OAA

Astrochemistry with ALMA: Star formation

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NGC 3603

Outline

- Where do stars form?
- Why do stars form?
- How do stars form?

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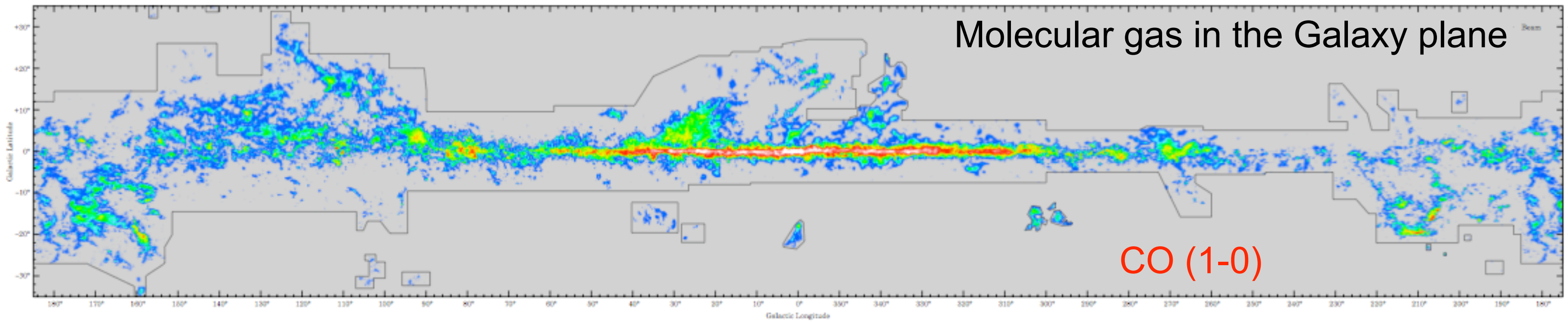
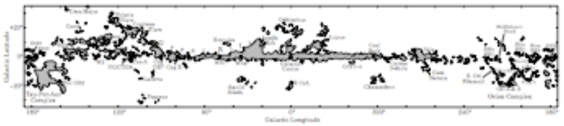
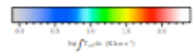
- How do stars form?

Where 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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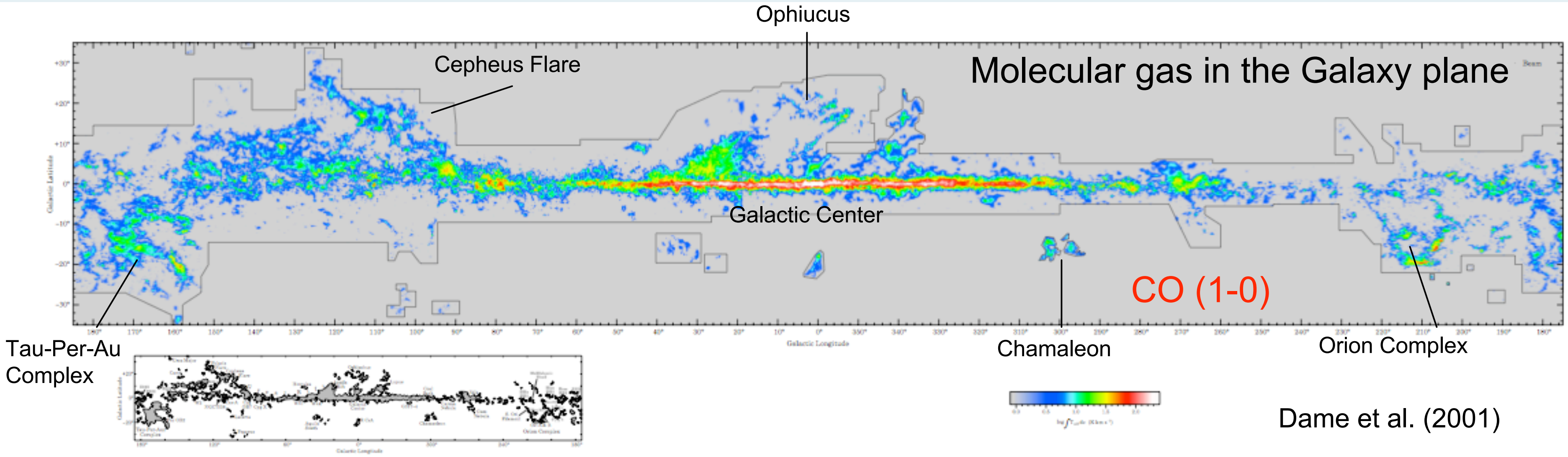

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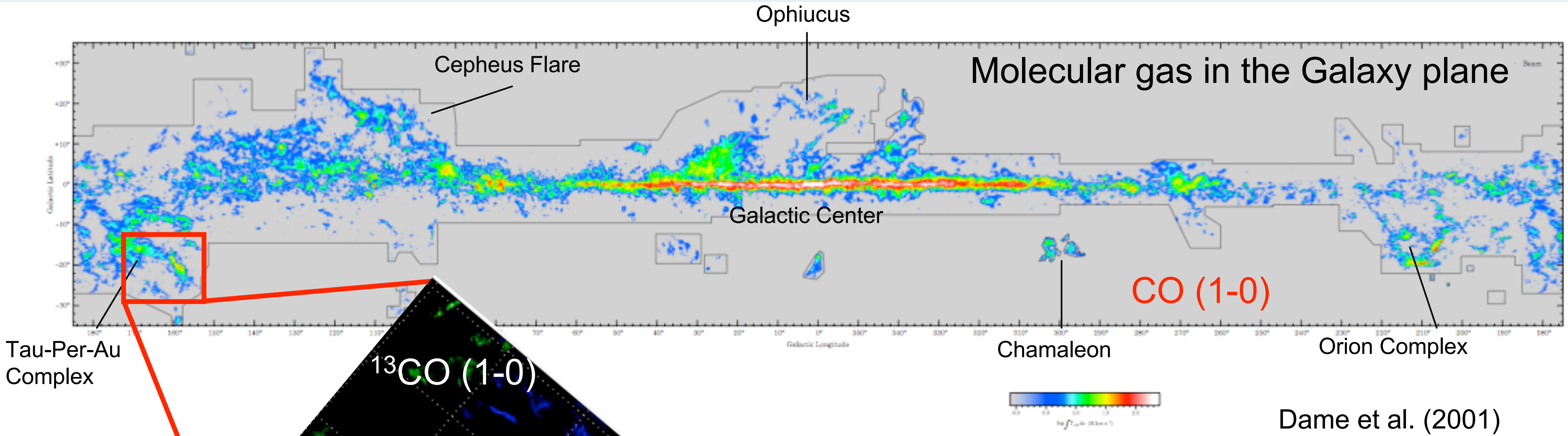

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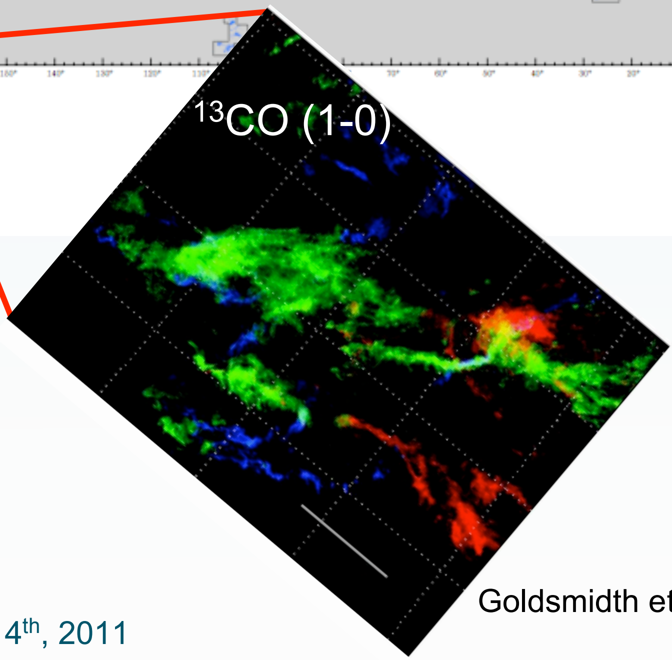
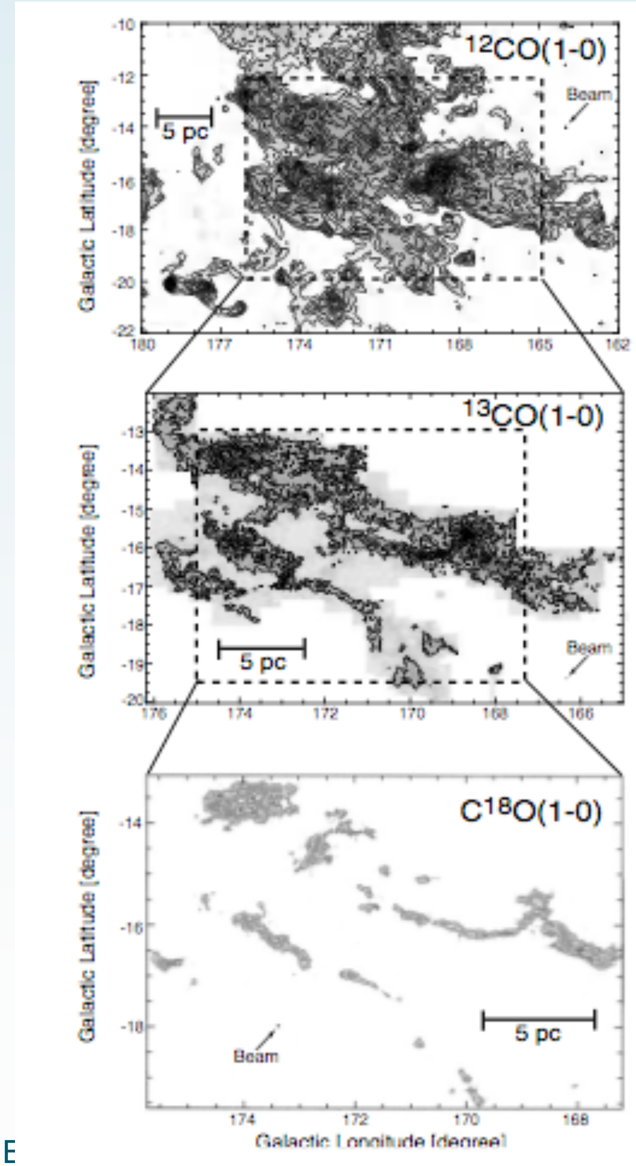


Goldsmidth et al. (2008)

Where do stars form?



- Each of these molecular lines probes a different density regime. Among the three lines shown here, $^{12}CO(1-0)$ probes the lowest, while $C^{18}O(1-0)$ probes the highest density regimes.

- By assuming LTE conditions: $T_k = T_{ex}(CO) = T_{ex}(^{13}CO) = T_{ex}$

  CO optically thick: $\tau^{12} \gg 1$

  ^{13}CO optically thin: $\tau^{13} \lesssim 1$

  Radiative Transfer Eq.: $T_L = [J_\nu(T_{ex}) - J_\nu(T_{BG})](1 - e^{-\tau})$

  where $J_\nu(T) = h\nu/k \,/ (e^{h\nu/kT} - 1)$

➔ T_{ex}, τ^{13}, $N(^{13}CO)$, $N(H_2)$, $M(H_2)$

Megeath et al. (2001)

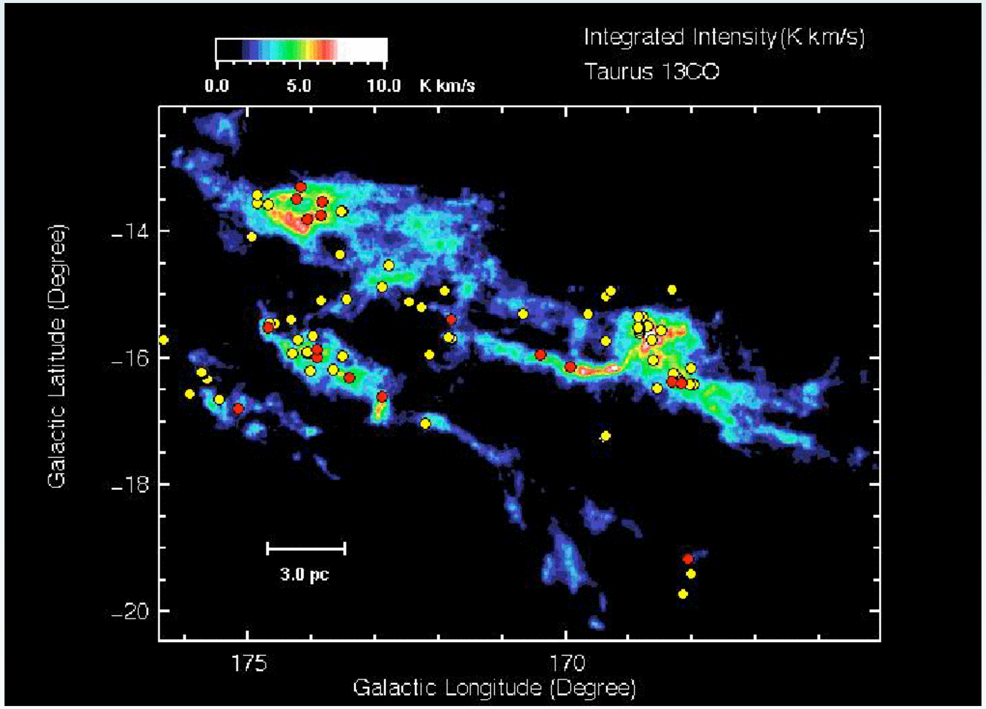
Mizuno et al. (1995)

Onishi et al. (1996)

Where do stars form?

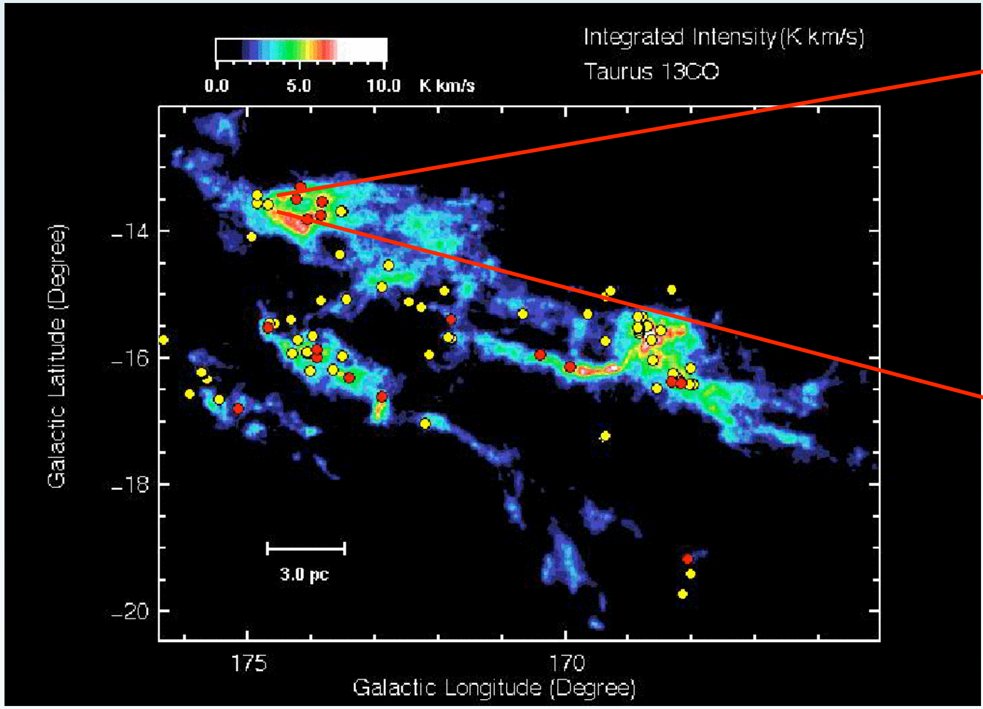
	Giant Molecular Clouds (GMCs)	Small molecular clouds (dark clouds)
Masses ($M_\odot$)	10^5 - 10^6	10^2 -10^3
Densities (cm^{-3})	10^2 - 10^3	10^2 - 10^4
Radii (pc)	10 - 100	2 - 5
Temperatures (K)	10 - 50	10
A_v (mag)	100	1 - 10

Where do stars form?



