# Radiative Processes in the Interstellar Medium

# (IV) Dust

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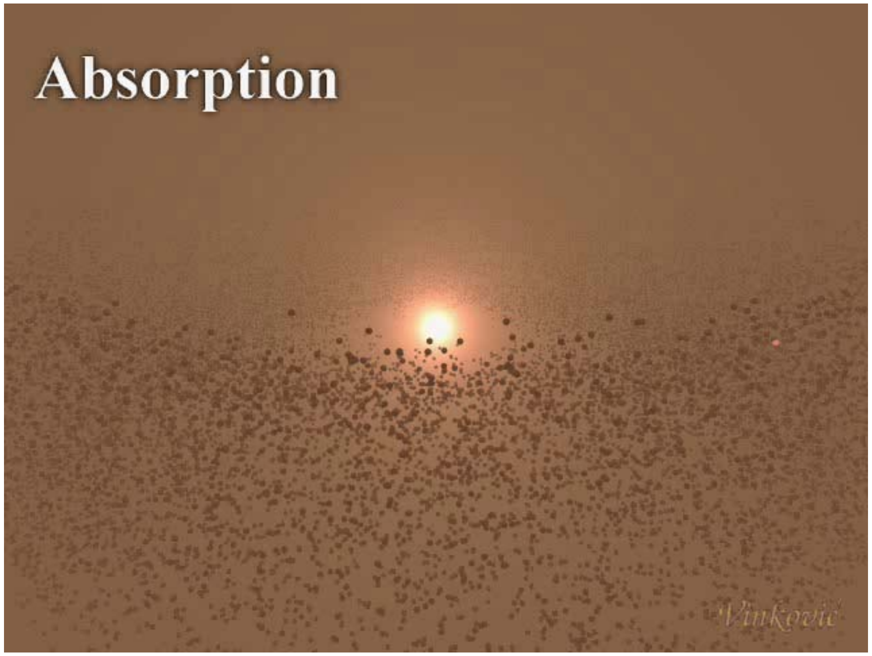
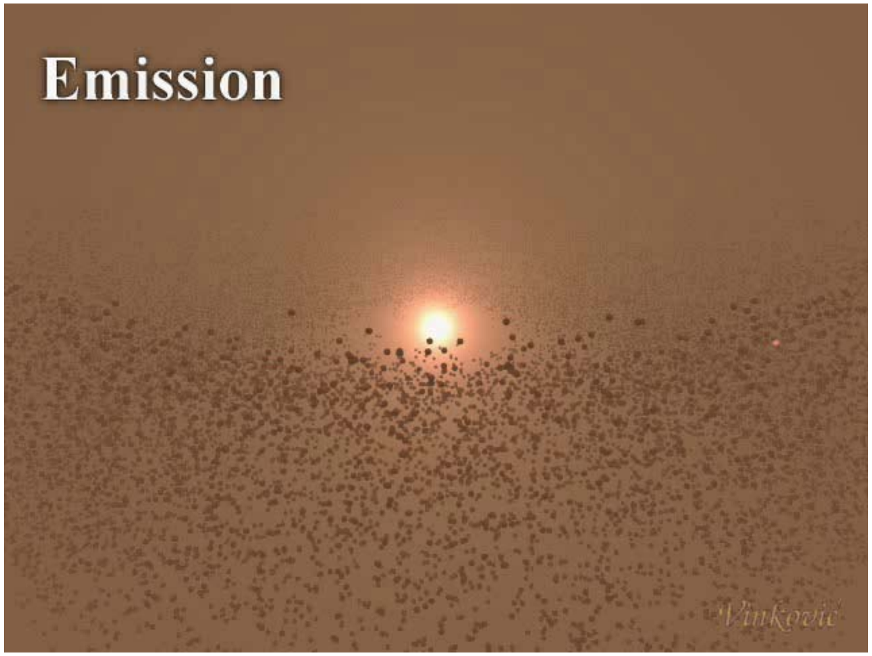
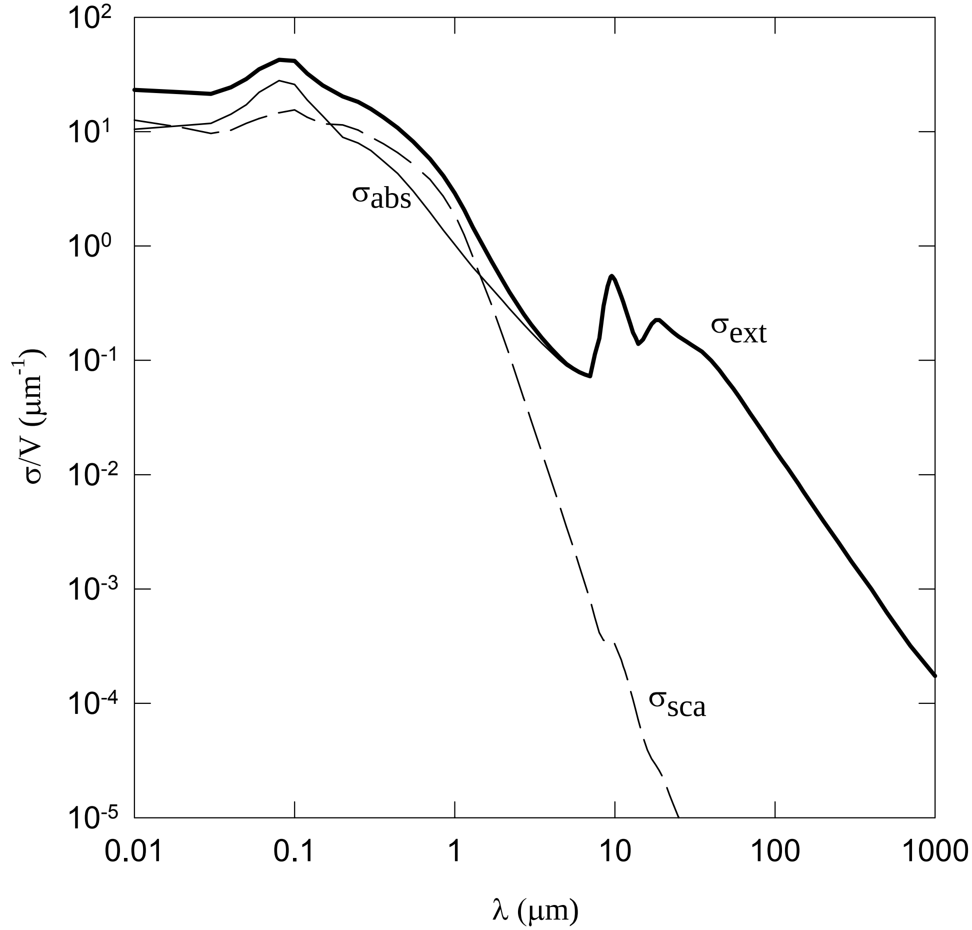
# Dust Radiative Interactions

$\kappa_\nu = n_d \sigma_\nu \quad \sigma_\nu = \pi a^2 Q_\nu \quad Q_{ext} = Q_{sca} + Q_{abs} \quad$ albedo: $\varpi = Q_{sca}/Q_{ext}$

**Standard ISM dust x-sections**




Apart from features: $Q_\nu = Q(x) \quad x = 2\pi a/\lambda$

# Dust Radiative Transfer

$$\frac{dI_\nu}{d\ell} = \varepsilon_\nu - \kappa_\nu I_\nu \qquad \kappa = \kappa_a + \kappa_s \qquad \varepsilon = \varepsilon_{em} + \varepsilon_s$$

$$\varepsilon_{em} = \kappa_a S_{th} = \kappa_a B_\nu(T_d)$$

$$\varepsilon_s = n_d \int I(\Omega')\sigma_s(\Omega',\Omega)d\Omega'$$

$$\sigma_s(\Omega',\Omega) = \sigma_s\, g(\Omega',\Omega)/4\pi \qquad \int g(\Omega',\Omega)d\Omega/4\pi = 1$$

$$\varepsilon_s = \kappa_s \int I(\Omega')g(\Omega',\Omega)d\Omega'/4\pi$$

Dust Source Function

$$S_\nu = (1 - \varpi_\nu)B_\nu(T) + \varpi_\nu \int I_\nu(\Omega')g(\Omega',\Omega)d\Omega'/4\pi$$

# Dust Temperature

Radiatively heated dust –
bolometric flux conservation:

$$\nabla \cdot \int \vec{F}_\nu d\nu = 0$$

Flux divergence relation: $\nabla \cdot \vec{F}_\nu = \kappa_\nu (\int S_\nu d\Omega - 4\pi J_\nu)$

