The earliest phases of high-mass stars within entire molecular cloud complexes

Frédérique Motte (CEA-Saclay, AIM)

Collaborators: S. Bontemps (Obs Bordeaux),
N. Schneider, J. Grac (CEA-Saclay),
P. Schilke, F. Wyrowski, K. Menten (MPIfR Bonn)
D. Lis (Caltech),
D. Broguière (IRAM)

Related work on posters by Bontemps et al., Hora et al., Motte et al., Schneider et al., Simon et al.

Seeking the precursors of high-mass stars

Criteria previously used to search for the progenitors of UCH IIs:

- high-luminosity sources — $> 10^3\ L_\odot$
- embedded in massive envelopes — red FIR colors, dense gas
- associated with hot dust & gas — hot core and masers
- without a developed H II region — no or weak cm free-free

⇒ High-luminosity IR protostar candidates (HMPOs)

Criteria to use to search for the even earlier phases:

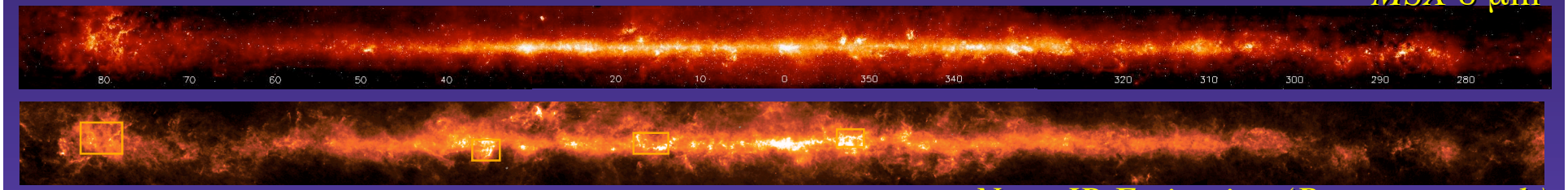
- small-scale cloud fragments — diameter = 0.01-0.1 pc
- which are dense — $\langle n_{H2} \rangle > 10^4$-$10^6$ cm^{-3}
- weak @ mid-IR λ — $< 10^3\ L_\odot$

⇒ High-mass IR-quiet protostars and massive pre-stellar cores

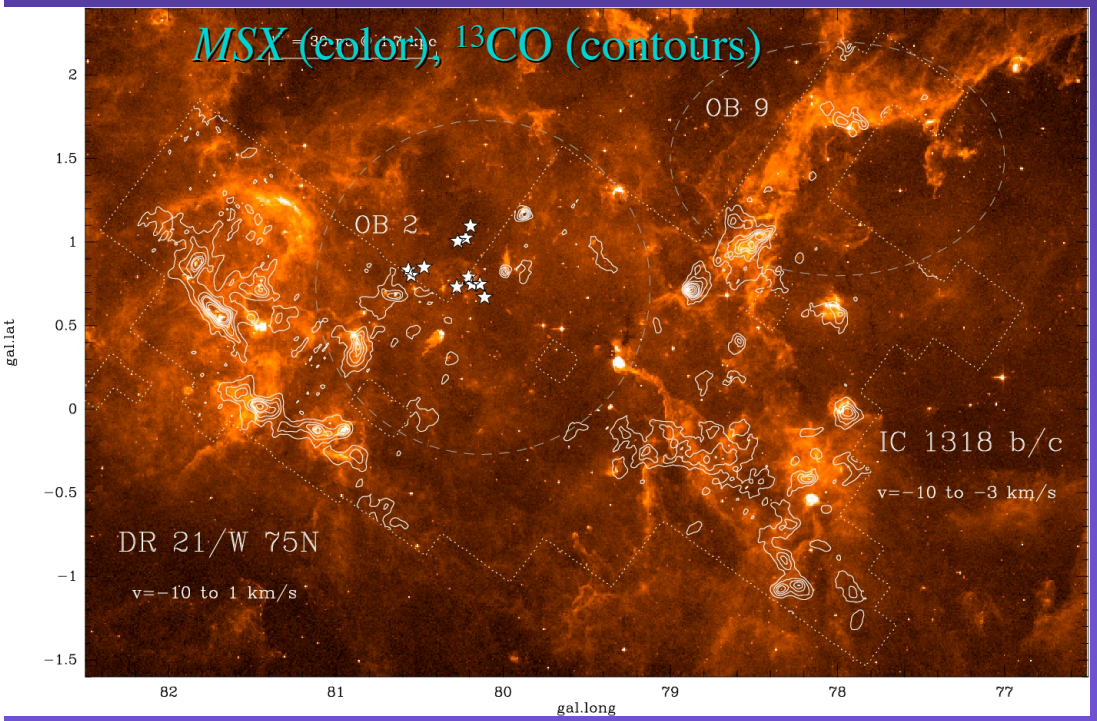
IR dark clouds (see talks by J. Jackson and N. Peretto) or (sub-)millimeter dense cores (see talk by F. Fontani and the present one).

Sub-millimeter study of entire, nearby, molecular complexes forming OB stars

MSX 8 μm



Near-IR Extinction (Bontemps et al.)

