High-mass star formation in star clusters

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ESO@50 workshop

Garching, September 3, 2012

25 years of research
by the Star Forming Group
at Universidad de Chile
using ESO telescopes.

1987: Comissioning of the Swedish ESO Submillimeter Telescope (SEST)

The first ESO telescope designed to work at sub-millimeter wavelenghts (3 mm – 0.8 mm)

Research Highlights

① Where are the sites of massive star formation?

Survey of CS(2-1) emission towards ~1400 IRAS sources with colors of UCHII regions.

Telescope: SEST

Bronfman, Nyman & May (1996)

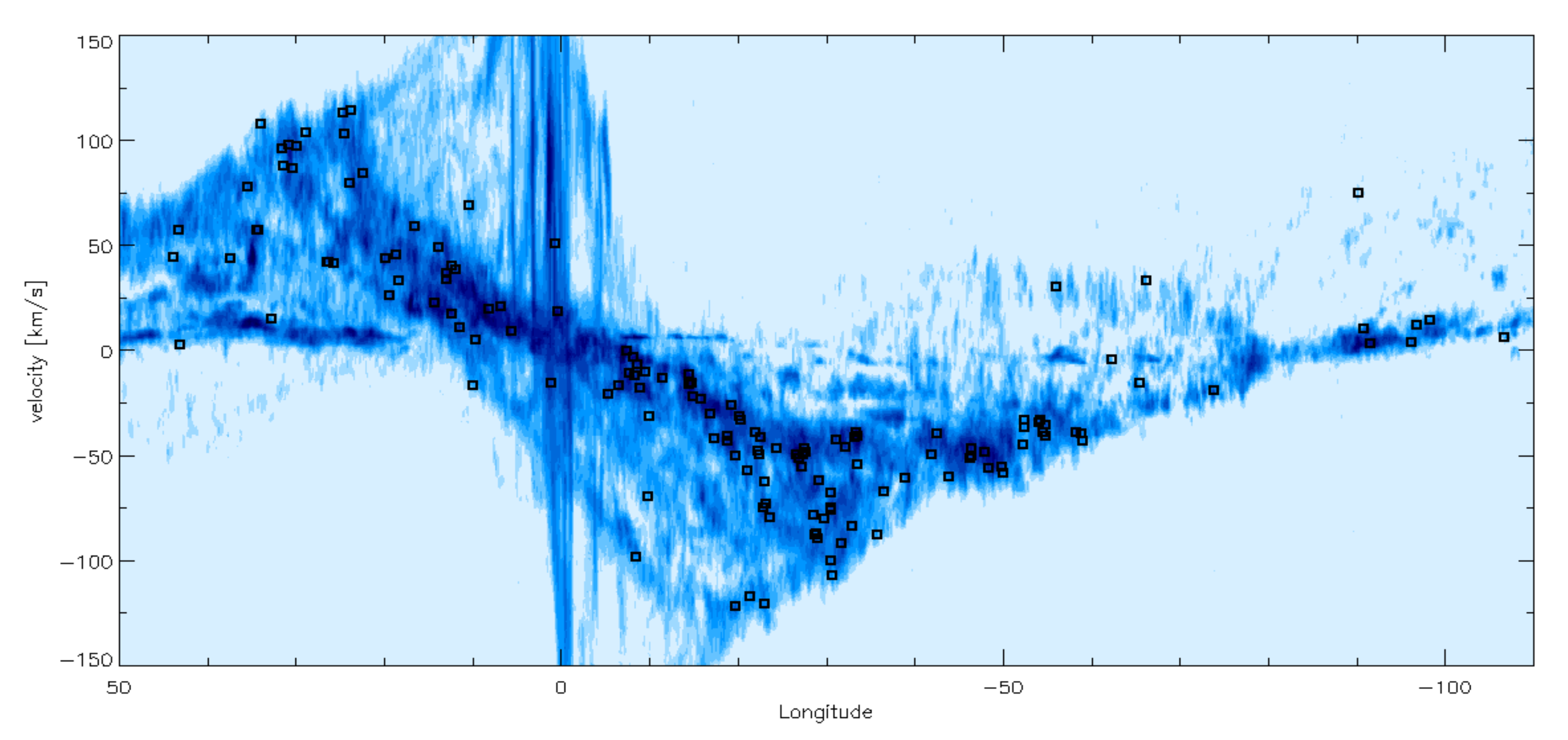
Results: ✧

✧ 60 % detection rate → regions of high density

✧ Cloud radial velocity → Kinematic distance

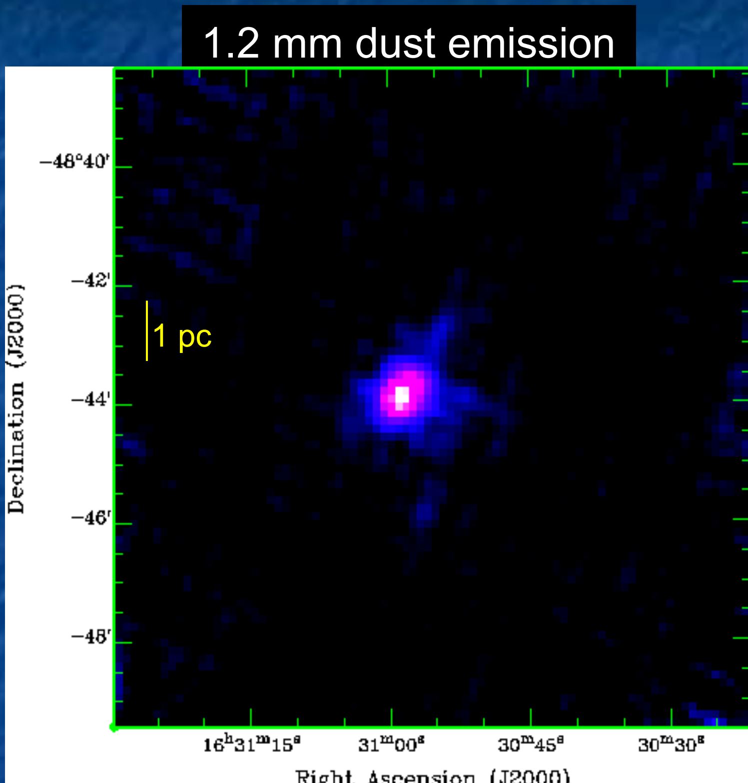
✧ Most (~ 90 %) are within large molecular clouds (GMCs)

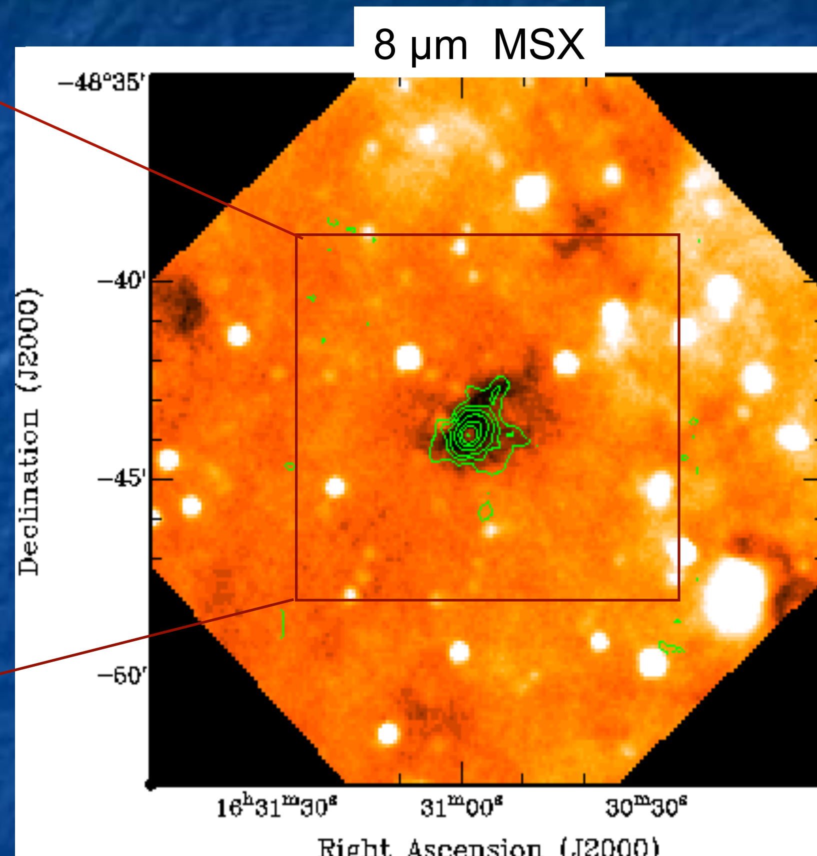
Blue: l-v diagram of CO emission   Squares: CS sources



✧ 10 % appear as isolated structures

e.g. IRAS 16272-4837





M ~ 2×10^3 $M_\odot$ Garay et al. 2002

Infrared dark cloud ($A_V > 100$)

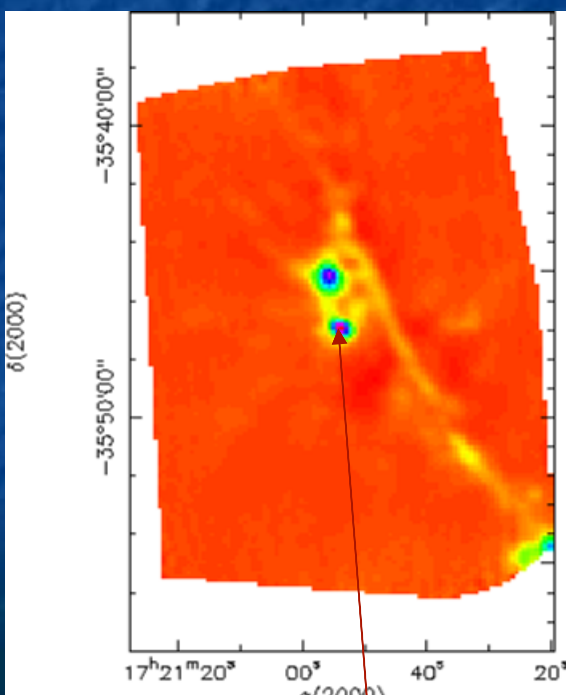
✧ Survey has been widely used as starting point for identifying high-mass protostellar candidates

② Which are the physical characteristics of regions harboring young massive stars?

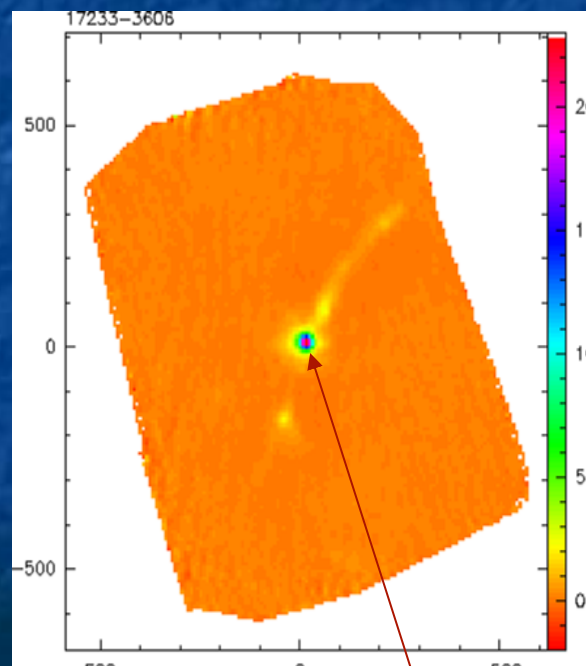
Survey of dust continuum emission at 1.2mm towards ~150 luminous IRAS sources detected by Bronfman et al.

