Planetary formation
Observational evidence

Planets and Astrobiology (2019-2021)

G. Vladilo and S. Ivanovski

Infrared excesses & circumstellar disks

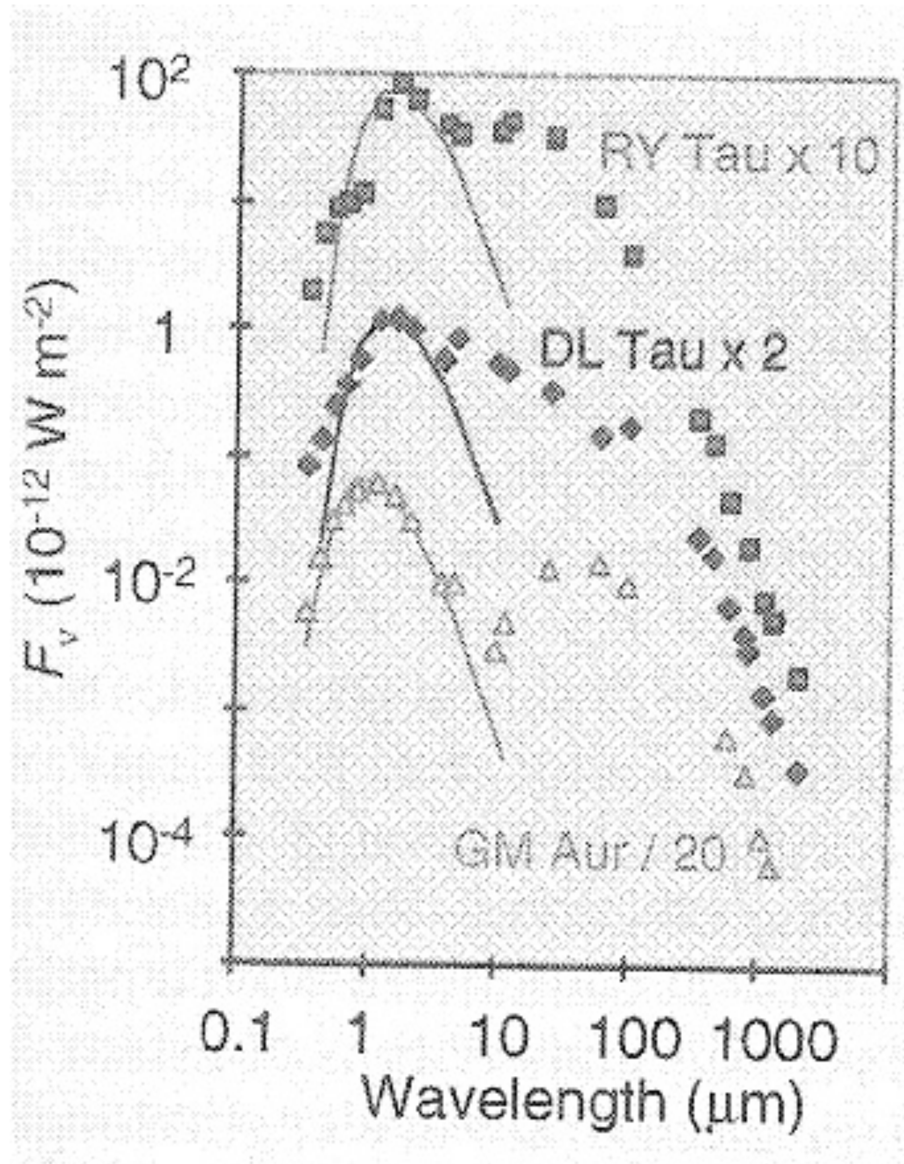
In the last decades observational evidence has accumulated that stars are born surrounded by circumstellar disks with dust and gas

Early evidence for circumstellar disks was found through the discovery of infrared excesses

Infrared excess

- The infrared excess is defined as an excess of the stellar infrared emission with respect to the black-body spectrum expected from the stellar effective temperature

In the far infrared the emission can be orders of magnitude more intense with respect to the expected stellar emission

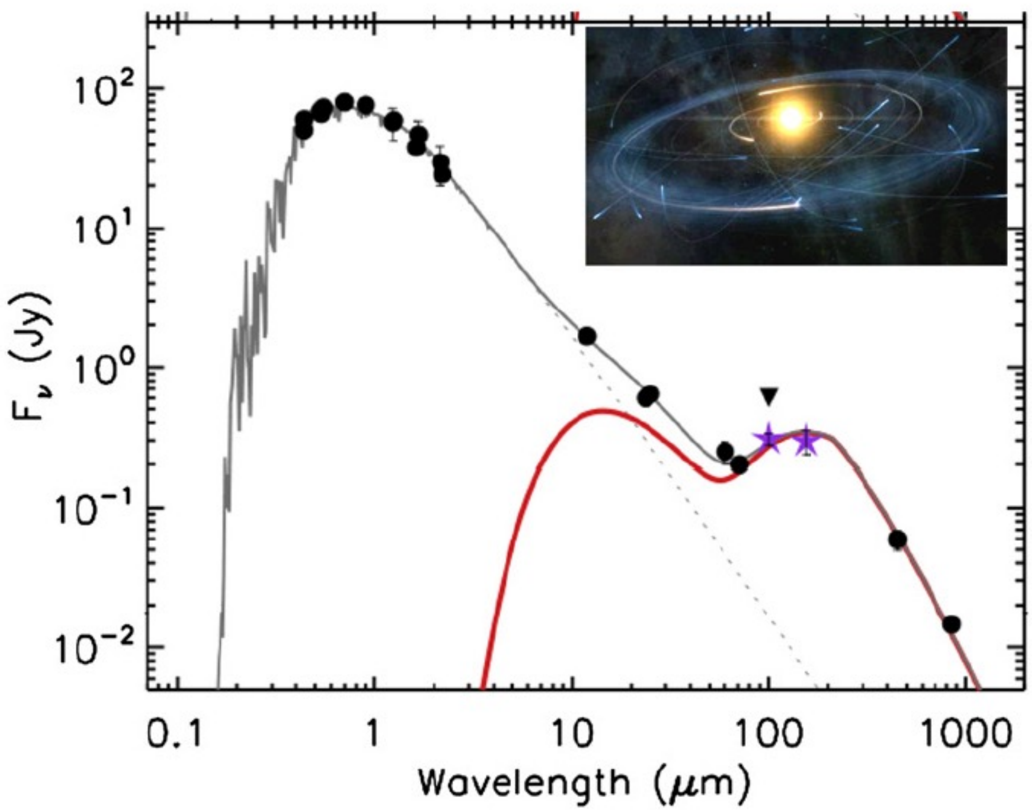


Infrared excess

Recent measurement of a double peaked infrared excess

Observations of η Corvi in the far IR

obtained with the instrument PACS on board of the Herschel satellite



Origin of the infrared excess

- The infrared excess is interpreted as due to thermal emission of circumstellar dust present at the epoch of star formation

