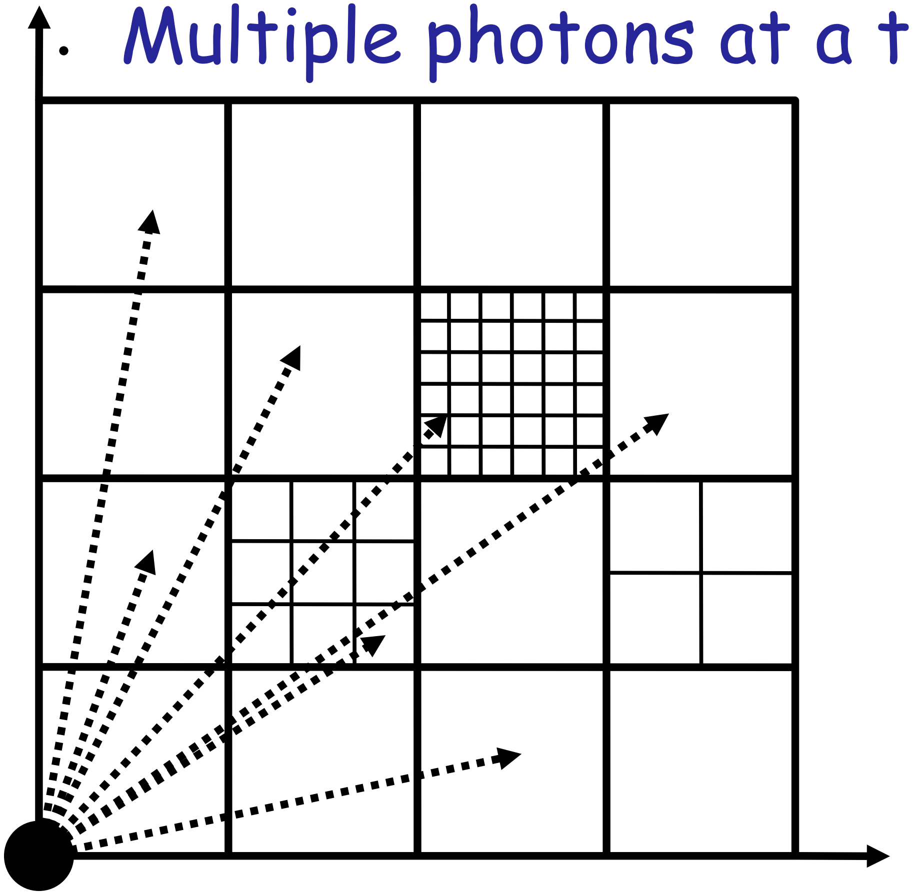


1. geometry
2. source
3. inter-action
4. temperature
5. detection

vectorized MC

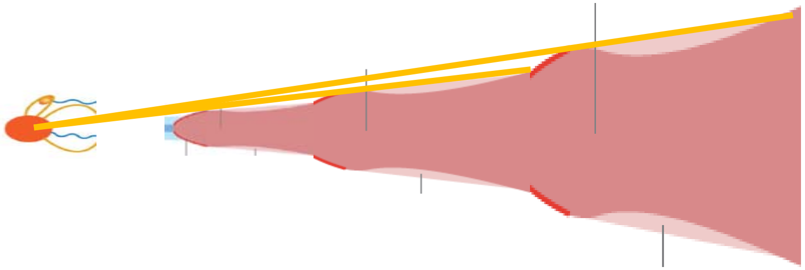
100 x faster

- Multiple photons at a time:



<u>Challenges:</u>

- ❖ Cell locked when hit by photon
- ❖ Parallel random number generator (Mersene Twister)
- ❖ Graphical Processing Units (CUDA)



Hydrostatic and radiation balance

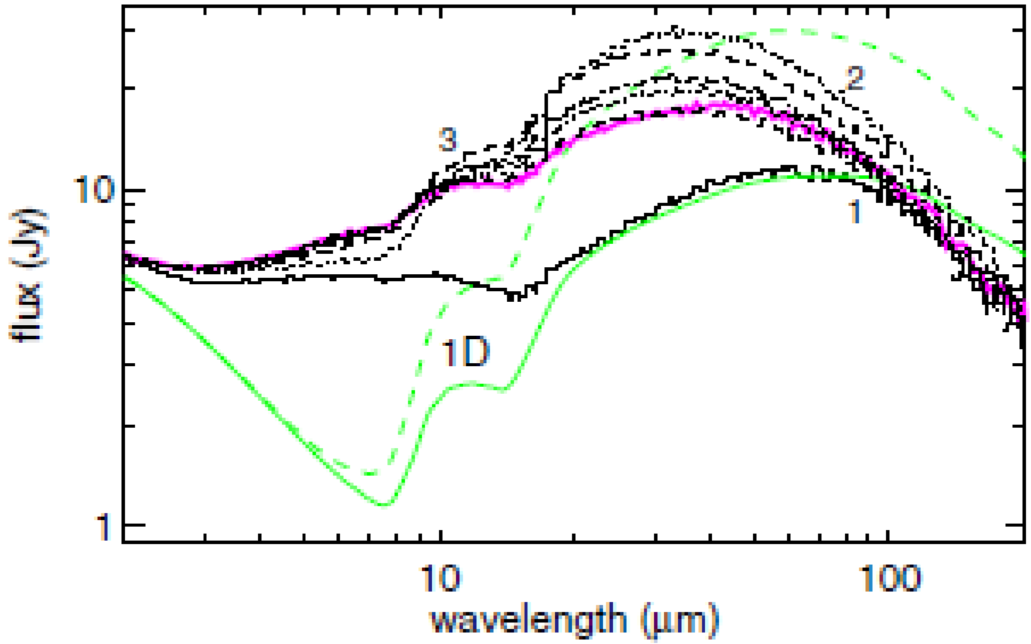
0) $$\rho(r,z) = \sqrt{\frac{2}{\pi}}\,\frac{\Sigma(r)}{H(r)}\,e^{-z^2/2H^2}$$

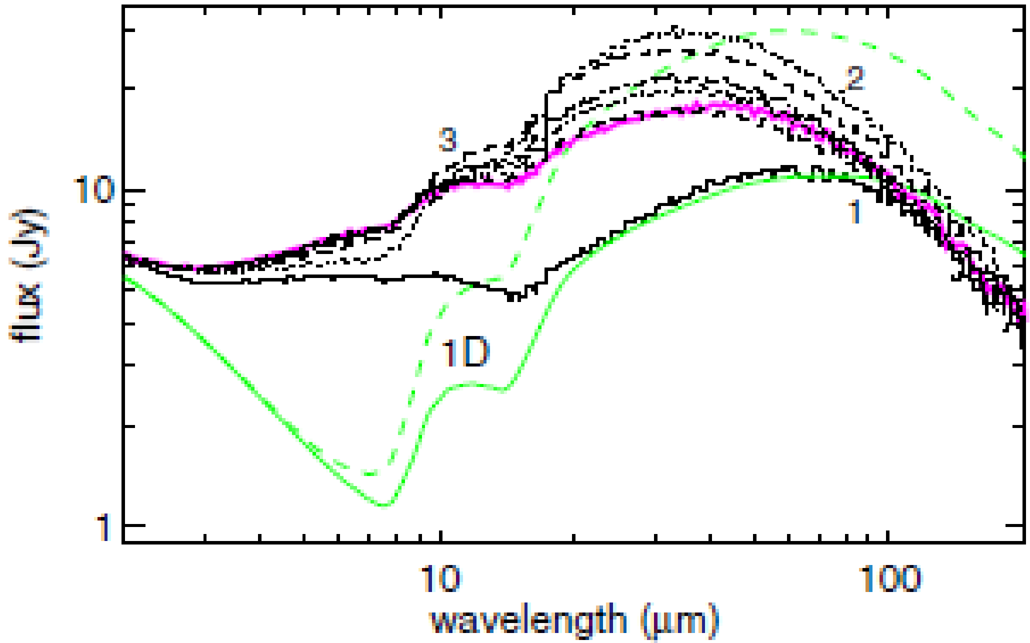
I) T(x,y,z) by MC

II) $$-\frac{z}{r}\frac{GM_*}{r^2} = \frac{1}{\rho}\frac{dP}{dz}$$

with pressure $P = \rho k T(z)/m$.