Telescope: SEST Receiver: SIMBA

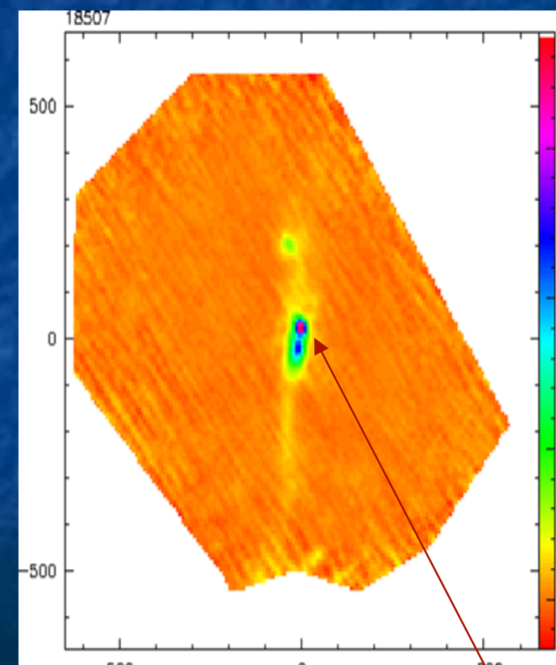
Faúndez et al. (2004)



IRAS 17175-3544



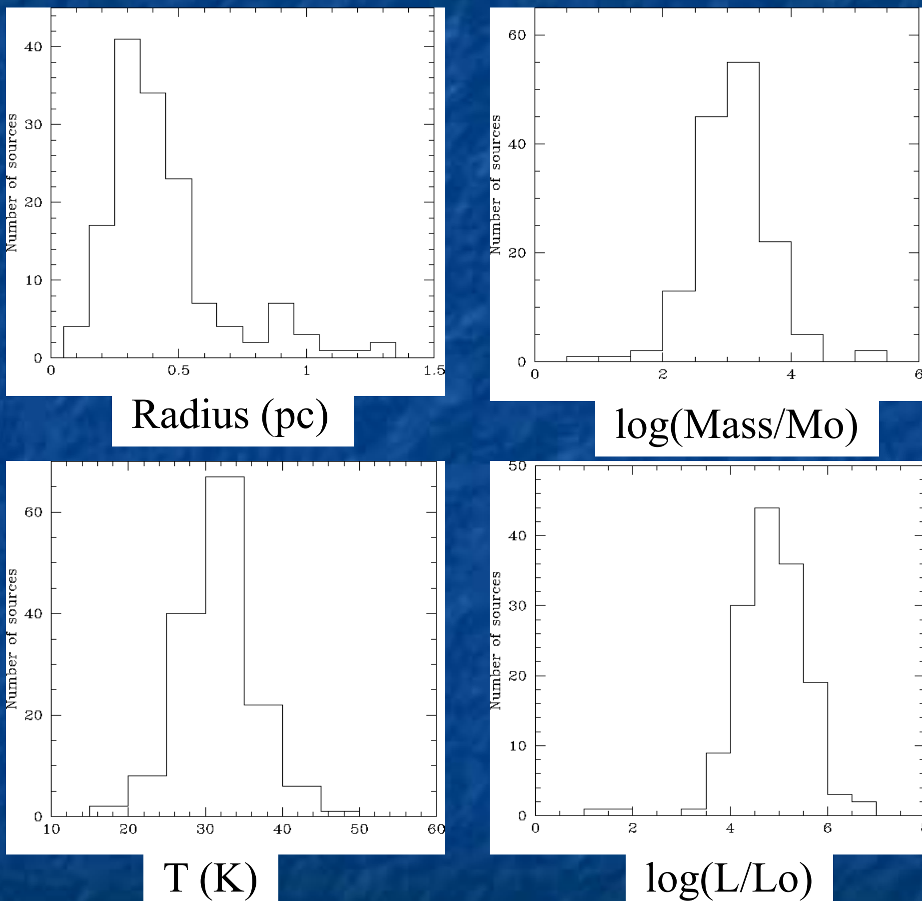
IRAS 17233-3606



IRAS 18507+0110

✧100 % detection rate: all IRAS sources associated with compact dust sources (at the resolution of 24″).

✧ Average physical characteristics of compact dust sources



Average parameters

R	~	0.4 pc
M_d	~	$5x10^3$ $M_\odot$
$n(H_2)$	~	$2x10^5$ cm^{-3}
$N(H_2)$	~	$5x10^{23}$ cm^{-2}
T_d	~	32 K

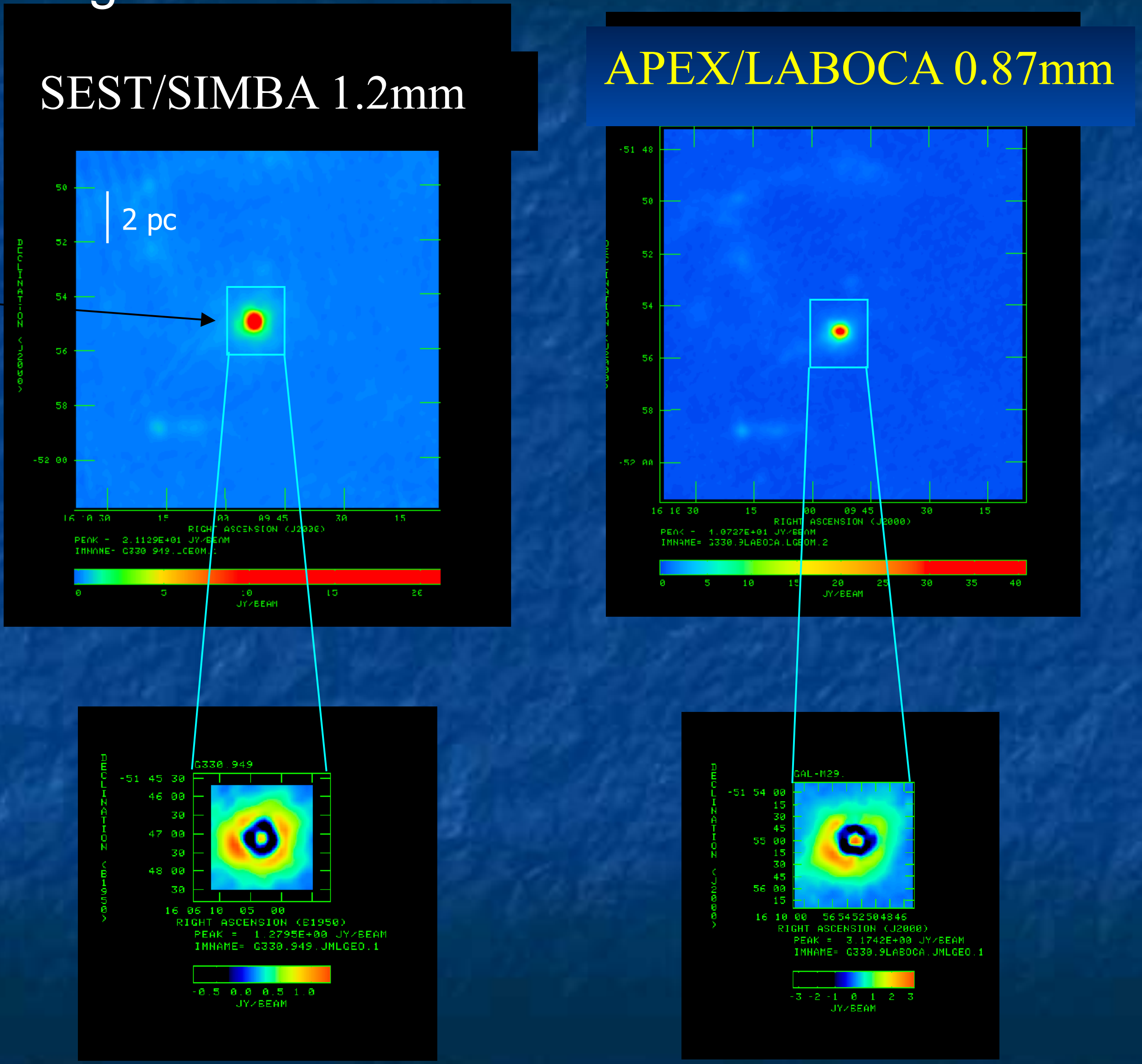
Faúndez et al. (2004)

⇨ High-mass stars are formed in regions with distinct physical parameters: *Massive and dense cores*

✧ Physical structure of massive and dense cores

- Non-Gaussian brightness distribution

e.g.,
G330.95-0.17
IRAS 16060-5146
$L = 1 \times 10^6\ L_\odot$



Residuals from
Gaussian fits

▪ Radial intensity profiles well fitted if the density structure has a power-law dependence with radius, $n \propto r^{-p}$, with $p \sim 1.8$

⇨ Massive and dense cores are highly centrally condensed

✧ Caveat

Faundez et al. survey was made towards luminous IRAS sources ($\langle L \rangle = 2 \times 10^5\ L_\odot$)

⇒ massive star has been already formed within massive dense core

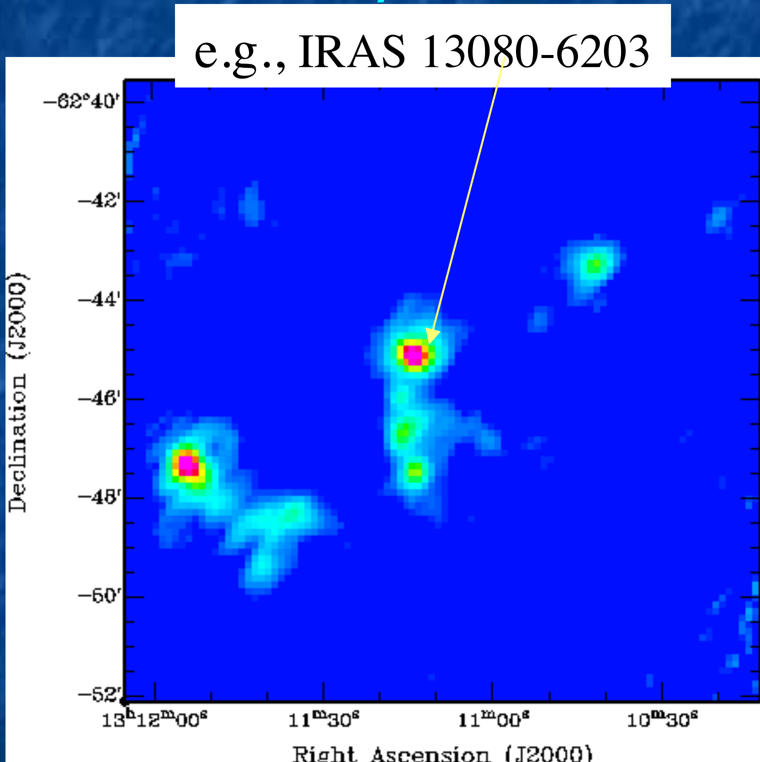
Not clear if the above correspond to the large scale (~ pc) initial conditions for the formation of massive stars.

