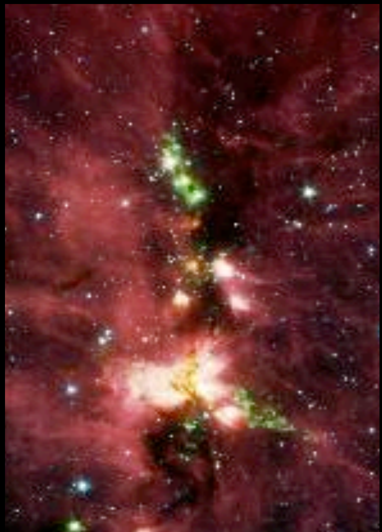
The earliest phases of high-mass star formation



Sylvain Bontemps (LAB/CNRS - Bordeaux Obs./University)

Open Questions

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

The initial conditions of massive star formation

- **Fragmentation** (CMF, evolution?)
- **Kinematics** (turbulent support, flows)
- **Mass segregation**, which stars form first?
- Accretion **rates** and early evolution.

with T. Csengeri, N. Schneider, F. Motte, P. Hennebelle, R. Klessen, C. Federrath, F. Gueth, HOBYS and ATLASGAL consortia.

Origin of massive stars?

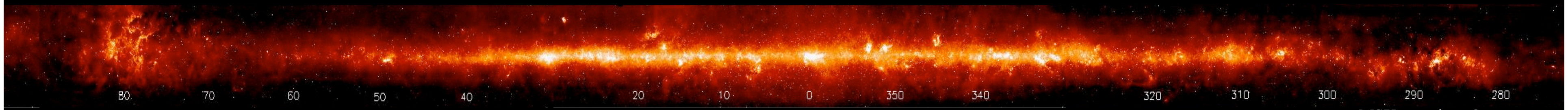
- Jeans or Bonnor-Ebert masses (pure gravitation?).
- Gravo-turbulent fragmentation (shocks) (Klessen et al. 00; Vazquez-Semadeni et al. 00; Padoan & Nordlund 02; others …).

Extreme, discriminating case or specific process?

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

- Slow evolution of turbulence supported massive dense cores toward collapse (McKee & Tan 2003; Krumholz & Mckee 2005; …).
- Fast gravo-turbulent fragmentation ($\sim \tau_{ff}$) + competitive accretion at the center of proto-clusters or hierarchical fragmentation (Bonnell et al. 2001; Vazquez-Semadeni et al. 07; …).
- Fast evolution and small-scale turbulent support (Hennebelle & Chabrier 2009).

Survey for the earliest phases of HMSF



MSX mosaic at 8 µm

1989-2010: 20 years from IRAS to Herschel

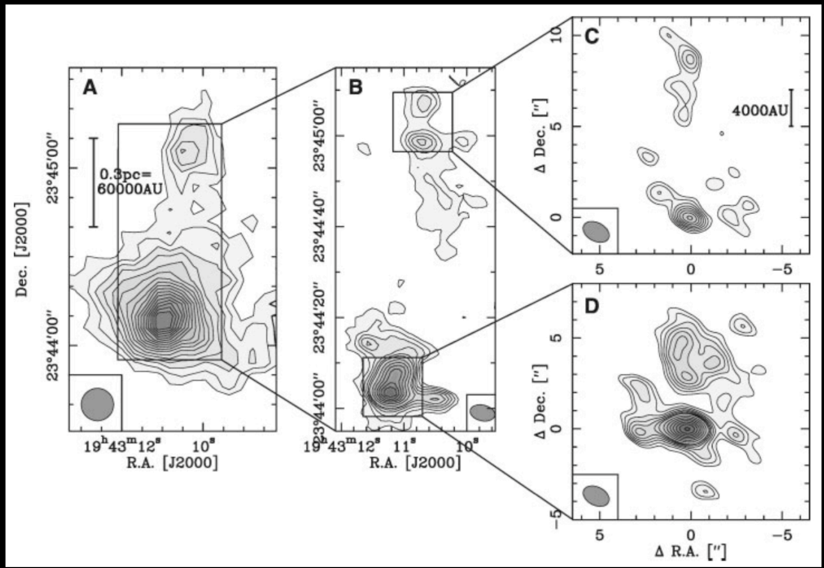
From UCHII regions (back) to the cold phases:

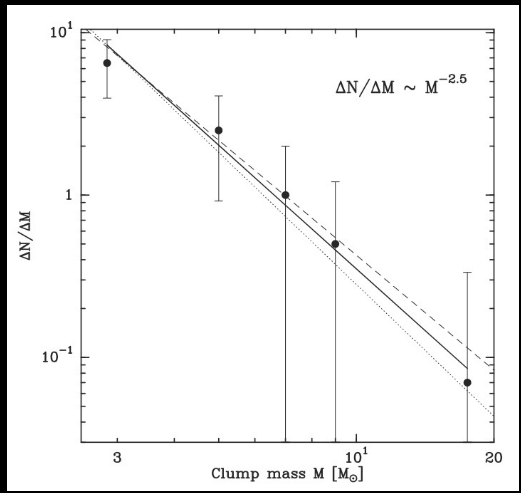
- IRAS: the ~ 2000 red, bright IRAS sources Wood & Churchwell (1989)
- Masers: samples of high-mass SFRs Molinari et al. (1996), Plume et al. (1997), all refs in Kurtz et al. (2000)
- pre-UCHII regions: IRAS sources, no cm Sridharan, Beuther et al. (2002)
- MM continuum: IRAS samples Muller et al. (2002),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

Core Mass Function in the high-mass regime

Not easy to get the statistics at the required spatial resolution:

- Beuther & Schilke 2004, Science 303, 1167.

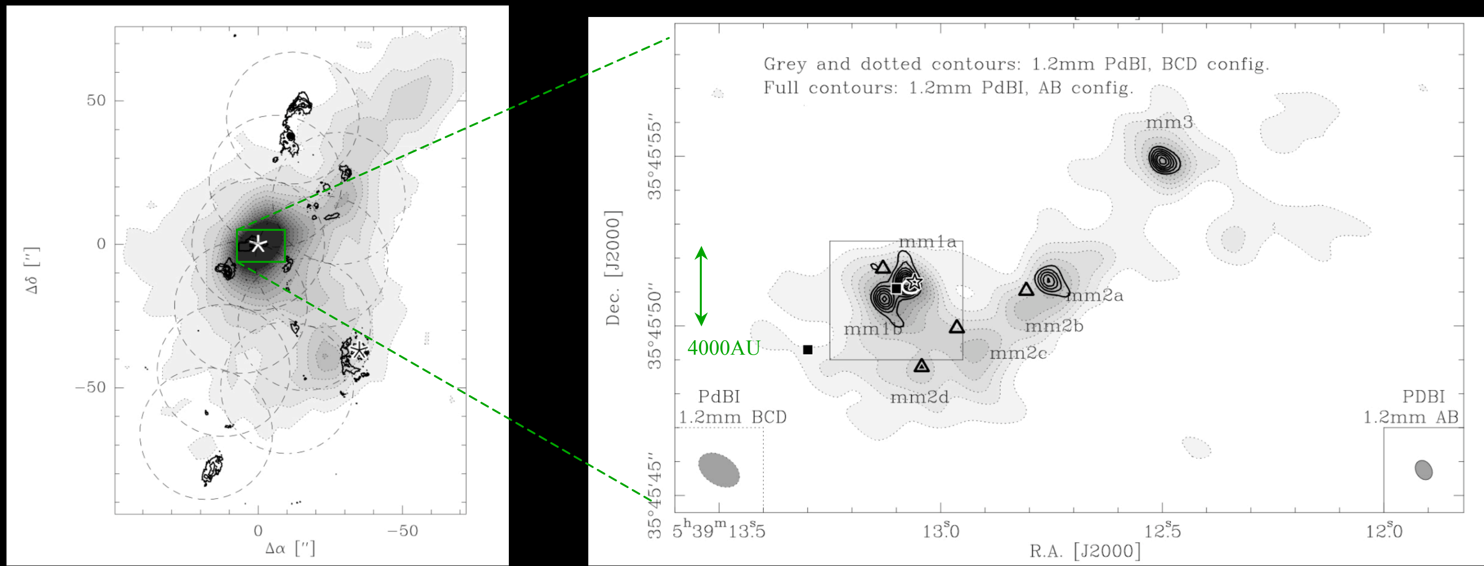




Fragmentation in massive clumps/cores

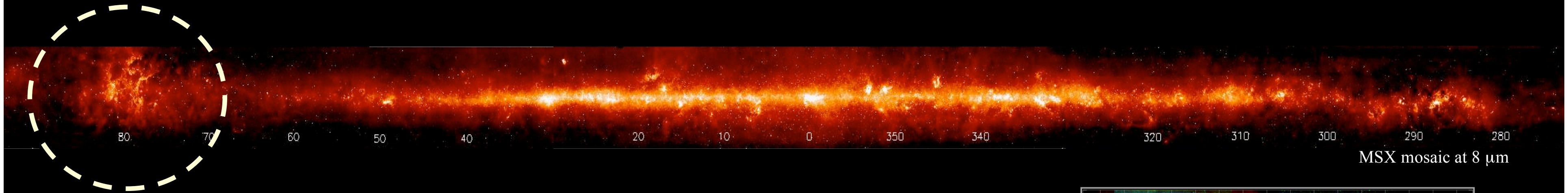
An unclear picture for the scales investigated and separations?

- Beuther et al. (2007); Leurini et al. (2007); Rodon et al. (2008); Brogan et al. (2010); Rathborne et al. (2007, 2009), Zhang et al. (2009, 2010).

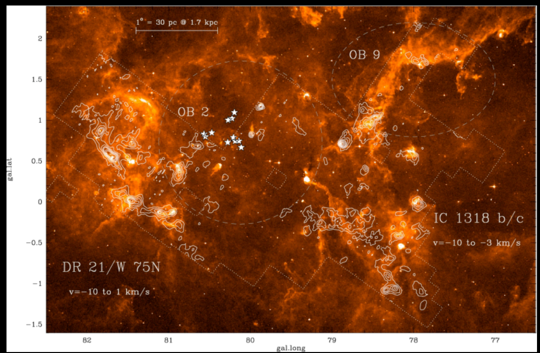


… massive star-forming regions at different (large) distances.

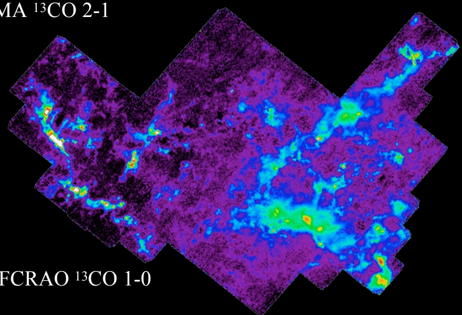
Fragmentation in MDCs in Cygnus X



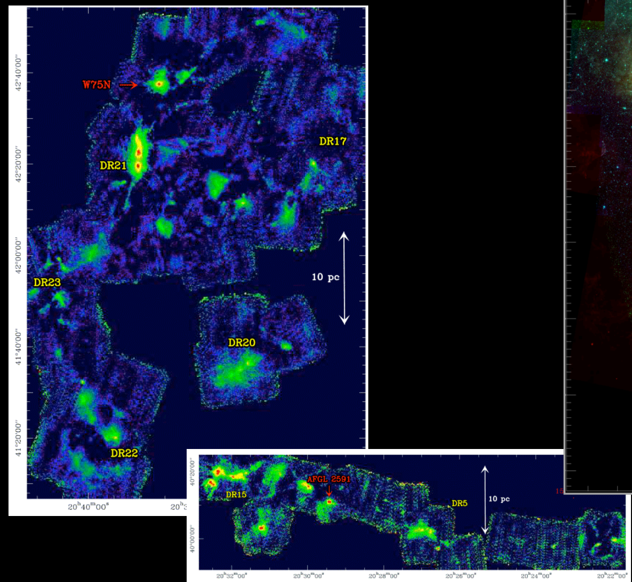
MSX mosaic at 8 µm



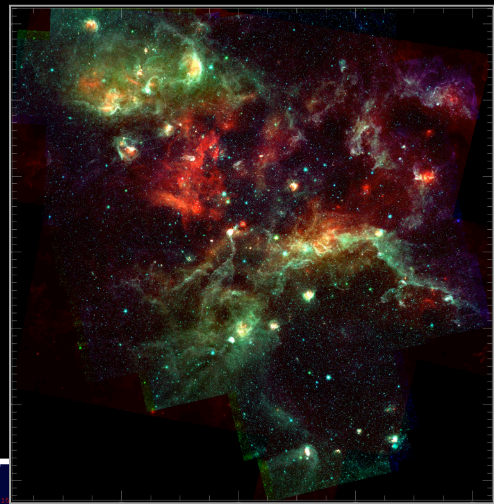
KOSMA ^{13}CO 2-1



FCRAO ^{13}CO 1-0

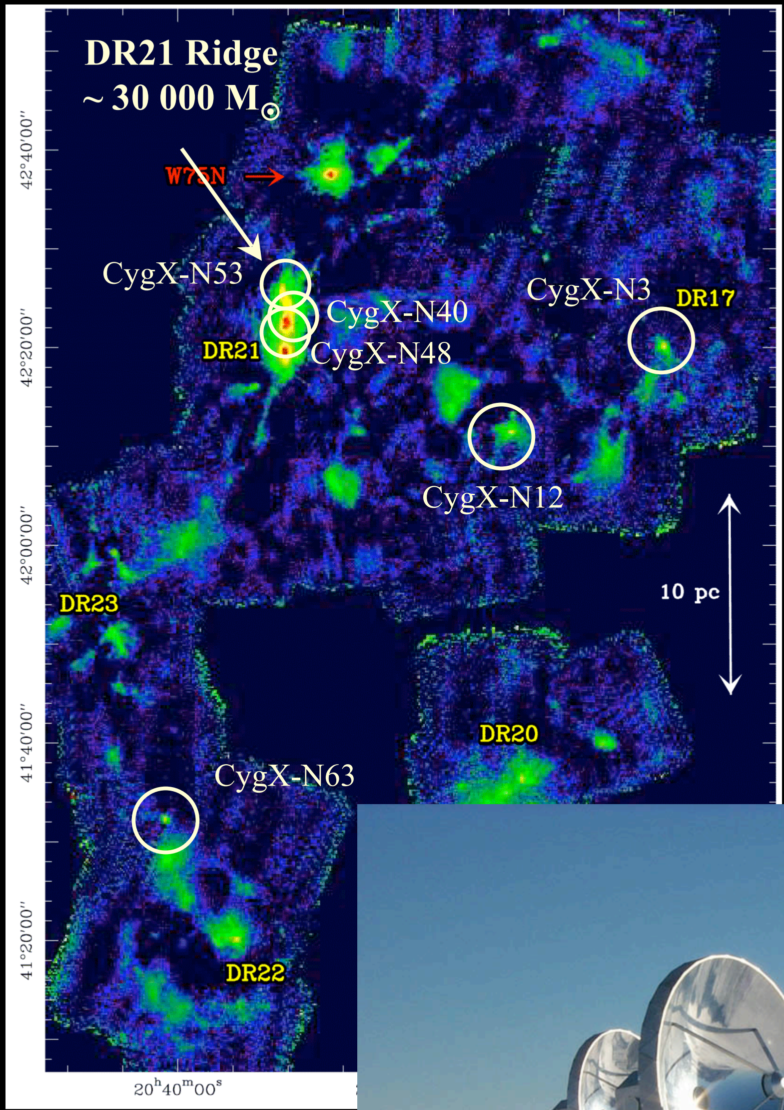


IRAM MAMBO 1.3mm



Spitzer Legacy CygnusX 3 - 70 µm

Schneider, Bontemps, Simon et al. (2006) Motte, Bontemps, Schilke et al. (2007) Hora et al. (2007)

