The earliest phases of high-mass star formation

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Open Questions

- Origin of the stellar masses?
- What regulates SF?
- Is there bimodal SF?
- How do massive stars form?
- Relationship with cluster formation?

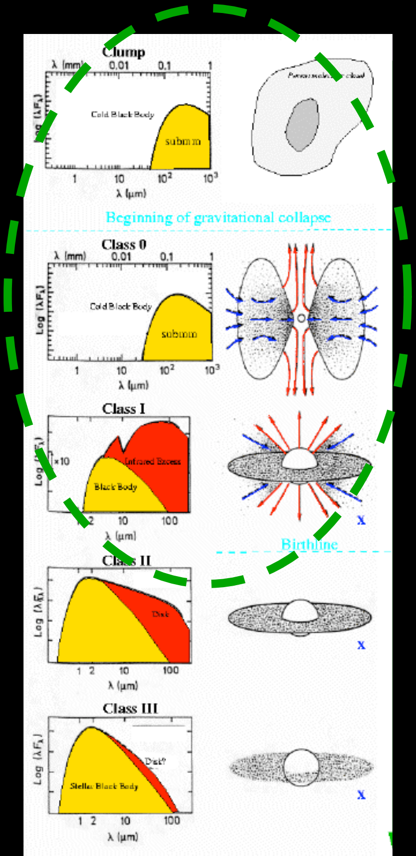
Observation of protostellar objects - earliest phases of SF

- Far-IR / Sub-millimeter radio Astronomy
- Large-scale MM surveys, HERSCHEL, MM interferometry

The general context

Star formation, IMF, high-mass stars

One of the most important open issues in Astrophysics:
- Stars are fundamental in Galaxy evolution.
- The mass (and metallicity) of a star determines its whole life.
- But we do not understand what determines the stellar masses.
- High-mass stars: dominate Gal. + least understood formation



Lada et al. (1987), Shu et al. (1987), André et al. (1993)

Pre-stellar cores + Collapsing protostars

Theoretically:
- Jeans Masses (the pure Gravitational view)
- Shu's scheme (ambipolar diffusion - 10^{-5} M_{sol}/yr collapse)
- Magnetic field dominated (Mouschovias, Ciolek, Basu …)
- Tan & McKee (2003): turbulent support → up to 10^{-3} M_{sol}/yr
- Krumholz et al. (2007): influence of radiation.
- Turbulent fragmentation (e.g. Ballesteros-Paredes et al. 2003).
- Competitive accretion (Bate et al. 2003; Bonnel et al. 2003).

Regulation of SF (origin of the low efficiency of SF, timescale)

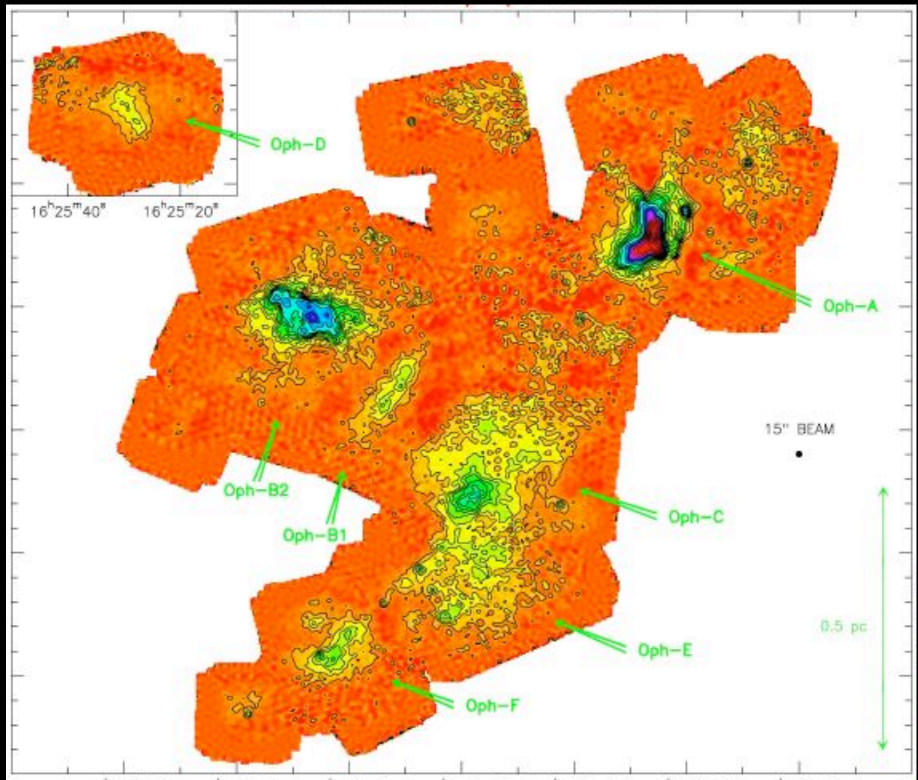
Fragmentation (origin of the IMF)

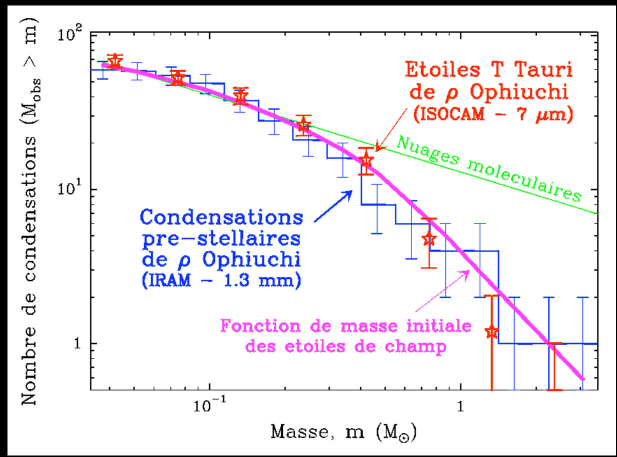
Low-mass SF: Origin of the IMF

Observations of low-mass stars:

• The local IMF is fairly known and seems to be uniform

• It seems that the IMF is determined before the gravitational collapse (Motte et al. 1998; … ; Nutter & Ward-Thompson 2007):





Motte, André and Neri et al.(1998)

Origin of massive stars?

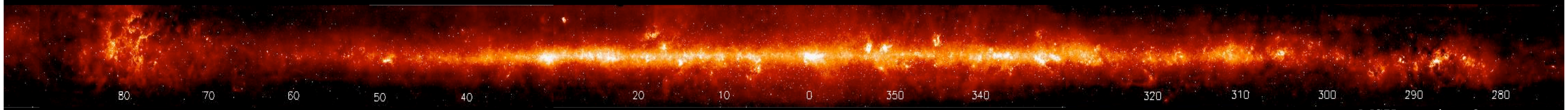
- Jeans or Bonnor-Ebert masses (pure gravitation?).
- Gravo-turbulent fragmentation + shocks (Klessen et al. 00; Vazquez-Semandari et al. 00; Padoan & Nordlund 02; others …).

Extreme, discriminating case or specific process?