T Tauri disk



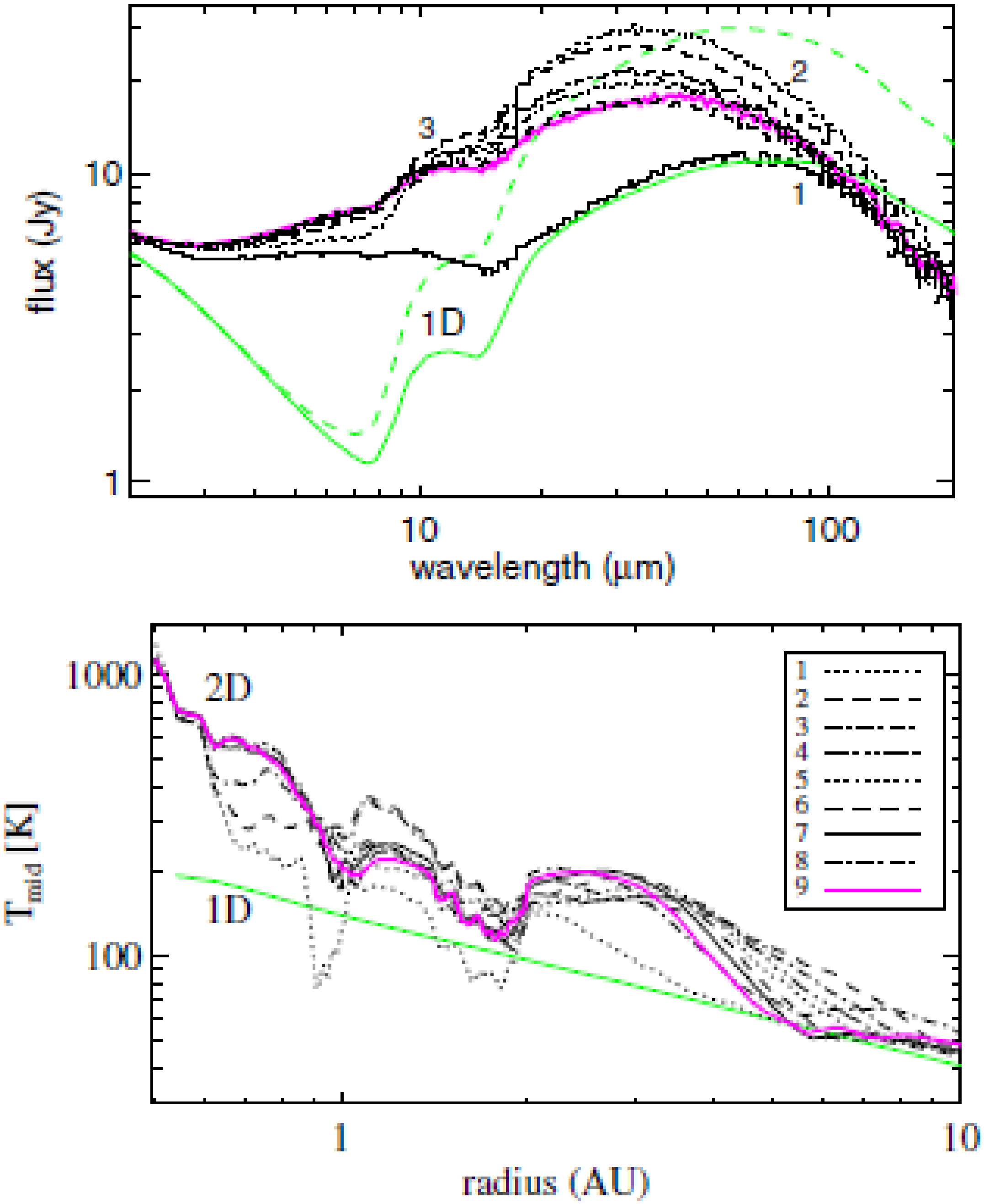


T Tauri disk

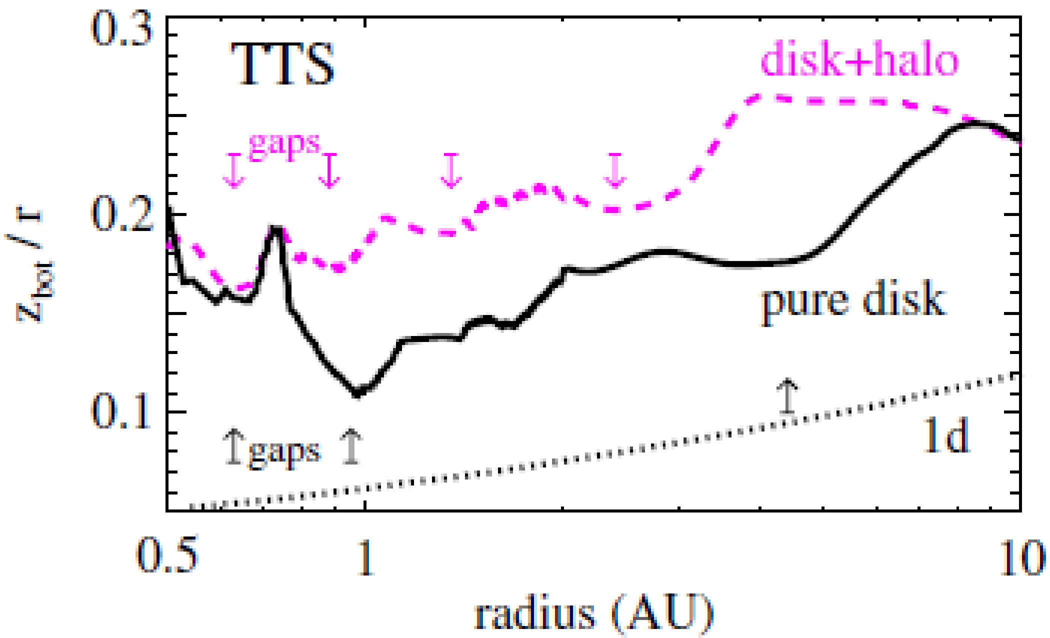
$\Sigma(1\ \mathrm{AU}) = 5\ \mathrm{g\text{-}dust/cm^2}$

