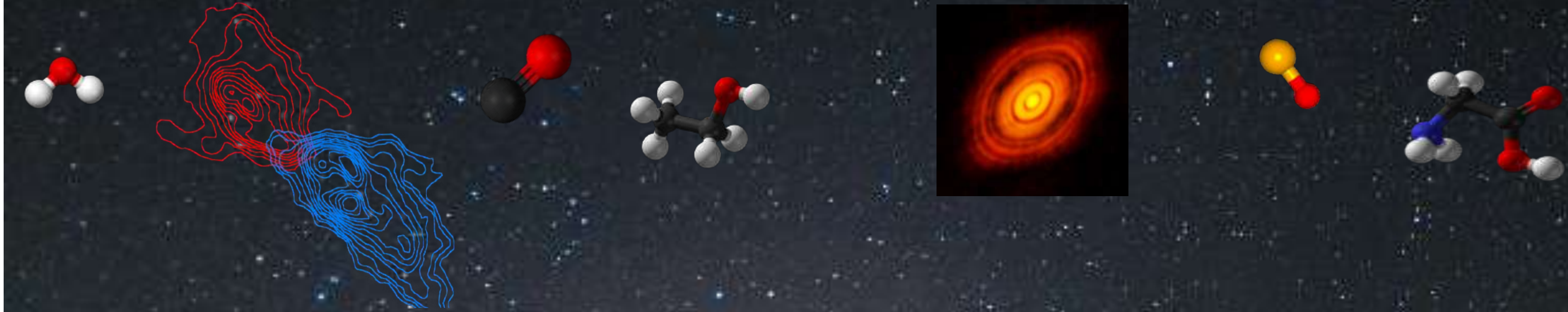

# An introductory course to the properties of the interstellar medium

## Lecture 2: The star formation process of both low- and high-mass stars

Maite Beltrán
INAF-Osservatorio Astrofisico di Arcetri

# Summary

1. Where and why do stars form
2. Star-formation theory of low-mass stars
3. Classification of low-mass young stellar objects
4. High-mass star-formation theory
5. Disk formation
6. Observation of protostellar disks
7. Deriving properties of disks

References:


"Notes on Star Formation", Mark Krumholz, 2016

"Accretion disks in luminous young stellar objects", Beltrán & de Wit, 2016

"Protoplanetary disks and their evolution", Williams & Cieza (2011)

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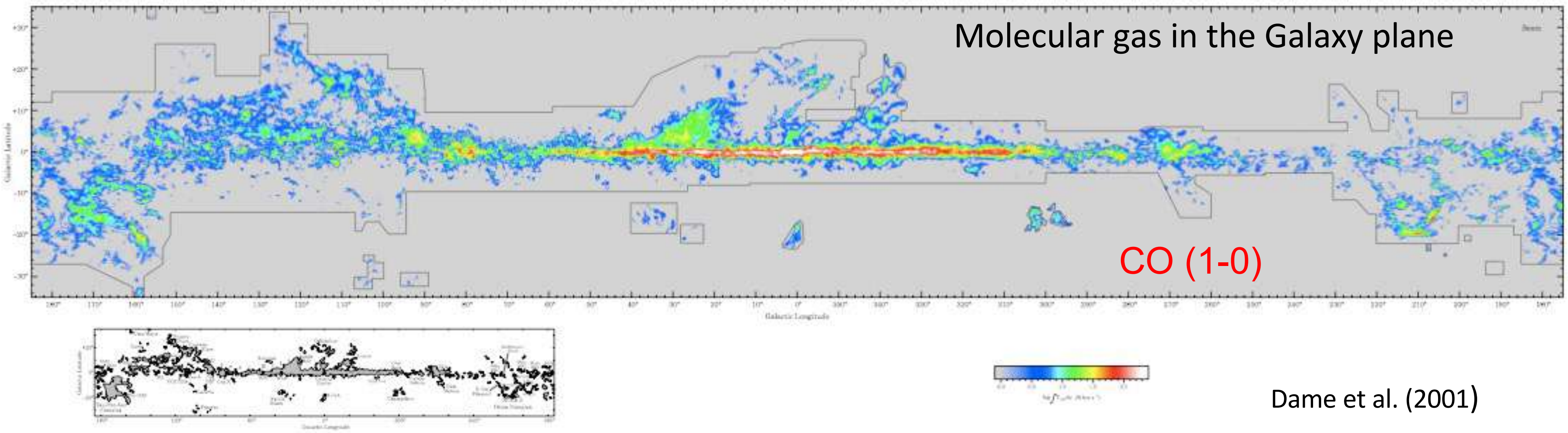
# 1. Where and why do stars form

Stars form in gas condensations of the ISM known as Molecular Clouds, the most massive (up to $10^6\ M_\odot$) and coldest objects (10 to 50 K) in our Galaxy




Dame et al. (2001)

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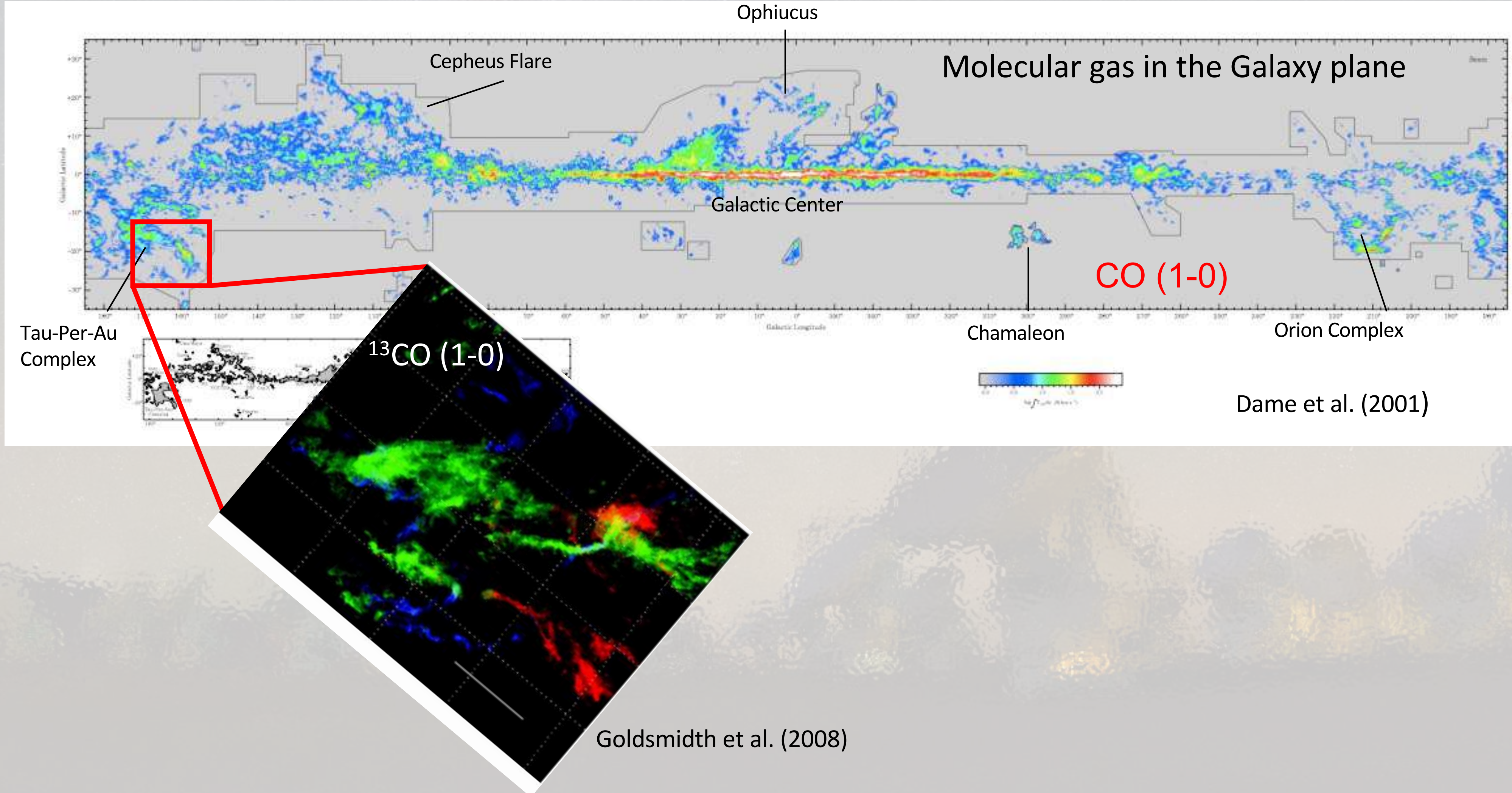


Dame et al. (2001)

Goldsmidth et al. (2008)

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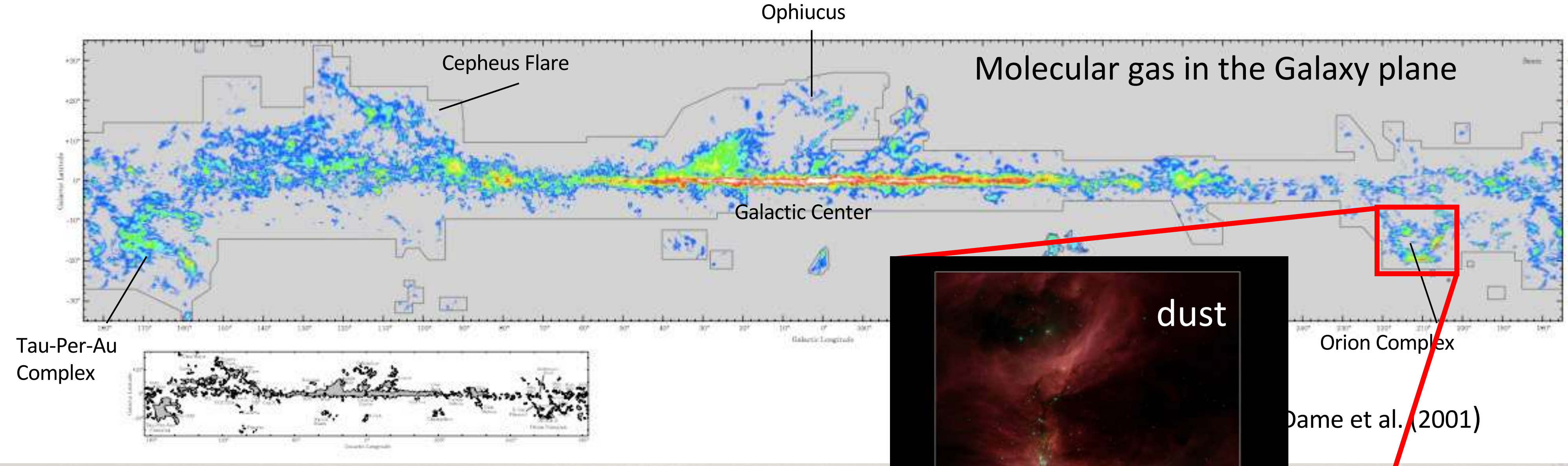
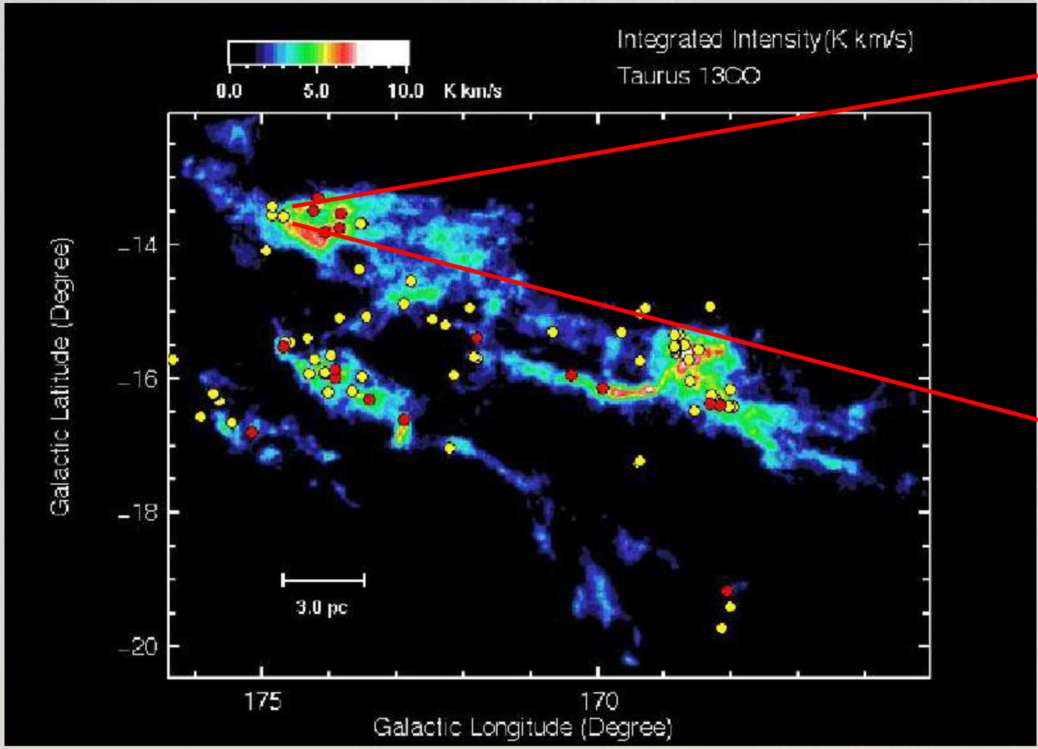
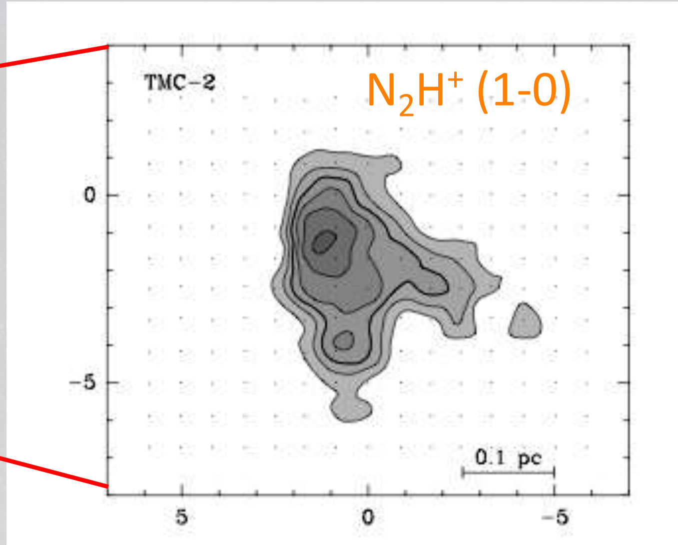



# 1. Where and why do stars form




Mizuno et al. (1995)




Caselli et al. (2002)

DENSE CORES

- densities ~ $10^4$-$10^5$ $cm^{-3}$
- temperatures ~ 10 – 20 K

# 1. Where and why do stars form

The main constituent of these dense cores is gas, although it also contains microscopic dust grains (100:1).

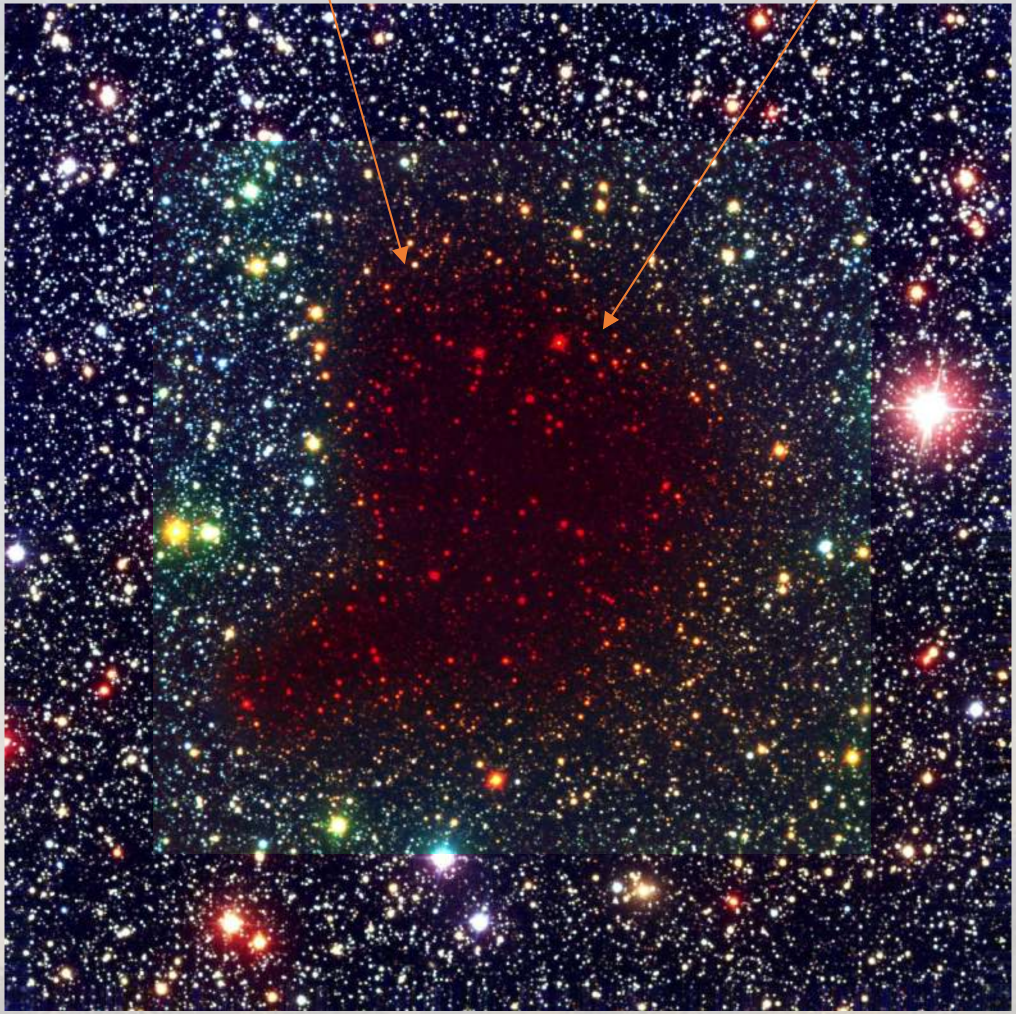
The clouds are so dense and cold that the hydrogen atoms are bound as molecules: *molecular hydrogen is the raw material for building new stars.*

Although this dust accounts for only a fraction of the cloud mass, it is enough to 'obscure' the star birth. Dense cores appear as IR-dark objects.

This dark cloud (B68) looks like empty space: in fact, it has more matter than the space surrounding it.