- How to collapse 20 à 200 M_{Jeans}?
- Radiation pressure above 10 $M_\odot$ can stop accretion/infall.
- Cluster formation and collective effects/feedbacks.

- *Gravo-turbulent fragmentation*: The few lucky ones?
- *The McKee's view*: slow evolution of turbulent massive dense cores toward collapse.
- *The Bonnell's view*: fast gravo-turbulent fragmentation (~ τ_{ff}) + competitive accretion at the center of proto-clusters.

Survey for the earliest phases of HMSF



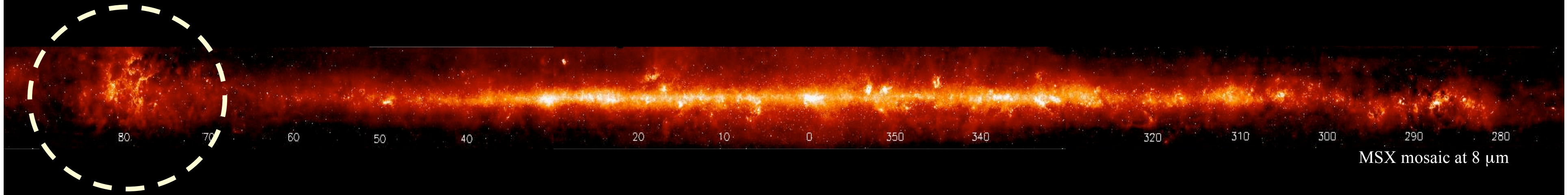
MSX mosaic at 8 µm

1989-2009: 20 years from IRAS to Herschel

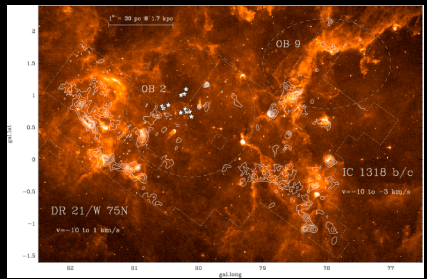
From UCHII regions (back) to the cold phases:

- IRAS: the ~ 2000 red, bright IRAS sources Wood & Churchwell (1989)
- Masers: samples of high-mass SFRs Molinari et al. (1996), Plume et al. (1997), all refs in Kurtz et al. (2000)
- pre-UCHII regions: IRAS sources, no cm Sridharan, Beuther et al. (2002)
- MM continuum: IRAS samples Muller et al. (2002), Faundez et al. (2004), …
- IRDCs: cold but not complete Simon, Rathborne et al. (2006); Pillai et al. (2006)
- MM complete imaging: W43, Cygnus X Motte et al. (2003, 2007)
- Galaxy-scale MM surveys: ATLASGAL Schuller et al. (2009) + Herschel FIR surveys soon…

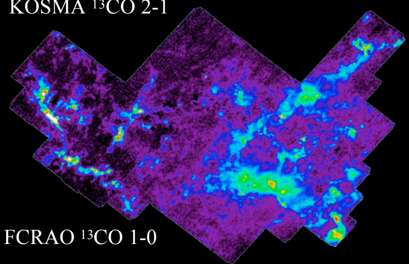
Survey for the earliest phases of HMSF



MSX mosaic at 8 µm

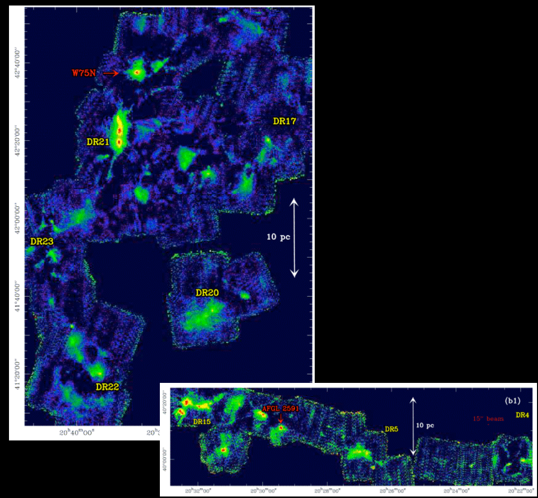


KOSMA ^{13}CO 2-1



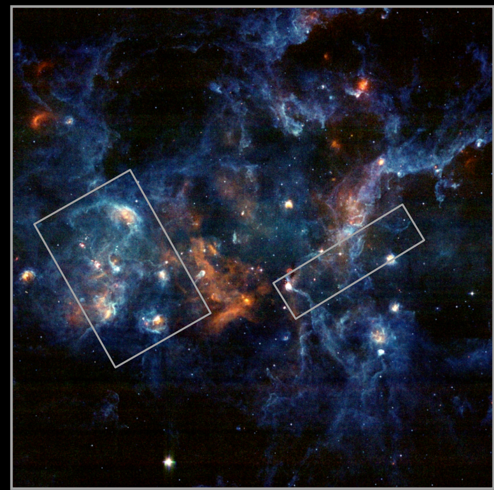
FCRAO ^{13}CO 1-0

Schneider et al. (2006)



IRAM MAMBO 1.3mm

Motte et al. (2007)