③ Are there pre-stellar massive and dense **cold** cores?

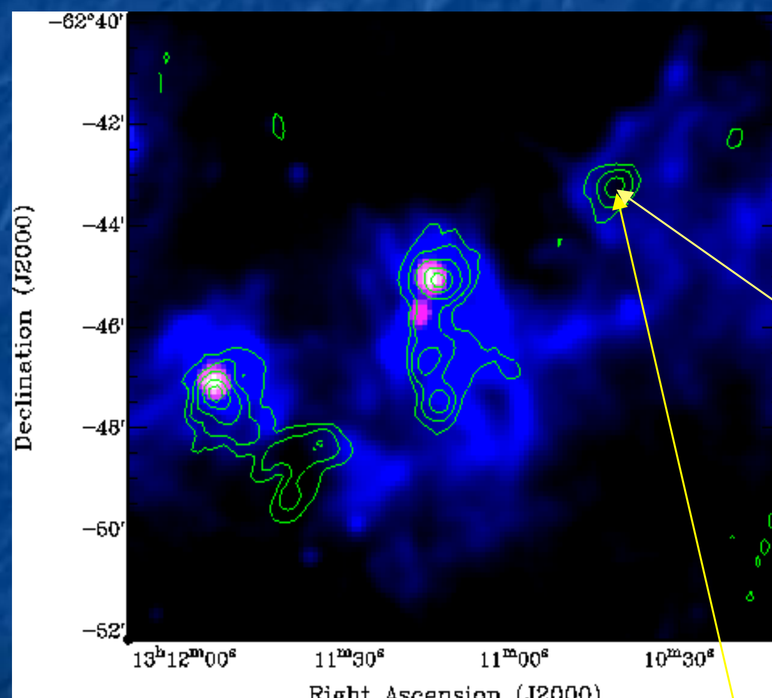
Search for mm-objects without MIR and FIR emission by cross correlating 1.2-mm/SIMBA, MSX and IRAS emission maps

Garay et al. (2004)

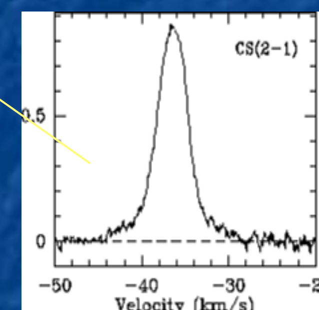
✧ Discovery of the first massive and dense cold cores



1.2-mm dust emission → Mass



Mid-infrared emission→ Temp.



Massive and dense cold core

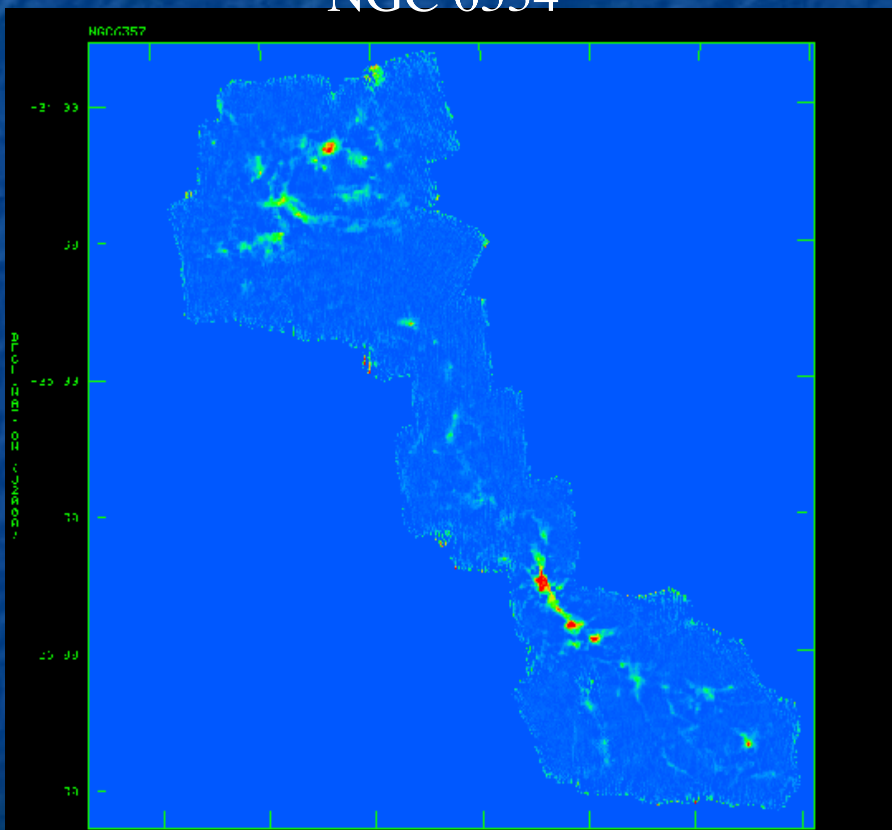
$M_d \sim 670\ M_\odot$
$R \sim 0.3$ pc
$n \sim 2\times10^5\ cm^{-3}$
$\Delta v \sim 5\ km\ s^{-1}$
$T_d < 15$ K

⇨ Initial conditions for the formation of high-mass stars

④ Which is the mass distribution of massive clumps within an entire GMC?

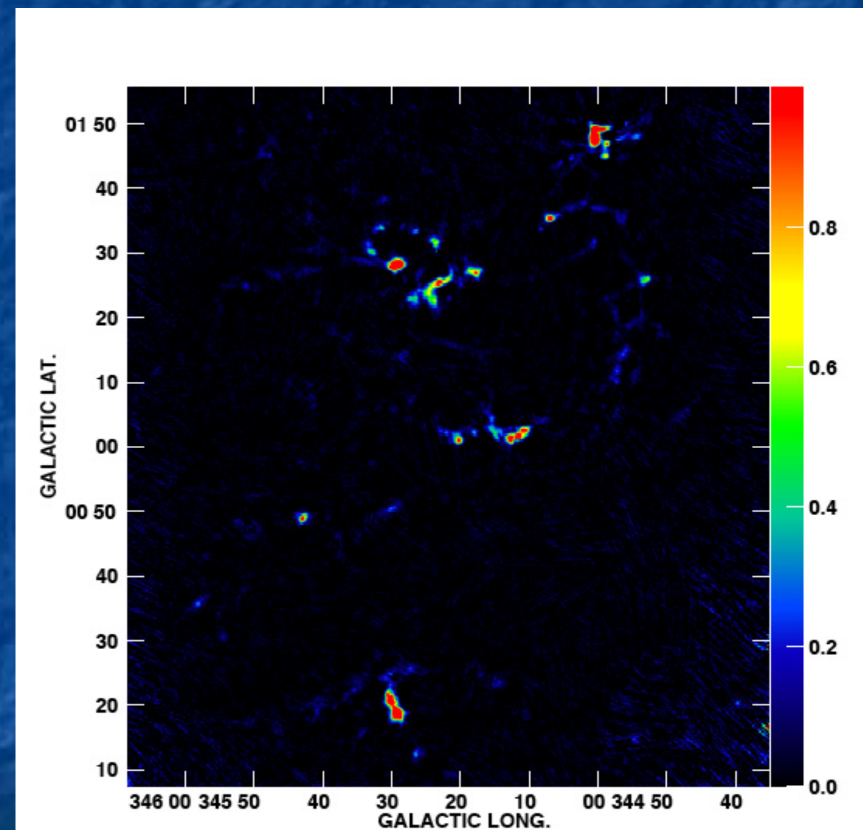
Survey of 1.2 mm emission towards whole GMCs

NGC 6334



Muñoz et al. (2007)

G345.5



Lopez et al. (2010)

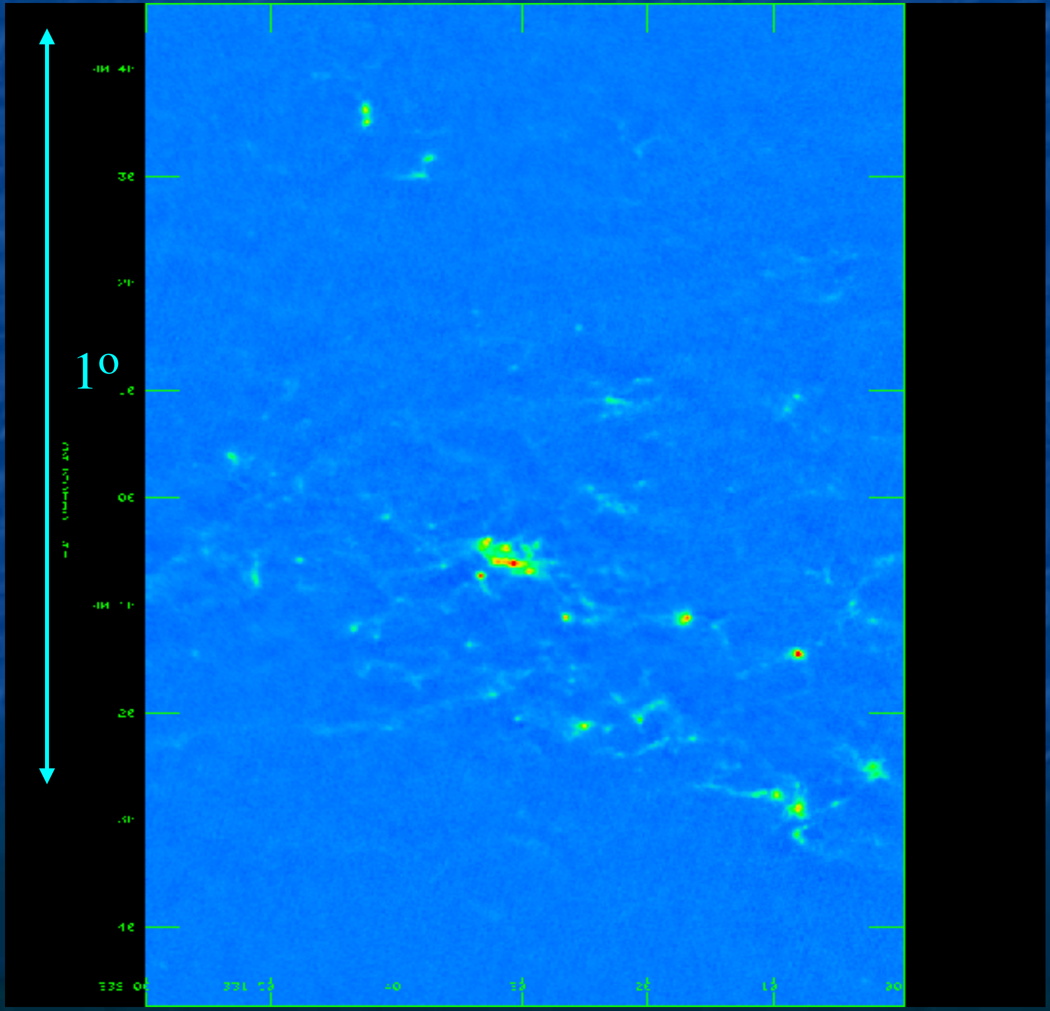
✧ Clump mass function: $dN/dM \propto M^{-1.6}$ $30 < M_c < 6000\ M_\odot$

⑤ An unbiased search for the maternities of massive stars.