Gas and dust absorb almost all the visible light from the background stars

The dust produces reddening



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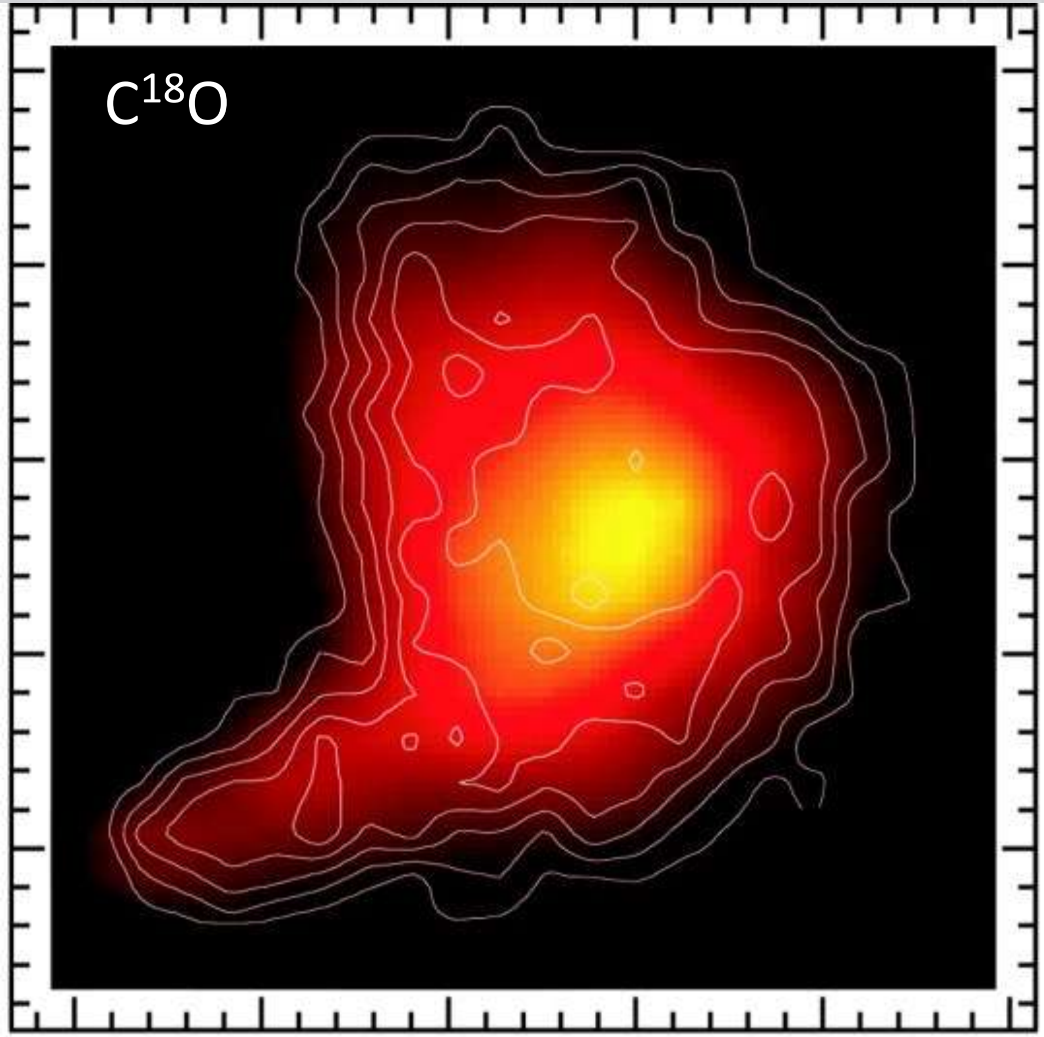

# 1. Where and why do stars form

Stars form by gravitational collapse of a dense core. Gravity plays a fundamental role in order to form a star, but alone it does not determine whether a dense core will become a star

Let's consider the idealized case of a uniform, spherical core of mass *M*, radius *R*, volume density *n*, mass density *ρ*, temperature *T*. The gas has a turbulent velocity $v_{turb}$ and some rotation, with rate Ω. B is the intensity of the magnetic field.

The core is supported against its own gravity by the sum of the thermal, turbulent, rotational and magnetic energy. Gravitational collapse is possible only if:

$$| E_{gr} | > E_{th} + E_{tur} + E_{rot} + E_{mag}$$

$$E_{gr} = -\frac{3}{5}\frac{GM^2}{R}$$

$$E_{rot} = \frac{1}{5} M R^2 \Omega^2$$

$$E_{th} = \frac{3}{2} NkT = \frac{3}{2}\frac{M}{\mu m_H} kT$$

$$E_{mag} = \frac{1}{6} B^2 R^3$$

$$E_{tur} = \frac{1}{2} M v_{tur}^2$$

# 1. Where and why do stars form

Let's suppose that magnetic, rotational and turbulent energies are negligible in comparison to the thermal one. Then, the core will be in hydrostatic equilibrium if the thermal pressure, which pushes the gas outward, balances gravity, which pulls the gas inward:

$$\frac{GM}{R} = \frac{5}{2}\frac{kT}{\mu m_H}$$

This is the well known Jeans criterium, namely that a homogeneous, spherical cloud mass of $M$, number density $n=\rho/\mu m_H$ and temperature $T$ will collapse under its own gravity if:

$$M > M_{cr,th} = M_{Jeans} \cong 6\, T^{3/2}\, n^{-1/2}$$

If we also include in the stability criterion, the rotational energy, then the critical mass is:

$$M > M_{cr,rot} = \frac{M_{cr,th}}{\left(1 - \frac{\Omega^2}{4\pi G\rho}\right)^{3/2}}$$

And if we consider the stability criterion for a core where gravity is balanced by magnetic energy:

$$M > M_{cr,mag} = \frac{1}{3\,\pi}\sqrt{\frac{5}{2\,G}}\,\Phi \cong 1\,M_{\odot}\left[\frac{B}{0.1\,\mu G}\right]\left[\frac{R}{0.1\,pc}\right]^{2}$$

where $\Phi$ is the magnetic flux ($\Phi = \pi\, R^2 B$)

Taking into account the Jeans mass

$$M > M_{cr,th} = M_{Jeans} \cong 6\,T^{3/2}\,n^{-1/2}$$

we can see that initial conditions to form a star are low temperatures and high densities, typical conditions of most dense cores.

For typical conditions of low-mass dense cores: $T$=10 K and $n$=$10^4$-$10^5$ cm$^{-3}$

➡ $M_{cr,th} = M_{Jeans} = 1\text{-}2\ M_{\odot}$

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2. Star-formation theory of low-mass stars
3. Classification of low-mass young stellar objects
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5. Disk formation
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# 2. Star-formation theory of low-mass stars

According to the standard star-formation theory, stars (at least those with masses comparable to the Sun) form by gravitational collapse of a dense molecular cloud of gas and dust in rotation.

# 2. Star-formation theory of low-mass stars

The formation of a low-mass isolated star is the simplest case to study.

If thermal, magnetic, turbulent and rotational support are all negligible when compared to gravity (free-fall), then a spherical core of mass *M*, radius *R*, and density ρ, will start to contract under its own gravity.

The equation of the motion is:

$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2}$$

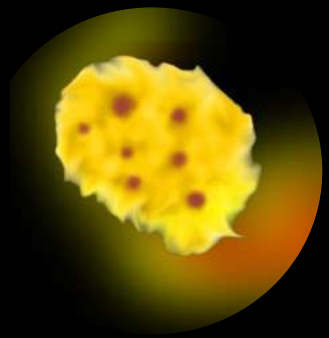
from where one can derive the free-fall velocity and the free-fall time (i.e., the time it takes for the core to collapse into a point):

$$v_{ff} \sim (GM)^{1/2} R^{-1/2}$$

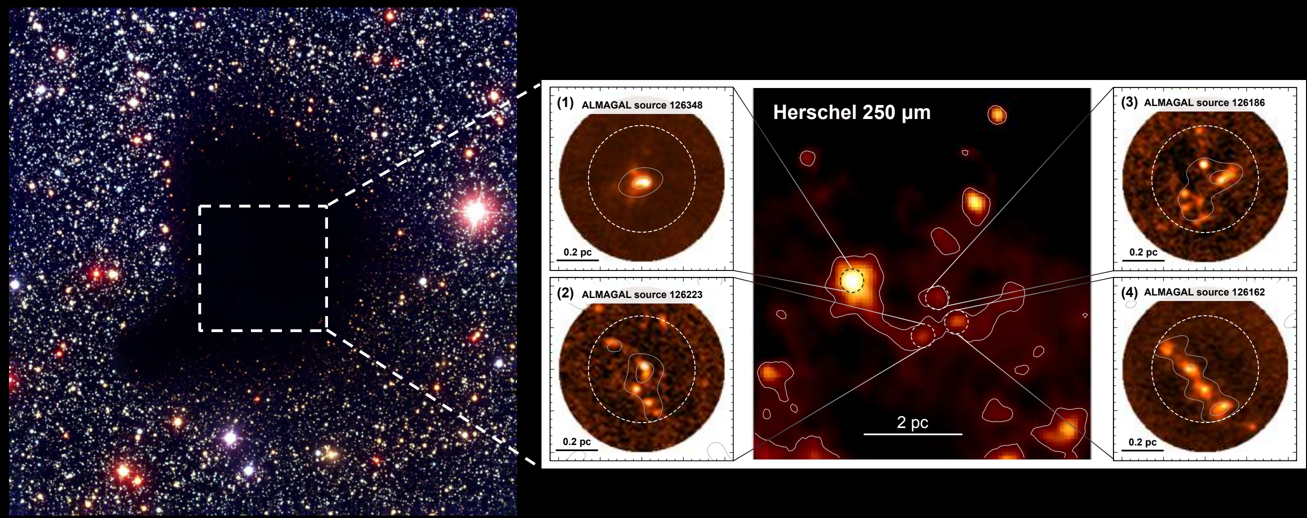
$$t_{ff} \cong (G\rho)^{-1/2}$$

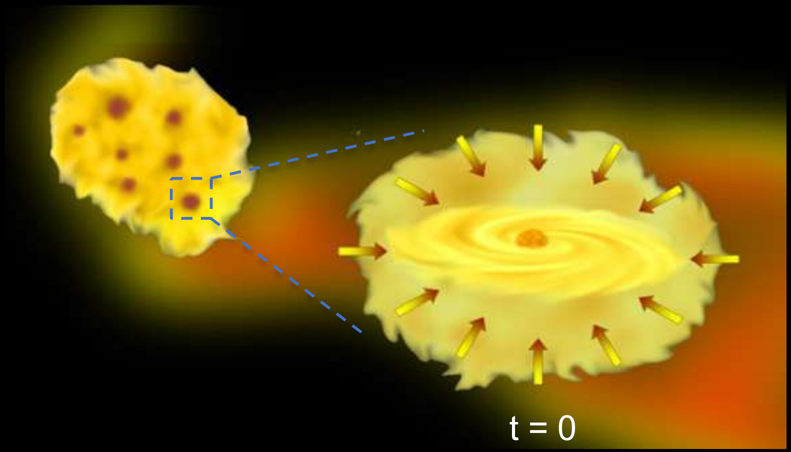
There are many solutions to the collapse problem, which differ in the initial conditions (density profile, rotation or not of the core) they assume: Larson 1969; Penston 1969; Shu 1977; Shu, Adams & Lizano 1987; Foster and Chevalier 1993; Henriksen et al. 1997