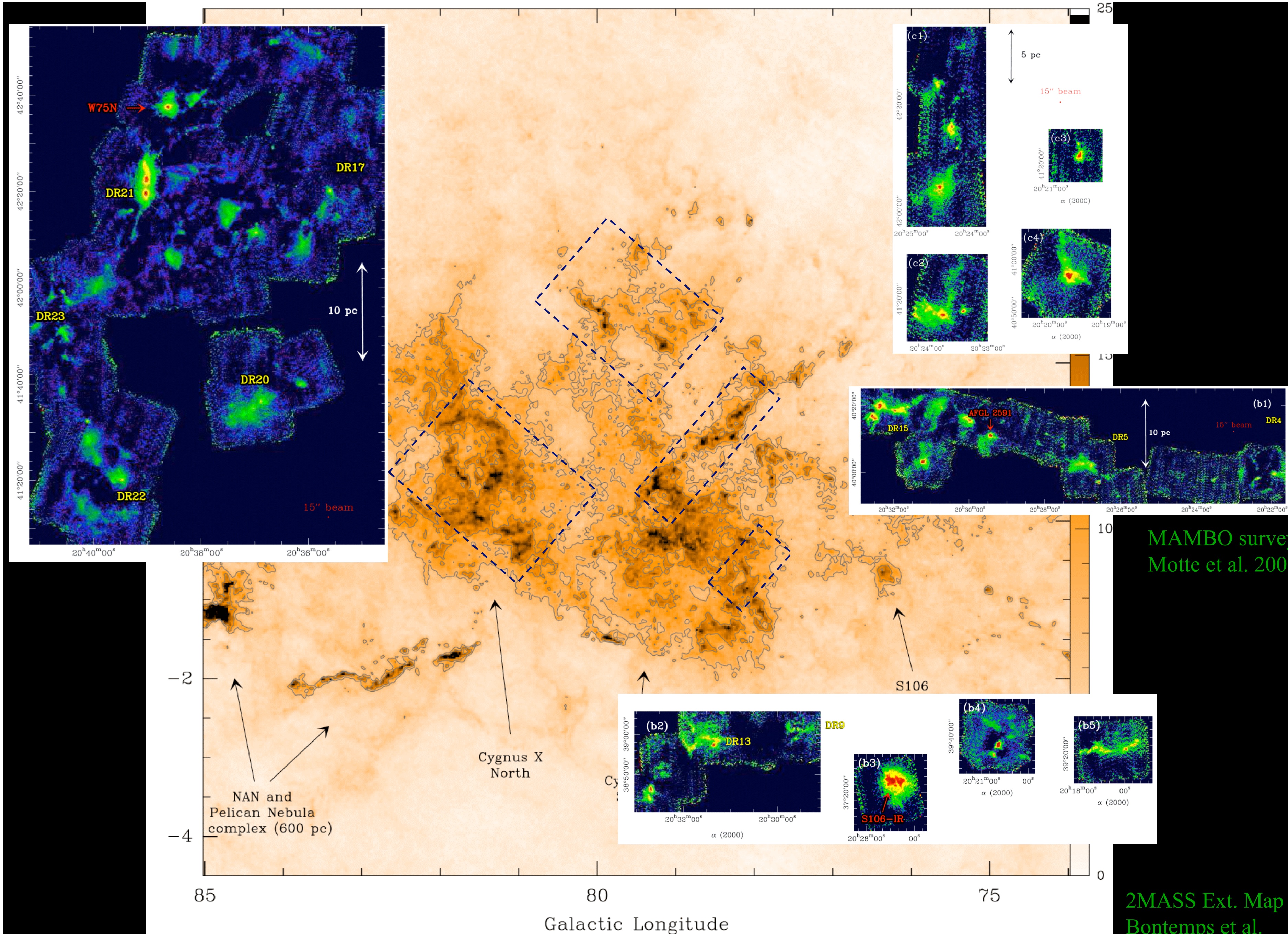
Spitzer Legacy CygnusX 3 - 70 µm

Hora, Bontemps et al. (2007)

Example of Cygnus X: rich complex at 1.7 kpc.

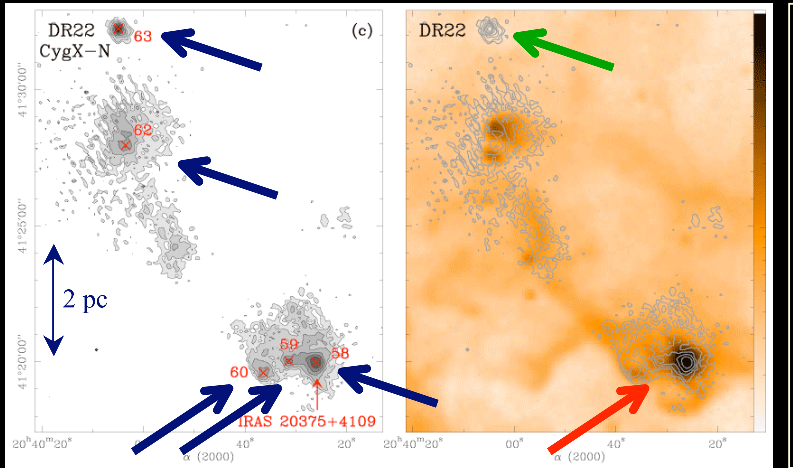
Complete survey (Motte et al. 2007).

High-resolution with the PdBI (Bontemps et al. 2009).

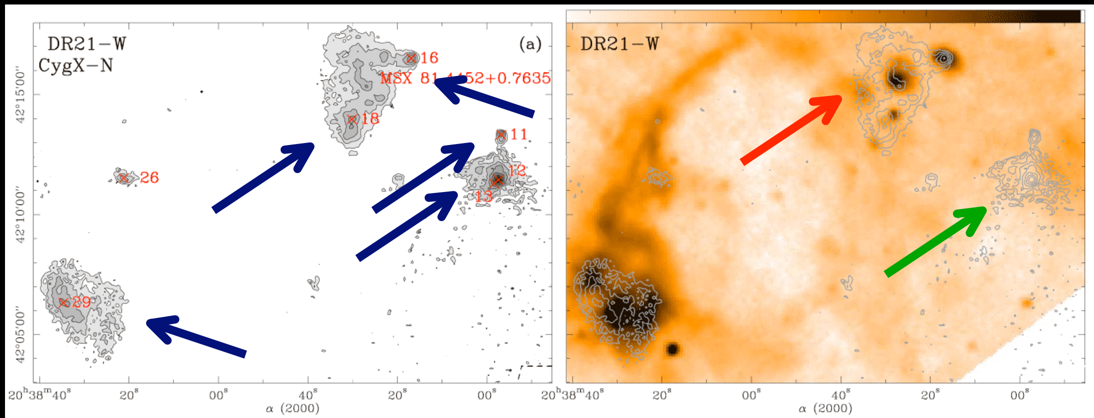


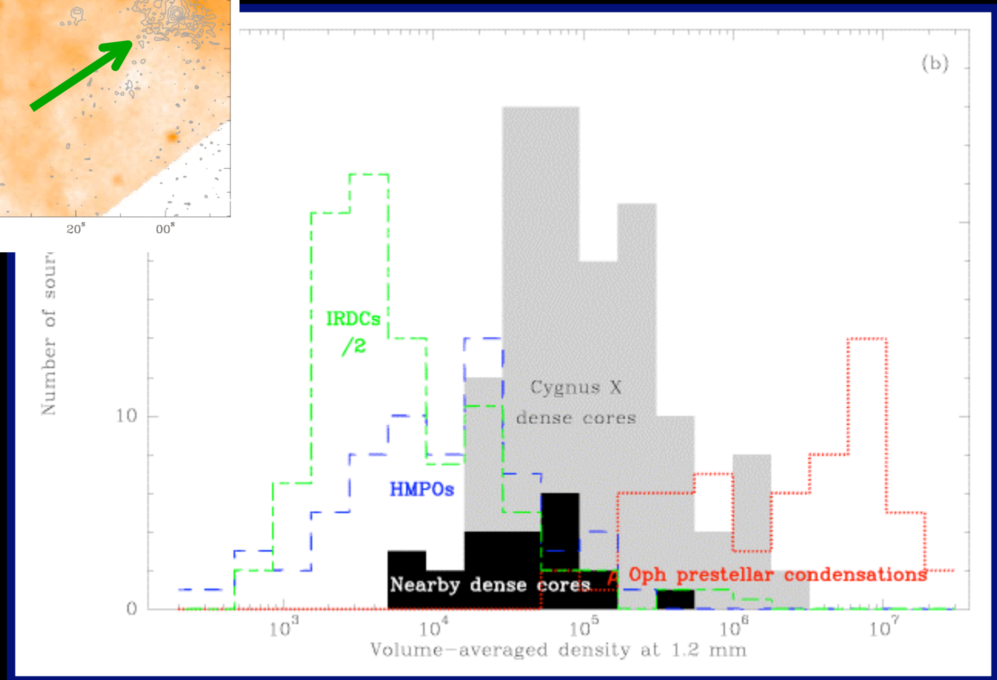
MAMBO survey
Motte et al. 2007

2MASS Ext. Map
Bontemps et al.