Dust Radiative Equilibrium

$$\int \kappa_{a\nu} B_\nu(T) d\nu = \int \kappa_{a\nu} J_\nu d\nu$$

# Dust Temperature (2)

$$\int \kappa_{a\nu} B_\nu(T) d\nu = \int \kappa_{a\nu} J_\nu d\nu$$

Heating by a star with $R_*$, $T_*$; optically thin dust:

$$T^4 Q_P(T) \propto r^{-2}$$

Planckian peak: $\lambda_P \sim 4 \mu m \, (1000 \text{ K}/T)$

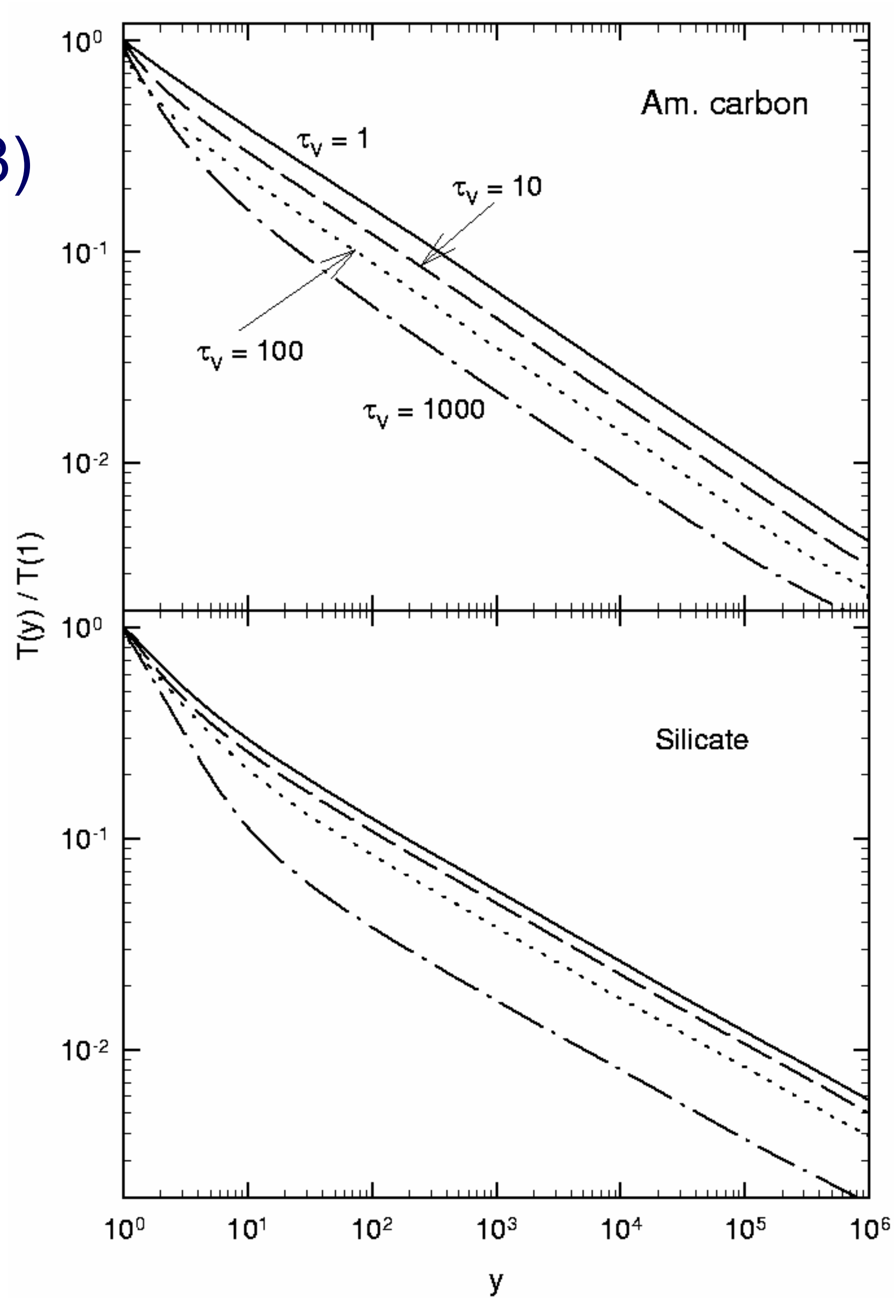
$$Q_P(T) \sim Q_a(\lambda_P)$$

$$Q_\lambda \sim 1/\lambda^n \Rightarrow Q_P(T) \sim T^n \qquad (n \sim 1 - 2)$$

$$T \propto r^{-2/(4+n)}$$

Slow temperature decline

# Dust Temperature (3)




T* = 2500 K

a = .05μm

$n_d \propto r^{-2}$

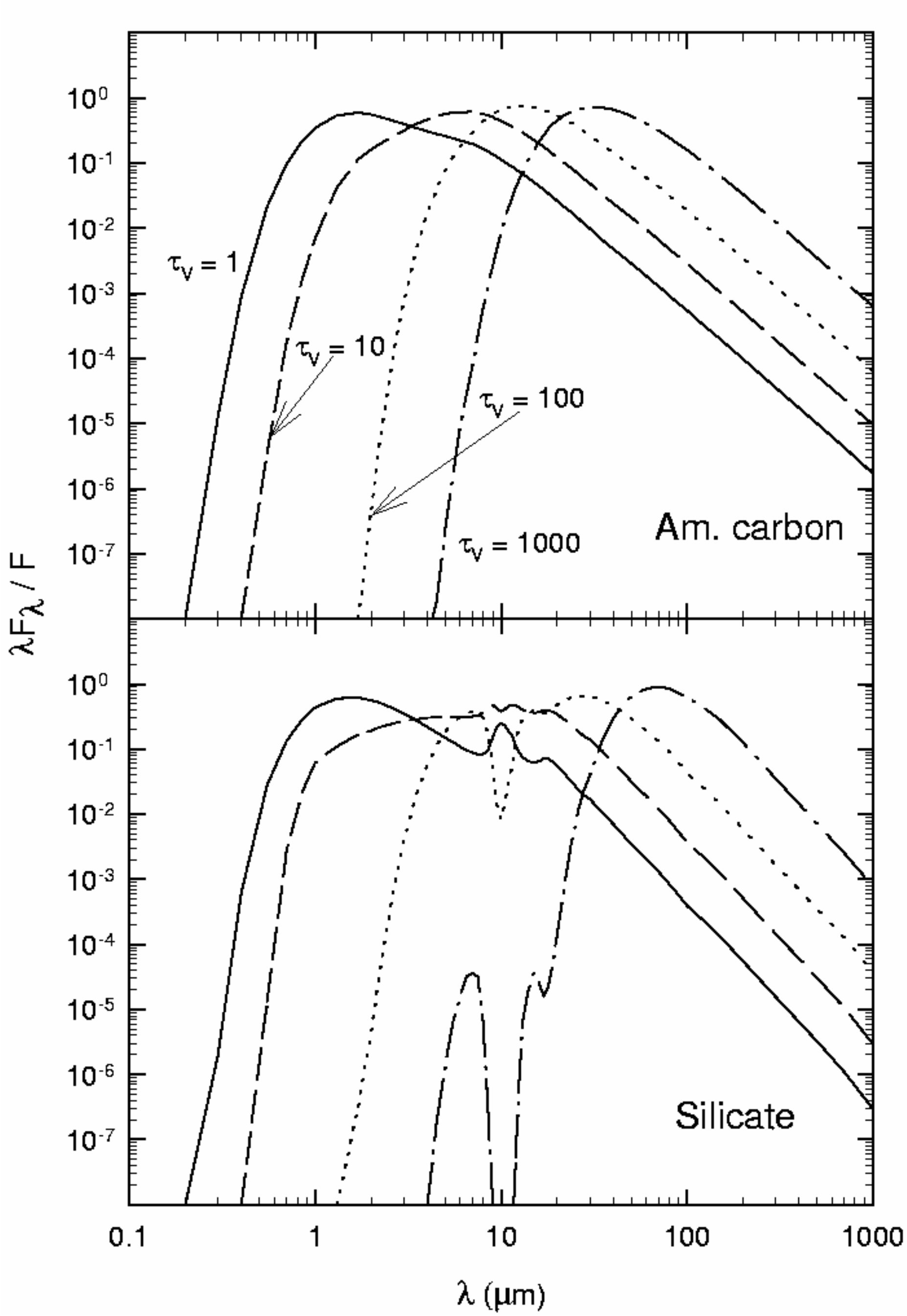
$T_1$ = 700 K

Ivezić & Elitzur '97

MNRAS 287, 799

Solutions by DUSTY http://www.pa.uky.edu/~moshe/dusty/

# SED




Single-T approximation:

$I_\lambda = B_\lambda(T)[1 - \exp(-\tau_\lambda)]$
$\{+ I_{in}\exp(-\tau_\lambda)\}$