# 2. Star-formation theory of low-mass stars

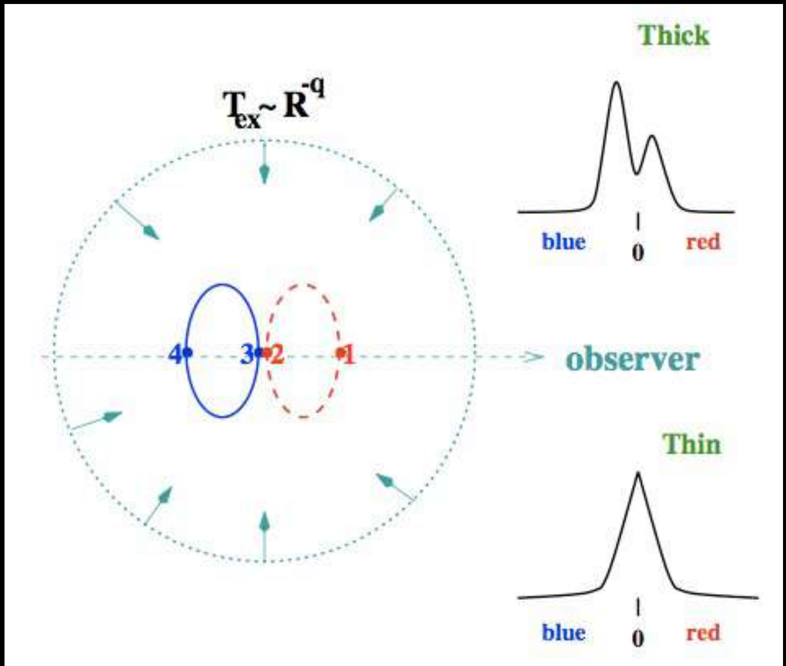


## 1. Pre-stellar dense core: fragmentation

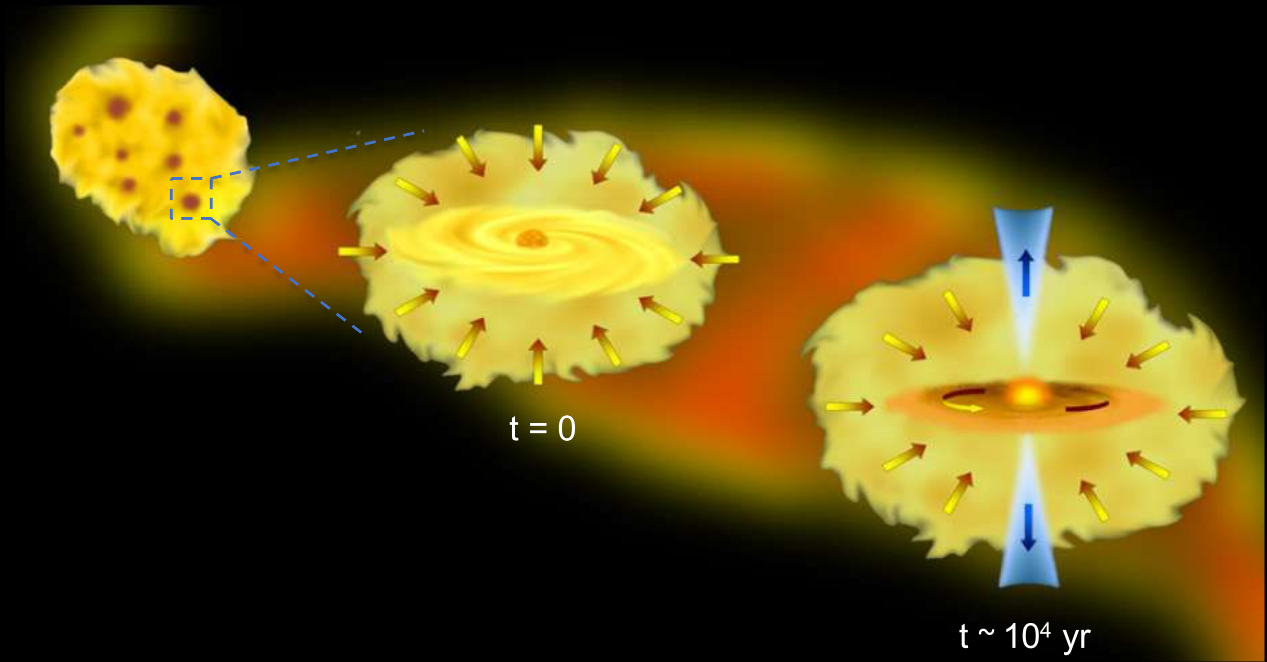




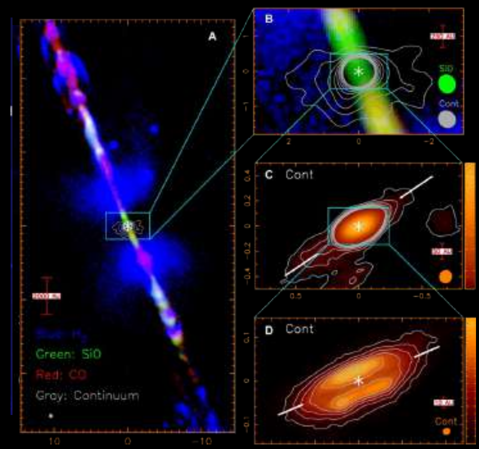

## 2. Gravitational collapse



# 2. Star-formation theory of low-mass stars

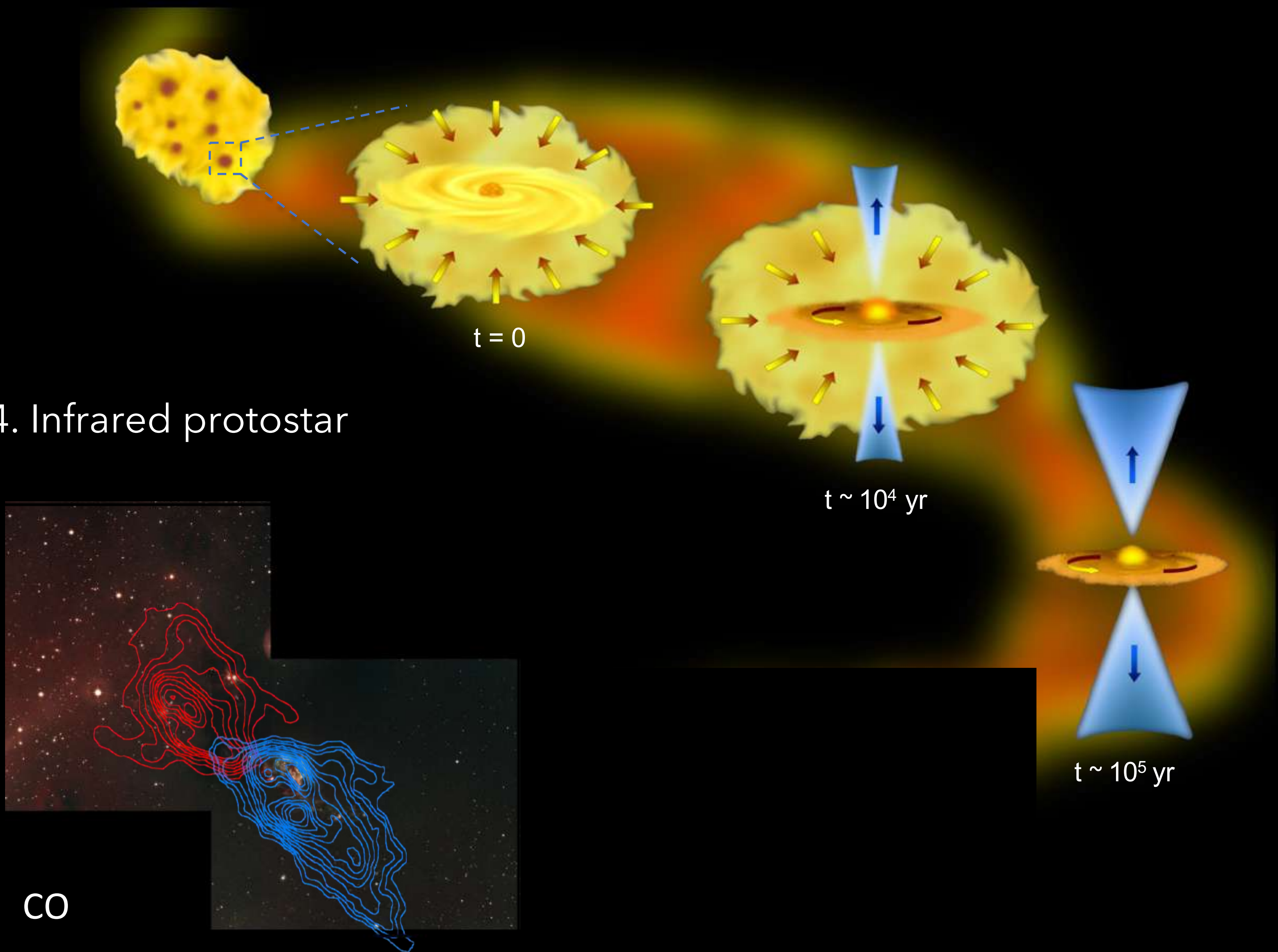



## 3. Protostar: envelopes, disks and jets/outflows

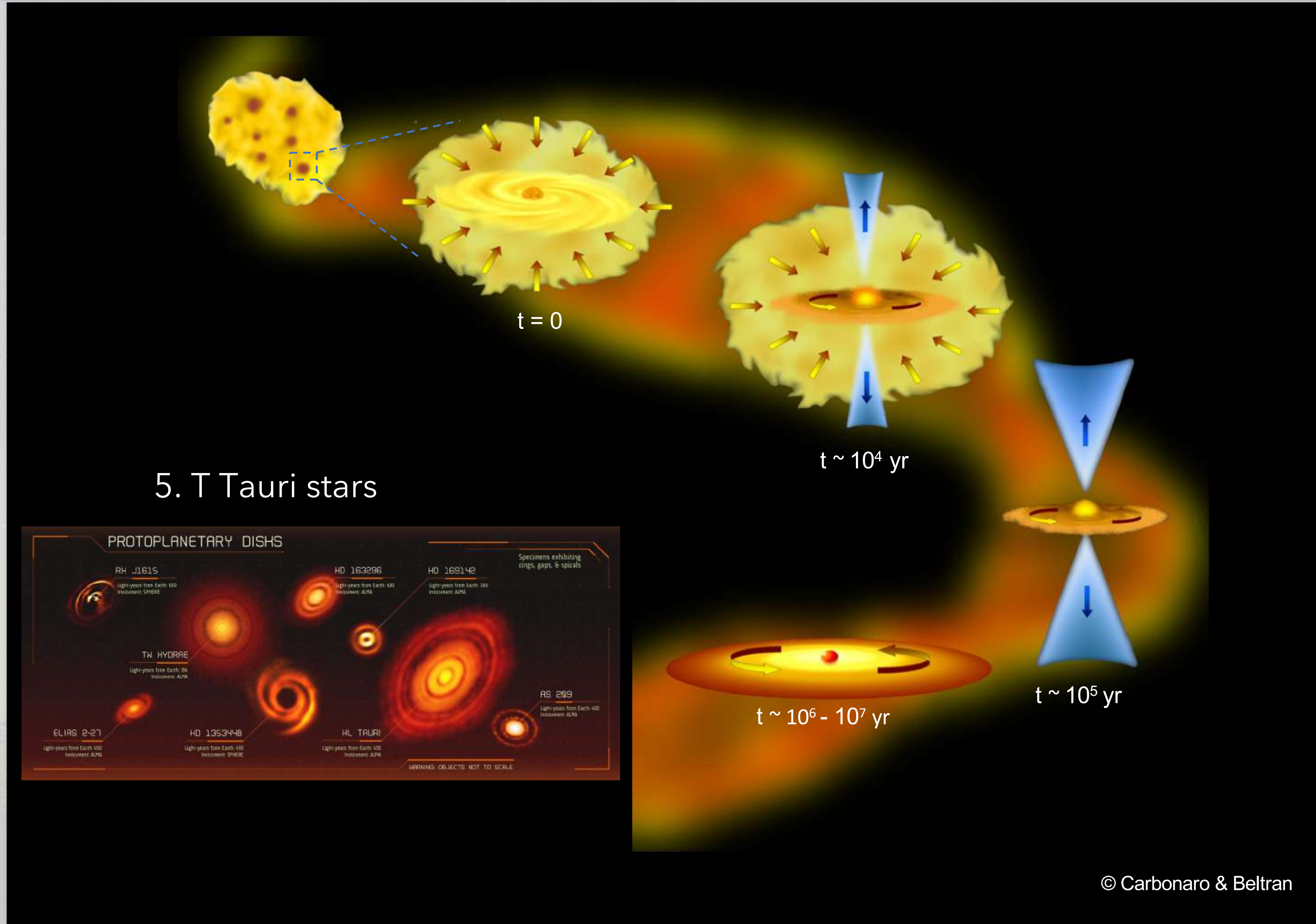



# 2. Star-formation theory of low-mass stars

4. Infrared protostar



# 2. Star-formation theory of low-mass stars



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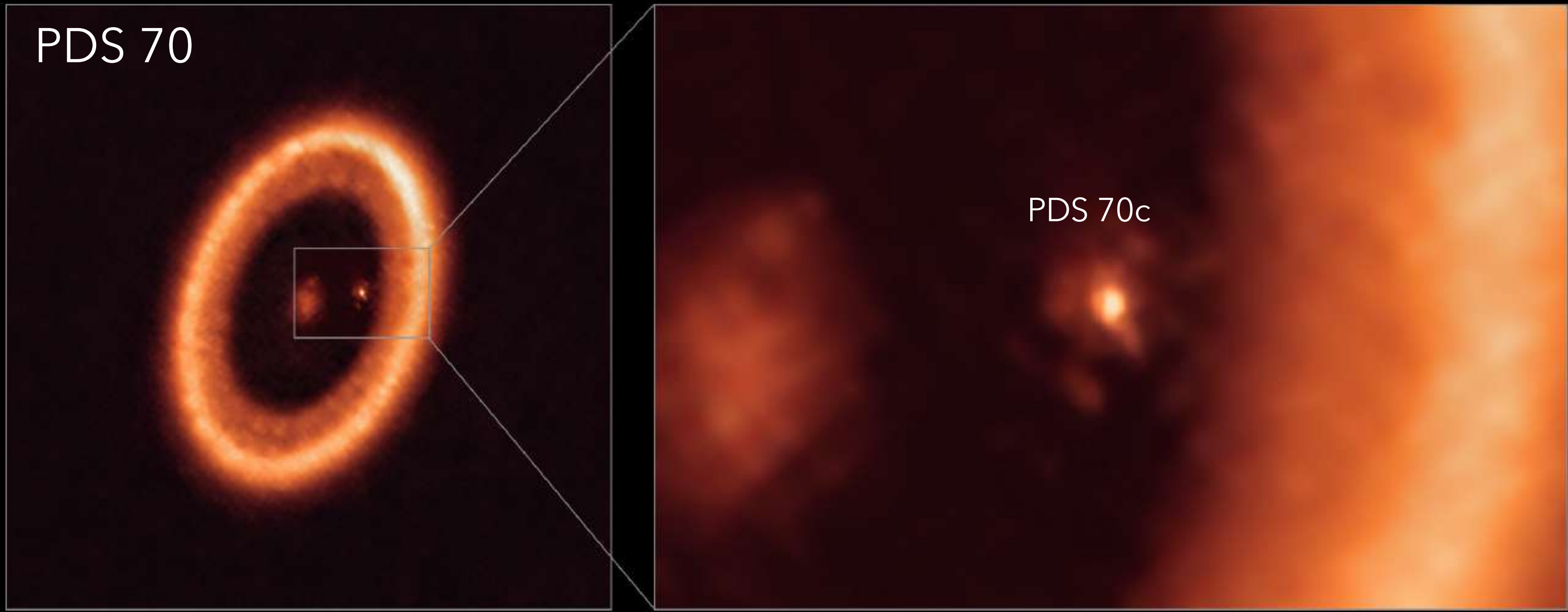
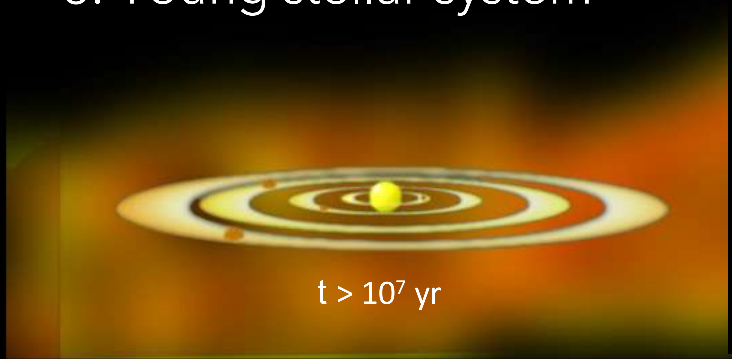



6. Young stellar system



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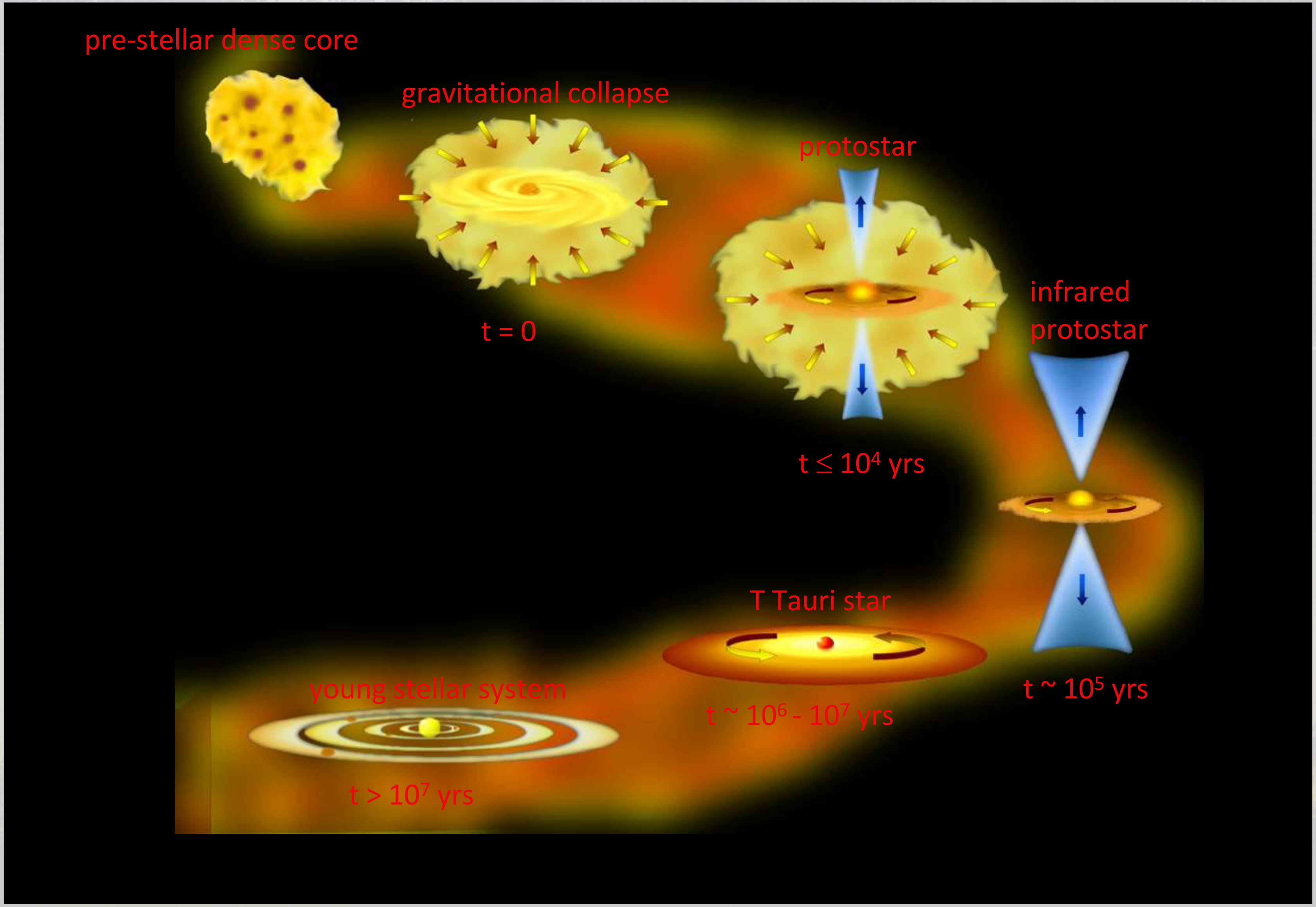

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3. **Classification of low-mass young stellar objects**
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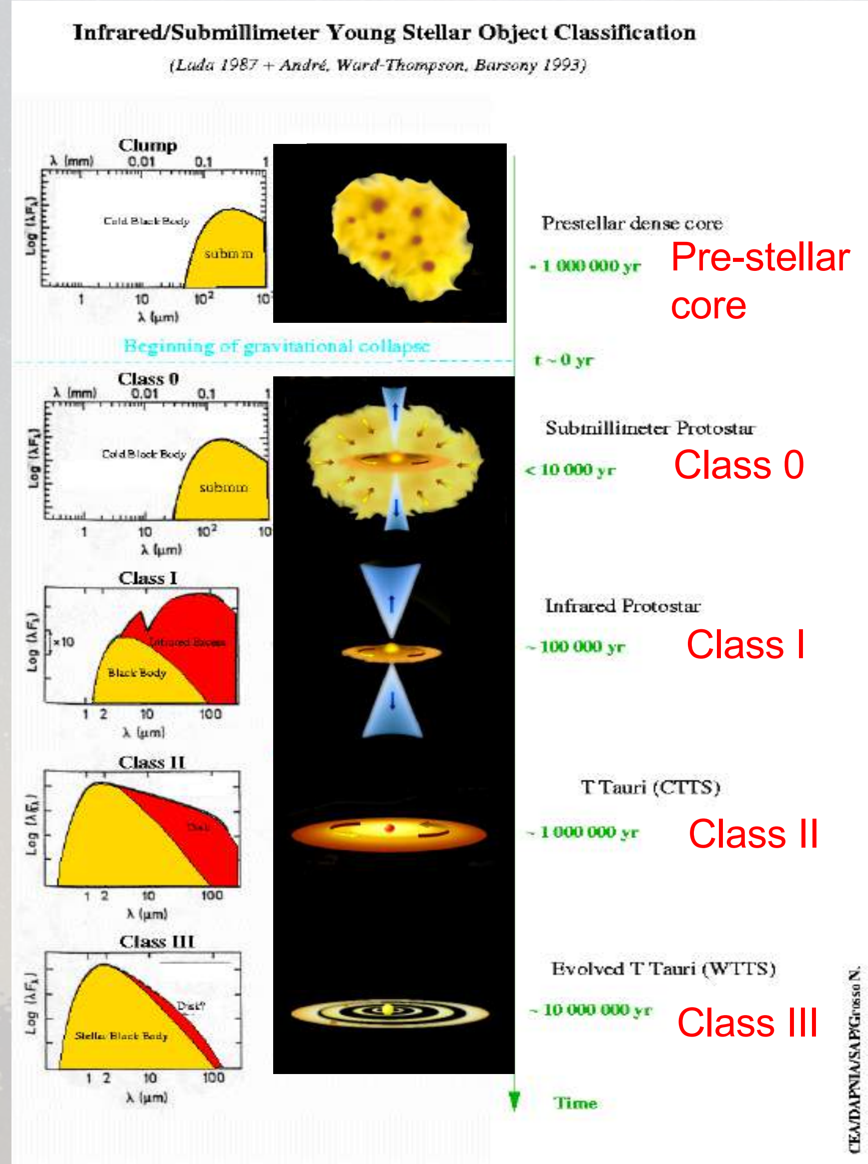
# 3. Classification of low-mass young stellar objects

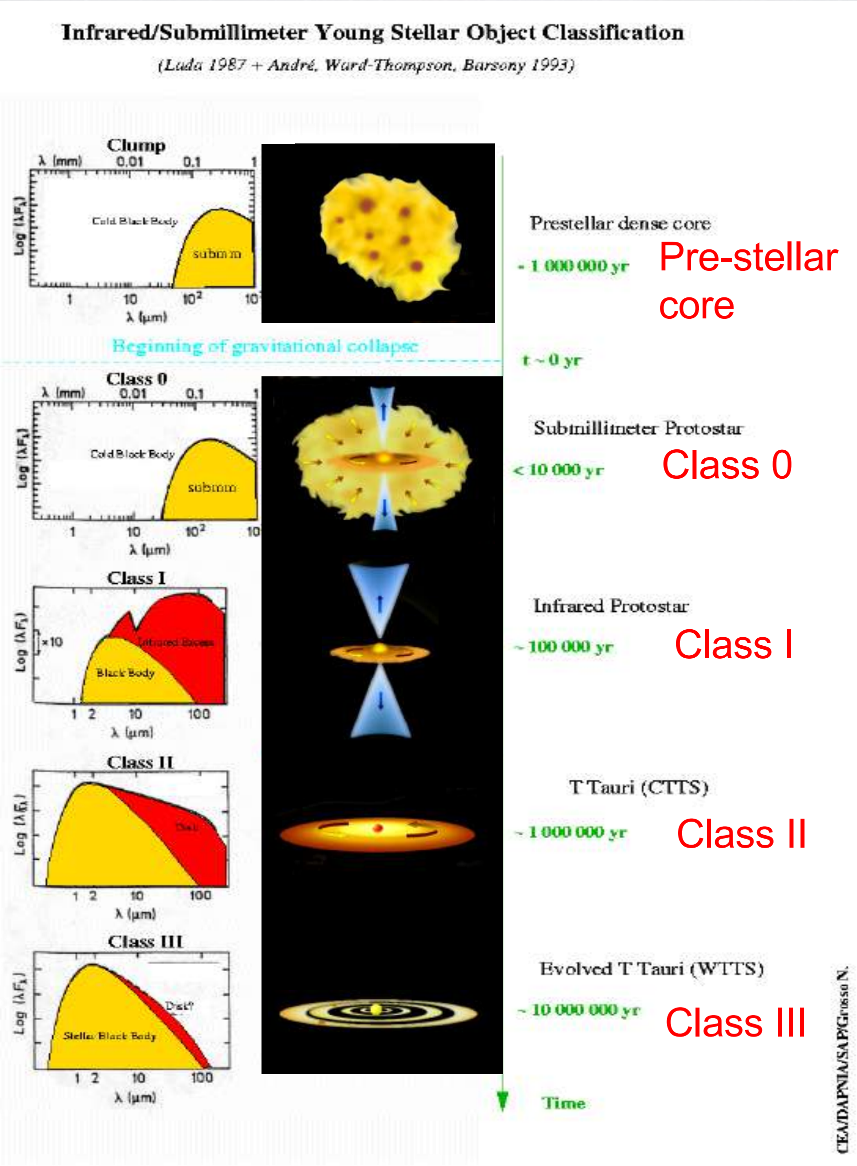



- Young stellar objects form deeply embedded in dense cores. An important fraction of the protostellar radiation emitted is absorbed by the circumstellar dust and re-emitted at longer wavelengths. The shape of the emitted spectrum or spectral energy distribution (SED) from near- to far-infrared wavelengths depends on the amount and distribution of the surrounding dust and on its temperature.

- YSOs are classified into four different evolutionary classes 0-I-II-III based on the slope of the SED between about 2 and 25 μm (Lada & Wilking 1984; Lada 1987; André, Ward-Thompson, Barsoni 1993)

$$\alpha_{IR} = \frac{d \log \nu F_\nu}{d \log \nu} = \frac{d \log \lambda F_\lambda}{d \log \lambda}$$

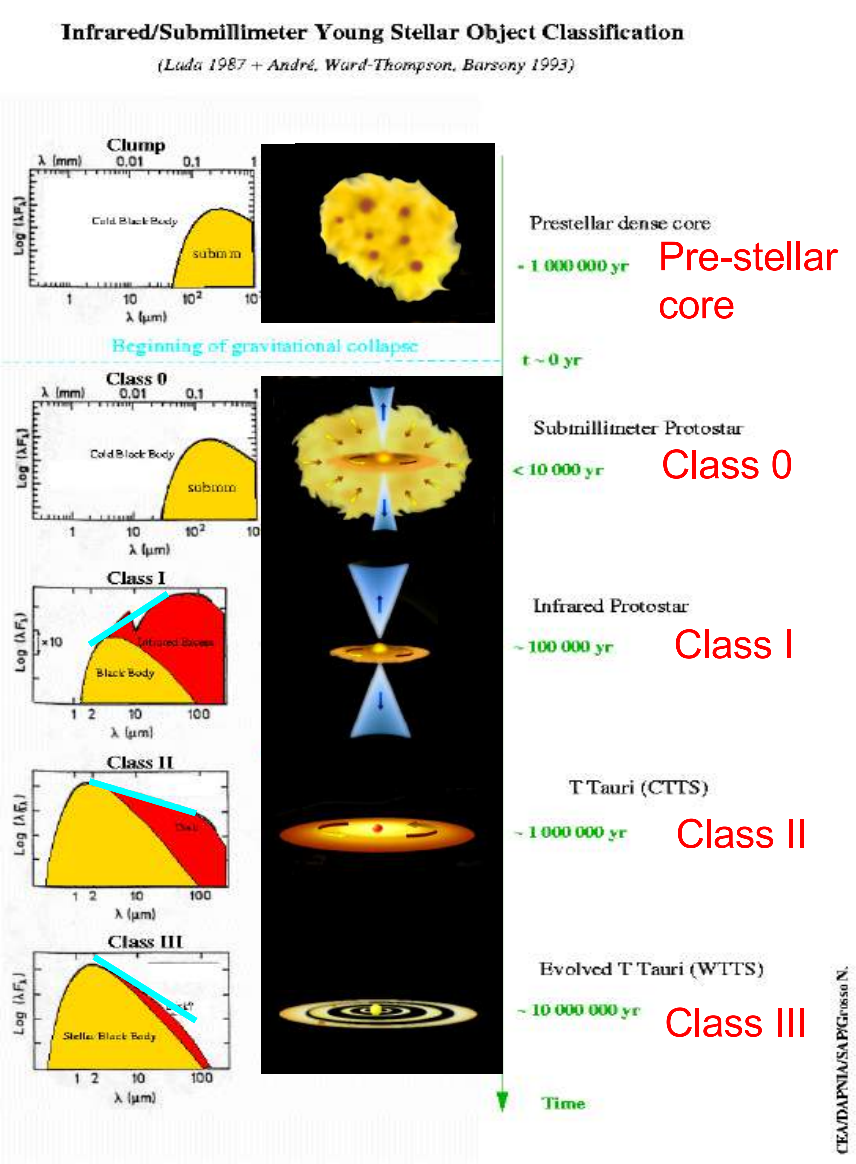
# 3. Classification of low-mass young stellar objects




