The Inner Regions of Protoplanetary Disks

C.P. Dullemond & J.D. Monnier

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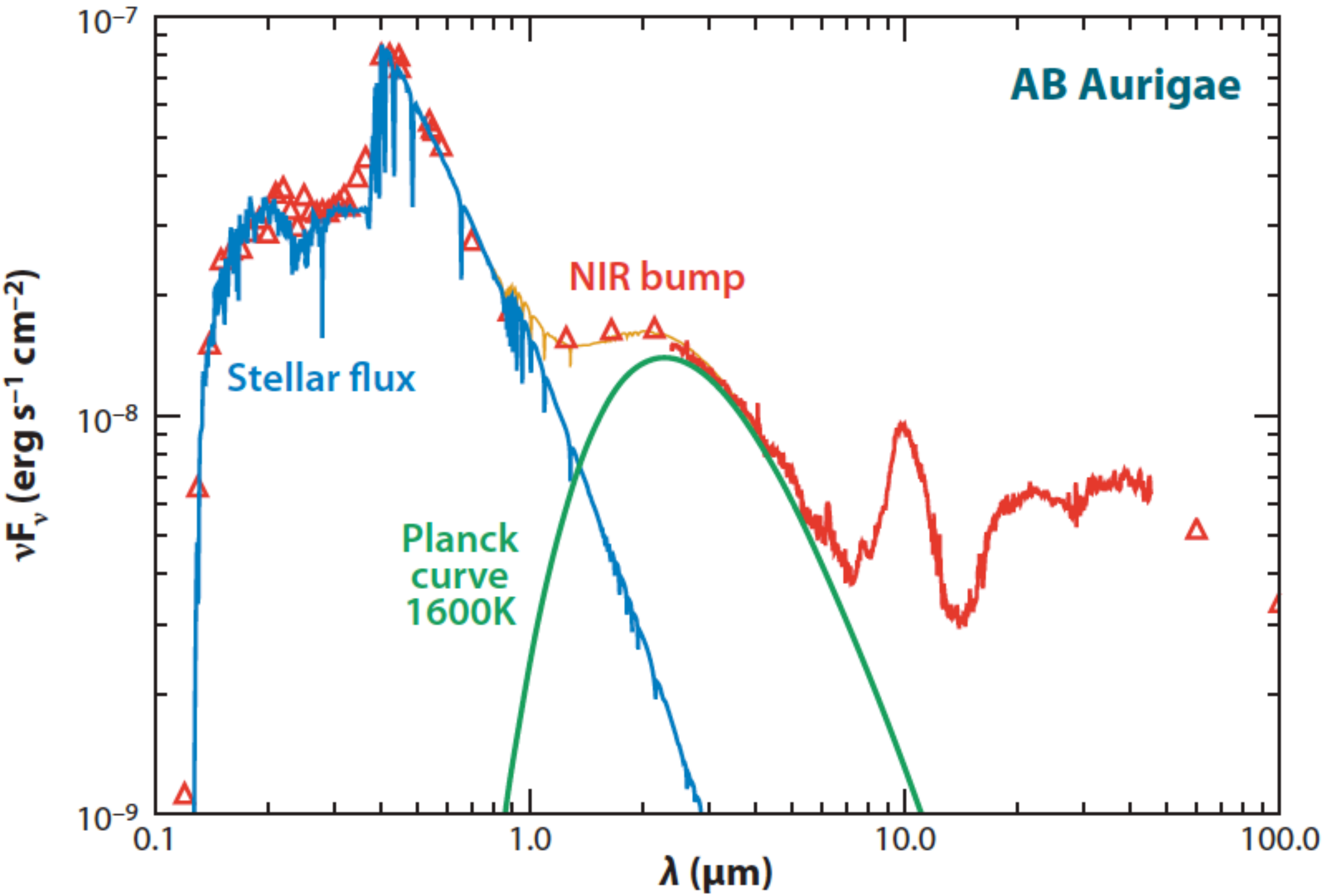
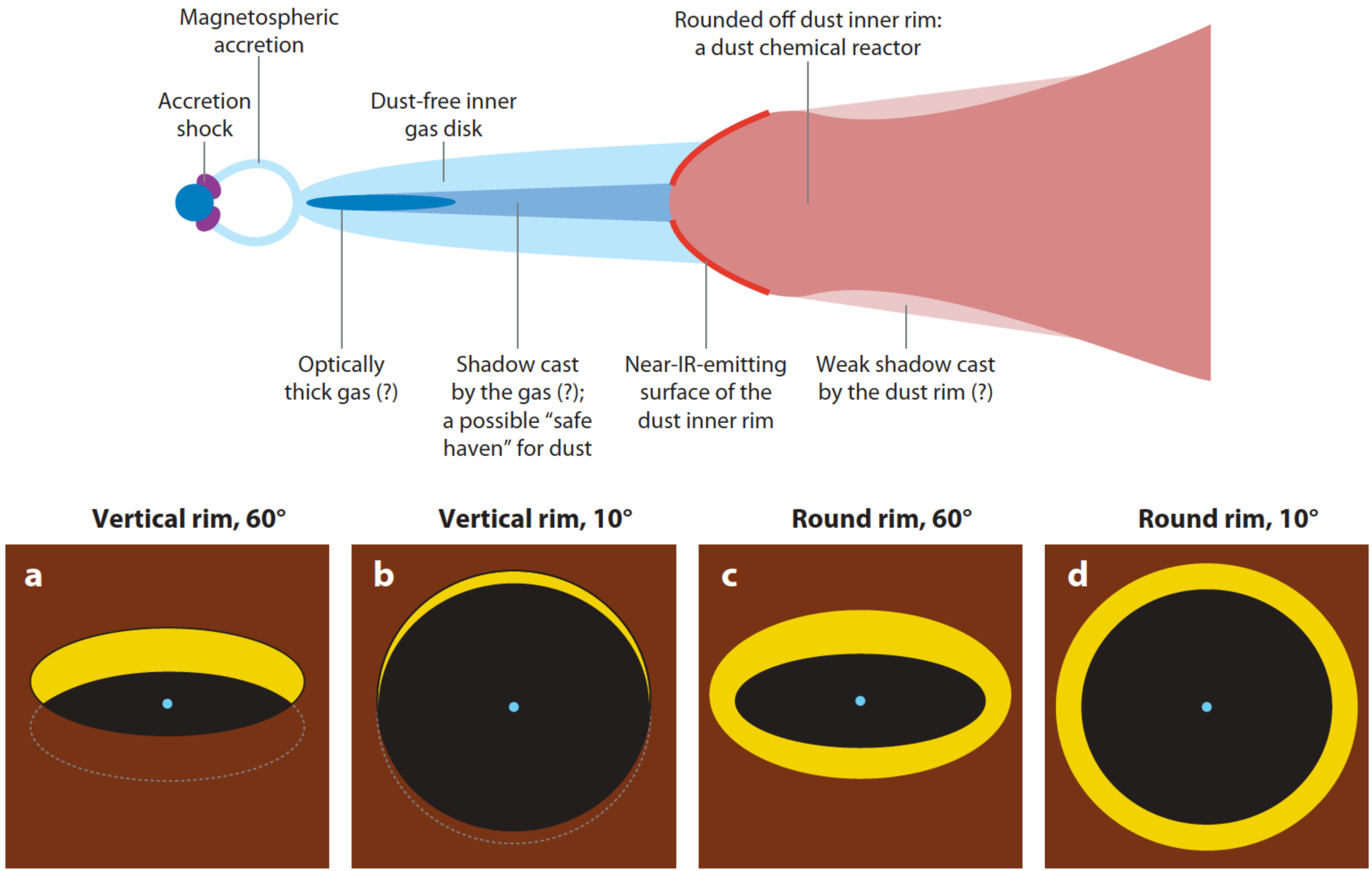
(cont'd)

NIR bump



AB Aurigae
NIR bump
Stellar flux
Planck
curve
1600K
10^{-7}
10^{-8}
10^{-9}
0.1
1.0
10.0
100.0
νF_ν (erg s^{-1} cm^{-2})
λ (μm)

