

# EARLY PHASES OF PROTOSTARS:

## Star formation and Protoplanetary Disks

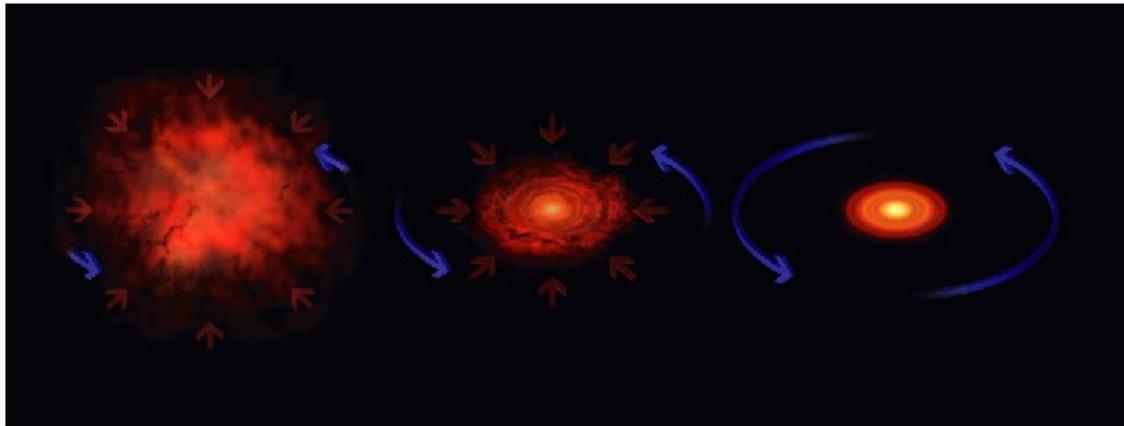
How do we observe them?





# Formation of stellar systems: 1. Introduction

- **Observation of stars at different stages of their life** has enabled us to retrace the processes of their formation and of their different stages in their evolution.



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- By studying them we can **constrain theories** of stellar and planetary formation and can develop timescales for the evolution of planetary development.
- And finally compare our own solar system to others.

## Formation of stellar systems: 2. Molecular Clouds

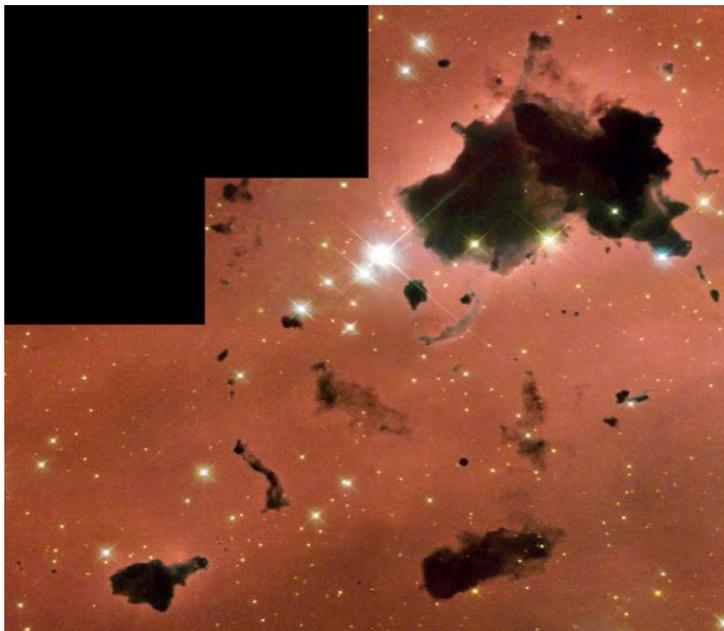
- **Nebular hypothesis:** Most widely accepted model explaining the formation and evolution of the solar system. This hypothesis of planetary formation is also thought to occur throughout the Universe.

“ (...) the solar system condensed from a **large rotating nebula.**”

*Immanuel Kant, 1755 <sup>[1]</sup>*

“(...) the planets have formed from **gas rings** ejected from the equator of the collapsing Sun.”

*Laplace, 1796 <sup>[1]</sup>*



- It is now believed that our sun, like other stars, formed from **dense interstellar clouds**, composed mainly of molecular hydrogen ( $H_2$ ).

Dark clouds in the star forming region IC 2944 from HST's WFPC2.

# Formation of stellar systems: Molecular clouds

Dense  
molecular  
clouds

Temperature	Density	state of hydrogen	Size	Mass
10 -20 K	$> 300 \text{ H cm}^{-3}$	molecular ( $\text{H}_2$ )	10-50 pc	$\sim 100\,000 M_{\odot}$

They are the **densest** and **coldest** forms of interstellar medium and form 50% of the overall mass of the interstellar medium.

*Where to look if we don't see through them in the visible part of the spectrum?*



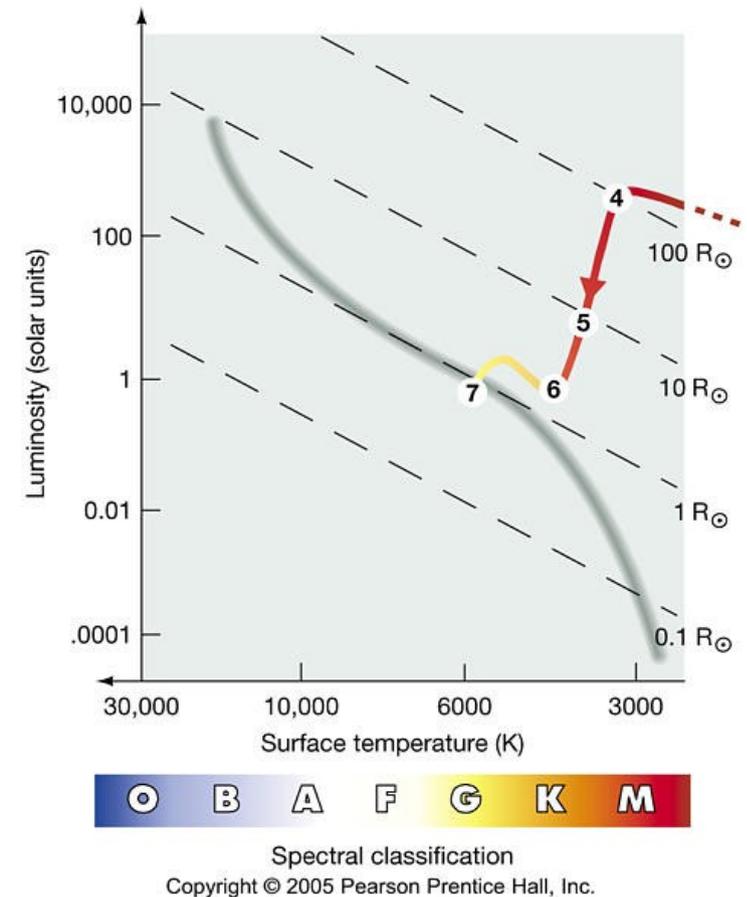
Stellar forming region DR21 in the constellation of Cygnus. Imagen taken from NASA's Spitzer Space Telescope.

- The **infrared** image reveals the presence of dust.
- Dust grains absorb UV light from the surrounding stars. It heats up and re-emits in the infrared.

# Formation of stellar systems: Molecular clouds

## ★ How do we know that young stars are related to the molecular clouds?

- 1) We see massive, luminous stars which cannot be older than about  $10^6$  yr.
- 2) In association with these we see often peculiar stars with emission lines (TTauri stars), thus assumed to be also young.
- 3) TT stars have lower luminosities and are redder than the massive O, B stars but are still considerably more luminous than MS stars of the same color.
- 4) Lower luminosities --> lower masses than O, B stars --> **contraction times longer**
- 5) SO, if TT stars were formed at the same time as their more massive associates ( $\sim 10^6$  yr) they have not had enough time to contract to the MS --> **still contracting!** ( $\tau_{cl} \propto M_c^{-0.5}$ )
- 6) Both O, B and TT stars appear in association with large dust complexes.