- Pre-stellar cores
  - Gravitationally bound cores that evolve toward higher degrees of central condensation, but with no central hydrostatic prostostellar object within the core yet.
  - Emit almost all of their radiation in the far-IR, submm, and mm.
  - Timescale **1 x $10^6$ yr**

- Class 0
  - YSOs in the main collapse and accretion phase.
  - Deeply embedded in the circumstellar material (envelope), with SED peaking at submm and mm $\lambda$'s. Not IR emission.
  - SED resembles a single blackbody at very low temperature.
  - Timescale **< 1 x $10^4$ yr**

# 3. Classification of low-mass young stellar objects




- Class I
  - SEDs broader than single blackbody distributions, and peak at far-IR or submm λ's.
  - Huge infrared excess ($\alpha_{IR} > 0$) due to large amounts of circumstellar dust in infalling envelopes. Generally not visible in the optical.
  - Timescale **~ 1 x 10⁵ yr**

- Class II or Classical T Tauri
  - SEDs peak at visible or near-IR and broader than single blackbody distributions
  - Strong IR excesses, and flat or decreasing spectral indices ($-1.6 < \alpha_{IR} < 0$).
  - IR excesses produced by optically thick, spatially flat (or flared) dusty circumstellar disks.
  - Timescale **~ 1 x 10⁶ yr**

- Class III or weak T Tauri
  - SEDs peak at visible and IR λ's and decrease longward of 2.2 mm ($\alpha_{IR}$ < -1.6).
  - SEDs consistent with single temperature blackbodies, interpreted as arising from reddened stellar photospheres of young stars with little or no circumstellar material.
  - Timescale **~ 1 x 10⁷ yr**

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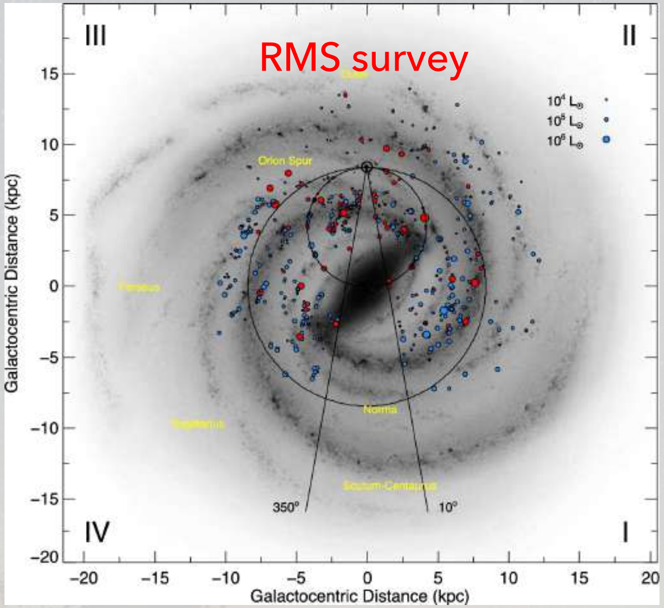
## Basic properties

- High-mass stars have masses > 8-10 $M_{\odot}$
- Luminosities > $10^4$ times higher than low-mass. Total luminosity dominated by high-mass stars.
- For each 30 $M_{\odot}$ star, there are 100 stars with1 $M_{\odot}$ (Salpeter's IMF).
- Short evolutionary timescales ~$10^5$ yr (McKee & Tan 2002): thousands of times shorter than low-mass stars (Sun: ~$10^7$ yr). And short lifetimes.
- Mainly located in the spiral arms of the galaxies, in which they formed because of their short lifetimes .
- Key elements in galaxies, they dominate their appearance and evolution.
- They are responsible for the production of heavy elements and influence the interstellar medium though energetic winds and supernovae. Produce enough UV to create HII regions.
- High-mass star-forming cores are the most chemically rich sources in the Galaxy and best reservoirs of Complex Organic Molecules, in particular prebiotic ones (building blocks of life).




Urquhart+ (2014)

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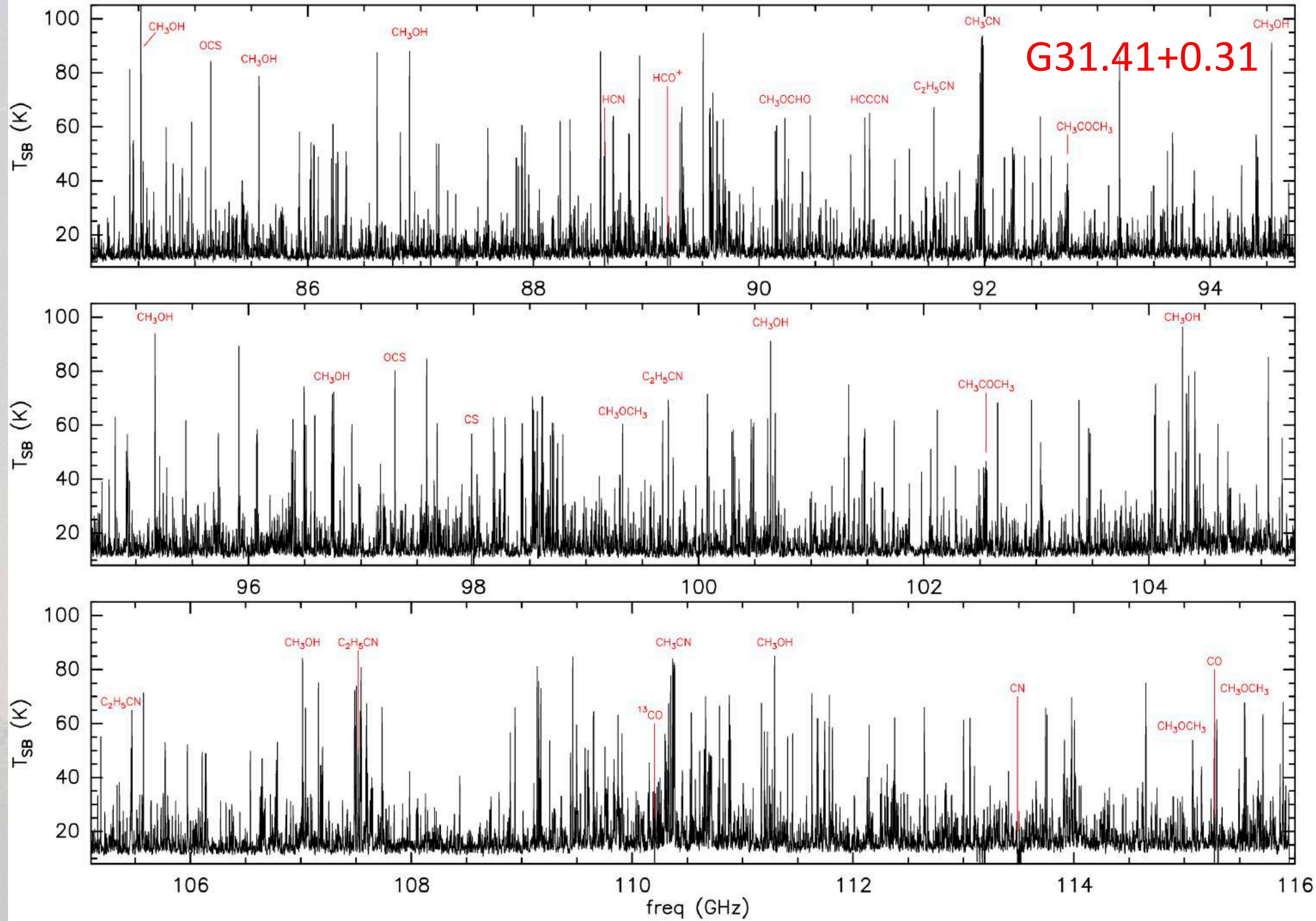
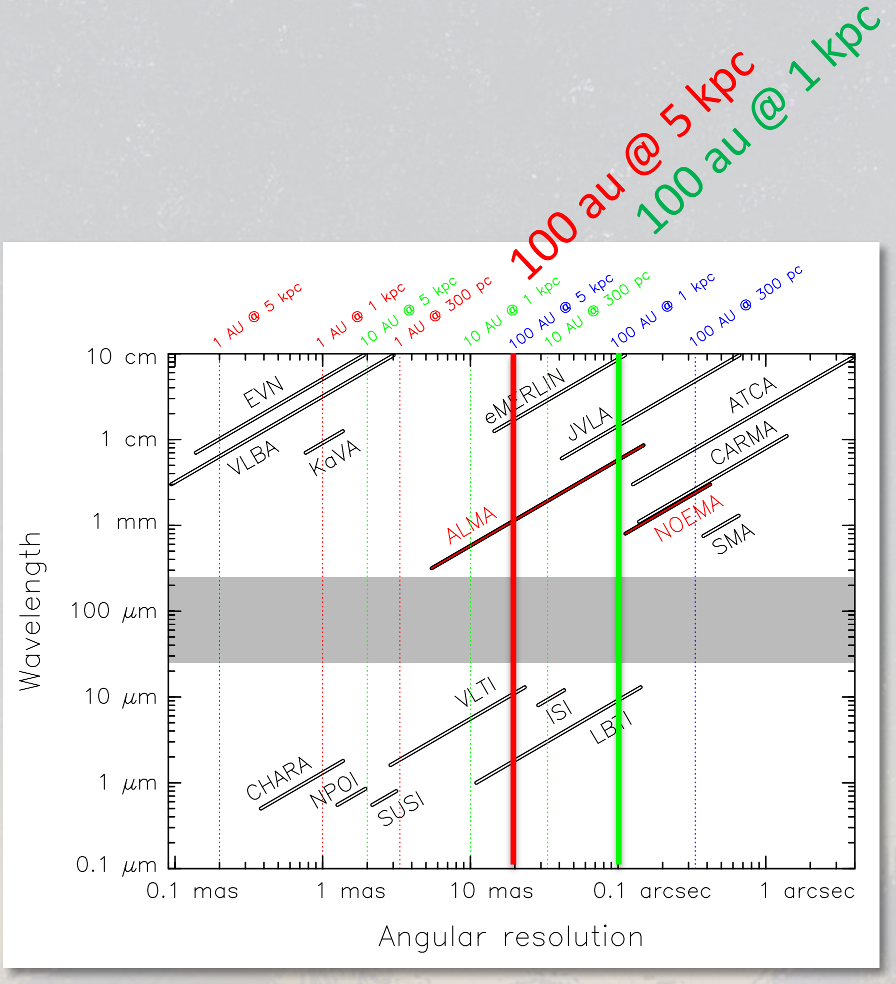
N90 in SMC


G31.41+0.31
CH3OH
OCS
CH3OH
CH3OH
HCN
HCO+
CH3OCHO
HCCCN
C2H5CN
CH3CN
CH3COCH3
CH3OH
CH3OH
CH3OH
OCS
CS
CH3OCH3
C2H5CN
CH3OH
CH3COCH3
CH3OH
C2H5CN
CH3OH
C2H5CN
13CO
CH3CN
CH3OH
CN
CH3OCH3
CO
CH3OCH3
TSB (K)
freq (GHz)

## Observational challenges

- Massive stars are rare objects found at large distances ➔ 5 kpc
- Short lifetimes, difficult to trace the earliest phases
- Massive stars embedded in rich clusters: only ~4% of O-field stars might have formed outside (de Wit+ 2005).Emission difficult to disentangle and confusion with other cluster members.
- Difficult to trace the primordial configuration of the molecular cloud and obtain the initial conditions.

HIGH-ANGULAR RESOLUTION AT CM-MM λ's IS A PRE-REQUISITE



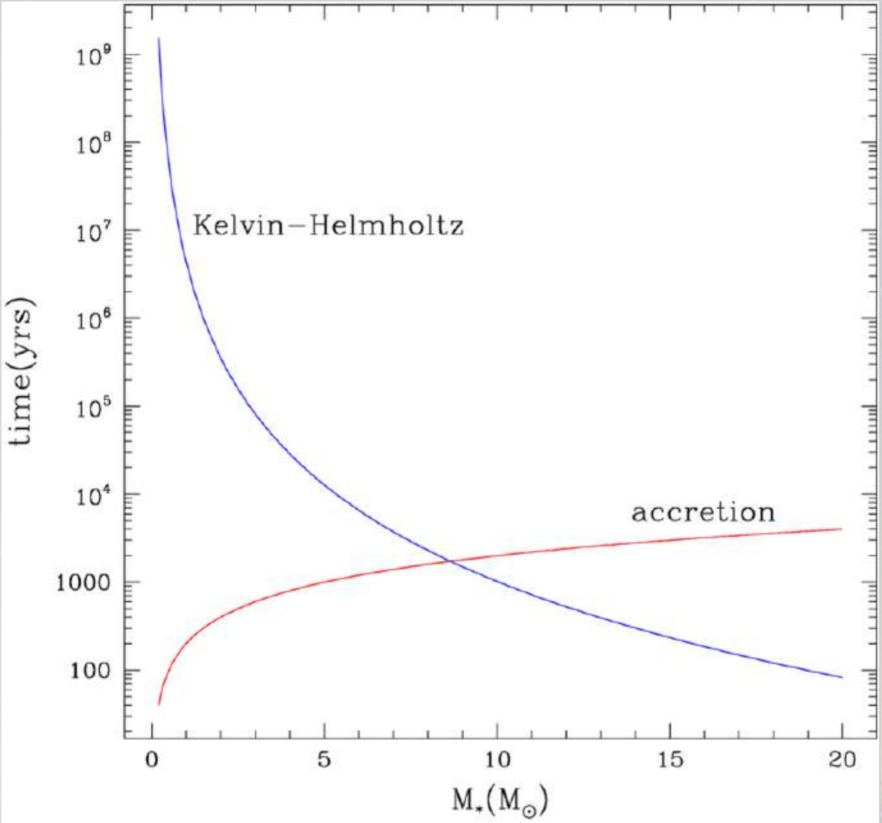

Beltrán & de Wit (2016)

## Theoretical challenges

- Two relevant timescales in star formation:
  accretion $t_{acc} = M_*/(dM_*/dt)$
  contraction $t_{KH} = GM_*/R_*L_*$
- Low-mass (< 8 $M_\odot$): $t_{acc} < t_{KH}$
  ➡ Pre-main sequence
- High-mass (> 8 $M_\odot$): $t_{acc} > t_{KH}$
  ➡ No pre-main sequence, accretion on ZAMS

⬇

Radiation pressure acting on dust grains become large enough to reverse the infall of matter

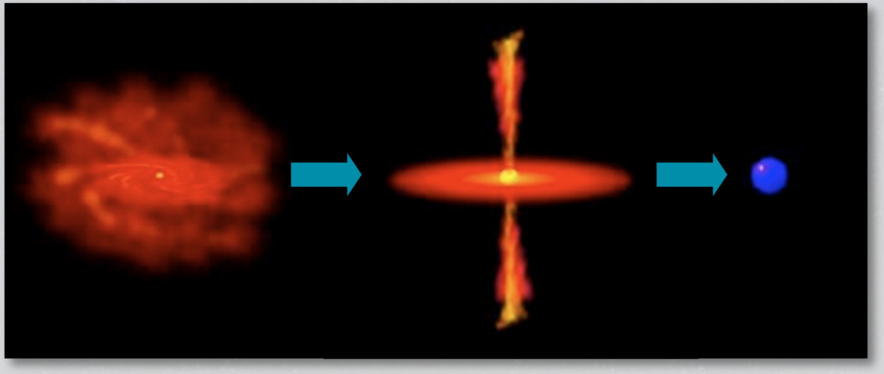


# 4. High-mass star-formation theory

- **MONOLITHIC COLLAPSE**: McKee & Tan (2002, 2003,2004)

1 core → 1 massive star

stars form via a monolithic collapse of a massive turbulent core: a massive star forms from a massive core and gathers its mass from this massive core alone. Given the non-zero angular momentum of the collapsing core, this model predicts the existence of protostellar accretion disks around massive stars.

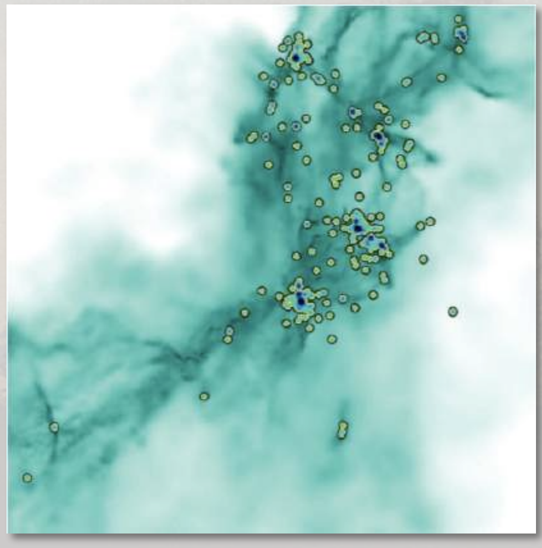


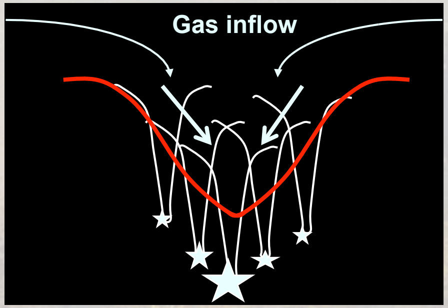
Courtesy of Luca Carbonaro

- **COMPETITIVE ACCRETION**: Bonnell et al. (1997, 2001, 2004)

Fragmentation in multiple cores

clouds fragment initially into cores of a Jeans mass of ~0.5-1 $M_{\odot}$. These cores subsequently form low-mass stars that compete to accrete the distributed gas in the molecular clump. This models predicts that massive stars should form exclusively in clustered environments. A special case of interaction is that causing a merging between low-mass stars, which is only predicted for unusually high stellar densities.