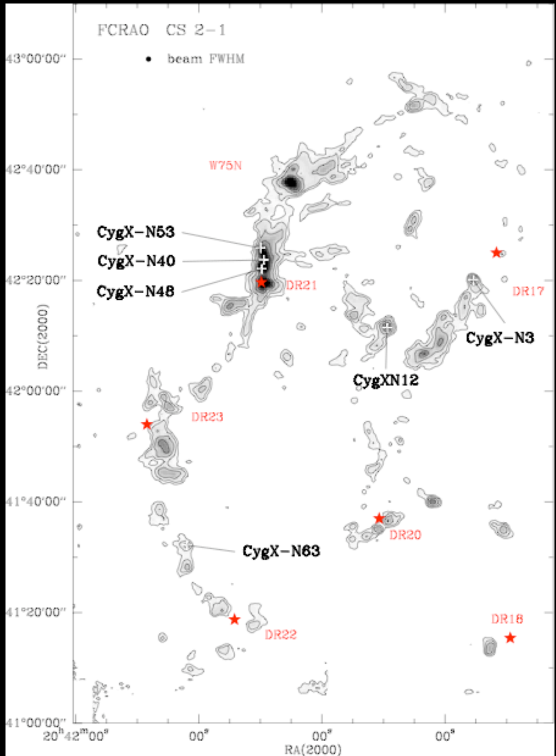


- A sample of 128 massive dense cores (MDCs)
- 33 are more massive than 40 $M_\odot$.
- Same nature than the low-mass dense cores?
- Bright and weak in the IR (IR-quiet).
- All IR-quiet are bright in SiO.
- Short formation timescale (less than 10^4 yr).





Fragmentation in the MDCs of Cygnus X?



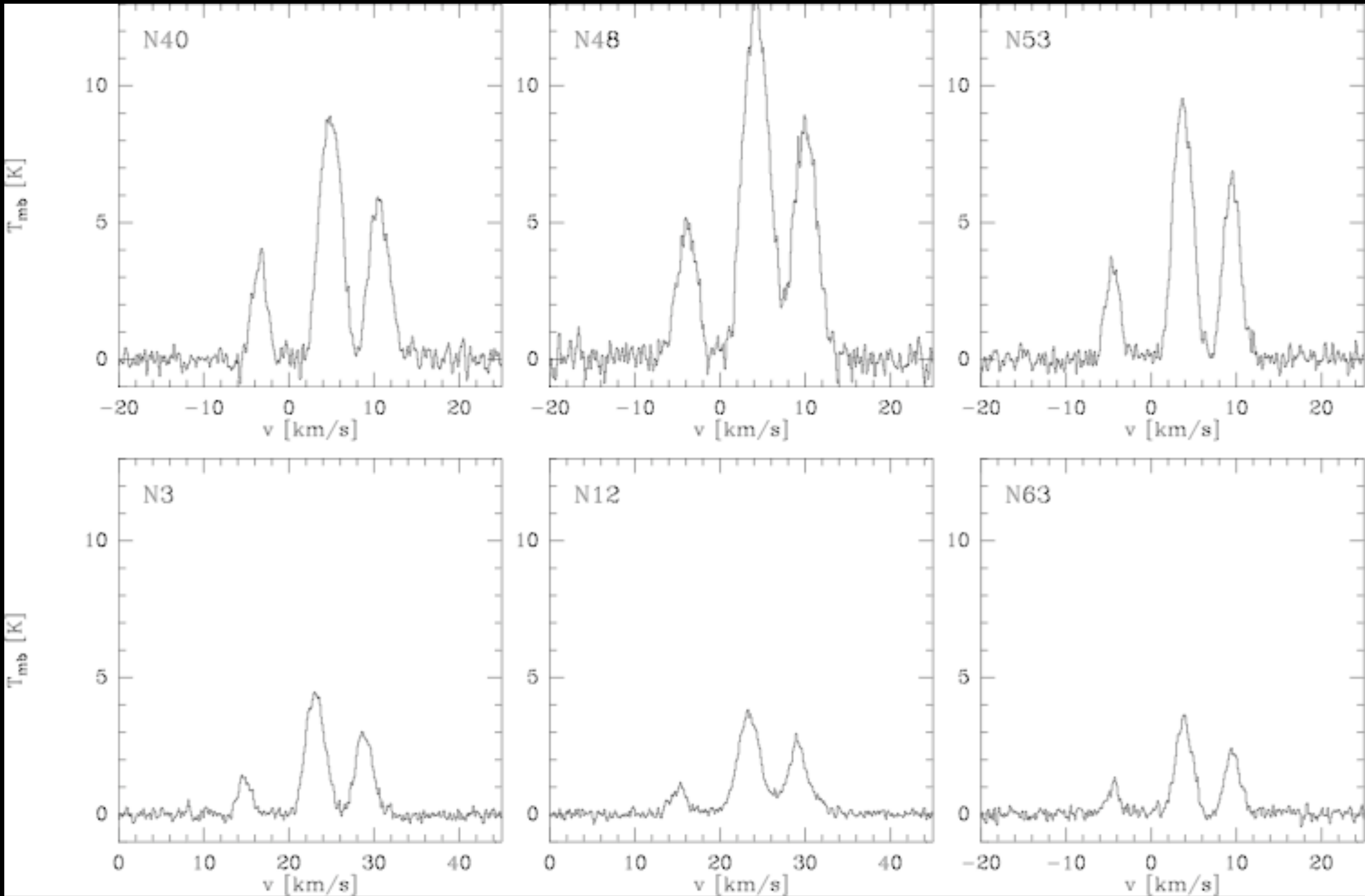
Bontemps et al., 2009, arXiv:0909.2315v1
CS data from FCRAO, Schneider et al.

Table 3.1: Global properties of five IR-quiet MDCs compared to the McKee & Tan [2003] prescriptions (last line).

