T Tauri Systems: Radiative Diagnostics

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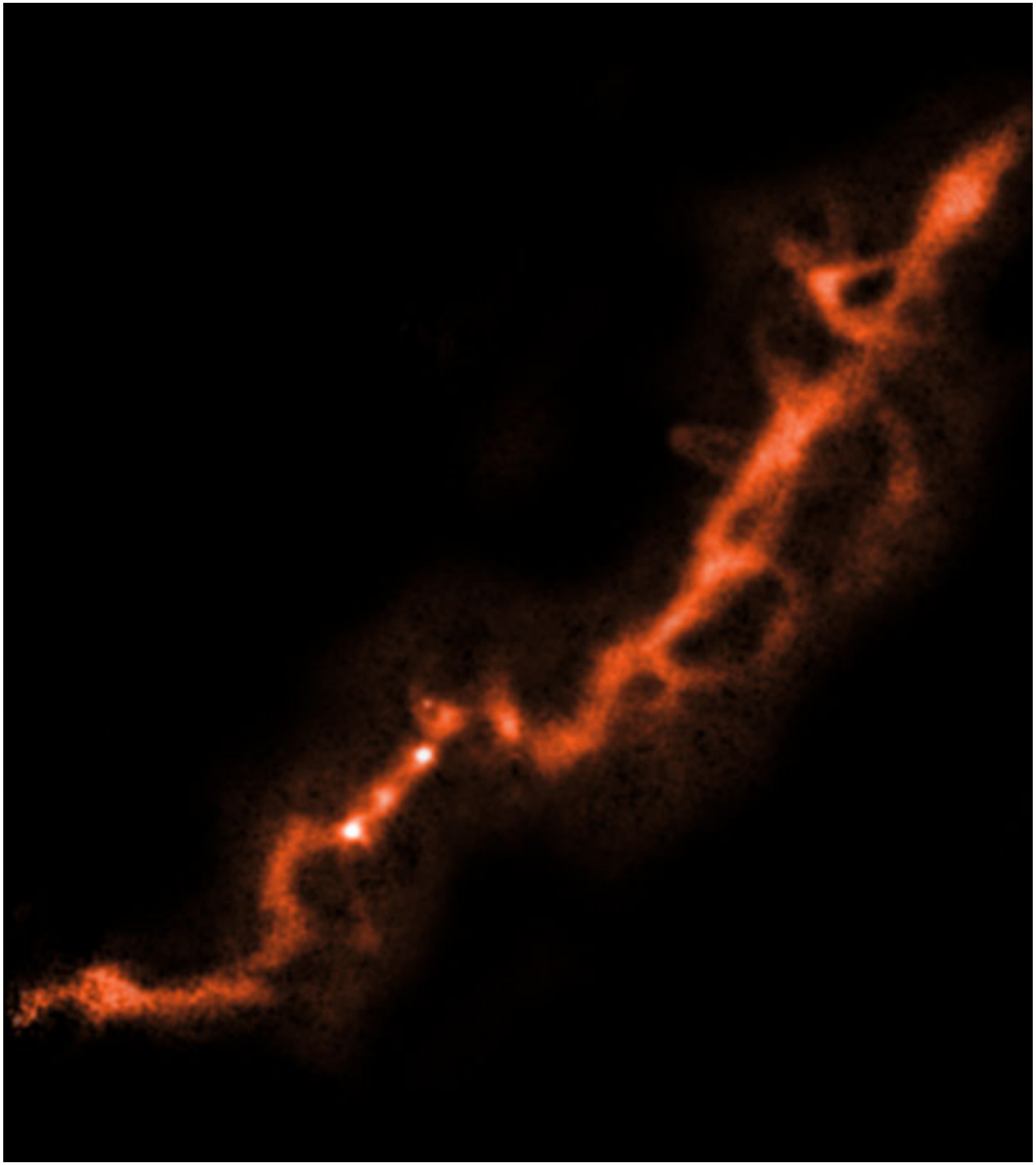
Outline

- What?
- Why?
- Classification
- Veiling
  - Structure
  - Mass accretion
- (Disk mass)
- Inner disk radii
- Gas spectrometry

What Are T Tauri Stars?

- Pre-main sequence stars
- Variable
- Strong emission
- Lithium

ESO/APEX



ESO/APEX

Why T Tauri Stars?

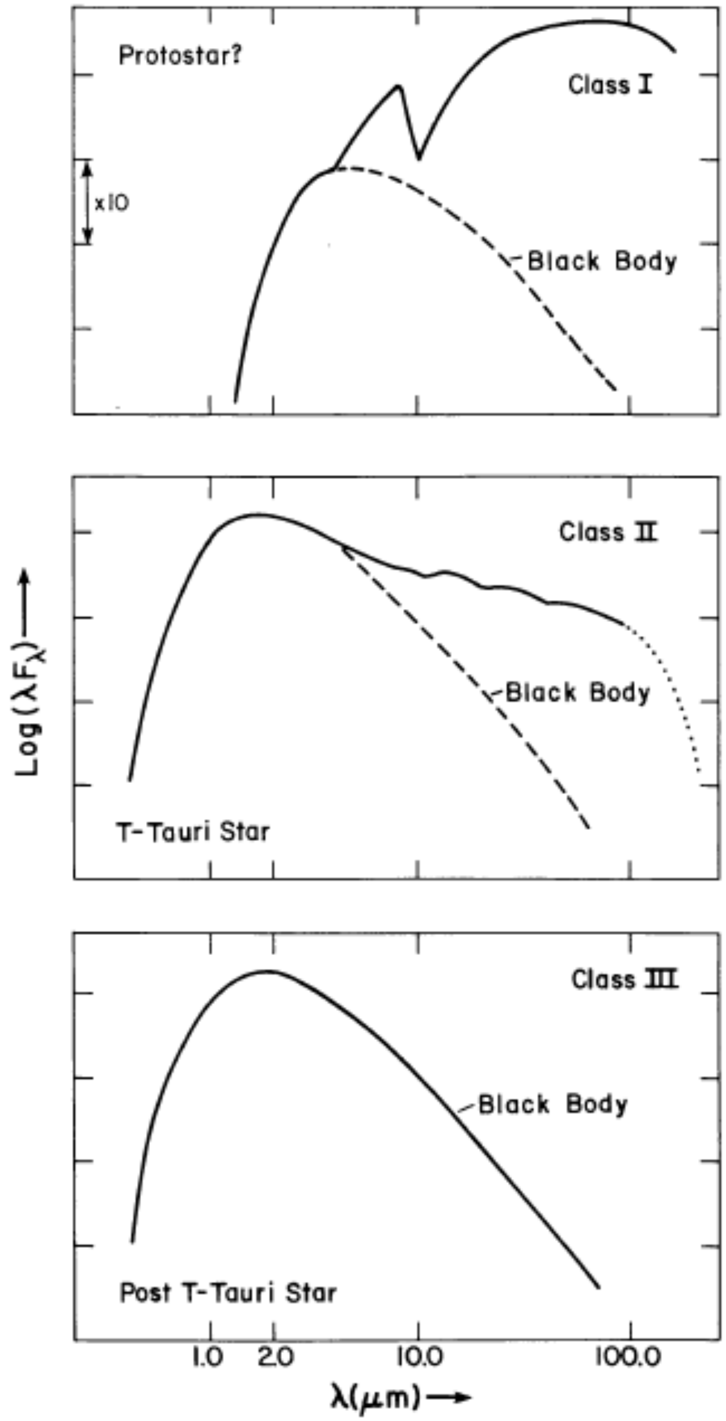
- Potential environment for planet formation
- Stage of evolution of most stars
- Unique physics