$\tau_\lambda < 1$: $I_\lambda \simeq B_\lambda(T)\tau_\lambda$

$\tau_\lambda > 1$: $I_\lambda \simeq B_\lambda(T)$

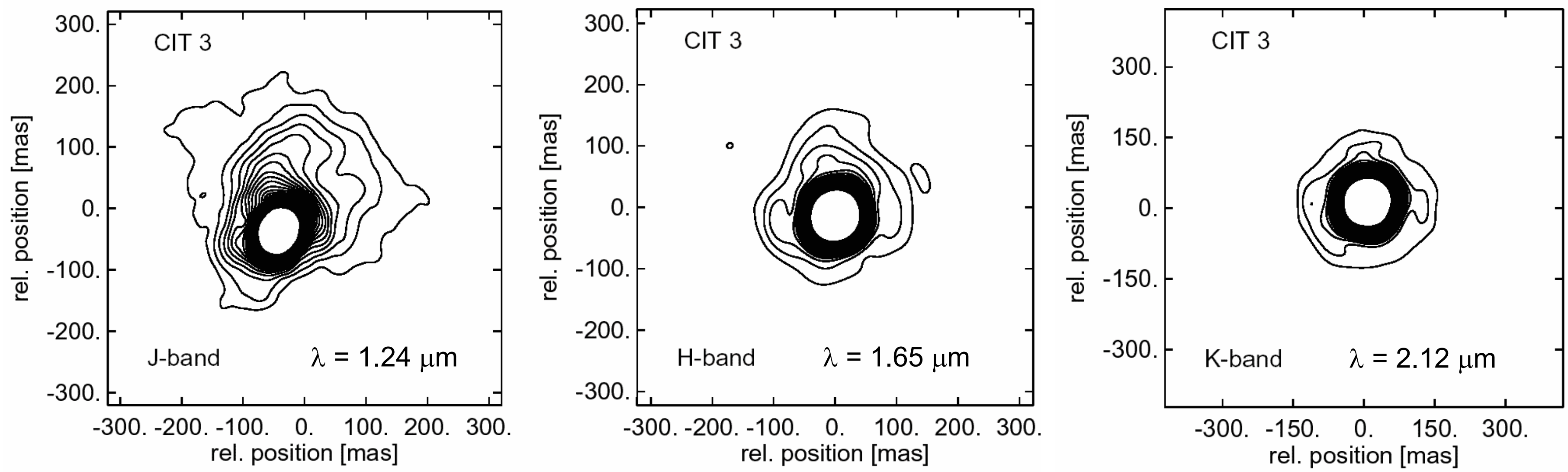
T gradient $\Rightarrow$ absorption feature

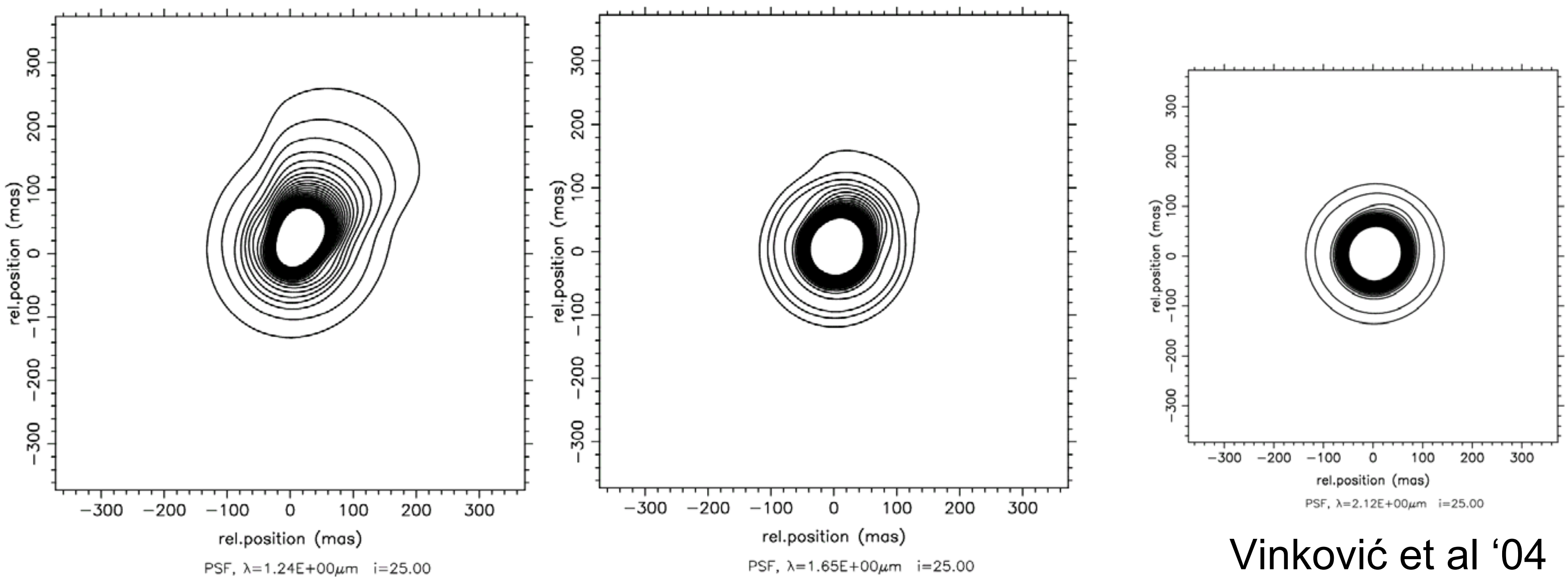
# Scattering vs Emission

- Dust sublimation at T $\gtrsim$ 1500 K
- No dust emission at $\lambda \lesssim 3$ $\mu$m
- Scattering traces the dust density distribution
- Emission reflects also the temperature profile

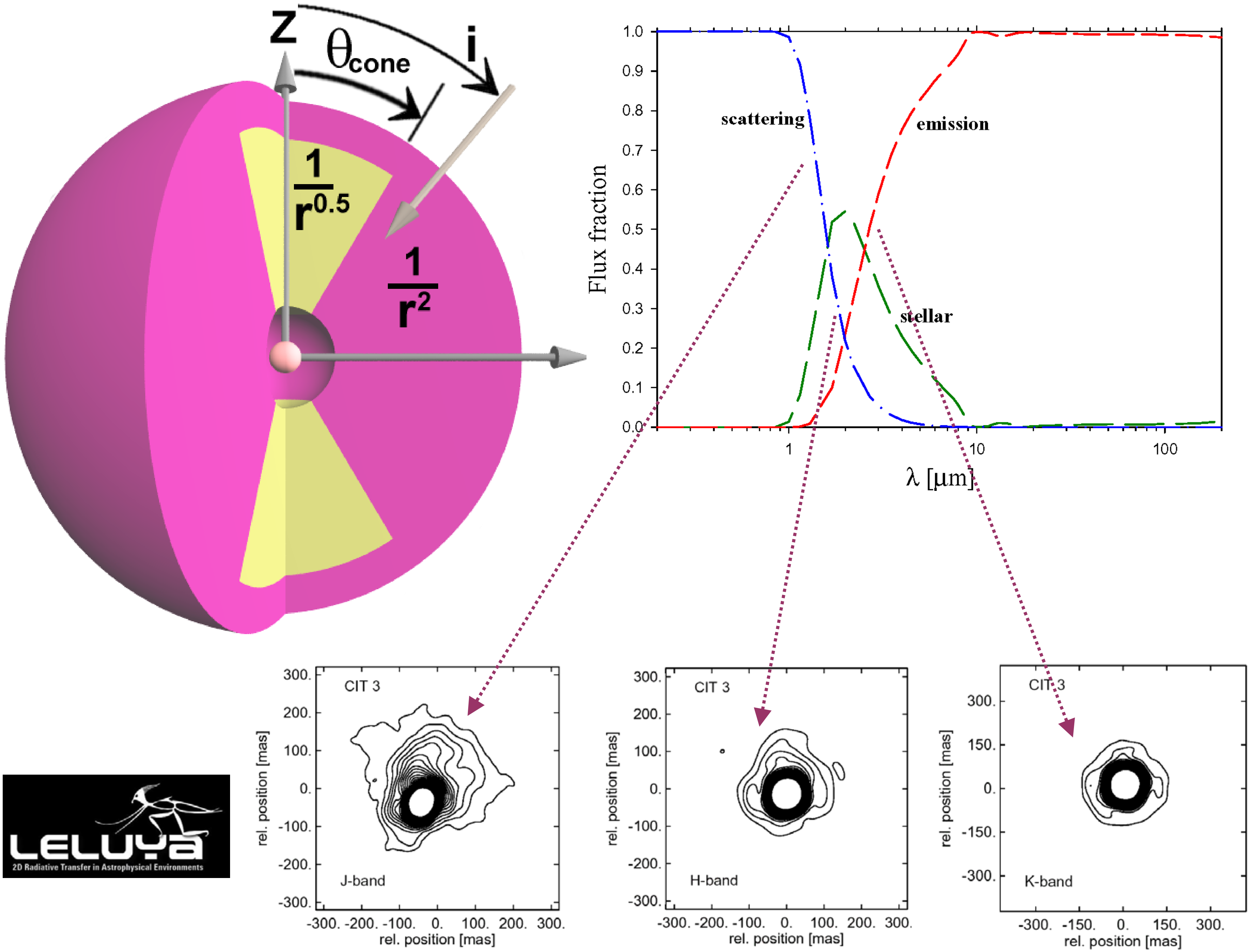
# IRC+10011 (CIT3)