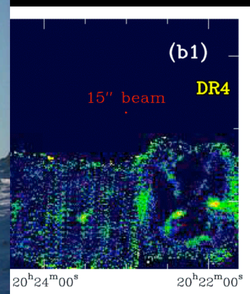


IRAM MAMBO 1.3mm

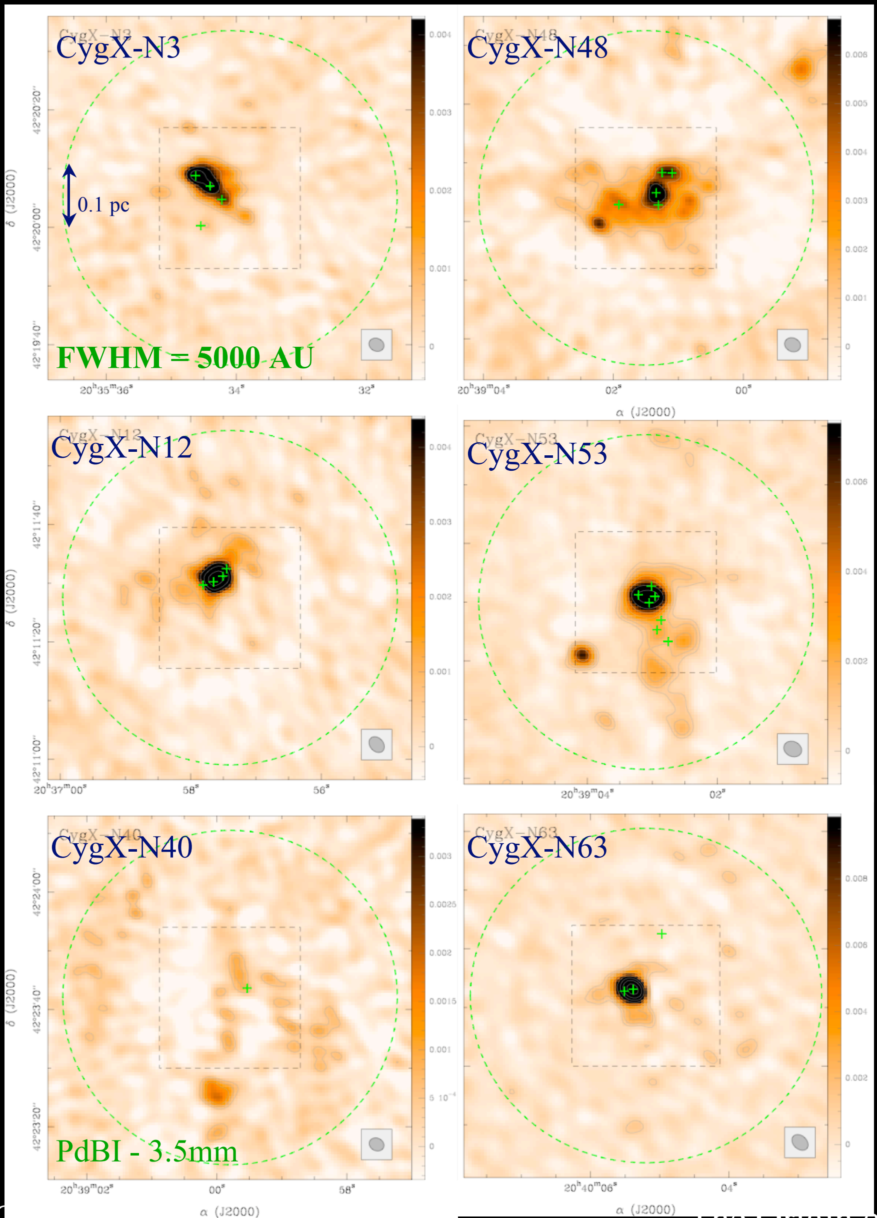
Motte, Bontemps, Schilke et al. (2007):
- 129 massive dense cores (MDCs)
- 33 are more massive than 40 $M_\odot$.
- All IR-quiet are bright in SiO.
- Short formation timescale.

IRAM PdBI: 6 massive IR-quiet MDCs:
- 60 to 200 $M_\odot$, down to 1700 AU.
- 1.3mm / 3mm continuum.
- $H^{13}CO^+$(1-0) line.

Talk of Timea Csengeri



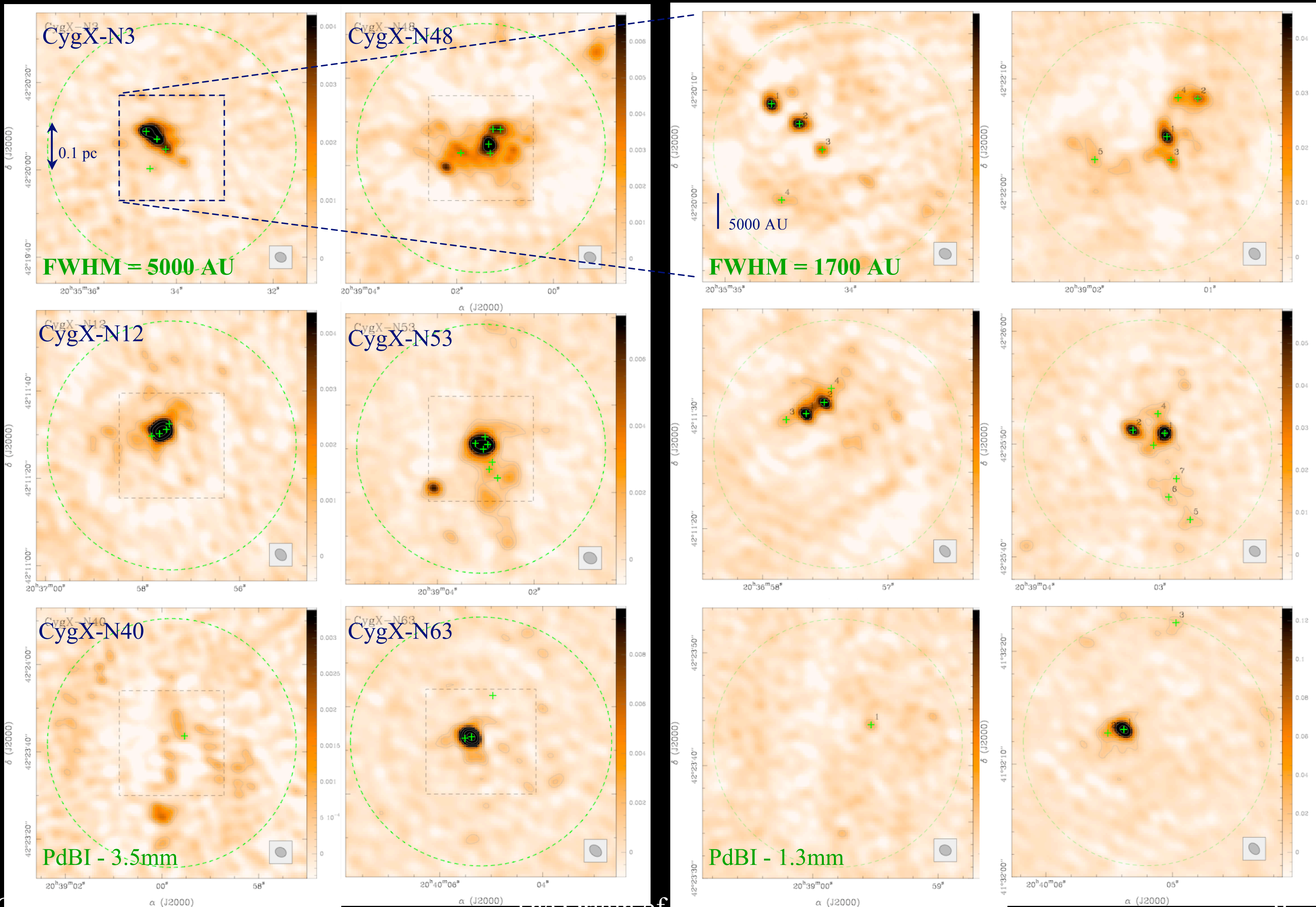
Fragmentation in MDCs in Cygnus X



PdBI continuum 3.5 mm
3 arcsec res. (5000 AU)

