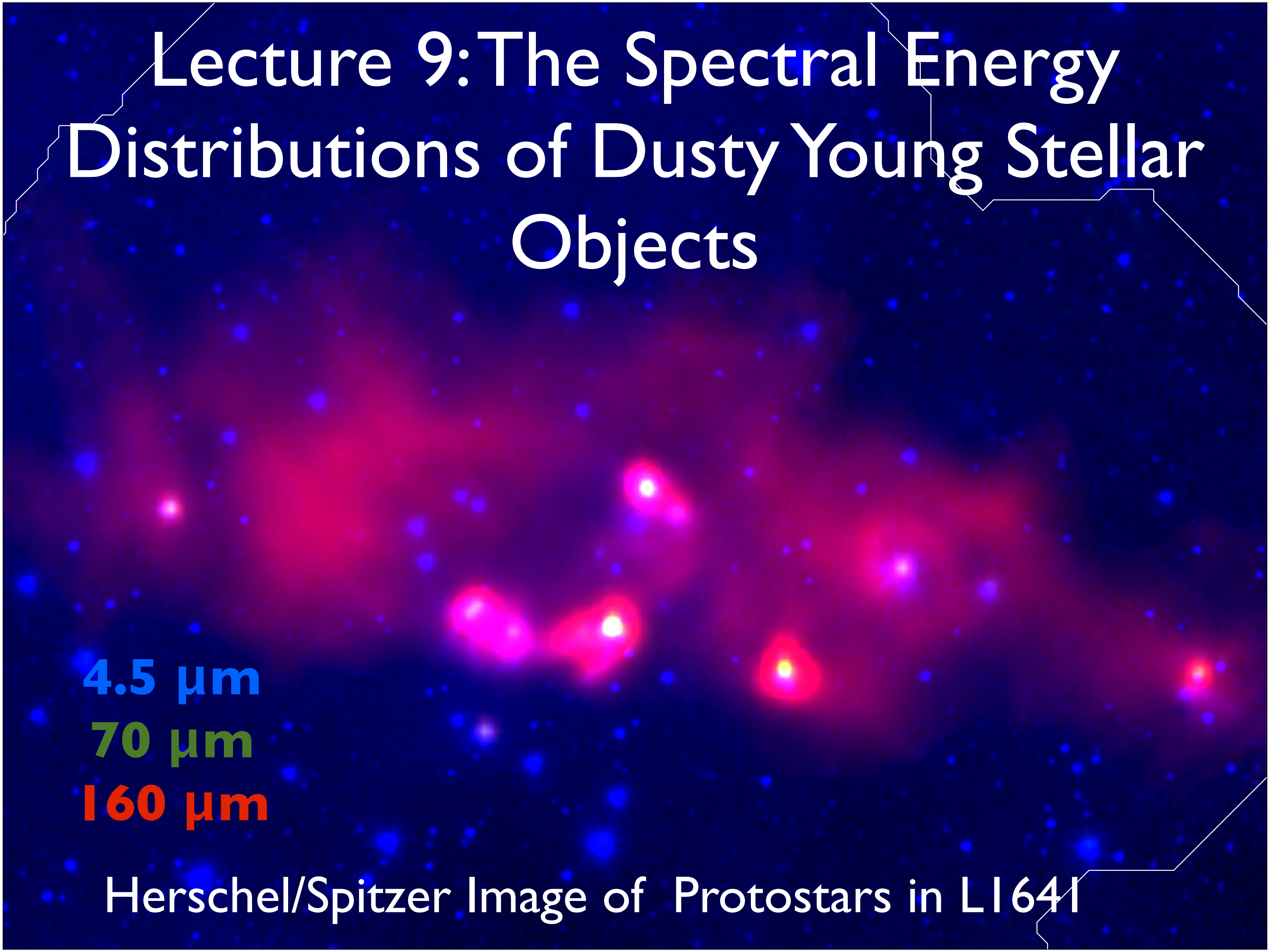
Lecture 9: The Spectral Energy Distributions of Dusty Young Stellar Objects



Herschel/Spitzer Image of Protostars in L1641

Review: From Cores to Stars

Pressure supported isothermal core bounded by Pressure and Gravity

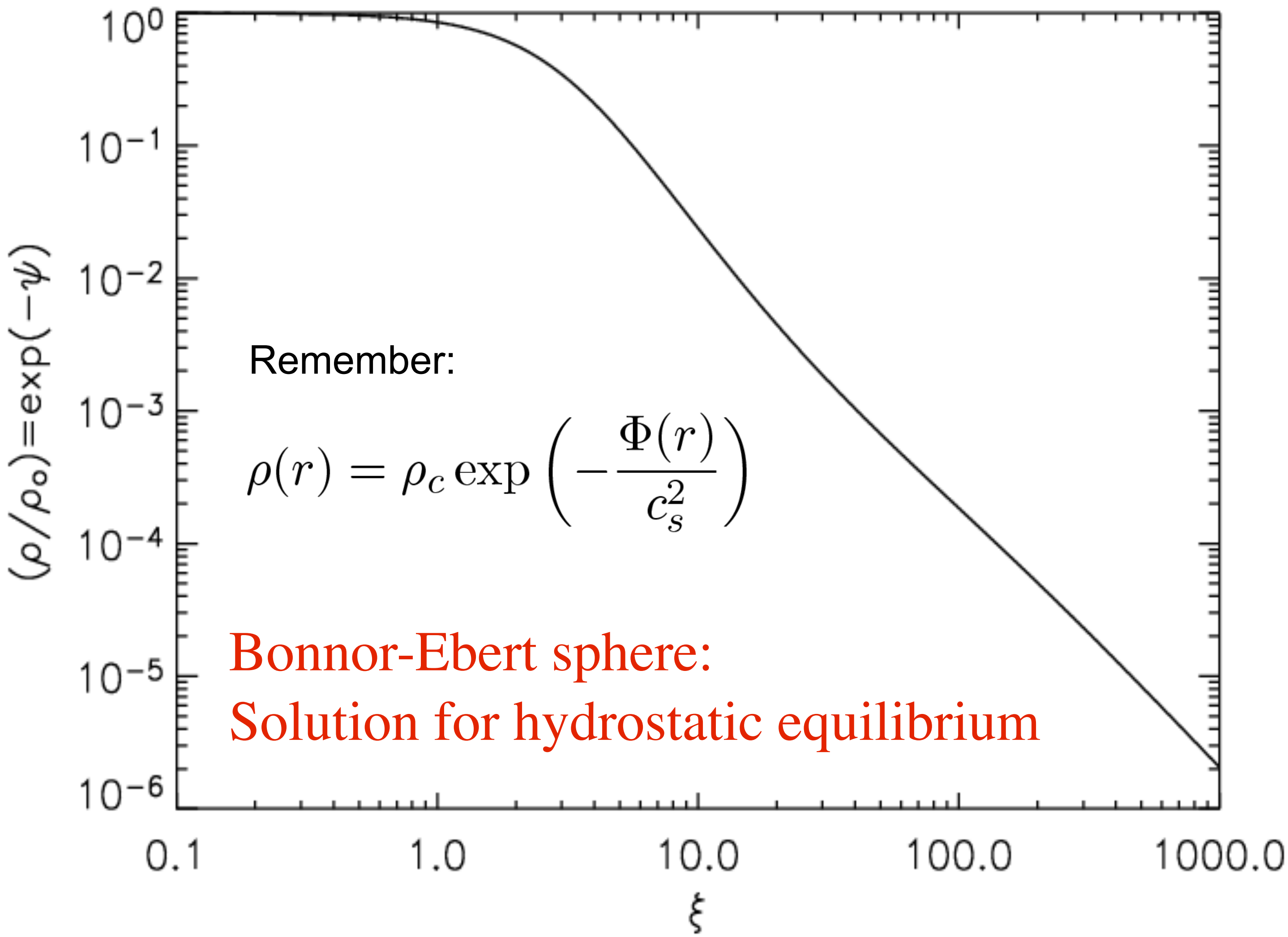


Figure pirated from K. Dullemond

Why Cores Collapse

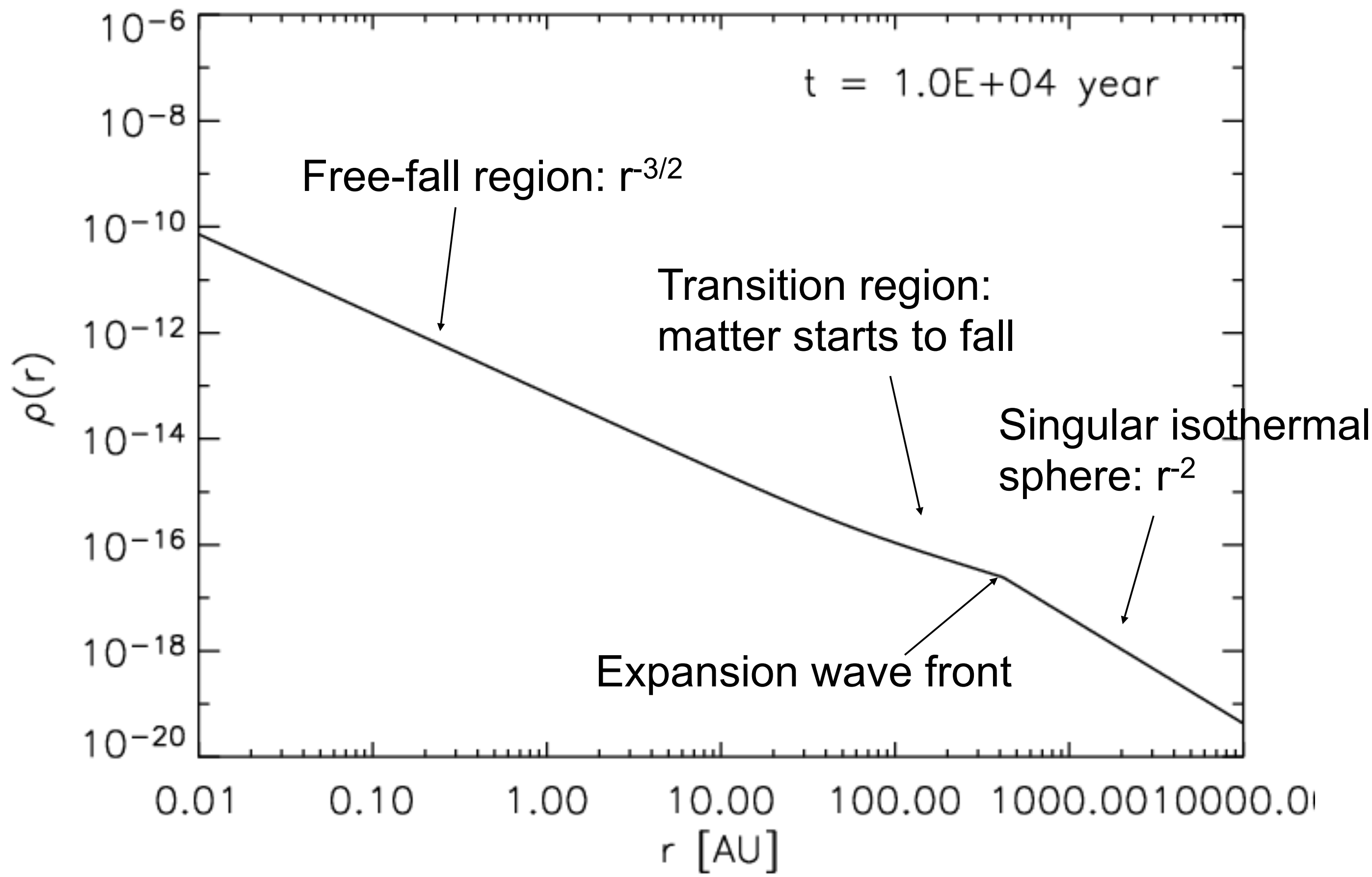
Gravitationally bound isothermal cores are intrinsically unstable:

As compressed, kinetic energy is constant ($K = 3/2\, M\, k\, T$), but gravitational potential energy decreases ($U = - GM^2/R$).

In contrast, a pressure bound core is not unstable. Instability in Bonner-Ebert sphere depends on whether core is primarily pressure confined or gravitationally bound.