Why Spectral Diagnostics?

- In most cases, we do not have spatially-resolved data for T Tauri systems, so we need a theoretical understanding of several factors that characterize the system:
  - Structure (e.g., flaring parameter, layers, inner/outer disk/envelope radii)
  - Temperature
  - Density, mass, mass accretion
  - Chemistry (dust)

Classification

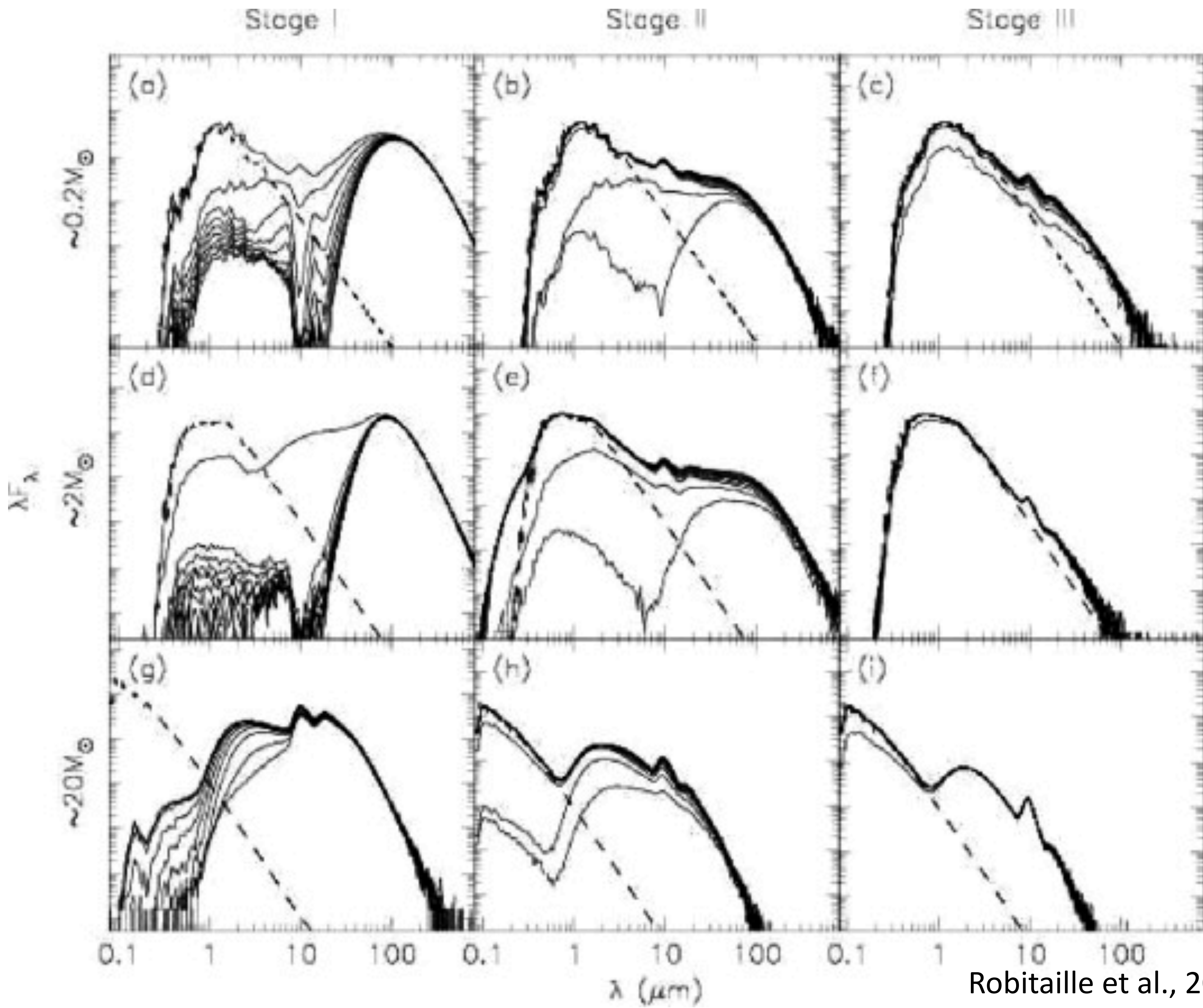
- Class 0
  - Protostar
- Class I
  - ‘Embedded’
  - Envelope-dominated
- Class II
  - Disk-dominated
- Class III
  - No disk, envelope


Protostar?
Class I
x10
Black Body
Class II
Black Body
T-Tauri Star
Class III
Black Body
Post T-Tauri Star
1.0
2.0
10.0
100.0
λ(μm)
Log(λFλ)