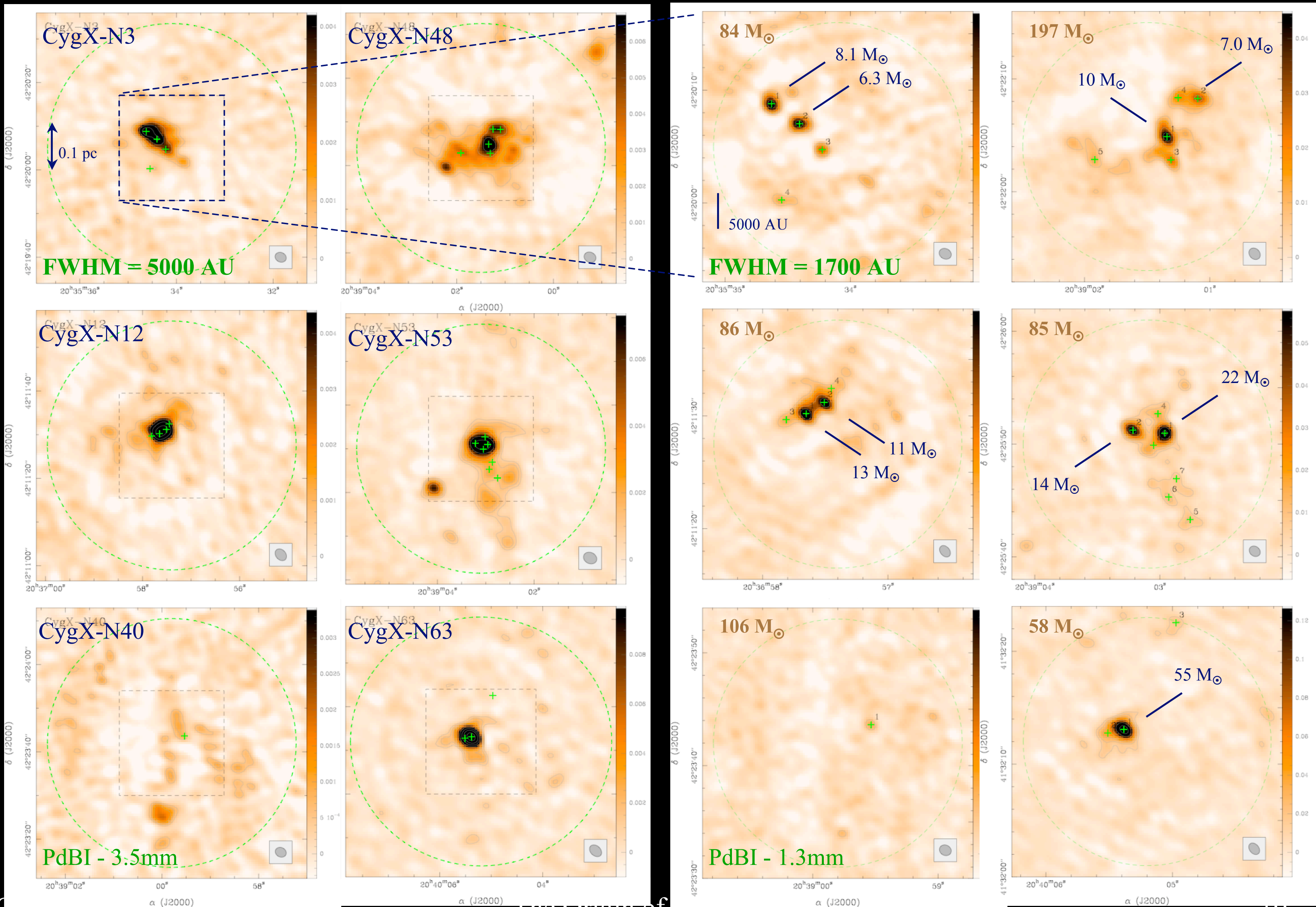
Fragmentation in MDCs in Cygnus X

Mass inside 3000 AU FWHM



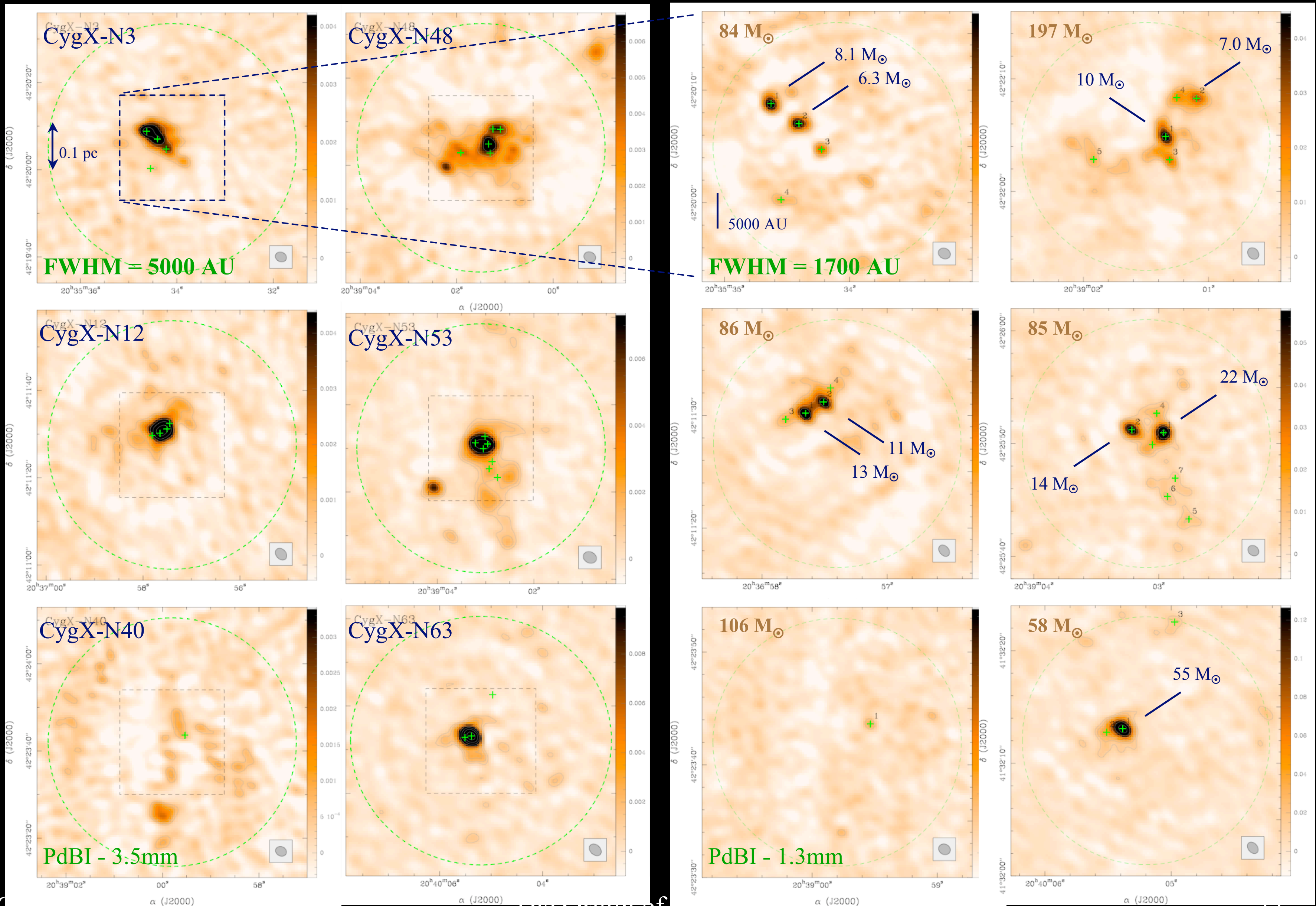
Fragmentation in MDCs in Cygnus X

Mass inside 3000 AU FWHM



Fragmentation in MDCs in Cygnus X

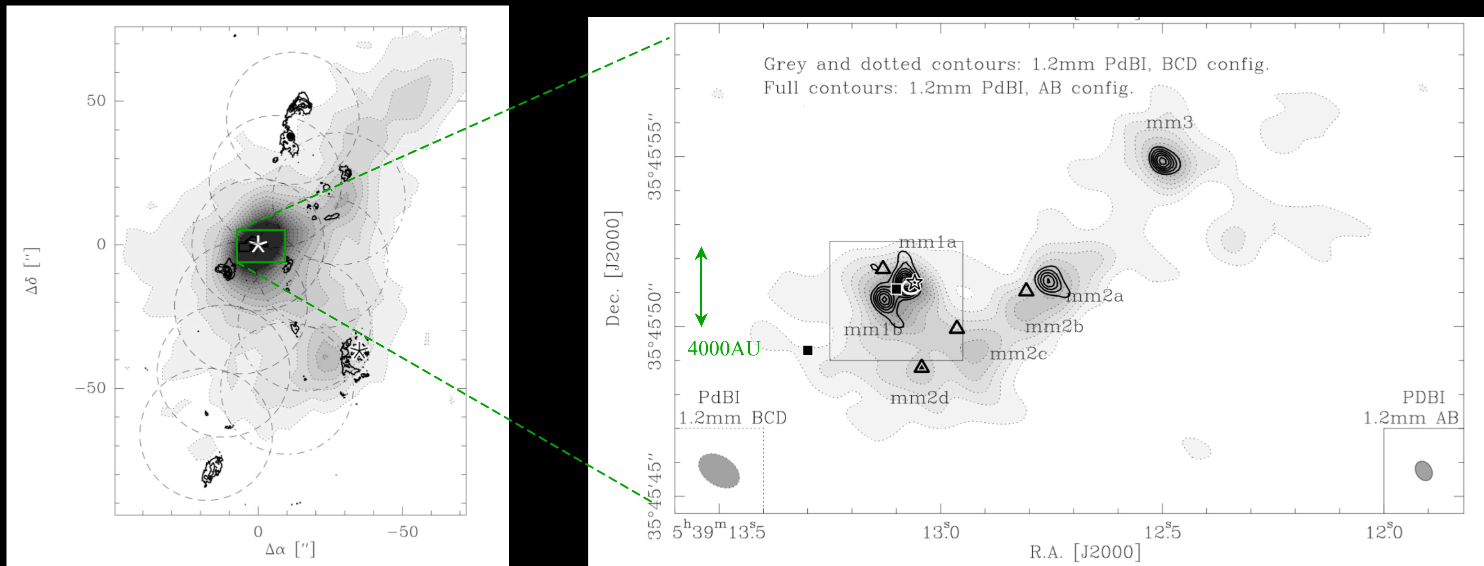
Mass inside 3000 AU FWHM



Fragmentation in massive clumps/cores

High-spatial resolution observations:

- Beuther et al. (2007); Leurini et al. (2007); Rodon et al. (2008); Brogan et al. (2010); Rathborne et al. (2007, 2009), Zhang et al. (2009, 2010).



MAMBO 1.3mm Beuther et al. (2002) IRAM PdBI 1.3mm Leurini et al. (2007)

… massive star-forming regions at different (large) distances.

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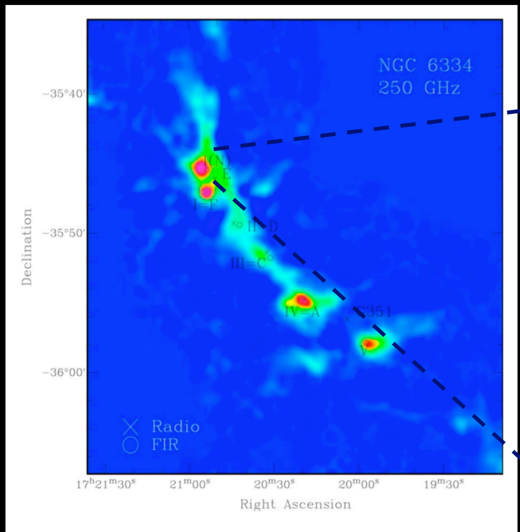
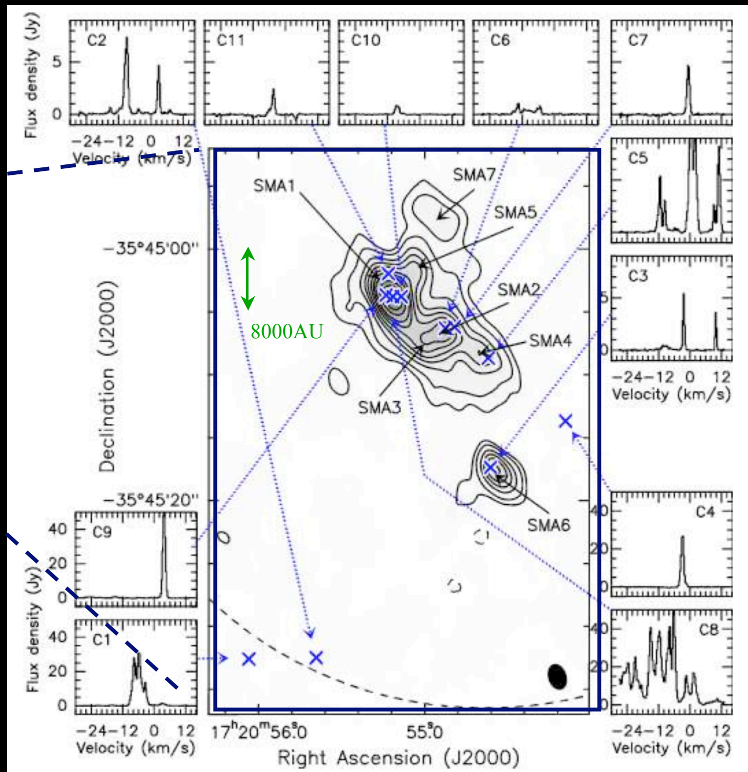
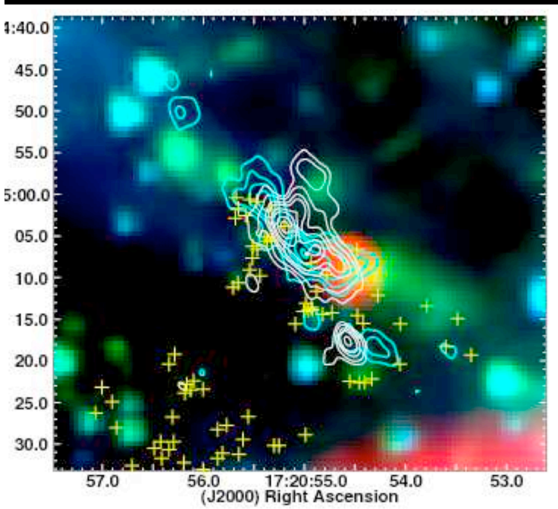


SEST/SIMBA 1.3mm Munoz et al. (2007)





Spitzer+SMA Brogan et al. (2010)

Fragmentation in massive clumps/cores

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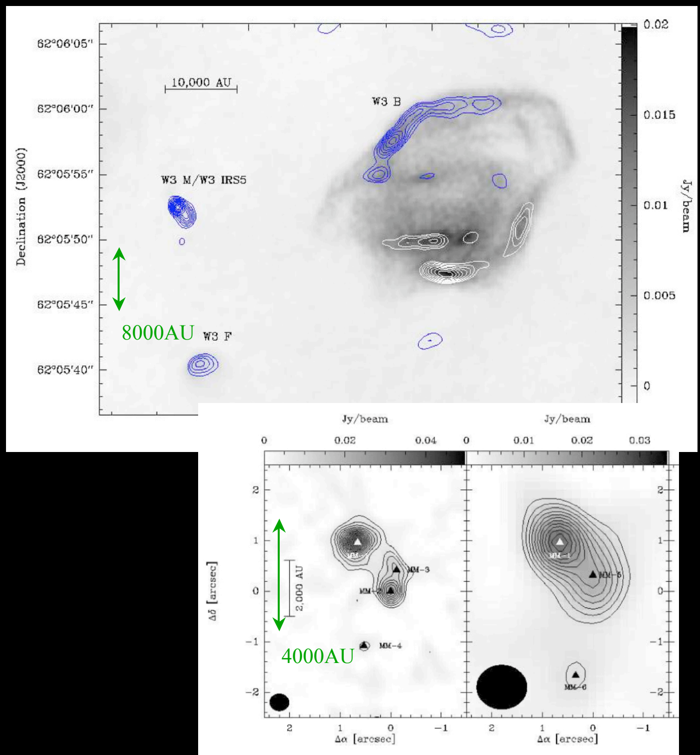
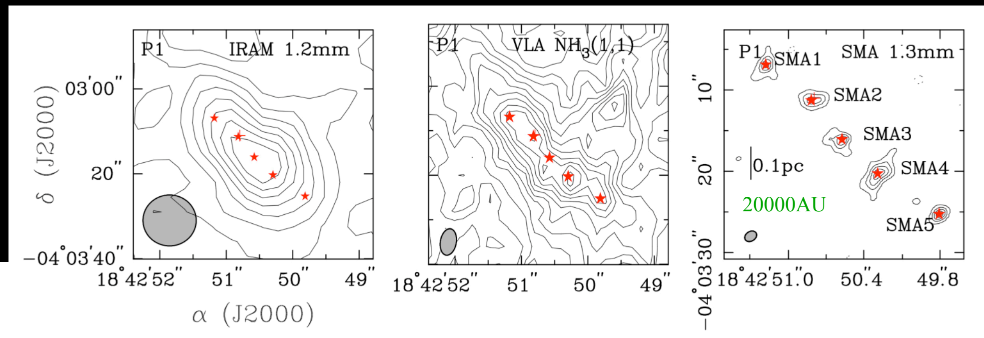
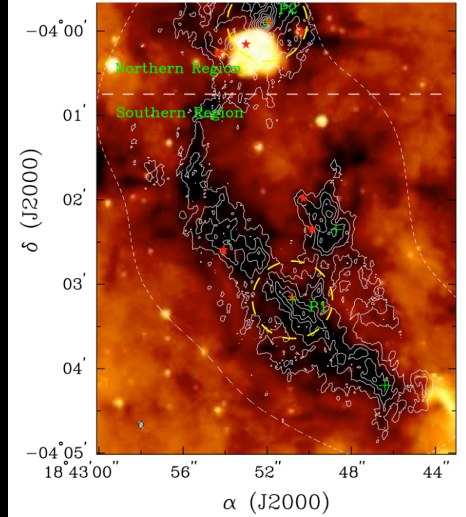
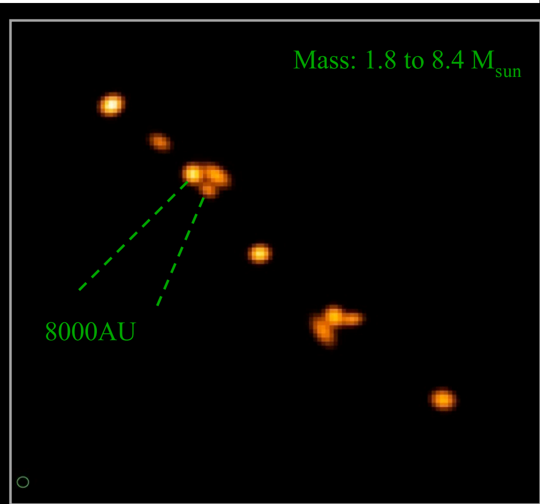


IRAM PdBI Rodon et al. (2008)





Rathborne et al. (2007)

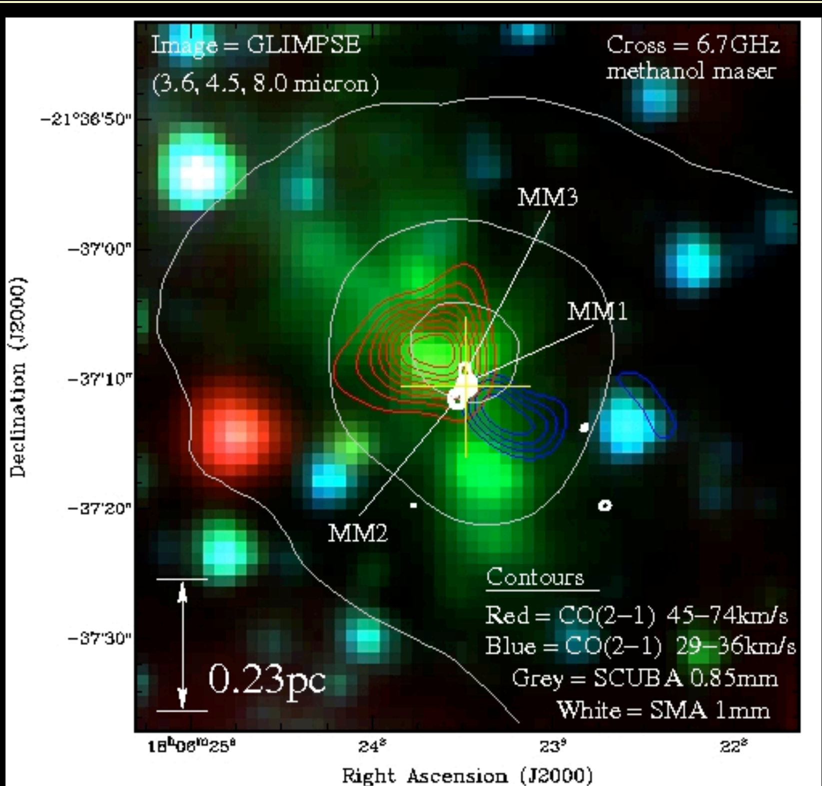


SMA - Zhang et al. (2009); Wang et al. (2010)

Fragmentation in massive clumps/cores

High-spatial resolution observations :

- Beuther et al. (2007); Leurini et al. (2007); Rodon et al. (2008); Brogan et al. (2010); Rathborne et al. (2007, 2009), Zhang et al. (2009, 2010); Longmore et al..



Longmore et al.