Thus, *collapse is a natural consequence of the isothermality.*

Inside-out collapse model of Shu (1977)



Note: free fall time shorter for dense gas, hence centrally condense core leads to inside-out collapse

$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{\frac{1}{2}}$$

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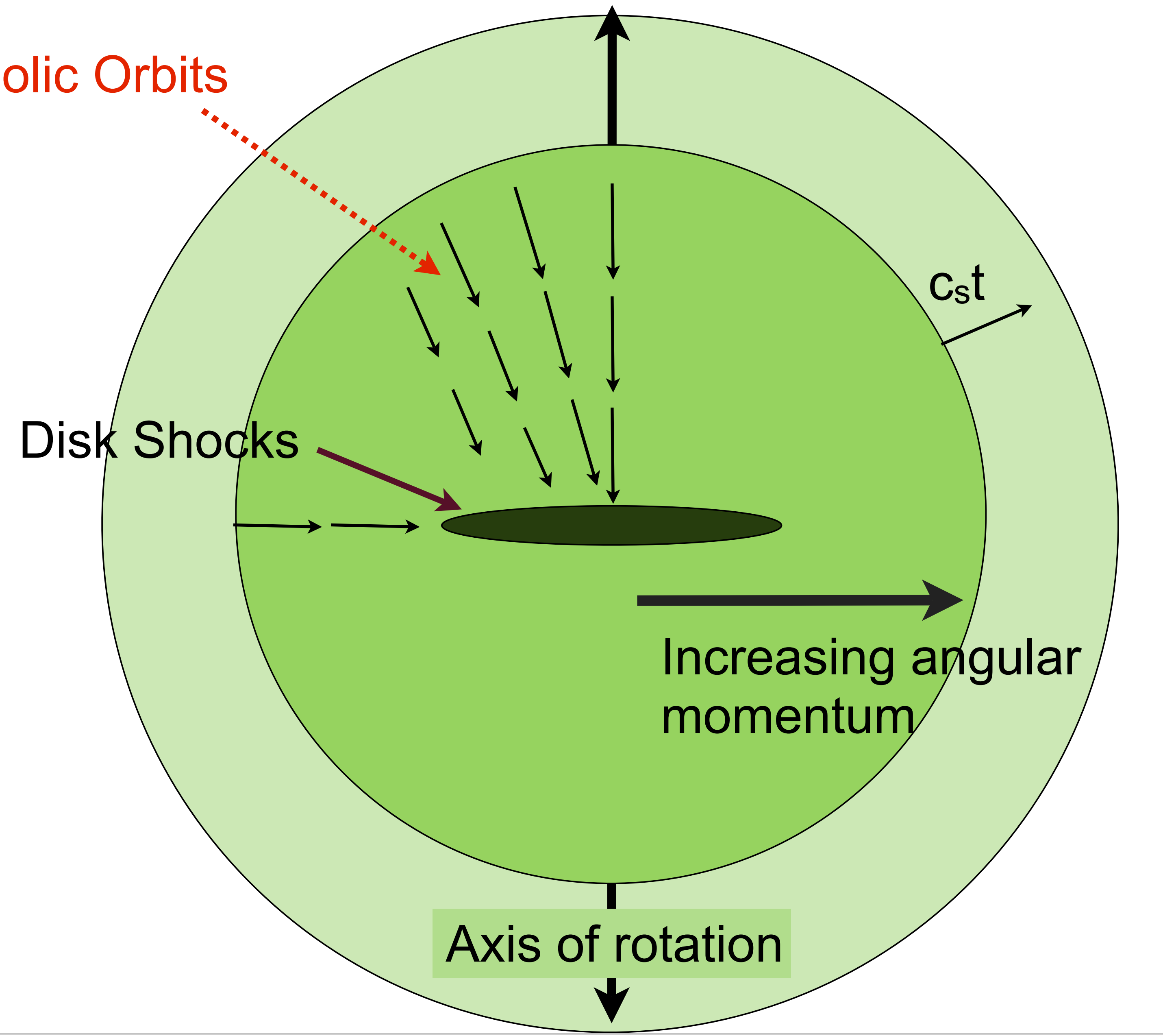
Angular Momentum leads to Disk



The Luminosity of Protostars

We derived in the previous lecture the infall rate for a thermally supported sphere, is $\dot{M} \approx c_s^3/G$. Assume that a fraction f falls onto the central protostar (the other fraction, $1-f$, might be carried off in an outflow). Also assume the central protostar has a mass M and a radius R. Then the luminosity generated by accretion is:

$$L_{acc} = f\frac{GM\dot{M}}{R} \tag{1}$$

The total luminosity is the sum of the accretion luminosity and the intrinsic luminosity of the source.

$$L_{tot} = L_{acc} + L_{int} \tag{2}$$

The accretion luminosity for a typical source, $\dot{M} = 5 \times 10^{-6}$ $M_\odot$ yr^{-1}, $M \sim 0.5$ $M_\odot$ and $R \sim 3$ $R_\odot$, then $L_{acc} = 16$ $L_\odot$.

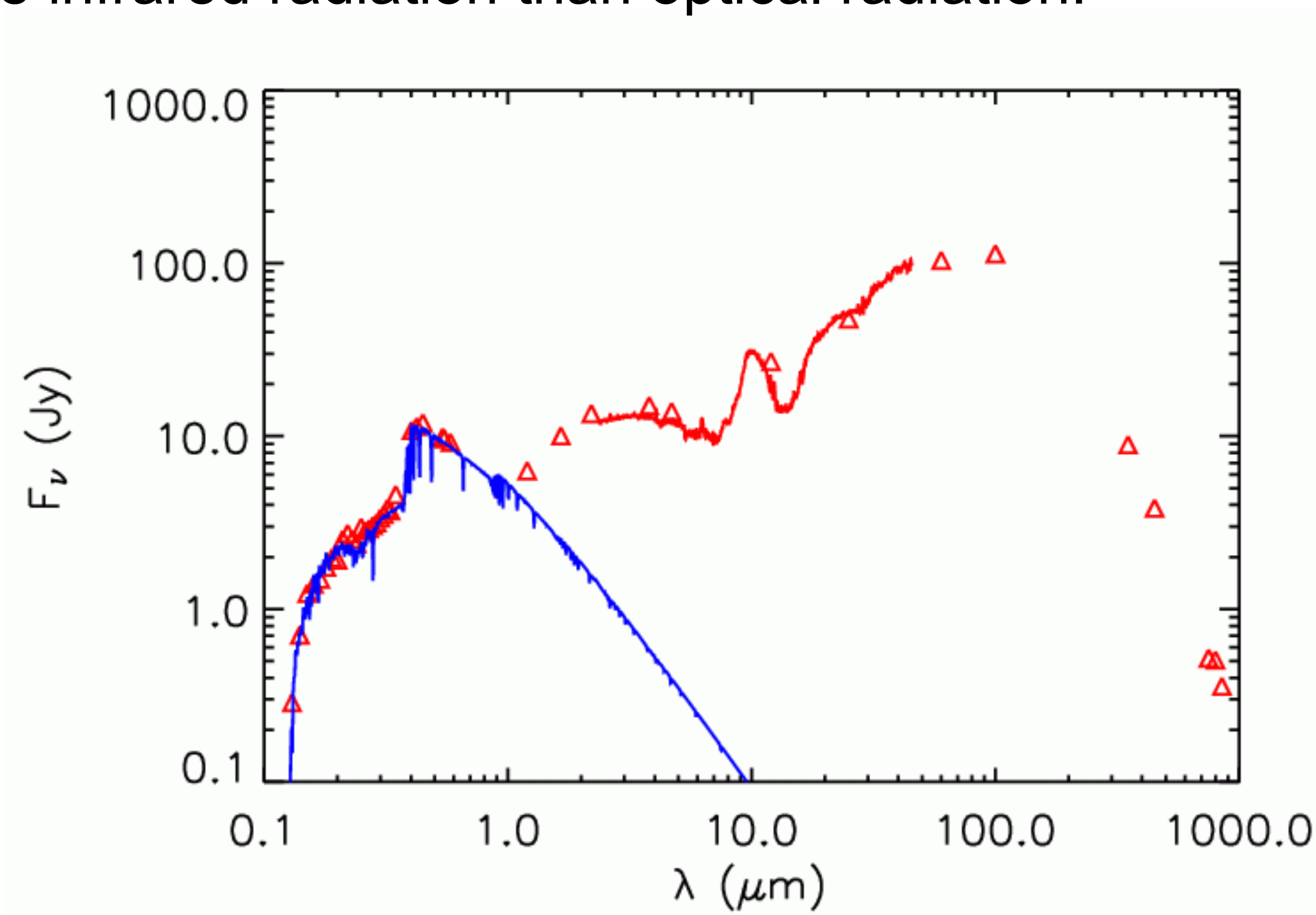
Observable Consequences in SEDs

- Protostars:
  - central protostar
  - disk surrounding protostar
  - infalling envelope
  - envelope flattened by rotation (lower optical depth along rotaton axis)
  - outflows clear cavities along rotation axis

- Pre-main sequence stars
  - central star
  - disk surrounding star

Spectral Energy Distributions (SEDs)

Plotting normal flux makes it look as if the source emits much more infrared radiation than optical radiation:



This is because energy is: $F_\nu \, d\nu = F_\nu \, \Delta\nu$

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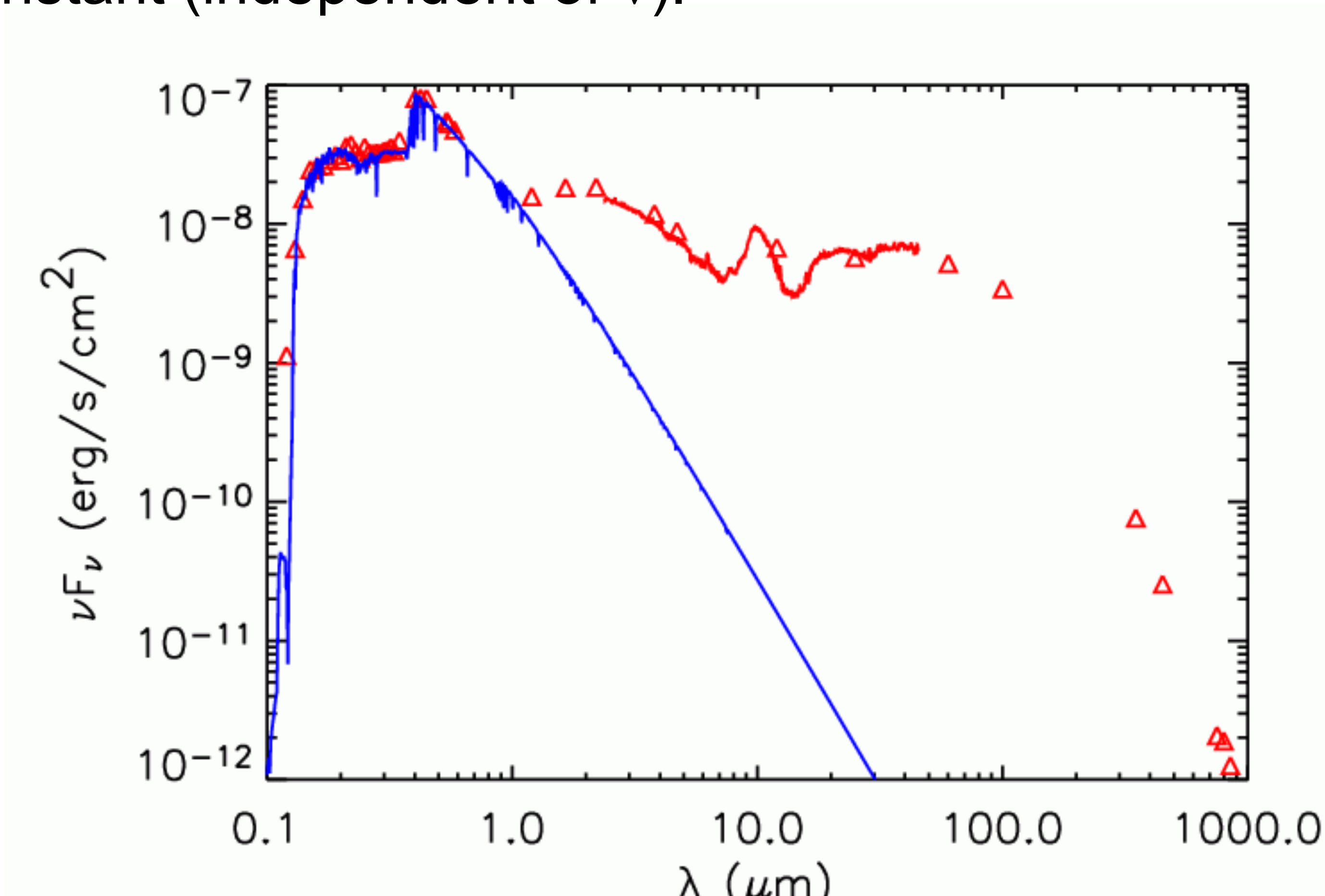
Spectral Energy Distributions (SEDs)

Typically one can say: $\Delta\nu = \nu\,\Delta(\log\nu)$ and one takes $\Delta(\log\nu)$ a constant (independent of ν).