Mizuno et al. (1995)

Where do stars form?



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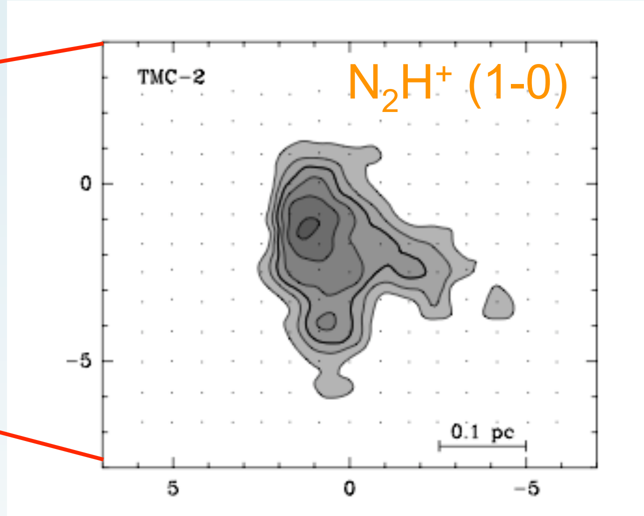
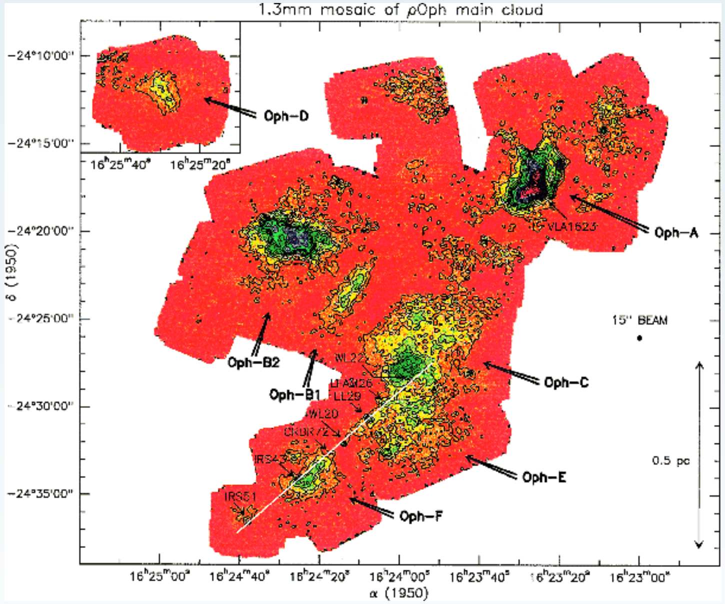


Caselli et al. (2002)

DENSE CORES

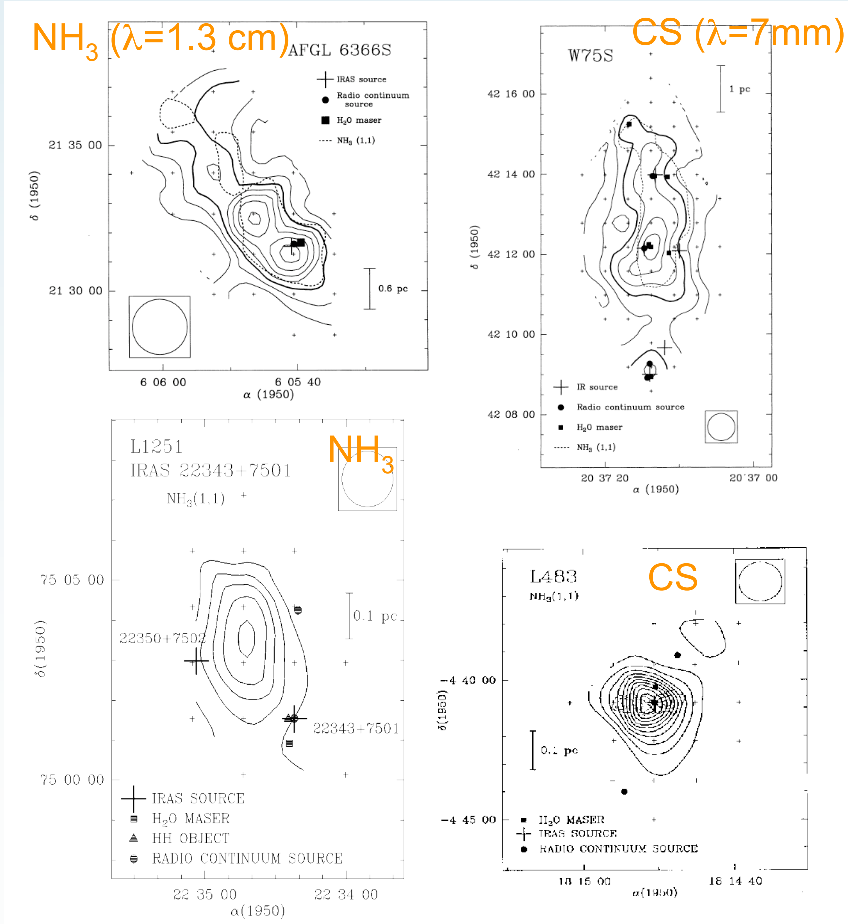
Where do stars form?

- Dust thermal emission at mm and submm λ's



Motte et al. (1998)

- Thermal emission from high-density tracers



Anglada et al. (1997); Morata et al. (1997)

Where do stars form?

	Dense cores in dark clouds	Dense cores in GMCs
Masses ($M_\odot$)	10	10^3
Densities (cm^{-3})	10^4	10^5
Radii (pc)	0.05	0.5
Temperatures (K)	10	20 - 100
Associations	Low-mass stars	OB stars

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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 core 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:

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

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

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

$$E_{tur} = \frac{1}{2}Mv_{tur}^2$$

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

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

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:

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

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

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

Why do stars form?

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

$$M > M_{cr,mag} = \frac{1}{3\pi}\sqrt{\frac{5}{2G}}\Phi \cong 1M_{\Theta}\left[\frac{B}{10\mu G}\right]\left[\frac{R}{0.1pc}\right]^{2}$$

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

❑ Taking into account the Jeans mass

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

the initial conditions to form a star are low temperatures and high densities, typical conditions of most dense cores.

❑ For T=10 K and n=10^4-10^5 cm^{-3}, $M_{cr,th} = M_{Jeans}$ = 1-2 $M_{\odot}$

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  - ➢ Low-mass star formation
  - ➢ High-mass star formation

Low-mass star formation

❑ 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:

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

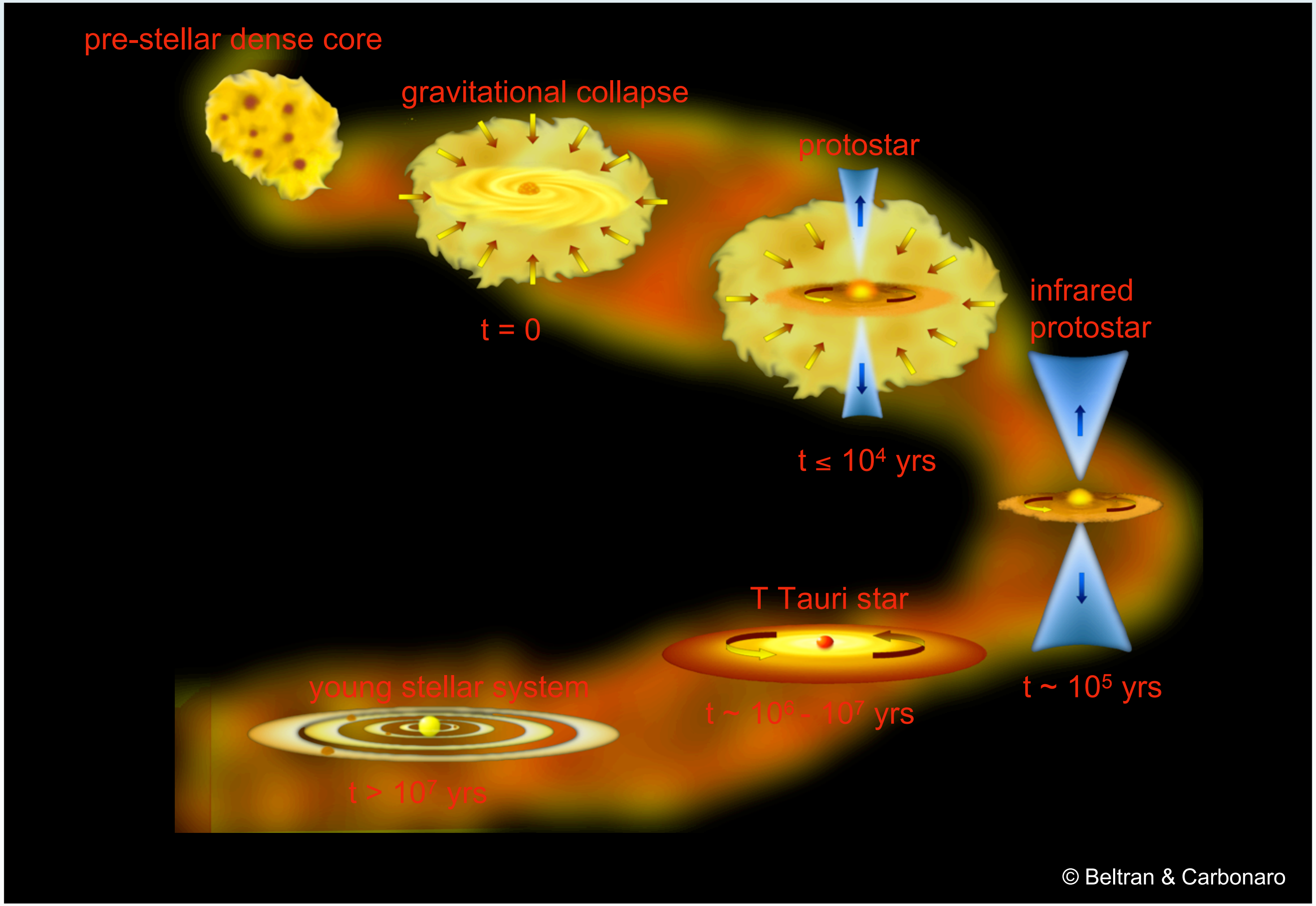
from where one can derive the free-fall velocity and the free-fall time (i.e., the time it takes for the core to collapse into a point):

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

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

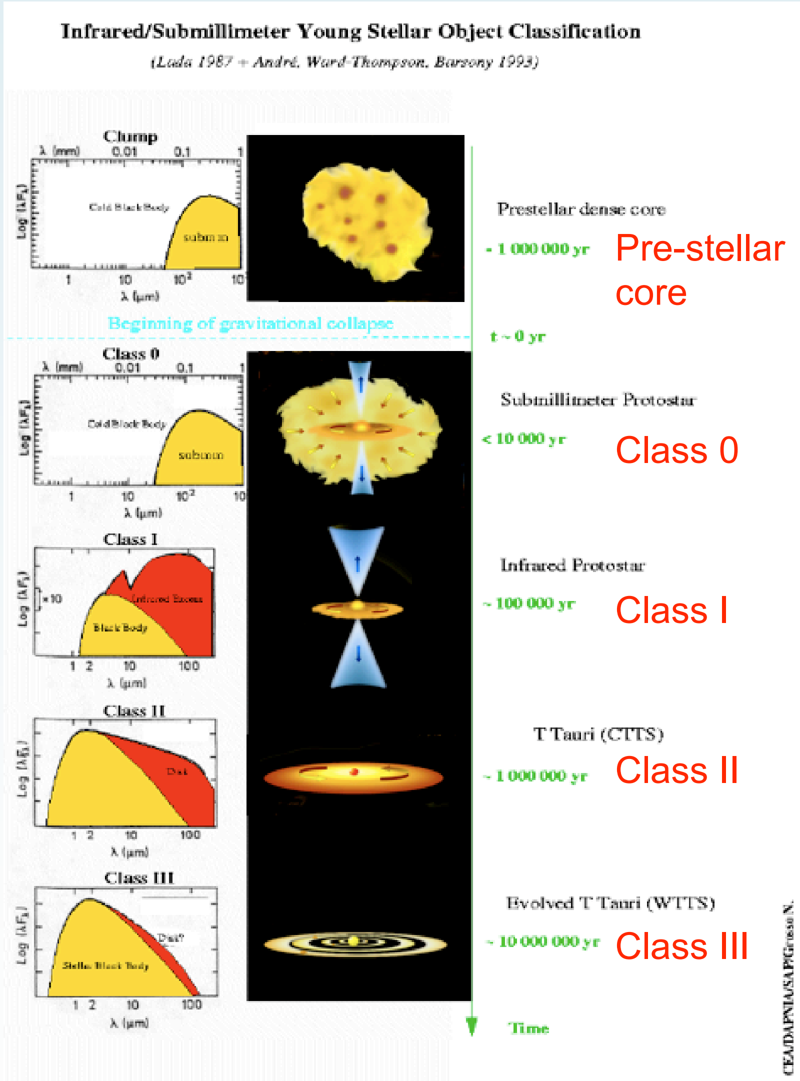
❑ There are many solutions to the collapse problem, which differ in the initial conditions (density profile, rotation or not of the core) they assume: Larson 1969; Penston 1969; Shu 1977; Shu, Adams & Lizano 1987; Foster and Chevalier 1993; Henriksen et al. 1997