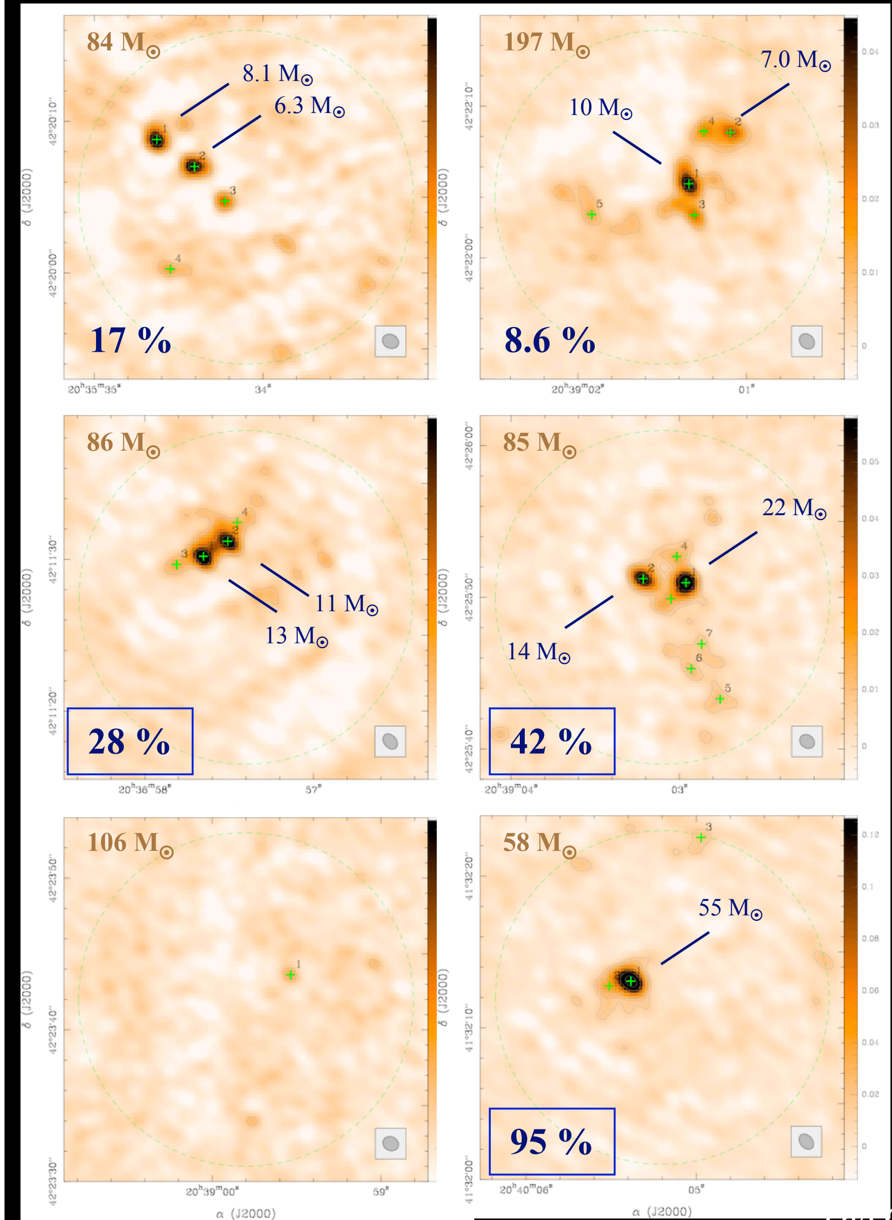
Fragment mass

- $M_{MM1} = 14M_{sun}$
- $M_{MM2} = 7M_{sun}$
- $M_{MM3} = 5M_{sun}$

Fragment separation

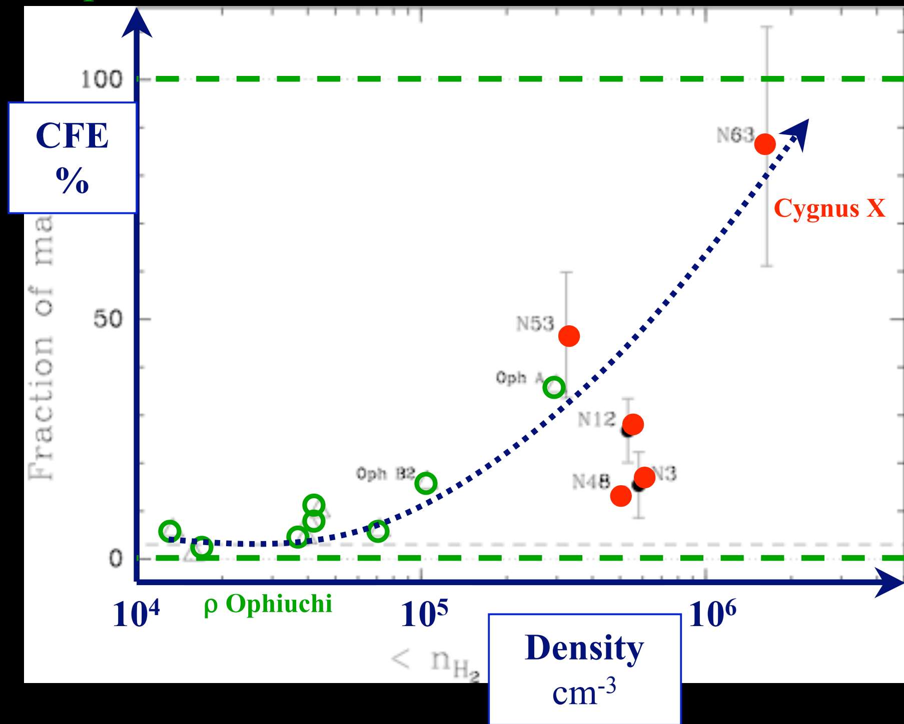
- ~0.02pc (4000 AU)

Fragmentation in MDCs in Cygnus X



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

Bontemps, Motte, Csengeri, Schneider (2010), A&A in press, arXiv0909.2315



Fragmentation in massive clumps/cores

High-spatial resolution observations :

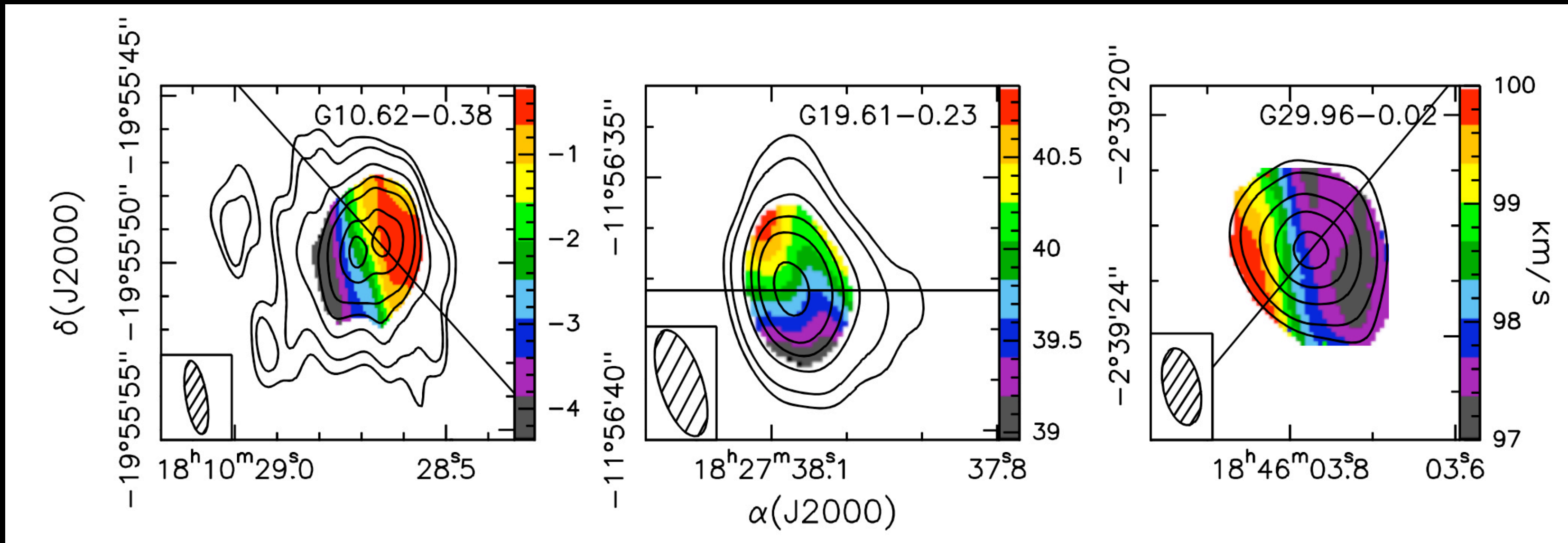
- Compact cores at 1000s AU scale of typical high-mass star masses.
- Size and separations similar to low-mass protostellar envelopes in clusters.
- In massive dense cores (100 M_{sun} in 0.1 pc size).
- In Cygnus X: three MDCs dominated by massive protostars.
- No mass to form low-mass stars.
- A primordial mass segregation observed.
- Origin of these higher masses than M_{Jeans}?
- Kinematics …

Longmore et al.

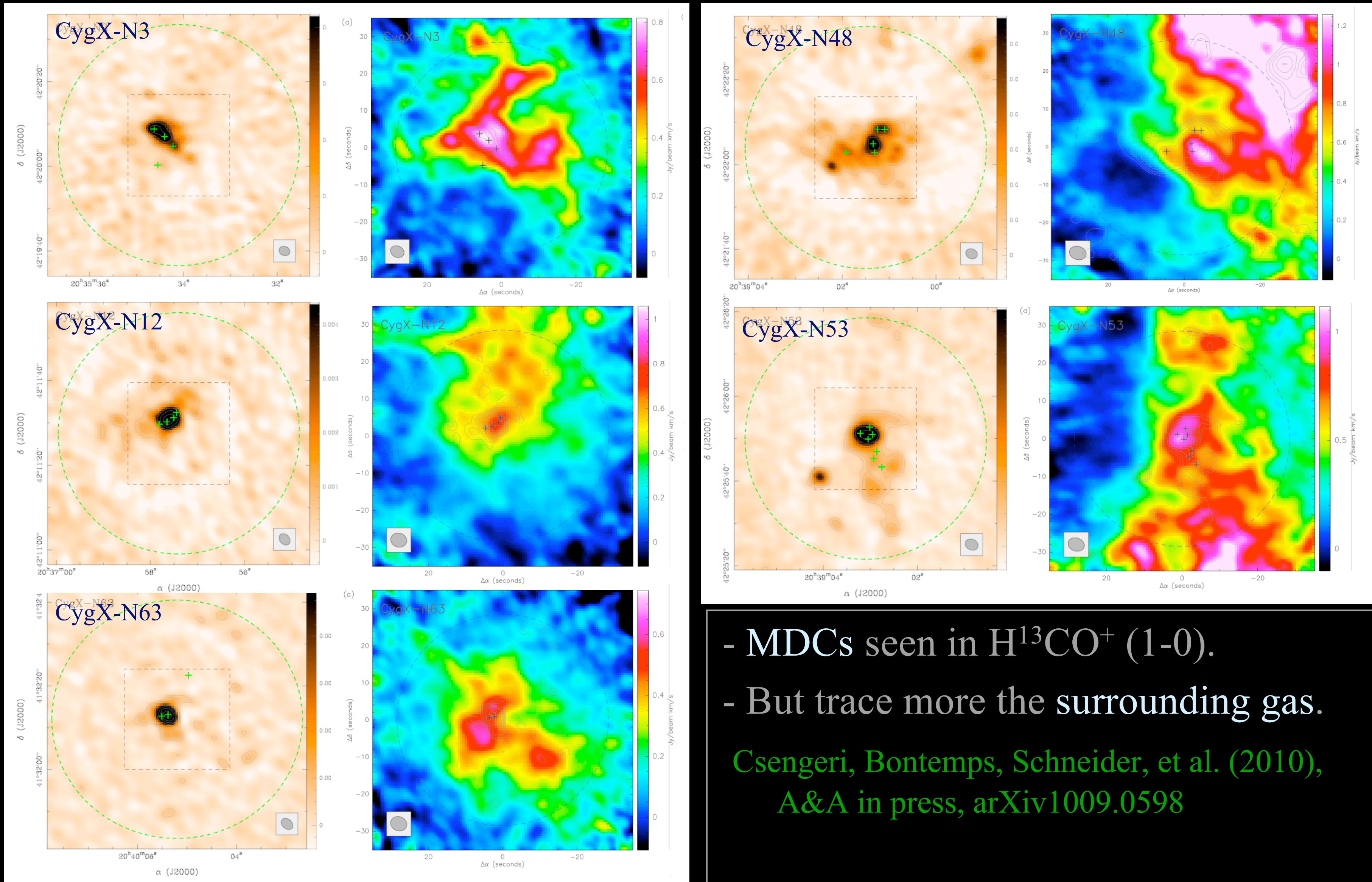
Kinematics in massive clumps/cores

The collapsing, rotating toroids:

- Beltran et al. (2004, 2006); Furuya et al. (2010).



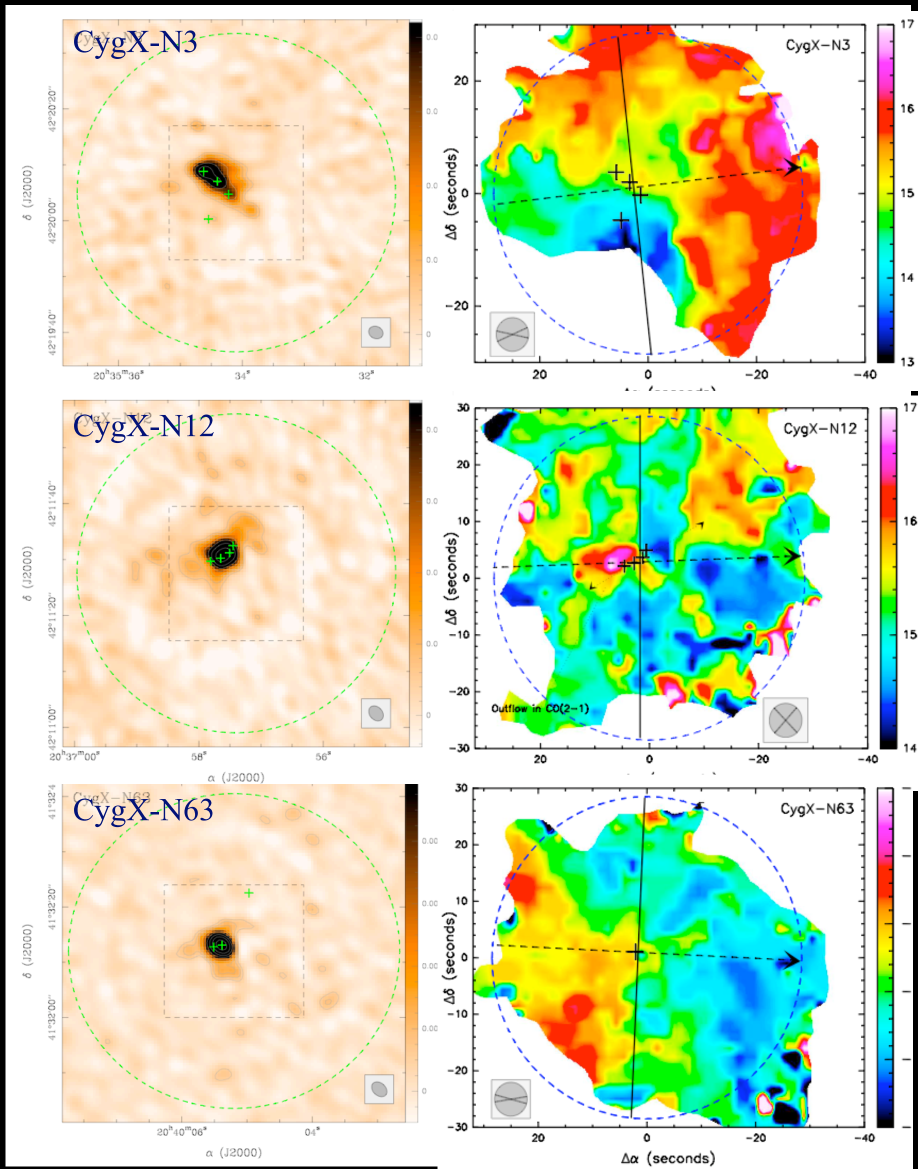
Dense gas at high resolution ($H^{13}CO^+$)

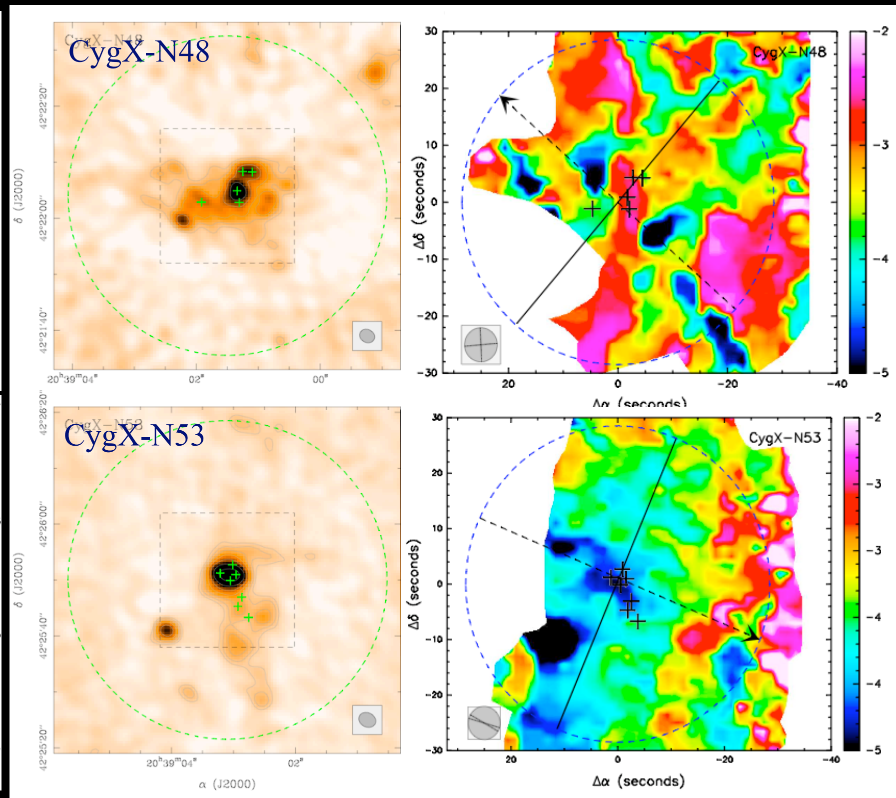


- MDCs seen in $H^{13}CO^+$ (1-0).
- But trace more the surrounding gas.