Dust rim



Magnetospheric accretion
Accretion shock
Dust-free inner gas disk
Rounded off dust inner rim: a dust chemical reactor
Optically thick gas (?)
Shadow cast by the gas (?); a possible “safe haven” for dust
Near-IR-emitting surface of the dust inner rim
Weak shadow cast by the dust rim (?)
Vertical rim, 60°
Vertical rim, 10°
Round rim, 60°
Round rim, 10°
a
b
c
d

Early vertical wall model

- Dullemond, Dominik & Natta (2001)
- Aim: simple model to get a first order understanding of the dust rim, without detailed RT modeling
- Assumptions:
  - disk mass = 0.01 M_{Sun}
  - optical depth where there is dust = very high
  - optical depth where theres is no dust = very low
  - vertical wall at R_{rim}
  - T_{dust} = 1500 K
  - wall radiates as blackbody

Early vertical wall model

- Wall's emission: $F_{\rm cool} = \sigma T_{\rm rim}^4$
- Star's emission: $F_{\rm heat} = L_*/(4\pi R_{\rm rim}^2)$
- Equating the two, we get the rim's radius: $$R_{\rm rim} = \sqrt{\frac{L_*}{4\pi\sigma T_{\rm rim}^4}} = R_* \left(\frac{T_*}{T_{\rm rim}}\right)^2$$
- (We used the Stefan-Boltzmann law) $$T_* = (L_*/4\pi R_*^2 \sigma)^{1/4}$$
- For AB Aur:
  - $R_* = 2.4\ R_{\rm Sun}$
  - $T_* = 10\,000$ K
  - $T_{\rm rim} = 1500$ K $\Rightarrow$ $R_{\rm rim} = 0.5$ au

Height of the rim?

- Height of the rim is important, because $H_{s,\mathrm{rim}}$ and R_{rim} together determines the covering factor
- Covering factor: fraction of the sky as seen from the star that's covered by the dust rim
- Determines the fraction of the stellar light that is absorbed by the rim
- Determines the NIR flux

$$L_{\mathrm{rim}} \simeq \omega L_*$$

$$\omega \simeq \frac{H_{s,\mathrm{rim}}}{R_{\mathrm{rim}}}$$

Height of the rim?

- Observed flux from the rim:
  (rim emission is 0 for face-on view, inconsistent with observations)

$$F_{\nu,\mathrm{rim}} \simeq 4 \sin i \, \frac{R_{\mathrm{rim}} H_{s,\mathrm{rim}}}{d^2} B_\nu(T_{\mathrm{rim}})$$

- What is $H_{s,\mathrm{rim}}$? How vertically extended is the dust rim?
- Keplerian rotation: $\Omega(R) = \Omega_K(R) \equiv \sqrt{GM_*/R^3}$
- Vertical force: $f_z \simeq -\Omega_K^2 z$
- Hydrostatic equilibrium: $dP/dz = -\rho f_z$

Height of the rim?

- Solution: $\rho_{\text{gas}}(R, z) = \frac{\Sigma_{\text{gas}}}{\sqrt{2\pi} H_p} \exp\left(-\frac{z^2}{2H_p^2}\right)$

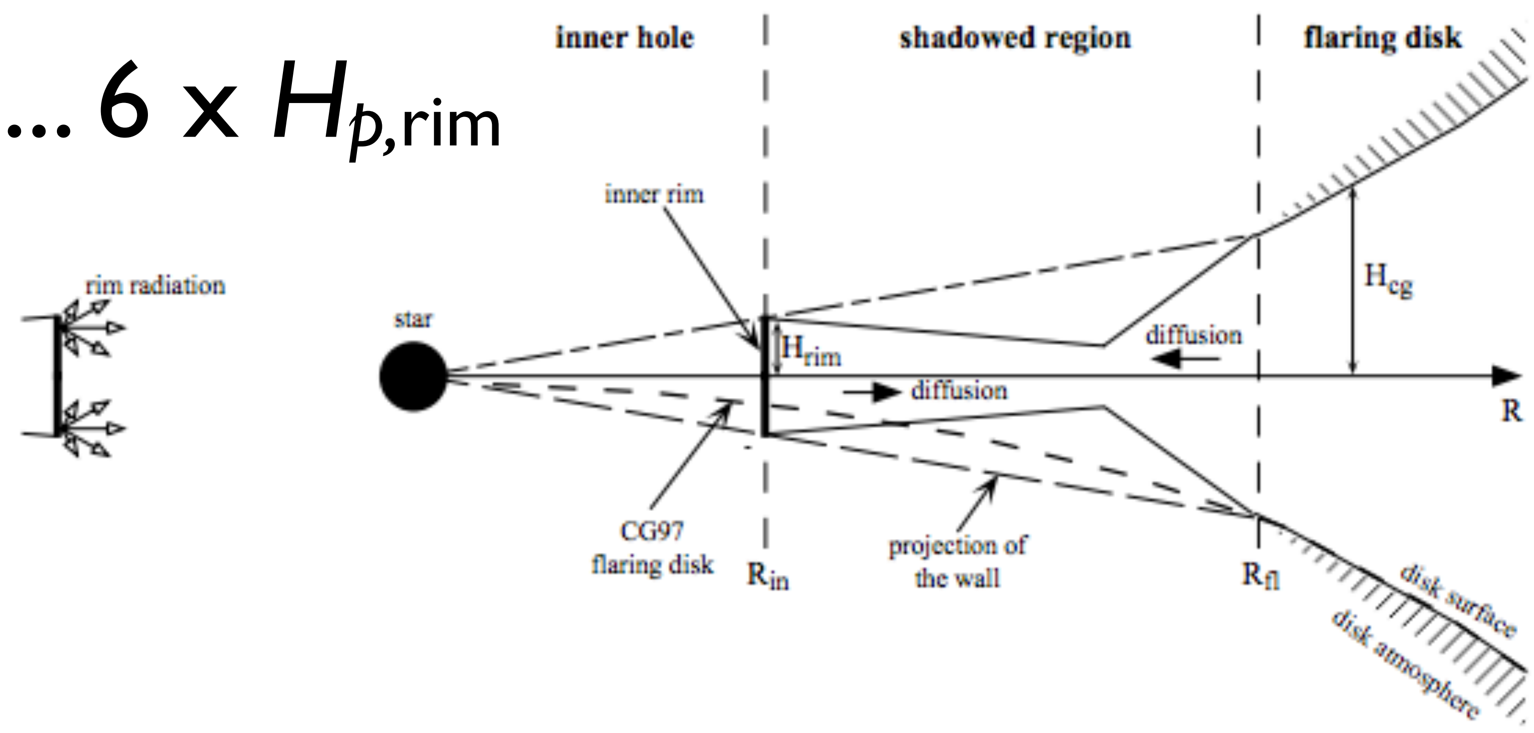
- Surface density: $\Sigma_{\text{gas}} \equiv \int_{-\infty}^{+\infty} \rho(z) dz$

- Pressure scaleheight: $H_p = \sqrt{\frac{kT R^3}{\mu_g G M_*}}$

- For AB Aur, we get $H_p = 0.036\ R_{\text{rim}}$

Height of the rim?

- $H_{s,\mathrm{rim}}$: surface height
- $H_{p,\mathrm{rim}}$: pressure scaleheight
- Surface height: above which stellar photons can pass beyond R_{rim} without being absorbed
- Dust opacity needs to be known
- In practice: $H_{s,\mathrm{rim}} = 3 \ldots 6 \times H_{p,\mathrm{rim}}$