Collapse of a slowly rotating core

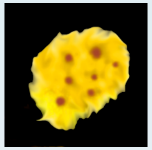


Spectral classification

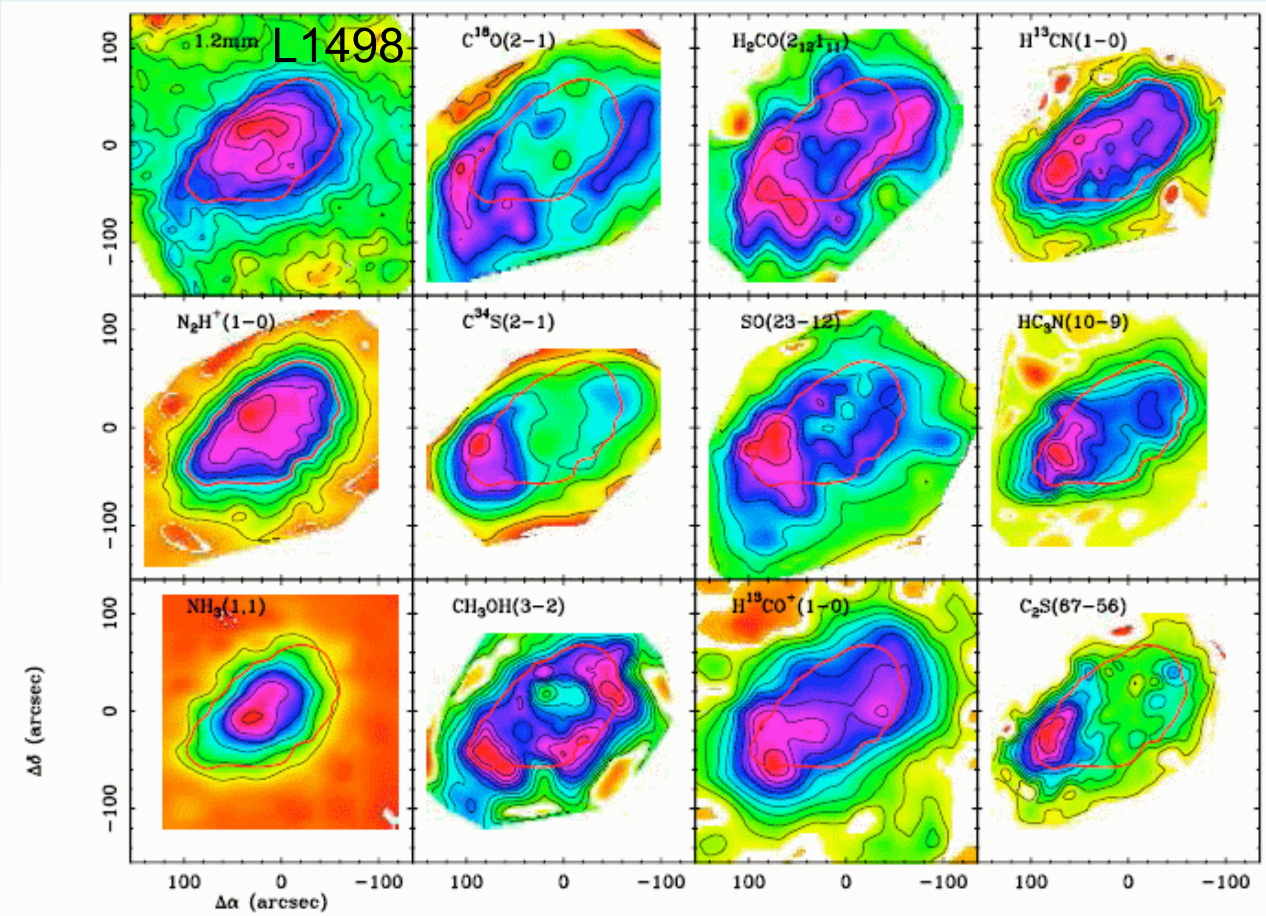
- CLASS 0: Main accretion phase. Most extincted and embedded objects. SED peaks at submm λ's and are not detected shortward of 20 μm. Single blackbody distribution with very low *T*.
- CLASS I: Broader SED than single BB. Longward of 2.2 μm, SED rises with increasing λ, producing a huge IR excess, consistent with a thick circumstellar disk + envelope.
- CLASS II or T Tauri: SED peaks at visible or NIR λ's. Longward of 2.2 μm, SED is flat or decreases. SED shows strong IR excess consistent with optically thick, spatially flat or flared dusty circumstellar disk.
- CLASS III: SED peaks at visible or IR λ's and decreases longward of 2.2 μm. SED consistent with the reddened stellar photosphere of a young star with little or no circumstellar material.



Observational evidences of protostars

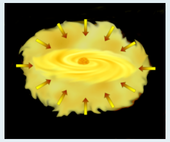


pre-stellar
dense cores



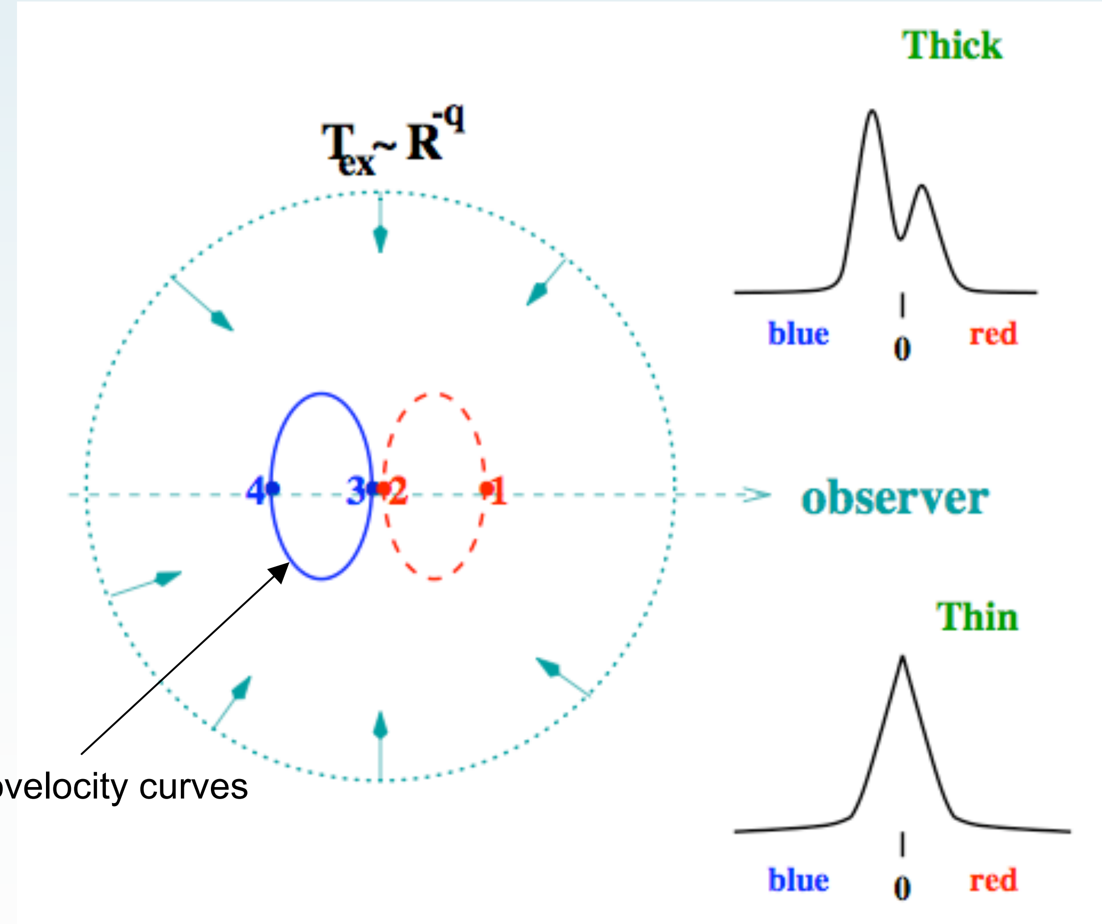
Tafalla (2005)

Observational evidences of protostars



gravitational
collapse
t = 0

❑ Molecular line observations have been used to derive density and velocity profiles in the cores to be compared to the predictions of collapse models



isovelocity curves

emission at Point 2 is absorbed in 1, and the emission in Point 4 is absorbed in 3.
T_{ex} (3) > T_{ex} (1)

all points contribute at the observed emission

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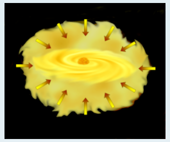

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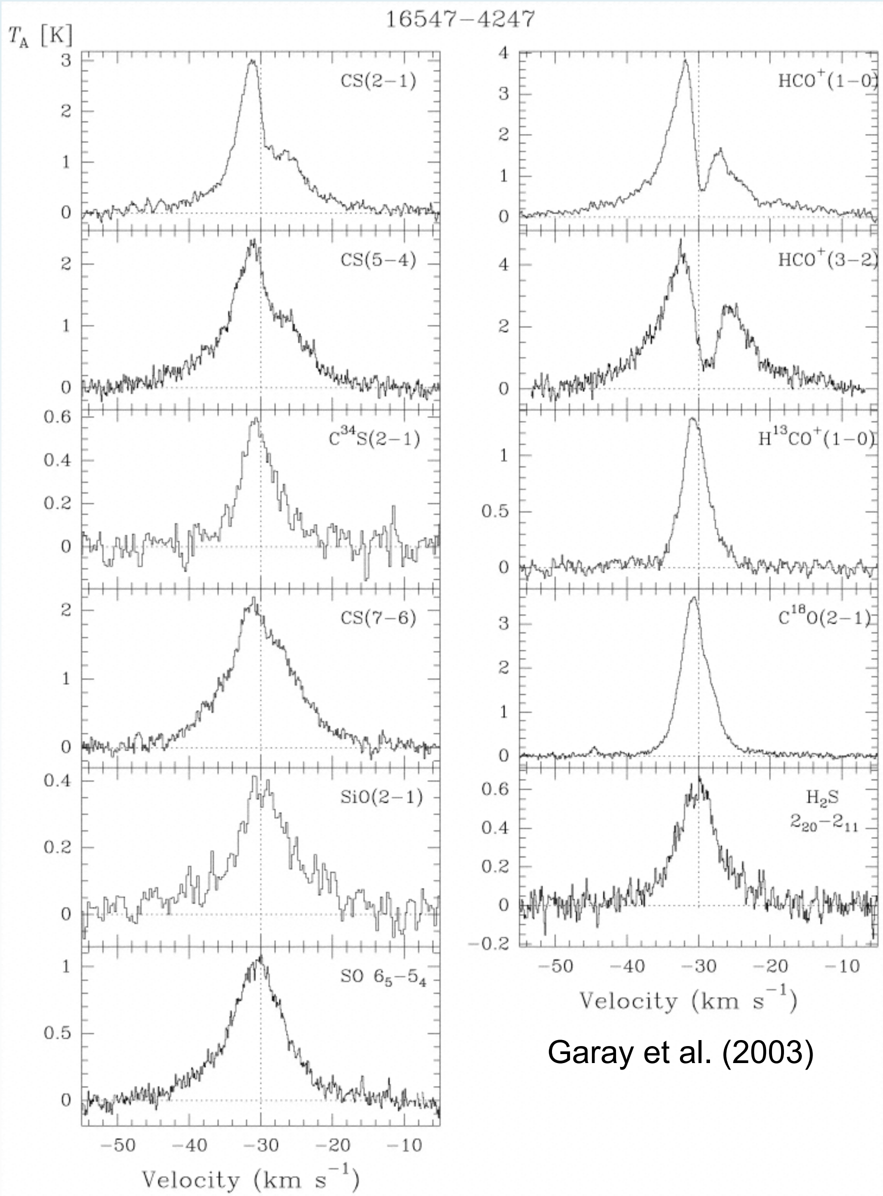

Garay et al. (2003)

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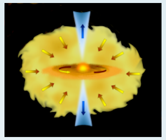
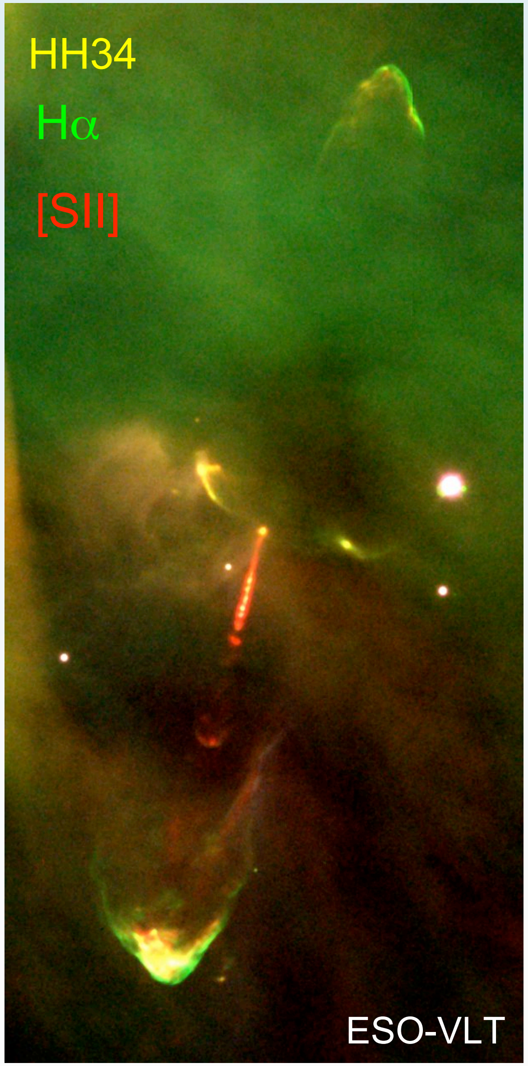
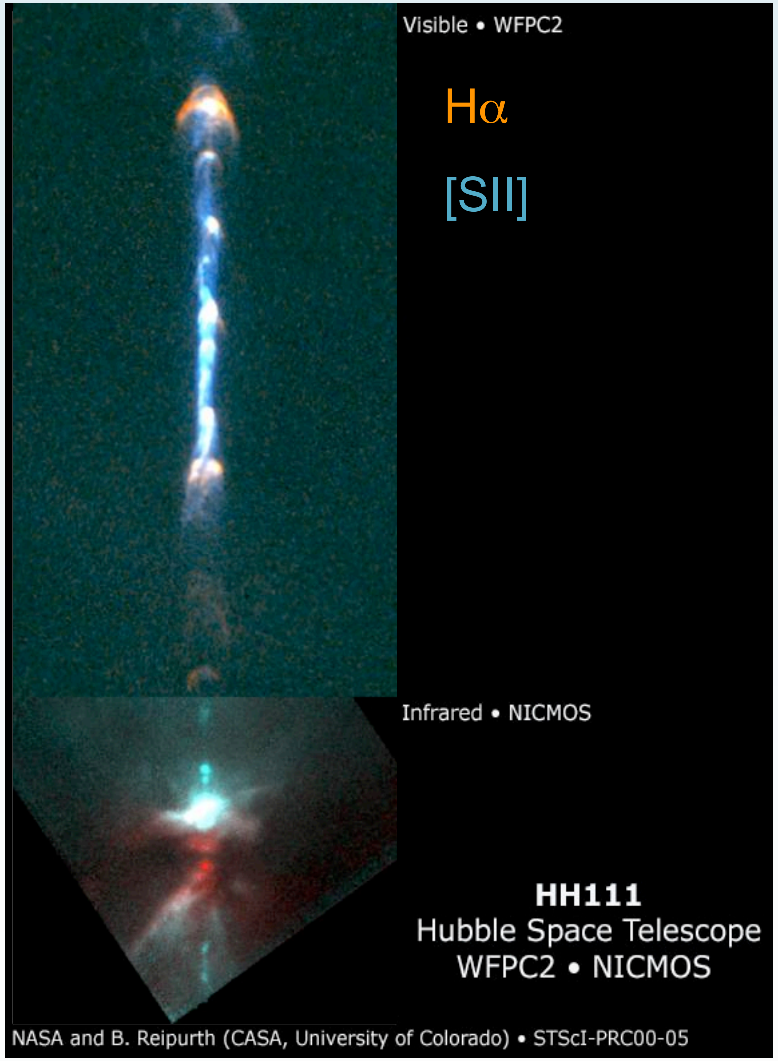


protostar

$t \leq 10^4$ yrs





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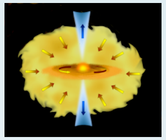

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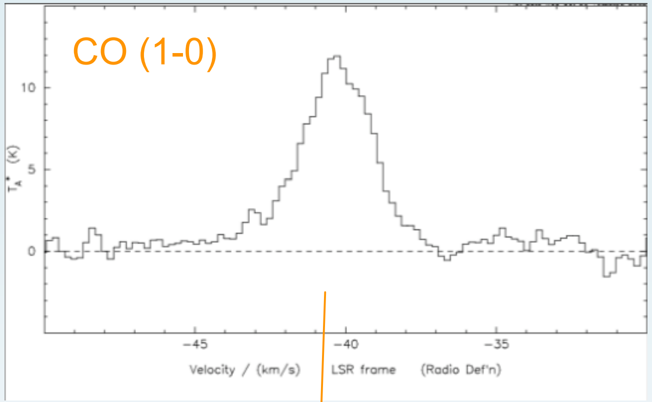

