PAH in 3D

Shadows, gaps and ring-like structures in proto-planetary disks

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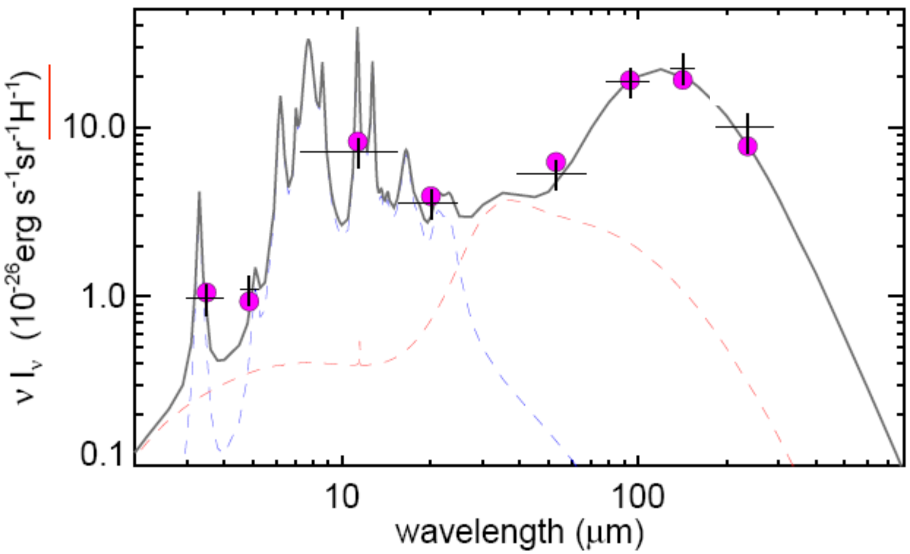
Peter Scicluna (PhD)

- ISM dust model
- Monte Carlo dust radiative transfer
- Proto-planetary disks: ring-like structures
- PAH destruction in proto-planetary disks

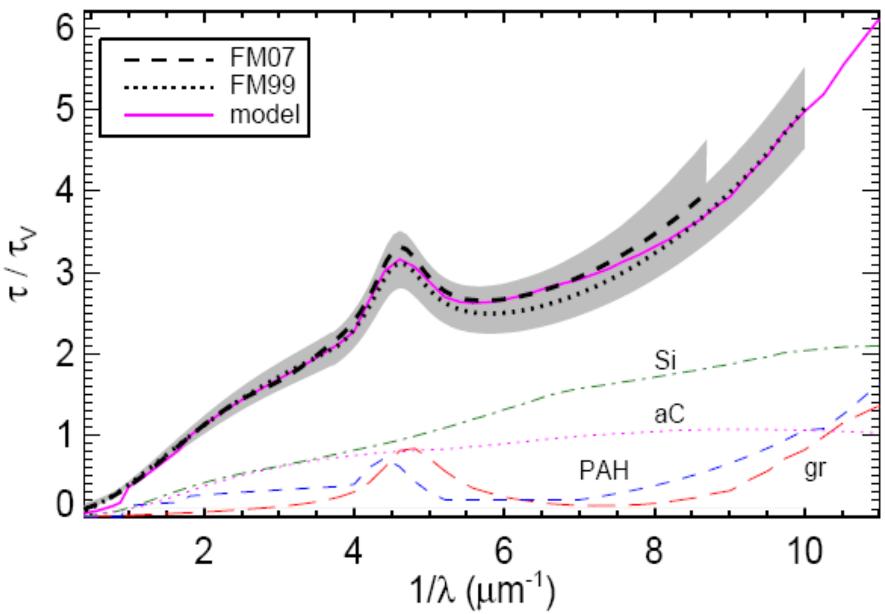
ISM dust

solar neighborhood



Abundances [X/H in ppm]:

31Si + 150aC + 50gr + 30PAH

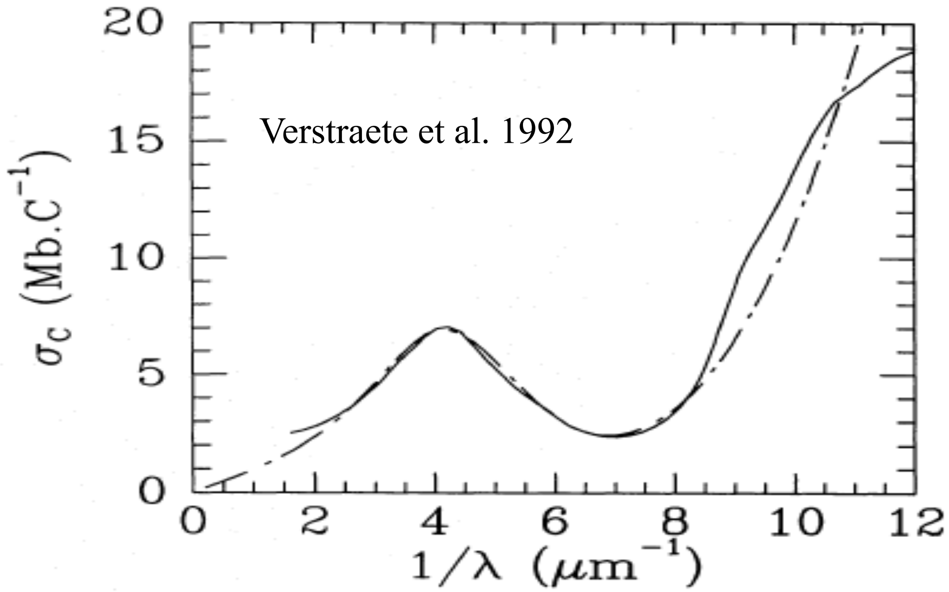


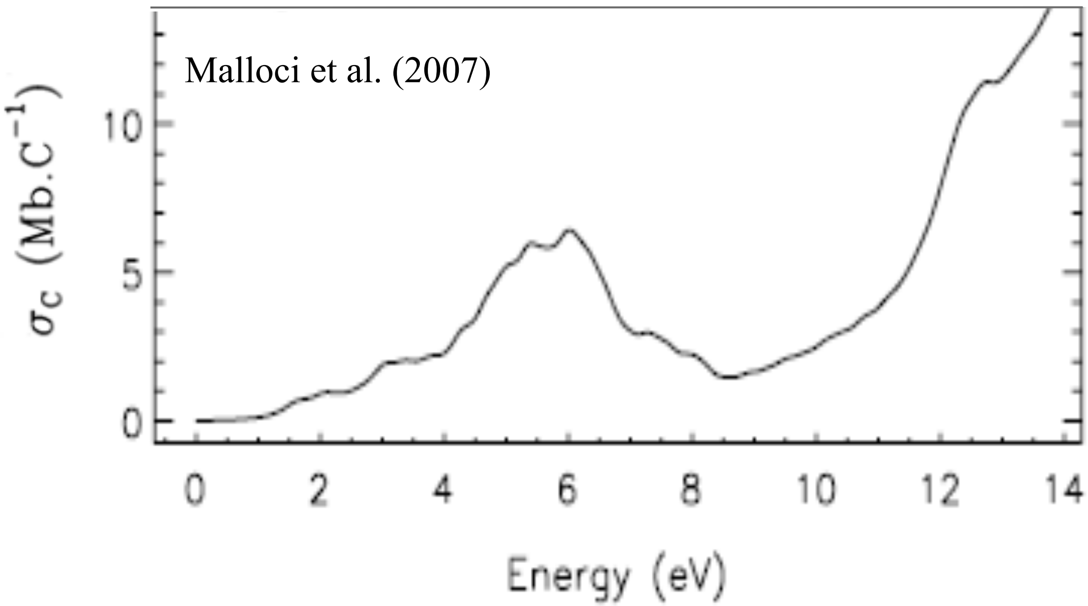
Si + aC : 60Å < a < 0.2-0.3μm ~ $a^{-3.5}$

Graphite : 5Å < a < 80 Å ~ $a^{-3.5}$

PAH : 30, 200 C

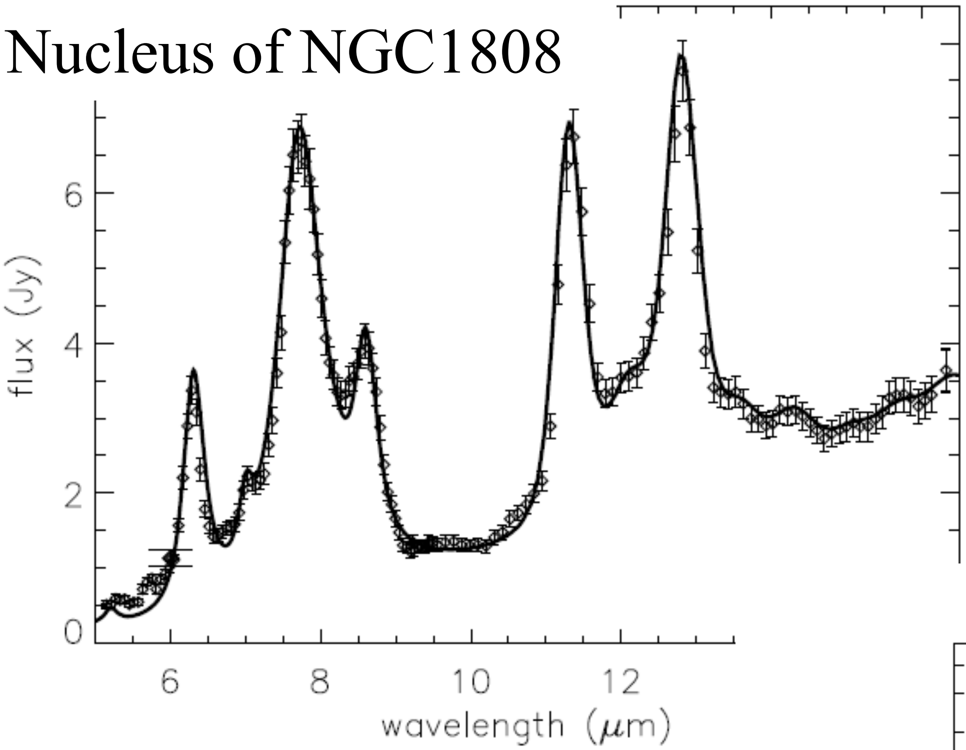
PAH absorption cross section +"2200" bump

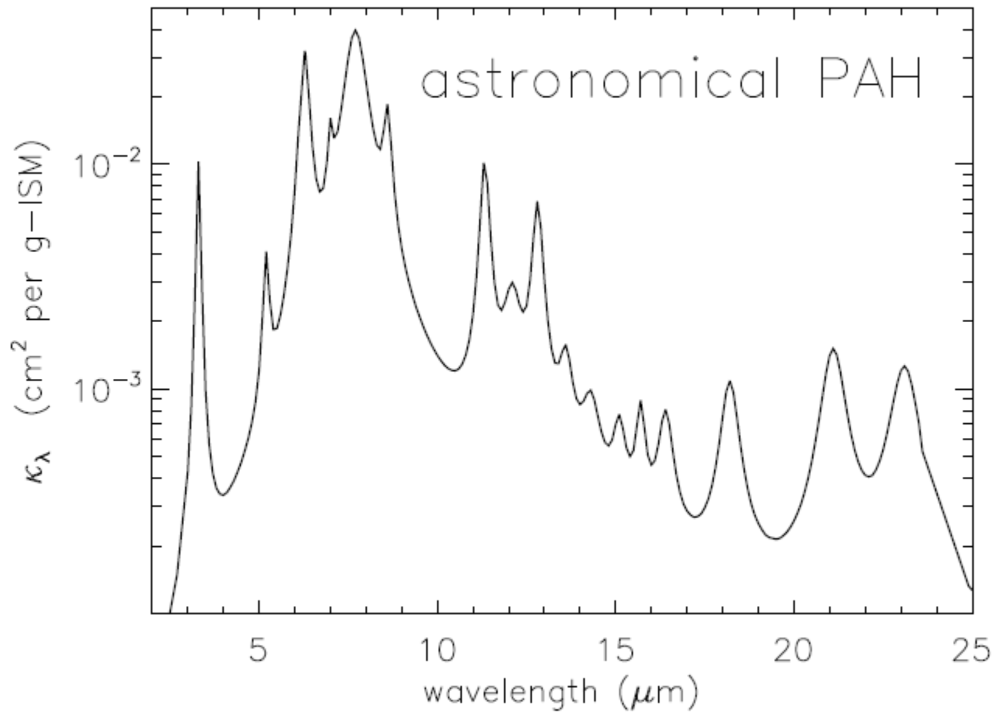




PAH emission cross section starbursts

Nucleus of NGC1808





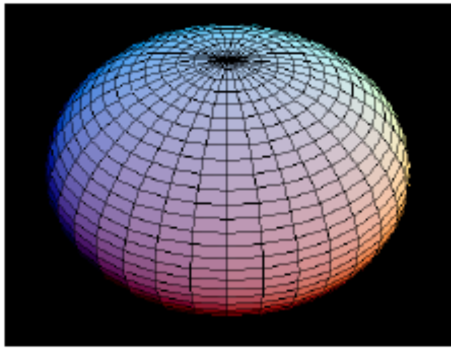
Siebenmorgen et al. (2001,2007)

Linear polarisation

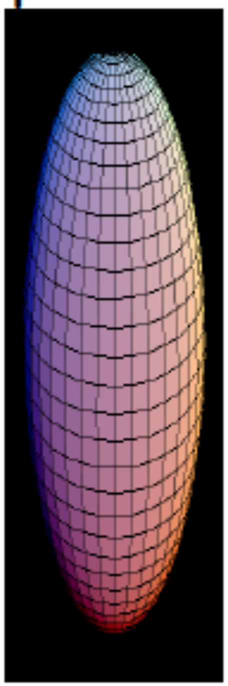
Serkowski

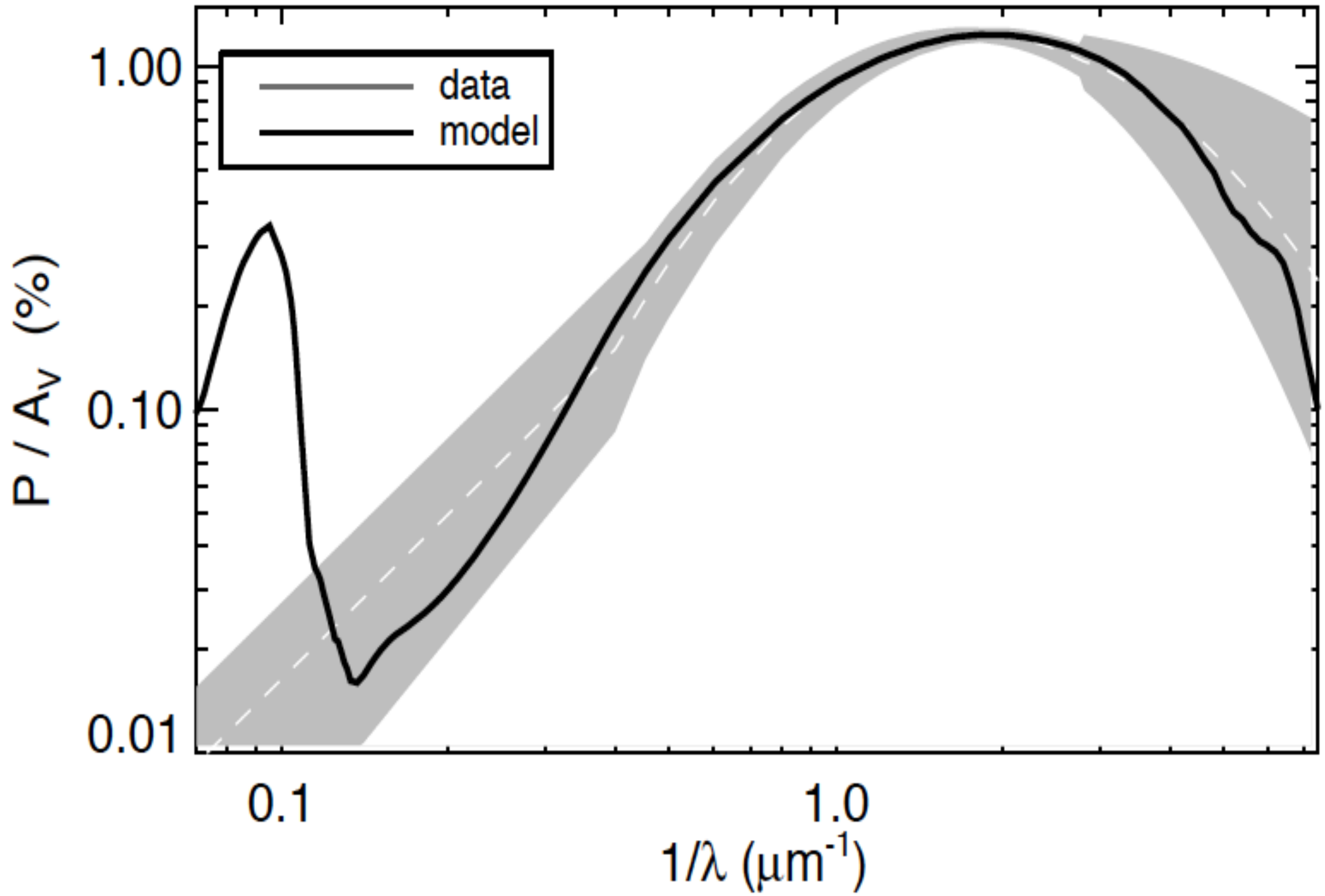
Voshchinnikov (2012)