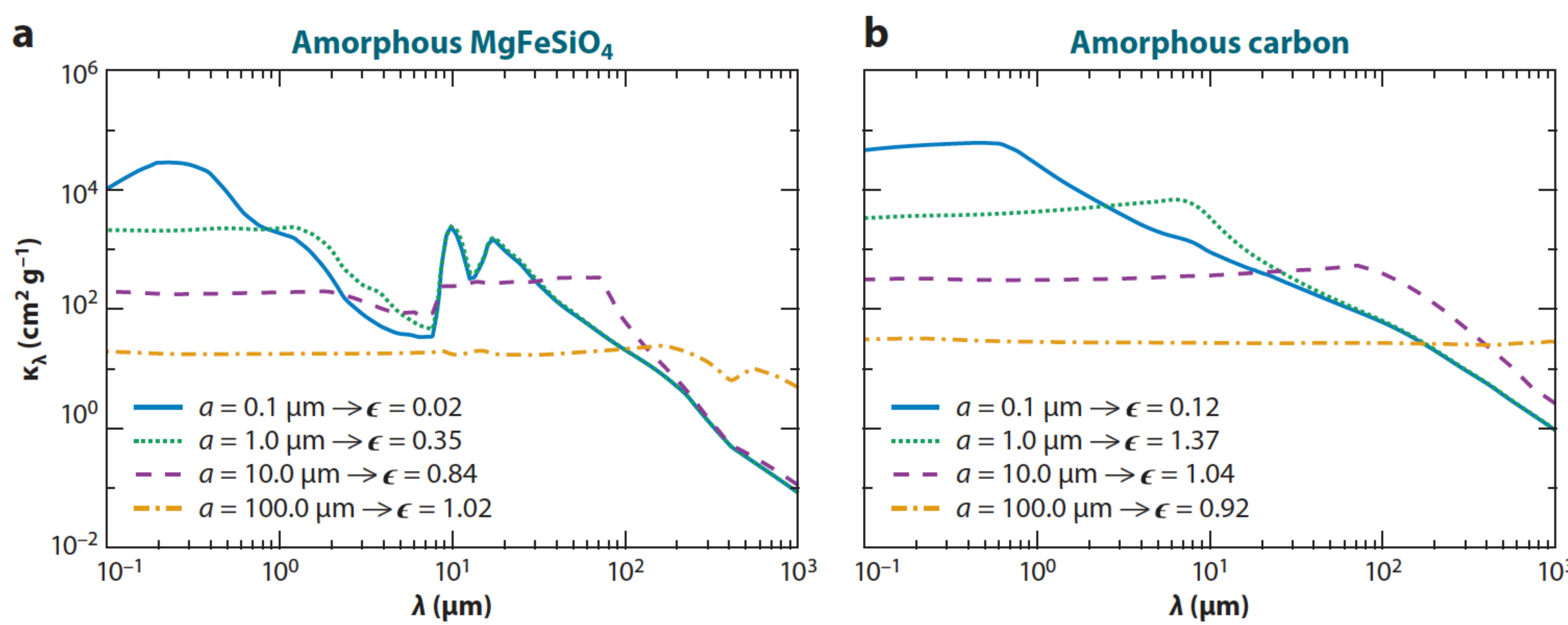
Temperature of dust

- Temperature of a single dust grain located at a distance *R* from the star in a completely optically thin environment?
- Assumptions:
  - dust grain: sphere of radius *a*
  - optical cross section = geometrical cross section (πa^2, gray opacity)
- Absorbed energy: $\pi a^2 L_* / 4\pi R^2$
- If the dust has a temperature of $T_{\rm gray}$, it emits as $4\pi a^2 \sigma T_{\rm gray}{}^4$

$$T_{\rm gray} = (R_* \,/\, (2R))^{1/2}\, T_*$$

Temperature of dust

- For AB Aur, if we take $R = R_{\mathrm{rim}} = 0.5$ au, we get $T_{\mathrm{gray}} = 1050$ K
- Problems:
  - we ignored backwarming by IR emission from dust further inside the wall (needs RT)
  - we assumed gray dust (λ-independent opacity)



Temperature of dust

- More precise dust temperature:

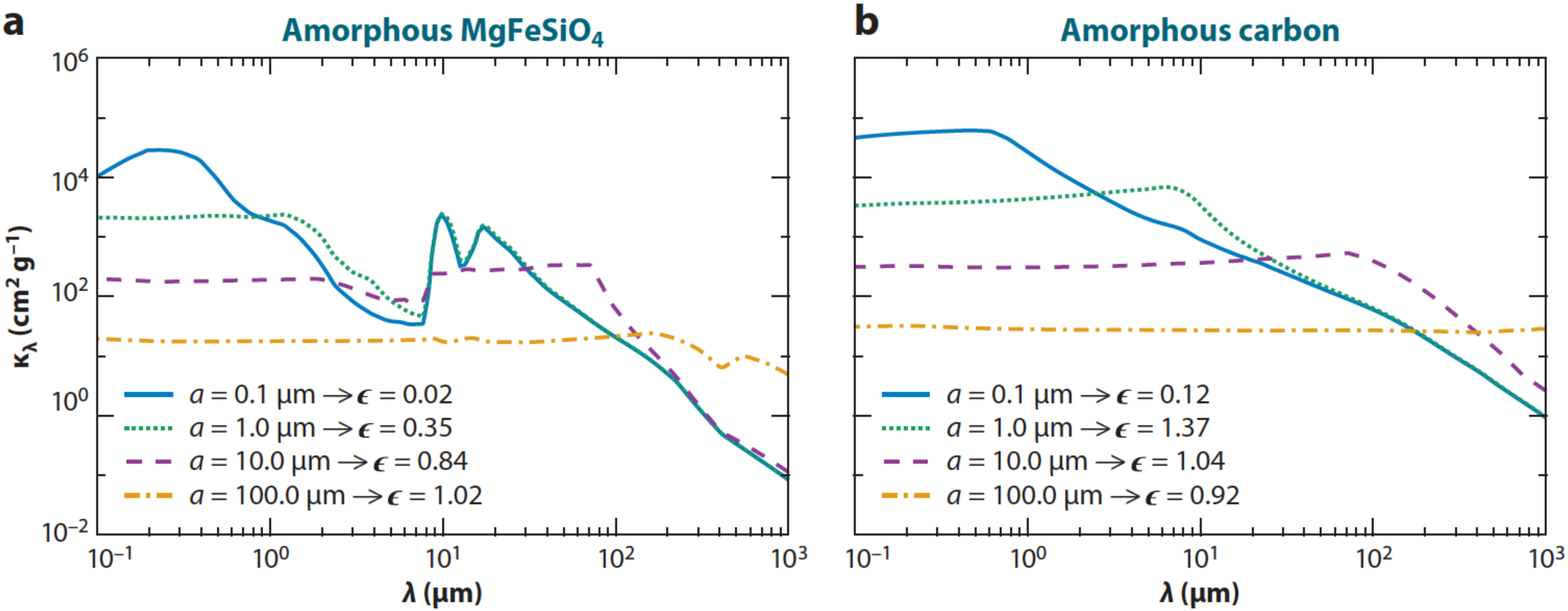
$$T_{\rm dust} = (R_* \,/\, (2R))^{1/2}\; T_* \varepsilon^{-1/4}$$

- ε: ratio of effectiveness of emission at the wavelength at which the dust radiates away its heat and absorption at stellar wavelengths ($T_{\rm dust}$-dependent!!!!)
- Implicit equation → needs numerical iteration

Cooling efficiency

- If $\varepsilon < 1$ then $T_{\mathrm{dust}} > T_{\mathrm{gray}}$
- If $\varepsilon > 1$ then $T_{\mathrm{dust}} < T_{\mathrm{gray}}$
- ε tells us how efficiently the dust can cool.
- For small (submicron) grains, κ_ν increases with ν, thus, $\varepsilon < 1$
- For larger (> 10 μm), $\varepsilon \approx 1$
- Large grains can survive closer to the star than small grains
- Crystalline grains can survive even closer, because they have a very low opacity in the V band, thus, $\varepsilon \gg 1$

Cooling efficiency



1D radiative transfer

- Without backwarming, for a single dust grain:

$T_{\text{dust}} = T_*(R_*/(2R))^{1/2}\ \varepsilon^{-1/4}$

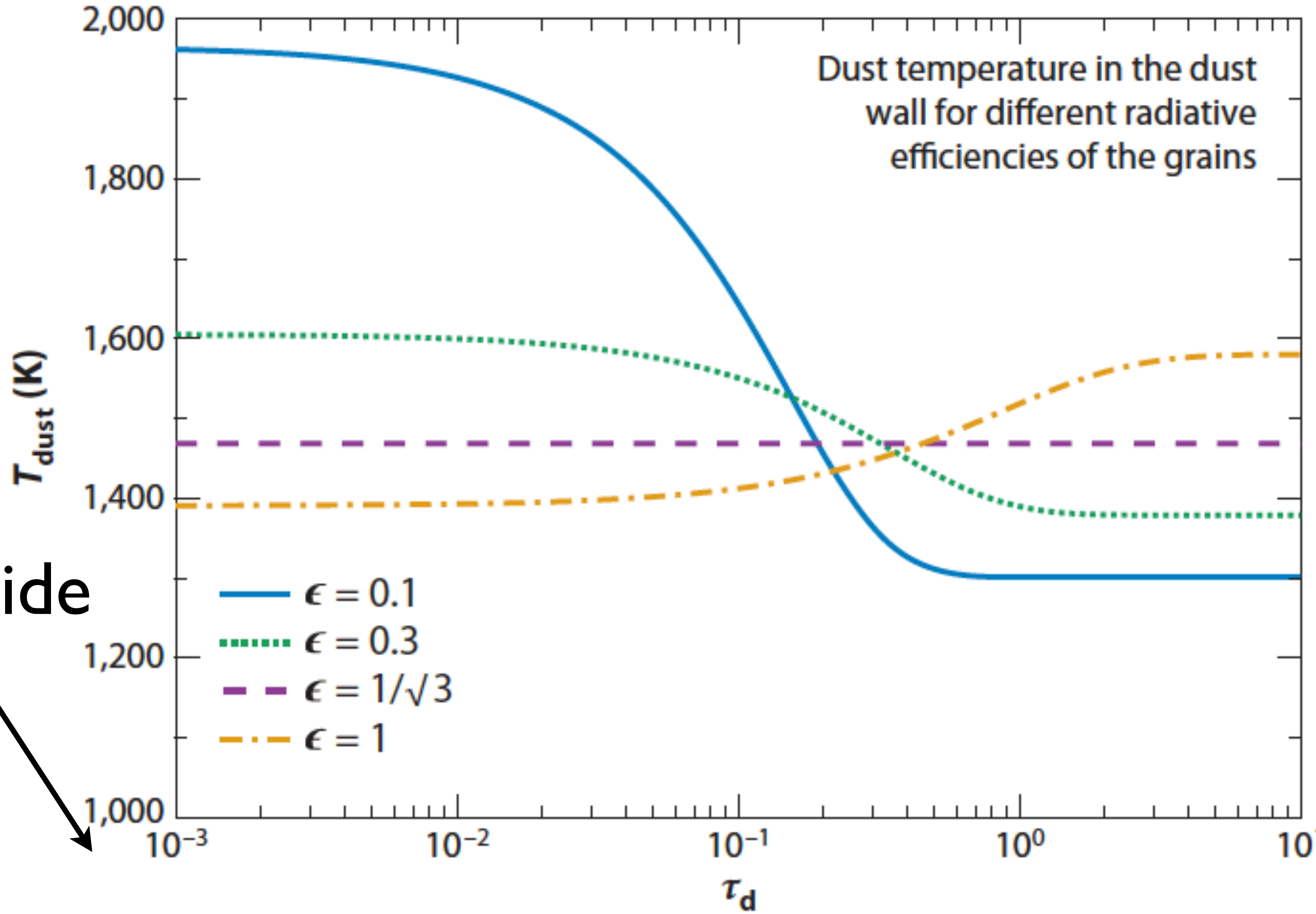
- With backwarming:

$T_{\text{dust}}\ (\tau_d) = T_*(R_*/(2R))(\mu(2+3\mu\varepsilon) + (1/\varepsilon-3\varepsilon\mu^2)\exp(-\tau_d/\mu\varepsilon)^{1/4}$

- $\mu = \sin\varphi$
- φ: the angle under which the stellar radiation enters the dust wall
- The exp part accounts for the extinction of the stellar light as it goes deeper into the rim

Dust temperature in the wall

Dust temperature for AB Aur in the 1D RT model
(we ignore dust evaporation/condensation)

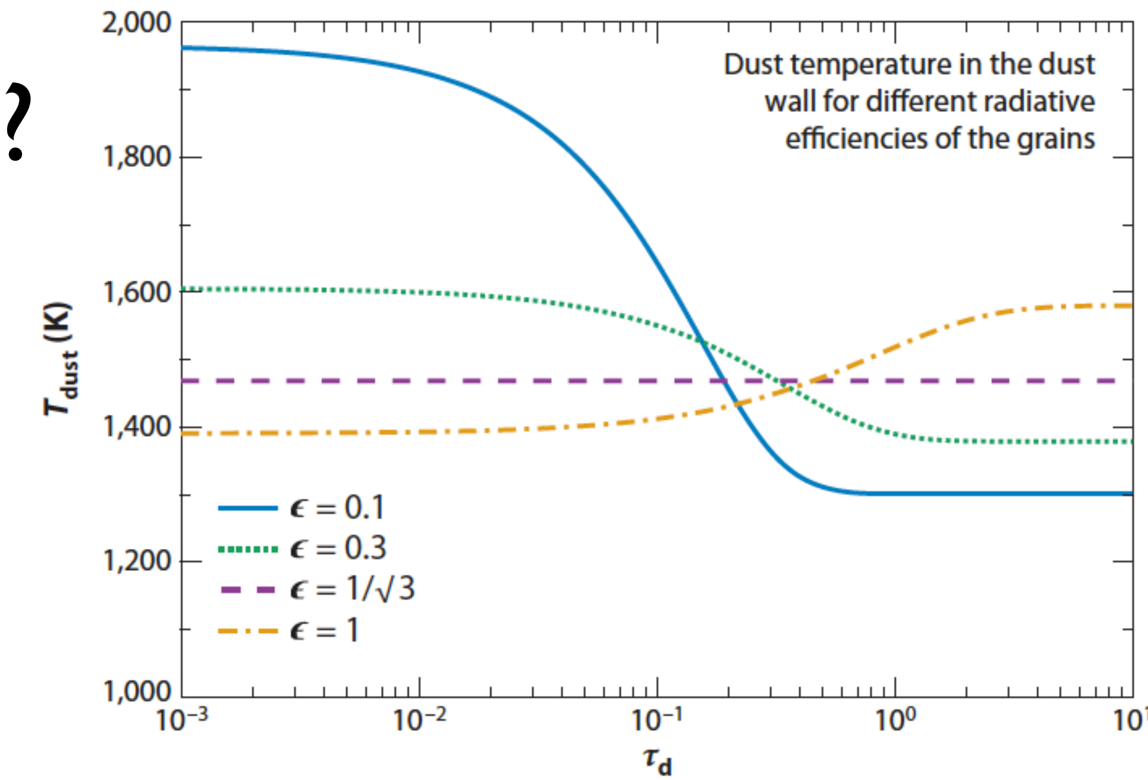


front side

back side

How sharp is the rim?

- What happens if T > 1500 K? The dust evaporates!
- For small grains, the stellar radiation "eats its way" outward into disk