Hofmann et al '01

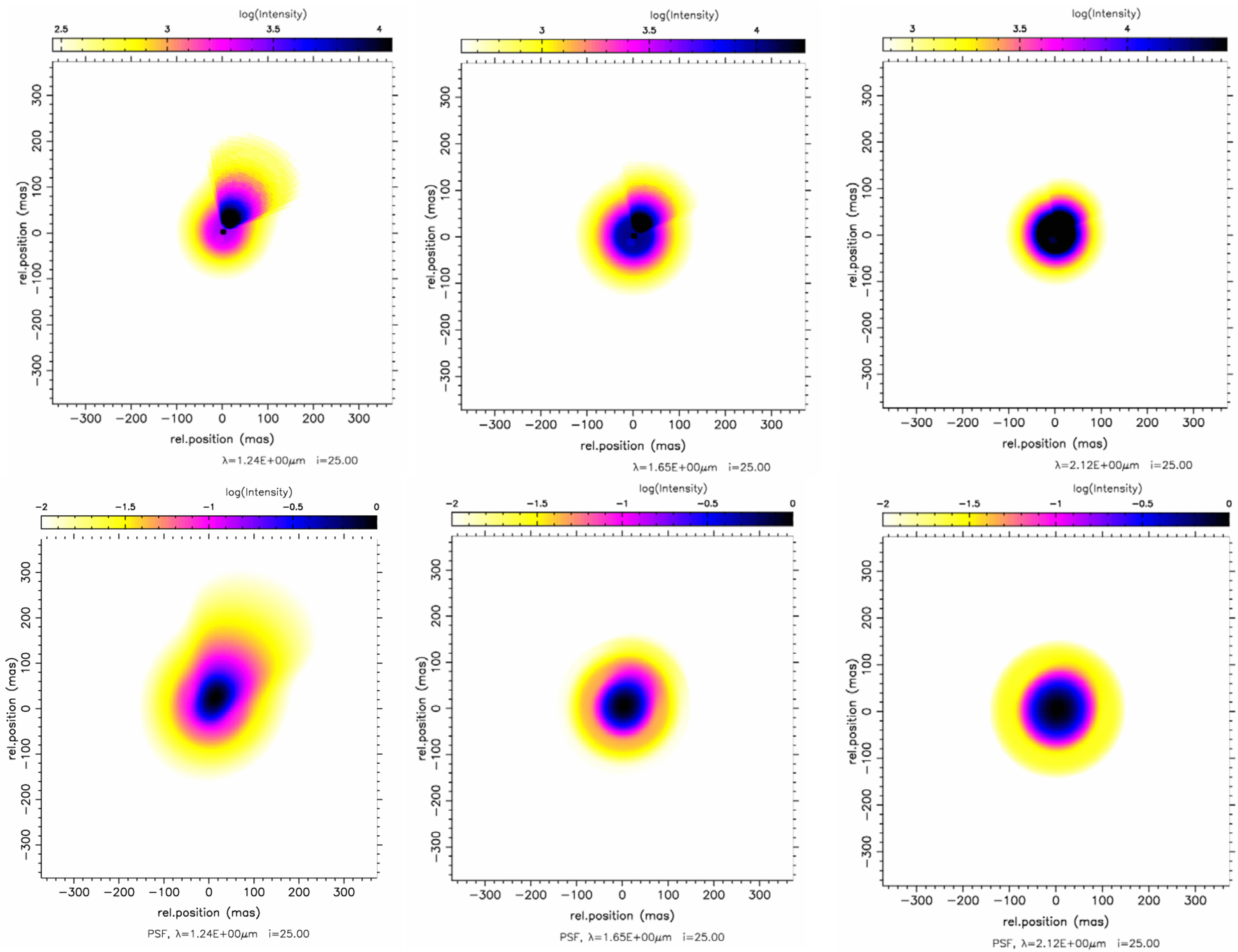



Vinković et al '04



Z
θcone
i
1/r^0.5
1/r^2
Flux fraction
scattering
emission
stellar
λ [μm]
CIT 3
J-band
H-band
K-band
rel. position [mas]
LELUYA
2D Radiative Transfer in Astrophysical Environments



log(Intensity)
rel.position (mas)
λ=1.24E+00μm i=25.00
λ=1.65E+00μm i=25.00
λ=2.12E+00μm i=25.00
PSF, λ=1.24E+00μm i=25.00
PSF, λ=1.65E+00μm i=25.00
PSF, λ=2.12E+00μm i=25.00

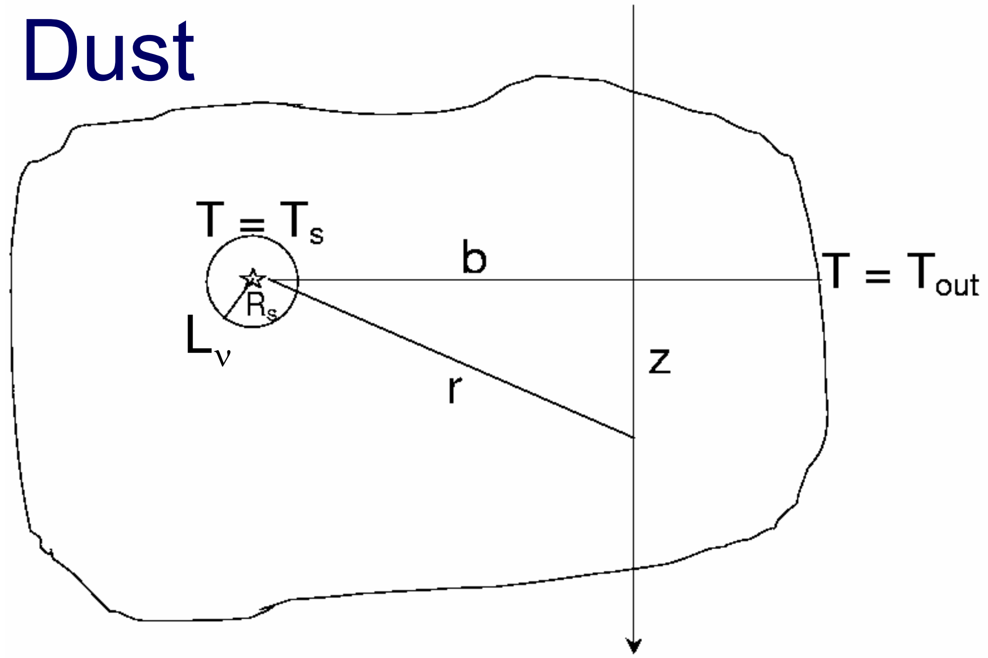
# Lesson #1

What you see is <u>not</u> necessarily what you get

(depending on the wavelength!)

# Optically Thin Dust

Vinković et al '03,
MNRAS 346, 1151

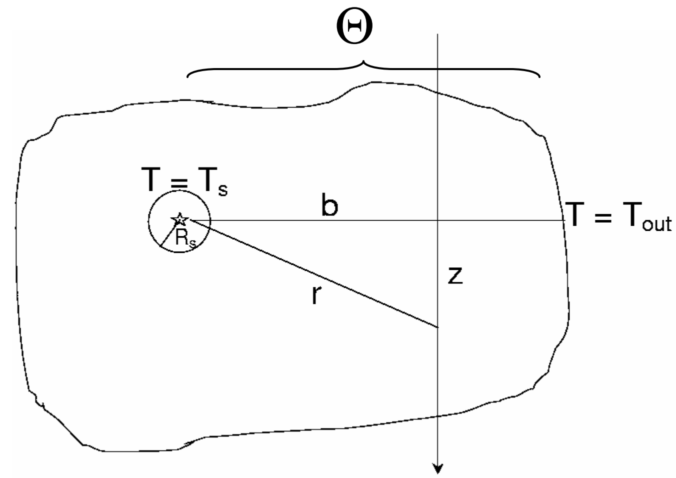



$$I_\nu(b) = \sigma_\nu \int [(1 - \varpi_\nu)B_\nu + \varpi_\nu J_\nu]\, n_d dz$$

$\lambda \lesssim 3\mu m$: $$I_\nu(\theta) = \frac{L_\nu}{4\pi}\varpi_\nu\sigma_\nu \int \frac{n_d dz}{r^2}$$ $\theta = b/D^2$

Because of $\varpi_\nu\sigma_\nu$, image size <u>decreases</u> with wavelength at the same brightness level

# Emission ($\lambda \gtrsim 3\mu m$)




$I_\nu(\theta) = \sigma_\nu \int B_\nu(T) n_d dz$

$B_\nu(T) \approx (2\nu^2/c^2)\, kT \qquad T > T_\nu$

$\approx 0 \qquad T < T_\nu$

$T_\nu = 0.56\, h\nu/k$

$\lambda_{out} = 100\mu m\, (40\ K/T_{out})$

$\lambda > \lambda_{out} \Rightarrow$ full contribution; size = $\Theta$

$\lambda < \lambda_{out} \Rightarrow$ truncate at $T(b) < T_\nu$

$$\theta_\lambda = \Theta \times \begin{cases} (\lambda/\lambda_{out})^{1/t} & \lambda < \lambda_{out} \\ 1 & \lambda > \lambda_{out} \end{cases}$$