oblate

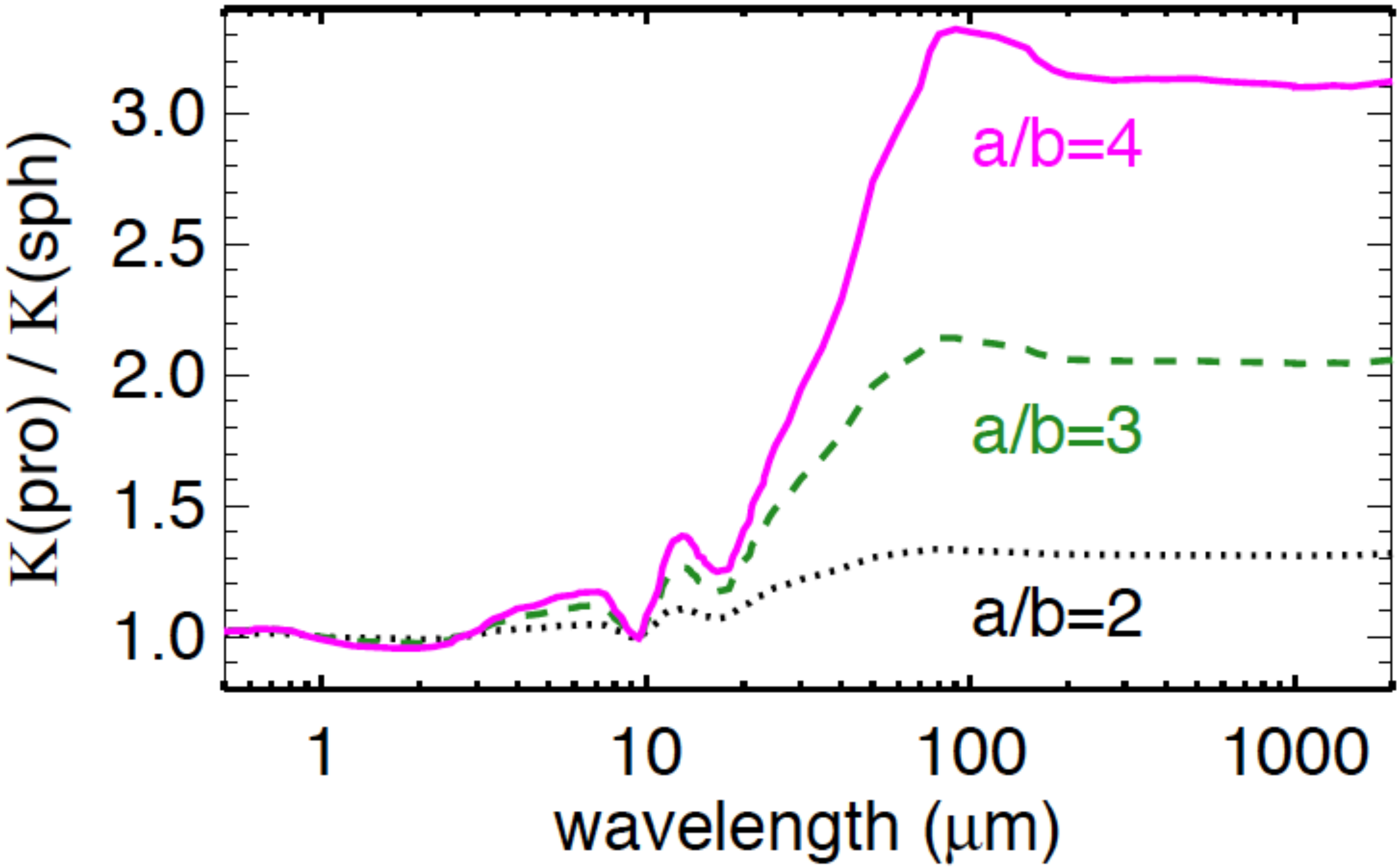


prolate

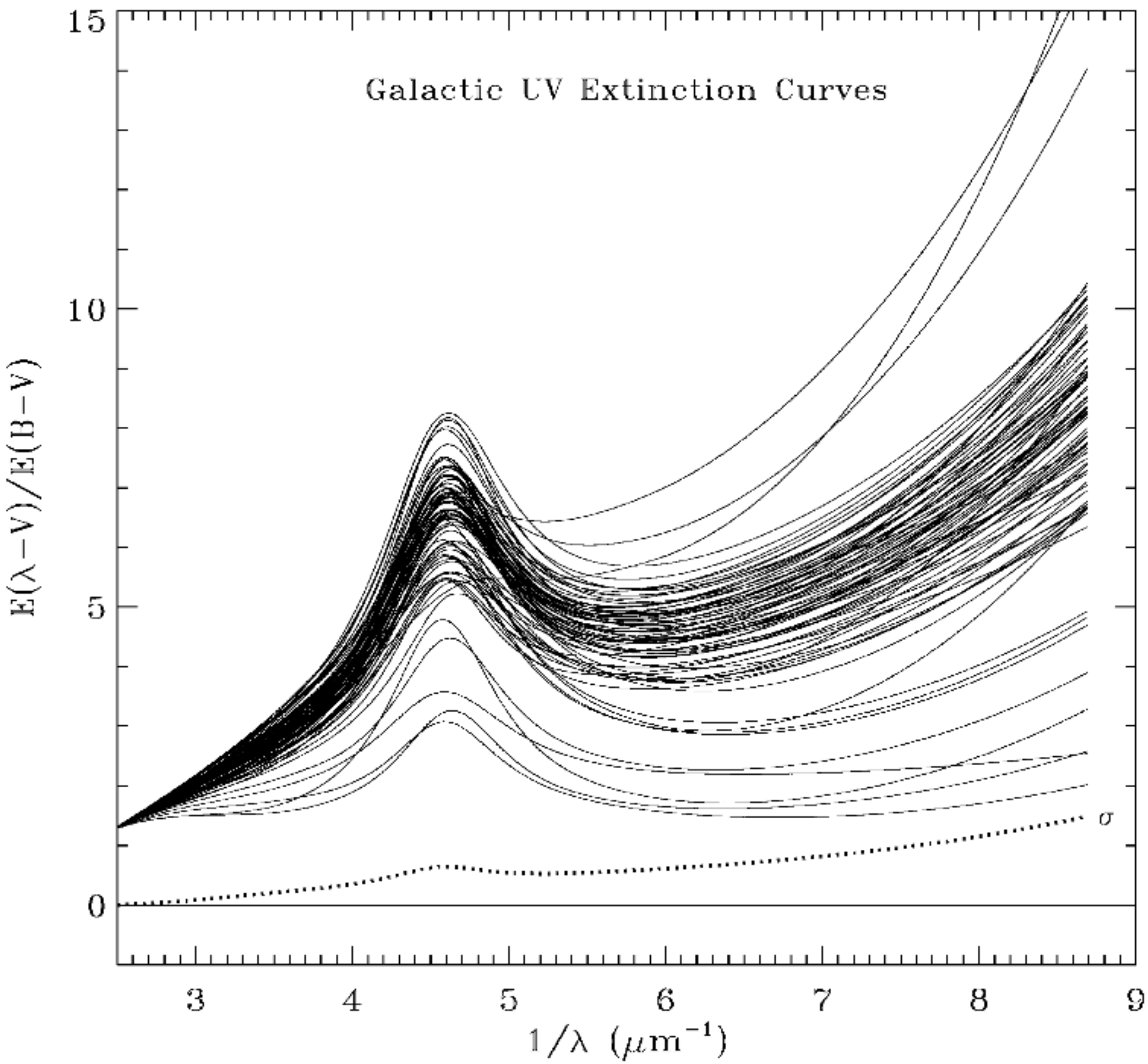




Extinction: Prolate/ Sphere

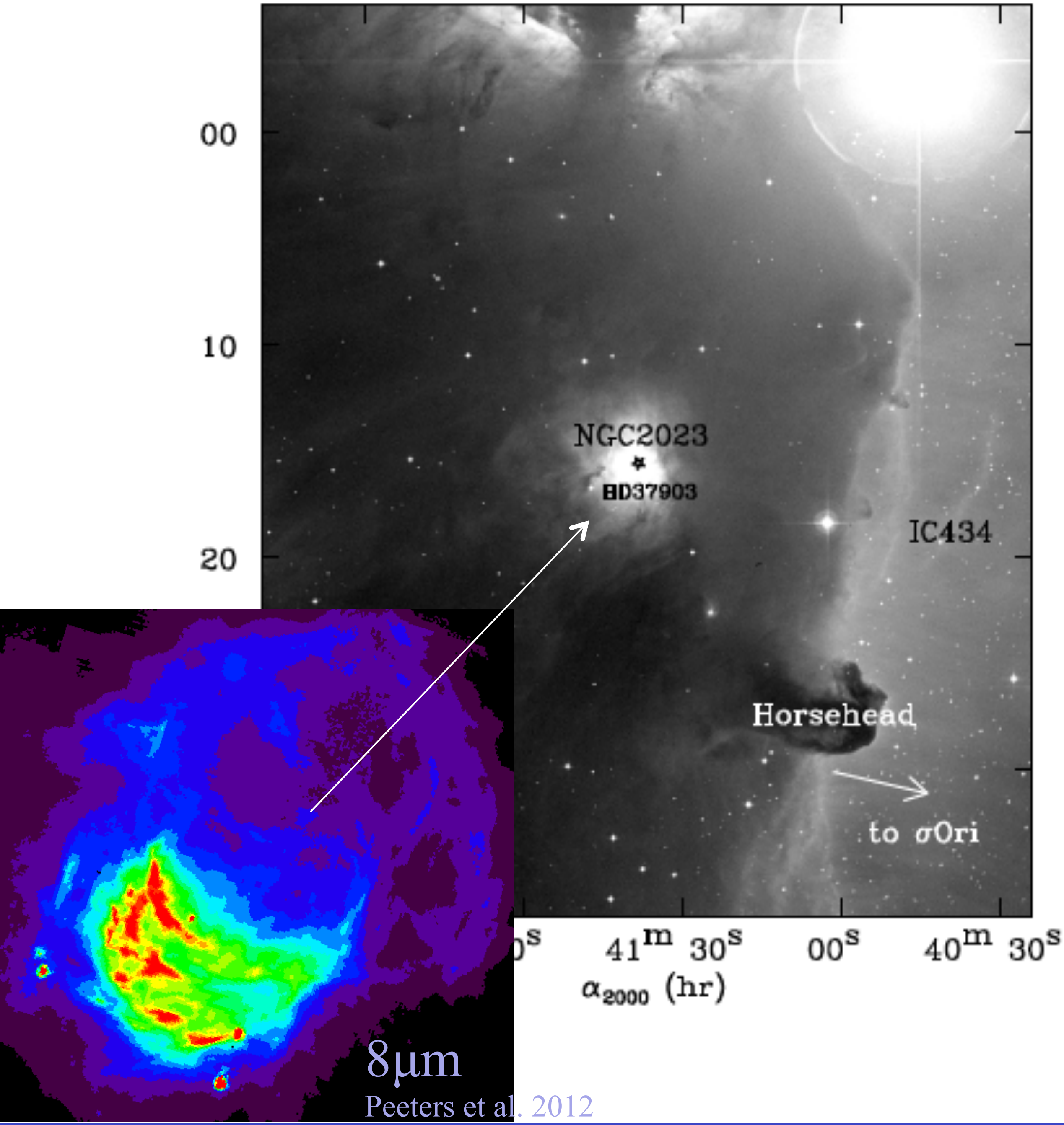


ISM dust
Fitzpatrick (99)



NGC2023

HD37903

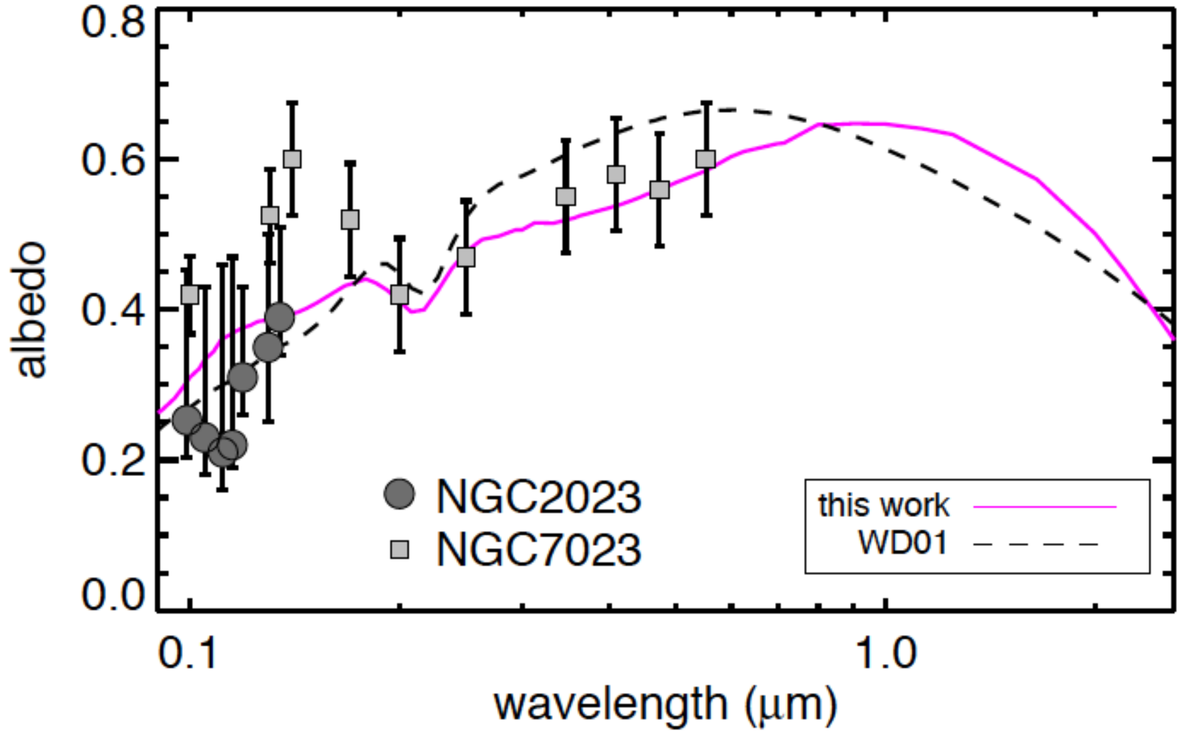


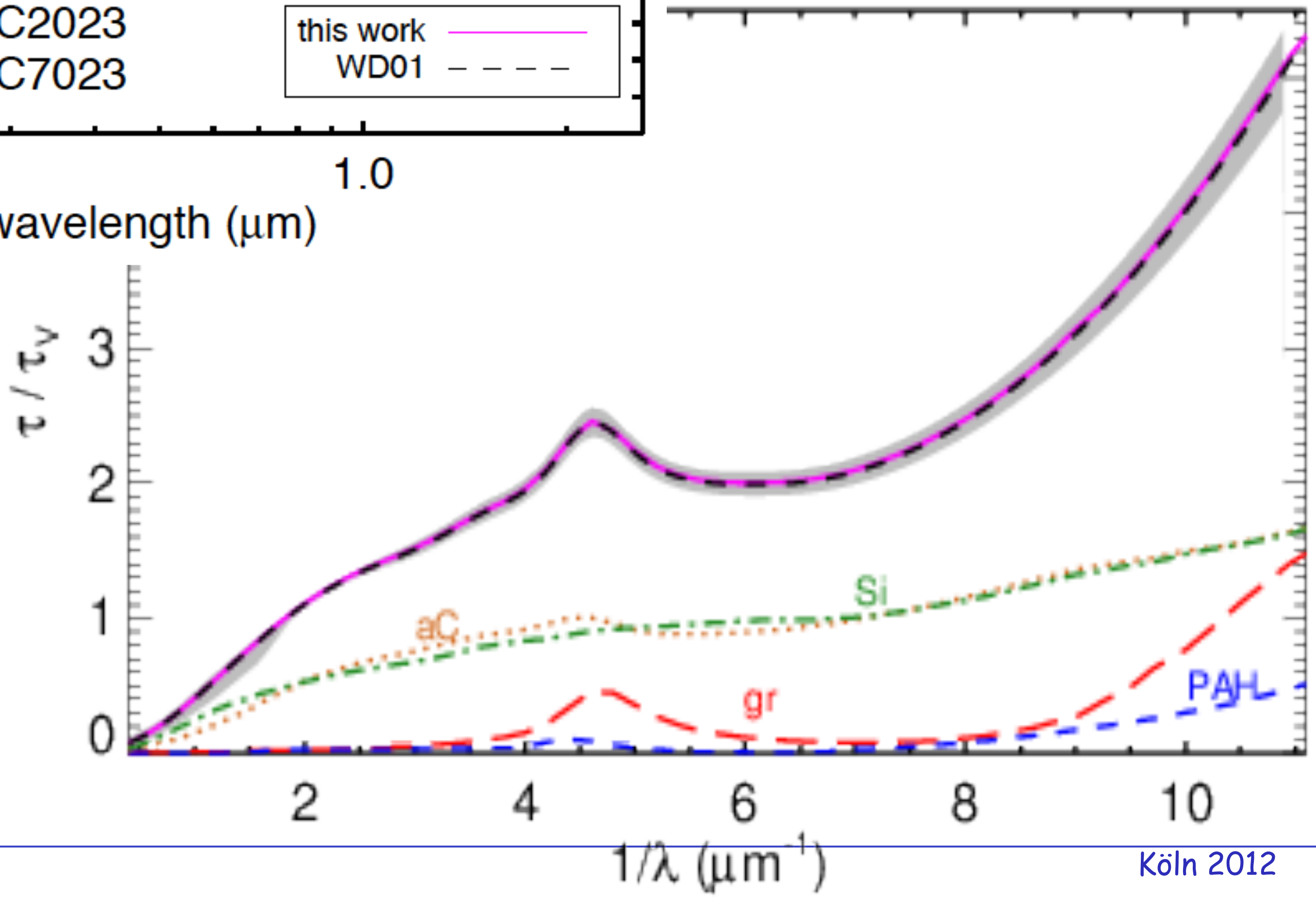
Dust model :