- The dust is expected to be only 1% by mass of the circumstellar material, the rest being in gaseous phase

- Despite its small mass contribution to the circumstellar material, the dust is, by far, the main contributor to the IR emission

- The dust emits over a large spectral interval, from ~ 2μm to ~ 1 mm, as the result of large gradient of temperature in the circumstellar material located at different distances from the star
  - From $T \sim 1000$ K in the proximity of the star down to $T \sim 30$ K in the outer regions at hundreds of AU from the star

- The dust material is expected to be distributed in the form of a circumstellar disk

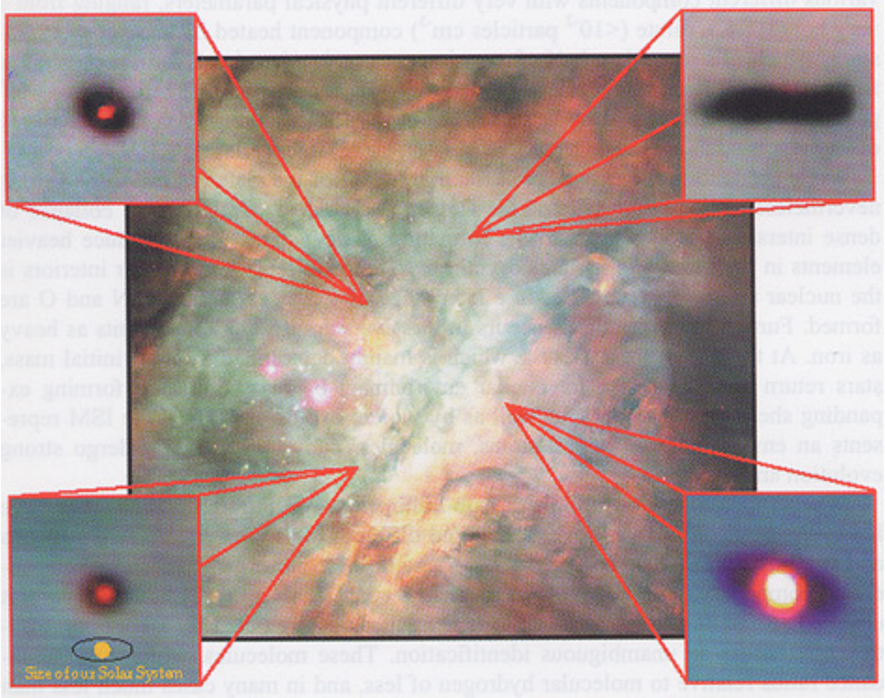
Circumstellar disks

- High resolution images have confirmed that the infrared excess is due to the presence of circumstellar disks of dust
  - Sizes

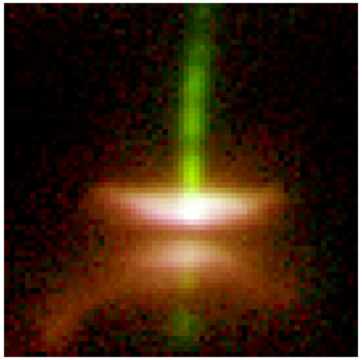
    Comparable to the Solar System size
  - Geometrical characteristics

    Relatively flat disks, thin in the inner regions (< 50 AU), they become gradually thicker in the outer regions

    The edges are truncated



Planetary Systems Now Forming in Orion
Credit: C. R. O'Dell and S. K. Wong (Rice U.), WFPC2, HST, NASA,



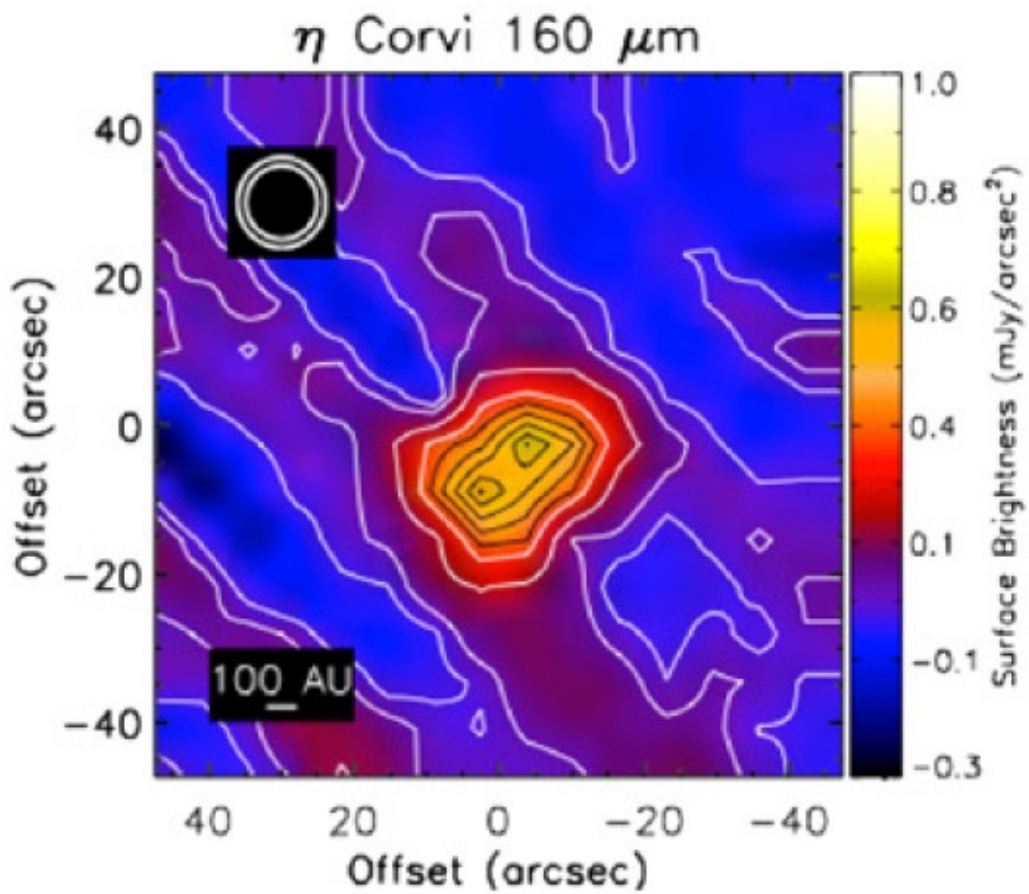
This Wide Field and Planetary Camera 2(WFPC2) image shows Herbig-Haro 30 (HH 30), the prototype of a young star surrounded by a thin, dark disk and emitting powerful gaseous jets. The disk extends 40 billion miles (about 64 billion kilometres) from left to right in the image, dividing the nebula in two. The central star is hidden from direct view, but its light reflects off the upper and lower surfaces of the disk to produce the pair of reddish nebulae. The gas jets are shown in green. **Credit:**Chris Burrows (STScI), the WFPC2 Science Team and NASA/ESA