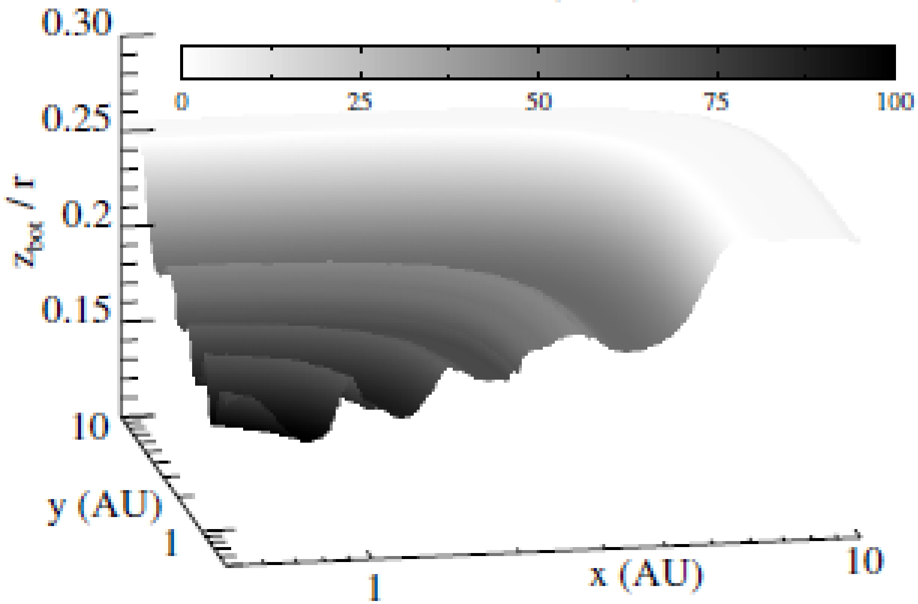
Parameter		T Tauri	Herbig Ae
Stellar luminosity	$L_* \ [L_\odot]$	2	50
Stellar mass	$M_* \ [M_\odot]$	1	2.5
Photospheric temperature	$T_* \ [\mathrm{K}]$	4000	10 000
Column density	$\Sigma(r) = \frac{\tau_\perp(1\mathrm{AU})}{K_\mathrm{V}}\left(\frac{r}{\mathrm{AU}}\right)^\gamma \ [\mathrm{g\text{-}dust/cm^2}]$	$r < 1$ AU:	$\gamma = 0.5$
		$r \geq 1$ AU:	$\gamma = -1$
Vertical optical depth	$\tau_\perp(1\ \mathrm{AU})$	10 000	
Dust density in halo	$\rho_\mathrm{halo}\ [\mathrm{g\text{-}dust/cm^3}]$	0 or 1.5×10^{-18}	
Inner disk radius	r_in	evaporation	
Outer disk radius	r_out [AU]	22.5	40

T Tauri disk


flux (Jy)
10
1
10
100
wavelength (µm)
3
2
1
1D
1000
100
1
10
radius (AU)
T_{mid} [K]
2D
1D
1
2
3
4
5
6
7
8
9

Gaps and ring-like structures without planet



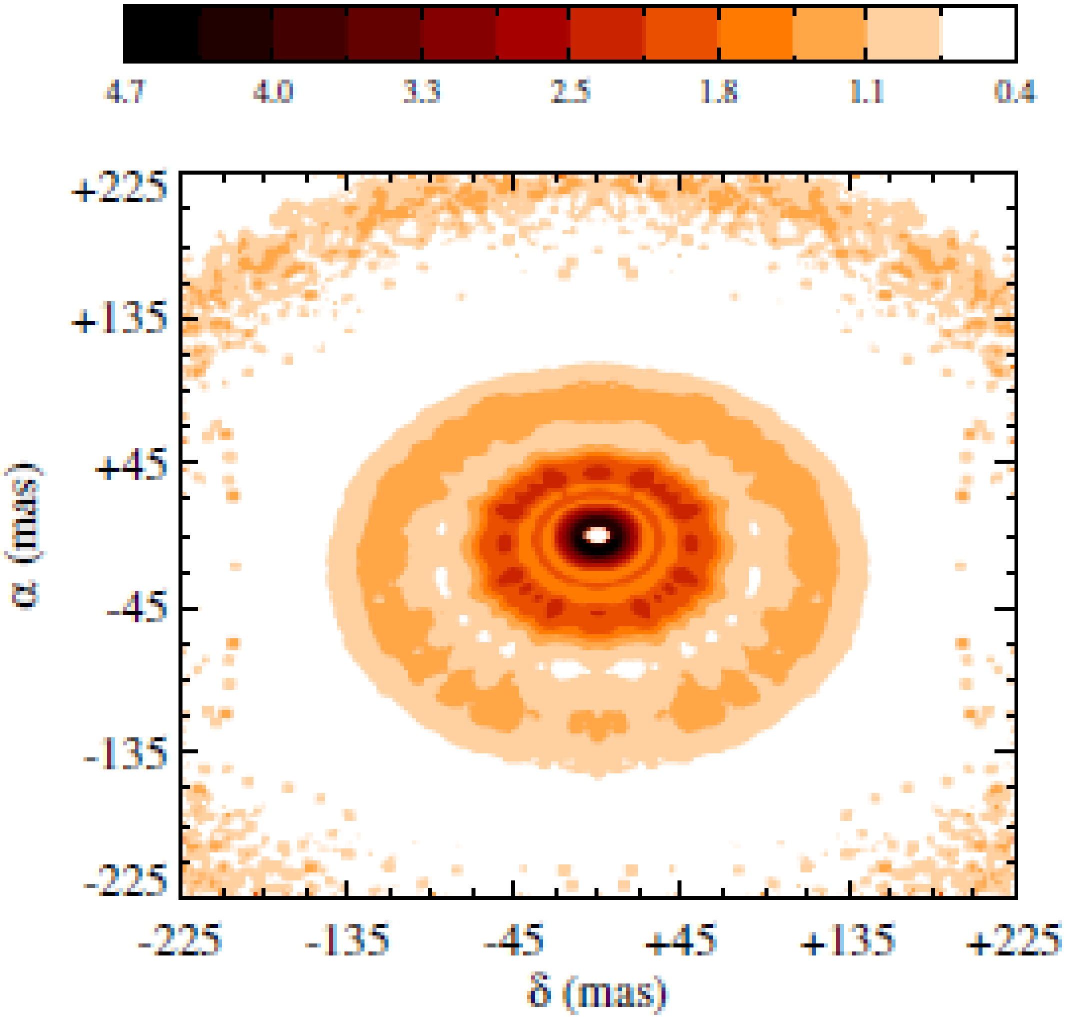


extinction layer

(photosphere)