- Extinction
- Emission
- Polarisation

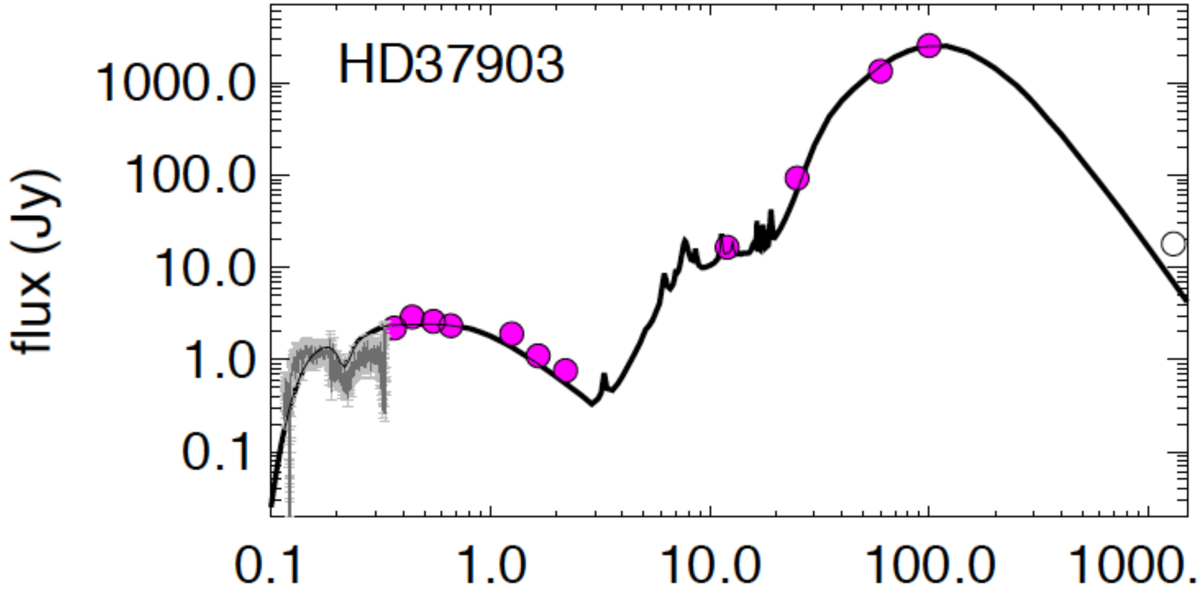
Albedo

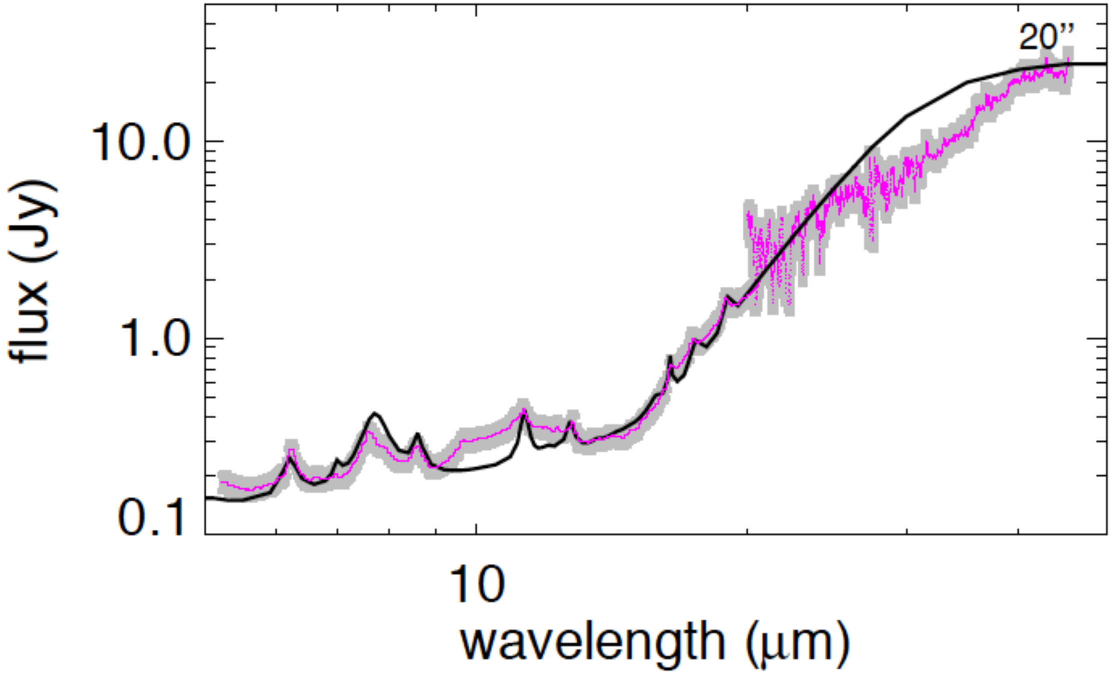
Extinction

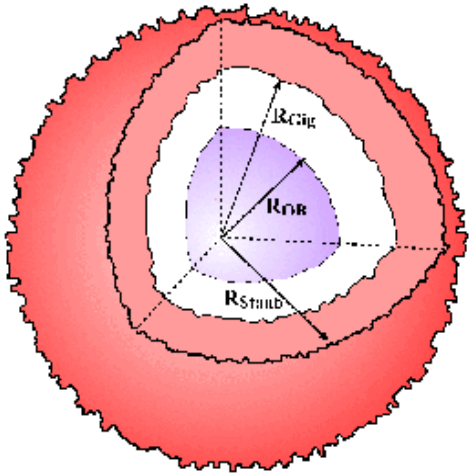




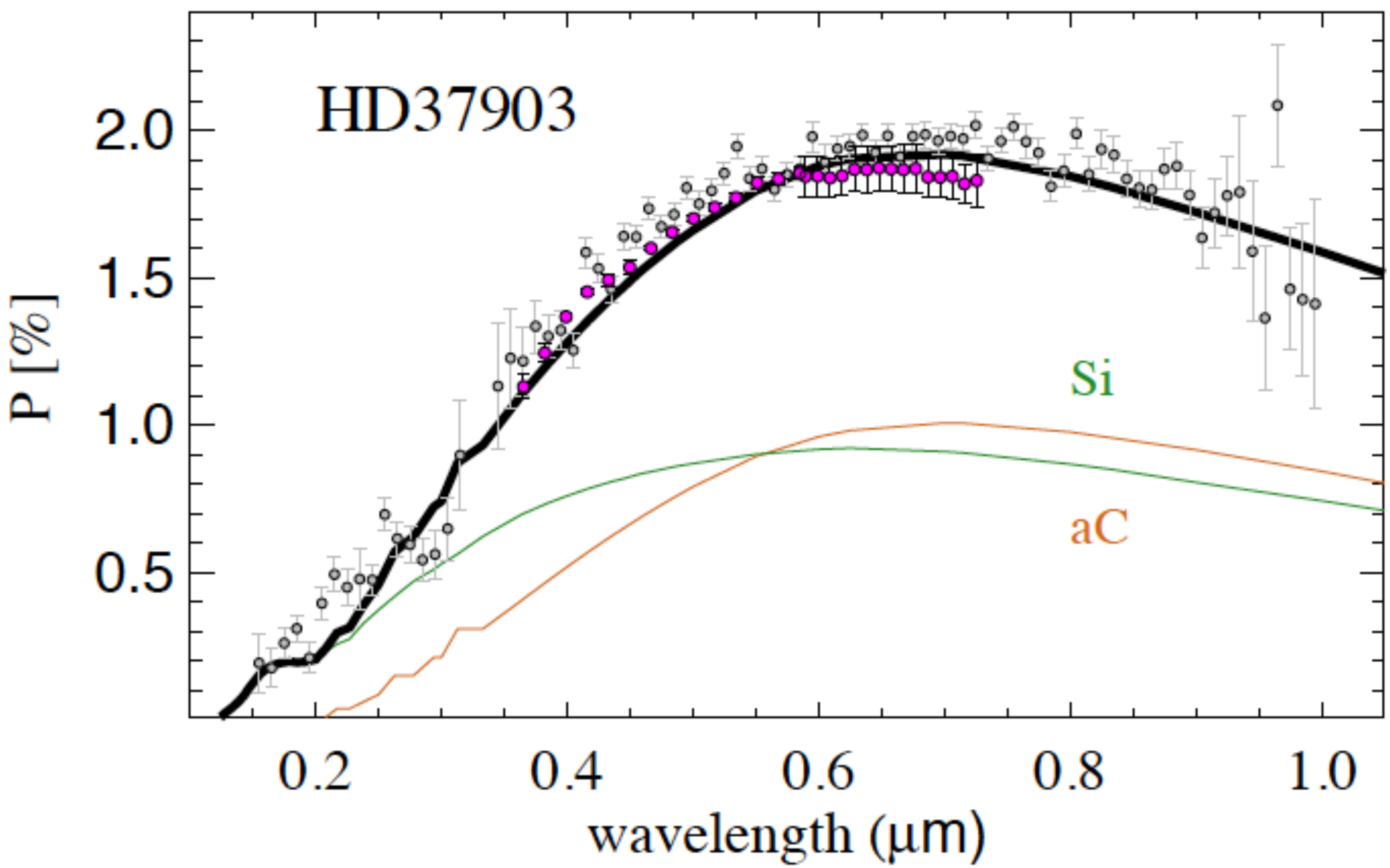
Emission


HD37903
flux (Jy)
1000.0
100.0
10.0
1.0
0.1
0.1
1.0
10.0
100.0
1000.0

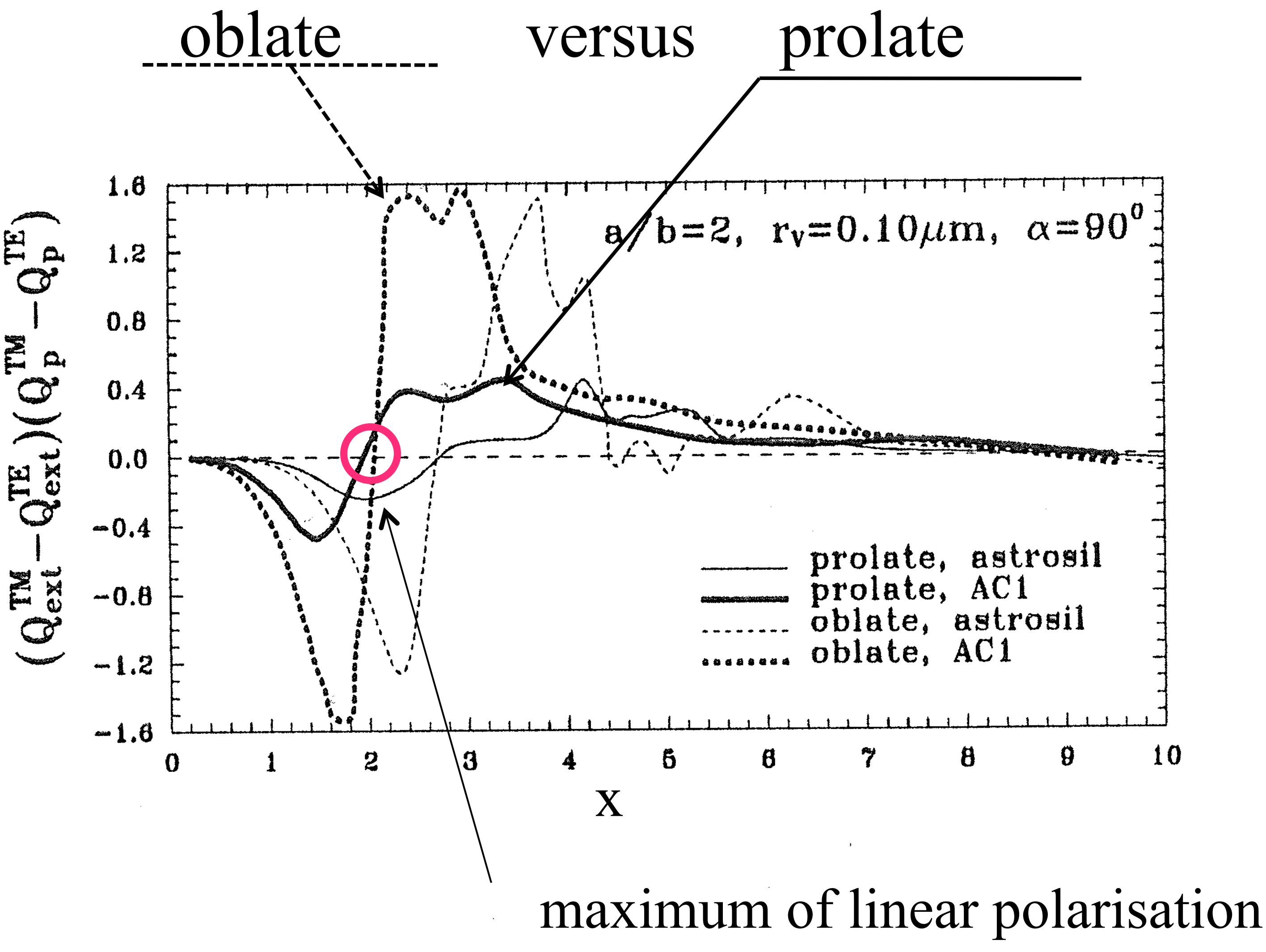

20"
flux (Jy)
10.0
1.0
0.1
10
wavelength (μm)



Polarisation

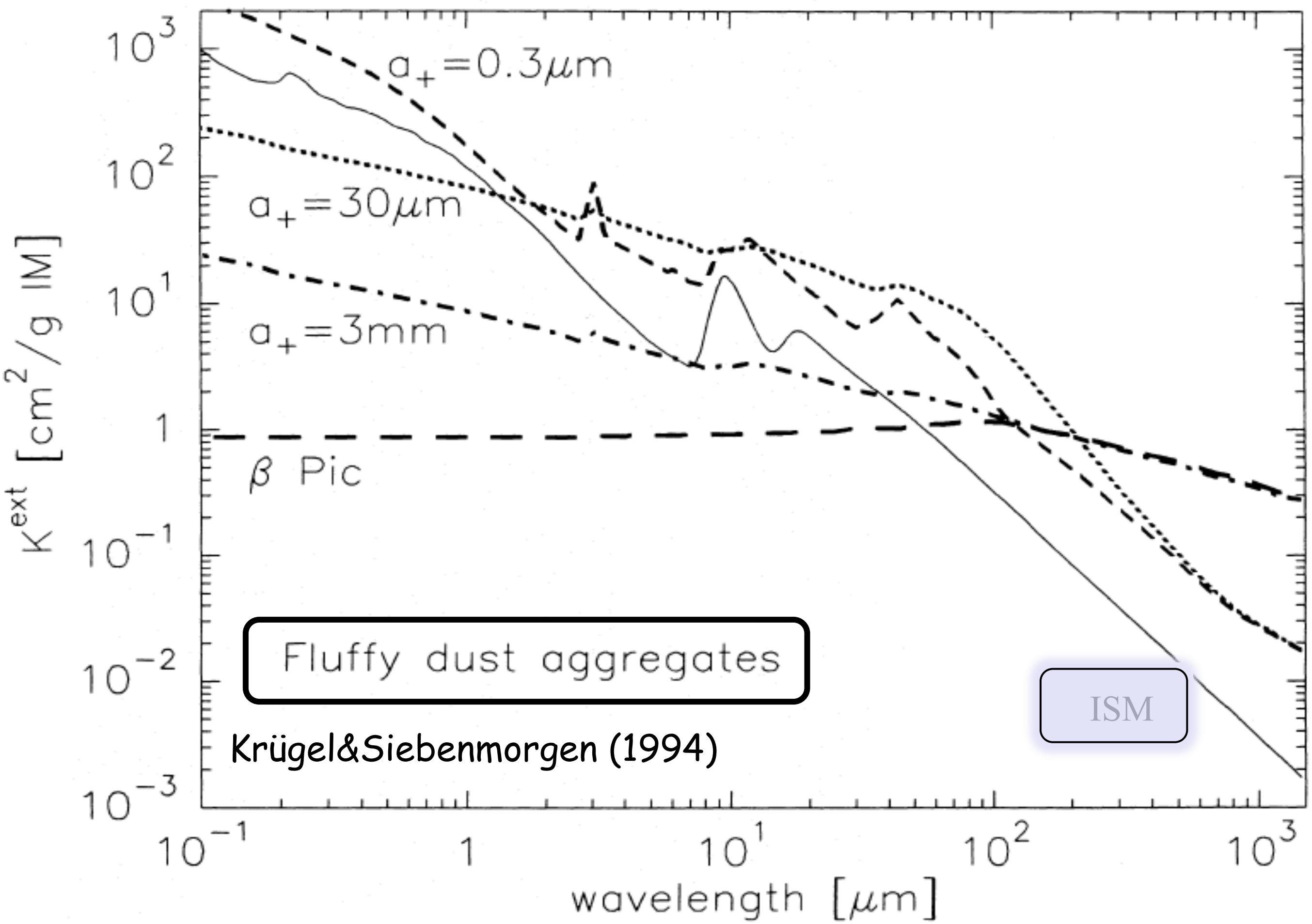


Circular polarisation of dust:



Voshchinnikov (2002, 2012)

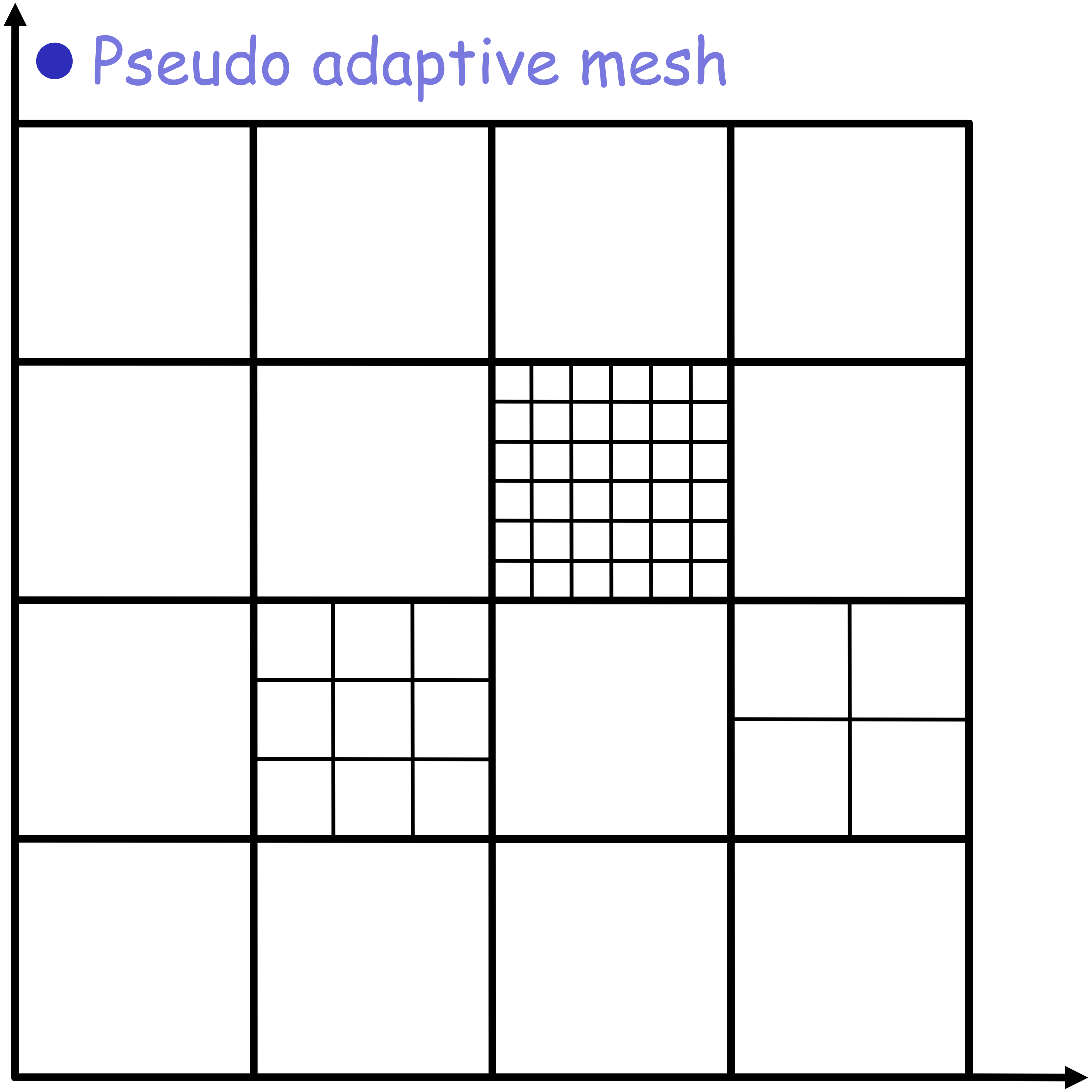
Homogenous versus composite grains



Krügel&Siebenmorgen (1994)