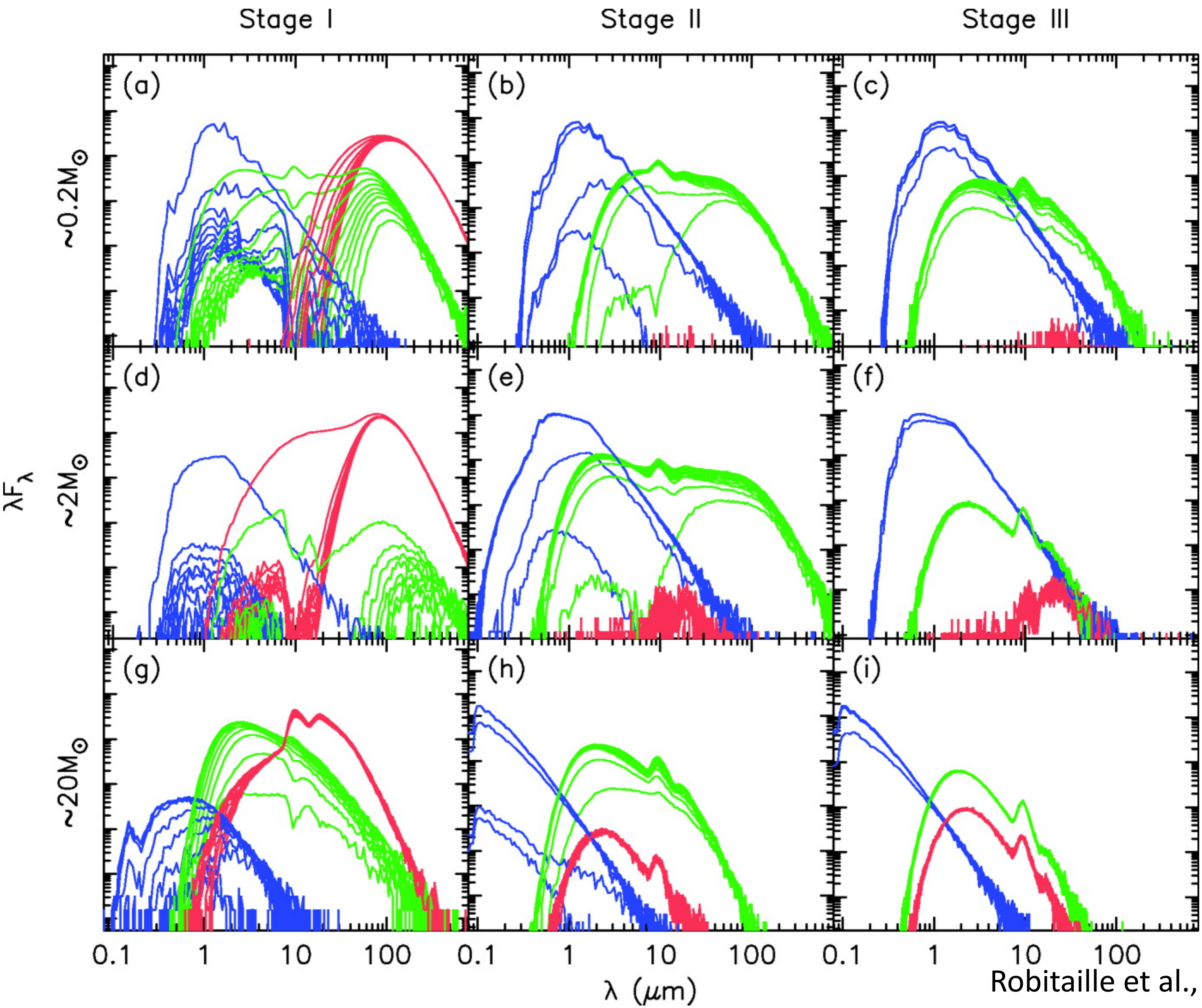
Lada, 1987

Classification II

- Spectral Index
  - Measure of slope of IR excess
    - $\alpha > 0$ Class I
    - $-2 < \alpha < 0$ Class II
    - $\alpha < -2$ Class III
- Classes based on spectral index do not necessarily represent an evolutionary stage
  - Inclination
  - Temperature
  - ‘Class’ vs. ‘Stage’



Robitaille et al., 2006



Robitaille et al., 2006

Veiling

- Irradiation versus accretion:

$$\dot{M}_{crit} = 3.3 \times 10^{-8} M_{\odot} yr^{-1}$$

- Mass accretion proportional to excess luminosity, or 'veiling':

$$L_{acc} \approx \frac{GM\dot{M}}{R}$$

$$L = (F + F_*)A = (1 - \frac{R}{R_{inner}})\frac{G\dot{M}M}{R} + F_*A = (1 - \frac{R}{R_{inner}})L_{acc} + F_*A$$