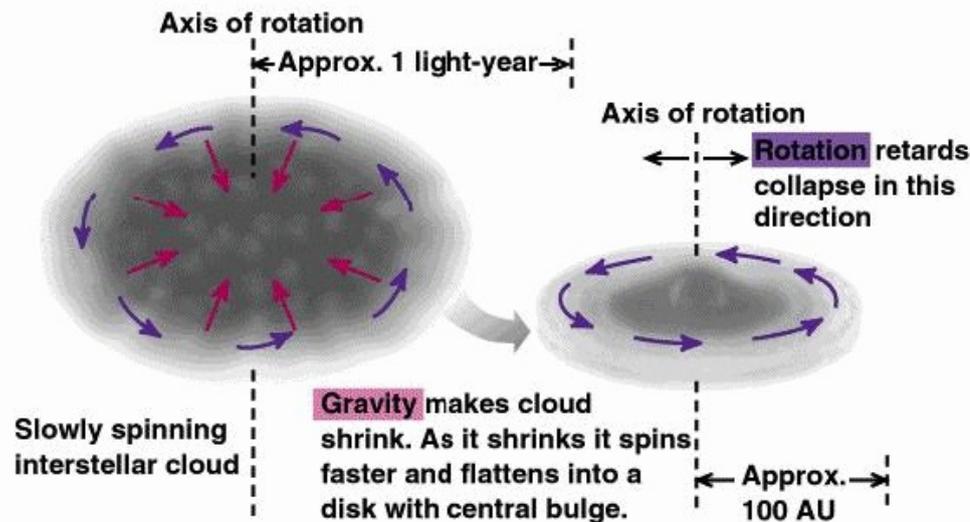
# Formation of stellar systems: 3. Cloud collapse

- **Cloud collapse:** Observations show that new stars can be formed in an environment of dense interstellar clouds. Under certain circumstances these clouds can become gravitationally unstable to contraction.

In equilibrium:

$$-E_g = 2E_k$$

$$\frac{3}{5} \frac{GM^2}{R} = \frac{3}{2} kT \frac{M}{m}$$



During collapse:

$$-\frac{1}{2}E_g > E_k$$

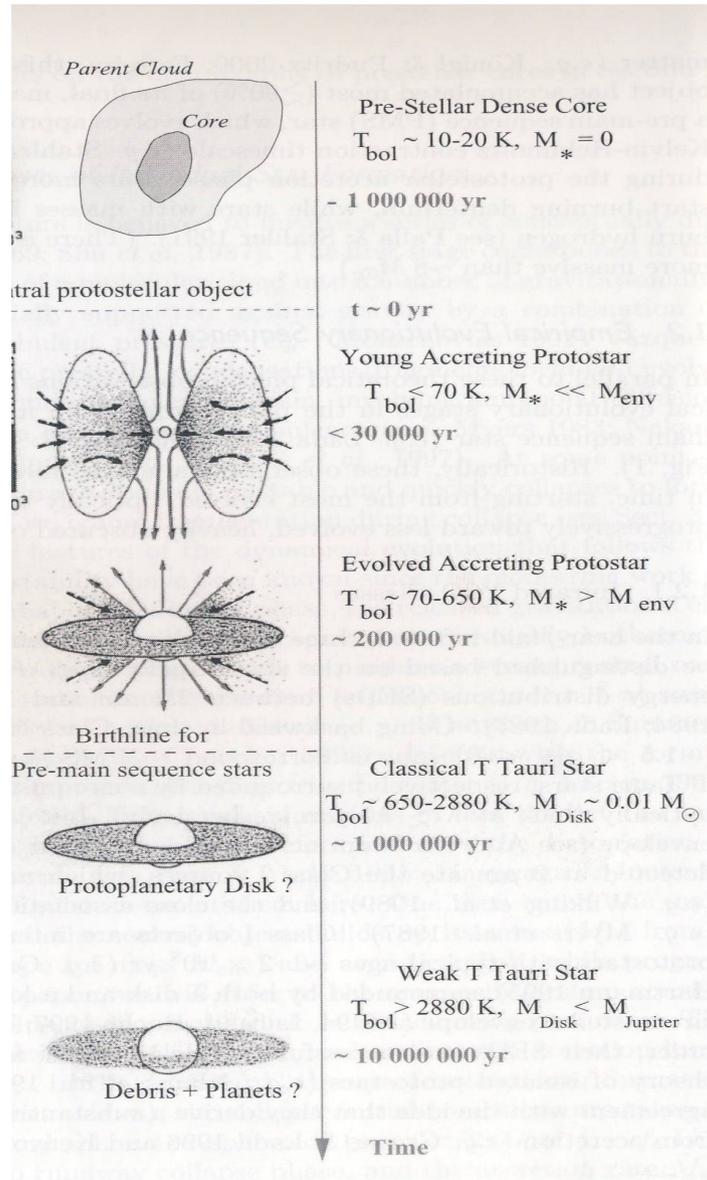
$$M > M_J = 9 \cdot 10^4 M_\odot \left( \frac{T_{(K)}^3}{n_{(m^{-3})}} \right)^{\frac{1}{2}}$$

For a MC with:

$$\left. \begin{array}{l} T=10K \\ n=100 \text{ cm}^{-3} \end{array} \right\} M_J \sim 10^2 M_\odot$$

To form a star it is not strictly necessary to have such massive clouds. There are **inhomogeneities** that will cause the cloud to **fragment** leading to the formation of more than one star.

# Formation of stellar systems: Cloud collapse (stages)



1) Isothermal phase

2) Adiabatic phase (Class 0)

3) Protostar (Class I)

4) "Classic" T Tauri phase (Class II)

5) "Weak" T Tauri phase (Class III)

3 stages  
of  
collapse



# Formation of stellar systems: Cloud collapse (Phase 1)

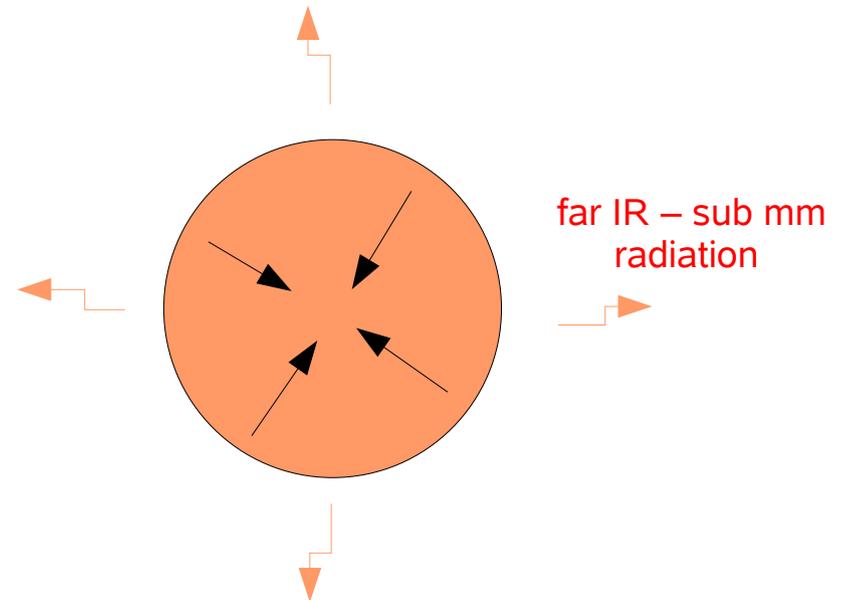
## Isothermal phase

### What is going on?

- $T \sim 10\text{K}$
- $\rho$  is **tenuous** enough for gravitational energy to dissipate through the radiation coming from the thermal excitation of the atoms.
- As a consequence of this, the temperature remains low and it keeps contracting.

### Where can we observe it?

Object observable through its infrared thermal emission.