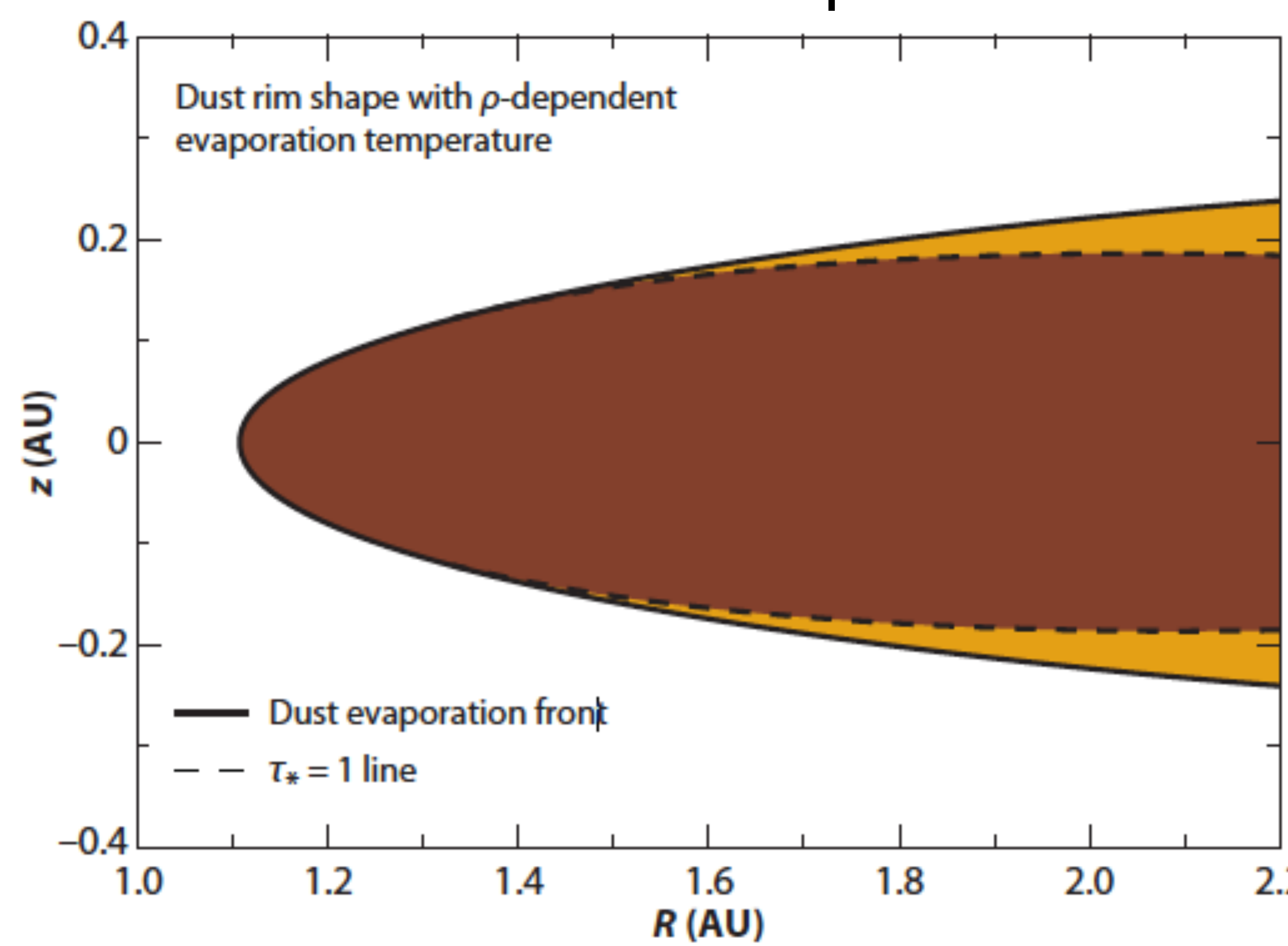
- Rim radius will be larger than for the simple blackbody solution:

$$R_{\rm wall} \simeq R_* \left(\frac{T_*}{T_{\rm evap}}\right)^2 \frac{1}{2\sqrt{\epsilon}} = \frac{R_{\rm wall,bb}}{2\sqrt{\epsilon}}$$

- Where is the transition between the hot inner dust-free zone and the cooler outer dusty disk?

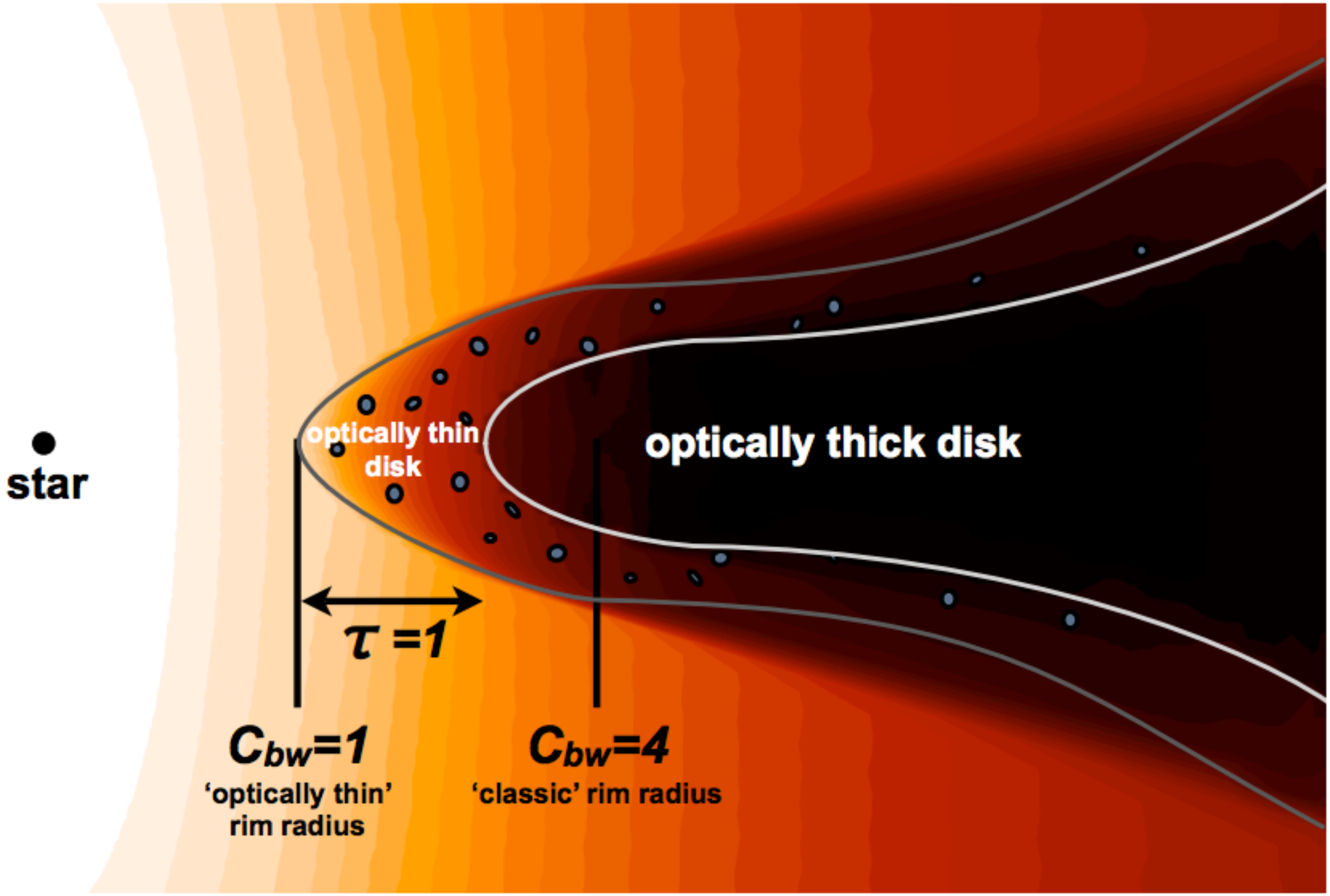
Evaporation/condensation

- Complex process, depends not only on T
- Depends also on the abundance of condensable atoms in the gas phase (partial pressure)
- For a given gas density, there is a critical T_{evap}:
  - Above T_{evap}, dust evaporates
  - Below T_{evap}, dust condensates



- Rounded-off rim model of Isella & Natta (2005)