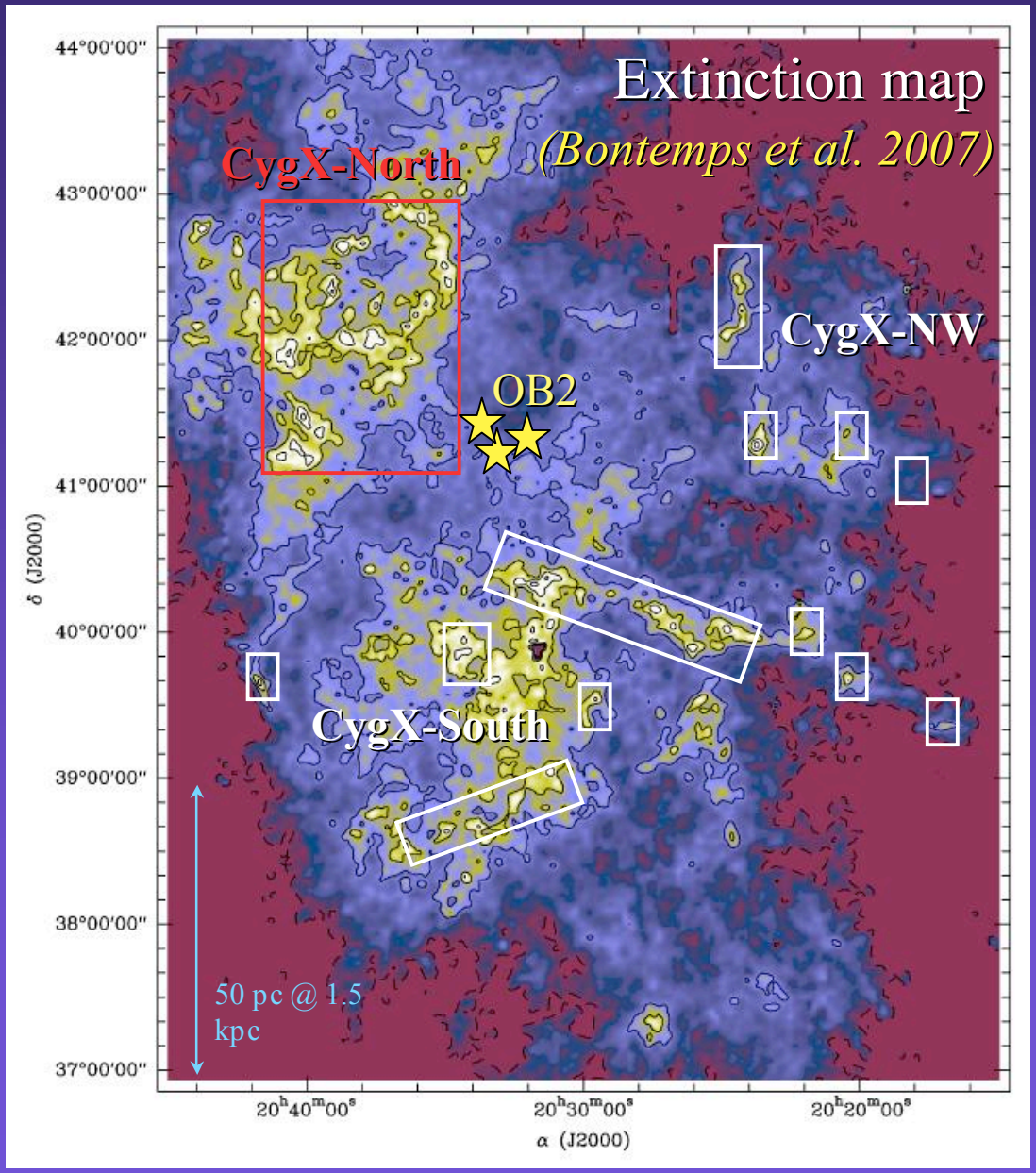


(Schneider et al. 2006)

\+ enough statistics
to survey high-mass protostars
\+ better spatial resolution
than most HMPOs or IRDCs surveys

Cygnus X complex:
massive (4 x 10^6 $M_\odot$)
@ 1.7 kpc
several OB associations.