# Formation of stellar systems: Cloud collapse (Phase 2)

## Adiabatic phase

### What is going on?

- $\rho$  increases -->  $\kappa$  increases
- $\kappa$  reaches the point where the energy released by the contraction cannot escape by radiation: **opaque**
- As a consequence of this, the **temperature rises** until contraction stops because of pressure built up:

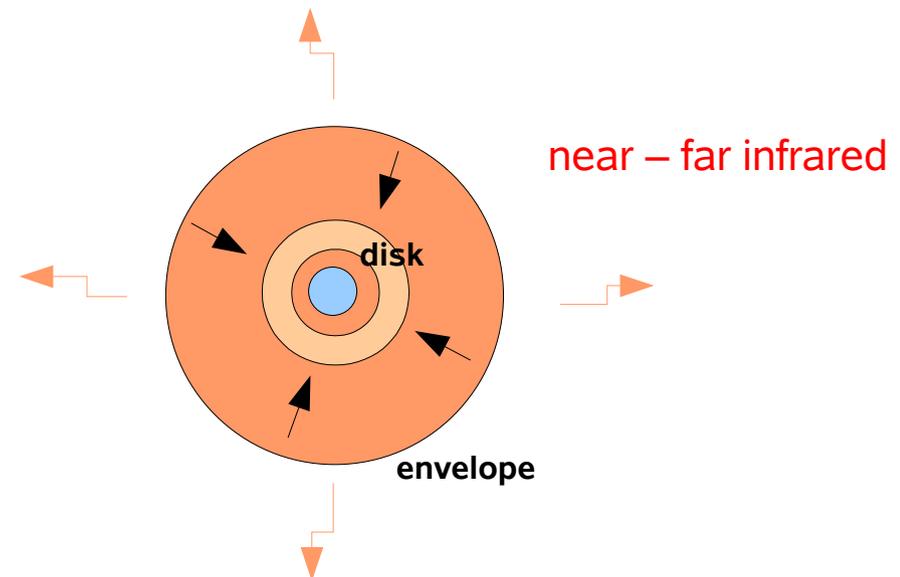
**Hydrostatic equilibrium**



**PROTOSTAR!!**  
(class 0)

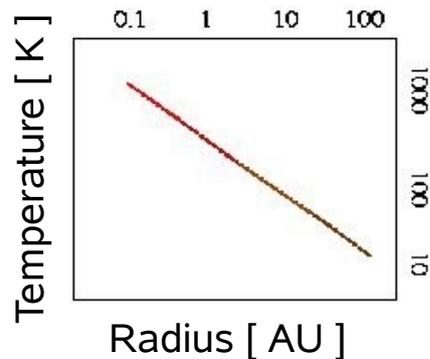
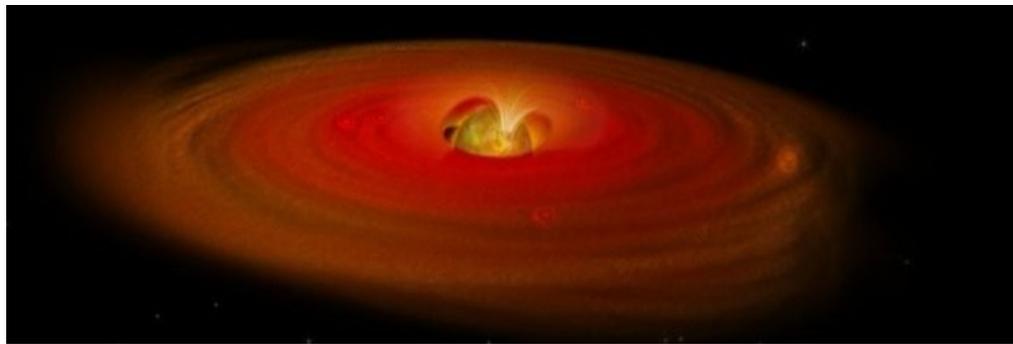
### Where can we observe it?

Only the cloud is detectable from radiation from the dust as a black body that peaks in the far infrared --> **SED's**

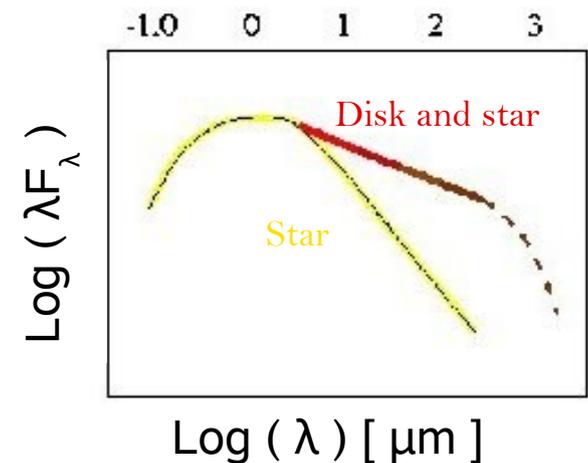
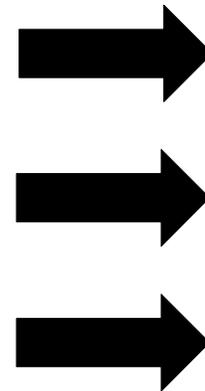


## ★ What can we say is going on in a given physical system from its spectral energy distribution (SED)?

Central star surrounded by a disk of gas and dust



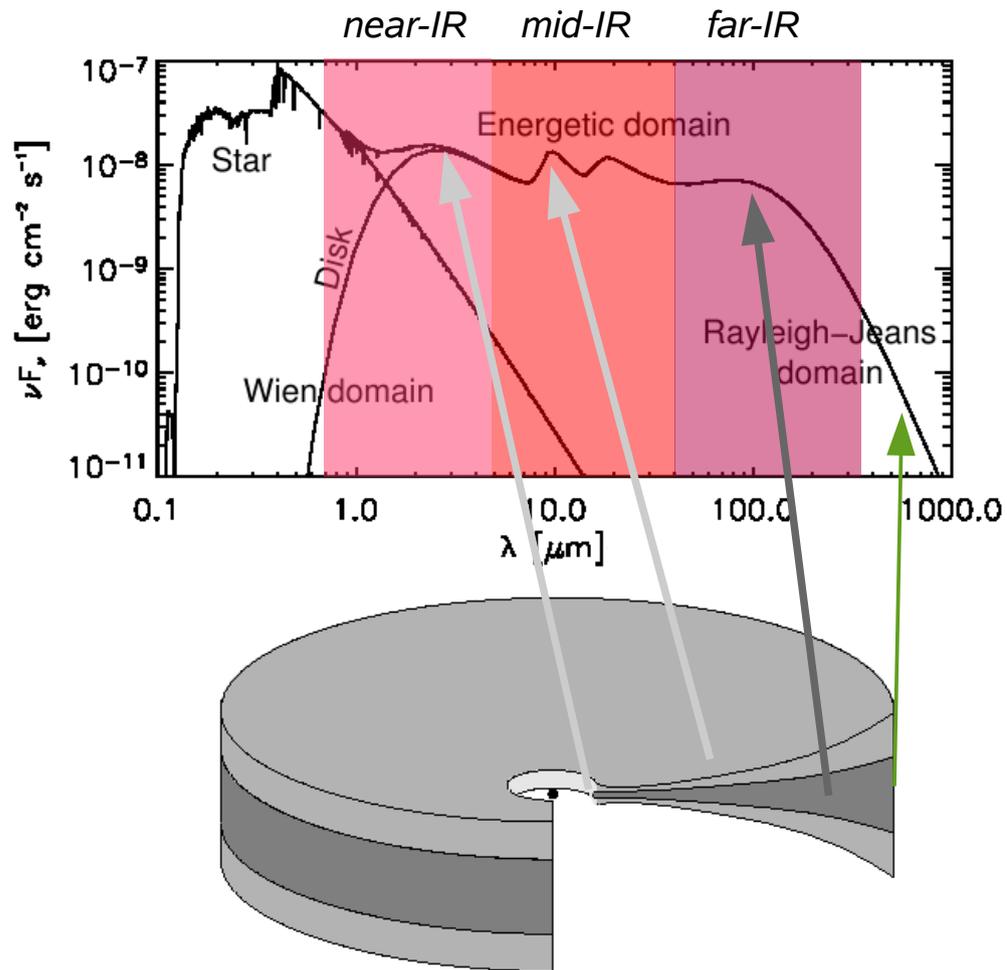
For every distance from the star the dust will be at a different and unique temperature:  
each radius emits at a characteristic peak wavelength.



The infrared excess seen is due to the gas and dust in the disk and envelope.

Modeling the SED allows to compare observations with what might be going on.

# Formation of stellar systems: SEDs (Multiwavelength Observations)



- **Near-infrared bump:** the inner rim, the infrared dust features from the warm surface layer, and the underlying continuum from the deeper (cooler) disk regions.
- **Near- and mid-infrared:** from small radii.
- **Far-infrared:** from the outer disk regions.

**(sub-)mm. emission** mostly comes from the mid-plane of the outer disk. This flux probes also the disk mass.



Differences in disk geometry are mainly reflected in the energetic domain.