In that case νF_ν is the relevant quantity to denote energy per interval in logν. NOTE: $\boxed{\nu F_\nu \equiv \lambda F_\lambda}$

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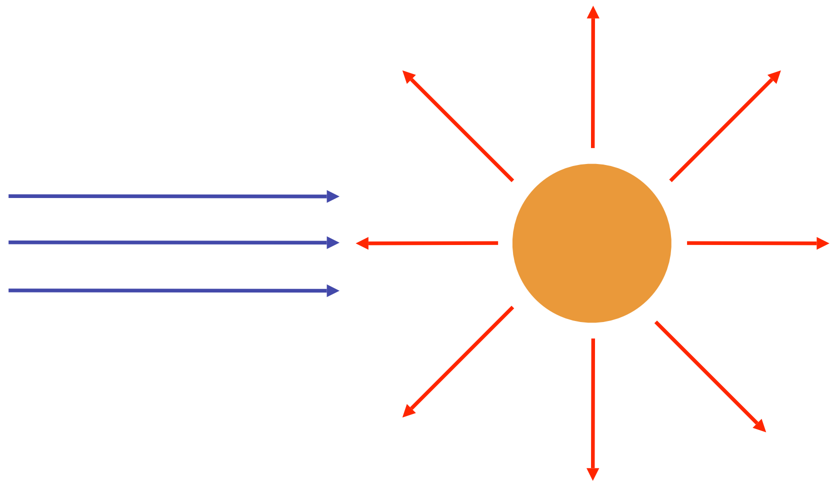
Temperature of a dust grain

Optically thin case:

Heating:



$$Q_+ = \pi a^2 \int F_\nu \, \epsilon_\nu \, d\nu$$

a = radius of grain

ϵ_ν= absorption efficiency (=1 for perfect black sphere)

Cooling:

$$Q_- = 4\pi a^2 \int \pi B_\nu(T) \, \epsilon_\nu \, d\nu$$

$$\kappa_\nu = \frac{\pi a^2 \epsilon_\nu}{m}$$

Thermal balance:

$$\int B_\nu(T) \, \kappa_\nu \, d\nu = \frac{1}{4\pi} \int F_\nu \, \kappa_\nu \, d\nu$$

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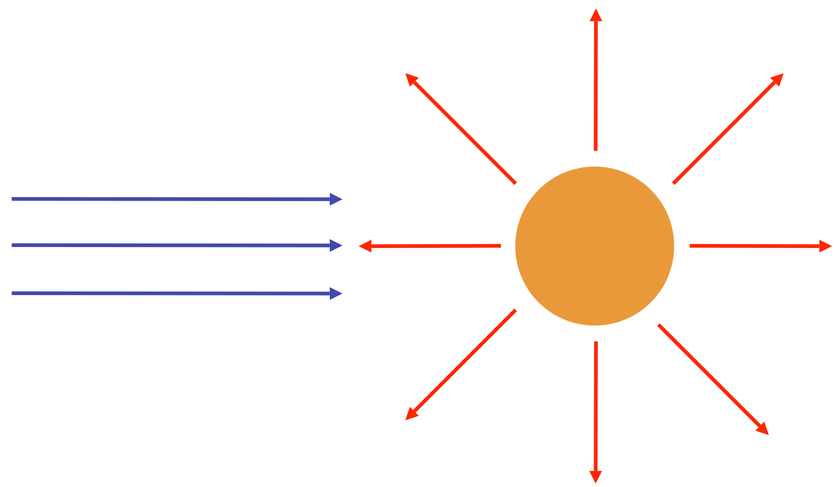
Temperature of a dust grain

$$\int B_\nu(T)\kappa_\nu \, d\nu = \frac{1}{4\pi}\int F_\nu \kappa_\nu \, d\nu$$



<u>Assume</u> grey opacity:

$$T^4 = \frac{1}{4\sigma}\frac{L_*}{4\pi r^2}$$

$$T = \sqrt{\frac{r_*}{2r}}\, T_*$$

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Reprocessing of Starlight and Dust Photospheres

Imagine a star with a radius $R_\star$ and temperature $T_\star$ surrounded by an optically thick shell of dust at a radius R_{shell}. Assuming that the shell is in temperature equilibrium, i.e. it is emitting as much power as it is absorbing, then.

$$L_{shell} = L_\star \tag{3}$$

which can be written as

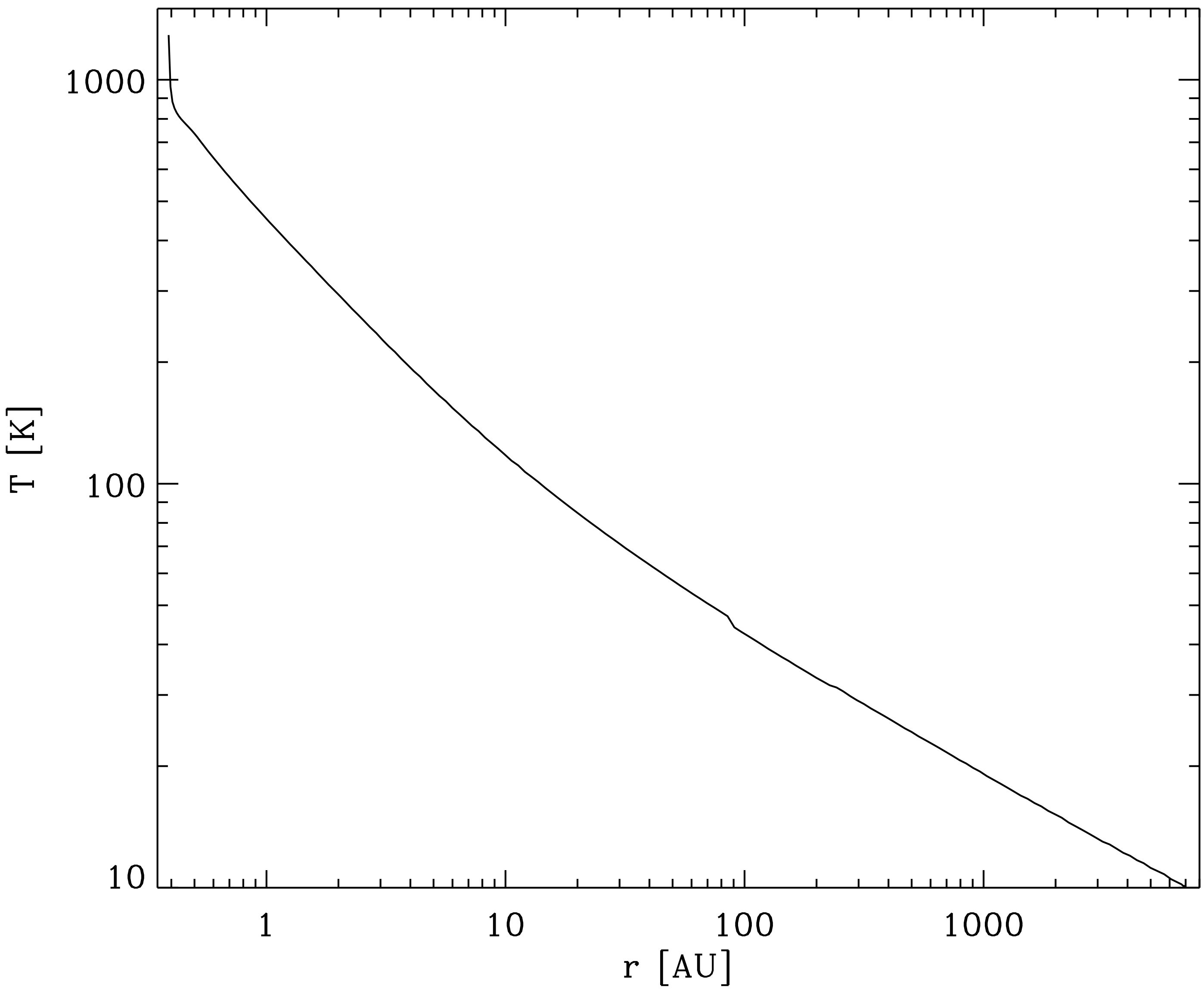
$$4\pi R_\star^2 \sigma T_\star^4 = 4\pi R_{shell}^2 \sigma T_{shell}^4 \tag{4}$$

where

$$\frac{T_{shell}}{T_\star} = \left(\frac{R_\star}{R_{shell}}\right)^{1/2} \tag{5}$$

Thus, the shell will appear as a cool blackbody

In reality, we don't have one temperature



The SEDs of Protostars (from Hartmann)

Let us assume spherical symmetry. Then

$$\rho(r) \approx \frac{\dot{M}}{4\pi r^2 v_{ff}} = \frac{\dot{M}}{4\pi(2GM)^{1/2}} r^{-3/2} \tag{6}$$

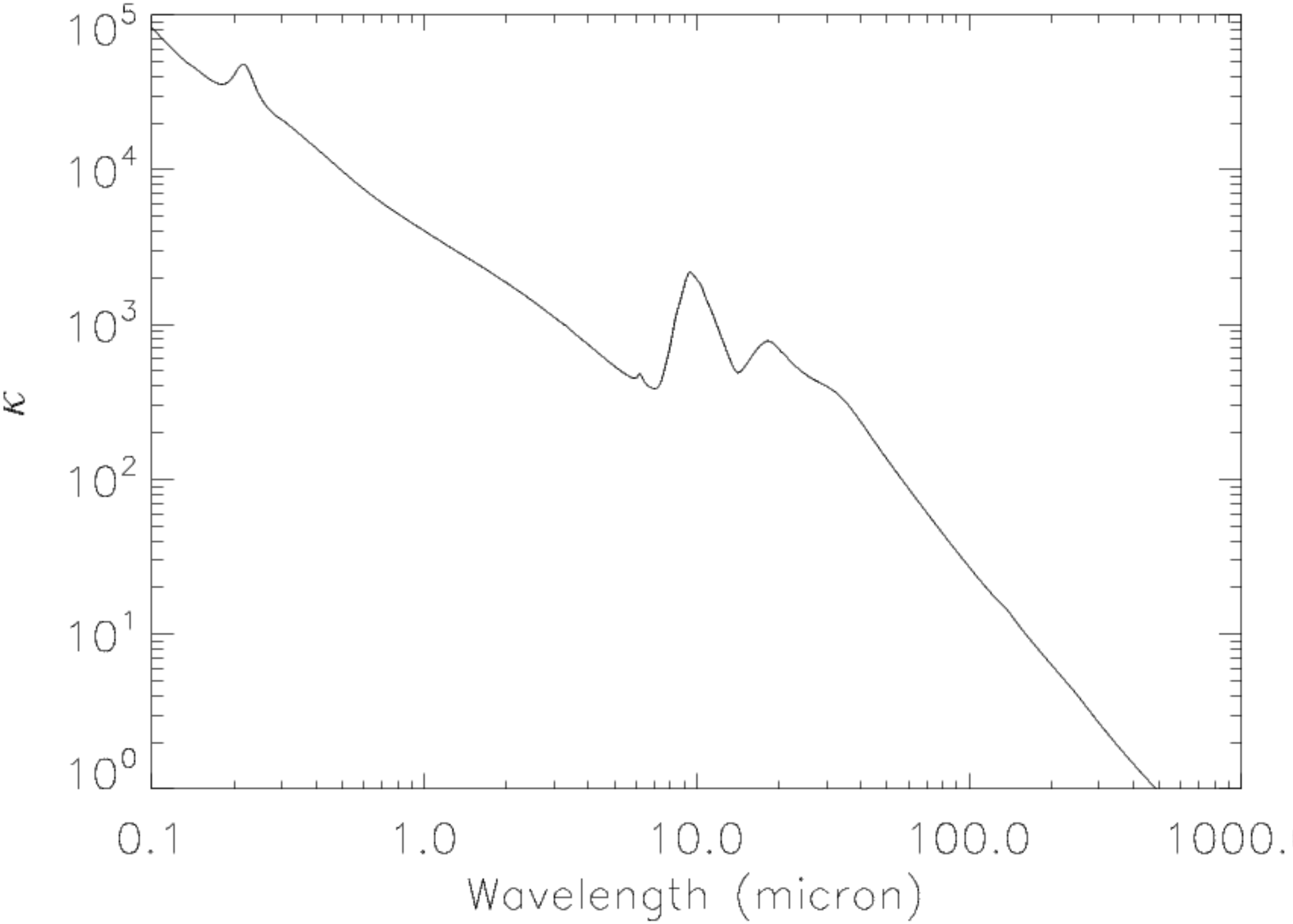
where $v_{ff} = \sqrt{2GM/r}$. As in the lecture, this can be integrated to find the optical depth integrating from infinity down to a radius of r.

$$\tau_\lambda = \frac{\kappa_\lambda \dot{M}}{2\pi(2GM)^{1/2}} r^{-1/2} \tag{7}$$

where κ_λ is the absorption per mass. Now, we can determine the radius r_λ where $\tau_\lambda = 2/3$.