Adapted from Bonnell (2004)

# 4. High-mass star-formation theory

## MONOLITHIC COLLAPSE

- 1 core → 1 massive star (or small multiple systems).
- Stellar mass pre-assembled in the collapsing core (isolated from rest of the cloud).
- Isolated massive star formation
- CMF similar to IMF
- Turbulent medium (high accretion rates: $\dot{M} >> 10^{-5}$ $M_{\odot}$/yr).
- Slow, quasi-static process
- Initial conditions: strongly peaked density distribution ($n \propto r^{-1.5}$)
- Disks and outflows should exist

## COMPETITIVE ACCRETION

- Fragmentation in multiple cores of thermal Jeans mass.
- Accretion of unbound gas from whole cloud (global collapse). No connection between mass of the core and final stellar mass.
- Massive stars always form in clusters. Most massive star at the center
- Lead to full IMF
- Bondi-Hoyle accretion ($\dot{M} \sim M^2$).
- Fast, dynamical process, gravity driven
- Initial conditions: uniform gas density
- Disks exist (1000s au) but are disturbed and semi-transient structure. Chaotic orientations

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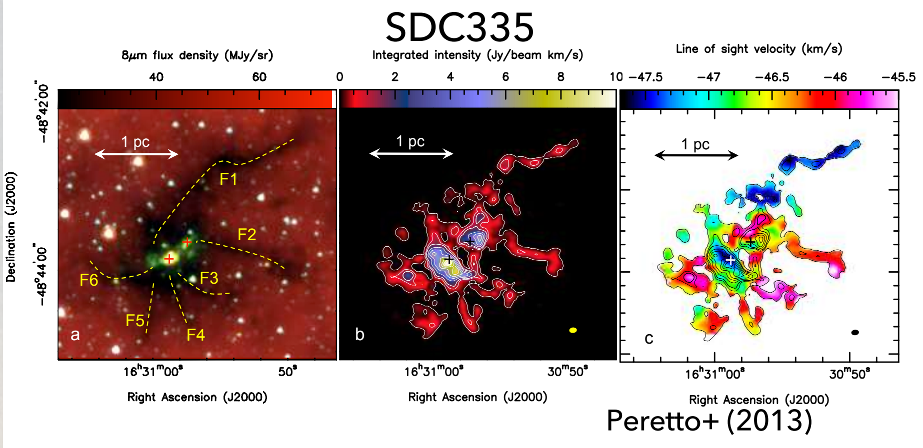

Peretto+ (2013)

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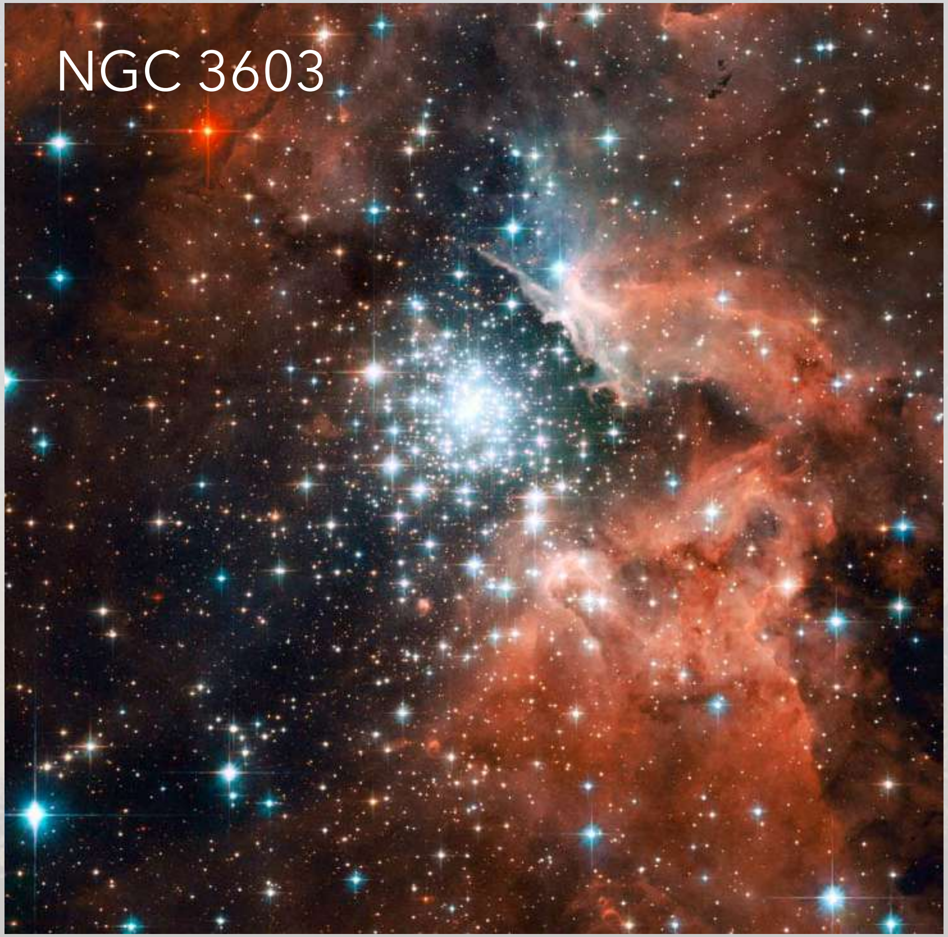

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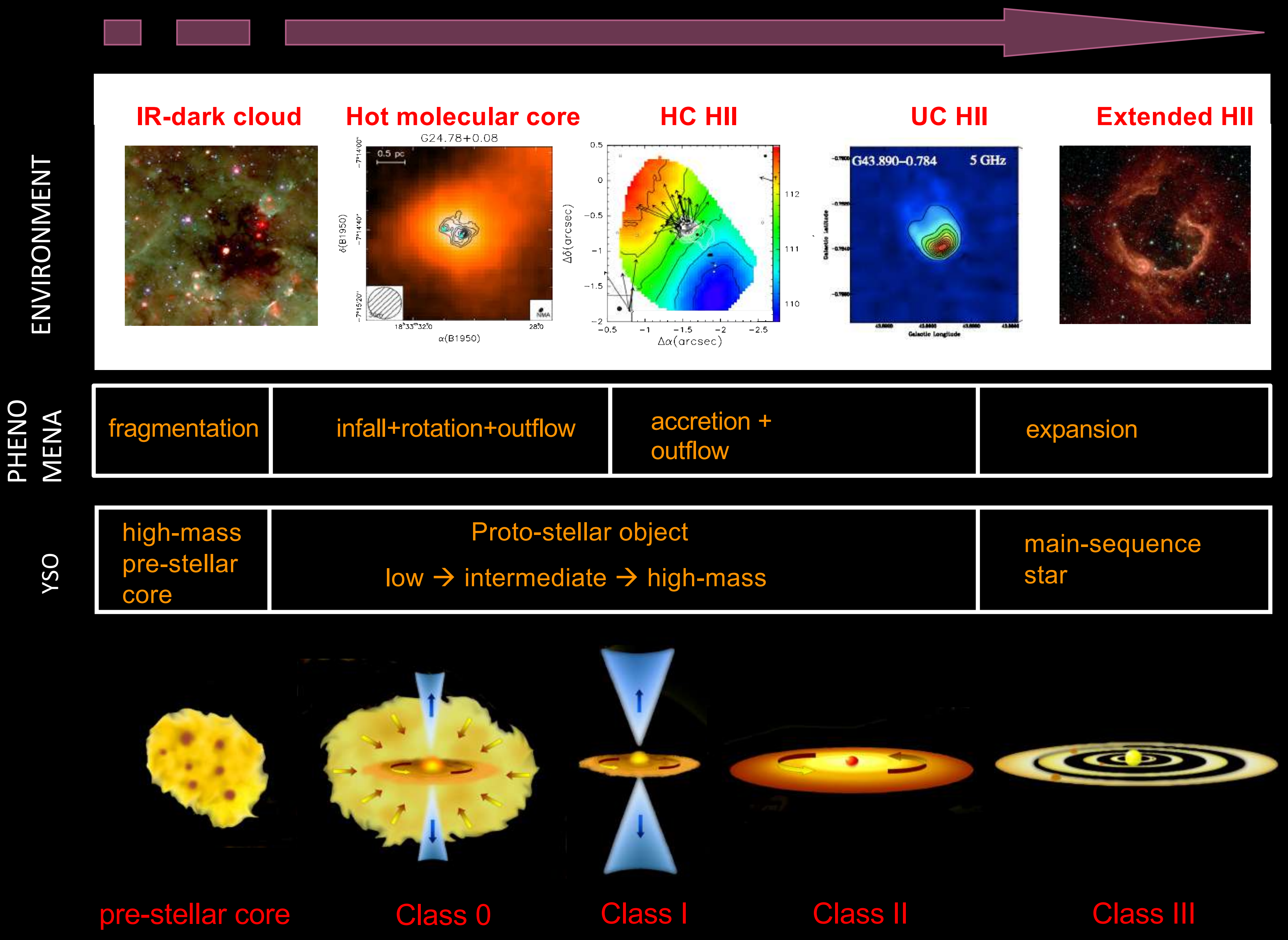
- Turbulent medium (high accretion rates: $\dot{M} >> 10^{-5}$ $M_{\odot}$/yr).
- Slow, quasi-static process
- Initial conditions: strongly peaked density distribution ($n \propto r^{1.5}$)
- Disks and outflows should exist

## COMPETITIVE ACCRETION

- Fragmentation in multiple cores of thermal Jeans mass.
- Accretion of unbound gas from whole cloud (global collapse). No connection between mass of the core and final stellar mass.
- Massive stars always form in clusters. Most massive star at the center
- Lead to full IMF
- Bondi-Hoyle accretion ($\dot{M} \sim M^2$).
- Fast, dynamical process, gravity driven
- Initial conditions: uniform gas density
- Disks exist (1000s au) but are disturbed and semi-transient structure. Chaotic orientations

# 4. High-mass star-formation theory



# Summary

1. Where and why do stars form
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# 5. Disk formation

Circumstellar disks are a natural outcome of the star formation process. Conservation of angular momentum of the infalling material onto the protostar plus gravity result in a rapidly spinning and flattened disk (centrifugally supported disk).

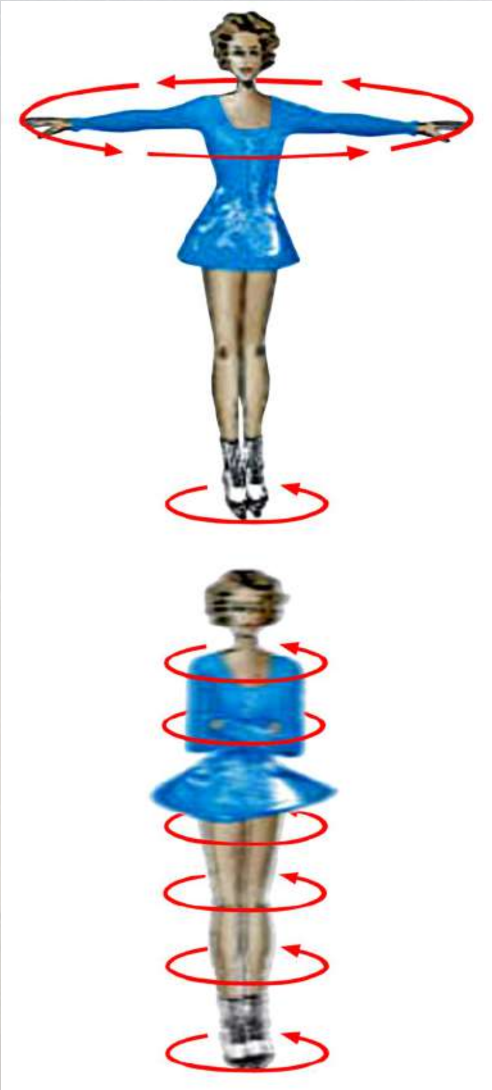
# 5. Disk formation

Circumstellar disks are a natural outcome of the star formation process. Conservation of angular momentum of the infalling material onto the protostar plus gravity result in a rapidly spinning and flattened disk.

$$j = m\,v\,r$$

mass of the rotating body, *m*
rotational velocity, *v*
distance of mass from rotational axis, *r*

# 5. Disk formation



disks are a natural outcome of the star formation process.
of angular momentum of the infalling material onto the
gravity result in a rapidly spinning and flattened disk.

$$j = m\,v\,r$$

mass of the rotating body, *m*
rotational velocity, *v*
distance of mass from rotational axis, *r*

# 5. Disk formation

In a molecular cloud, *m* is very high ($10^3$-$10^4$ $M_\odot$) as well as *r* (1 – few pc), so even if *v* is small, the angular momentum is large. When the material falls onto the surface of the protostar (very small *r*), *v* has to increase orders of magnitude.

# 5. Disk formation

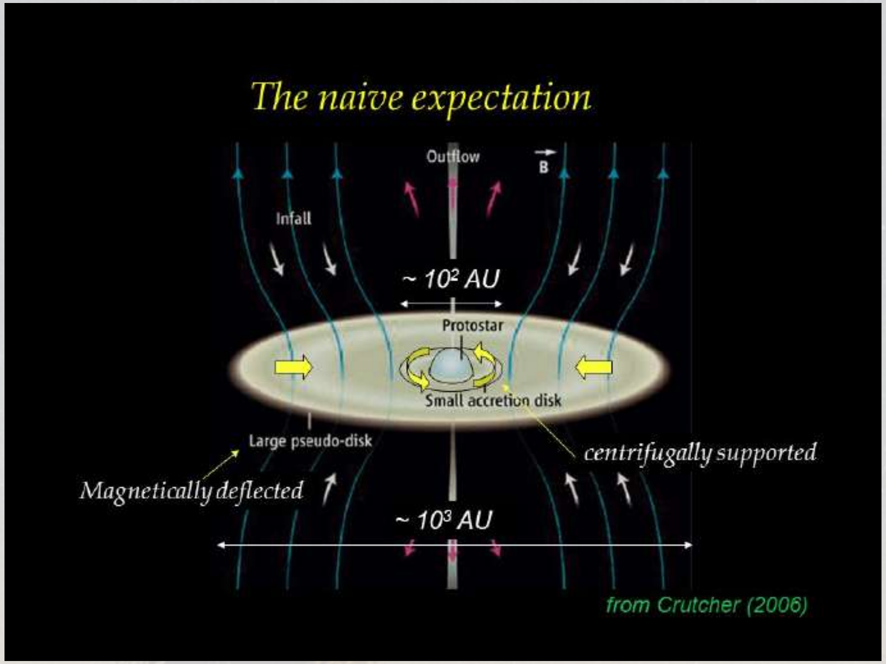
Angular momentum removal


jets and outflows

# 5. Disk formation

Angular momentum removal

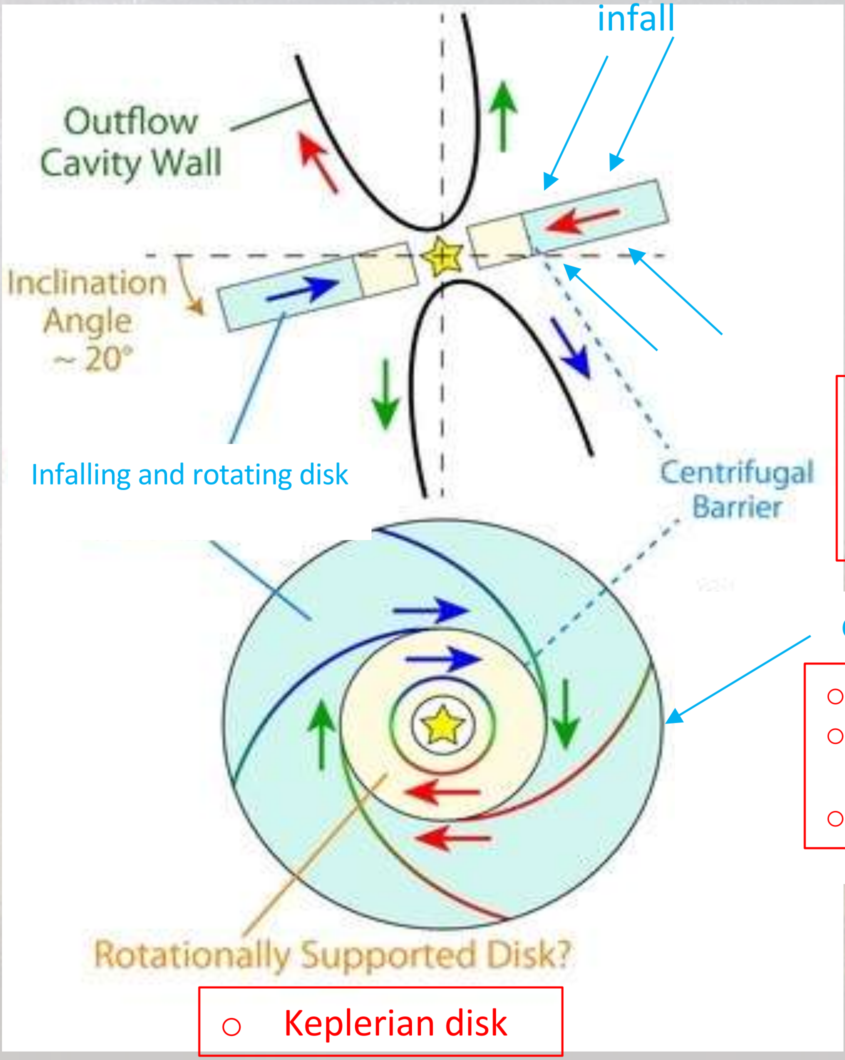

jets and outflows




catastrophic magnetic braking (Galli+ 2006)

# 5. Disk formation

The disk extends up to the **centrifugal radius** and the rotationally supported (Keplerian) disk extends out to the **centrifugal barrier**, where the gravitational force is balanced by the centrifugal force, which is expected to grow rapidly with time,




- Infalling matter piles up.
- Inside this radius, only pure rotation motions Keplerian motions

- Infalling region
- Inside this radius, rotation+radial motions
- Spiral-like trajectories

- Keplerian disk

$(M_{disk} < M_{\star})$

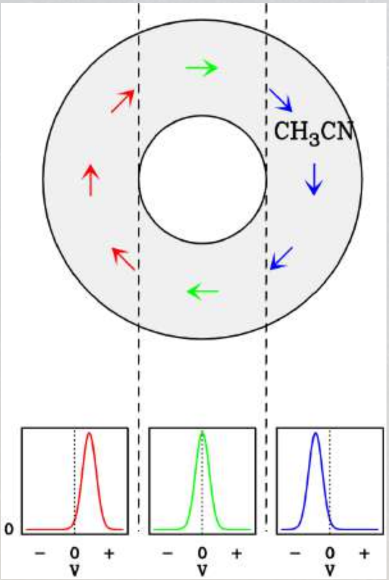
Adapted and modified from Oya+ (2014)

Theoretical model for very young protostellar disks developed by Stahler+ (1994)

# 5. Disk formation

## ROTATION:

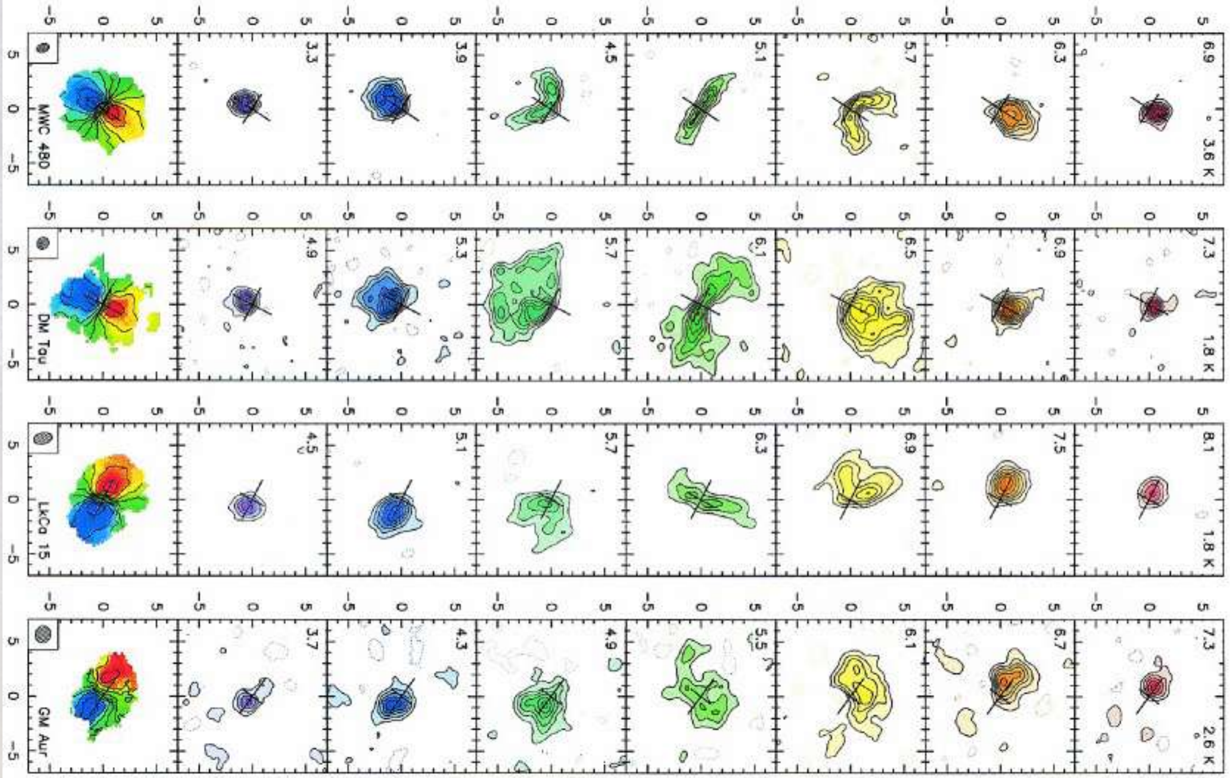
rotating disk




line of sight to the observer

Courtesy of R. Cesaroni

$^{12}$CO(2-1)




Simon+ (2000)

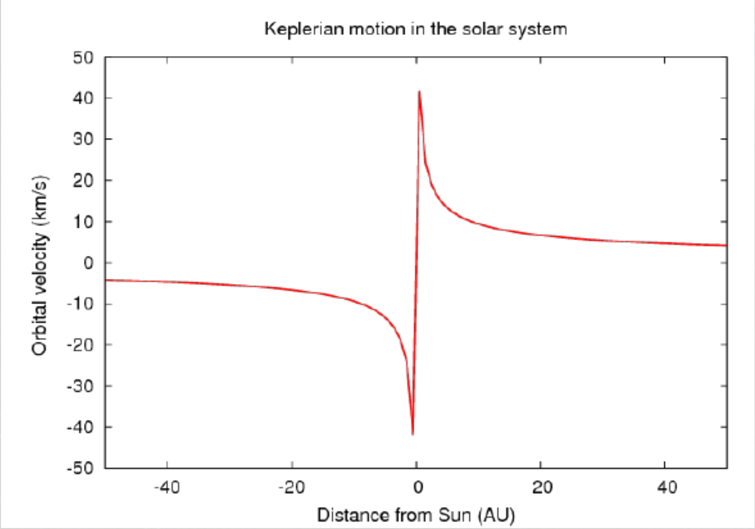
- Doppler effect: V = c($\nu_0$- $\nu$)/$\nu_0$ along line of sight → velocity field
- Velocity field: if ROTATION then velocity gradient along the major axis
- $v(r) = \sqrt{\frac{G\,M_\star}{r}}\,\sin i$ → Direct measurement of $M_\star$