3D Monte Carlo Radiative Transfer

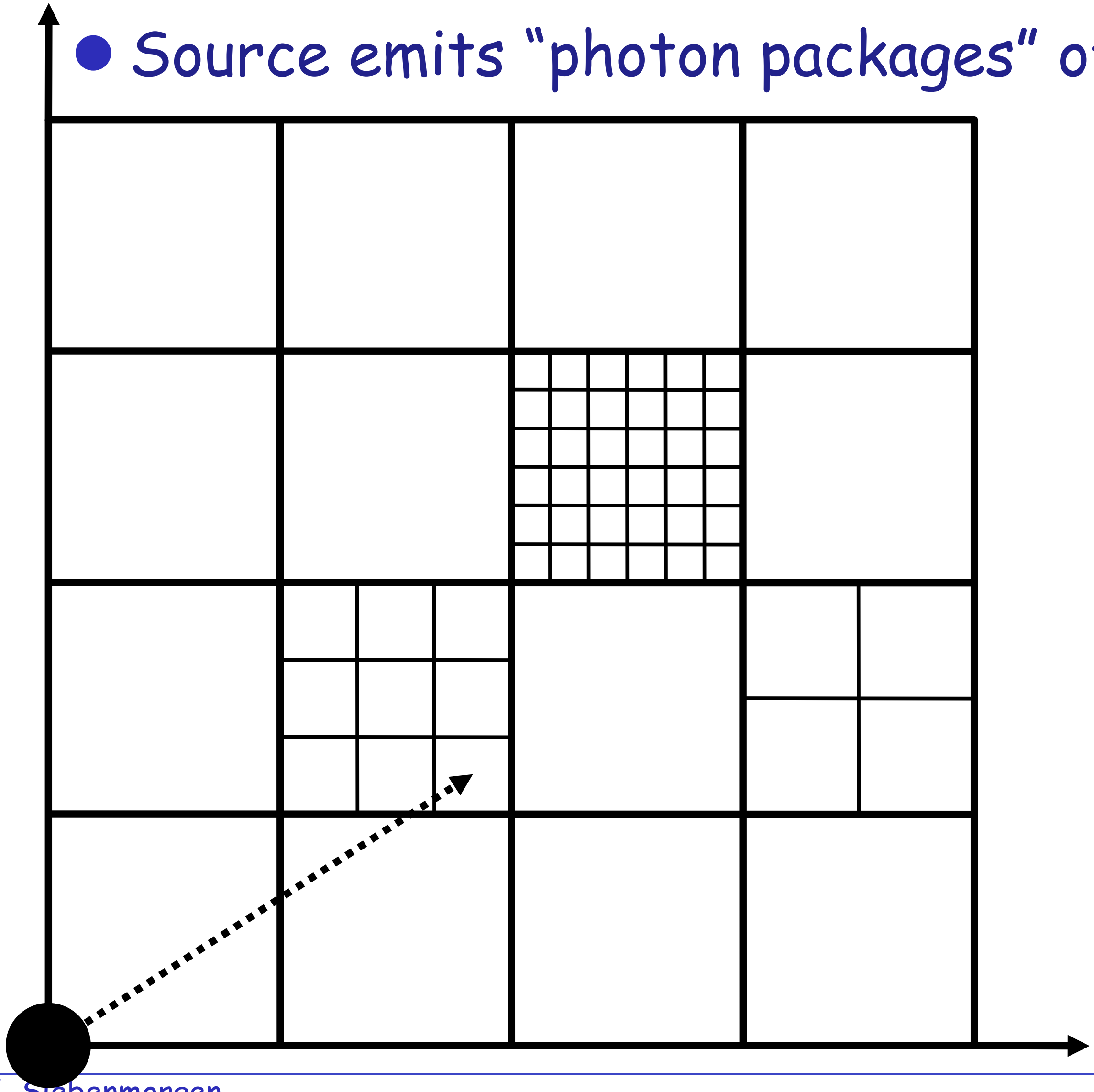
- Arbitrary dust distribution
- Pseudo adaptive mesh



1. geometry

Monte Carlo

- Source emits "photon packages" of equal energy

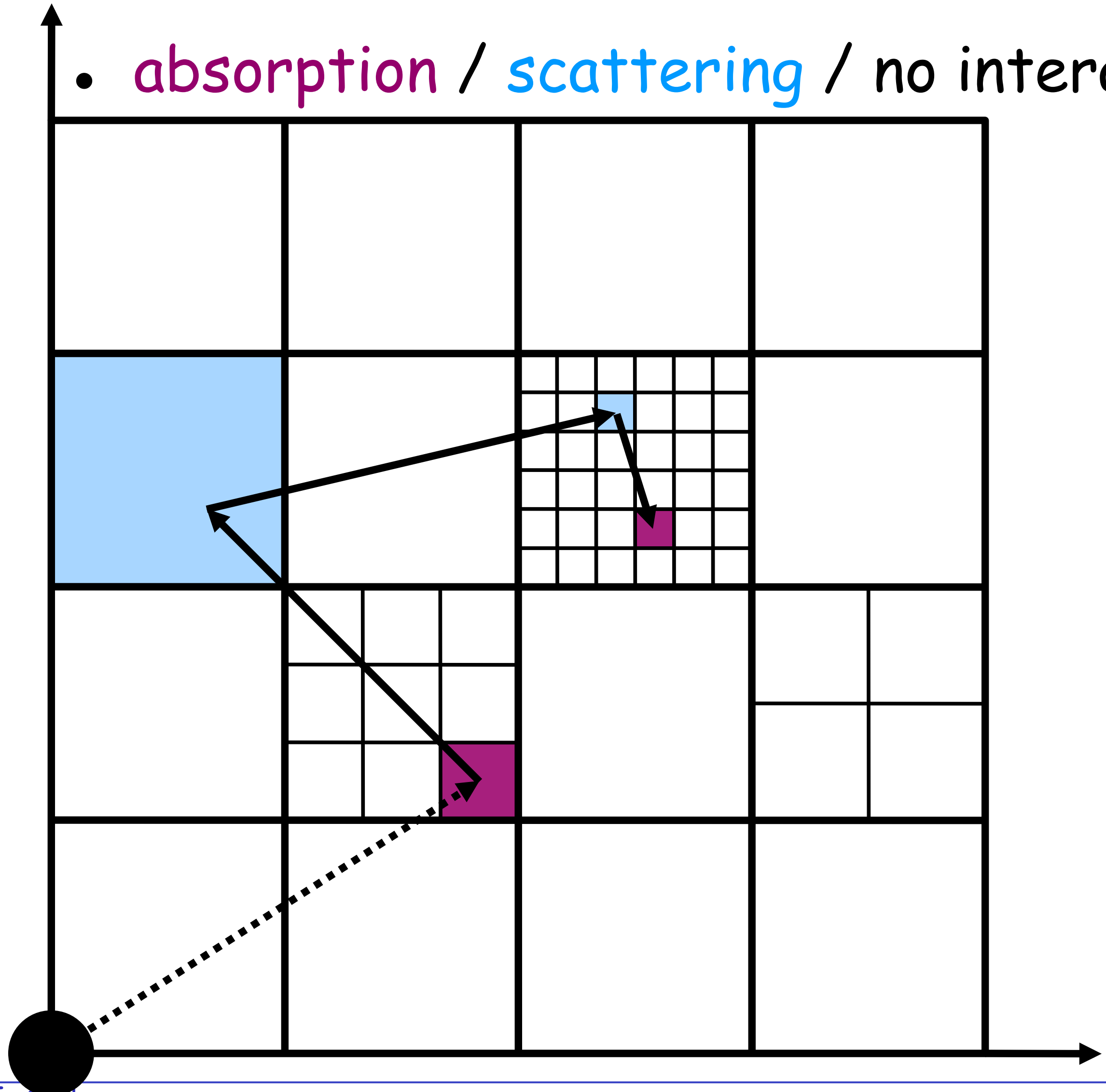


1. geometry
2. source

Monte Carlo

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

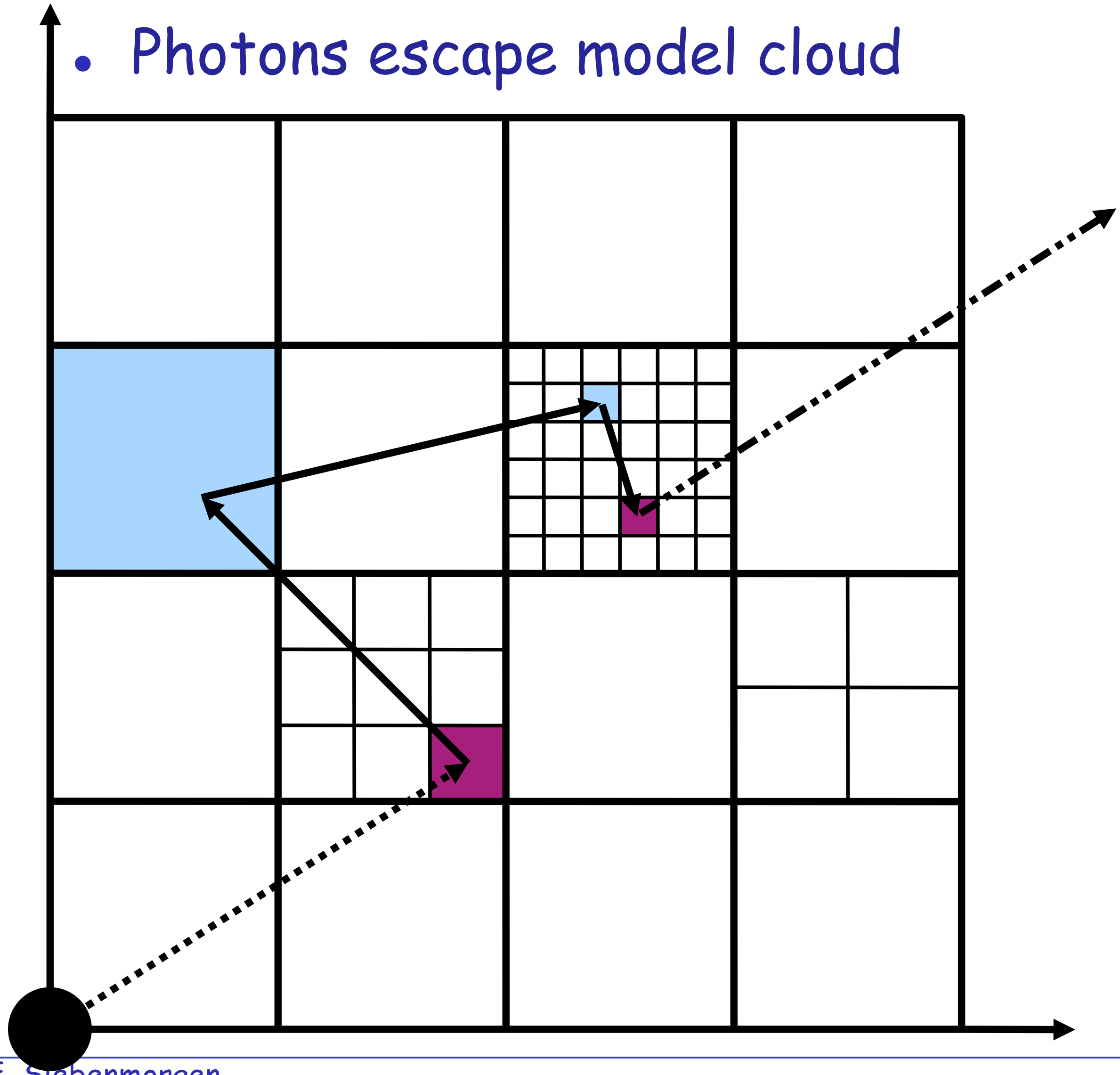
- absorption / scattering / no interaction



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

Monte Carlo

- Photons escape model cloud



1. geometry
2. source
3. inter-action
4. temperature
5. detection
6. <u>Lightechos:</u>

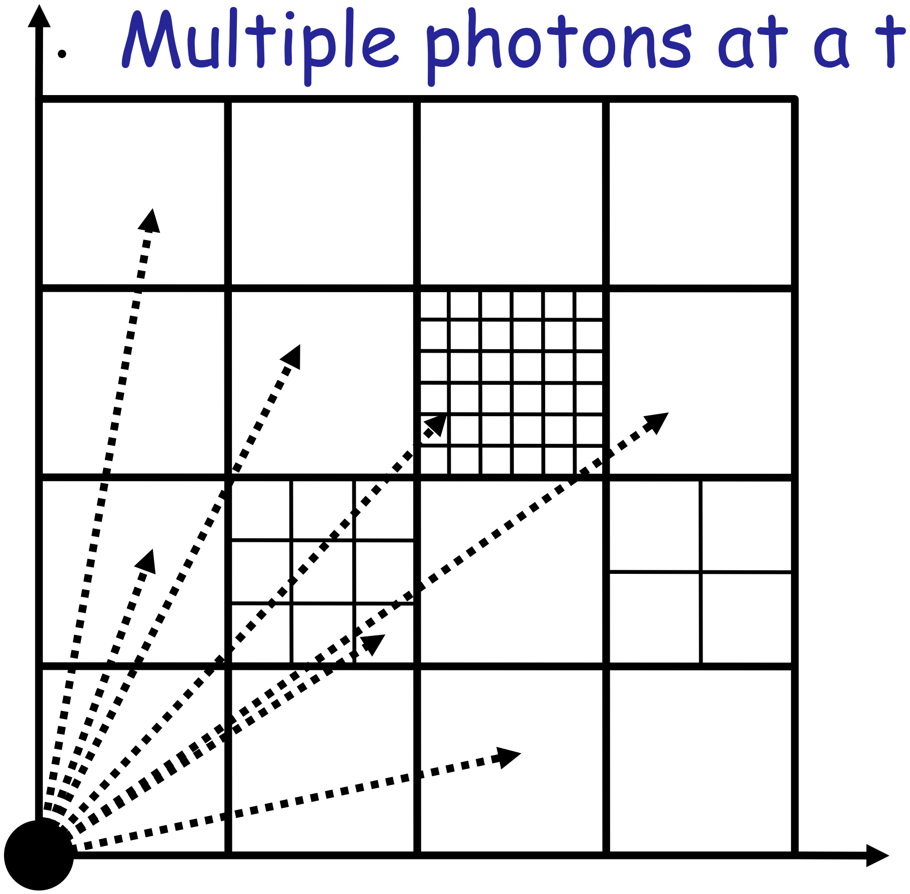
   time as 4th

   dimension?

vectorized MC

100 x faster

- Multiple photons at a time:

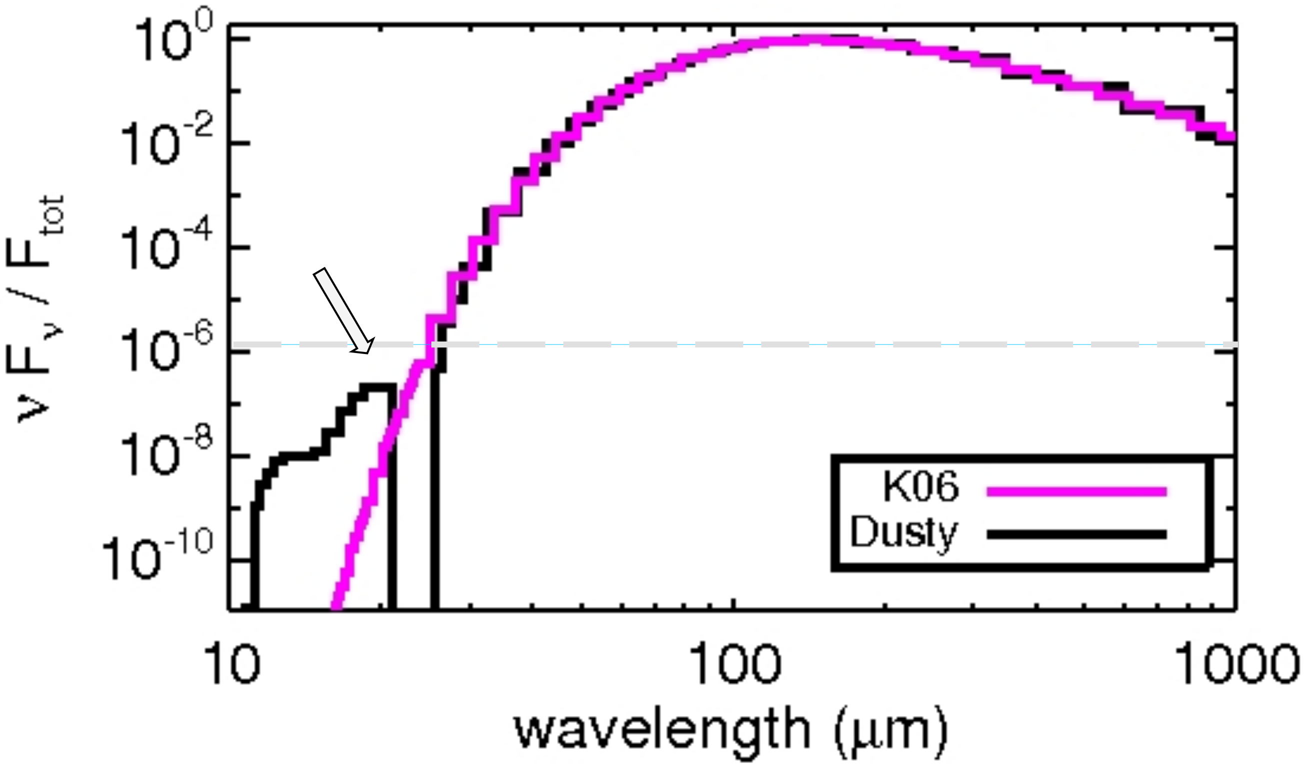


Challenges:

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

Comparison of 2 ray tracing codes

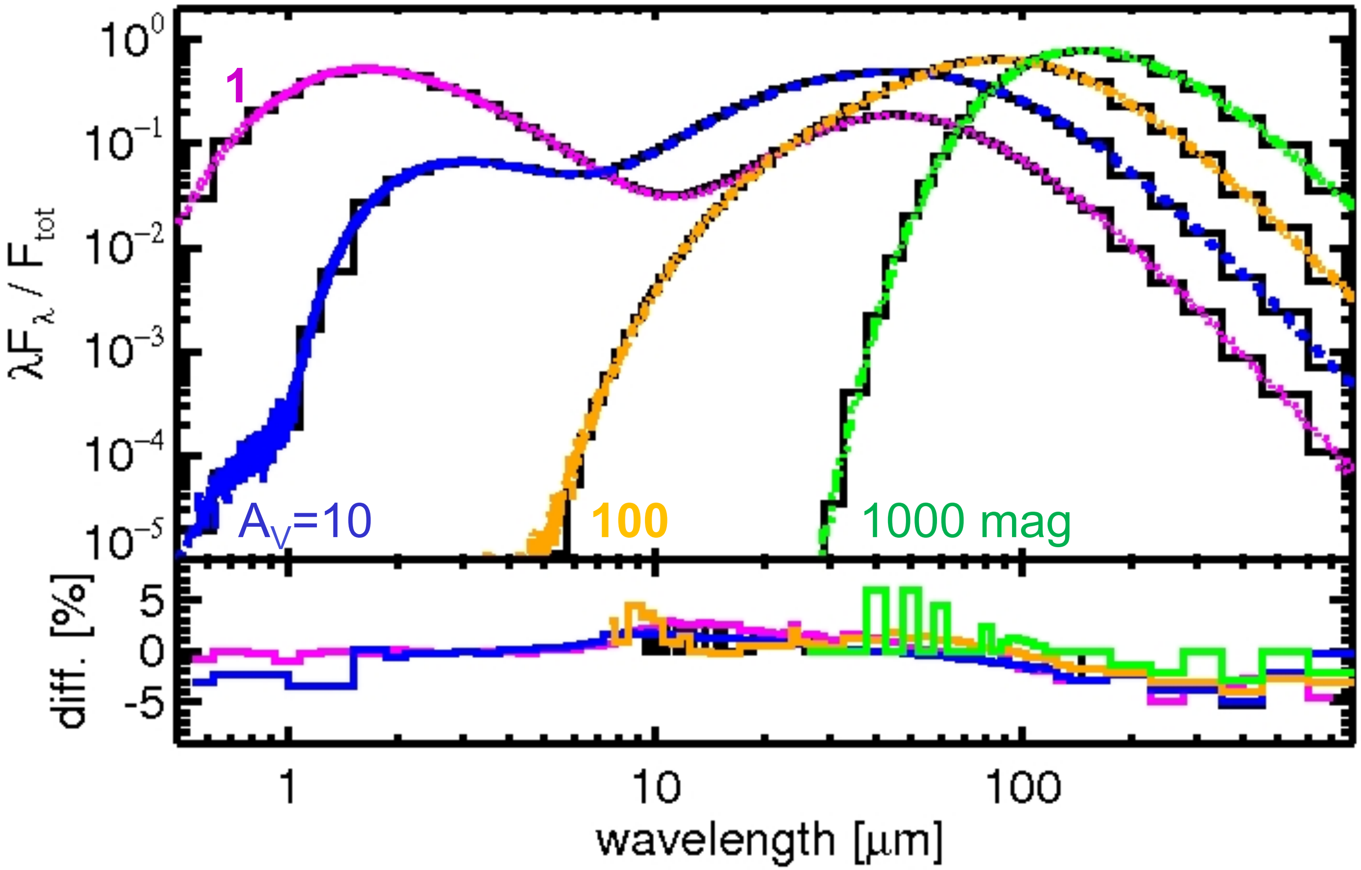
Dust sphere: A_V = **1000mag**, heated by star



K06 : Krügel (2006)

Dusty : Iveciz et al. (1999)

MC versus benchmark



Sphere

$T_* = 2500K$

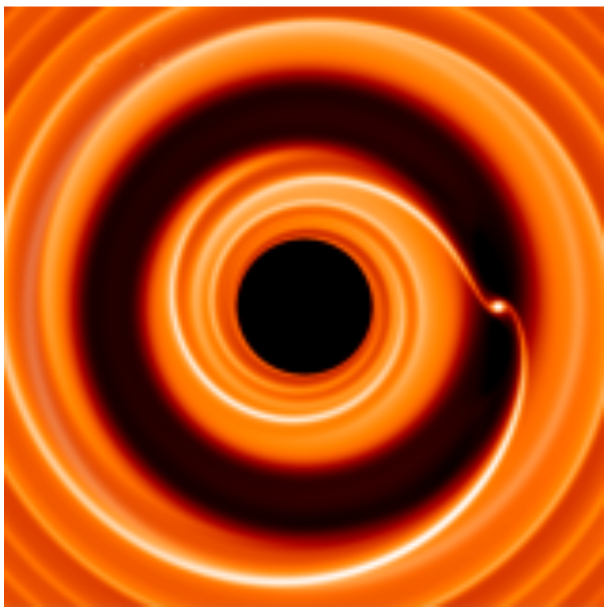
$\rho(r)$ = const.