$T = 2/(n + 4)$

SED: $\lambda > \lambda_{out} \Rightarrow F_\nu \propto \nu^2 \sigma_\nu$

$\lambda < \lambda_{out} \Rightarrow F_\nu \propto \nu^2 \sigma_\nu \theta_\lambda^{3-(p+t)}$ p density index

CLOUD COMPRESSION

⇓

COLLAPSE

⇓

FRAGMENTATION

⇓

PROTOSTRAS

| | |
|---|---|
| $M < M_c$ | $M > M_c$ |
| ⇓ | ⇓ |
| PMS STARS | MS STARS |
| ⇓ | |
| MS STARS | |

- Envelope evolves on free-fall time scale:

$$t_{ff} = 2x10^5\ (10^4\ cm^{-3}/n)^{1/2}\ years$$

- Hydrostatic PMS low-mass ($M \lesssim 3M_\odot$) core evolution:

$$t_{pms} \sim 3x10^7 (M_\odot/M)^3\ years$$

| | |
|---|---|
| $M \lesssim 2\ M_\odot$ | T-Tauri |
| $2\ M_\odot \lesssim M \lesssim 10\ M_\odot$ | Herbig Ae/Be |
| $M \gtrsim 10\text{–}15\ M_\odot$ | no PMS |

# Protostellar Accretion Disks

- $R \sim$ 10's — 100's AU
- $M \sim .01 — .1\ M_\odot$

Observational Evidence:

√ T Tau stars ($M \lesssim 2\ M_\odot$)

? Herbig Ae/Be stars
($2\ M_\odot \lesssim M \lesssim 10\ M_\odot$)

IR ?

??? High mass ($M \gtrsim 10\ M_\odot$)

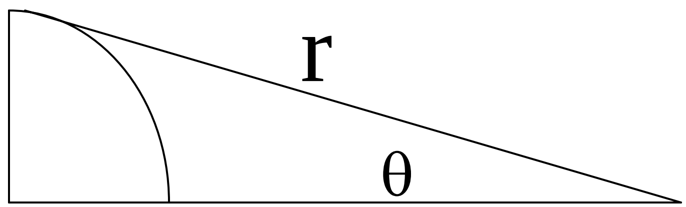
# Protostellar Accretion Disks

Geometrically thin, optically thick:

$$\tau \sim nR = \frac{nR^3}{R^2} \sim \frac{M}{R^2}$$

$I_\lambda = B_\lambda(T)$, need temperature distribution

# Illuminated Disk



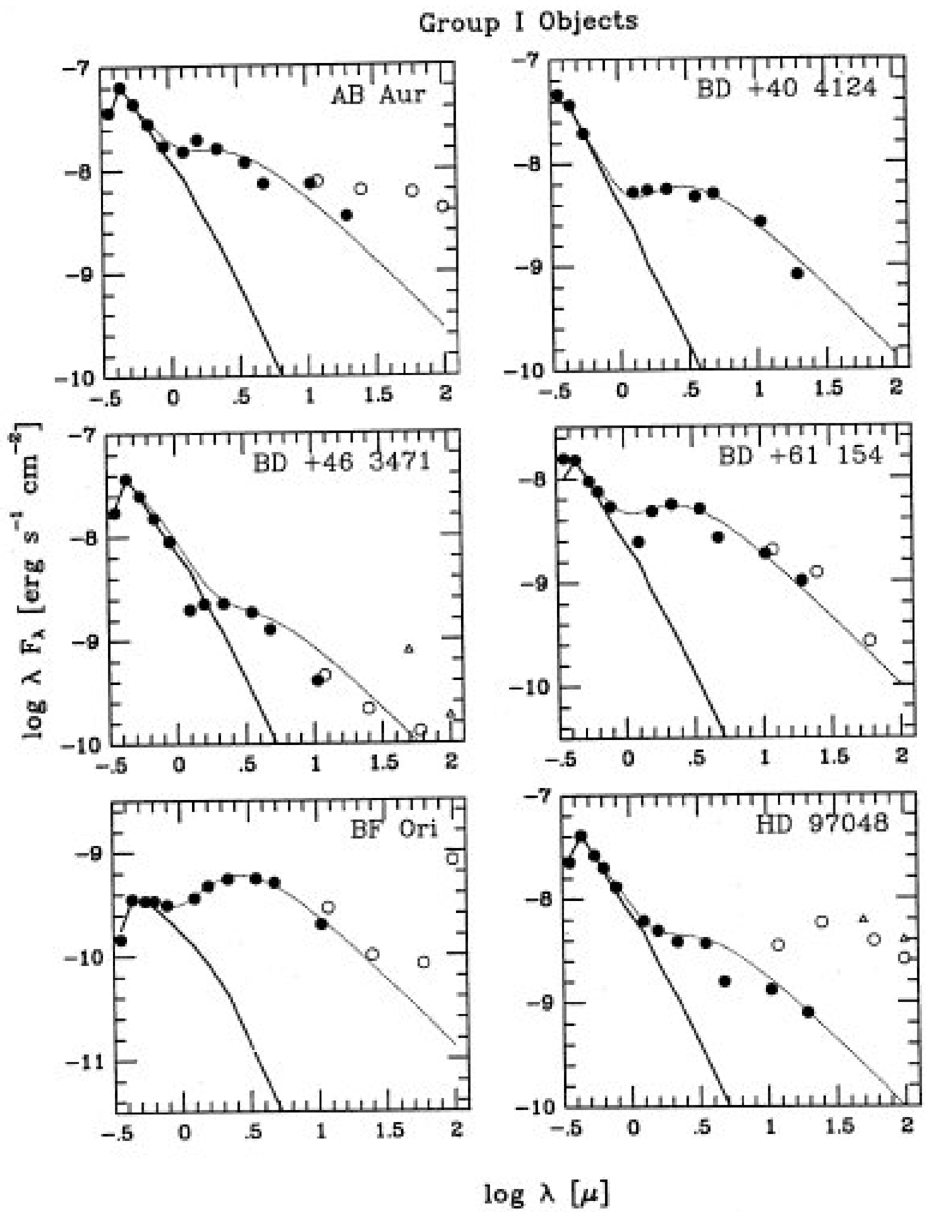

- Heating: $F_{abs} = \frac{L_*}{4\pi r^2} \sin\theta \propto r^{-3}$
- Cooling: $F_{em} = \sigma T^4$
- Balance: $T \propto r^{-3/4}$ (accretion too!)

yields:

$$\lambda F_\lambda \propto \lambda^{-4/3}$$

Hillenbrand et al '92

- Group 1 (30):
  $\lambda F_\lambda \propto \lambda^{-4/3}$, disks
- Group 2 (11):
  flat or rising SED, star/disk with additional shell
- Group 3 (6):
  small IR excess



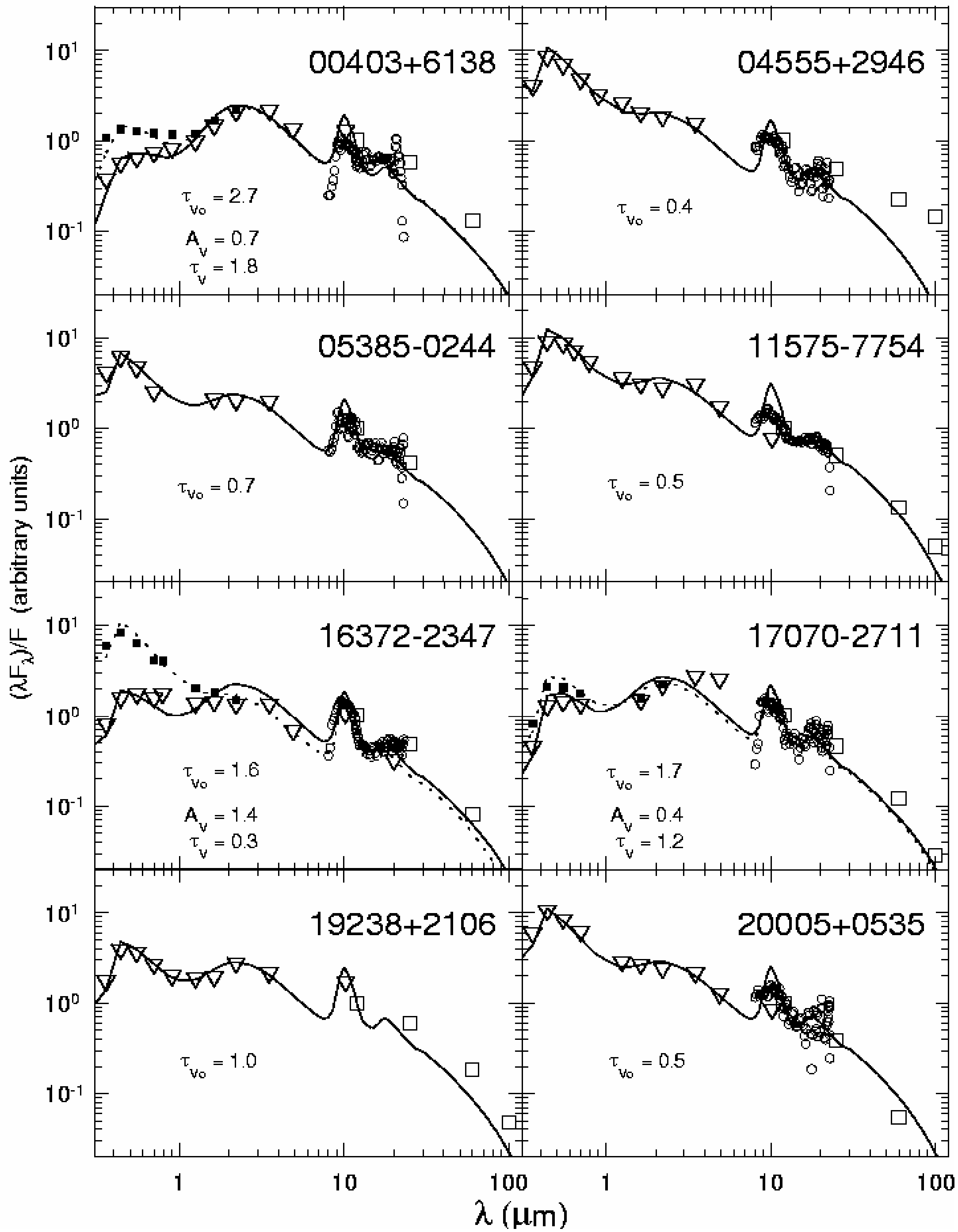
# Problems:

- Hartman et al ’93:
  accretion rates are excessive

- Di Francesco et al ’94:
  group 1 IR emission is extended!

MIE '97:

$\rho \propto r^{-3/2}$



Mannings & Saregnt ’97:

2.6 mm incompatible with MIE:

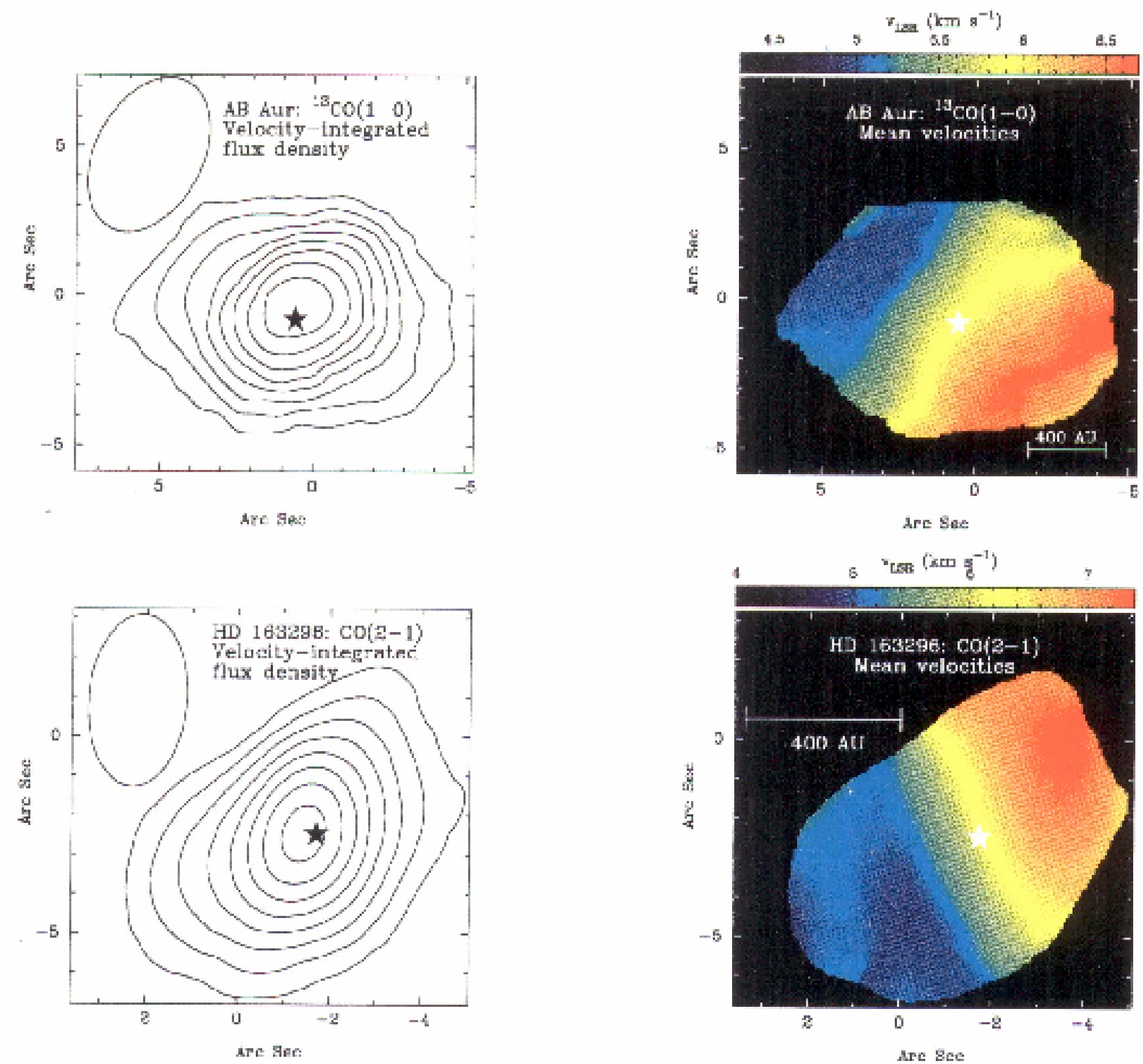
$\tau_V \sim 10^2 – 10^3$ — nonsense!

In particular

| | MWC480 | MWC683 |
|---|---|---|
| MS | $\tau_V > 10^3$ | 600 |
| MIE | $\tau_V = 0.4$ | 0.3 |

Conclusion: DISKS!

indeed:


AB Aur: $^{13}$CO(1–0)
Velocity-integrated flux density
AB Aur: $^{13}$CO(1–0)
Mean velocities
$v_{LSR}$ (km s$^{-1}$)
400 AU
HD 163296: CO(2–1)
Velocity-integrated flux density
HD 163296: CO(2–1)
Mean velocities
400 AU
Arc Sec

# However…

## Extrapolate from 2.6 mm with $F_\nu \propto \nu^{1/3}$ — too little 2.2 μm!

- IR best explained with optically thin envelopes, inconsistent with mm
- mm emission best explained with optically thick disks, inconsistent with IR

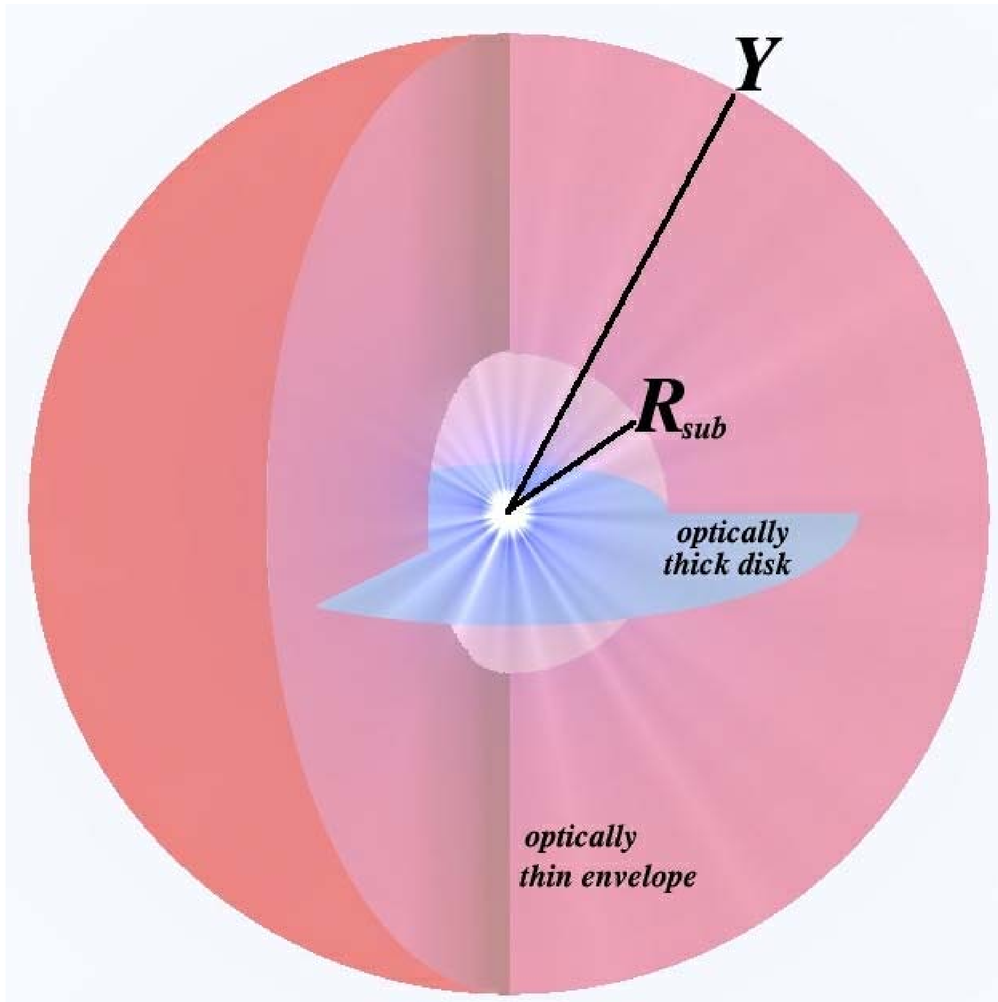
Also, MWC 137 imaging:

$\theta$(50 μm) = 66"± 2"

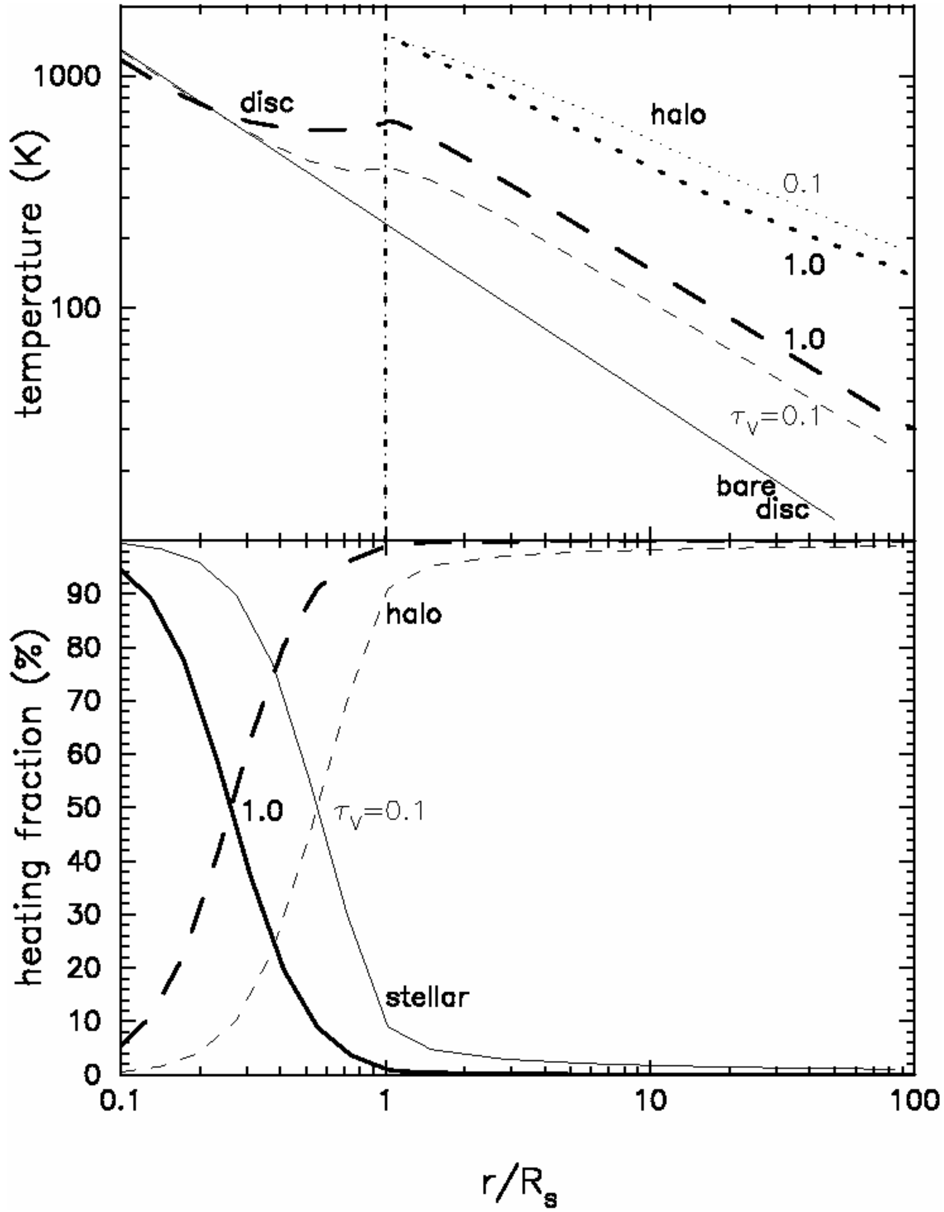
$\theta$(100 μm) = 58"± 2"

How can that be?

Disk Imbedded in Envelope:



Halo's impact on disk heating



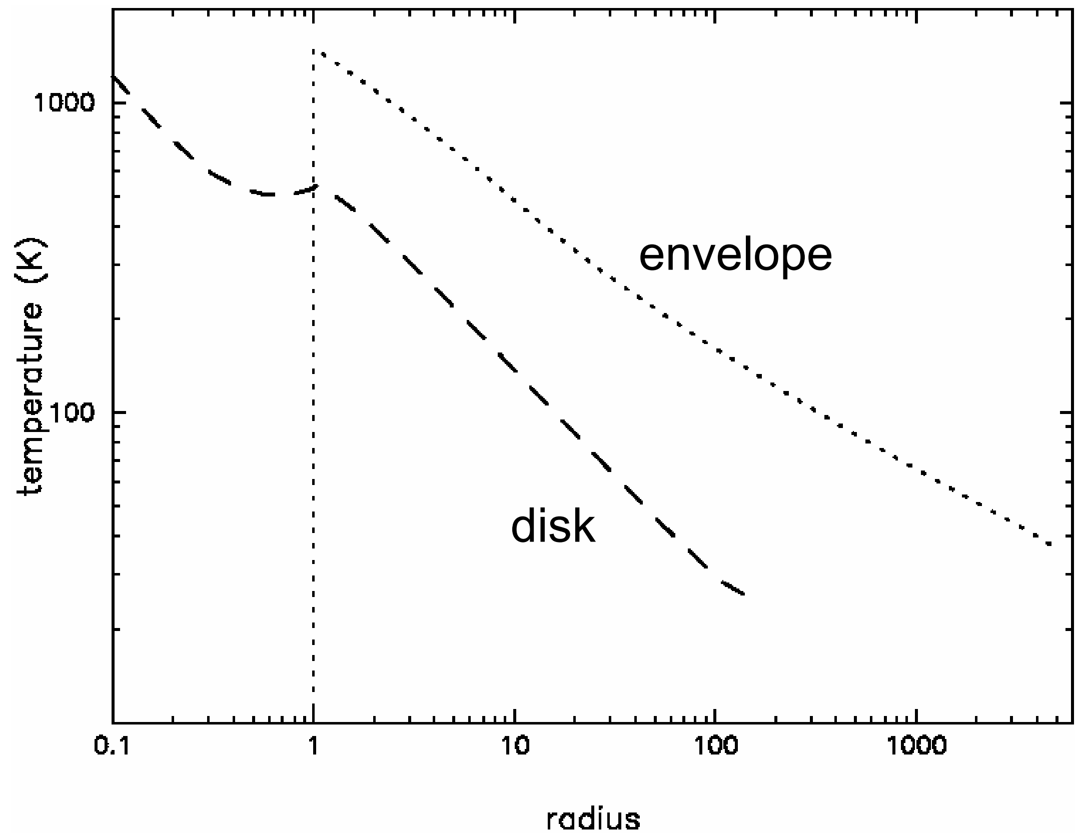
## Disk Imbedded in Envelope:

envelope ( $\kappa \propto \lambda^{-1.5}$):