The disk - infrared excess connection

Recent observation of a circumstellar disk from the same source that shows infrared excees

Imaging in the far IR of
η Corvi obtained
with the instrument PACS on board of the Herschel satellite

Lisse et al. (2012)



Masses of circumstellar disks

Dust masses are calculated from (sub)millimiter wavelength observations of dust

- Mass in dust:

  $\sim 10^{-4} - 10^{-3}\ M_{\odot}$

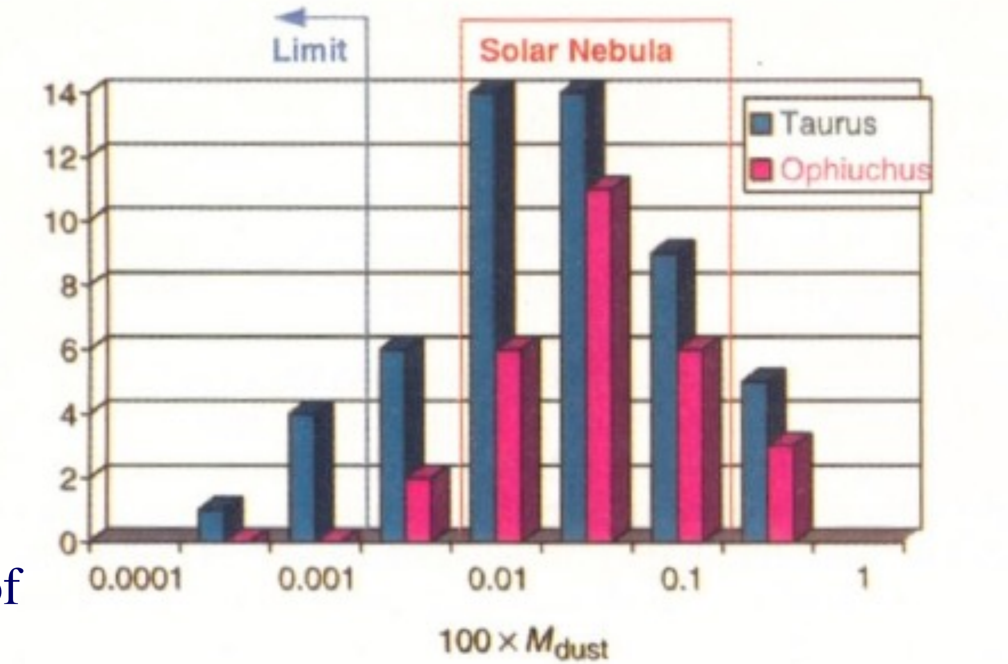
  The mass in dust is sufficient to produce 10 times more planets than those of the Solar System

The total mass is then estimated by adopting a gas-to-dust ratio by mass of ~100

- Total mass (dust+gas):

  $\sim 0.01 - 0.1\ M_{\odot}$

  The total mass is in the range of the mass of solar nebula that gave birth to the Solar System

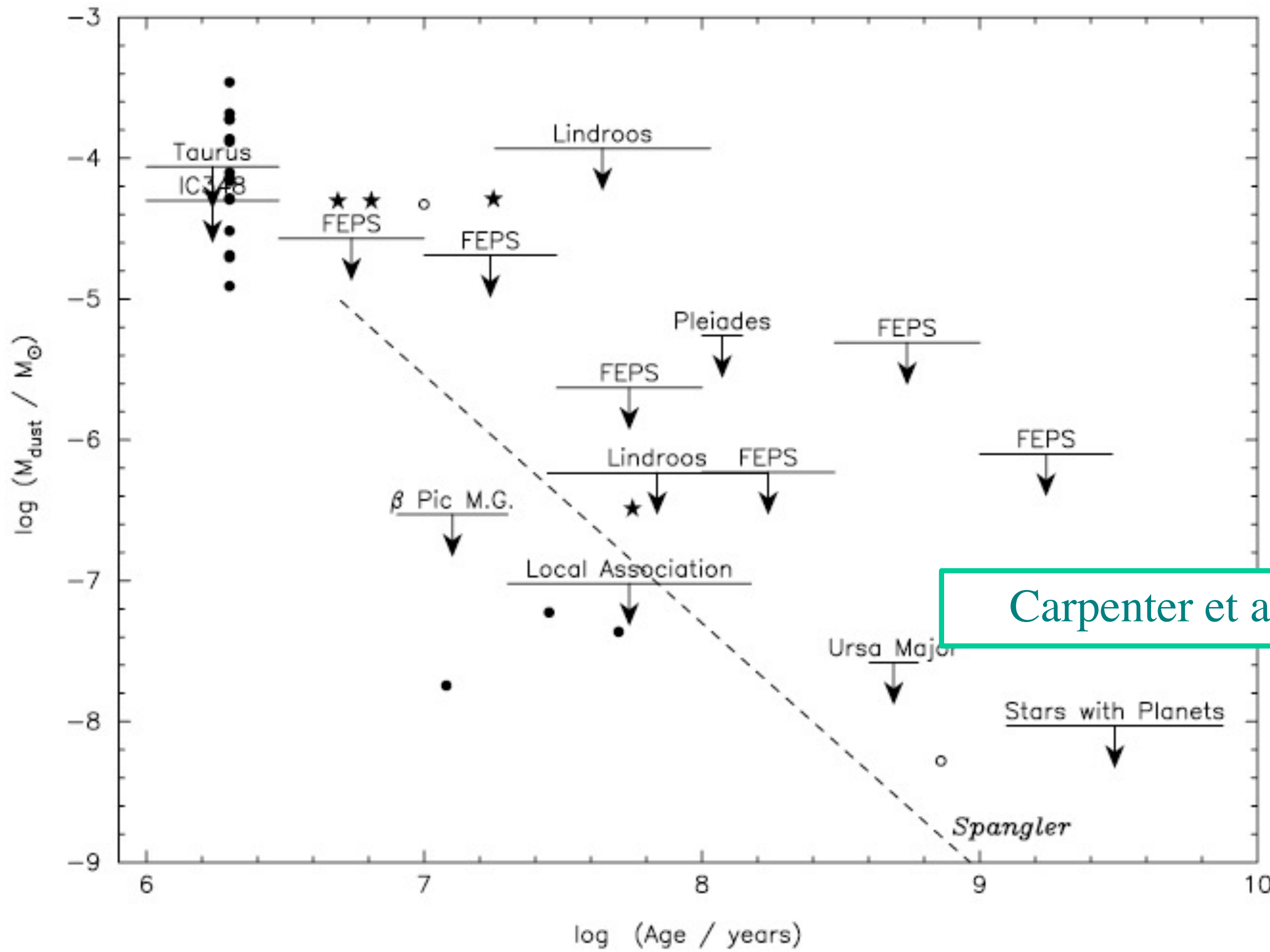


Mass distribution of disks compared with the range of masses of the Solar Nebula

Beckwith & Sargent (1996)