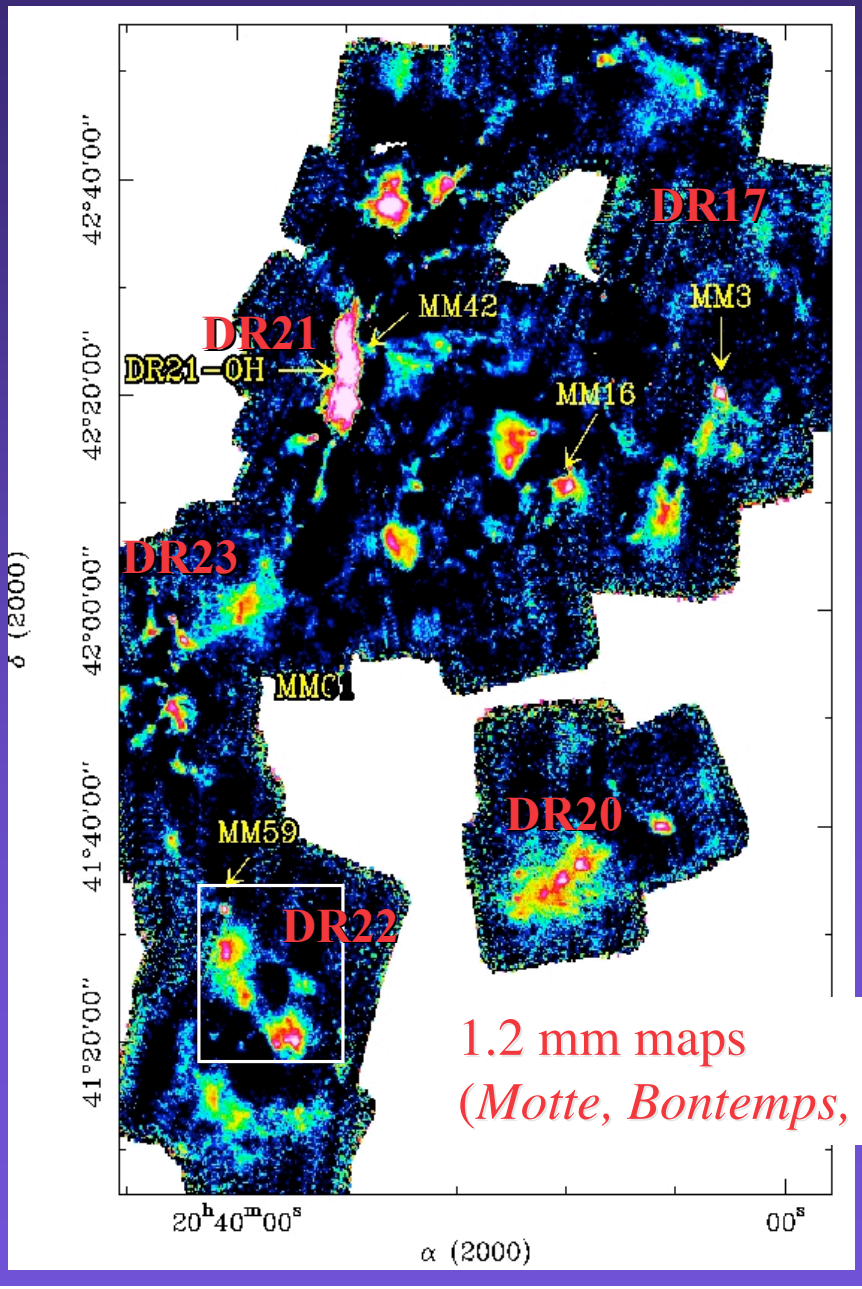
A 1.2 mm continuum survey of Cygnus X



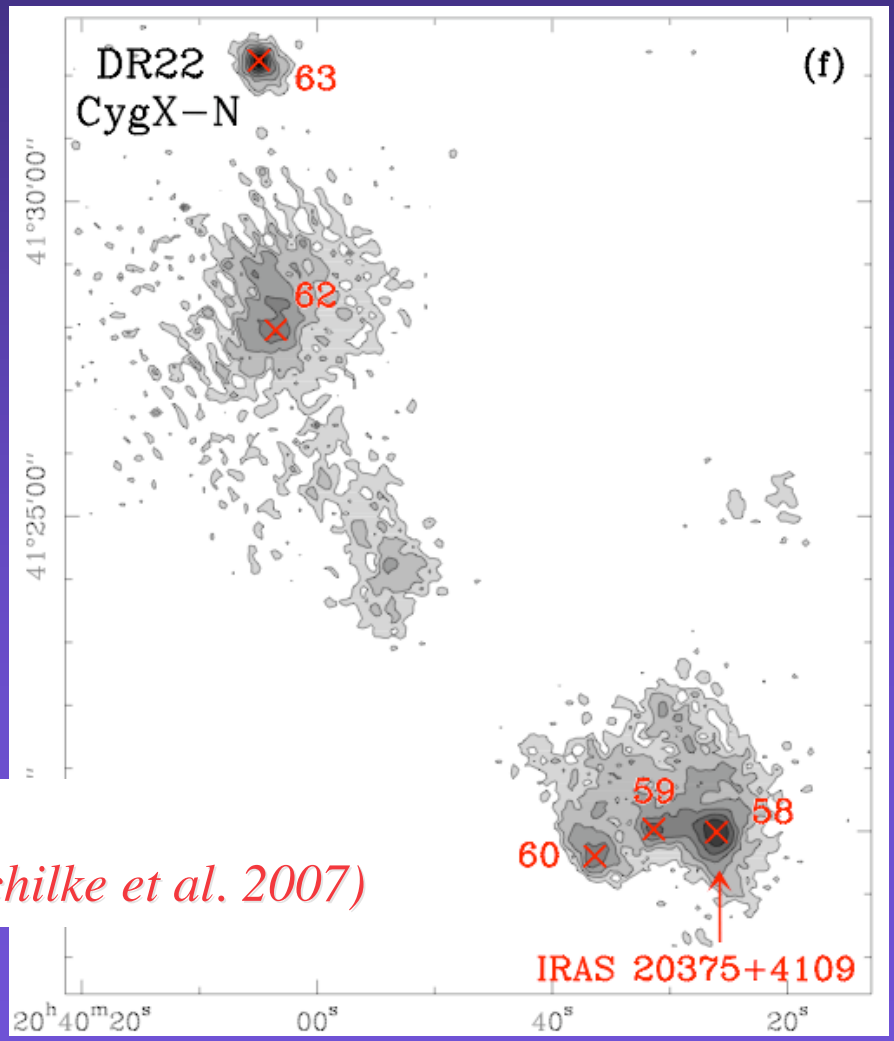
The Cygnus X complex:
~ 3 deg^2 of molecular clouds with $A_v > 15$ mag (from extinction map).