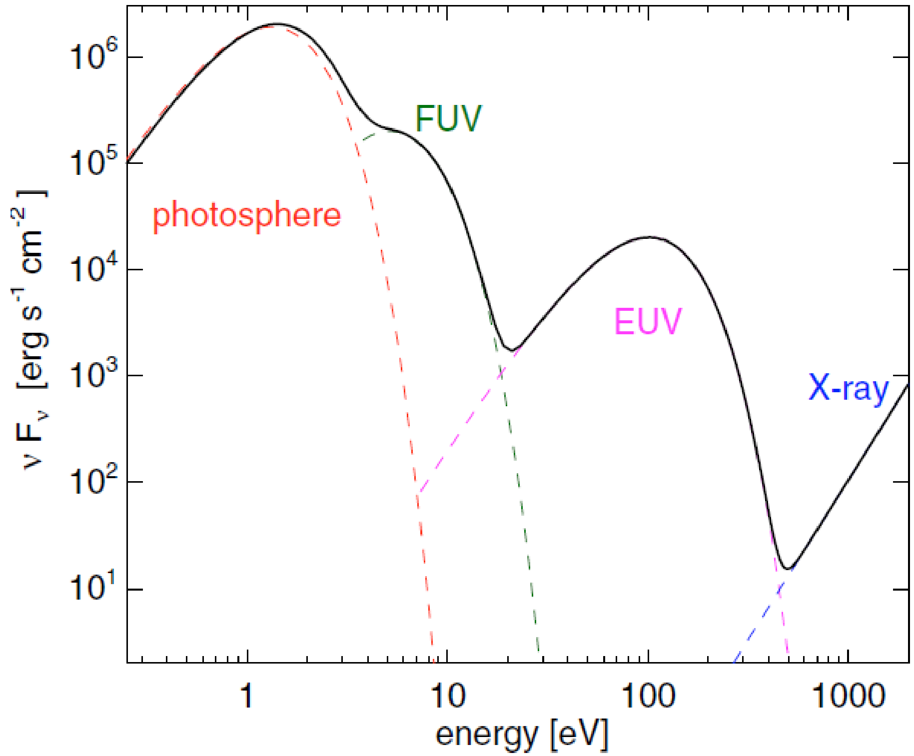
$\tau(z_{bot}) := 1$

Gaps and ring-like structures in the mid-IR



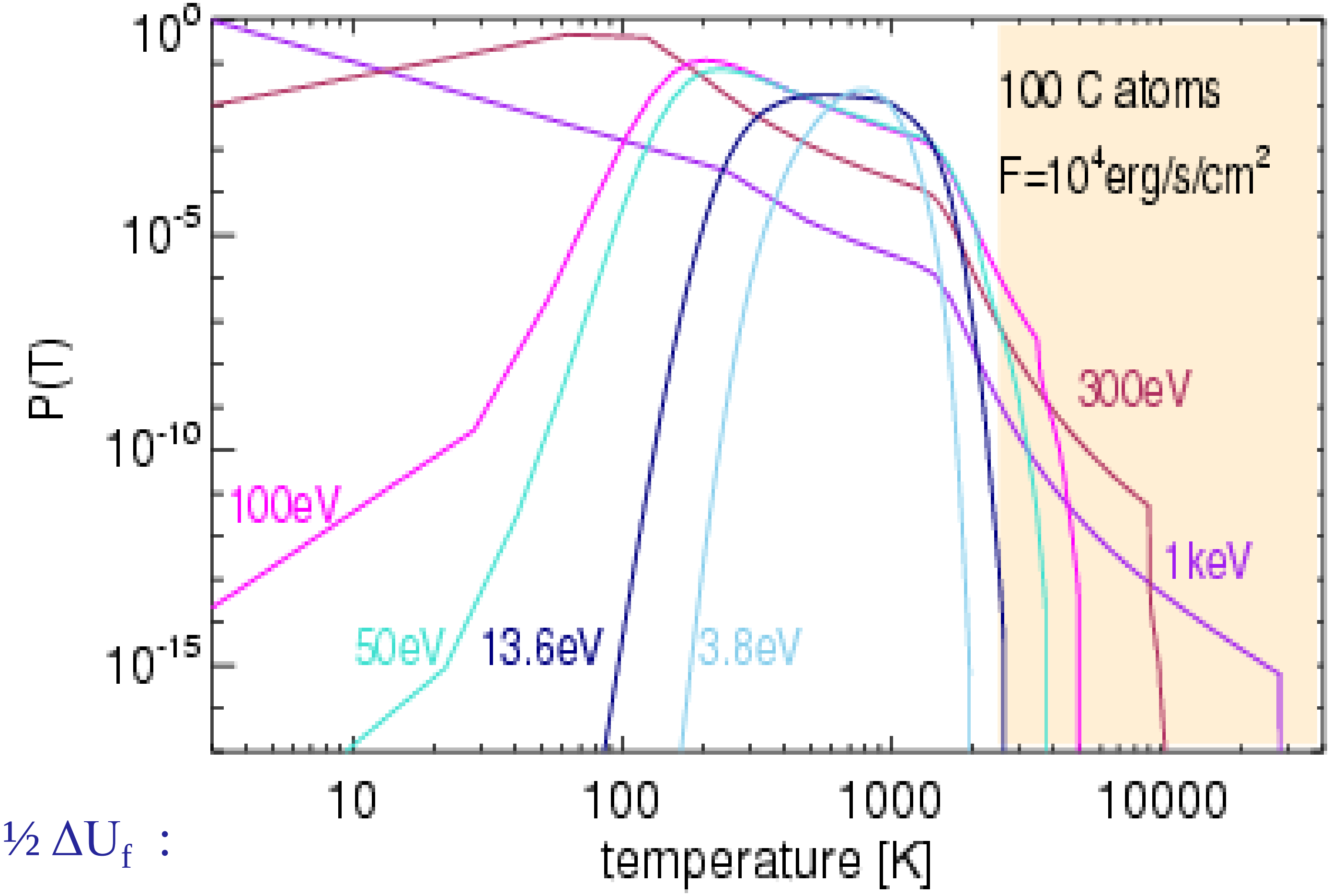
PAH emission from disks

- PAH excitation/destruction
- MC model
- PAH detections statistics



The spectral energy distribution of our T Tauri model star at 1 AU

PAH in a mono-energetic heating bath

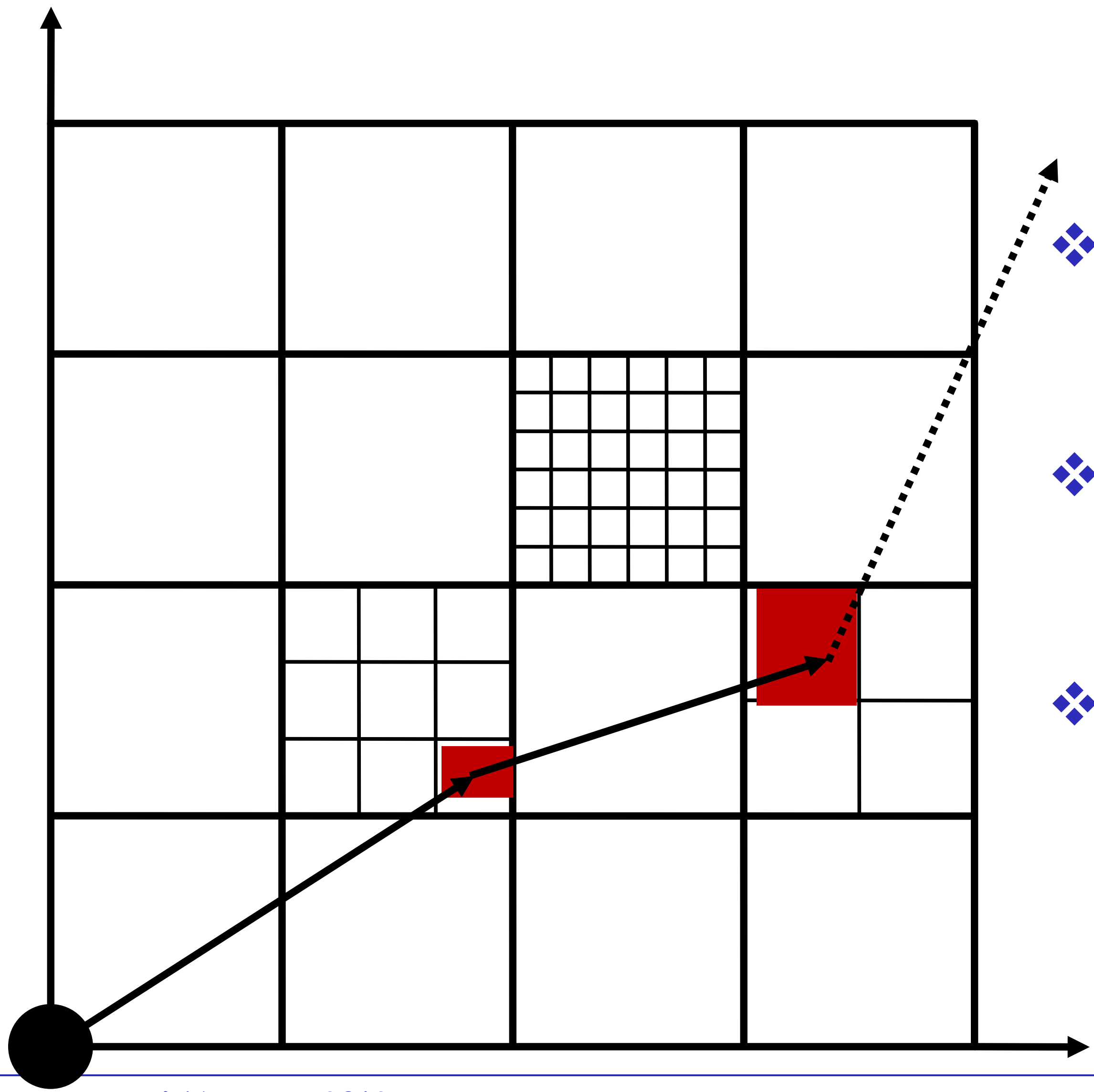


if $| U_f - U_i - h\nu | < \frac{1}{2} \Delta U_f$:

$$A_{fi} = K_\nu F_\nu / h\nu$$

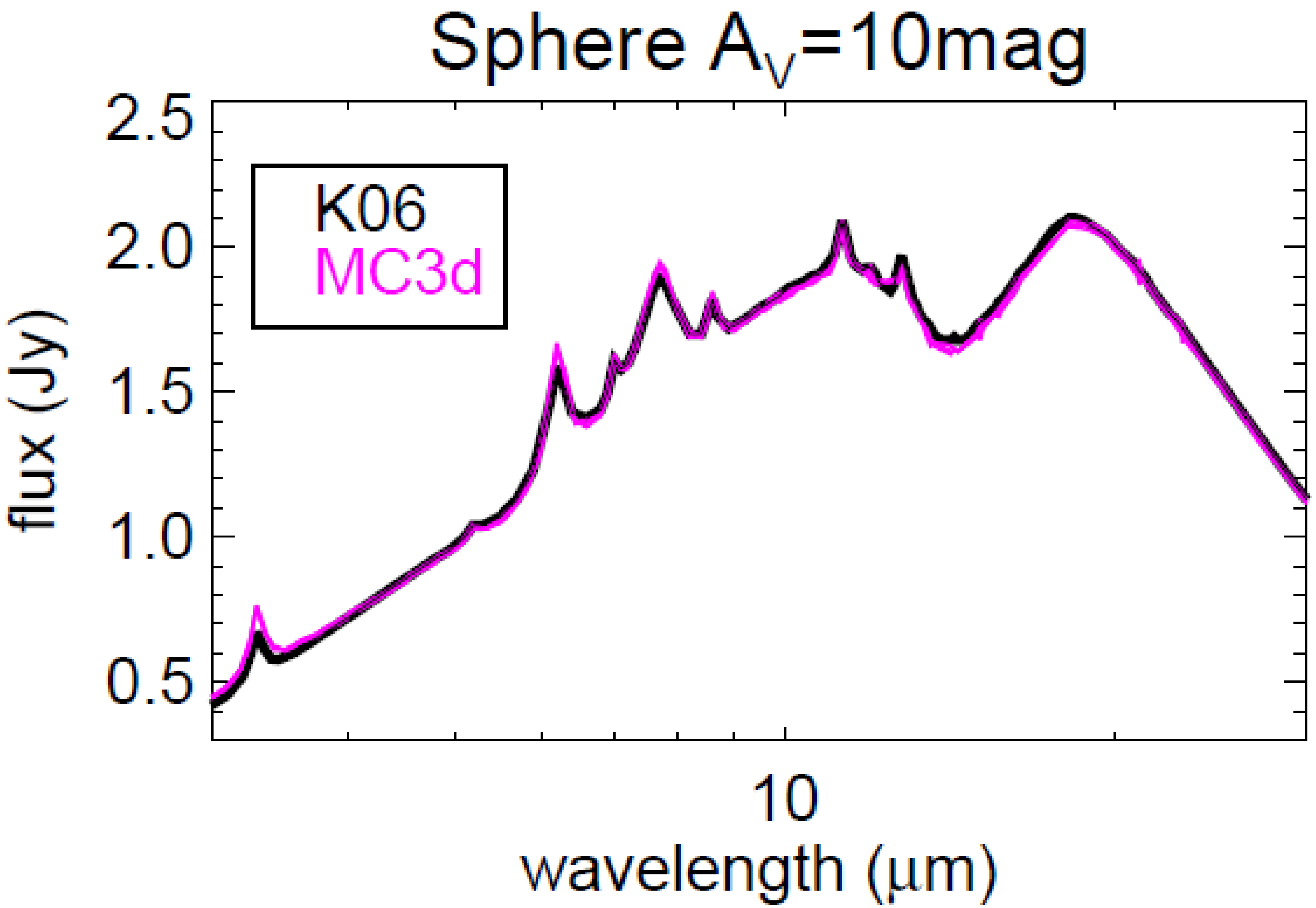
Siebenmorgen & Krűgel (2010)