(Dullemond et al. 2007)

At short  $\lambda$ 's SED is in the "Wien domain":

$$B_{\lambda}(T) \approx \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda kT}}$$

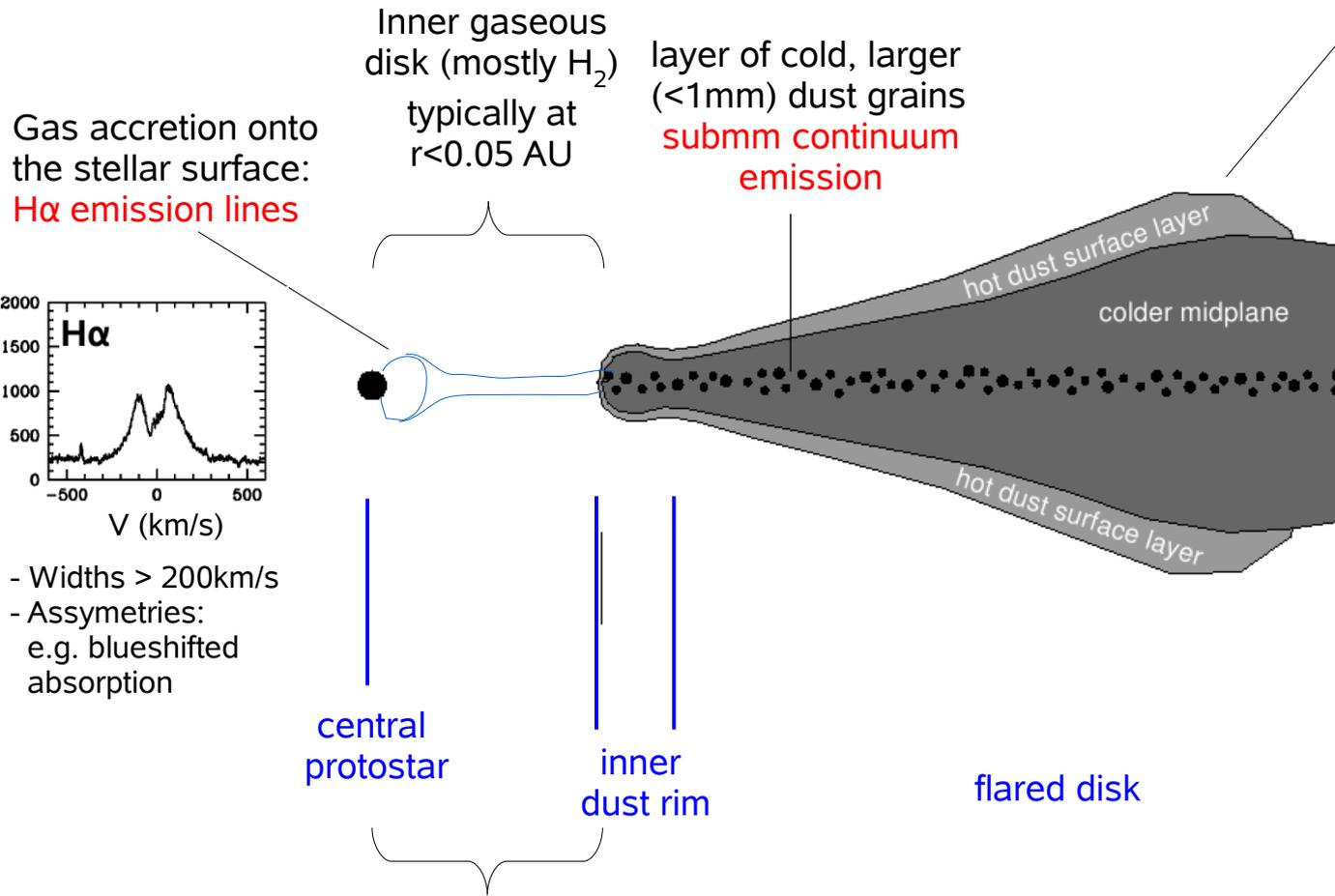
At long  $\lambda$ 's the SED is in the "Rayleigh-Jeans domain":

$$B_{\nu}(T) \approx \frac{2k\nu^2}{c^2} T$$

# Formation of stellar systems: Disk structure

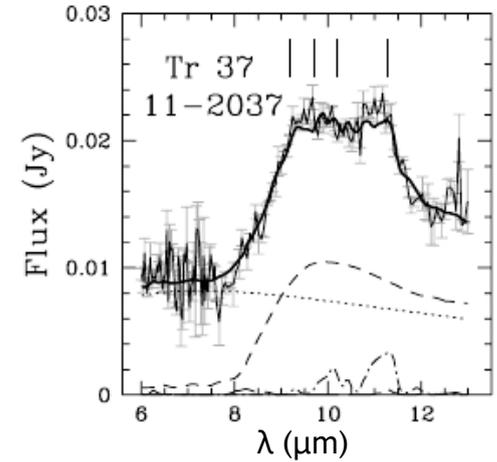
## Disk structure

(Dullemond et al. 2007)



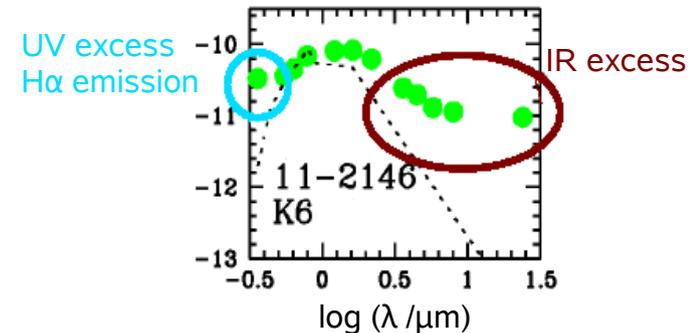
Dust sublimation due to high temperatures ( $T > 1500$ K)

1) Optically THIN disk :  
**Silicate emission** from small (<6 $\mu$ m), warm (150-450K) grains.



Silicate emission at 9.7 $\mu$ m  
(IRS spectrum: Sicilia et al. 2007)

2) Optically THICK disk:  
**IR excess** from outer most grains.



# Formation of stellar systems: SEDs (modeling)

- Temperature distribution of the disk

$$T(R) = T_s \left( R / R_* \right)^{-p}$$

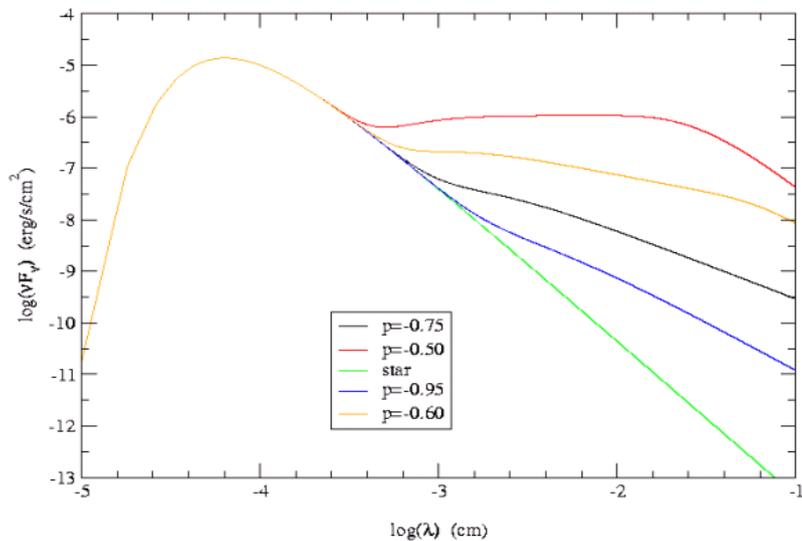
R: distance from star

$R_*$ : Radius of star

$T_s$ : Normalization factor

p: power ( $0 < p \leq 2$ )

Material, size and shape of the dust particles affects the temperature distribution and thus the shape of the SED.