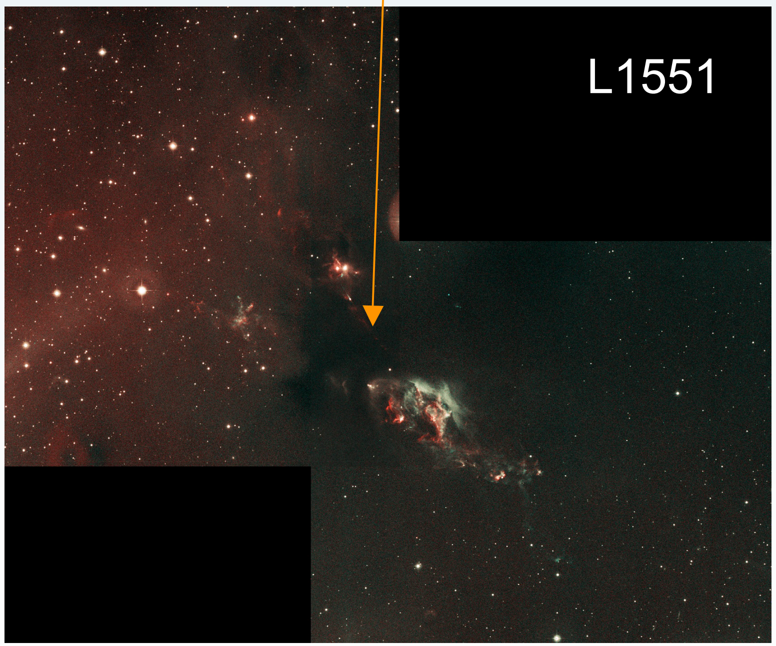

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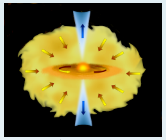

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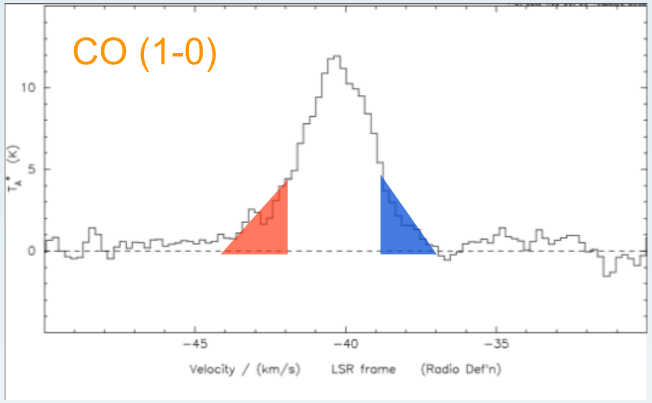
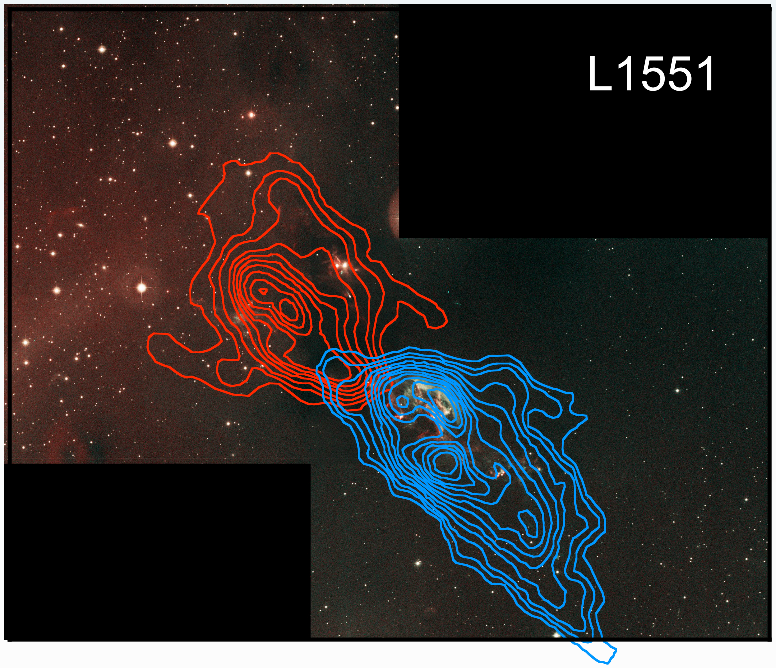
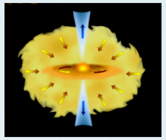




Properties		
Mass	M	3 $M_\odot$
Size of lobes	R	0.5 pc
Velocity	V	25 km/s
Outflow age	$t=R/V$	2 x 10^4 yrs
Kinetic energy	$E_k=1/2MV^2$	10^{45} ergs
Mechanical luminosity	E_k/t	0.1 $L_\odot$

Observational evidences of protostars



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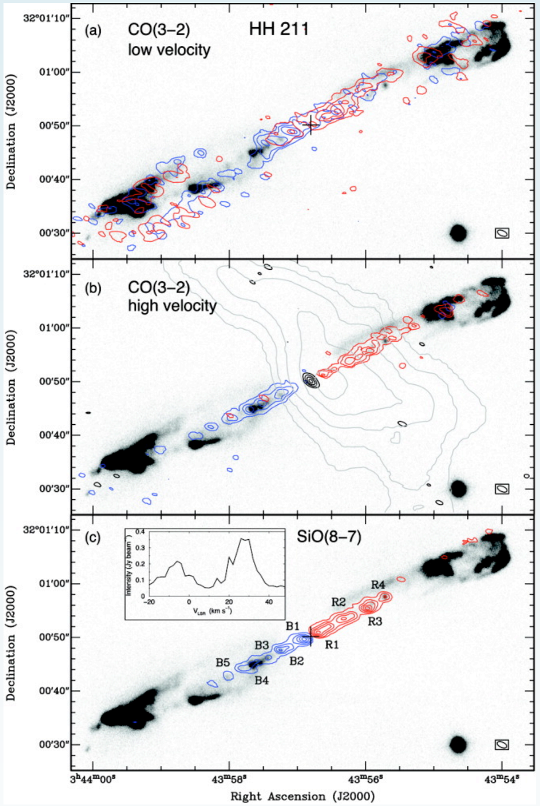
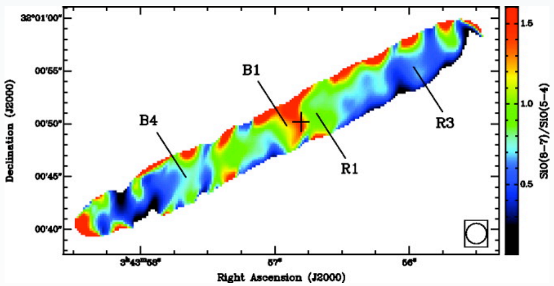
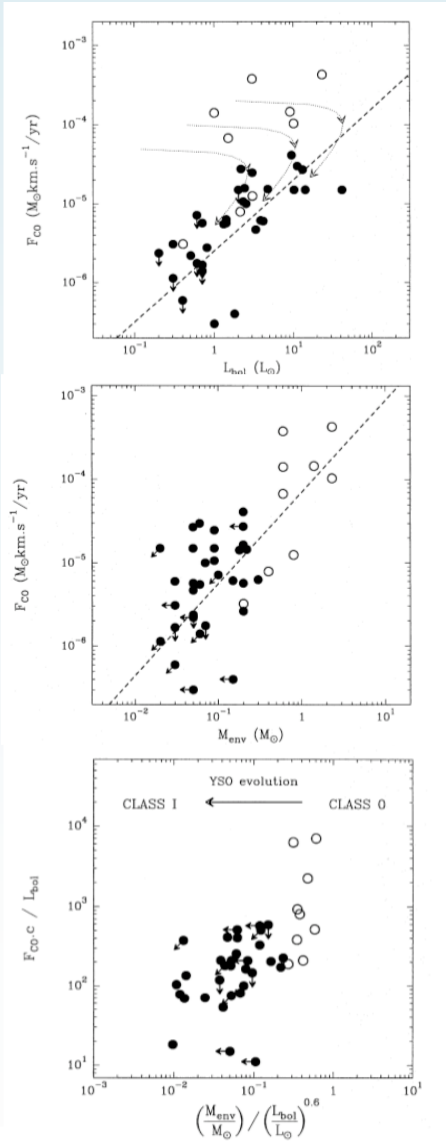




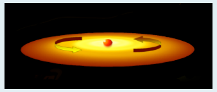
Palau et al. (2006)

- ❑ outflow momentum flux is proportional to the bolometric luminosity of central object
- ❑ outflow momentum flux is proportional to the circumstellar envelope mass
- ❑ decline of outflow activity during accretion phase and decrease of mass accretion/infall rate
- ❑ $\dot{M}_{out} = 20\ \dot{M}_{jet} = 6\ \dot{M}_{acc}$ (V_{jet}/V_{out}= 20: Beuther et al. 2002) and ($\dot{M}_{jet}$ = 0.3 $\dot{M}_{acc}$: Tomisaka 1998; Shu et al. 1999)

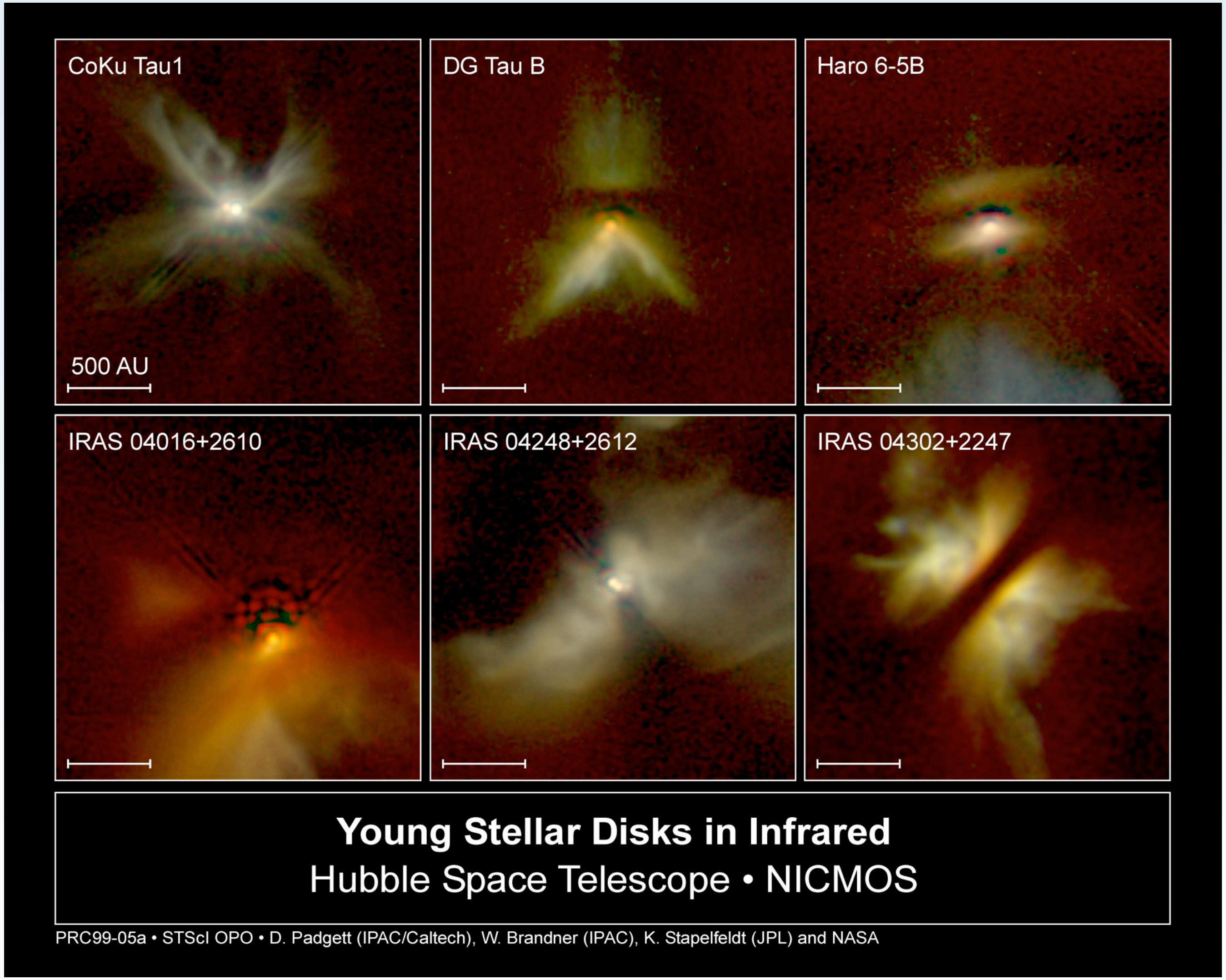


Bontemps et al. (1996)

Observational evidences of protostars

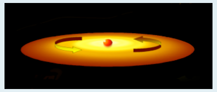


T Tauri
t ~10^6 -
10^7 yrs



Padgett et al. (1999)

Observational evidences of protostars



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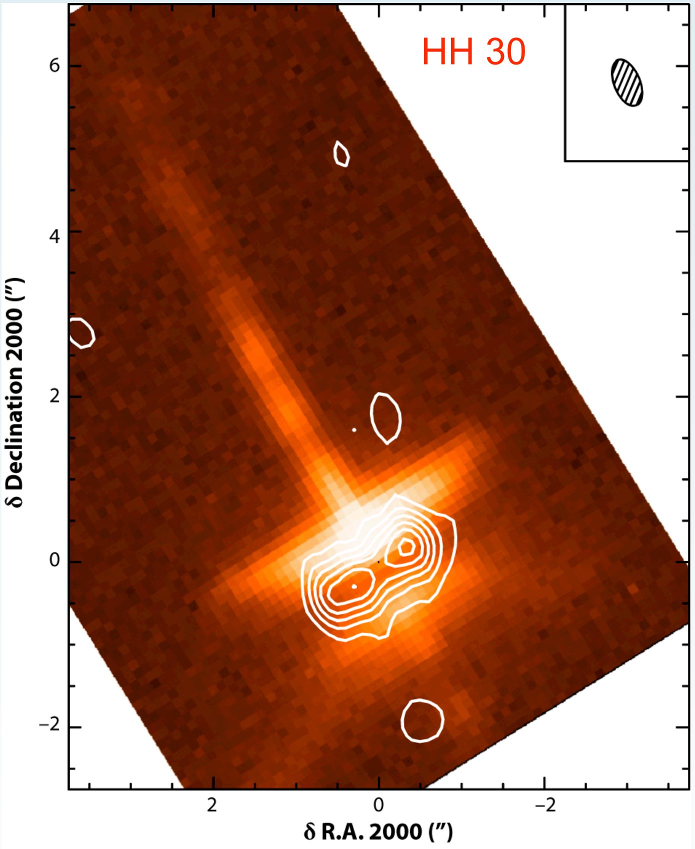
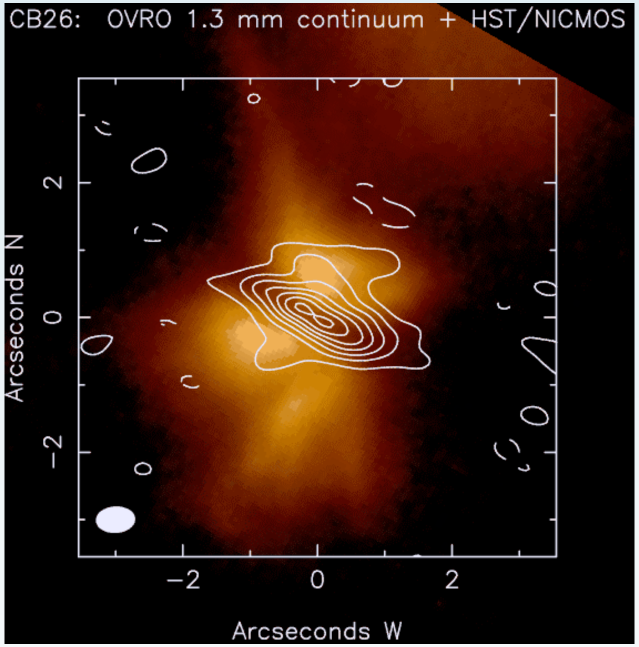
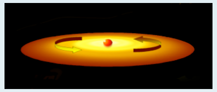