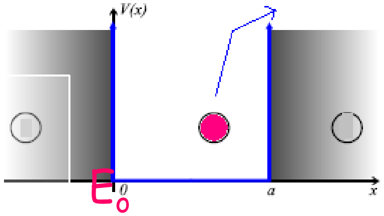
Monte Carlo + PAH

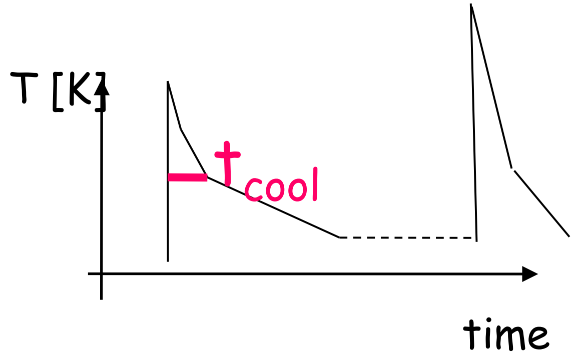


- store PAH absorption events of each cell
- compute PAH emission
- neglect PAH self absorption

Monte Carlo + PAH







Unimolecular dissociation

Arrhenius form:

$t_{dis} \sim \exp(E_o/kT) / \nu_0 \quad \ll t_{cool} \sim 1s$

$t_{abs} \sim 1h$

$T_{min} = E_o/k \ln(\nu_0) \sim 2000K; \quad E_o \sim 5eV; \quad \nu_0 = 10^{13}Hz$

$\Delta E = 3N_c\, kT_{min} \sim 0.1\, N_c \cdot E_b \Rightarrow$ $\mathbf{N_c < 2\, \Delta E}$ /[eV]