Mass evolution of circumstellar dust

Mass of circumstellar dust versus age of the star:
the mass in dust evolves, decreasing with time



Carpenter et al. (2005)

Protoplanetary disks

- All the observational evidence, including masses, surface densities and sizes, is consistent, also from a quantitative point of view, with the hypothesis that the solid component in circumstellar disks is the material that gives rise to planetary formation
  - For this reason circumstellar disks are also called protoplanetary disks

- The decrease of the mass of circumstellar dust is consistent with a scenario in which dust coagulates leading to accretion of the solid component in protoplanetary and planetary bodies

  Also other effects are likely to contribute to the decrease of dust mass: dust sublimation and dust astration (accretion by the star)

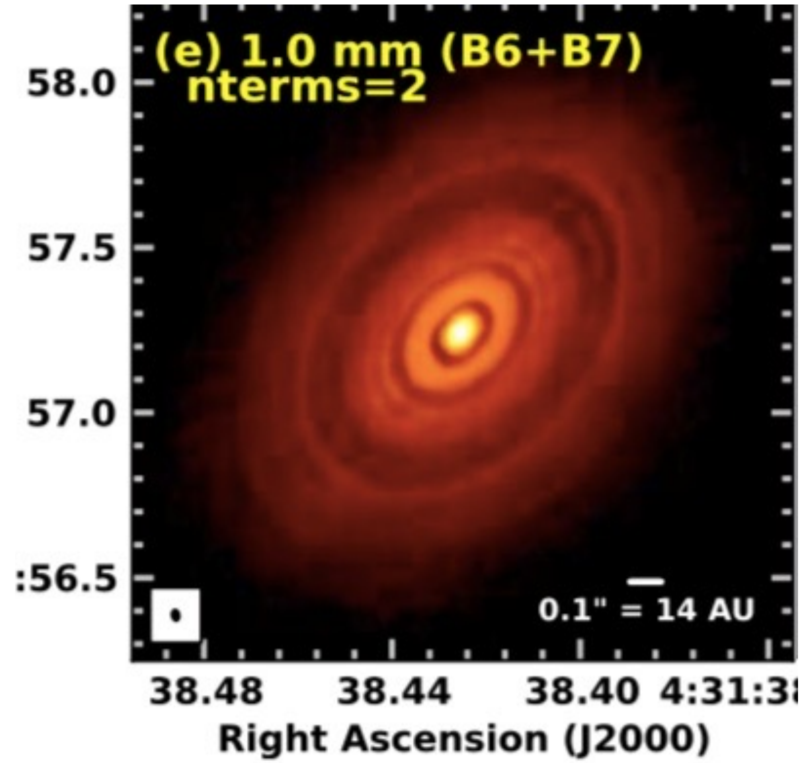
Observations of protoplanetary disks

- ALMA (Atacama Large Millimeter/submillimeter Array)
  ESO + international collaboration
- Altitude: in large part > 5000 m above sea level
  Low water vapour absorption
- Antennas: 54 x 12.0 m and 12 x 7.0 m
- Possibility of interferometric mode, with baselines from 150 m to 16 km
- Max angular resolution in interferometric mode: ~ 10^{-2} arcsec

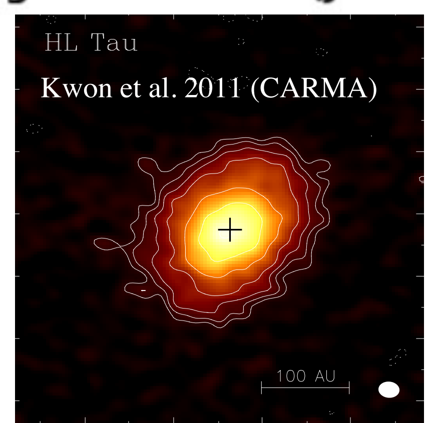
ALMA observations of protoplanetary disks: HL Tau

ALMA partnership Brogan et al. (2015)

- Millimetric continuum emission of HL Tau (young (0.5–1 Myr) solar-like star in Taurus)
- Unprecedented resolution of a few AU at a distance of 140 pc
- A pattern of bright and dark rings observed at all wavelengths
- Several characteristics of these rings, including an increase in eccentricity with radius and numerous resonances, suggest that the dark rings are gaps arising from the process of planet formation
- Opening of a new era in the study of protoplanetary disks that promises to unearth the architecture of extrasolar multi-planetary systems during their epoch of formation



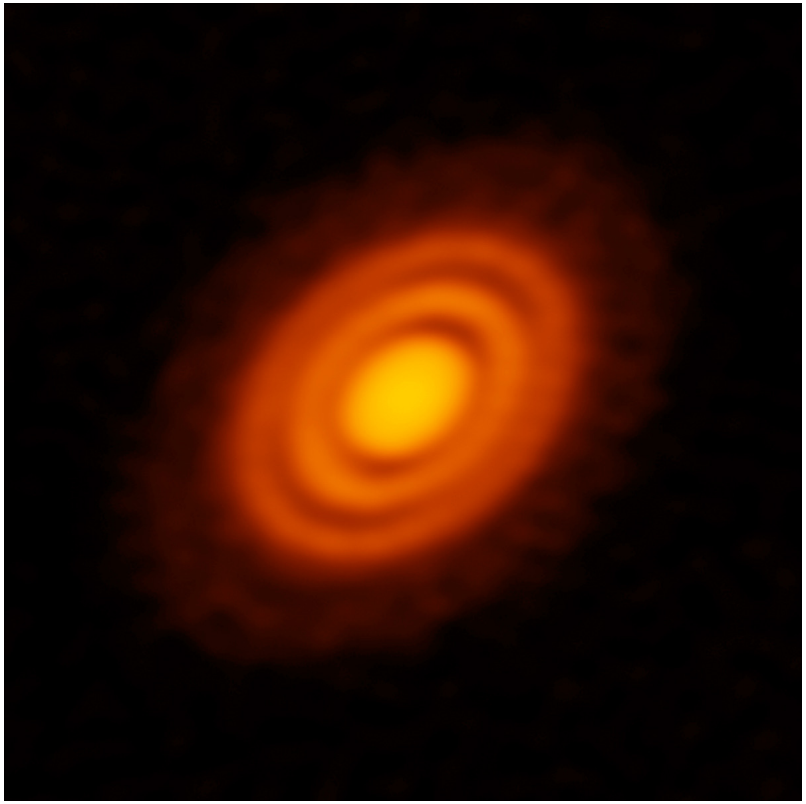
Before ALMA



ALMA observations of protoplanetary disks: HD163296

Isella et al. (2017)