$$r_\lambda = \frac{9\kappa_\lambda^2 \dot{M}^2}{32\pi^2 GM} \tag{8}$$

Dust Absorption in the IR



From Hartmann

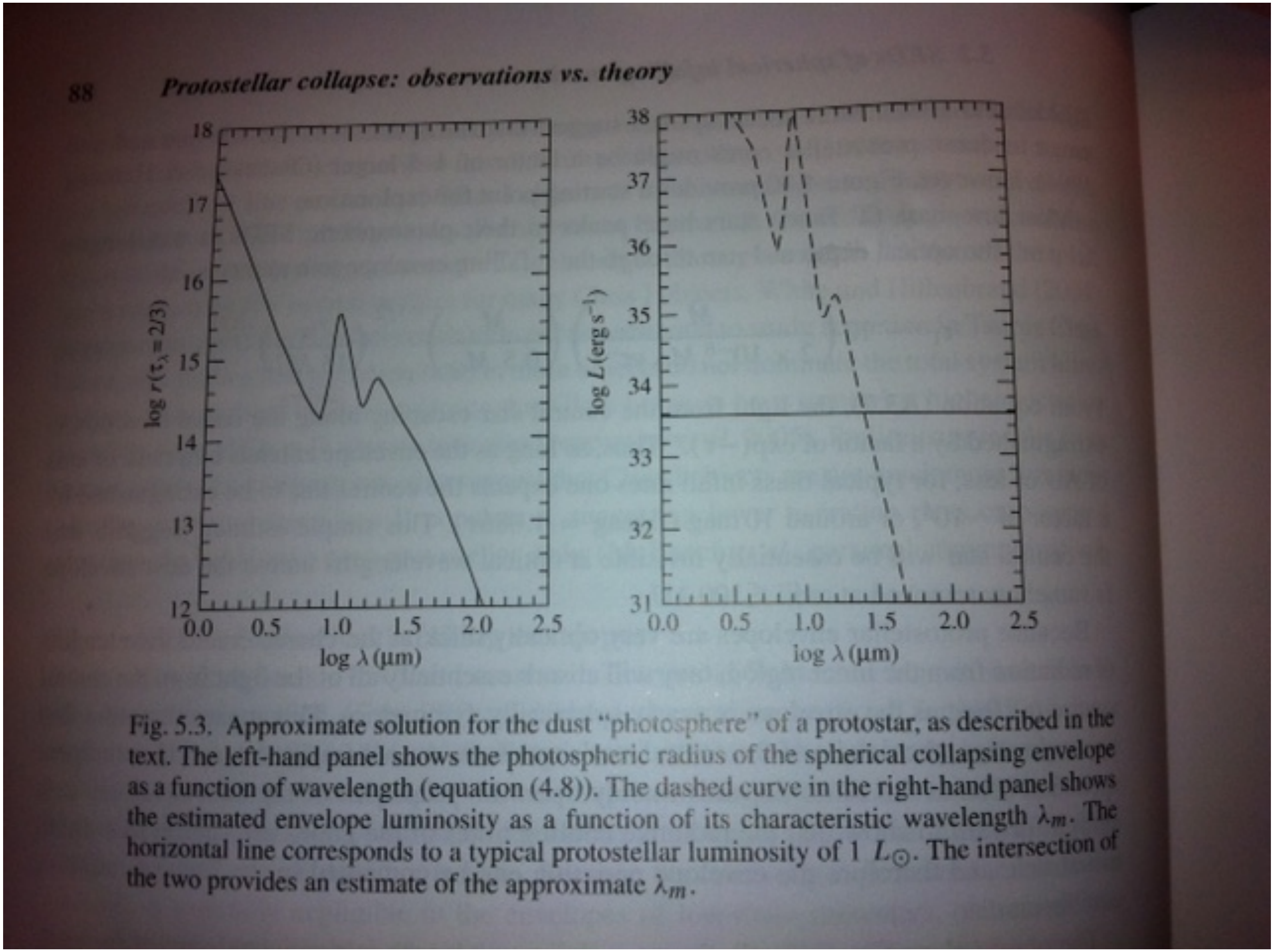


Fig. 5.3. Approximate solution for the dust "photosphere" of a protostar, as described in the text. The left-hand panel shows the photospheric radius of the spherical collapsing envelope as a function of wavelength (equation (4.8)). The dashed curve in the right-hand panel shows the estimated envelope luminosity as a function of its characteristic wavelength λ_m. The horizontal line corresponds to a typical protostellar luminosity of 1 $L_\odot$. The intersection of the two provides an estimate of the approximate λ_m.

SED of Protostars

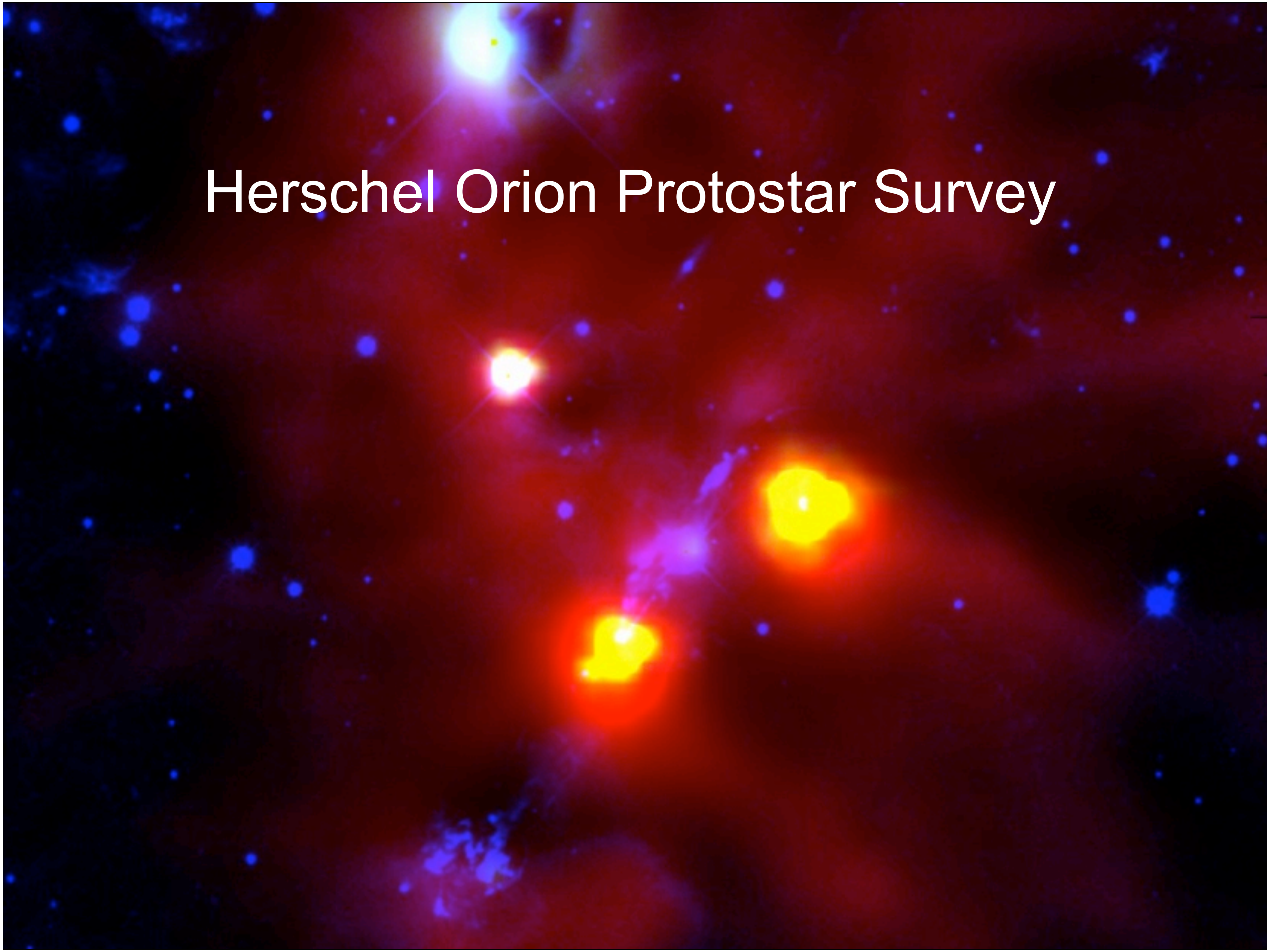
Using Wien's law, $\lambda_m[\mu m] = 2900/T_m[K]$, we can approximate the luminosity of the protostar as a blackbody.

$$L = 4\pi r_{\lambda m}^2 \sigma T_{\lambda m}^4 \tag{9}$$

$$\frac{\lambda_m}{\lambda_o} = \left(\frac{2900}{\lambda_0}\right) \left(\frac{4\pi\sigma}{L}\right)^{1/(4+4\beta)} \left(\frac{9\dot{M}^2\kappa_o^2}{32\pi GM}\right)^{1/(2+2\beta)} \tag{10}$$

or, by adopting the extinction law $\kappa_\lambda = 0.2(\lambda/100\mu m)^{-2}$

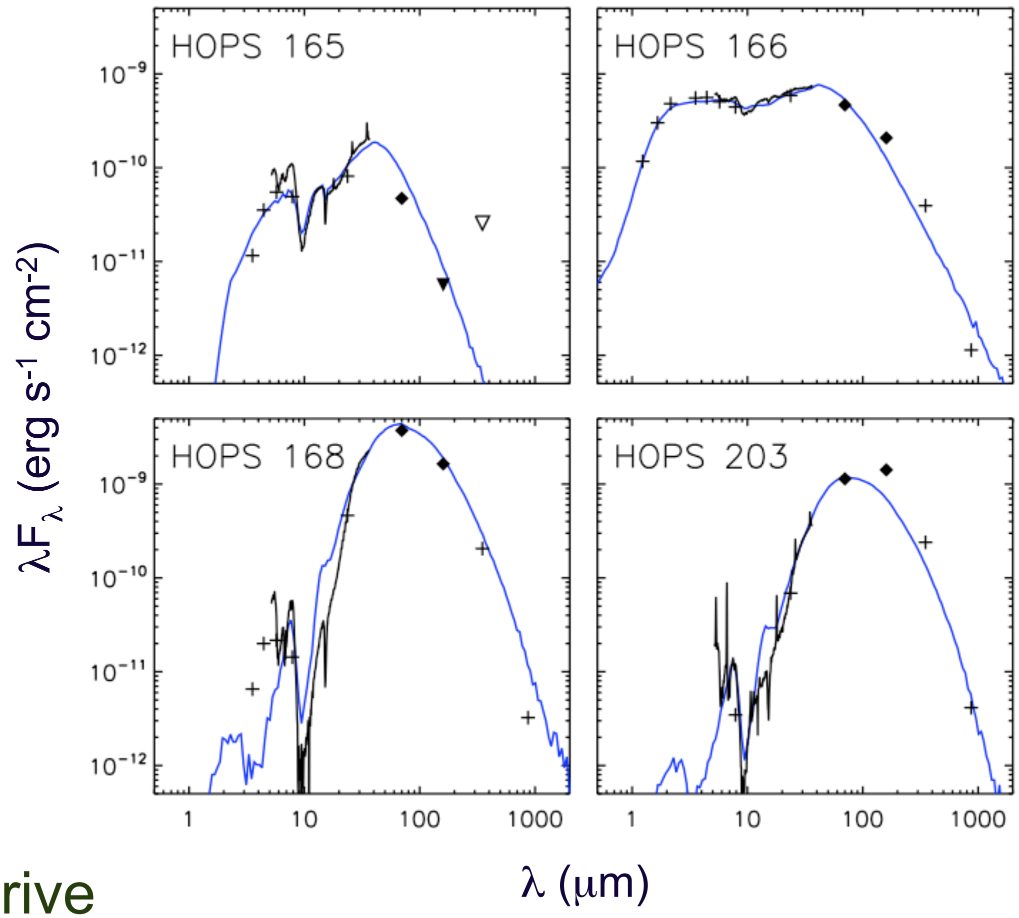
$$\lambda_m[\mu m] \approx 30 \left(\frac{L}{L_\odot}\right)^{-1/12} \left(\frac{\dot{M}}{2\times10^{-6} M_\odot \ yr^{-1}}\right)^{1/3} \left(\frac{M}{M_\odot}\right)^{-1/6} \tag{11}$$


Herschel Orion Protostar Survey

Real Protostars (Will Fischer)