Csengeri, Bontemps, Schneider, et al. (2010), A&A in press, arXiv1009.0598

Dense gas at high resolution ($H^{13}CO^+$)

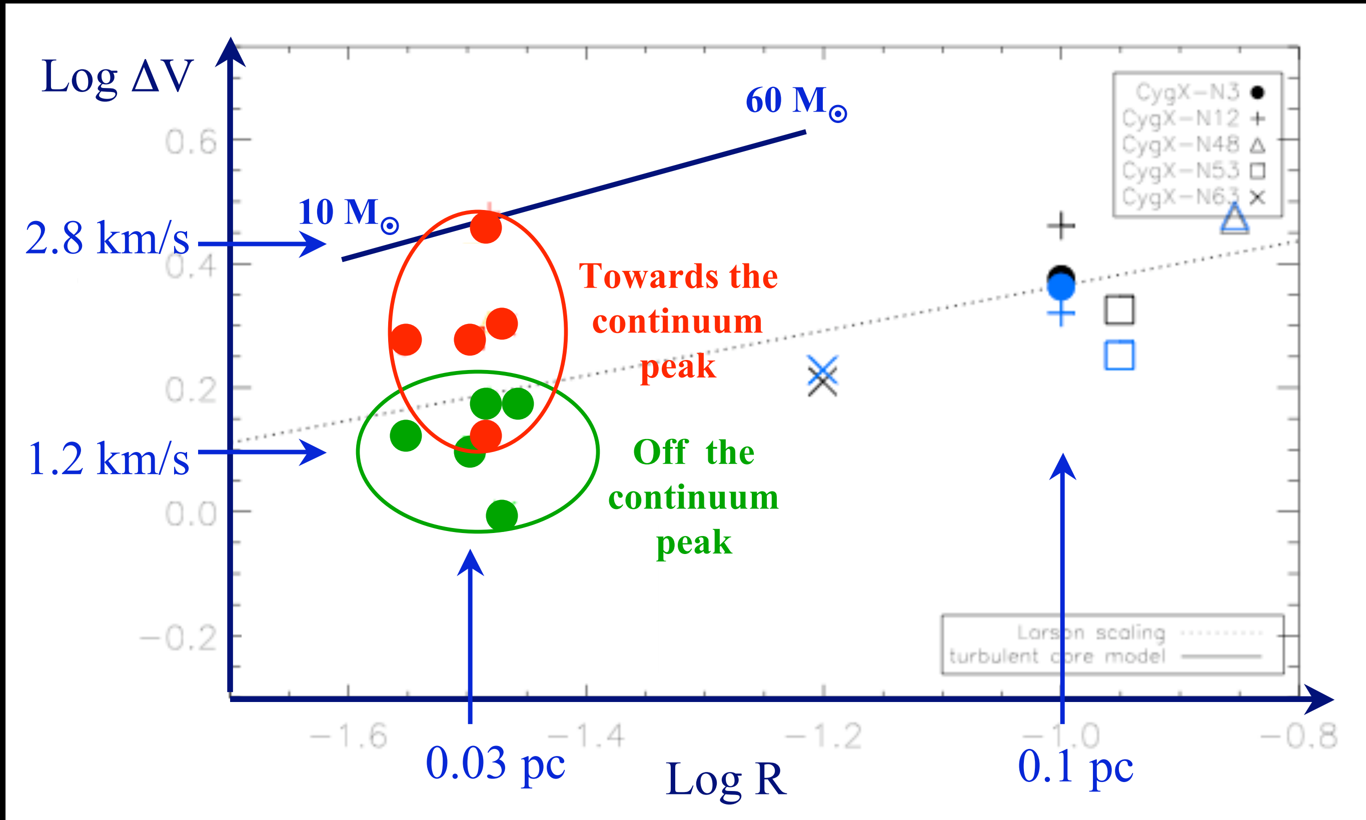




- MDCs seen in $H^{13}CO^+$ (1-0).
- But trace more the surrounding gas.
- Not very simple geometries.

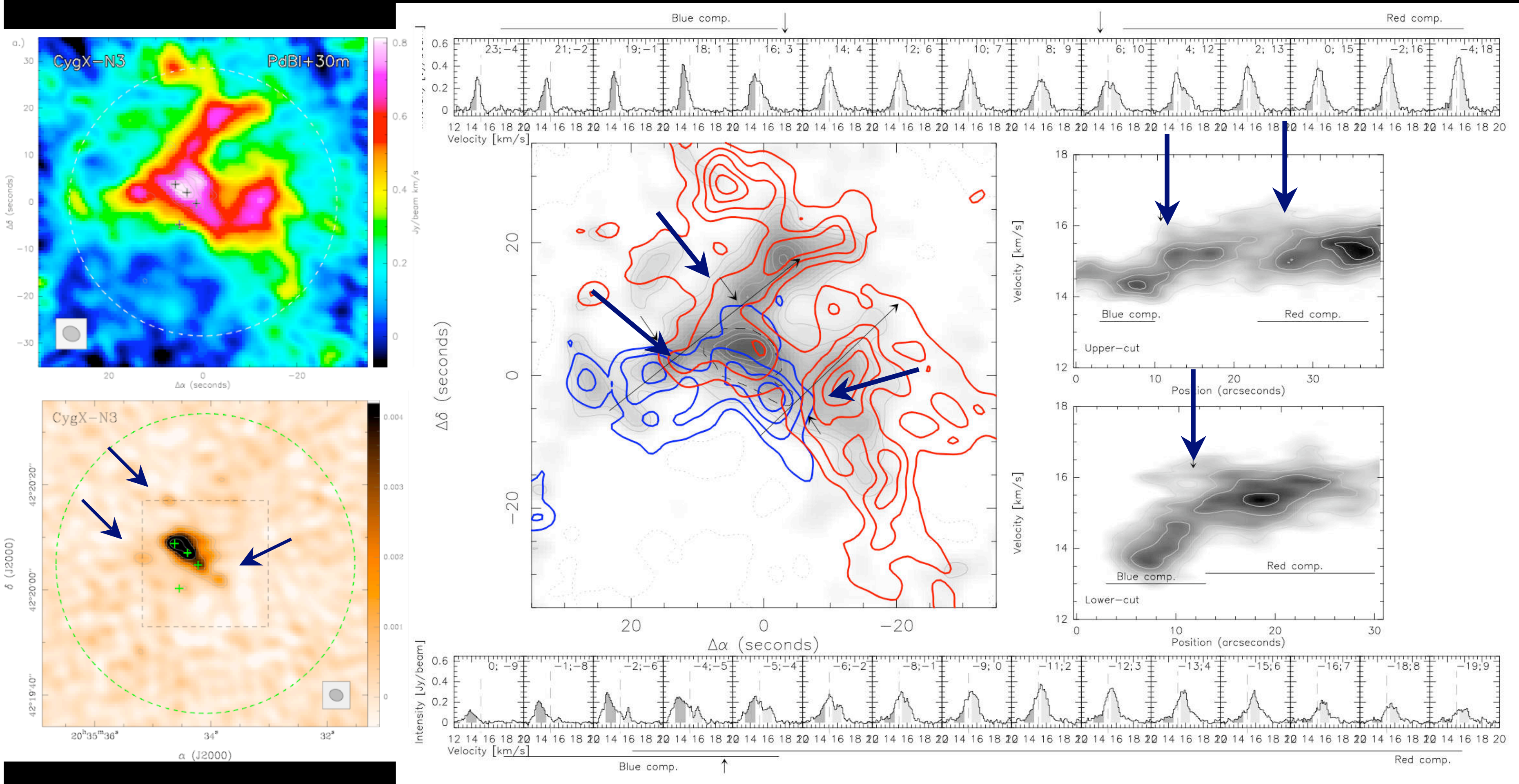
Csengeri, Bontemps, Schneider, et al. (2010), A&A in press, arXiv1009.0598

Level of turbulent support



- Level of micro-turbulence cannot support the MDCs.
- These MDCs have indications of global collapse.
- They are not in equilibrium (Mass/M_{vir} > 1).

MDCs dominated by flows



- No solid rotation, some angular momentum observed.
- Flows, most probably convergent (e.g. Vazquez-Semadeni et al. 2009)

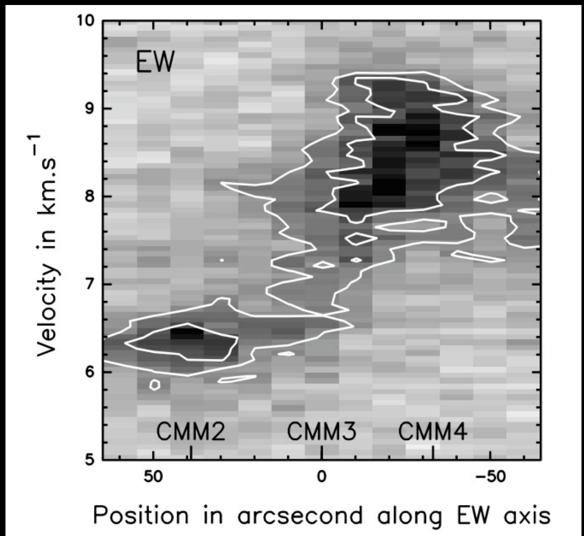
Kinematics in massive clumps/cores

The collapsing, rotating toroids:

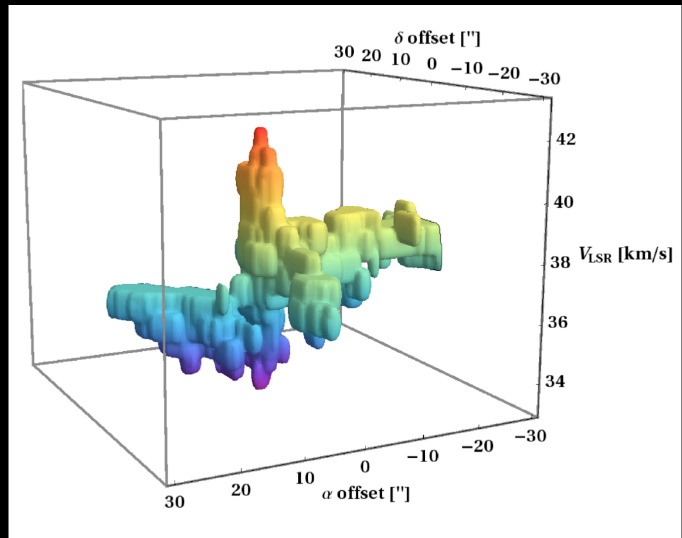
- Beltran et al. (2004, 2006); Furuya et al. (2010).

Velocity Discontinuities:

- Peretto et al. (2006); Rodon et al. (2008); Galvan-Madrid et al. (2010)

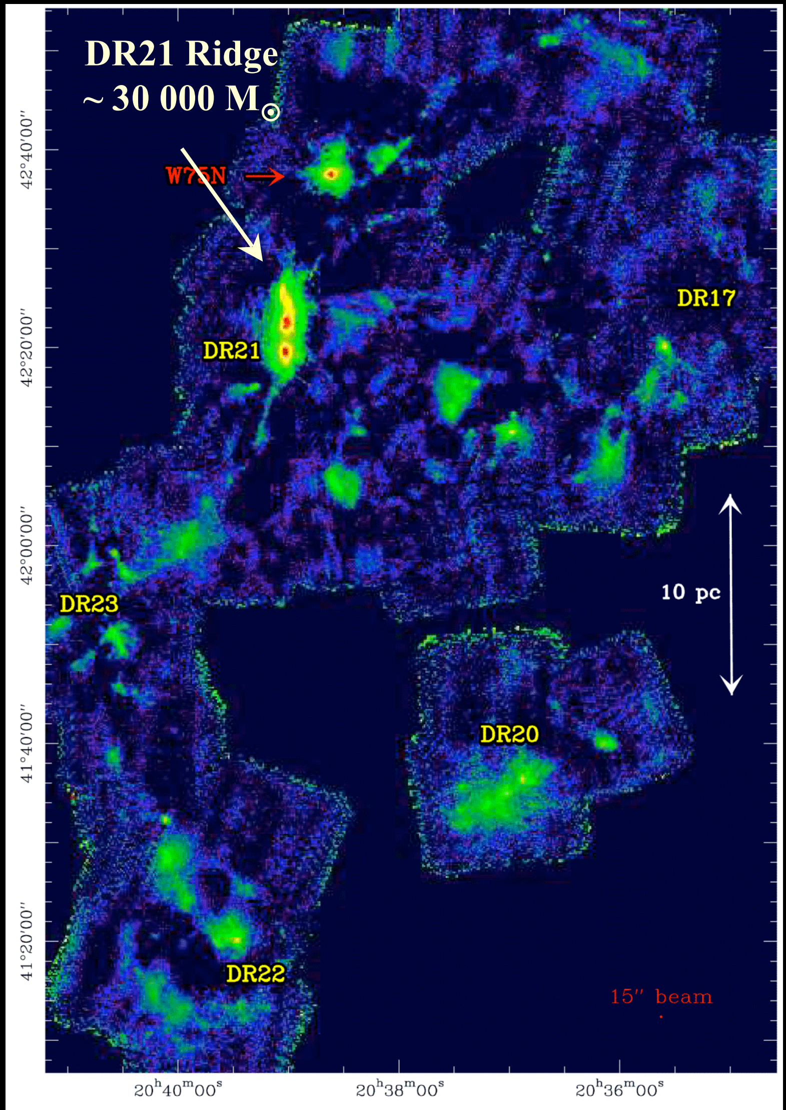


Peretto et al. (2006)