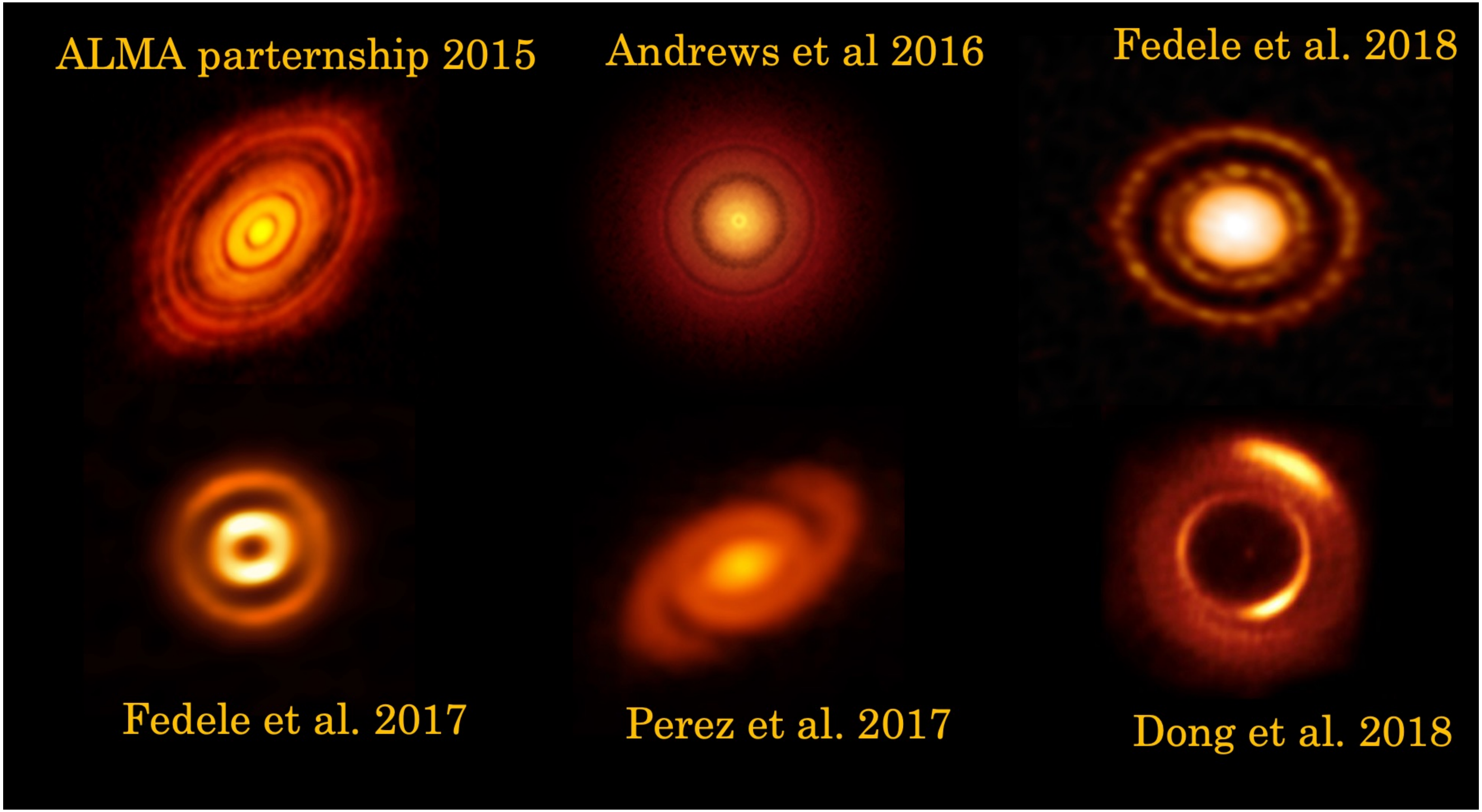
- The gas-to-dust ratio varies across the disk
- The middle and outer rings could be due to the gravitational torque exerted by two Saturn-mass planets orbiting at 100 and 160 A.U. from the star



ALMA "Discography"

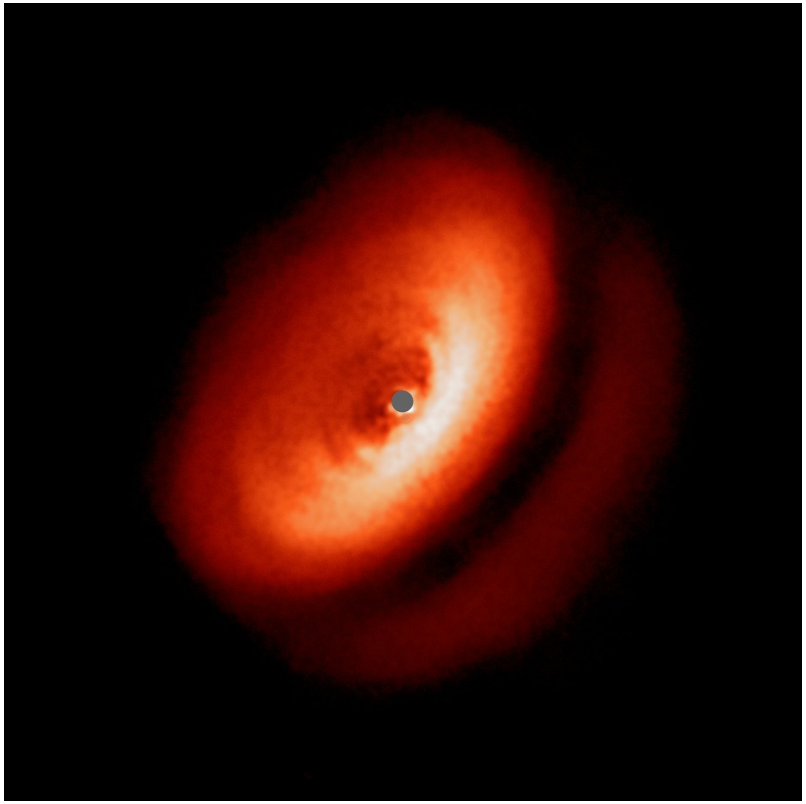
Dust rings and gaps are common

Evidence of ongoing planet formation



Near-Infrared

- Stellar radiation absorbed and re-emitted in the infared by dust orbiting around the star
- Dominated by small grains (~ micron size)
- Tracer of the disk atmosphere