Chiang E, Youdin AN. 2010.
Annu. Rev. Earth Planet. Sci. 38:493–522



Sauter et al. (2009)

Observational evidences of protostars



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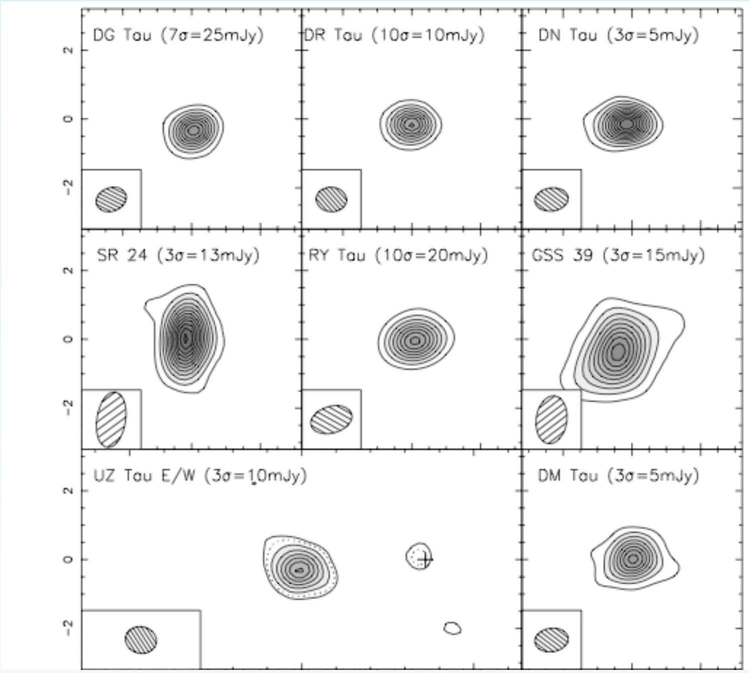


Isella et al. (2009)

Properties		
Mass	M	0.003-0.3 $M_\odot$
Inner radius	R_{inn}	1 to few R_*
Mass accretion rate	$\dot{M}$	10^{-8} $M_\odot$ /yr
Outer Radius	R_{out}	100 AU

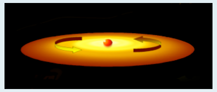
Natta (2000)

Table 4
Dust Properties

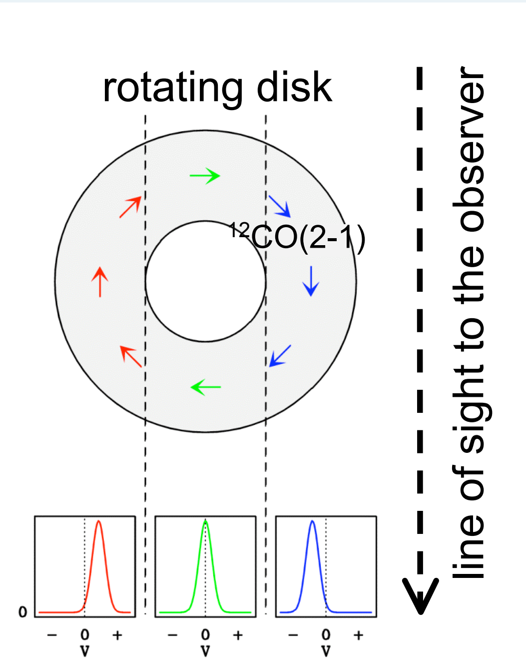
Object	α	β	$a_{max} = 100$ mm		$q = 3$	
			q	$k_{1.3}$[a]	a_{max}[b]	$k_{1.3}$[a]
CY Tau	2.6	0.7	3.5	0.6	1	3.9
DG Tau	2.3	0.5	3.1	0.2	22	0.39
DM Tau	2.9	1.1	4.0	1.8	0.16	6.6
DN Tau	2.7	0.8	3.7	1.2	0.55	5.6
DR Tau	2.4	0.6	3.3	0.3	1.9	2.6
GO Tau	3.4	1.5	4.5	0.4	0.13	6.8
LkCa15	3.5	1.7	4.7	0.3	0.13	6.8
RY Tau	2.5	0.7	3.5	0.6	1.0	3.9
UZ Tau E	2.6	0.7	3.5	0.6	1.0	3.9
GM Aur	3.1	1.3	4.2	1.1	0.14	6.7
GSS 39	2.8	0.9	3.8	1.6	0.3	7.4
SR 24	2.6	1.1	4.0	1.8	0.16	6.6
TW Hya	2.5	0.8	3.6	0.9	0.55	5.6
MWC 275	2.9	1.0	3.9	1.9	0.185	7.0

Isella et al. (2009)

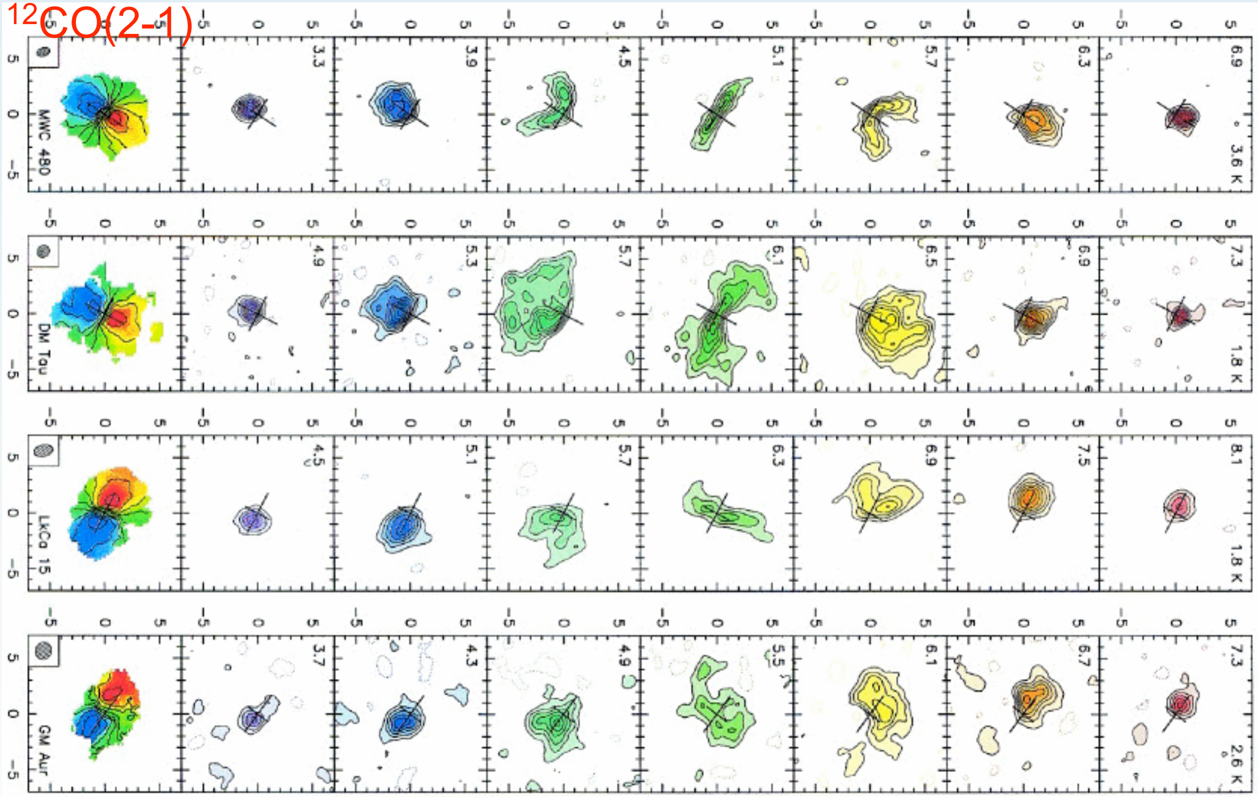
Observational evidences of protostars



T Tauri
t ~10^6 - 10^7 yrs



Courtesy of R. Cesaroni



Simon et al. (2000)

- Derive disk parameters: T_k, M_{gas}
- Velocity field: if ROTATION then velocity gradient along the major axis
- $v(r) = \sqrt{(G M_*/r)} * \sin(i)$ → Direct measurement of stellar M_*

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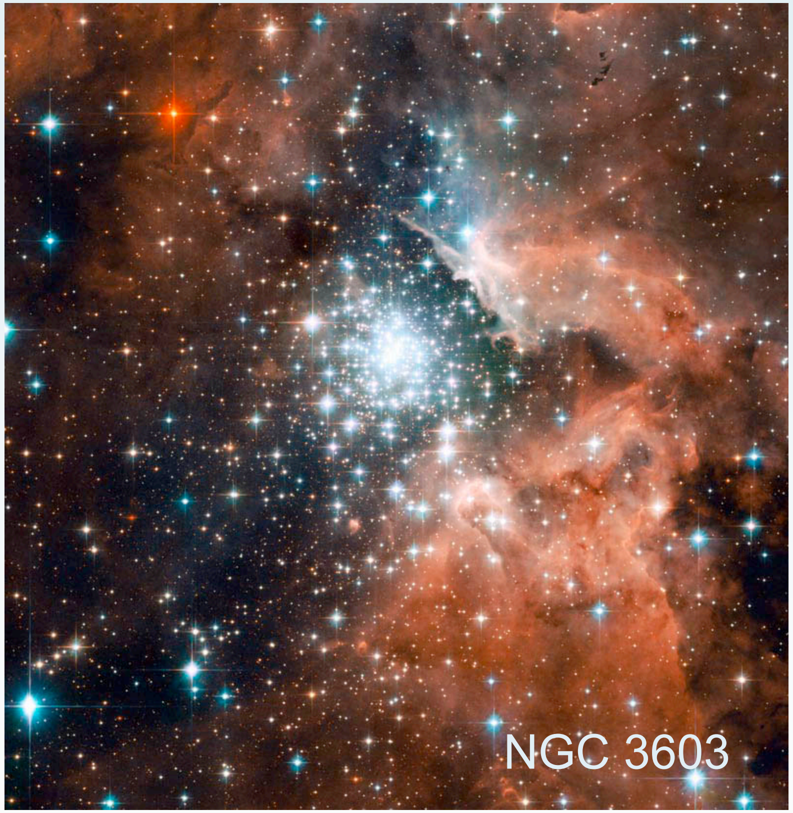
  - High-mass star formation

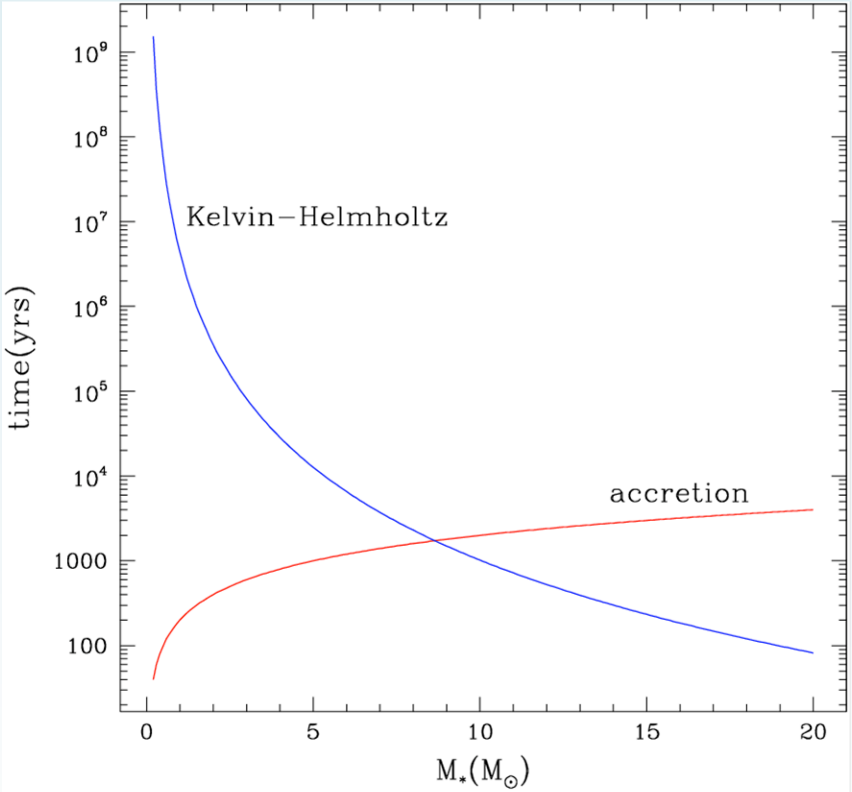
High-mass star formation



- Massive stars are rare objects: for each 10 $M_\odot$ formed, a hundred 1 $M_\odot$ stars are formed.
- Rare objects than statistically form at large distances ➔ 4 kpc
- Massive stars form in clusters: only 4±2% of O-field stars are formed outside clusters (de Wit et al. 2006)
- Difficult to trace the primordial configuration of the molecular cloud

HIGH ANGULAR RESOLUTION AT (SUB)MM λ's IS A PRE-REQUISITE

Low-mass versus high-mass scenario



- Two relevant timescales in SF:
  i. accretion t_{acc} = $M_*/(dM/dt)$
  ii. contraction t_{KH} = GM_*/R_*L_*

- Low-mass (< 8 $M_\odot$): evolution dominated by accretion timescale: $t_{acc} < t_{KH}$
  ➡ Pre-main sequence

- High-mass (> 8 $M_\odot$): evolution dominated by the KH timescale: $t_{acc} > t_{KH}$
  ➡ No pre-main sequence, accretion on ZAMS

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

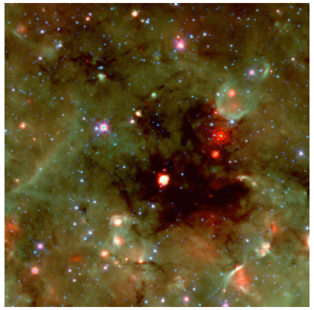
Low-mass versus high-mass scenario

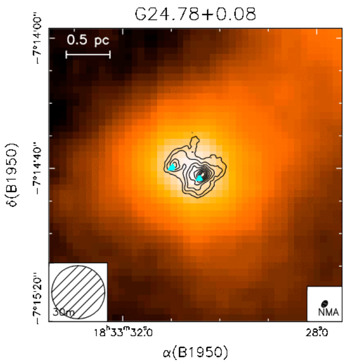
❑ COMPETITIVE ACCRETION: Bonnell & Bate (2002) predict that clouds fragment initially into cores of a Jeans mass of ~0.5-1 $M_{\odot}$. These cores subsequently form low-mass stars that accrete the distributed gas in the molecular clump. Protostars located near the center of the gravitational potential accrete at a higher accretion rate because of a stronger gravitational pull, and thus experience a faster mass growth

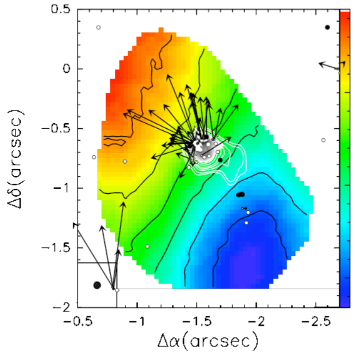
❑ CORE ACCRETION: McKee & Tan (2002) propose a turbulent accretion model, in which stars form via a monolithic collapse of a molecular cloud. The heating from the embedded protostars increases the gas temperature, and thus the Jeans mass (100 $M_{\odot}$: Krumholz et al. 2007). The model predicts that massive cores fragment weakly, so one should never find a massive core that has converted a significant fraction of its mass in low mass stars

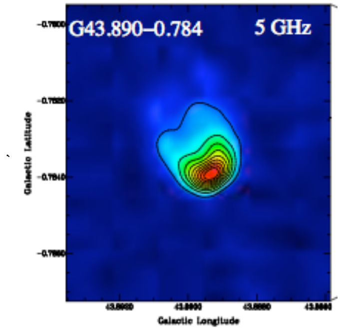
Evolutionary sequence for high-mass stars