MAMBO-2 mapping at the IRAM-30m (1.2 mm):
Beam = 11"
~ 0.09 pc @ 1.7 kpc
Sensitivity up to ~ 10 '
~ 5 pc
Spatial dynamical range
> 50

Cloud structure probed by MAMBO-2



Dense cores (~ 0.1 pc) within clumps (~ 1 pc):



1.2 mm maps
(*Motte, Bontemps, Schilke et al. 2007*)

A complete sample of dense cores

Dense cores extracted from clumps emission with a multi-resolution analysis of the cloud structure (cf. *Motte et al. 2007)*

➡ 129 dense cores (compact cloud fragments, ~ 0.1 pc):

- <diameter> = 0.03 to 0.2 pc
- mass = 4 to 1000 $M_{\odot}$
- $< n_{H2} > \sim 10^{4}$-10^{6} cm^{-3} (volume-averaged)

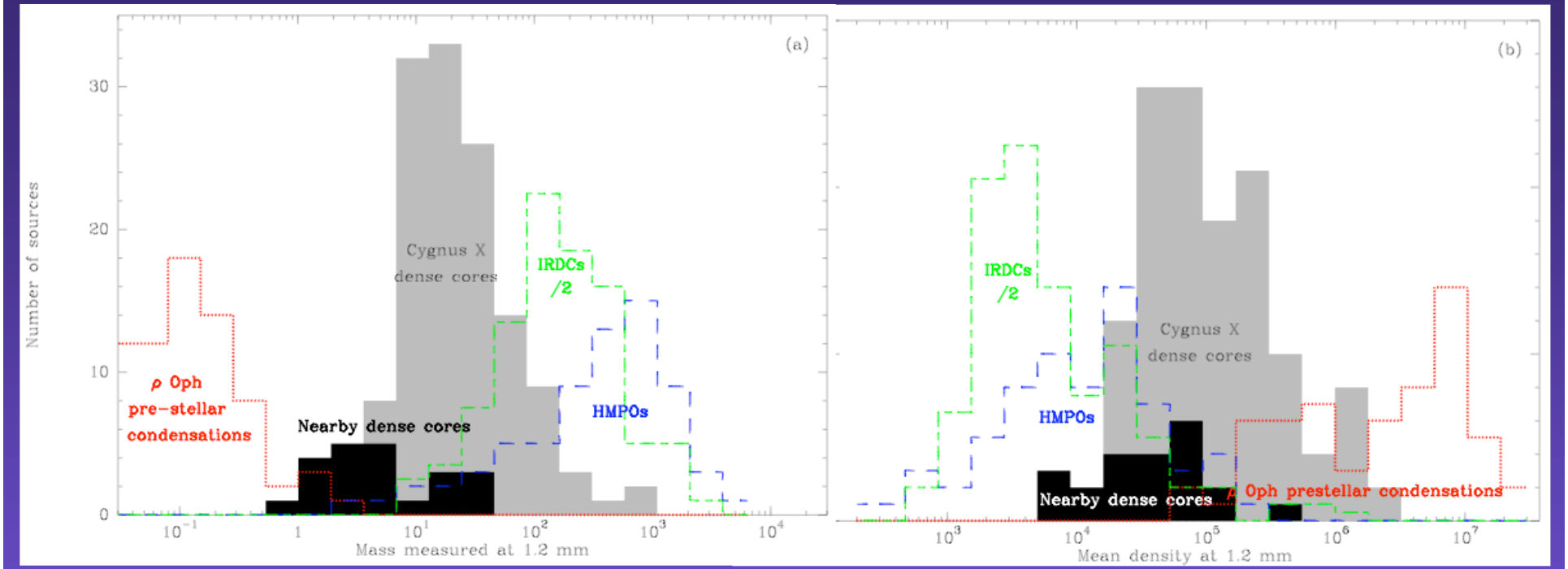
+ unbiased census of massive young stellar objects (from infrared-quiet objects to high-luminosity IR sources)

+ homogeneous sample (d = 1.7 kpc)