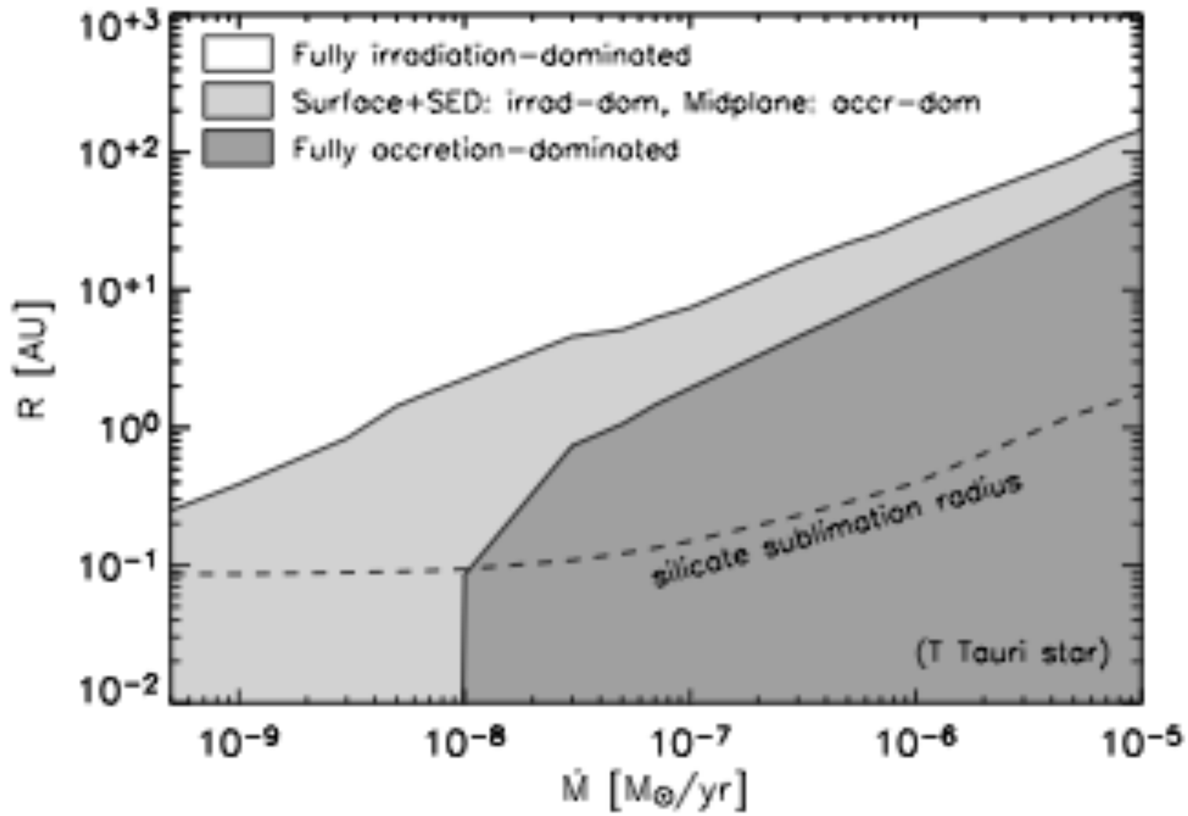


Fig. 3.— Characteristic radii of a disk around a $0.9\ M_\odot$ star with $T_* = 4000$ K and $R_* = 1.9\ R_\odot$ at different accretion rates. The silicate sublimation radius is the dust 'inner rim'. Figure based on models by *D'Alessio et al*. (1998).

Dullemond et al., 2006

Structure

- First-order
  - Parallel-plane disk
  - Irradiation angle due to finite stellar size, $\phi = .4 \frac{r_*}{r}$
  - Irradiation flux, $F = \frac{1}{2} \phi \frac{L_*}{4\pi r^2}$,
  - Equation with blackbody radiation temperature yields $T \propto r^{-3/4}$
- A $T \propto r^{-q}$ relation yields $\alpha = (4q - 2)/q$