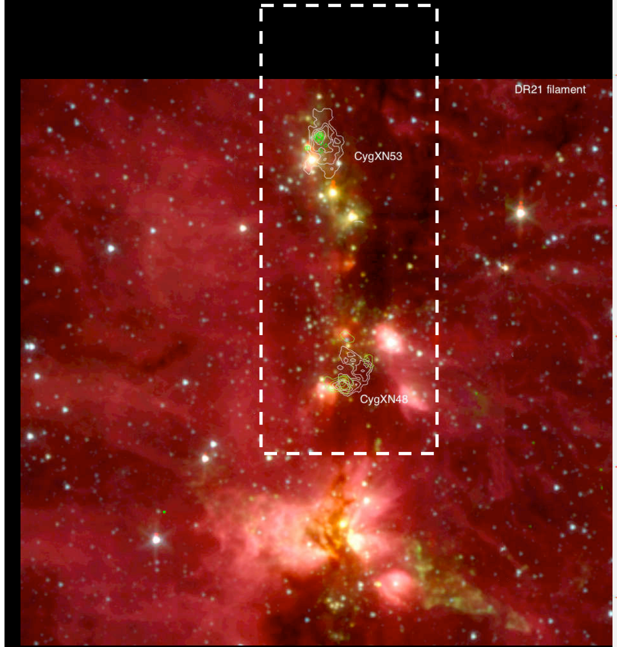


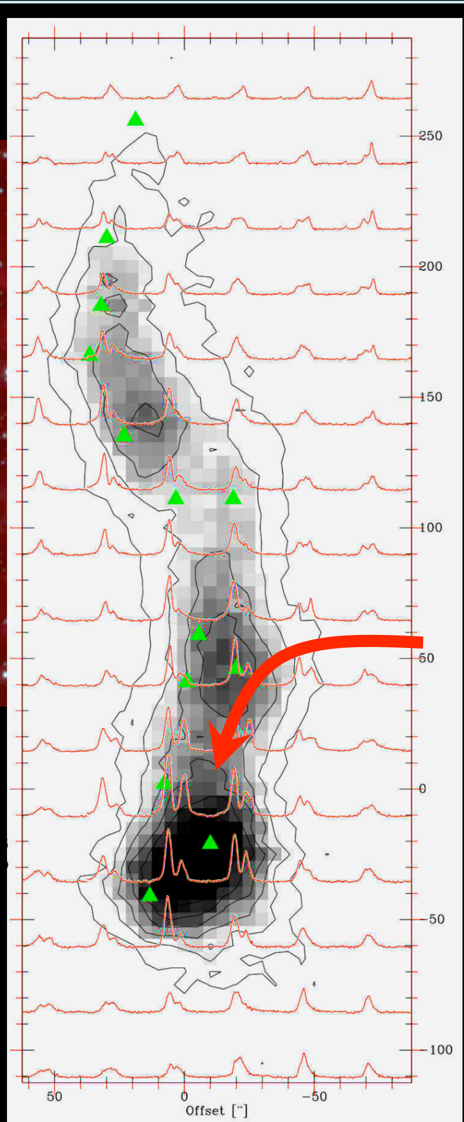
Galvan-Madrid et al. (2010)

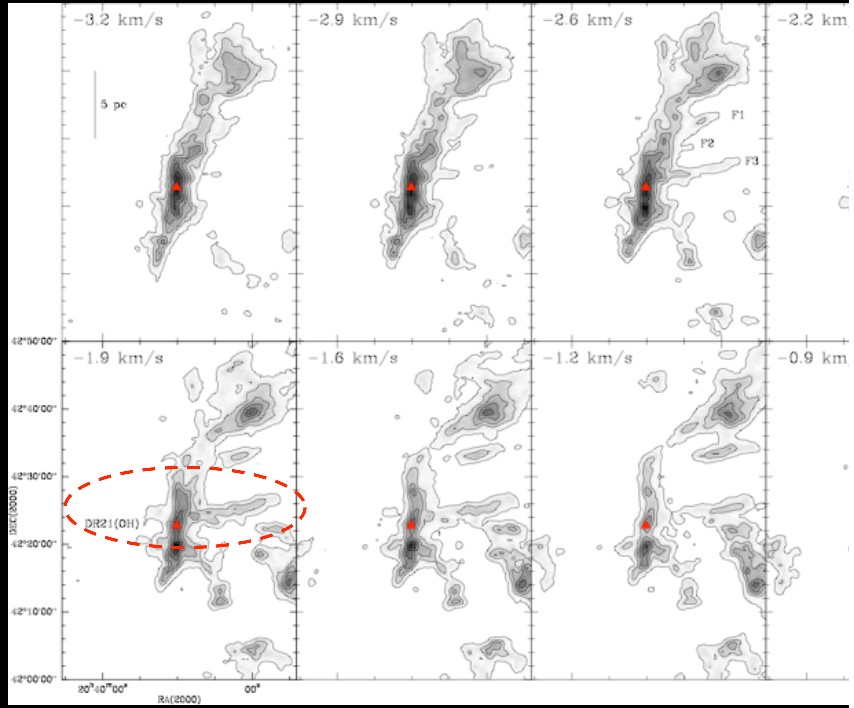
Flows at large scales in the DR21 ridge



Flows at large scales in the DR21 ridge



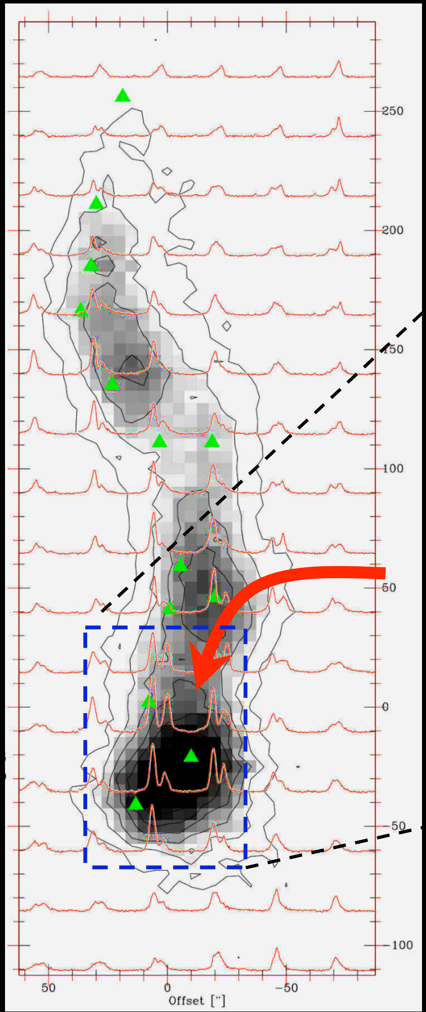




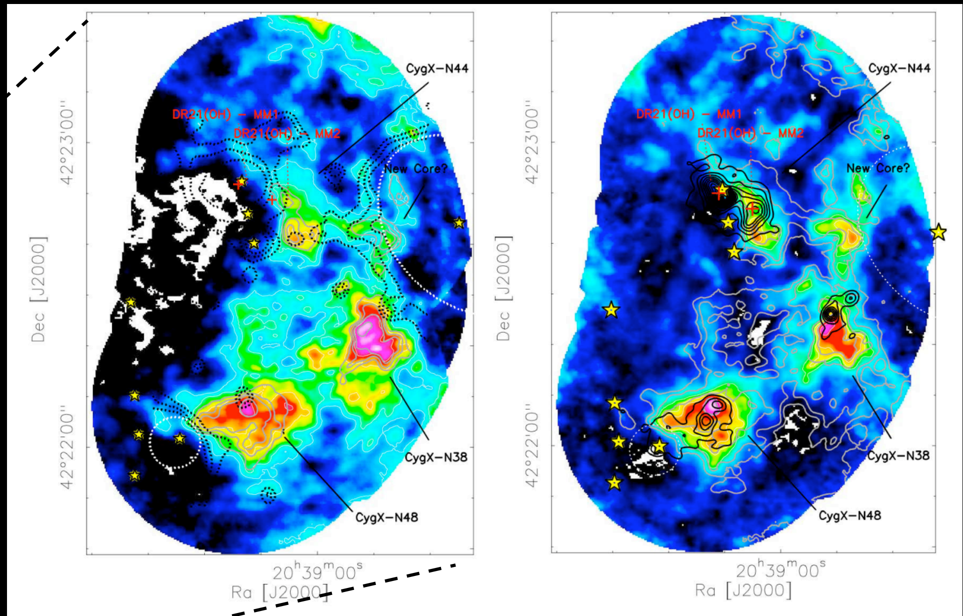
Schneider, Csengeri, Bontemps, Motte, Hennebelle, Federrath, Klessen (2010), A&A in press, arXiv1003.4198

- Global collapse of the ridge.
- Sub-filaments flowing down on the ridge.

DR21(OH): a clump in hierarchical fragmentation



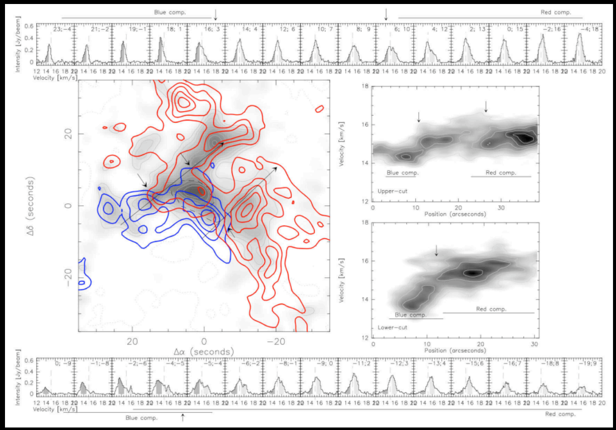
An IRAM PdBI mosaic at 1 and 3 mm



Csengeri, Bontemps, et al. (2010), A&A Letter, in prep

Talk Timea Csengeri

- The clump splits into 3 MDCs 0.1 - 0.2 pc size.
- Dynamic dominated (τ_{cross} >~ τ_{ff}).
- Individual protostars at the scale of 0.02 pc.



Conclusions

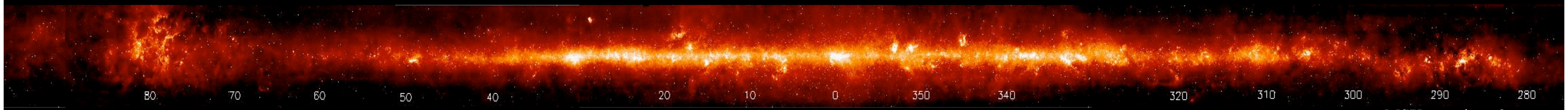
Fragmentation

- **Individual** OB star precursors.
- Primordial **mass segregation** observed.
- **Diversity** (evolution, initial cdtions ?)

Kinematics and turbulent support

- **Turbulent support** is **not enough** at the scale of MDCs.
- If it acts, it is at the **proto-stellar envelope scale** (< 0.03 pc).
- Higher (?) V_{rms} at **small scale/high density**.
- **MDCs** forming massive star **are not in equilibrium**.
- **Flows dominates evolution** from 10 to 0.03 pc.
- No flow **favoring higher mass cores** observed.
- Observed **hierarchical fragmentation** for cluster formation.

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, ESO large program.
- BOLOCAM/CSO: only north, reduced spatial resolution.
- SCUBA2/GPS: only north (to be started in 2011).

Herschel imaging survey of OB Young Stellar objects

A guaranteed time key programme with Herschel Space Observatory

HOBYS

F. Motte, A. Zavagno, S. Bontemps

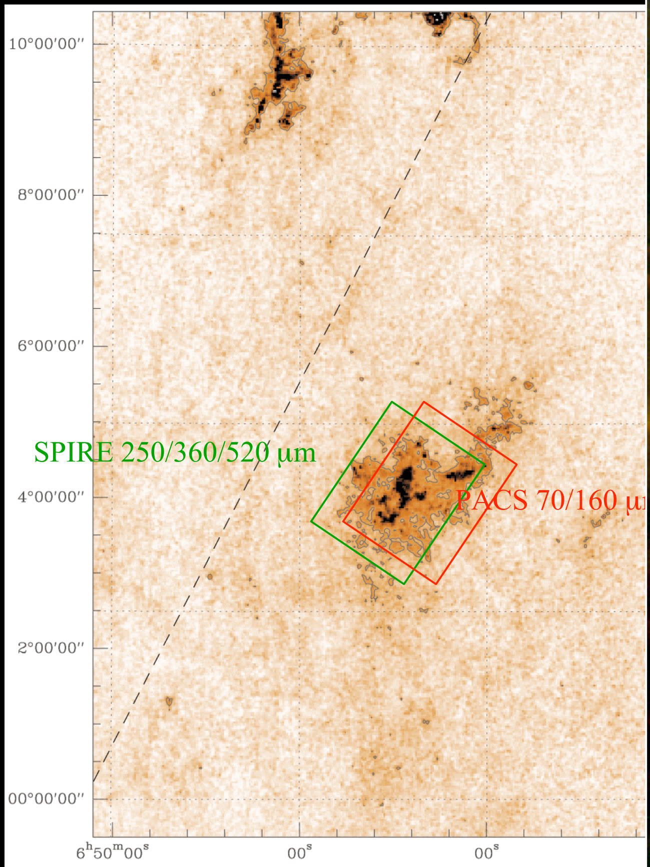
SPIRE consortium SAG3 (85 hrs) - PACS Marseille (19 hrs) - HSC (22 hrs)

and the HOBYS consortium

- Identify and characterise the precursors of OB stars
  - High-mass analogues of prestellar cores – do they exist?
  - Massive IR-quiet protostellar dense cores
  - Massive IR-bright protostellar dense cores
- Measure core/envelope mass and bolometric luminosity
  - Constrain submm component of SED
  - Build an evolutionary diagram
  - Estimate lifetime of each evolutionary stage
- Assess the importance of triggering
  - By comparing well-behaved HII regions to more common HMSF regions (see talk: Zavagno)

http://hobys-herschel.cea.fr

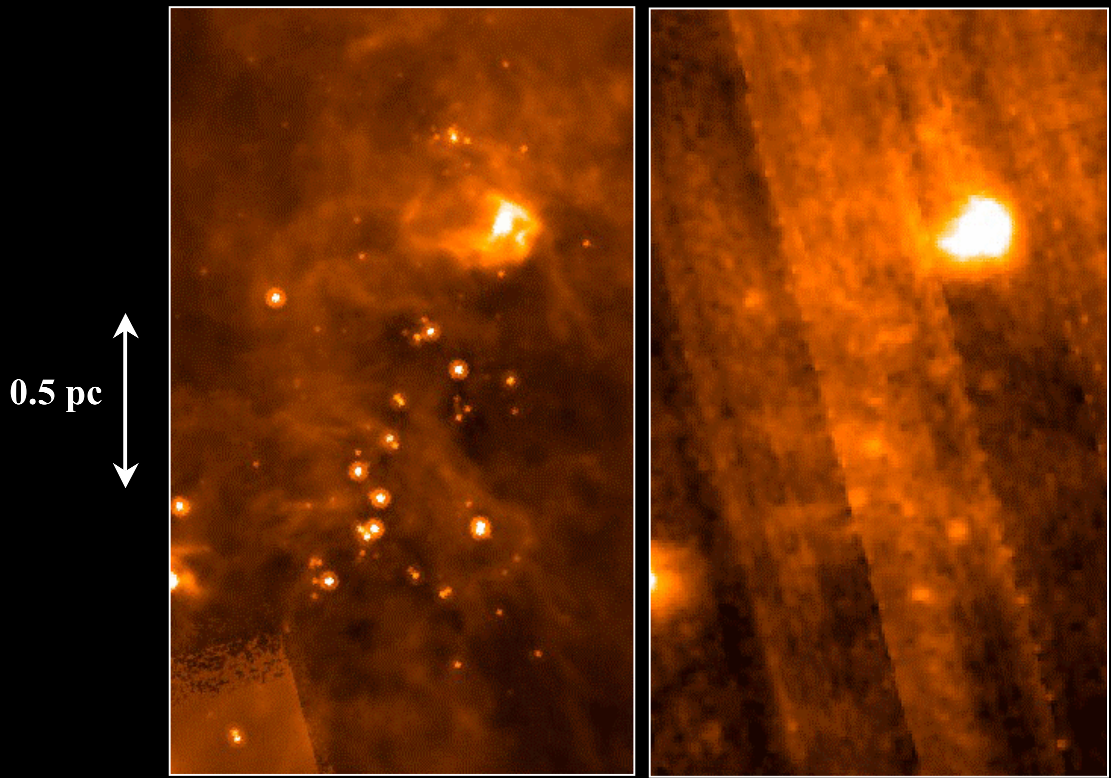
- All massive GMCs at less than 3 kpc.
- Motte et al. (2010); Schneider et al. (2010); Hennemann et al. (2010); Di Francesco et al. (2010)
- Rosette Molecular Cloud: 1600 pc; 3.5 x 10^5 $M_\odot$



2MASS extinction map - Bontemps et al.