- contains low- to intermediate-mass young stellar objects

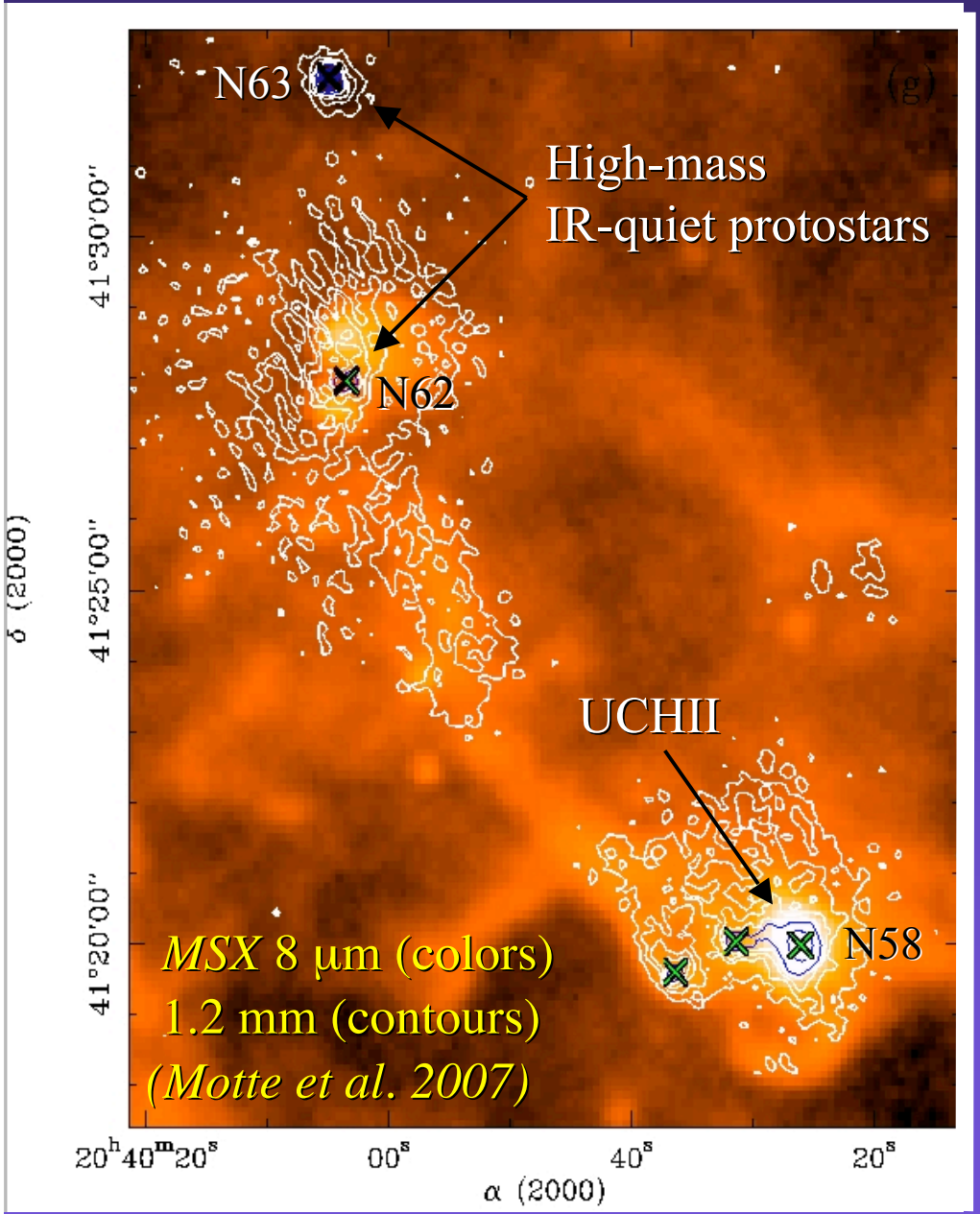
- needs follow-ups to identify high-mass protostars

A sample of high-density cores



	HMPOs clumps	IRDCs clumps	Cygnus X dense cores	Nearby low-mass dense cores	ρ Ophiuchi condensations
FWHM sizes	0.5 pc	0.5 pc	0.1 pc	0.1 pc	0.01 pc
Mass	290 $M_\odot$	150 $M_\odot$	24 $M_\odot$	5 $M_\odot$	0.15 $M_\odot$
Mean Density	8 10^3 cm^{-3}	6 10^3 cm^{-3}	1 10^5 cm^{-3}	3 10^4 cm^{-3}	2 10^6 cm^{-3}
	(Beuther et al. 2002)	*(Rathborne et al. 2006)*	*(Motte et al. 2007)*	*(Ward-Thompson et al. 1999)*	*(Motte et al. 1998)*