Name	Mass [$M_\odot$]	Size [AU]	$< n_{H_2} >$ [cm^{-3}]	σ_{turb} [$km.s^{-1}$]	M_{vir} [$M_\odot$]	M_{Jeans} [$M_\odot$]	Σ_{cl} [$g.cm^{-2}$]	τ_{ff} [yr]
CygX-N3	84.0	20300	5.29×10^5	0.98	91.0	1.1	1.45	6.0×10^4
CygX-N12	86.0	20400	5.33×10^5	0.89	75.5	1.1	1.47	5.9×10^4
CygX-N48	197.0	27300	5.10×10^5	1.28	209	1.1	1.88	6.1×10^4
CygX-N53	85.0	24000	3.24×10^5	0.76	64.8	1.4	1.05	7.6×10^4
CygX-N63	58.0	12300	1.64×10^6	0.72	29.8	0.62	2.73	3.4×10^4
McKee&Tan03	60.0	11700	5.60×10^5	1.27	54.7	1.1	1.00	5.8×10^4

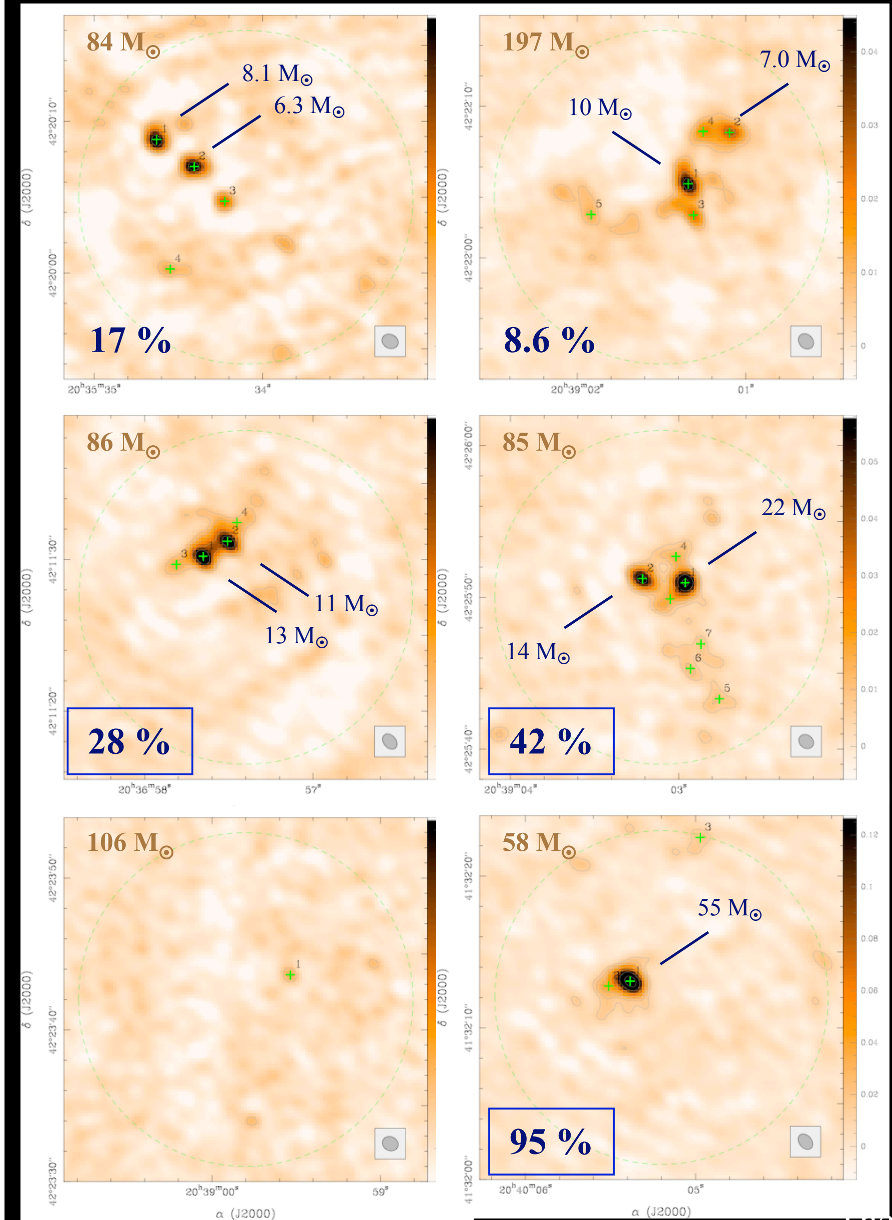
- These MDCs are McKee&Tan's "prototypes"
- Fragmentation according to Dobbs et al. (2005).
- Ten times more massive than in nearby regions.
- Should form OB stars … but how?
- High resolution PdBI down to ~1 arcsec (1700 AU):
  Bontemps et al. (2009), astroph:0909.2315v1

Fragmentation in the MDCs of Cygnus X?



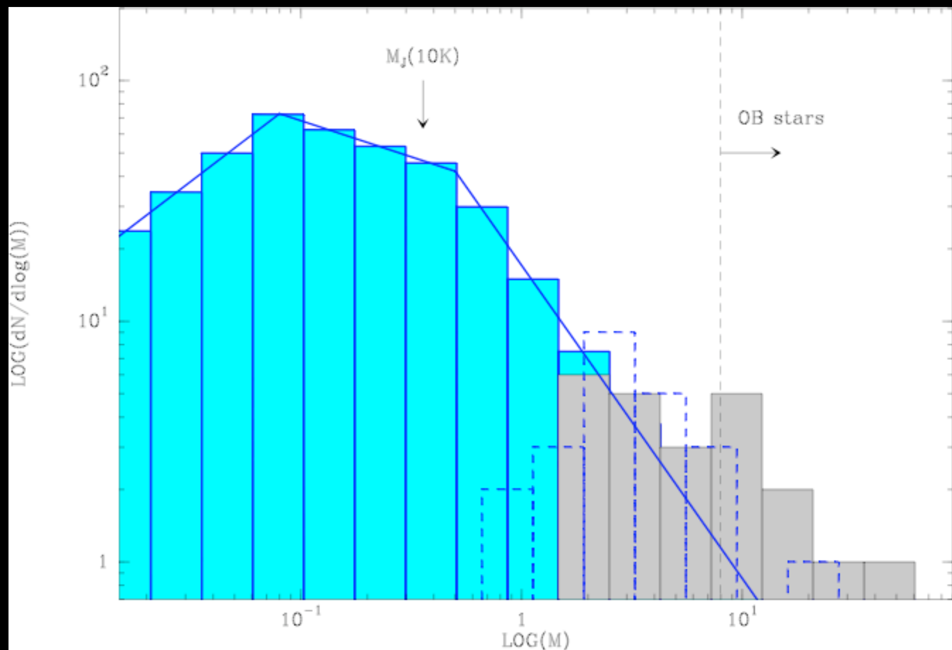
N_2H^+ (1-0) - IRAM 30m

Fragmentation in the MDCs of Cygnus X?



- IMF/SFE 30%: M_{max}= 3.3 $M_\odot$ (80 stars).
- In 3 cores: more than ~30% in 2 protostars.
- Not a normal gravo-turbulent fragmentation.
- Not monolithic collapse either.
- Primordial mass segregation.