IM Lup (VLT/SPHERE, Avenhaus et al. 2018)

The connection betweenYoung Stellar Objects (YSOs) and planetary formation

- Young Stellar Objects are classified in classes
  - Class 0, I, II e III
  - The classification is mostly based on the slope of the emission spectrum in the infrared and (sub)millimetric spectral bands

- The classification is interpreted in terms of an evolutionary sequence
  - Representative of the early evolutionary stages of solar-type stars
  - There is a gradual transition between subsequent classes

- The classification provides:
  - an evolutionary interpretation for a variety of observational evidence (collimated jets, T Tauri stars, infrared excesses, protoplanetary disks)
  - a reference frame for understanding the process of planetary formation

Classification of Young Stellar Objects (YSOs)

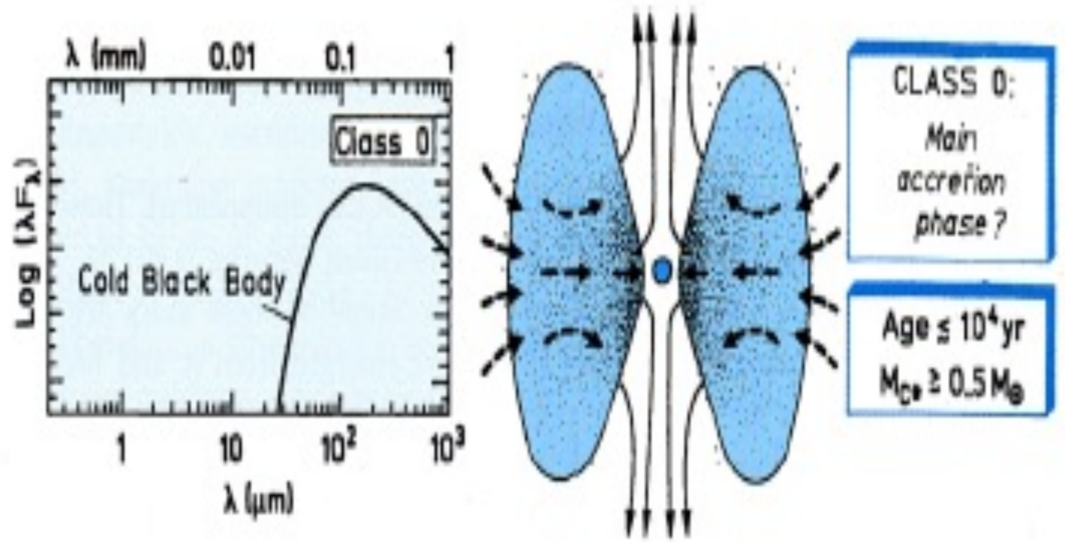
Table 1 Classification of young stellar objects

Class	SED slope	Physical properties	Observational characteristics
0	–	$M_{\text{env}} > M_{\text{star}} > M_{\text{disk}}$	No optical or near-IR emission
I	$\alpha_{\text{IR}} > 0.3$	$M_{\text{star}} > M_{\text{env}} \sim M_{\text{disk}}$	Generally optically obscured
FS	$-0.3 < \alpha_{\text{IR}} < 0.3$		Intermediate between Class I and II
II	$-1.6 < \alpha_{\text{IR}} < -0.3$	$M_{\text{disk}}/M_{\text{star}} \sim 1\%$, $M_{\text{env}} \sim 0$	Accreting disk; strong Hα and UV
III	$\alpha_{\text{IR}} < -1.6$	$M_{\text{disk}}/M_{\text{star}} \ll 1\%$, $M_{\text{env}} \sim 0$	Passive disk; no or very weak accretion

slope of the spectral energy distribution (SED) between about 2 and 25 μm,

$$\alpha_{\text{IR}} = \frac{d \log \nu F_\nu}{d \log \nu} = \frac{d \log \lambda F_\lambda}{d \log \lambda}. \quad (1)$$

Class 0: young protostars



A collapsing envelope with radius $10^3 - 10^4$ AU hides the protostar.

The dust in the envelope is too cold (~30 K) to irradiate in the IR.

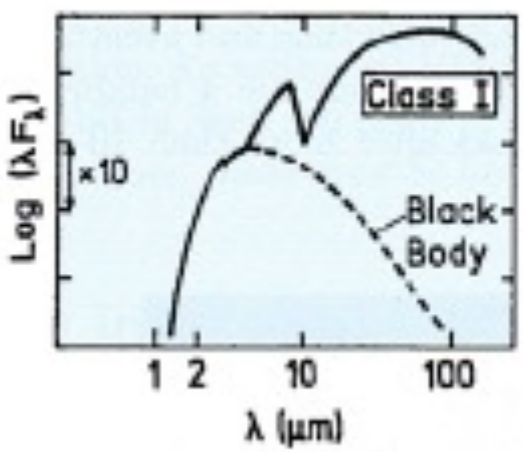
Only millimetric emission can be detected.

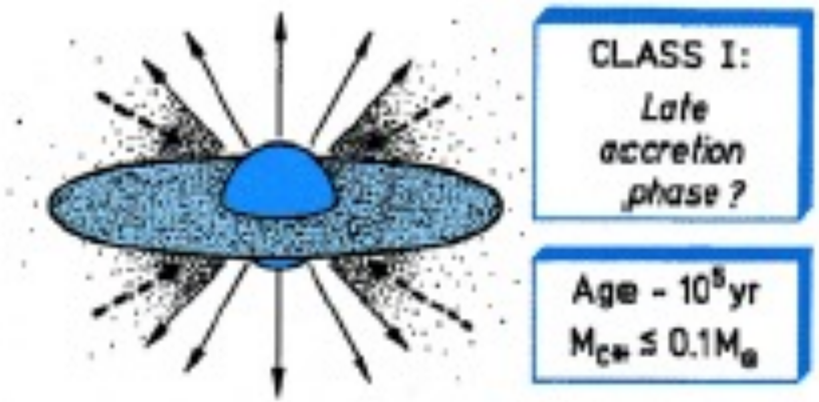
A central disk with radius 200-300 AU starts to form.