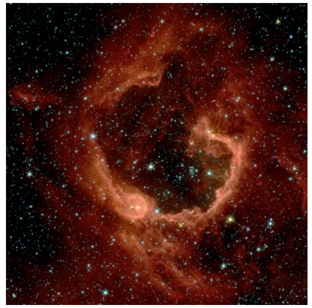
IR-dark cloud **Hot molecular core** **HC HII** **UC HII** **Extended HII**











fragmentation *Infall+rotation +outflow* *accretion* *expansion*

Infrared dark clouds

- Massive stars form in parsec scale high-density clumps (10^4 to 10^5 cm^{-3}) within Giant Molecular Clouds (GMCs) (density of order 100-1000 cm^{-3}) ➔ IR-Dark Clouds (IRDCs)

- IRDCs are detected in absorption at 8 μm and up to 24 μm (70 μm) with Spitzer, MSX, Herschel (Egan et al. 1998, Carey et al. 1998)

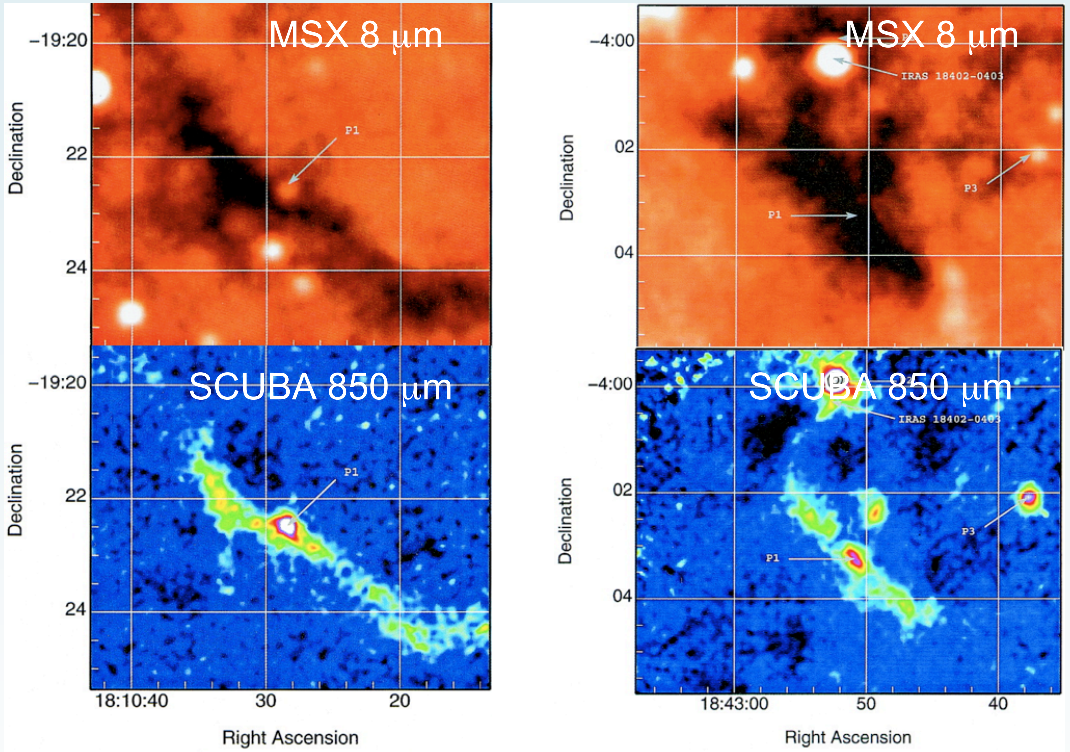
- At submillimeter and millimeter λ's are seen in emission.

- IRDCs have sizes 1-5 pc

  $M \sim 10^3 - 10^4 M_\odot$

  $n \sim 10^5$ cm^{-3}

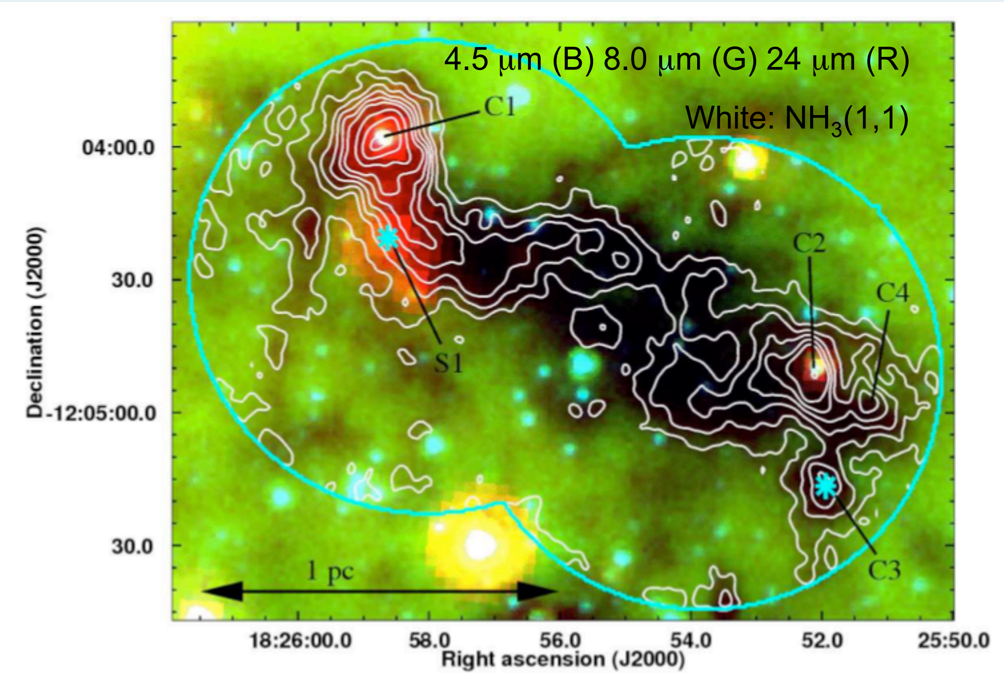
  $T < 20$ K



Carey et al. (2000)

Infrared dark clouds: early phase chemistry

- Recent works have started to study the chemical properties of IRDCs to compare them with HMPOs and low-mass pre-stellar cores:



Devine et al. (2011)

Species	Transition	E_l^a (K)	ν (MHz)
NH_3	$(J, K = 1, 1)$	22.70	23 694.496
NH_3	$(J, K = 2, 2)$	63.89	23 722.633
NH_2D (para)	$1_{11}-1_{01}$	16.55	85 926.3
NH_2D (ortho)	$1_{11}-1_{01}$	15.98	110 153.6
NHD_2 (ortho)	$1_{10}-1_{01}$	13.33	110 812.9
NHD_2 (para)	$1_{10}-1_{01}$	13.09	110 896.7
$C^{18}O$	$J = 1-0$	0.0	109 782.1734
$C^{18}O$	$J = 2-1$	5.27	219 560.3568
$C^{17}O$	$J = 2-1$	5.39	224 714.3850
$H^{13}CN$	$J = 1-0, F = 2-1$	0.0	86 340.184
$HC^{15}N$	$J = 1-0$	0.0	86 054.961

Note: ^{a} E_l is the lower energy level of the transition.

Pillai et al. (2007)

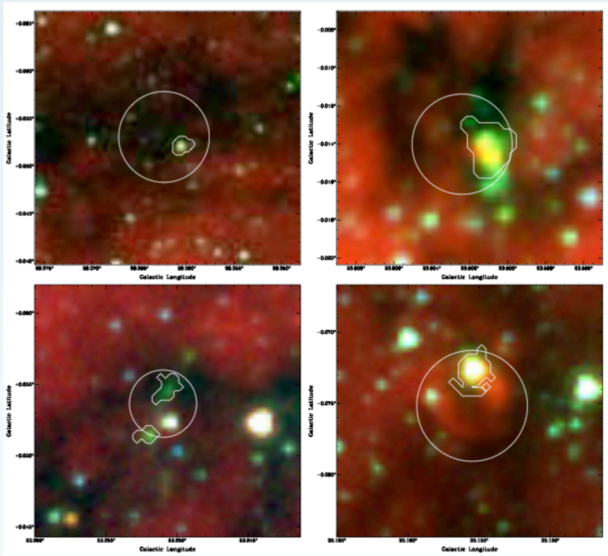
Single dish observations that ALMA can do easily even at early science

Infrared dark clouds: SF activity

- Many of these cores show evidence for active star formation including:

1. Enhanced, slightly extended 4.5 μm emission, the so-called "green-fuzzies", which indicates shocked gas, and broad spectral lines of SiO (Jiménez-Serra et al. (2010):

- IRAC 3-color (8.0 μm: red, 4.5 μm: green, 3.6 μm: blue)



Chambers et al. (2009)

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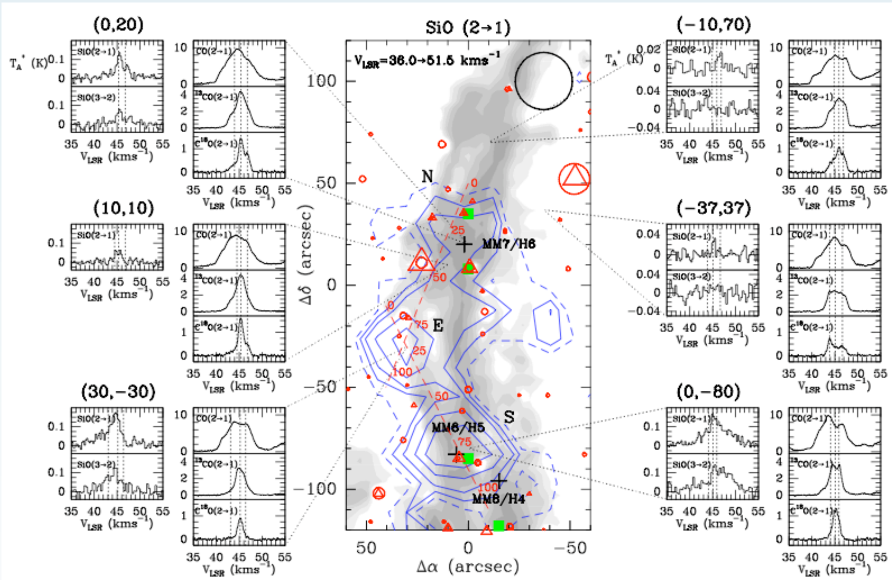
1. Enhanced, slightly extended 4.5 μm emission, the so-called "green-fuzzies", which indicates shocked gas, and broad spectral lines of SiO (Jiménez-Serra et al. (2010):

   ❑ i) by a large-scale shock, perhaps remnant of the IRDC formation process; ii) by decelerated or recently processed gas in large-scale outflows driven by 8 μm and 24 μm sources; or iii) by an undetected and wide spread population of lower mass protostars.

Blue - SiO

G035.39-00.33



Jiménez-Serra et al. (2010)

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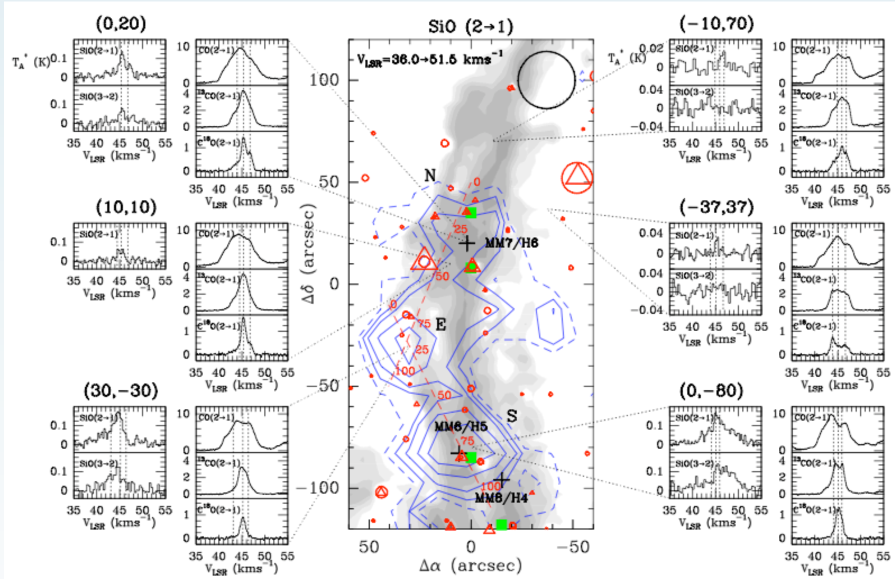
2. Bright, 8 μm (red sources) or 3.6 μm (blue sources) emission, or 24 μm (deeply embedded protostars):

   ❑ Red cores: are probably HII regions, ionized by OB stars which formed within the IRDC.

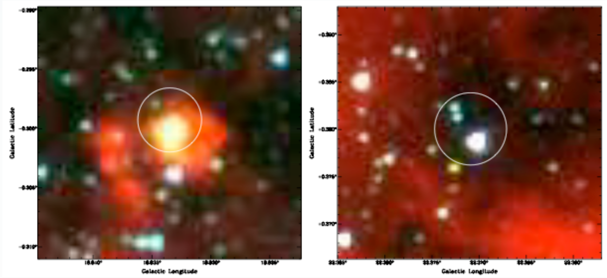
   ❑ Blue cores are predominantly unextincted stars

Blue - SiO

G035.39-00.33



Jiménez-Serra et al. (2010)



Chambers et al. (2009)

Hot molecular cores

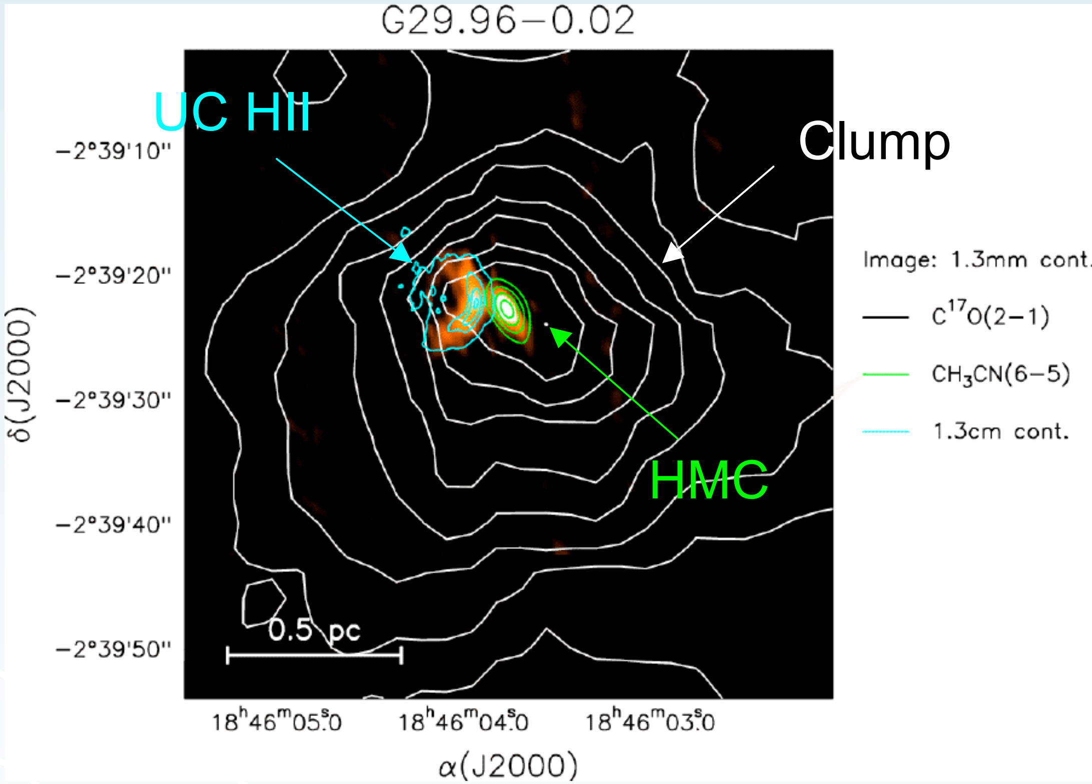
- Hot molecular cores, the cradles of OB stars, have sizes <0.1 pc