Nature of the most massive dense cores



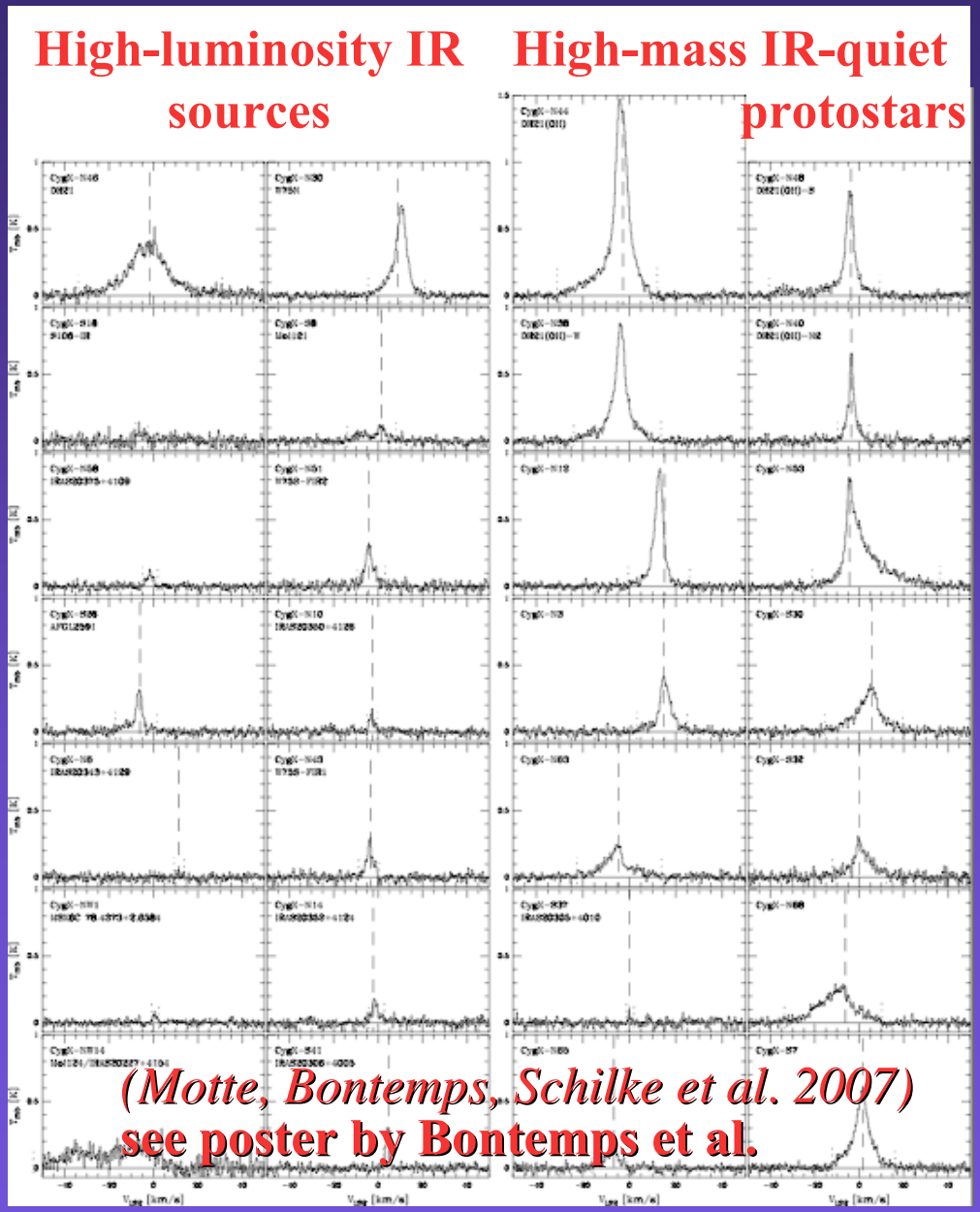
1. Selection of the Cygnus X dense cores with mass > 40 $M_\odot$

2. Inspection of *MSX* images and measurement of the 21 μm flux

In Cygnus X, we identify:
- 15 embedded UCH II s (35%)
- 10 high-luminosity (> 10^3 $L_\odot$) IR protostars (25%)
- 17 high-mass infrared-quiet protostars or starless cores (40%)

3. Search for protostellar activity signatures (outflow, maser, …)

SiO outflows of high-mass protostars



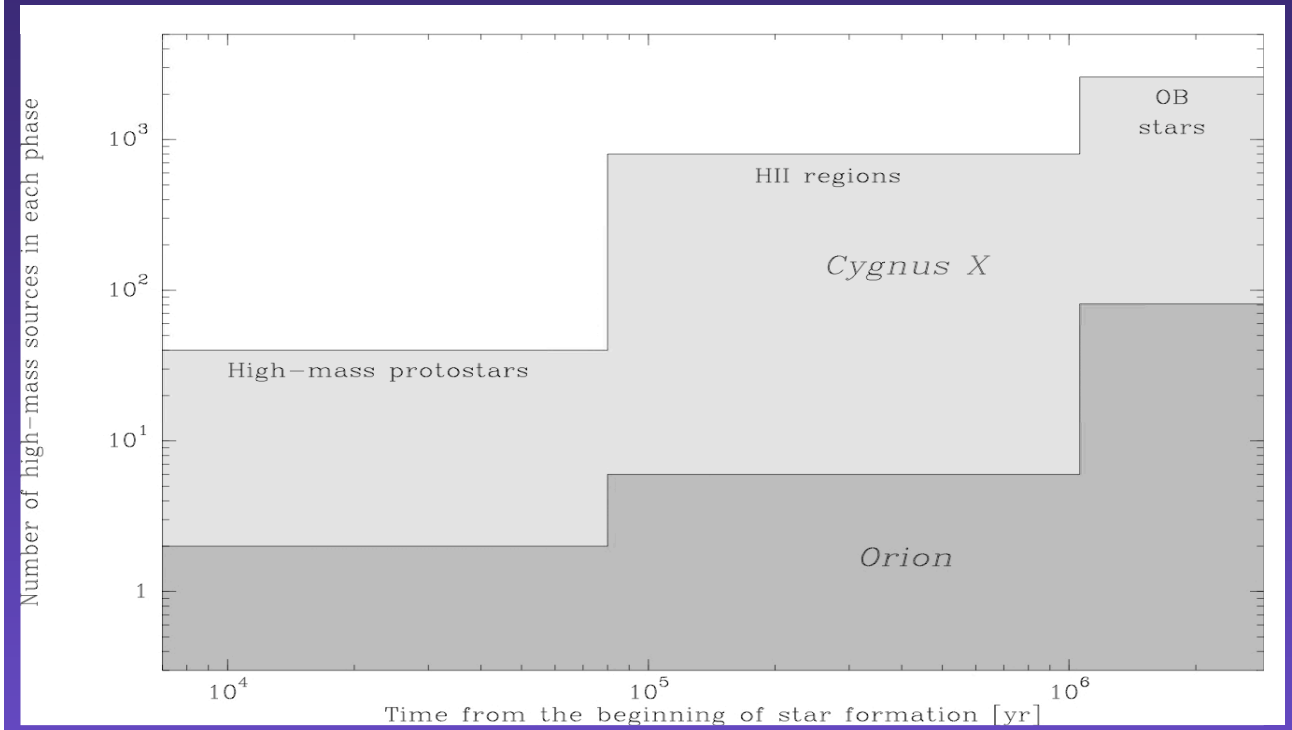
- SiO lines typical of single powerful outflows:
strong line, clear line wings with a regular shape.