The accretion rate of the protostars is $10^{-5} - 10^{-6}\ M_{\odot}$/yr.

An intense collimated jet is generated.

Class I: evolved protostars





The envelope is still optically obscure, but becomes more tenuous

The envelope becomes warmer and emits intensely in the IR.

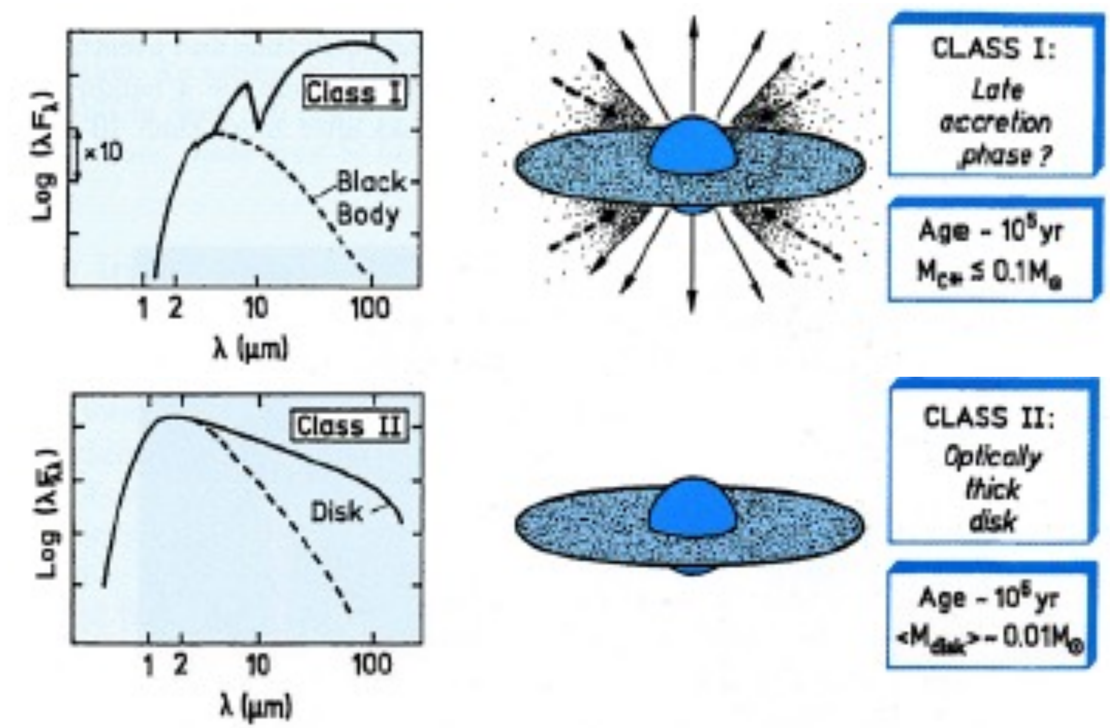
Accretion persists. The protostar is fed by an accretion disk with a radius of a few hundreds AU.

Molecular jets are still present, but less collimated.

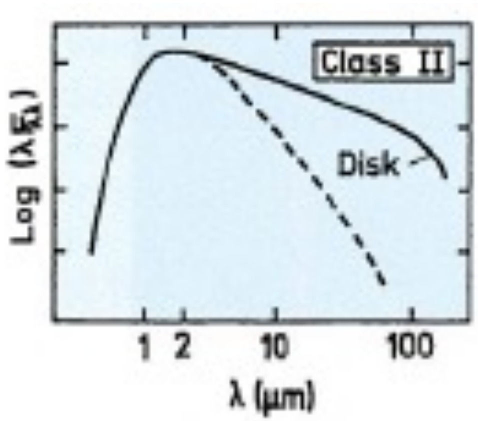
This stage lasts for about 10^5 yr.

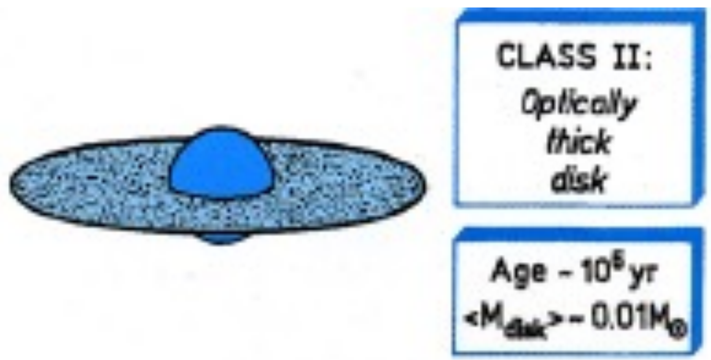
Class FS: Flat spectrum

Class FS is intermediate between Class I and Class II
and is characterized by a flat IR spectrum