$$T \propto r^{-0.36}$$

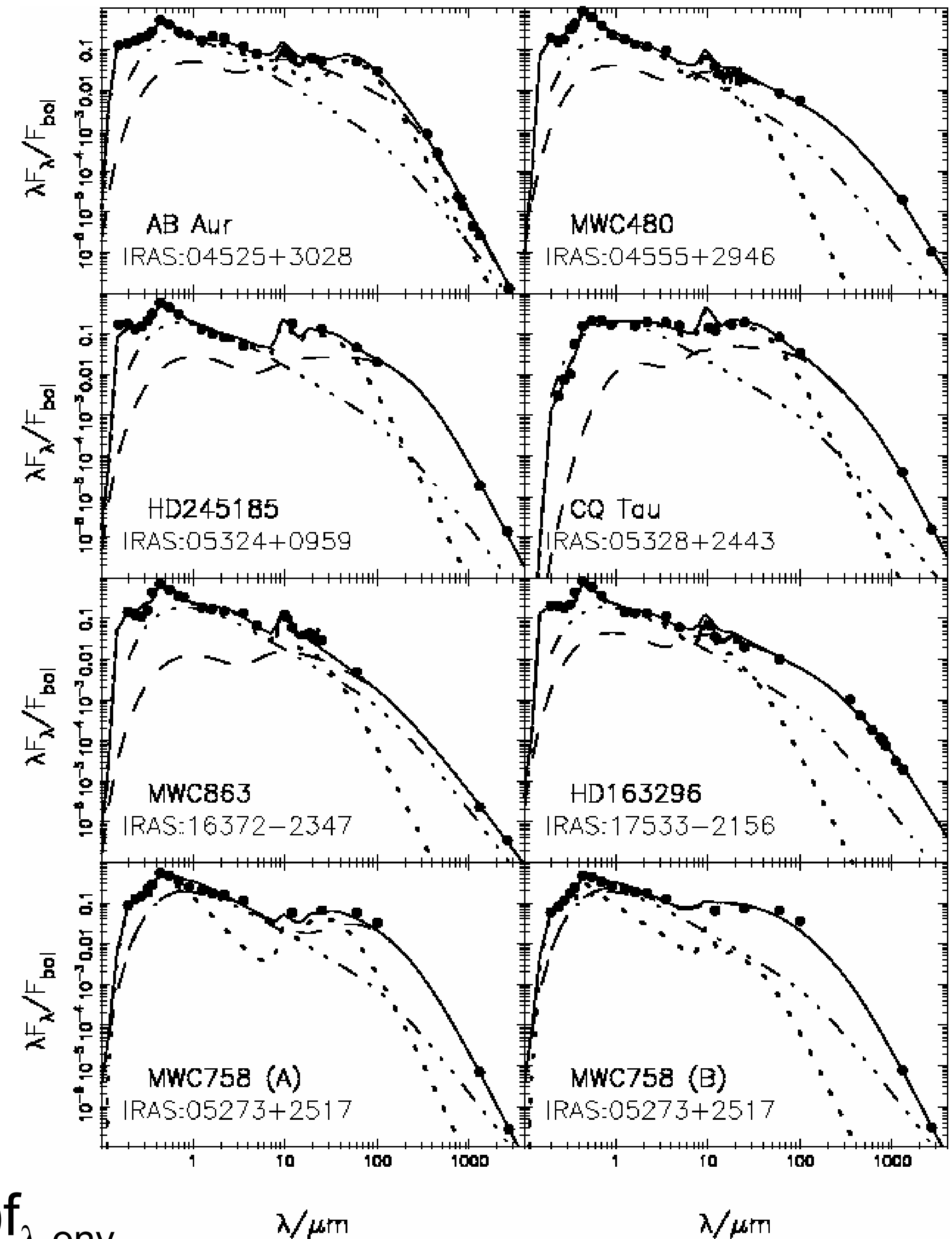
"standard" disk:

$$T \propto r^{-0.75}$$




- At the same radius, disk is cooler than envelope
- Smaller disk still contains cooler material

MIVE '99



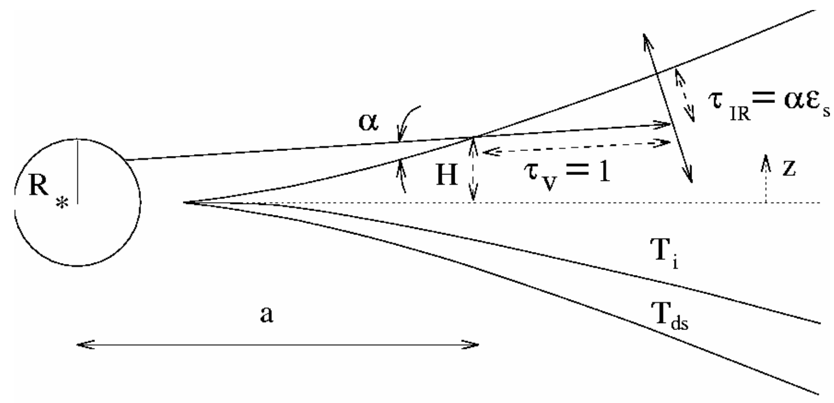

$$f_\lambda = \rho f_{\lambda,disk} + (1 - \rho) f_{\lambda,env}$$

2 distributions:

- Disk: compact mm emission
- Envelope:
  - IR emission
  - Disk heating

# ??? Uniqueness ???

Chiang & Goldreich '97:



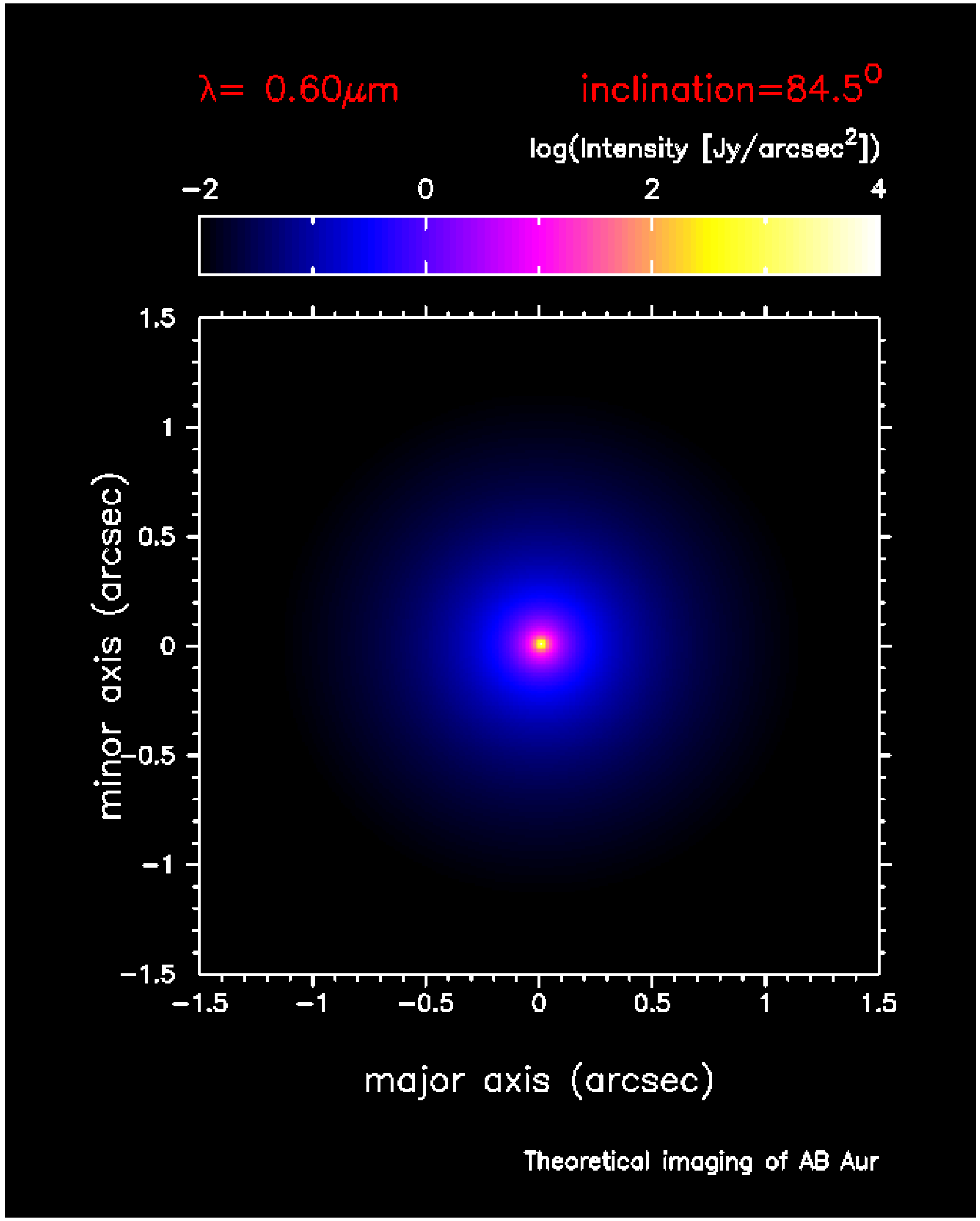

- Disk surface layer may mimic shell with density profile $\eta$

$$F_{CG} = \frac{2\pi R_s^2}{D^2} q_\nu \int B_\nu(T)\alpha\, a da \qquad F_{sph} = \frac{4\pi R_s^2}{D^2} q_\nu \int B_\nu(T)\eta\, y^2 dy$$

Flaring profile $\alpha$ $\Leftrightarrow$ spherical density profile $\alpha(r)/r$

**SED degeneracy!!!**

Multi-wavelength imaging essential for determining the geometry



λ= 0.60μm
inclination=84.5°
log(Intensity [Jy/arcsec²])
−2
0
2
4
1.5
1
0.5
0
−0.5
−1
−1.5
minor axis (arcsec)
−1.5
−1
−0.5
0
0.5
1
1.5
major axis (arcsec)
Theoretical imaging of AB Aur