~5% for $\tau \rightarrow 0$

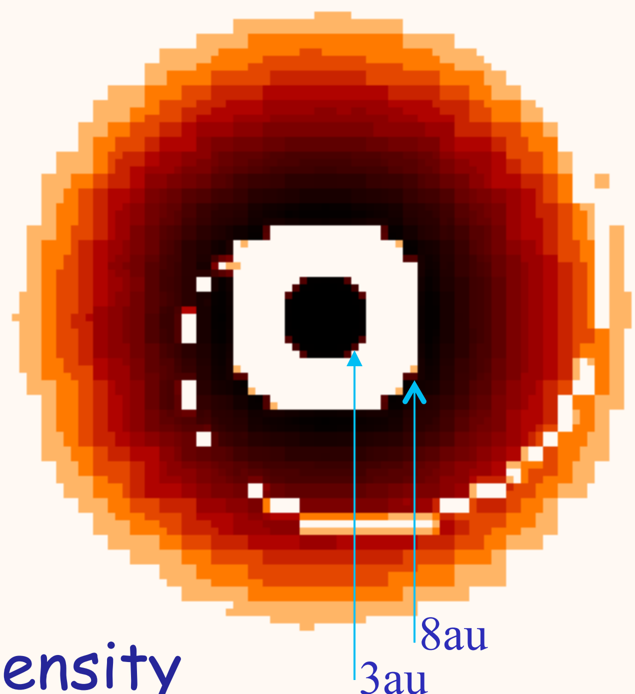
MC methods

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

3D
proto-planetary disk
+ spiral

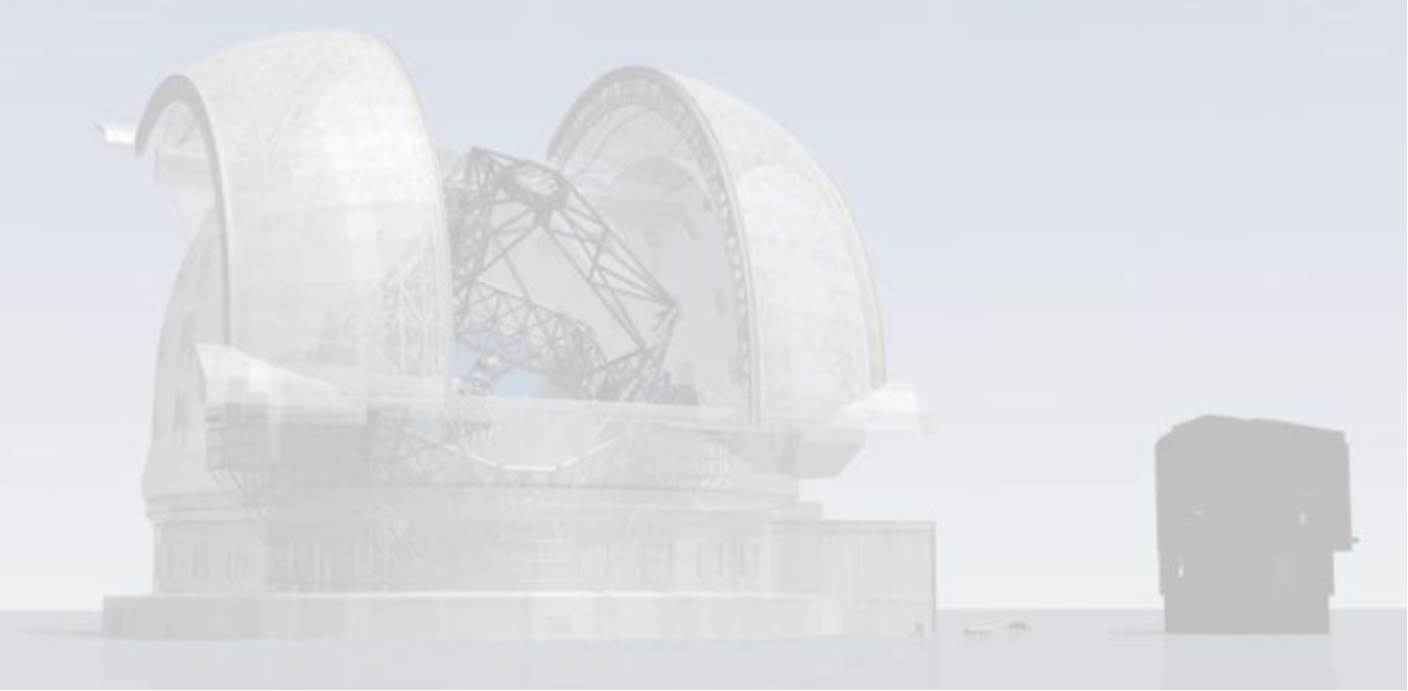


MHD (Fargo)



density

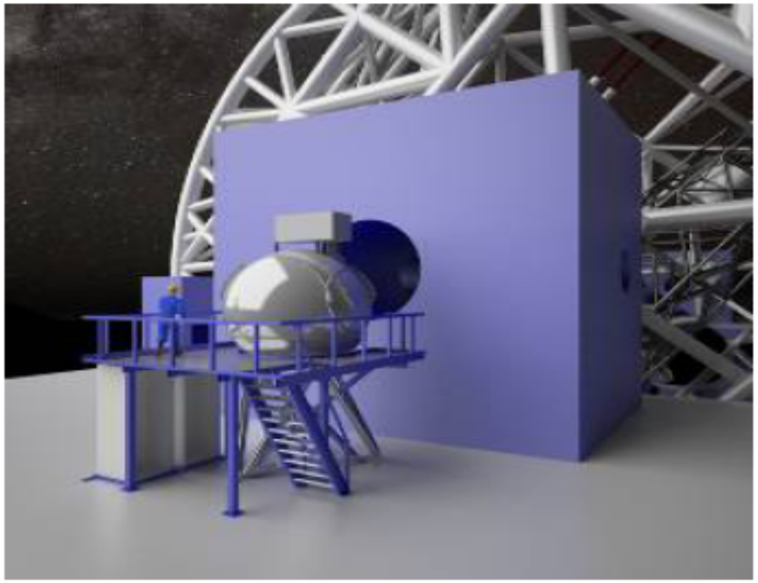
$T_* = 5800K$
$L_* = L_{sun}$
$A_v = 10mag$

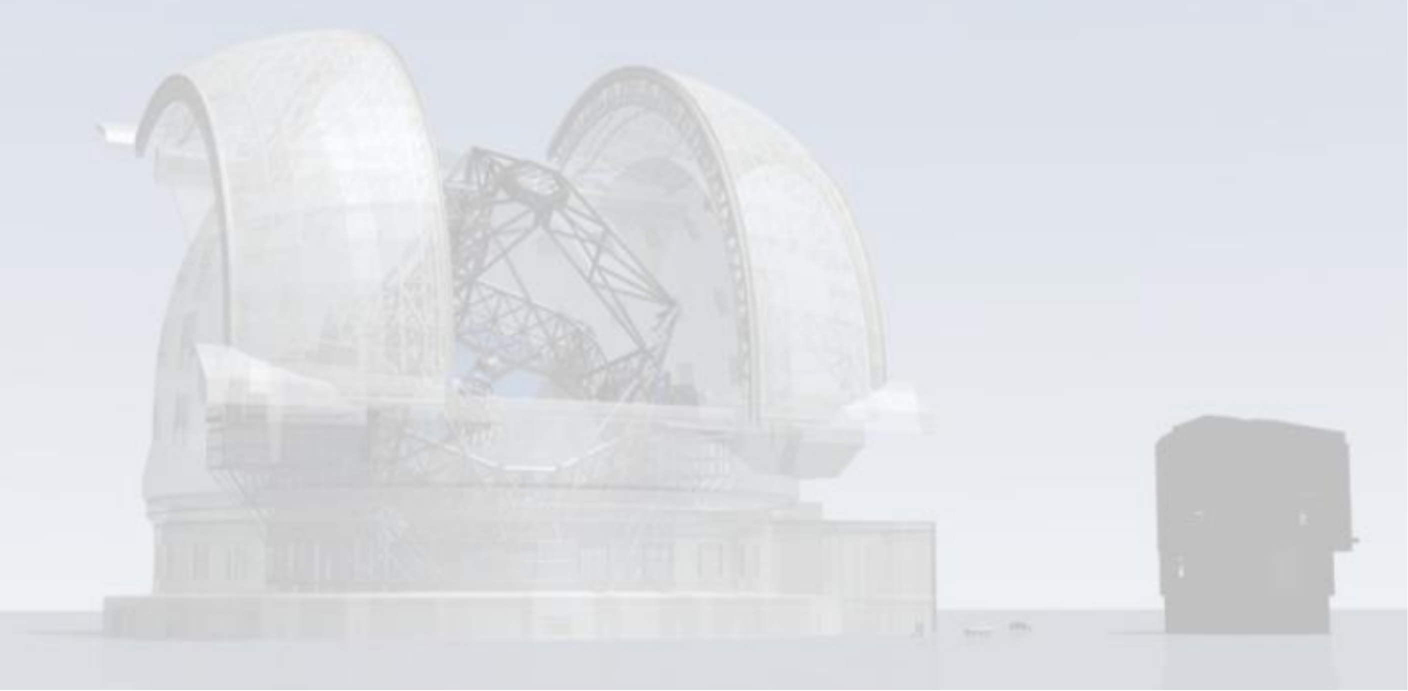


ELT 42m
PAH imaging

METIS

Mid-infrared
E-ELT Imager and
Spectrograph



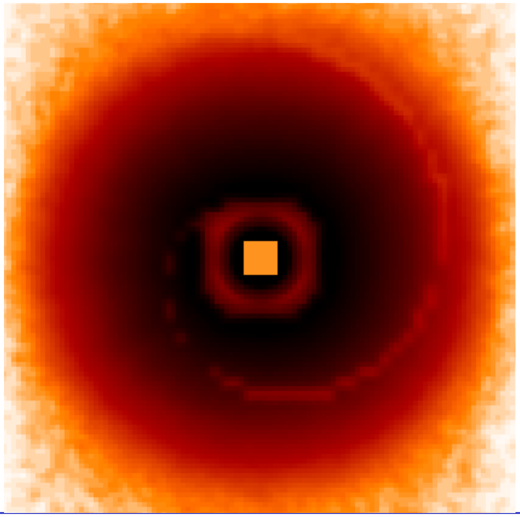


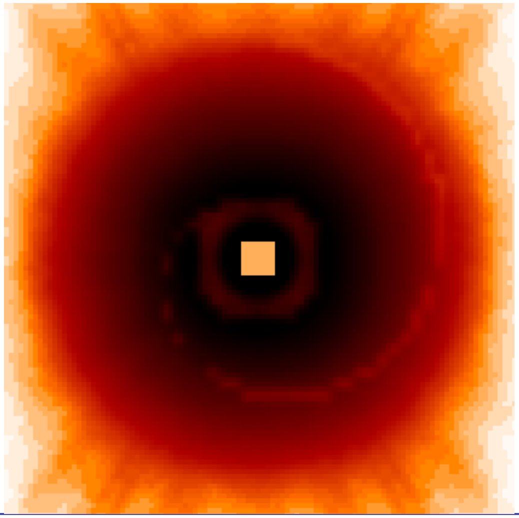
ELT 42m

PAH imaging

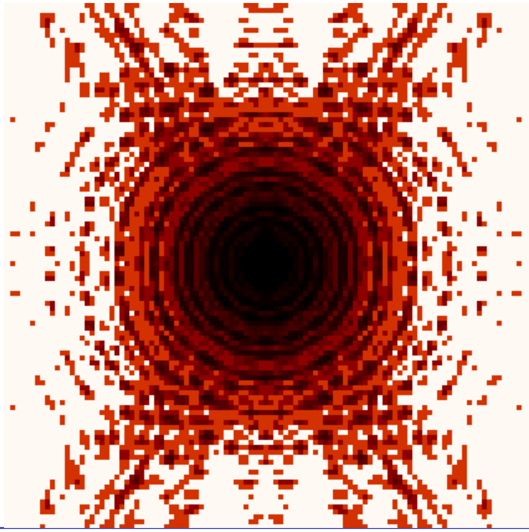
D = 50pc
50mas
at 11.3µm

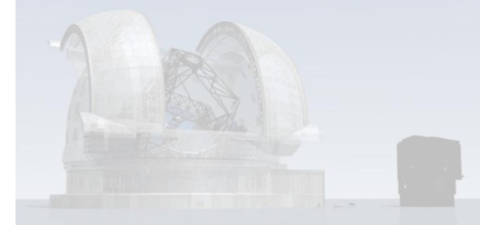
dual band + coronograph



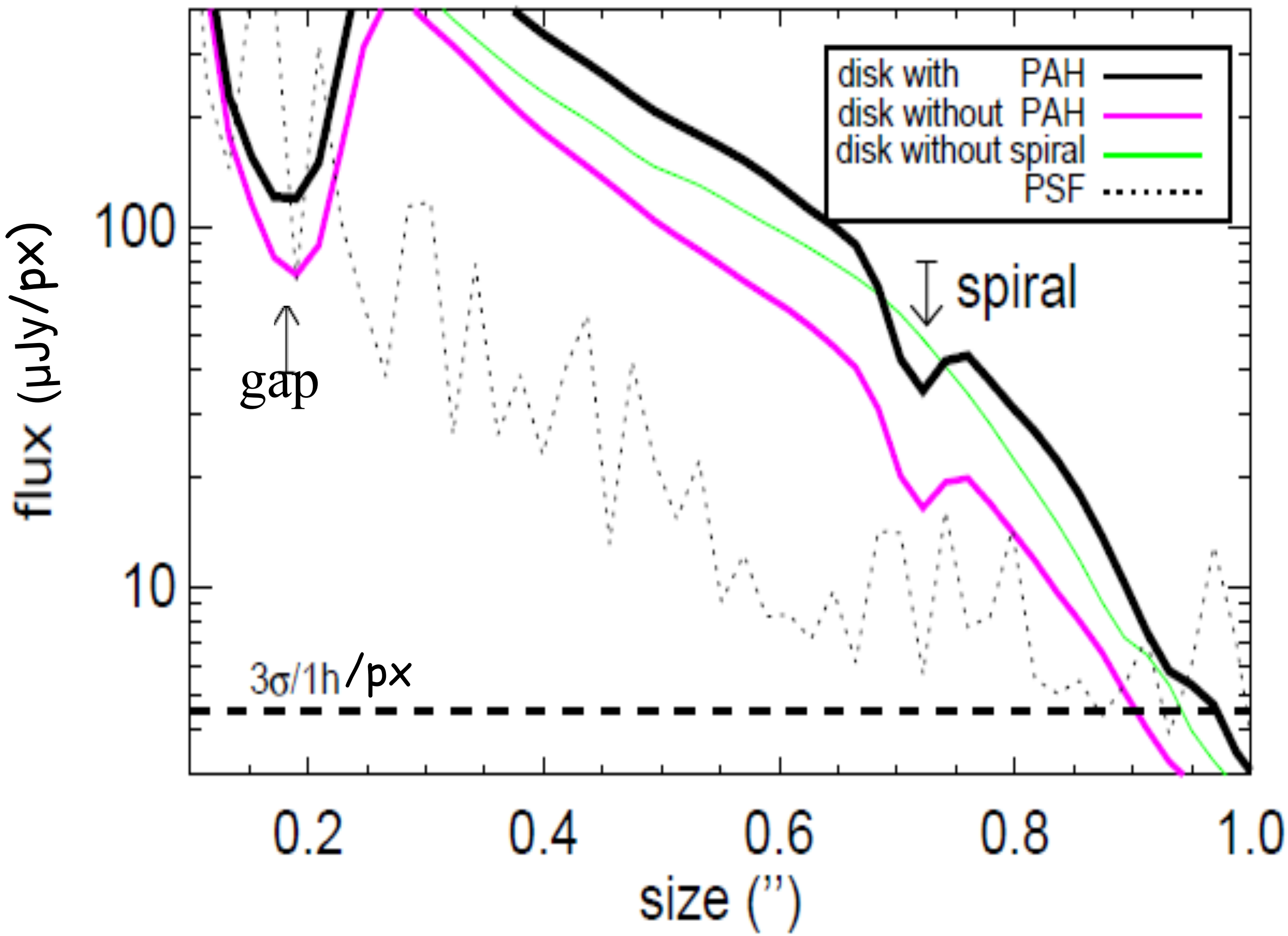


PSF





MIR imaging



D = 50pc
50mas
at 11.3µm

Shadows in planet forming disks

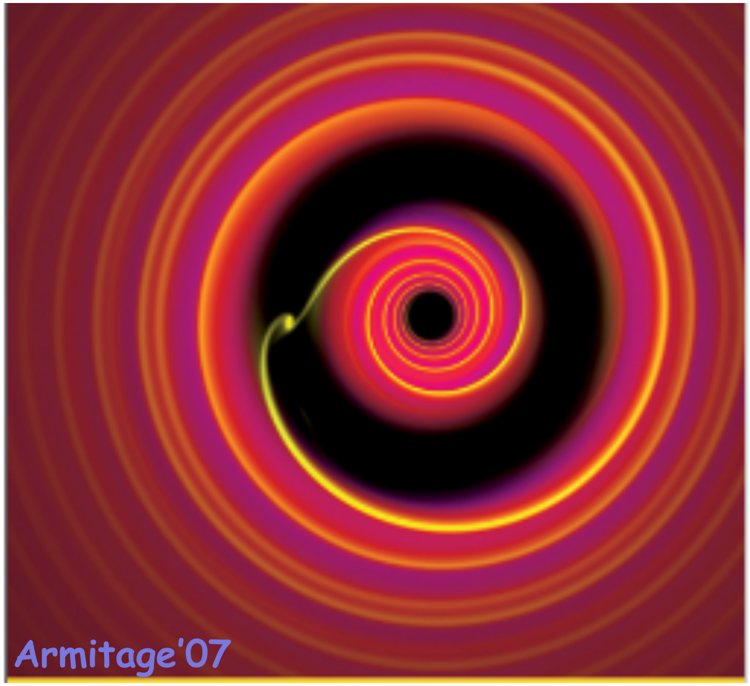
- Gaps and ring-like structures:

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

Gaps and ring-like structures in hydro-dynamical simulations

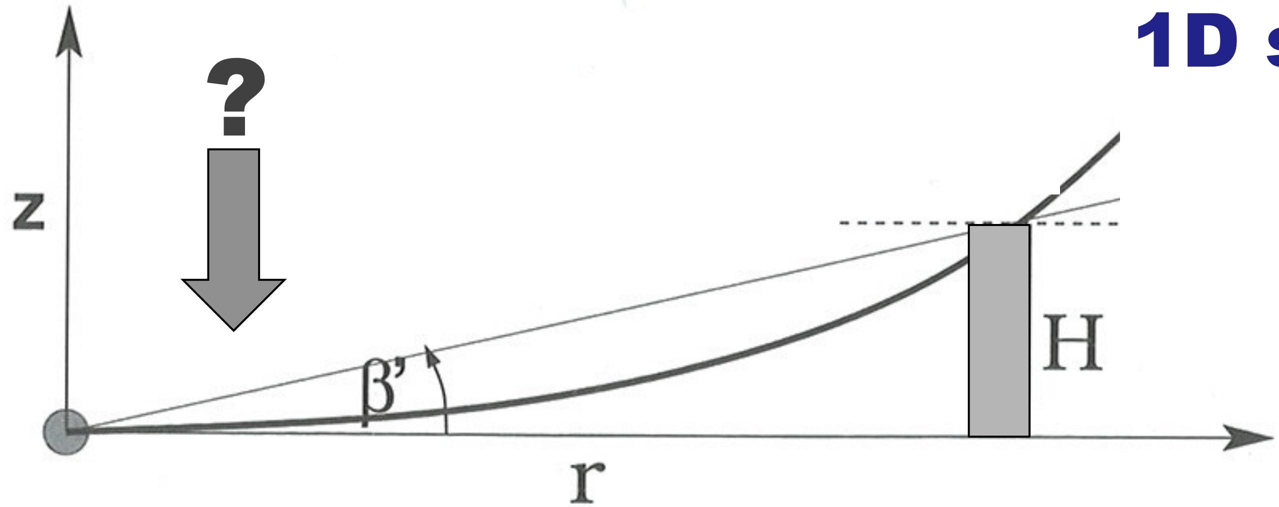


Lagrange et al, β Pic planet detection, Science'10:

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

Radiative transfer

1D slab geometry



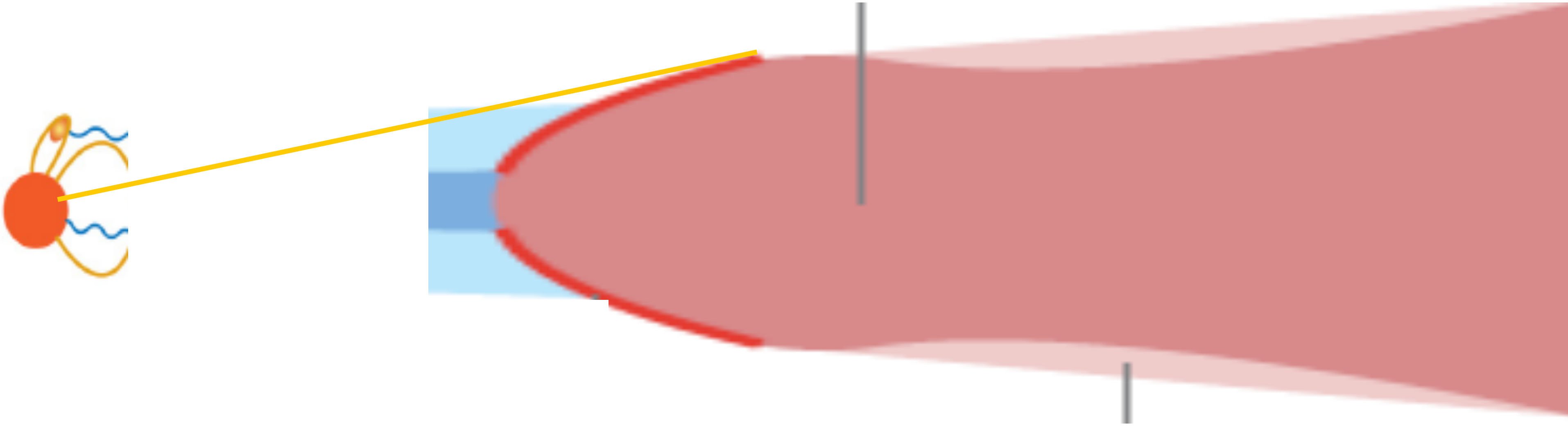
Initially we assume that the disk is isothermal in z, and the density is given by

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

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

Dullemond et al.2001
Kama et al. 2010

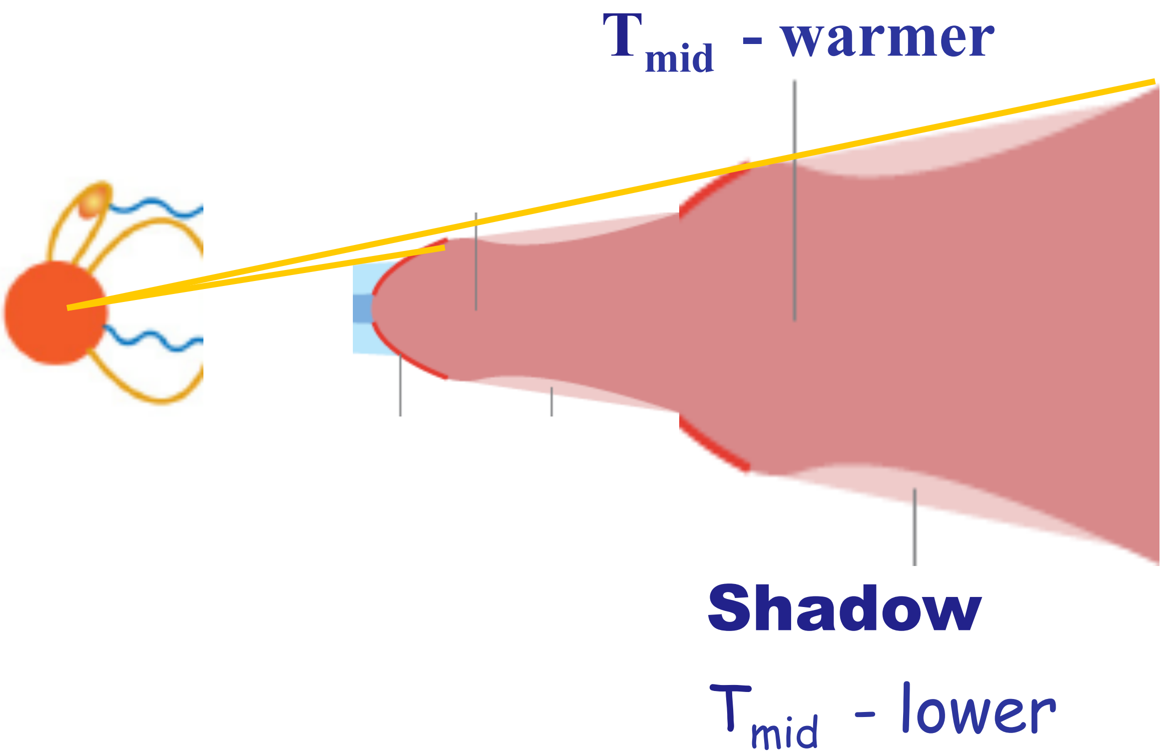
Puffed up inner rim



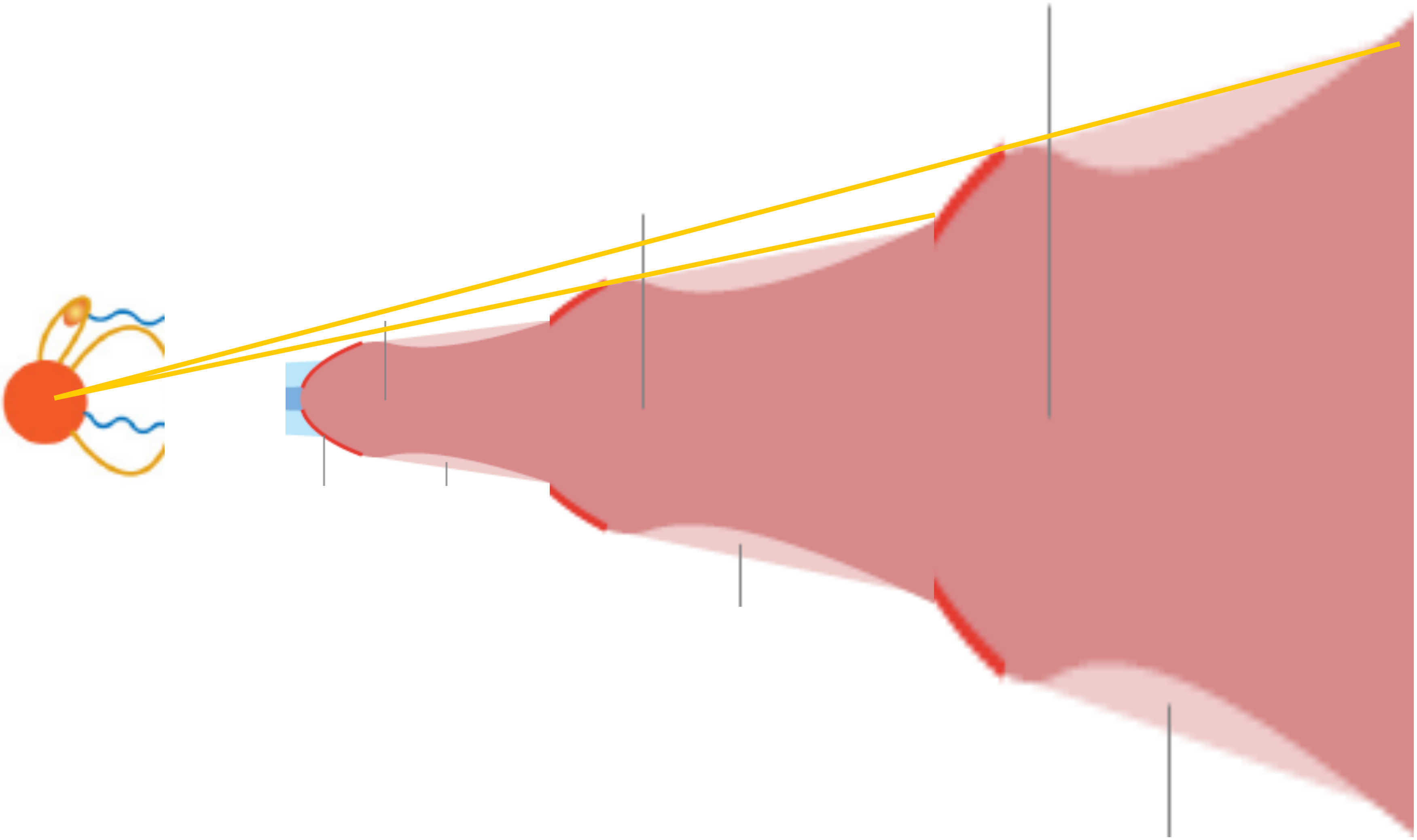
Shadow

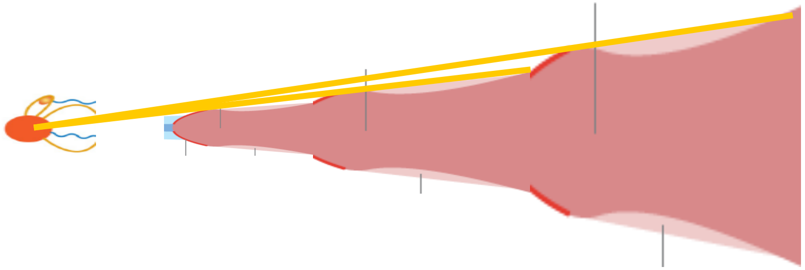
T_{mid} - lower

Puffed up second rim



Puffed up **third** rim





Hydrostatic and radiation balance

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

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

II) $$-\frac{z}{r}\frac{\mathrm{GM}_*}{r^2} = \frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}z}$$

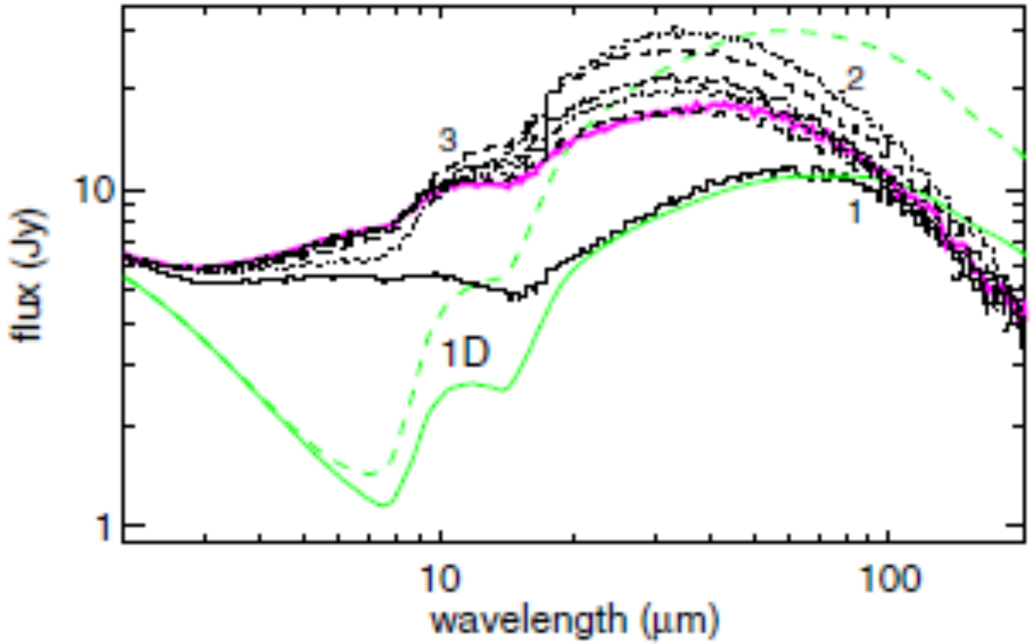
with pressure $P = \rho k T(z)/m$.

Proto-planetary disk models

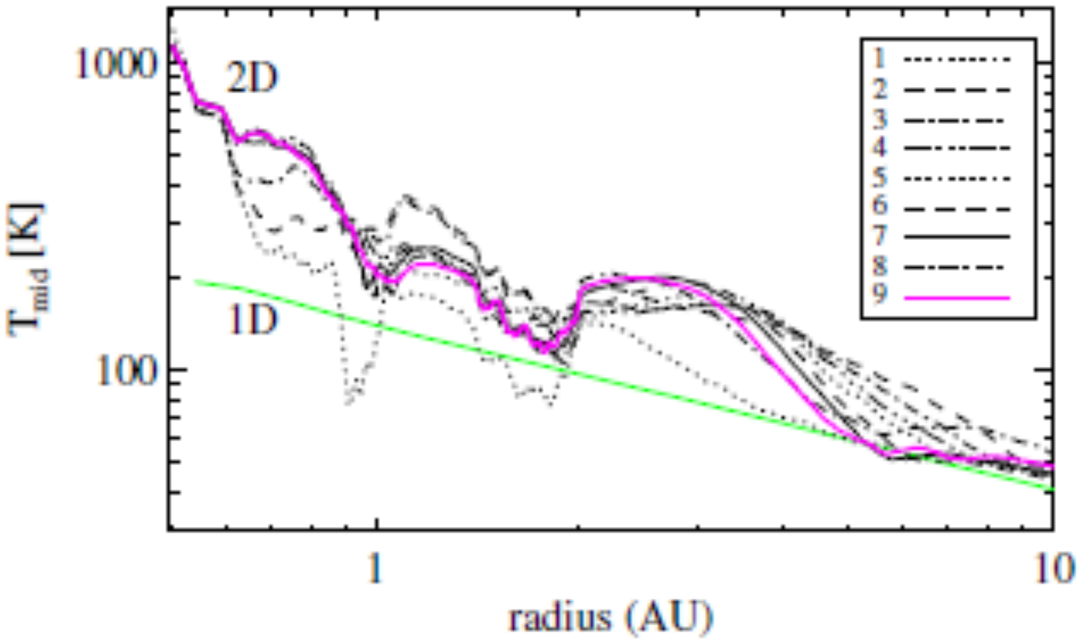
$\Sigma(1\text{ AU}) = 5\text{ g-dust/cm}^2$

Parameter		T Tauri	Herbig Ae
Stellar luminosity	$L_* [L_\odot]$	2	50
Stellar mass	$M_* [M_\odot]$	1	2.5
Photospheric temperature	T_* [K]	4000	10 000
Column density	$\Sigma(r) = \frac{\tau_\perp(1\text{AU})}{K_V}\left(\frac{r}{\text{AU}}\right)^\gamma$ [g-dust/cm^2]	$r < 1$ AU:	$\gamma = 0.5$
		$r \geq 1$ AU:	$\gamma = -1$
Vertical optical depth	$\tau_\perp(1\text{ AU})$	10 000	
Dust density in halo	ρ_{halo} [g-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