- IR-quiet cores drive SiO outflows several x brighter than high-luminosity IR sources or low-mass class 0s

⇒ IR-quiet cores > 40 $M_\odot$ are *all* harboring one high-mass protostar.

⇒ Not a single massive pre-stellar dense core is found!

Lifetime of massive YSOs in Cygnus X



Estimates:

- Free-fall time for $2\ 10^5$ cm^{-3} dense cores

- Statistical lifetimes relative to OB stars

(Motte et al. 2007)

	OB stars	HII regions	High-luminosity IR sources	High-mass IR-quiet protostars	Starless cores
Nb in Cygnus X	2 600	~ 800	23	17	< 1
Statistical lifetime	$2\ 10^6$ yr	~ $6\ 10^5$ yr	**~ $2\ 10^4$ yr**	**~ $1\ 10^4$ yr**	**< $8\ 10^2$ yr**
Predicted Low-mass analogs		10^4-10^5 yr	**0.2-50 10^4 yr** **$2\ 10^5$ yr**	**$8\ 10^4$ yr (free-fall)** **$2\ 10^4$ yr**	**$8\ 10^4$ yr (free-fall)** **$2\ 10^5$ yr**

Conclusions of « cloud structure » surveys

Our unbiased study of the Cygnus X molecular cloud complex:

- provides the first lifetime estimates of

high-mass protostars (3 10^4 yr) and pre-stellar cores (< 10^3 yr)

- shows that the high-mass star formation process is

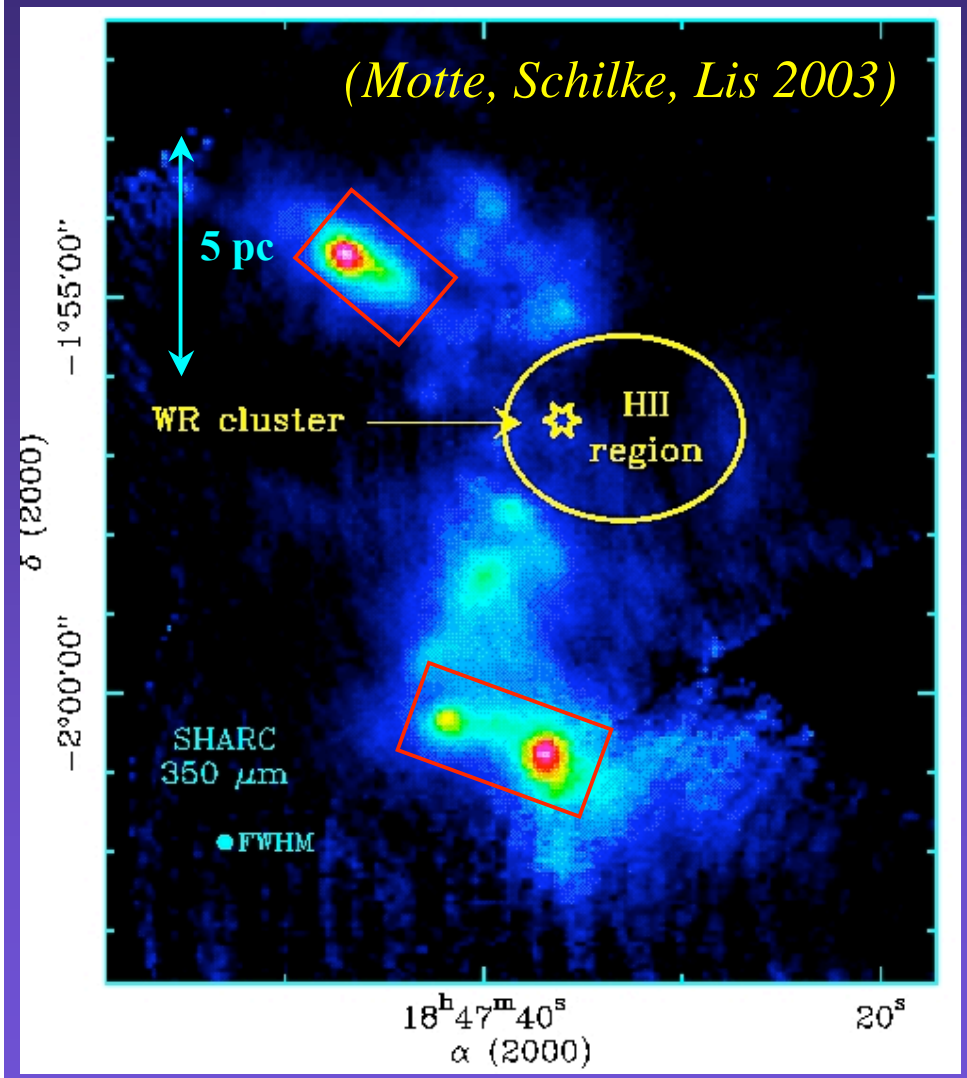
⇒ rapid compared to low-mass star formation in nearby clouds.