PAH unstable

1) single **hard** photon : independent of distance

2) many **soft** photons : ~AU

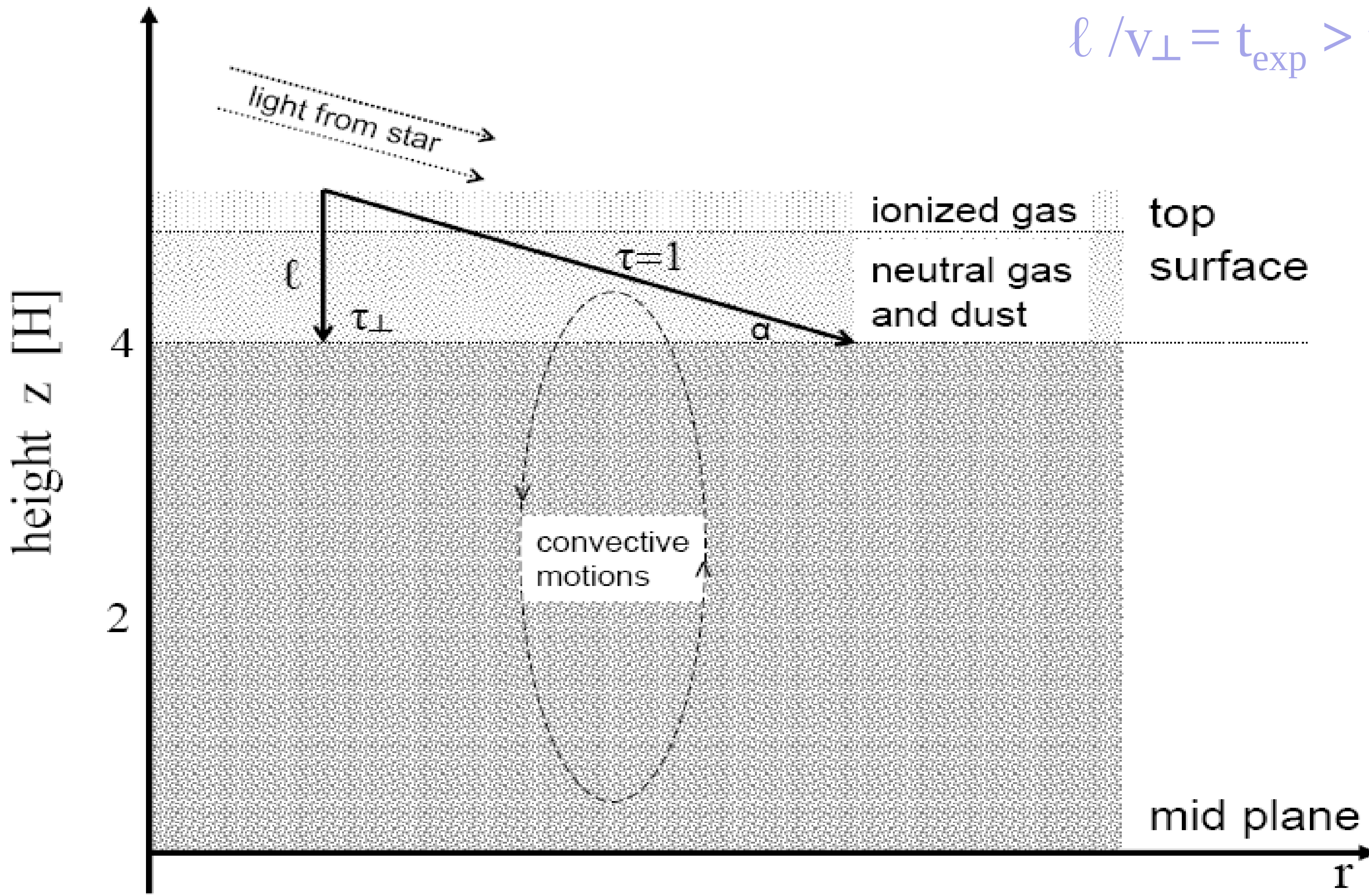
Siebenmorgen & Krügel (2010)