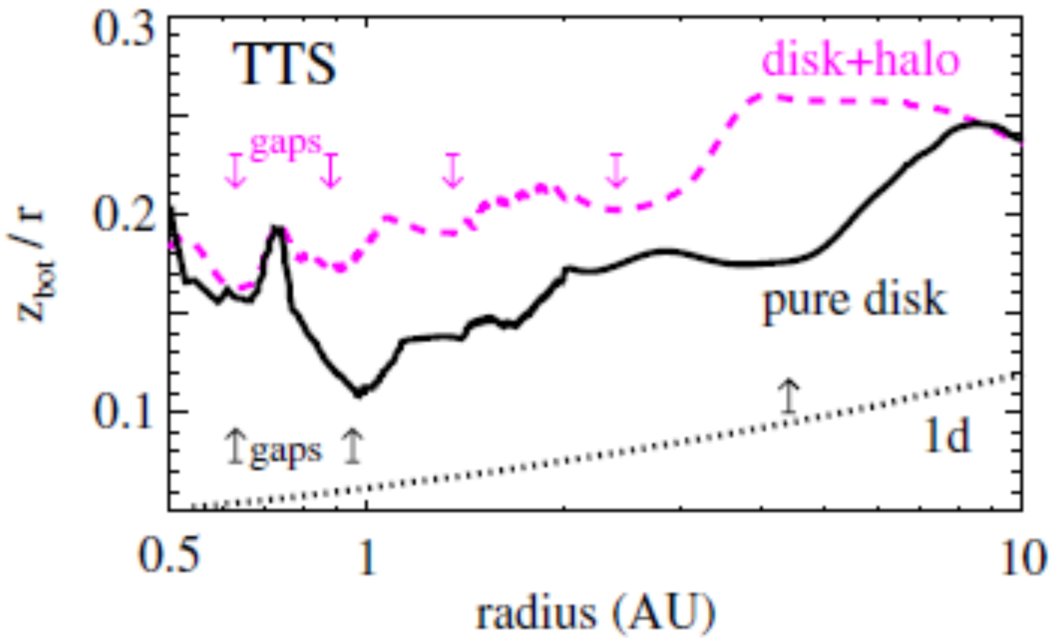


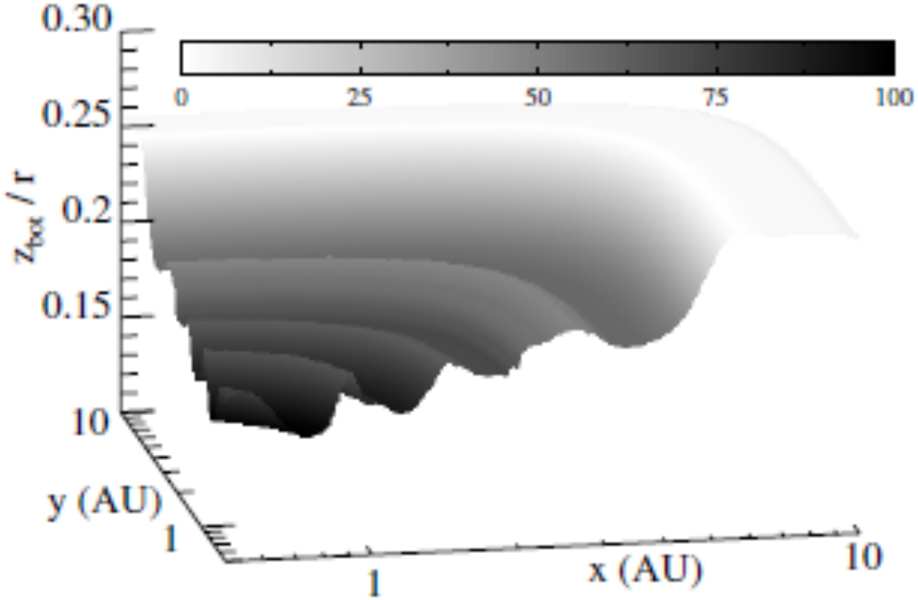
flux (Jy)
wavelength (µm)
10
1
10
100
3
2
1
1D



T_mid [K]
radius (AU)
1000
100
1
10
2D
1D
1
2
3
4
5
6
7
8
9

Gaps and ring-like structures without planet



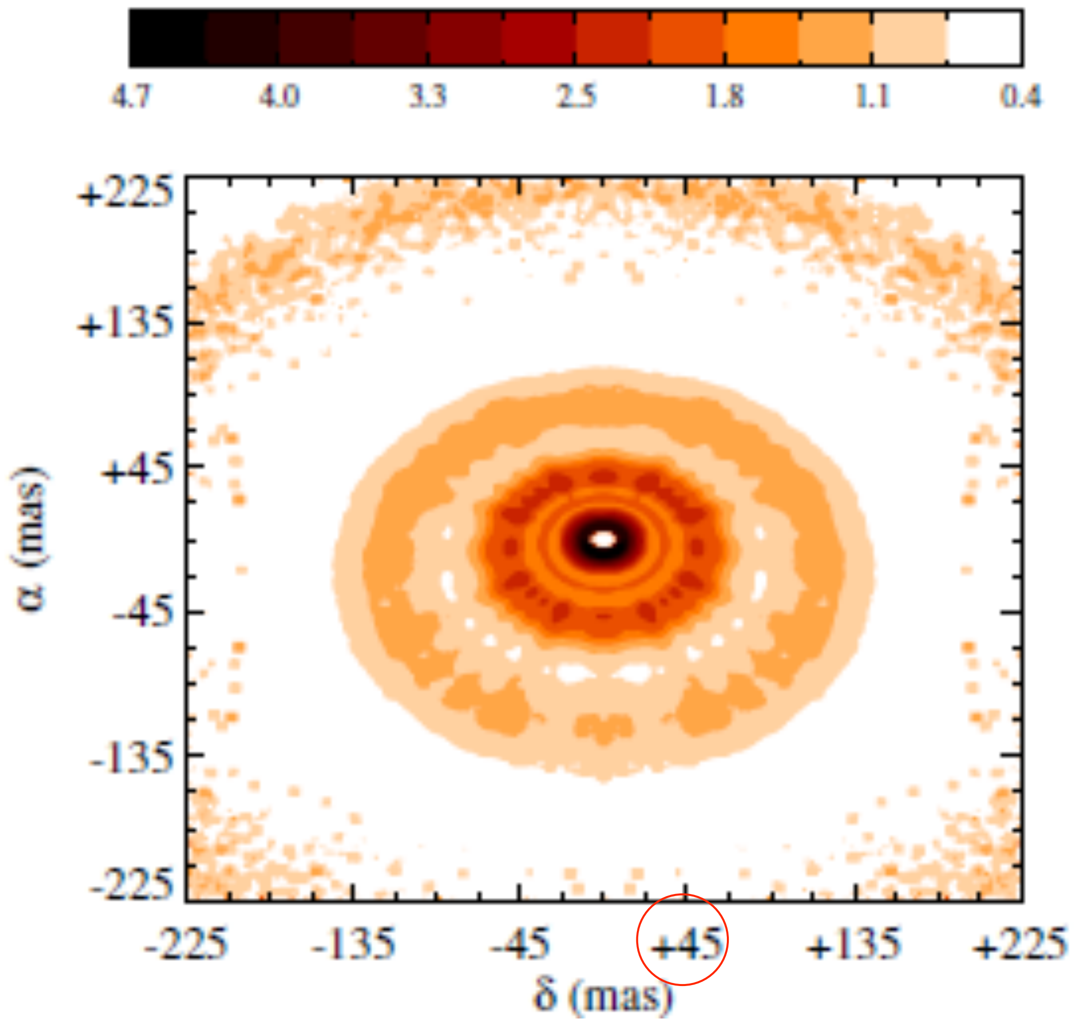


extinction layer

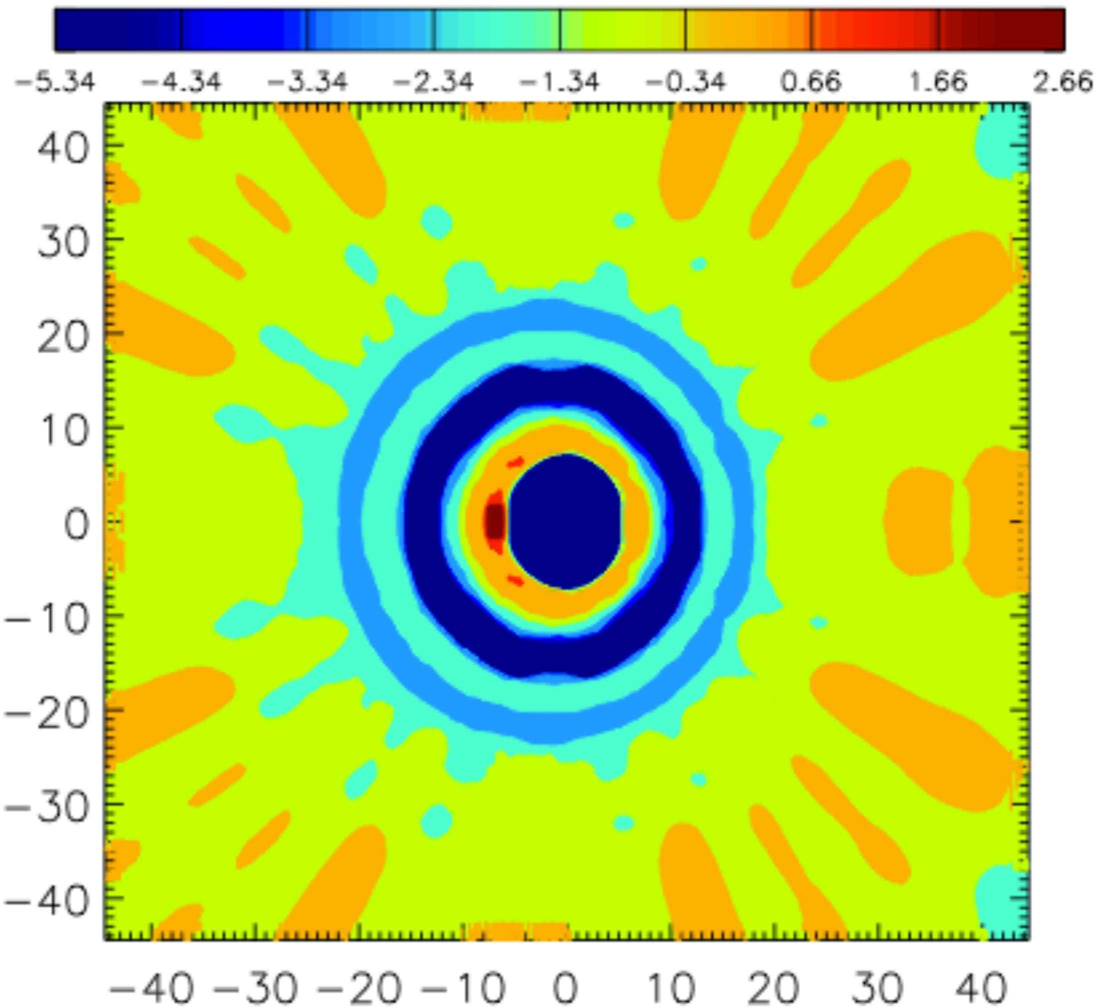
(photosphere)

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

Gaps and ring-like structures in the mid-IR emission

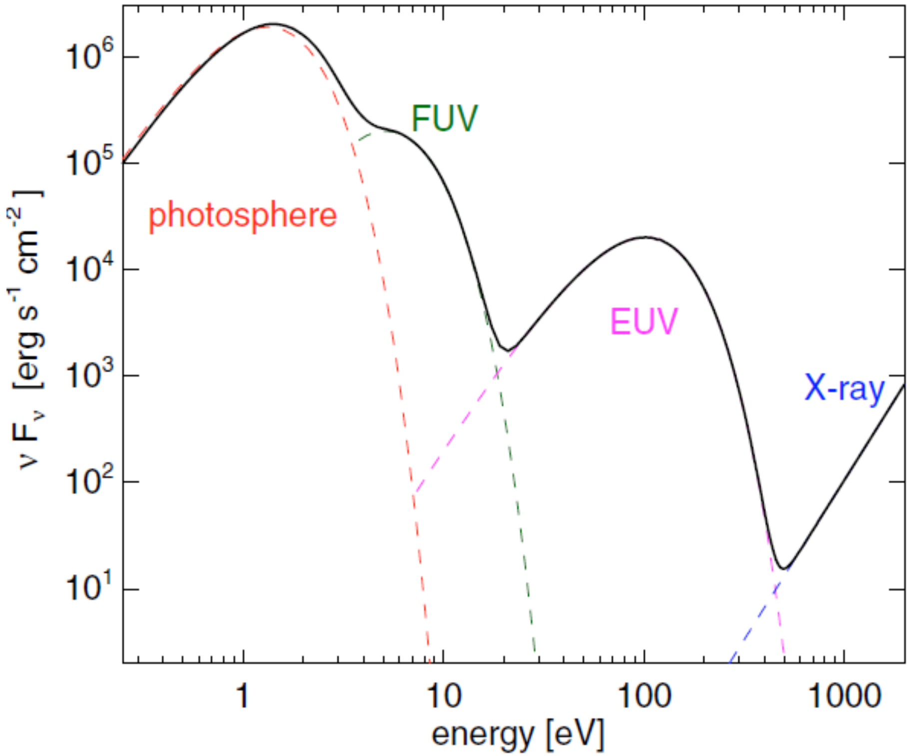


Gaps and ring-like structures in scattered light



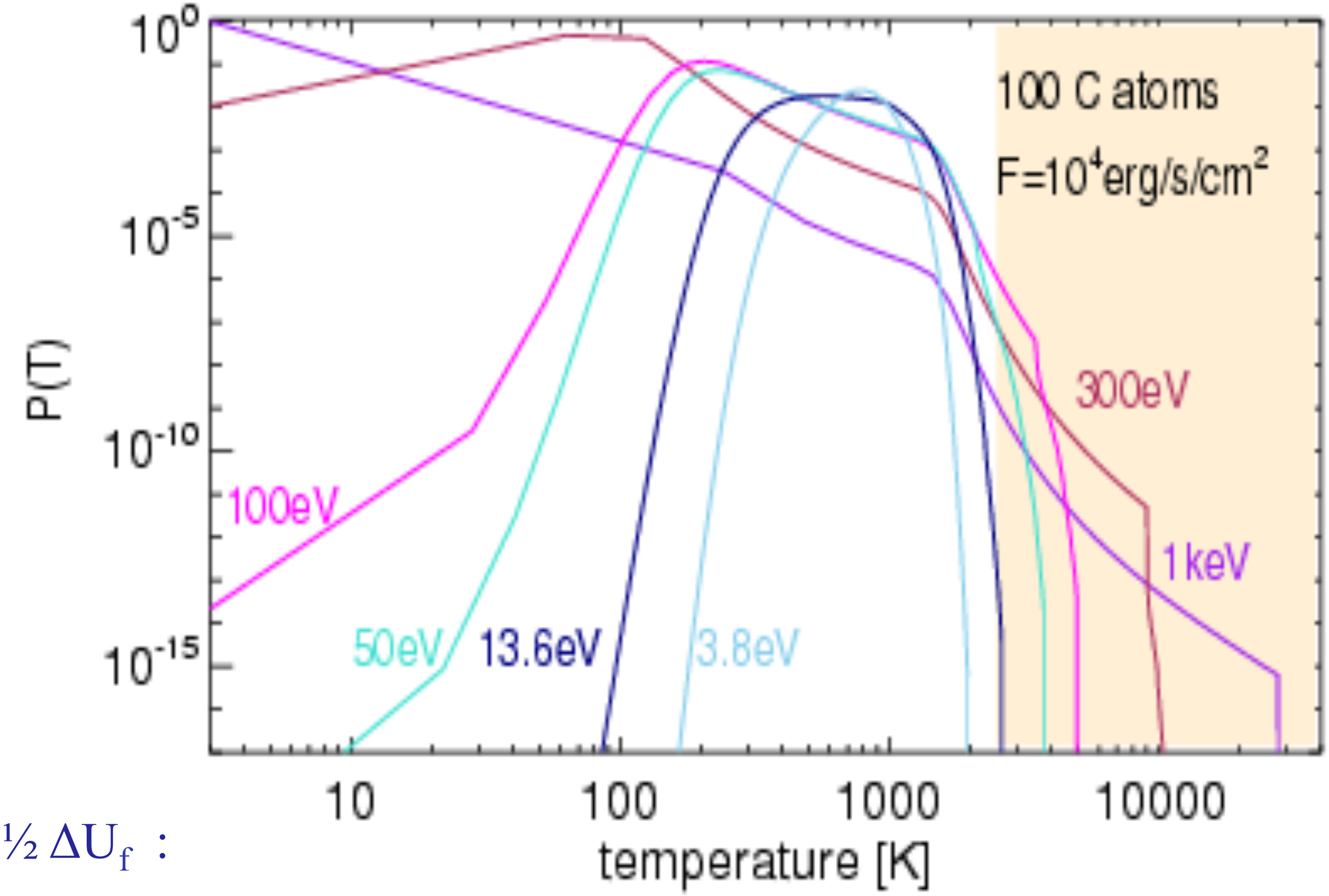
PAH emission from disks

- PAH detection statistics
- PAH excitation / destruction



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

PAH in a mono-energetic heating bath

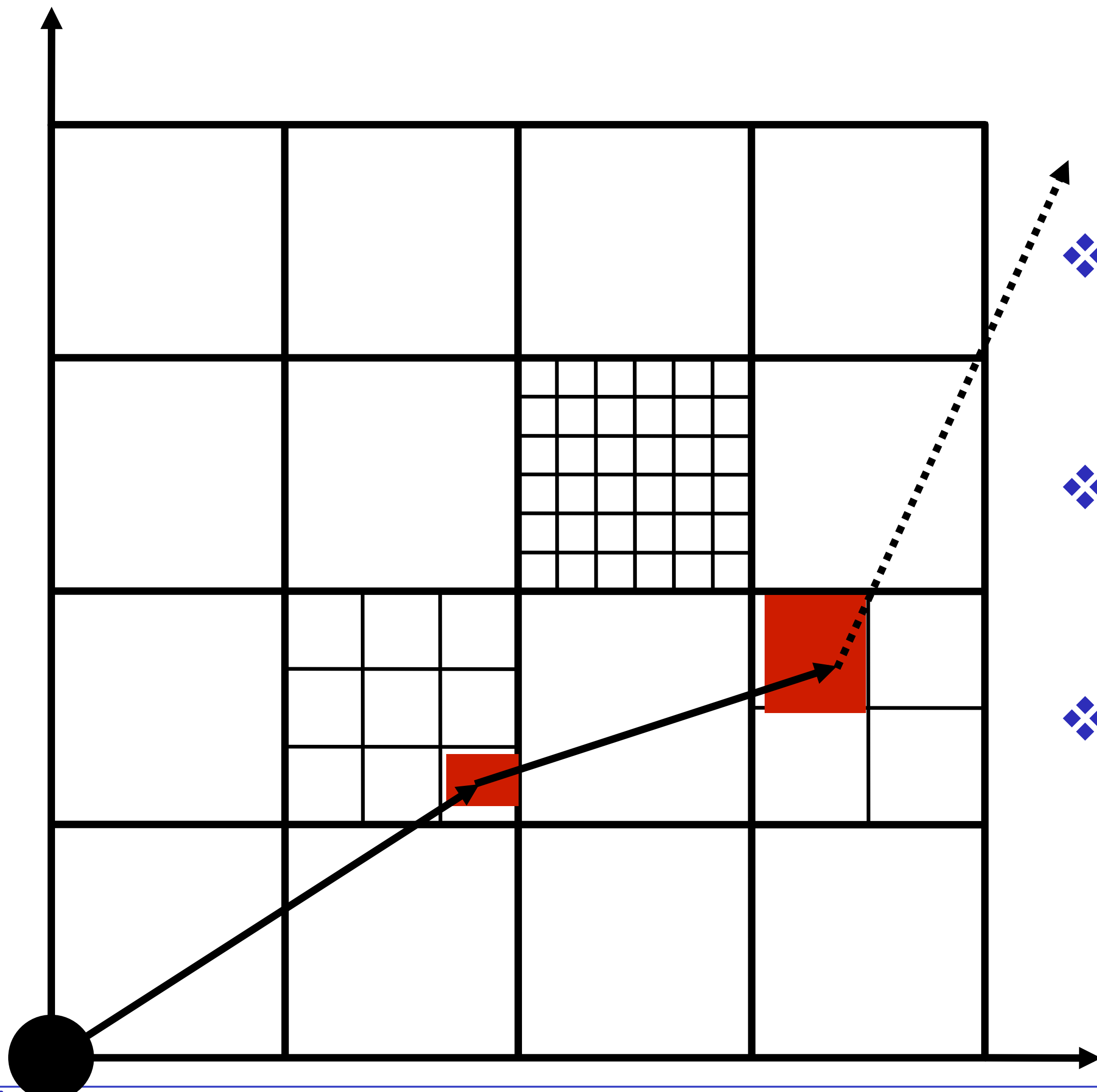


if $| U_f - U_i - h\nu | < \frac{1}{2} \Delta U_f$:

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

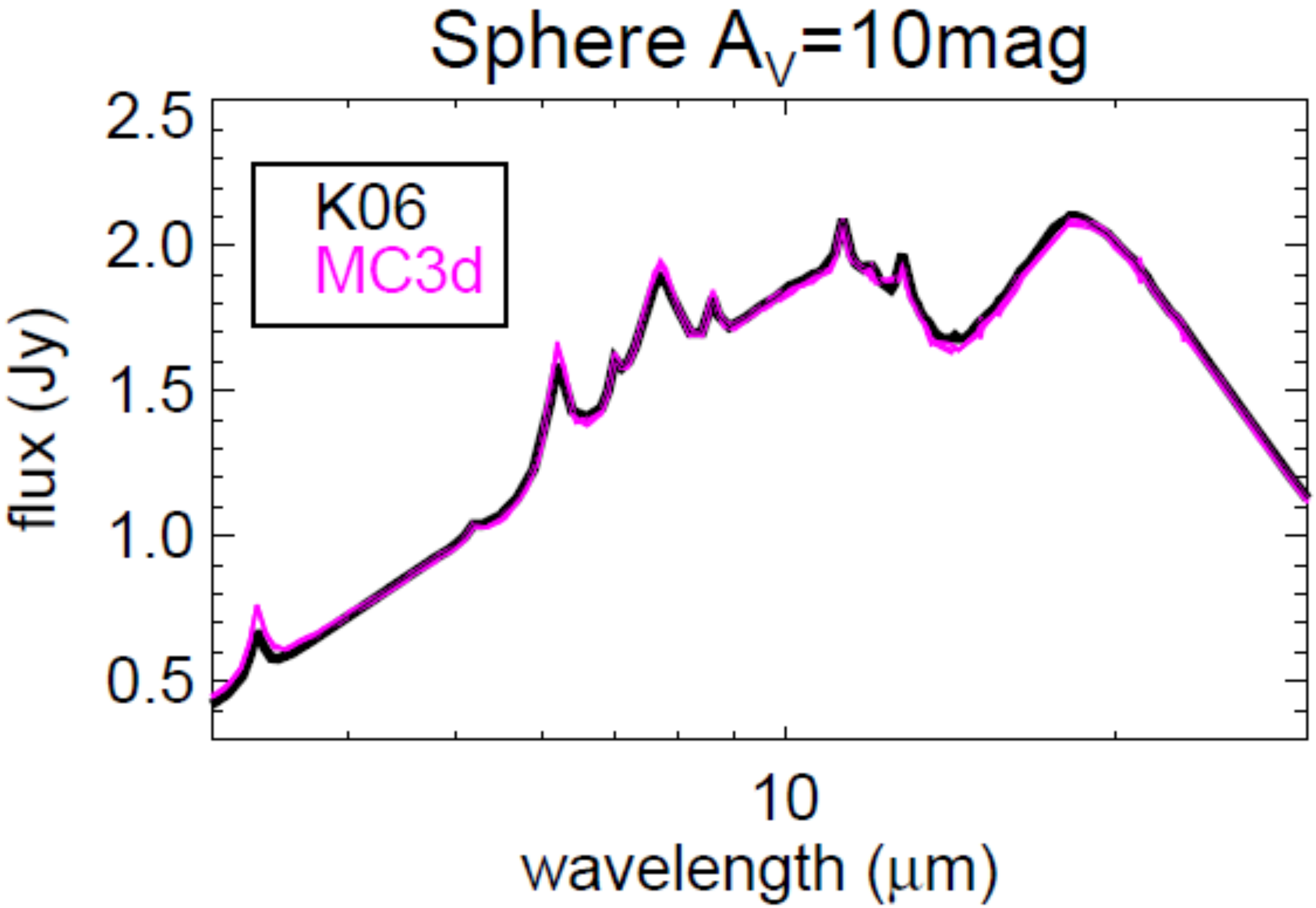
Siebenmorgen & Krűgel (2010)

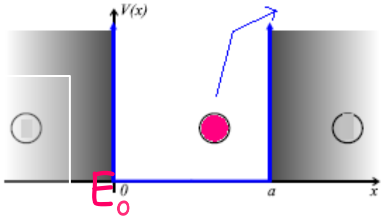
Monte Carlo + PAH

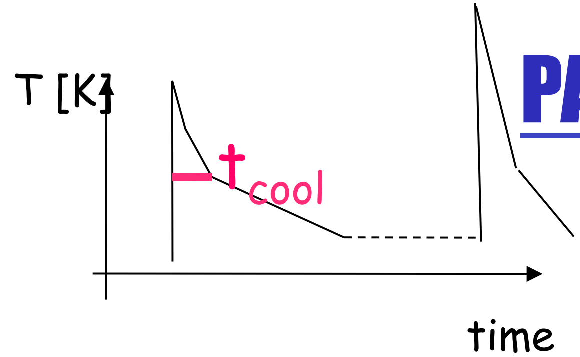


- store PAH absorption events of each cell
- compute PAH emission
- neglect PAH self absorption

MC versus benchmark







PAH destruction

Unimolecular dissociation

Arrhenius form:

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

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

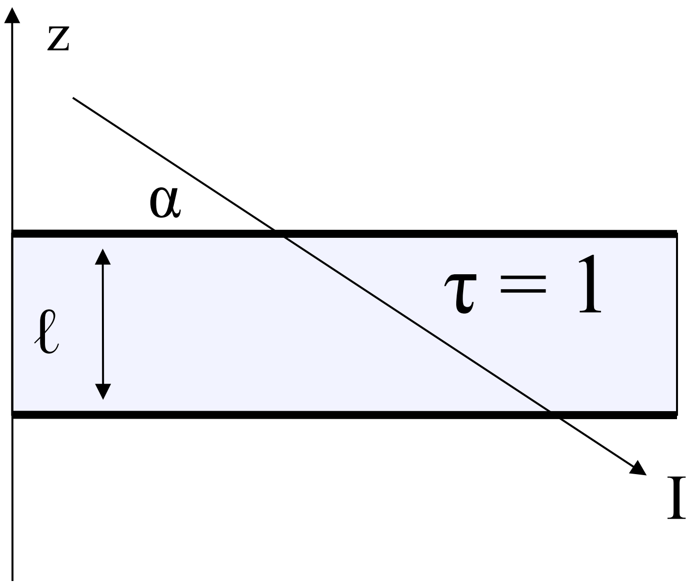
$\Delta E = 3N_c\, kT_{min} \quad \sim 0.1\, N_c \cdot E_b \quad \Rightarrow \quad$ $\mathbf{N_c < 2\, \Delta E}$ /[eV]

PAH unstable

1) single **hard** photon : independent of distance
2) many **soft** photons : ~AU

Siebenmorgen & Krűgel (2010)

Sufficient X-ray photons?



} top extinction layer $\Sigma_\ell = \alpha/\kappa$

$$\frac{\#\,\mathrm{C\ in\ PAH}}{\#\ \mathrm{hard}\ \gamma\ \mathrm{absorption/sec}} = h\nu \cdot 4\pi r^2/L\kappa$$

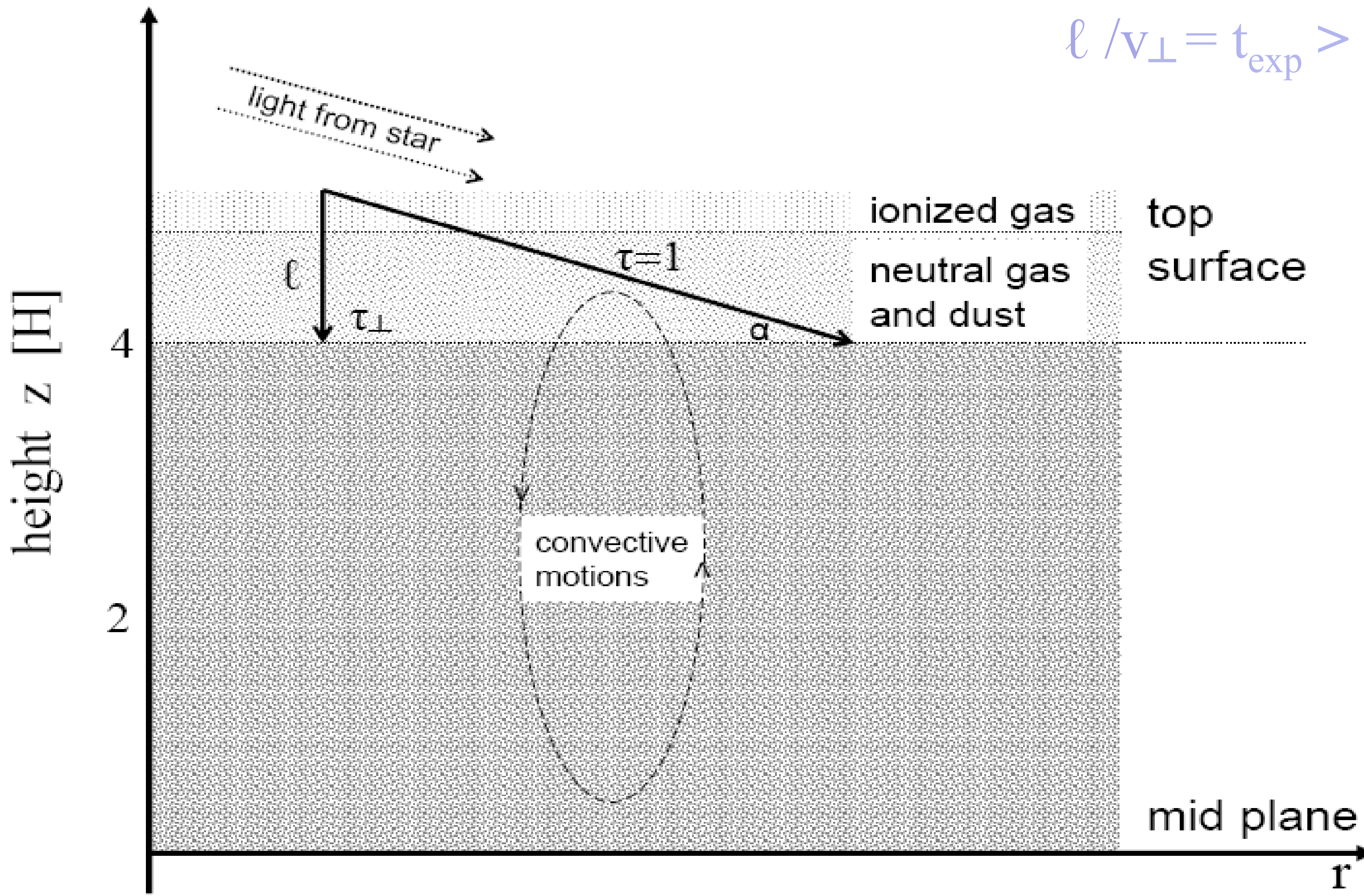
↑

'PAH removal time' << T Tauri pahse

Disk lifetime => PAH replenishment

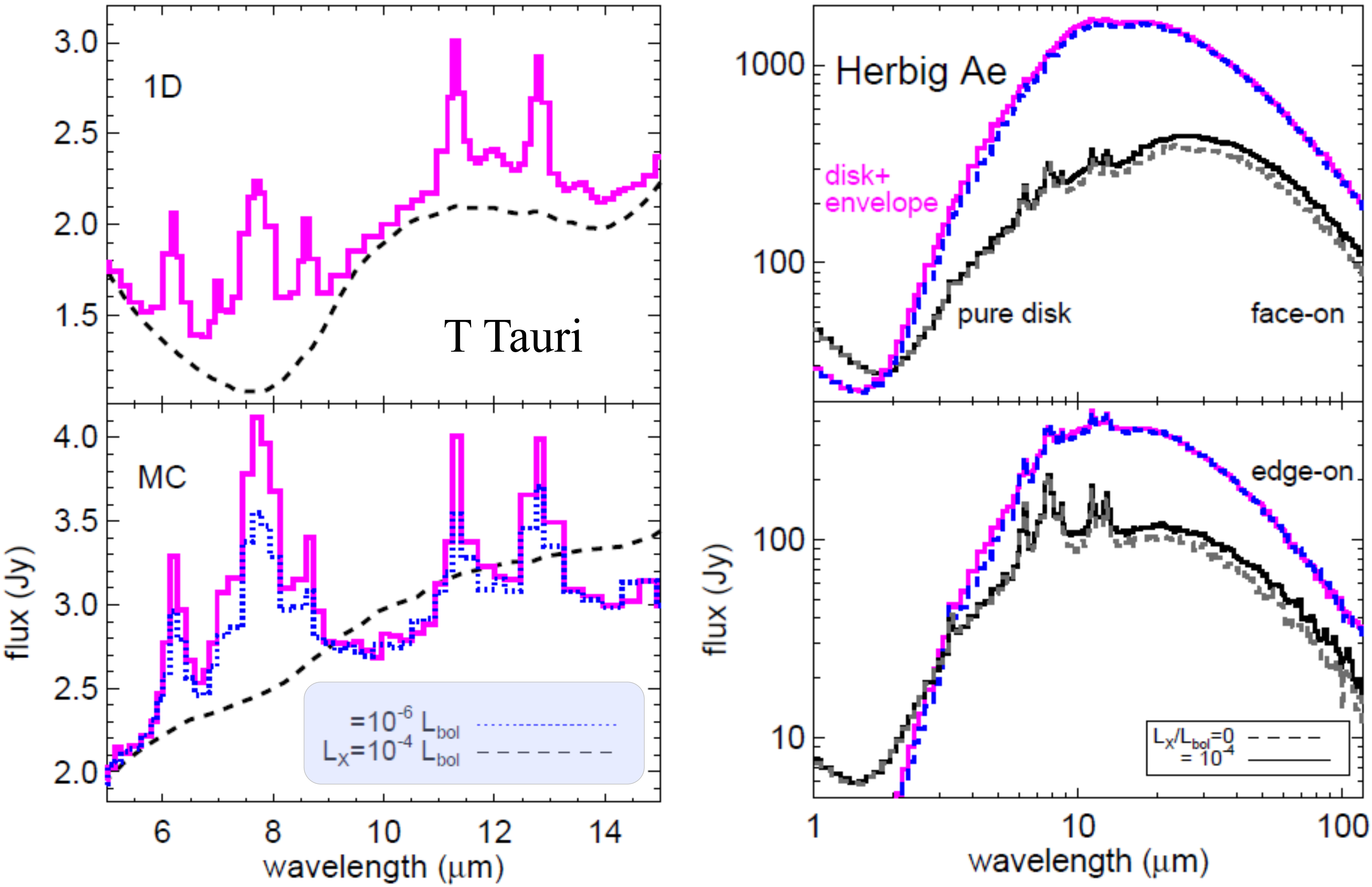
Vertical mixing

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



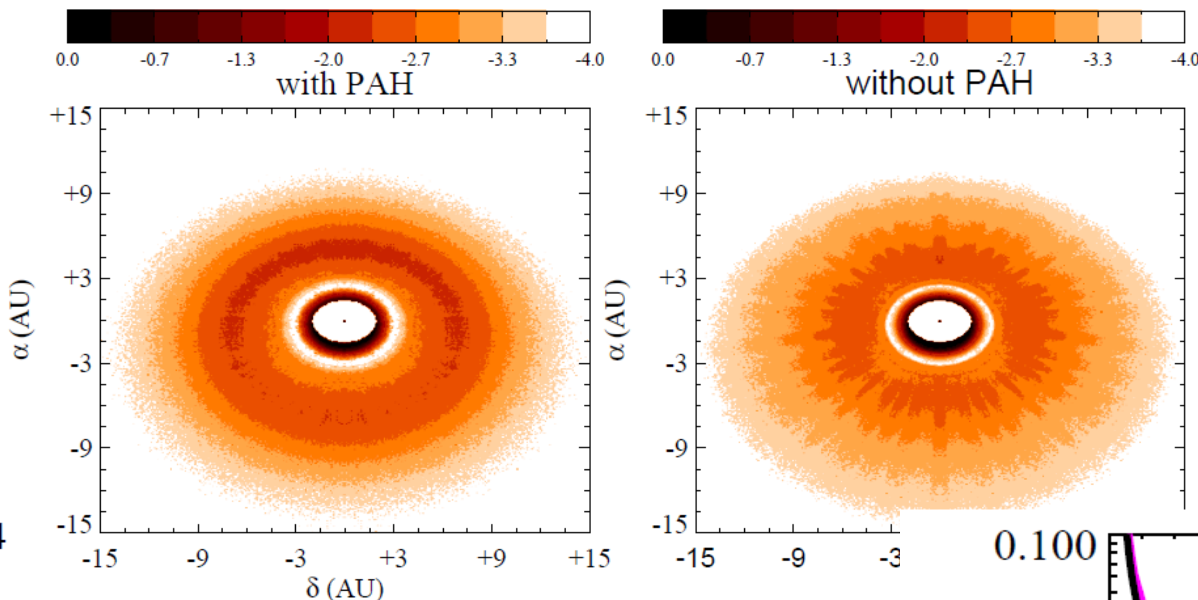
Siebenmorgen & Krűgel (2010)

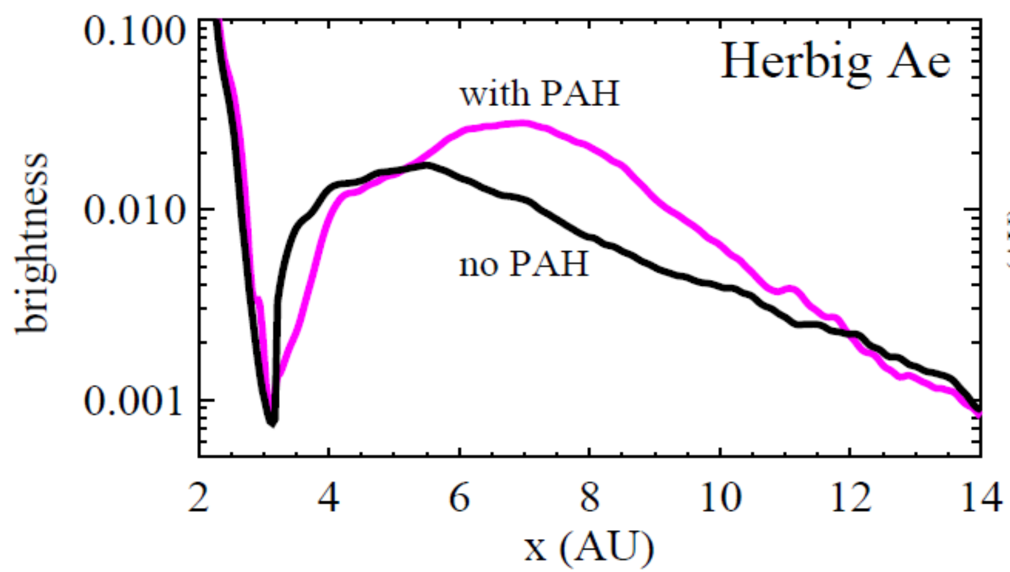
PAH emission from disks



PAH in 3D

Mid-IR emission from Herbig disks





Siebenmorgen & Heymann (2012)

Shadows in planet forming disks

- Dust model for:

  extinction, emission, linear and circular polarisation

- Gaps and ring-like structures:

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

PAH band ratios:
ionisation ⟷ dehydrogenation