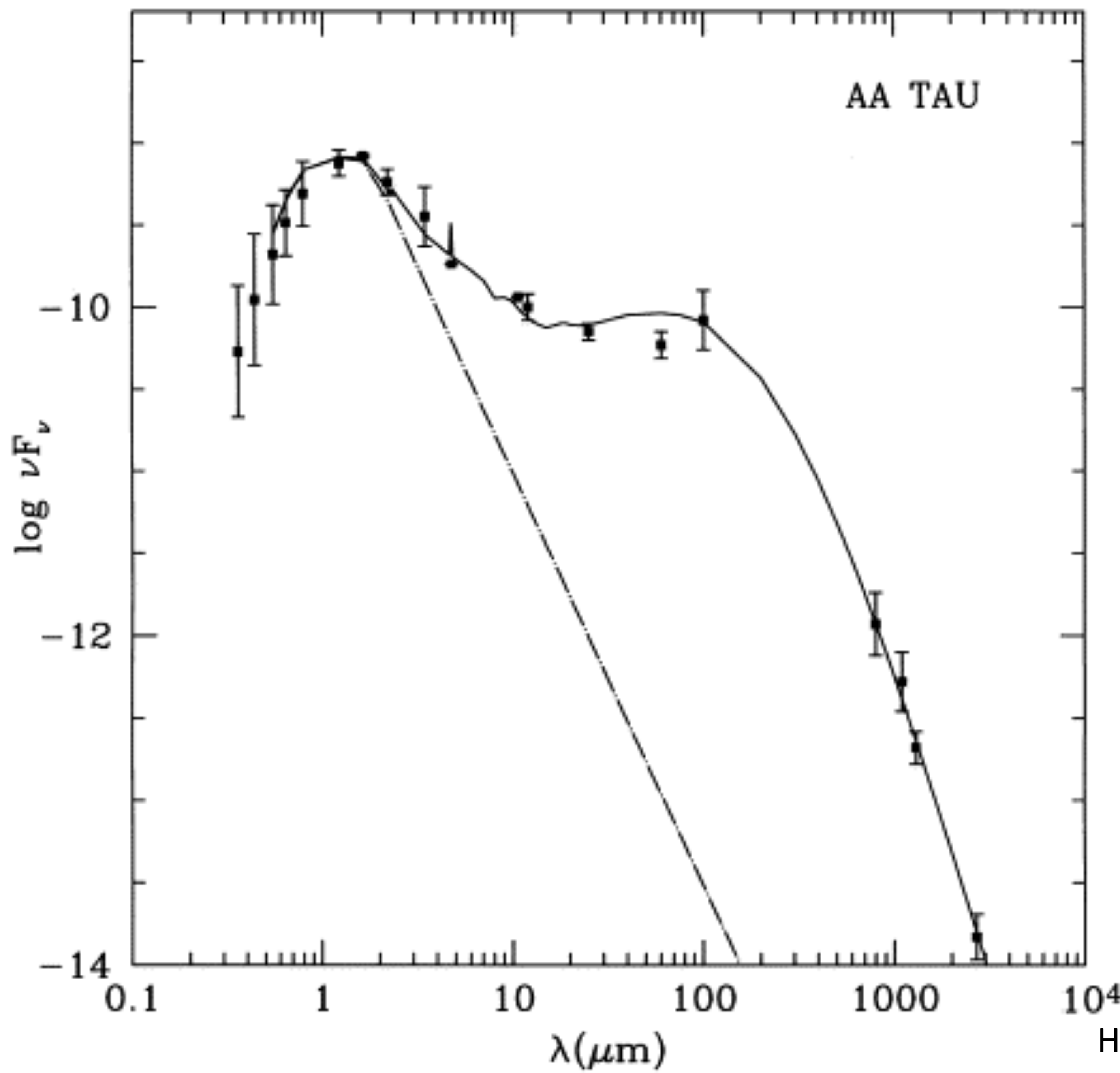
Structure II

- Second-order correction
  - Flaring parameter, β

$$\phi = .4\frac{r_*}{r} + r\frac{d(H_s/r)}{dr}$$

$$H_p = \sqrt{\frac{kT_{mid}r^3}{\mu m_p G M_*}}$$

  - For numerical calculations, $T_{mid} \propto r^{-.5}$

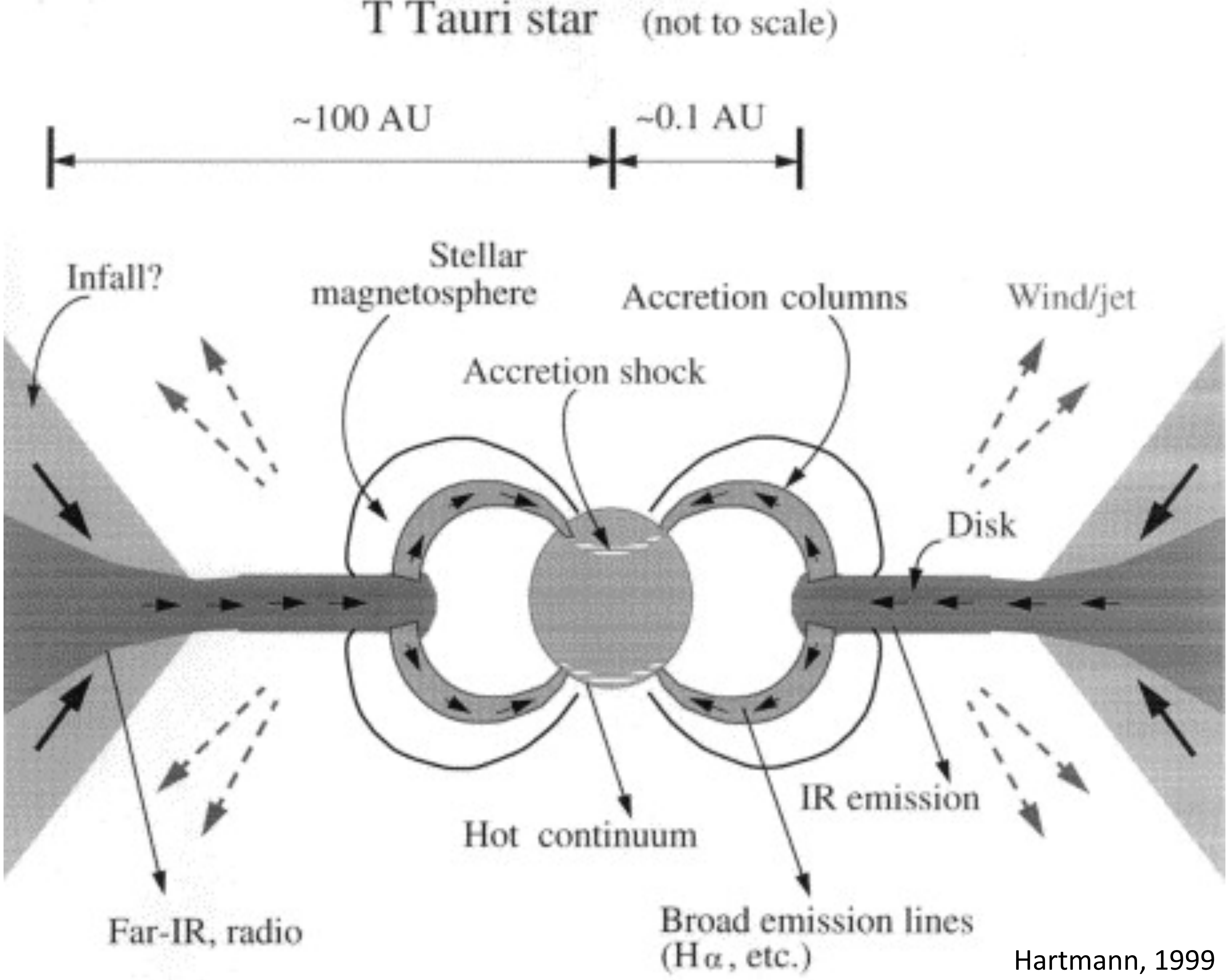


Hartmann, 1999

Fig. 2. Spectral energy distribution (SED) of the typical T Tauri star AA Tau, compared with a "flared disk" mo

Structure III

- Further corrections
  - Varying temperature with height
  - Gas temperature not coupled to dust temperature
  - Viscous heating deep in disk



Hartmann, 1999

Mass Accretion

- If stellar spectrum is known, continuum emission can be deduced
- Gullbring et al., 1998: slab model to connect observed excess flux to total excess flux