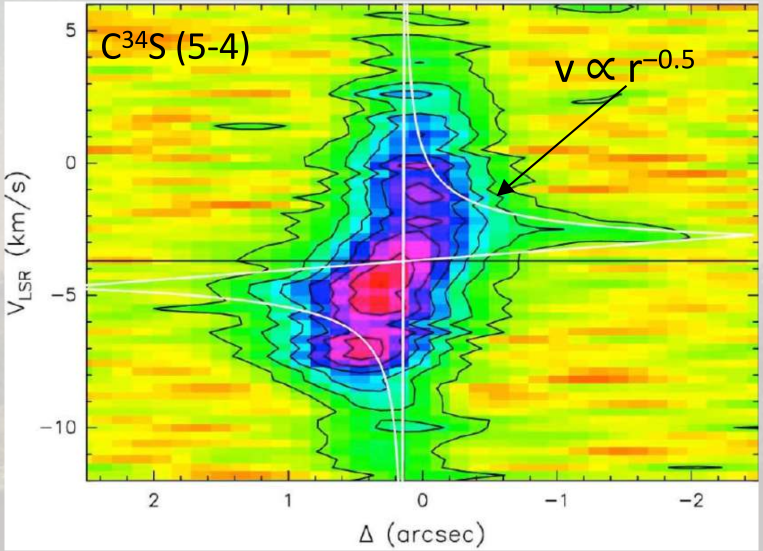
For pure Keplerian disks →

## ROTATION:

If disk masses are a small fraction of the central stellar mass. Their motions are therefore expected to be Keplerian

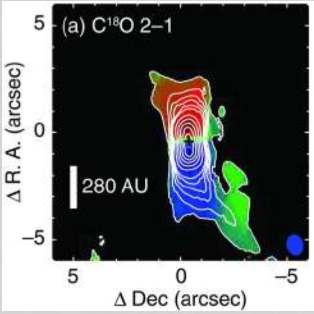
$$v_{rot}(r) = \sqrt{\left(\frac{G\,M_{\star}}{r}\right)} \propto r^{-1/2}$$

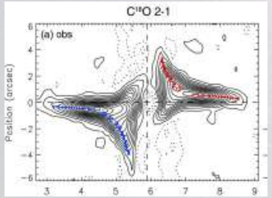


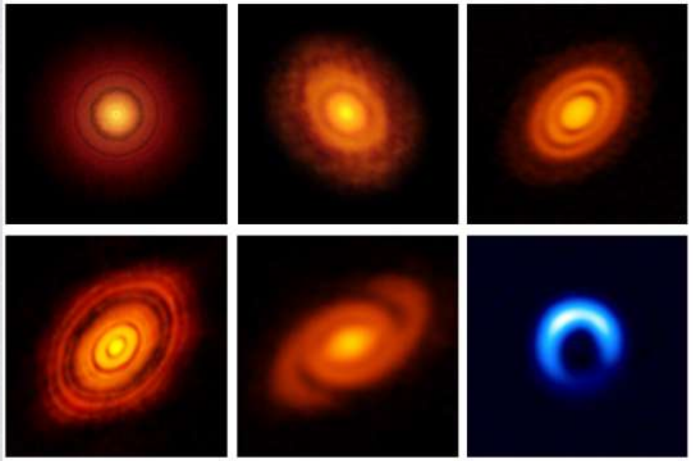



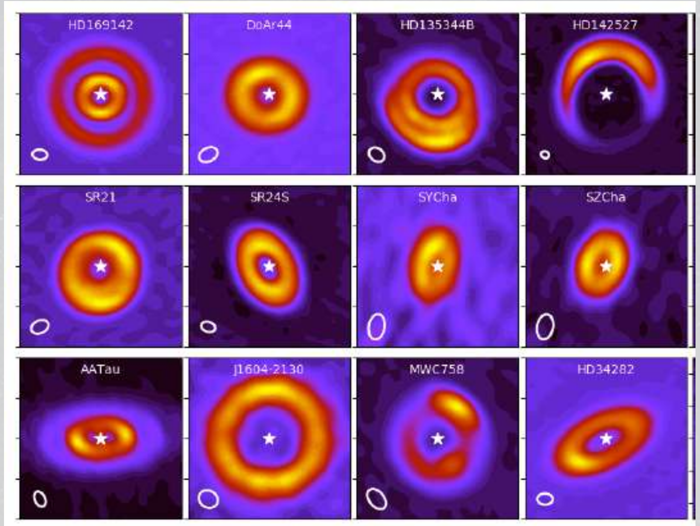
# 5. Disk formation

LOW-MASS

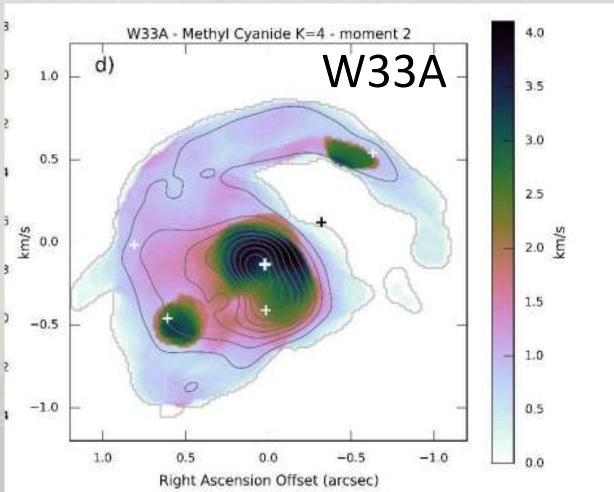


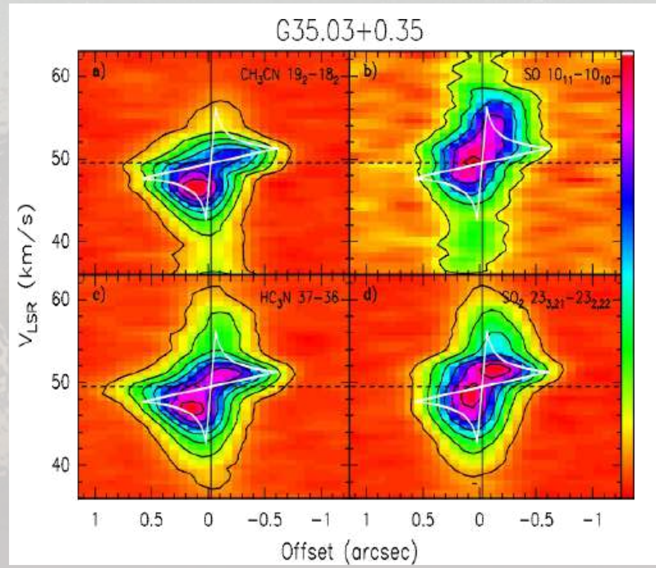






HIGH-MASS



# 5. Disk formation

## Disks in low-mass protostars

Natta (2000)

| Properties | | |
|---|---|---|
| Mass | $M$ | 0.003-0.3 $M_{\odot}$ |
| Inner radius | $R_{inn}$ | 1 to few $R_{*}$ |
| Outer Radius | $R_{out}$ | ~100 AU |

Recent ALMA observations suggest $\lesssim$ 30 au

# 5. Disk formation

## Disks in high-mass protostars

- $L_{bol} < 10^5\,L_{\odot}$ ⇨ $M_{\star}$ = 7-25 $M_{\odot}$
- $R_{disk}$ a few 100 - $10^3$ au
- $M_{disk} \sim$ a few $M_{\odot}$ ⇨ $M_{disk} \lesssim M_{\star}$

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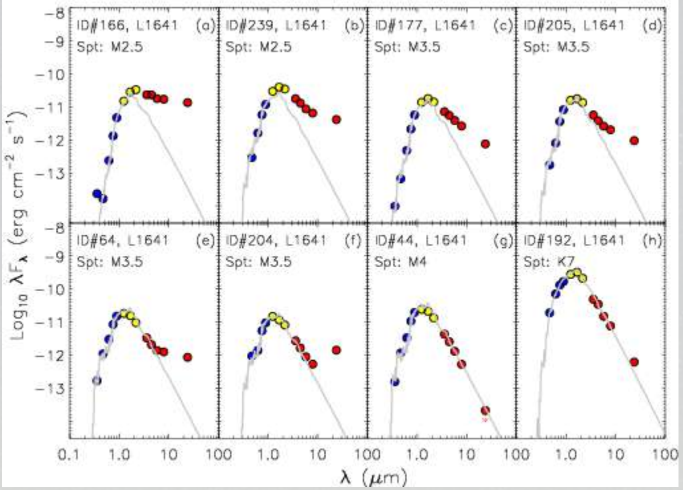
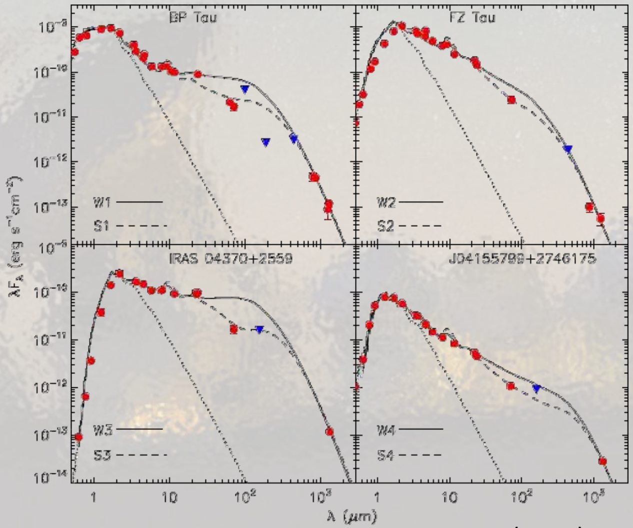
## Evidence for disk features around young stellar objects comes from:

1. SED fitting: a flat and geometrically thin distribution account for the SED (produced by the dust emission) from the optical to the mm (including the IR excess). Especially for TTauri stars, because the extinction towards most of them is very low.

evolutionary stage →




Liu+ (2017)

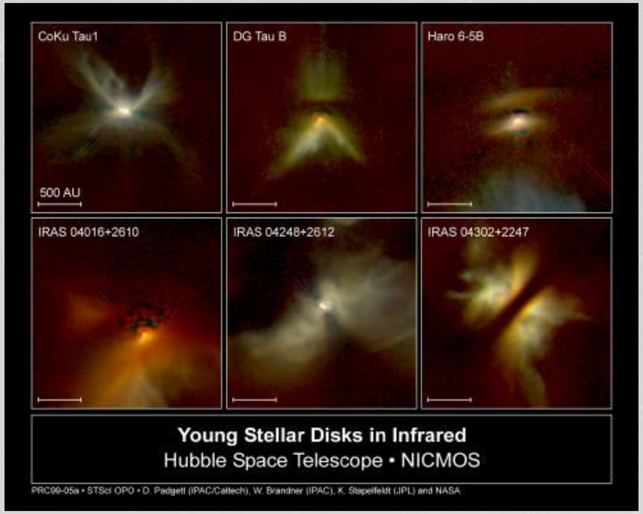
# 6. Observation of protostellar disks

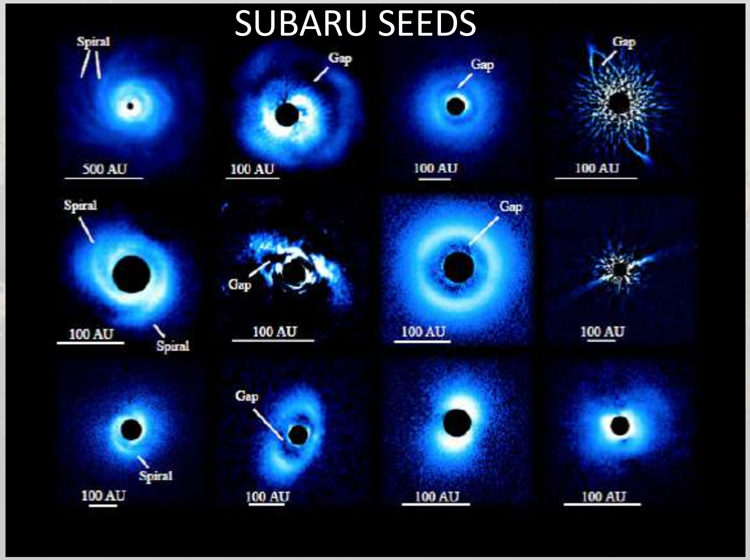
Evidence for disk features around young stellar objects comes from:

1. SED fitting: a flat and geometrically thin distribution account for the SED (produced by the dust emission) from the optical to the mm (including the IR excess). Especially for TTauri stars, because the extinction towards most of them is very low.

2. Imaging: adaptive optics (AO) systems on ground-based telescopes and the Hubble Space Telescope (HST) started to image these disks. Dust grains at the disk surface scatter the stellar light, revealing the disk geometry of circumstellar matter.

Padgett+ (1999)



# 6. Observation of protostellar disks

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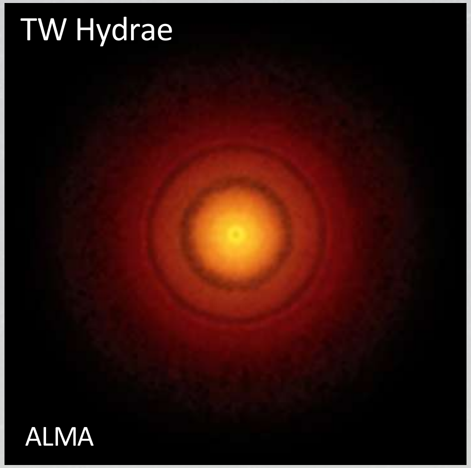
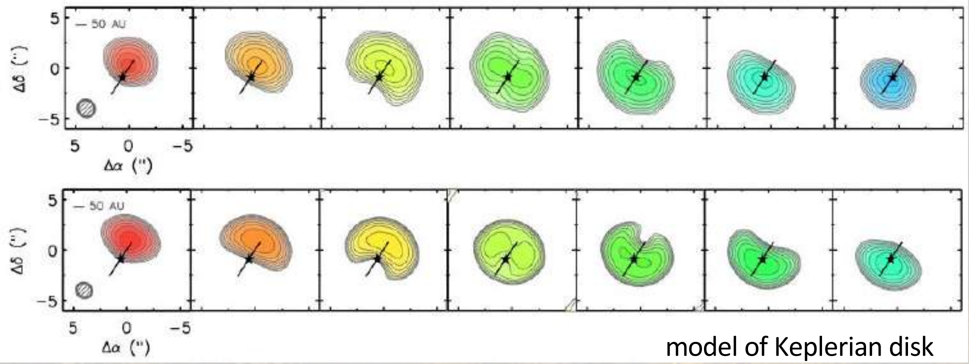
3. Gas and dust imaging: imaging embedded disks requires long wavelengths to see through the envelopes and arcsecond or higher resolution to match the disk sizes. Large millimeter arrays such as ALMA or NOEMA interferometers meet these requirements and also filter out extended structures so that the emission from the compact disk dominates on long baselines. Mapping the line emission from the gas gives information on the kinematics of the disk.

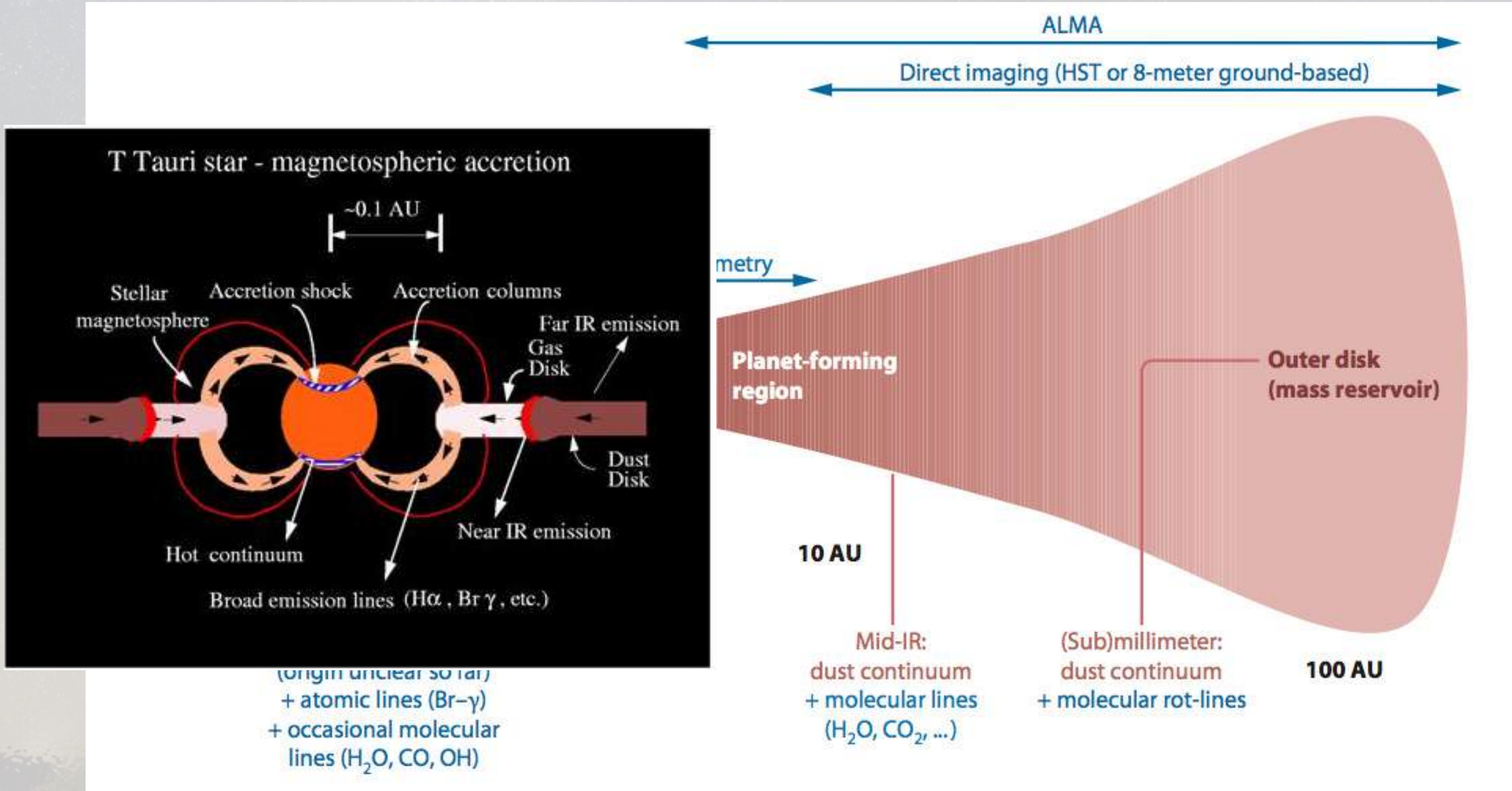



observations




model of Keplerian disk

# 6. Observation of protostellar disks




Dullemond & Monnier (2010)

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7. **Deriving properties of disks**

## Estimating disk masses

The mass of the disk determines its dynamical state, a critical property for the evolution of the disk.

- The state can be typified as either self-gravitating and in non-Keplerian rotation or centrifugally supported. The bulk of the disk material is cold and its total mass can be estimated by the thermal emission from dust.

- The dust emits as a blackbody characterized by a single temperature $T_d$ modified by the effect of the absorption coefficient → greybody

$$S_\nu = B_\nu(T_d)(1 - e^{-\tau_\nu})\Omega_s$$

where $B_n$ is the Planck function at the dust temperature $T_d$, $\Omega_s$ is the source solid angle and $\tau_\nu$ is the optical depth.

- The optical depth is proportional to the column density and can be expressed as:

$$\tau_\upsilon = \kappa\upsilon \int \rho \, dl$$

where the absorption coefficient $\kappa_\upsilon$ is proportional to the frequency as $\nu^\beta$, where $\beta$ varies typically between 0 and 2.