Large scale survey of dust continuum emission at submillimeter wavelengths (ATLASGAL, 0.87 mm)

Telescope: APEX

Receiver: LABOCA



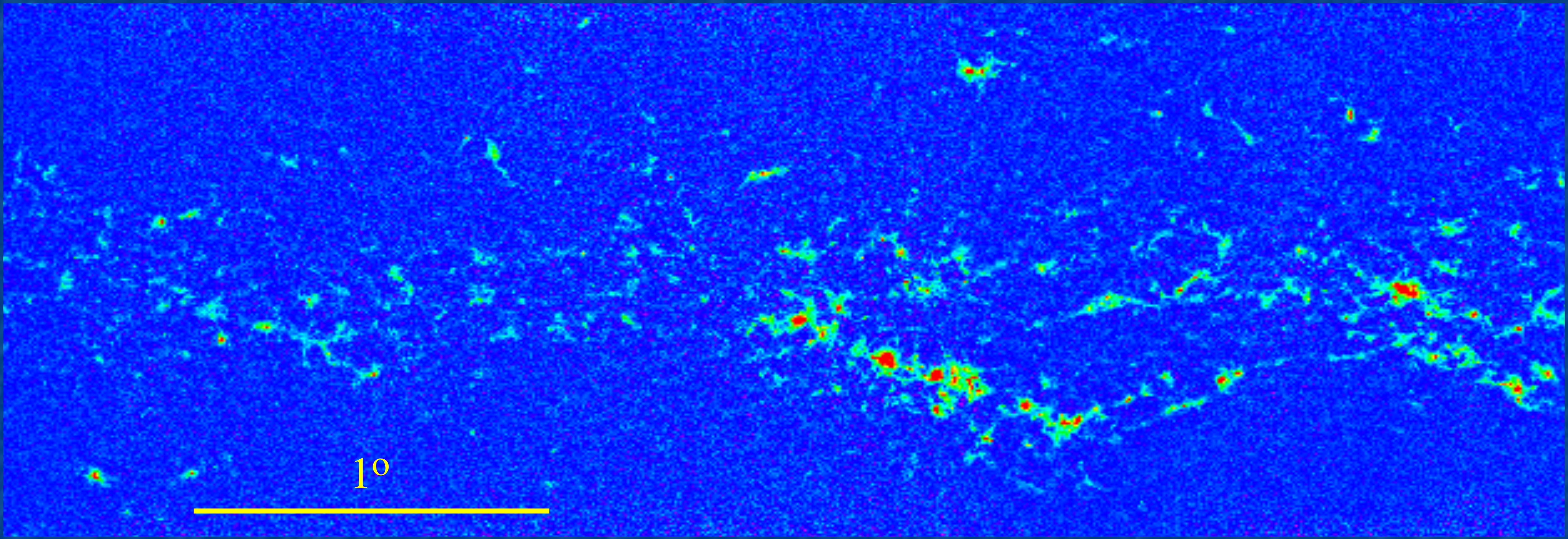
Emission traces regions with high column densities: N > 3×10^{22} cm^{-2}.

✧ 7000 compact sources detected within 95 deg^2 of Galactic Plane

✧ 2/3 have no bright IR counterpart.

Contreras et al. (2012)

✧ ATLASGAL also showed that filaments are ubiquitous along the Galactic Plane



✧ Massive and dense cores are usually found within these filaments.

⑥ Physical processes within maternities of massive stars.

6.1 Collapse?

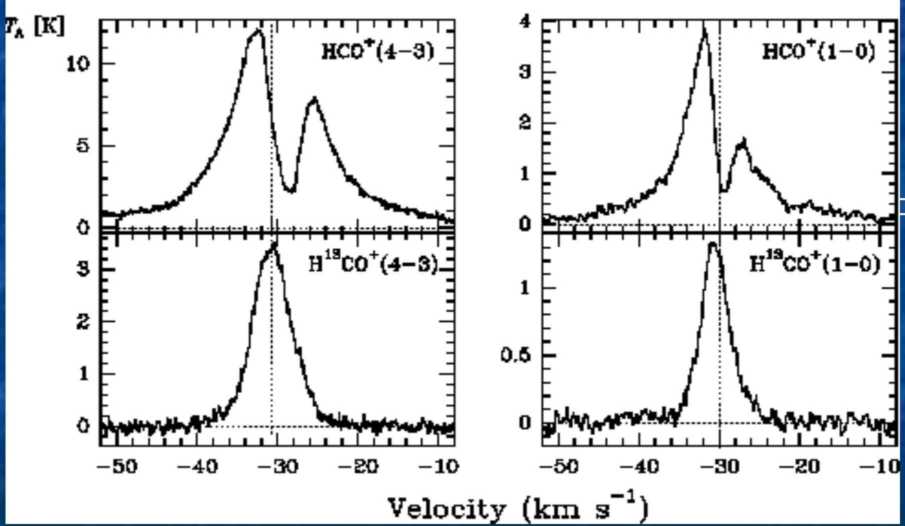
Mardones (2003) analyzed the CS(2-1) lines profiles of 639 MSFRs taken from the survey of Bronfman et al. (1996).

✧ About 5 % show self-absorbed line profiles indicating large scale infalling motions.

IRAS 16547-4247

Optically thick lines →

Optically thin lines →



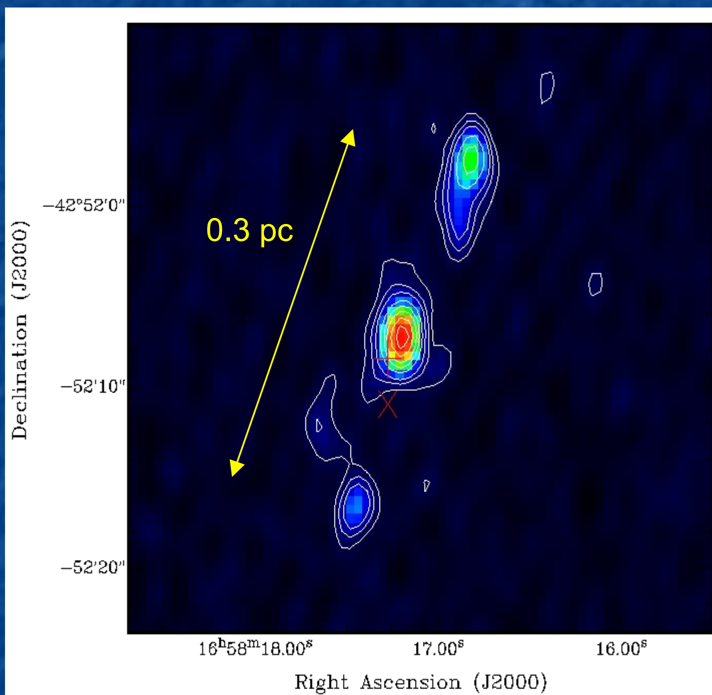
large scale infalling motions

✧ Massive and dense core undergoing intense accretion phase

$V_{inf} \sim 1$ km s^{-1} $\dot{M}_{inf} \sim 1\times10^{-2}\ M_\odot\ yr^{-1}$

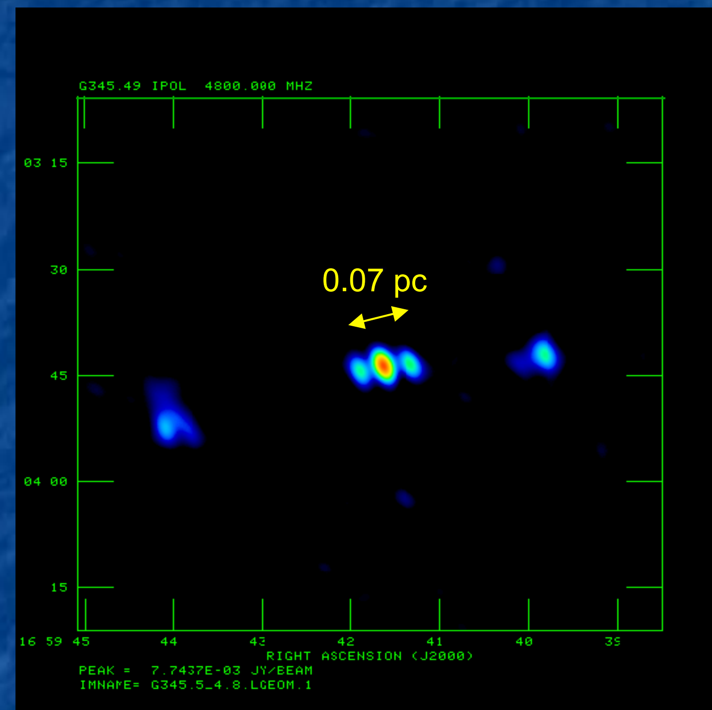
6.2 Ionized Jets?

ATCA survey of radio continuum emission toward luminous massive proto-stellar objects



Triple radio continuum source toward IRAS 16547-4247 ($L = 6\times10^4\ L_\odot$)

Garay et al (2003)



Triple radio continuum source toward IRAS 16562-3959 ($L = 7\times10^4\ L_\odot$)

Guzman et al. (2010)

✧ Jets are found associated with luminous YSOs

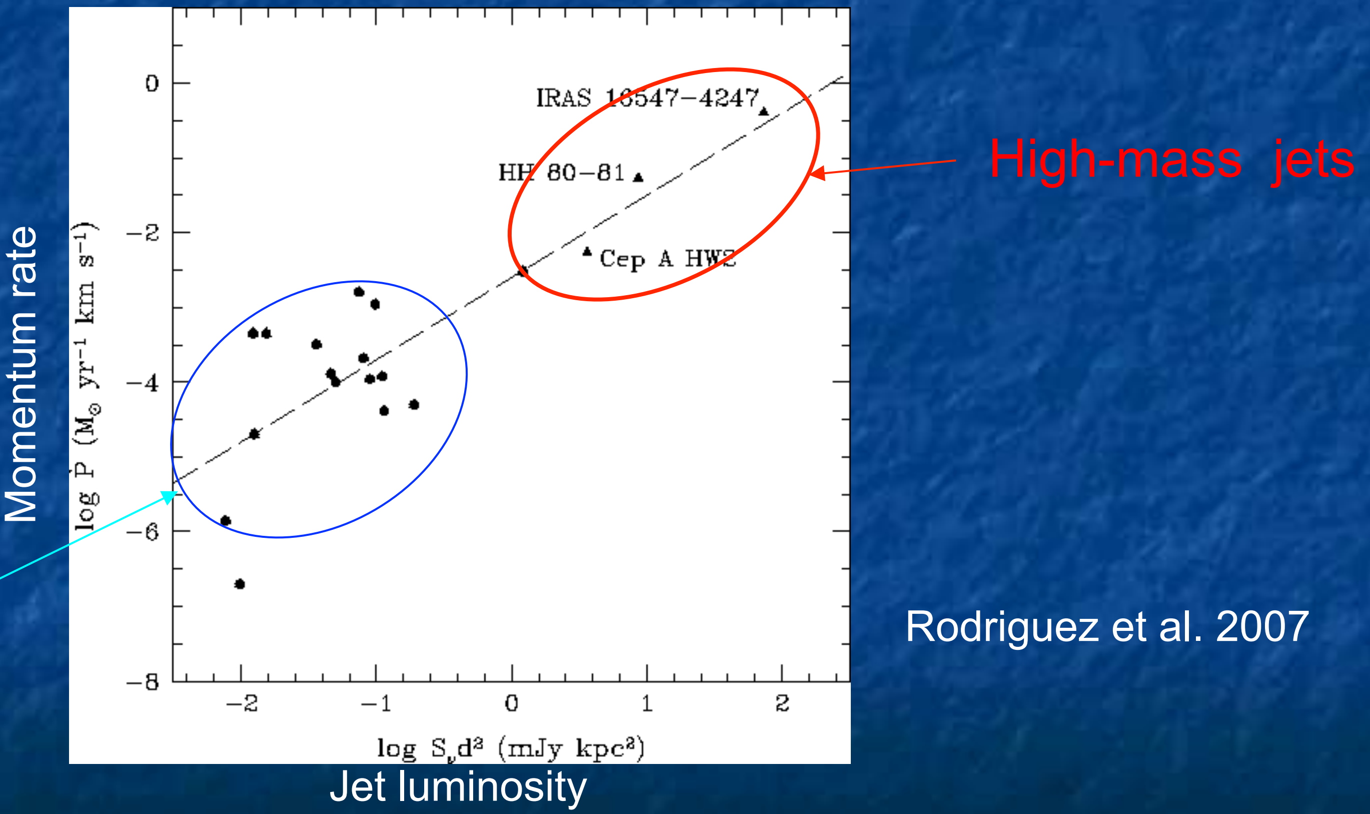
Characteristics of jets associated with high-mass YSOs