- Characteristics of a SED

Slope (value of p):

flatter slope --> small p --> small grains

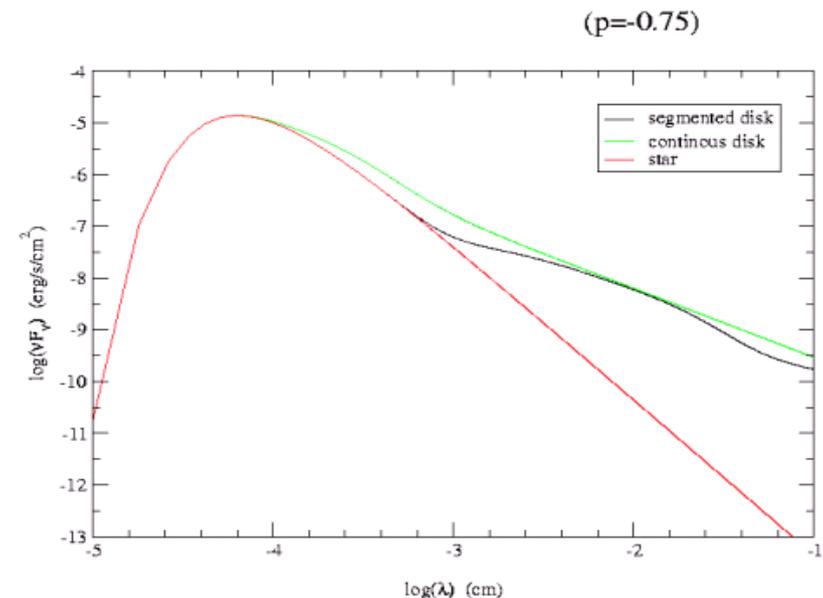
steep slope --> big p --> big grains

Shape:

$\lambda_{\max}$  --> dust dominated (longer  $\lambda$ 's)

star dominated (shorter  $\lambda$ 's)

dips --> gaps in the disk --> planets?



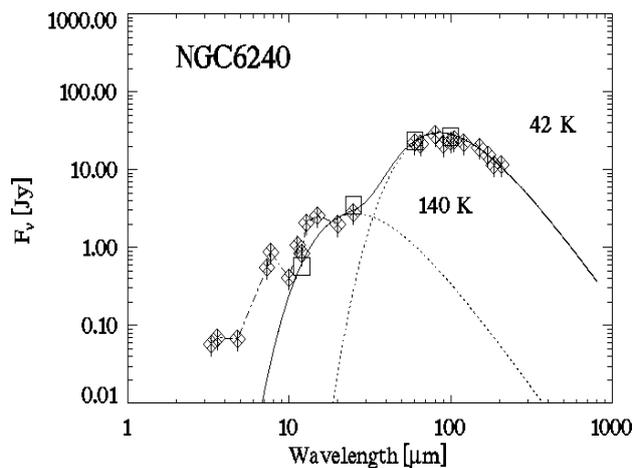
# Formation of stellar systems: SEDs (Classes)

3 main classes of young stellar objects (YSO) can be distinguished based on the slope of their **SEDs** (André et. al. 1994):

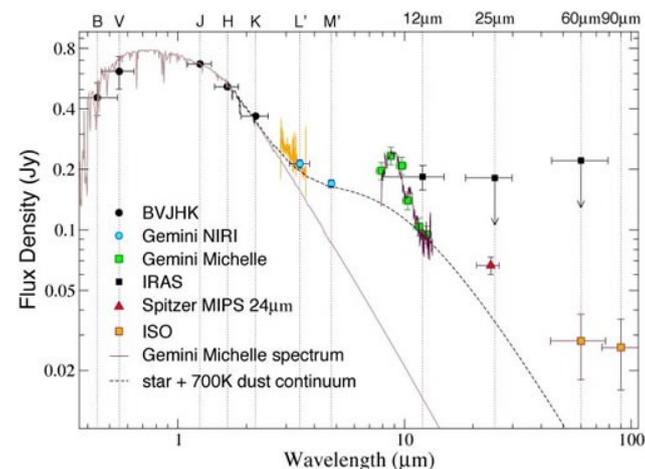
$$\alpha_{\text{IR}} = d \log(\lambda F_{\lambda}) / d \log(\lambda) \quad \text{for } \lambda = [2.2, 10-25] \mu\text{m}$$

- $\alpha_{\text{IR}} > 0$  (Class I)
- $-1.5 < \alpha_{\text{IR}} < 0$  (Class II)
- $\alpha_{\text{IR}} < -1.5$  (Class III)

→ related to the amount of dust in the disk + envelope



NGC 6240 ([www.ipac.caltech.edu](http://www.ipac.caltech.edu))

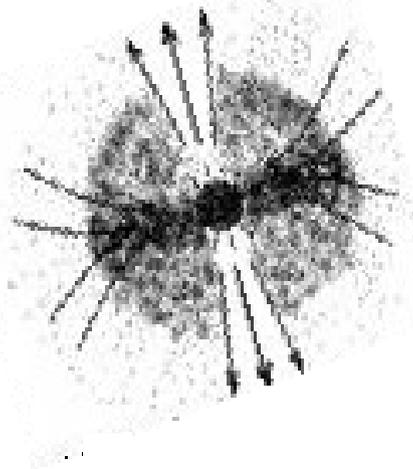


HD 23514 in the Pleiades star cluster (<http://www.gemini.edu>)

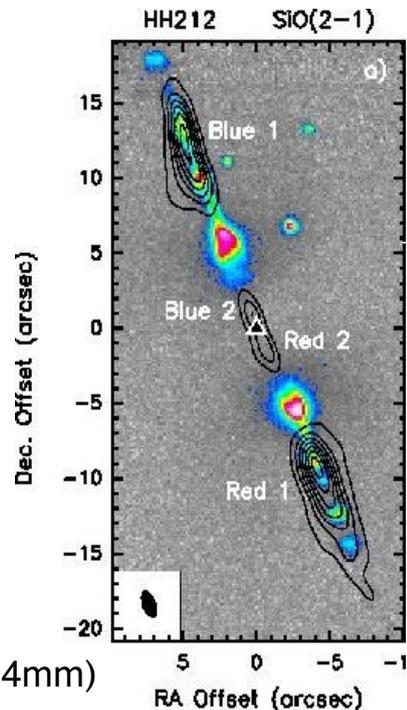
# Formation of stellar systems: 4. Class 0 vs. Class I sources

## CLASS 0

- Associated with formed (hydrostatic) YSOs
- Visible at  $\lambda \geq 25\mu\text{m}$
- Indirect evidence for a central YSO:
  - cm radio continuum emission
  - Presence of a collimated CO outflow
- Presence of a dust envelope in sub-mm.
- $L_{\text{submm}}/L_{\text{bol}} \gg 0.5\% \rightarrow M_{\text{env}} \gg M_*$  (André 2003)
- $\dot{M}_{\text{jet}} \sim 10^{-6} M_{\odot}/\text{yr}$  (Bontemps et al. 1996)
- $\dot{M}_{\text{acc}} \sim 10^{-5} M_{\odot}/\text{yr}$

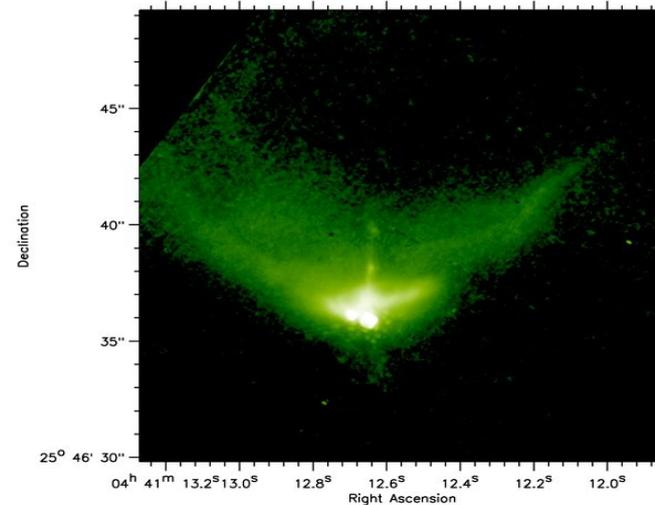
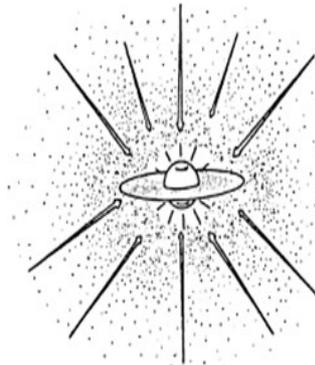


HH 212 outflows in SiO(2-1) (3.4mm)  
(Codella et al. 2007)