# 7. Deriving properties of disks

Estimating disk masses

- Under the assumption that the emission at (sub)millimeter wavelengths is fully optically thin and in the Rayleigh-Jeans regime, one can use:

$$M_{dust} = \frac{S_v\, d^2}{k_v\, B_v(T_d)}$$

- Where Bv in the R-J regime is

$$B_v(T_d) = \frac{2kv^2}{c^2} T_{\mathrm{d}}$$

- Assuming a gas-to-dust ratio of 100, then:

$$M_{gas} = 100 \frac{S_v\, d^2}{k_v\, B_v\,(T_d)}$$

## Uncertainties in disk masses

- Gas-to-dust mass ratio in a disk is usually assumed to be 100, the typical value for the interstellar medium (ISM). Only 1% of the disk mass is in dust particles. BUT the physical conditions dominating the disk are likely to be much unlike those found in the ISM. The gas-to-dust ratio could actually be lower in circumstellar disks due to gas removal. Dust related processes such as grain growth and dust settling could result in a predominantly gaseous disk atmosphere that would be subject to photo-evaporation leading to gaseous disks winds or to the selective accretion of gas onto the central star (e.g., Williams & Best, 2014). These processes would result in an overestimate of the disk mass based on dust emission.

- Recent gas-to-dust mass ratio studies point to a factor 150 (Draine 2011)

- An estimate of the dust temperature $T_d$ can be obtained by fitting SED with black-body curves. Alternatively, by assuming local thermodynamic equilibrium (LTE), one could adopt the rotation temperature of high-density molecular tracers. BUT if dust and gas are not perfectly coupled, then $T_d$ can differ by a few degrees from the temperature estimated of the high-density tracers (Goldsmith, 2001; Juvela & Ysard, 2011).

- The principal source of uncertainty is the dust opacity coefficient $k_\nu$. It depends on the composition and properties of the dust particles themselves, in particular on the dust opacity power-law index β, ($k_\nu \propto \nu^\beta$). Different studies have computed different dust opacity laws (e.g., Hildebrand, 1983; Draine & Lee, 1984; Ossenkopf & Henning, 1994) that yield disk mass estimates differing by a factor 4–5 (Beuther et al., 2002a).

- An additional source of uncertainty on the disk mass relates to the achieved spatial resolution. Insufficient angular resolution makes it very difficult to disentangle the disk emission from that of the envelope and would lead to serious overestimates of the disk mass. Interferometers have the advantage of spatially filtering out the most extended envelope emission, and decrease the bias on the disk mass estimates.

# 7. Deriving properties of disks



Estimating inner and outer radii

- Disk outer radii are estimated from either resolved dust continuum emission or from line emission of high-density tracers. Such observations are performed at long wavelengths, given the low temperatures of the outer disk.

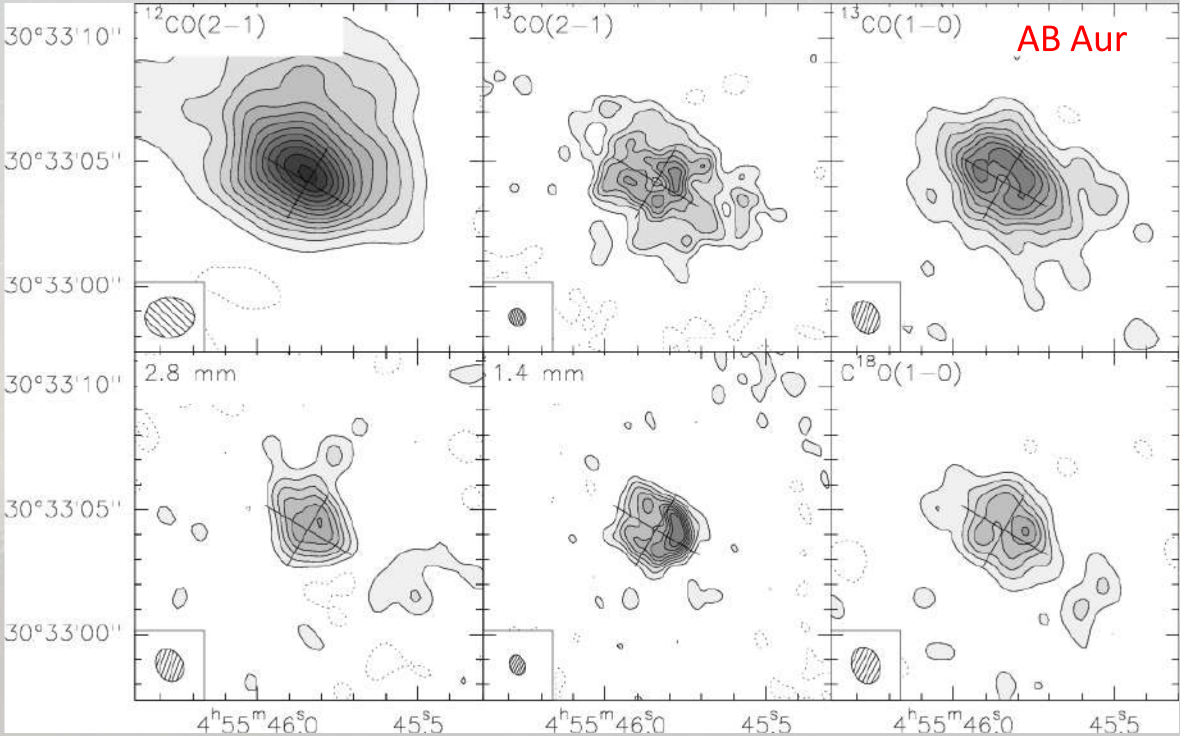
- Direct spatial information on the inner disk and its associated accretion physics requires a linear resolution between 10 AU and approximately the stellar radius. For most stars, such scales are only indirectly accessible through spectroscopic techniques like high-resolution spectroscopy, spectro-astrometry and spectro-polarimetry, i.e. techniques that have proven their efficacy in the optical and near-IR wavelength range.

## Estimating surface density

- The projected surface density Σ is a power-law of the radius ($\propto R^{-p}$), and assuming a flat cylindrical disk, can be estimated as

$$\Sigma(R) = \frac{M_{gas}}{\pi R^2}$$

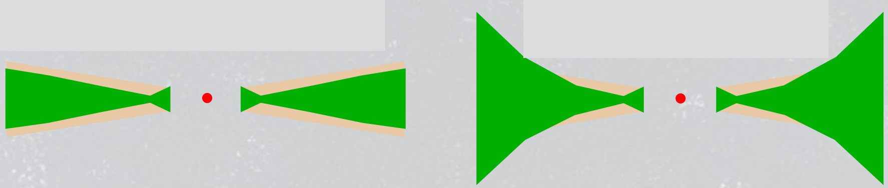
- Dust size vs. gas size: dust sizes ≠ gas sizes (In Class II YSOs, size from rotational CO lines is larger than from dust continuum: Piétu+ 2005; Isella+ 2007).




Piétu+ (2005)

# 7. Deriving properties of disks

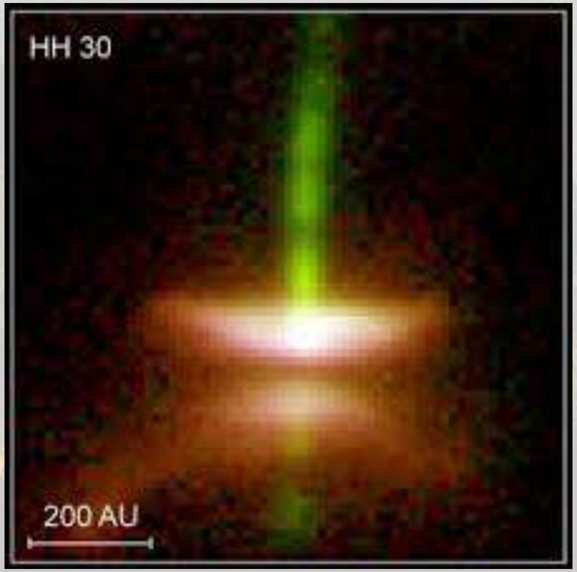
## Estimating scale height profiles



- Protoplanetary disks can be "flat" or flared with a vertical scale height that increases with radius.
- Characterizing the disk scale height is essential for modeling the thermal, ionization, and chemical structure of disks and for interpreting atomic and molecular line observations. It is also important for understanding disk evolution as the outer parts, with their low densities and large-scale heights, are particularly susceptible to photoevaporative losses.
- For an azimuthally symmetric disk in hydrostatic equilibrium, the density is a function of both radius, *R*, and vertical height, *Z*:

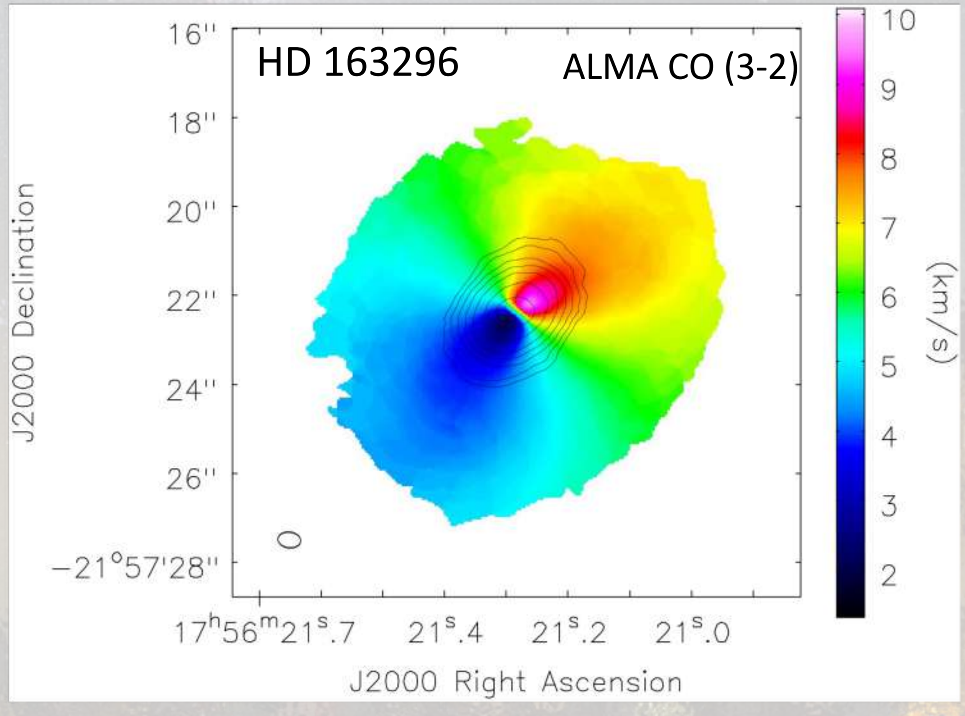
$$\rho(R,Z) = \frac{\Sigma(R)}{\sqrt{2\,\pi}H}\, exp\left(-\frac{Z^2}{2H^2}\right)$$

where *H(R)* is the scale height, which depends on the competition between disk thermal pressure and the vertical component of stellar gravity. $H(R) \propto R^h$ with $h \approx$ 1.3-1.5 (D'Alessio+ 1998; Dullemond+ 2002)



## Estimating rotating velocity

- A *first moment* map or **velocity-weighted** map represents the average velocity of the gas at each pixel
- $V_{rot}$ is often estimated as half the range of the velocity gradient measured over the resolved disk of a high-density molecular tracer (e.g., Beuther et al. 2008; Beltrán et al. 2011a).

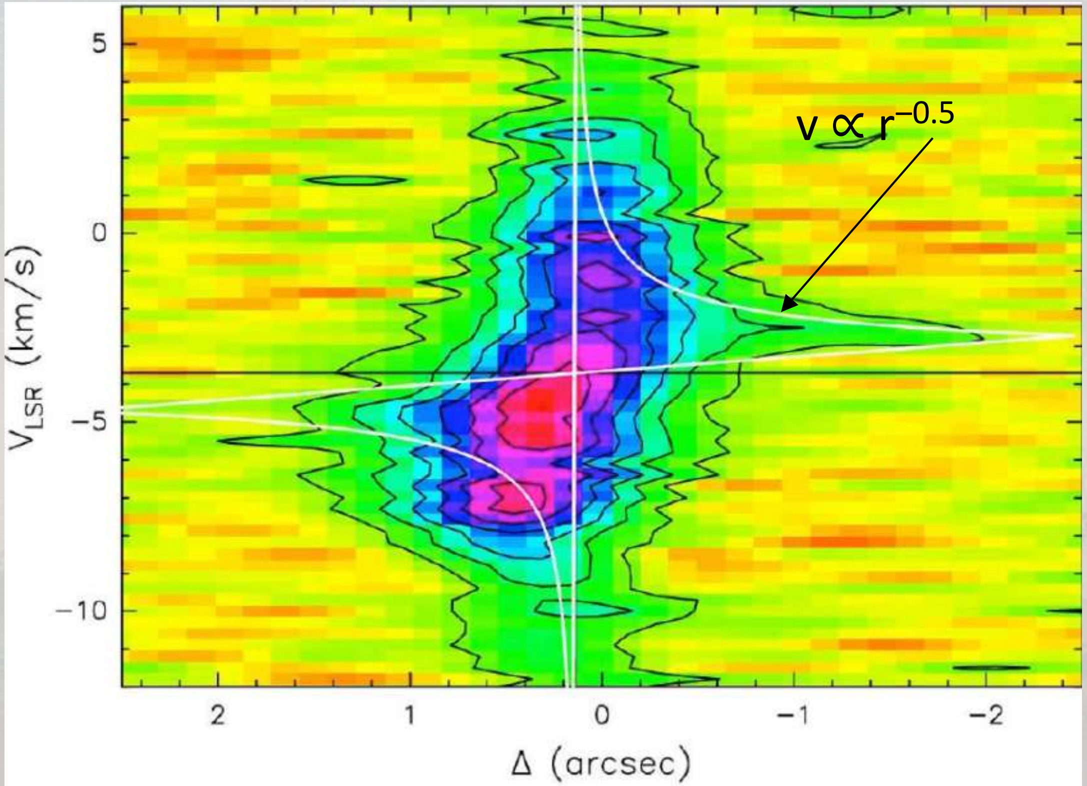



de Gregorio-Monsalvo+ (2013)

## Estimating rotating velocity

- If the disk is in Keplerian rotation:

$$v_{rot}(r) = \sqrt{\left(\frac{G\,M_\star}{r}\right)} \propto r^{-1/2}$$



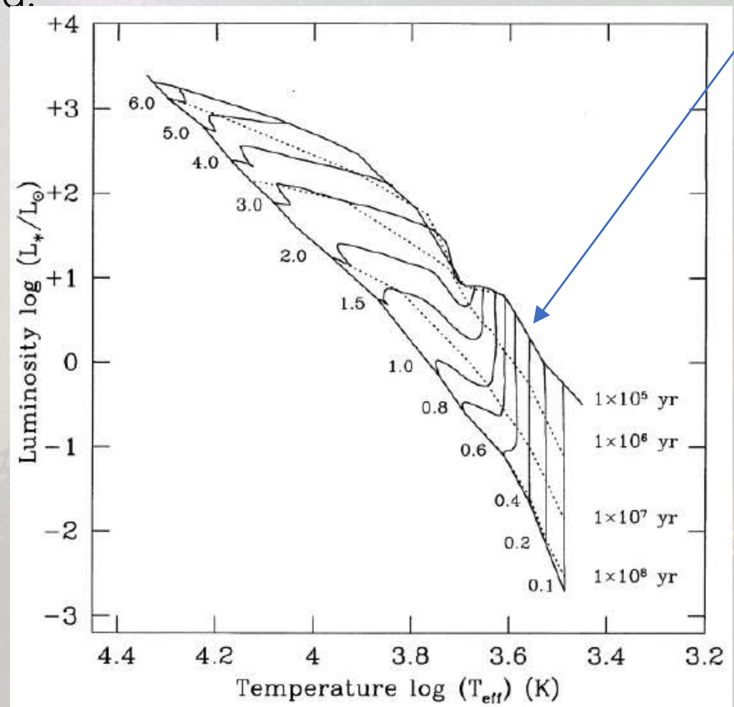
Estimating the mass of the (proto)star

1. Dynamically: modeling the rotation in a Keplerian disk:

$$M_\star = M_{dyn} = \frac{{v_{rot}}^2 R}{G}$$

where $v_{rot}$ is the rotation velocity of the disk and $R$ the outer radius.

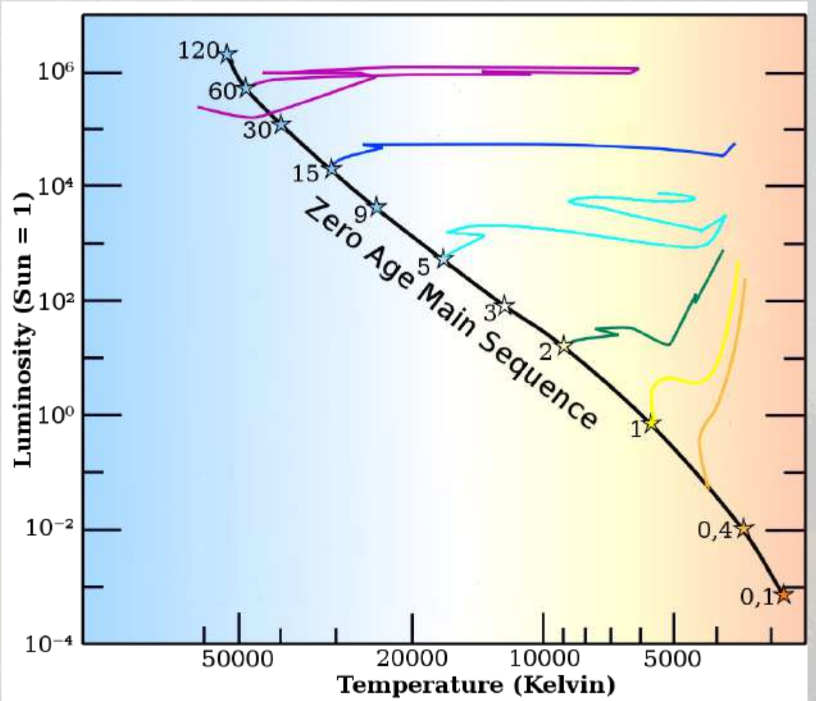
2. LOW-MASS: From the bolometric luminosity, assuming that the YSO is at the birthline → pre-main sequence star starts to contract to reach the ZAMS. Accretion has ended.