Velocity : 1000-3000 km s^{-1}

Size : 0.01 pc

Momentum rate: 10^{-2} - 10^{-1} $M_\odot$ km s^{-1} yr^{-1}

10^3 times more luminous and energetic than low-mass jets !

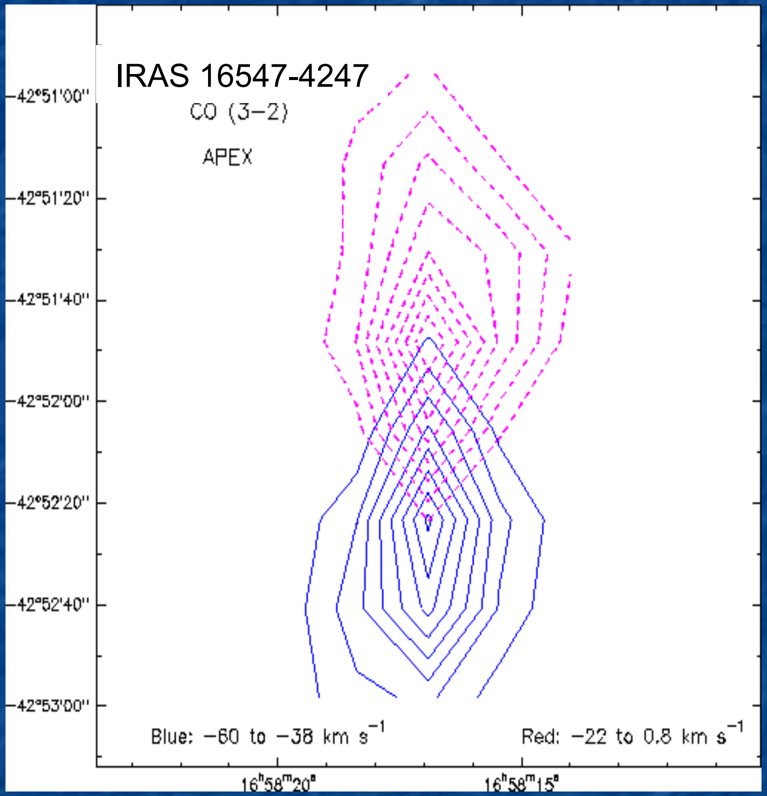


Rodriguez et al. 2007

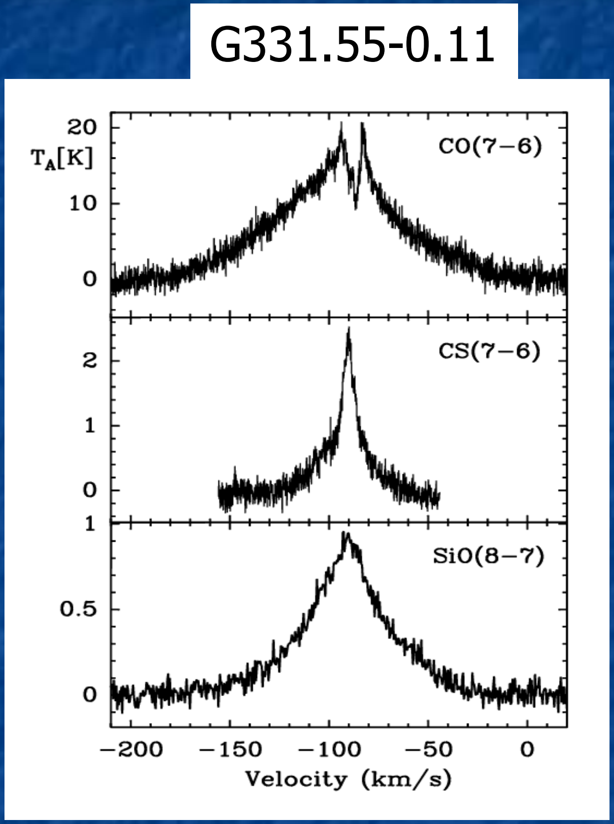
✧ Jets associated with luminous YSOs are powerful

6.3 Molecular outflows?

APEX survey of molecular line emission toward luminous massive proto-stellar objects



Garay et al. (2007)



Bronfman et al. (2008)

✧ Bipolar flow is a common phenomenon toward high-mass protostellar objects

✧ Bipolar outflows associated with luminous YSOs are energetic, collimated and have high velocities.

Average parameters of bipolar outflows associated with high-mass YSOs:

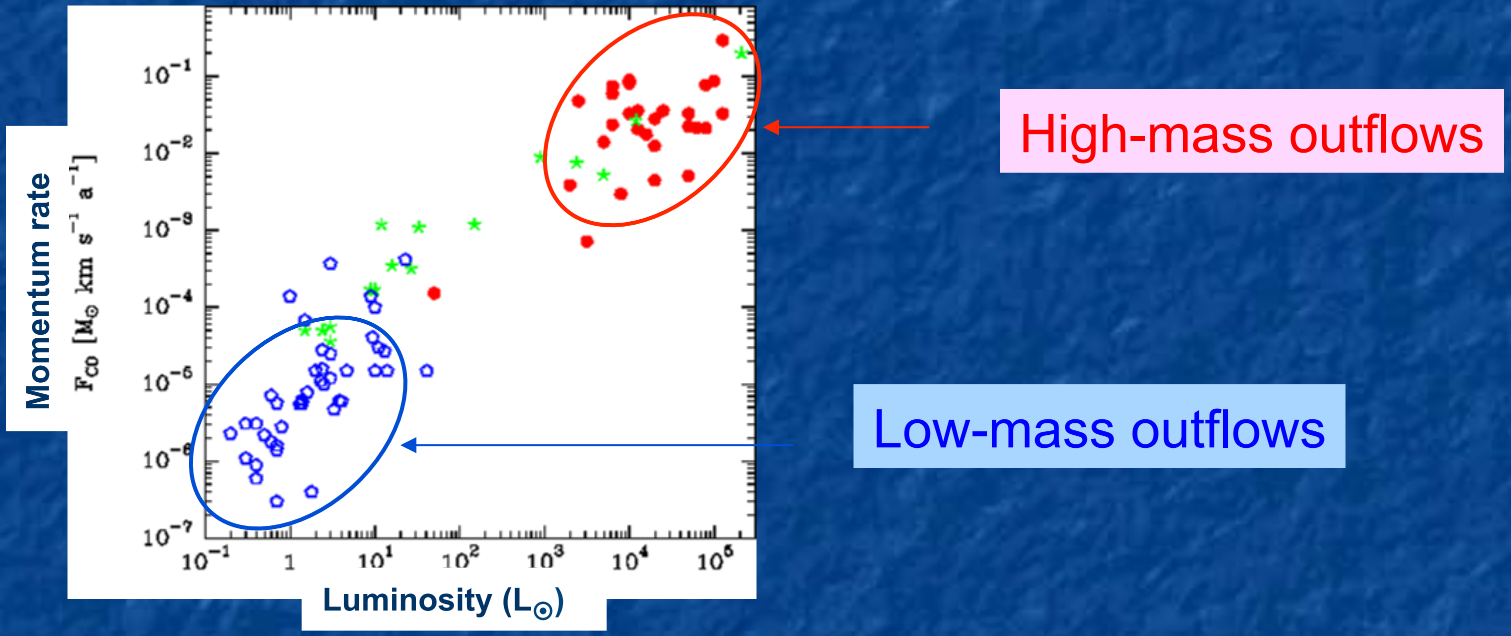
Mass	:	60 $M_{\odot}$
Mass outflow rate	:	1×10^{-3} $M_{\odot}$ yr^{-1}
Mechanical force	:	2×10^{-2} $M_{\odot}$ km s^{-1} yr^{-1}
Kinetic energy	:	2×10^{47} ergs
Mechanical luminosity	:	25 $L_{\odot}$

⇨ 10^2 – 10^3 times more massive and energetic than low-mass outflows

6.4 Mechanism of formation of massive stars?

Evidence:

- strong correlation between outflow parameters and luminosity of driving source.