  T >100 K

  $n \sim 10^7$ cm^{-3}

  $L > 10^4 L_\odot$

- Sometimes associated with embedded HC / UC HII regions



Hot molecular cores

- Hot molecular cores, the cradles of OB stars, have sizes <0.1 pc

  T >100 K

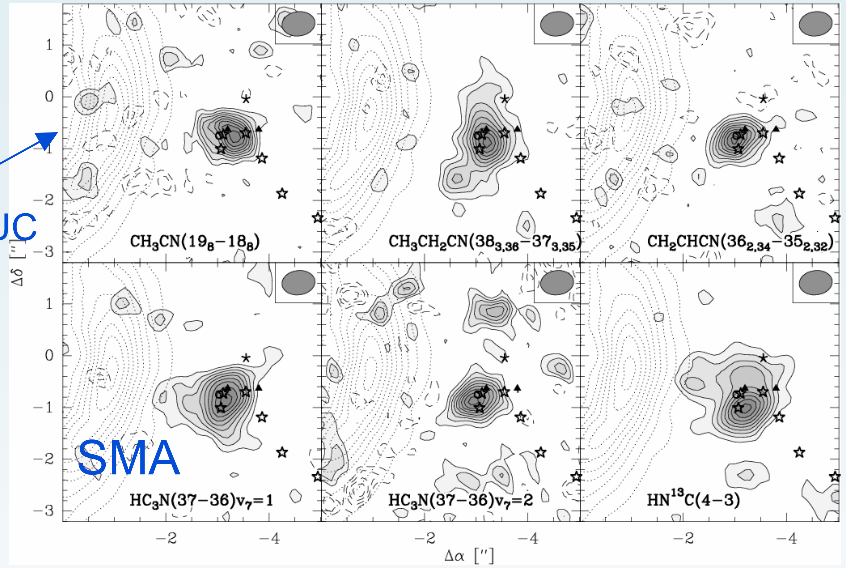
  n~10^7 cm^{-3}

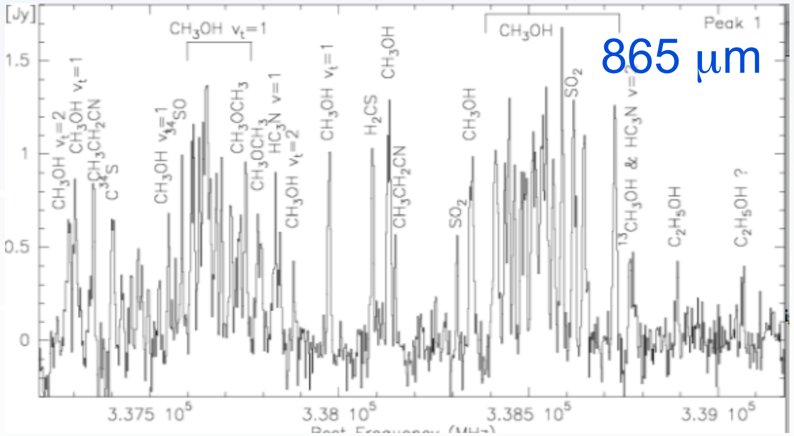
  L >10^4 $L_\odot$

- Sometimes associated with embedded HC / UC HII regions
- Rich chemistry : evaporation of dust grain mantles
- Associated with outflow, infall, and rotation

G29.96-0.02

cometary UC HII region

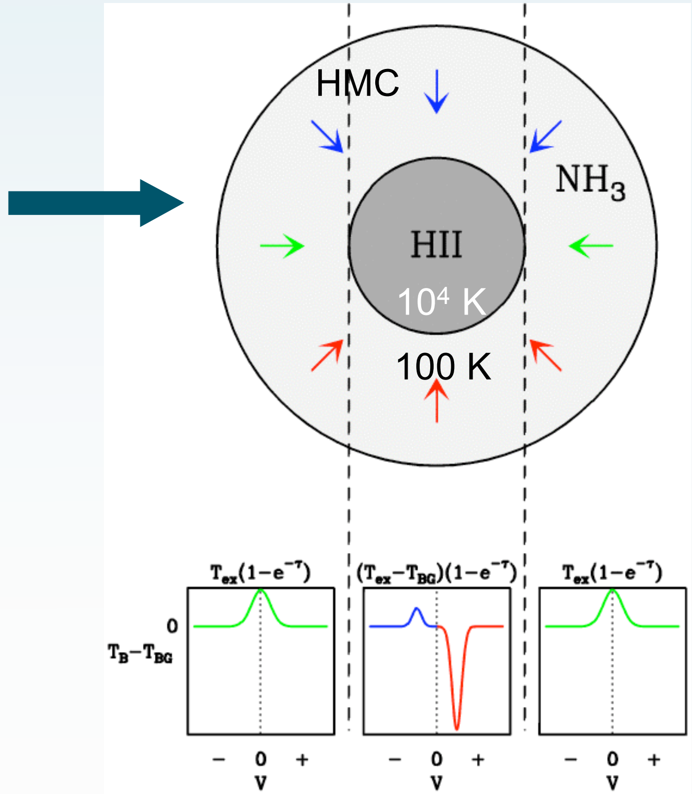




Beuther et al. (2007)

Hot molecular cores: infall

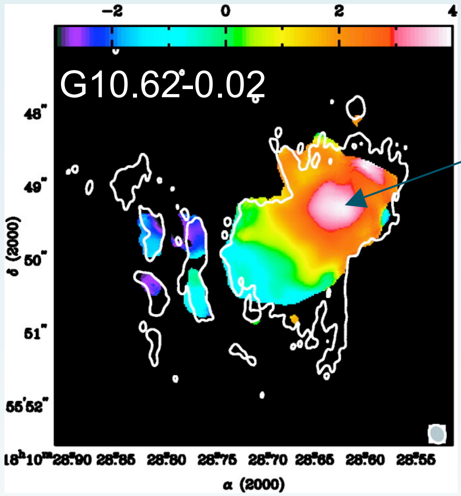
- Important to test models for OB star formation, but difficult to detect/recognize: e.g. line broadening towards star may be due to optical depth and/or turbulence
- Few direct detections of gas infall towards massive YSOs.
- Inverse P-Cygni profiles (or red-shifted absorption) towards bright embedded sources have been detected:
  - hypercompact HII regions (very bright at cm λ's) as for G10.62 (Keto et al. 1988; Sollins 2005) or G24.78 A1 (Beltran et al. 2006)
  - a strong compact millimeter source as for W51 North (Zapata et al. 2008), G31.41+0.31 (Girart et al. 2009; Frau et al., in preparation), G19.61-0.23 (Wu et al. 2009)



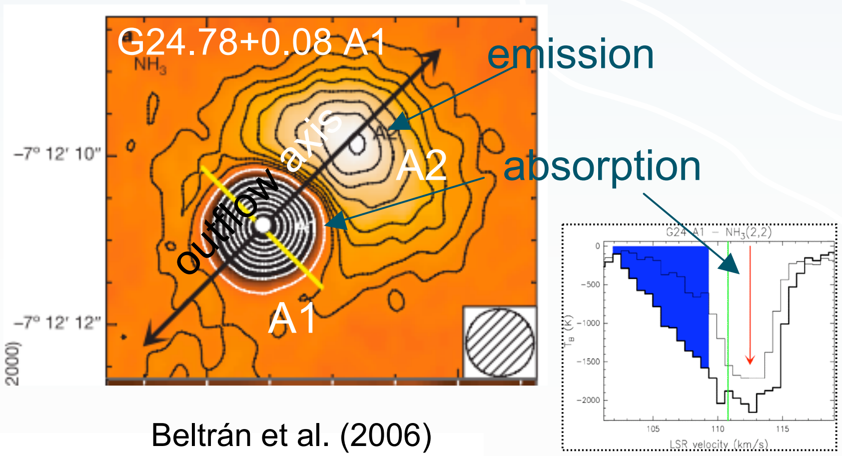
Courtesy of R. Cesaroni

Hot molecular cores: infall

❑ NH_3 absorption against HII region

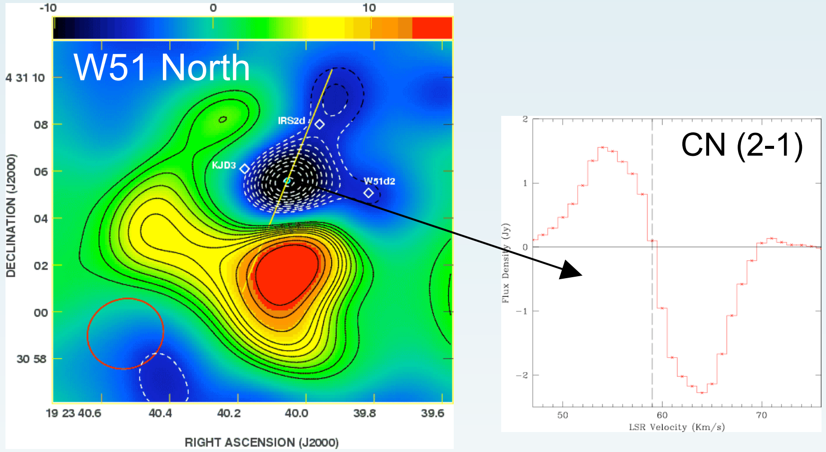


Sollins et al. (2005)

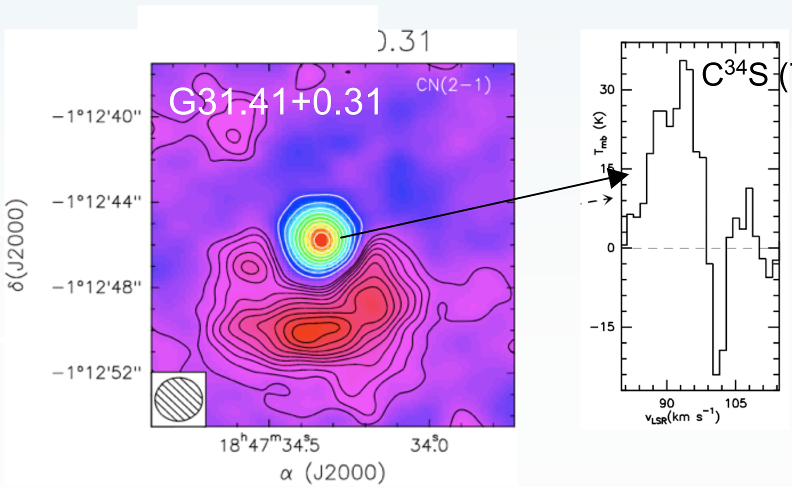


Beltrán et al. (2006)

❑ Absorption against strong mm source



Zapata et al. (2008)



Girart et al. (2009); Frau et al. in preparation

Hot molecular cores: infall

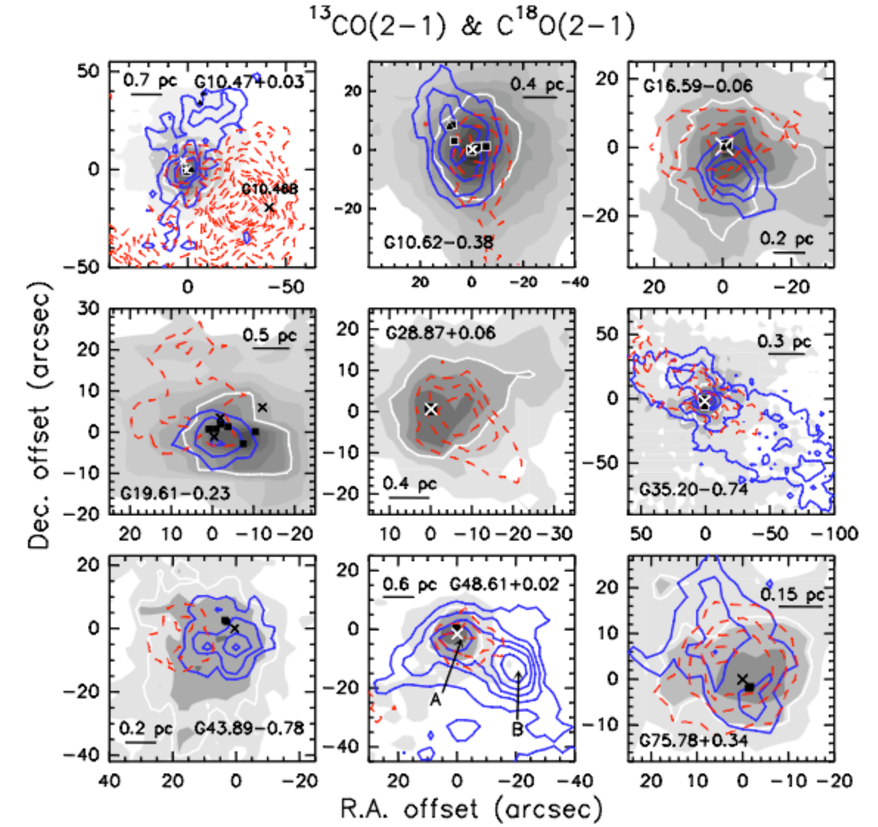
HMC	$M_{core}(M_\odot)$	R (pc)	V_{infall} (km/s)	Infall rate ($M_\odot$/yr)
G10.62-0.38	82	0.02	4	3×10^{-3}
G24.78+0.08 A1	130	0.02	2	4×10^{-4} - 10^{-2}
W51 North	90	0.07	4	4×10^{-2} - 7×10^{-2}
W51e2	140	0.01	3.5	6×10^{-3}
G31.41+0.31	490	0.04	3.1	3×10^{-3} - 3×10^{-2}
G19.61-0.23	415	0.03	4	$>3\times10^{-3}$

- The infall rates estimated are very high, probably sufficient to quench the formation of an UC HII region and allow the formation of an O-type star.

- For G24.78 A1 the rate needed for the ram pressure to overcome the thermal pressure of the HII region is ~2×10^{-4} ($M_\odot$/yr) → Infall rate is large enough to brake or slow down the expansion of the HII region (Beltrán et al. 2006). This conclusion is strengthened if one takes into account the effect of stellar gravity.

Hot molecular cores: outflow

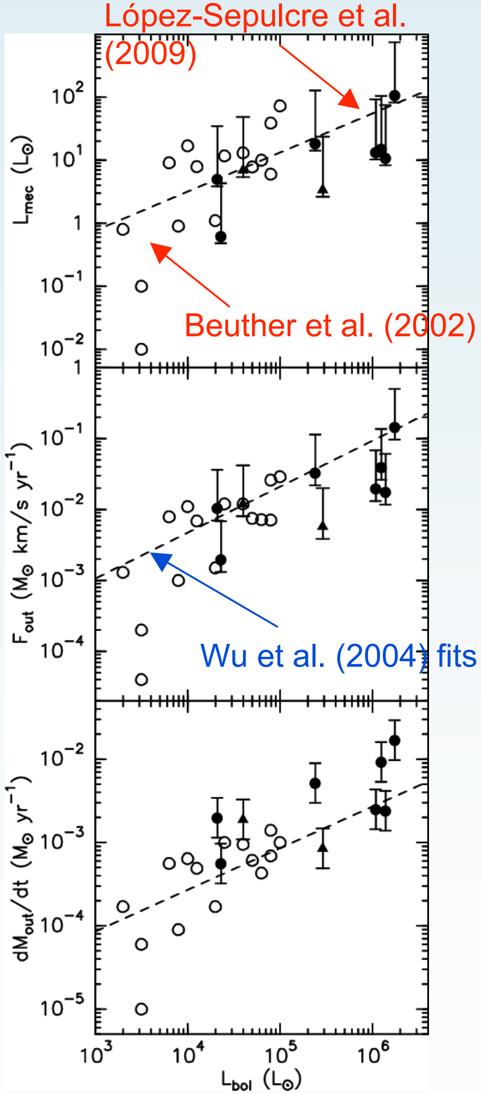
- Molecular outflows are an ubiquitous phenomenon in massive star formation up to 10^6 $L_\odot$ (e.g Shepherd & Churchwell 1996).