⇒ supersonic during its protostellar and starless phases (convergent flows? global contraction?).

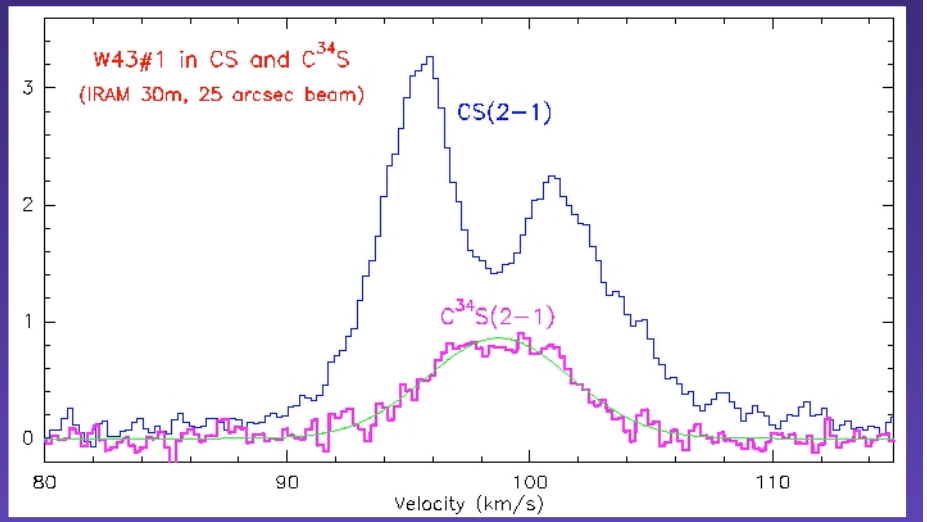
- suggests that high-mass stars are forming in molecular clouds where turbulent processes might dominate.

Similar sub-millimeter studies of other complexes (NGC 6334-6357, NGC 7538) are ongoing. Preliminar results confirm the Cygnus X results.

Insights on « cloud kinematics »: Global collapse of the clouds in W43



W43: 10^6 $M_\odot$, 20 pc, @ 5.5 kpc



Large-scale inward motions observed with HCO^+ and CS lines:

$V_{in} = 2$ km s^{-1} on ~ 3 pc

Inducing fast protostellar collapse?

$\Rightarrow$ accretion rate ~ 10^{-3} $M_\odot$ yr^{-1}

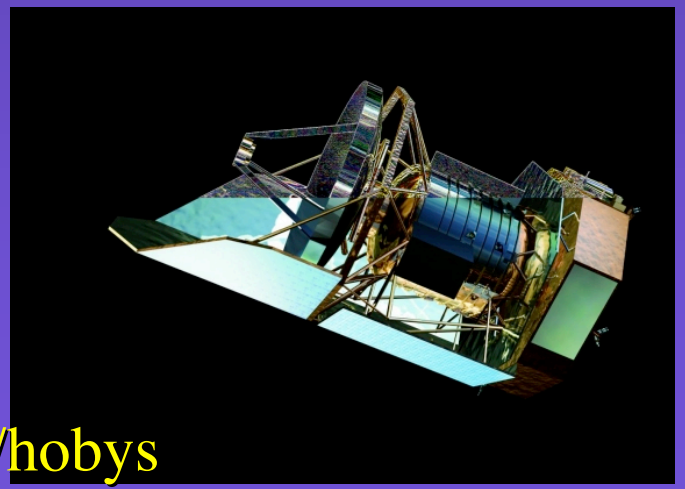
(Motte, Belloche et al.; see also Williams & Garland 2002; Peretto et al. 2005)

HOBYS: the *Herschel* imaging survey of OB Young Stellar objects

An *Herschel* GT key program dedicated to the earliest phases of high-mass star formation:

126 hours = 85 hr of SPIRE GT from the SAG3 (star formation) team
+ 19 hr of PACS GT from LAM/OAMP Marseille
+ 22 hr GT from the *Herschel* Science Center

Coordinators: Motte, Zavagno, & Bontemps



see also http://starformation-herschel.iap.fr/hobys