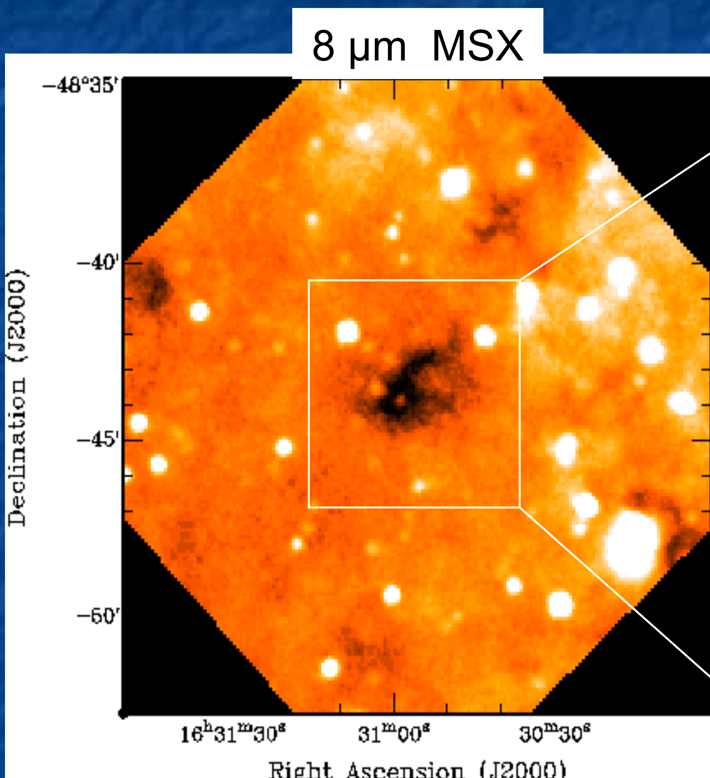


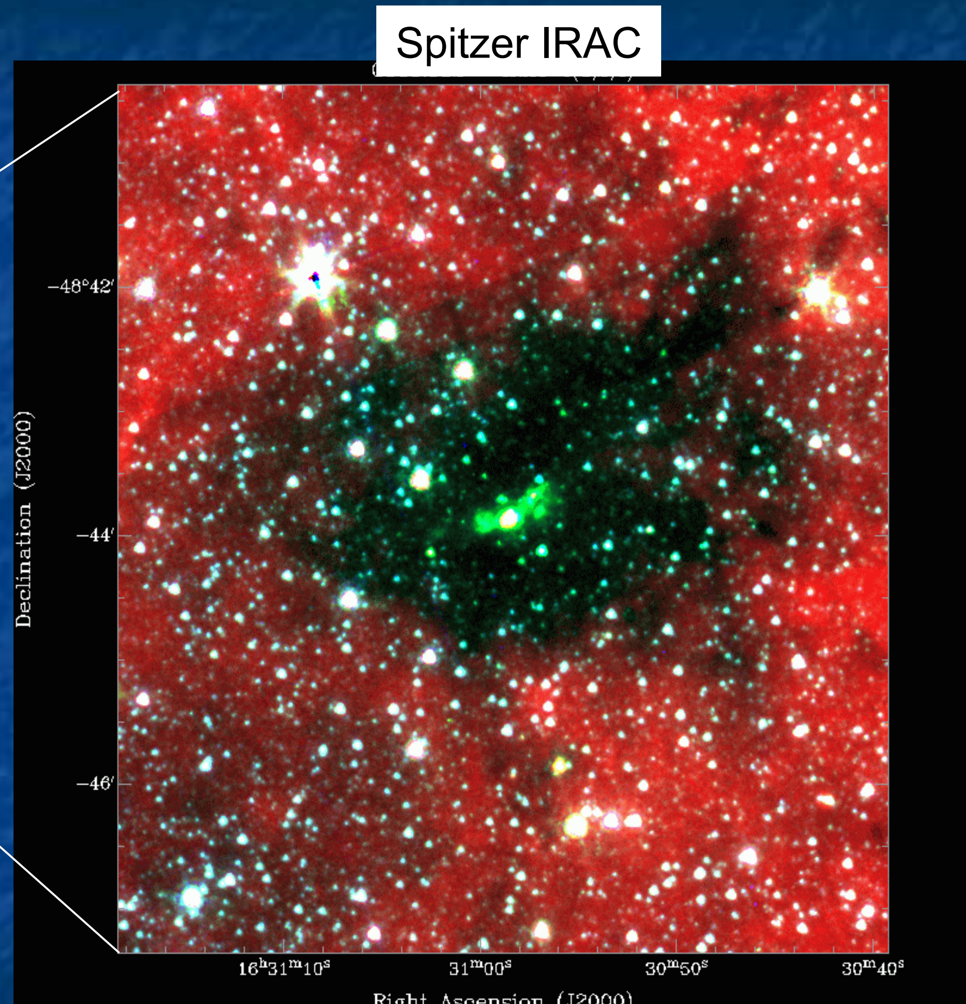
- infalling motions with high accretion rates (§ 6.1)
- presence of ionized jets (§ 6.2)
- presence of powerful bipolar molecular outflows (§6.3)

⇨ Massive stars form in a scaled-up version of low-mass star formation but in a high-density environment.

Massive stars are formed dominantly in star clusters

e.g., IRAS 16272-4837



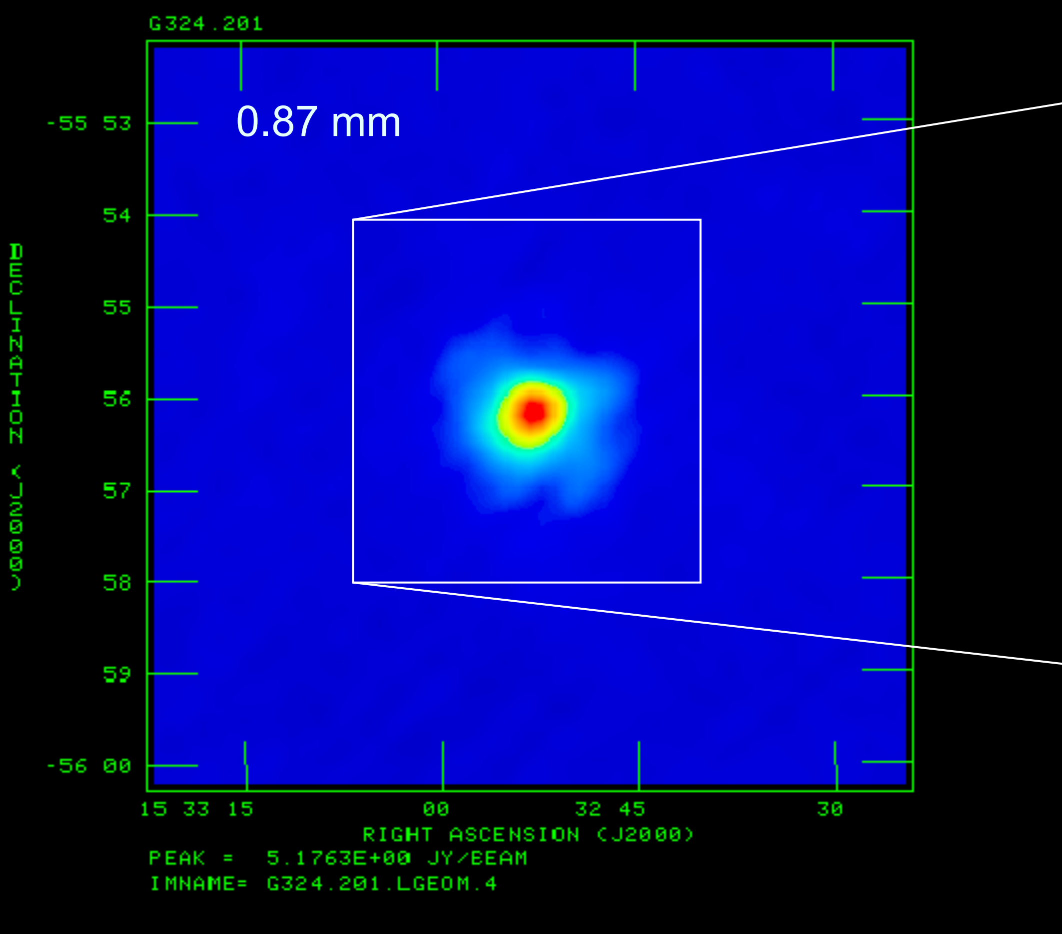


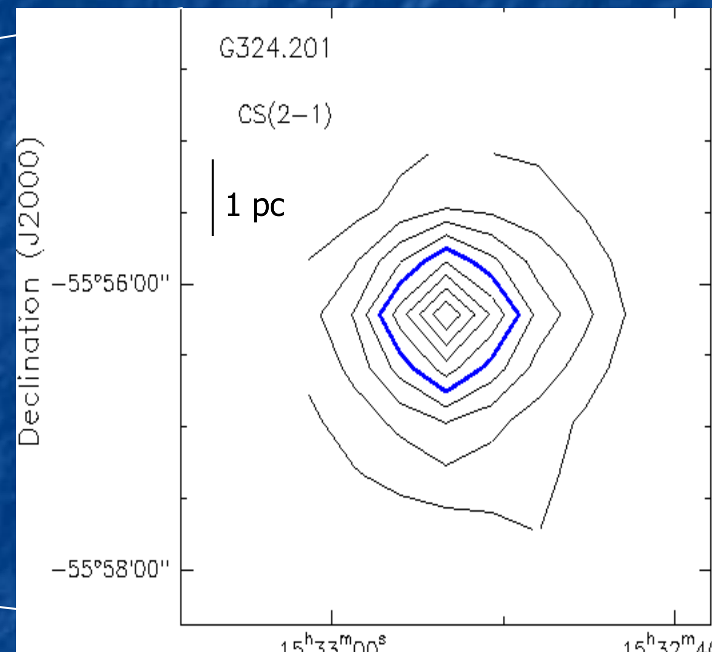
Morales et al. (2009)

Spatial distribution of massive stars expected to provide useful information about formation mechanism.

⑦ Which is the spatial distribution of YSO's within maternities

e.g., G324.201+0.119 massive and dense core



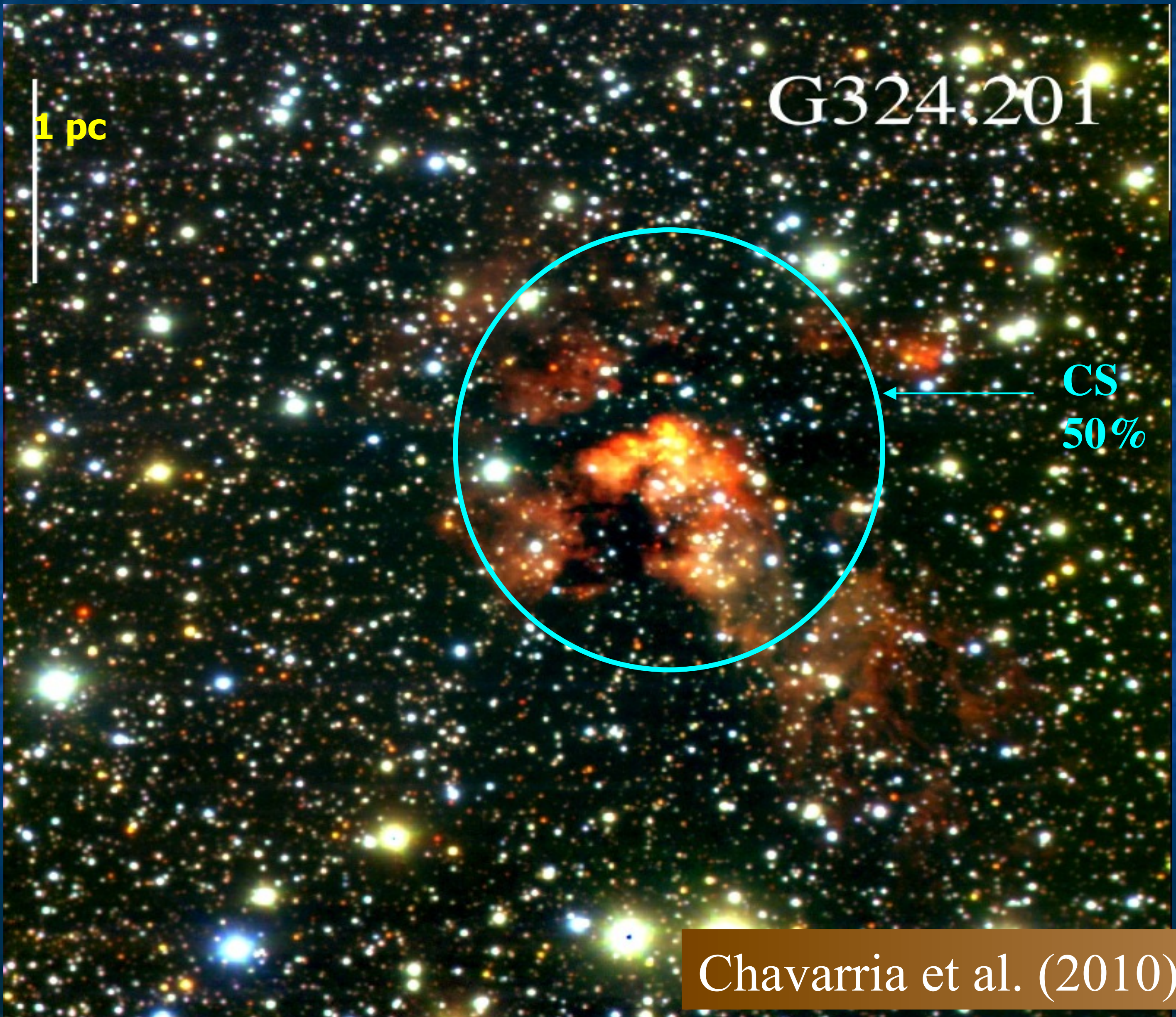


$M \sim 5\times10^3\ M_\odot$ $R \sim 0.5$ pc
$L \sim 6\times10^5\ L_\odot$ $\Delta v \sim 4$ km s^{-1}