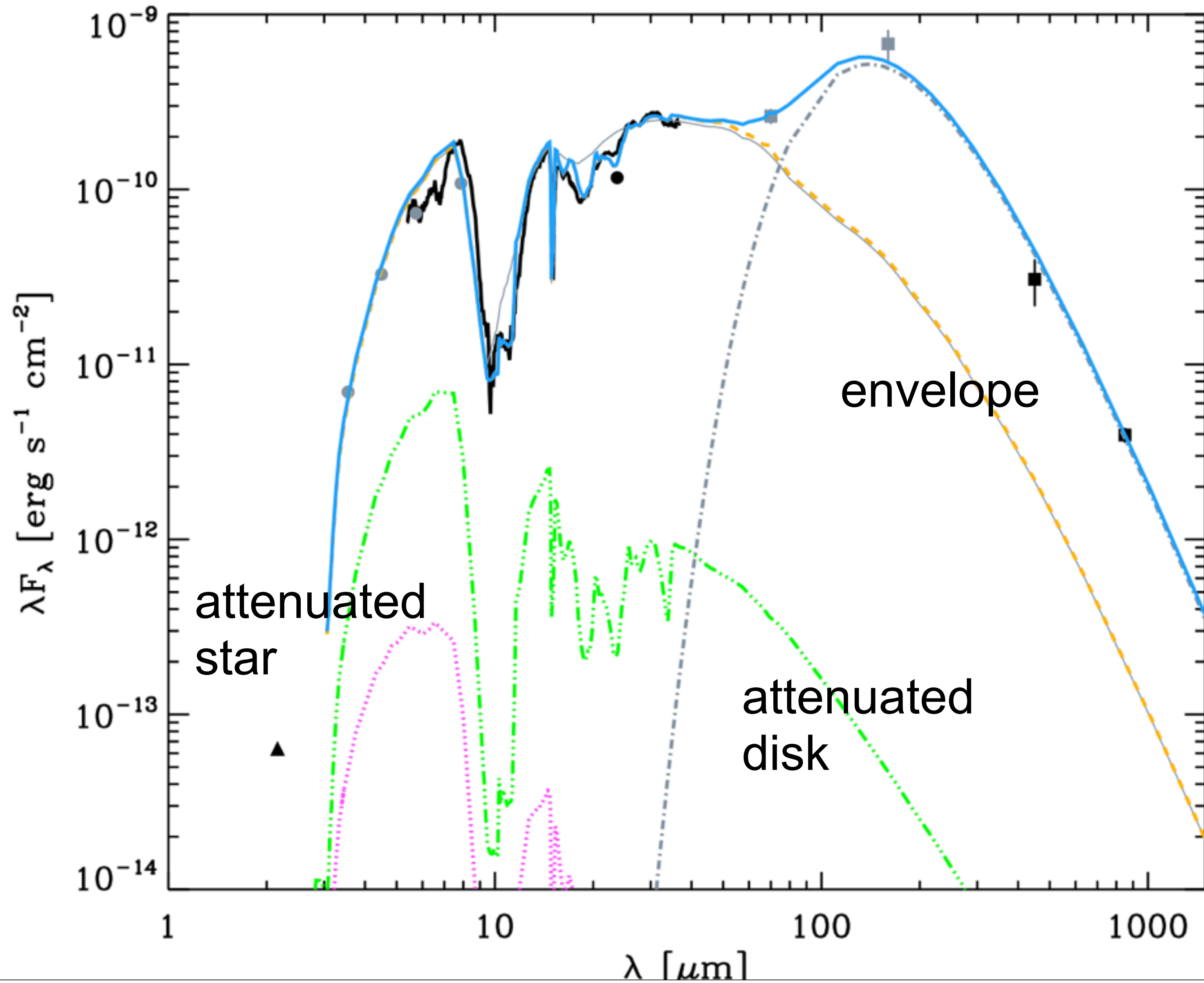
	L (L_{sun})	dM_{env}/dt (M_{sun}/yr)	L_{acc} / L
165	12	2×10^{-7}	0.1
166	23	4×10^{-7}	0.2
168	84	3×10^{-5}	~ 1
203	23	2×10^{-5}	~ 1

- Modeled SEDs with B. Whitney's RT code
- Key parameters
  - Luminosity
  - Envelope density
- With stellar parameters, derive
  - Envelope infall rate
  - Accretion luminosity
- HOPS 168, 203: $dM_{disk}/dt = dM_{env}/dt$ implies $M_{star} \sim 0.1\ M_{sun}$
  - Episodic accretion would allow larger masses



(Fischer et al. 2010, A&A special issue)

HOPS 68 - a flattened protostar with external heating



The Protostars HOPS 68

or, by adopting the extinction law $\kappa_\lambda = 0.2(\lambda/100\mu m)^{-2}$

$$\lambda_m[\mu m] \approx 30 \left(\frac{L}{L_\odot}\right)^{-1/12} \left(\frac{\dot{M}}{2 \times 10^{-6} M_\odot \; yr^{-1}}\right)^{1/3} \left(\frac{M}{M_\odot}\right)^{-1/6} \tag{11}$$

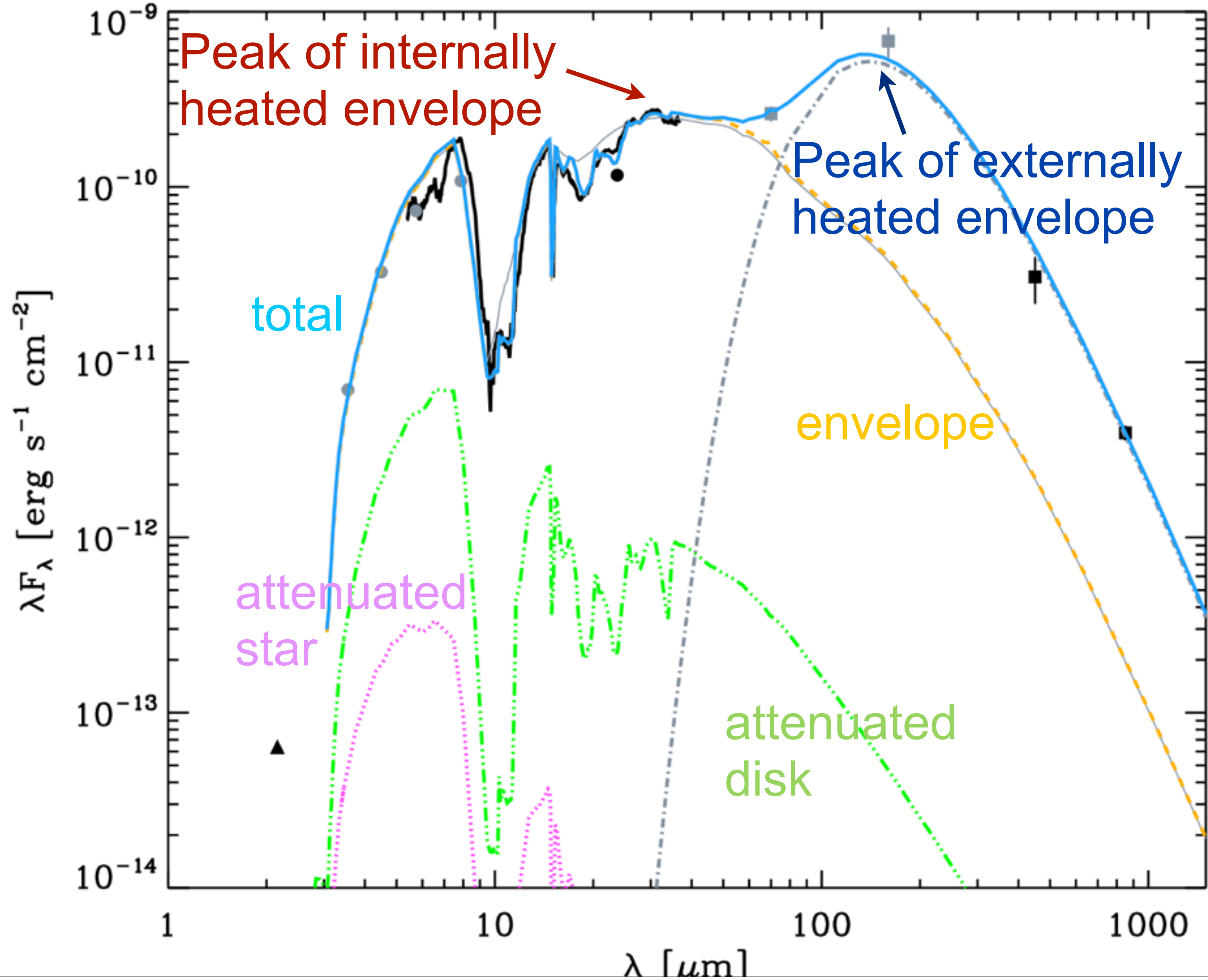
Table 2
Best-Fit Model Parameters

Parameter	Value
Sheet-Collapse	
L $[L_\odot]$	1.3
$\eta_{\rm star}$	0.3
η	2.0
R_c [AU]	0.5
$R_{\rm min}$ [AU]	0.39
$R_{\rm max}$ [AU]	7000
ρ_1 $[10^{-14}$ g cm$^{-3}]$	5.7
i [deg]	41
θ [deg][a]	18
$\zeta_{\rm for}/(\zeta_{\rm for} + \zeta_{\rm sil})$ ..	0.17

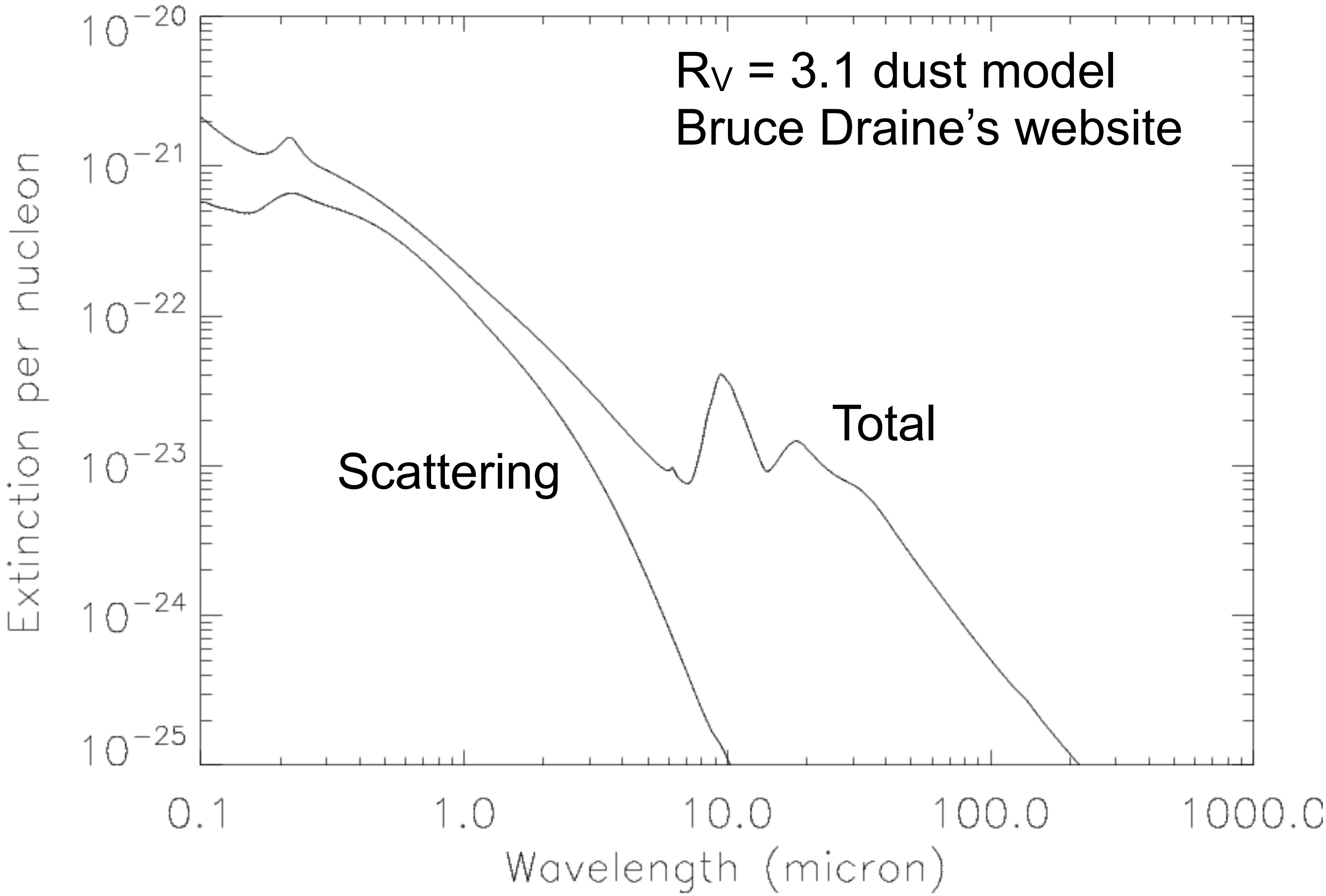
From Poteet, submitted. Using the inner envelope density and assumed stellar mass, we get:

$$\dot{M} = 7.6 \times 10^{-6} \; M_\odot \; {\rm yr}^{-1}$$

HOPS 68 - a protostar with external heating

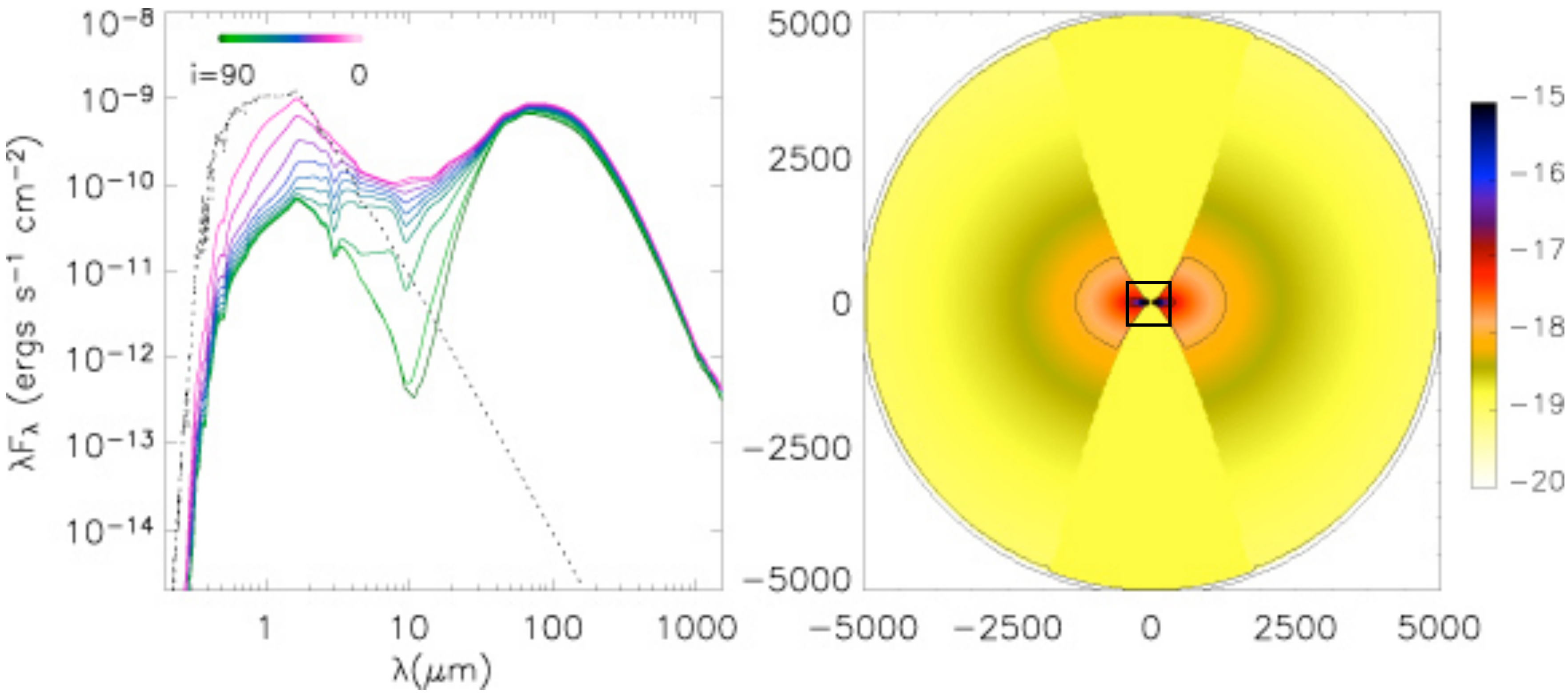


The Contribution from Scattering



Spectra of collapsing cloud + star + disk

Whitney et al. 2003



Class I

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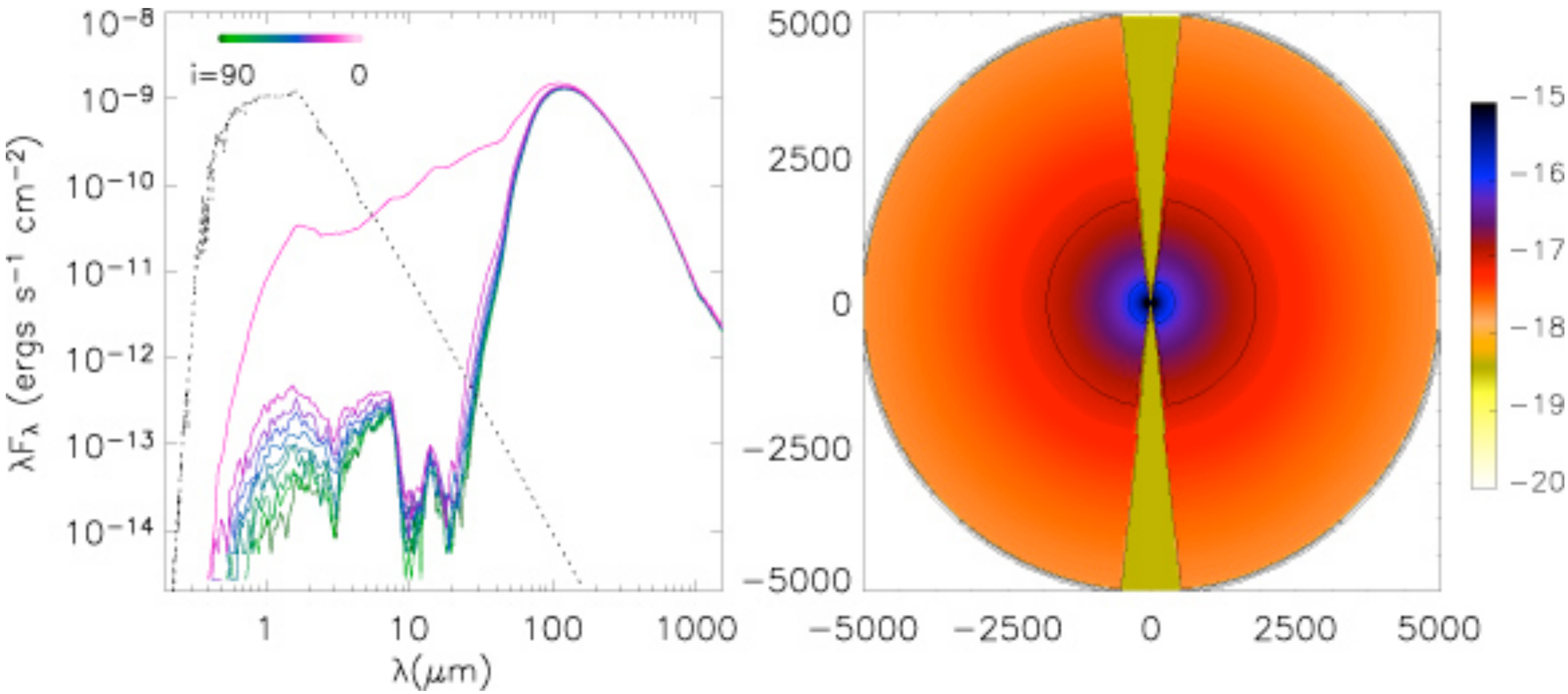
Spectra of collapsing cloud + star + disk

Whitney et al. 2003



Class 0

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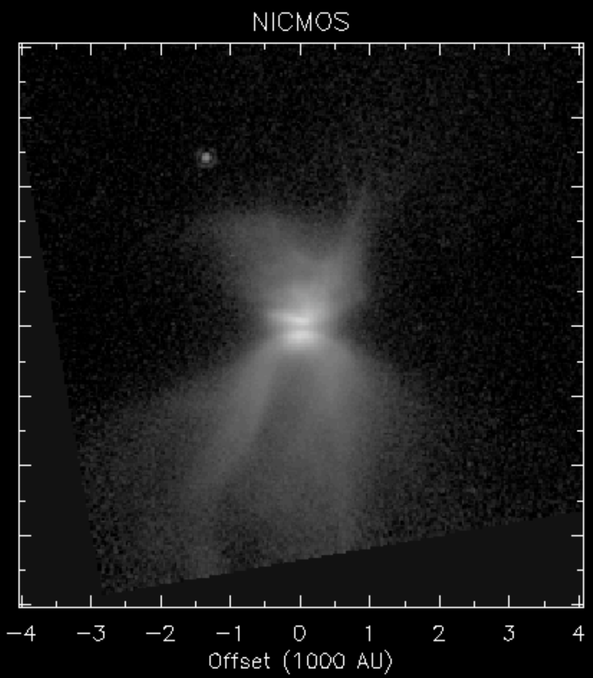
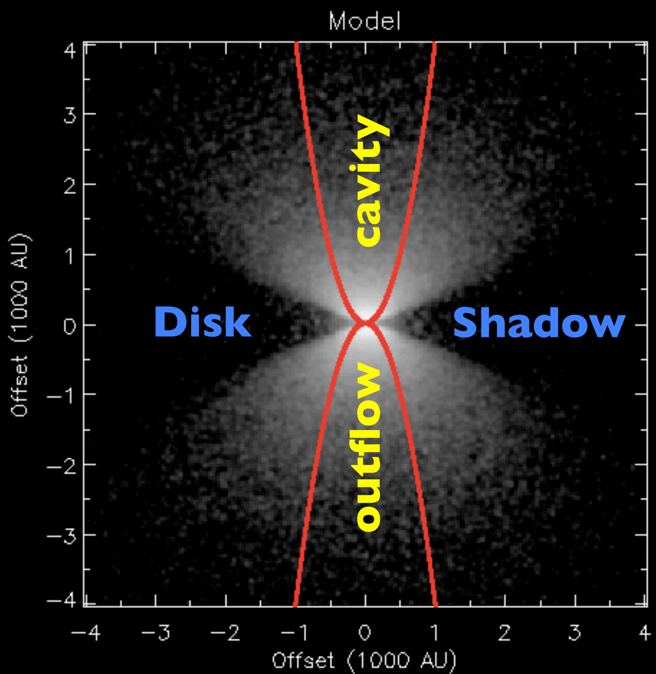
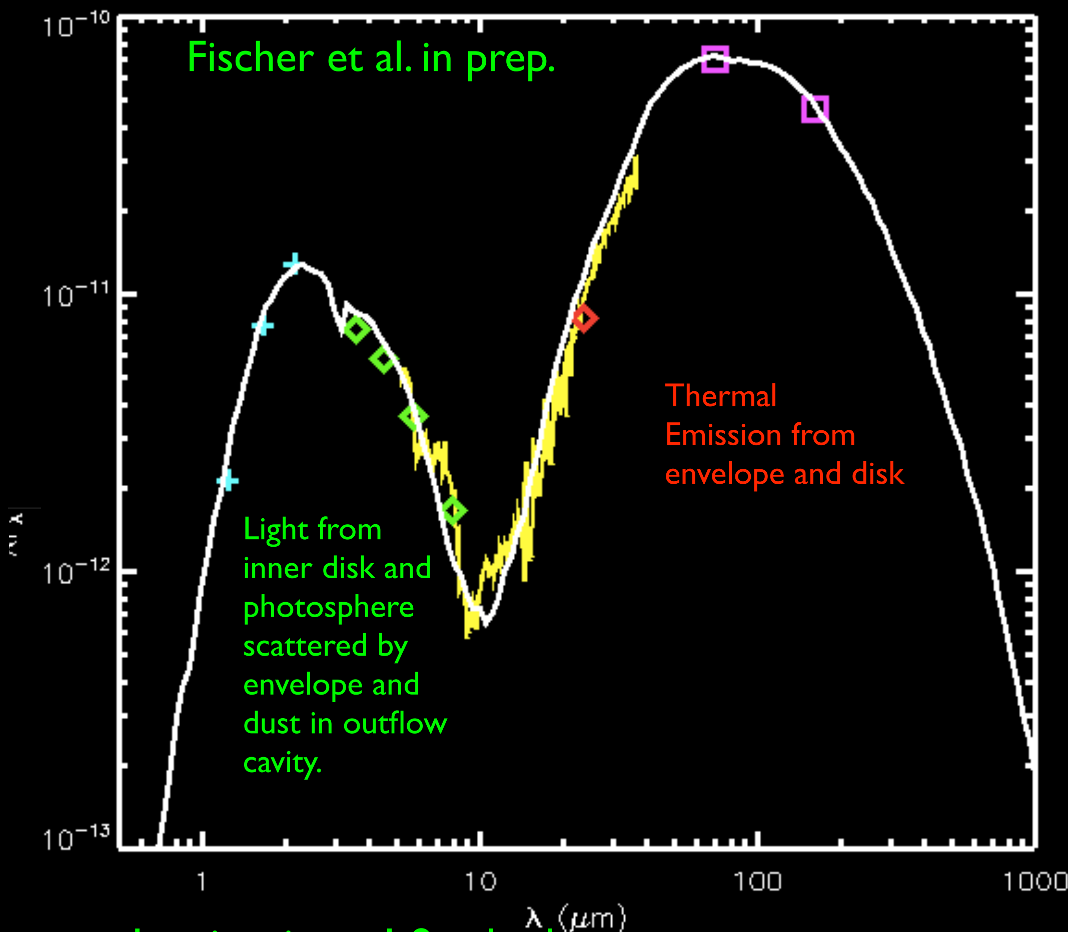
HOPS 136: A Case Study of an Edge-on Protostar