Bontemps et al. (2009), astroph:0909.2315



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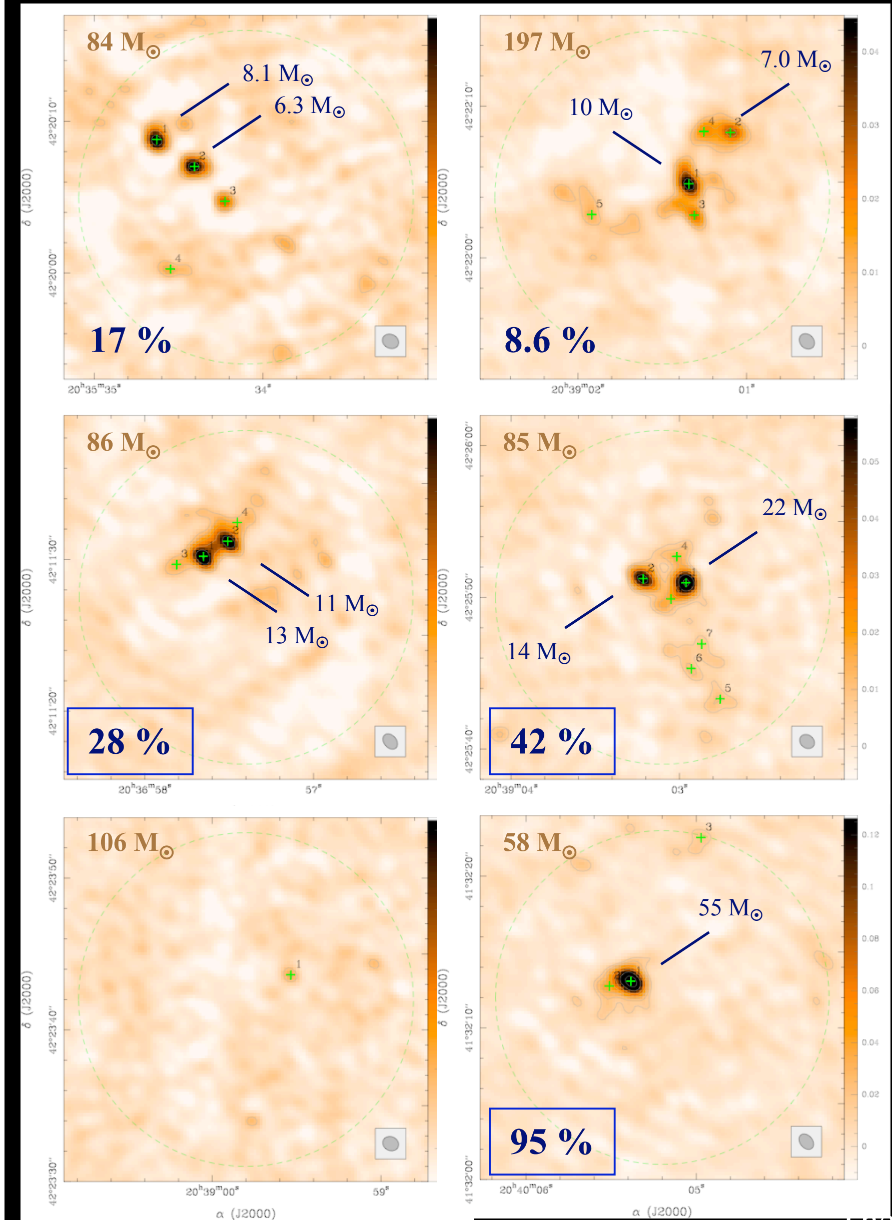

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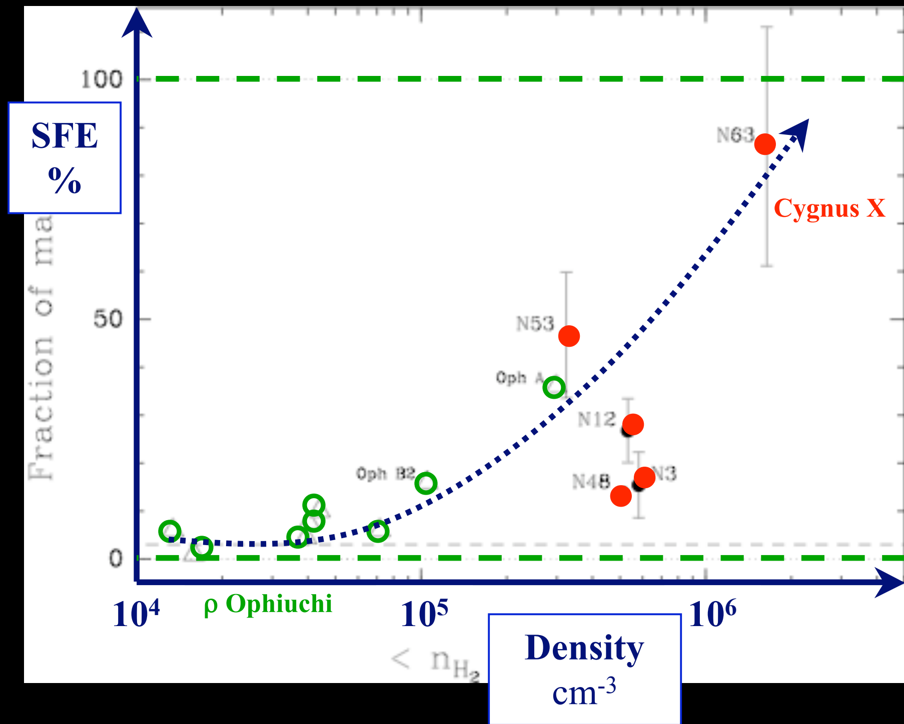
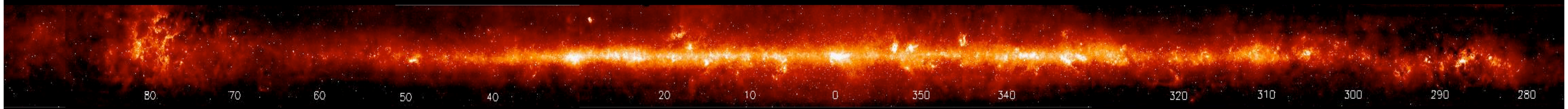


Intermediate Conclusions

- Earliest phases for high-mass SF are observable.
- Individual massive protostars at scales of ~ 2000 AU.
- Seems to show extreme fragmentation properties in dense cores.
- More with line kinematics (see talk of Timea).
- More statistic required.
- See also Rathborne et al. (2007), Beuther et al. (2007), Rodon et al. (2008), Zhang et al. (2009).