## CLASS I

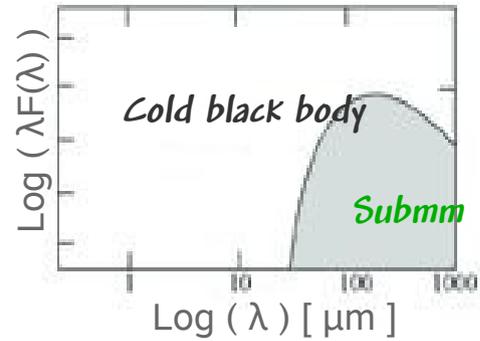
- Associated with late active mass accretion phase
- Rising SEDs at  $\lambda \geq 2\mu\text{m}$
- Less collimated CO outflows
- $L_{\text{submm}}/L_{\text{bol}} \sim 0.5\% \rightarrow M_{\text{env}} \leq M_*$
- $\dot{M}_{\text{jet}} \sim 2 \times 10^{-8} M_{\odot}/\text{yr}$  (Bontemps et al. 1996)
- $\dot{M}_{\text{acc}} \sim 2 \times 10^{-7} M_{\odot}/\text{yr}$



TMC-1 at 1.6  $\mu\text{m}$  ( $i=40^\circ - 70^\circ$ )  
(Terebey et al. 1993)

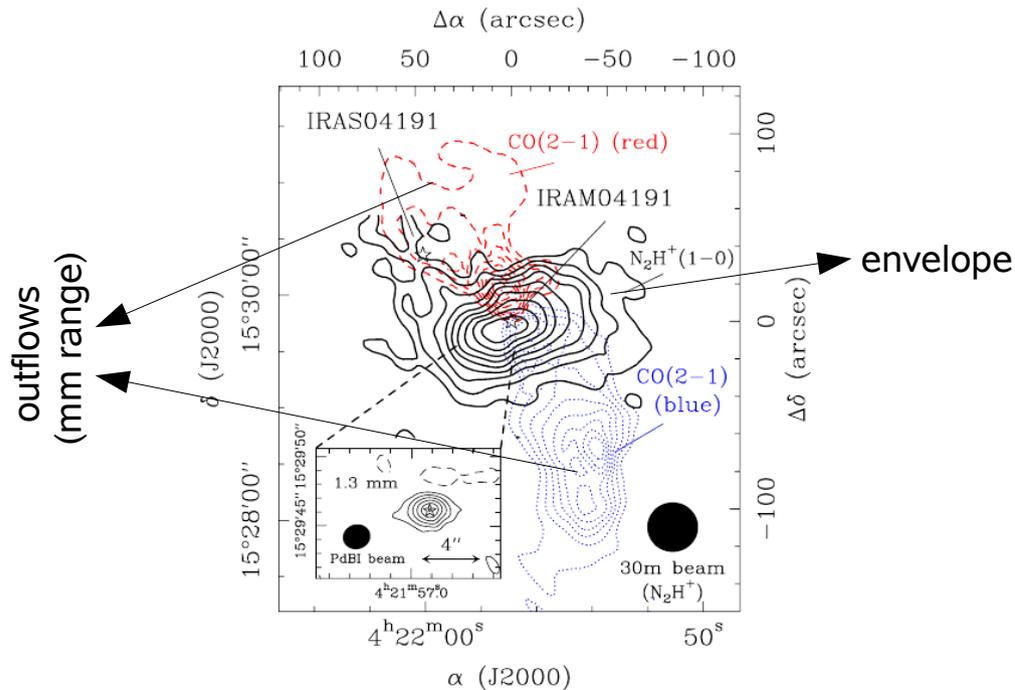


# Formation of stellar systems: 4. Class 0 (observations)

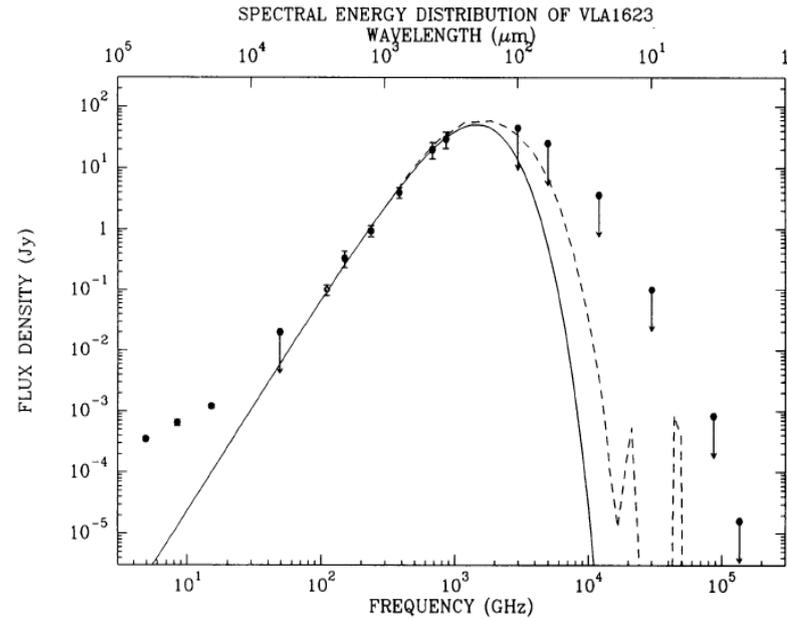


## OBSERVED CLASS 0 SOURCES:

**IRAS 04191**  
(Belloche et al. 2001)

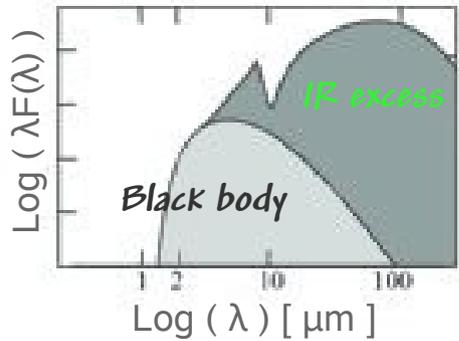


**VLA 1623**  
(André et al. 1993)



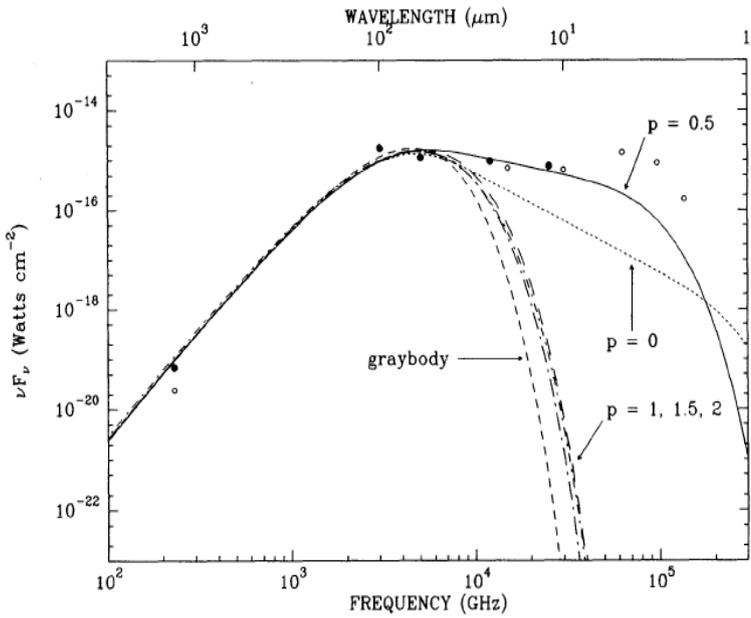
- Dots are the observational data.
- Solid curve is a fit of a 20K blackbody.
- Dashed curve is a "best-fit" resulting from a modeling with a radiative transfer code.

# Formation of stellar systems: 4. Class I (observations)



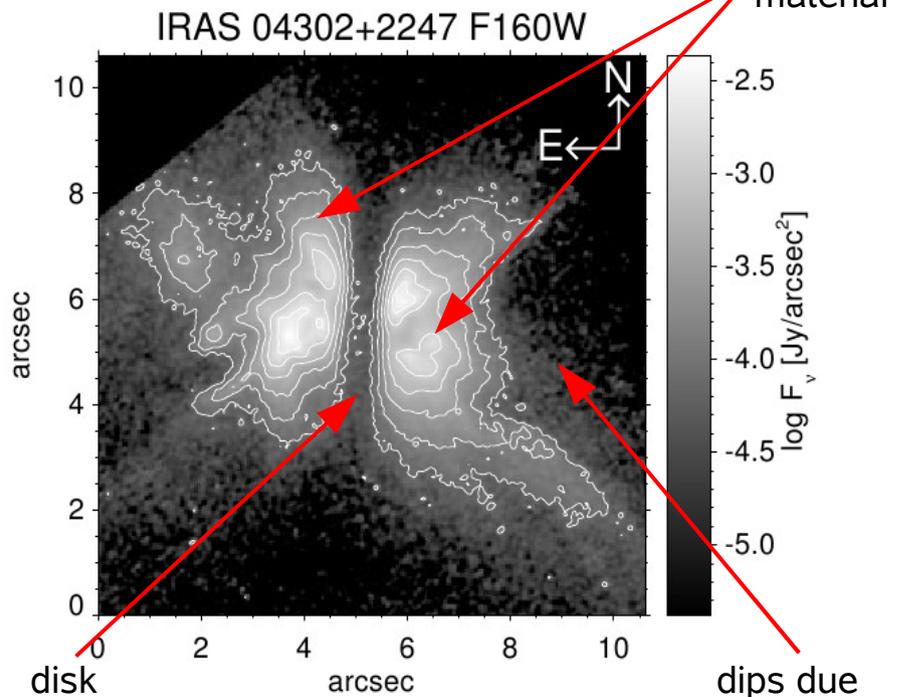
## OBSERVED CLASS I SOURCES:

$\rho$  Oph source EL 29  
(André & Montmerle 1994)



- Dots are observational data.
- Dashed line is a greybody model.
- Other lines are examples of circumstellar envelope fits.