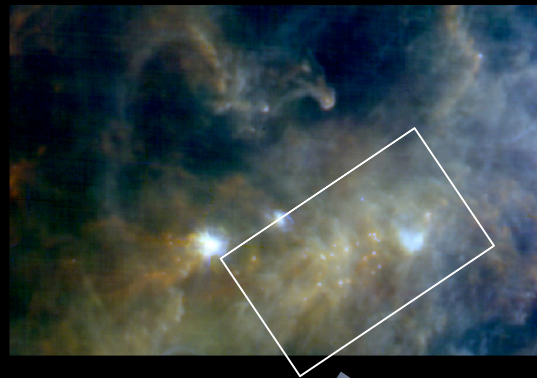
PACS + SPIRE 70, 160, 250 μm

Individual Protostars in Rosette (1.6 kpc)



Rosette Molecular Cloud - HOBYS - Hennemann et al. (2010)

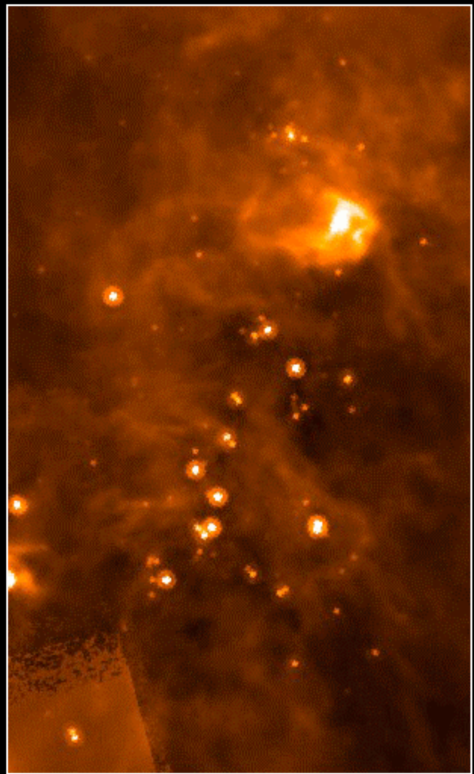
Individual Protostars in Rosette (1.6 kpc)

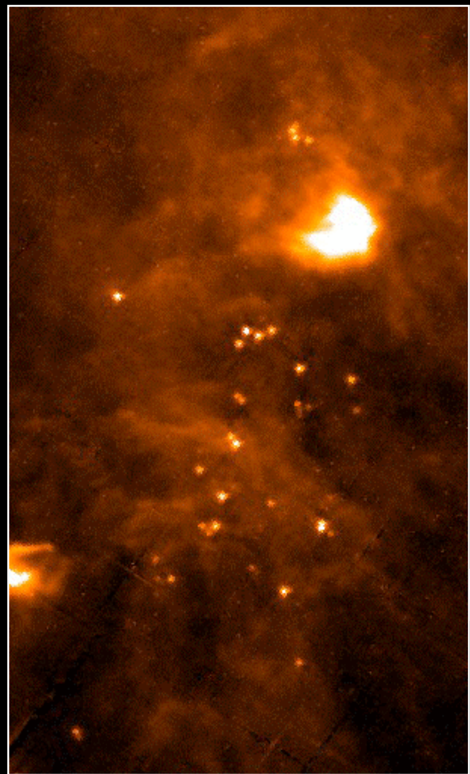


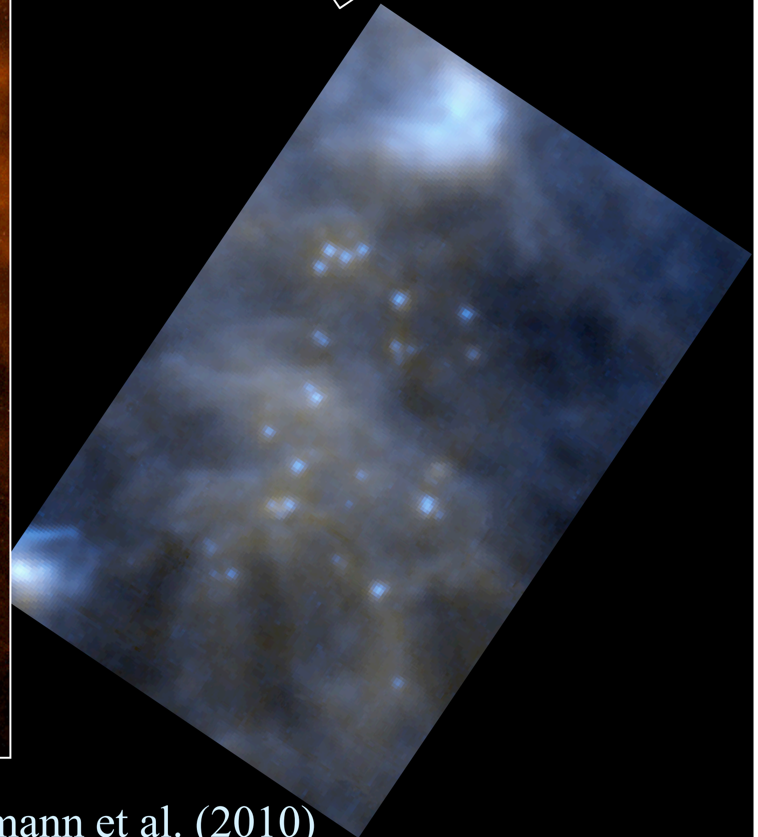
Spitzer 24 μm

Herschel 70 μm

0.5 pc

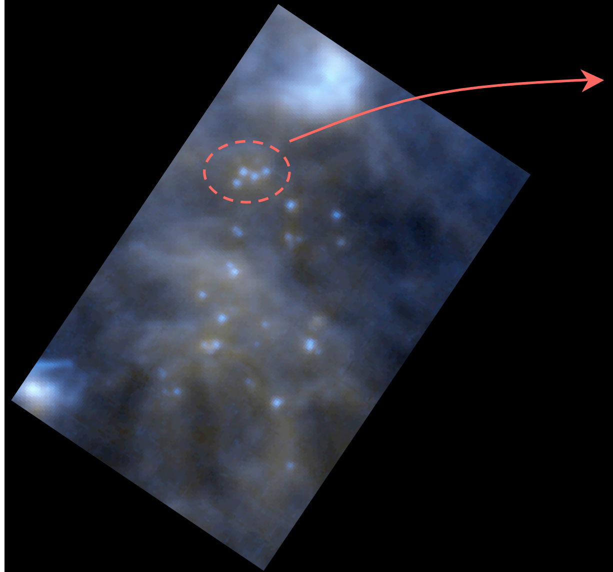


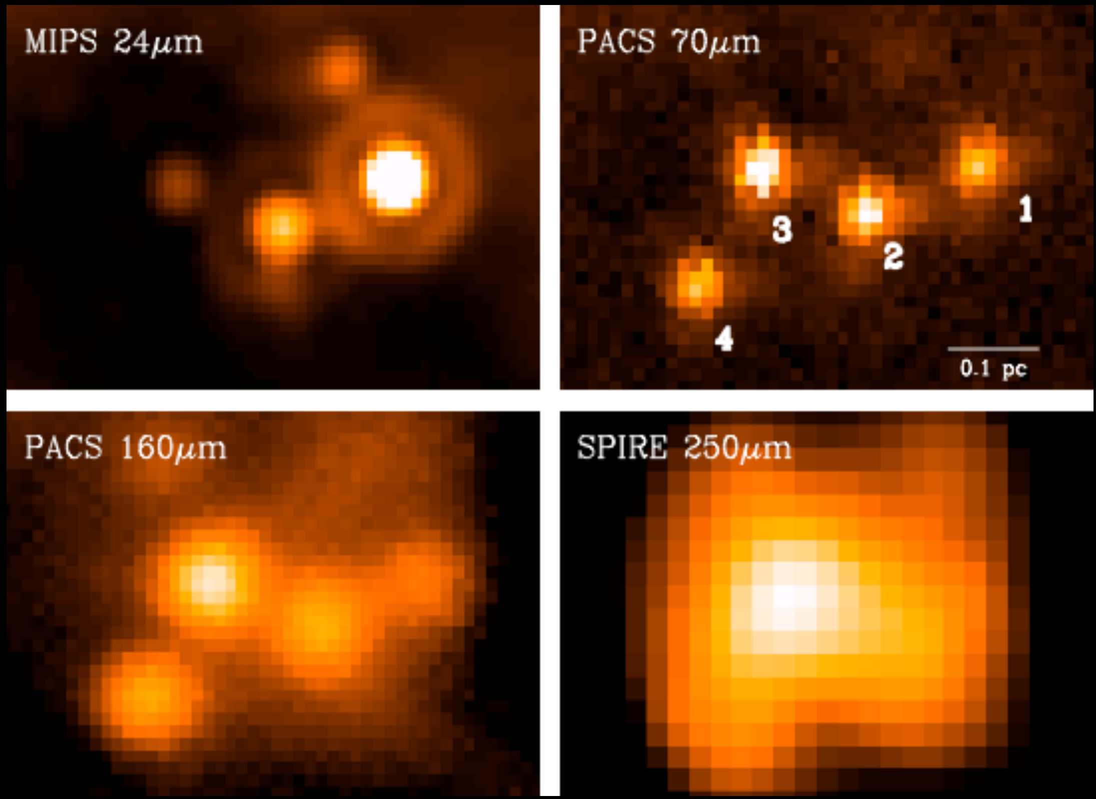




Rosette Molecular Cloud - HOBYS - Hennemann et al. (2010)

Herschel-only protostars



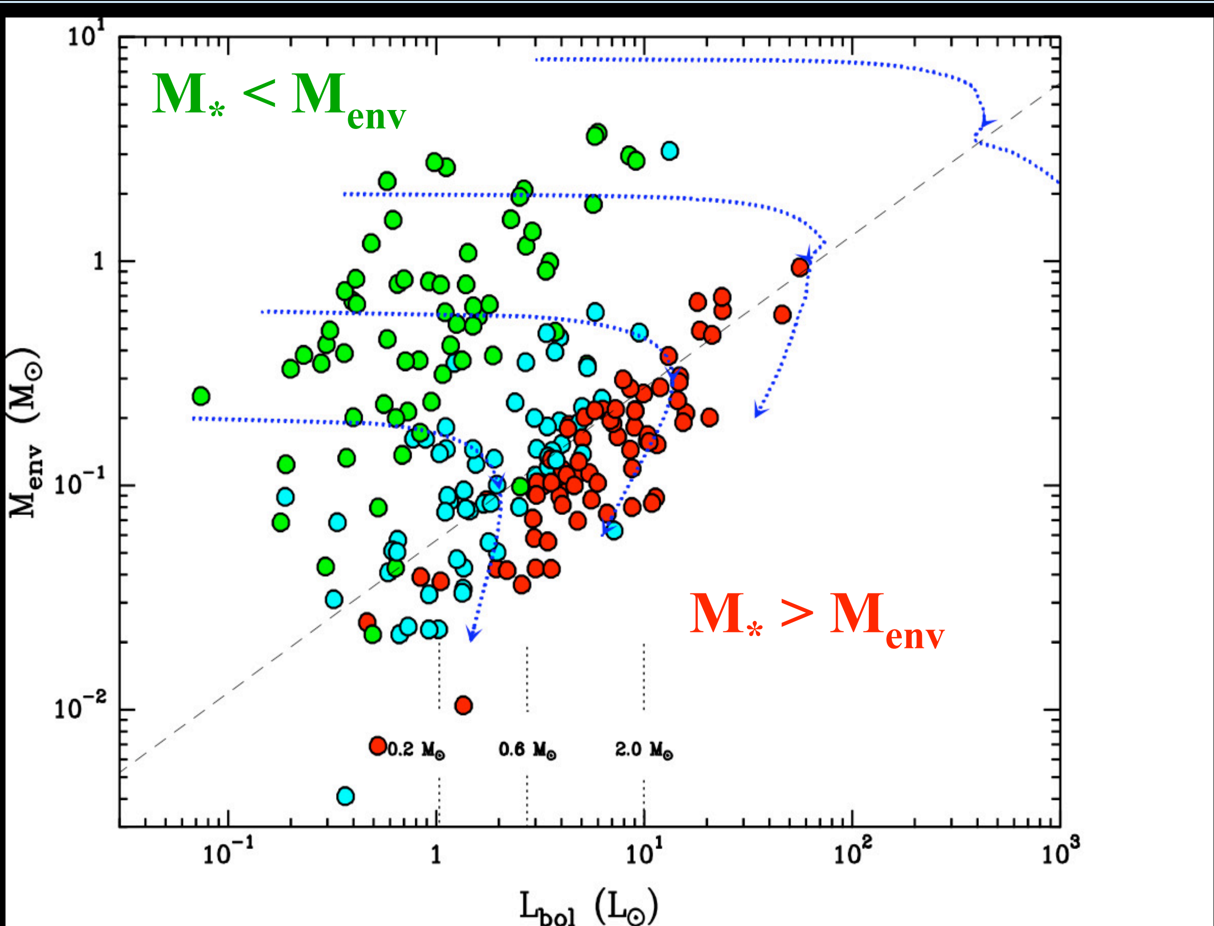


Rosette HOBYS - Hennemann et al. (2010)

Evolutionary diagram

- An evolutionary diagram with $L_{70\text{-}500\mu m}$ for the whole sample.
- $L_{>350\mu m}/L_{70\text{-}500\mu m} > 3$ % (green dots); $L_{>350\mu m}/L_{70\text{-}500\mu m} < 1$ % (red dots).
  to discriminate Class 0 from Class I YSOs (see André et al. 2000).

Aquila
(260 pc)
Protostars:



Bontemps et al.
(2010)
A&A special issue

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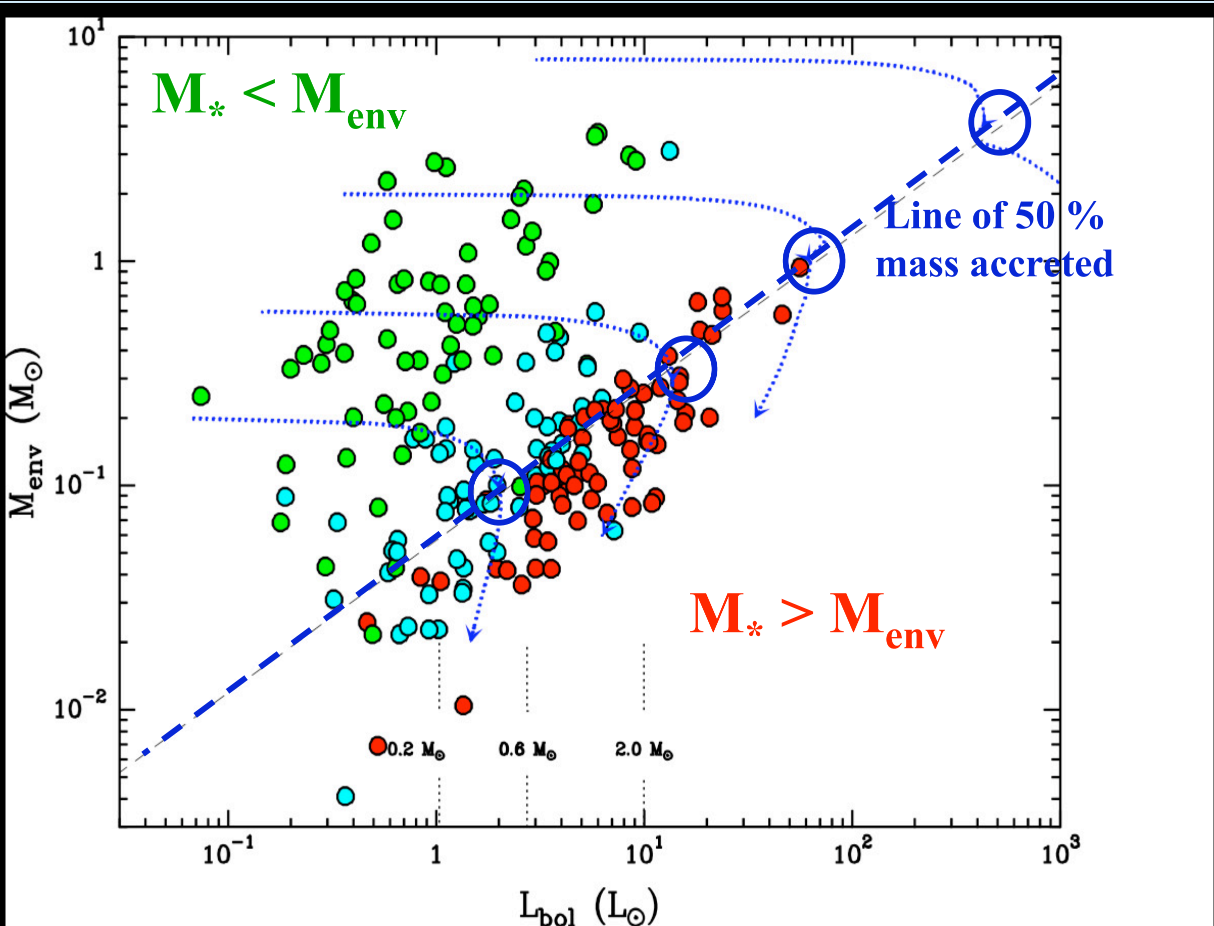