Large surveys required: at galactic scales



MSX mosaic at 8 μm

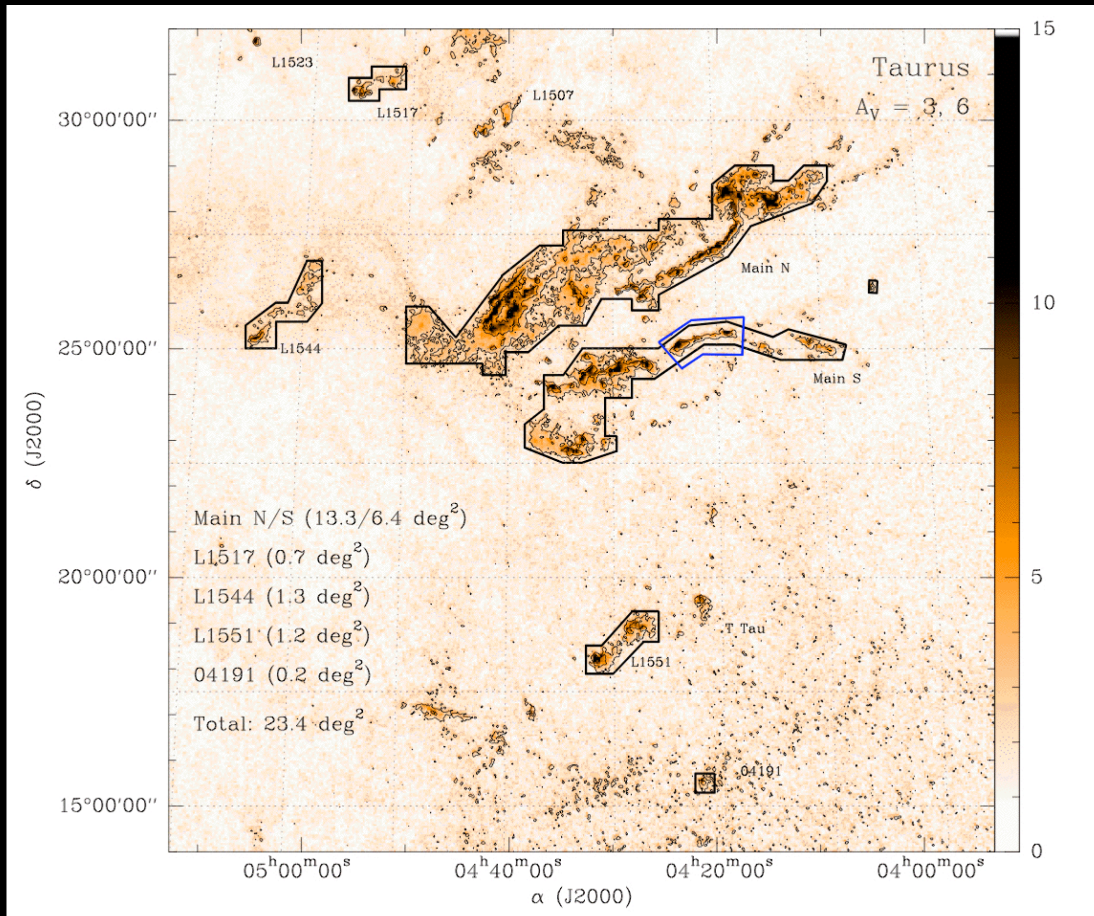
Herschel

- Gould Belt: survey up to 0.5 kpc - 145 deg^2 - 110 to 500 μm.
- HOBYS: survey of 0.5 to 3 kpc - 22 deg^2 - 70 to 500 μm.
- Hi-GAL: the whole galactic plane (240 deg^2 - fast scanning 70 to 500 μm).

Survey at millimeter wavelength

- ATLASGAL: 1st complete survey, APEX large program.
- BOLOCAM/CSO: only north, reduced spatial resolution.
- SCUBA2/GPS: only north (to be started in 2010).

GT key program from SPIRE & PACS consortium/HSC by André et al.



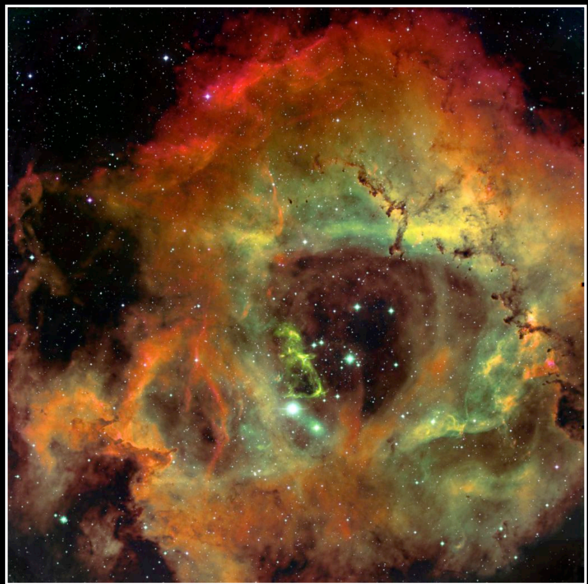
Herschel imaging survey of OB Young Stellar objects

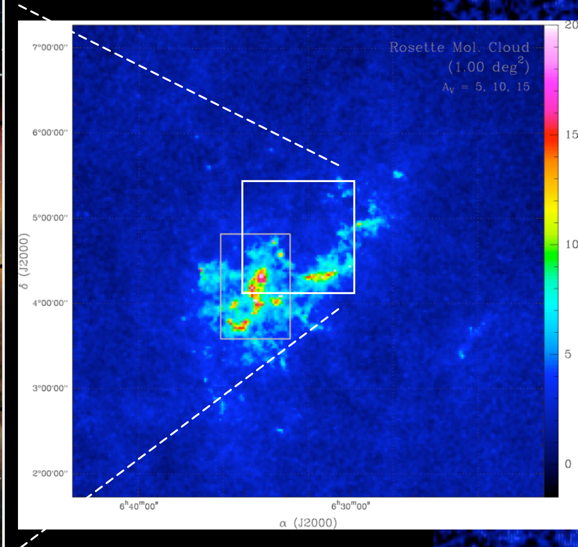
A guaranteed time key programme with Herschel Space Observatory

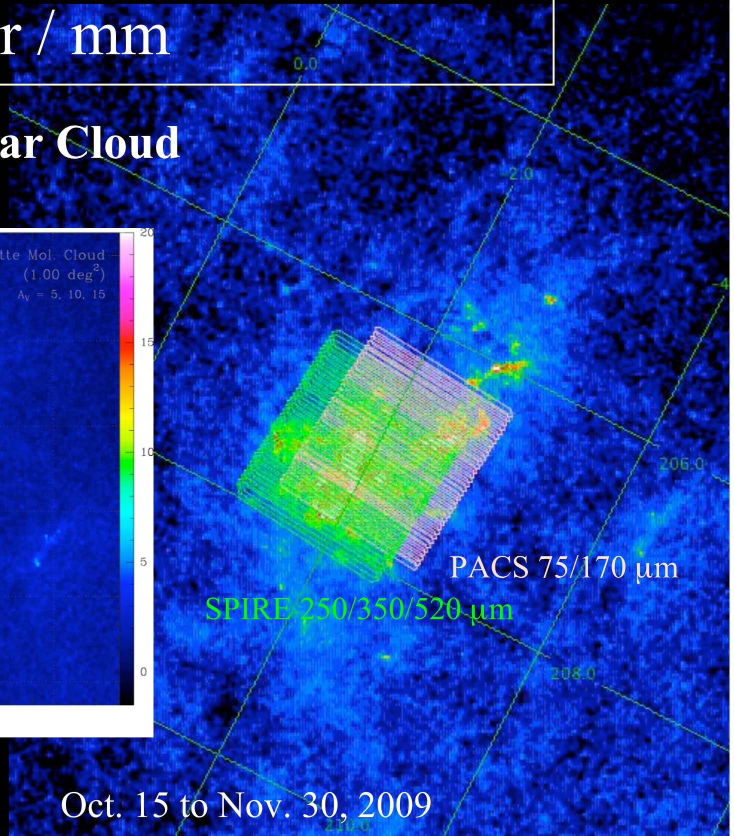
GT key program from SPIRE consortium/HSC by Motte et al.