Taurus star forming region  
(Padgett et al. 1998)



HST/NICMOS at 1.6μm  
broadband photometry.

CIRCUMSTELLAR ENVELOPE MODELS FOR EL 29

Model <sup>a</sup> (1)	$p$ (2)	$R_{in}$ (AU) (3)	$T_{in}$ (K) (4)	$\langle T_{dust} \rangle$ (K) (5)	$M_{env}$ ( $M_{\odot}$ ) (6)	$A_V$ (7)
1.....	0.0	0.1	1600	35.1	0.10	~14
2.....	0.5	1	630	35.9	0.09	~20
3.....	1.0	300	60	34.2	0.12	~21
4.....	1.5	300	60	35.6	0.09	~22
5.....	2.0	300	55	34.3	0.10	~31
6 <sup>b</sup> .....	Graybody	...	...	40.0	0.08	~13

# Formation of stellar systems: 4. Accretion and outflows

## ACCRETION

- Inward motions can be traced by optically thick molecular lines which exhibit asymmetric double-peaked profiles with a stronger blue peak:

- CS (2-1) transition ( $\sim 3\text{mm}$ )

(Belloche et al. 2002)

- CO (2-0) transition ( $\sim 2.3\ \mu\text{m}$ )

(Antoniucci et al. 2007)

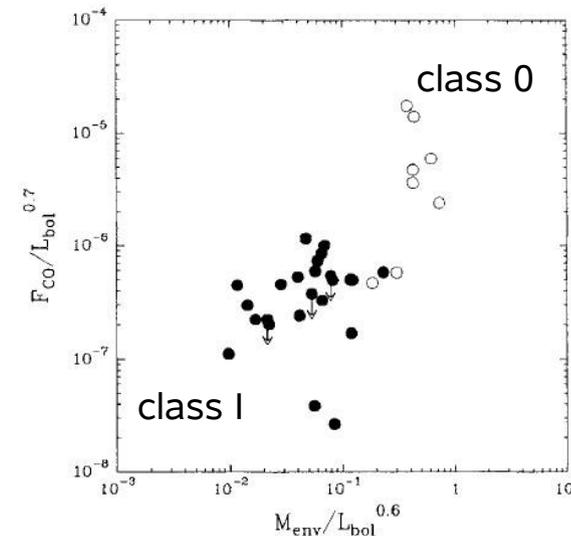
- From thermal fluxes at submm and far-IR wavelengths:

-->  $M_{\text{env}}$

- It's also possible to retrieve the mass accretion rates through the  $L_{\text{acc}}$  (related to the H I Br $\gamma$  flux (Antoniucci et al. 2007) ) using the formula:

$$\dot{M}_{\text{acc}} \sim \frac{L_{\text{acc}} R_*}{GM_*}$$

## OUTFLOWS



Study of 36 near-IR (class I) and 9 far-IR/submm (class 0) protostars using maps of CO(2-1) line.  
(Bontemps et al. 1996)

From mm transitions of CO(2-1) (1.2mm):  
(Belloche et al. 2002)

--> outflow activity from jets

--> difference in classes (evolution)

# Formation of stellar systems: 4. Evolutionary sequence?

One expects (independently of details of protostellar theory) **YSO** to become warmer and to be surrounded by progressively smaller amounts of circumstellar material as they evolve.

- Evolutionary indicators:

- Peak of the SED -->  $\lambda_{\text{max}}$

- Decrease of circumstellar mass -->  $M_{\text{env}}$

- Accretion mass rates -->  $\dot{M}_{\text{acc}}$

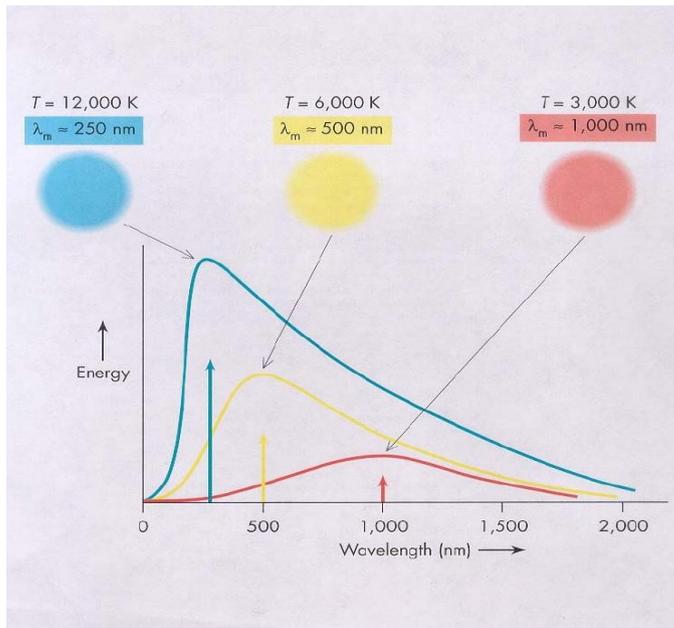
- Jets, outflow mass rates -->  $\dot{M}_{\text{jet}}$

# Formation of stellar systems: SEDs (Blackbody radiation)

## Spectral energy distribution (SED)

or

Radiative flux as a function of wavelength ( $F_\lambda$ )



**Blackbody:** Theoretical object that is a perfect emitter and absorber of radiation. Its energy spectrum depends only on the temperature of the body.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

**Wien's law:** The temperature of a blackbody is inversely proportional to the wavelength peak of emission.

$$\lambda_m = 2.89 \times 10^{-3} / T(\text{k})$$

No object is a perfect blackbody, but it is still possible to approximate most objects as blackbodies. Stars act almost exactly like a blackbody.

# Formation of stellar systems: SEDs (Multiwavelength Observations)

## Optically thick disks:

As soon as the grains absorb the radiation from the central star and emit their own, it immediately is absorbed again by the surrounding grains throughout the entire disk. **Only the radiation emitted by the outer most grains in the disk** can be observed so the material of the grains and the density of the disk do not play a large role in the SED. The **size of the grains is the dominant factor**.

*Dust grains that are larger than the wavelength of incoming radiation absorb that radiation very efficiently, i.e., grains that are larger than the peak wavelength they emit, emit that radiation effectively, they tend to cool off closer to the star.*