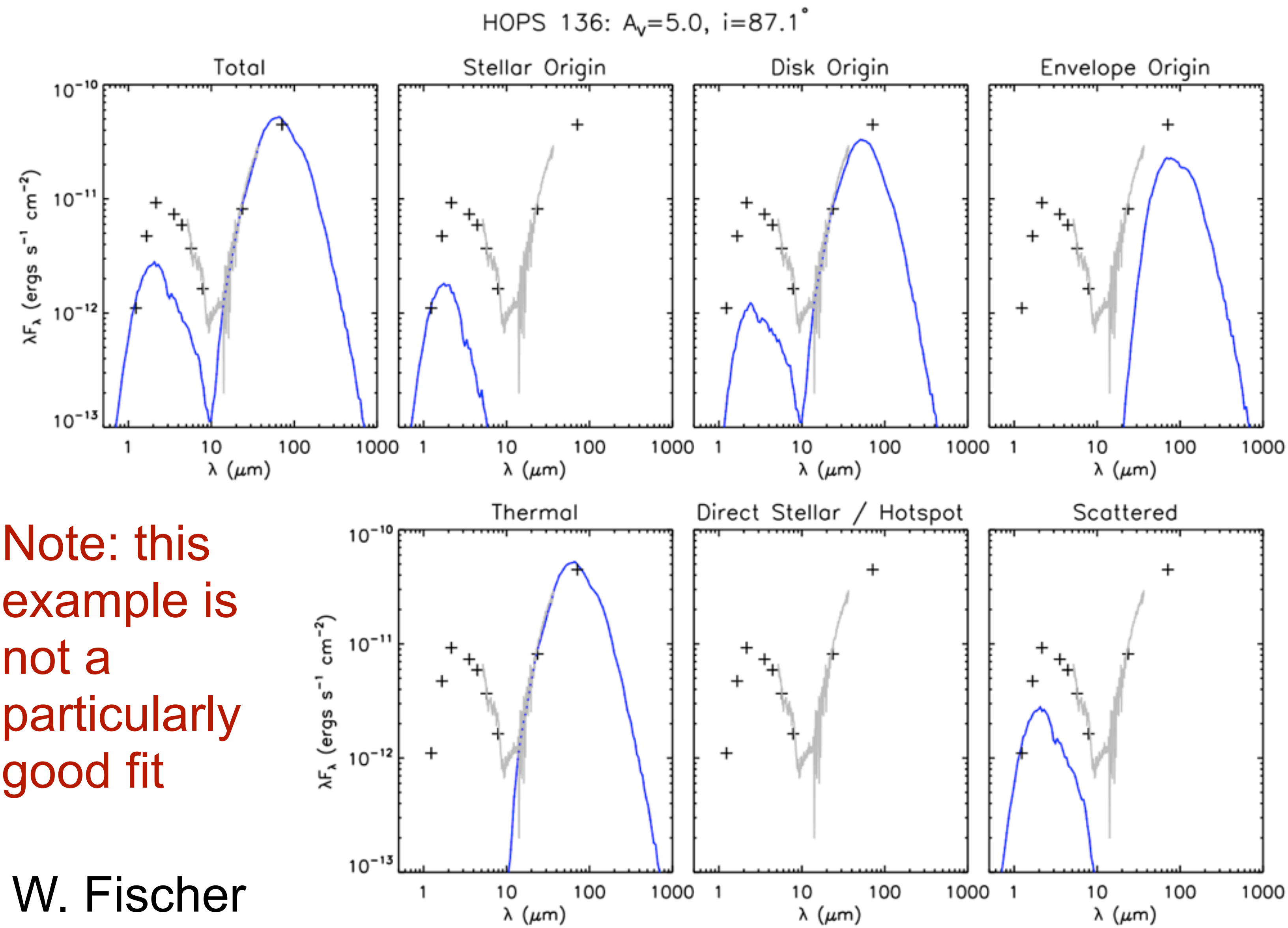
Luminosity = 1.8 solar lum.

Mass infall = 3×10^{-6} solar masses per year

Rc = 500 AU

Inclination = 90° (opposed to 81° from Robitaille fitter)

Plus we have a disk, seen in absorbed scattered light: Models of HOPS 136



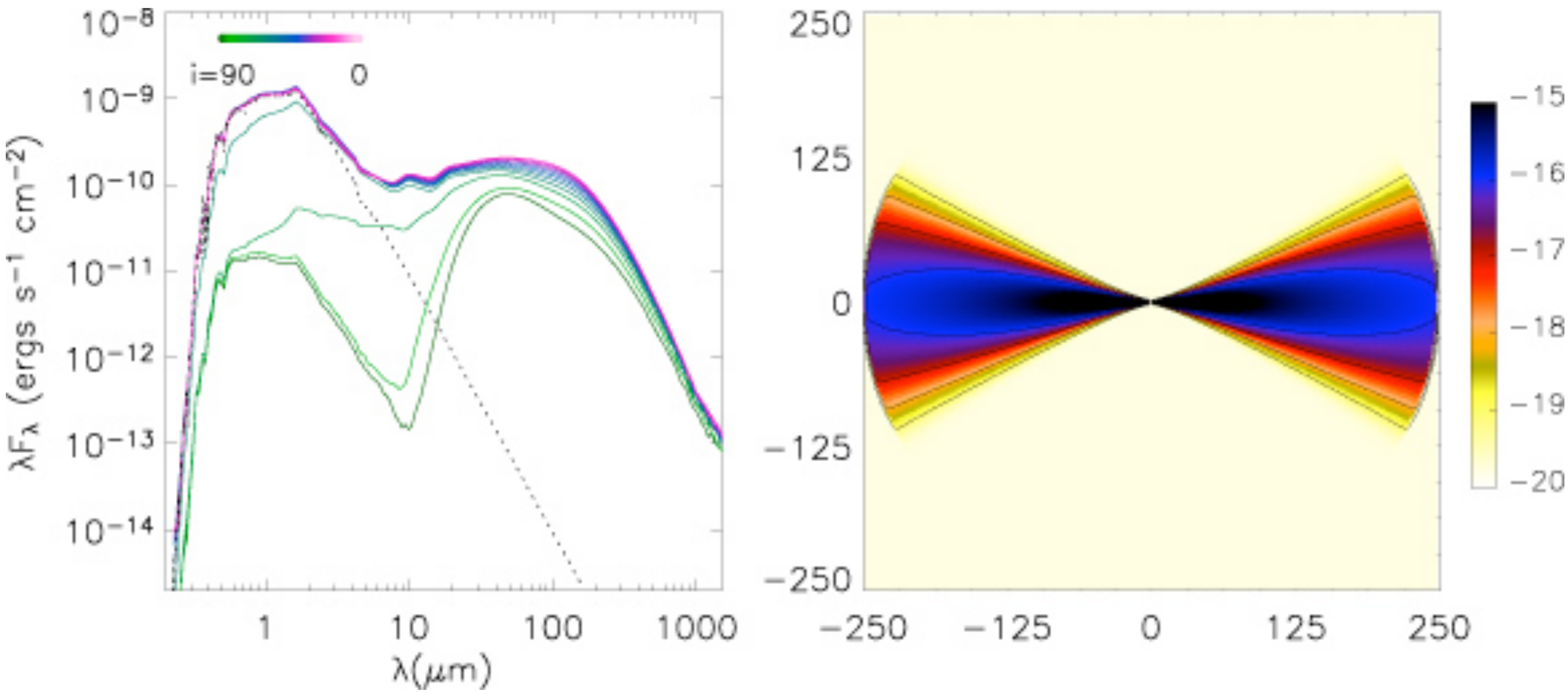
Note: this example is not a particularly good fit

W. Fischer

Disks

Spectra of collapsing cloud + star + disk

Whitney et al. 2003



Class II

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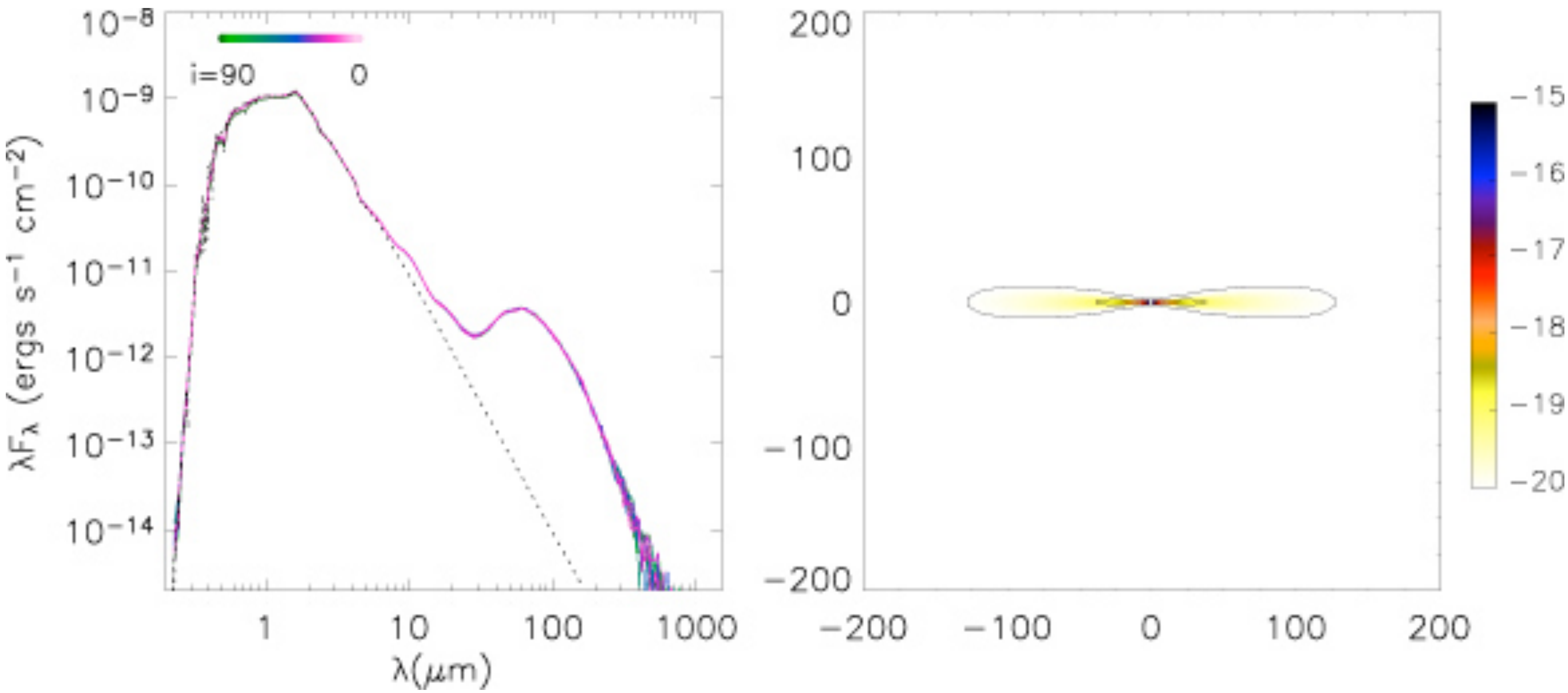
Spectra of collapsing cloud + star + disk

Whitney et al. 2003



Class III

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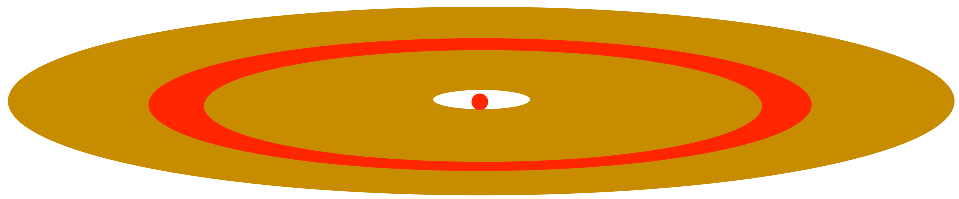
Calculating the SED from a flat disk

Assume here for simplicity that disk is vertically isothermal: the disk emits therefore locally as a black radiator.



$$I_\nu(r) = B_\nu(T(r))$$

Now take an annulus of radius r and width dr. On the sky of the observer it covers:

$$d\Omega = \frac{2\pi\, r\,dr}{d^2}\cos i$$

and flux is:

$$F_\nu = I_\nu\, d\Omega$$

Total flux observed is then:

$$F_\nu = \frac{2\pi \cos i}{d^2}\int_{r_{\rm in}}^{r_{\rm out}} B_\nu(T(r))\, r\,dr$$