Evaporation/condensation

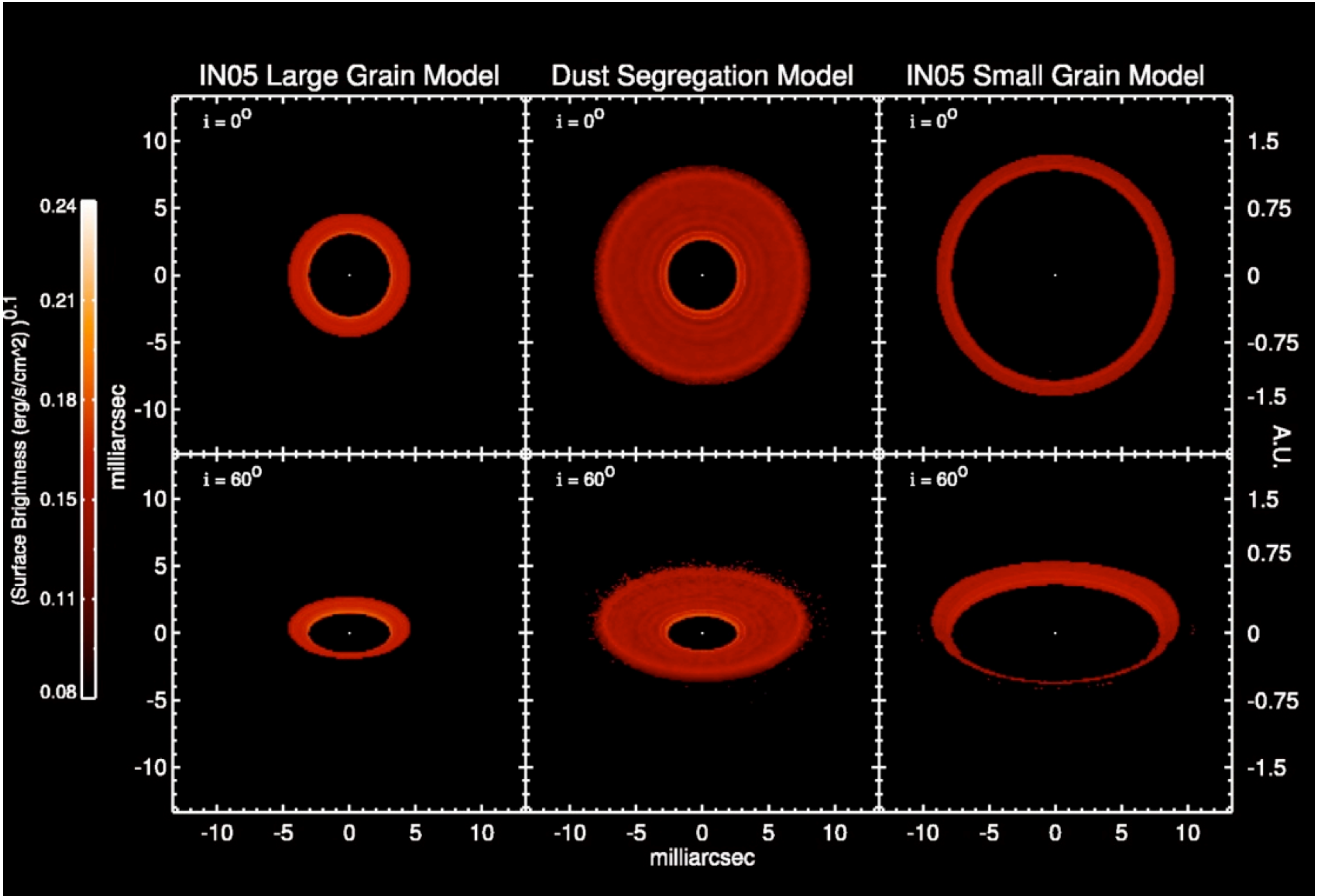


Kama, Min & Dominik (2007)

2D radiative transfer

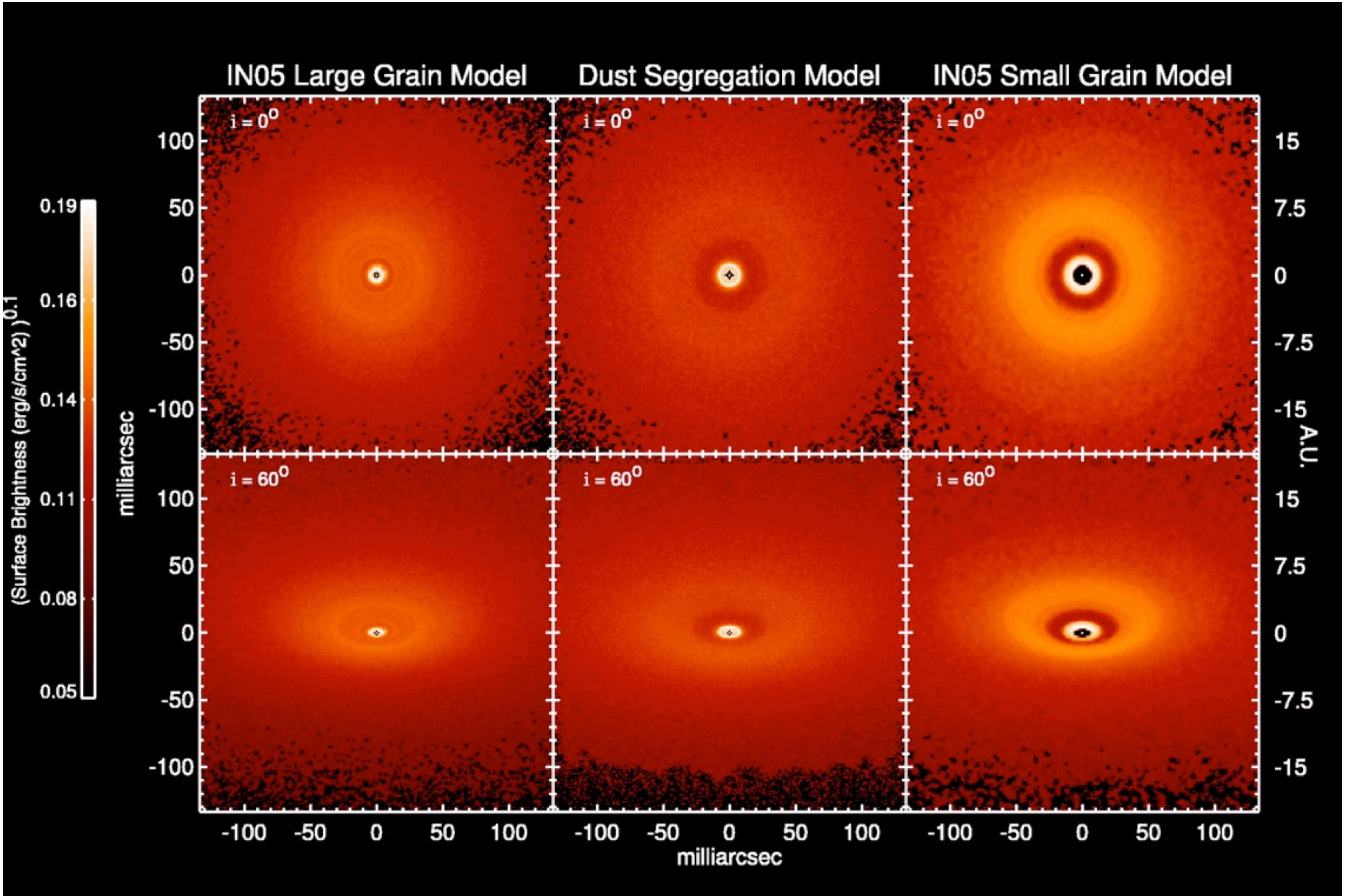
- In fact it's 3D (light is allowed to move in all three spatial directions)
- But we assume axial symmetry (*T* and other parameters only depend on *R* and *z*) → 2D
- Numerical solution of the transfer equation
- In 2D/3D, the usual method: Monte-Carlo RT
- Follows an ensemble of N photons in statistical terms as they travel through the medium; scattering and absorption is handled; finally the exiting photons make up the model image