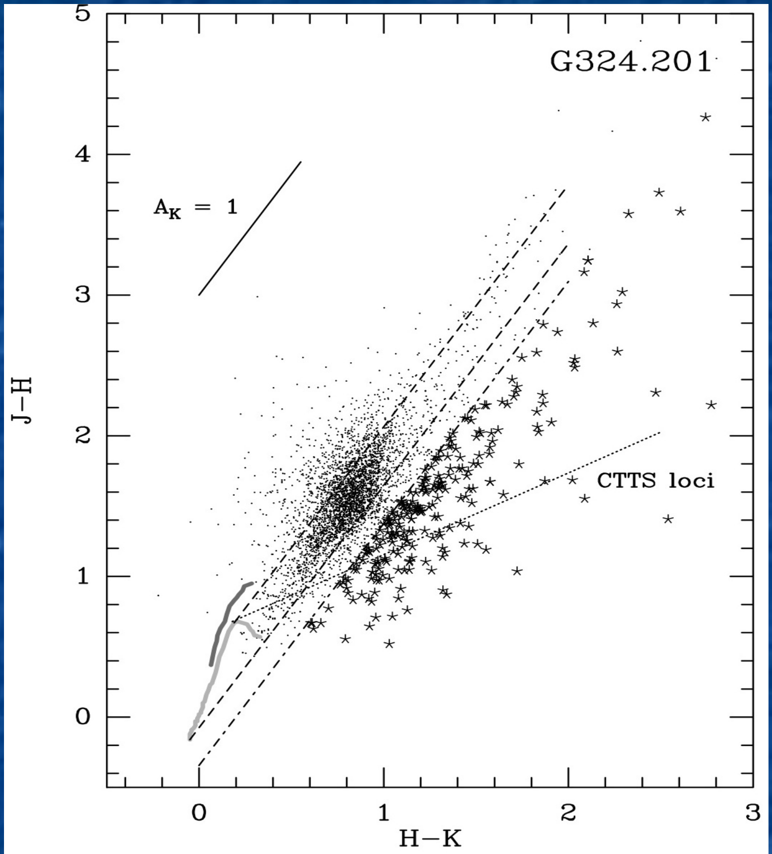
Probe must penetrate deeply into core and be sensitive to stars in a wide range of masses: infrared observations with high angular resolution (0.1").

Deep J, H, K imaging

Telescope: VLT Instrument: ISAAC



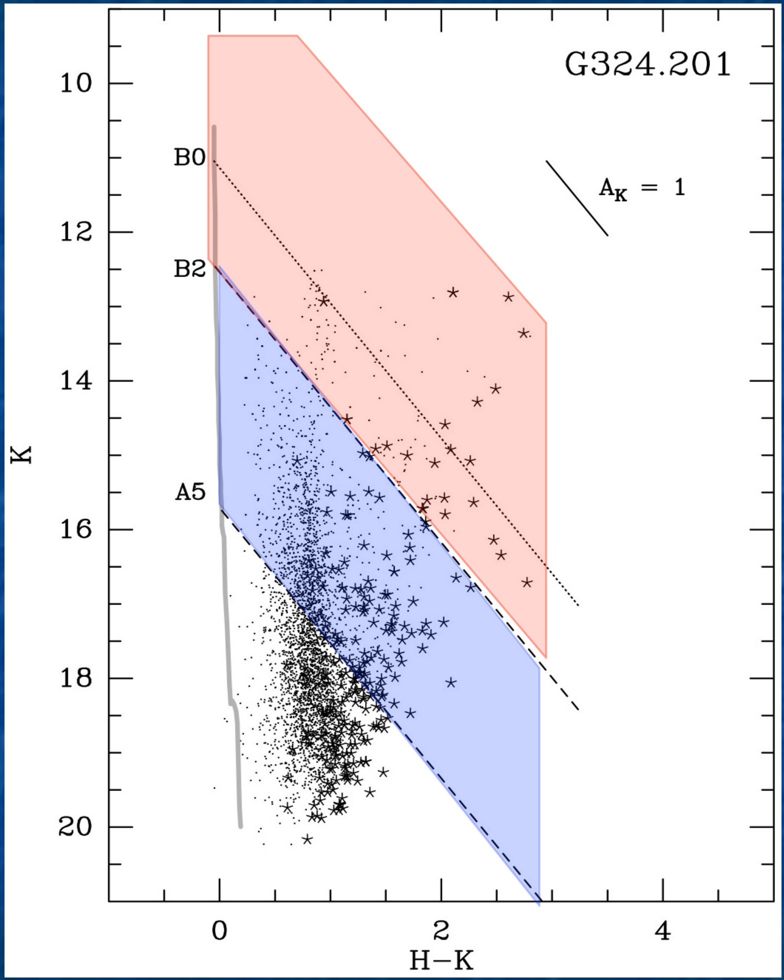
YSOs identified from color-color diagram



⋆: YSOs.

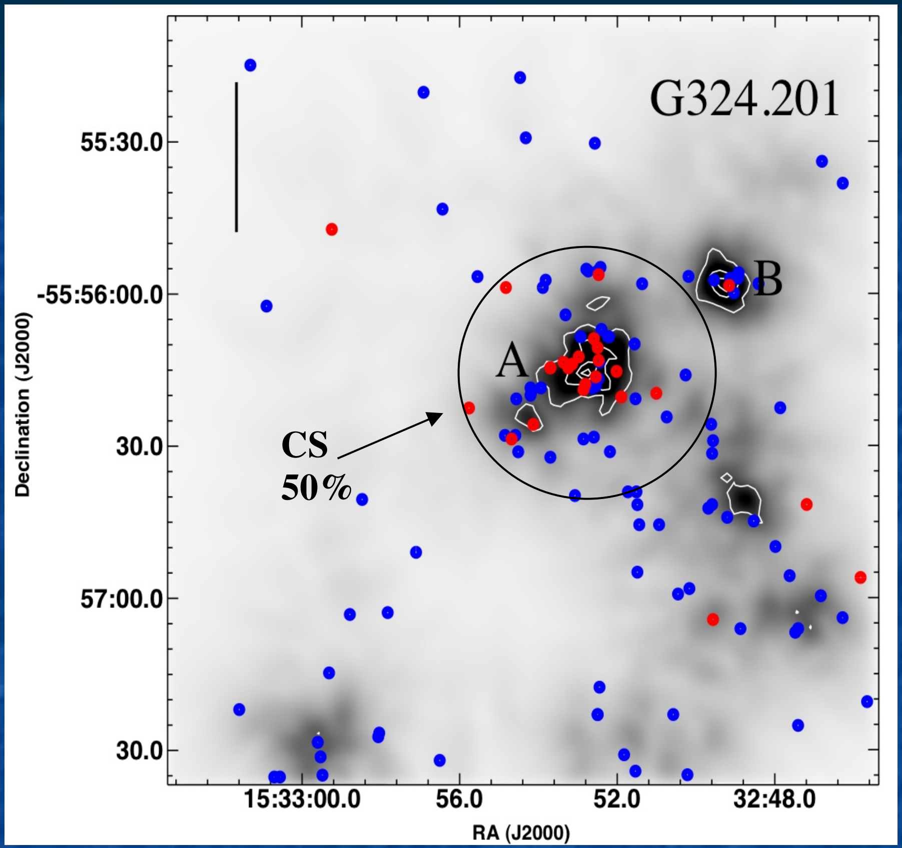
(≡ objects with IR-excess).

S.T. estimate from color-magnitude diagram

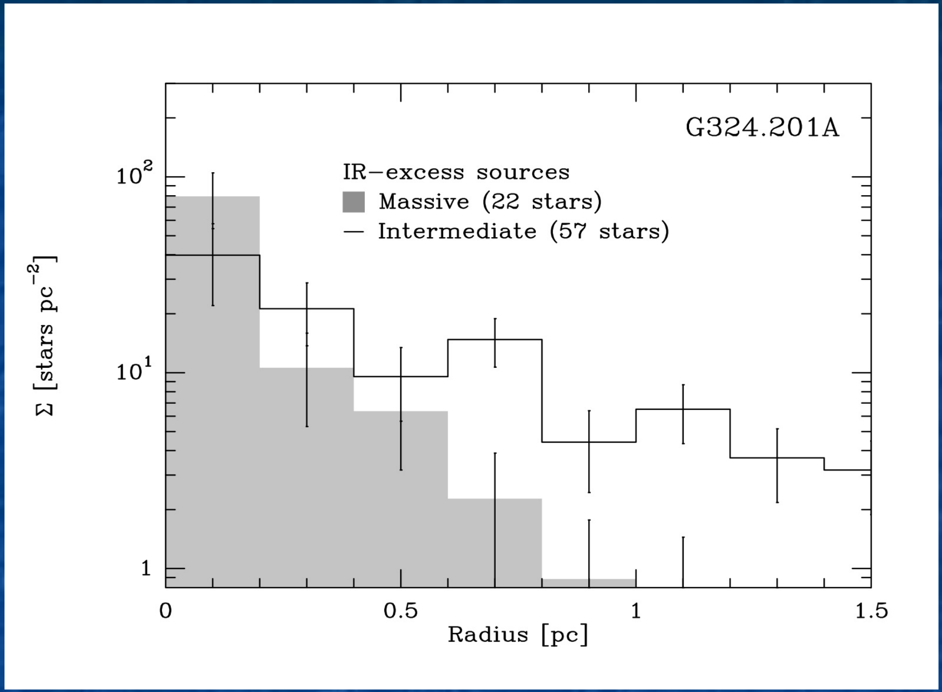


- High-mass (B2 < S.T.)
- Intermediate-mass (A5 <S.T.< B2)

Spatial distribution of YSOs



Radial surface density of YSOs



✧ High concentration of massive stars at the center of the core.

Which is the reason for the mass segregation in young massive and dense cores?