$$T_{slab}^4 \approx T_{bl}^4 \tau$$

$$T_{bl}^4 = \frac{GM\dot{M}}{4\pi R_*^3 \sigma f}$$

  - Found constant factor of 3.5

Mass Accretion II

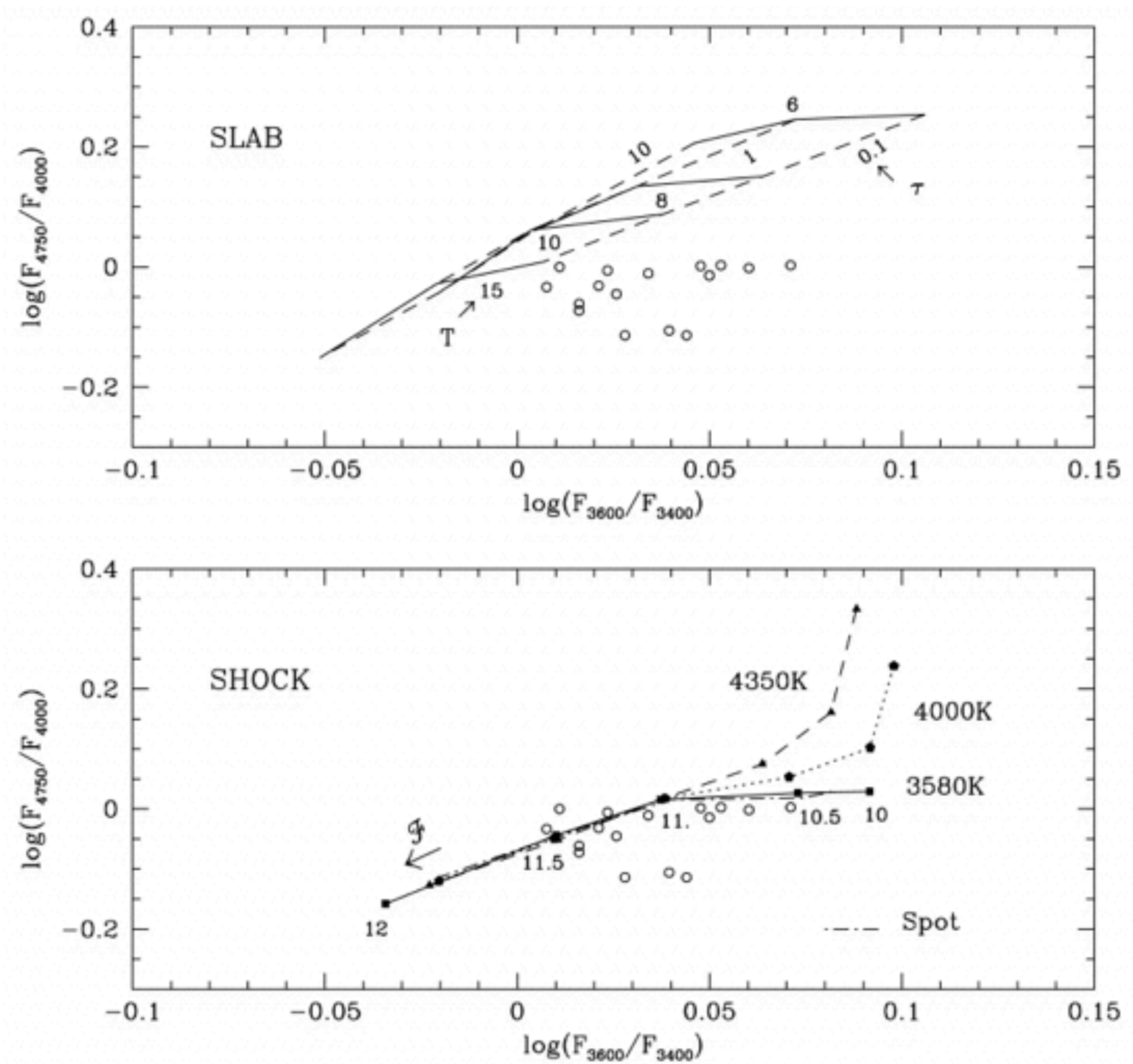
- Calvet and Gullbring, 1998: magnetospheric accretion
- Assume free fall velocity at shock:

$$v_s = \left|\frac{2GM}{R}\right|^{1/2} \left|1 - \frac{R}{R_i}\right|^{1/2}$$

$$= 307 \text{ km s}^{-1} \left(\frac{M}{0.5\, M_\odot}\right)^{1/2} \left(\frac{R}{2R_\odot}\right)^{-1/2} \zeta^{1/2} , \qquad \zeta = \left(1 - \frac{R}{R_i}\right),$$

Ignoring energy addition due to pressure work as well as thermal energy of the accreting gas,

$$F = \frac{1}{2}\rho v^3$$



Calvet and Gullbring, 1998

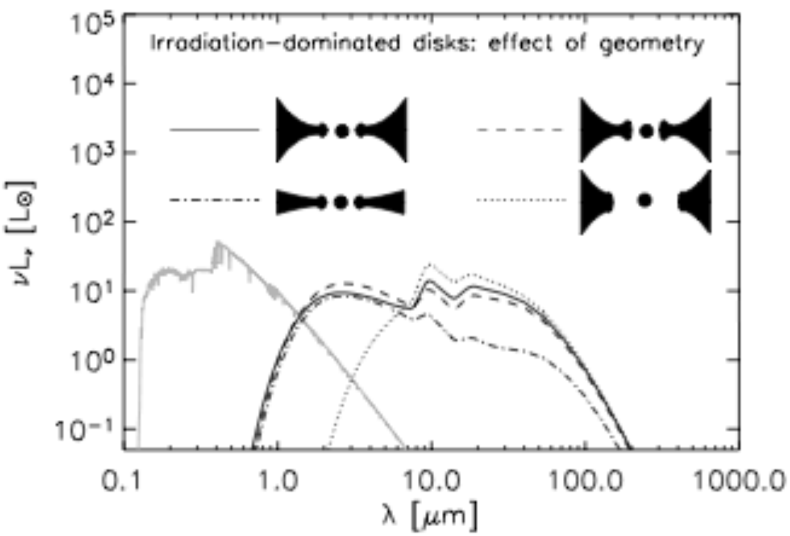


Fig. 5.— Overall SED shape for *non-accreting* disks with stellar irradiation, computed using the 2-D radiative transfer tools from *Dullemond & Dominik* (2004a). The stellar spectrum is added in grey-scale. Scattered light is not included in these SEDs. Solid line is normal flaring disk with inner dust rim; dashed line is when the rim is made higher; dot-dashed line is when the flaring is reduced (or when the disk becomes 'self-shadowed'); dotted line is when the inner rim is at 10× larger radius.

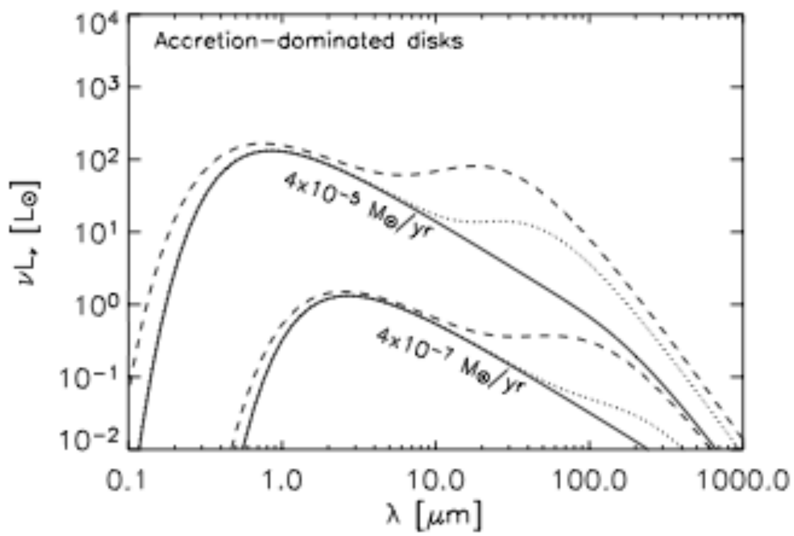


Fig. 6.— Overall SED shape for accreting disks *without* stellar irradiation for two accretion rates. A simple Shakura-Sunyaev model is used here with grey opacities. Solid line: pure Shakura-Sunyaev model (star not included); dotted line: model with disk-self-irradiation included; dashed line: model with disk-self-irradiation *and* irradiation by the magnetospheric accretion column on the star included.