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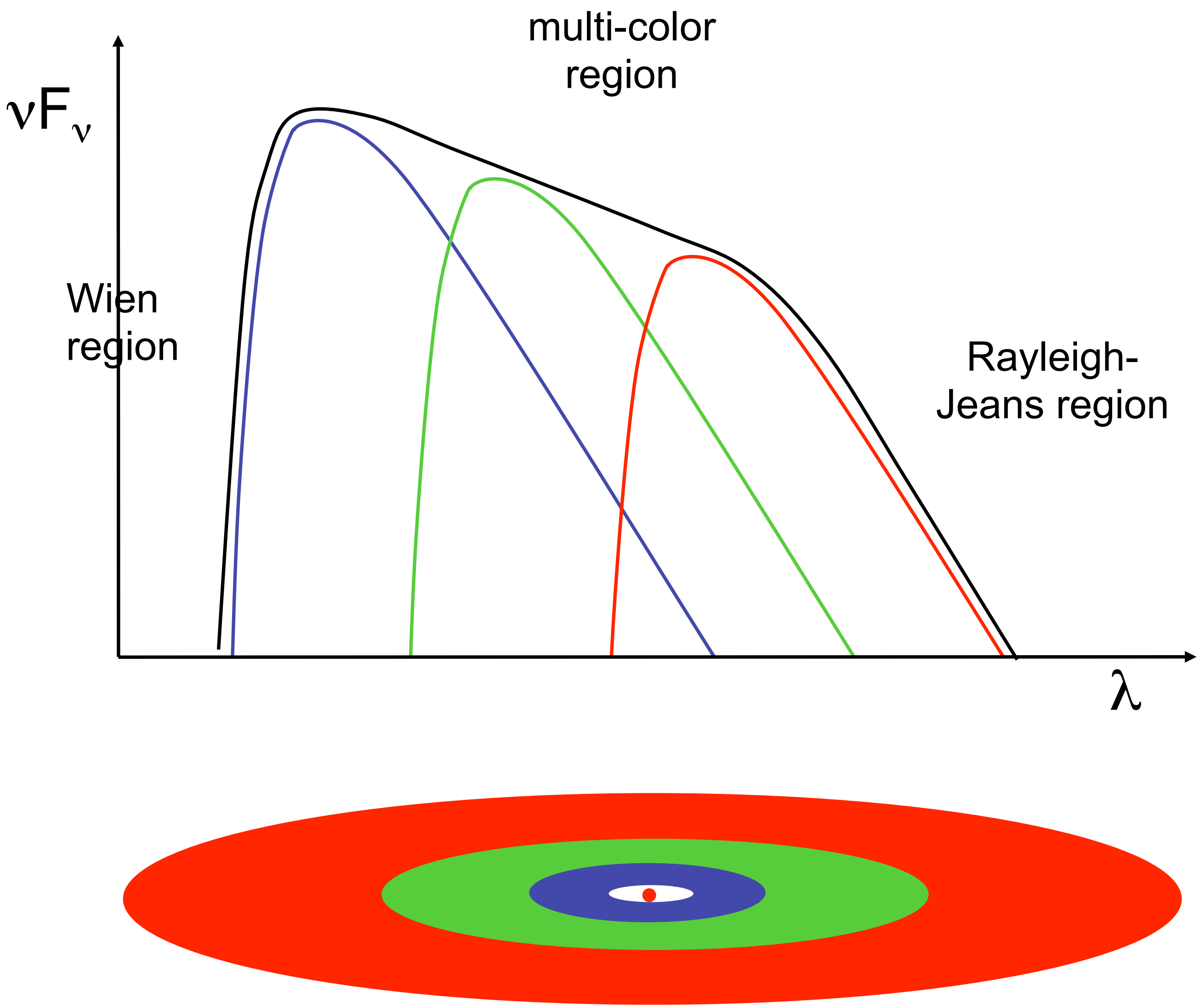
Multi-color blackbody disk SED



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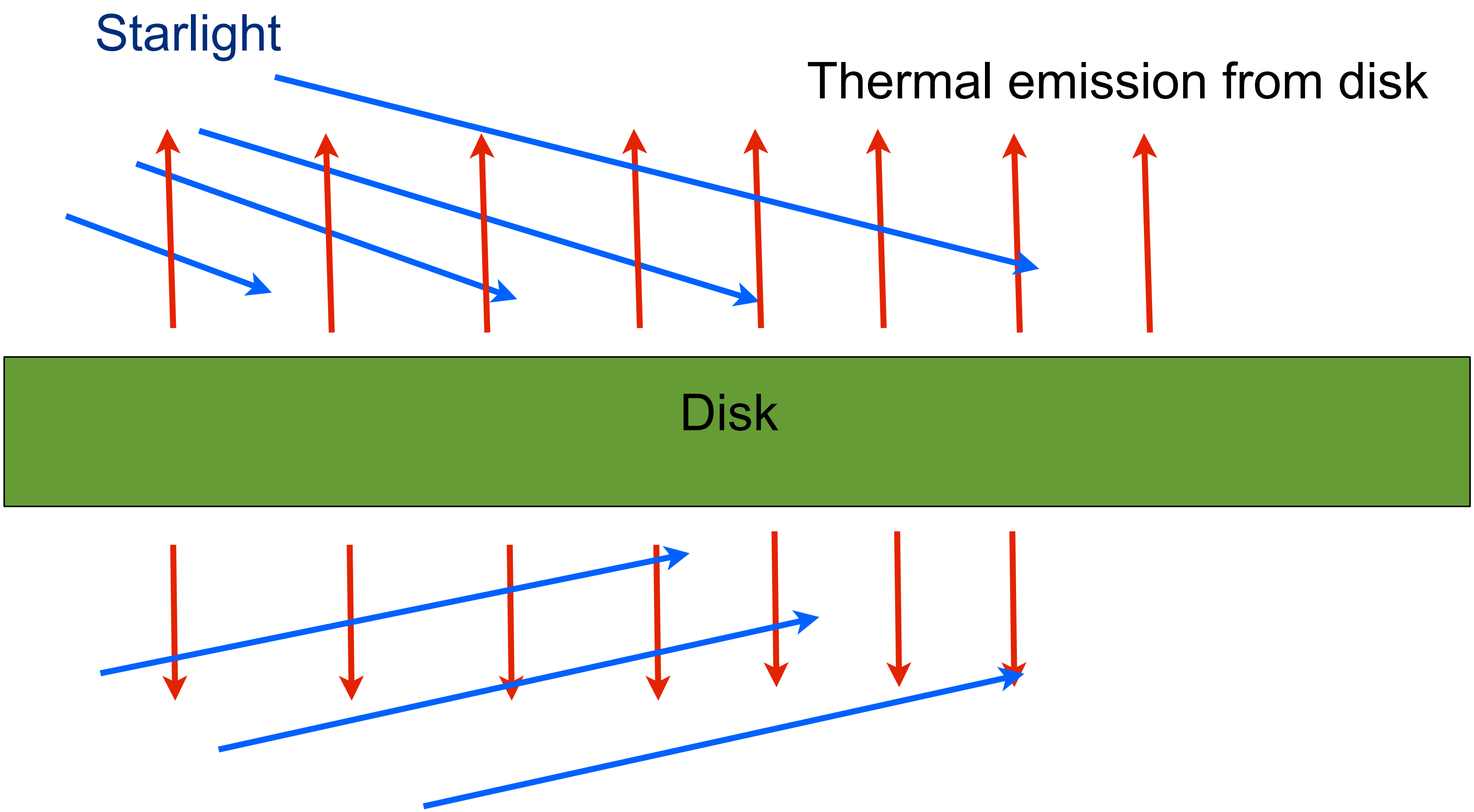
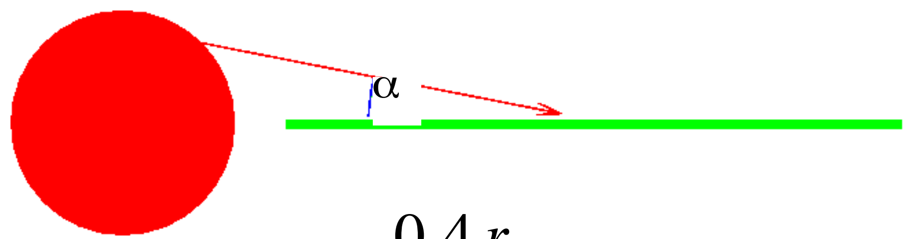
Heating and Coolings of Disks



Flat irradiated disks



$$\alpha \cong \frac{0.4\, r_*}{r}$$

Irradiation flux:

$$F_{\mathrm{irr}} = \alpha \frac{L_*}{4\pi\, r^2}$$

Cooling flux:

$$F_{\mathrm{cool}} = \sigma T^4$$

$$T = \left(\frac{0.4\, r_* L_*}{4\pi\sigma r^3} \right)^{1/4}$$

$$\boxed{T \propto r^{-3/4}}$$

Similar to active accretion disk, but flux is fixed.
Similar problem with at least a large fraction of HAe and T Tauri star SEDs.

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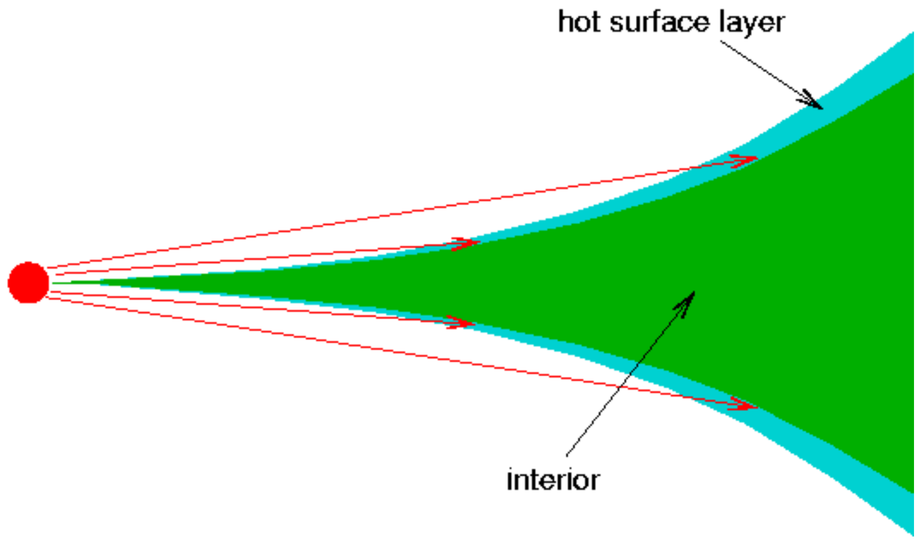
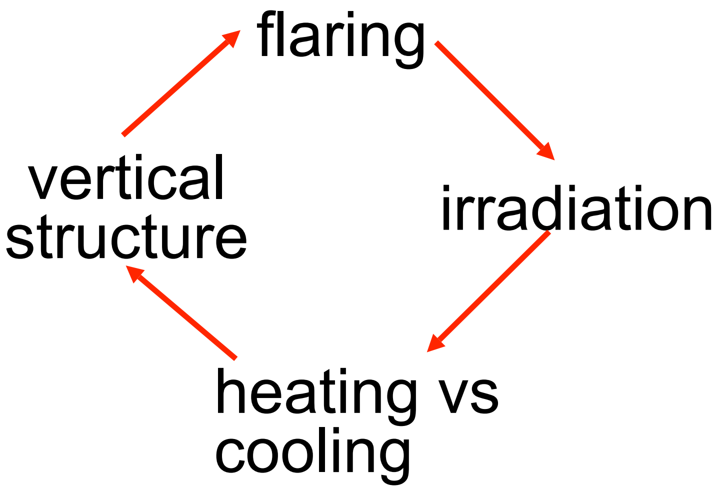
Flared disks





- Kenyon & Hartmann 1987
- Calvet et al. 1991; Malbet & Bertout 1991
- Bell et al. 1997;
- D'Alessio et al. 1998, 1999
- Chiang & Goldreich 1997, 1999; Lachaume et al. 2003

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Summary

Spectral Energy Distributions: distribution of power over large portion of the electromagnetic spectrum. Usually constructed from a mixture of photometry and spectroscopy from many different instruments.

SEDs are a major source of information on protostars and stars with disks.

Dust temperature for a grain being heated directly by a star decreases $T = k\ r^{-1/2}$

An optically thick shell (were the primary form of opacity is dust) can reprocess radiation to a lower wavelength, creating an effective low temperature dust photosphere. $T_{shell} = k\ R_{shell}^{-1/2}$

The radius of the dust photosphere depends on the wavelength and opacity - this pushes the peak of the protostellar SED into the far-IR

Scattering of light from the inner star and disk by the envelope may also fill in protostellar SEDs at wavelengths < 10 μm.

Disks can be modeled as a series of concentric annuli each heated to a different temperature.

For a passively heated flat disk, the temperature goes as $T = k\ r^{-3/4}$