Bontemps et al.
(2010)
A&A special issue

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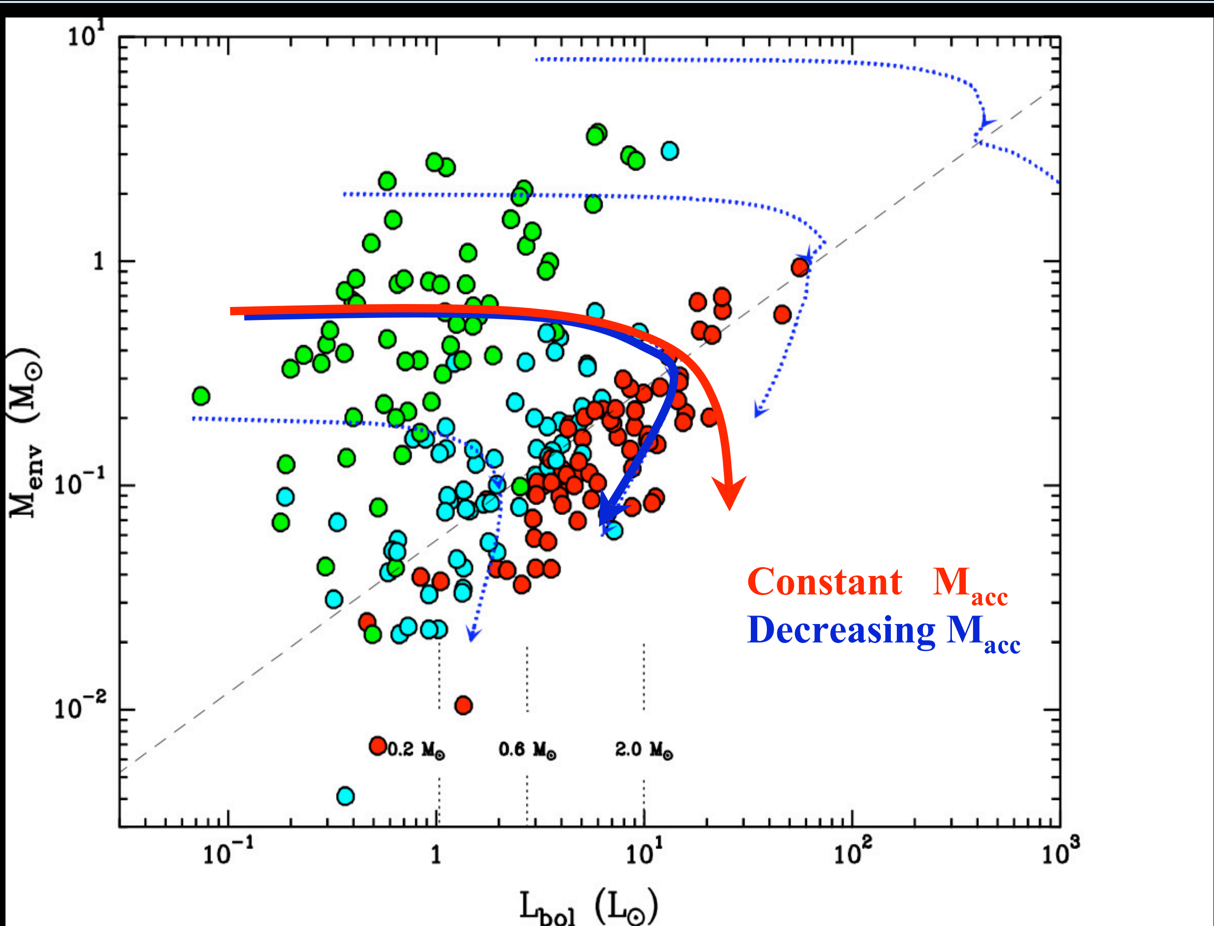

Tracks: toy model from Bontemps et al. (1996)

Bontemps et al. (2010) A&A special issue

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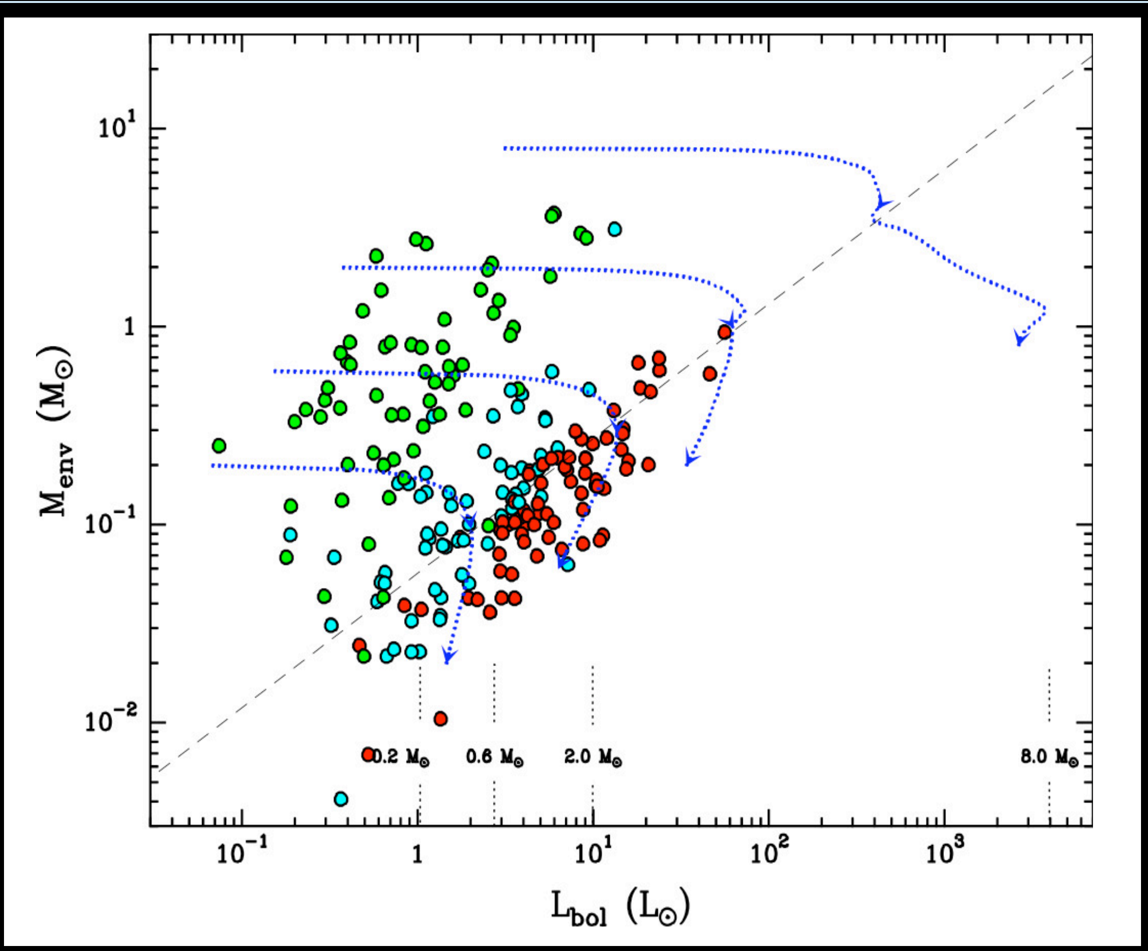

Tracks: toy model from Bontemps et al. (1996)

Bontemps et al. (2010) A&A special issue

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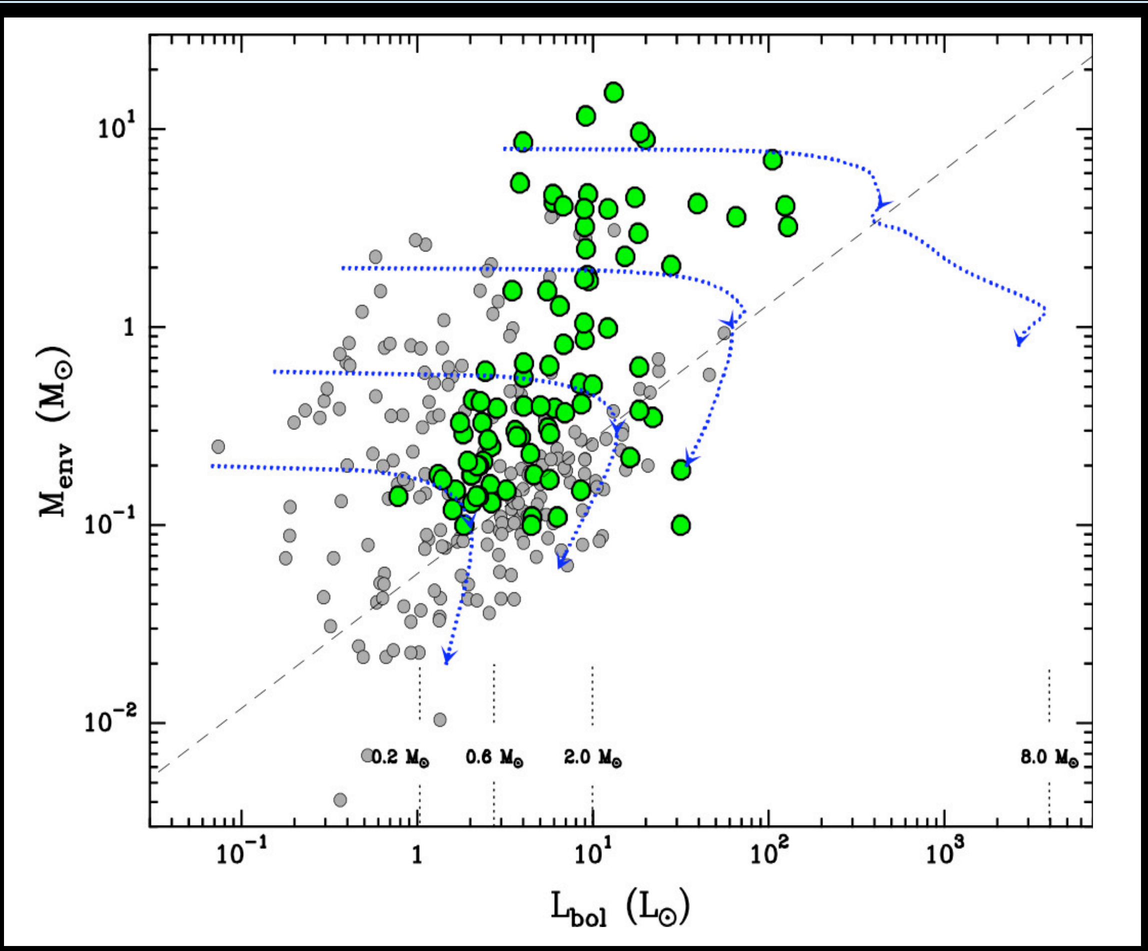
Aquila
(260 pc)
Protostars:

The
Rosette
protostars

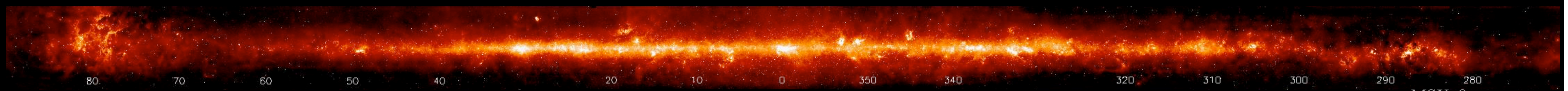


Tracks: toy model from Bontemps et al. (1996)

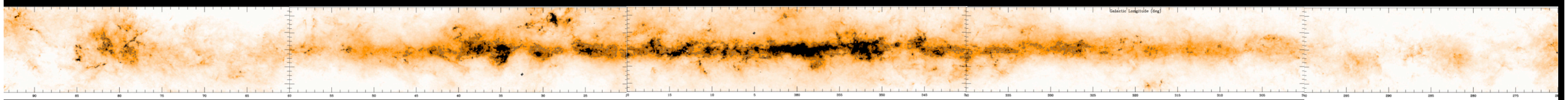
Hennemann et al. (2010)
A&A special issue

Galaxy wide surveys

Optical Image



MSX 8 µm

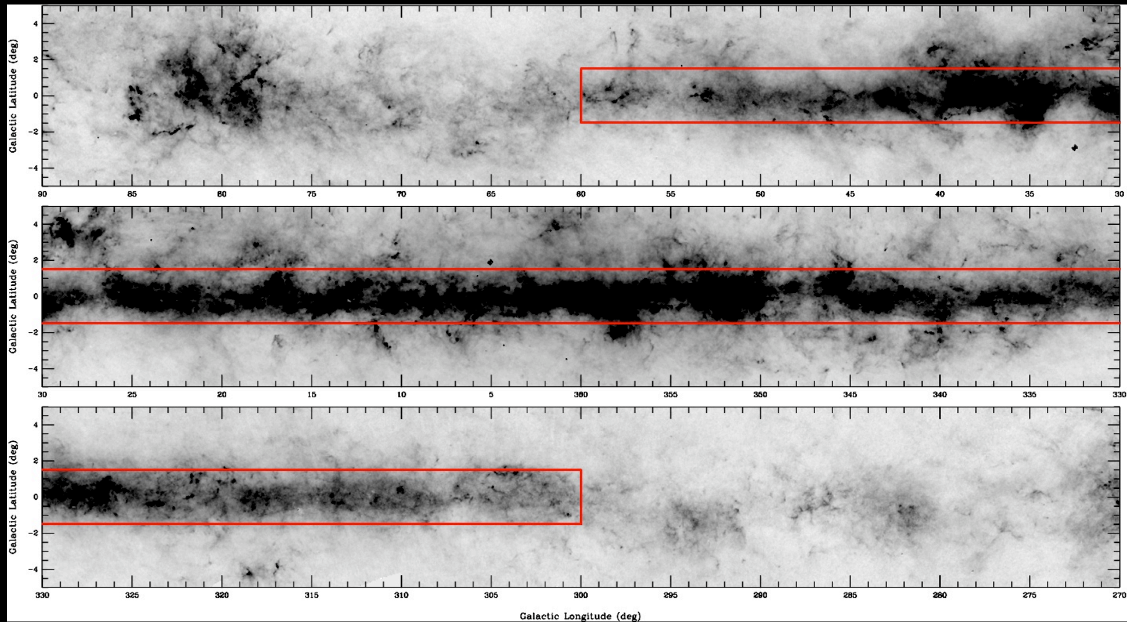


Extinction map - Bontemps et al.

- ATLASGAL: APEX Telescope Large Area GALactic survey
- HOBYS: Herschel imaging surveys of OB Young Stellar objects
- Hi-GAL: Herschel imaging survey of the whole GP.

ATLASGAL

Schuller, et al. (2009) A&A 504, 415



- Large program ESO/APEX (2008-2009).
- APEX/LABOCA @ 870 µm.
- 400 hrs = 240 (MPG) + 40 (Chili) + 120 (ESO).
- 360 squ. deg. (lon=+- 60 deg; lat = +- 1.5 deg).