2D radiative transfer



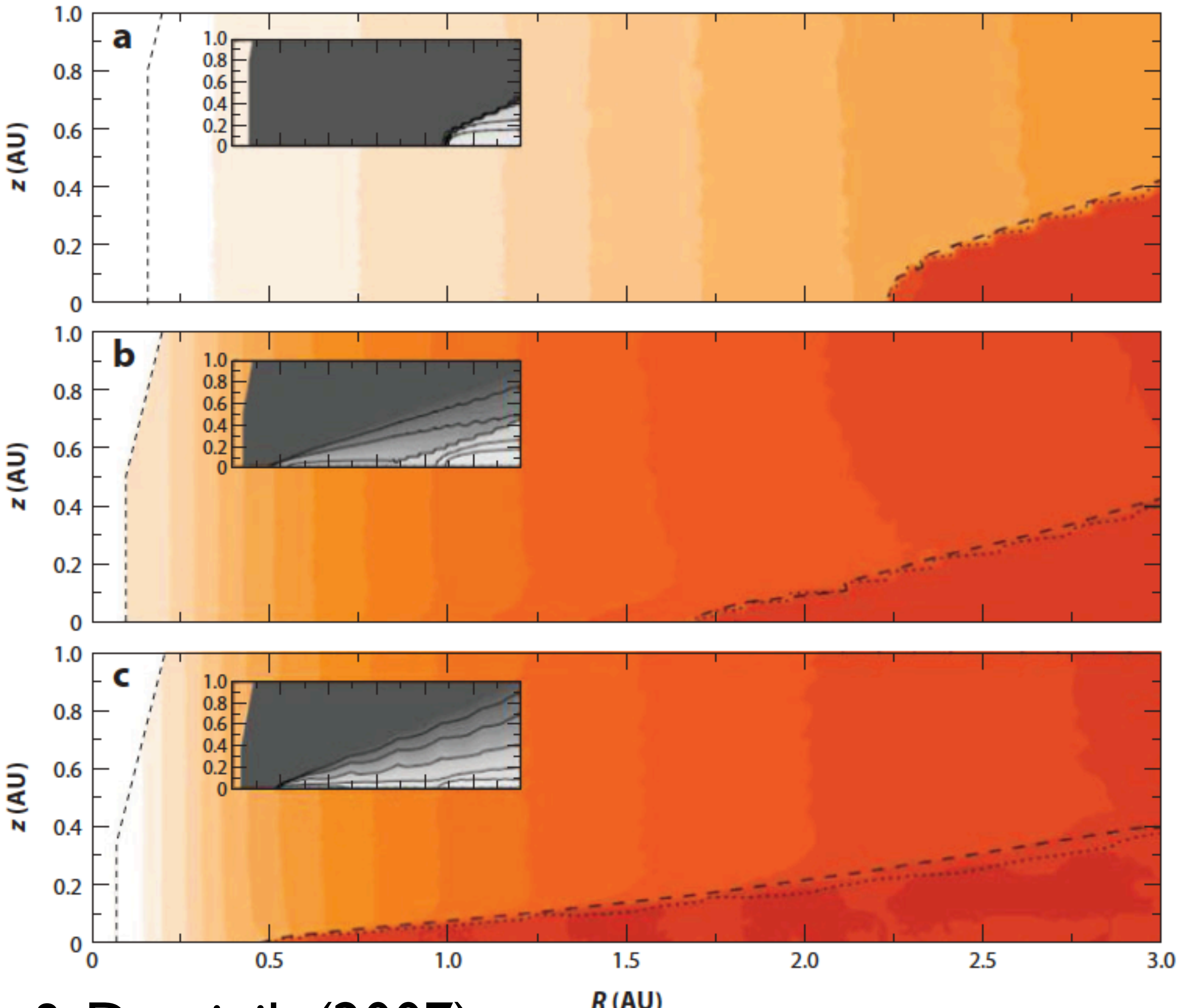
Synthetic 2.2 μm images by Tannirkulam, Harries & Monnier (2007)

2D radiative transfer



Synthetic 10.7 µm images by Tannirkulam, Harries & Monnier (2007)

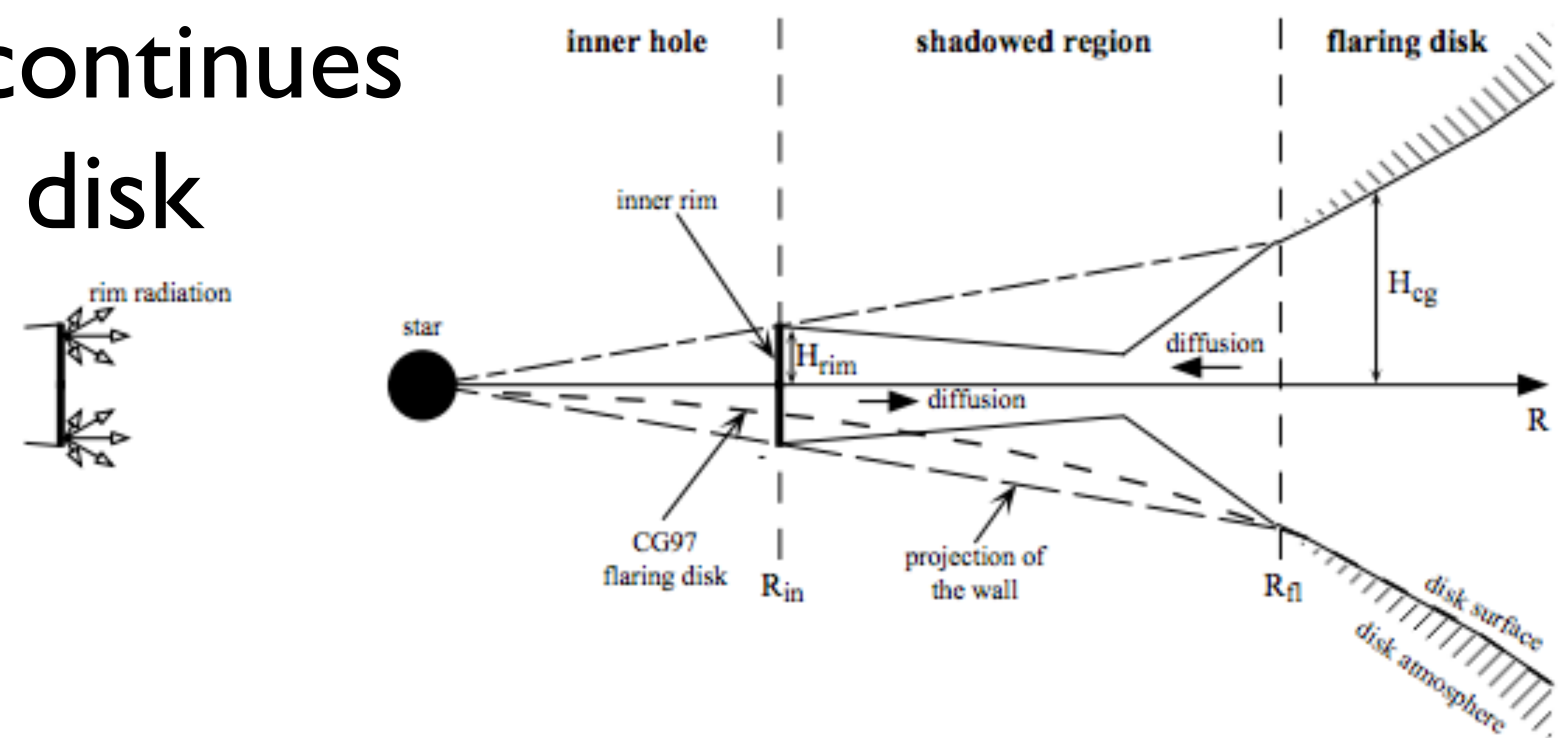
2D radiative transfer



Kama, Min & Dominik (2007)