Palla & Stahler (1999)

Estimating the mass of the (proto)star

2. HIGH-MASS: From the bolometric luminosity, assuming that the YSO has reached the ZAMS.



# 7. Deriving properties of disks

## Estimating the mass of the (proto)star

3. From free-free centimeter emission, assuming it comes from an optically thin HII region. One can deduce the Lyman-continuum photons emitted per second ($N_{Ly}$) (e.g., Mezger and Henderson 1967) and relate it to the spectral type (Martins et al. 2005; Lanz and Hubeny 2007; Davies et al. 2011)

$$S_\nu = B_\nu(T_B)(1 - e^{-\tau_\nu})\Omega_s$$

$$T_B = \frac{S_\nu c^2}{2\,\nu^2 k_B \Omega_s}$$

The emission measure:

$$EM\ (cm^{-6}\ pc) = s_\nu\ \nu^{0.1} T_e^{0.35}\ \theta_S{}^{-2}$$

where $T_e$ is the electron temperature, usually assumed to be $10^4$ K

The electron density:

$$n_e(cm^{-3}) = S_\nu^{0.5}\ \nu^{0.05}\ T_e^{0.175}\ d^{-0.5}\ \theta_S^{-1.5}$$

And the number of Lyman-continuum photons per second ($s^{-1}$):

$$N_{Ly} = S_\nu\ \nu^{0.1}\ T_e^{-0.45}\ d^2$$

## Estimating the mass of the (proto)star

| Mass ($M_\odot$) | $T_{\rm eff}$ (K) | Log ($L_\star/L_\odot$) | $R_\star$ ($R_\odot$) | $BC_V$ | $M_V$ | Log$Q_{\rm Lyc}$ (phot s$^{-1}$) | $t_{\rm KH}$ ($\times 10^3$ yr) |
|---|---|---|---|---|---|---|---|
| 6 | 19 000 | 3.01 | 3.0 | −1.83 | −0.95 | 43.33 | 367.1 |
| 9 | 22 895 | 3.57 | 3.9 | −2.28 | −1.89 | 44.76 | 175.5 |
| 12 | 26 743 | 3.96 | 4.5 | −2.64 | −2.52 | 46.02 | 107.8 |
| 15 | 29 783 | 4.26 | 5.1 | −2.88 | −3.01 | 47.03 | 76.2 |
| 20 | 33 824 | 4.61 | 6.0 | −3.22 | −3.56 | 48.00 | 51.8 |
| 25 | 36 831 | 4.86 | 6.7 | −3.47 | −3.93 | 48.46 | 40.2 |
| 30 | 38 670 | 5.02 | 7.3 | −3.61 | −4.19 | 48.69 | 36.7 |
| 35 | 40 596 | 5.18 | 8.0 | −3.75 | −4.45 | 48.90 | 31.7 |
| 40 | 42 610 | 5.34 | 8.7 | −3.89 | −4.71 | 49.09 | 26.3 |
| 50 | 44 589 | 5.52 | 9.8 | −4.03 | −5.02 | 49.31 | 24.1 |
| 60 | 46 647 | 5.70 | 11.0 | −4.18 | −5.33 | 49.43 | 20.4 |
| 70 | 47 662 | 5.81 | 12.0 | −4.25 | −5.53 | 49.51[a] | 19.7 |
| 80 | 48 694 | 5.92 | 13.1 | −4.32 | −5.74 | 49.58[a] | 18.2 |
| 90 | 49 449 | 6.02 | 14.1 | −4.37 | −5.92 | 49.65[a] | 17.4 |
| 100 | 49 913 | 6.09 | 15.0 | −4.41 | −6.06 | 49.70[a] | 17.0 |
| 110 | 50 381 | 6.16 | 16.0 | −4.44 | −6.21 | 49.76[a] | 16.4 |
| 120 | 50 853 | 6.23 | 17.1 | −4.47 | −6.36 | 49.81[a] | 15.5 |

Davies+ (2011)

| Sp Type | $T_{\rm eff}$ ($10^3$ K) | log($L$) ($L_\odot$) | $M$ ($M_\odot$) | $M_{\rm V}$ (mag) | $t_{\rm K-H}$ ($10^4$ yr) | $t_{\rm MS}$ ($10^6$ yr) |
|---|---|---|---|---|---|---|
| O3 | 44.8 | 5.86 | 70.8 | −5.9 | 1.6 | 2.9 |
| O4 | 42.9 | 5.60 | 52.3 | −5.3 | 1.9 | 3.3 |
| O5 | 40.9 | 5.36 | 39.4 | −4.9 | 2.3 | 3.9 |
| O5.5 | 39.9 | 5.27 | 36.5 | −4.7 | 2.5 | 4.2 |
| O6 | 38.9 | 5.17 | 33.5 | −4.6 | 2.8 | 4.5 |
| O6.5 | 37.9 | 5.08 | 30.6 | −4.4 | 3.1 | 4.9 |
| O7 | 36.9 | 4.98 | 27.5 | −4.2 | 3.3 | 5.4 |
| O7.5 | 35.9 | 4.88 | 24.7 | −4.1 | 3.6 | 5.9 |
| O8 | 34.9 | 4.78 | 22.9 | −3.9 | 4.1 | 6.5 |
| O8.5 | 33.9 | 4.69 | 21.0 | −3.7 | 4.5 | 7.2 |
| O9 | 32.9 | 4.59 | 19.4 | −3.6 | 5.1 | 8.1 |
| O9.5 | 31.9 | 4.50 | 18.1 | −3.4 | 5.7 | 8.9 |
| B0 | 29.5 | 4.27 | 14.9 | −3.1 | 7.3 | 12.0 |
| B0.5 | 27.3 | 4.04 | 12.7 | −2.7 | 10.0 | 16.4 |
| B1 | 25.0 | 3.80 | 10.7 | −2.3 | 13.6 | 23.6 |
| B1.5 | 23.0 | 3.58 | 9.0 | −1.9 | 17.4 | 33.8 |
| B2 | 21.5 | 3.37 | 7.9 | −1.5 | 24.3 | 48.7 |
| B2.5 | 20.2 | 3.18 | 6.9 | −1.2 | 31.5 | 69.2 |
| B3 | 19.0 | 3.01 | 6.0 | −0.9 | 37.9 | 96.4 |

Mottram+ (2011)

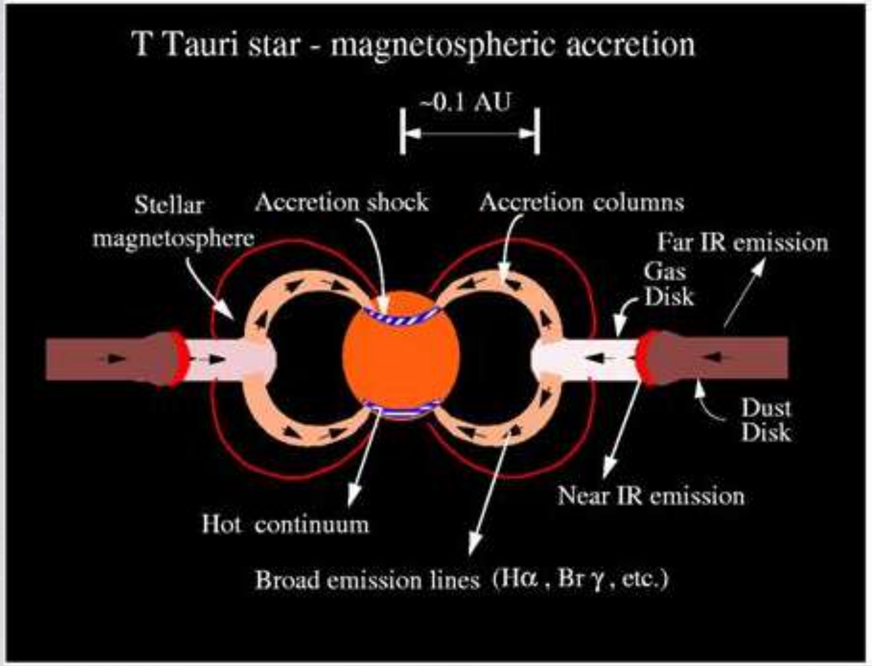
## Estimating accretion rates

- Inner disk is truncated by stellar magnetic field at 3-5 R*. Matter flows onto stars following magnetic field lines (e.g. Hartmann 1998)
- Accretion luminosities $L_{acc}$ can be derived from:
  - excess emission/veiling at optical and UV: Accretion luminosities can be derived from the flux released when the material impacts the stellar surface, which appears as excess flux in relation to the photospheric one.
  - Broad emission lines: Hα, Hβ, Hγ, Brγ there is a correlation between accretion luminosity and line luminosity
- The mass accretion rate $\dot{M}_{acc}$ is then computed from the accretion luminosity

$$\dot{M}_{acc} = L_{acc} \frac{R_*}{G\, M_*}$$

where $R_*$ and $M_*$ are radius and mass of the pre-main sequence star.

Magnetospheric accretion



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- The mass a… rom the accreti…

where $R_*$ a… main seque…

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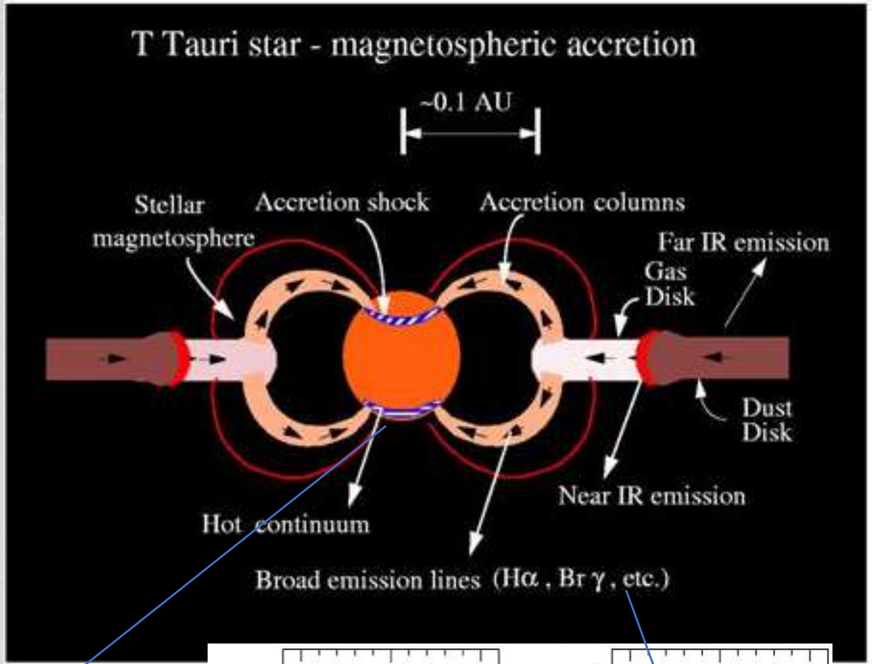
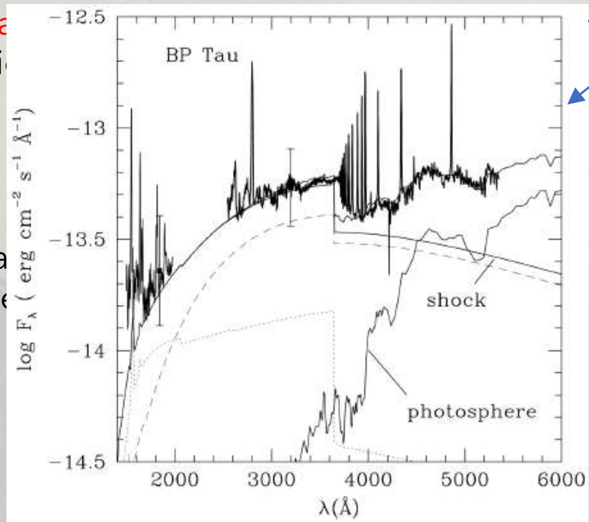
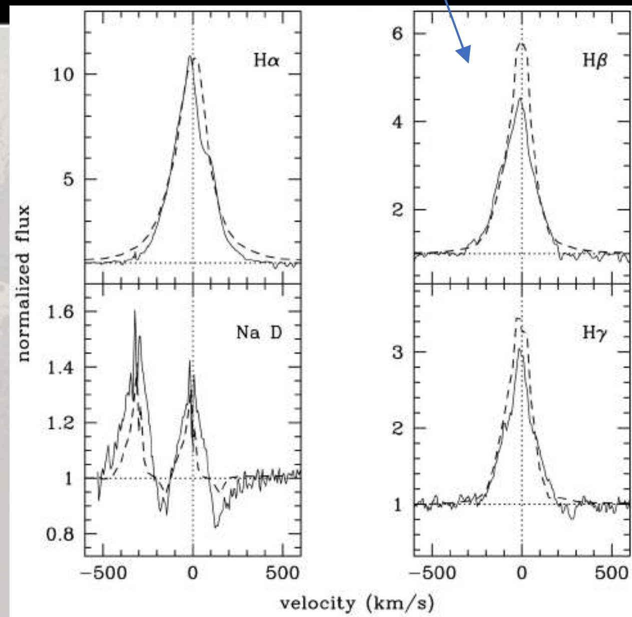



Gullbring+ (2000)



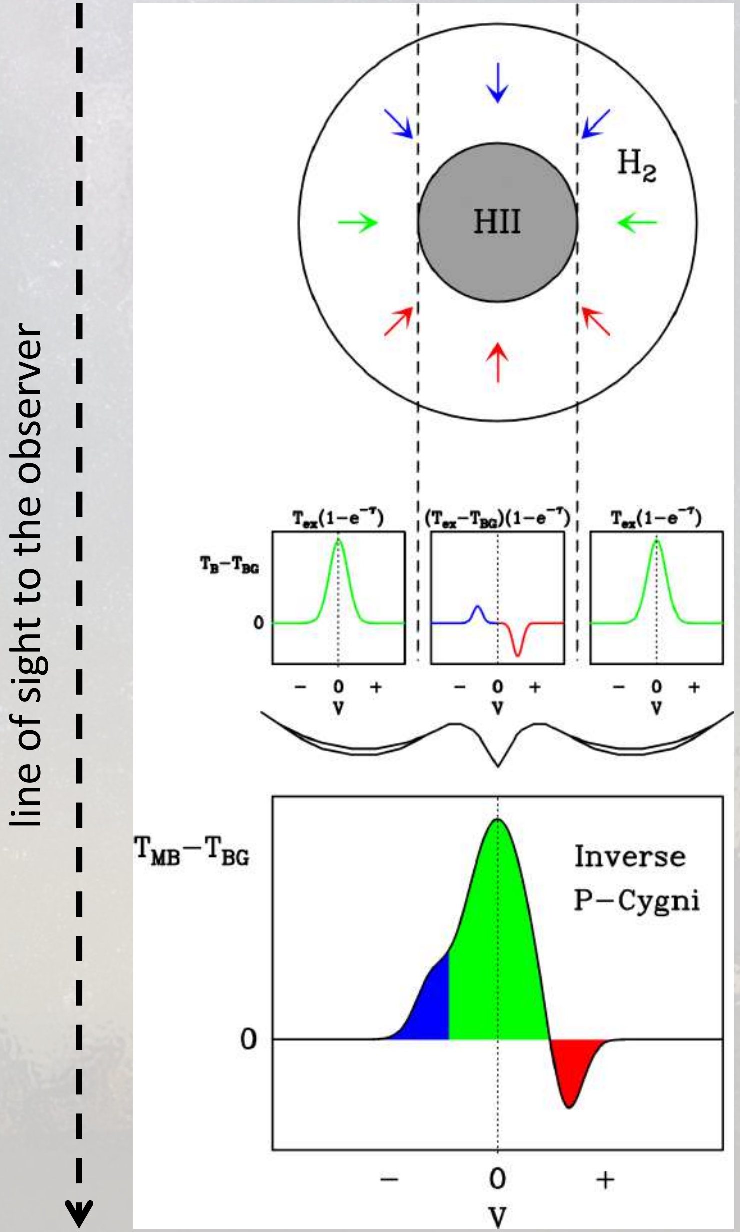
## Estimating infall and accretion rates

- Infall rate can be estimated:

  1. From inverse P-Cygni profiles (or red-shifted absorption) towards bright embedded sources

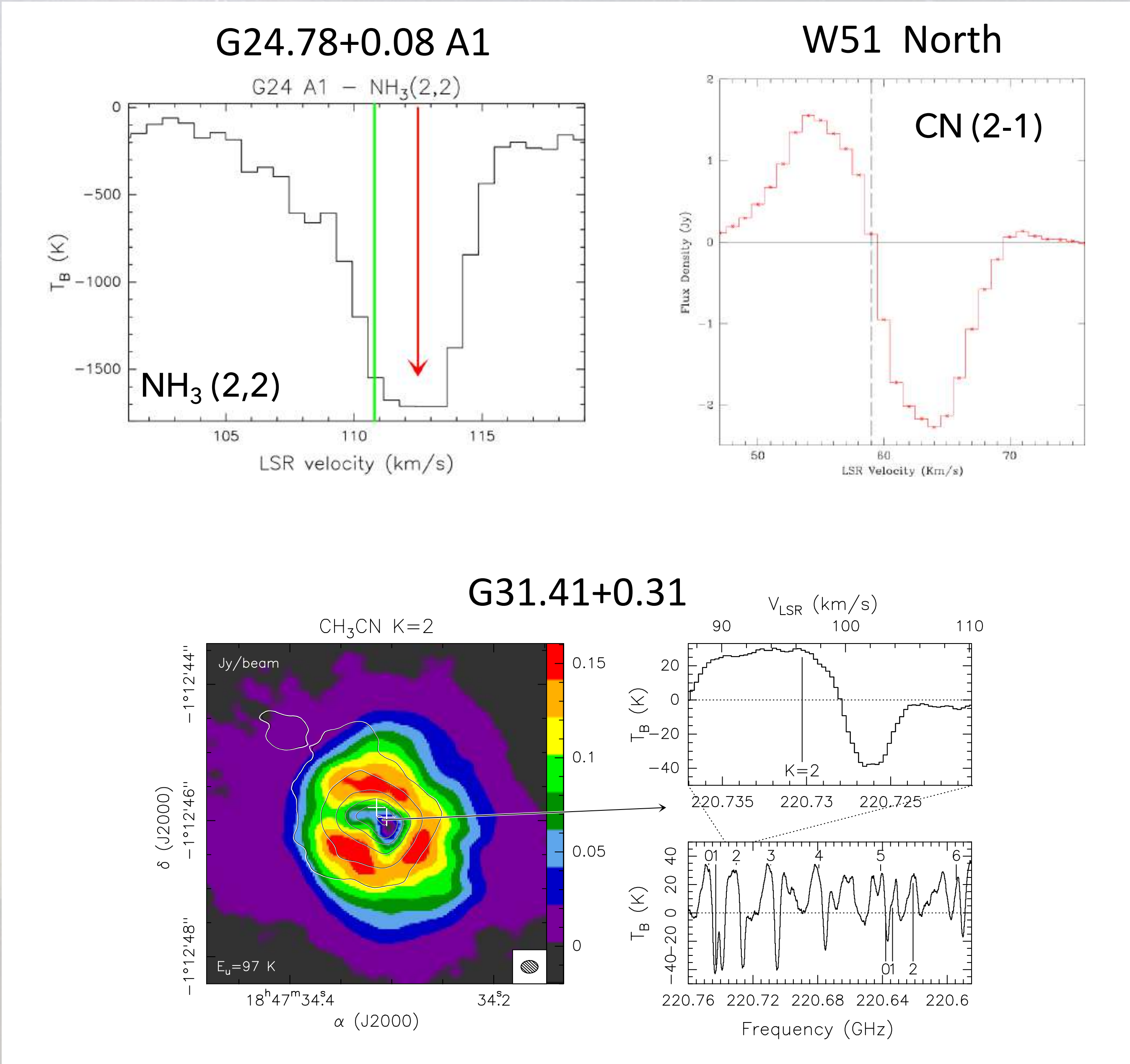
     Since the continuum source (dust or HII region) is very bright (~1000 K) it is easy to observe the colder molecular gas (~100 K) in absorption against it. The absorption is observed at positive velocities relative to the stellar velocity if the material surrounding the (proto)star is infalling onto the central star.

# 7. Deriving properties of disks




infalling
envelope

# 7. Deriving properties of disks



# 7. Deriving properties of disks

## Estimating infall and accretion rates in high-mass YSOs

- Infall rates can be estimated:

  1. From inverse P-Cygni profiles (or red-shifted absorption) towards bright embedded sources

$$\dot{M}_{inf}^{red-abs} = \left(\Omega/_{4\,\pi}\right) 2\,\pi\, m_{H2} N R_0^{1/2} R^{1/2} V_{inf}$$

where $\Omega$ is the solid angle, $N$ is the gas column density, $R_0$ is the radius of the continuum source, $V_{inf}$ is the infall velocity ($V_{inf}$= $|V_{lsr} - V_{redshifted}|$), and $R$ is the radius at which $V_{inf}$ is measured.

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2. Assuming $V_{inf} = V_{rot}$

$$\dot{M}_{inf}^{vrot} = 2\,\pi\,\Sigma\, R\, V_{inf}$$

3. From the free-fall time: Assuming that all the material will collapse in a free-fall time

$$\dot{M}_{inf}^{ff} = \frac{M_{gas}}{t_{ff}}$$

# 7. Deriving properties of disks

Estimating infall and accretion rates in high-mass YSOs

- Accretion rate onto the central star can be estimated from the mass loss rate of the associated outflow. Assuming conservation of the momentum rate of the outflow and of the internal jet entraining the outflow, then $\dot{M}_{out}$ is related to the mass loss rate of the internal jet $\dot{M}_{jet}$ as

$$\dot{M}_{out} = \dot{M}_{jet} \frac{V_{jet}}{V_{out}}$$

- Assuming furthermore a ratio between the jet velocity $V_{jet}$ and the molecular outflow velocity $V_{out}$ of ~20 (e.g., Beuther et al. 2002) and a ratio between $\dot{M}_{jet}$ and the mass accretion rate onto a low-mass protostar $\dot{M}_{acc}$ of approximately 0.3 (following the theory of Tomisaka 1998 and Shu et al. 1999), one finds that

$$6\,\dot{M}_{acc} = 20\,\dot{M}_{jet} = \dot{M}_{out}$$

$$\dot{M}_{acc} = \frac{\dot{M}_{out}}{6}$$