- The "3 kpc opportunity" with Herschel: HOBYS
- Luminosities and masses to test evolutionary scenarios.
- 75, 170, 250, 350 et 520 µm + Spitzer / mm

Science Demonstration Phase: **The Rosette Molecular Cloud**

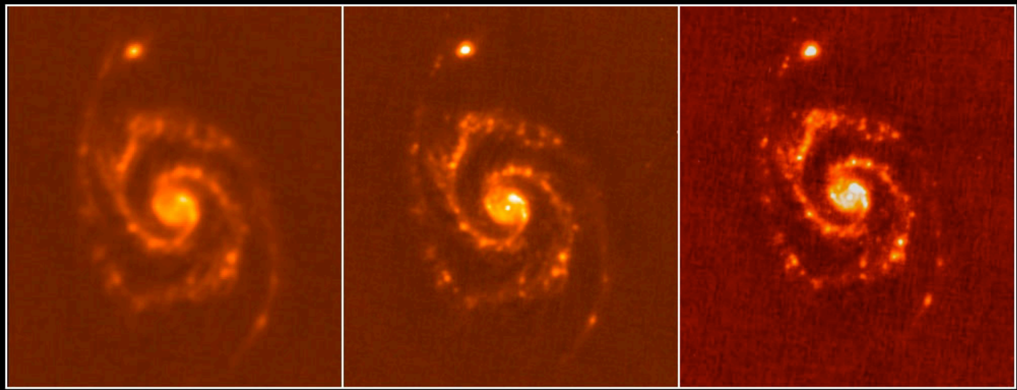






Herschel in space

Herschel/PACS Images of M51 ("Whirlpool Galaxy")



160 µm 100 µm 70 µm

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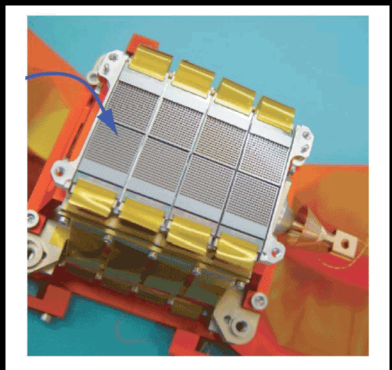


SDP: Oct. - Nov. 2009

Meeting in Dec.

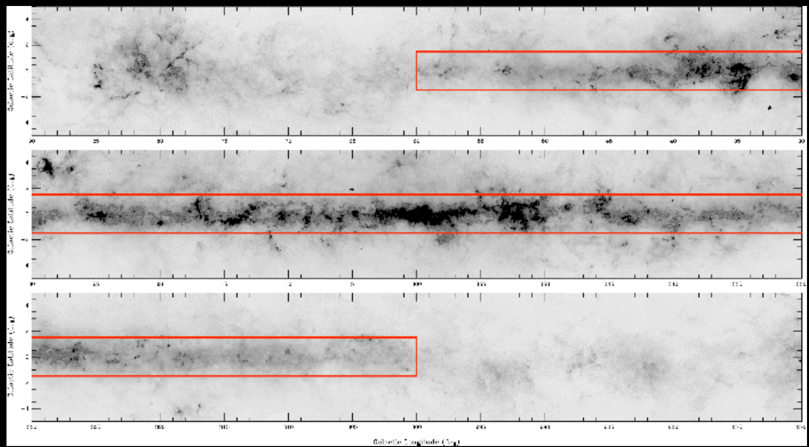
Launch: May 14, 2009.

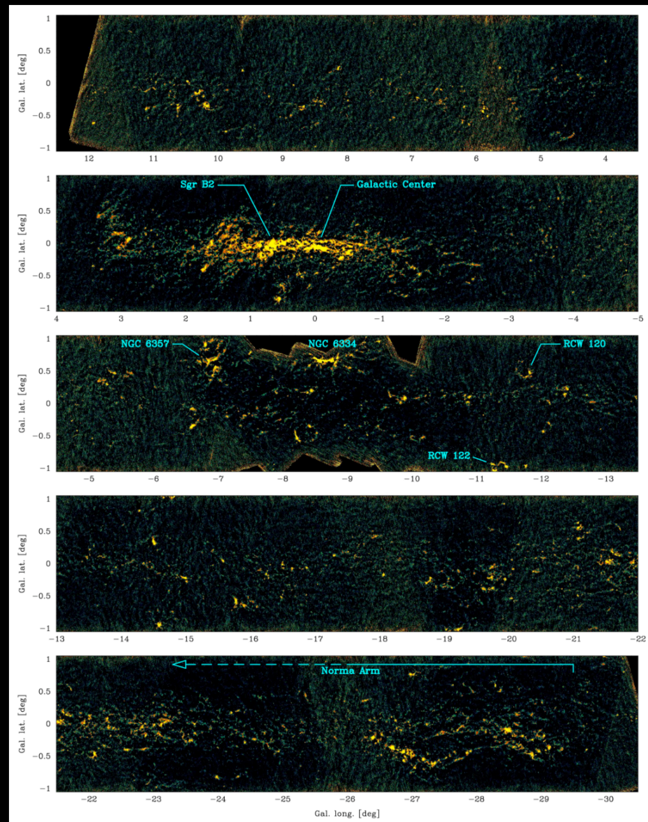
First light: June 15, 2009

ATLASGAL - The APEX Telescope Large Area Survey of the Galaxy at 870 μm

F. Schuller[1], K. M. Menten[1], Y. Contreras[1,2], F. Wyrowski[1], P. Schilke[1], L. Bronfman[2], T. Henning[3], C. M. Walmsley[4], H. Beuther[3], S. Bontemps[5], R. Cesaroni[4], L. Deharveng[6], G. Garay[2], F. Herpin[5], B. Lefloch[7], H. Linz[3], D. Mardones[2], V. Minier[8], S. Molinari[9], F. Motte[8], L.-Å. Nyman[10], V. Reveret[10], C. Risacher[10], D. Russeil[6], N. Schneider[8], L. Testi[11], T. Troost[1], T. Vasyunina[3], M. Wienen[1], A. Zavagno[6], A. Kovacs[1], E. Kreysa[1], G. Siringo[1], and A. Weiß[1]

Schuller et al. 2009, astroph:0903.1369





- -60° to +60° & -1.5° to 1.5°
- 2007-2009, good image quality, 18 arcsec resolution.
- ALMA to resolve protostars.
- Hi-GAL (Molinari et al.) will cover the same area.

Summary

Open Questions

- Origin of the **stellar masses**?
- What **regulates** SF?
- How do **massive stars** form?
- Relationship with **cluster formation**?

Observation of protostellar objects - earliest phases of SF

- **Far-IR** / **millimeter** / radio Astronomy
- Large-scale MM surveys, **HERSCHEL**, MM interferometry

Results from Cygnus X

- **Direct fragmentation** to high-mass protostars?
- Primordial **mass segregation** observed.