PAH destruction time << Disk lifetime

=> PAH replenishment

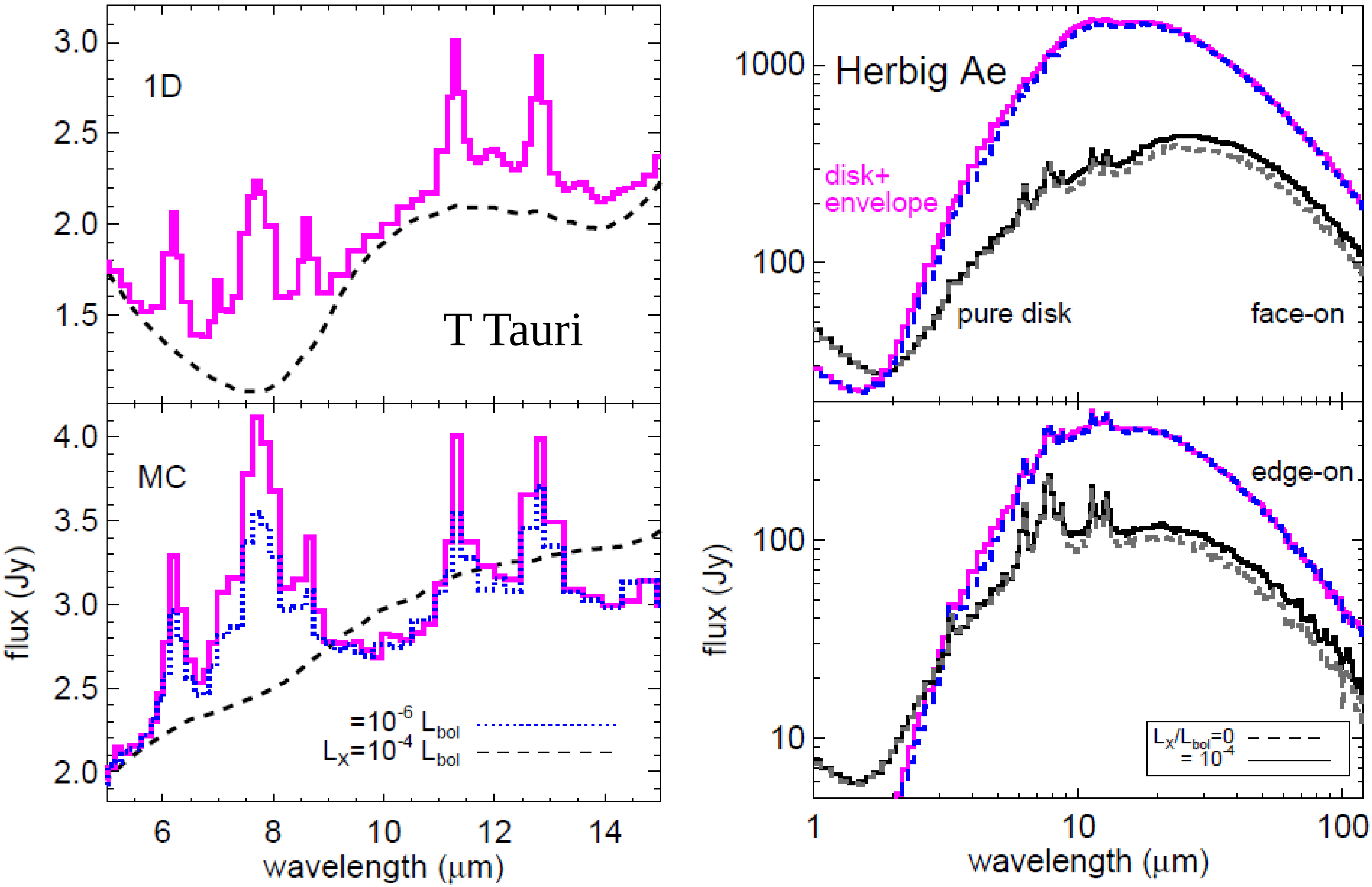
Vertical mixing

$\ell / v_{\perp} = t_{exp} > t_{dis}$

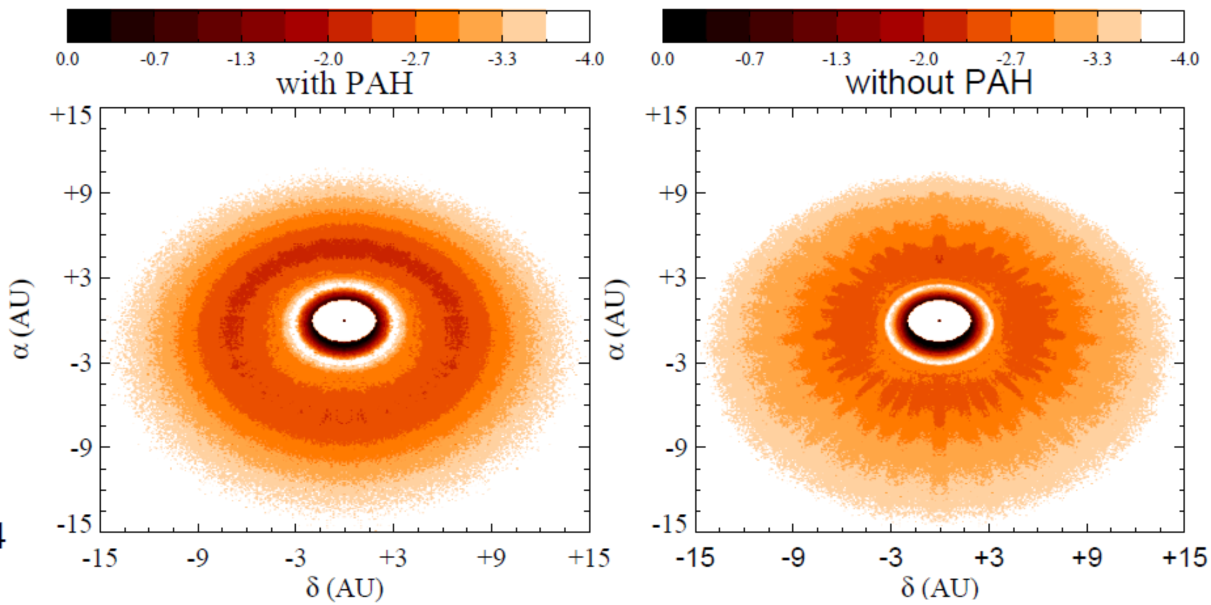


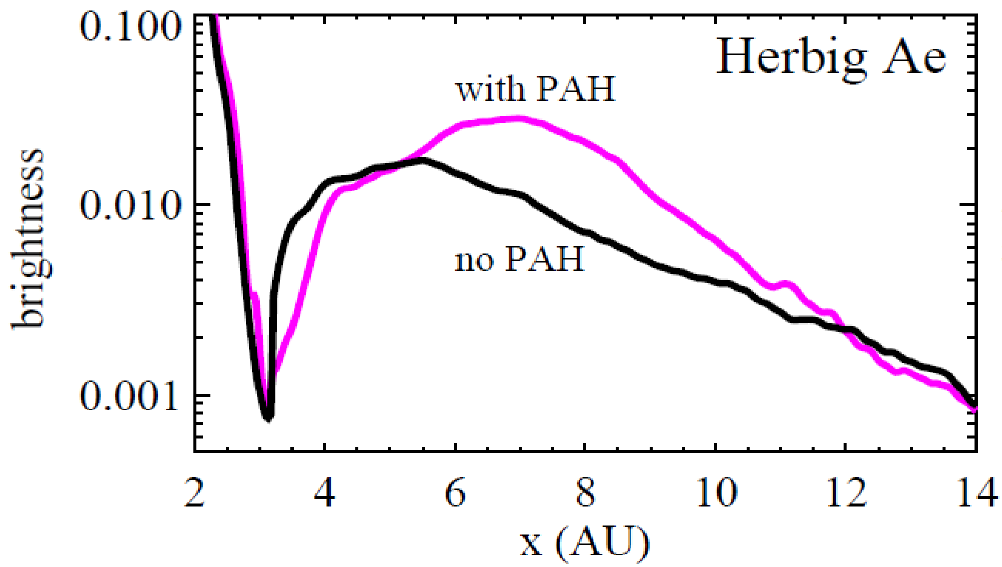
Siebenmorgen & Krügel (2010)

PAH emission from disks



Mid-IR emission from Herbig disks





Siebenmorgen & Heymann (2012)