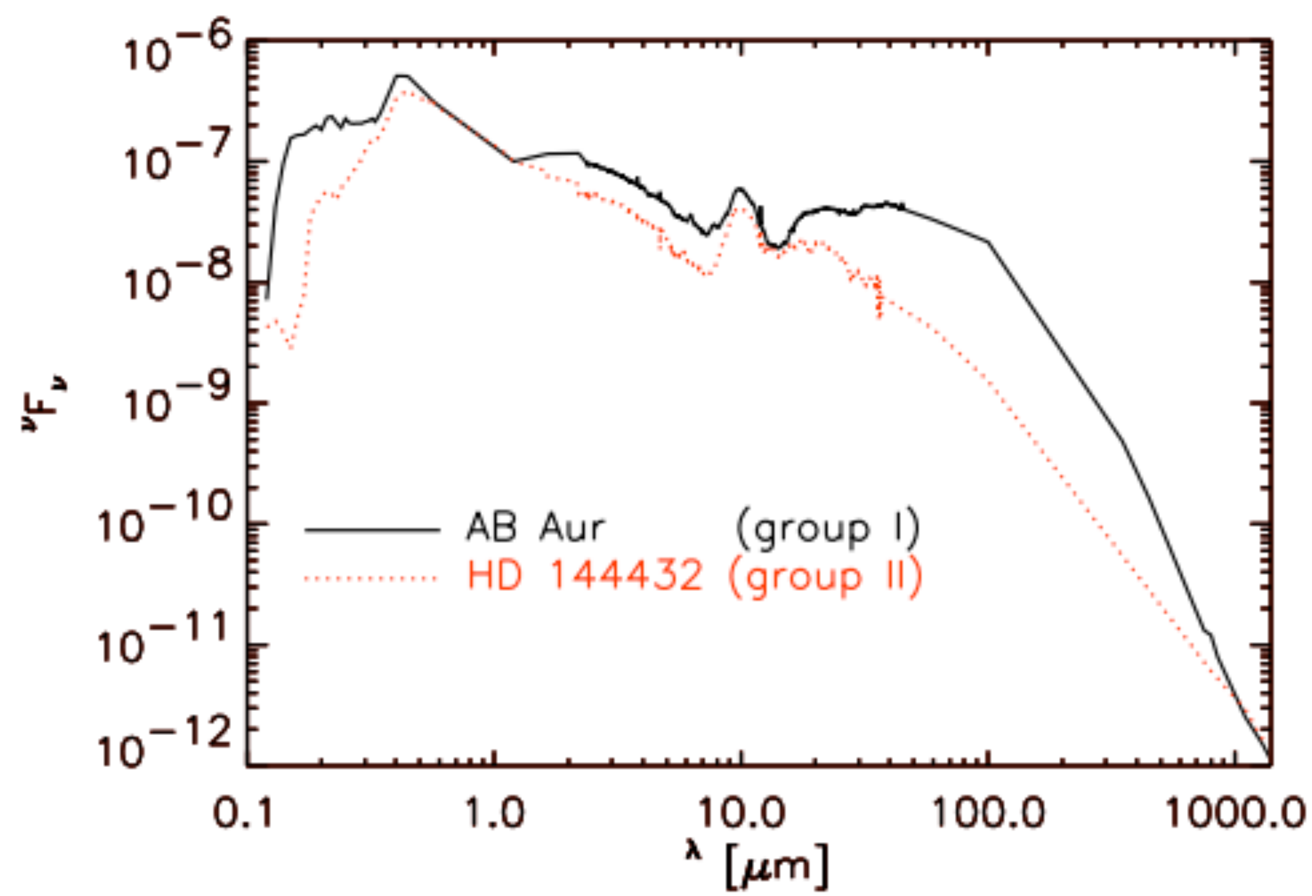
Shadowing

- Inner rim is puffed-up, because it gets direct frontal irradiation → becomes much hotter than the disk behind it
- The rim should cast a shadow on the inner few au of the flaring disk
- Ever farther, the disk pops out of the shadow and continues like a normal flaring disk (or not)



Shadowing

- Radiative diffusion is important
- Disk will never collapse completely



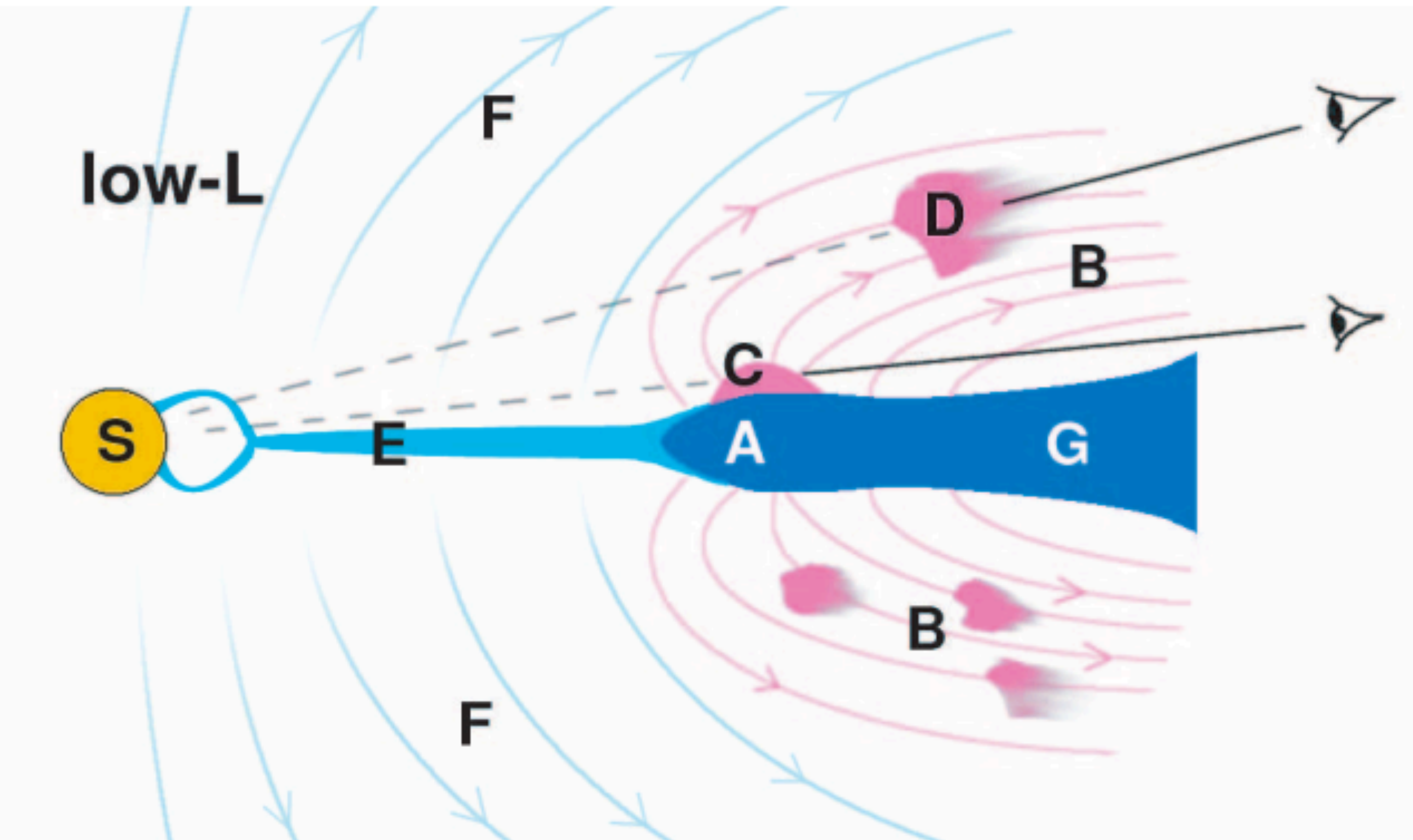
Meeus et al. (2001)

Dullemond & Dominik (2004)

Can the dust rim explain the NIR bump?

- Answer is not conclusive
- Simple models reproduce the bump well (single-temperature BB wall)
- More complicated, more realistic models predict flatter and weaker bumps than observed (temperature dispersion smears out the flux)
- Sources with strong NIR bump: rim + second component (spherical envelope)

Can the dust rim explain the NIR bump?



Vinković & Jurkić (2007)

A: puffed-up inner rim

B: dusty outflow (halo)

C: variable rim height

D: dust clumps

E: opt. think disk

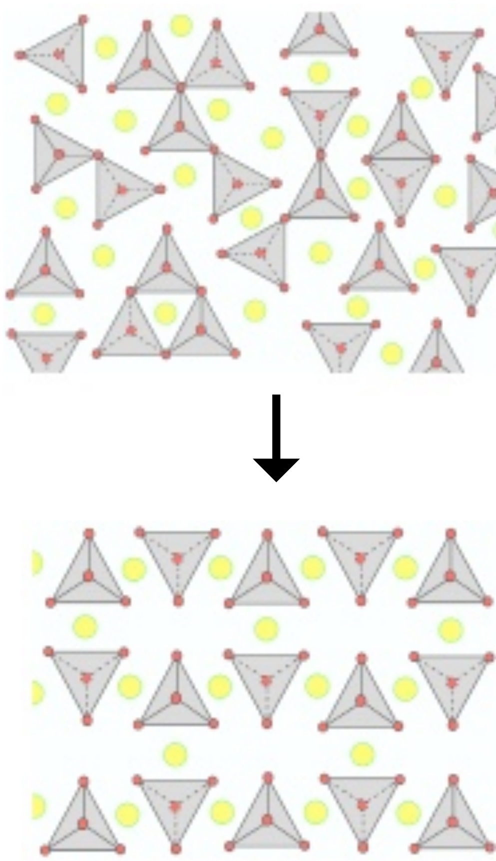
F: gaseous stellar/disk wind

G: opt. thick disk

Alternative explanation: bright emission from the gas inside the dust rim

Behind the wall

- Inner rim is a powerful dust chemical reactor:
  - amorphous dust grains get annealed
  - iron may be expelled from the silicates
  - pure iron grains may form
  - carbon dust may combust



- Interesting physics:
  - colliding particles may stick or melt together
  - thermally processed material may be transported to the planet-forming zone