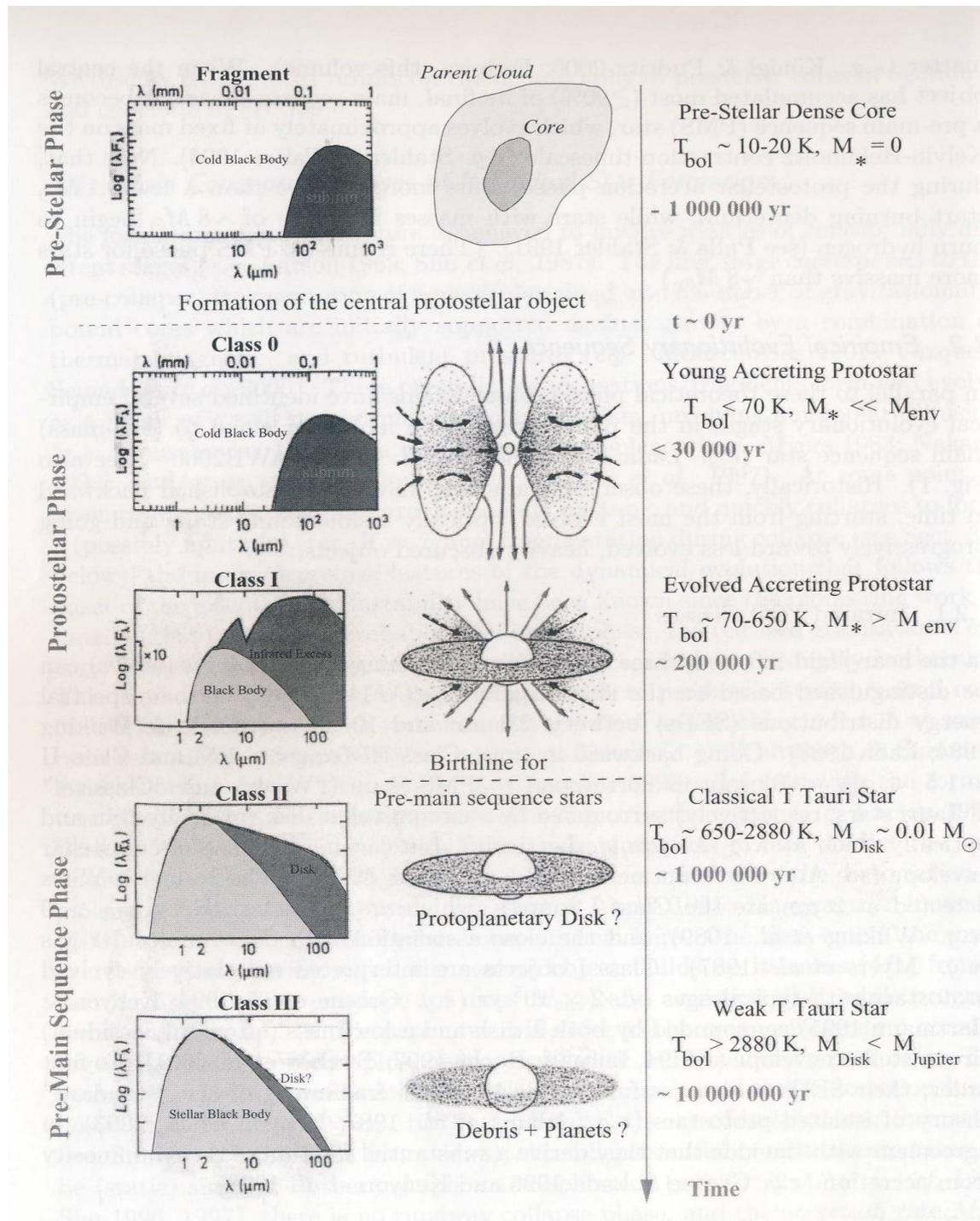
*Grains smaller than the wavelength of incoming radiation do not absorb that radiation very well, i.e., do not efficiently emit radiation at wavelengths larger than their diameter, they will remain hotter at larger radii.*

## Optically thin disks:

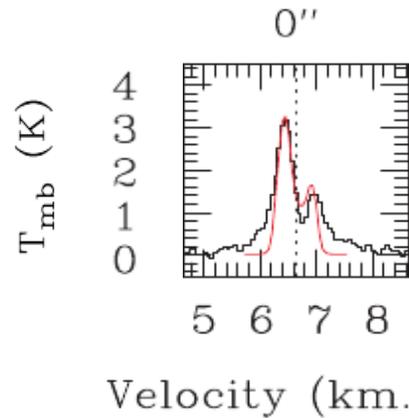
The energy emitted from the grains within the disk is not immediately absorbed again by the surrounding grains. **Energy emission from grains throughout the disk**, not just the ones present at the surface is observed so the **density of the disk and the material of the disk play a larger role**.

*The longer a wavelength, the harder it is for grains to emit that wavelength of radiation (does not take effect until considering wavelengths longer than 100  $\mu\text{m}$ ).*

# Formation of stellar systems: Evolution



# Formation of stellar systems: Outflow velocities



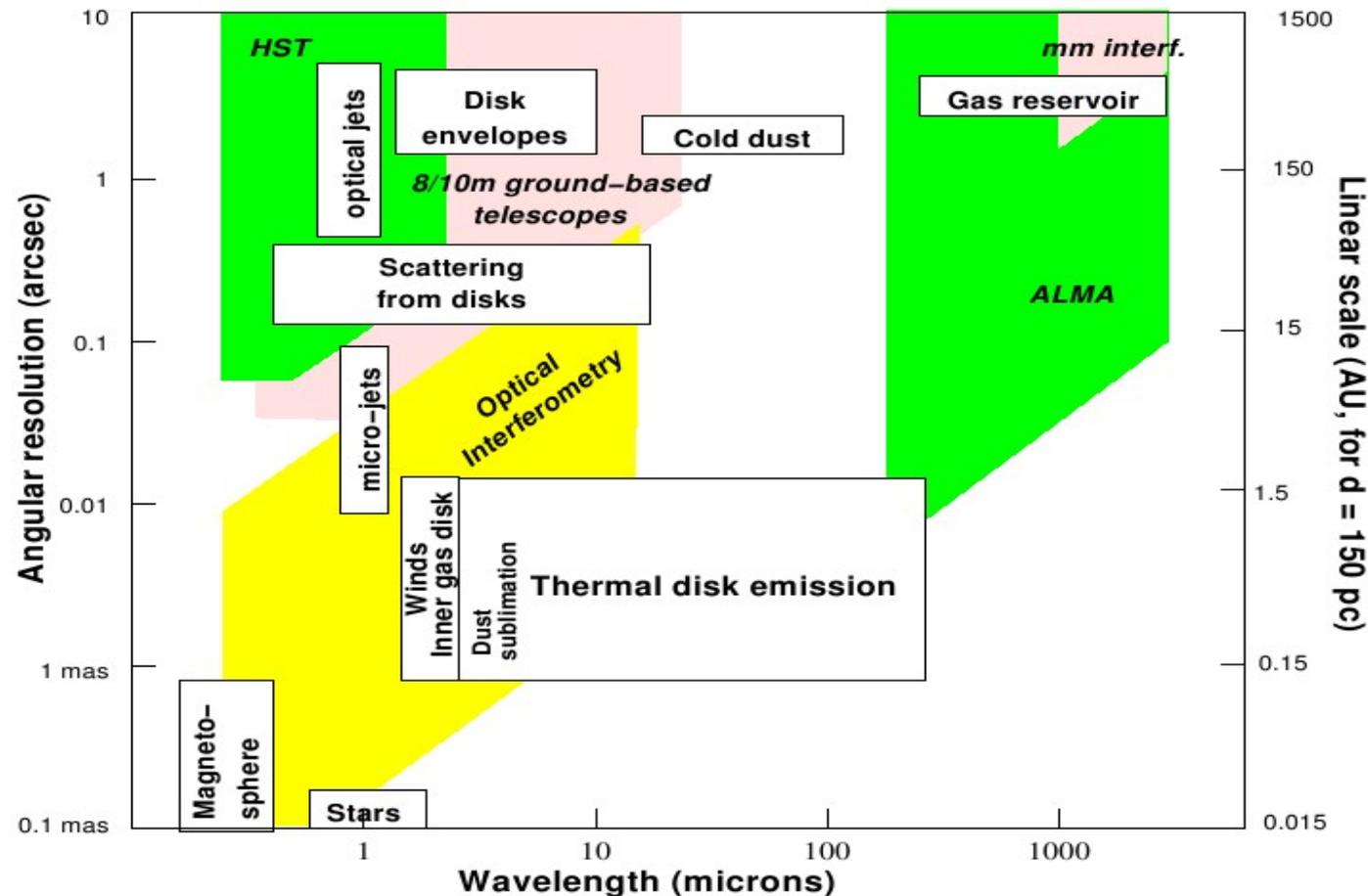
The double peaked profiles show two **outflow patterns**. From the fit of synthetic spectra one can retrieve the velocities.

Spectra along the axis perpendicular to the outflow in the optically thick CS(1-2) line.



# PROTOSTELLAR ENVELOPES: Why do we Need Multiwavelength Observations?

Optical interferometers are ideally suited to directly probe the innermost regions of the circumstellar environment around young stars.



*Observational phase-space (spectral domain and angular resolution) for optical interferometers, and for complementary techniques (shaded polygons). Also outlined over the most relevant phase-space regions (rectangular boxes) are the main physical phenomena associated with young stellar objects. (Millan-Gabet et al. 200?)*