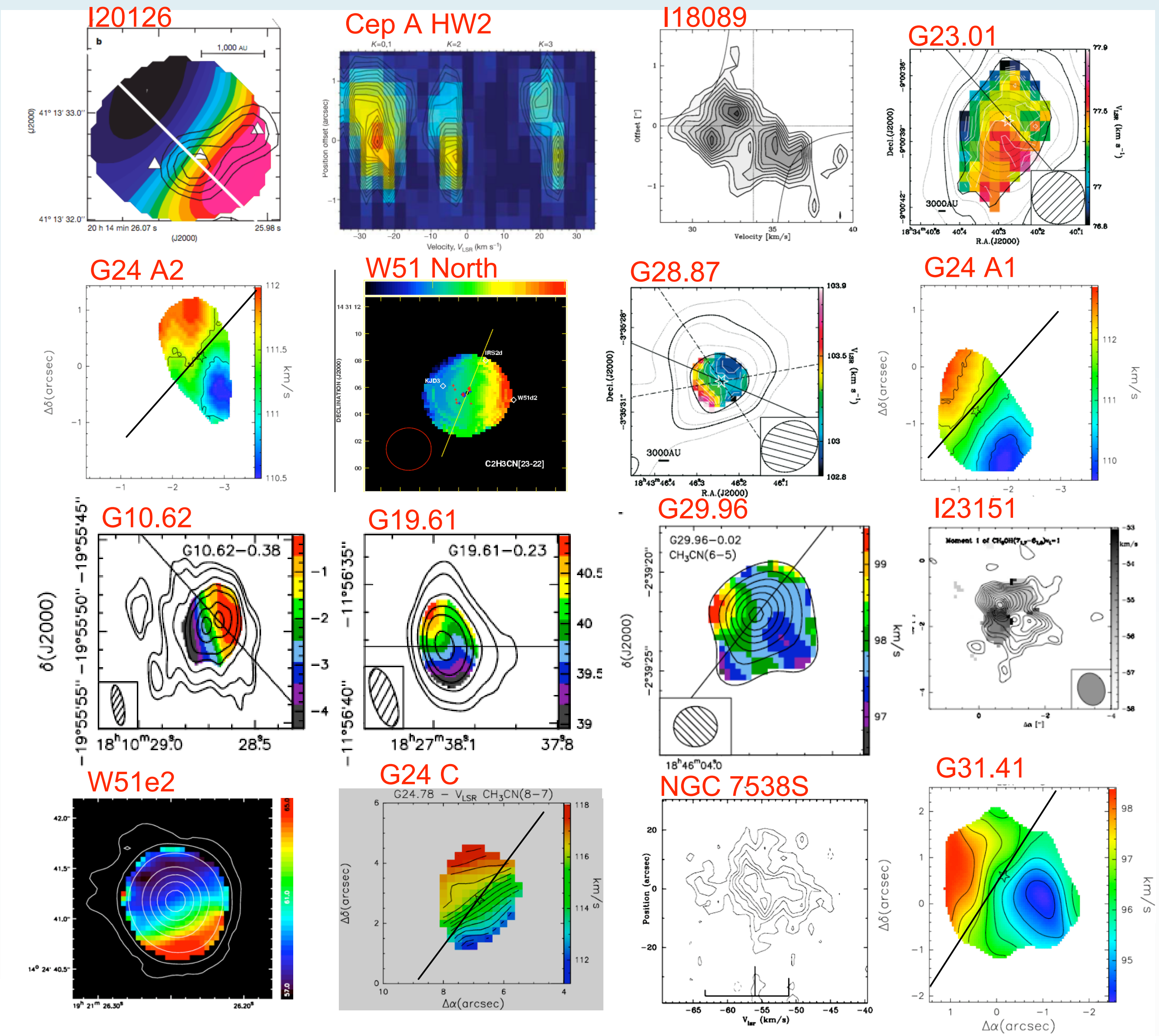
López-Sepulcre et al. (2009)

- Beuther et al. (2002), Wu et al. (2004), and López-Sepulcre et al. (2009) show continuity in the correlation between mechanical luminosity, mechanical force, mass loss rate and bolometric luminosity from low-mass to high-mass.

- The luminosity of the powering source determines the outflow energetics, and the driving mechanisms are similar for all luminosities.



Hot molecular cores: rotation



Beltrán et al. (2004, 2010)

Beuther & Walsh (2008)

Beuther et al. (2007)

Cesaroni et al. (2005)

Furuya et al. (2008)

Keto & Klaassen (2008)

Patel et al. (2005)

Sandell et al. (2003)

Zapata et al. (2008) ...

.... and many more

Disks versus toroids

- DISKS

  $M_{\text{"disk"}} \sim 4\text{-}20\ M_\odot < M_{star}$

  size ~ 1000 AUs

  $L < 10^4\ L_\odot$ (M < 20 $M_\odot$) ➡ early B-type stars

  centrifugally supported disks in Keplerian rotation

- TOROIDS

  $M_{\text{toroid"}} \sim$ a few 100 $M_\odot \gg M_{star}$

  size ~ several 1000 AUs

  $L > 10^5\ L_\odot$ (M > 20 $M_\odot$) ➡ early O-type stars

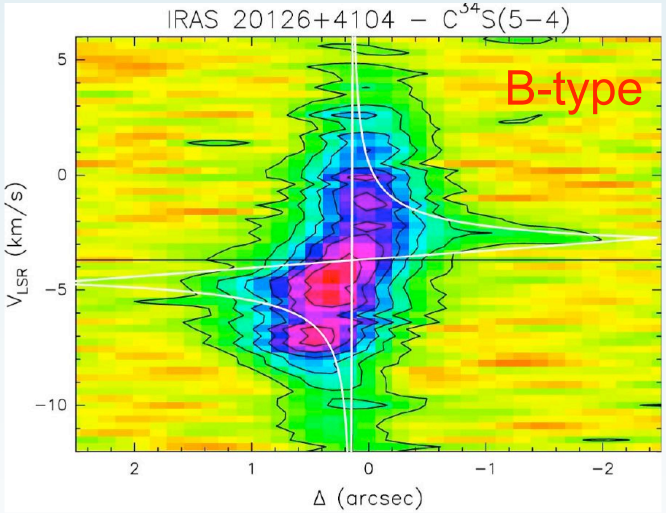
  Not centrifugaly supported and NO Keplerian rotation on scales of 10^4 AU.

  Could never reach equilibrium and be transient entities with timescales of the order of $t_{ff} \sim 10^4$ yr

Hot molecular cores: rotation

NO REAL ACCRETION DISKS HAVE BEEN IMAGED YET TOWARDS O-TYPE (PROTO)STARS

- ❑ Accretion disks could embedded inside the rotating toroids (Cesaroni et al 2006), and difficult to disentangle from the large-scale, massive structures with current instrumentation ➔ ALMA
- ❑ Circumstellar disks around O-type stars could be rapidly destroyed or truncated (< 30 AU) by tidal interactions or encounters with stellar companions (Bonnell et al. 2003; 2004; 2005), or (less likely) by the powerful ionizing flux of the early-type star (photo-evaporate d disks: Hollenbach et al. 2000).
- ❑ Alternatively, circumstellar disks could never be created.

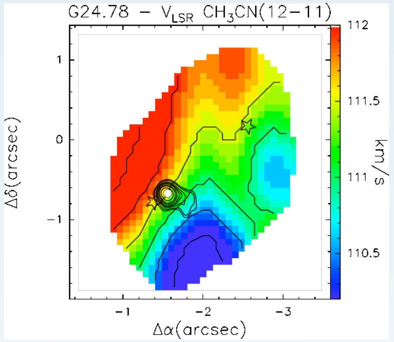


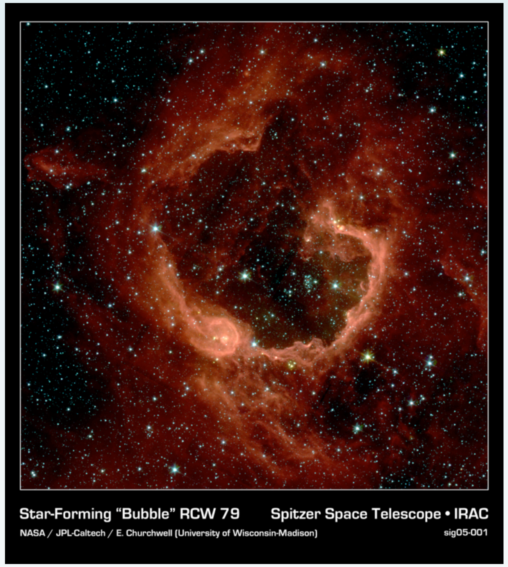
Cesaroni et al. (2005)

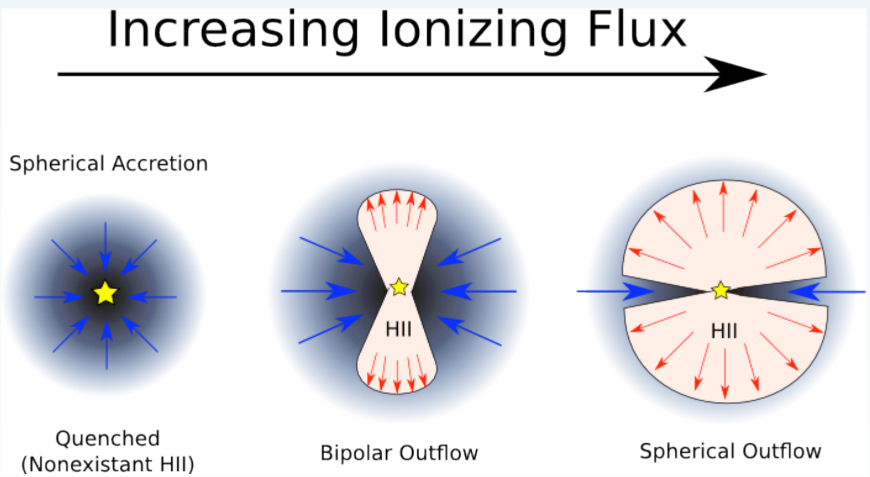
➔ ALMA sensitivity and resolution ABSOLUTELY needed because able to detect a disk up to distances of 20 kpc.

Hypercompact to extended HII regions

❑ The UV photons of the newly formed OB star will heat and ionize the circumstellar material. As the heated region grows, it will eventually breakthrough the the core to become a visible HC HII regions, which will expand to become an extended HII region.





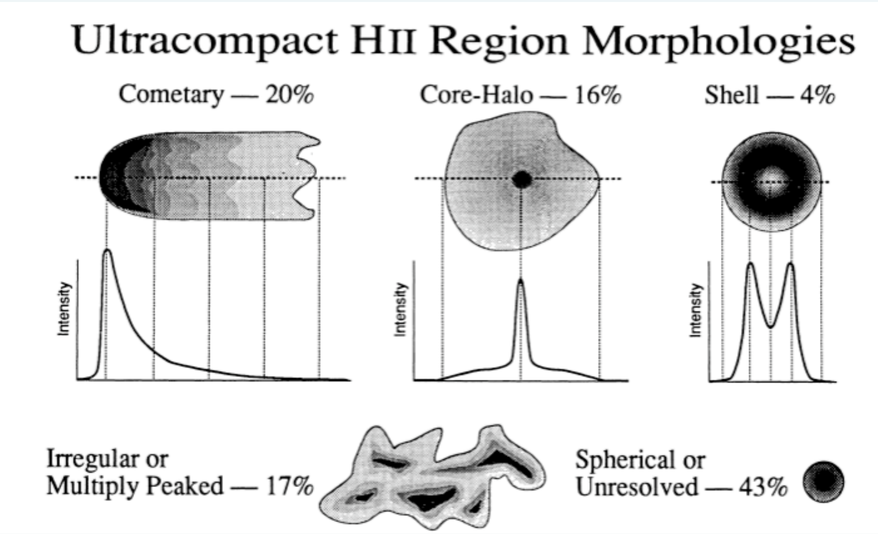


Hypercompact to extended HII regions

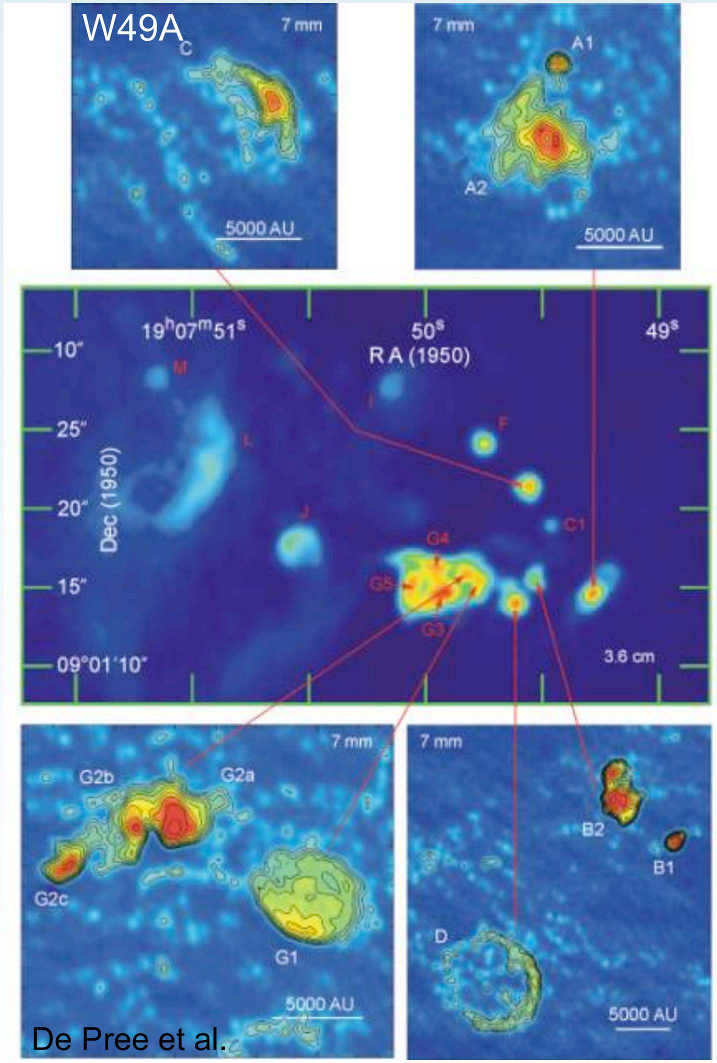
Table 3. Physical Parameters of HII Regions

Class of Region	Size (pc)	Density (cm^{-3})	Emis. Meas. ($pc\ cm^{-6}$)	Ionized Mass ($M_\odot$)
Hypercompact	$\lesssim 0.03$	$\gtrsim 10^6$	$\gtrsim 10^{10}$	$\sim 10^{-3}$
Ultracompact	$\lesssim 0.1$	$\gtrsim 10^4$	$\gtrsim 10^7$	$\sim 10^{-2}$
Compact	$\lesssim 0.5$	$\gtrsim 5 \times 10^3$	$\gtrsim 10^7$	~ 1
Classical	~ 10	~ 100	$\sim 10^2$	$\sim 10^5$
Giant	~ 100	~ 30	$\sim 5 \times 10^5$	$10^3 - 10^6$
Supergiant	>100	~ 10	$\sim 10^5$	$10^6 - 10^8$

Kurtz (2005)



Wood & Churchwell (1989)



De Pree et al.