Dullemond et al., 2006

Veiling II

- Luminosity problem
  - Luminosity given by mass accretion is larger than observed by an order of magnitude
  - Also, the accretion rates are too small to account for main sequence masses
- Solutions?
  - Outflows eject accretion energy?
  - Kenyon et al. 1990: instability might account for highly-accreting FU Ori objects
    - FU Ori objects account for only 5-20% of mass of stars forming near us

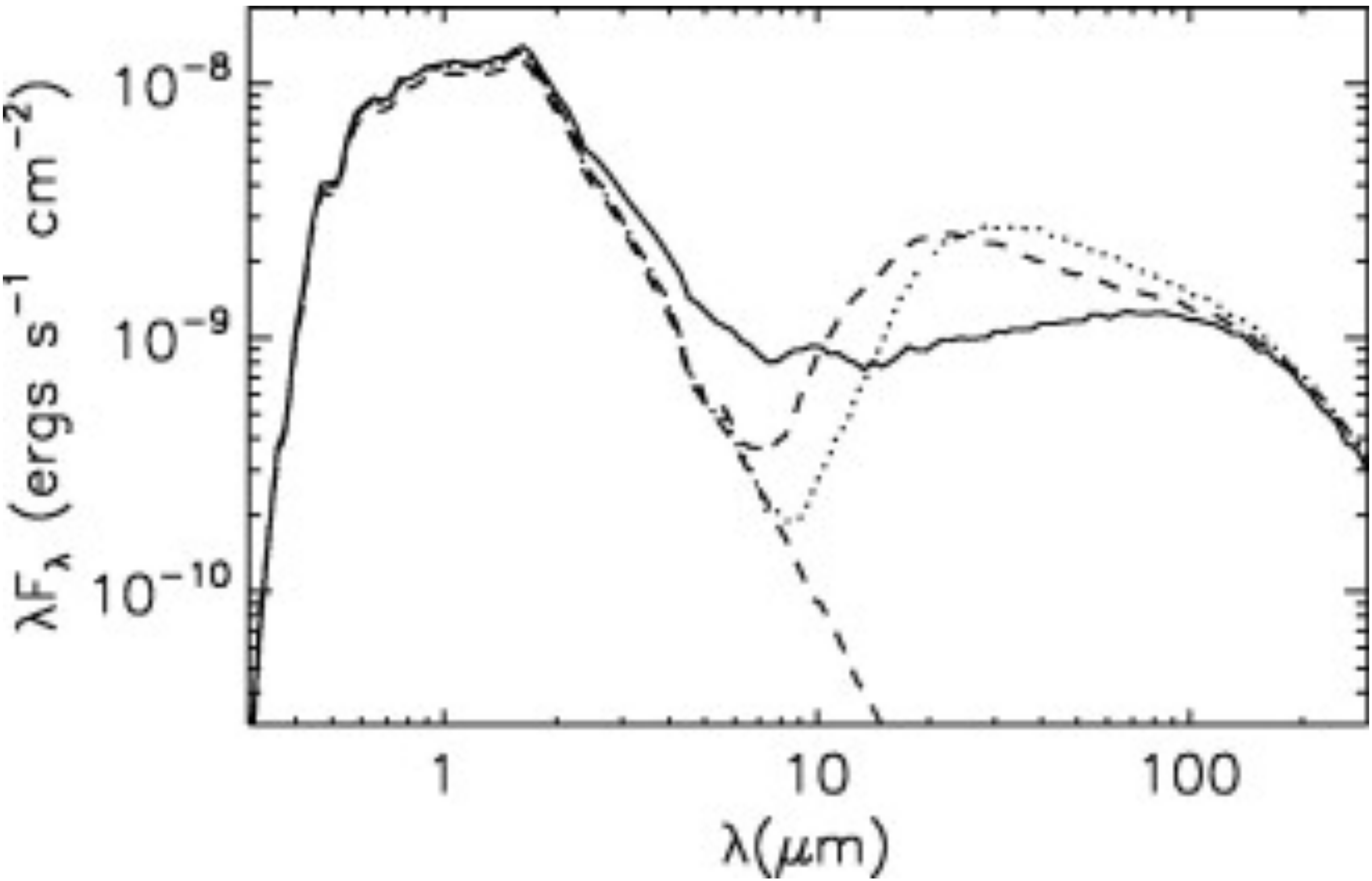
Inner Radius

- Envelope vs. disk
- Gas vs. dust

$$r_{sub} \sim .01AU \text{ for } L_* \sim L_\odot$$

$$r_{sub} \propto \sqrt{L_*}$$

- Or does magnetic field truncate inner radius at or within corotation radius ($\sim 3R_*$)?



Wood, 2008

Gas Spectrometry

- CO
  - Abundant
  - Fundamental transition has large A value
  - Symmetry in overtone lines indicates from rotating regions
  - Emission indicates ‘temperature inversion’
  - Measurements suggests higher gas temperatures than allowed for gas-dust equilibrium models
  - Probe inner radius and beyond