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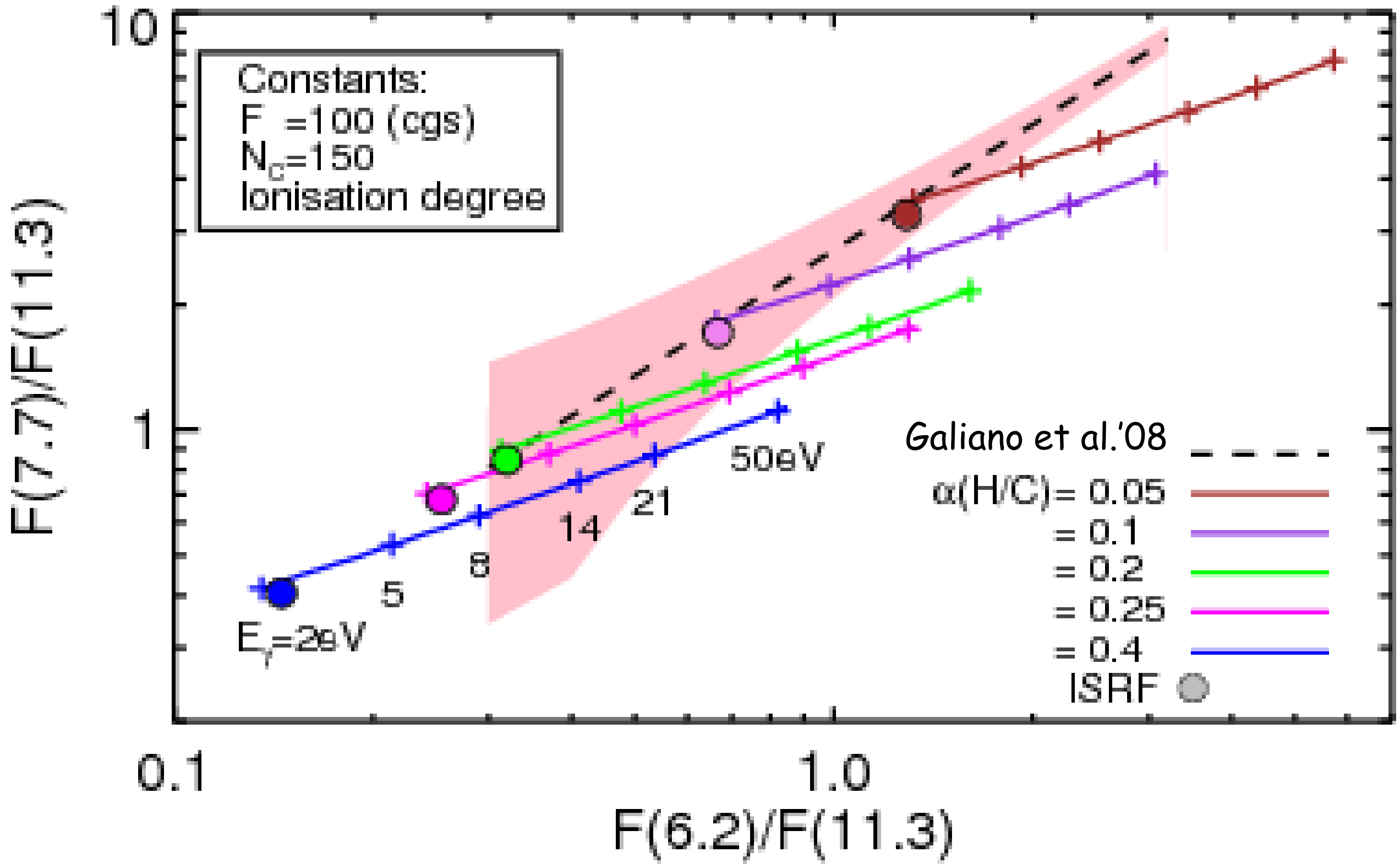
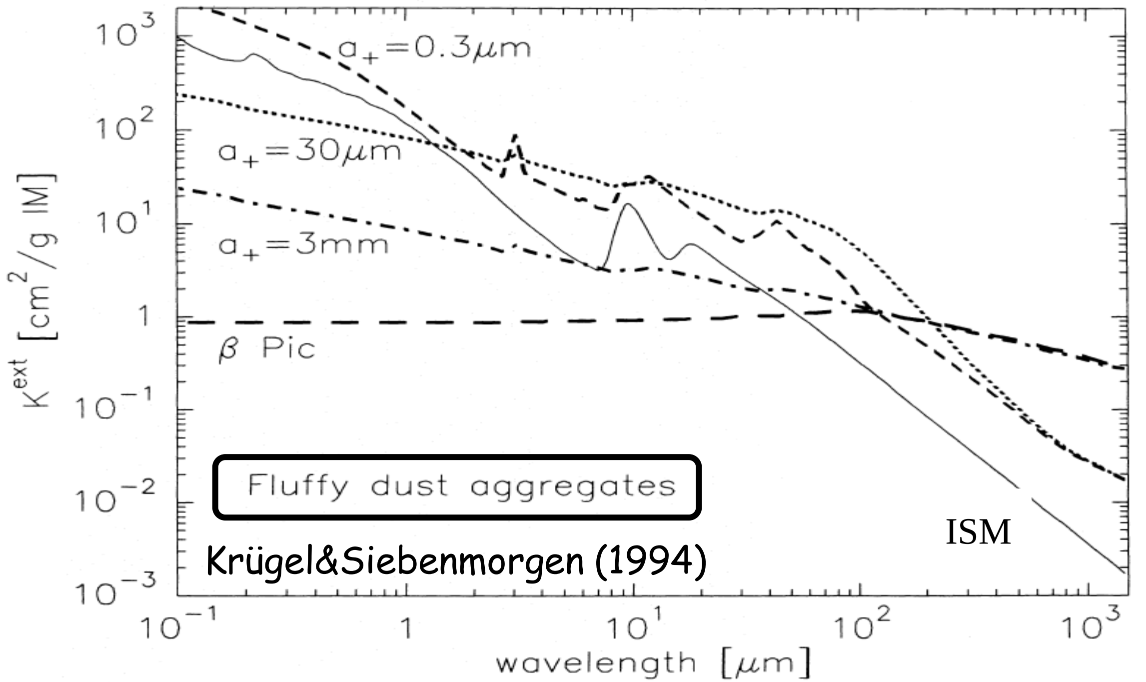
MC methods

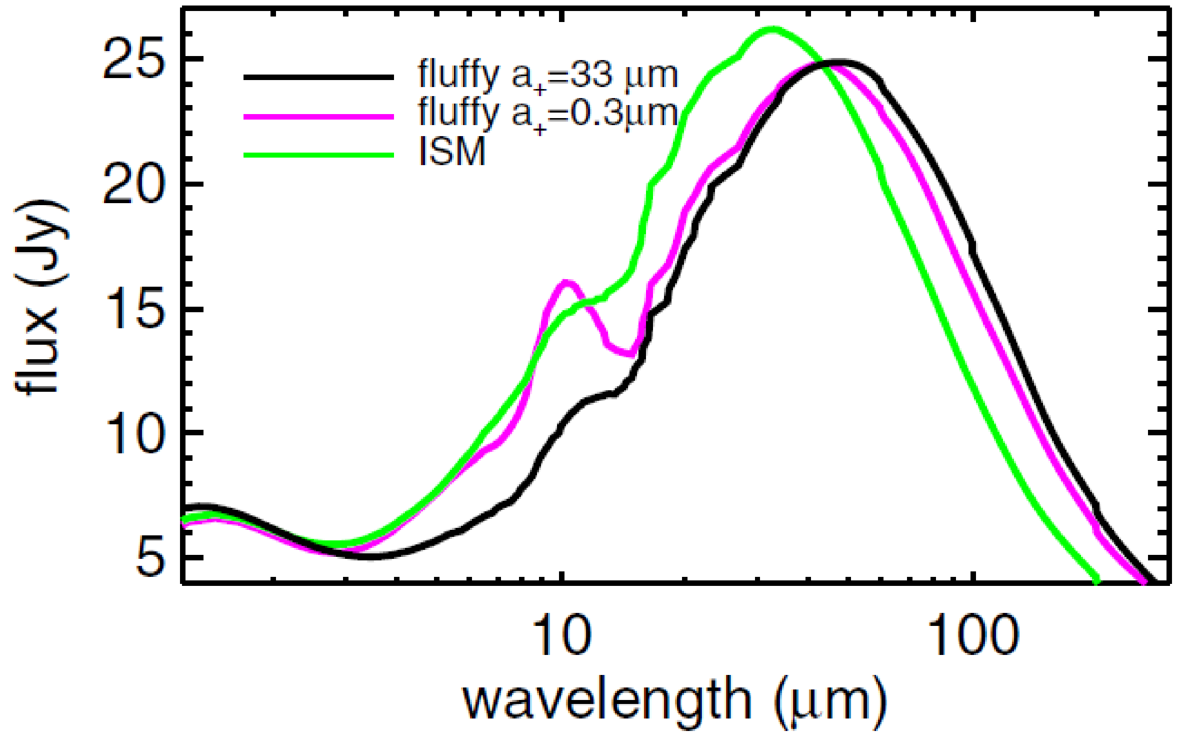
Method	Parallelization	Advantage	Time Benchmark sphere τ~1000)
Lucy	YES (but floating)	Optical thin	>1h
Bjorkman & Wood	Partly (not independent)	No iteration	5min
Heyman & Siebenmorgen (2012)	YES	GPU	<1min

PAH band ratios:
ionisation ⟷ dehydrogenation



Dust mineralogy





Siebenmorgen & Heymann 2012