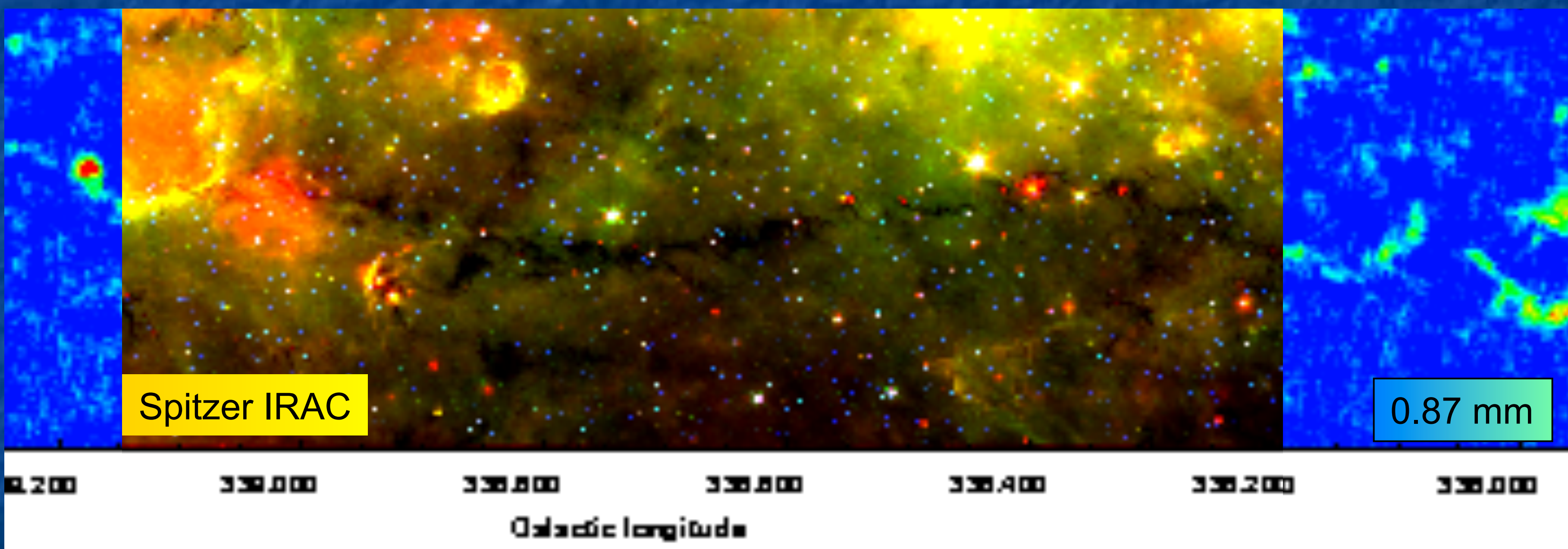
✧ Dynamical friction produced by the massive gaseous background onto the stars !

⑧ Which are the physical characteristics of the filaments?

Dust continuum and molecular line observations towards five massive (~10^4 $M_\odot$) filaments in different evolutionary stages.

Telescope: APEX   Receivers: LABOCA, SABOCA

e.g., Filament A



Flux density → Dust mass (M_d)

Radial intensity profile → Column density profile (Σ)

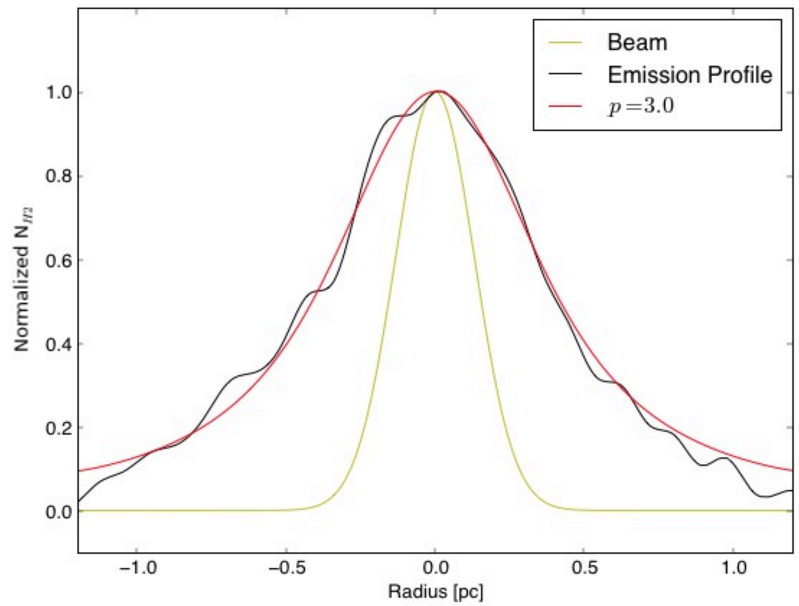
Line width → Virial mass (M_v)

✧ $M_d < M_v$

→ Additional mechanism needed to support filament against expansion.

✧ Column density profiles best fitted with power law indices for the density between 2-3

Filament A



For a filament in equilibrium:

$$\rho \propto \frac{1}{r^p} \quad \text{or} \quad \Sigma \propto \frac{1}{r^{p-1}}$$

p=4 for a pure gravitational bound filament

p=3 for an isothermal filament with magnetic support

⇨ To be stable filaments require the presence of a toroidal magnetic field.

Still far from reaching a deep understanding of the process of formation of high-mass stars.

Many open questions …

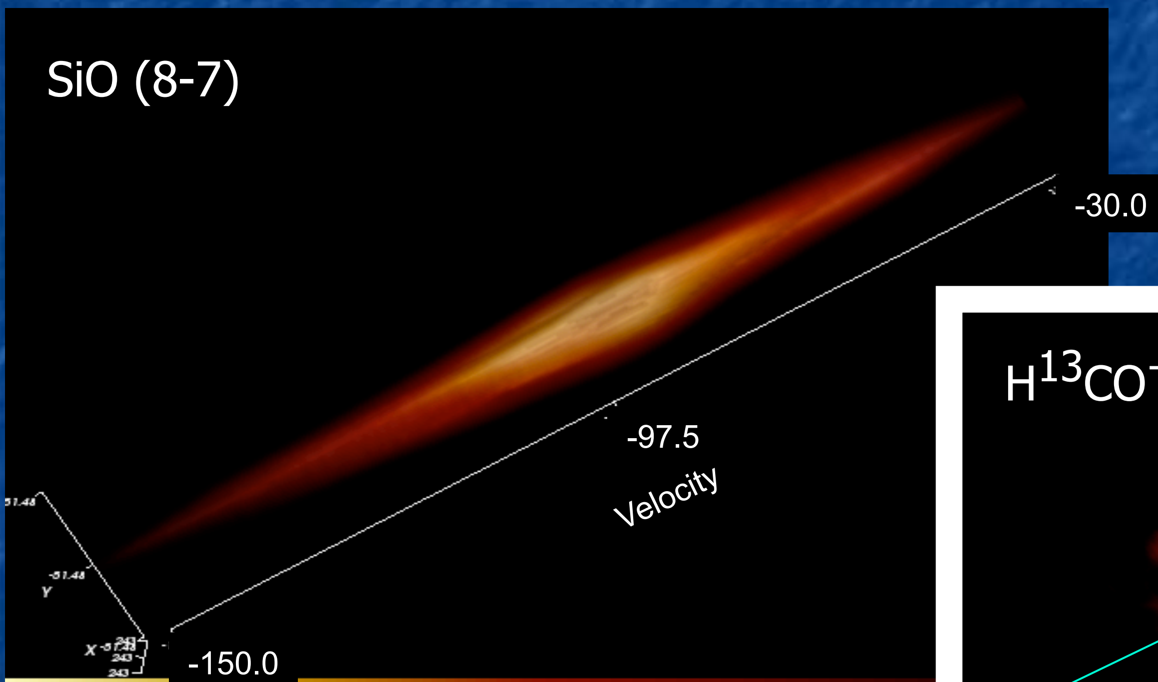
⑨ Understanding the link between outflow and accretion at scales of ~100 AU.

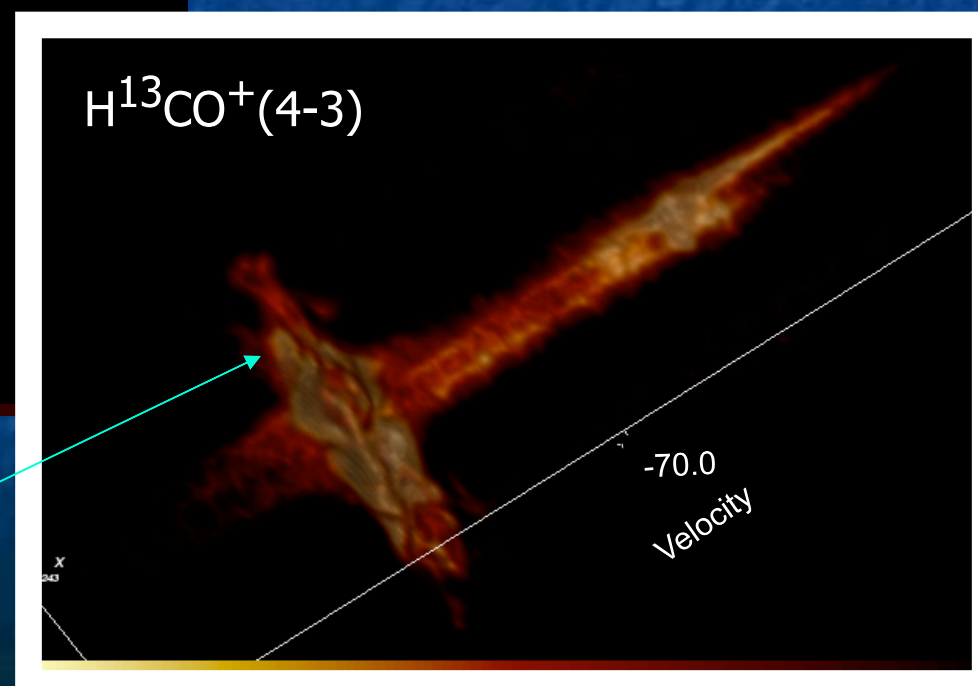
Telescope: ALMA

Cycle: 0

G331.55-0.11 outflow

Merello et al. (2013)

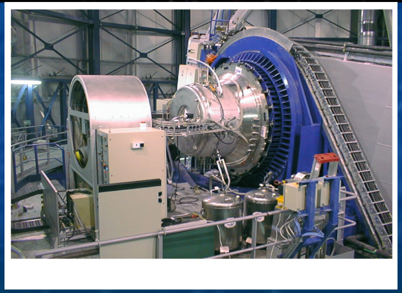




Accretion disk !

END

APEX



✦ Atacama Pathfinder EXperiment (APEX)

Diameter: 12 m
Frequency range:
210 – 1390 GHz

Is there an outflow-disk-jet connection for massive YSOs?

Massive YSOs associated with bipolar outflows, disks and/or jets

Object	L_{bol}	Disk		Bipolar flow	Jet
		Mass	Radius		
	($L_\odot$)	($M_\odot$)	(AU)		
AFGL 490	2×10^3	10	8500	Y	N
W3(H_2O)	3×10^3	10	<500	Y	Y
G192.16-3.82	3×10^3	15	65	Y	Y
AFGL 5142	4×10^3	1 50	6000	Y	N
IRAS 20126+4104	1×10^4	10	850	Y	Y
Cepheus A HW2	1×10^4	200	750	Y	Y
IRAS 18162-2048	2×10^4	30	<4000	Y	Y
IRAS 23385+6053	2×10^4	370	5000	Y	N

Jets || Bipolar outflows ⊥ Disks