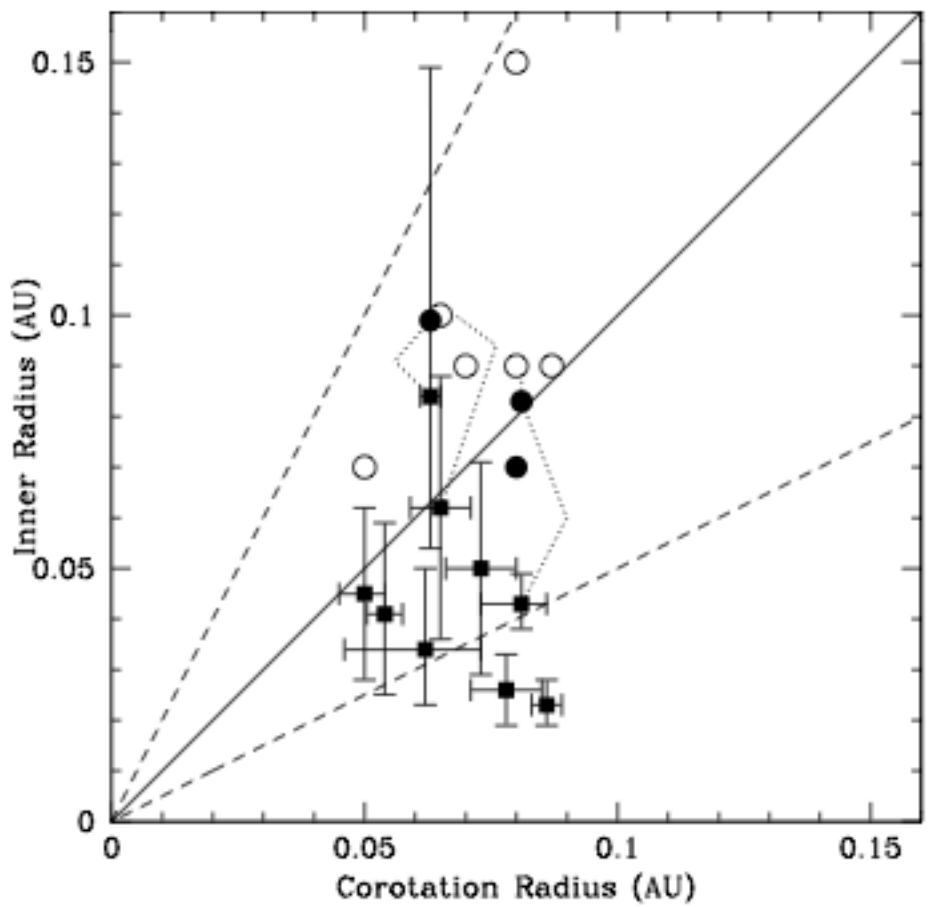


Fig. 2.— Gaseous inner disk radii for TTS from CO fundamental emission (filled squares) compared with corotation radii for the same sources. Also shown are dust inner radii from near-infrared interferometry (filled circles; *Akeson et al.*, 2005a,b) or spectral energy distributions (open circles; *Muzerolle et al.*, 2003). The solid and dashed lines indicate an inner radius equal to, twice, and 1/2 the corotation radius. The points for the three stars with measured inner radii for both the gas and dust are connected by dotted lines. Gas is observed to extend inward of the dust inner radius and typically inward of the corotation radius.

Najita et al., 2007

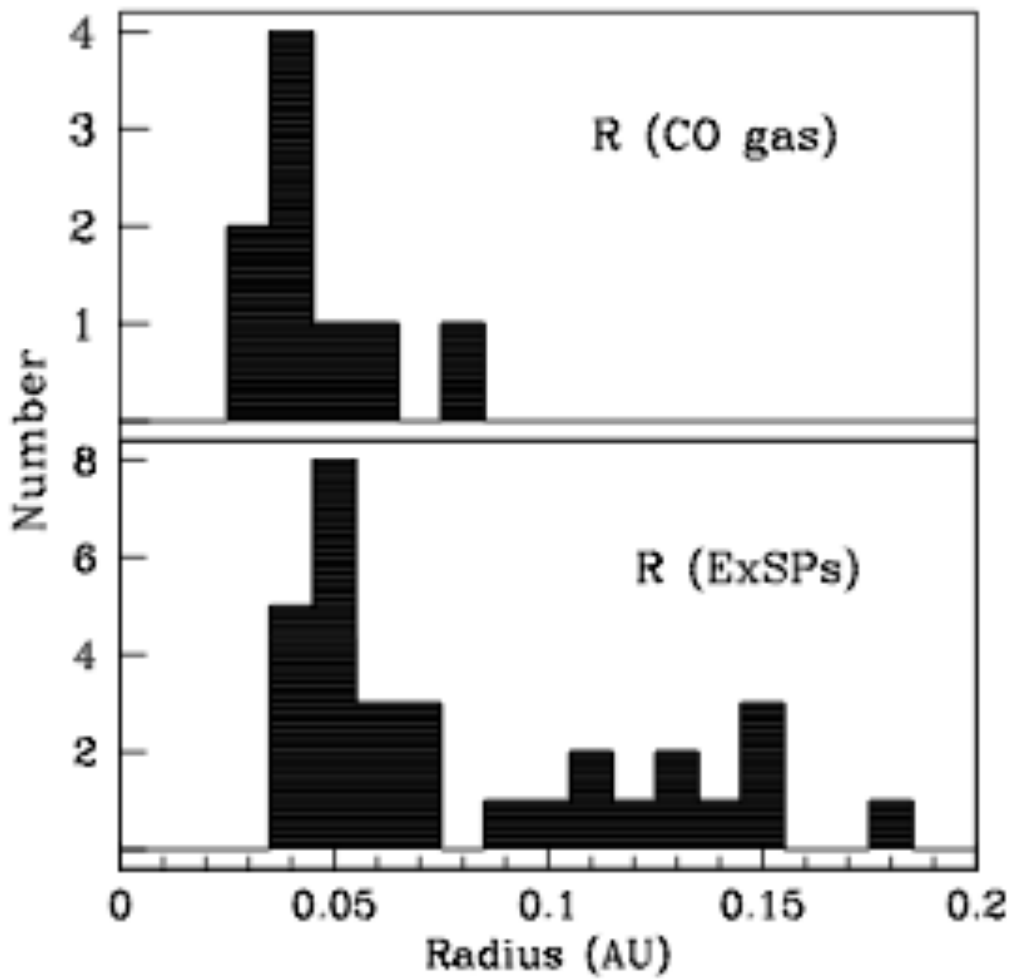


Fig. 3.— The distribution of gaseous inner radii, measured with the CO fundamental transitions, compared to the distribution of orbital radii of short-period extrasolar planets. A minimum planetary orbital radius of ~0.04 AU is similar to the minimum gaseous inner radius inferred from the CO emission line profiles.

Najita et al., 2007

What Now?

- Luminosity problem remains unresolved
- Reason for inner radius?
- Effect of binary?
- Reason for mass accretion?
- More complete samples
- More spatially-resolved spectra

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