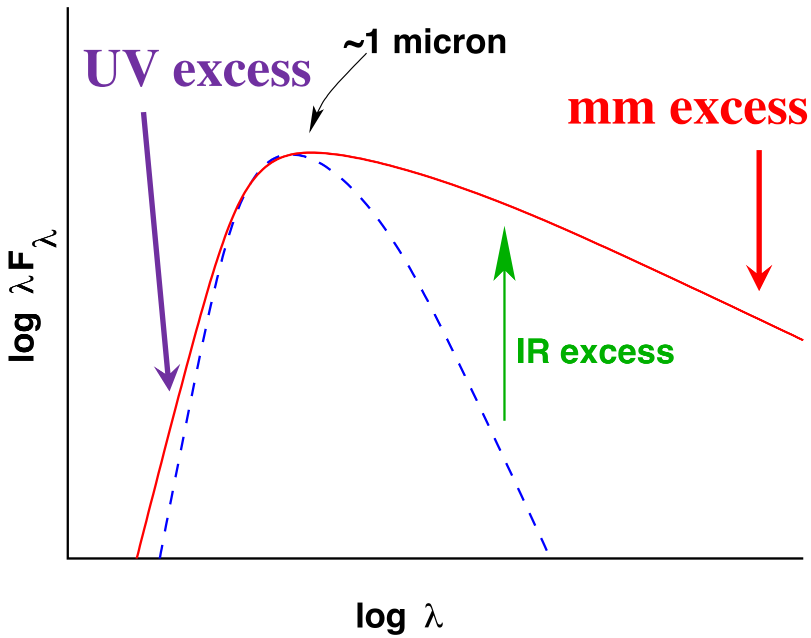
Class II: classic T Tauri stars 1/2



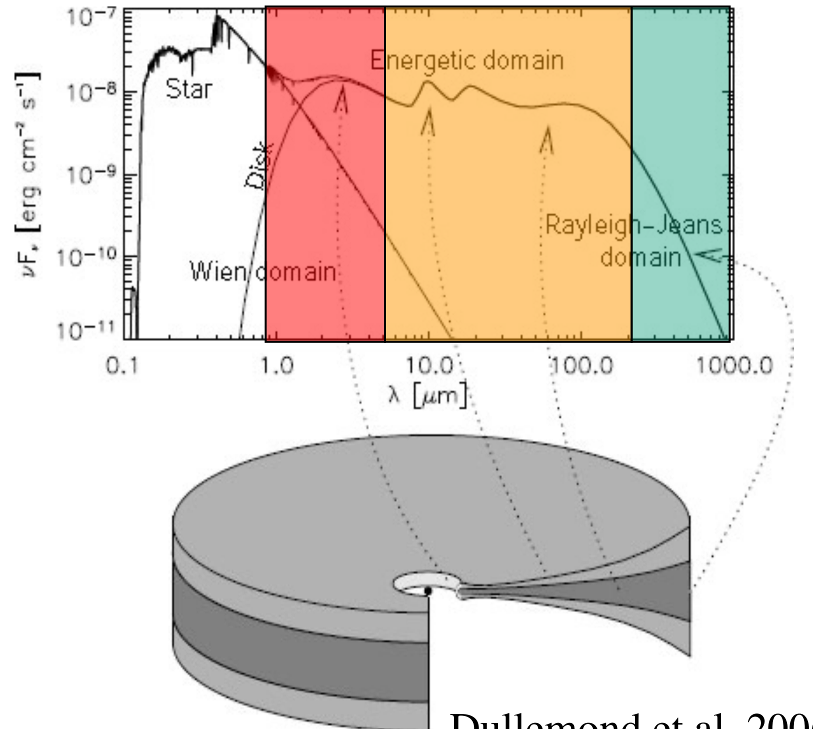


The envelope disappears, star accretion has finished
and the protostellar phase ends.
The protostar has become a classic T-Tauri star.
The infrared excess and circumstellar disk are still present.
Molecular jets diminish and disappear.

Class II: classic T Tauri stars 2/2



Courtesy: D. Fedele



Dullemond et al. 2006

Infrared & millimeter excess due to circumstellar dust

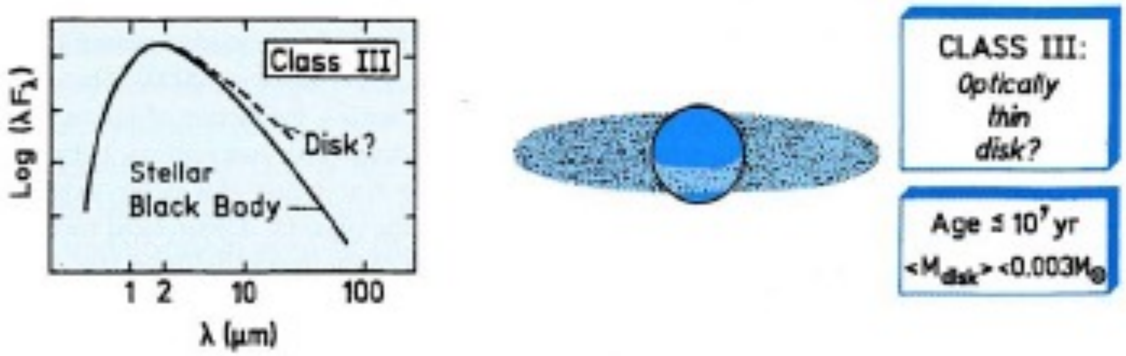
NIR (1 – 5 μm) : Scattering by small (mm-size) and hot (10^3 K) dust grains

MIR/FIR (5 – 300 μm) : Thermal emission of warm (~10^2 K) dust from atmosphere

mm / cm (> 300 μm) : Thermal emission by cold (10-20 K) dust from disk interior

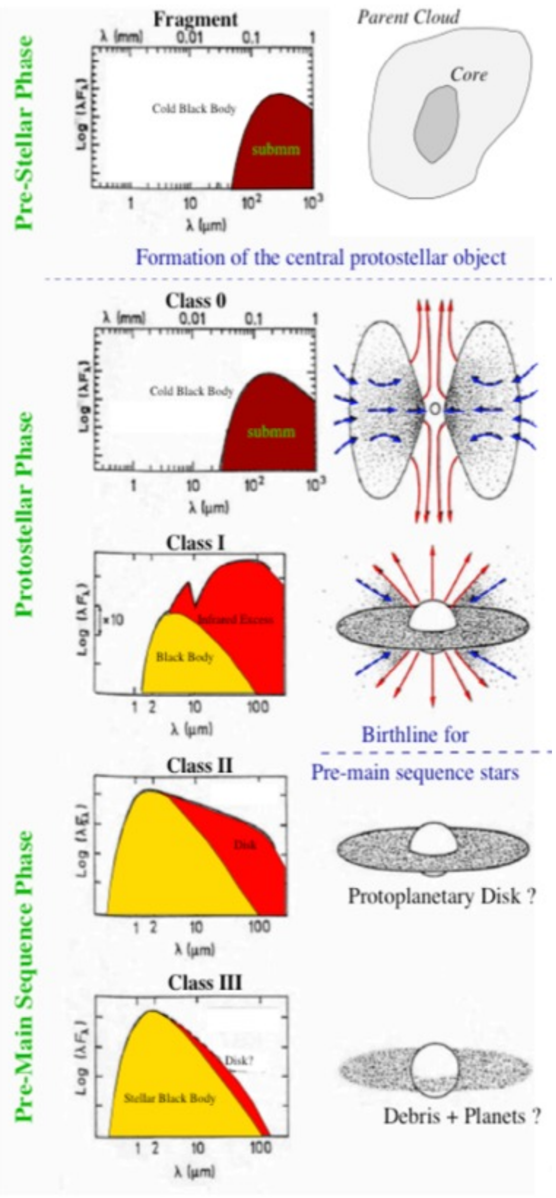
Ultraviolet excess due to hot gas at the stellar/disk boundary

Class III: weak-line T Tauri stars



The star has characteristics of a weak-line T-Tauri star.
The infrared excess and circumstellar disk disappear
on a short time scale (~10^5 yr).
The Class III stage lasts for about 10^6 -10^7 yr.
Molecular jets are completely absent.

Summary on Classification of Young Stellar Objects (YSOs)



Andre et al 2002

Planetary formation in the context of stellar evolution: evolution in the HR diagram

Beckwith & Sargent (1996)